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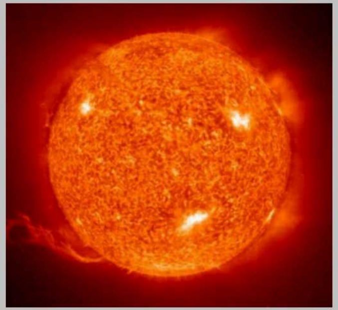
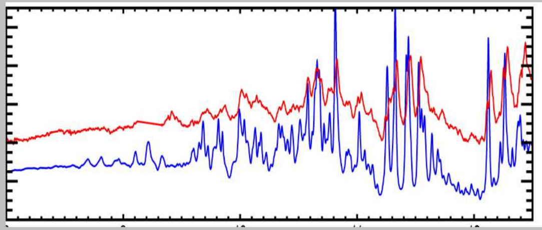
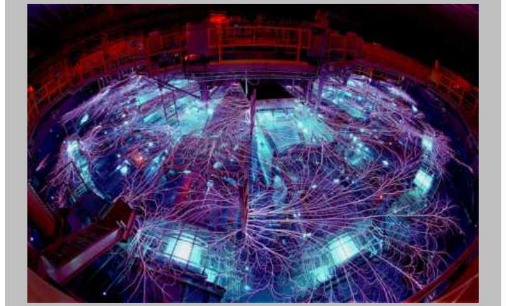
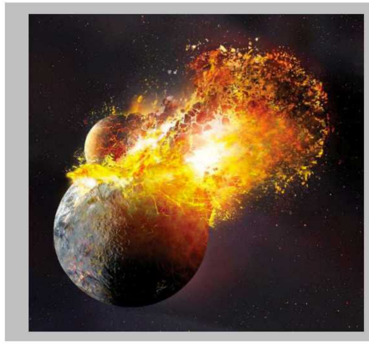
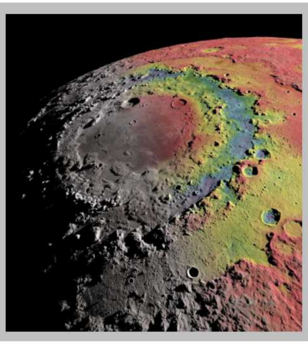
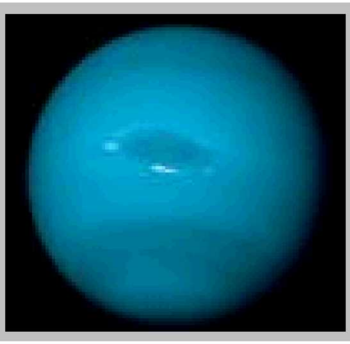

Z-Machine Presentation

Thomas R. Mattsson, Manager for HEDP Theory and Science
Campaign 1, Primary Assessment Technology

CISAC Fellow visit May 12, 2019

SAND2019-

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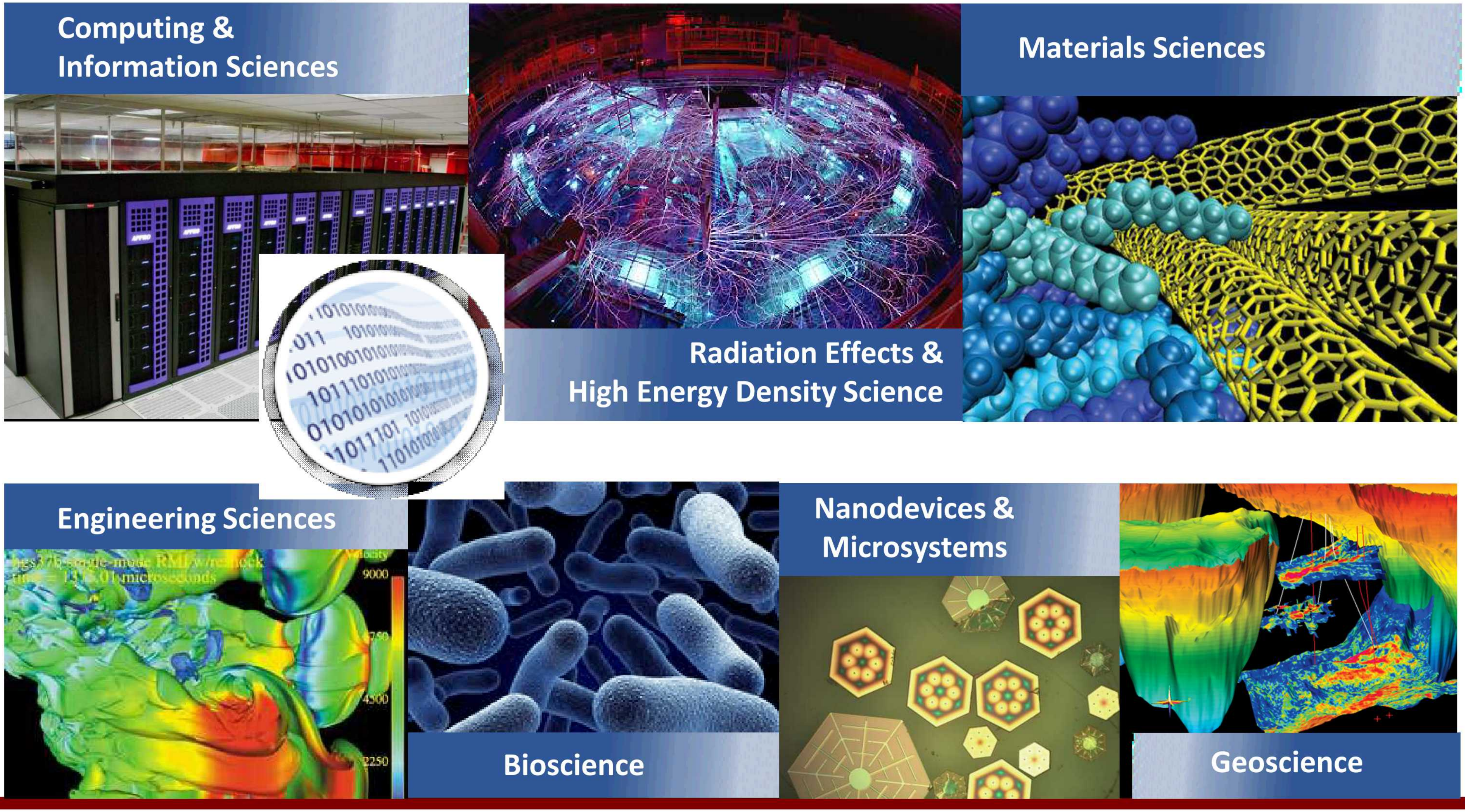
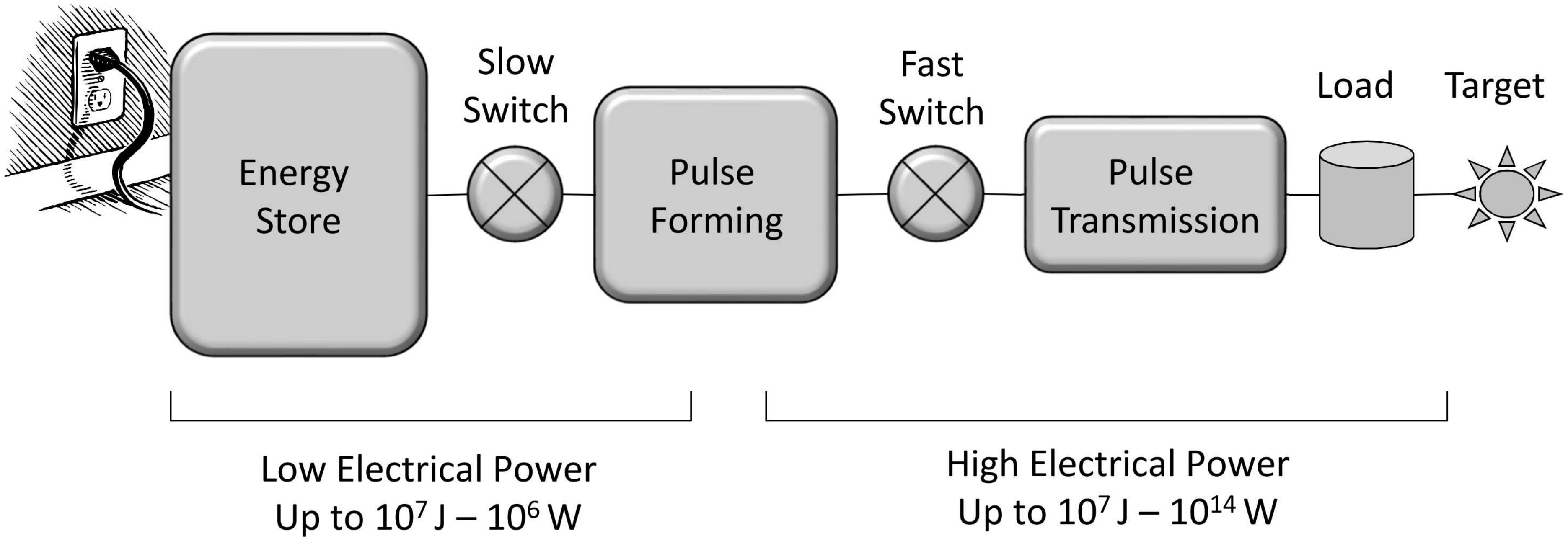
Pulsed power plays a key role in Sandia's REHEDS Research Foundation, one of 7 critical disciplines at Sandia supporting our national security missions



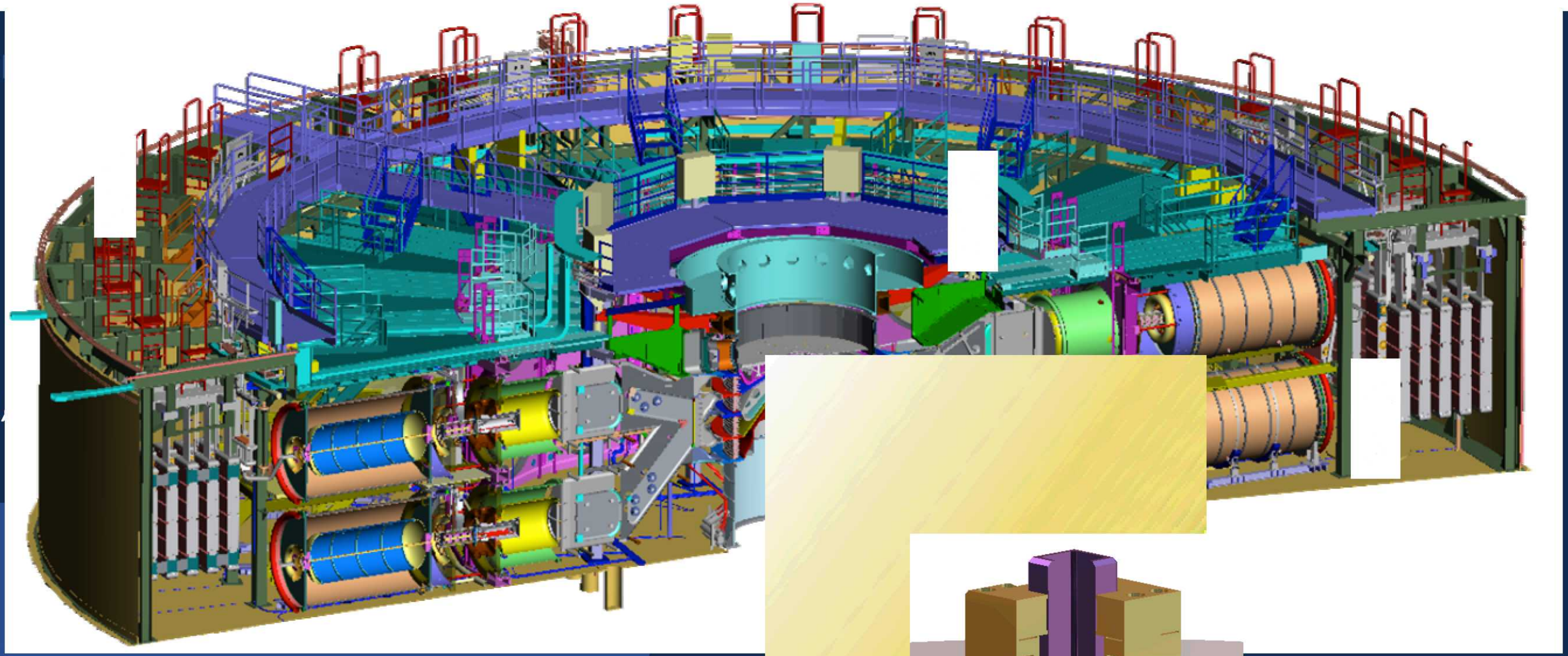
Pulsed power: The temporal compression of electrical energy to produce short bursts of high power



Sandia's Z Machine is a unique platform for multi-purpose research on high energy density (HED) environments

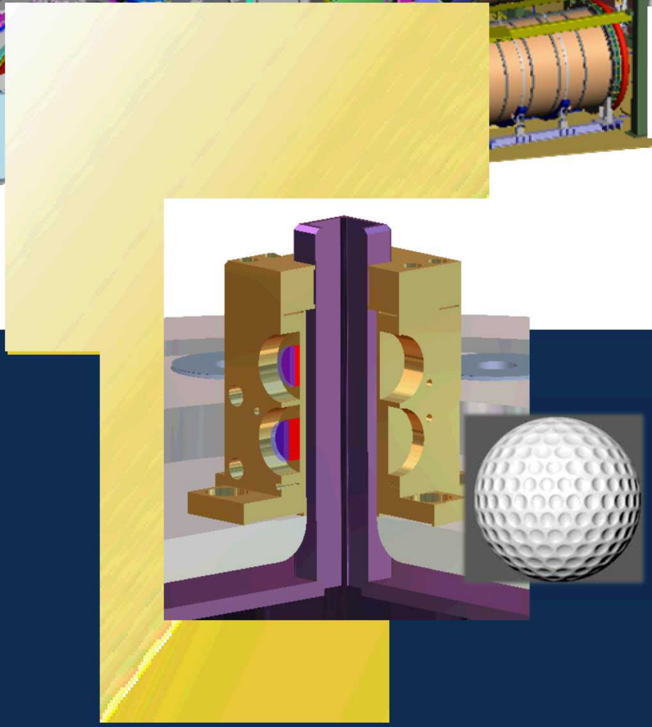
Sandia National Laboratories

Acknowledge teams:
Z operations, cryogenics, diagnostics, theory/ simulations, target design and -fabrication, engineering, and management



I ~ 26 MA,
τ ~100-1000 ns
X-ray power > 250 TW
X-ray energy > 2 MJ

- Pulsed Power Technology
- Radiation Sources/-Physics
- Inertial Confinement Fusion
- Materials at high pressure/EOS



MHD: currents and the corresponding magnetic fields create matter and radiation in extreme conditions

Sandia National Laboratories

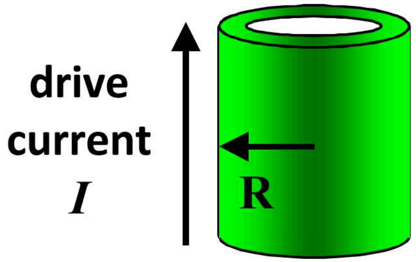
Current x magnetic field

Magnetic field as scalar pressure

$$\rho\left(\frac{\partial \mathbf{u}}{\partial t}+(\mathbf{u}\cdot\nabla)\mathbf{u}\right)=\frac{\mathbf{J}\times\mathbf{B}}{c}-\nabla P\approx\frac{1}{4\pi}\mathbf{B}\bullet\nabla\mathbf{B}-\nabla\left(P+\frac{B^2}{8\pi}\right)$$

Pressure

velocity field

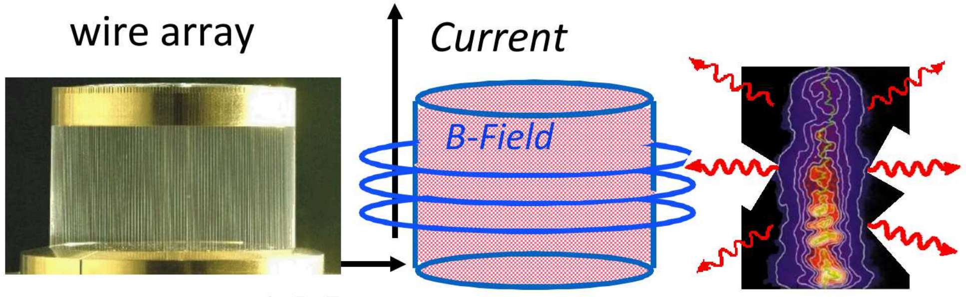


- 25 MA at 1cm radius is 1 Mbar
- 25 MA at 1mm radius is 100 Mbar

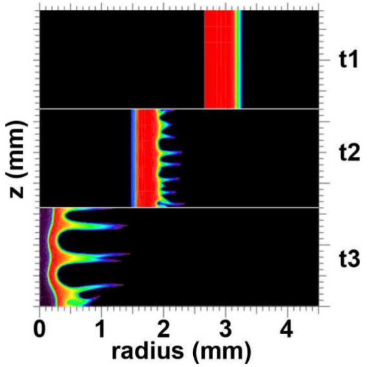
- Using pulsed power (current) as a source has advantages
  - *Can create high pressures without making material hot*
  - Generated over long time scales with control over the time history
  - Large samples and energetic sources (2 MJ to load of 20 MJ stored)
- Integrated projects with theory/simulations/experiment
  - Develop, design, analyze, and optimize experiments

We use magnetic fields to create HED matter in different ways for different applications

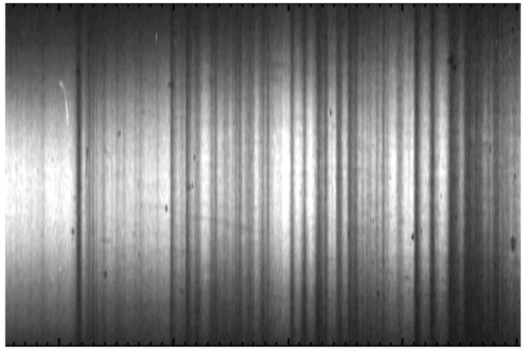
Radiation physics from Z-Pinch X-ray Sources



Atomic- and plasma physics

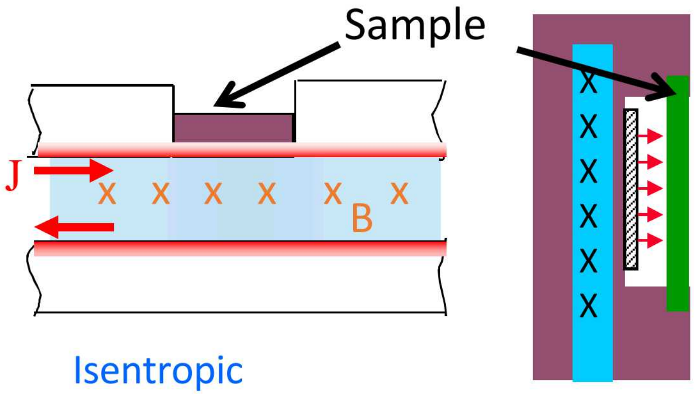


MRT instabilities



Iron spectrum

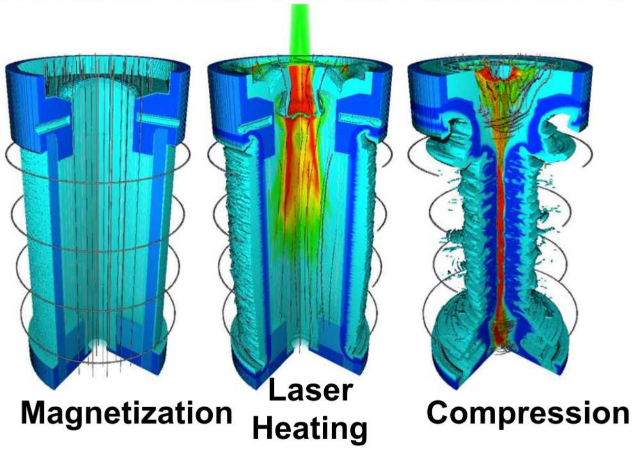
Materials Properties: EOS



Isentropic Compression

Flyer Plate

Inertial confinement fusion



The stockpile stewardship program needs data for materials under HED (High Energy Density) conditions

- **A broad range of materials**
  - Pu and U for LANL and LLNL
  - Be, DT, Li, CH for National ICF program
  - Stainless steel, W, Ta, water for pulsed power technology
  - Other materials from Al to Zn for a range of applications in HED science

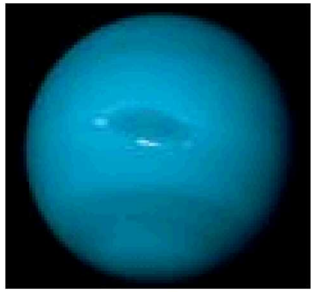
The Nation's Nuclear Deterrence is not only the hardware – it is also the people of the NNSA Labs

Scientists, engineers, and others with the education, knowledge, skills, and resources to stay at the very forefront of science.

Avoiding Technological Surprise is an important part of what we do.

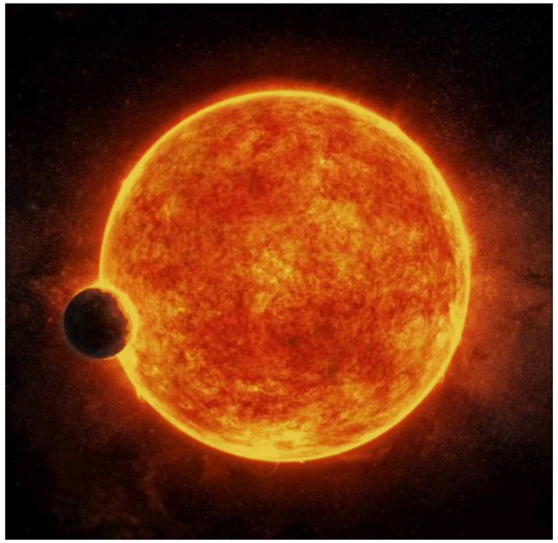
Planetary science also needs data for materials under HED conditions

- **Planetary science – Earths and super-earths**
  - Silicates, MgO, and iron/iron alloys
  - Determining the vaporization threshold for iron – and implications for planetary formation, Nature Geoscience 2015.
  - Sarah Stewart – recent MacArthur Fellow "Genius award" is a part of the collaboration on planetary science.
- **Planetary science – Jupiter, Saturn, Uranus, Neptune, and exo planets [e.g. hot Neptunes]**
  - Water, metallization of hydrogen/deuterium: Science 2015



We seek to turn planetary science quantitative by high fidelity modeling and high-precision experiments

Vaporization during planet formation and evolution is a key mechanism – large uncertainty in the onset of vaporization



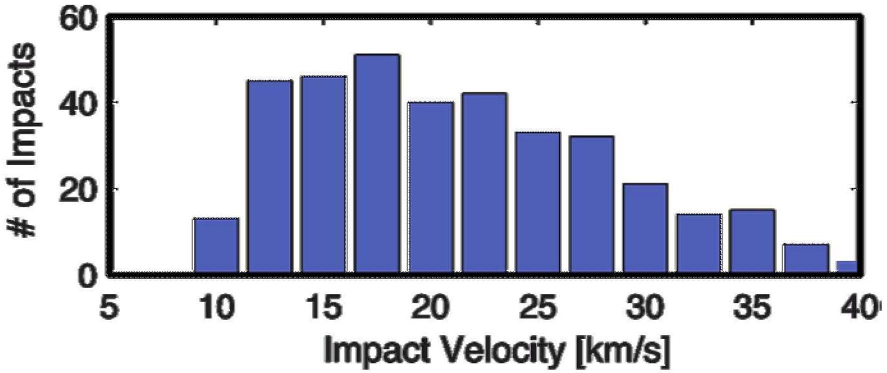
- Giant impacts and the origin of the moon
- Addition and removal of planetary atmospheres
- Chemical evolution of planets
- Exoplanets! Wide range of interiors and atmospheres, mass-radius diagrams
- Ted Talk by Professor Sarah T. Stewart "Where did the Moon come from? A new Theory"

Giant impacts vaporize portions of planets

D. Crawford, 2011
CTH calculation

Z experiments provide material properties in HED conditions to address the moon formation mystery

Does an iron meteor:
- plow into a planet as a bullet?
- splatter as a drop of rain?
- vaporize into a cloud of iron to return as iron rain?



We determined that vaporization is significantly easier than previously thought, changing the way we understand giant impacts.

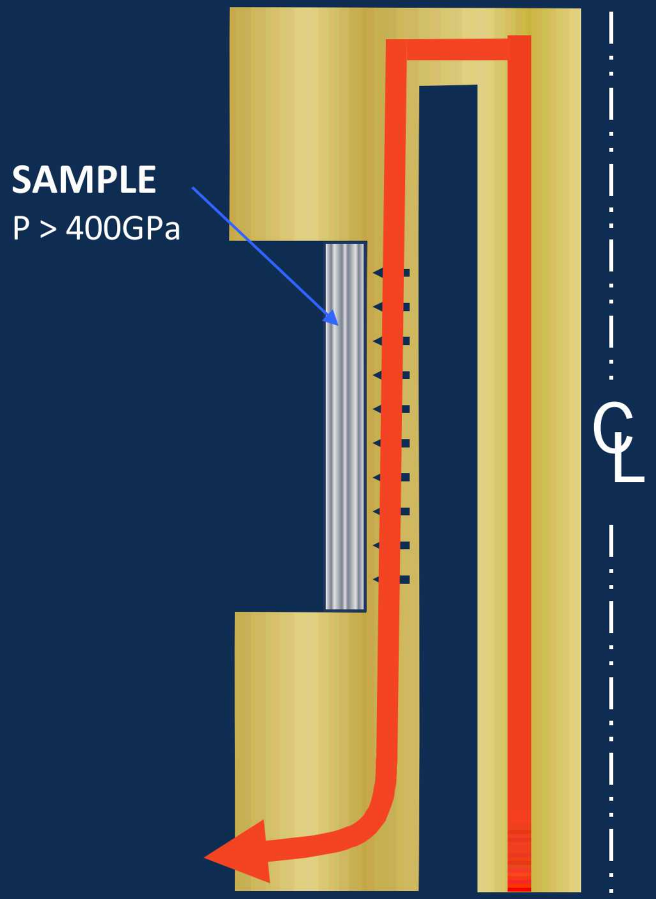
See Sarah's TED talk for an example

Simulations of planetary dynamics suggest high impact velocities.

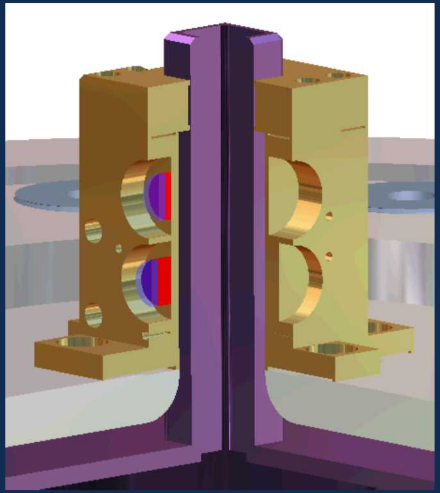
These velocities are directly accessible on the Z-machine!

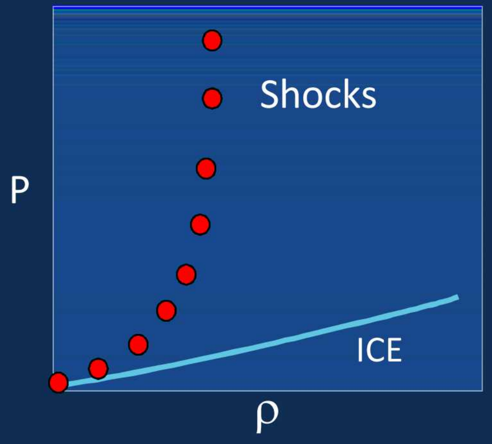
Impact vaporization of planetesimal cores in the late stages of planet formation, R.G. Kraus, S. Root, R.W. Lemke, S.T. Stewart, S.B. Jacobsen, and T.R. Mattsson, Nature Geoscience 2015 DOI: 10.1038/NGEO2369

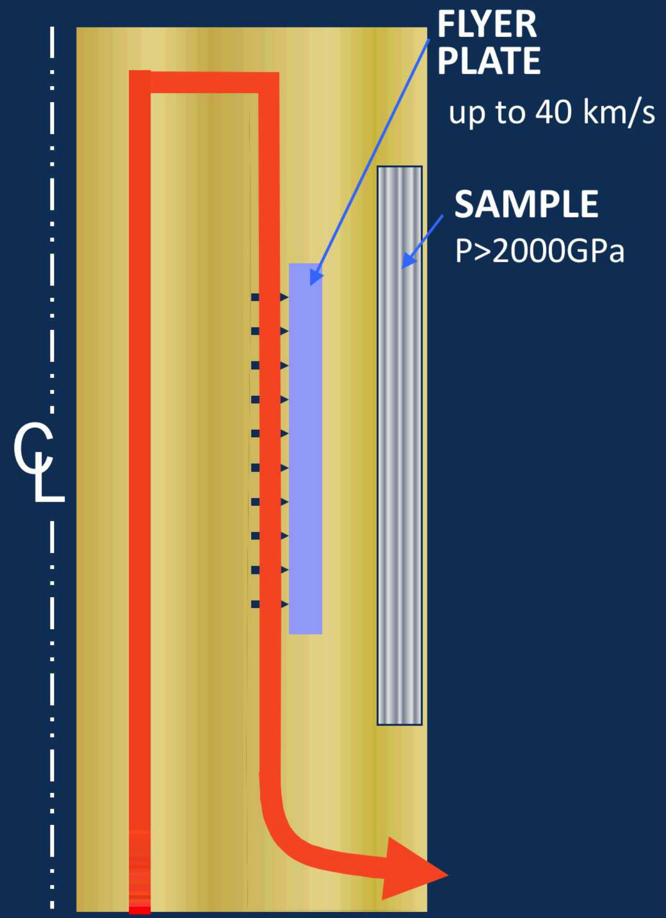
Isentropic compression and shock wave experiments map different regions of phase space



Isentropic Compression Experiments:
Gradual pressure rise in sample



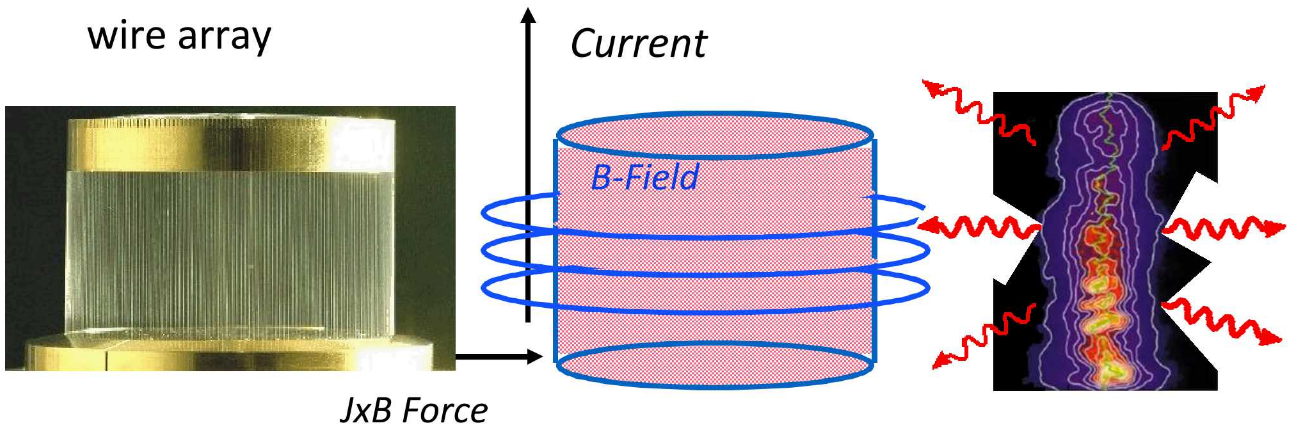




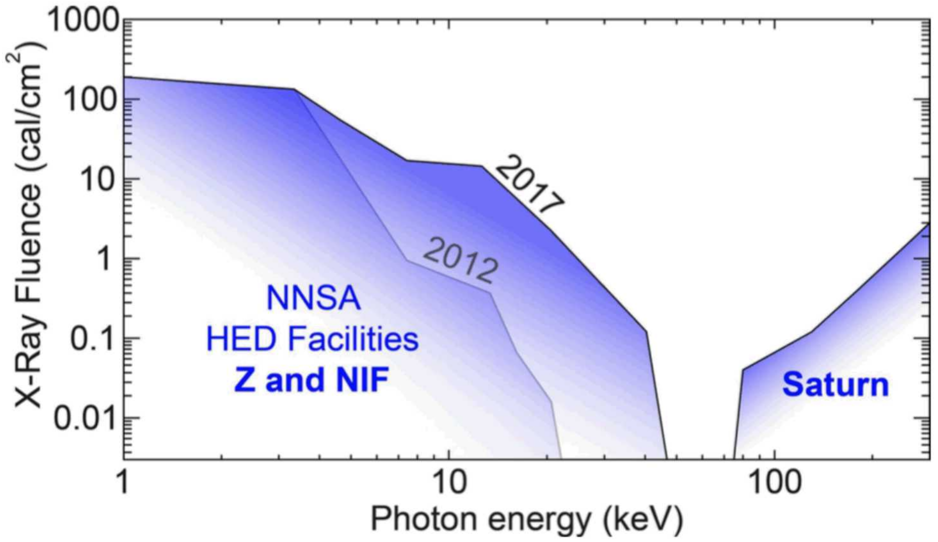
Shock Hugoniot Experiments:
Shock wave in sample on impact

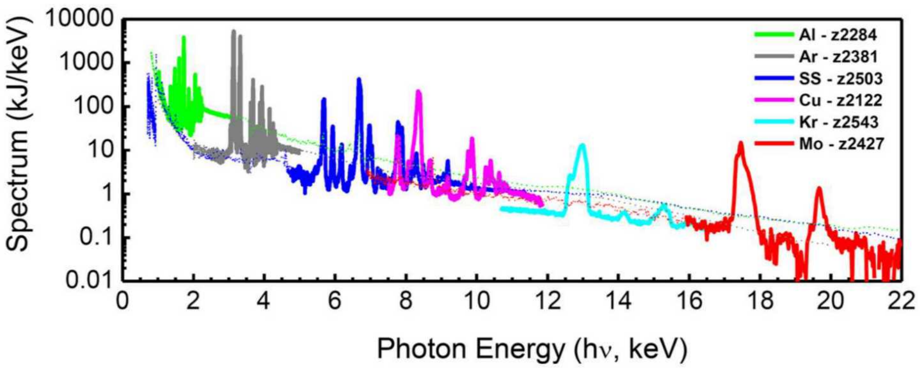
Radiation driven experiments to study fundamental atomic- and plasma physics is a major part of the ZFSP

Radiation physics from Z-Pinch X-ray Sources



Sandia and Lawrence Livermore National Laboratories are collaborating to produce record levels of >10 keV x rays



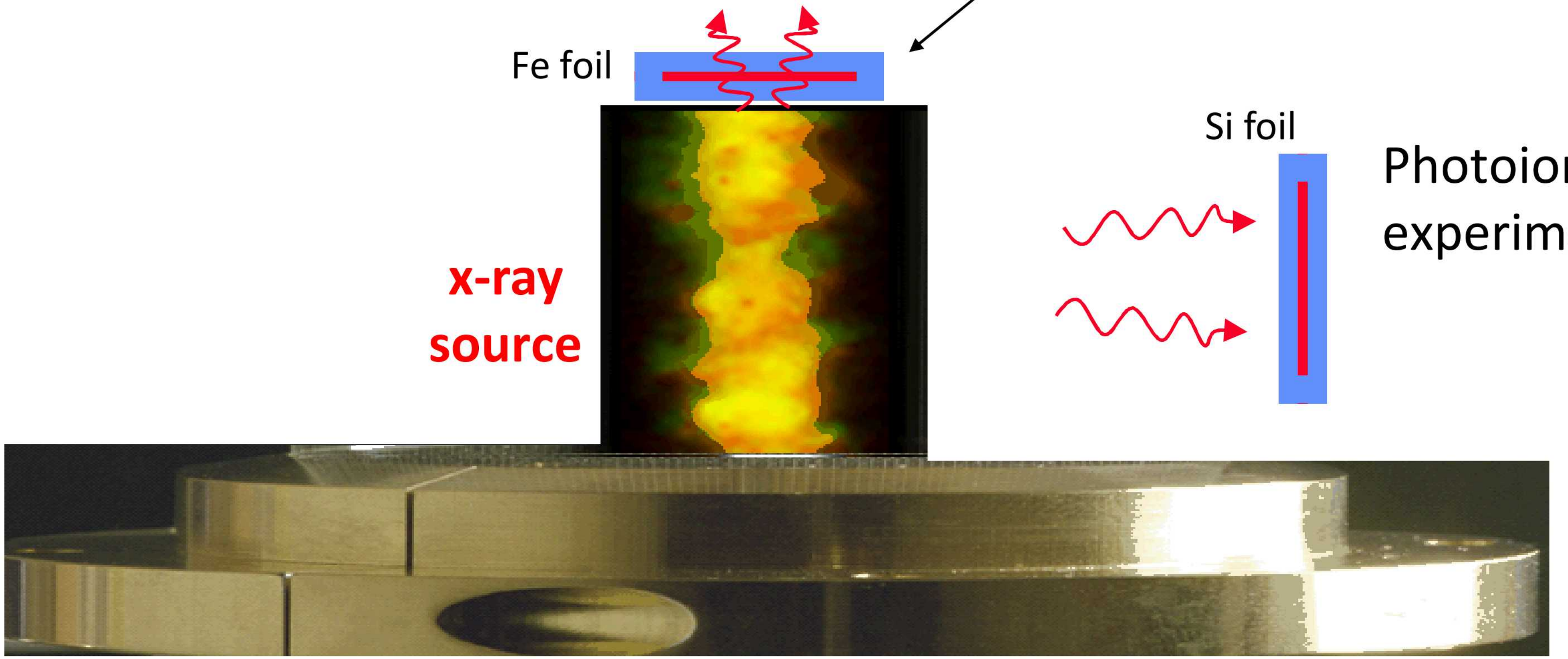


These x-ray sources are being used to study physics models for matter exposed to rapid, intense doses of x rays

e.g., Studies of high-rate thermal degradation of polyethylene, where ~3 keV x-rays can heat ~100 microns of material at ~10^{12} K/s.
Lane & Moore, Phys. Chem. A 122 (2018).

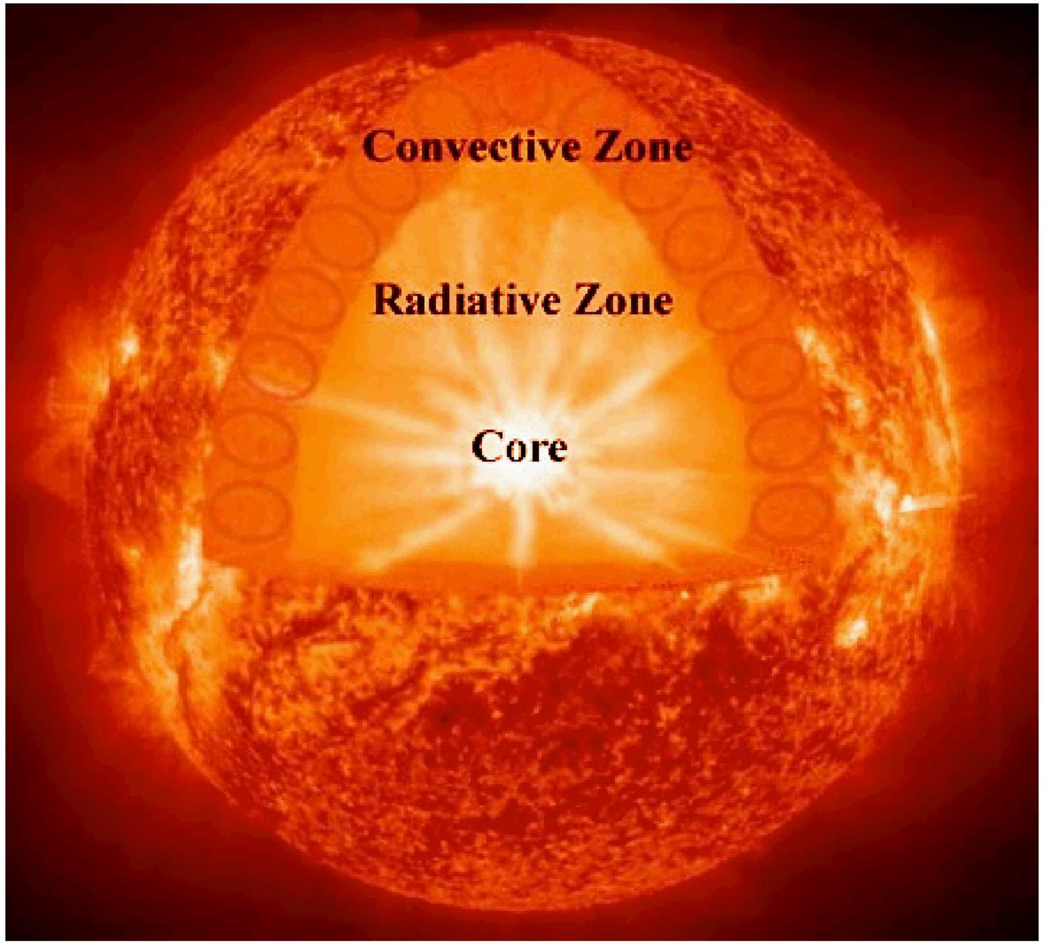
D.J. Ampleford *et al.*, Phys. Plasmas 21, 056708 (2014).

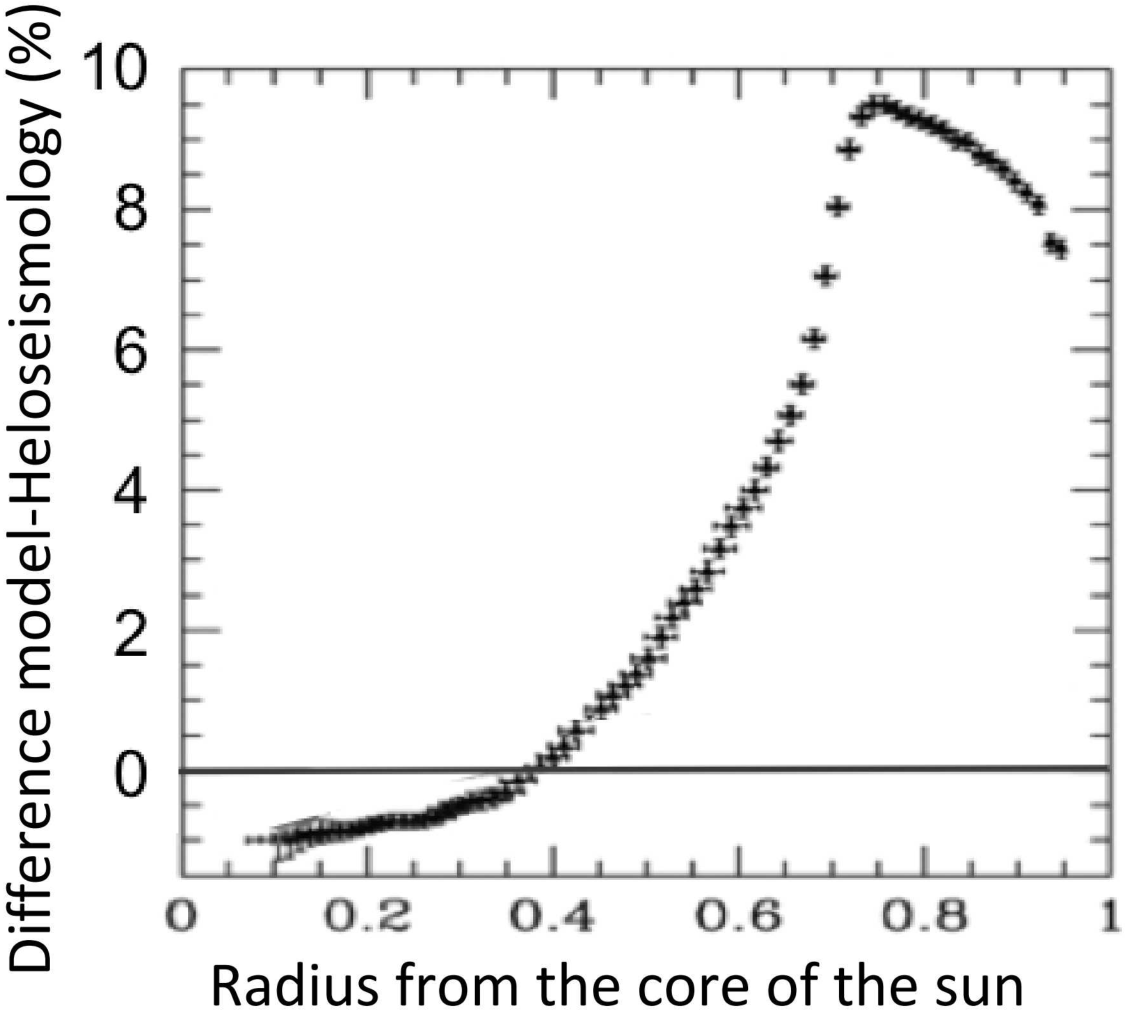
The Z machine uses 27 million Amperes to create x-rays, and perform multiple benchmark experiments simultaneously



Sanford, *PoP* (2002); Bailey et al., *PoP* (2006); Slutz et al., *PoP* (2006); Rochau et al., *PPCF* (2007)

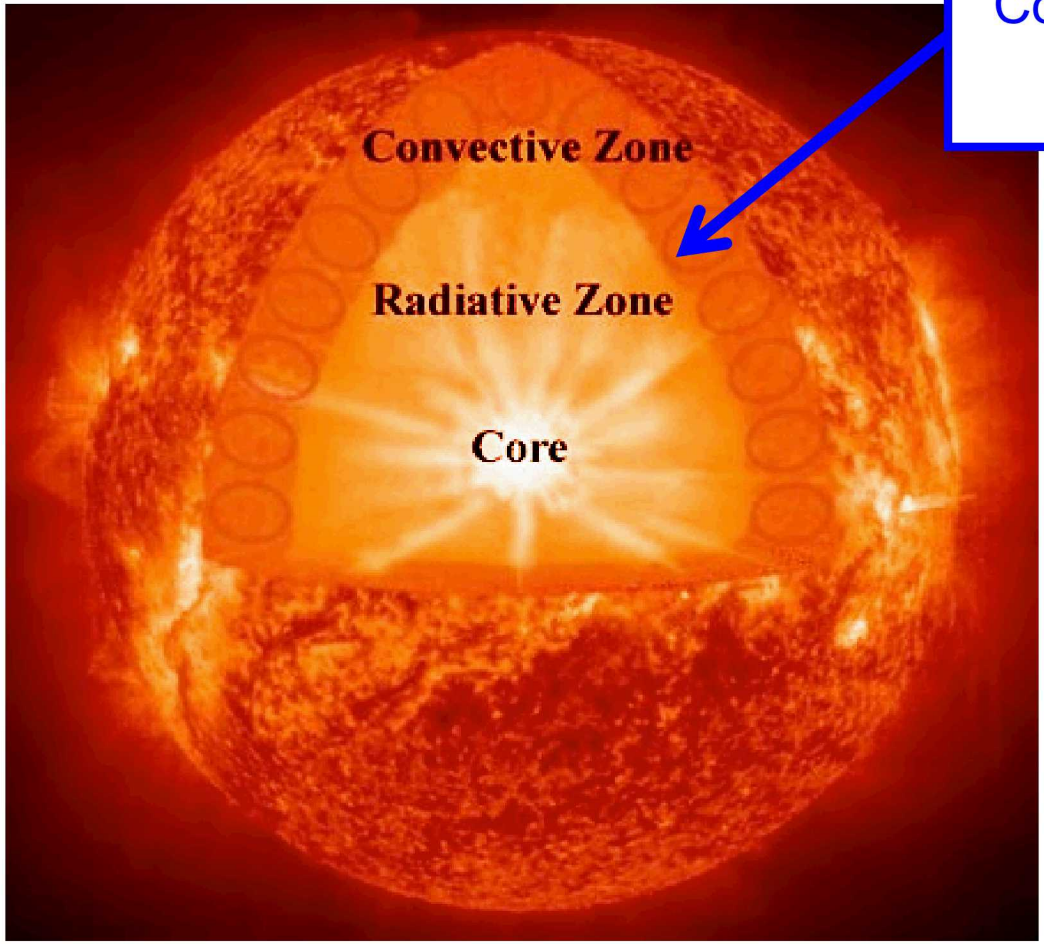
Modeled solar structure disagrees with observations

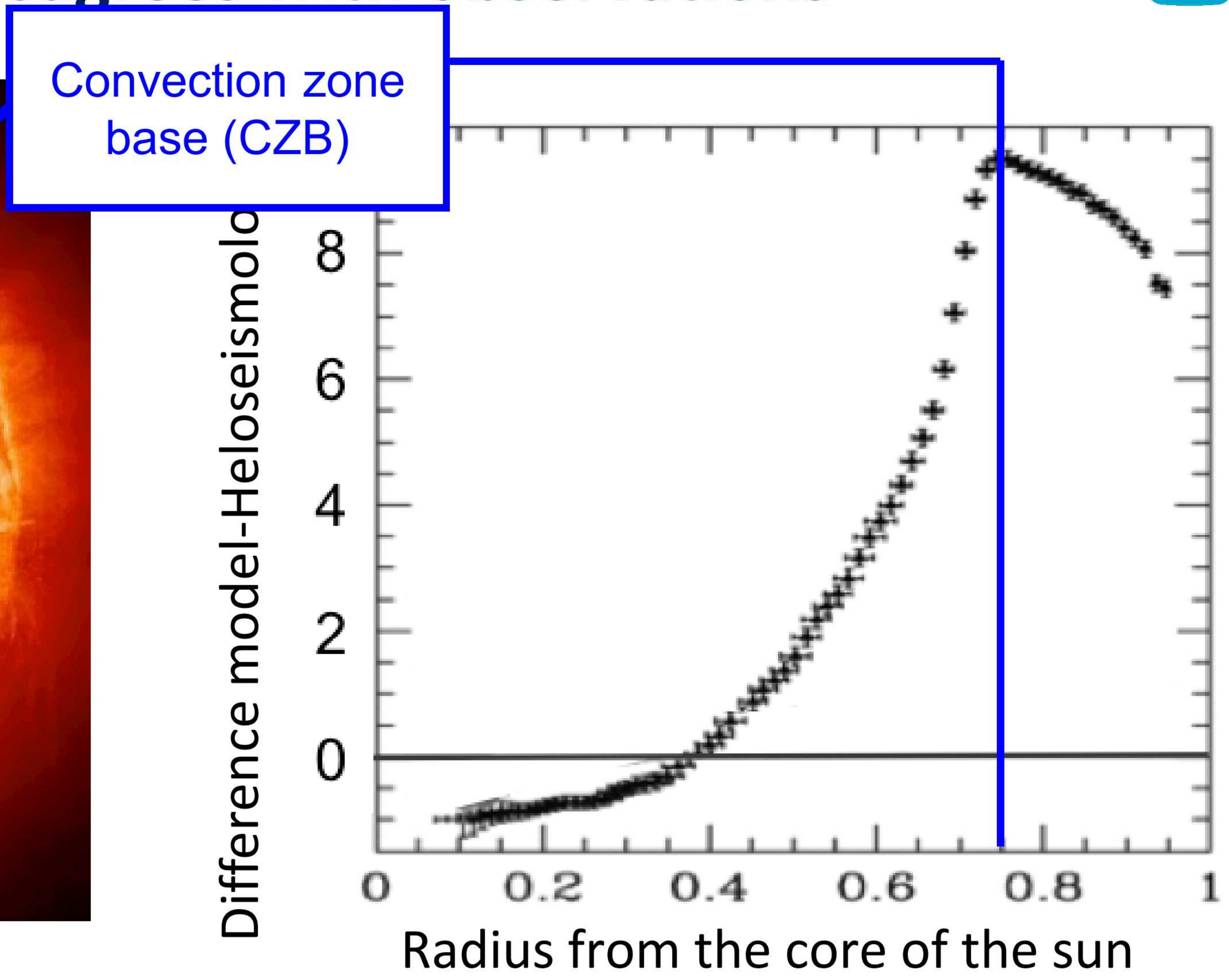




[1] S. Basu and H. M. Antia, Physics Reports 457, 217 (2008).

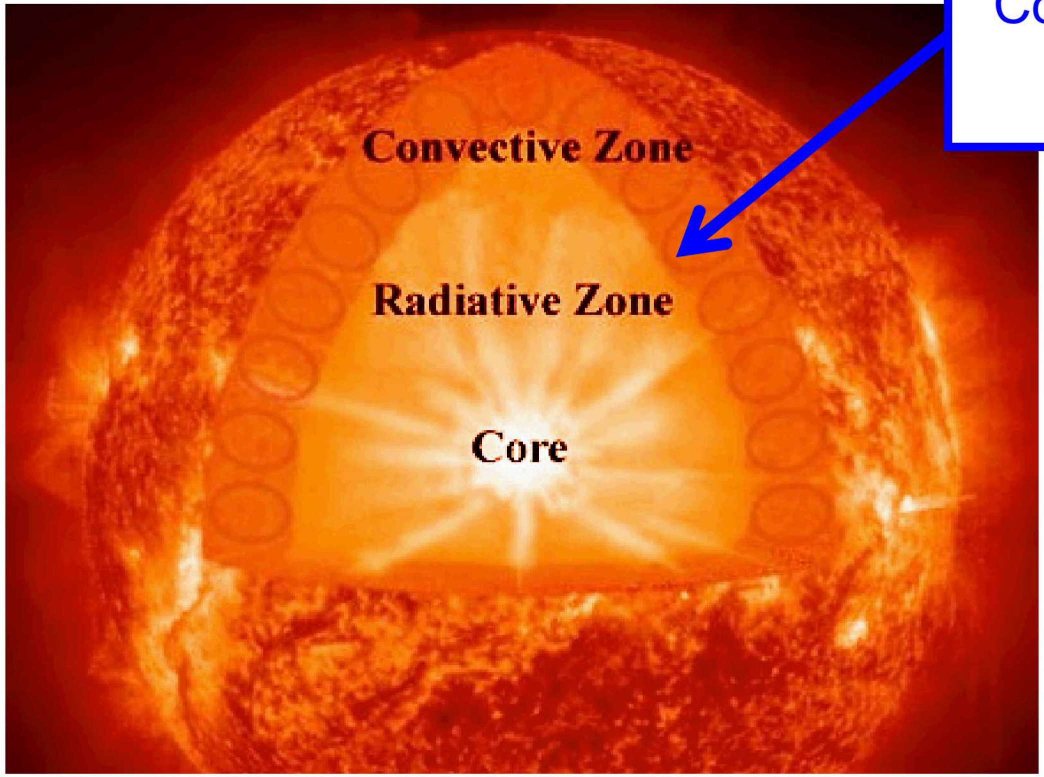
Modeled solar structure disagrees with observations

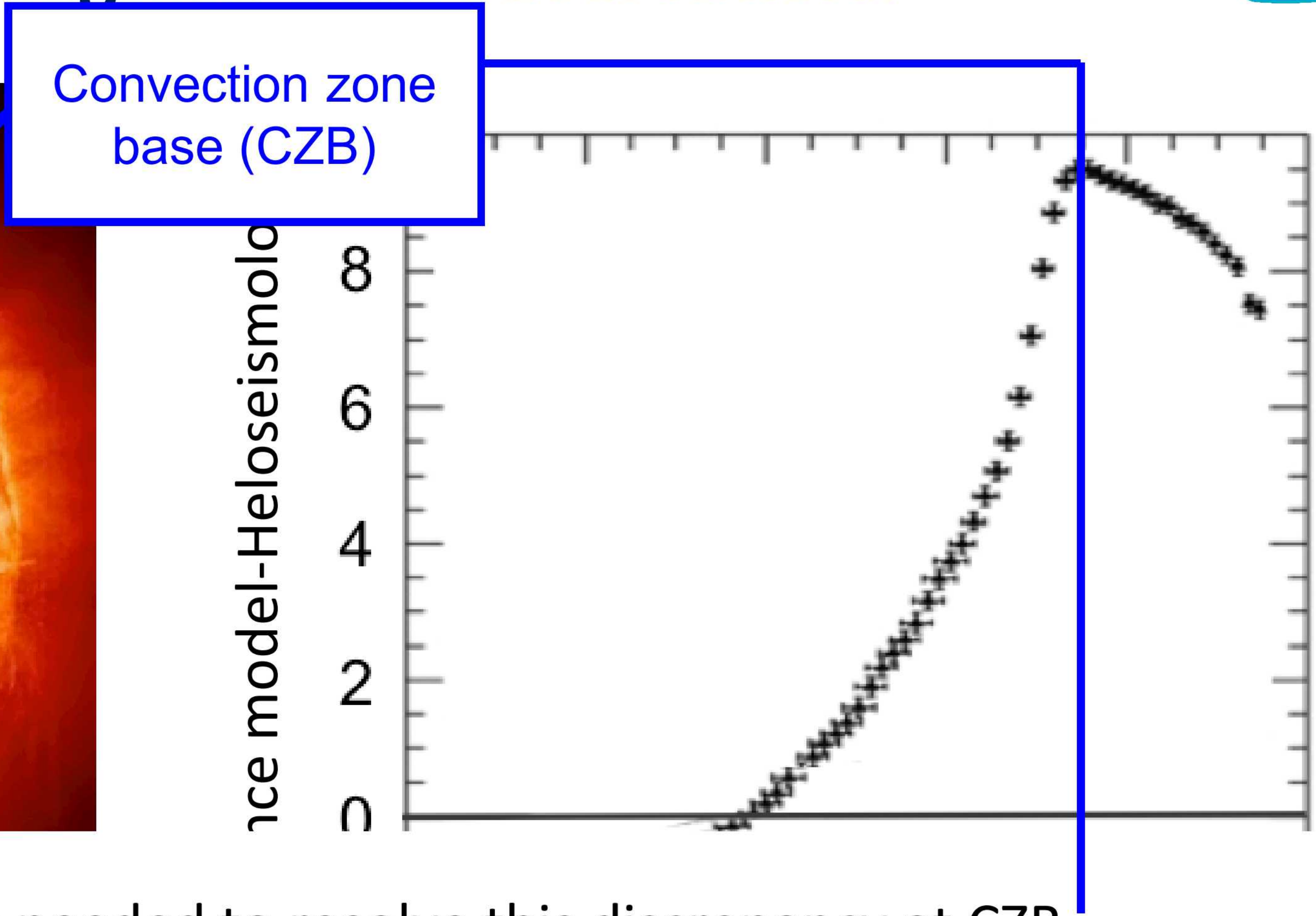




[1] S. Basu and H. M. Antia, Physics Reports 457, 217 (2008).

Modeled solar structure disagrees with observations



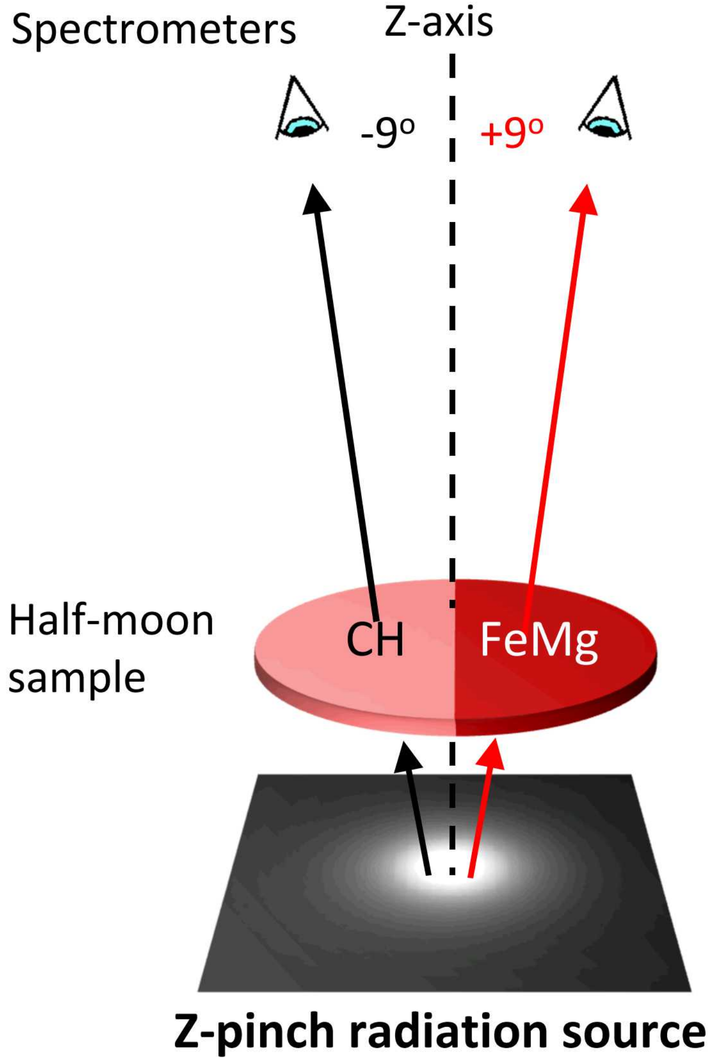


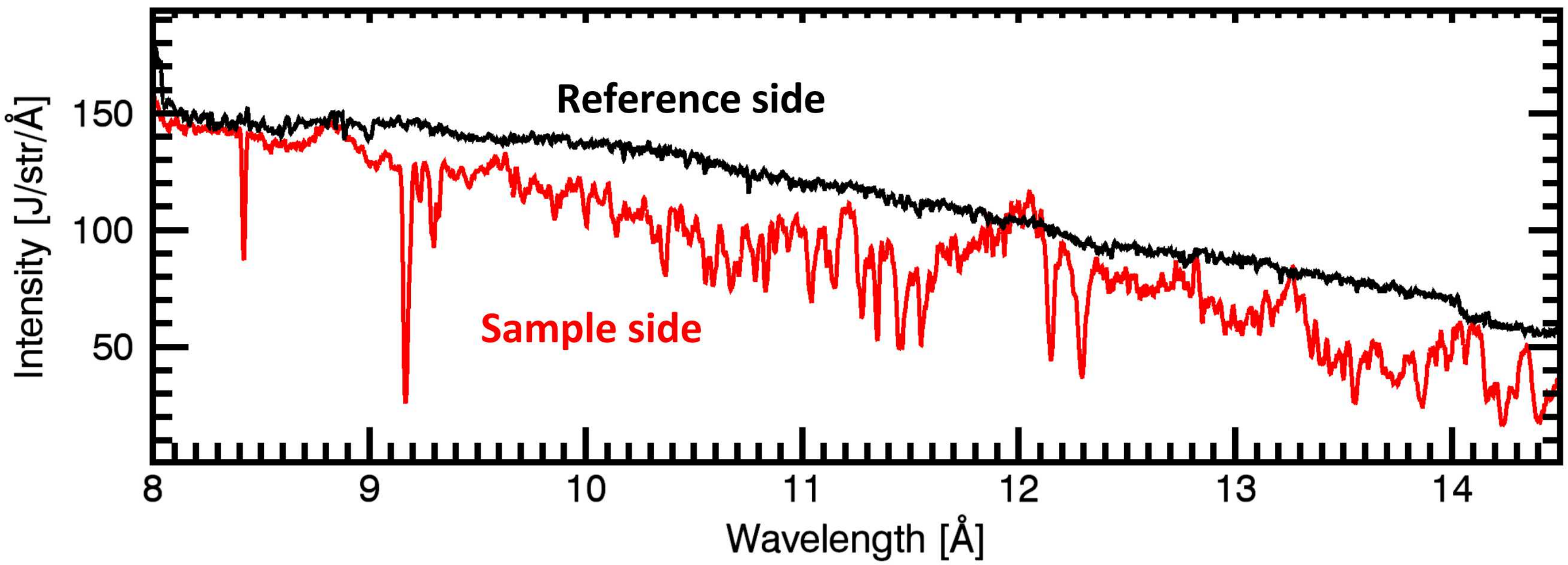
- 17% mean-opacity increase is needed to resolve this discrepancy at CZB
- Calculated opacity has never been tested at solar interior conditions

Objective: Measure Fe opacity at conditions approaching the CZB

[1] S. Basu and H. M. Antia, Physics Reports 457, 217 (2008).

High-temperature Fe opacities are measured using the Z-Pinch opacity science platform



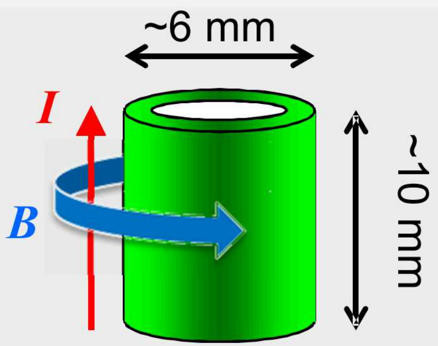


Modeled opacity shows severe disagreement as conditions approach ones in the solar interior

Bailey et al., *Nature* 517, 56 (2015).

Magnetic direct drive provides an alternative way to do ICF using an axial B-field to reduce confinement requirements

Magnetic Direct Drive (MDD)



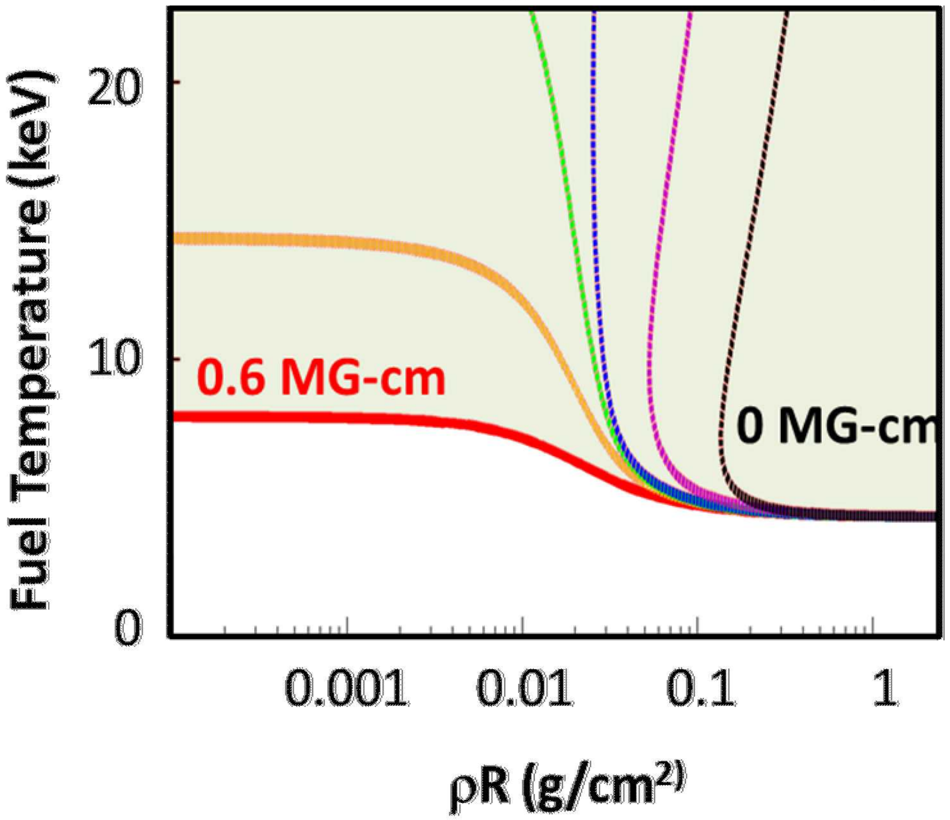
Drive Pressure

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

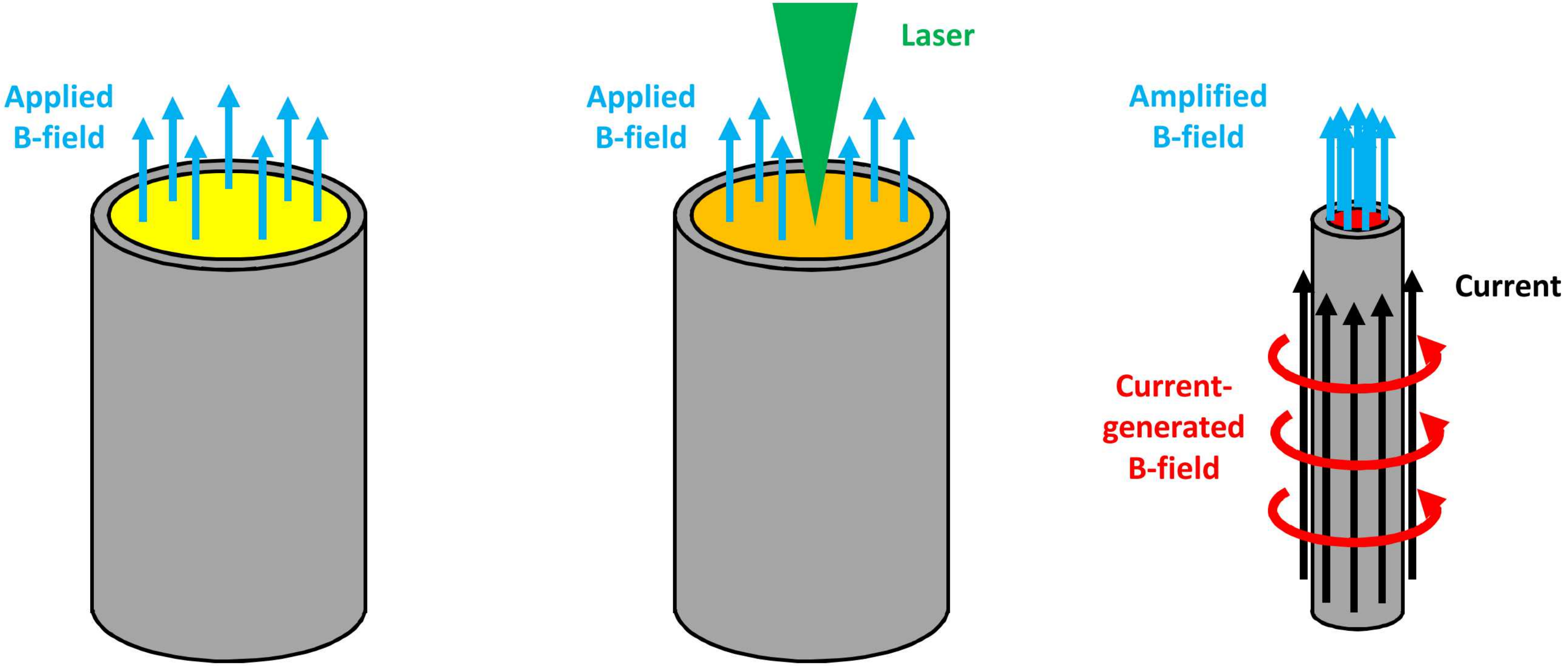
- Cylindrical convergence
  - Harder to achieve high ρr
- Thick liners (~500 μm)
  - Harder to achieve high velocity

Imposing an axial B-field relaxes ρr requirements

Curves of self-heating from DT fusion alphas



Magnetized Liner Inertial Fusion (MagLIF) relies on three stages to produce fusion relevant conditions



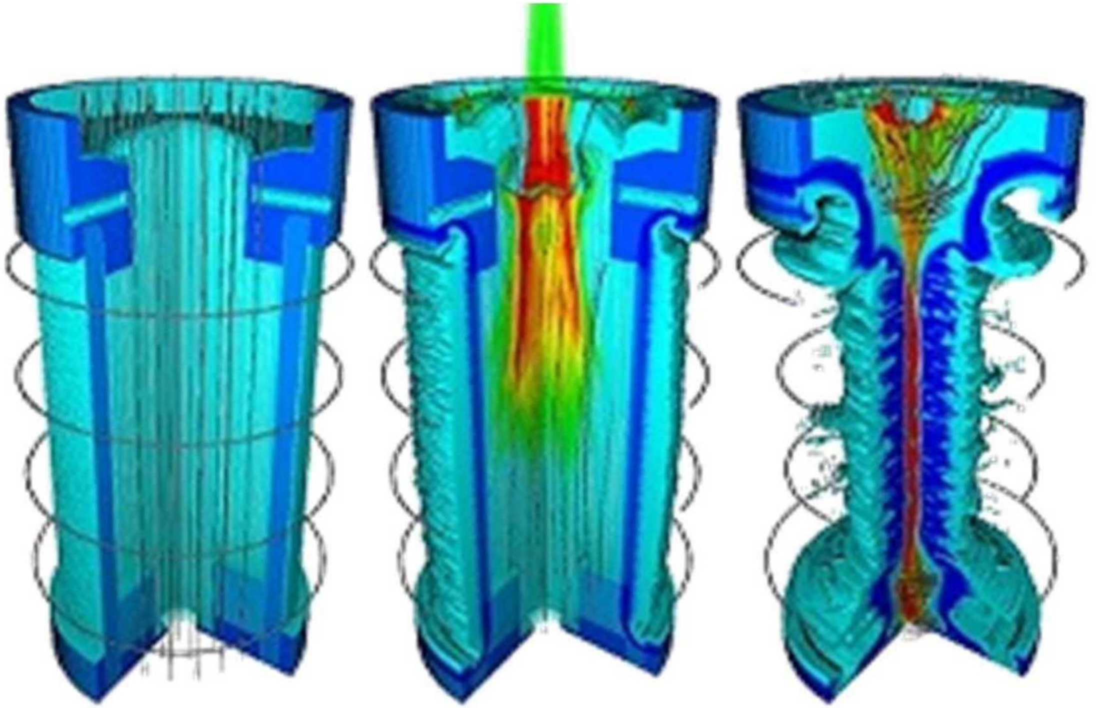
Apply axial magnetic field

Heat the magnetized fuel (e.g., with a laser)

Compress the heated and magnetized fuel

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

Magnetized Liner Inertial Fusion (MagLIF) relies on three stages to produce fusion relevant conditions

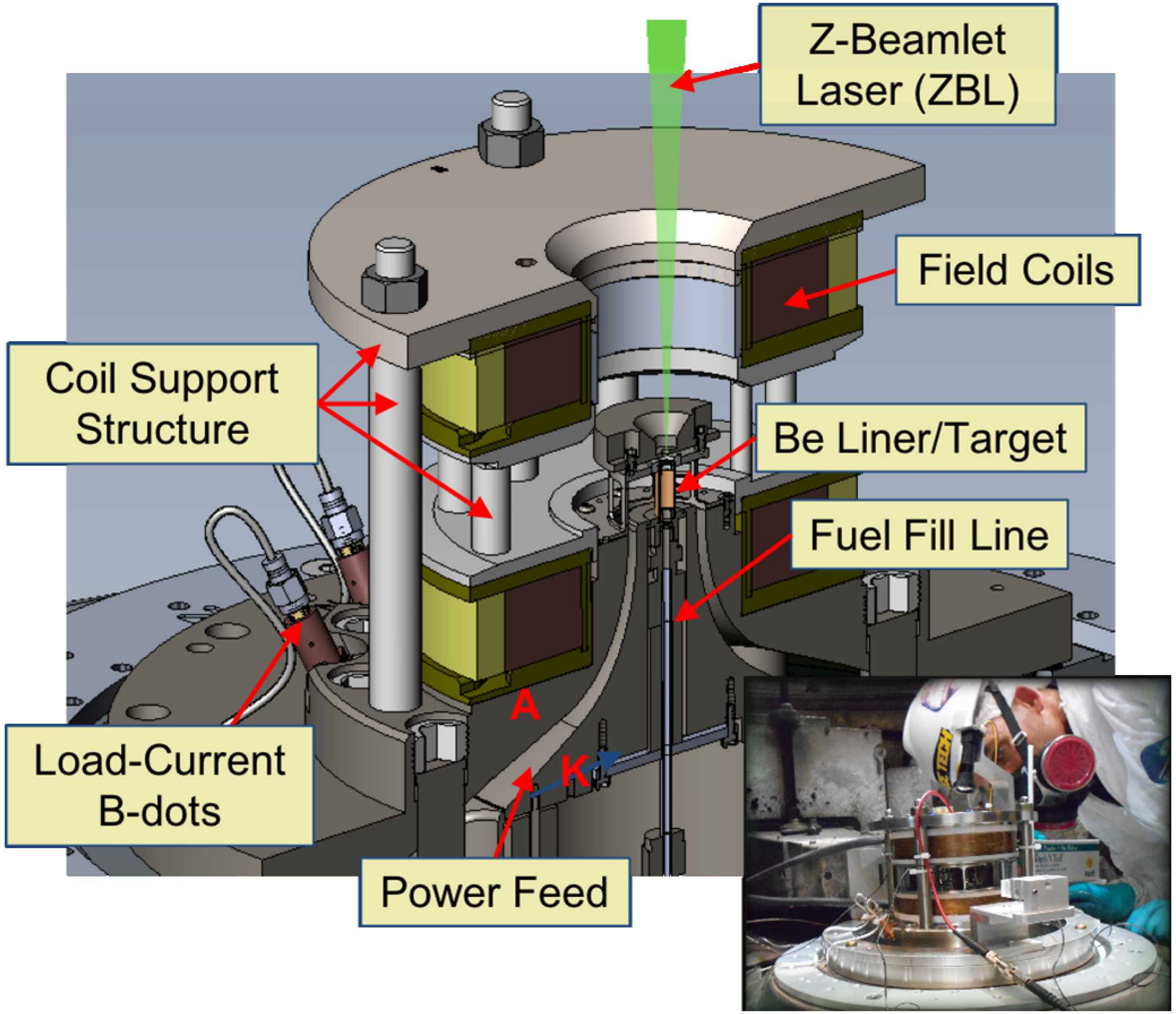


Configuration of initial MagLIF Experiments (ca. ~2014)

Sandia National Laboratories

- **Field Coils**: Helmholtz-like coil 10-30 T axial field ~3 ms rise time

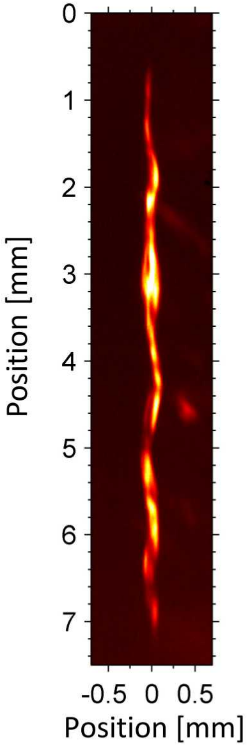
- **ZBL**: 1-4 kJ green laser, 1-4 ns square pulse w/ adjustable prepulse (prepulse used to help disassemble laser entrance window)



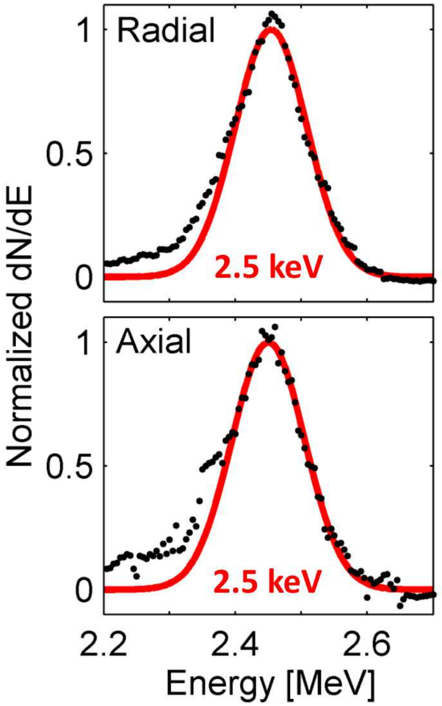
M.R. Gomez *et al.*, Phys. Rev. Lett. (2014); D.C. Rovang *et al.*, RSI (2014).

We have demonstrated key aspects of magneto-inertial fusion on Sandia's Z facility

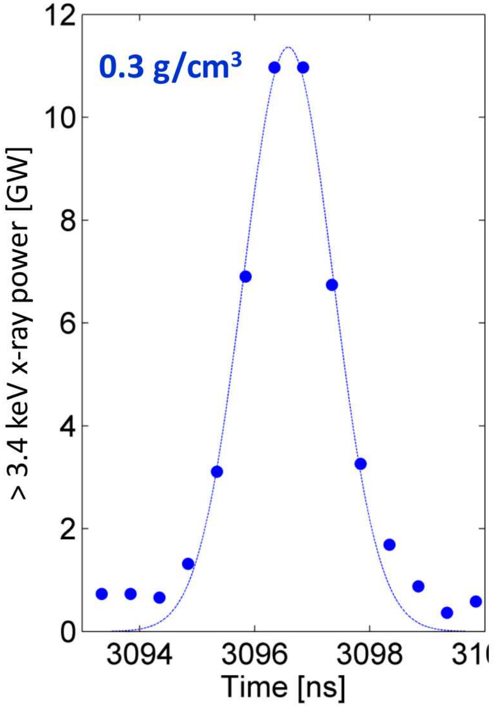
Well-behaved stagnation volume



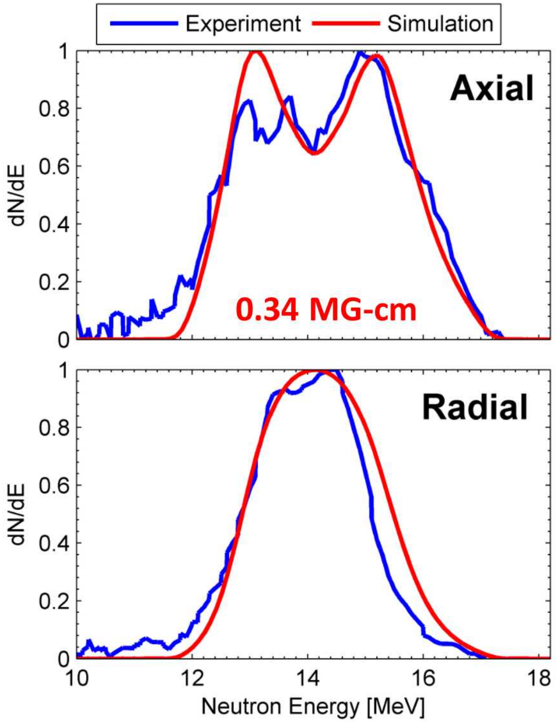
Relevant temperatures



Relevant densities



Relevant fuel magnetization

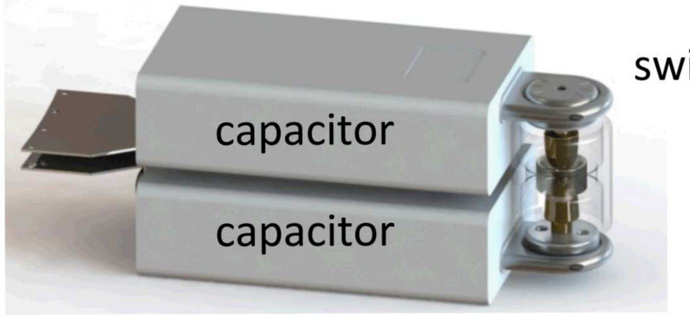


Differences in nTOF shape of secondary DT peak due to magnetization of tritons

M.R. Gomez *et al*., Phys. Rev. Lett. 113, 155003 (2014);
K.D. Hahn *et al.,* RSI 85 (2014);
S.B. Hansen *et al*., Phys. Plasmas 22, 056313 (2015);
P.F. Schmit *et al*., Phys. Rev. Lett. 113, 155004 (2014).

We are exploring a modular architecture that can scale to 300-1000 TW and is twice as electrically efficient as Z

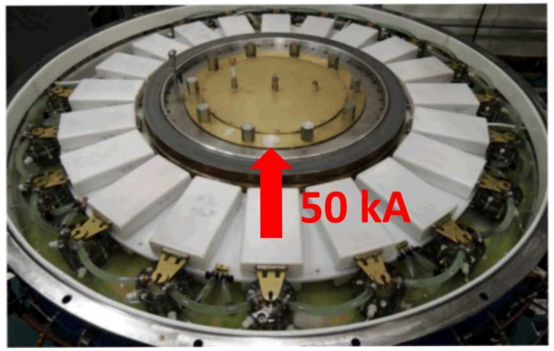
Brick – "quantum" of the next gen systems
Single step pulse compression to 100 ns



switch

5.2 GW/800 J per brick

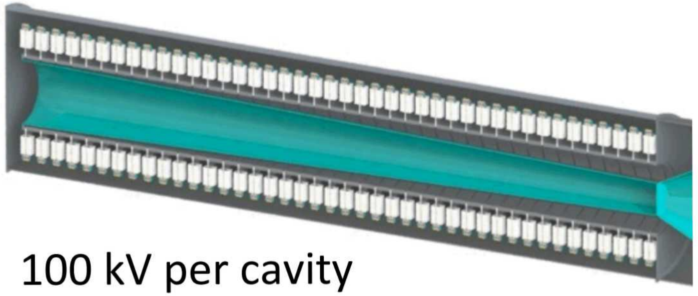
Cavity – multiple bricks in parallel



50 kA per brick

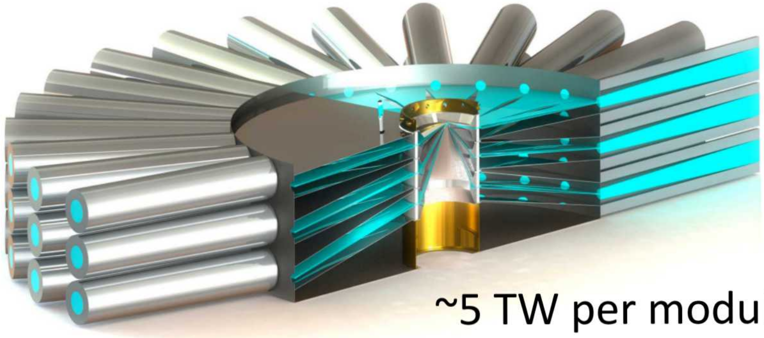
Module – multiple cavities in series

Linear Transformer Driver (LTD)



100 kV per cavity

Machine – multiple modules and levels in parallel

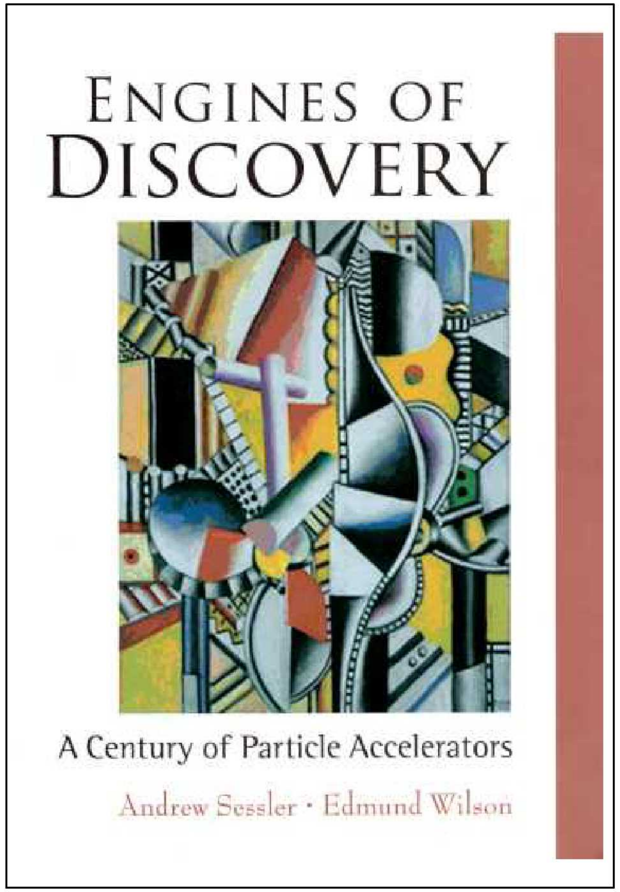


~5 TW per module

Next-gen machines: 20,000-200,000 bricks, 33-60 cavities/module, and 65-800 modules!

W.A. Stygar *et al.*, PRSTAB (2007); W.A. Stygar *et al.*, PRSTAB (2015); W.A. Stygar *et al.*, Proc. IEEE PPC (2017).

Pulsed power machines can be “engines of discovery” for HED science, just as particle accelerators have been – the future is exciting!



- Classical particle accelerators have numerous applications to fundamental understanding of the universe and structure of matter, to probing of matter, and to industrial and medical applications.
  - Induced radioactivity, Isotope enrichment, antiproton, nuclear structure, J/ψ (quarks), tau lepton, W, Z particles, top quark, Higgs boson
  - Industrial (hardening, sterilization)
  - Medical use (imaging, therapy)
  - Research (x-ray and particle probes)
  - 14 Nobel prizes for accelerators or using accelerators
- Pulsed power accelerators are engines of discovery for HED science
  - Intrinsic material properties (EOS, conductivity, strength, structure of materials)
  - Radiation transport, atomic physics, opacity
  - Magnetized plasma physics
  - Fusion ignition (”chief unsolved problem in plasma physics”)

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

- **10 teams won shots on the 18-19 allocation**
  - Carnegie Institution of Washington
  - Lawrence Livermore National Laboratory
  - Northwestern University
  - Sandia National Laboratories
  - UC Davis/ Harvard
  - University of Rostock, Germany
  - UN Reno
  - UT Austin x 2
  - Washington State University
- **12+ students are currently involved**
  - Former students have done very well
- **Resources over 8 years**
  - 100 dedicated ZFSP shots (5-7% of all Z shots)
  - Ride-along experiments on Z program shots, guns, DICE, and THOR

- **Science with far-reaching impact**
  - Nature, Nature Geoscience, SCIENCE
  - 6 Phys. Rev. Lett, 3 Physics of Plasmas, 5 Physical Review (A,B,E)
  - About 40 total peer reviewed publications and 10 conference proceedings
  - 70+ invited presentations

- **Popular outreach**
  - National Public Radio, "All things considered", 2014
  - Discover Magazine
    - Reportage 9/16/2012
    - *Iron rain #62 in top 100 Science stories in 2015*
  - Albuquerque Journal Front Page 9/2017
  - Twice local TV coverage on planetary science

The ZFSP greatly benefits Sandia's and NNSA mission on both short- and long term

Sandia National Laboratories

- **Direct recruiting**
  - Rick Kraus (Ph.D. Harvard) – Lawrence Fellow, now staff at LLNL
  - Ross Falcon (Ph.D. UT Austin) – postdoc at Sandia
  - Taisuke Nagayama (Ph.D. UN Reno) – staff at Sandia
  - Mark Schoeble (Ph.D. UT Austin) – staff at Sandia

- **Growth in the HED science community**
  - HEDLP funding to Harvard and UT Austin
  - Active participation in the academic community of HED science – attracting new academic partners

- **Direct methods development**
  - The platform for shock experiments developed jointly with Harvard is now our standard setup for science campaign experiments
  - The work on Fe opacity has served an important role for platform development and provides international peer review benefitting research in science campaigns

- **Development of technical staff**
  - An opportunity for Sandia staff to do leading research and participate fully in the international research community