SAND2020-6864C

Sandia National Laboratories

Pulsed Power Z-Pinch Program at Sandia

PRESENTED BY

Dr. Daniel Sinars, Director of the Pulsed Power Sciences Center at Sandia National Laboratories

ZNetUS Workshop | January 6-8, 2020

U.S. DEPARTMENT OF ENERGY NNSA

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Laboratory pulsed power science and technology at Sandia National Laboratories is making electrifying progress

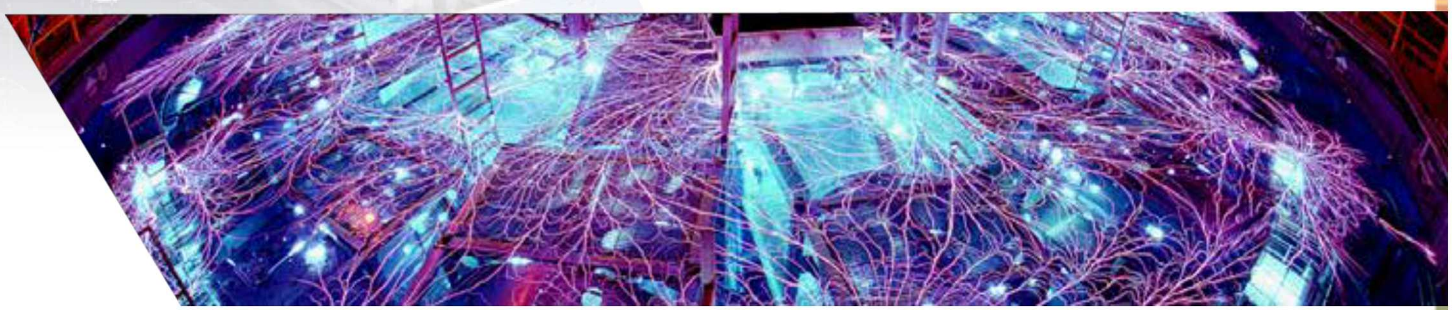
- Sandia National Laboratories "Z" facility, the world's largest pulsed power machine, is used for a wide range of fundamental, use-inspired, and applied research in high energy density science.
- While Z has existed in its current configuration since 1996, we have set multiple facility records in the last few years, such as peak pressure in material samples (>7.5 Mbar), cold and warm x-ray fluence on target samples, and neutron yield.
- Sandia enjoys a scientifically productive relationship with the academic community through its Z Fundamental Science Program.
  - ZNetUS could be an opportunity for us to expand our collaborations in other ways.
- Pulsed power driver technology is seeing a significant increase in investment.
  - Sandia just announced that it will be investing $40M over the next several years in Laboratory Directed Research and Development funds to push foundational technology research. We are planning for a number of new academic collaborations as part of this initiative.
- We are developing new tools for understanding power flow physics, where the energy from Z is coupled to the high energy density targets at its center.
- Sandia has proposed a >60 MA pulsed power facility to the NNSA for advanced mission work, which could nominally be in place around 2032 or later.
  - NNSA is also looking at the case for intermediate-scale facilities

SANDIA NATIONAL LABORATORIES

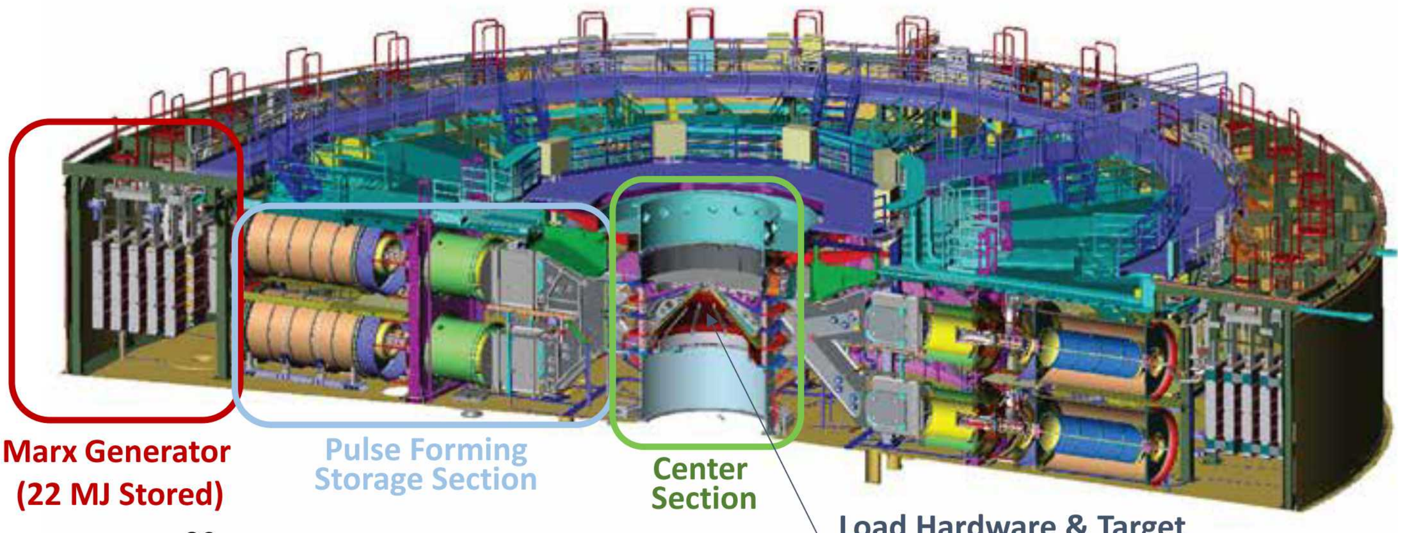
A federally funded research and development center managed and operated by National Technology & Engineering Solutions of Sandia, LLC.

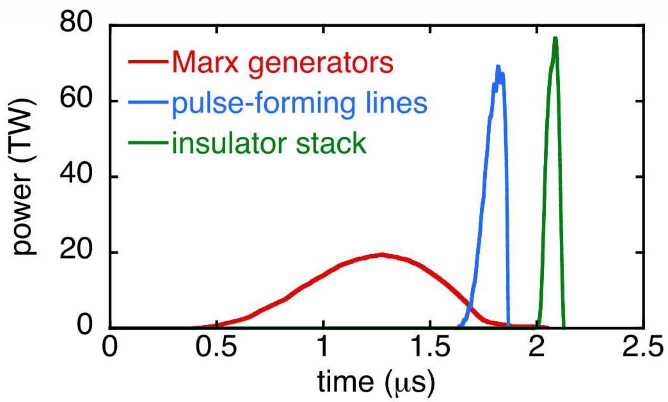
Sandia works on a diverse portfolio of research:

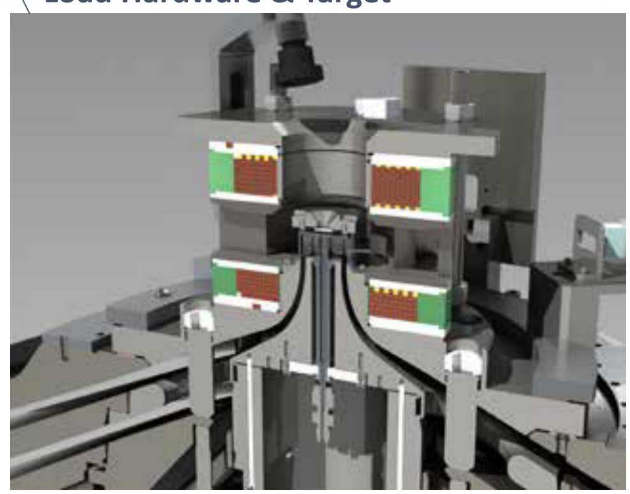
- Advanced Science & Technology
- Nuclear Deterrence
- National Security Programs
- Energy & Homeland Security
- Global Security



Z compresses energy in space and time to generate fusion conditions at its center

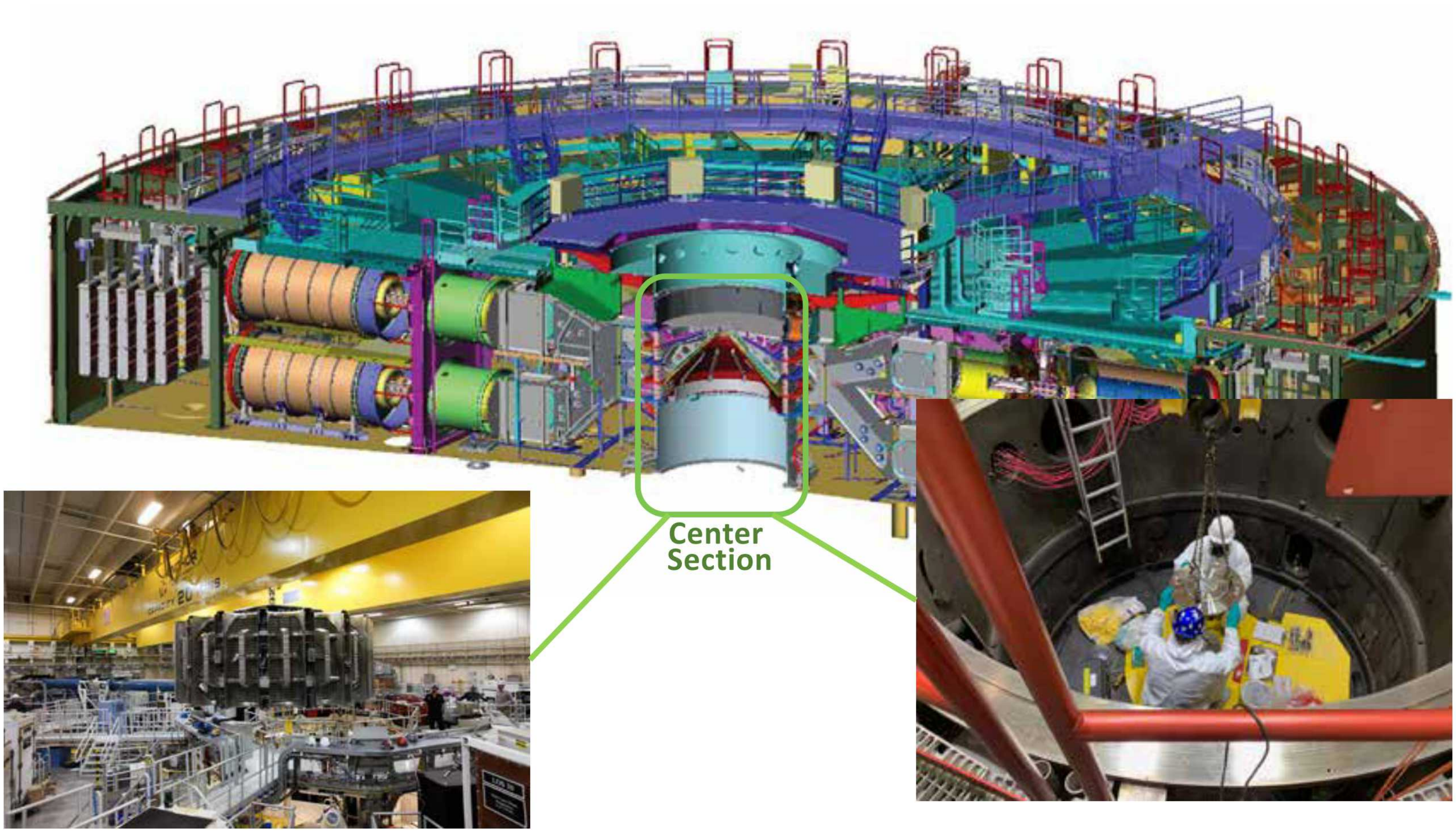






Z today couples several MJ out of 22 MJ stored to the load hardware region at the machine center.

Workers on Z fire ~150 shots per year under challenging working conditions



Z experiments release the energy of a few sticks of dynamite

The Z facility is supported by the multi-kJ Z-Beamlet & Z-Petawatt lasers, which can also be operated independently

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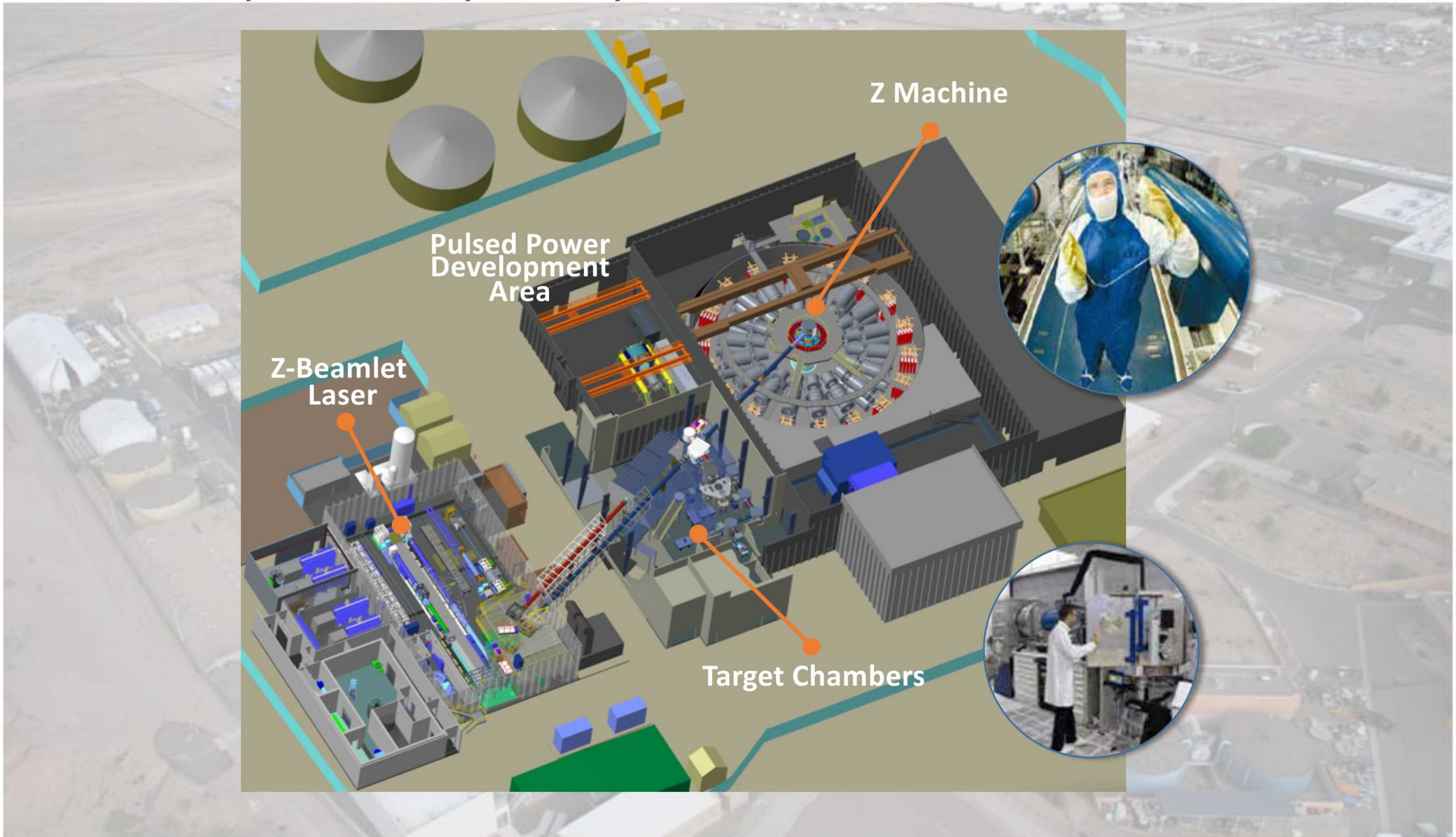
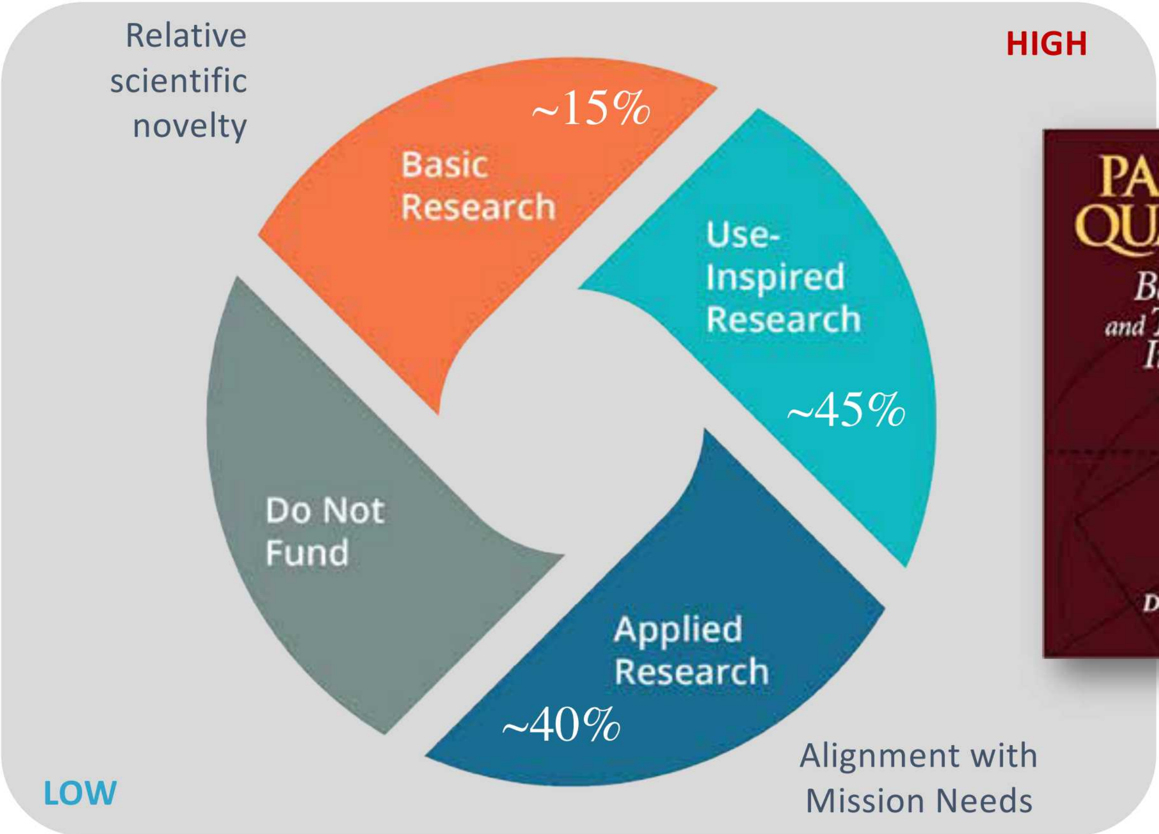


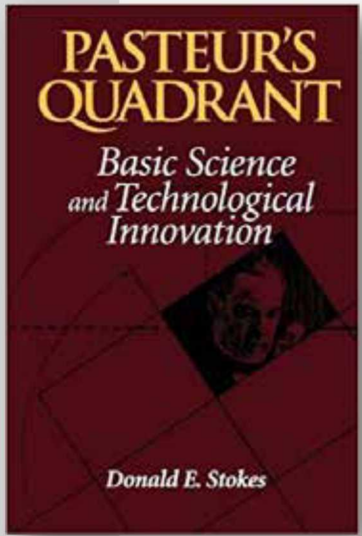
P.K. Rambo *et al.*, Applied Optics 44 (2005); P. Rambo *et al.*, Proc. SPIE 10014 (2016).

Creating High Energy Density Matter and Extreme X-ray Environments for Different Applications

Majority of Z research is "use-inspired"

Conducting open, novel science in the pursuit of applications benefiting the mission of the NNSA





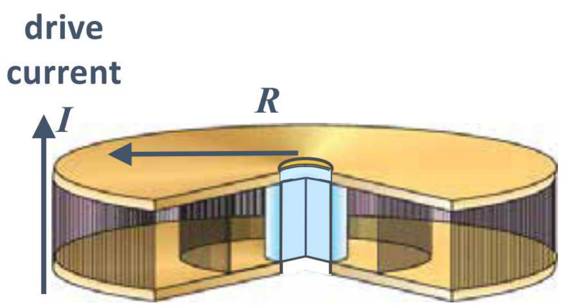
Basic

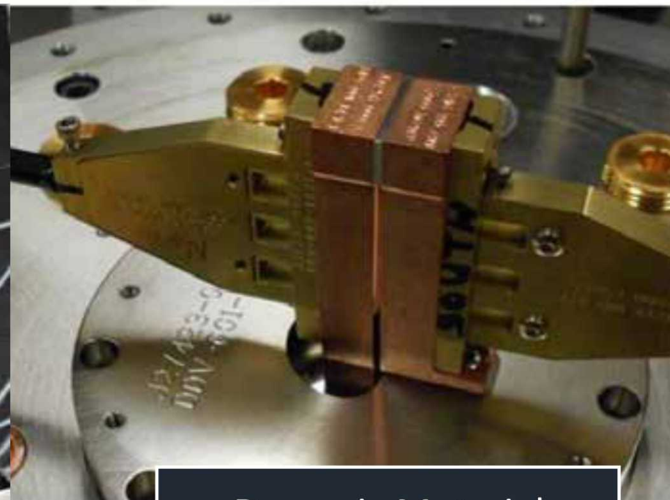
Use-Inspired

Applied

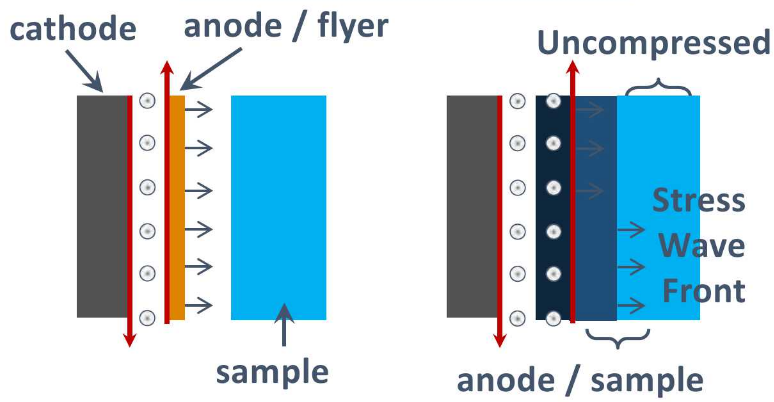
Precision tools for high energy density science

Radiation Science

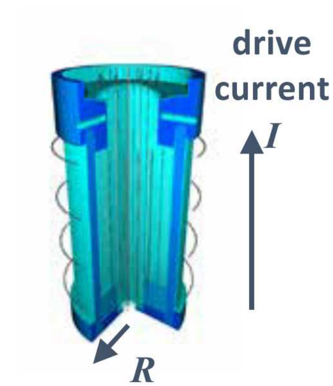




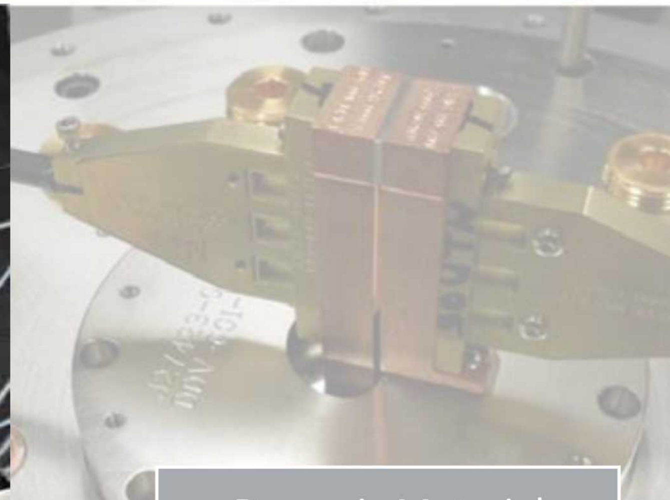
Dynamic Material Properties



Inertial Confinement Fusion



Radiation Science

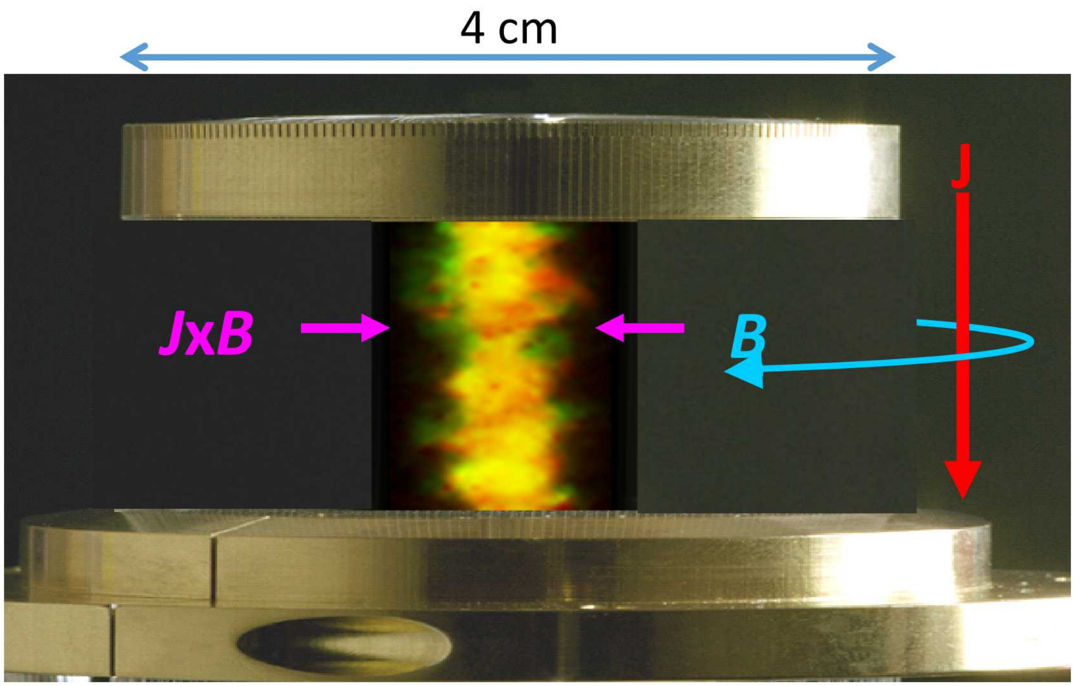


Dynamic Material Properties

Inertial Confinement Fusion

The Z machine uses 26 mega-amperes of current to create >1 mega-joule of x rays

Basic

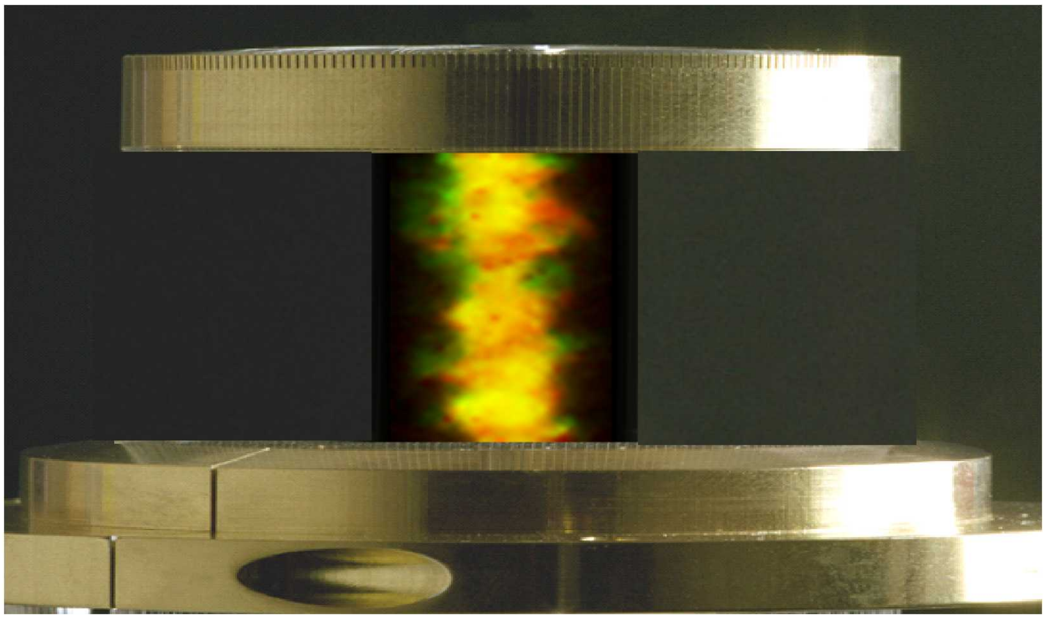


	ZR > 2011
Marx Energy	20.3 MJ
Ipeak	25.8 MA (1.5%)
Peak Power	220 TW (10%)
Radiated Energy	1.6 MJ (7%)

Sanford *et al.*, *PoP* (2002); Bailey *et al.*, *PoP* (2006); Slutz *et al.*, *PoP* (2006); Rochau *et al.*, *PPCF* (2007); Rochau *et al.*, PoP (2014).

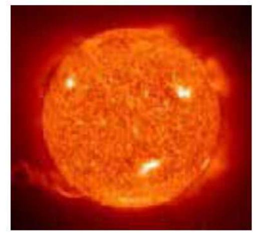
We collaborate with several institutions to do multiple radiation-driven basic science experiments on a single Z shot

Basic



Partners: LLNL, LANL, University of Texas, Ohio State, West Virginia U., U. Nevada-Reno, CEA

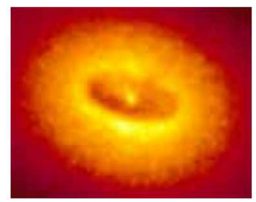
Stellar opacity



Question:
Why can't we predict the location of the convection zone boundary in the Sun?

Achieved Conditions:
T_e ~ 200 eV, n_e ~ 10^{23} cm^{-3}

Accretion disk



Question:
How does ionization and line formation occur in accreting objects?

Achieved Conditions:
T_e ~ 20 eV, n_e ~ 10^{18} cm^{-3}

White dwarf

Question:
Why doesn't spectral fitting provide the correct properties for White Dwarfs?

Achieved Conditions:
T_e ~ 1 eV, n_e ~ 10^{17} cm^{-3}

Sanford *et al.*, *PoP* (2002); Bailey *et al.*, *PoP* (2006); Slutz *et al.*, *PoP* (2006); Rochau *et al.*, *PPCF* (2007); Rochau *et al.*, PoP (2014).

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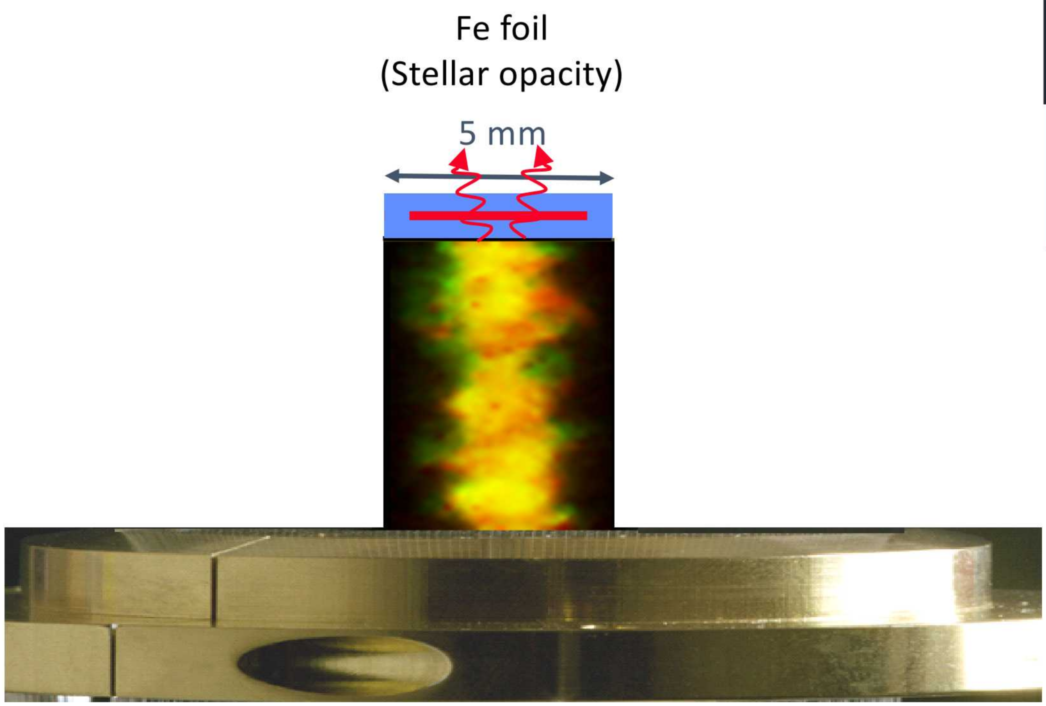
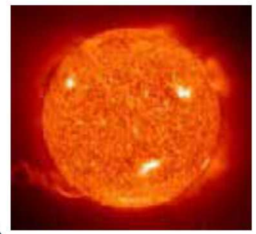


Partners: LLNL, LANL, University of Texas, Ohio State, West Virginia U., U. Nevada-Reno, CEA

Basic

Stellar opacity

2016 Dawson Award



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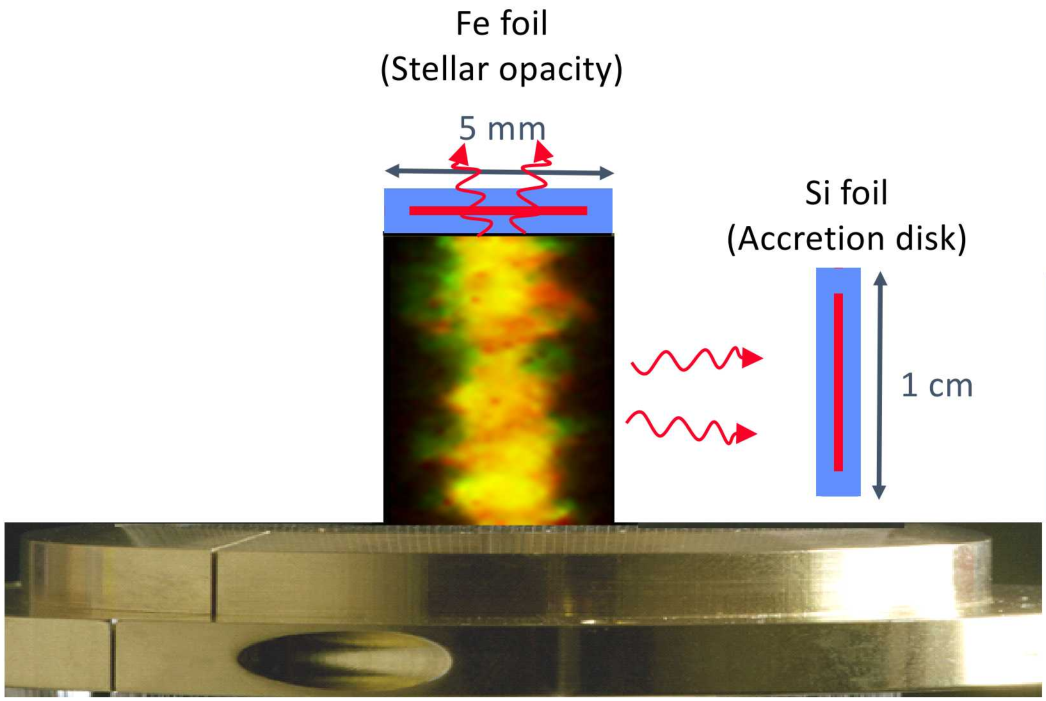

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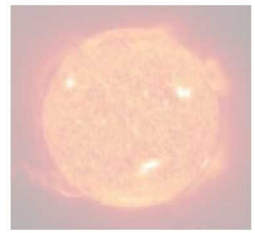

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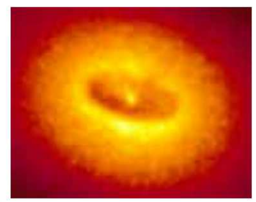
Accretion disk

G.P. Loisel *et al.*, PRL (2017)



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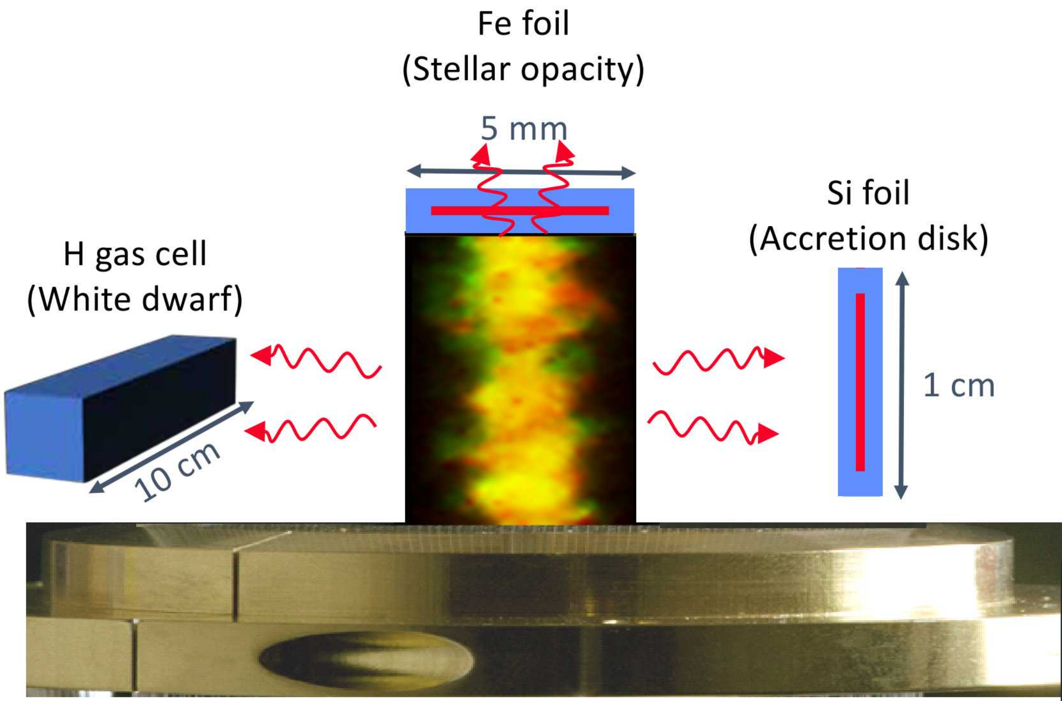

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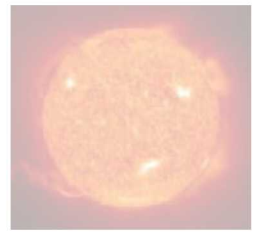

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M-A. Schaeuble PO9.00012

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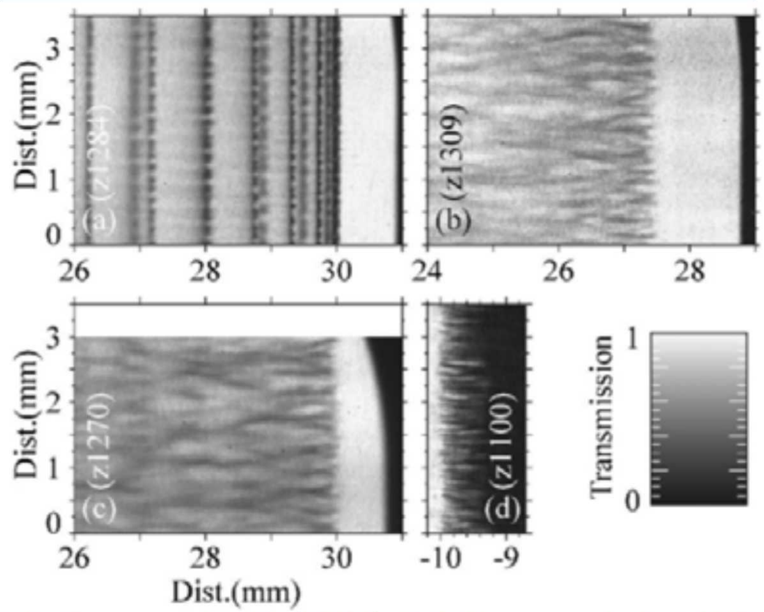
Z-pinches are highly efficient converters of electrical energy into soft X-rays (50-90%), but magnetized implosions are themselves a rich topic of plasma physics

Use-Inspired

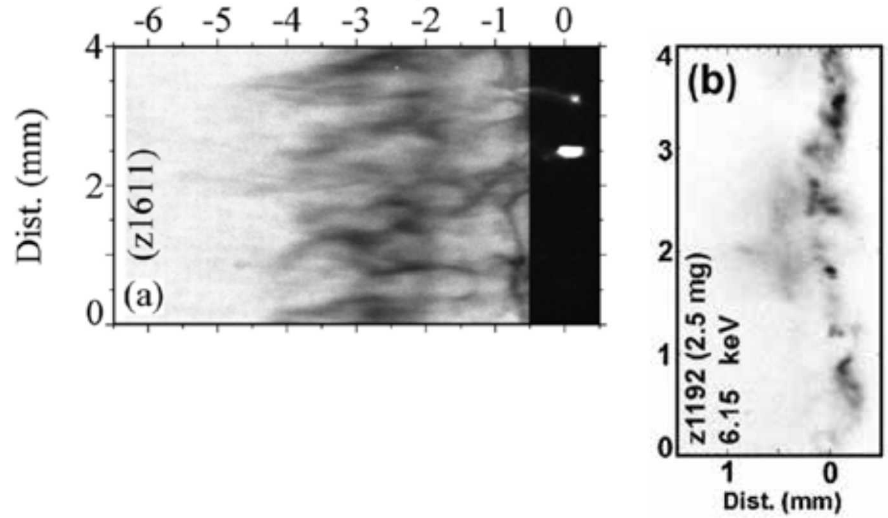
How do wire arrays turn into plasma?
Can we model wire array implosion instabilities?
What are the conditions at stagnation?

Examples of complex wire array ablation dynamics



D.B. Sinars et al., PRL (2004); D.B. Sinars et al., PoP (2005).

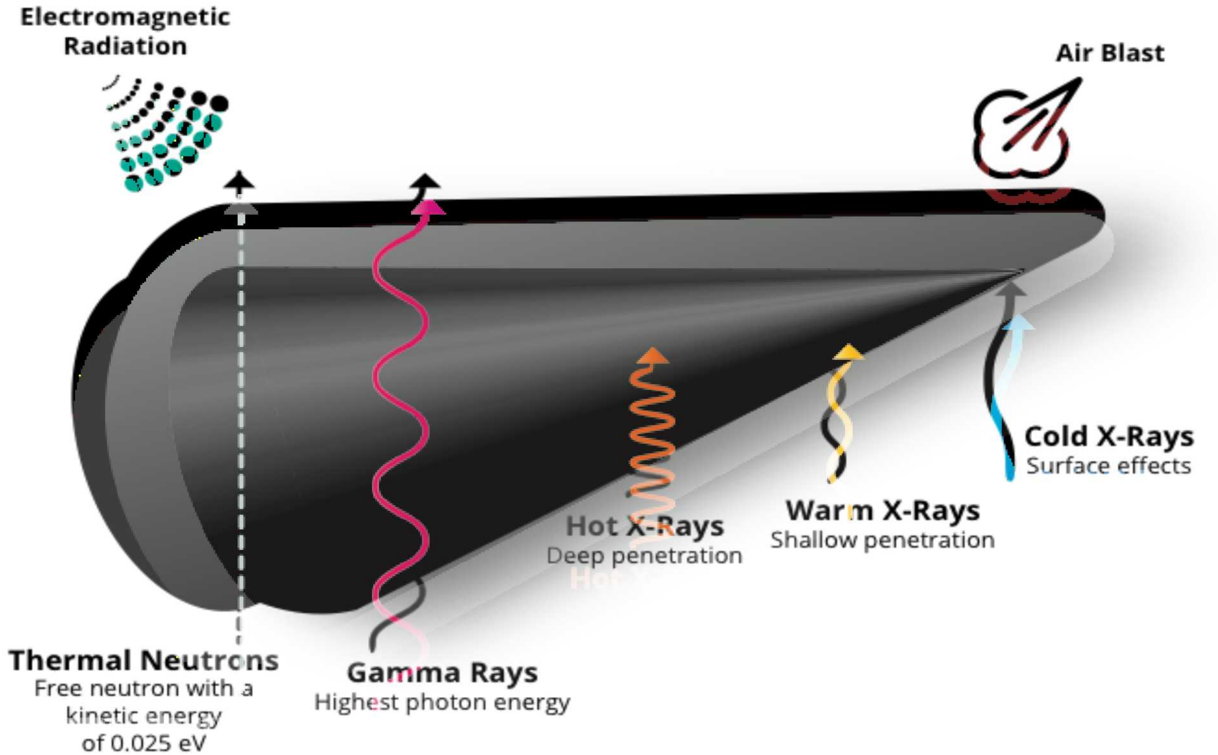
Examples of complex 3D implosion instabilities and bright x-ray spot formation



D.B. Sinars et al., PRL (2008).

A major mission focus for Sandia is assessing the effects of hostile environments on nuclear weapons systems

Applied



Z is one of three pulsed power facilities used at Sandia for this mission

Applied

Z Machine
Cold/warm X-rays; fast fusion neutrons

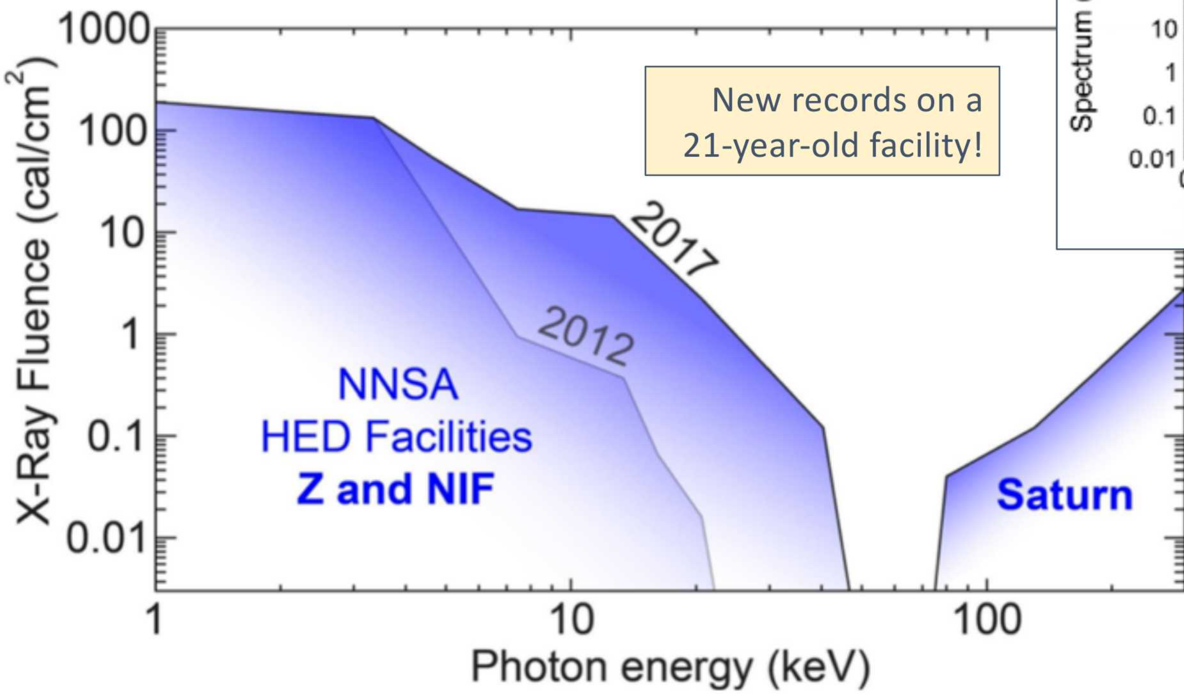
Annular Core Research Reactor Fission neutrons

HERMES III Gamma rays

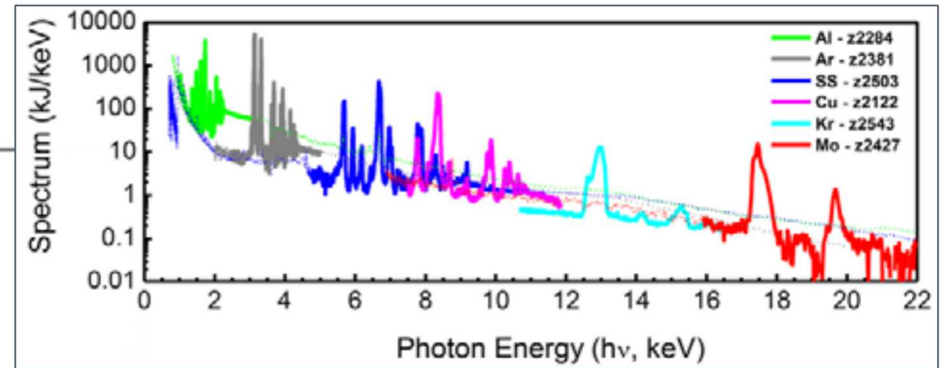
Saturn Hot X-rays

Sandia and Lawrence Livermore National Laboratories are collaborating to produce record levels of >10 keV X-rays using a variety of Z-pinch sources*

Applied



New records on a 21-year-old facility!

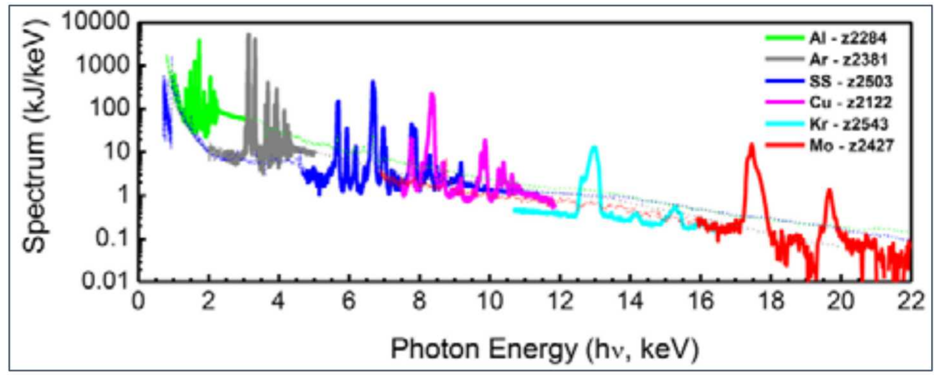


Z and NIF are developing advanced x-ray sources that provide unprecedented >10 keV yields

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

Sandia and Lawrence Livermore National Laboratories are collaborating to produce record levels of >10 keV X-rays using a variety of Z-pinch sources*

Applied

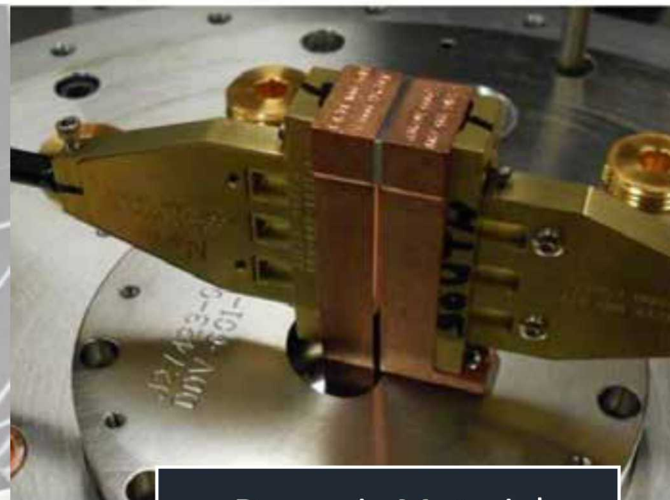


These x-ray sources are being used to study physics models for matter exposed to rapid, intense doses of x rays

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).

Radiation Science



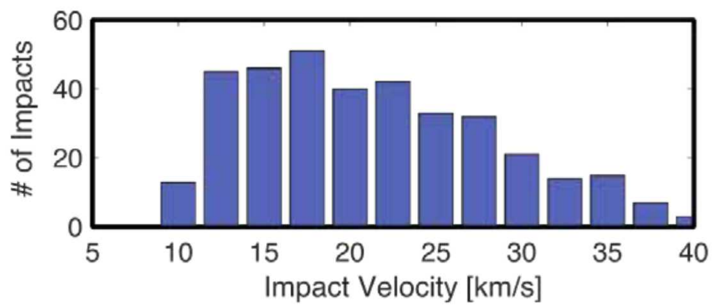
Dynamic Material Properties

Inertial Confinement Fusion

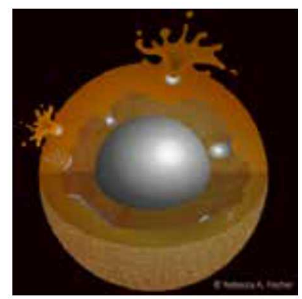
A major question in planetary physics is how the iron content in the earth and moon got there, and why they are isotopically similar

Basic

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?



Simulations of planetary dynamics suggest high impact velocities



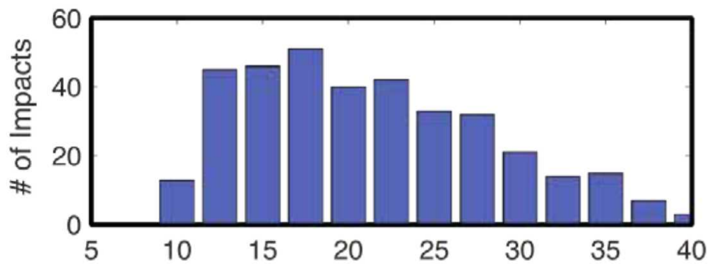
Fluid instabilities do not sufficiently mix the incoming iron cores to explain observed iron content in the mantle or the similarity in isotopics between the earth and the moon.*

Partners: Harvard, UC Davis, LLNL

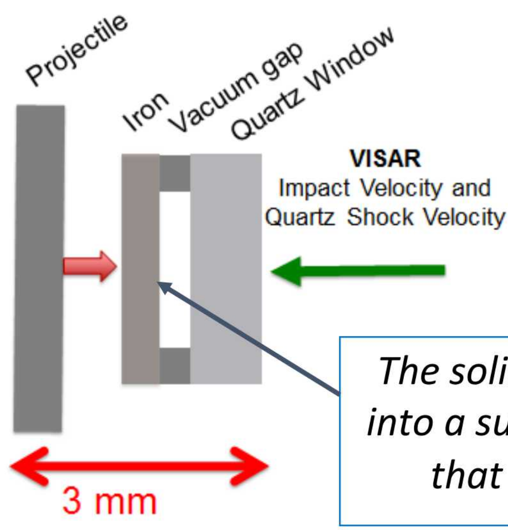
*N-body simulations from Raymond et al. 2009

Z was used to study the vaporization of iron under velocities relevant to planet-forming impacts

Basic

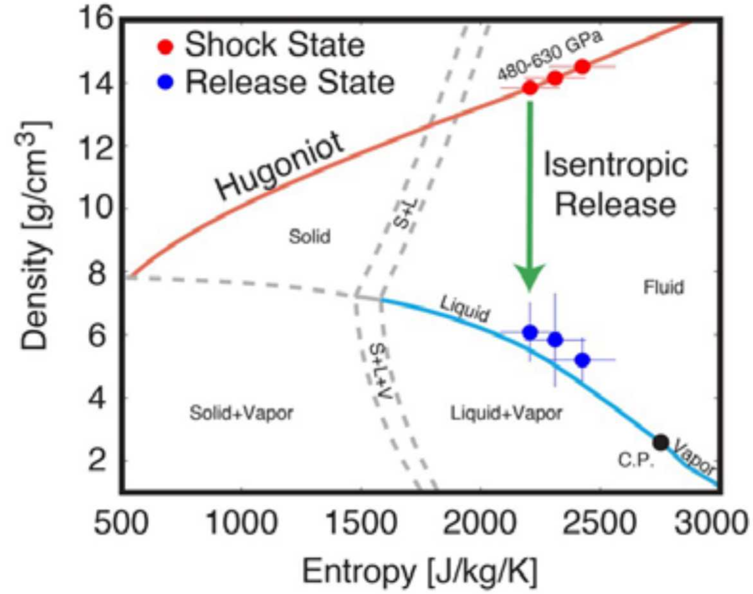


- On Z, we can launch flyer plates up to 40 km/s
- It is possible to directly probe the full range of planetary impact conditions



The solid iron sample turns into a supercritical iron fluid that hits the window

Iron Shock and Release Data



Partners: Harvard, UC Davis, LLNL

Sandia applies techniques and diagnostics matured on our use-inspired platforms to directly address mission needs in more challenging experiments

Applied

Z is a unique platform for dynamic materials research

- Large samples, high pressures, and relevant loading paths
- Containment capability allows us to field a wide range of hazardous materials without relying on surrogacy

Compared response of 5- and 52-year-old Pu samples to improve pit aging analysis for certification models

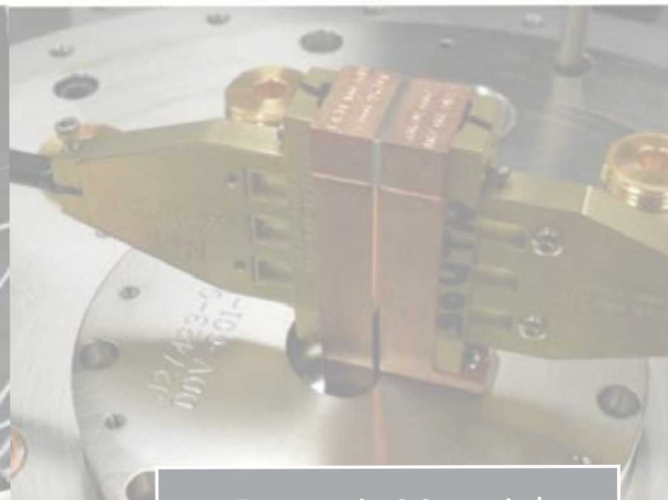
Conducted high-pressure uranium experiments on Z to benchmark LANL and LLNL EOS models

New capabilities are being developed over the next several years to extend our impact for mission work

Partners: LANL, LLNL

Los Alamos NATIONAL LABORATORY

Radiation Science

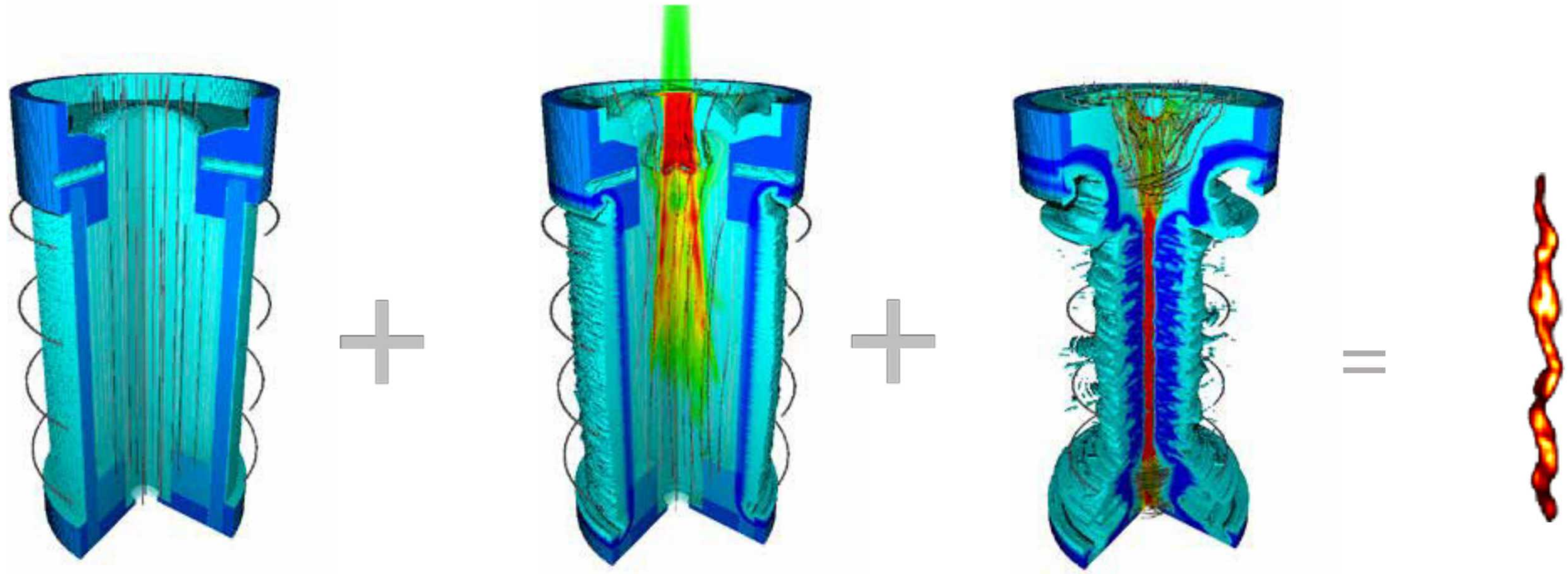


Dynamic Material Properties

Inertial Confinement Fusion

Magnetized Liner Inertial Fusion (MagLIF) is a magneto-inertial fusion (MIF) concept

Relies on three components to produce fusion conditions at stagnation



Magnetization
- Suppress radial thermal conduction losses
- Enable slow implosion with thick target walls

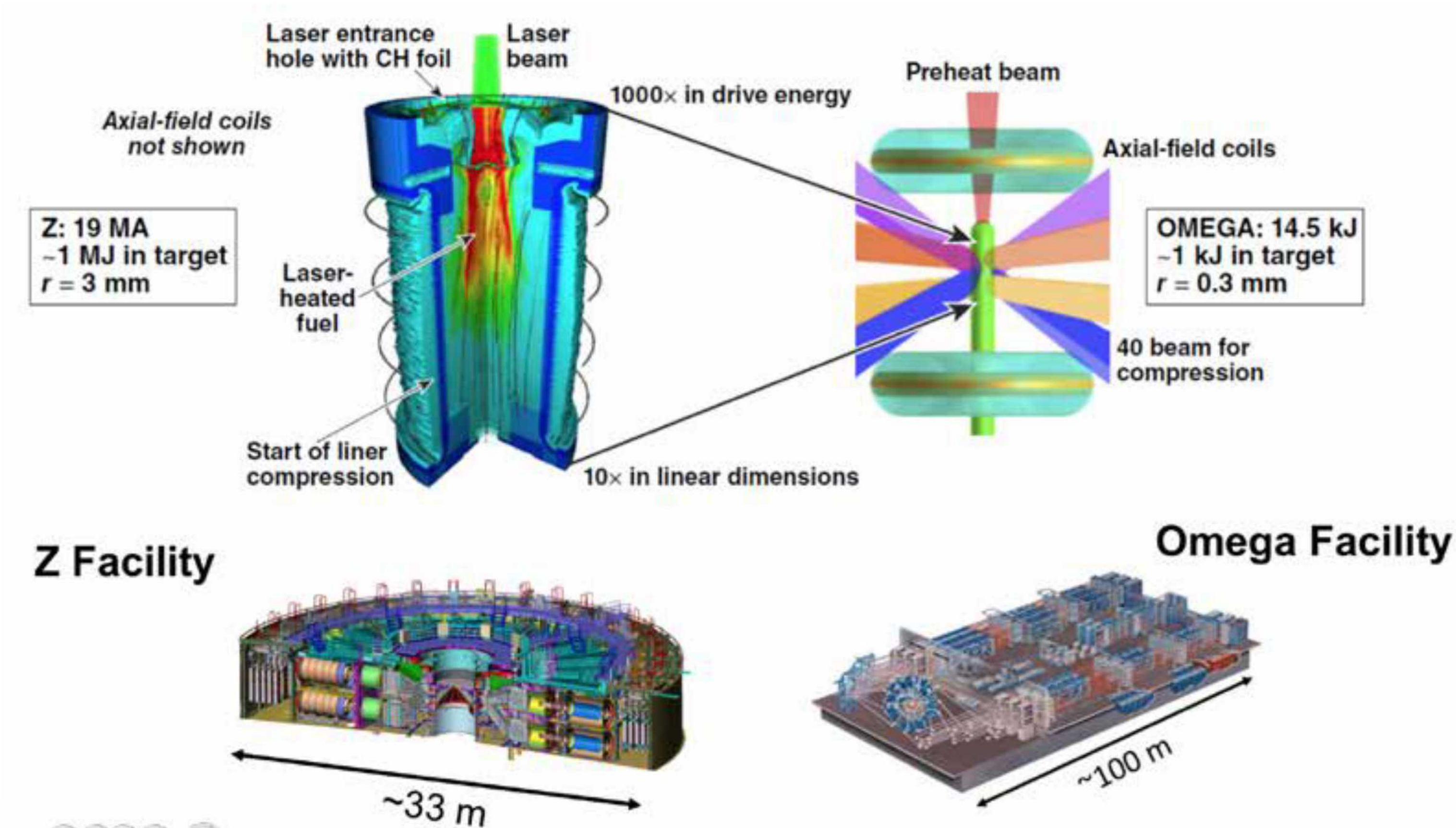
Preheat
- Ionize fuel to lock in B-field
- Increase adiabat to limit required convergence

Implosion
- PdV work to heat fuel
- Flux compression to amplify B-field

Stagnation
- Several keV temperatures
- Several kT B-field to trap charged fusion products

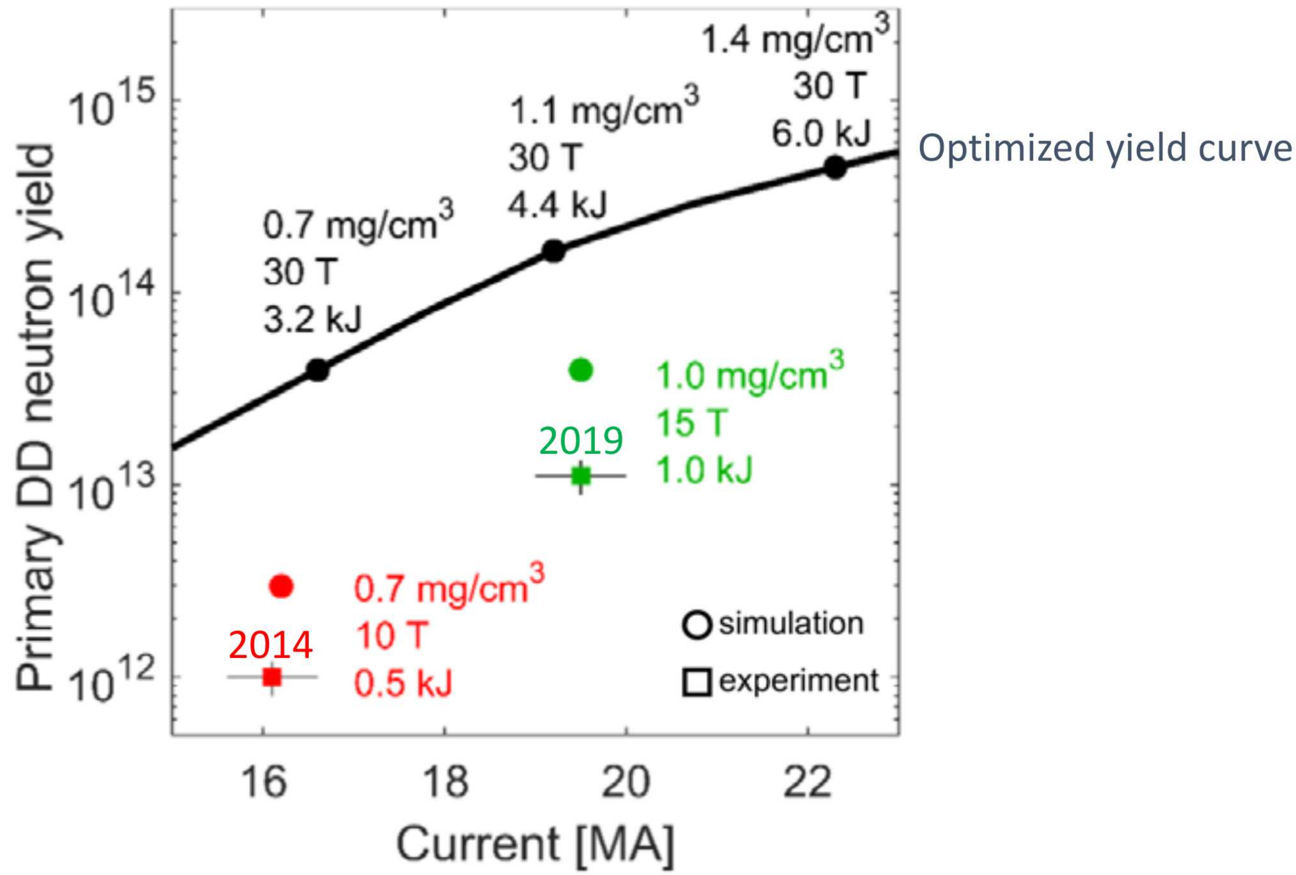
S.A. Slutz *et al.*, Phys. Plasmas (2010); A.B. Sefkow *et al.*, Phys. Plasmas (2014); S.A. Slutz *et al.*, Phys. Plasmas (2018).

MagLIF has been demonstrated to work well over a range of 1000x in energy



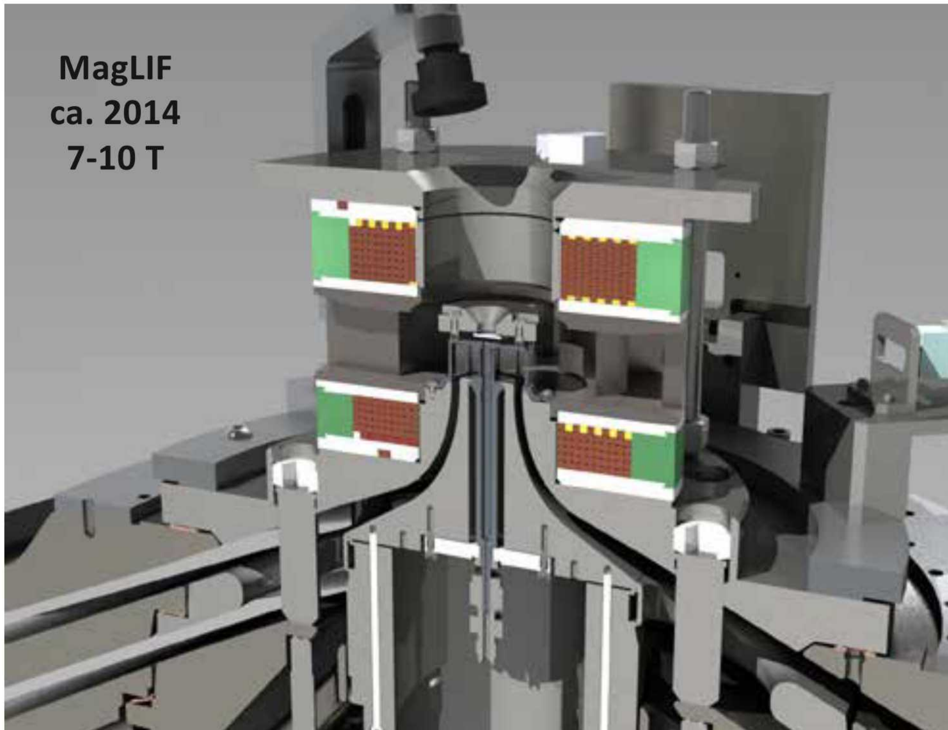
J.R. Davies *et al.*, Phys. Plasmas (2017); D.H. Barnak *et al.*, Phys. Plasmas (2017).

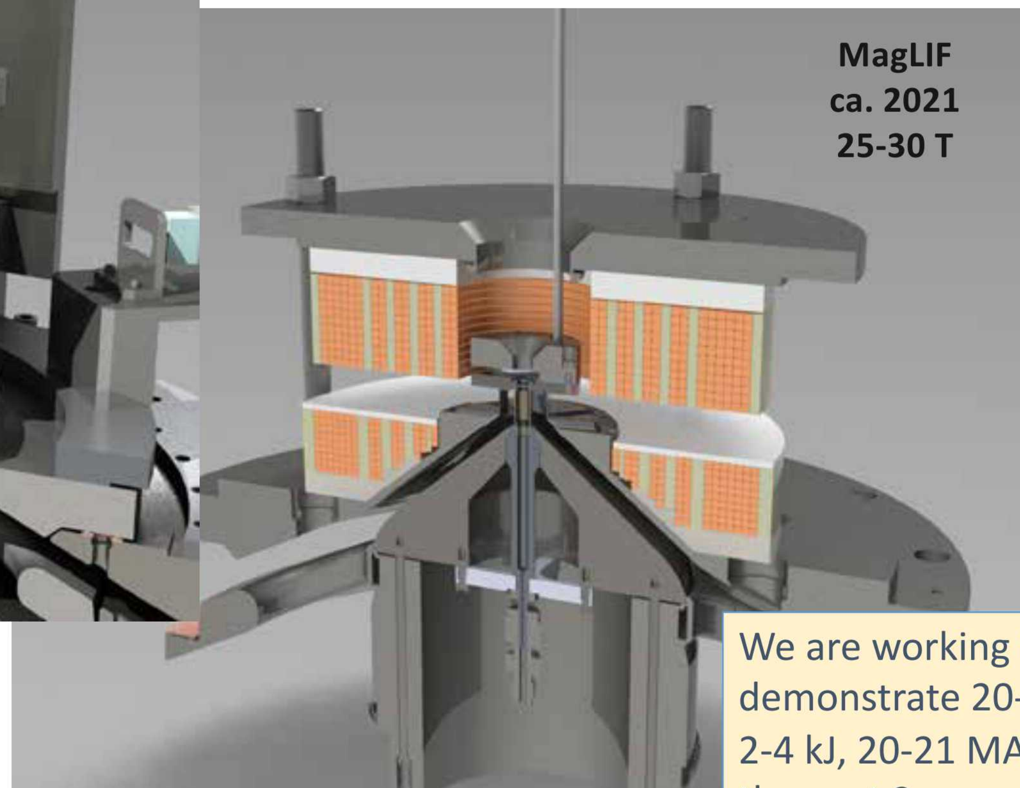
We have made substantial progress over the past five years in understanding MagLIF plasmas, and in beginning to scale MagLIF to higher yields



M.R. Gomez, S.A. Slutz, C.A. Jennings *et al.*, manuscript under preparation (2019).

We will continue to test MagLIF scaling through further increases in magnetization, preheat, and drive current

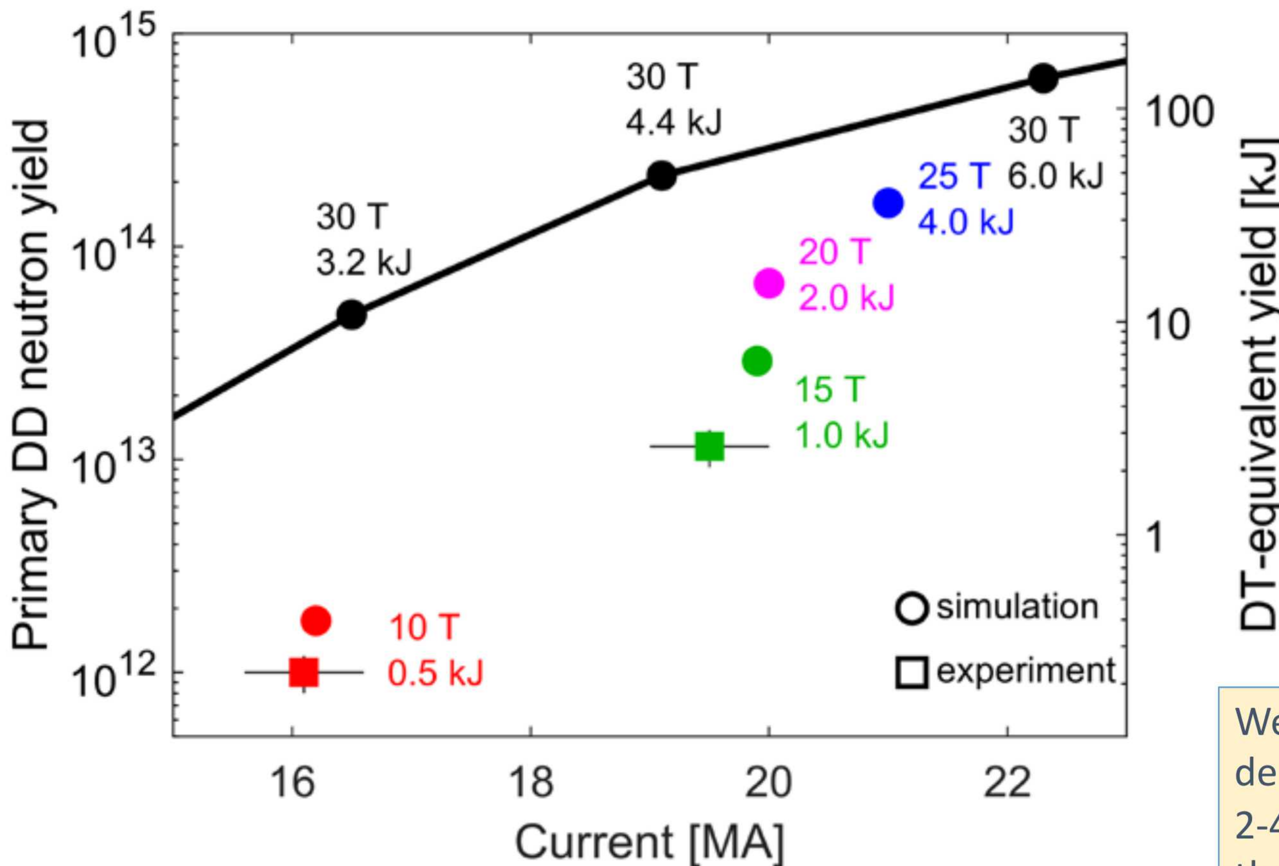




We are working to demonstrate 20-25 T, 2-4 kJ, 20-21 MA in the next 2 years

S. A. Slutz, et al., Phys. Plasmas (2018); Invited APS-DPP talk by M. Gomez GI3.00004.

We will continue to test MagLIF scaling through further increases in magnetization, preheat, and drive current; 10s of kJ DT-equivalent yield possible in next 2 years



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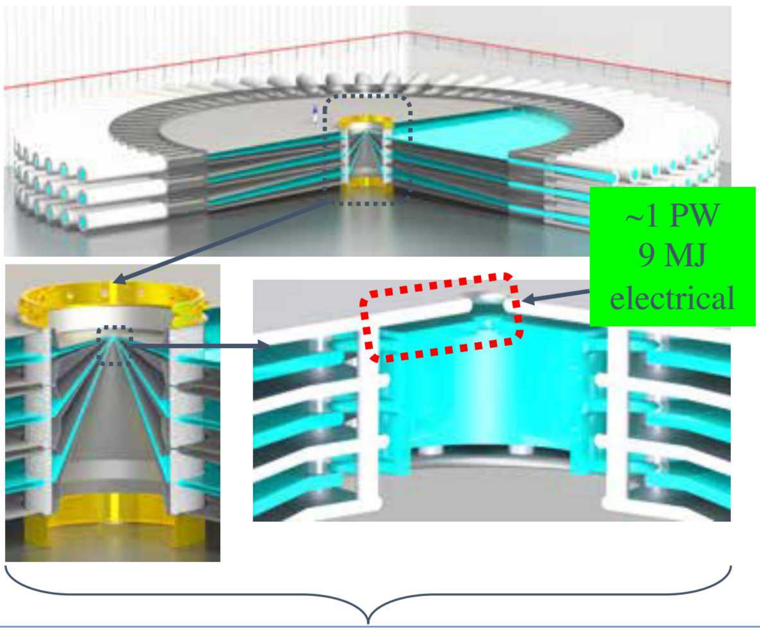
Fusion drives exciting fundamental and use-inspired science! it is also intended as an enabling tool for stockpile stewardship applications

Applied

Yield	High Energy Density Science Applications
~0.01 MJ	• Interplay of thermonuclear fusion burn and mix • Nuclear physics data (reaction-in-flight, fission, and radiochemistry)
>0.1 MJ	• Transport of charged particles in plasmas • Threshold for fusion-fission physics
~few MJ	• Threshold for enabling complex mix physics studies. • Robust radiation and charged particle transport • Robust fusion-fission experiments
20-30 MJ	• Higher fidelity versions of the above experiments are possible • Neutron sources for outputs and environmental studies
>500 MJ	• Use of fusion targets to drive complex experiments • Use of fusion targets for material properties (EOS, opacity) research • Combined neutron and x-ray environments for outputs and effects studies

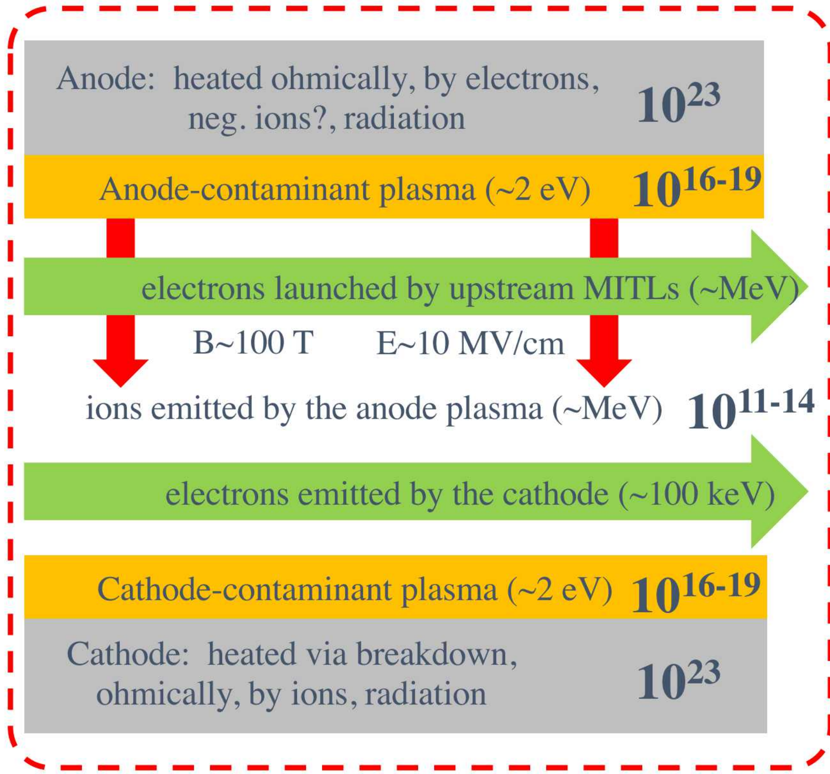
Excerpt from NNSA 2018 ICF Framework Document

We are investing in driver-target coupling physics, which spans a rich intermediate-density regime of plasma physics



- How do plasmas form from surfaces?
- How well insulated are the gaps during the current pulse?

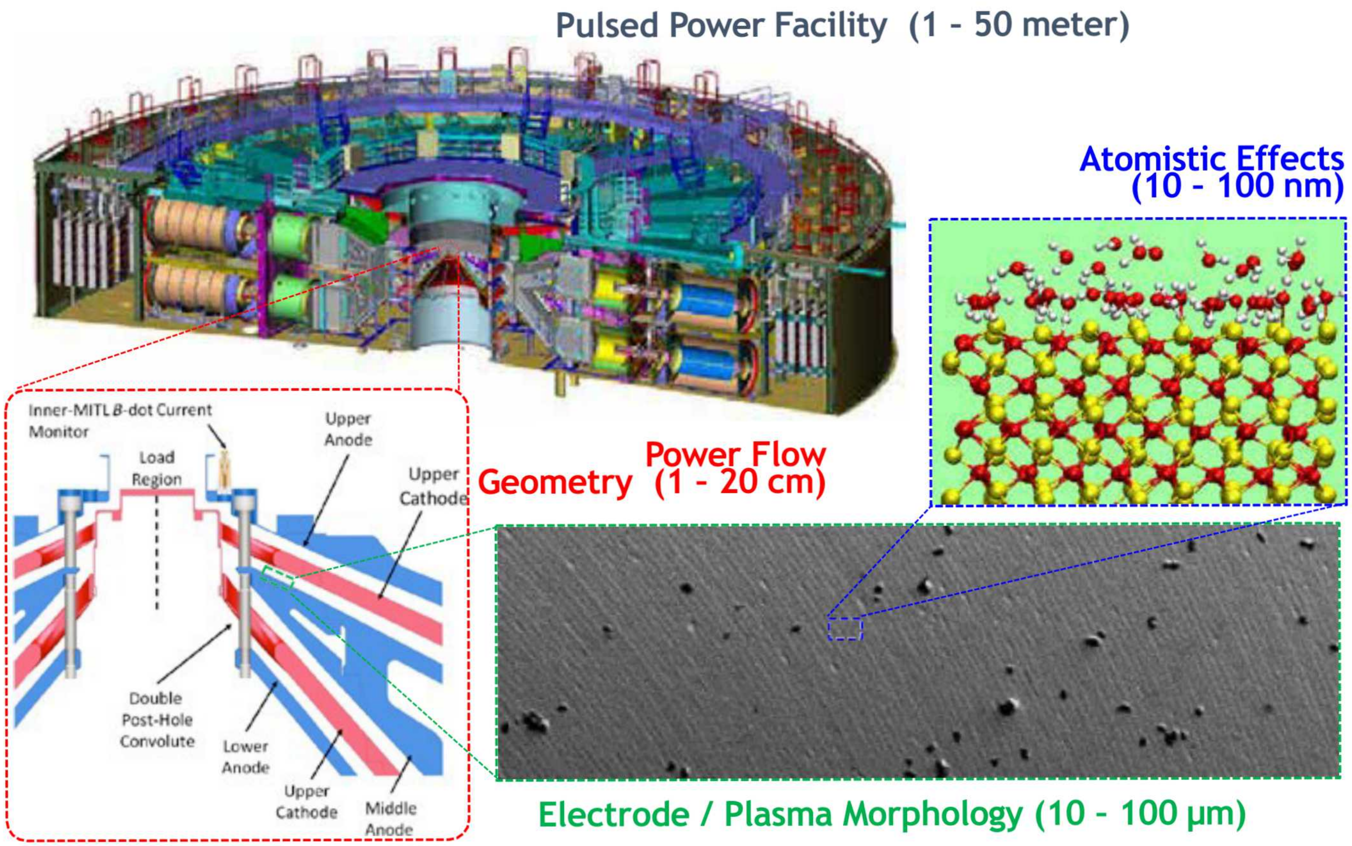
Section of a "vacuum" transmission line



Multi-scale and non-neutral plasmas crossing PIC and Continuum regimes

We are using both program and internal laboratory funding to conduct a range of basic to applied power flow physics research

Voss Scientific



Basic

- Surface desorption physics
- Multi-scale simulation of a plasma expanding into vacuum

Use-Inspired

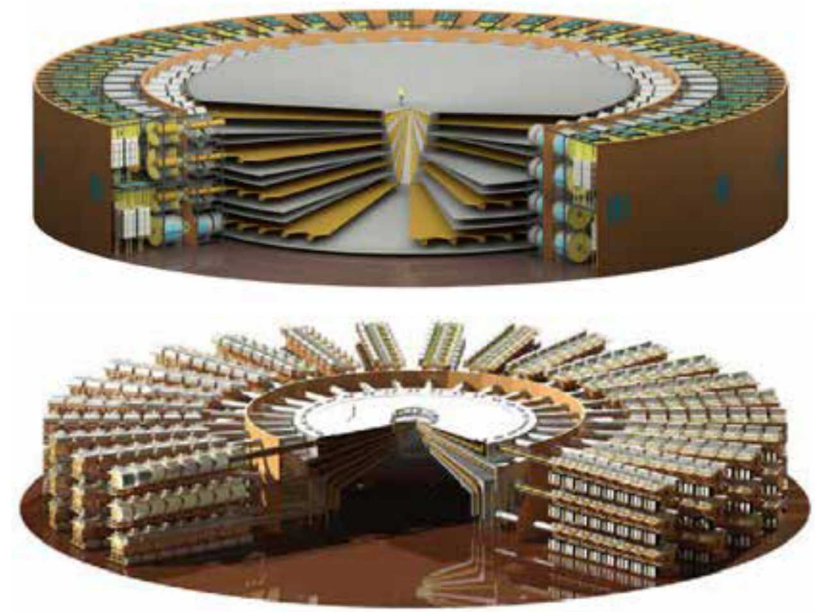
- Hybrid fluid/particle-in-cell algorithm development

Applied

- Spectroscopy measurements of plasma conditions on Z
- 3D double post hole Z convolute simulation
- Combined power flow and target simulations

Sandia has proposed a next generation pulsed power facility to the NNSA

- **World's most powerful warm x-ray and fast fusion neutron source**
  (hostile nuclear survivability)
- **Enabling capability for high energy density physics**
  (nuclear explosive package certification)
- **It would attract and test tomorrow's stewards of pulsed power and fusion research**
- **It would provide a venue for scientific and technical innovation for national security**
- **It would demonstrate inertial fusion energy target concepts at relevant scales**



Proposed project start date ~2025
Proposed project completion date ~2032

Z will celebrate ~35 years of z-pinch physics in 2030, with some parts of infrastructure ~45 years old.

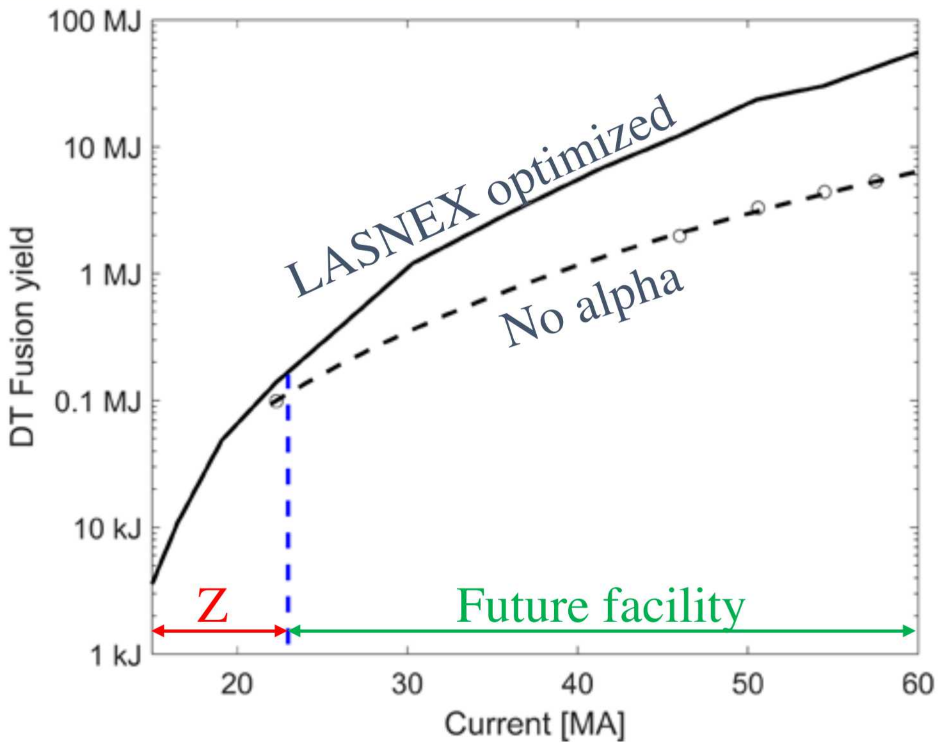
Sandia is evaluating pulsed power architectures

- ~3x diameter of Z today
- Deliver 800-1000 TW of electrical energy
- Couple ~10 MJ to fusion targets
- Require new operations concepts to reduce manual labor and potential worker hazards

Future Science Opportunities

Achieving close to 100 kJ (DT-equivalent) yield on Z with MagLIF within 5 years would improve the credibility of scaling to multi-MJ fusion yields on a future facility

2D clean simulated MagLIF performance



- At >60 MA, MagLIF appears capable of >10 MJ yields
- Most credible scaling is for gas (volume) burning targets; ice-burning targets may be capable of higher gains*
- Program of work on Z, NIF, and Omega continues to address scaling physics
  - 3D Effects
  - Mix
  - Magnetization
  - Implosions

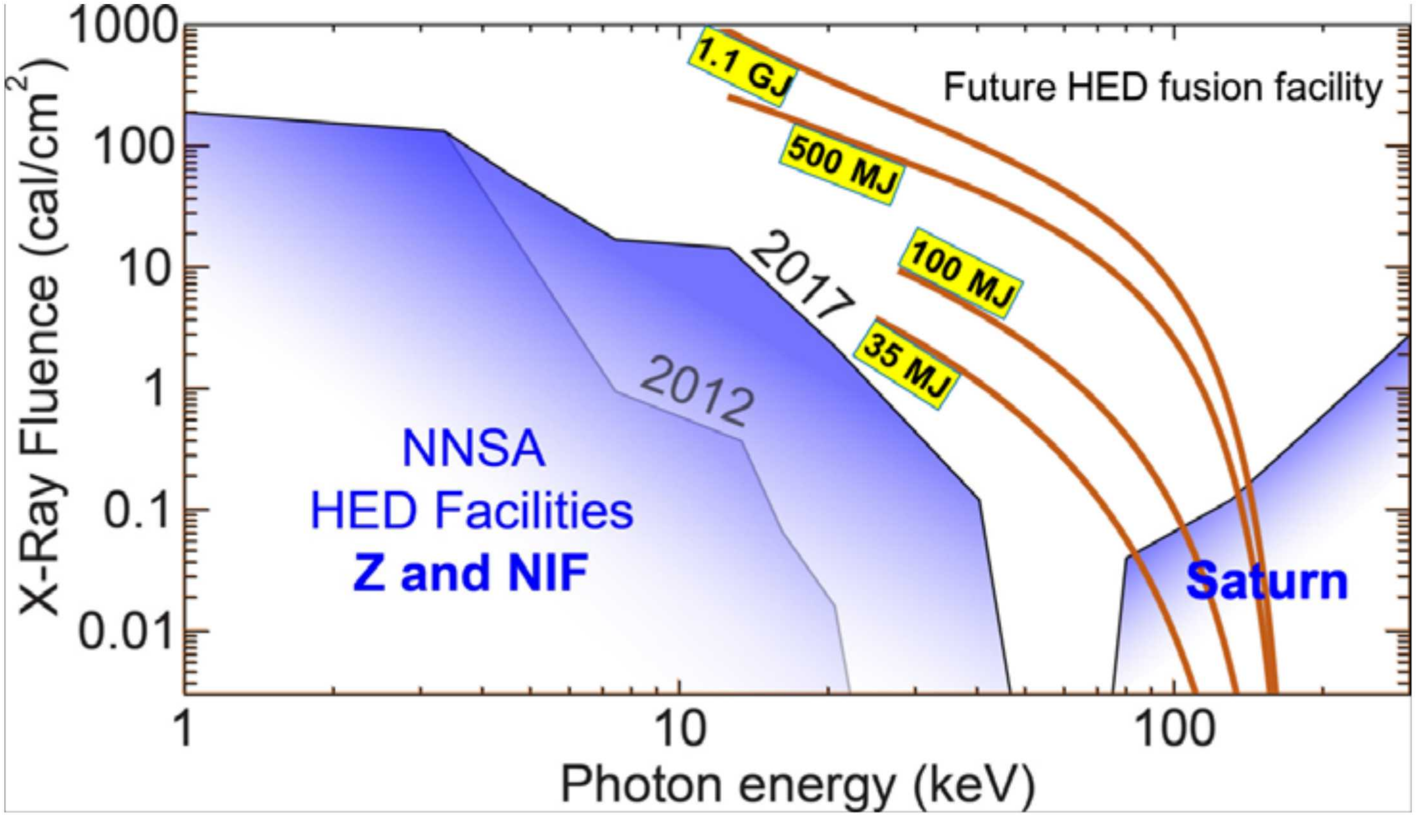
S. A. Slutz *et al.*, Phys. Plasmas (2018); * Slutz & Vesey, Phys. Rev. Lett. (2012).

Future high yield fusion facilities would create hot plasmas that would provide even more powerful sources of 10-100 keV X-rays

Basic

Use-Inspired

Applied



Such a Z-pinch driver would also be capable of powerful radiation-only x-ray sources.

Assured Survivability and Agility with Pulsed power (ASAP) is a $40M, 7-year internal Laboratory-Directed R&D project

Amplify pulsed power's impact on Sandia's intellectual leadership in hostile survivability while enabling its application to and usefulness for Sandia's broader national security missions and nuclear weapon science.

1. Reinvigorate the focus on **pulsed power science and technology** at Sandia
2. Mature the fundamental S&T that is needed for a **next-generation** pulsed power capability for both existing and new national security missions
3. Establish the science basis for understanding **combined hostile effects** and fundamental responses in these environments
4. Enable more flexible, agile, and capable means of designing and evaluating **survivable weapons and sensors**
5. Enable higher-fidelity experimental capabilities over multiple levels of assembly for **qualification assessments** in hostile environments

~$7M

~$18M

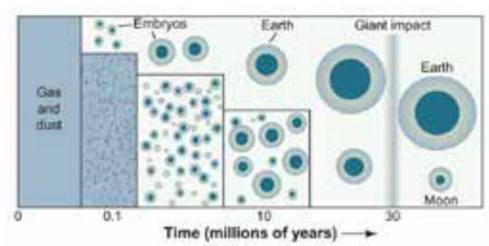
~$11M

~$4M Academic collaborations

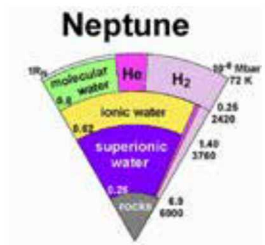
- For additional details: kpeters@sandia.gov, (505) 284-1211

There is a growing community of practice in pulsed power research on Z and smaller-scale facilities

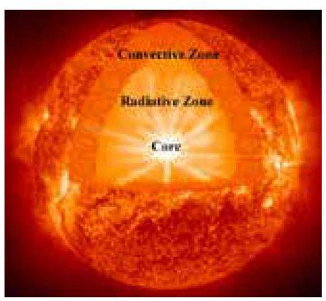
Z Fundamental Science Program



Earth and super earths
Properties of minerals and metals



Jovian Planets
Water and hydrogen



Stellar physics
Fe opacity and H spectra

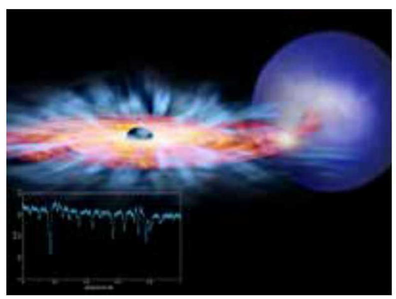


Photo-ionized plasmas
Range of ionization param. ξ

- Awards for next 1-year period (Summer 2020 – Summer 2021) just announced in late December
- We expect to host another ZFSP workshop in summer 2020 to help coordinate proposals and research
- Coordinated by Marcus Knudson
- Topics include
  - Pulsed power technology
  - Magneto-inertial fusion
  - Astrophysical plasmas and planetary science
  - MHD and hybrid code development
  - Magnetized HED

https://www.sandia.gov/Pulsed-Power/workshop/2019.html

Laboratory pulsed power science and technology at Sandia National Laboratories is making electrifying progress

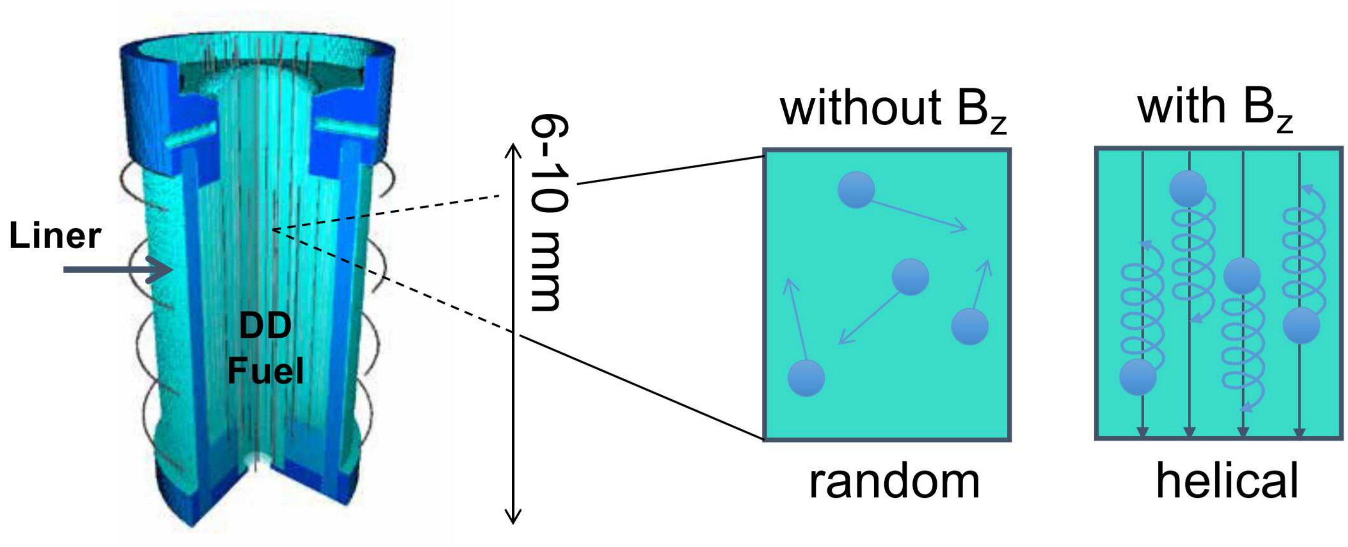
- Sandia National Laboratories "Z" facility, the world's largest pulsed power machine, is used for a wide range of fundamental, use-inspired, and applied research in high energy density science.
- While Z has existed in its current configuration since 1996, we have set multiple facility records in the last few years, such as peak pressure in material samples (>7.5 Mbar), cold and warm x-ray fluence on target samples, and neutron yield.
- Sandia enjoys a scientifically productive relationship with the academic community through its Z Fundamental Science Program.
  - ZNetUS could be an opportunity for us to expand our collaborations in other ways.
- Pulsed power driver technology is seeing a significant increase in investment.
  - Sandia just announced that it will be investing $40M over the next several years in Laboratory Directed Research and Development funds to push foundational technology research. We are planning for a number of new academic collaborations as part of this initiative.
- We are developing new tools for understanding power flow physics, where the energy from Z is coupled to the high energy density targets at its center.
- Sandia has proposed a >60 MA pulsed power facility to the NNSA for advanced mission work, which could nominally be in place around 2032 or later.
  - NNSA is also looking at the case for intermediate-scale facilities

BACKUP SLIDES

MagLIF is a Magneto-Inertial Fusion (MIF) concept

Relies on three components to produce fusion conditions at stagnation

Use-Inspired



Magnetization: 10-30T at t=0

- **Reduces electron heat loss during implosion**
- **Traps charged particles at stagnation**

Magnetization

- Suppress radial thermal conduction losses
- Enable slow implosion with thick target walls

S.A. Slutz *et al.*, Phys. Plasmas (2010); A.B. Sefkow *et al.*, Phys. Plasmas (2014); S.A. Slutz *et al.*, Phys. Plasmas (2018).

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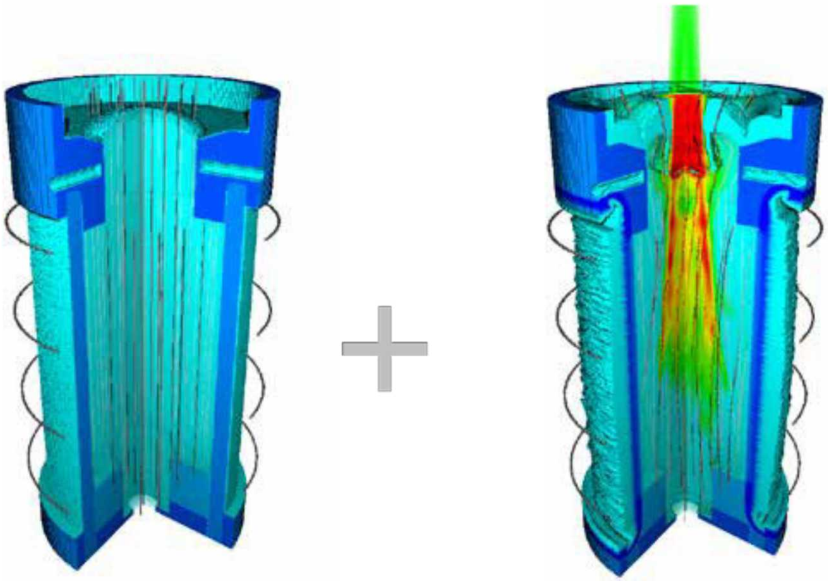

- **Laser preheat: 100-200 eV**
  - **Uses Z-Beamlet Laser (other heating methods possible)**
  - **Relax convergence requirement**
  - **$CR=R_{initial}/R_{final}$= 120 → 20-40**

Magnetization
- Suppress radial thermal conduction losses
- Enable slow implosion with thick target walls

Preheat
- Ionize fuel to lock in B-field
- Increase adiabat to limit required convergence

S.A. Slutz *et al.*, Phys. Plasmas (2010); A.B. Sefkow *et al.*, Phys. Plasmas (2014); S.A. Slutz *et al*., Phys. Plasmas (2018).

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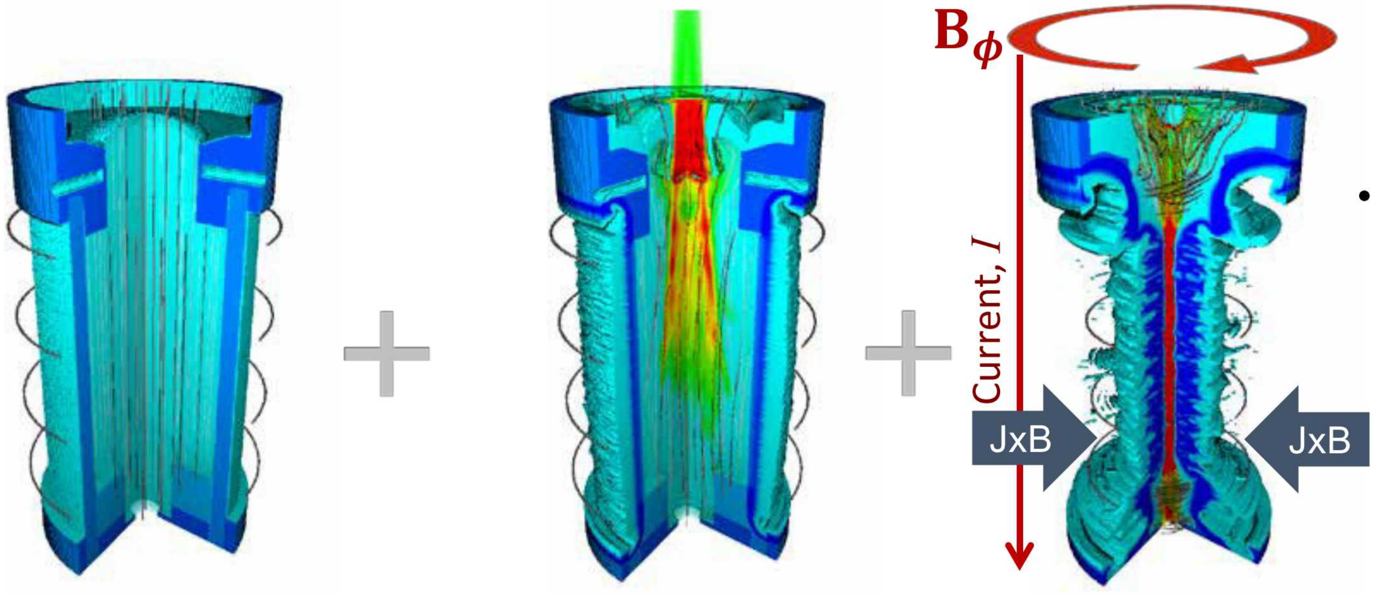

- **Magnetically Driven Implosion**
  - **"Only" ~100 km/s (vs. ~380 km/s on NIF)**
  - **B-field amplified to >10,000 T**

Magnetization
- Suppress radial thermal conduction losses
- Enable slow implosion with thick target walls

Preheat
- Ionize fuel to lock in B-field
- Increase adiabat to limit required convergence

Implosion
- PdV work to heat fuel
- Flux compression to amplify B-field

S.A. Slutz *et al.*, Phys. Plasmas (2010); A.B. Sefkow *et al.*, Phys. Plasmas (2014); S.A. Slutz *et al.*, Phys. Plasmas (2018).