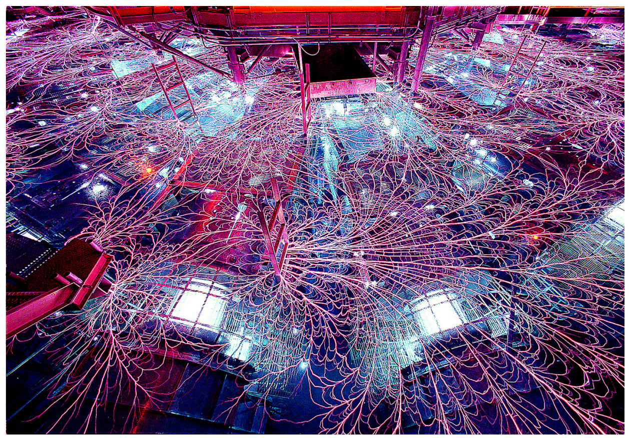
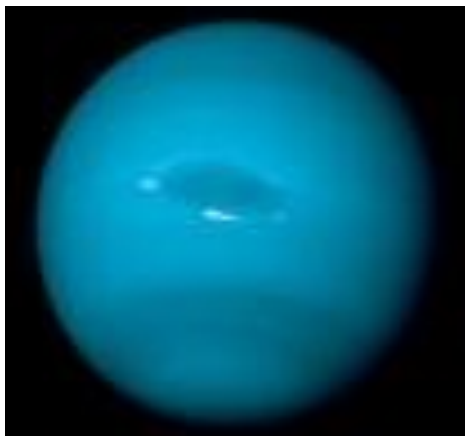
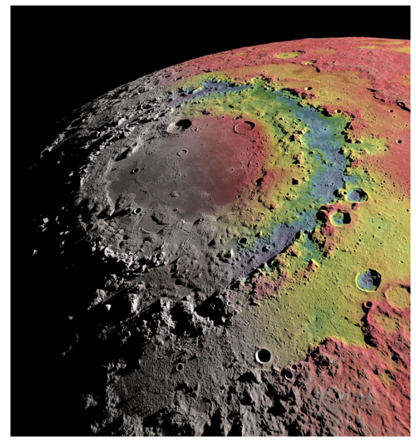
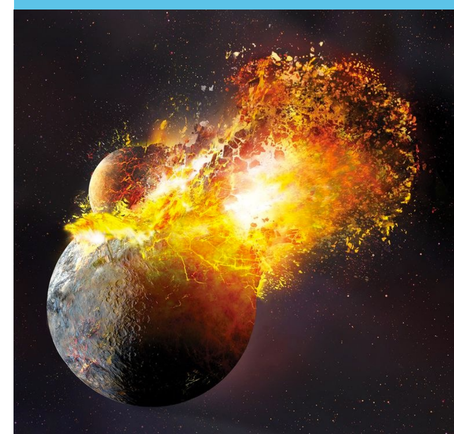
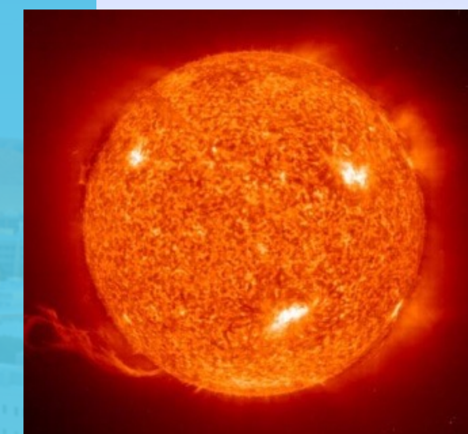
Sandia National Laboratories

Z Fundamental Science Program

PRESENTED BY

Daniel Sinars

Director, Pulsed Power Sciences Center

Program Executive for Inertial Confinement Fusion & Assessment Science

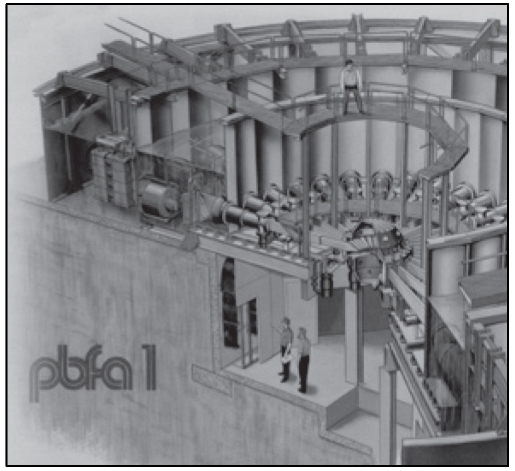
UK Royal Society
28 November 2022

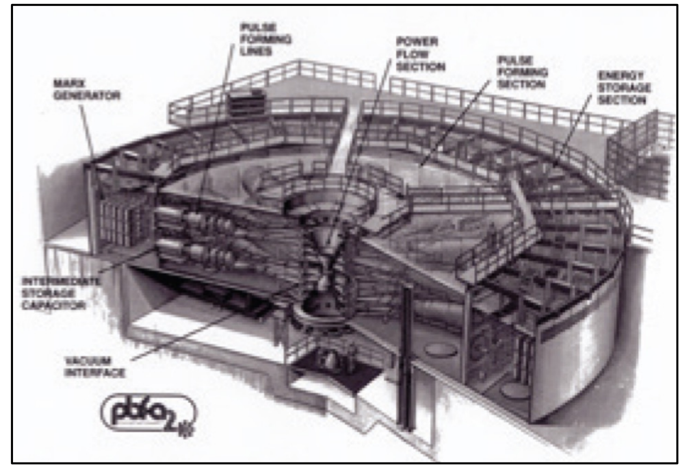
U.S. DEPARTMENT OF ENERGY NNSA

Sandia National Laboratories is a multimission laboratory managed and operated by National Technology and Engineering Solutions of Sandia LLC, a wholly owned subsidiary of Honeywell International Inc. for the U.S. Department of Energy's National Nuclear Security Administration under contract DE-NA0003525.

Sandia is the home of three of the world's biggest pulsed power machines built in the 1980s for survivability and fusion research

Particle Beam Fusion Accelerator 1 (1980): Built to study light ion beams for fusion target research

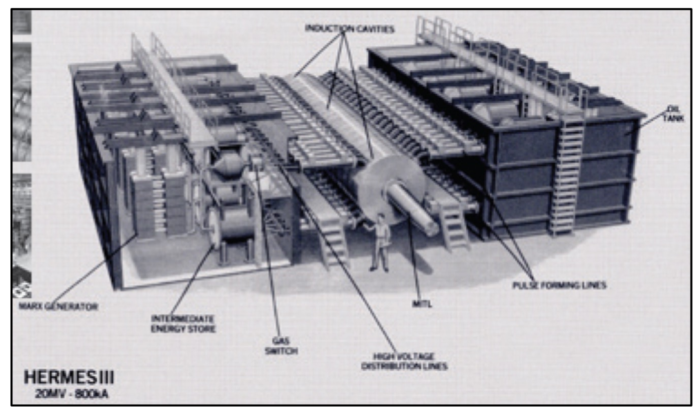




★ Focus of today's talk

PBFA-2 (1985): Largest pulsed power machine in the world, converted to "Z machine" in 1996

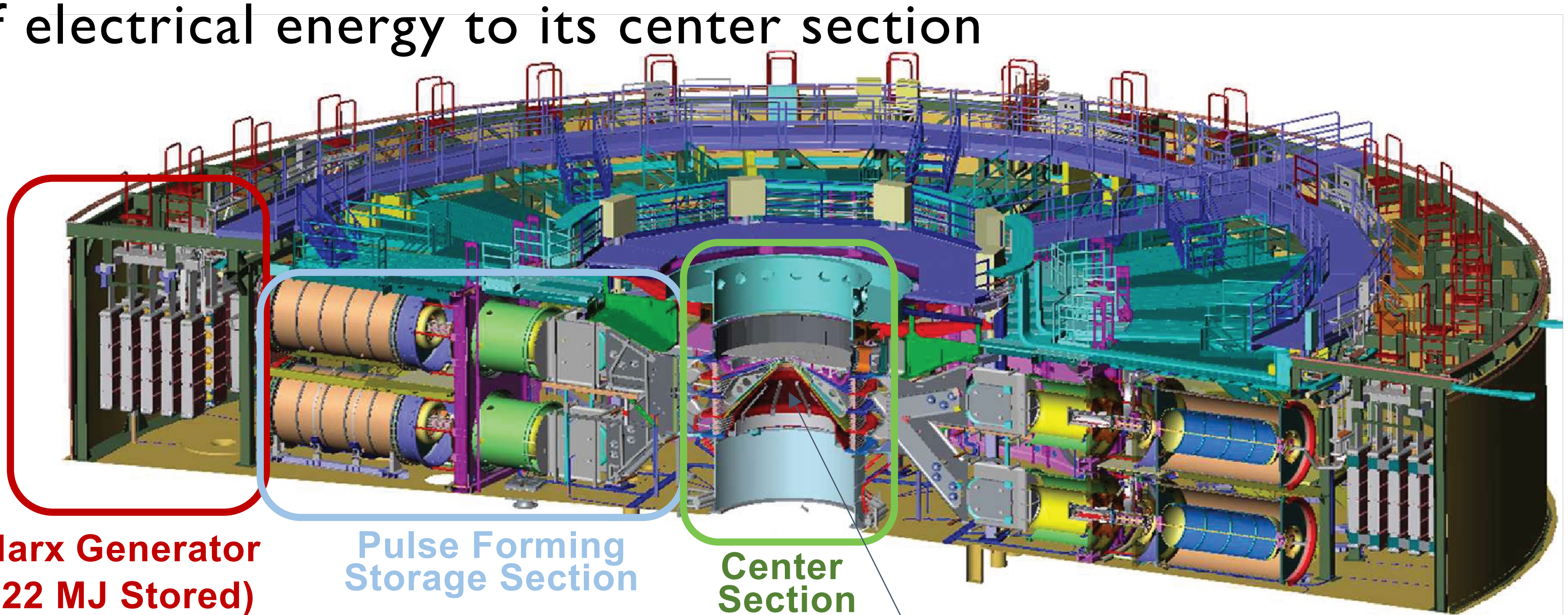
PBFA-1 converted into Saturn (1987): The world's largest, large-area hot x-ray simulator

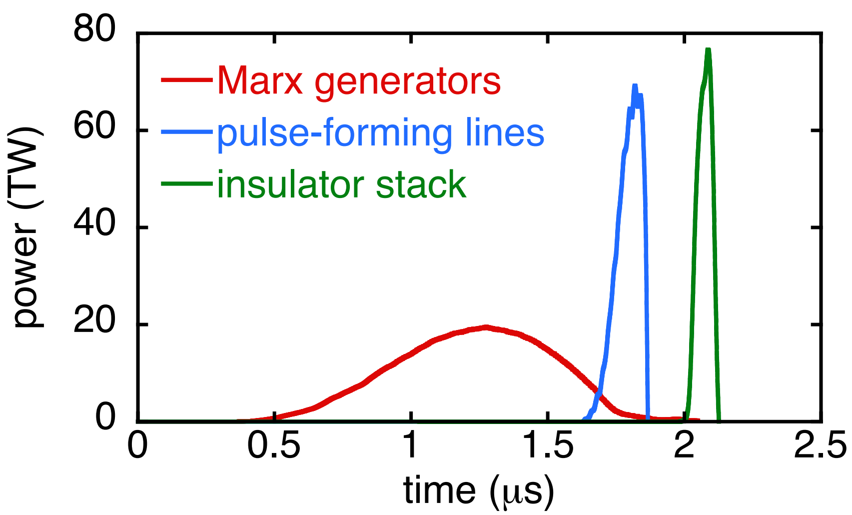


Hermes-III (1988): The world's most powerful gamma-ray accelerator

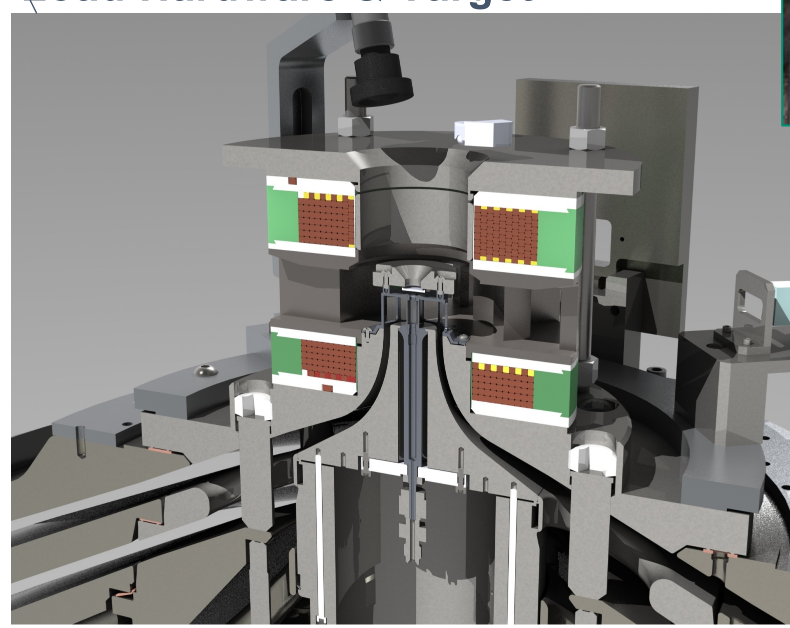
TA-IV at Sandia is a hub of pulsed power and related capabilities

Z, the world's largest pulsed power machine, delivers 80 TW and 6 MJ of electrical energy to its center section





Load Hardware & Target



Post-shot

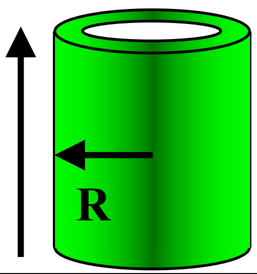
Z today couples several MJ out of 22 MJ stored to the load hardware region at the machine center.

Pulsed power can generate ~100 Mbar drive pressures, which can be used to obtain even higher pressures such as those in 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/m³)

1 Mbar = 10^{11} J/m³, threshold of High Energy Density regime

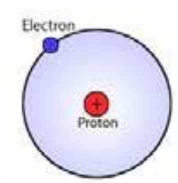
Z Storage capacitor

2e-6 Mbar

TNT

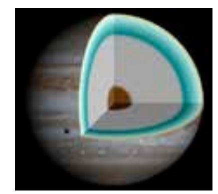
0.07 Mbar

Internal Energy of H atom



1 Mbar

Metallic H in Jupiter's core



30 Mbar

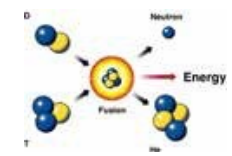
Z Magnetic Drive Pressure

~100 Mbar

Center of Sun

250,000 Mbar

Burning ICF plasma



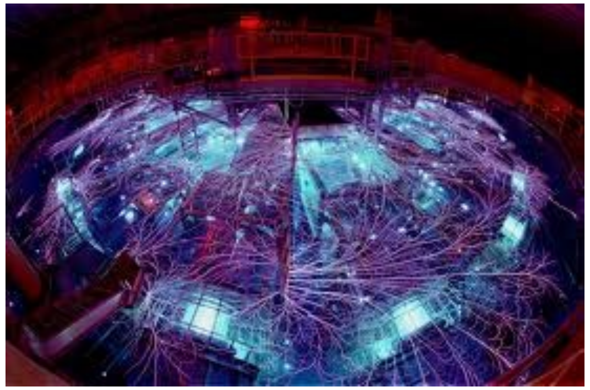
800,000 Mbar

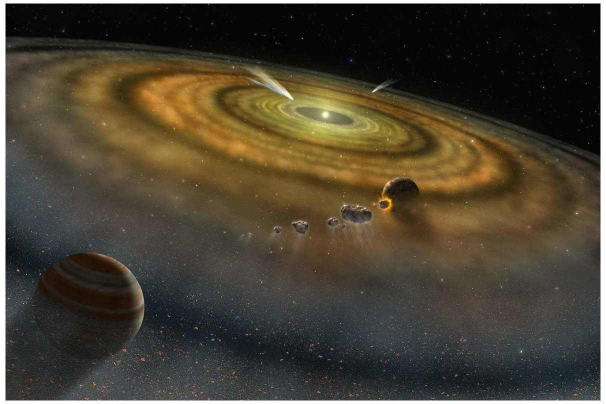
Push on samples

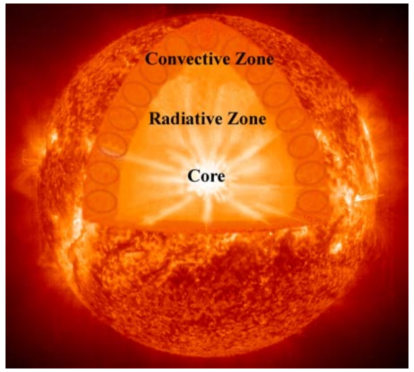
Compress fuel at high velocity

Pulsed power is exquisitely suited for HED science

- **Sandia's Z machine is ideal for Mbar material experiments**
  - Compression of solids and liquids
  - Generate conditions found in the interiors of gas giants and the Earth/super earths, other exoplanets
- **The Z machine produces MJs of x-rays**
  - Radiation effects on materials
  - Fundamental properties of matter
- **Fundamental plasma physics**
  - Spectroscopy and plasma conditions: line broadening and opacity
- **Strong integration between experiments, theory, and simulations**
  - From quantum mechanics to MHD and beyond



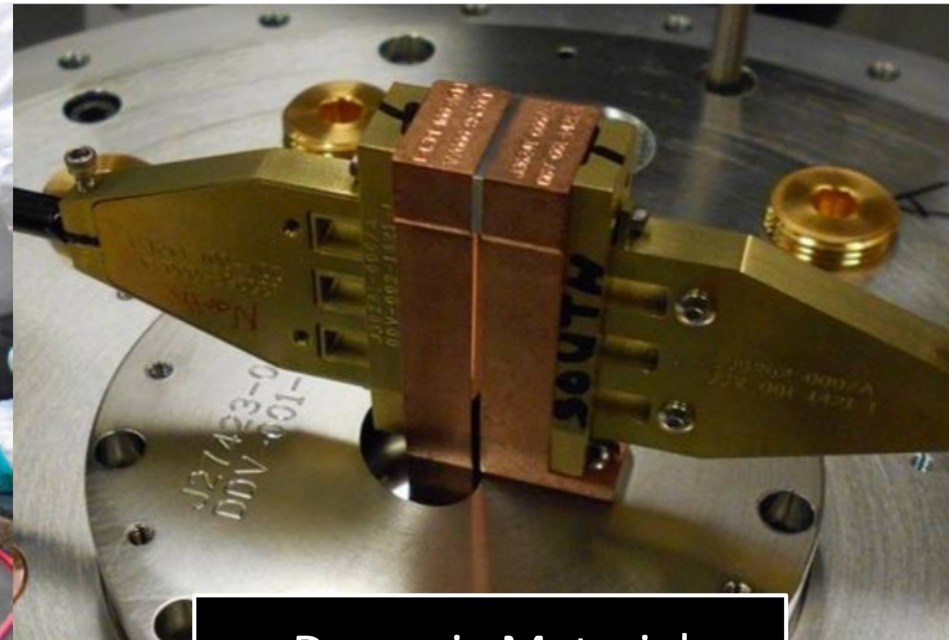




See "Review of pulsed-power-driven high energy density physics research on Z at Sandia," published July 2020 in Physics of Plasmas for greater detail

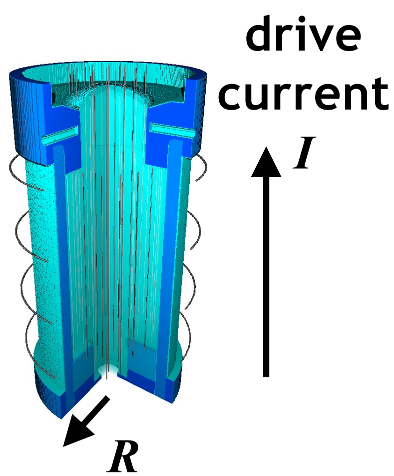
Precision tools for high energy density science

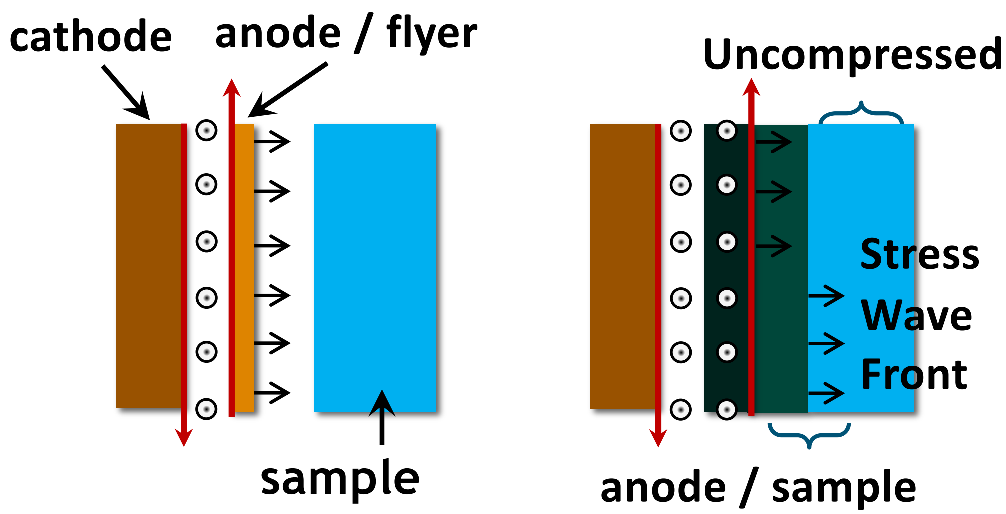
Inertial Confinement Fusion

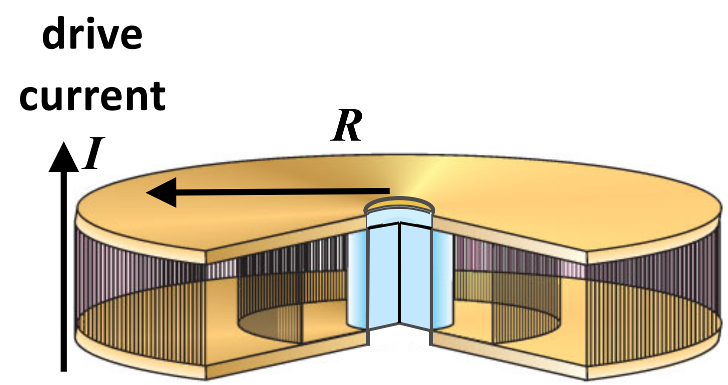


Dynamic Material Properties

Radiation Science



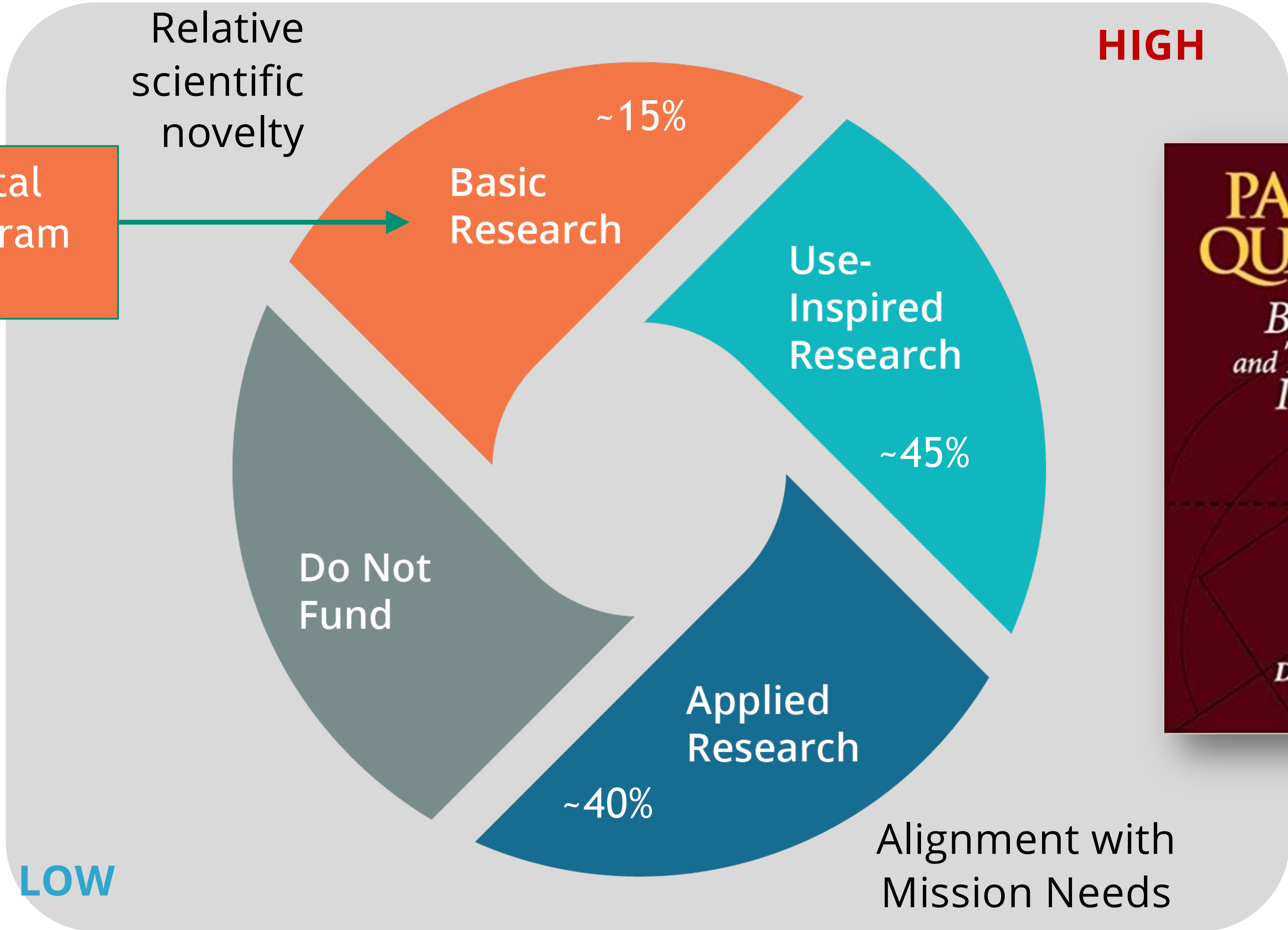


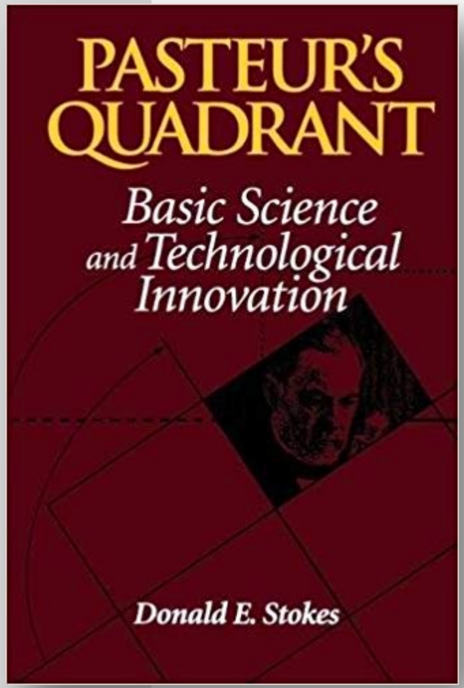


Majority of research on Z is "use inspired"

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

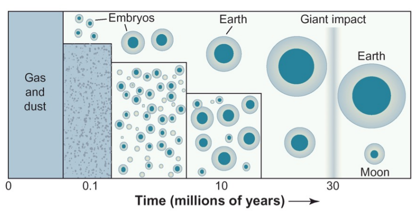
Z Fundamental Science Program sits here



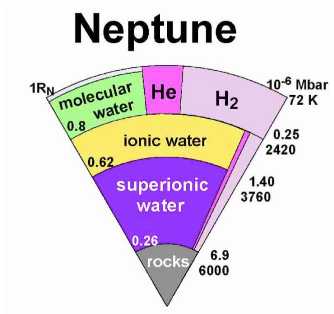


- Basic
- Use-Inspired
- Applied

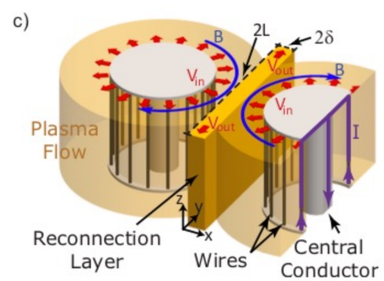
Z Fundamental Science Program began in 2010 and is a path for universities and industry to collaborate with Sandia



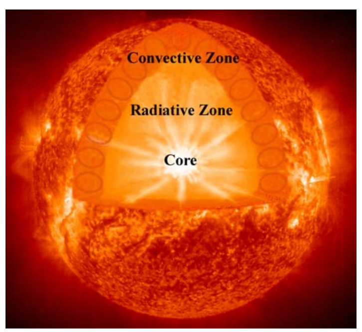
Earth and super earths



Giant Planets



Magnetic reconnection



Stellar physics

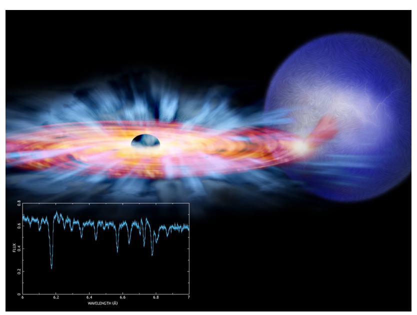
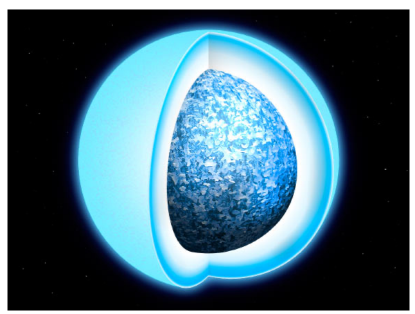


Photo-ionized plasmas



White dwarfs

Resources allocated over 12 years

- 141 dedicated ZFS shots (8.5% of all Z shots)
- Ride-along experiments on Z program shots, guns, DICE, and THOR

Science with far-reaching impact

- Science, Nature, Nature Geoscience, Nature Communications
- Several Phys. Rev. Lett, Phys. Rev. (A,B,E), Phys. Plasmas, Rev. Sci. Instrum., etc.

Enabled by NNSA support and peer review

- NNSA allows us to use up to 10% of the shots for the program and pays for Z operations costs
- Z is not a user facility, so proposals must involve a Sandia scientist to help them be successful
- External researchers are required to support themselves (i.e., have a research grant)
- Annual call process including a summer workshop
- We use external peer review to evaluate proposals

ZFS Workshop is a key aspect of making this successful

- Annual Workshop has been held since 2010
- Combination of Plenary Sessions and Breakout Sessions
  - Plenary sessions provides updates on Z facility and diagnostic capabilities
  - Breakout sessions provide opportunities for in depth discussions
- Student / Post Doc Poster Session
  - NNSA Academic Programs provides travel support for ~20-25 students each year
- 2022 Workshop was back to in-person format after two years of virtual meetings
  - 124 attendees (56 external to Sandia) from 24 institutions and 2 countries
  - Included 29 students and 13 post docs
  - Virtual component bumped this to 139 attendees (70 external) 29 institutions

ZFS Program 2022 Call for Proposals opened in June

- ZFSP call for proposals timeline:
  - –June 15: call for proposals open
    - Award period: July 1, 2023 through June 30, 2025
  - –August 3-5: ZFS Workshop
  - –September 15: call closes
  - –October/November: evaluation and selection
    - Facility review: experimental feasibility, safety, and diagnostics
    - Scientific review of international panel mid-November
    - Mid-December, distribution of shots
  - –December 15: notification of awards
    - Expectation is to allocate 14 shots

Two-year award period


Sandia National Laboratories
Pulsed Power Sciences

Call for Proposals Package for the Z Facility Fundamental Science Program for the Period July 1, 2023 to June 30, 2025

Issue Date: June 15, 2022

Due Date: September 15, 2022

Point of Contact: Dr. Marcus D. Knudson
Senior Scientist, Pulsed Power Sciences Center
Sandia National Laboratories
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Albuquerque, NM 87185-1195
(505) 844-1575
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NNSA

Sandia National Laboratories

Sandia National Laboratories is a multimission laboratory managed and operated by National Technology & Engineering Solutions of Sandia, LLC, a wholly owned subsidiary of Honeywell International Inc., for the U.S. Department of Energy's National Nuclear Security Administration under contract DE-NA-0003525.

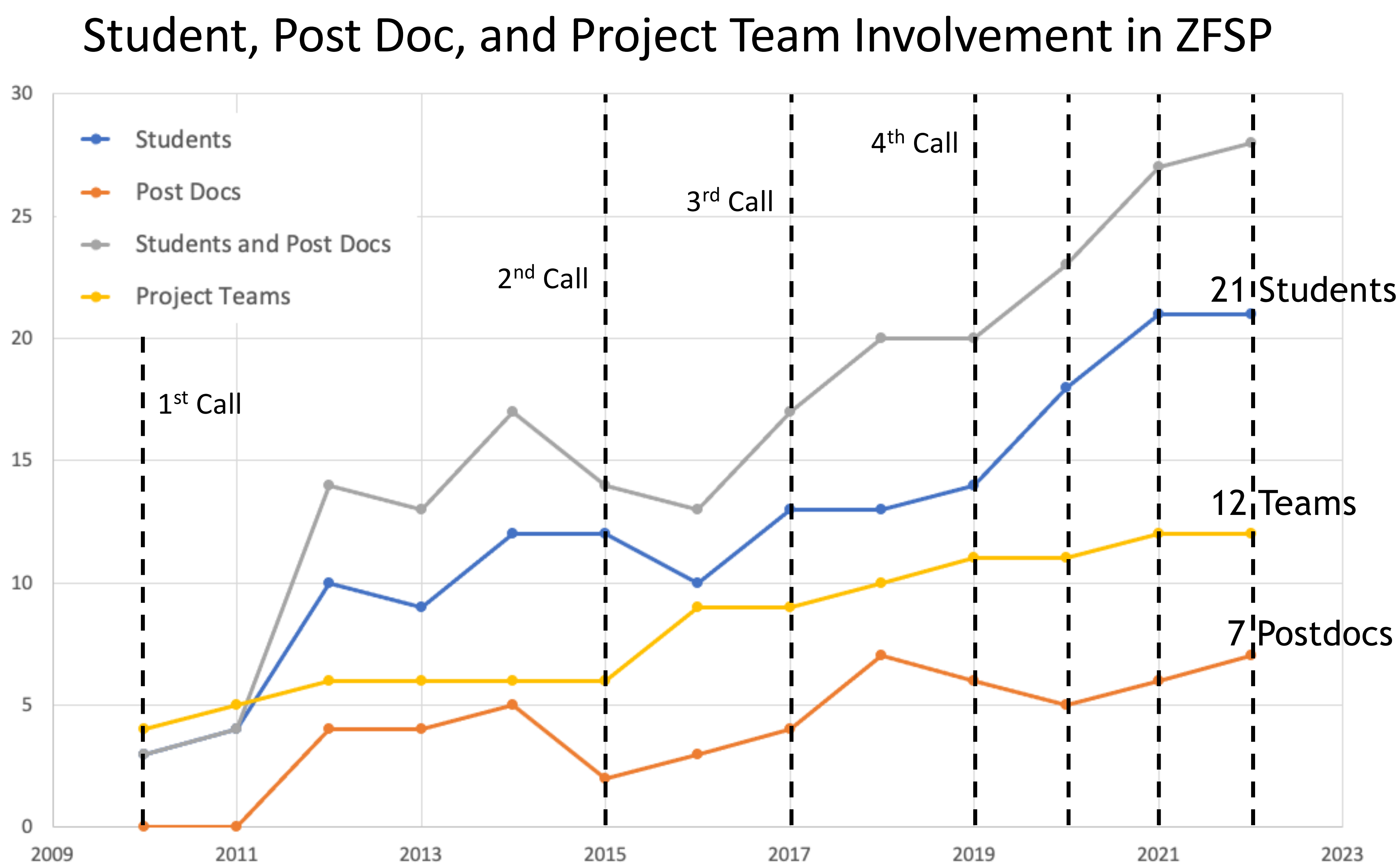
ZFSP has seen steady growth in academic participation

We have increased participation in part through an increased cadence in the Call for Proposals

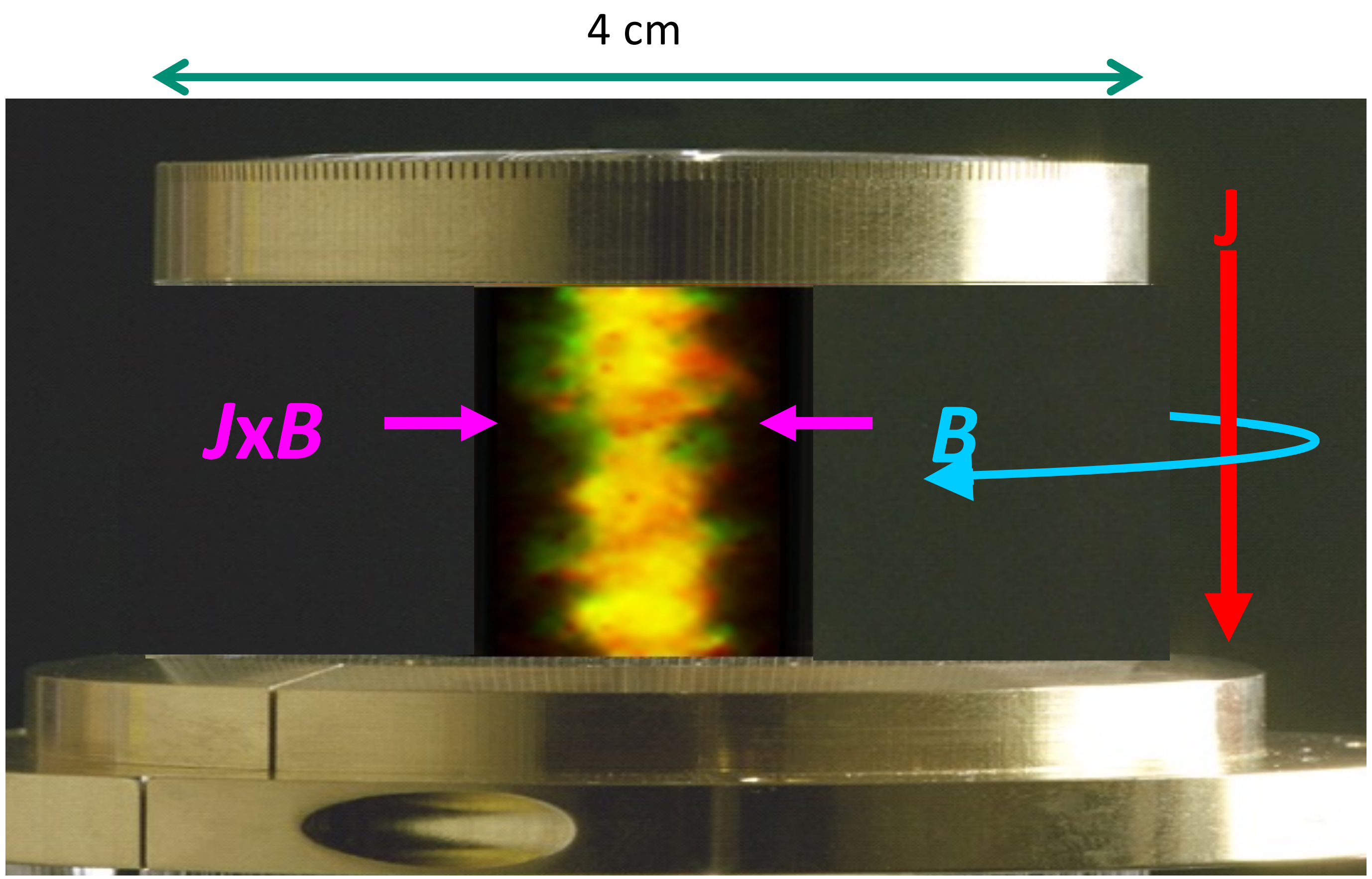
Participation is also strongly tied to the annual ZFS Workshop

Projects participating in the ZFSP have produced 21 PhDs in 12 years (~2/year)

6 former students or postdocs are at an NNSA lab today



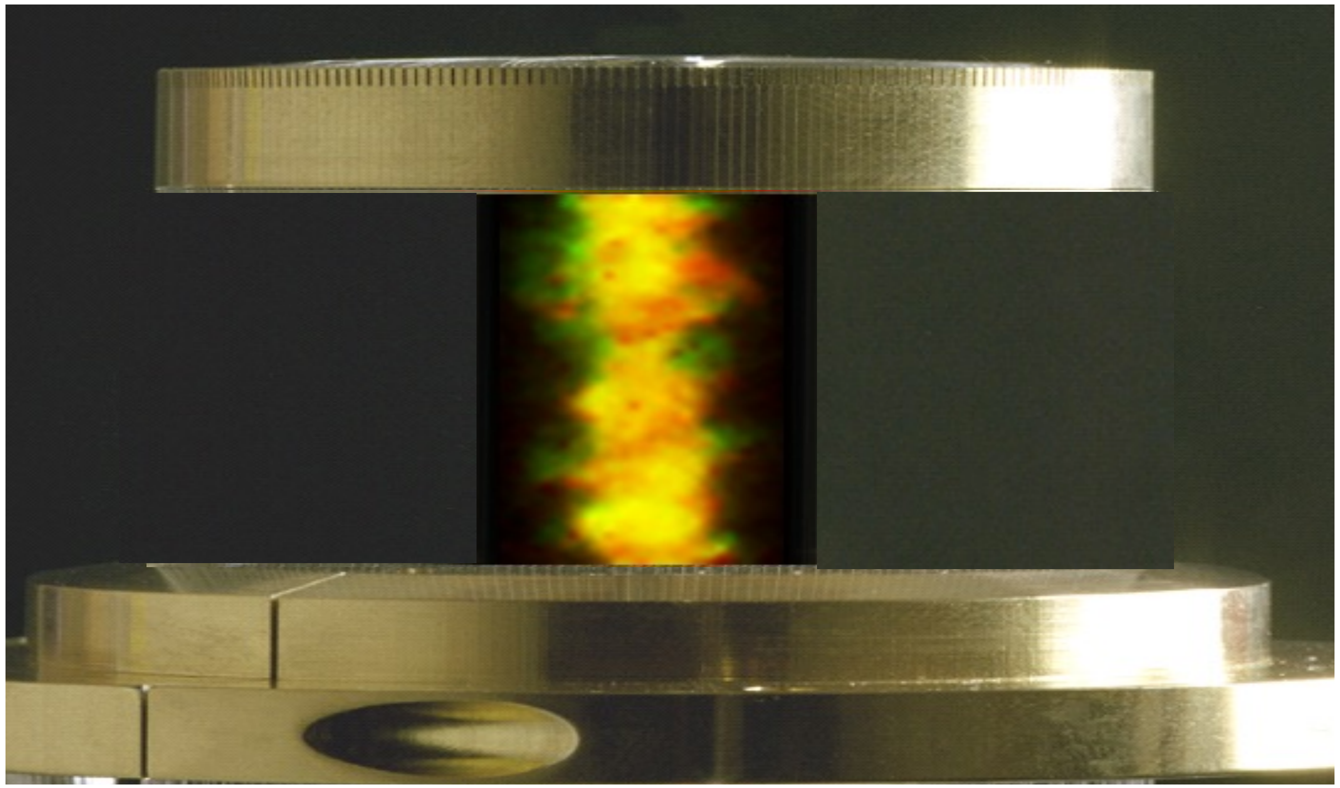
Wire-array implosions on Z use 26 MA of current to create >1 MJ of x rays that can be used to drive multiple experiments



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

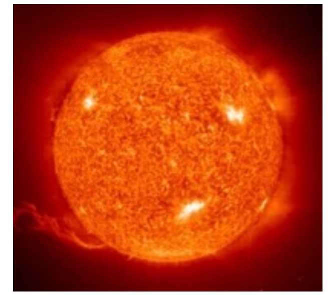
Sanford *et al.*, *PoP* (2002); Bailey *et al.*, *PoP* (2006); Slutz *et al.*, *PoP* (2006); Rochau *et al.*, *PPCF* (2007); Rochau *et al.*, PoP (2014).

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



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:
$T_e \sim 200$ eV, $n_e \sim 10^{23}$ cm^{-3}

Accretion disk

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

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

White dwarf

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

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

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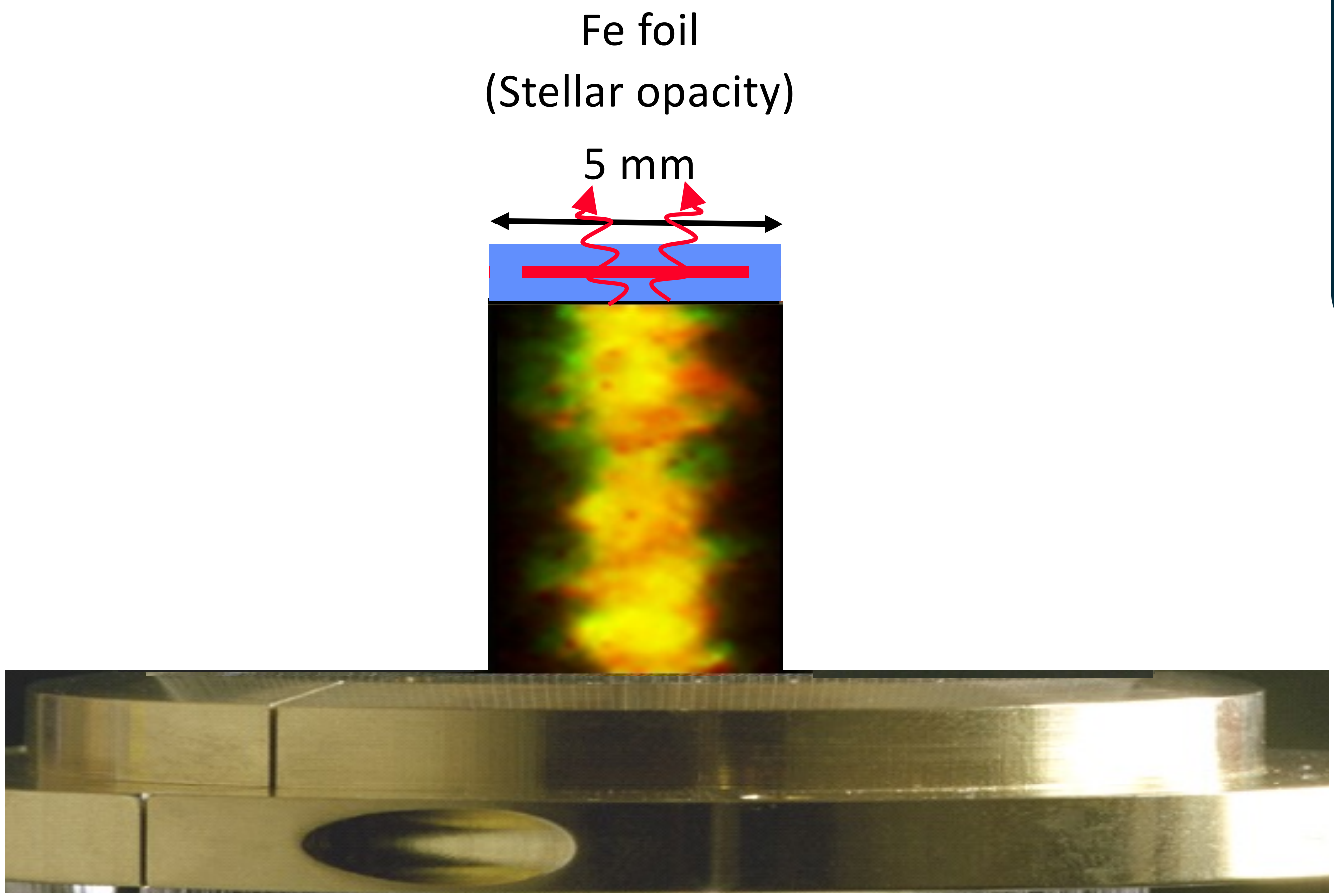

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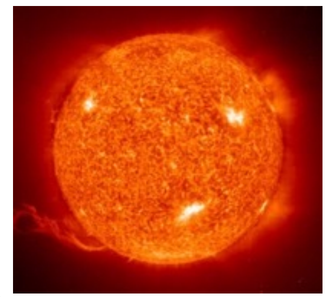
2016 Dawson Award



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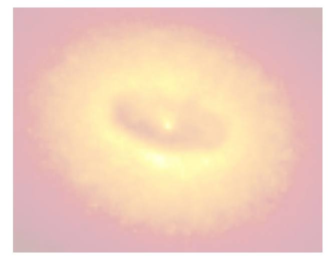

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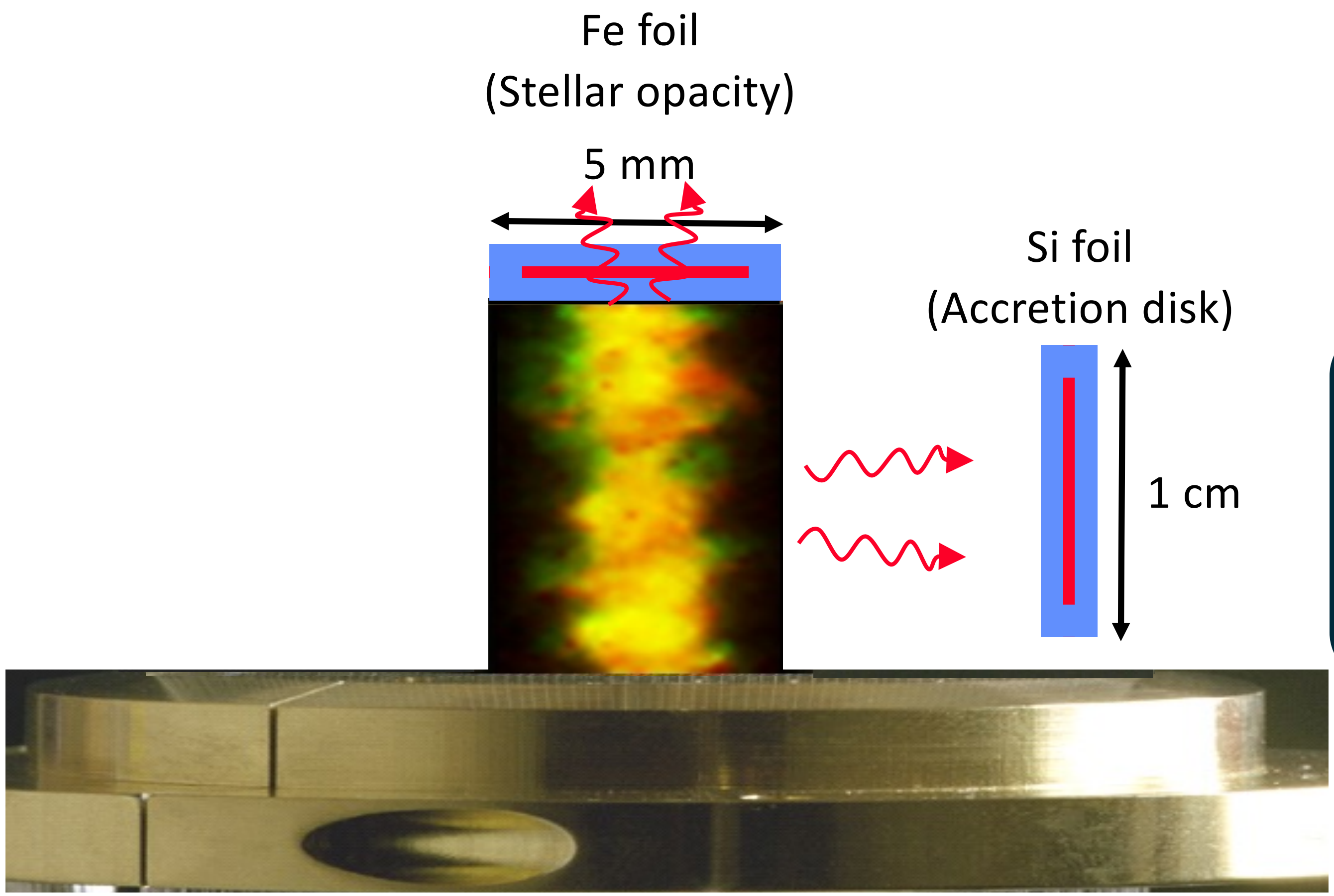

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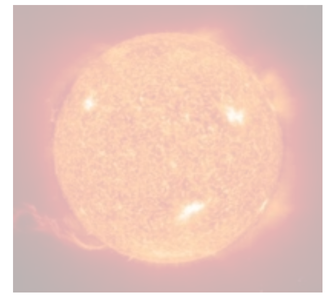

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G.P. Loisel *et al.*, PRL (2017)

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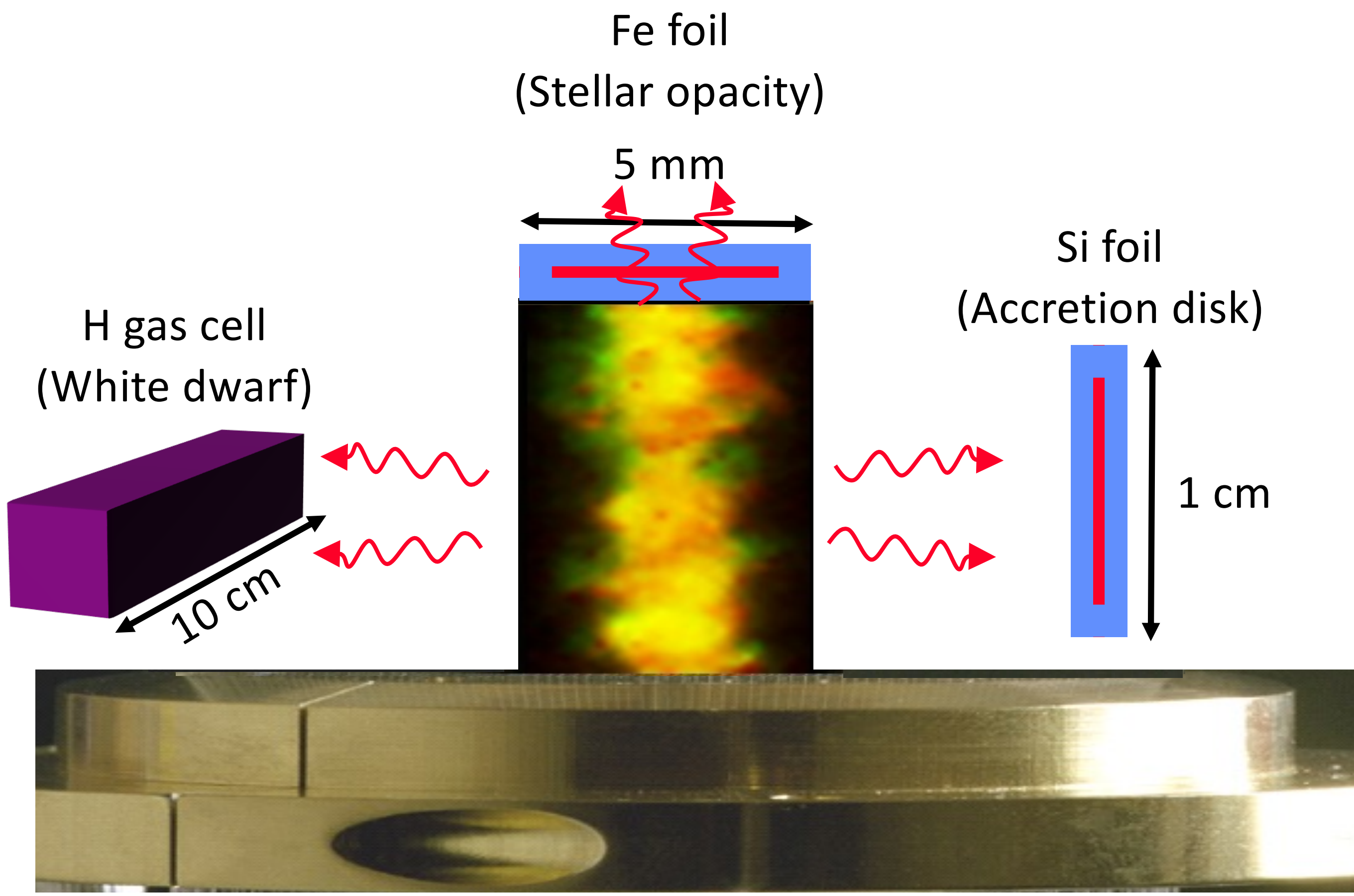

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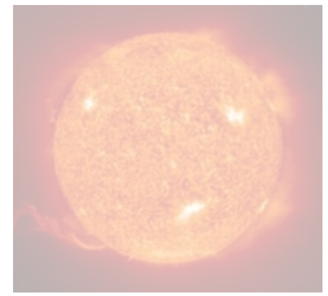

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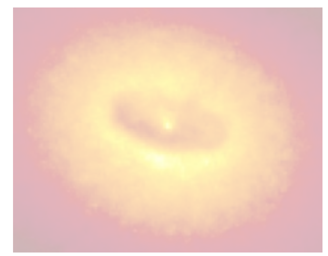

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D.E. Winget *et al.*, HEDP (2020)

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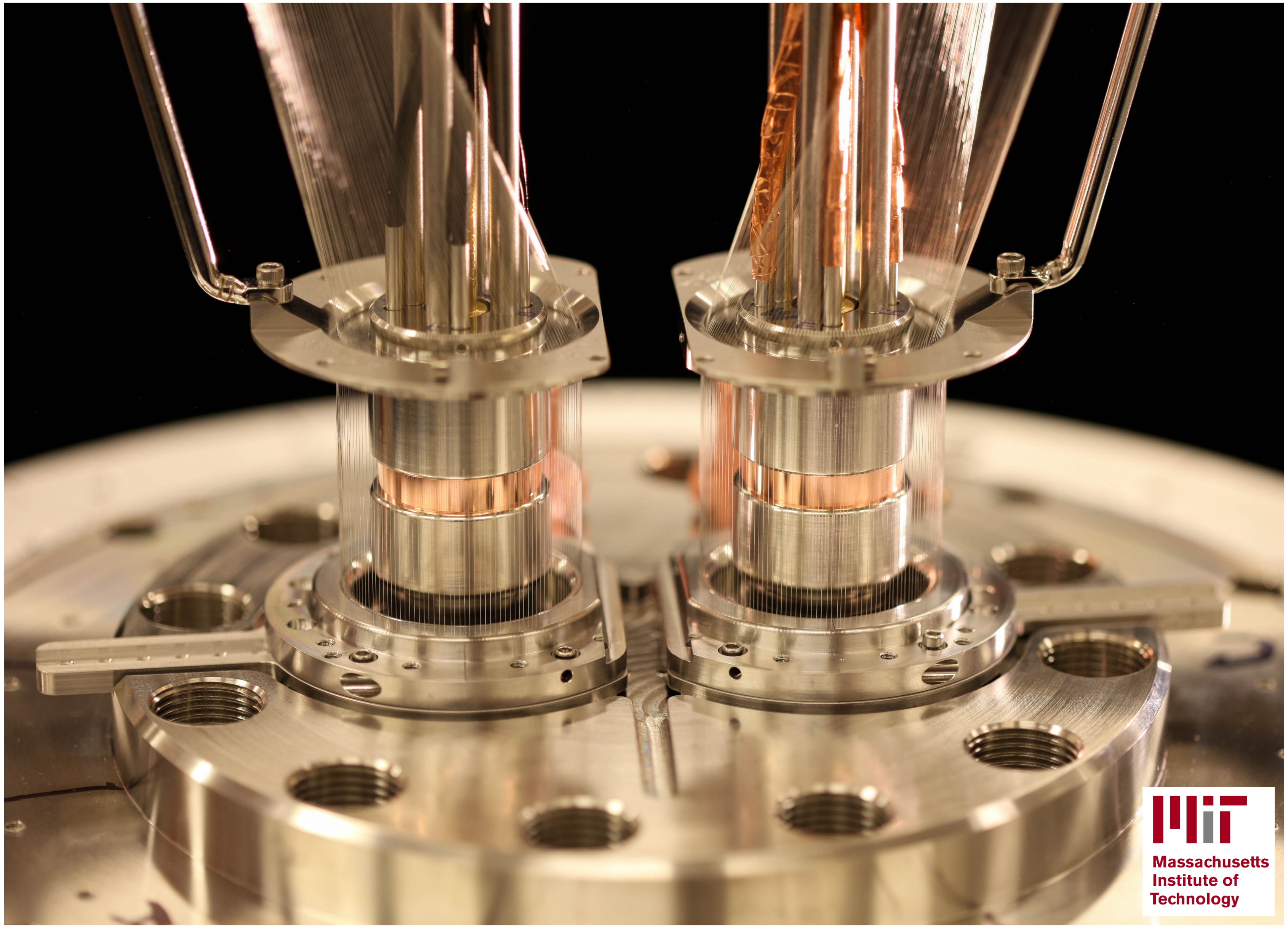
This year we launched a new platform for magnetic reconnection on Z that was inspired by prior work on the United Kingdom's Magpie facility

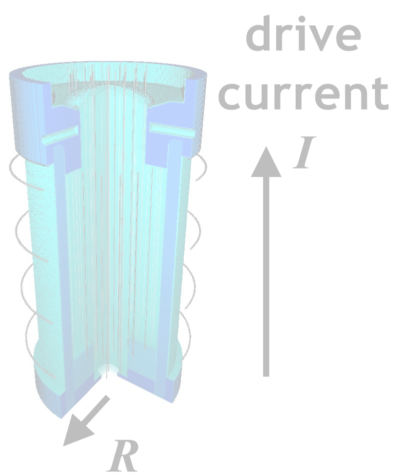
Magnetically
Ablated
Reconnection
on **Z**

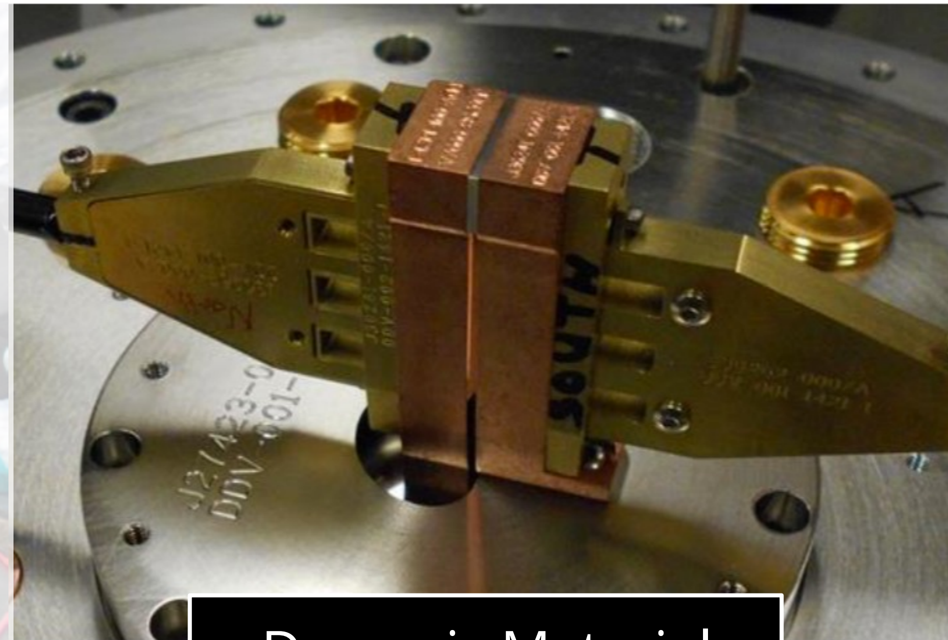
- Extreme astrophysical environments are characterized by strong magnetic fields and strong radiative cooling
  - Difficult to resolve from remote measurements
- MARZ is a new magnetized flow platform on Z to produce strongly cooled, highly magnetized plasmas
- The Z facility is uniquely able to drive these flows to the extreme conditions necessary to observe phenomena such as radiative collapse and shock oscillations



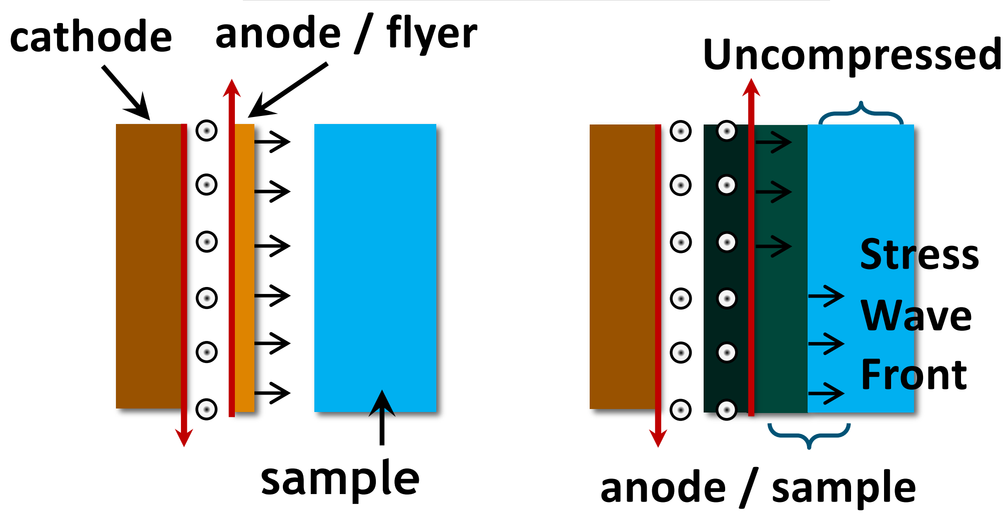
Z is a precision tools for high energy density science

Inertial Confinement Fusion

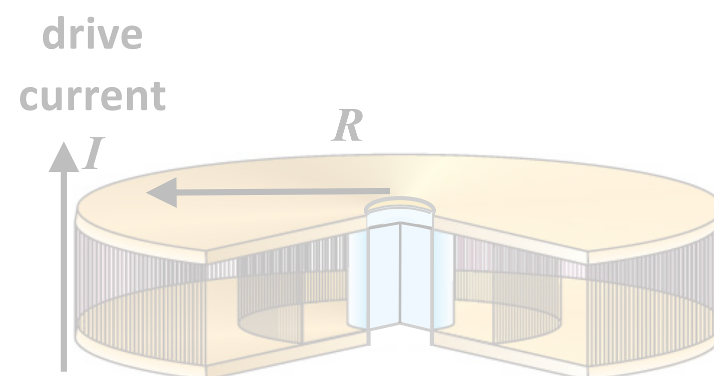




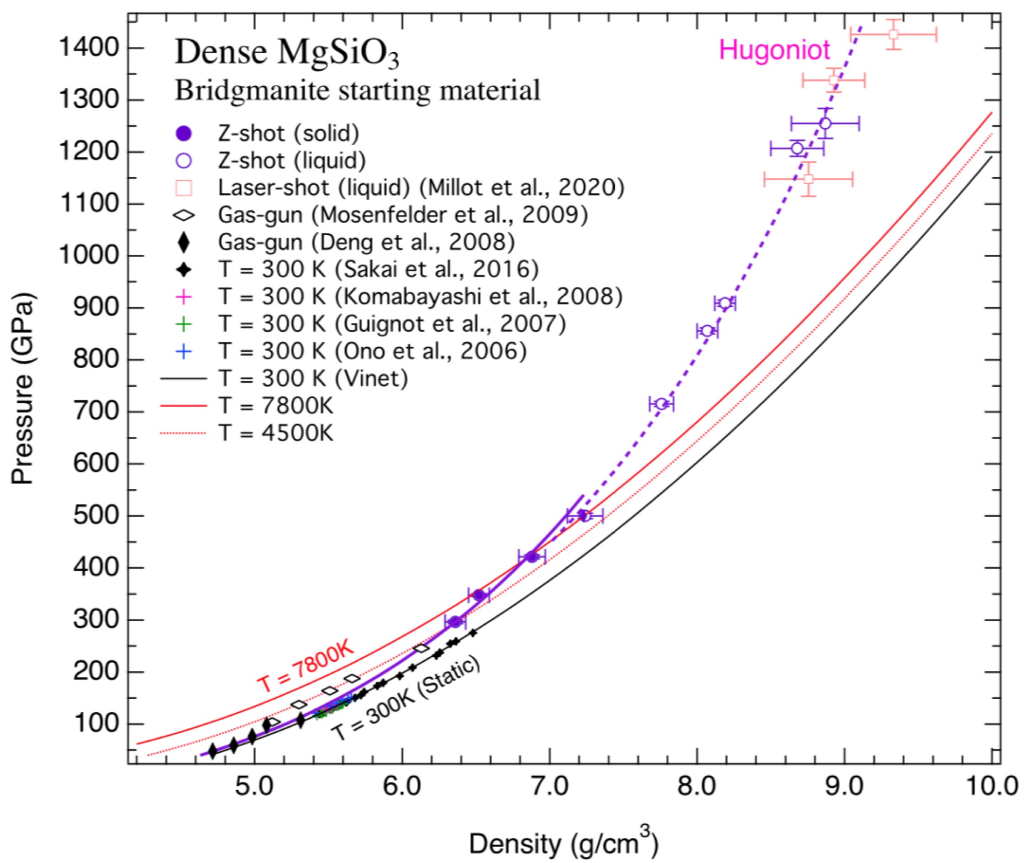
Dynamic Material Properties

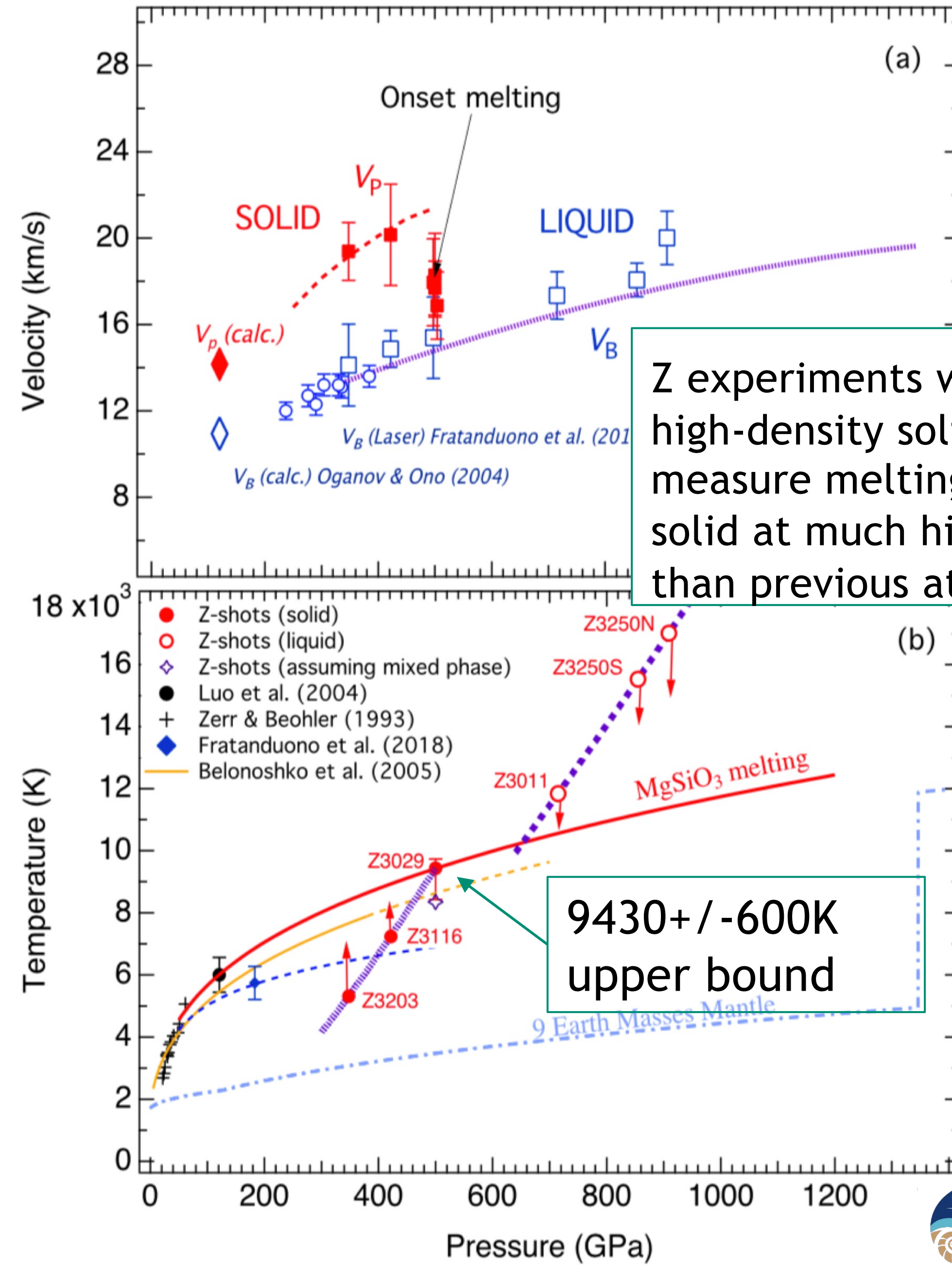


Radiation Science



Bridgmanite: dense high-pressure polymorph of $MgSiO_3$





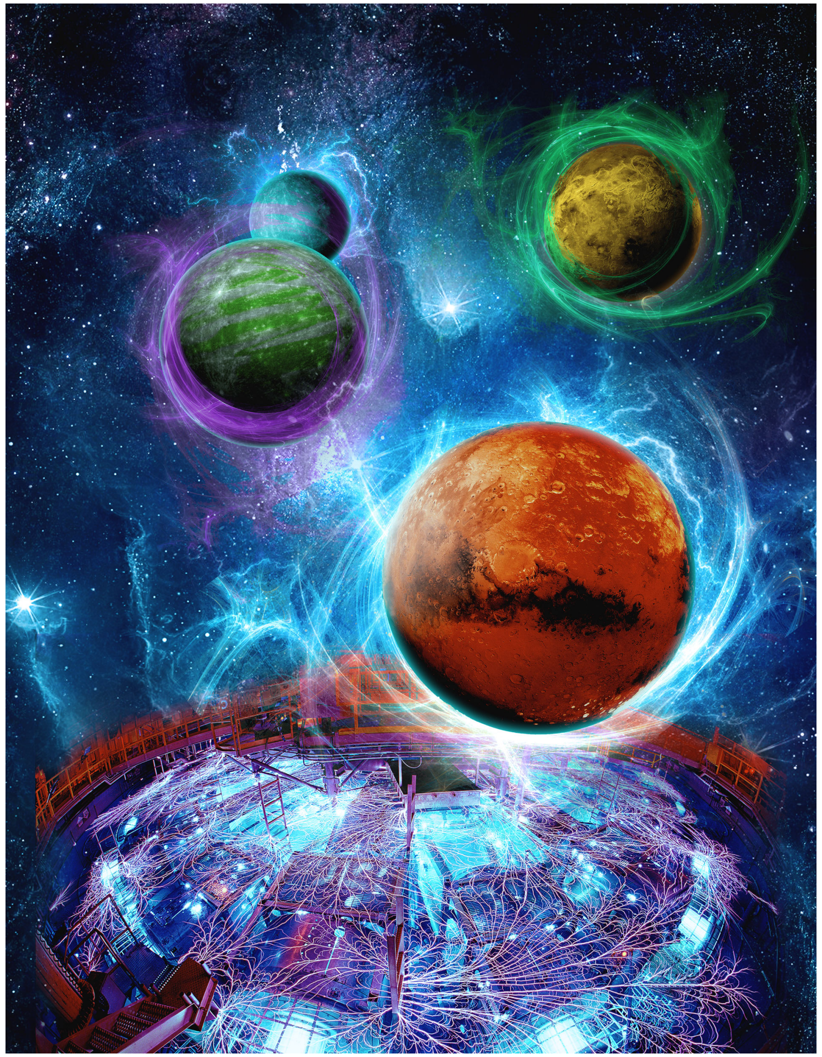
Z experiments with large, high-density solid samples measure melting point of solid at much higher pressure than previous attempts

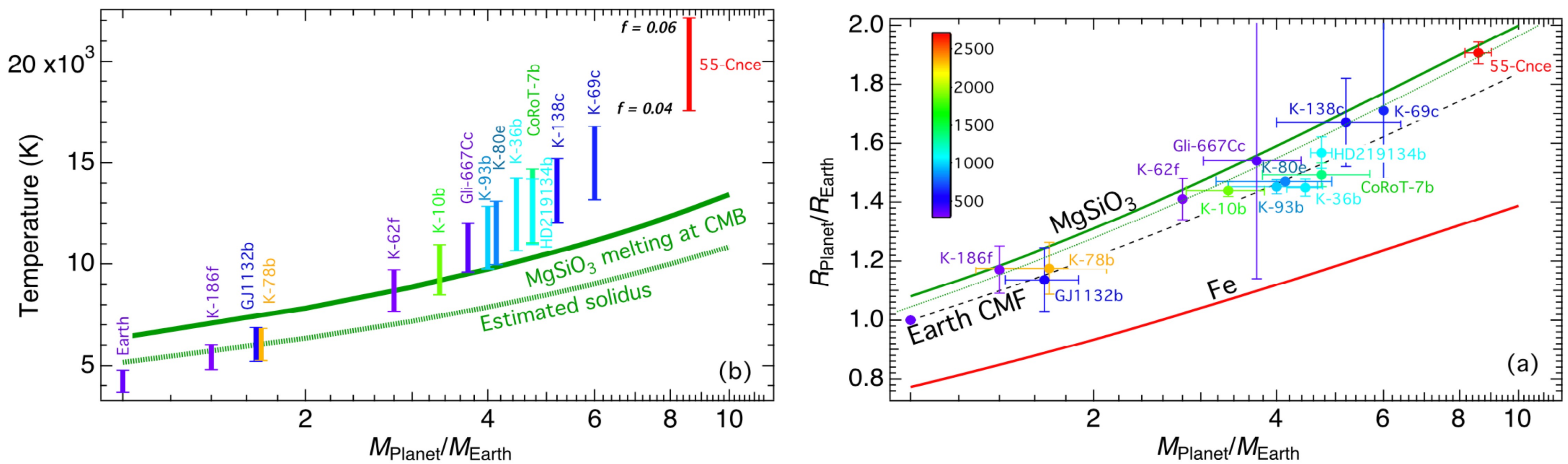
9430+/-600K upper bound

Shock and release measurements in Bridgmanite reveal an extraordinarily high melt temperature at high pressures

Fei *et al.*, Nature Communications 12, 876 (2021)

Implications for super-Earth mantles

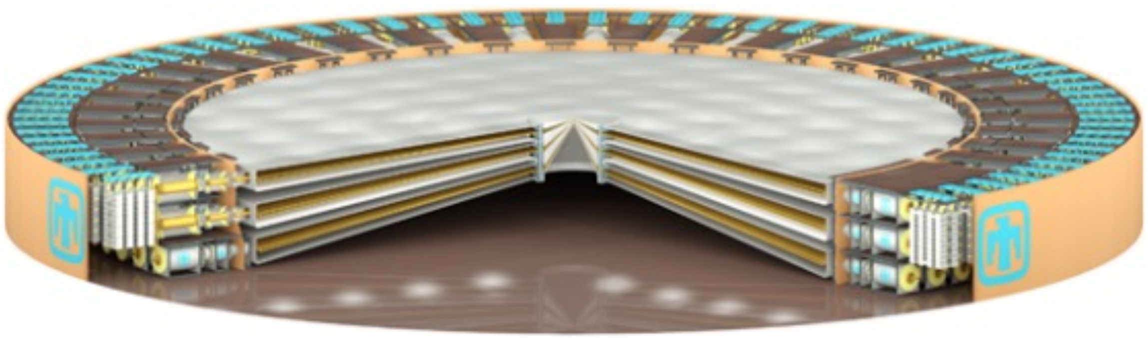




This work has identified a subset of seven super-Earths worthy of further analysis in that they may have similar ratios to Earth in their iron, silicates, and volatile gases in addition to interior temperatures conducive to maintaining magnetic fields

Fei *et al.*, Nature Communications 12, 876 (2021)

The NNSA is presently refining the requirements for a Next Generation Pulsed Power (NGPP) machine



Mission need and requirements finalized in 2023

Main project funding beginning in ~2026

Project completion in the 2030s

NGPP will:

Be the world's most powerful warm x-ray source

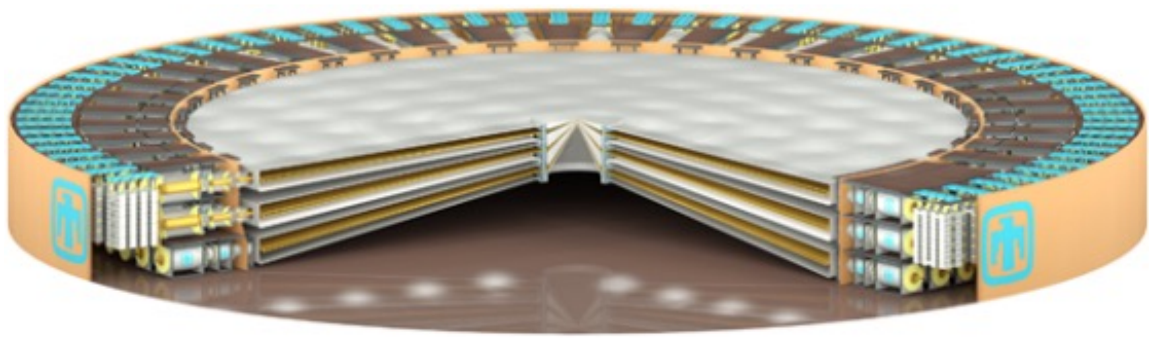
Support fusion yields up to ~100 MJ

Provide advanced capability for high energy density physics (e.g., dynamic materials)

Advance the state-of-the-art for fast pulsed power technology

Provide a venue for scientific and technical innovation for national security

We have computationally evaluated >30,000 designs for NGPP as we continue to work with the NNSA on mission need and requirements



Advanced marx generator example provides 50-70 MA with low technical risk

Parameter	Example NGPP Option	Z
Diameter	300’	108’
Marxes	75 @ 2400 kJ (180 MJ)	36 @ 600 kJ (22 MJ)
Capacitors	13,500 @ 2.95 µF	2,160 @ 2.65 µF
Power at Stack	602 TW	85 TW
Forward Energy at Stack	54 MJ (short pulse)	6 MJ (short pulse)

Other pulsed power architectures also being evaluated using the same tools

NGPP will allow the NNSA to evaluate pulsed power as a path toward high yield (>200 MJ) in the laboratory and provide complementary capabilities relative to the National Ignition Facility

Key Physics Parameter	Importance	Z	Example NGPP Option	NIF
Energy to target (“Strength”)	Larger targets decrease sensitivity to target defects; more fuel mass enables high yield; increases x-ray yield; enables larger material samples	0.5-2.5 MJ (varies w/ inductance)	~10-20 MJ (varies w/ inductance)	2.1 MJ
Peak power to target (“Power”)	Faster energy delivery helps counter radiation and electron heat conductivity losses (→higher temp)	85 TW	~600 TW	400-450 TW
High Energy Density (“Control”)	100-200 Gbar needed to ignite; improves x-ray conversion efficiency for >10 keV	~2 Gbar in MagLIF targets achieved	>100 Gbar in MagLIF targets predicted	>200 Gbar in fusion targets achieved

These parameters will increase platform options for fundamental science on a future facility

- ~10 MJ thermal x-ray sources might be possible
- Higher-temperature plasmas for laboratory astrophysics (e.g., opacity)
- Larger sample/plasma sizes due to more energy (generally increases accuracy)
- Etc.

Closing thoughts regarding fundamental science on future large pulsed power machines based on our ZFSP experience

Pulsed power machine design

- Ability to tailor pulse shapes from ~100 to 1000 ns allows us to do a wide range of dynamic materials science including quasi-isentropic compression experiments that complement shock/Hugoniot tests.
- This is accomplished through the ability to trigger different modules at different times. Marx-based architectures may be better suited for this than intrinsically short-pulse architectures (handling back-reflections may be a challenge.)

Diagnostics

- The limits of your measurements defines the limits of your science. We have invested ~$10-15M annually in diagnostics on Z over the last decade. NIF has seen $40-50M of diagnostic investments annually. We are making challenging measurements!

Platforms

- It is rare for the Z Fundamental Science proposals to develop a new platform (MARZ is an exception). Most of them utilize an existing programmatic platform and adapt it to their specific application.

Modeling & simulation

- Modeling tools are critical for experimental design. Limited access to or expertise with advanced radiation-magneto-hydrodynamic tools tends to constrain the "boldness" of new HED science platforms from partners.
- Often, such tools are needed not only to design experiments but to interpret complex data from them.

Backup materials

Proposals reviewed by independent, external review panel

- Applications are technically evaluated based on four scientific/technical criteria:
  - Scientific and technical soundness and quality of the proposed method/approach, and the feasibility/likelihood of accomplishment of the stated objective
  - The overall scientific/technical merit of the project and its relevance and prospective contribution to its field of research
  - The competence, experience, and past performance of the applicant, principal investigator and/or key personnel
  - The demands of the project in terms of resource requirements (equipment, beam time, etc.) and/or other requirements (facility hardware modifications, component development, etc.) vis-à-vis competing demands.

Two-year award period

Sandia National Laboratories
Pulsed Power Sciences

Call for Proposals Package for the Z Facility Fundamental Science Program for the Period July 1, 2023 to June 30, 2025

Issue Date: June 15, 2022

Due Date: September 15, 2022

Point of Contact: Dr. Marcus D. Knudson
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NNSA

Sandia National Laboratories

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6 teams awarded shots from the CY19 Call for Proposals

shots: CY20 / CY21 / CY22

Nagayama et al. **with Jim Bailey POC** **(ZAPP lead)**
- Laboratory tests of stellar interior opacity models

Loisel et al. **with Taisuke Nagayama and Jim Bailey POCs**
- Laboratory tests of photoionized plasma emission formation for accretion-powered objects

Dunlap et al. **with Taisuke Nagayama and Jim Bailey POCs**
- Atomic processes in white dwarf atmospheres in the laboratory

Kuranz et al. **with Taisuke Nagayama and Jim Bailey POCs** New Team
- Cosmologically relevant radiation-driven heat fronts (proof-of-concept)

ZAPP
Z Astrophysical Plasmas Project
9 shots: 2 / 5 / 2
actual: 2 / 4 / 3

Jacobsen et al. **with Sakun Duwall POC**
- Formation and evolution of Earth-like and Super-Earth planets

5 shots: 2 / 3 / 0
actual: 2 / 3 / 0

Redmer et al. **with Chad McCoy and Sakun Duwall POCs**
- Jovian planets on Z: Towards an improved understanding of Jupiter- and Neptune-like planets and the HED matter inside

4 shots: 2 / 2 / 0
actual: 1 / 1 / 1

Clark et al. **with Jean-Paul Davis POC**
- Origin of Earth's water: Role of hydrous melts at extreme PT conditions

3 shots: 1 / 1 / 1
actual: 1 / 1 / 1

3 teams awarded shots from the CY20 Call for Proposals

\# shots: CY21 / CY22 / CY23

Jacobsen et al. with Jean-Paul Davis and Sakun Duwal POCs New Team

- Origin of the ultra-low velocity zones atop Earth's core-mantle boundary: shock-ramp compression of iron-rich (Mg,Fe)O

4 shots: 1 / 2 / 1
actual: 0 / 2 / 2

Oleynik et al. with Patricia Kalita and Tom Ao POCs New Team

- Phase transitions in SiC in the interiors of carbon-rich exoplanets

USF UNIVERSITY OF SOUTH FLORIDA

4 shots: 1 / 2 / 1
actual: 0 / 2 / 2

Hare et al. with Kathy Chandler POC New Team

- MARZ: Magnetically Ablated Reconnection on Z

Massachusetts Institute of Technology

4 shots: 1 / 2 / 1
actual: 0 / 3 / 1

7 teams awarded shots from the CY21 Call for Proposals

Nagayama et al. **with Jim Bailey POC** **(ZAPP lead)**
- Laboratory tests of stellar interior opacity models

Cho et al. **with Guillaume Loisel and Jim Bailey POCs**
- Laboratory tests of photoionized plasma emission formation for accretion-powered objects

Dunlap et al. **with Guillaume Loisel and Jim Bailey POCs**
- Atomic processes in white dwarf atmospheres in the laboratory

Kuranz et al. **with Taisuke Nagayama and Jim Bailey POCs**
- Cosmologically relevant radiation-driven heat fronts (proof-of-concept)

Jaar et al. **with Guillaume Loisel and Jim Bailey POCs**
- Thermal stability of x-ray photoionized plasmas (proof-of-concept)

shots: CY22 / CY23 / CY24

ZAPP

Z Astrophysical Plasmas Project

6 shots: 0 / 3 / 3

actual: 0 / 4 / 3

Jacobsen et al. **with Patricia Kalita POC**
- Formation and evolution of Earth-like and Super-Earth planets

3 shots: 1 / 2 / 0

actual: 1 / 2 / 0

Tracy et al. **with Chad McCoy and Sakun Duwal POCs**
- Melting of iron-bearing Bridgmanite

Carnegie Science

3 shots: 1 / 2 / 0

actual: 1 / 2 / 0

2022 participation by institution

Active ZFS Projects:

Carnegie Institution for Science

Harvard University

Massachusetts Institute of Technology

Northwestern University

University of Texas at Austin

University of California at Davis

University of Colorado at Boulder

University of Michigan

University of Nevada at Reno

University of South Florida

University of Rostock

Participated at the ZFS Workshop:

Cornell University

Imperial College

Michigan State University

Princeton University

University of California at San Diego

University of Illinois at Chicago

University of New Mexico

University of Rochester

California Institute of Technology

Instituto de Ciencias Espaciales (Institute of Space Sciences)