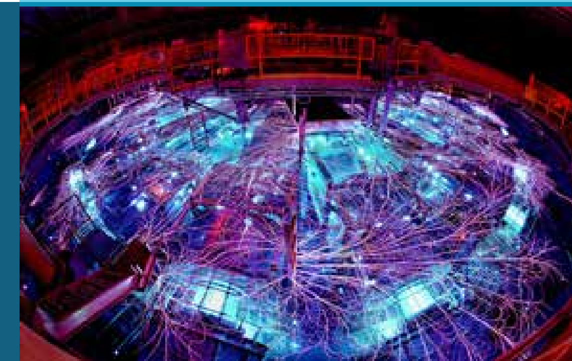
SAND2021-1191PE

Sandia National Laboratories

From Astrophysics to Z: An overview of science on the world's largest pulsed power machine



Presented by

Dr. Daniel B. Sinars, Sandia National Laboratories
Director, Pulsed Power Sciences Center
Program Executive for Office of Experimental Sciences

Los Alamos National Laboratory (LANL) Physics and Theoretical Division Colloquium,
Los Alamos National Laboratory, February 4, 2021.

U.S. DEPARTMENT OF ENERGY NNSA

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Exceptional science and pulsed power technology in the national interest

Outline

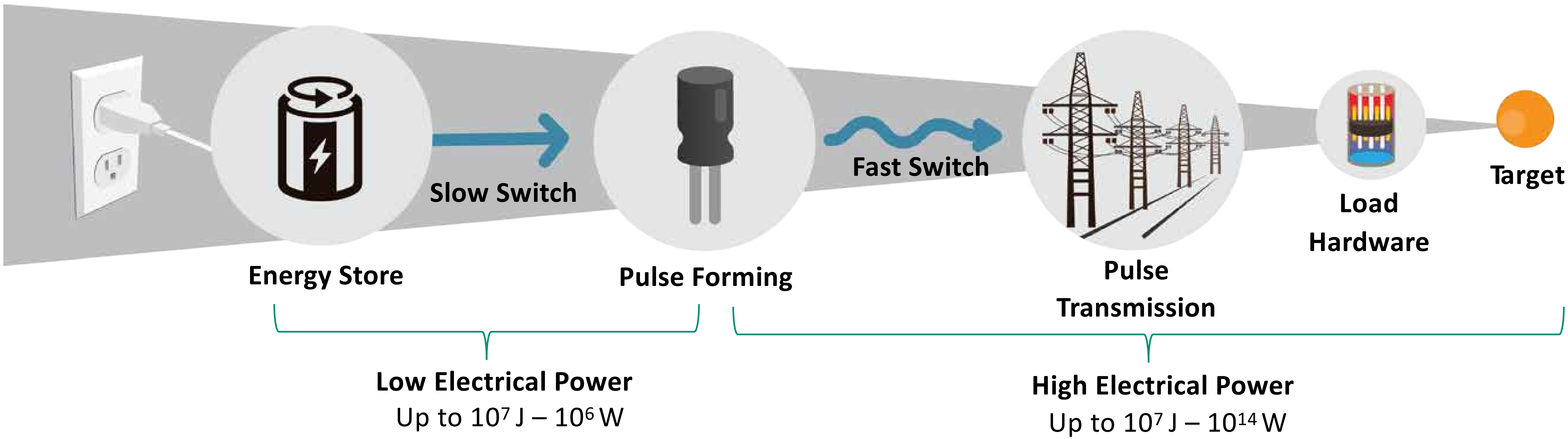
- Introduction to Pulsed Power & Z
- Overview of High Energy Density Science on Z
  - Radiation Science
  - Dynamic Materials Science
  - Fusion Science
- Future Science Opportunities
  - Next 10 years on Z
  - Thoughts on what lies beyond Z

Today's talk is based in large part on content published in a recent review paper: D.B. Sinars *et al.*, Phys. Plasmas (2020).

Sandia's Z Pulsed Power Facility

The Earth's largest pulsed power machine:
The central focus of today's talk

How does pulsed power work?



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

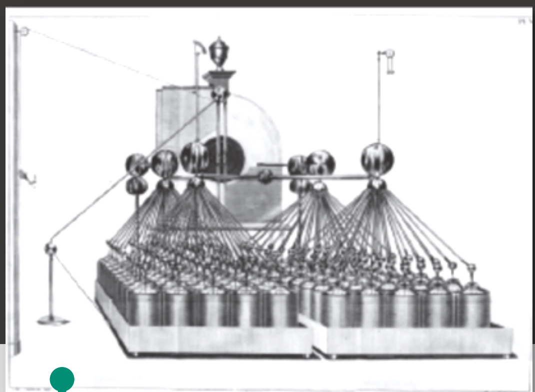
Pulsed power can be used to create conditions similar to those found in or caused by the detonation of nuclear weapons.

Pulsed power has a long history in plasma physics and electrical research

1790-2019

SANDIA PULSED POWER HISTORY

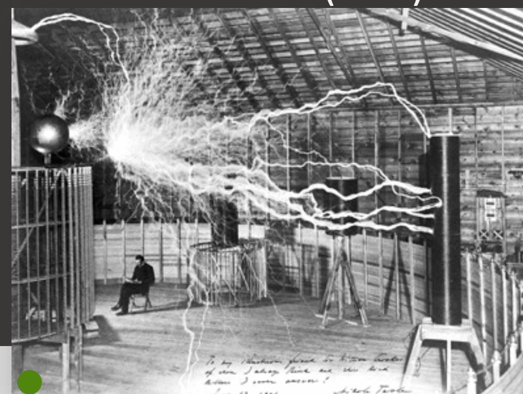
Martinus van Marum



1790

- The earliest Z-pinch experiment of record
- 1 kJ energy storage
- 100 Leyden jars
- Used to study 1m long wire explosions

Tesla's Lab (GW)



1900

1920

Invention of the Marx Generator

Today 36 Marx generators are used on Z

1971

Gerold Yonas initiated the particle-beam fusion program at Sandia

PBFA-II (20 TW)

1985

Sandia PBFA-II Light Ion Beams

Sandia's Z Facility (80 TW)

1996

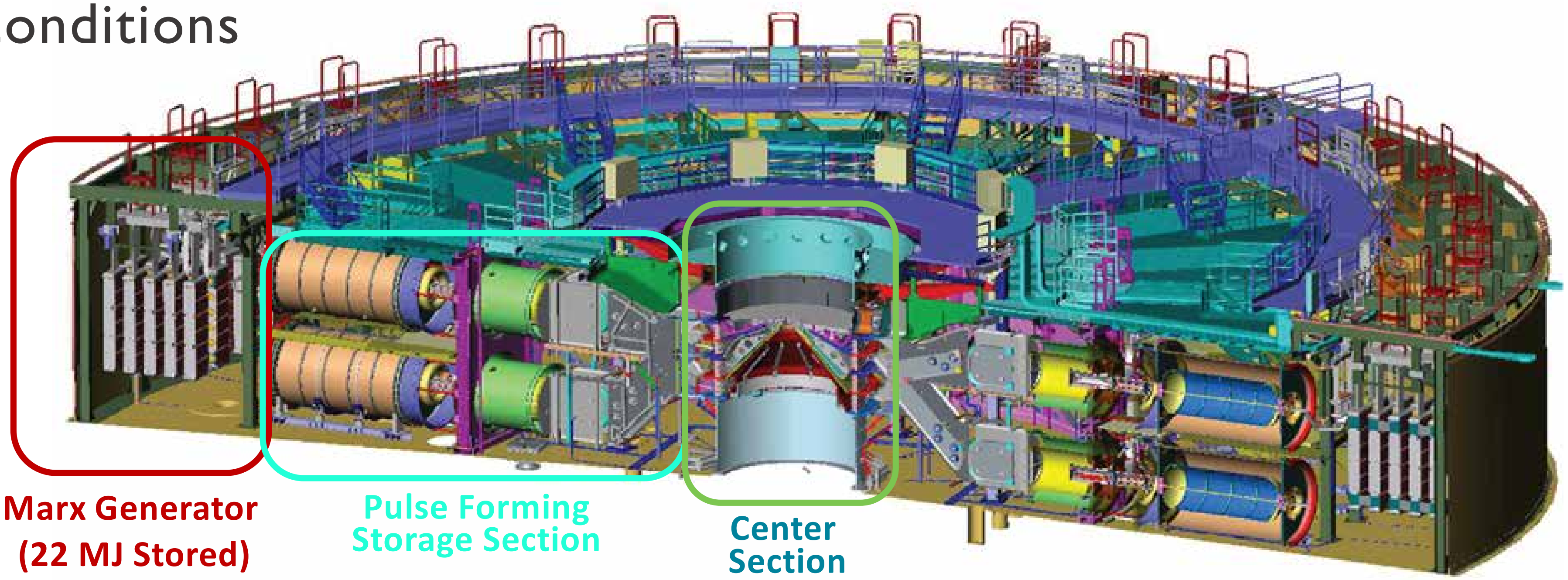
PBFA-II converted to Z; 11 MJ stored

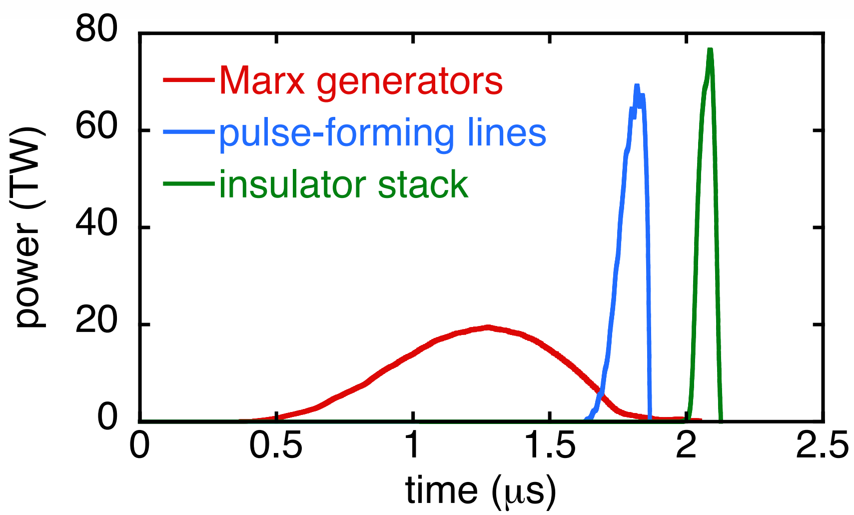
2007

Z Refurb

22 MJ stored

Z compresses energy in space and time to generate high energy density (HED) conditions





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

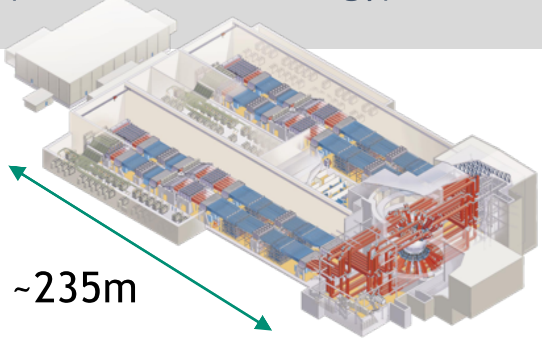
Z is an "Engine of Discovery" for stewardship and fundamental HED science

Z is one of three flagship facilities in the Inertial Confinement Fusion Program


Lawrence Livermore National Laboratory

National Ignition Facility (NIF)

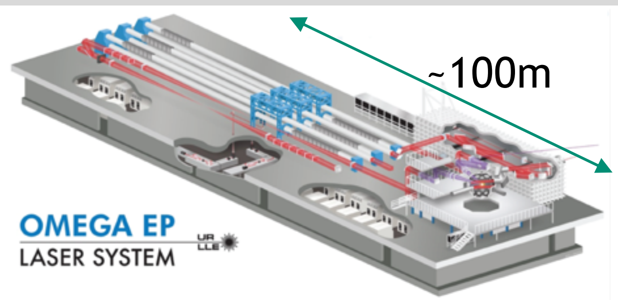
- Largest Laser on Earth
- Primary facility for Laser Indirect Drive fusion
- 400 TW / 1.8 MJ (Max Power & Energy)




University of Rochester

OMEGA Laser Facility

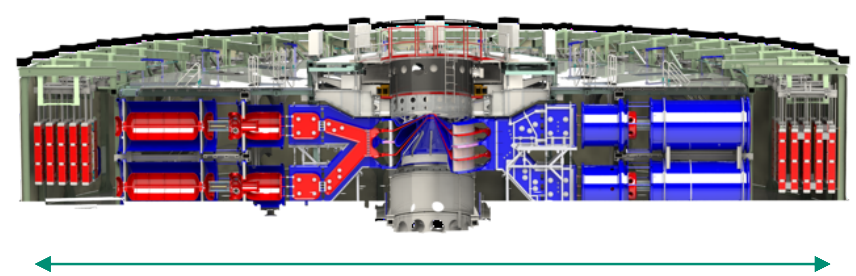
- High shot-rate academic laser facility
- Primary facility for Laser Direct Drive fusion
- 20 TW/.03 MJ (Max Power & Energy)




Sandia National Laboratories

Z Facility

- Largest Pulsed Power Facility on Earth
- Primary facility for Magnetic Direct Drive fusion
- 80 TW / 3 MJ (Max Power & Energy)

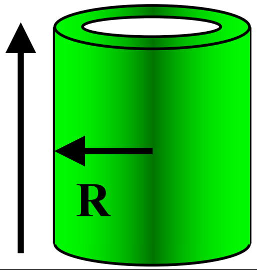


Pulsed power can generate ~100 Mbar drive pressures, which can be used to obtain even higher pressures such as those in inertial fusion

Magnetically Driven Implosion

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

drive current *I*



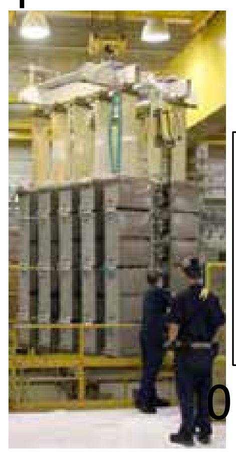
100 MBar at 26 MA and 1 mm

100 GPa = 1 Mbar ≈ 10^6 atmospheres

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

1 Mbar = 10^{11} J/m^3

Z Storage capacitor

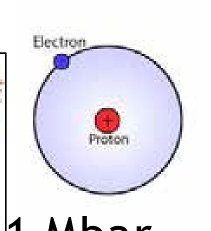


2e-6 Mbar

TNT

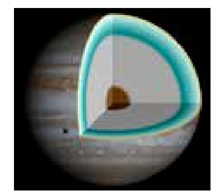
0.07 Mbar

Internal Energy of H atom



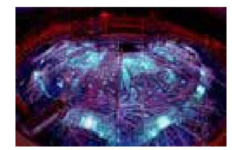
1 Mbar

Metallic H in Jupiter's core



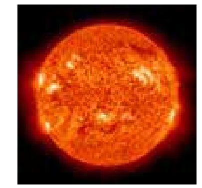
30 Mbar

Z Magnetic Drive Pressure



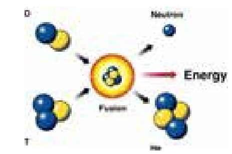
~100 Mbar

Center of Sun



250,000 Mbar

Burning ICF plasma



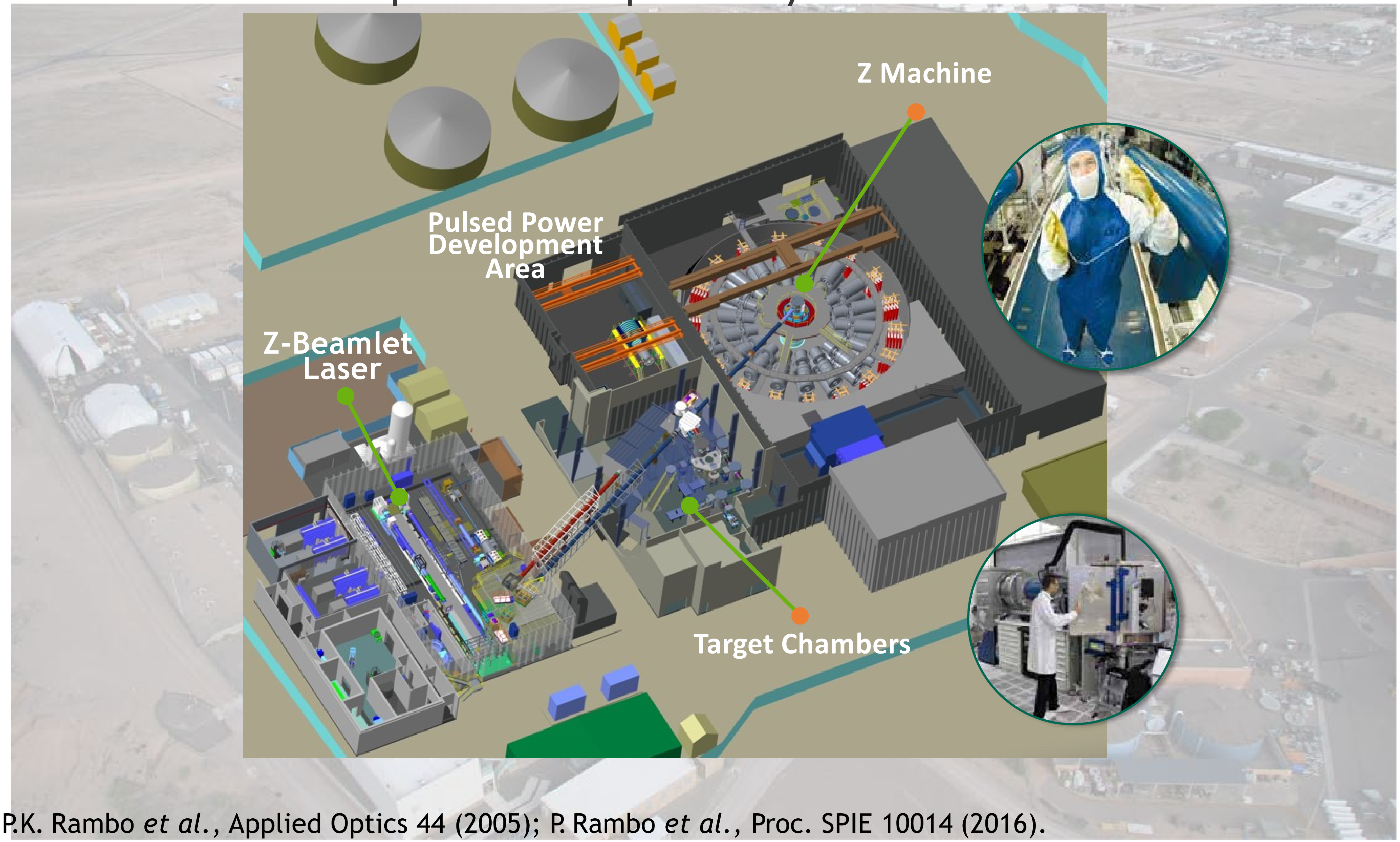
800,000 Mbar

Push on samples

Compress fuel at high velocity

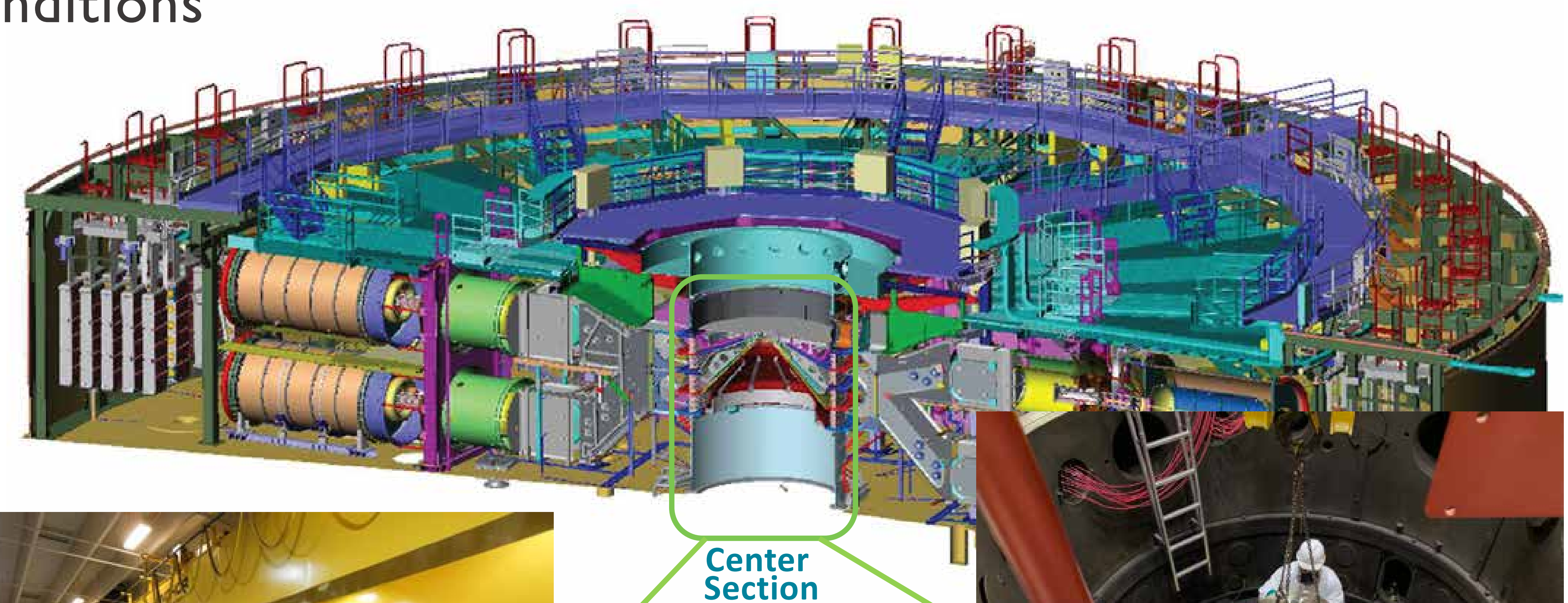
The Z facility is supported by the multi-kJ Z-Beamlet & Z-Petawatt lasers, which can also be operated independently

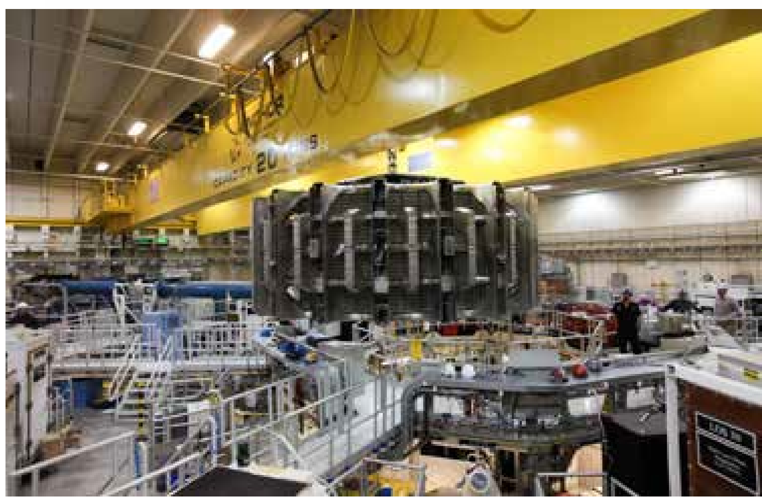
The Z facility is supported by the multi-kJ Z-Beamlet & Z-Petawatt lasers, which can also be operated independently



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

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





Z has its own YouTube Video Channel:

https://www.youtube.com/playlist?list=PL871791E99629ED7D

Z dissipates several MJ of energy within the center section, equivalent to several sticks of dynamite

Z has its own YouTube Video Channel:

https://www.youtube.com/playlist?list=PL871791E99629ED7D

Z is used to create High Energy Density matter and extreme x-ray environments for different applications

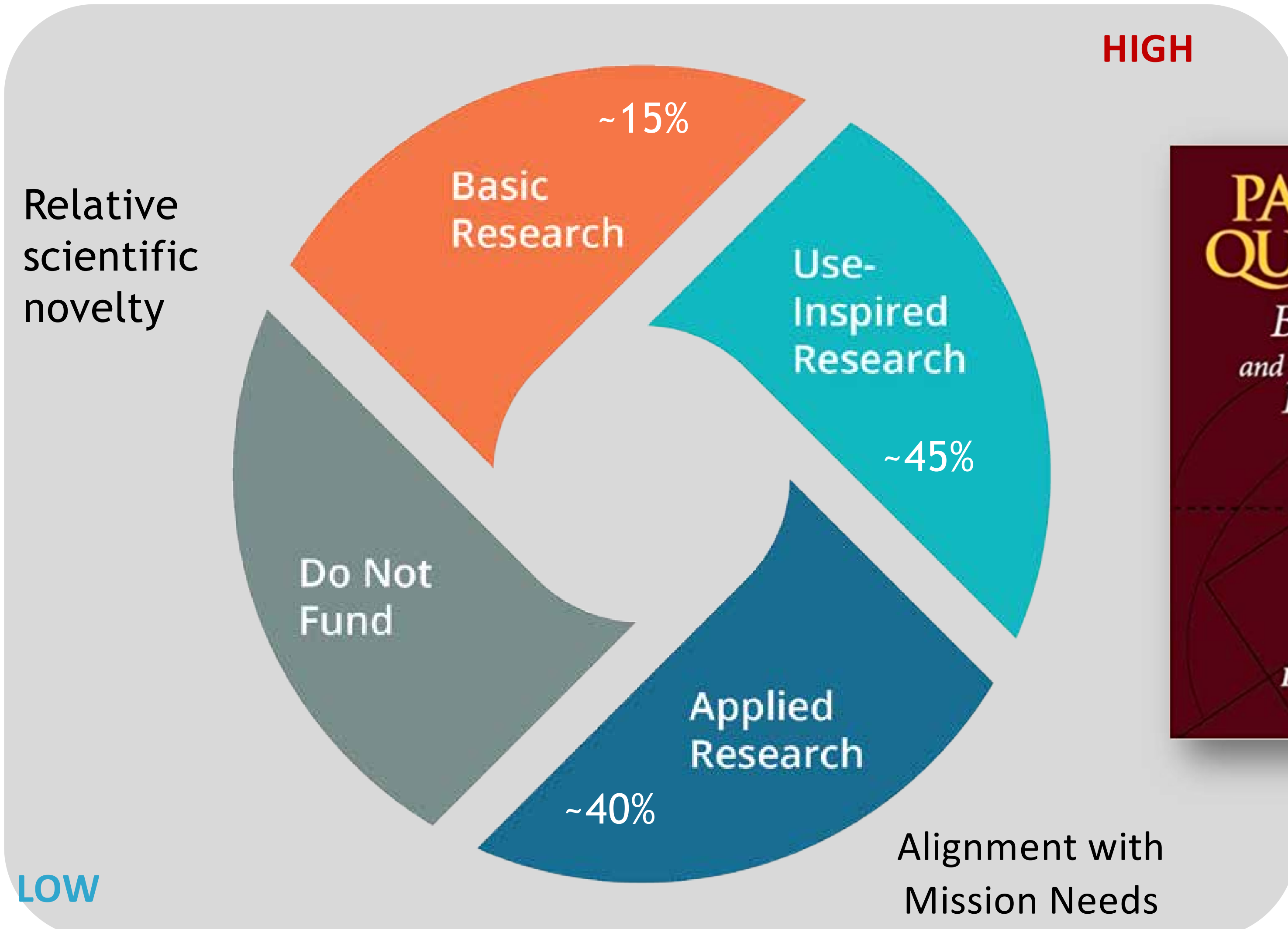
Majority of Z research is “use-inspired”

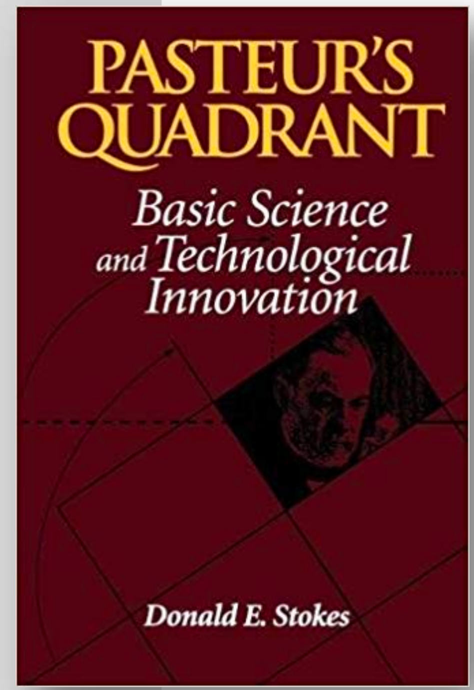
Conducting open, novel science while benefiting the mission of the NNSA

Basic

Use-Inspired

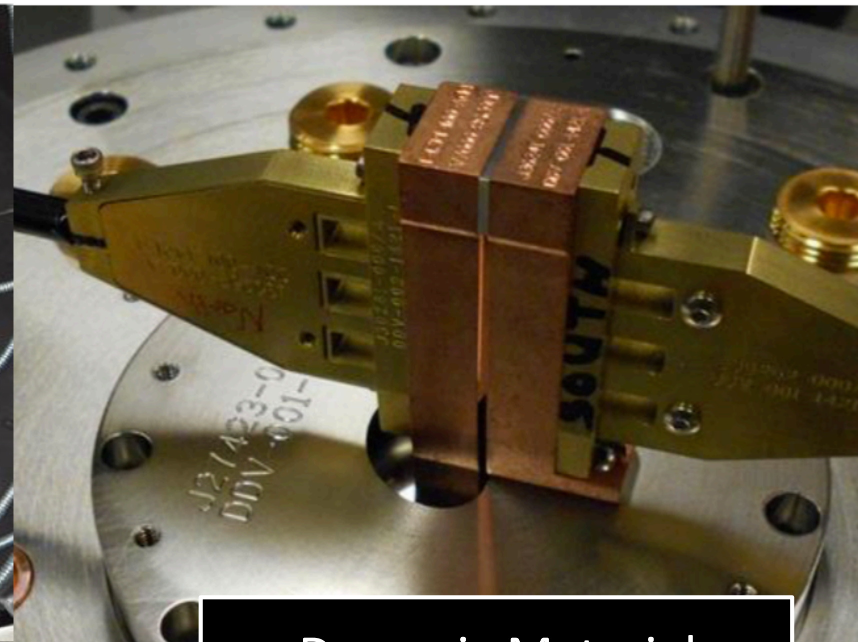
Applied





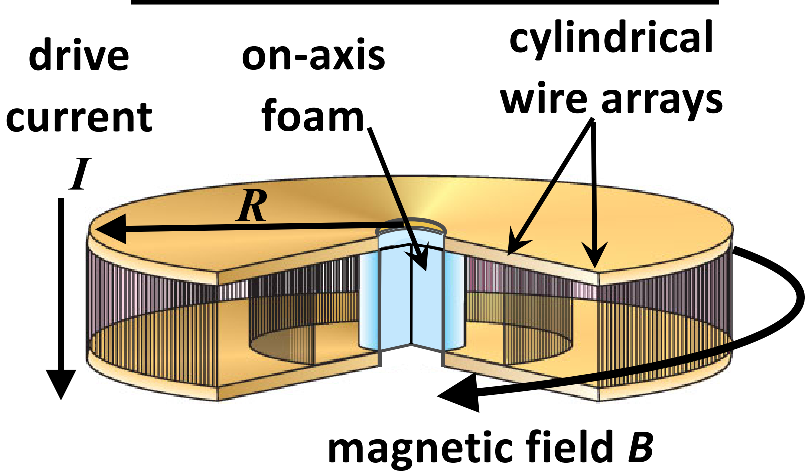
Precision tools for high energy density science

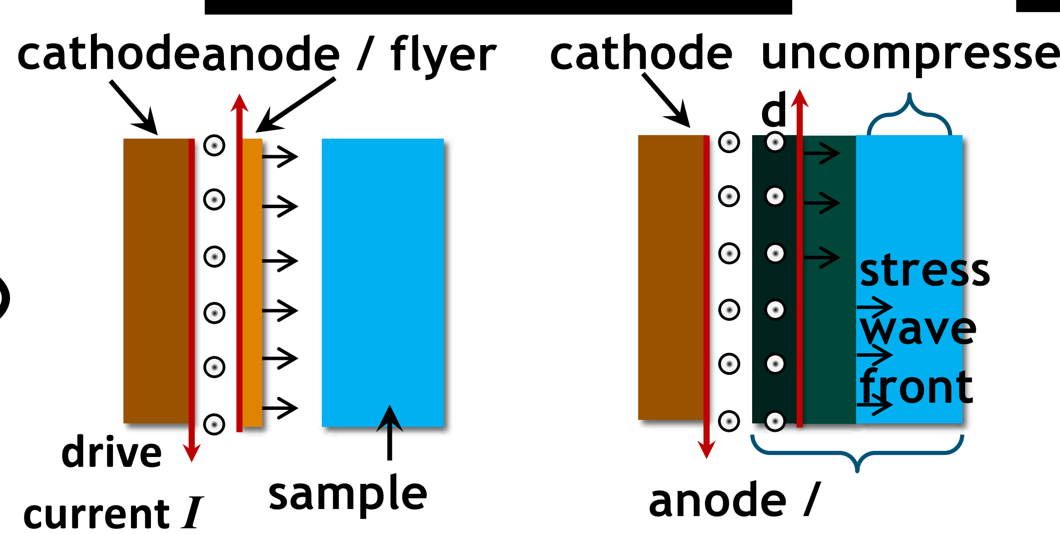
Radiation Science

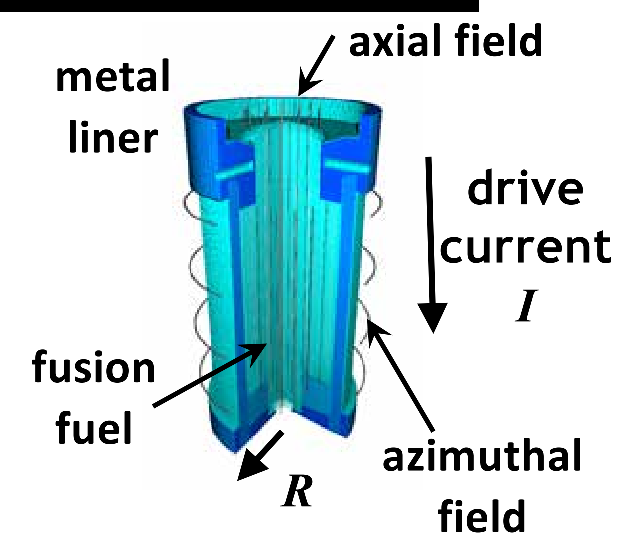


Dynamic Material Properties

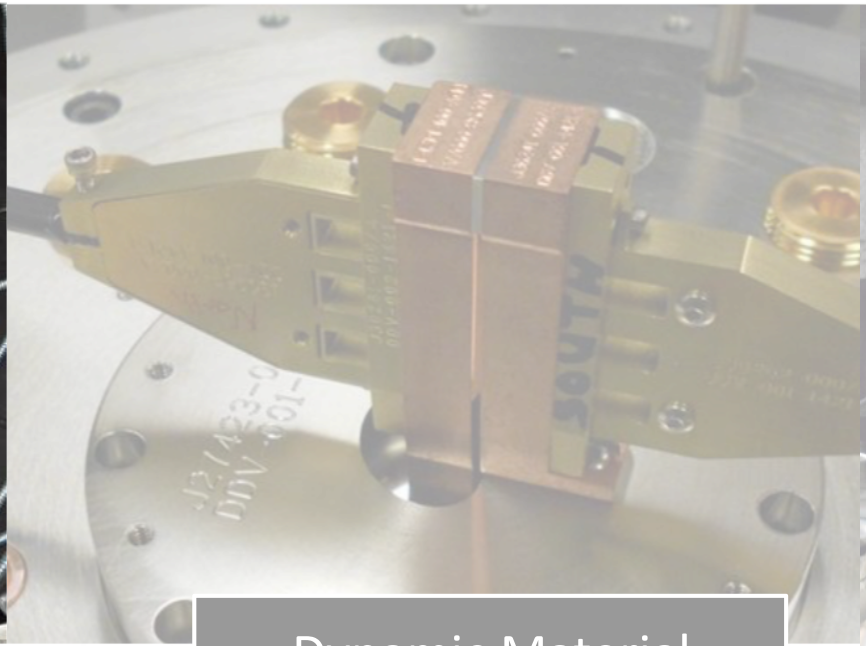
Inertial Confinement Fusion







Radiation Science

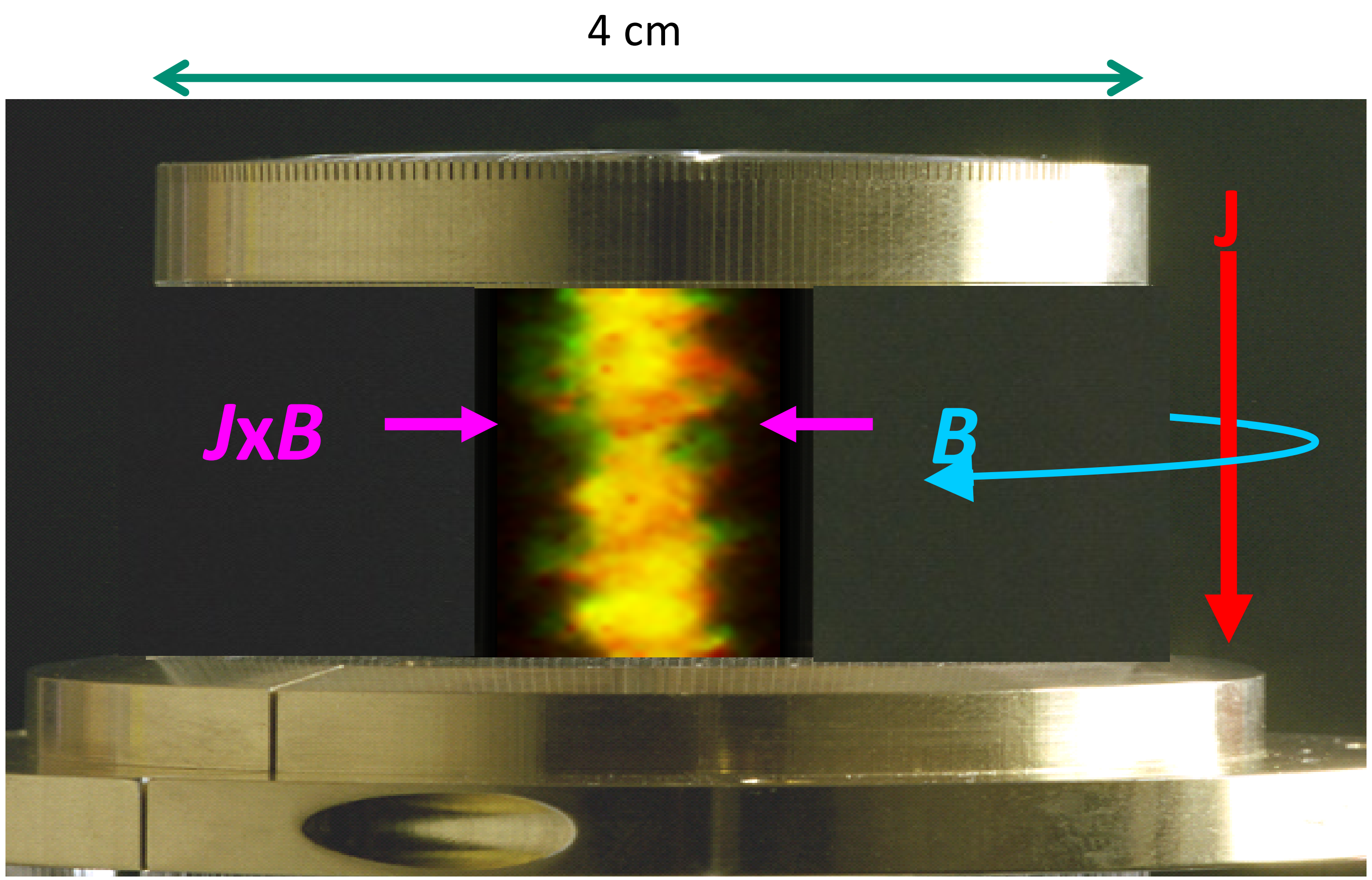


Dynamic Material Properties

Inertial Confinement Fusion

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

Basic

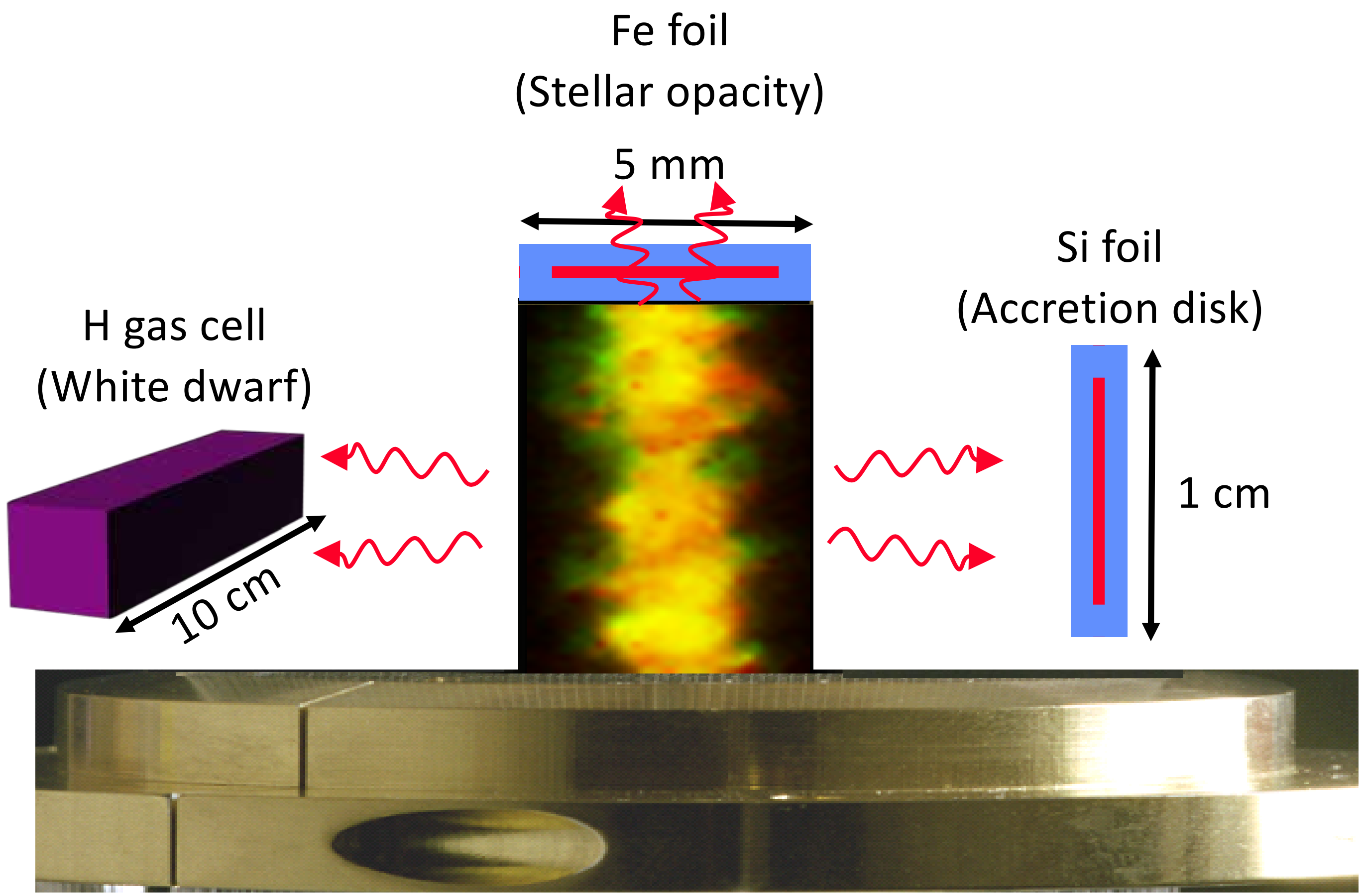


	ZR > 2011
Marx Energy	20.3 MJ
Ipeak	25.8 MA (1.5%)
Peak Power	220 TW (10%)
Radiated Energy	1.6 MJ (7%)

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).

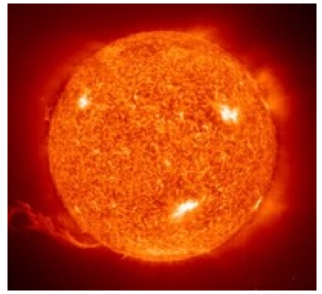
We collaborate with several institutions to do multiple radiation-driven basic science experiments on a single Z shot

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

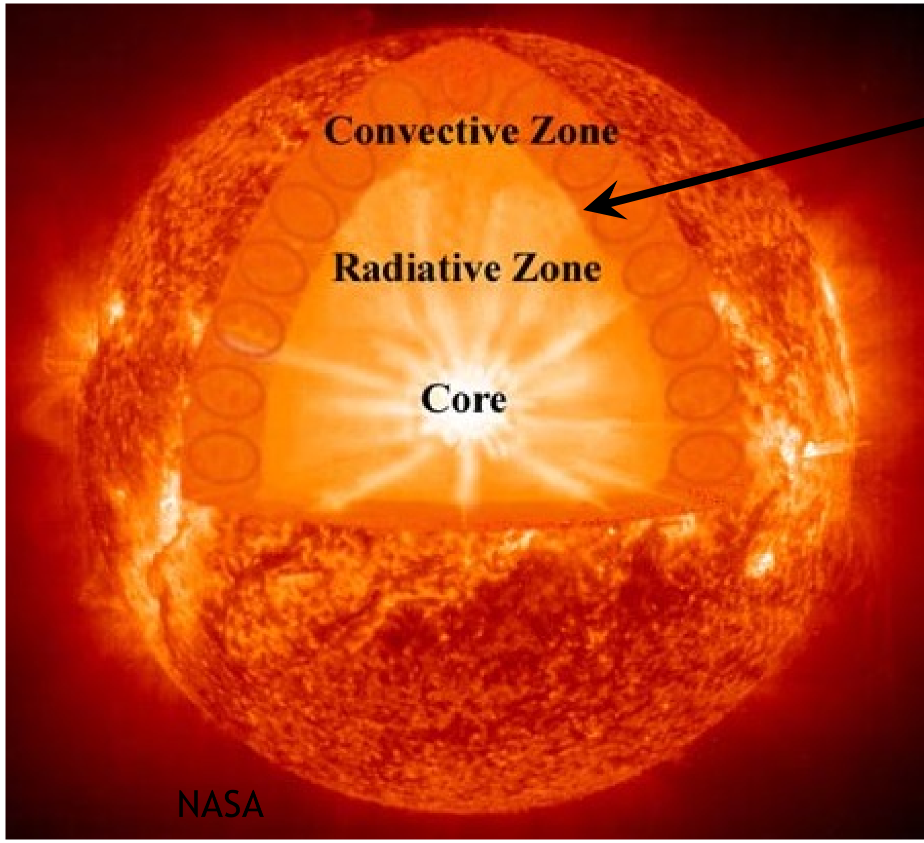
Question:
Why doesn’t spectral fitting provide the correct properties for White Dwarfs?

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).

Is opacity-model uncertainty responsible for disagreements between solar interior structure models and helioseismology data?

Basic



Convection-Zone (CZ) Boundary
Models are off by 10-30 σ

Models depend on:

- Composition (revised in 2005*)
- EOS as a function of radius
- The solar matter *opacity*
- Nuclear cross sections

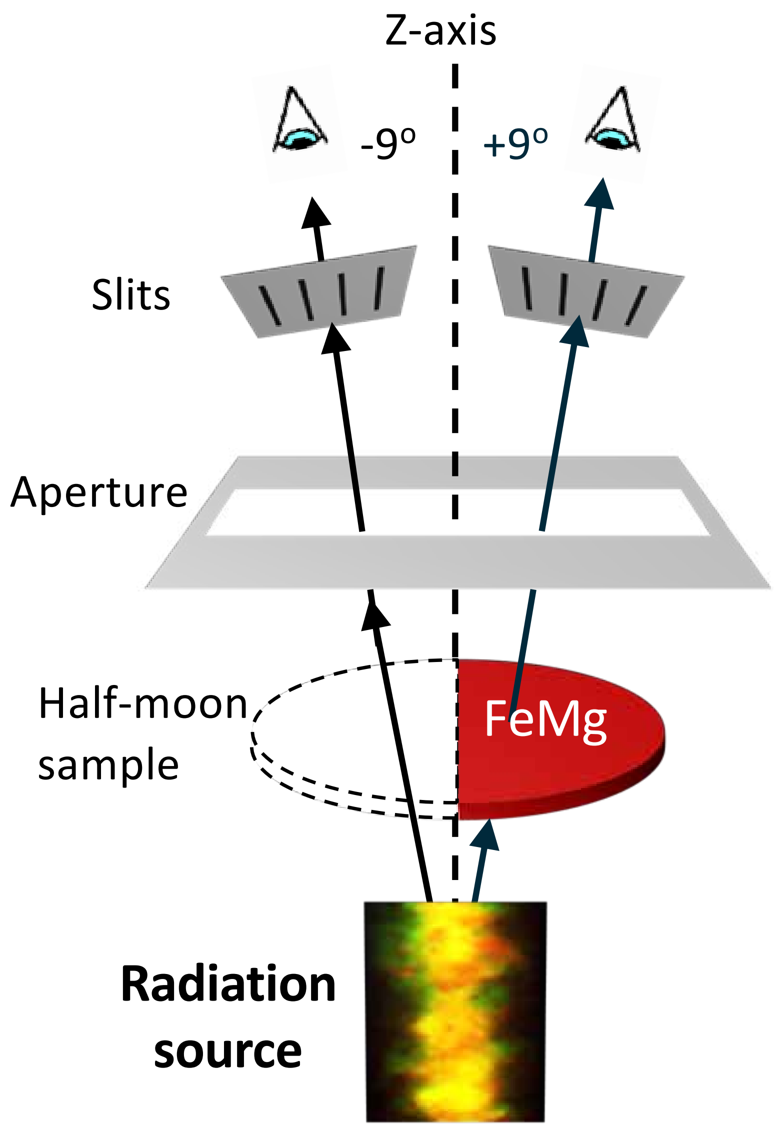
Question: Is opacity uncertainty the cause of the disagreement?

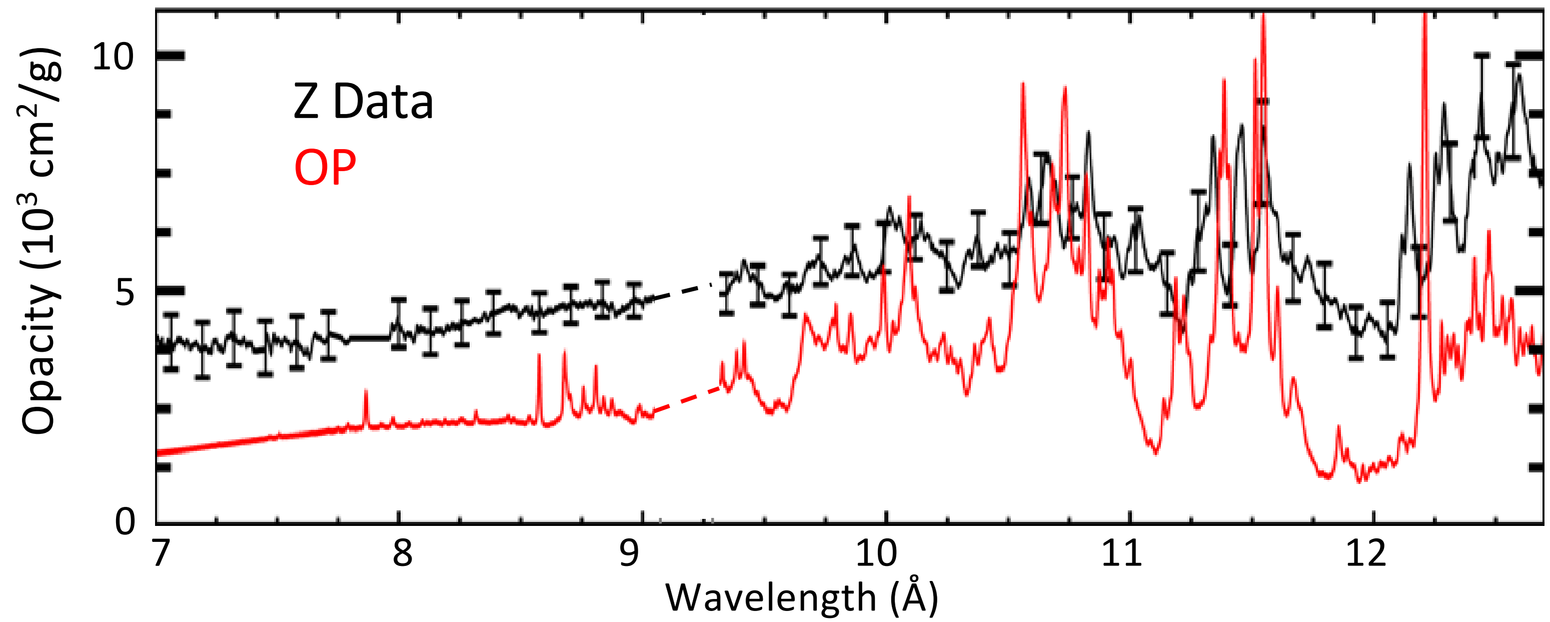
Objective: Measure Fe opacity at CZ base conditions.

*M. Asplund *et al*, Annu. Rev. Astro. Astrophys. **43**, 481 (2005).

The measured iron opacity accounts for roughly half the change needed to resolve the solar discrepancy

Basic





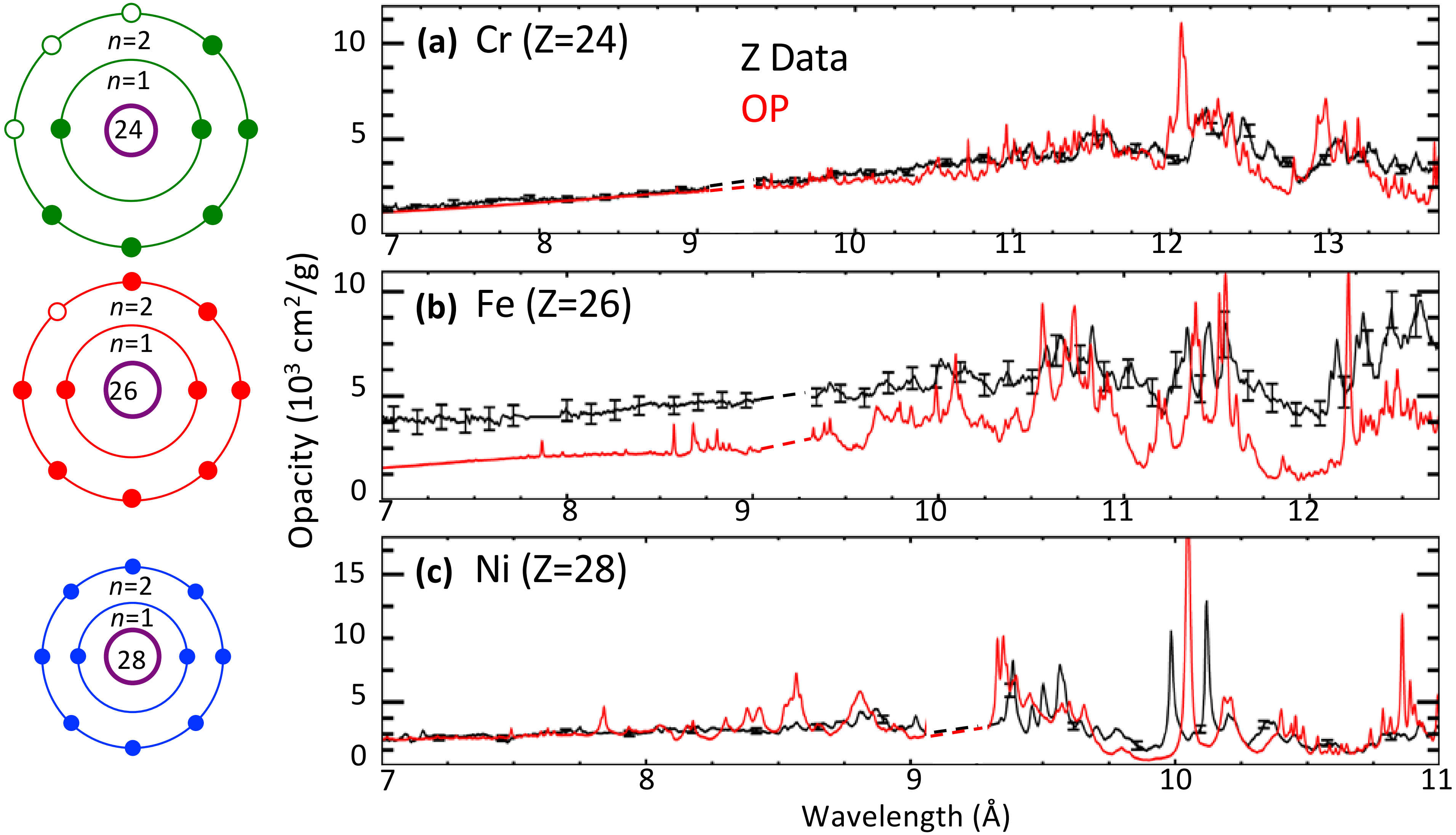
We need to understand what's causing the iron model-data discrepancy

- **Is the experiment flawed?**
- **Do opacity models miss important physics?**

J.E. Bailey *et al.*, A higher-than-predicted measurement of iron opacity at solar interior temperatures, Nature (2015)
T. Nagayama *et al.*, Systematic Study of L-shell Opacity at Stellar Interior Temperatures, Phys. Rev. Lett. (2019)

First systematic opacity study at stellar interior conditions reinforced confidence in experiments and suggested opacity-model refinements

Basic



Experiments with multiple elements help test hypotheses for:

- **Experiment flaws**
- **Model refinements**

New opacity models closer to the Z data* are under development

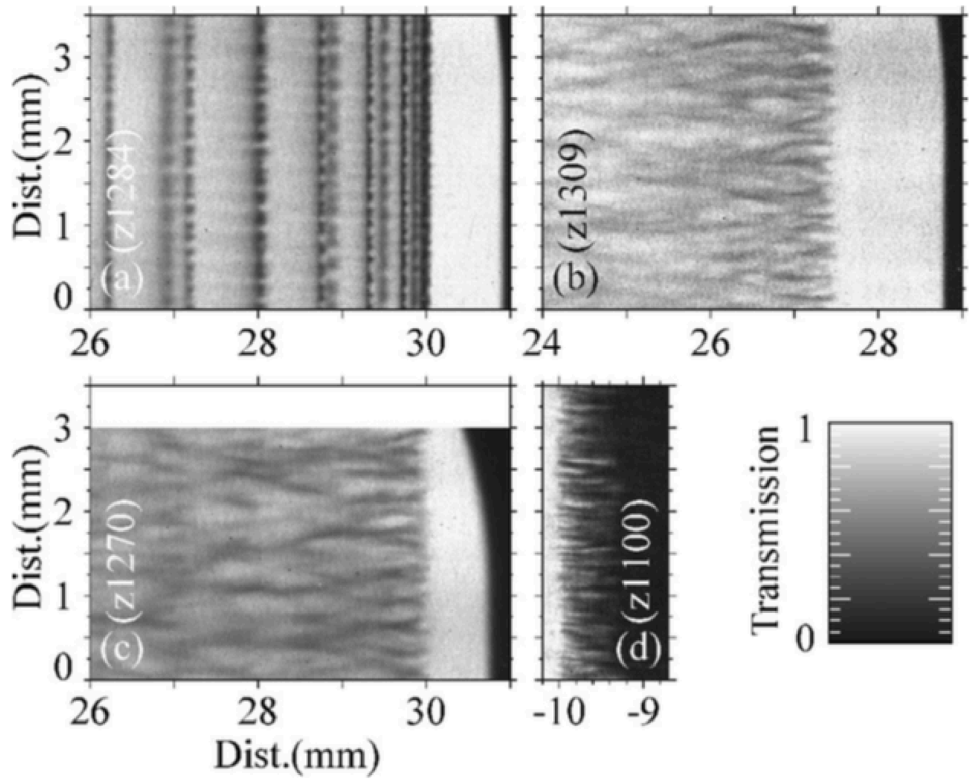
J.E. Bailey *et al.*, A higher-than-predicted measurement of iron opacity at solar interior temperatures, Nature (2015)
T. Nagayama *et al.*, Systematic Study of L-shell Opacity at Stellar Interior Temperatures, Phys. Rev. Lett. (2019)

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

Use-Inspired

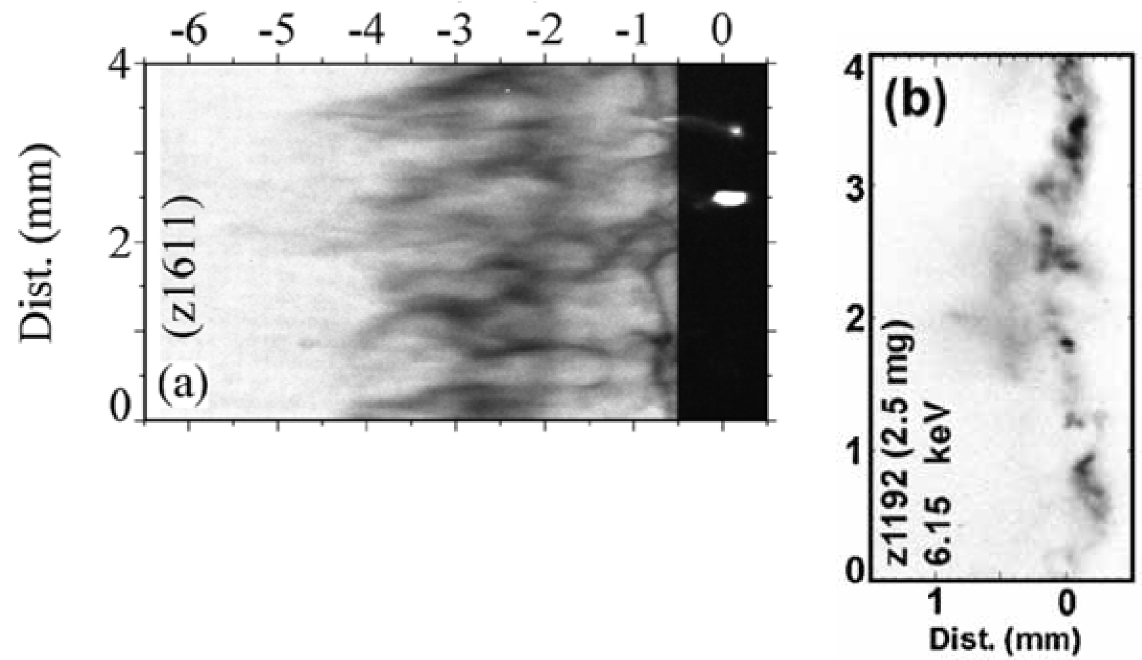
How do wire arrays turn into plasma?
Can we model wire array implosion instabilities?
What are the conditions at stagnation?

Examples of complex wire array ablation dynamics



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

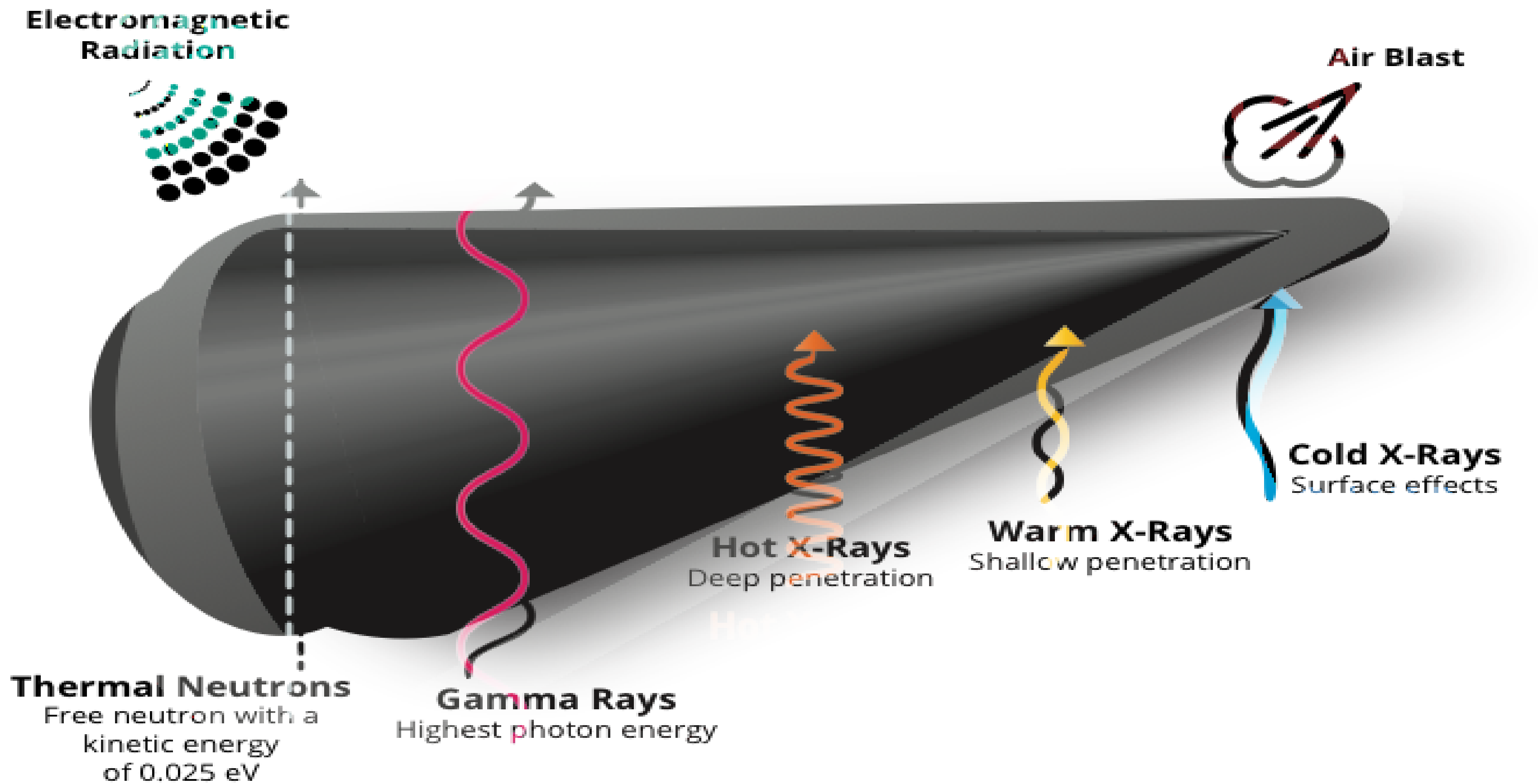
Examples of complex 3D implosion instabilities and bright x-ray spot formation



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

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

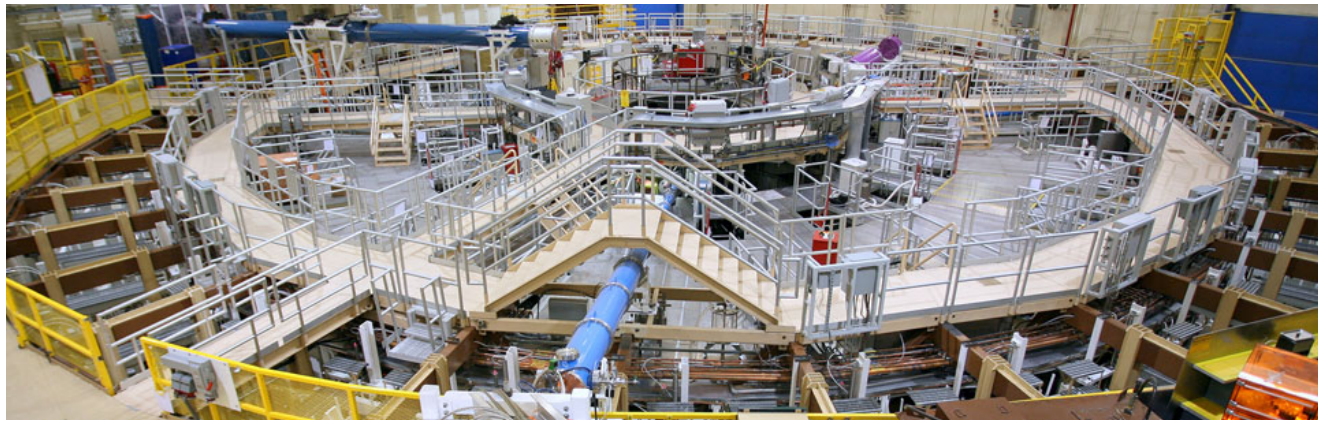
Applied



Prompt Neutrons
Neutrons with kinetic energy > 10 MeV

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

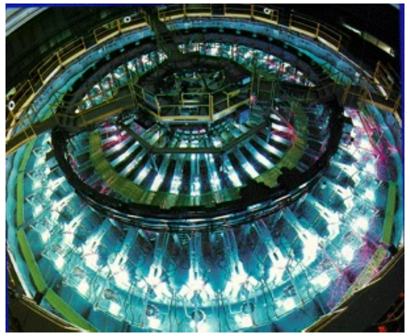
Applied



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

Annular Core Research Reactor
Fission neutrons

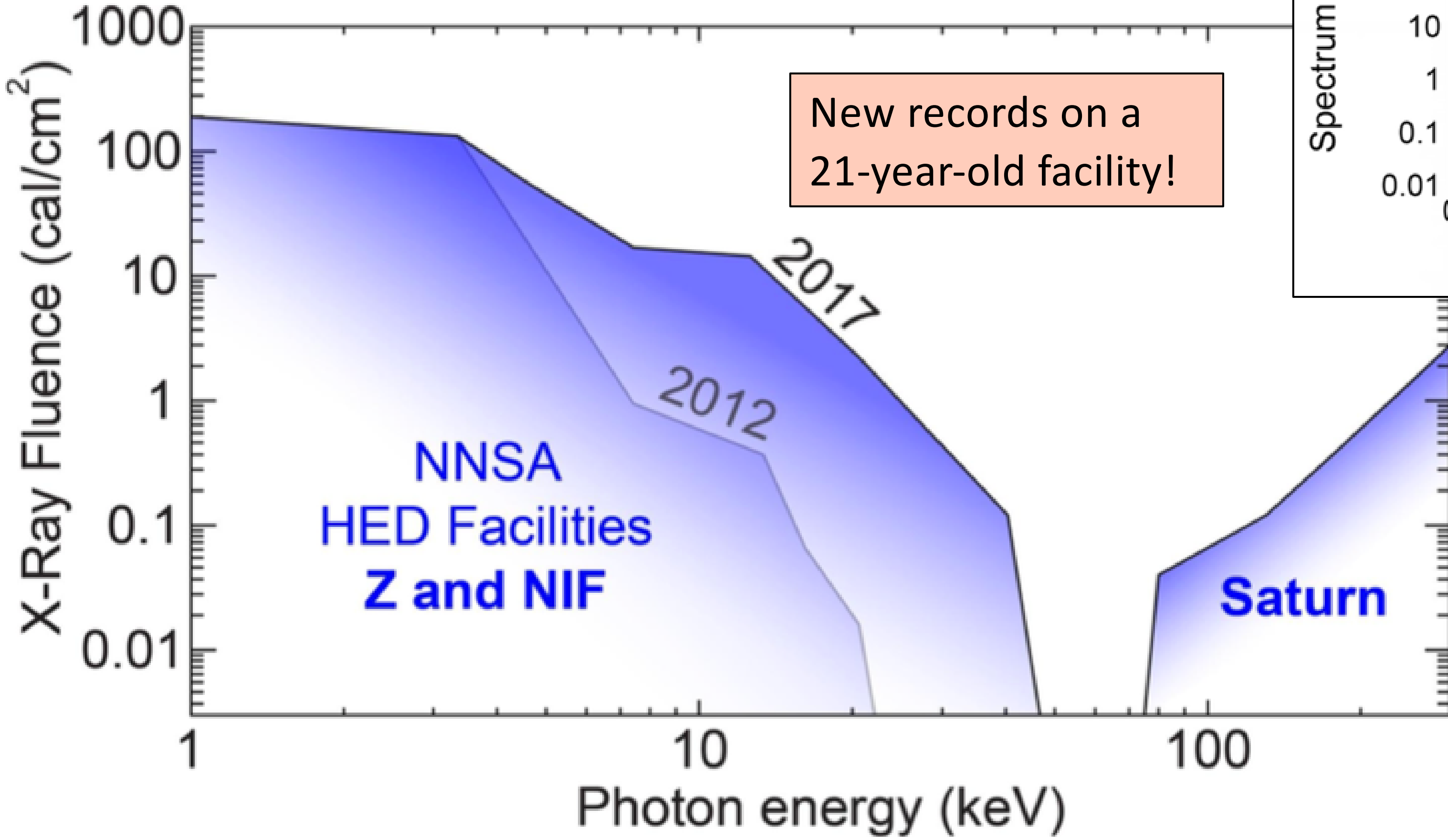
HERMES III
Gamma rays



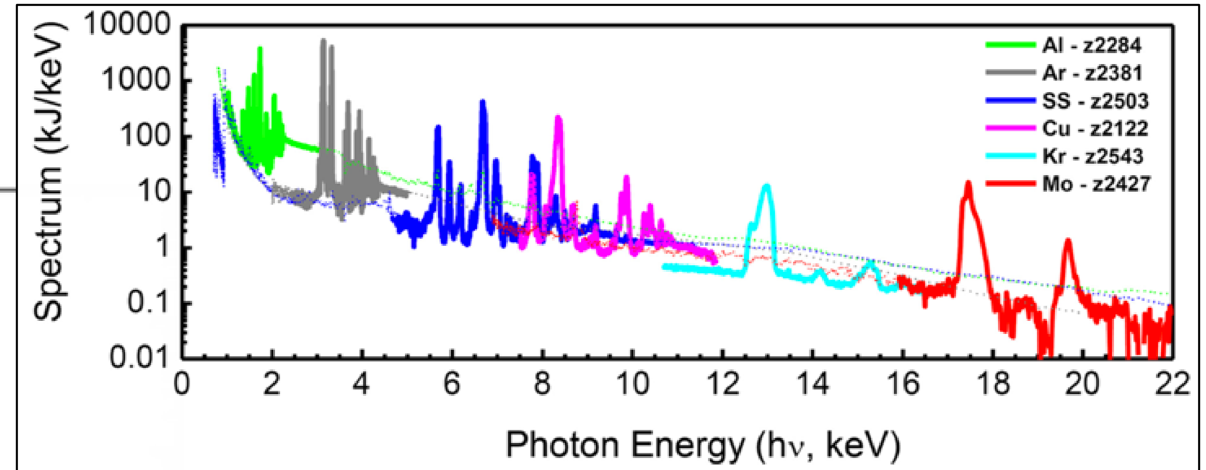
Saturn
Hot X-rays

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!

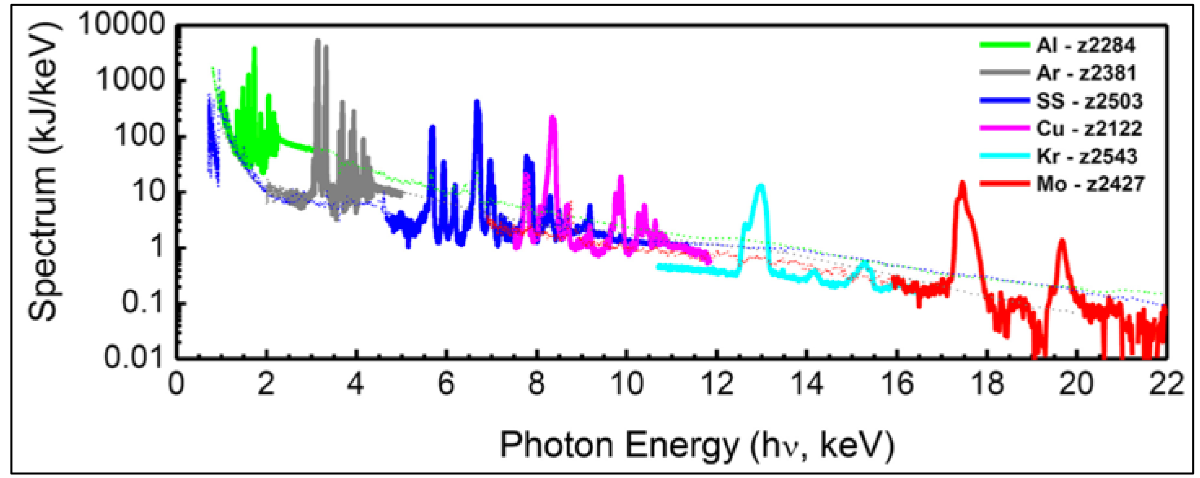


Z and NIF are developing advanced x-ray sources that provide unprecedented >10 keV yields

* 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*

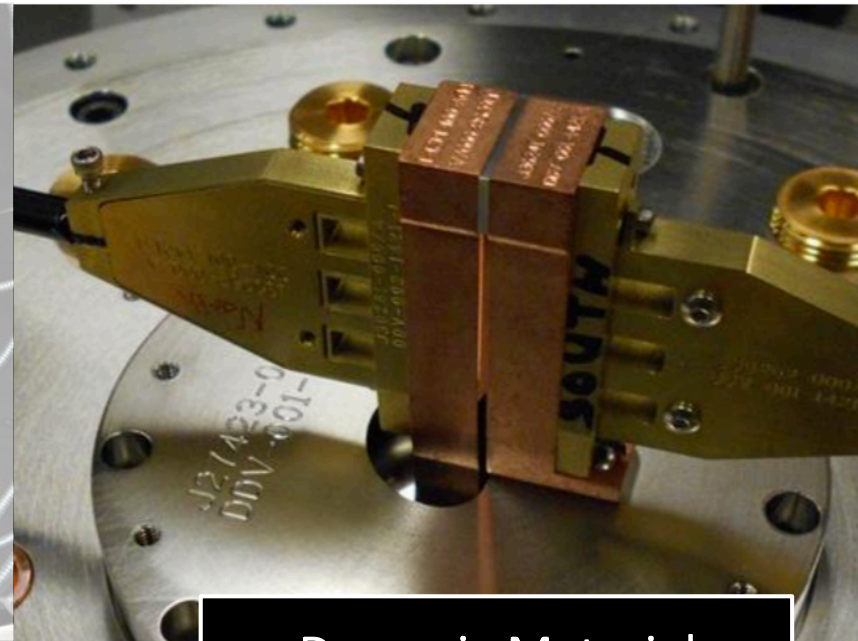
Applied



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).



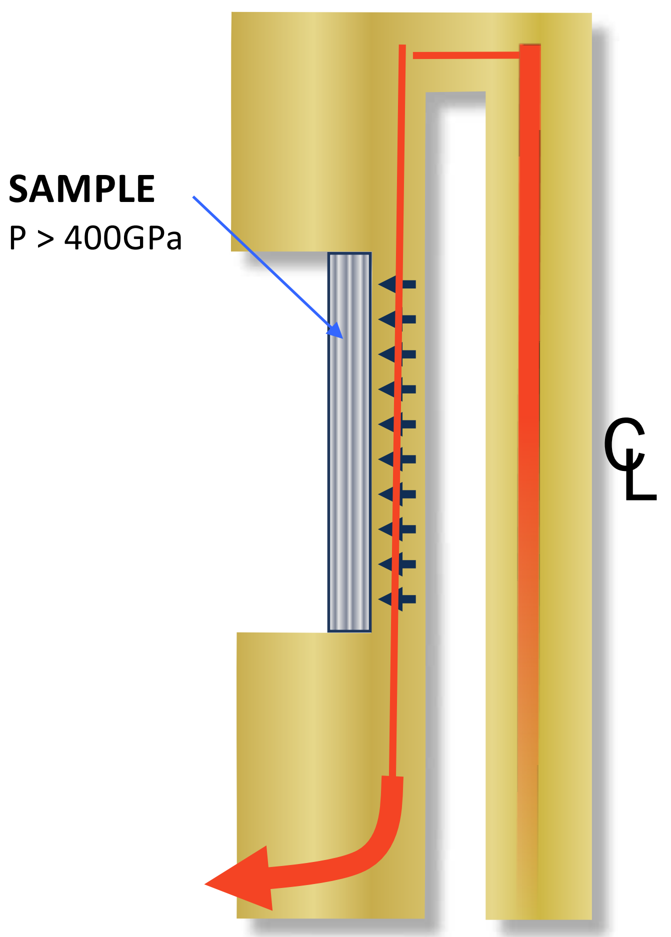
Radiation Science

Dynamic Material Properties

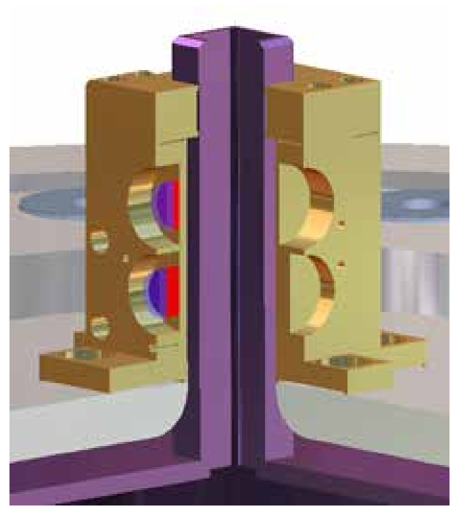
Inertial Confinement Fusion

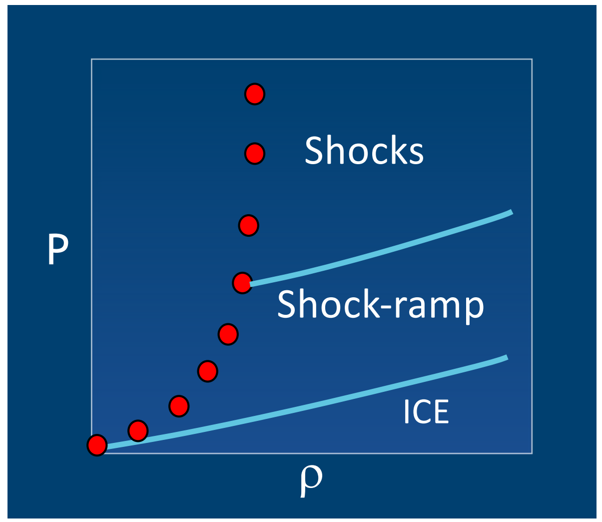
While roughly 1/3 of our Z shots are for dynamic materials, I will survey this topic only briefly—Thomas Mattsson’s seminar to you two weeks ago covered our materials research on Z very nicely!

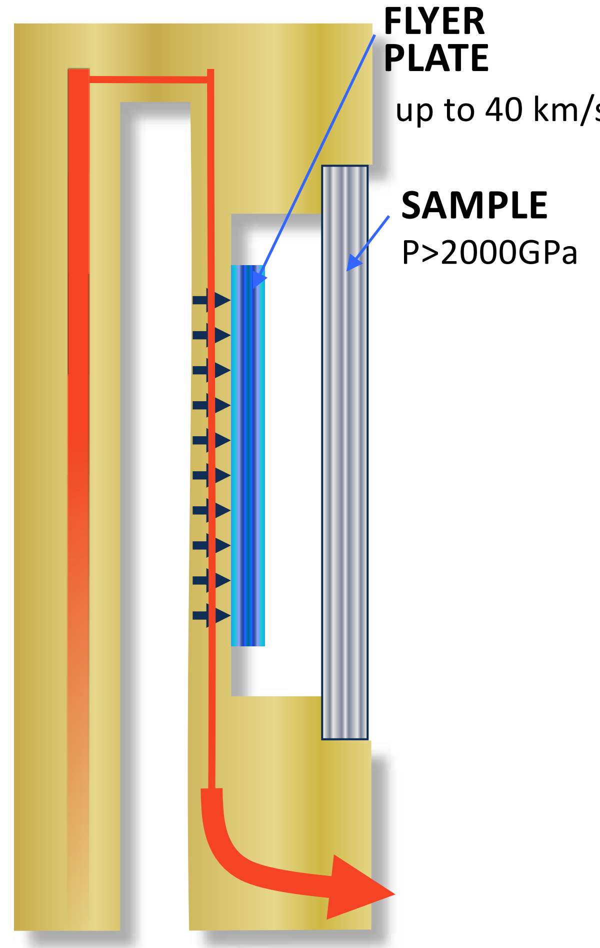
Isentropic compression and shock wave experiments map different regions of phase space



Isentropic Compression Experiments:
Gradual pressure rise in sample







Shock Hugoniot Experiments:
Shock wave in sample on impact

Z provides critical data on the dynamic response of materials (equation of state, strength) relevant to both astrophysics and nuclear weapons

Basic

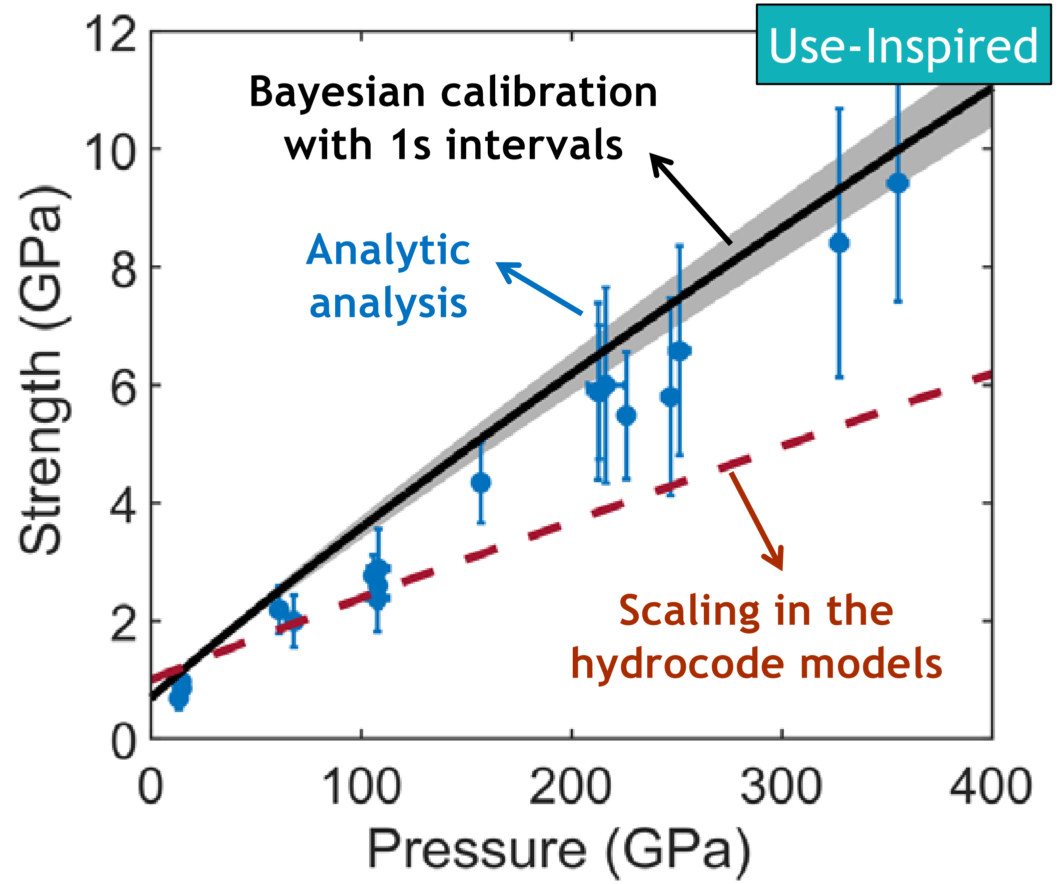
Data from Z on iron allowed scientists to conclude* that iron rain following a meteor impact dispersed iron over the surface of the growing earth

- **Explains the iron-enriched mantle of the earth**
- **Explains the comparatively low abundance of other elements on the moon due to its lower escape velocity**

* *Impact vaporization of planetesimal cores in the late stages of planet formation*, R.G. Kraus et al., Nature Geoscience 2015

Partners: Harvard, UC Davis, LLNL

Use-Inspired



Data from 15 measurements studying tantalum

- **Suggest typical pressure hardening in strength models commonly used in NNSA hydro codes is too low/soft**

Partners: LANL, 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 hazardous materials research

- Large samples, high pressures, and relevant loading paths
- Containment capability allows us to study many different hazardous materials

This is a long-standing partnership with LANL!

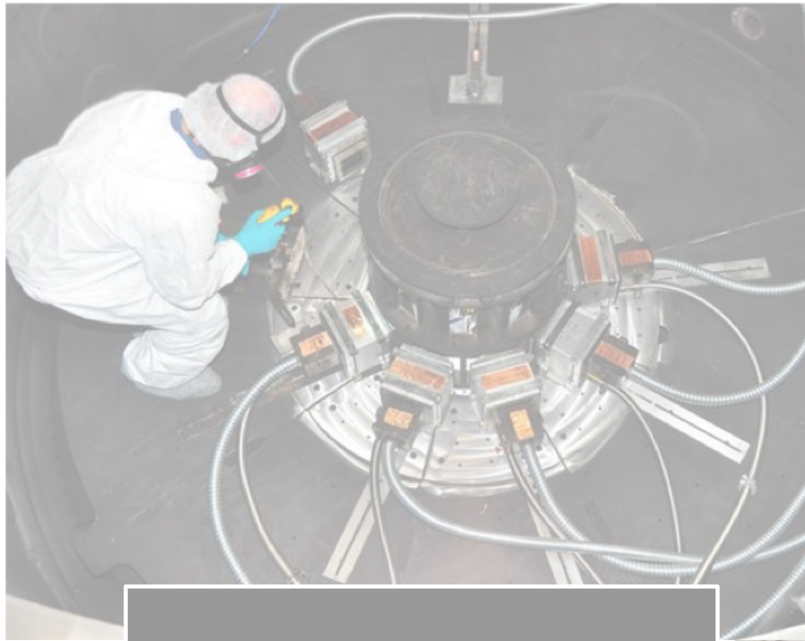
- First such experiments were conducted jointly in 2006, with >20 experiments to date
- LANL produces, machines, measures, and mounts the Pu targets in load hardware provided by Sandia

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

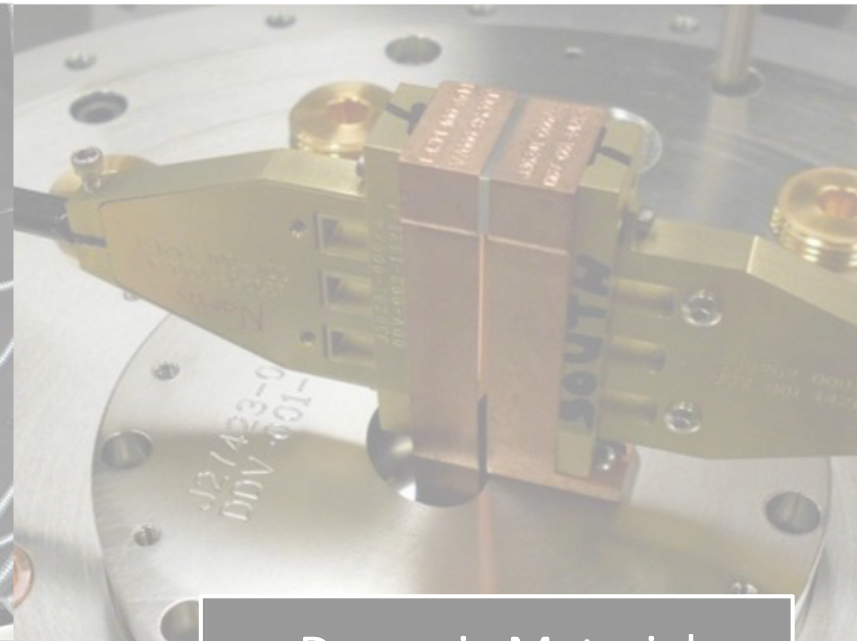
Conducted high-pressure uranium experiments on Z to benchmark LANL and LLNL EOS models

New capabilities are being developed to extend our impact for mission work. Our first “stripline” Pu experiment in 2020 reached record pressures with high accuracy.

LANL team: Freibert, Moore, Dattelbaum, Tolar, Crockett, and others



Radiation Science

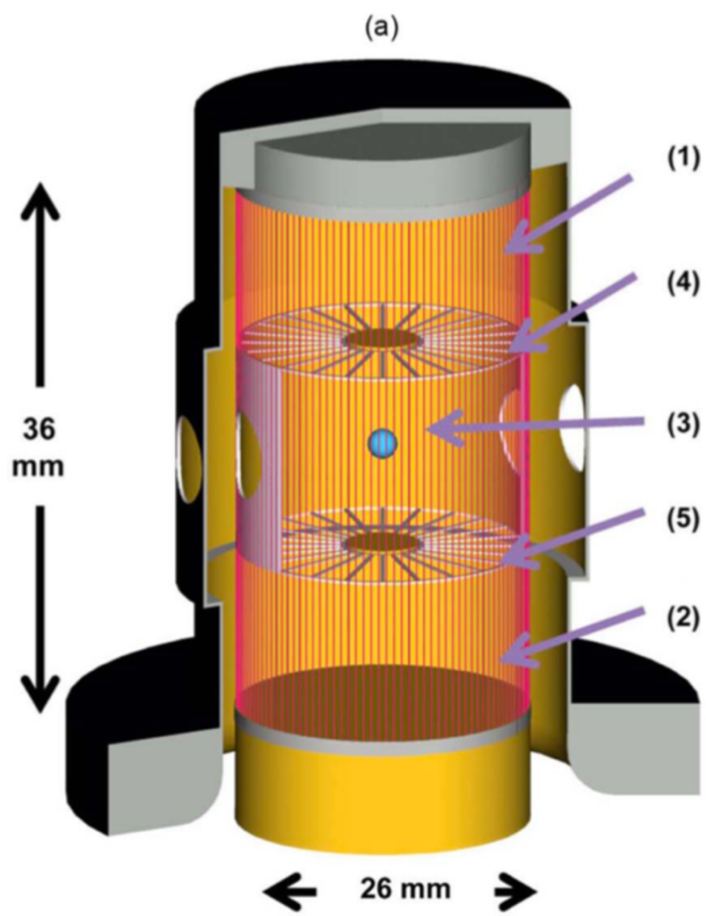


Dynamic Material Properties

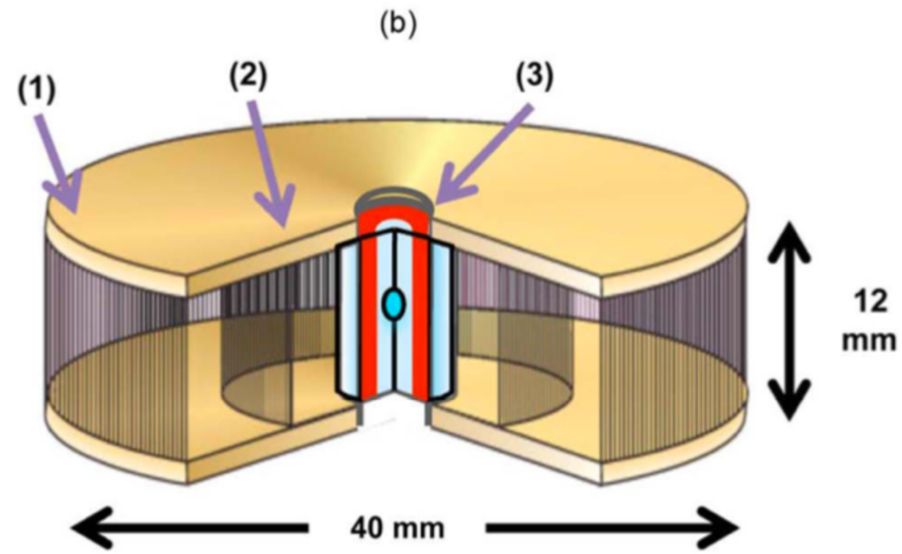
Inertial Confinement Fusion

In 2007, the Sandia Inertial Confinement Fusion (ICF) program switched from indirect drive (radiation-driven) to magnetic direct drive target research*

Basic



Double-ended Hohlraum



Z-pinch Dynamic Hohlraum (with capsule!)

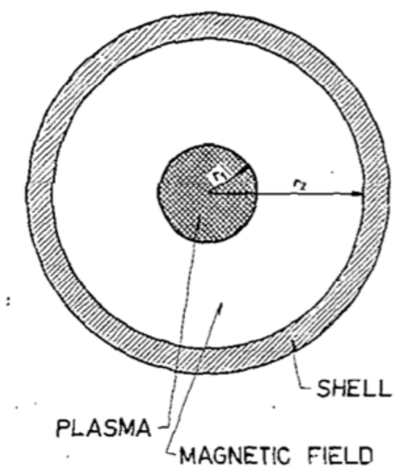
Today there is renewed interest from LANL and LLNL in studying magnetic indirect drive e.g., R.E. Olson *et al.*, HEDP 36, 100749 (2020)

* M.E. Cuneo *et al.*, IEEE Trans. Plasma Sci. (2012).

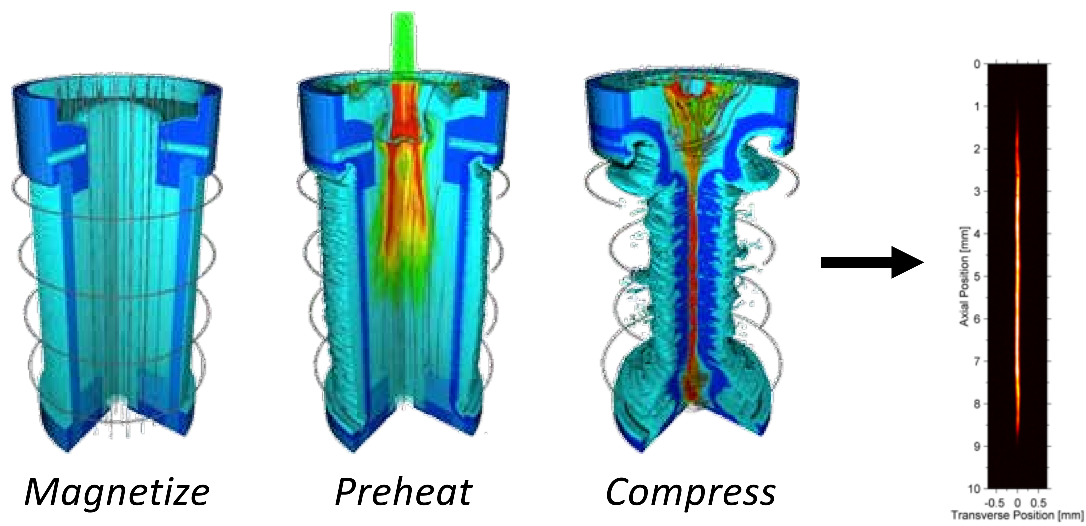
Sandia's shift to magnetic direct drive was partly motivated by the opportunity to demonstrate ideas that have been around for decades

The benefits of magnetizing inertially confined fusion fuel have been understood for ~60 years.

Magneto-inertial fusion scheme, ca. 1962 (Linhart et al.)



The thrill of discovery is thriving in modern magneto-inertial fusion (MIF) research!

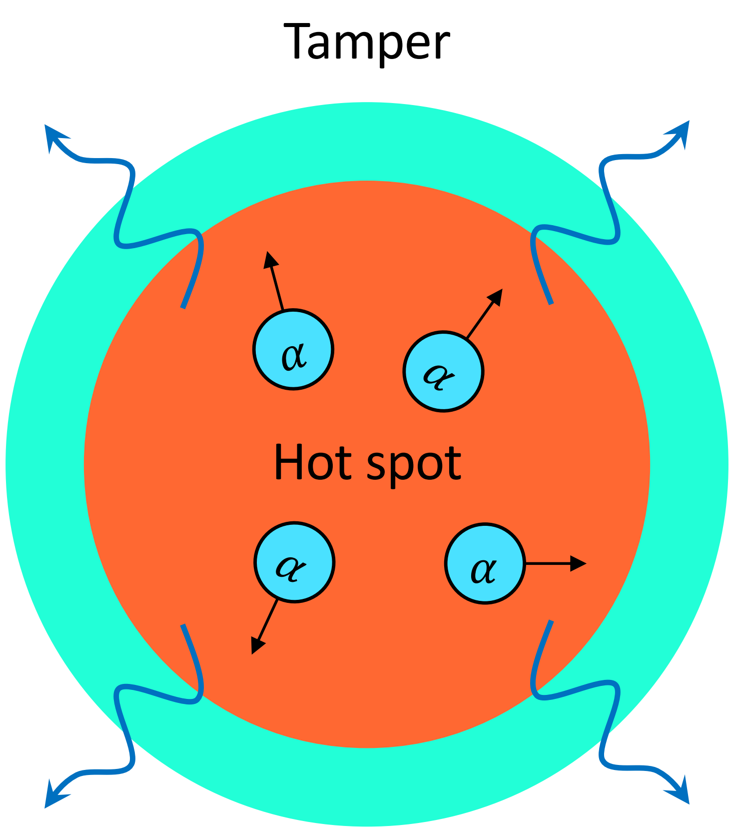


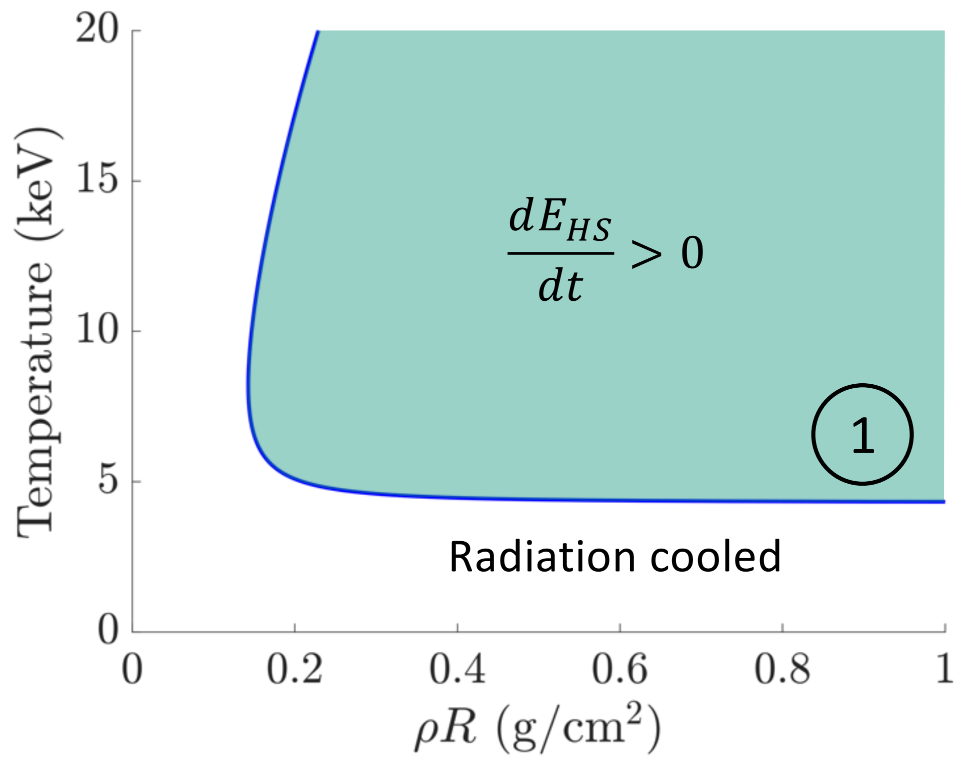
Magnetized Liner Inertial Fusion (MagLIF) has demonstrated the fundamental principles of MIF and is an engine of discovery in the field.

Burning ICF plasmas must satisfy a few important criteria

$$\frac{dE_{HS}}{dt} = \left(\text{Alpha heating}\right) - \left(\text{Radiation losses}\right) - \left(\text{Conduction losses}\right)$$

Positive energy balance





<u>Hot spot self-heating criteria</u>

(1) $T_{HS} \gtrsim 4.3$ keV

Atzeni & Meyer-ter-Vehn (2004)
Betti et al., POP 17, 058102 (2010)

Burning ICF plasmas must satisfy a few important criteria

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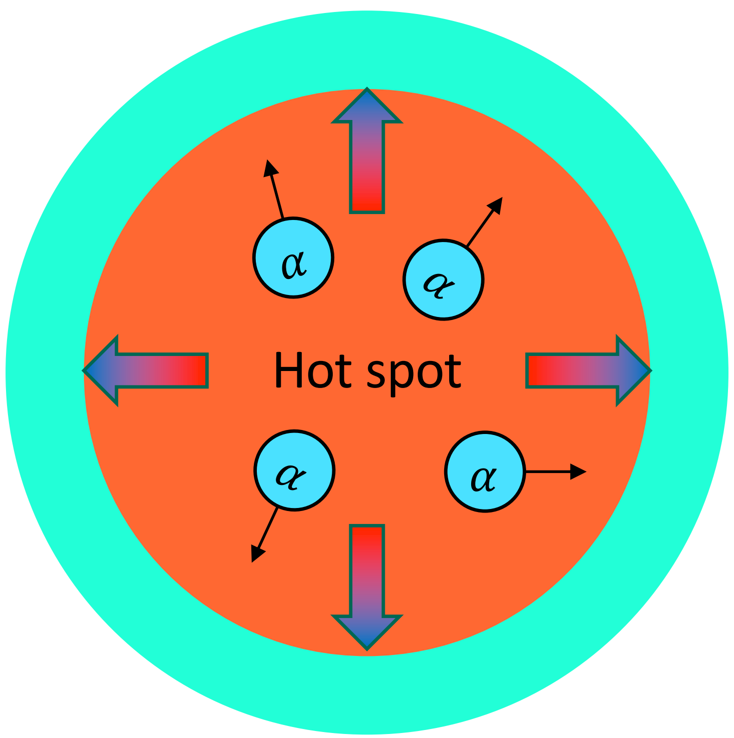
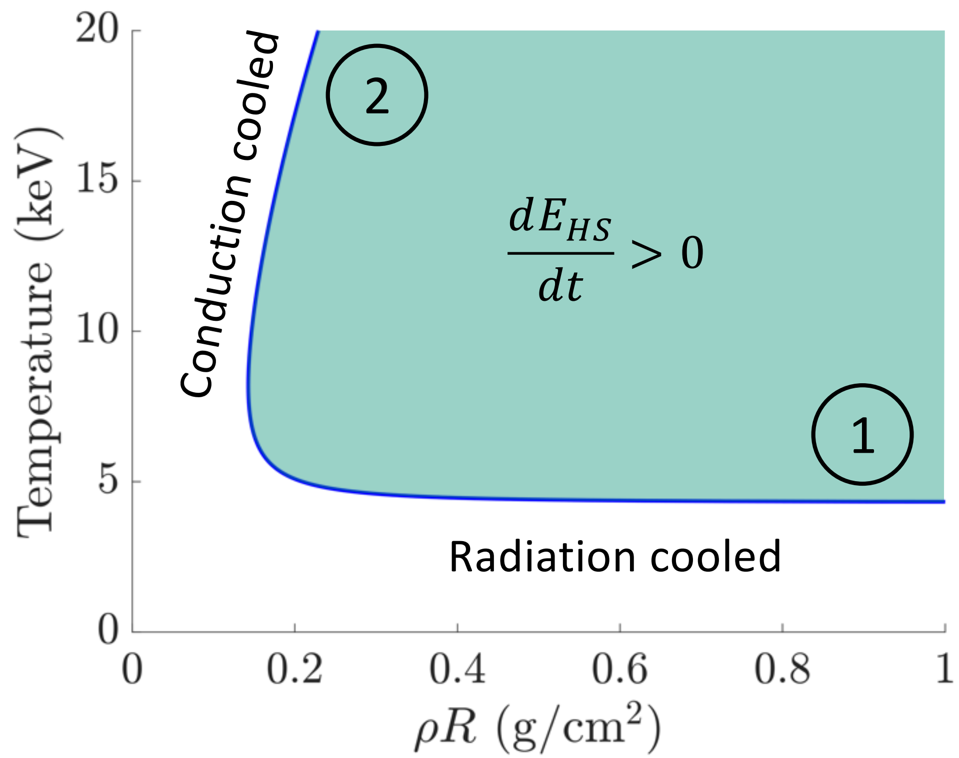




Hot spot self-heating criteria

1. $T_{HS} \gtrsim 4.3$ keV
2. $(\rho R)_{HS} \gtrsim 0.2$ g/cm^2

Atzeni & Meyer-ter-Vehn (2004)
Betti et al., POP 17, 058102 (2010)

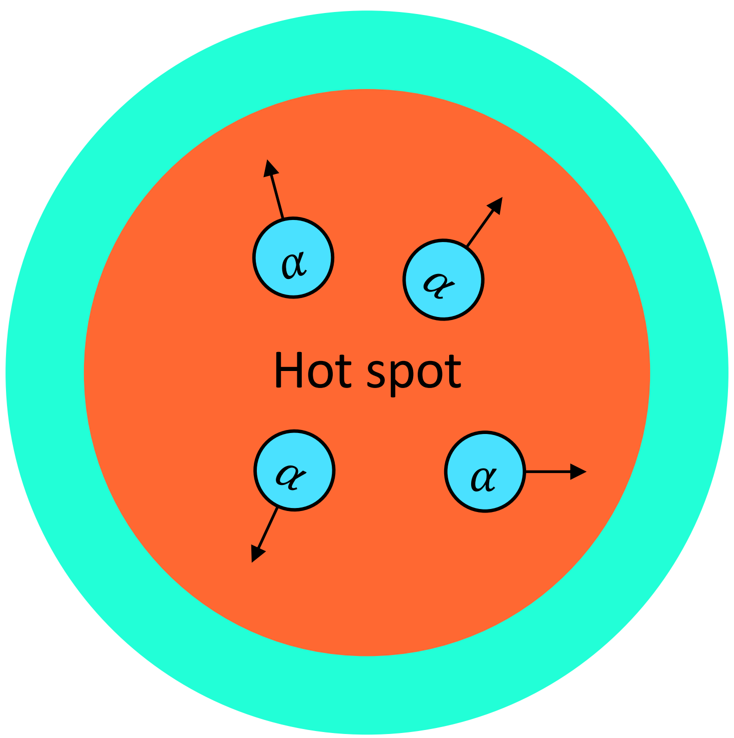
Burning ICF plasmas must satisfy a few important criteria

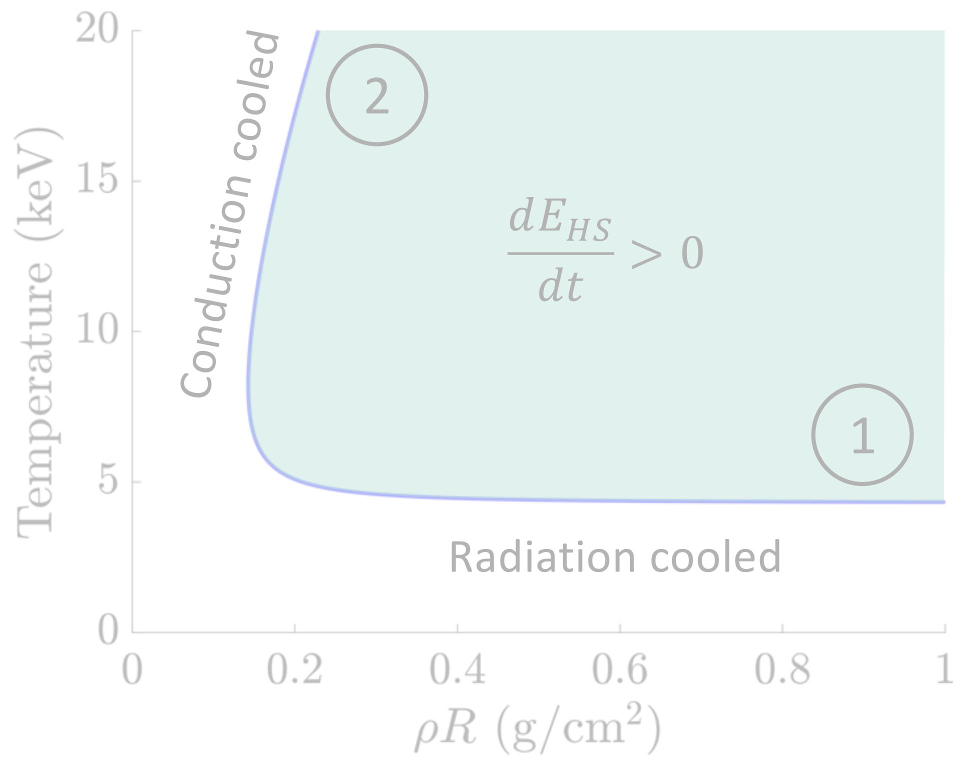
$$\underbrace{\frac{dE_{HS}}{dt} = \begin{pmatrix}\text{Alpha}\\\text{heating}\end{pmatrix} - \begin{pmatrix}\text{Radiation}\\\text{losses}\end{pmatrix} - \begin{pmatrix}\text{Conduction}\\\text{losses}\end{pmatrix}}_{\text{Positive energy balance}}$$

Energy reproduction (Lawson): $\begin{pmatrix}\text{Total } \alpha\\\text{energy}\end{pmatrix} > \begin{pmatrix}\text{Hot spot}\\\text{energy}\end{pmatrix}$

$$1 < \chi \propto P_{HS}\tau_E\left[\frac{\langle\sigma v\rangle}{T_{HS}^2}\right]$$

Tamper





Hot spot self-heating criteria

1. $T_{HS} \gtrsim 4.3$ keV
2. $(\rho R)_{HS} \gtrsim 0.2$ g/cm^2
3. $\chi > 1$ (Lawson)

Atzeni & Meyer-ter-Vehn (2004)
Betti et al., POP 17, 058102 (2010)

These are challenging conditions to achieve, but magnetic fields offer some relief

<u>Hot spot self-heating criteria</u>

1. $T_{HS} \gtrsim 4.3 \text{ keV}$
2. $(\rho R)_{HS} \gtrsim 0.2 \text{ g/cm}^2$ → The hot-spot areal density can be lowered significantly with B-fields
3. $\chi > 1$ (Lawson)

Magnetization locally reduces heat flows across field lines (noted by Fermi in 1945, Los Alamos Report 344, Sept. 17)

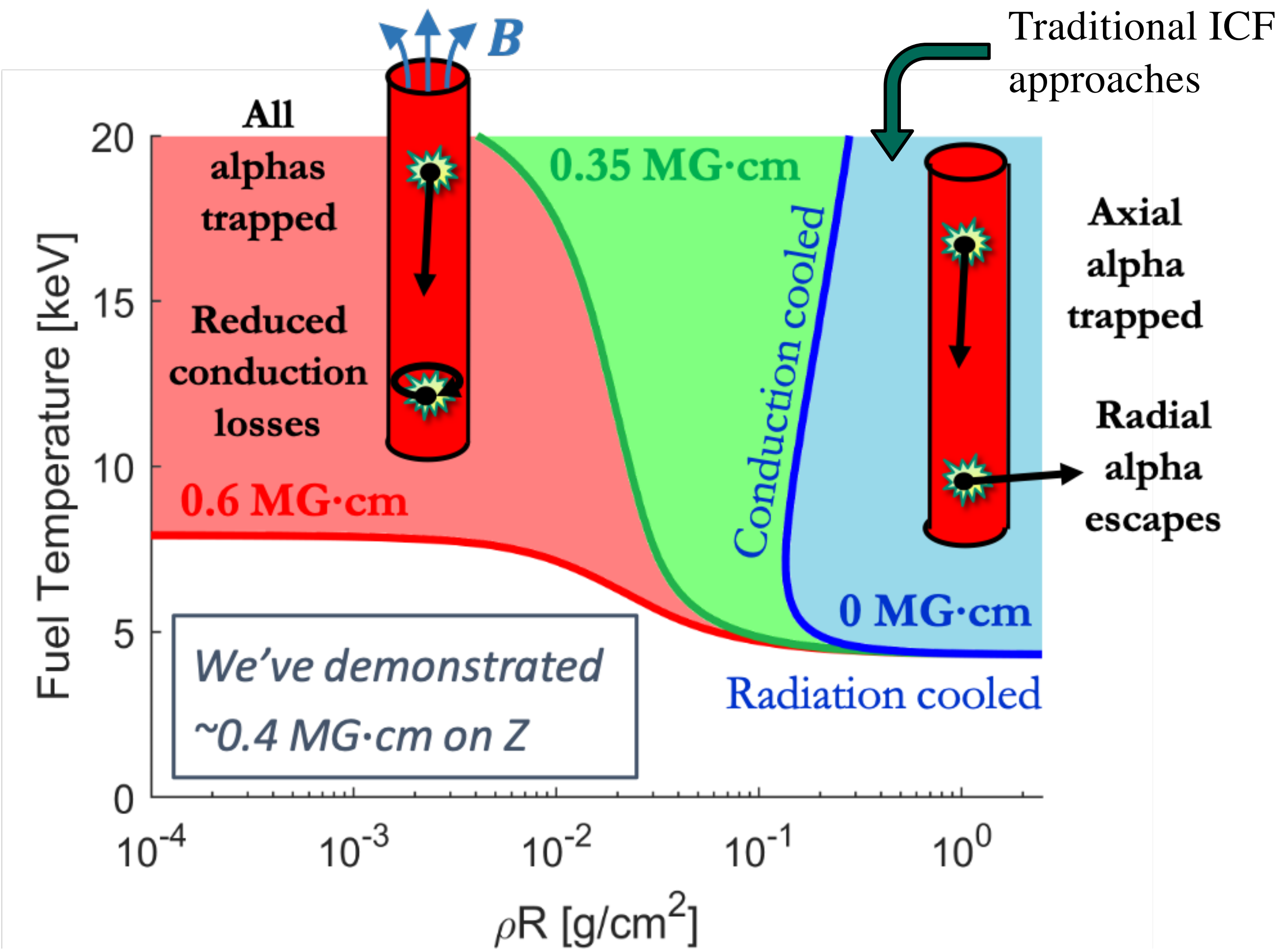
$$\text{Perpendicular heat flux} \propto (\omega_{ce}\tau_e)^{-2}$$

Magnetic fields globally confine DT alpha particles:

$$\frac{\text{hot spot radius}}{\alpha \text{ gyroradius}} \approx 4[BR(\text{MG}\cdot\text{cm})]$$

Magnetic fields open the door to a broader range of new paths to achieve fusion in the laboratory

Consider an axially magnetized, cylindrical hot spot:



Lower fuel $(\rho R)_{HS}$ reduces fuel compression and pressure requirements:

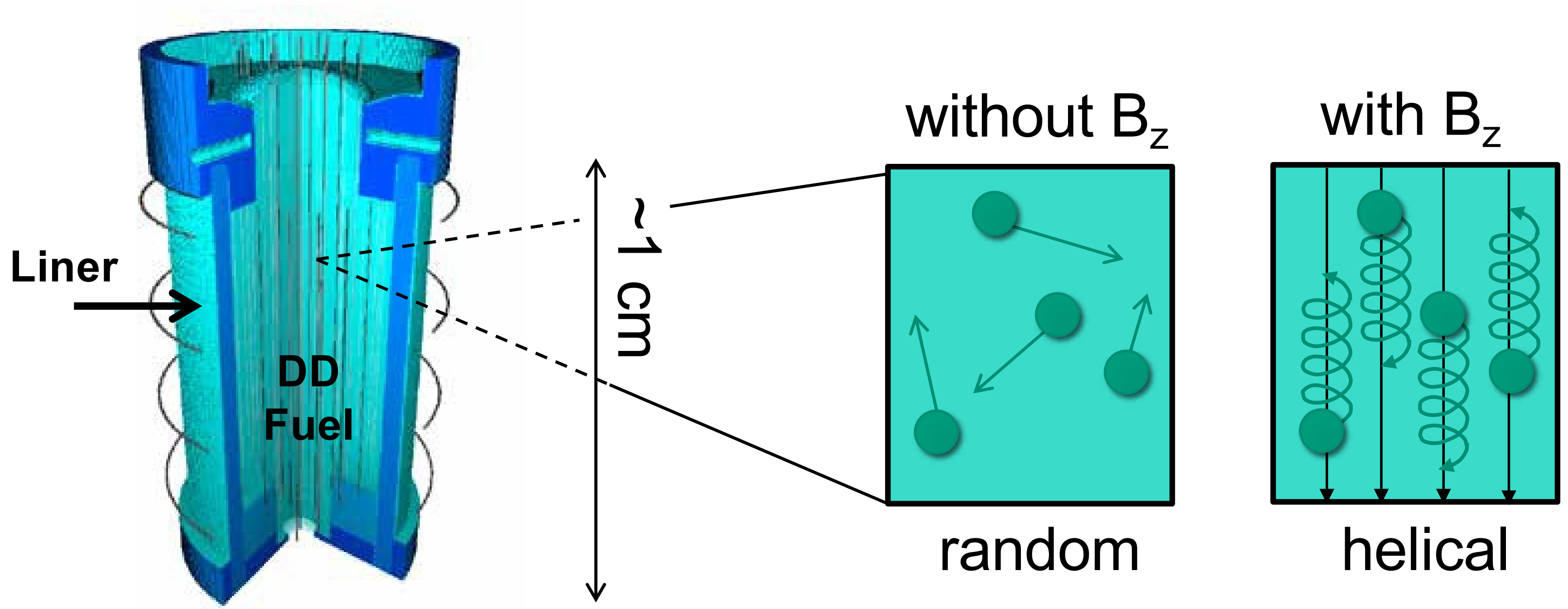
$$Y_{DT} \propto M_{HS} \propto \frac{(\rho R)_{HS}^2}{\rho_{HS}} \propto \frac{T_{HS}(\rho R)_{HS}^2}{P_{HS}}$$

How do we access these new plasma states?

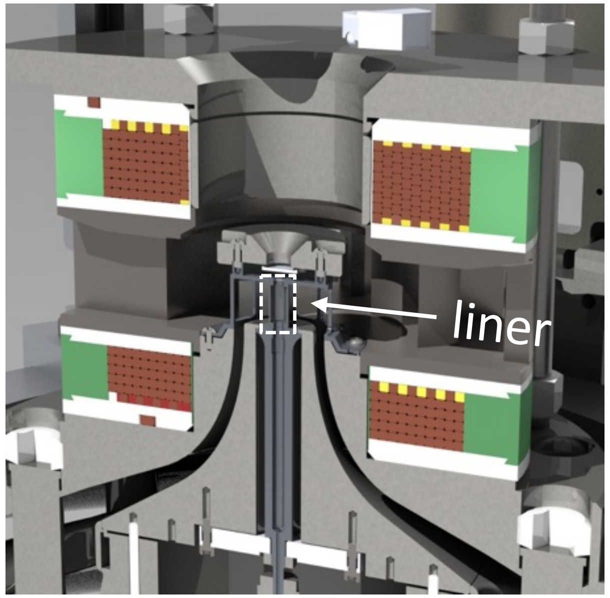
Basko et al., Nucl. Fusion 40, 59 (2000)
Schmit et al., PRL 113, 155004 (2014)
Knapp et al., POP 22, 056312 (2015)

MagLIF is a concept enabling the study of all aspects of Magneto-Inertial Fusion

Relies on three components to produce fusion conditions at stagnation



External coils: ~7-20 T at t=0



Magnetization

- Suppress radial thermal conduction losses
- Enables slow, stable liner implosions

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 is a concept enabling the study of all aspects of Magneto-Inertial Fusion

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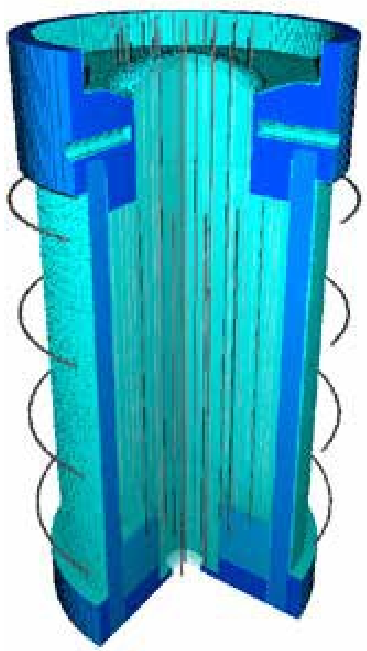
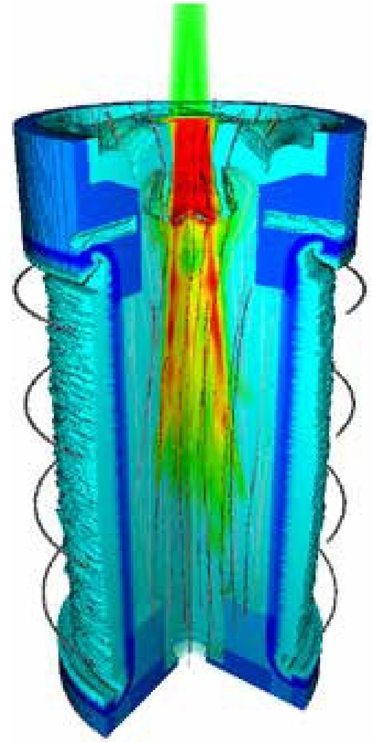




$$n_i \sim 10^{20} \text{cm}^{-3}$$
$$T \sim 100\text{–}200 \text{ eV}$$
$$\omega_{ce}\tau_e \sim 1$$
$$\beta \sim 10^3$$

Z Beamlet Laser: up to ~2 kJ preheat

Plus ≈12 addt'l offline expts/quarter

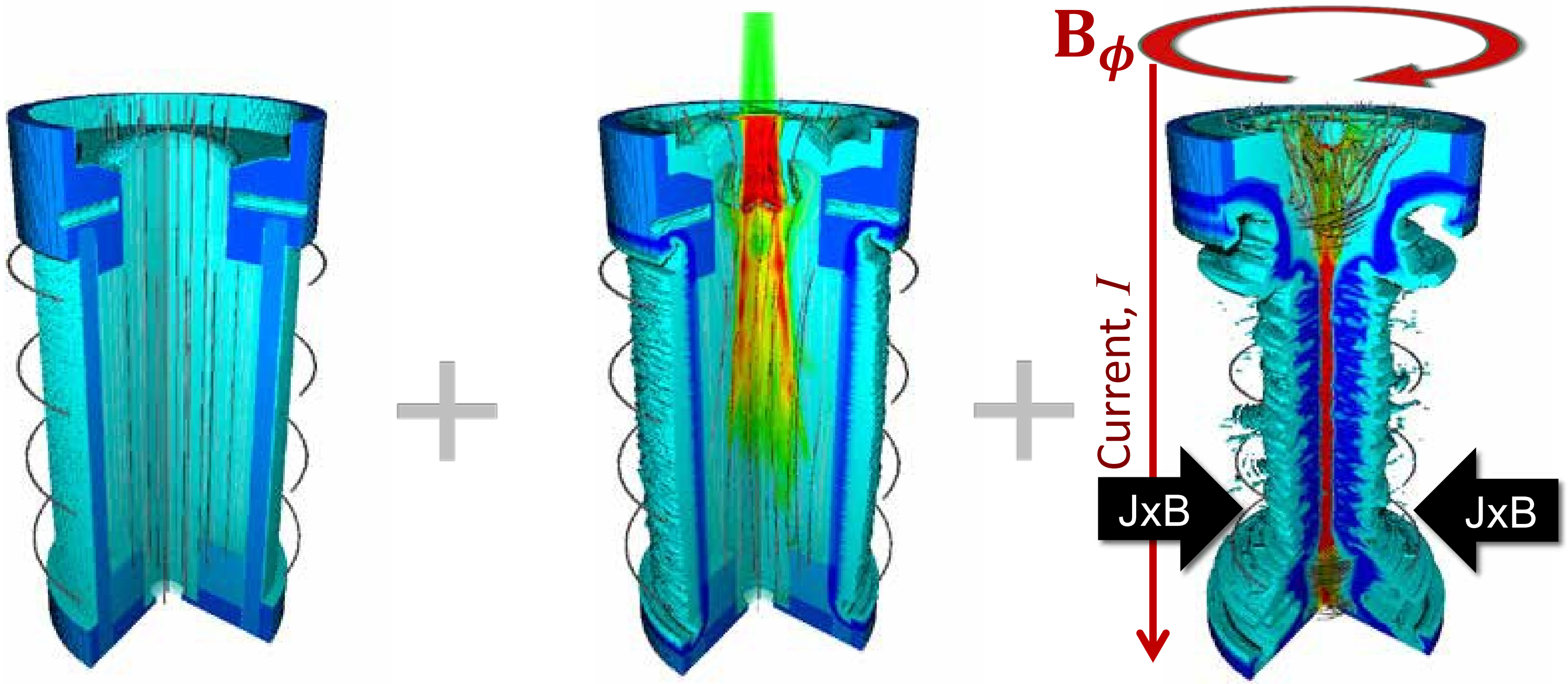
Magnetization
- Suppress radial thermal conduction losses
- Enables slow, stable liner implosions

Preheat
- Pressurize fuel for ~adiabatic compression
- Limit convergence needed to reach multi-keV

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

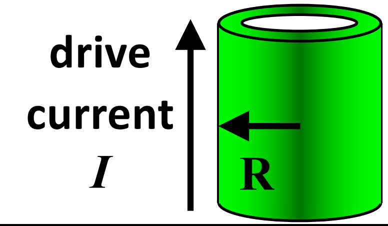
MagLIF is a concept enabling the study of all aspects of Magneto-Inertial Fusion

Relies on three components to produce fusion conditions at stagnation



Magnetically Driven Implosion

$$P_{mag}(\text{Mbar}) = 62\left(\frac{I/20\text{ MA}}{R/1\text{ mm}}\right)^2$$



~7 Mbar → ~100 Mbar during expt.

Magnetization
- Suppress radial thermal conduction losses
- Enables slow, stable liner implosions

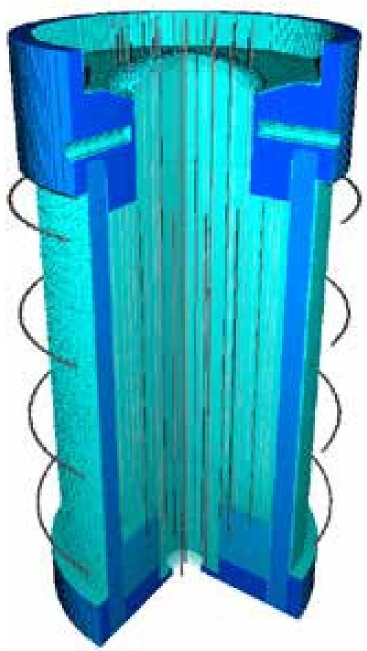
Preheat
- Pressurize fuel for ~adiabatic compression
- Limit convergence needed to reach multi-keV

Implosion
- ~Adiabatic PdV work
- Flux compression to amplify B-field
- ~100 km/s implosion

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 is a concept enabling the study of all aspects of Magneto-Inertial Fusion

Relies on three components to produce fusion conditions at stagnation



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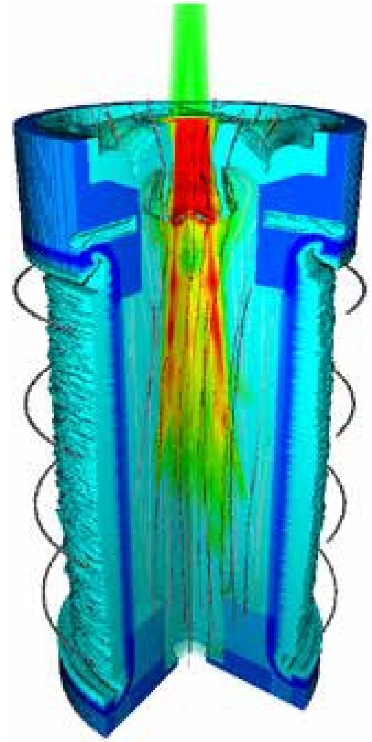

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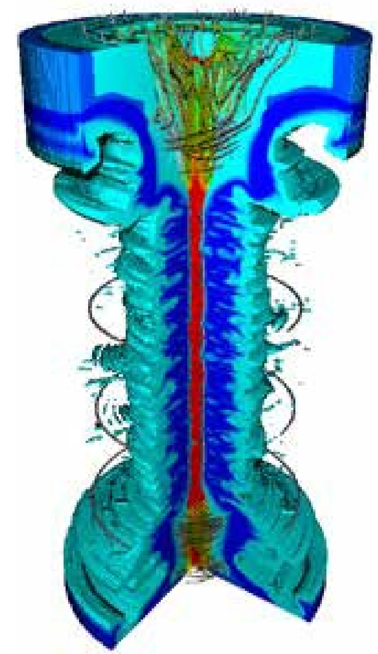

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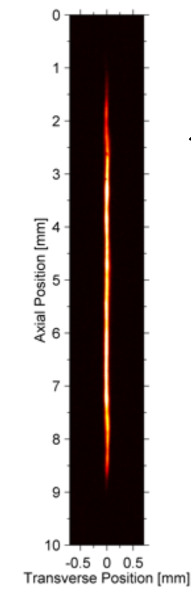


$n_i \sim 10^{23} \text{cm}^{-3}$

$P \sim$ Gbar

$\omega_{ce}\tau_e \sim 30$

$\beta \gtrsim 10$

Magnetization
- Suppress radial thermal conduction losses
- Enables slow, stable liner implosions

Preheat
- Pressurize fuel for ~adiabatic compression
- Limit convergence needed to reach multi-keV

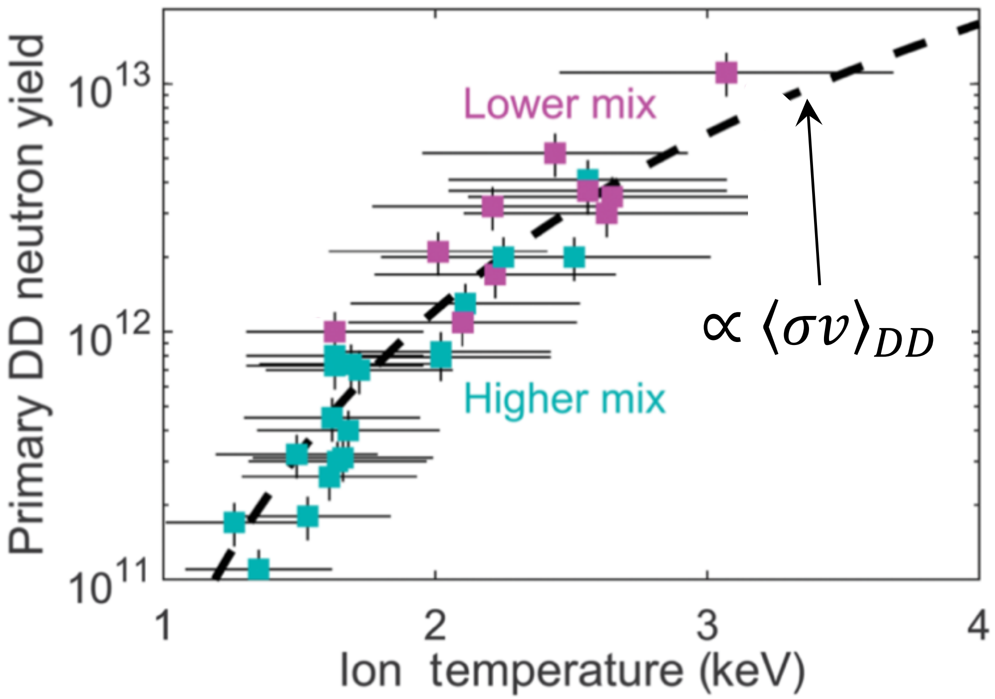
Implosion
- ~Adiabatic PdV work
- Flux compression to amplify B-field
- ~100 km/s implosion

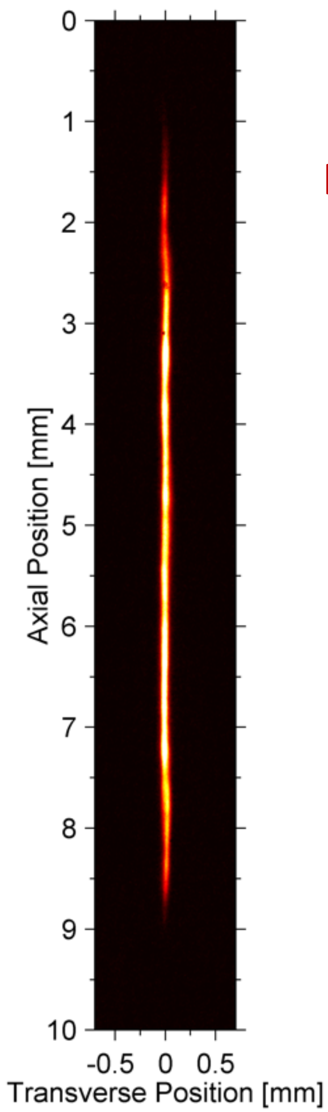
Stagnation
- Several keV plasma temperatures
- Several kT B-field to trap charged fusion products

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 experiments have demonstrated the fundamental principles of MIF

Thermonuclear neutrons, multi-keV temperatures from high aspect-ratio, cylindrical fuel assemblies.





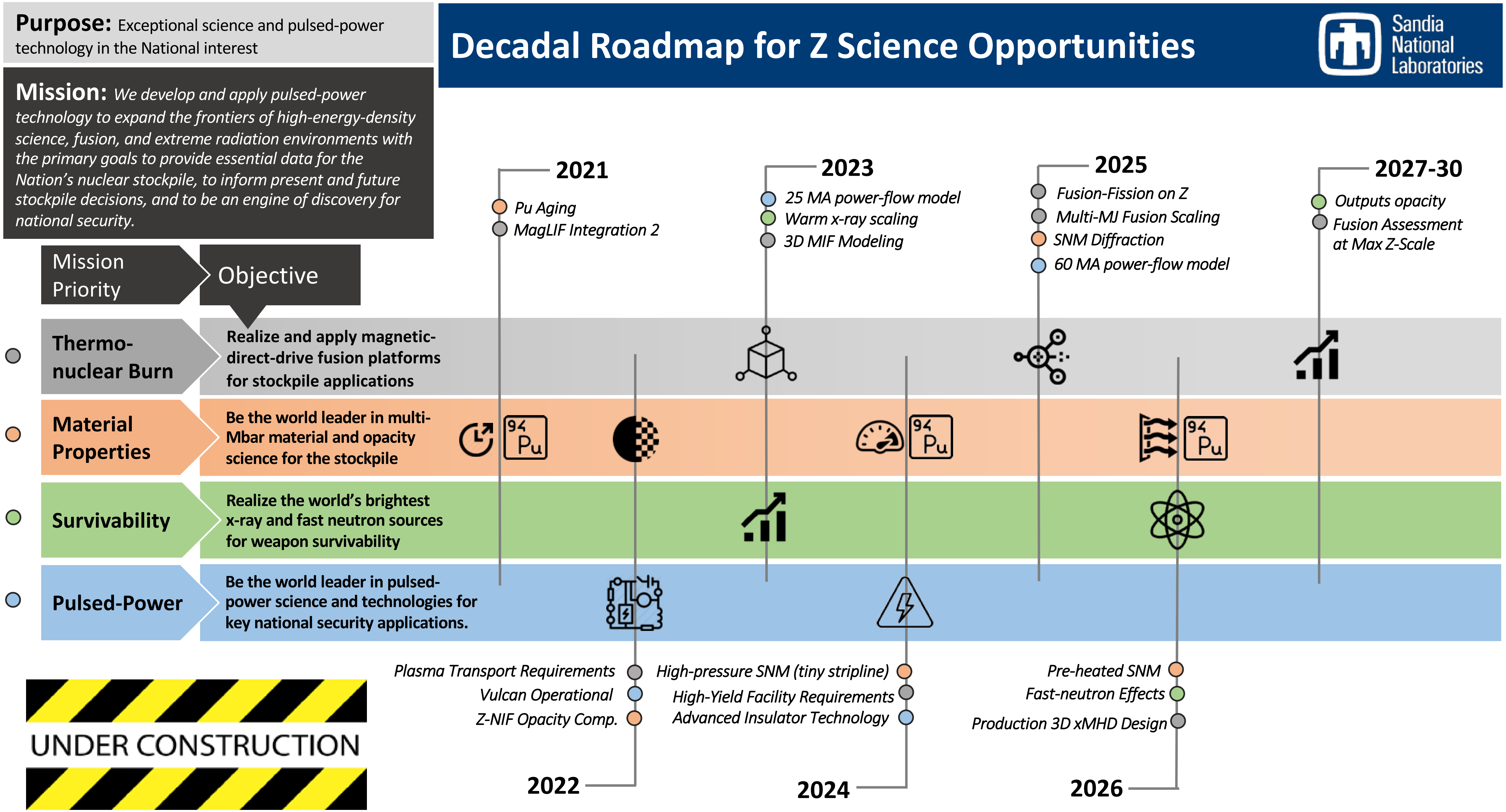
Hallmark of MIF: significant fusion only when both the **laser preheat** and **magnetization** stages are present.

DD neutron yields

	No B-field	B-field
No Preheat	3×10^9	1×10^{10}
Preheat	4×10^{10}	Up to 10^{13}

Gomez et al., PRL 113, 155003 (2014)
Gomez et al., PRL 125, 155002 (2020)

Future Science Opportunities


Purpose: Exceptional science and pulsed-power technology in the National interest
Decadal Roadmap for Z Science Opportunities
Sandia National Laboratories
Mission: We develop and apply pulsed-power technology to expand the frontiers of high-energy-density science, fusion, and extreme radiation environments with the primary goals to provide essential data for the Nation's nuclear stockpile, to inform present and future stockpile decisions, and to be an engine of discovery for national security.
Mission Priority
Objective
Thermo-nuclear Burn
Realize and apply magnetic-direct-drive fusion platforms for stockpile applications
Material Properties
Be the world leader in multi-Mbar material and opacity science for the stockpile
Survivability
Realize the world's brightest x-ray and fast neutron sources for weapon survivability
Pulsed-Power
Be the world leader in pulsed-power science and technologies for key national security applications.
2021
Pu Aging
MagLIF Integration 2
2022
Plasma Transport Requirements
Vulcan Operational
Z-NIF Opacity Comp.
2023
25 MA power-flow model
Warm x-ray scaling
3D MIF Modeling
2024
High-pressure SNM (tiny stripline)
High-Yield Facility Requirements
Advanced Insulator Technology
2025
Fusion-Fission on Z
Multi-MJ Fusion Scaling
SNM Diffraction
60 MA power-flow model
2026
Pre-heated SNM
Fast-neutron Effects
Production 3D xMHD Design
2027-30
Outputs opacity
Fusion Assessment at Max Z-Scale
94 Pu
UNDER CONSTRUCTION

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

MIF offers multiple unique paths to reach higher fusion performance while balancing physics risks

Use-Inspired

Scaling up preserves/improves:

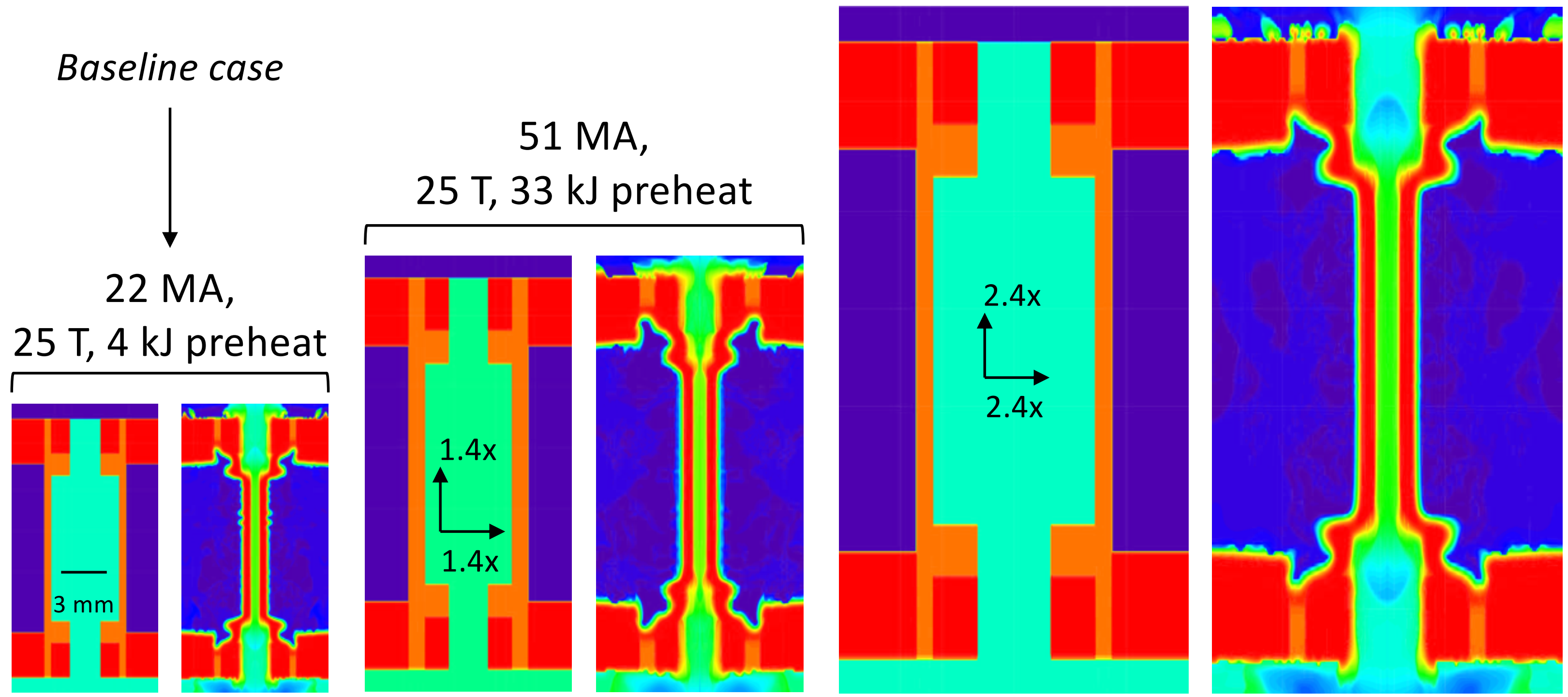
- Liner trajectory
- MRT susceptibility (IFAR)
- Mix kinematics
- Most/all energy losses
- Most transport processes

Baseline case

22 MA,
25 T, 4 kJ preheat

51 MA,
25 T, 33 kJ preheat

52 MA,
25 T, 54 kJ preheat



100 ns rise
0.13 MJ
$\chi_{\mathrm{no}\ \alpha} = 0.7$

100 ns rise
13 MJ
$\chi_{\mathrm{no}\ \alpha} = 4.3$

240 ns rise
25 MJ
$\chi_{\mathrm{no}\ \alpha} = 4.0$

Implosion-time conserving

Pressure-velocity conserving (Euler scaling)

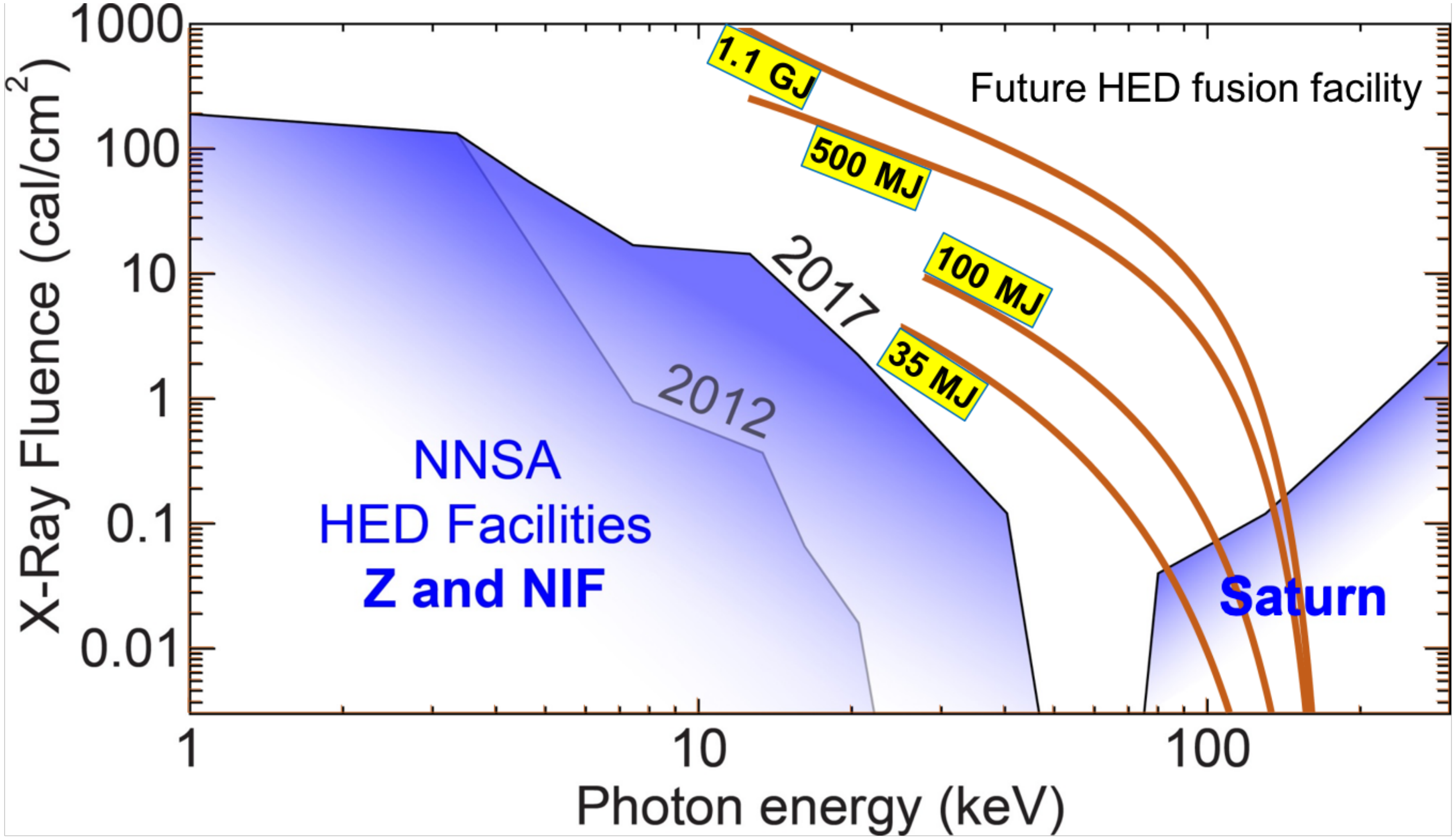
 Schmit & Ruiz, POP 27, 062707 (2020)

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.

Sandia has proposed a Next Generation Pulsed Power facility to the NNSA to get us farther down the path to high yield

Z today — Range of facilities being examined

Vacuum stack energy Range of currents	**7 MJ** 15 MA long pulse 28 MA short pulse	**24 MJ** 22 MA long pulse 50 MA short pulse	**51 MJ** 31 MA long pulse 70 MA short pulse	**75 MJ** 38 MA long pulse 85 MA short pulse
ICF		1 MJ Volume Burn; Alpha heating	3-30 MJ Volume Burn; Ignition and ice burn	>30-100 MJ High yield
DMP	7 MBar	15 MBar	20 MBar	30 MBar
Hostile Survivability (x-ray fluence >10keV)	15 cal/cm^2@ 5 cm		38 cal/cm^2 @ 10 cm 17 cal/cm^2 @ 15 cm	
Hostile Survivability (DT neutron fluence)	9e12 @ 10 cm	3e14 @ 10 cm	>9e14 @ 10 cm (3MJ) >2e15 @ 20 cm (30MJ)	>9e15 @ 10 cm (30MJ) >3e15 @ 30 cm (100MJ)

Mike Cuneo's talk in two weeks (Feb. 18) will discuss our pulsed power technology work in more detail

Thank you for your attention!

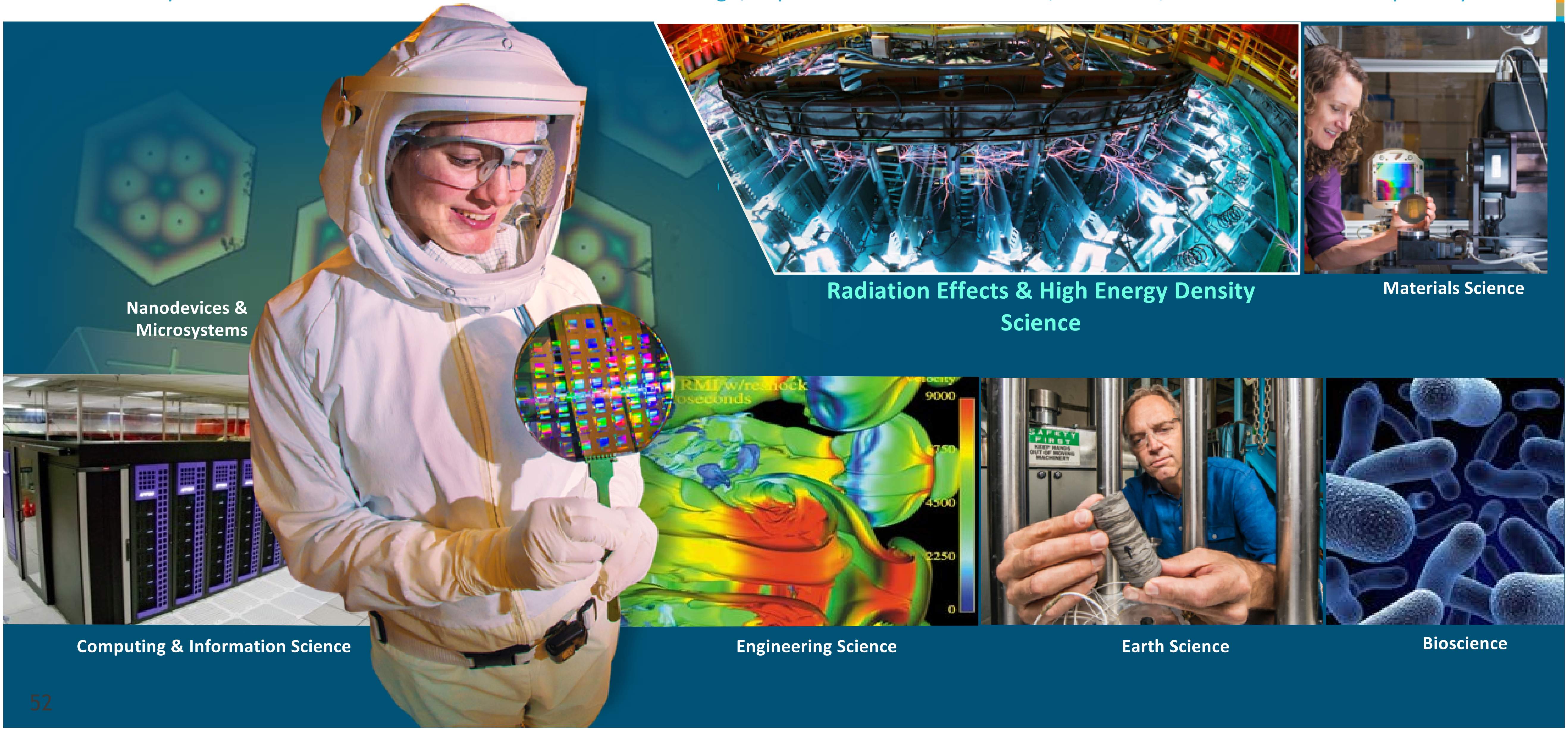
- Introduction to Pulsed Power & Z
- Overview of High Energy Density Science on Z
  - Radiation Science
  - Dynamic Materials Science
  - Fusion Science
- Future Science Opportunities
  - Next 10 years on Z
  - Thoughts on what lies beyond Z

Today's talk is based in large part on content published in a recent review paper:
D.B. Sinars *et al.*, Phys. Plasmas (2020).

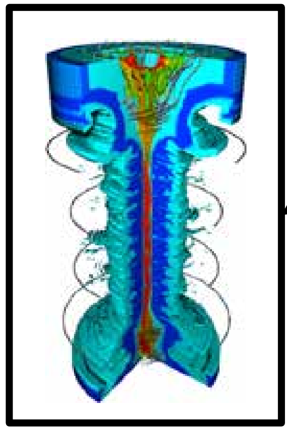

Thank you for your attention!
Exceptional service in the national interest
Sandia National Laboratories

Discipline-based Research Foundations steward core science & technology capabilities

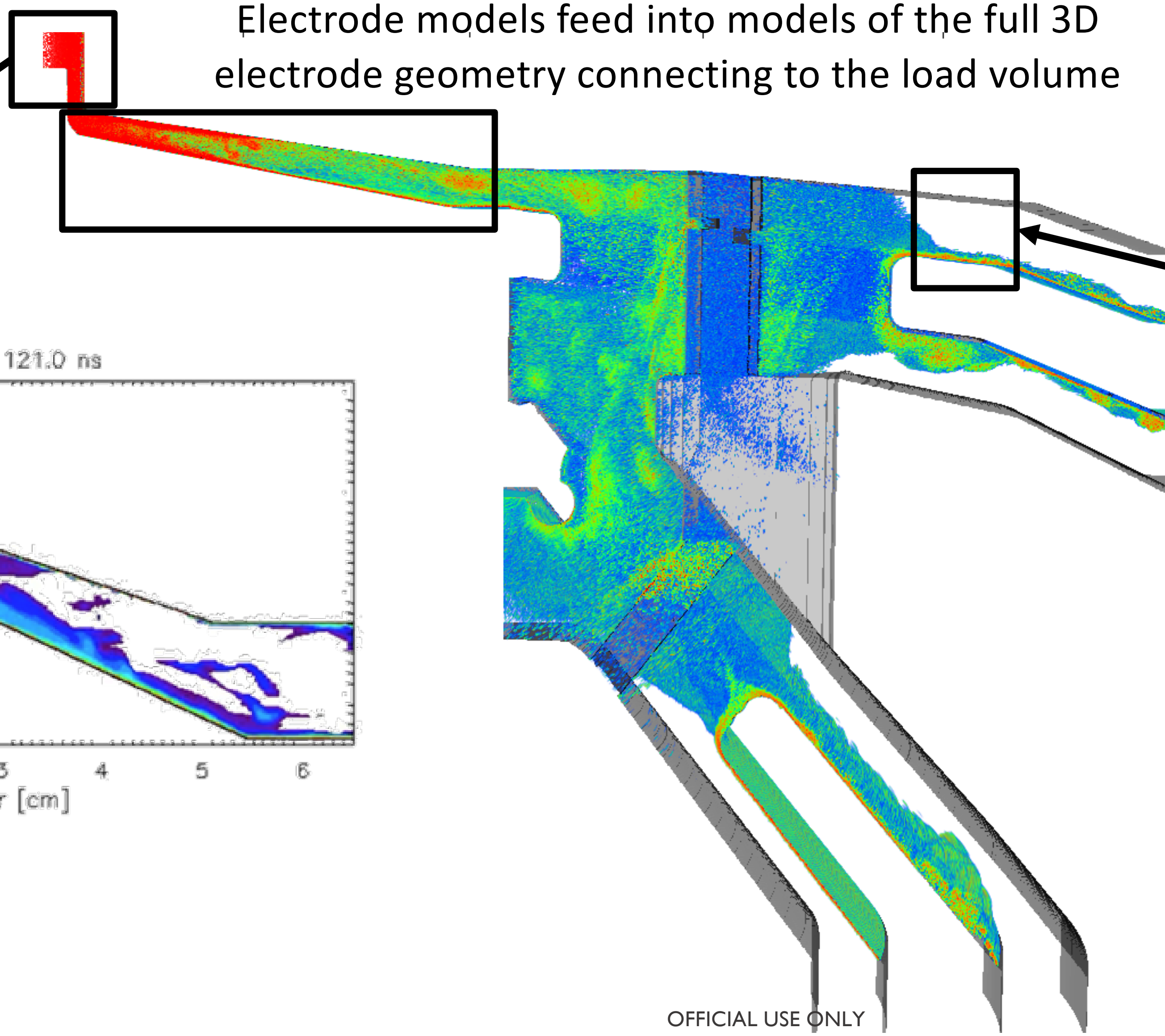
Purpose: Conduct fundamental/discovery research and use-inspired research in disciplines germane to, and inspired by, national security mission needs to advance the frontiers of knowledge, explore innovative solutions, and build/maintain technical capability.

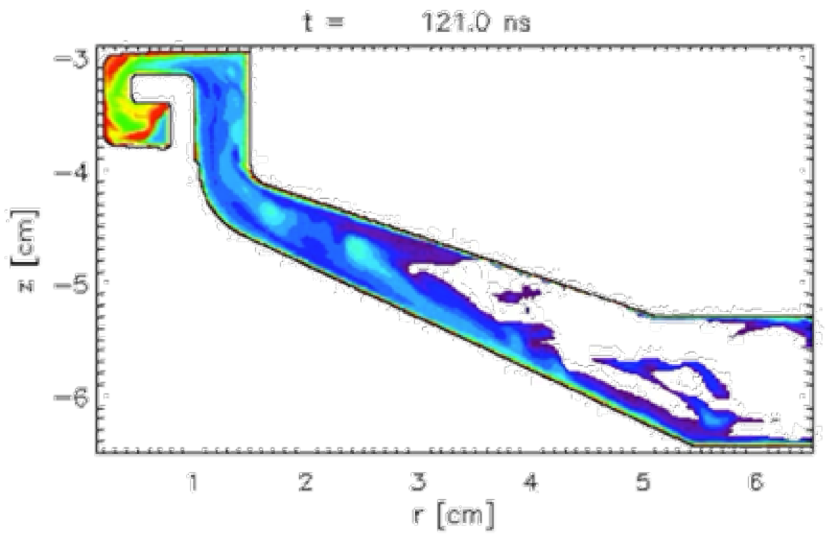


Algorithmic advances in PIC/FLUID hybrid modeling / surface science being developed for full system multi-scale modeling capability

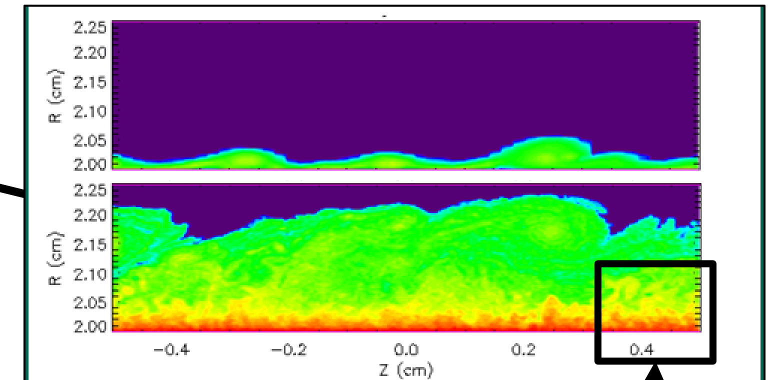


Electrode models feed into models of the full 3D electrode geometry connecting to the load volume



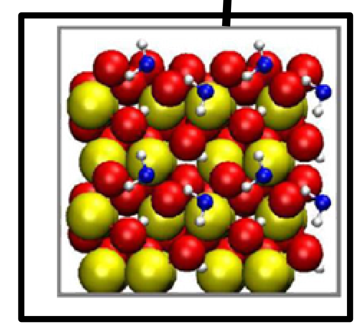


Plasma formation, heating, expansion



Predictive surface models incorporated into PIC and PIC/Fluid hybrid models

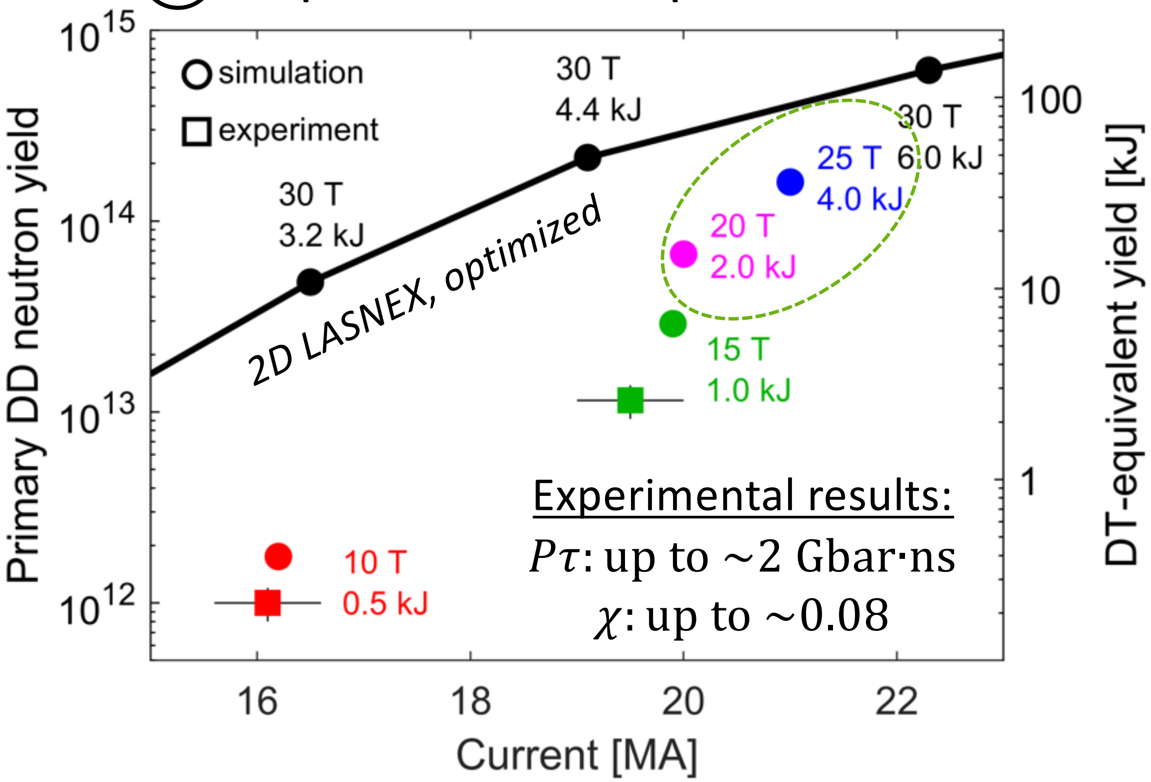
DFT calculations of H2O binding energy



Forward-looking performance/scaling question: **Where are we going?**

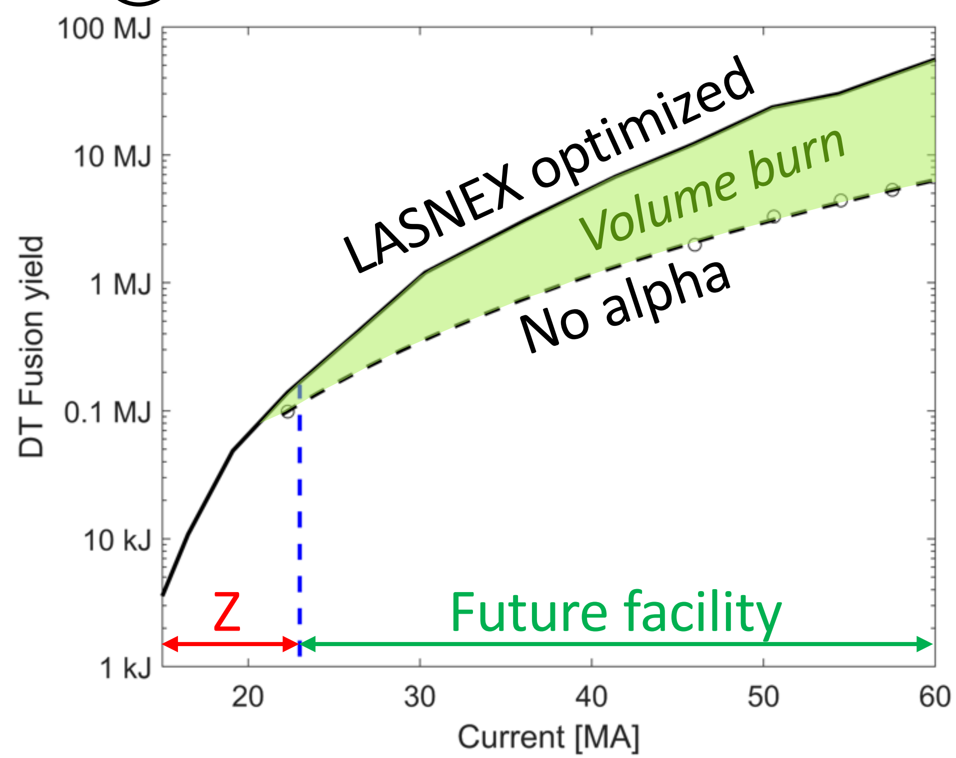
Two major thrusts:

① Improve baseline performance



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

② Mature understanding of scaling

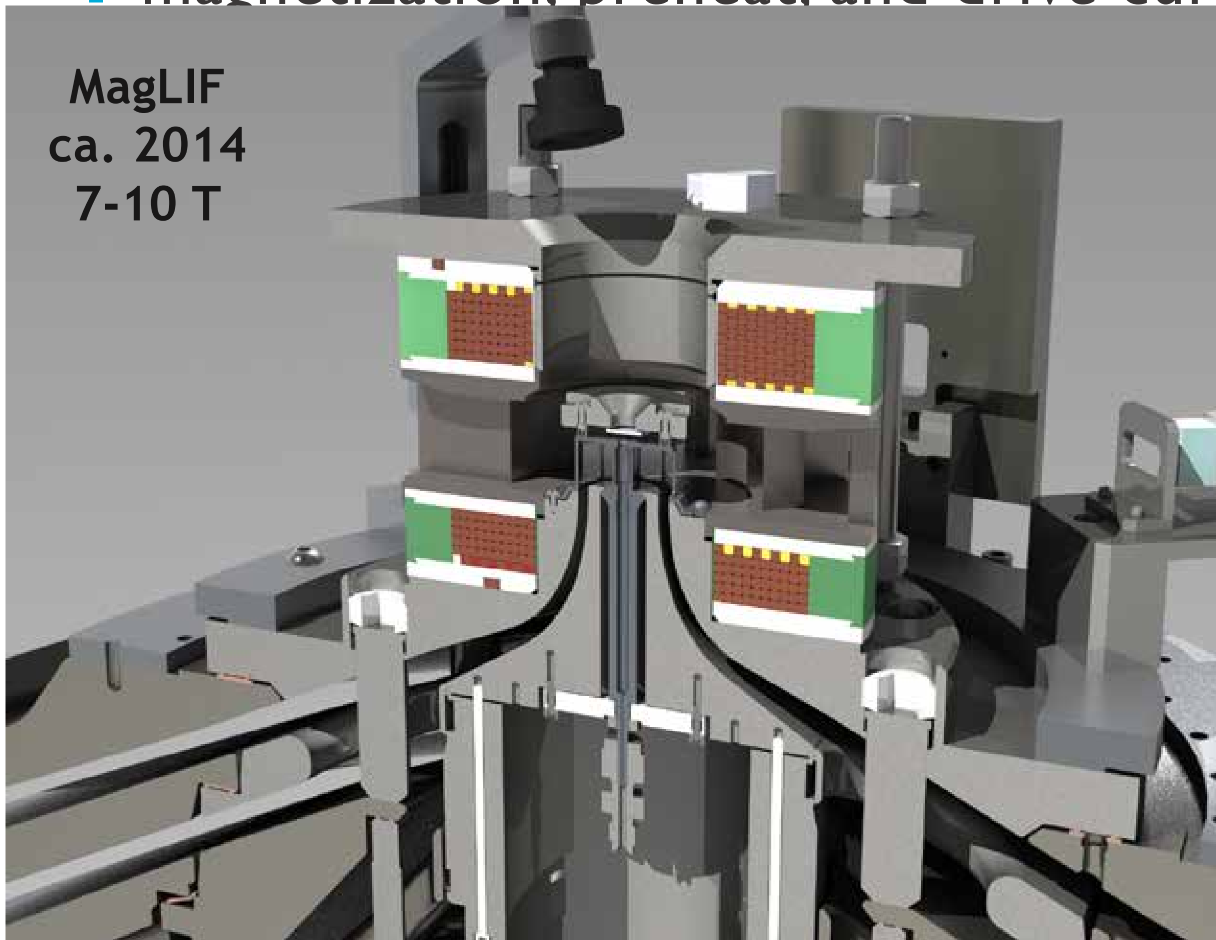


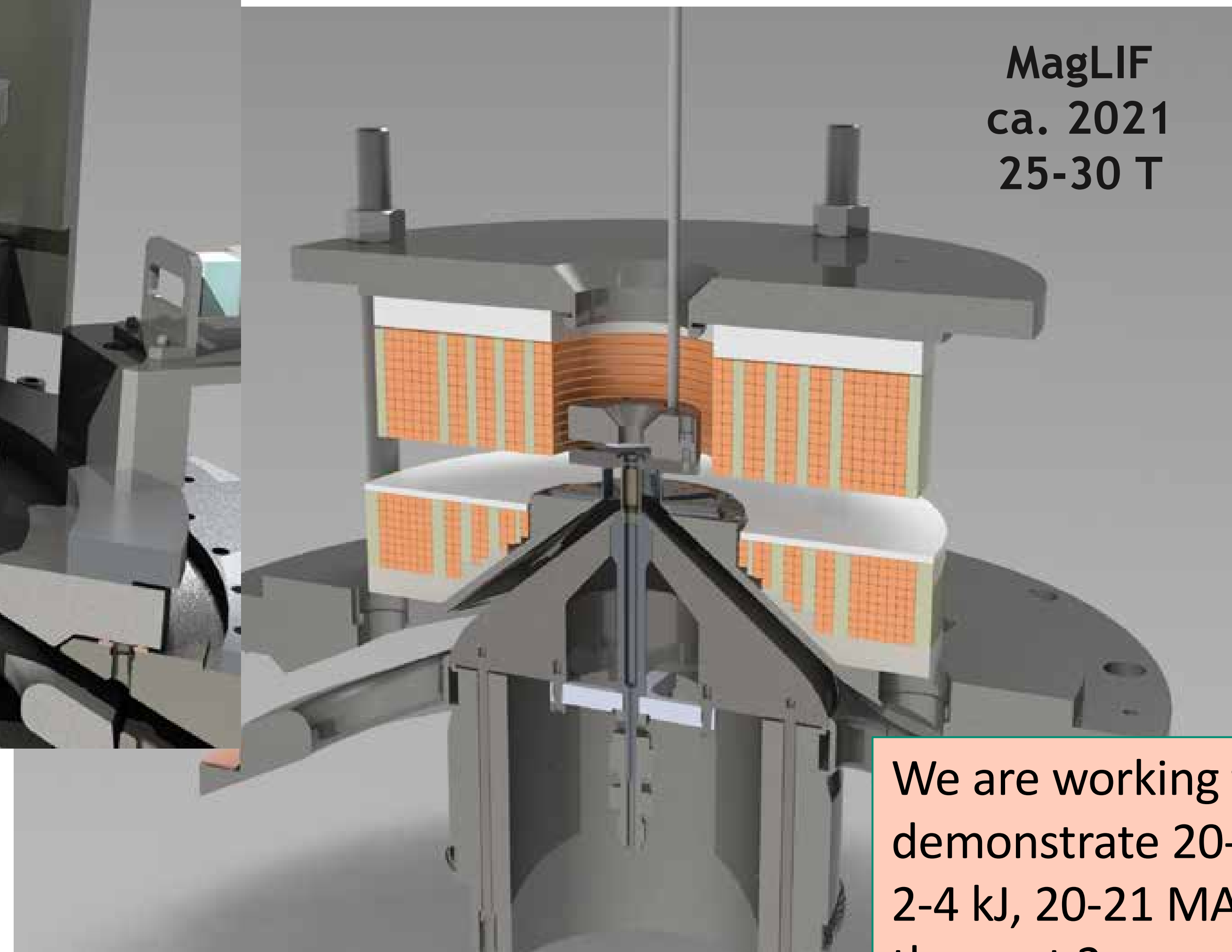
Question: What physics risks could prevent us from reaching these conditions?

Slutz et al., POP 23, 022702 (2016)
Slutz et al., POP 25, 112706 (2018)

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

Use-Inspired





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