SAND2016-4005PE

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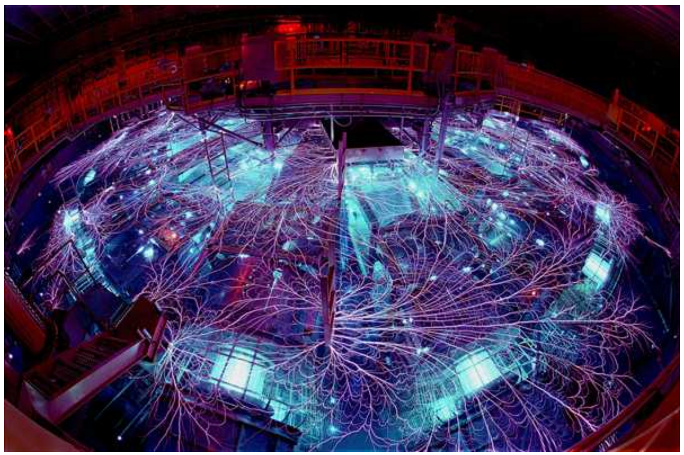
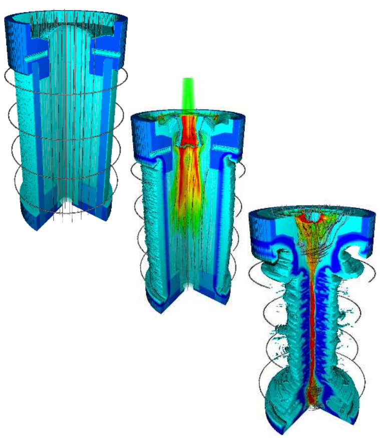
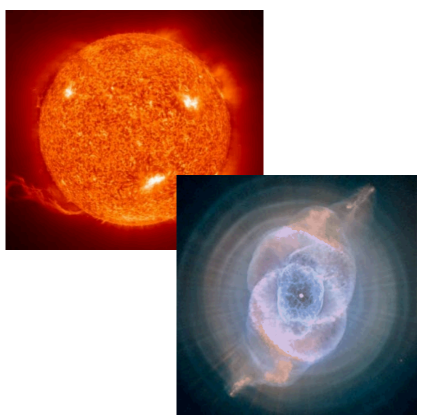


# Z Facility: Capabilities and Science

**Patrick Knapp**
High Energy Density Experiments Dept.
Sandia National Laboratories





*OMEGA Laser Users Group*
*LLE, Rochester, NY*
*April 29, 2016*

Pulsed Power Sciences
Harnessing Extreme Environments

U.S. DEPARTMENT OF ENERGY
NNSA National Nuclear Security Administration



SAND2015-7067 PE

# Thanks to my many colleagues & collaborators:

Sandia National Laboratories

D. B. Sinars,[1] M. E. Cuneo,[1] M. C. Herrmann,[2] C. W. Nakhleh,[3] B. E. Blue[2], E. M. Campbell,[5] S. A. Slutz,[1] M. R. Gomez,[1] C. A. Jennings,[1] S. B. Hansen,[1] R. W. Lemke,[1] M. R. Martin,[1] T.R. Mattsson, [1] M.D. Knudson, [1] M.P. DesJarlais, [1] K.D. Cochrane, [1] L. Shulenburger, [1] D. Flicker, [1] S. Root, [1] J. Benage, [1] M. Geissel, [1] I.C. Smith, [1] M. Schollmeier, [1] T. Ao, [1] P.K. Rambo, [1] R. A. Vesey,[1] A. B. Sefkow,[1] R. D. McBride,[1] T. J. Awe,[1] P. F. Schmit,[1] E. C. Harding,[1] A. J. Harvey-Thompson,[1] M. R. Lopez,[1] M. Jones,[1]J. L. Porter,[1] G. A. Rochau,[1] K. J. Peterson,[1] W. A. Stygar,[1] J. S. Lash,[1] M. K. Matzen,[1] ***and many more…***

[1]*Sandia National Laboratories, Albuquerque, NM*

[2]*Lawerence Livermore National Laboratory, Livermore, CA*

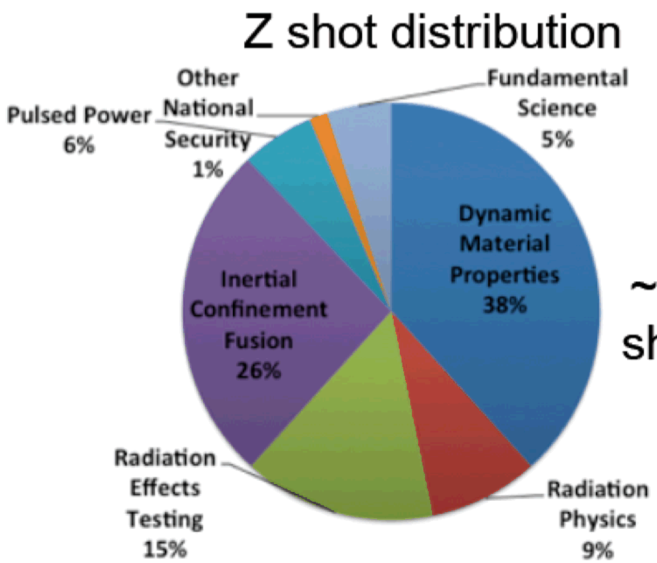
[3]*Los Alamos National Laboratory, Los Alamos, NM*

[4]*General Atomics, San Diego, CA*

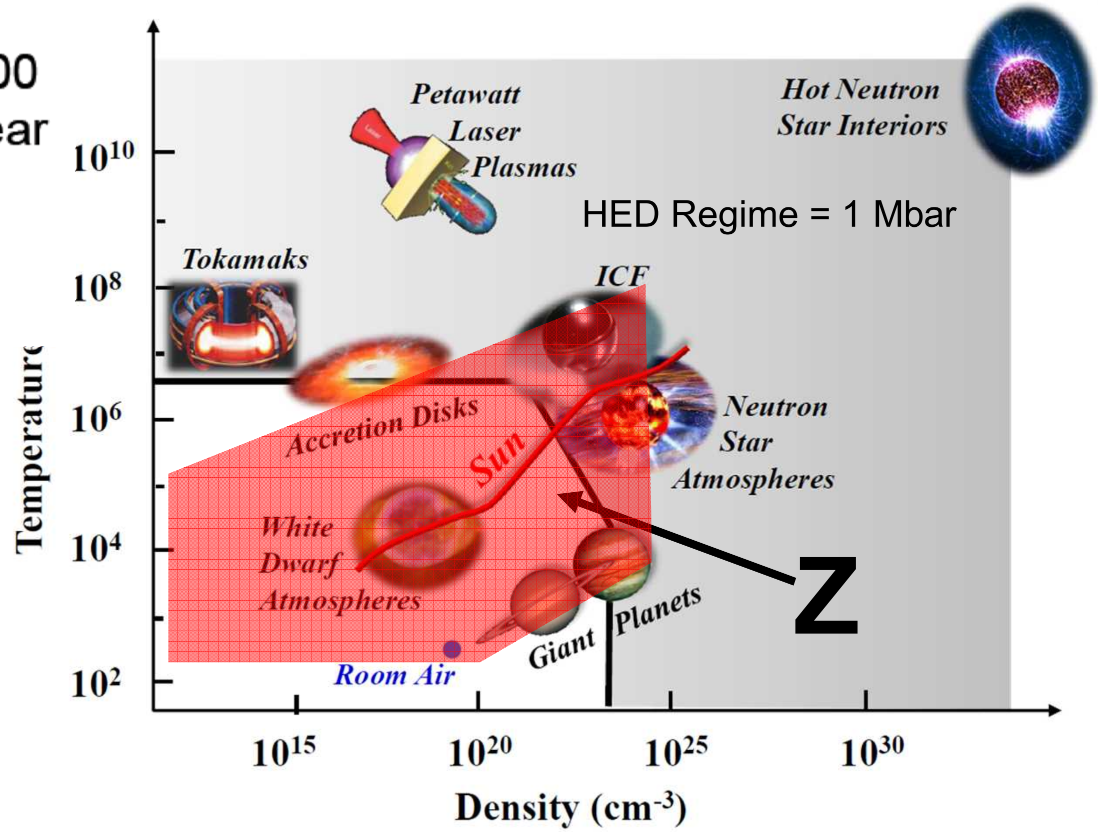
[5]*Laboratory for Laser Energetics, University of Rochester, NY*

# Sandia offers a dynamic work environment where you can have an impact in a wide range of disciplines

Sandia National Laboratories




~150-200 shots/year

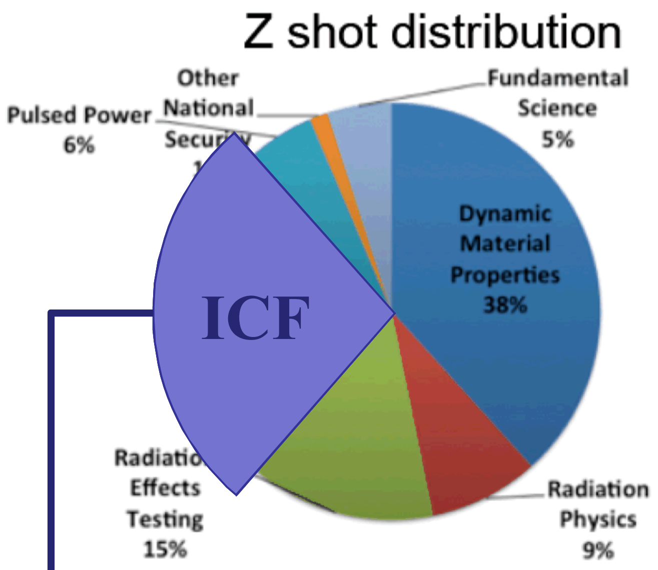



**Z supports a large variety of missions**

- Inertial Confinement Fusion
- Dynamic Material Properties
- Radiation Effects Testing
- Radiation Physics
- Pulsed Power Development
- Other National Security Applications
- …and more

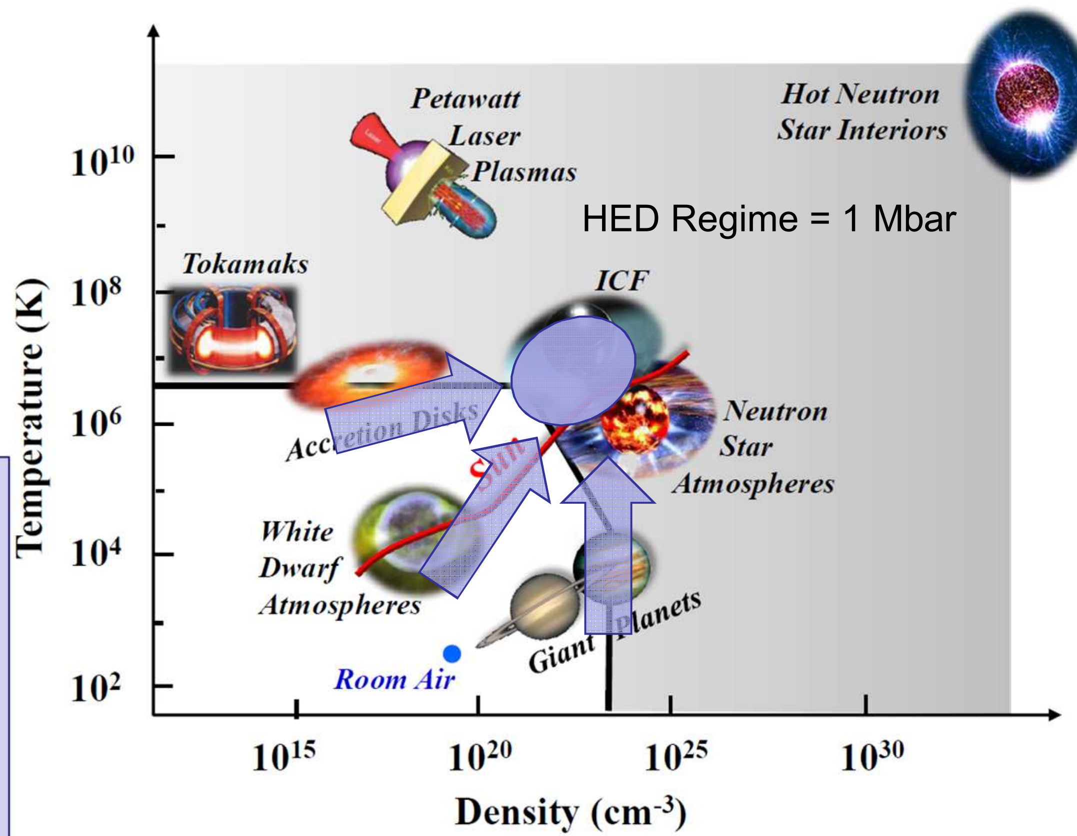
# Sandia offers a dynamic work environment where you can have an impact in a wide range of disciplines

Sandia National Laboratories

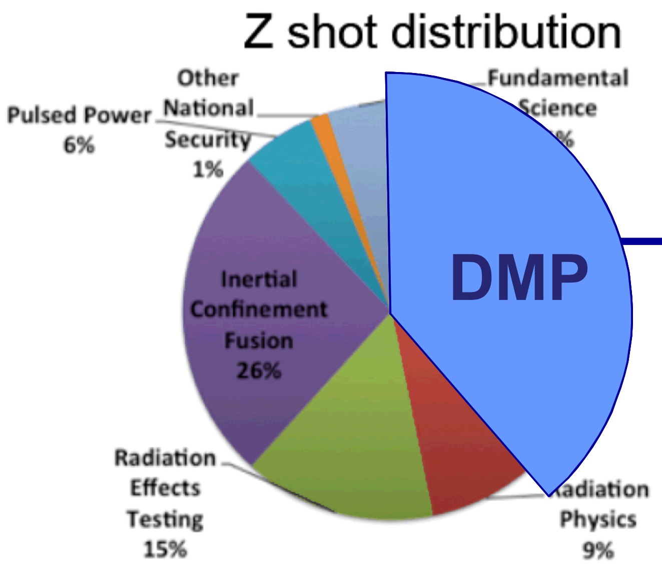



**Inertial Confinement Fusion**

- ~30% of shots
- >15 PRL's from 2010 to 2015
- >30 peer-reviewed publications
- >10 invited conference presentations
- Physics Viewpoint: R. Betti, *"Magnetic fields lock in the heat of fusion"*

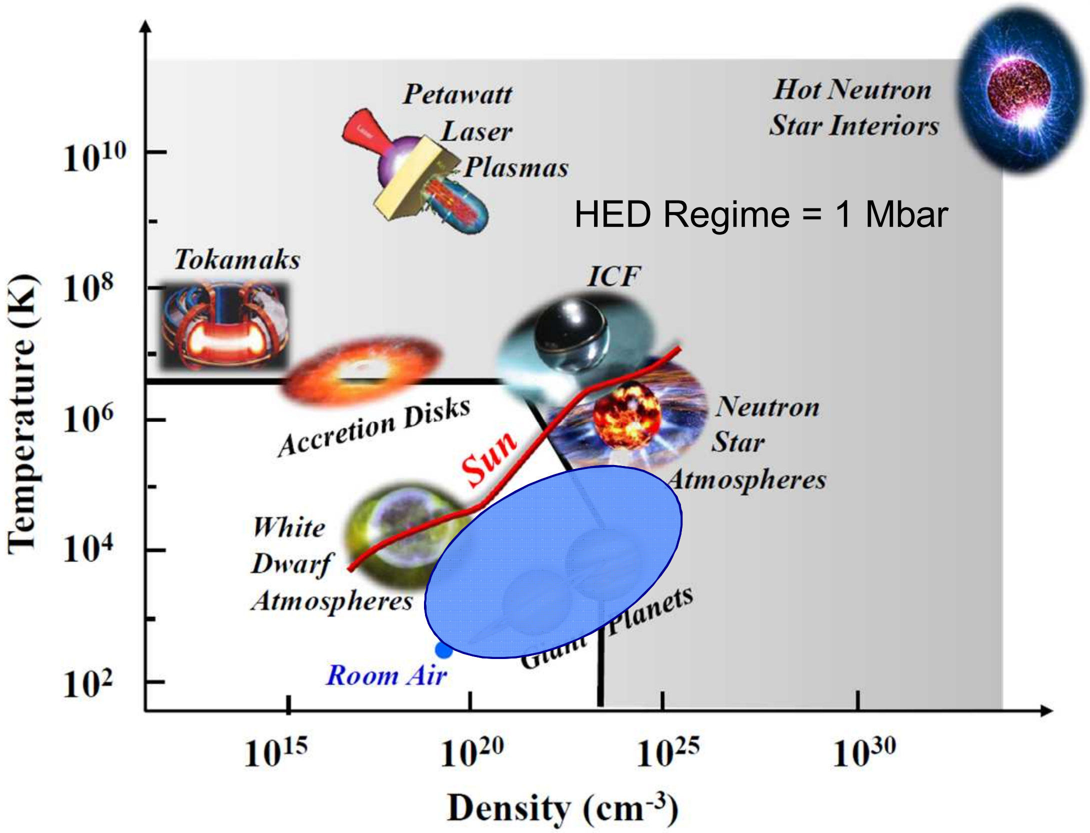


# Sandia offers a dynamic work environment where you can have an impact in a wide range of disciplines

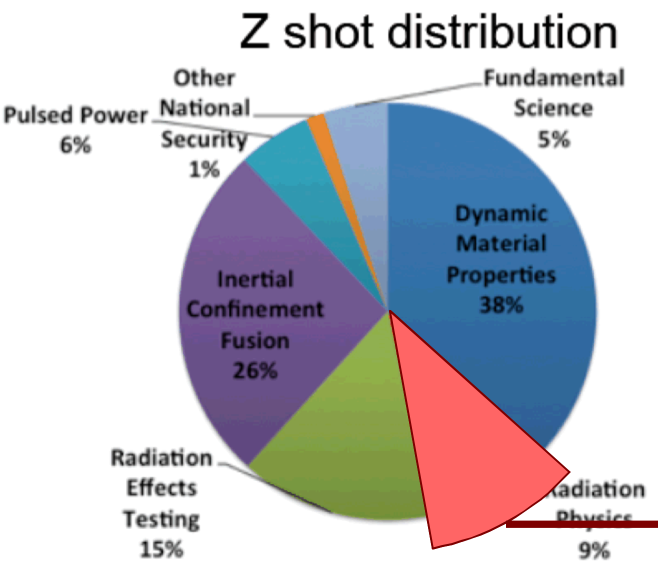



**Dynamic Material Properties**

- ~30% of shots
- 1 Science, 1 Nature Geoscience
- 8 PRL's from 2010 to 2015
- *"Iron rain" #62 in top 100 Science stories in 2015*
- >>30 other publications

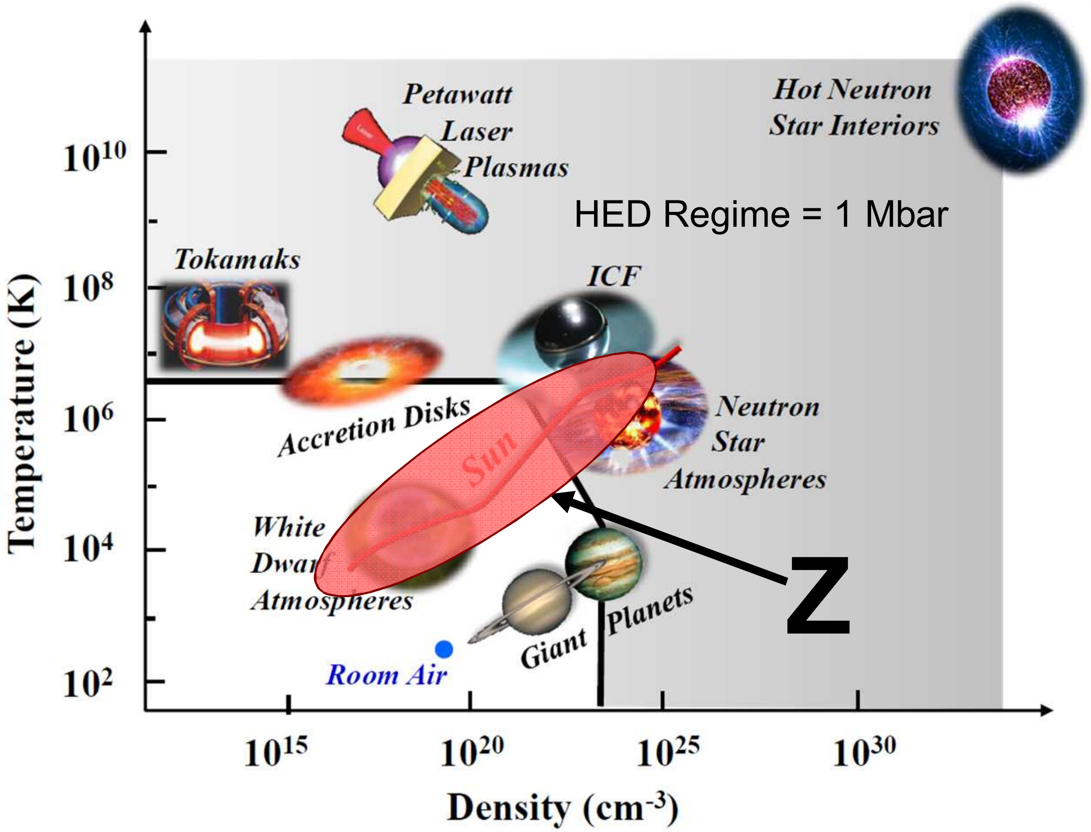


# Sandia offers a dynamic work environment where you can have an impact in a wide range of disciplines



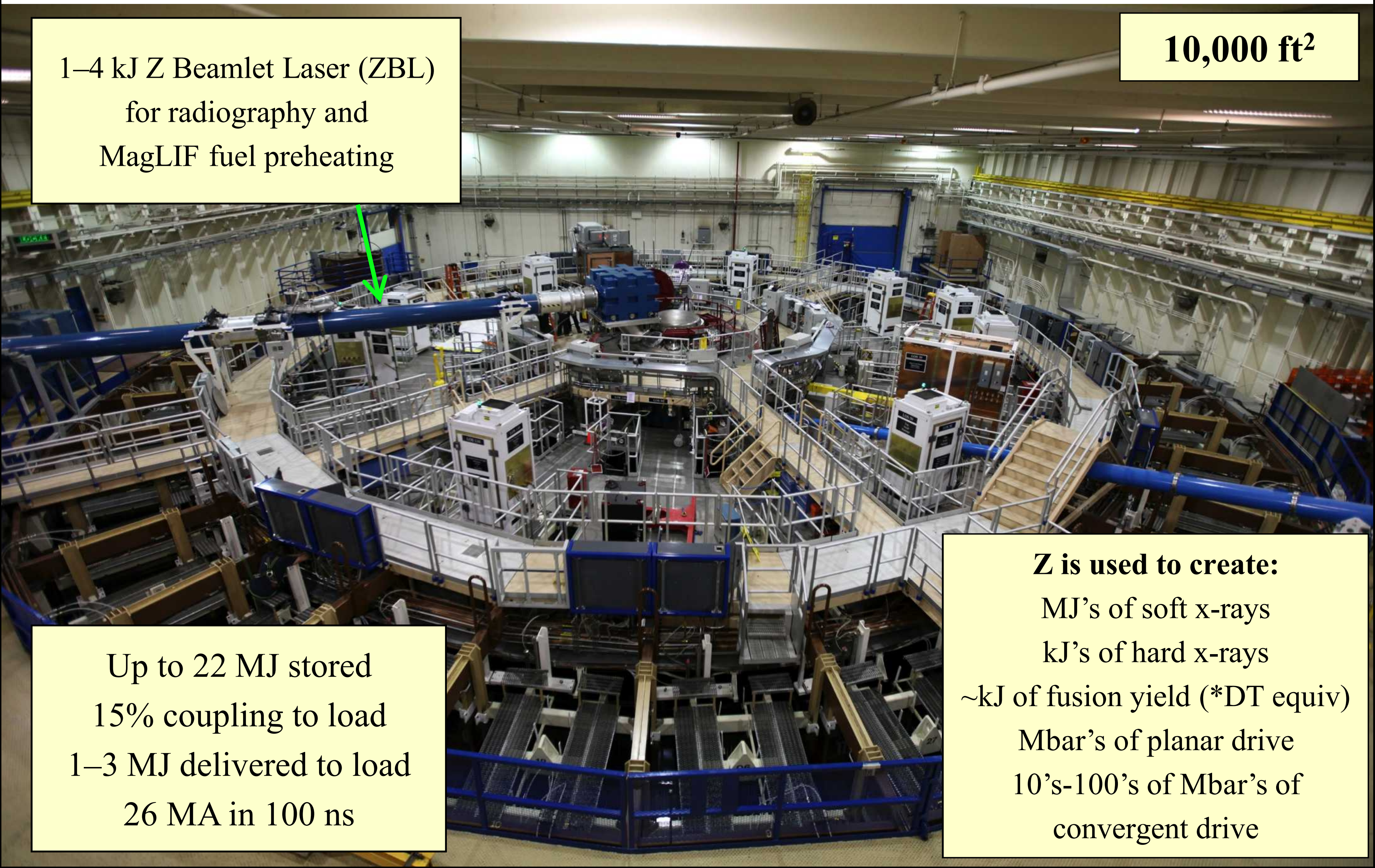

## Radiation Physics

- ~9% of shots
- 1 Nature Publication
- 18 peer-reviewed articles
- >10 popular press articles
- >15 invited conference presentations
- 6 grad students & 3 post-docs



# The Z facility combines the multi-MJ Z pulsed-power accelerator with the multi-kJ Z Beamlet Laser (ZBL)

Sandia National Laboratories



1–4 kJ Z Beamlet Laser (ZBL) for radiography and MagLIF fuel preheating

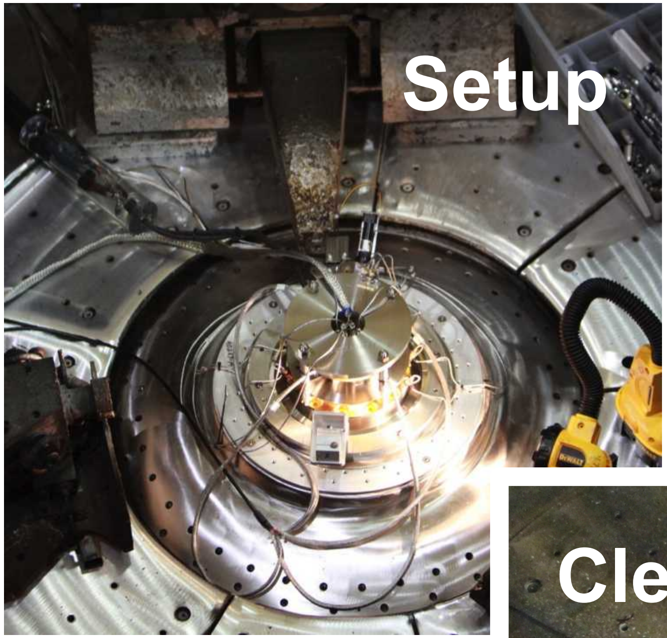
**10,000 ft$^2$**

Up to 22 MJ stored
15% coupling to load
1–3 MJ delivered to load
26 MA in 100 ns

**Z is used to create:**
MJ’s of soft x-rays
kJ’s of hard x-rays
~kJ of fusion yield (*DT equiv)
Mbar’s of planar drive
10’s-100’s of Mbar’s of convergent drive

# Z is a fun and challenging place to conduct high impact experiments

- Shot rate of ~1/day
- 150-200 shots/year



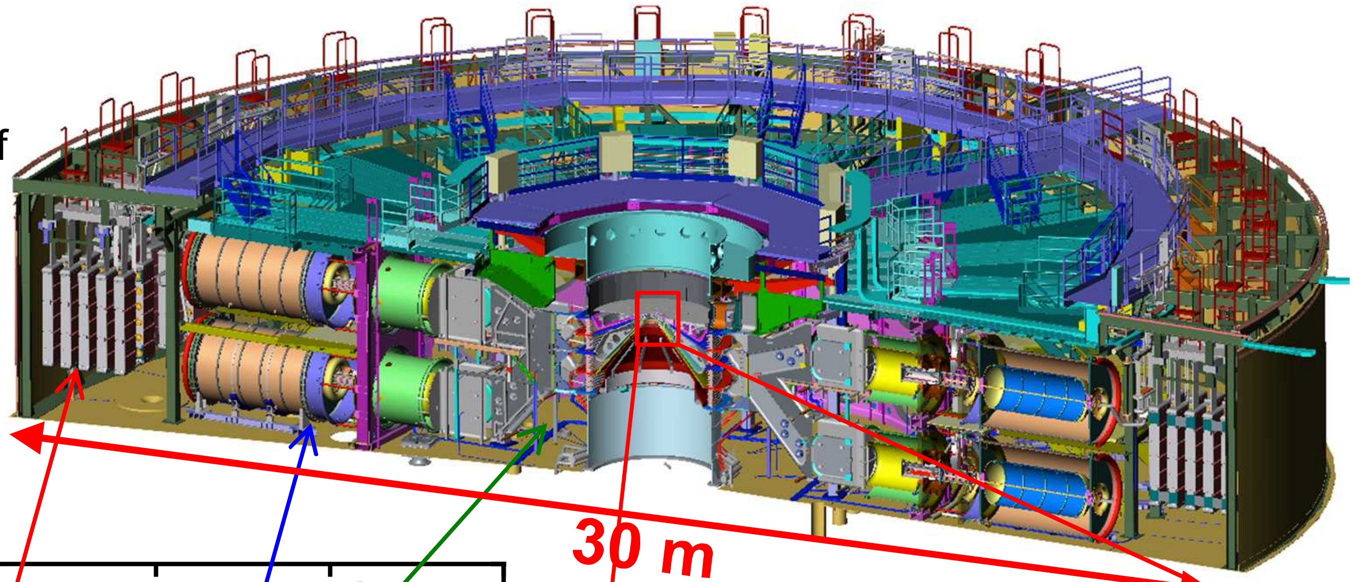


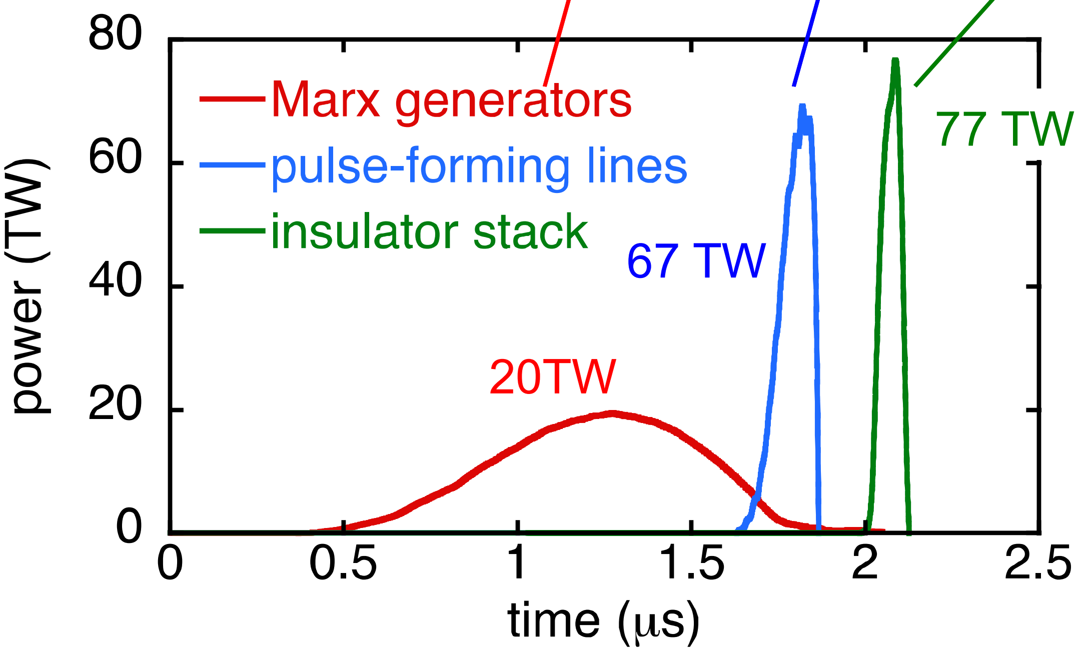

- MJ’s of magnetic energy to the load
- Equivalent to detonating a few sticks of dynamite
- Harsh debris, shock, and radiation environment make fielding experiments unique and challenging

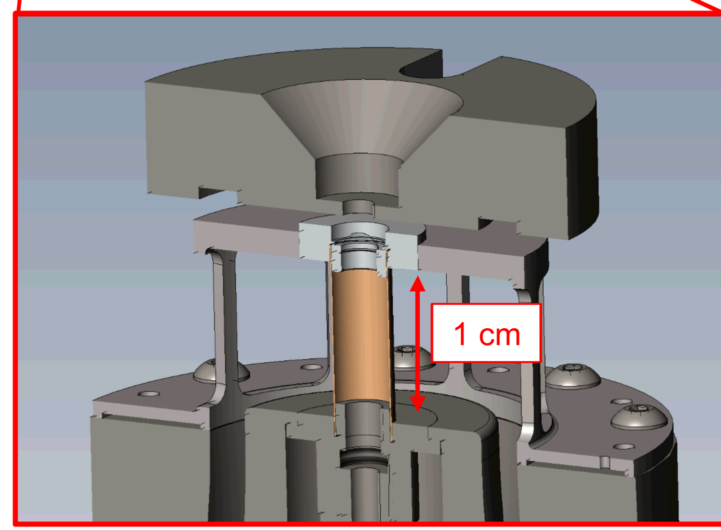
# Pulsed-power is all about energy compression in both space and time

Energy compression achieved by a sequence of storage and switching techniques :

- Voltages are added in series
- Currents are added in parallel



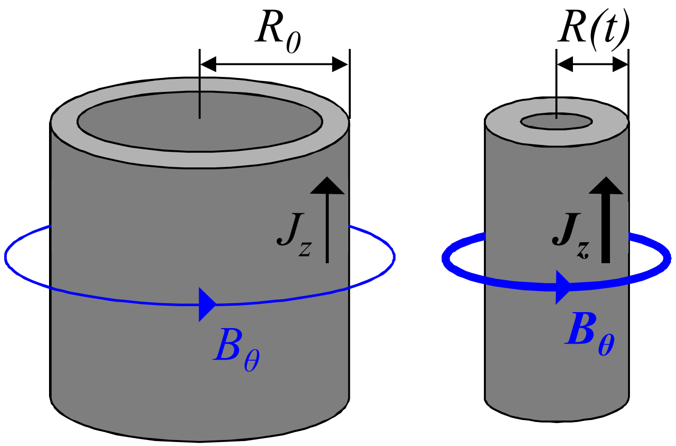



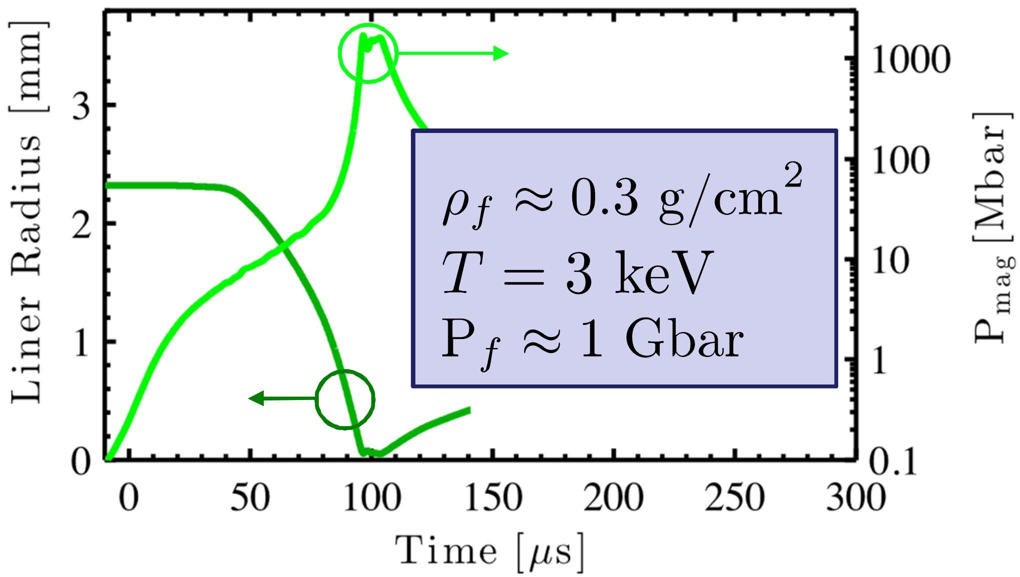
# Magnetically-Driven Cylindrical Implosions are Efficient: Implosion Drive Pressure is Divergent!

Sandia National Laboratories

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

$$\rho\left(\frac{\partial \mathbf{u}}{\partial t} + (\mathbf{u}\cdot\nabla)\mathbf{u}\right) = \frac{\mathbf{J}\times\mathbf{B}}{c} - \nabla P$$




By varying the magnetic pressure pulse shape, liner dimensions, and duration of drive, Z can access a wide variety of end states

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

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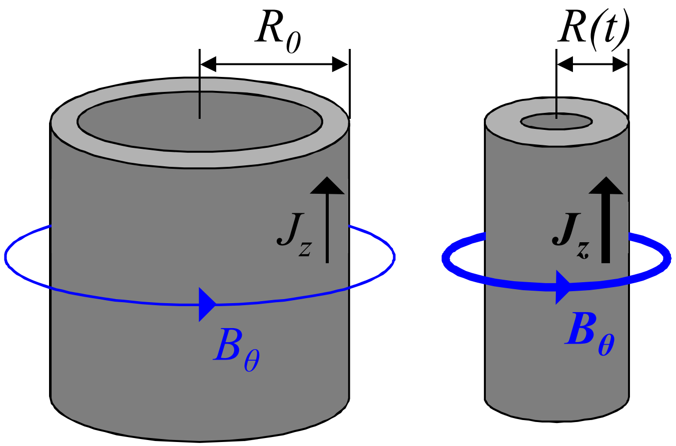
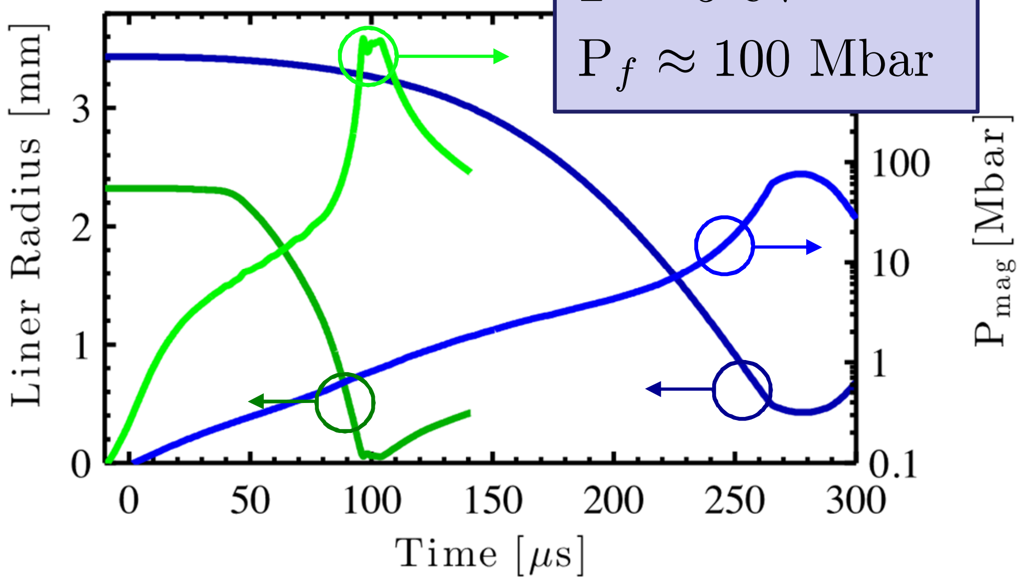


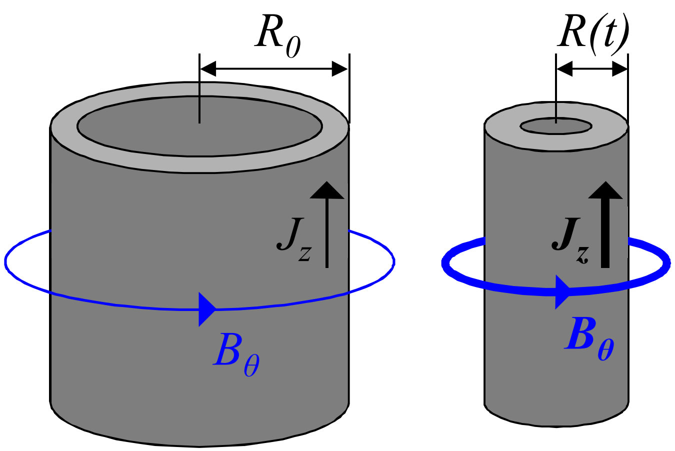




$\rho_f \approx 10\ \mathrm{g/cm^2}$
$T \approx 5\ \mathrm{eV}$
$P_f \approx 100\ \mathrm{Mbar}$

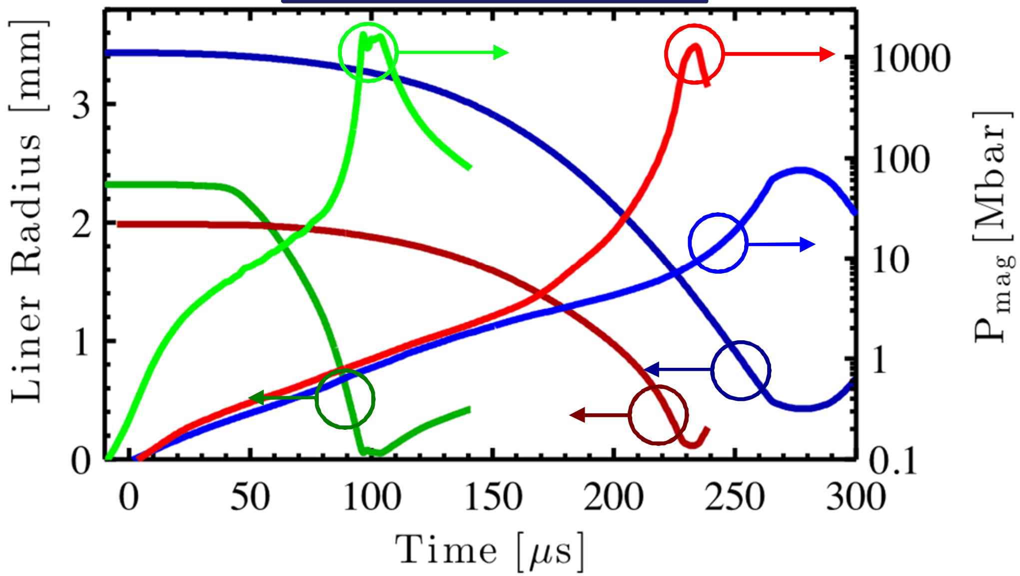
By varying the magnetic pressure pulse shape, liner dimensions, and duration of drive, Z can access a wide variety of end states

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

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




$\rho_f \approx 60\ \mathrm{g/cm^2}$
$T \approx 10\ \mathrm{eV}$
$\mathrm{P}_f \approx 2\ \mathrm{Gbar}$

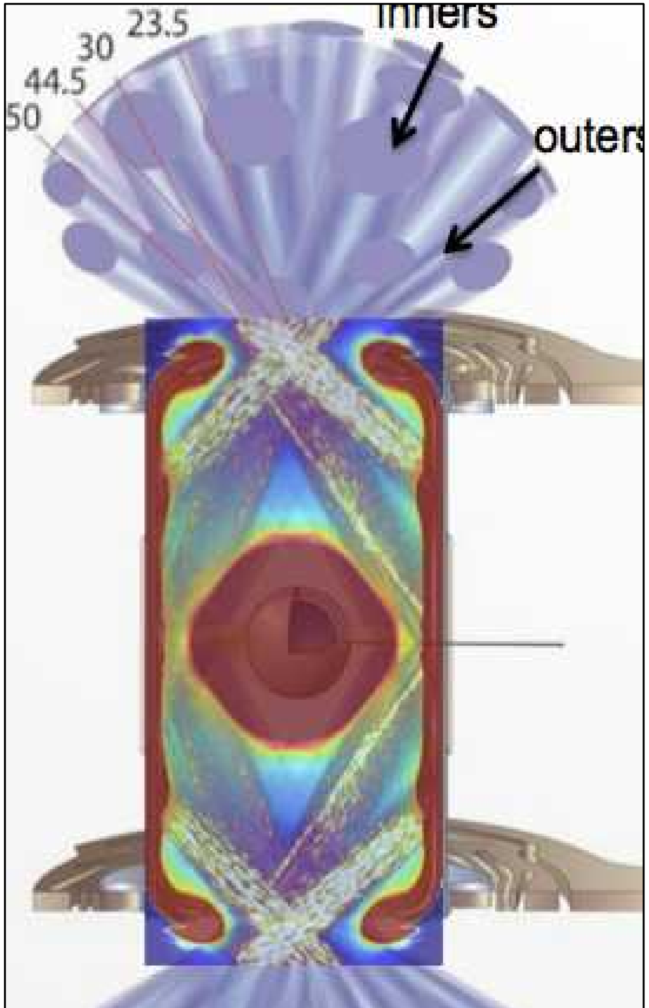



By varying the magnetic pressure pulse shape, liner dimensions, and duration of drive, Z can access a wide variety of end states

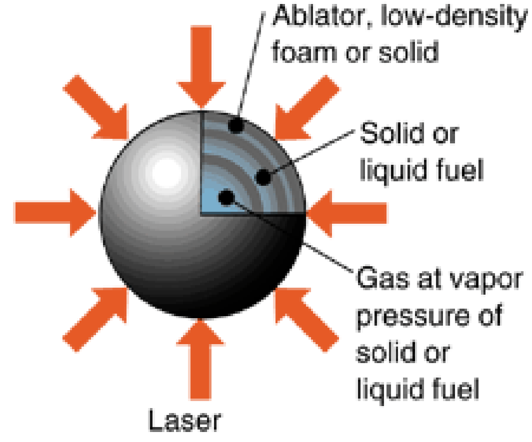
# ICF research using magnetic direct drive is part of the mainline national program

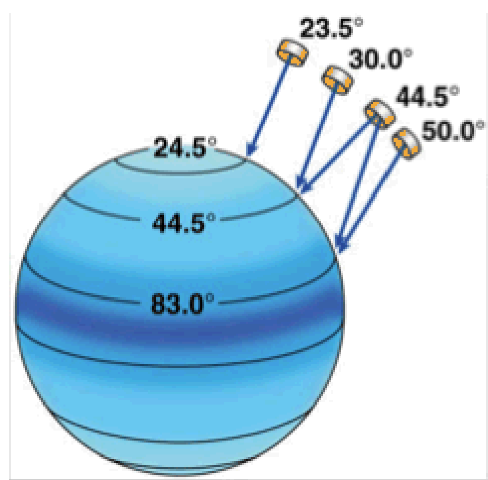
Sandia National Laboratories

| Radiation-driven implosions | Laser-driven implosions | Magnetically-driven implosions |
|---|---|---|



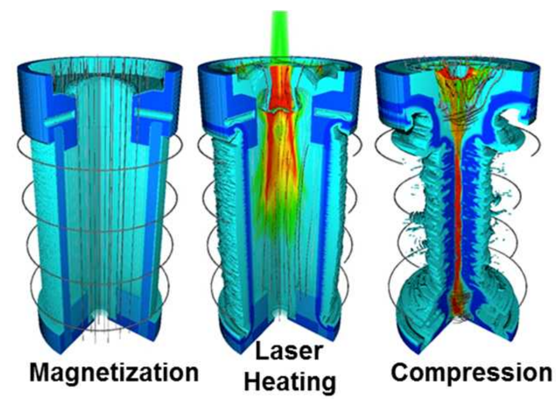

NIF at Lawrence Livermore National Laboratory




OMEGA laser at LLE University of Rochester

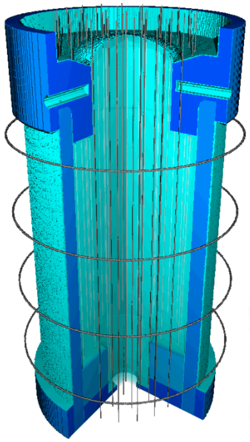
Sandia's ICF program is performing experiments on all 3 major U.S. facilities




Z Facility at Sandia National Laboratories

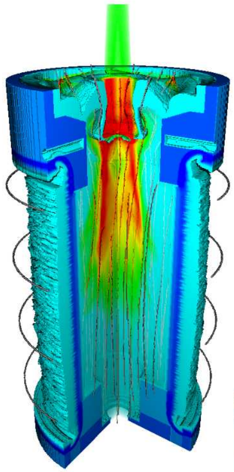
# MAGnetized Liner Inertial Fusion: A promising path to laboratory fusion

Sandia National Laboratories



## Magnetization

- 10-30 T axial B-field
- 3 ms risetime
- ~1 mg/cm$^3$ initial density

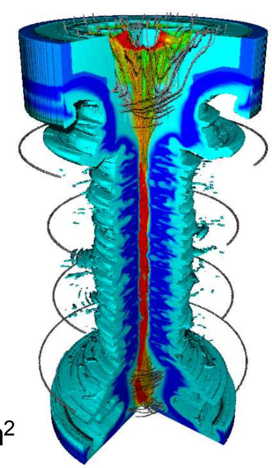


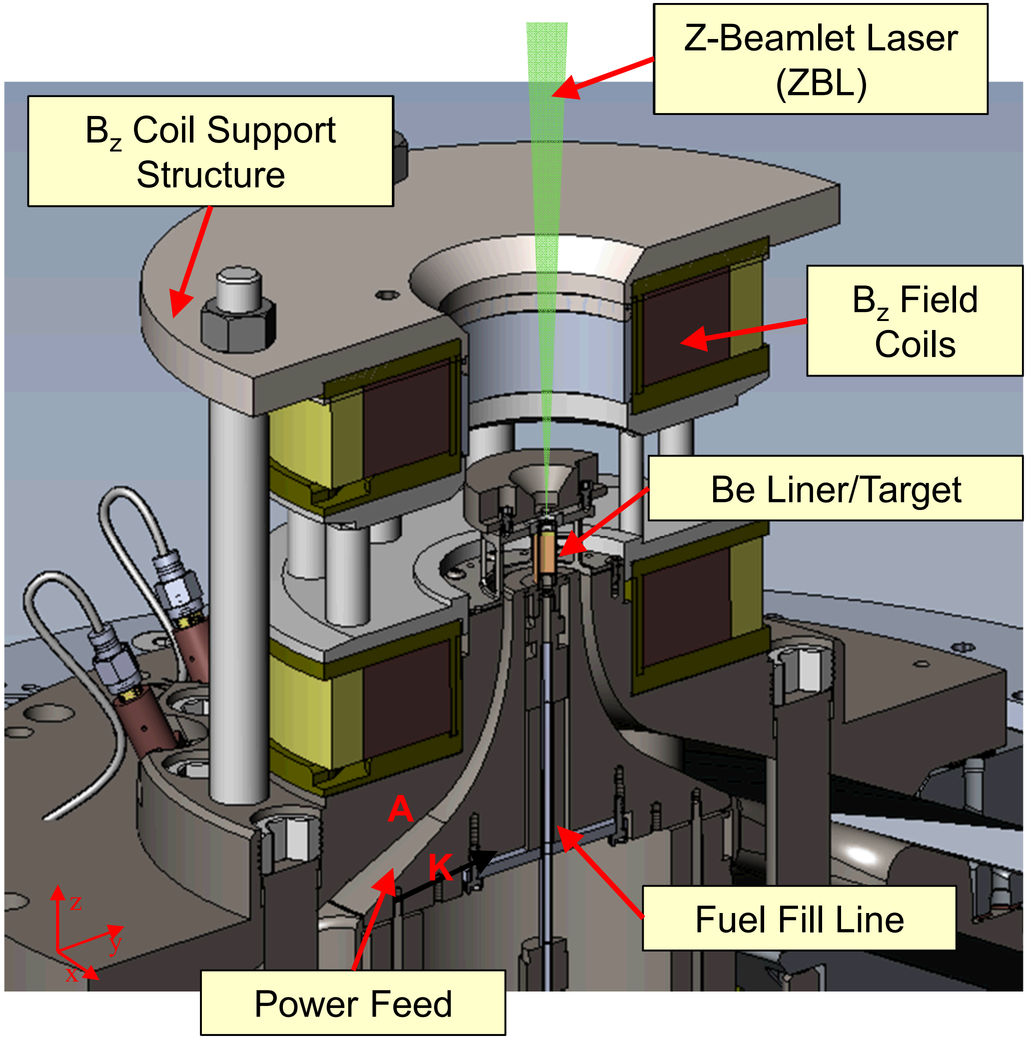
## Laser Heating

- 1-4 kJ, 1-4 ns
- 2ω, f/10 beam
- ~50 ns from preheat to stagnation

## Implosion and Stagnation

- CR = 25-40
- Burn duration 1-2 ns
- Flux compression >>100x $B_0$
- $\rho R_f$ ~ 0.01 g/cm$^2$, $\rho L_f$ ~2 g/cm$^2$





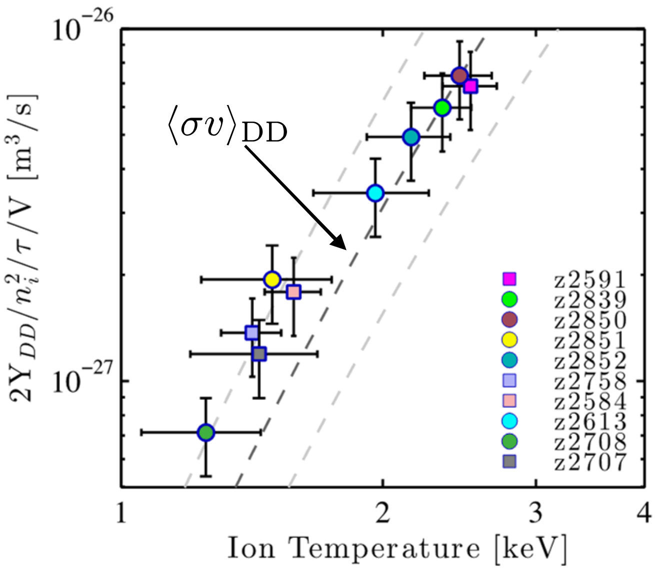


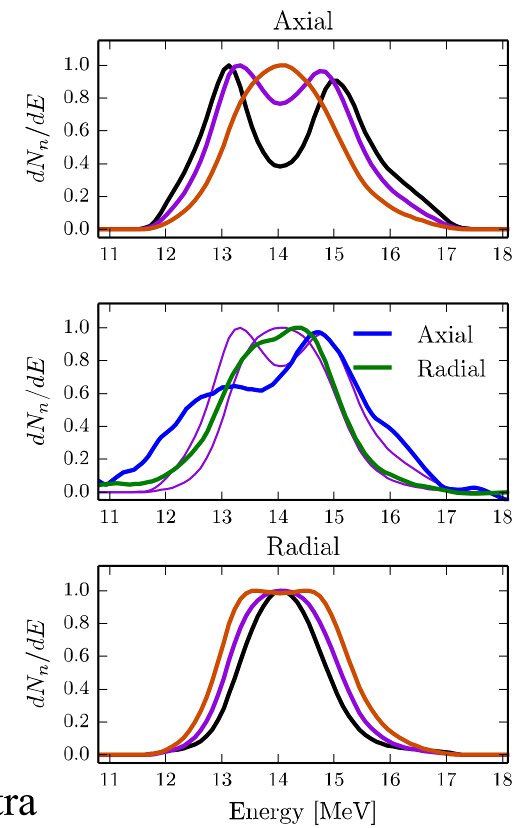
S. A. Slutz, *et al.*, Phys. Plasmas **17** 056303 (2010)
A.B. Sefkow, *et al.*, Phys. Plasmas, **21** 072711 (2014)

# MagLIF experiments have successfully demonstrated key aspects of magneto-inertial fusion

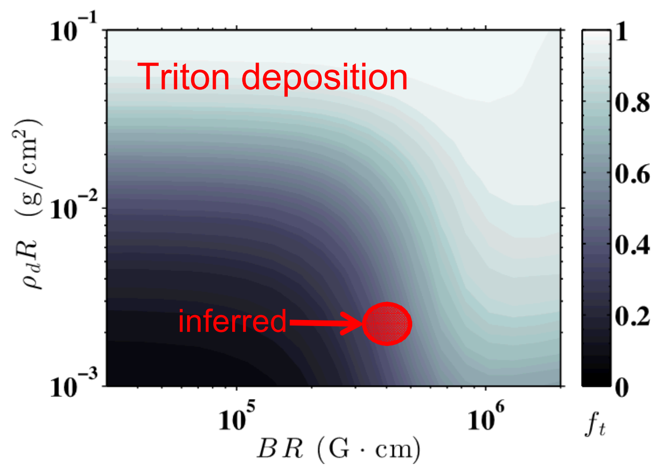
Sandia National Laboratories

## Thermonuclear neutron generation




## Confinement of fusion products




- Isotropic, Gaussian DD neutron spectra
- DD neutron yields = 3e12
- Ion temps = 2.5-3 keV
- Electron temps = 3.1 keV (from x-ray spectroscopy)

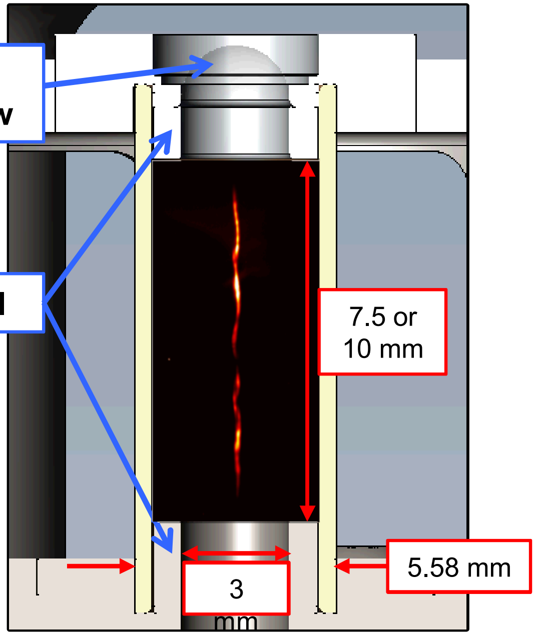
5 MG*cm

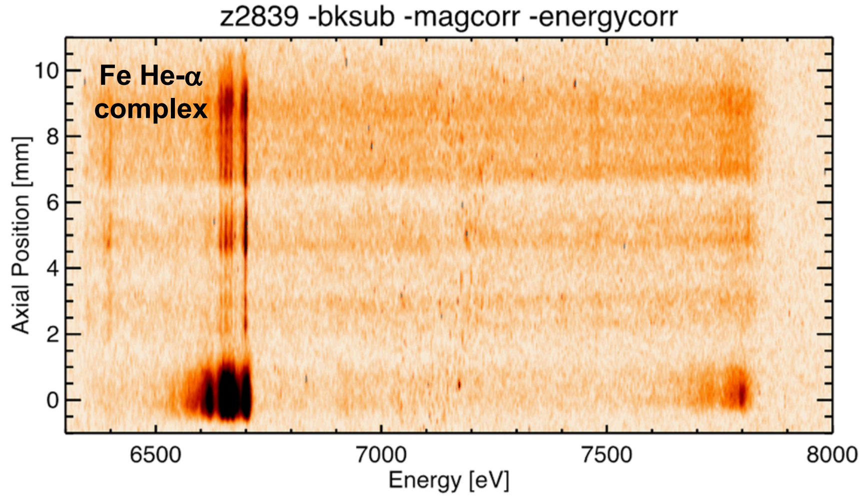
- Magnetized, trapped T's, α's!
- Important for fusion ignition!

M.R. Gomez et al., Phys. Rev. Lett. **113**, 155003 (2014)

P.F. Knapp and P.F. Schmit et al., Phys. Plasmas, **22**, 056312 (2015)
P.F. Schmit and P.F. Knapp et al., PRL 113, 155004 (2014)

# High resolution x-ray instruments allow us to peer into the stagnation plasma



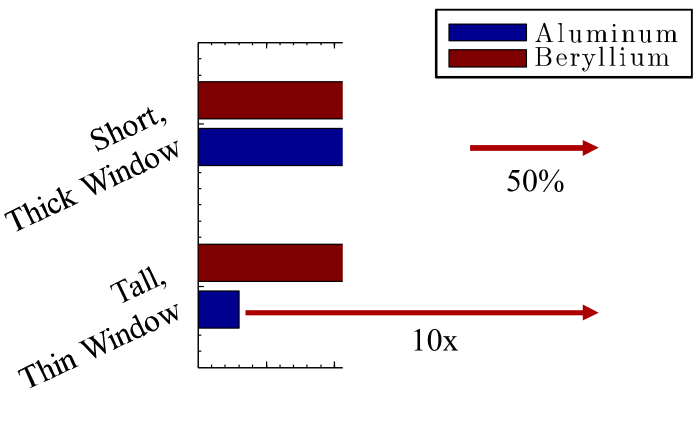




ws a narrow plasma
ght helical structure

gh sensitivity
npurities mixed into the

$T_e$=1.5-2 keV, $n_e$=1e23

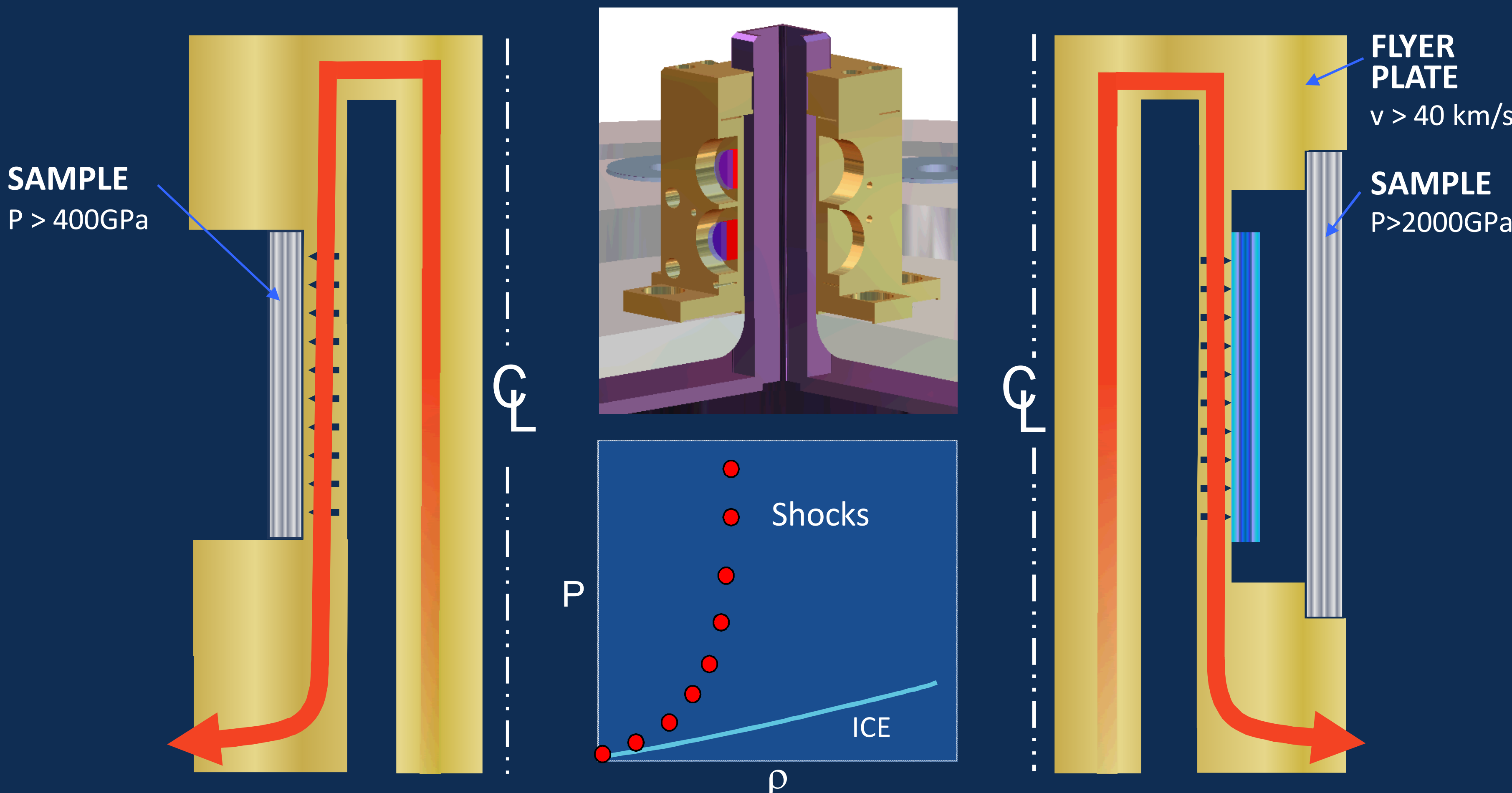
ant, but manageable level






E.C. Harding et al., Rev. Sci. Inst. 86, 043504 (2015)

# Magnetic drive can produce multi-Mbar shocks, isentropic compression or shock-ramp loading paths in planar material samples

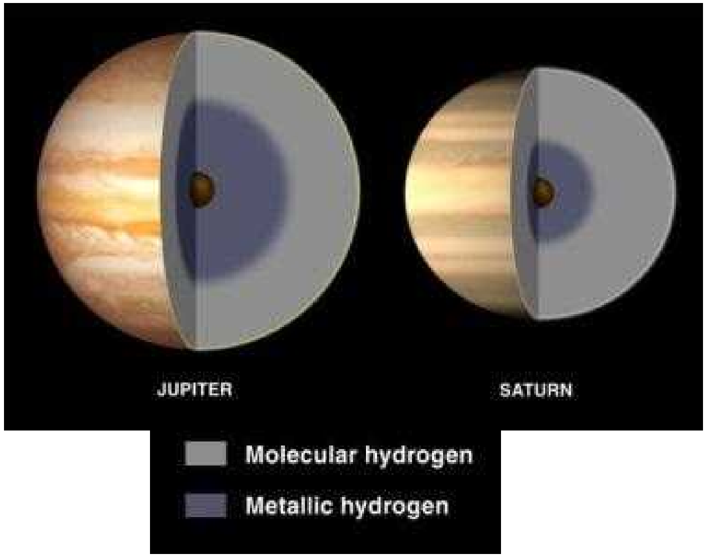



**Isentropic Compression Experiments:**
Gradual pressure rise in sample

**Shock Hugoniot Experiments:**
Shock wave in sample on impact

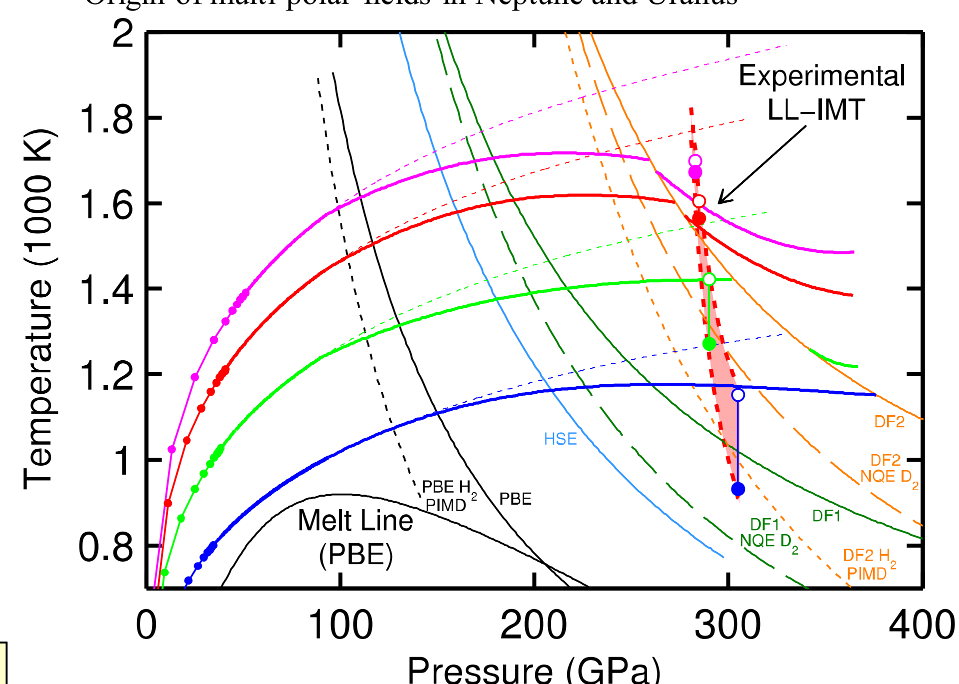
# Understanding the properties of hydrogen is crucial for understanding giant planets

Sandia National Laboratories



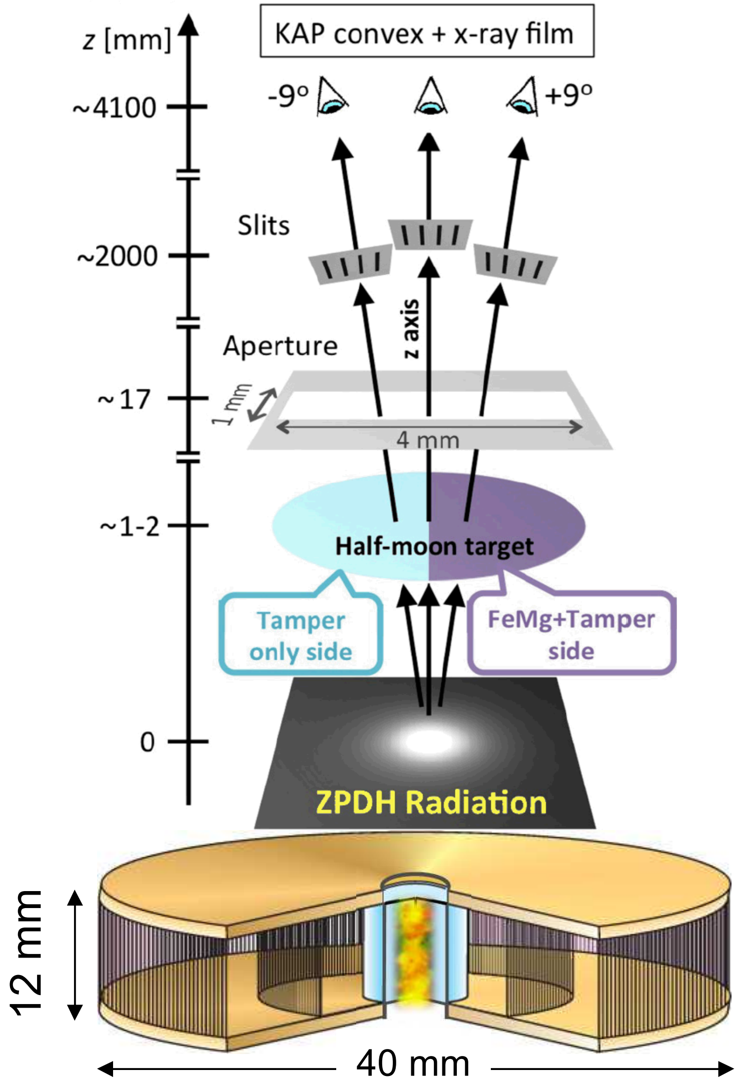

- **Experiments used a new shock + ramp drive to locate the Liquid-Liquid Insulator-to-Metal**
- ***Insensitivity to T suggests density-driven transition***
  - ρ at the transition is inferred to be ~2-2.1 g/cc in deuterium
  - Qualitatively different transition than in shock experiments (T driven)

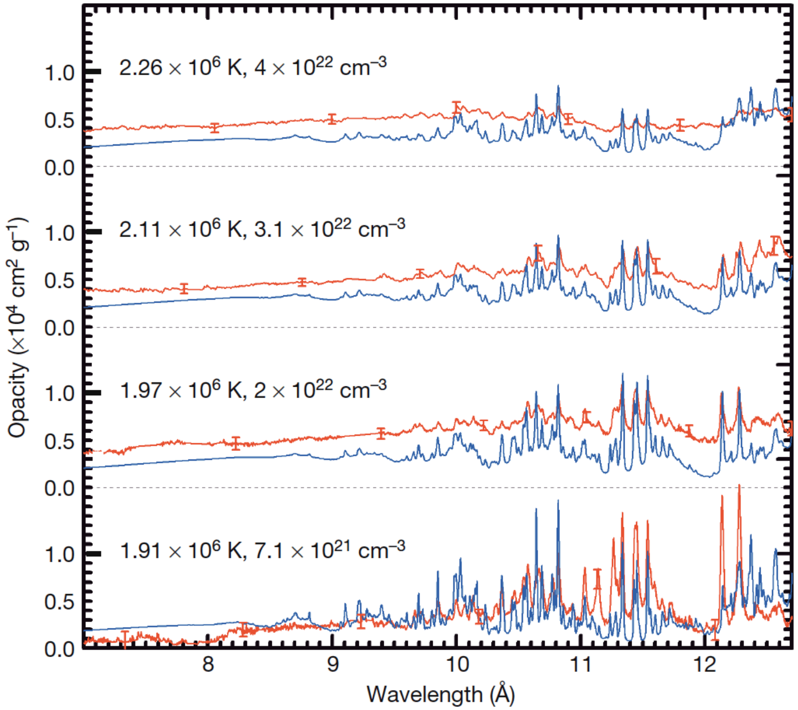
- **Present structure**
  - Layers of different composition while fulfilling observational constraints
- **Evolution**
  - Discrepancies in modeling the evolution of Jupiter and Saturn – the "Saturn age problem"
  - Why is Saturn so luminous?
- **Magnetic fields**
  - Origin of multi-polar fields in Neptune and Uranus

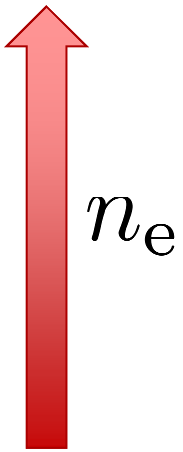



M.D. Knudson, M.P. Desjarlais, A. Becker, R.W. Lemke, K.R. Cochrane, M.E. Savage, D.E. Bliss, T.R. Mattsson, and R. Redmer, Science 348 1455, 26 June 2015.

# The Opacity platform on Z has uncovered a discrepancy with solar opacity models that can potentially explain discrepancies with models of the solar interior



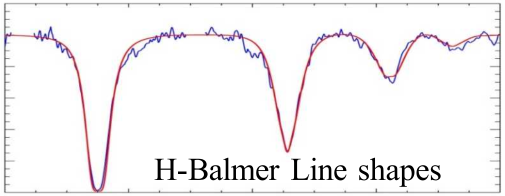

- Measured Fe opacity at solar interior conditions is higher than predicted
- Agreement gets worse as density increases
- This result is controversial and has generated a LOT of work *attempting* to explain the discrepancies!

T. Nagayama et al., Phys. Rev. E **93**, 023202 (2016)

J. E. Bailey, T. Nagayama, G. P. Loisel et al., *Nature* 517, 56–59 (01 January 2015).

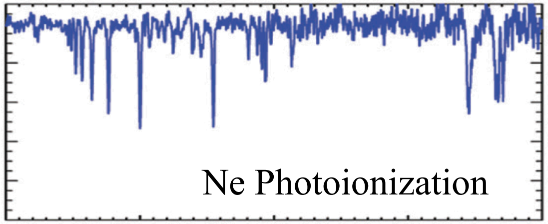
# The copious soft x-ray emission from the dynamic hohlraum is used to drive other astrophysical experiments

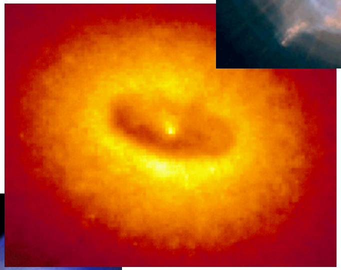
R. E. Falcon, et al., HEDP, Volume 9, Issue 1, March 2013, Pages 82-90



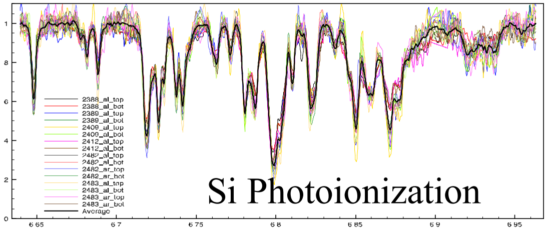

White Dwarf Photosphere

I.M. Hall, et al., Phys. Plasmas, **21**, 031203 (2014)

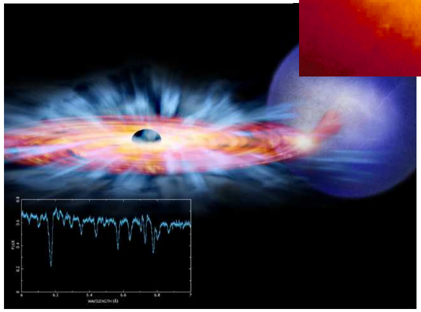


Photoionized Plasmas


G.A. Rochau, et al., Phys. Plasmas, **21**, 056308 (2014)



Black Hole Accretion Disks

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.*

This work represents several large collaborations with university partners through the Z Fundamental Science Program

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

*Nature editor, Nature 503 (2013)

# 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
  - 18 shots FY15, 12 planned for FY16, 20 shots requested for FY17
- **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

- We have a workshop coming up:
  - Sunday, **July 31** (evening) through Wednesday, **August 3** (12 noon)
- **We have travel funding for students!**
- Current teams involved in ZFS campaigns will be giving talks with breakout sessions
- A call for proposals is currently open
- Come see what it is about and how you can get involved!

http://www.sandia.gov/Pulsed-Power/workshop/

# Modeling and theory and integral part of the experimental design and analysis processes

- Most experiments are difficult, if not impossible, to learn from without the help of models
- As such, we are actively involved in numerous theory and modeling efforts in a variety of disciplines
- These areas have *very* active external collaborations

**Microphysics**

- Quantum Monte Carlo
- Density Functional Theory
- TD-DFT
- Atomic modeling

**Integrated Modeling**

- Coupled PIC and rad-hydro modeling
- Extended MHD (2-fluid physics)
- 3D modeling

# Modeling and theory and integral part of the experimental design and analysis processes

Sandia National Laboratories

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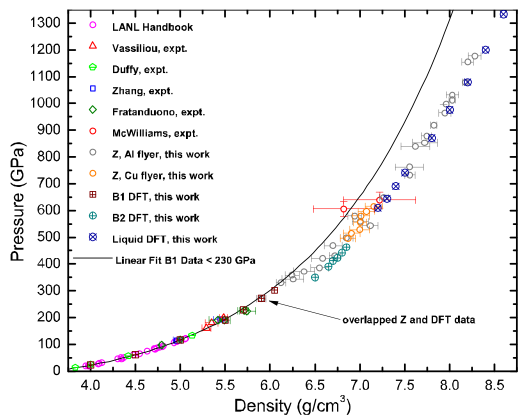
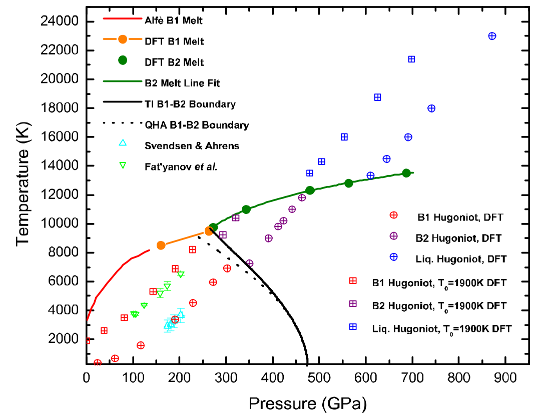
**Integrated M**

- Coupled I
- Extended
- 3D modeling

**Shock Response and Phase Transitions of MgO at Planetary Impact Conditions**




Hugoniot of MgO from Z-experiments and DFT, showing evidence of phase transitions and inadequacy of extrapolating from low pressure data.




Experimental and Calculated phase diagram of MgO showing a large coexistence region between the B2 solid and the liquid along the principal Hugoniot.

*S. Root, L. Shulenburger, R. W. Lemke, D. H. Dolan, T. R. Mattsson and M. P. Desjarlais, "Shock Response and Phase Transitions of MgO at Planetary Impact Conditions", PRL. **115**, 198501 (2015), Editor's Suggestion, http://dx.doi.org/10.1103/PhysRevLett.115.198501

This work suggests that much higher impact velocities would be necessary to melt the MgO in the earth than many proposed scenarios for the Moon forming impact require.

# Modeling and theory and integral part of the experimental design and analysis processes

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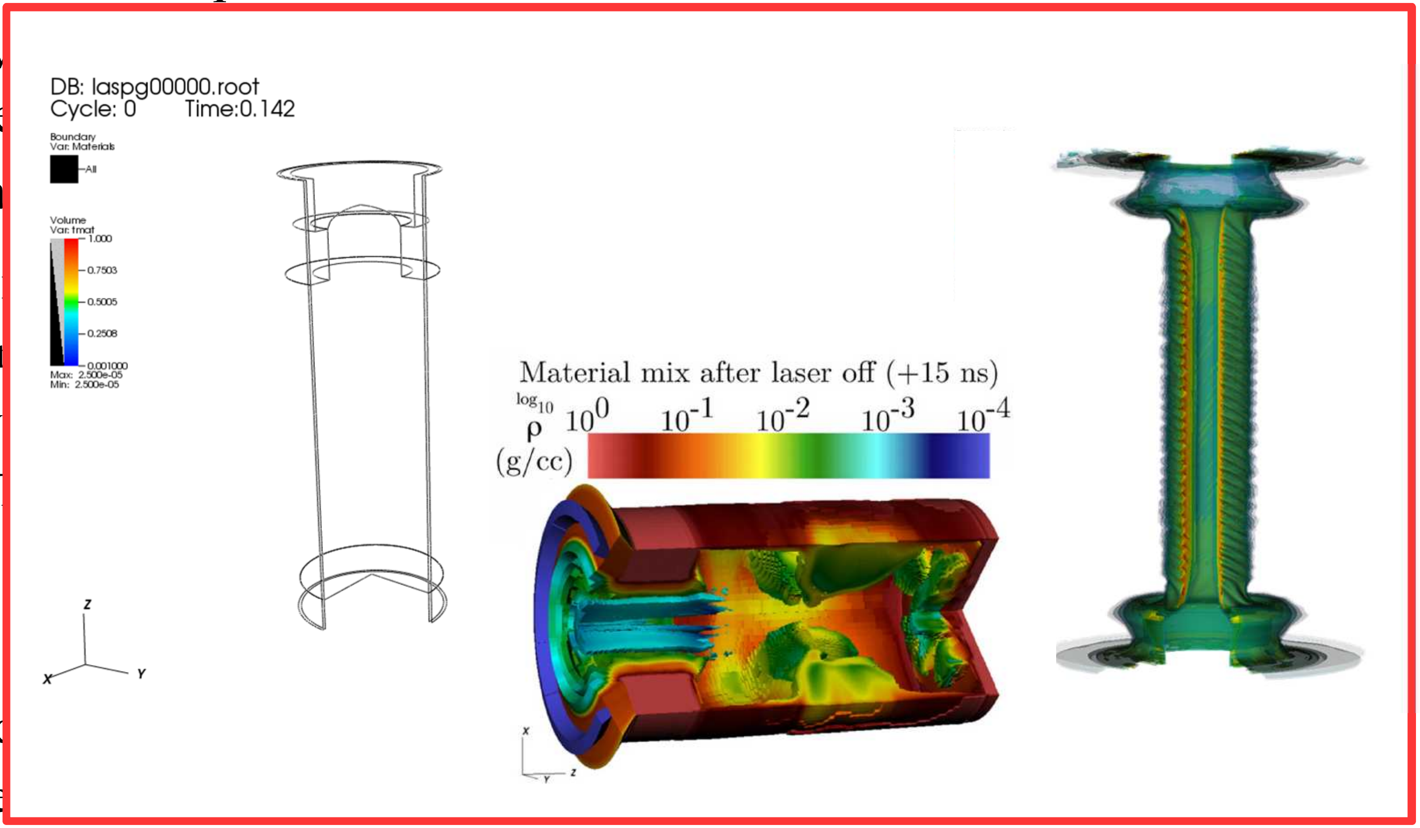
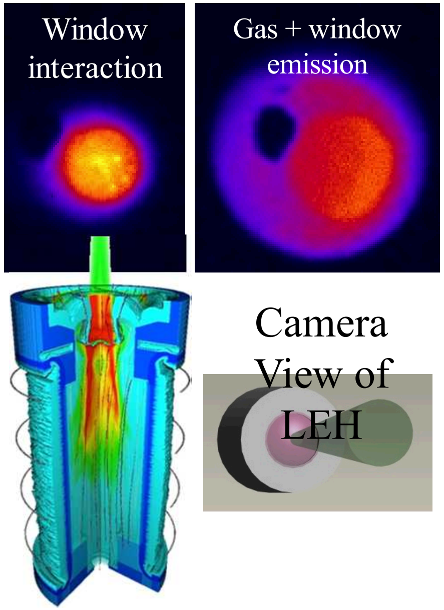


# We are undertaking a number of exciting new endeavors over the next 1-5 years

- Continuing upgrades to ZBL laser
  - Upgraded to 4 kJ in 4 ns, and are preparing to go > 6 kJ
  - Co-injection of the ZPW beam with the ZBL beam
- Preparing for tritium operations at Z
- X-ray diffraction using ZPW to generate hard x-rays
- New radiation-hardened CMOS imaging technology for single line-of-sight imaging in HED experiments is being developed at SNL in cooperation with LLNL, LLE, and GA
  - Integral part of the national diagnostics plan
- We are designing a line VISAR system in collaboration with LLNL
  - Should be operational next FY
- We have a path to upgrading Z over the next ~3 years to enable 95 kV operations -> potentially up to 30 MA

**MagLIF Laser Preheating on Z***

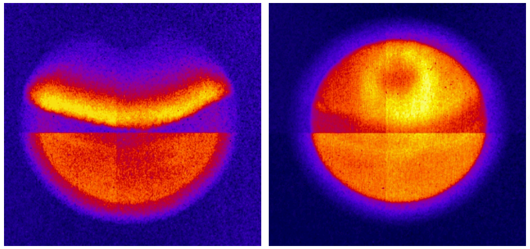
(9-ns gate separated by 10 ns)



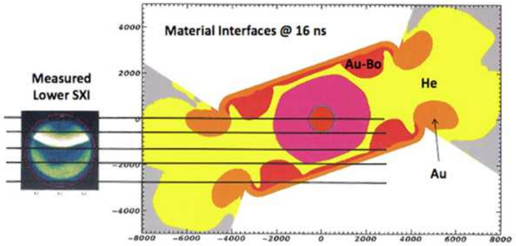

Camera View of LEH

**LEH Imaging on NIF****

(2-ns gate separated by 4 ns)



Camera View of LEH



# Beyond 2020: Z300 & Z800

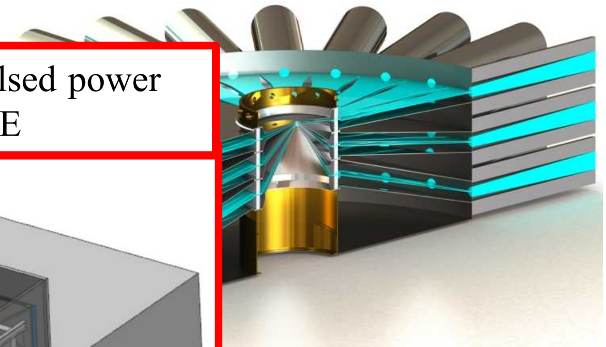
Sandia National Laboratories

## LTD Driver Architecture

**(Linear Transfo**

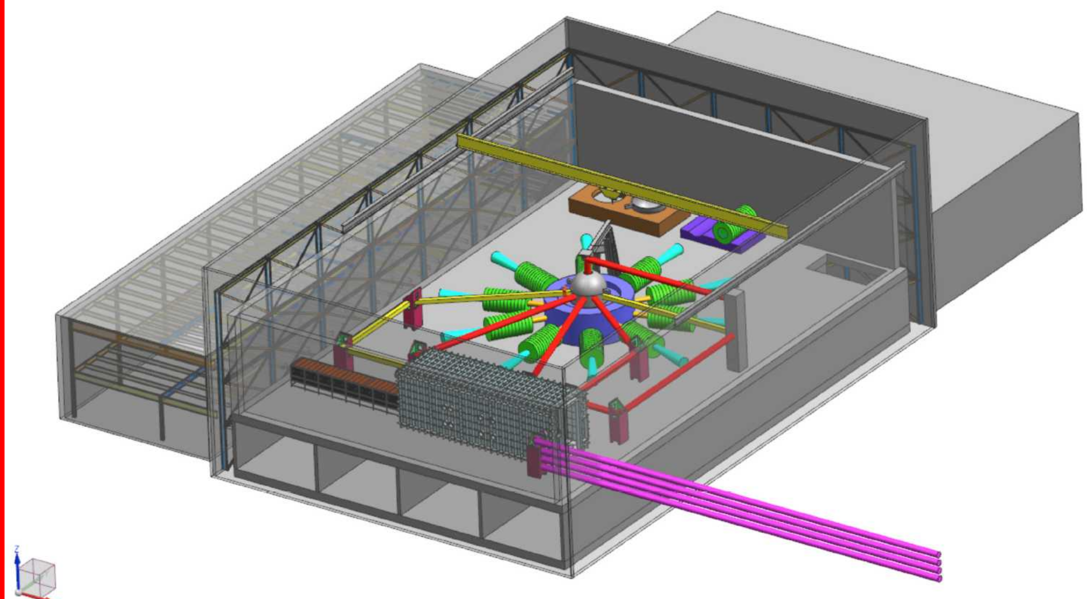
- A leap forward in
- ~2x as efficient a
- Can be made toda readiness level)
- We have an active exploit this techn

**Z300:**



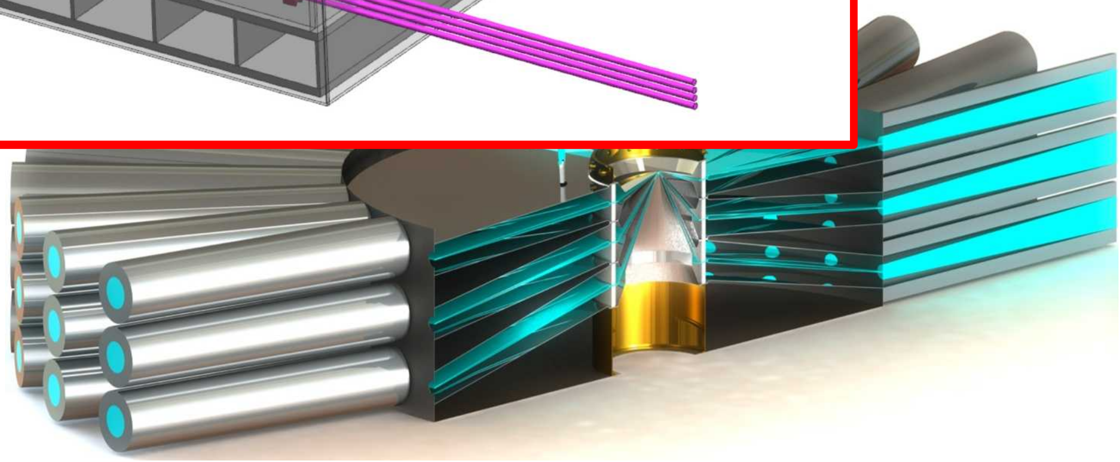
e current Z building

Currently discussing construction of a smaller scale pulsed power facility to couple to the EP laser system at LLE



**We are act**

***– Puls***



- 890 TW delivered
- 130 MJ stored
- 60–65 MA
- 110–120 ns rise
- 52 m in diameter
- 5400 LTD cavities!

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

# Sandia is a fast-paced, exciting, and challenging place to perform high impact science

- The mission space on Z is constantly evolving as we innovate and explore new opportunities
- Our magnetic direct drive fusion program is rapidly progressing
  - Very fast-paced
  - Large variety of work to be done
  - Huge opportunities for discovery!
- Our dynamic materials program is a world leader in precision, novel, and high-quality experiments and advanced theoretical work
- Our fundamental science program is breaking ground by making detailed measurements of fundamental physical processes, impacting a wide range of disciplines
  - Astronomy, ICF, planetary science, atomic physics, materials science, etc.
- Sandia is internationally recognized as a place where high quality and innovative science is done
  - 7 APS fellows, 2 IEEE fellows
  - 2 PECASE award winners, 2 DOE early career award winners since 2010
- **We have positions open *today*, with more to come in the near future!**
  - ICF/HED target design group (theory and computation)
  - Experimentalists needed in ICF
  - HED theory group
  - Nuclear and particle diagnostics
  - X-ray imaging and spectroscopy diagnostic physicist