Research Highlights From The Sandia Z Accelerator

PRESENTED BY

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Sandia National Laboratories

SSGF / LRGF Program Review | June 23, 2022

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SAND2022-8381C

These are exciting times to be working in pulsed power

1. The world's largest pulsed power facility, Z, is used for a spectrum of research spanning:
   - Fundamental/Basic Science
   - Use-inspired Science
   - Applied/Mission Science
2. Pulsed power has matured into a precision tool for high energy density science encompassing:
   - **Inertial Confinement Fusion**
   - **Dynamic Material Properties**
   - **Radiation Science**
3. Over the next decade, significant scientific opportunities abound, such as:
   - Achieving 30-100 kJ DT-equivalent yields using magneto-inertial fusion principles
   - Measuring solidification in dynamic materials experiments with unprecedented precision
4. We are laying the groundwork for a next step in pulsed power sometime after 2030
   - The 26 MA, 80 TW Z facility will celebrate 35 years of Z-pinch operation in 2030
   - Opportunity to build a >60 MA, >800 TW facility capable of coupling ~10 MJ to fusion targets by ~2032

SANDIA NATIONAL LABORATORIES

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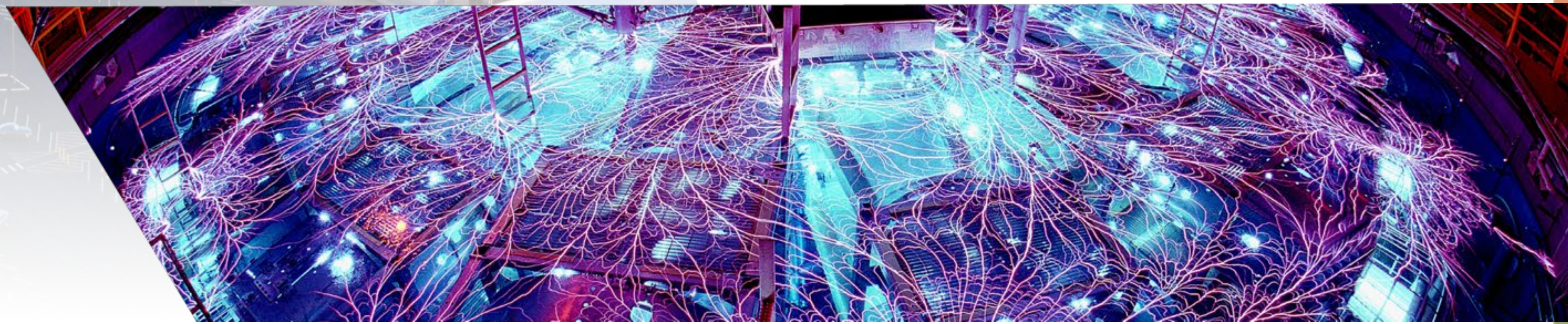
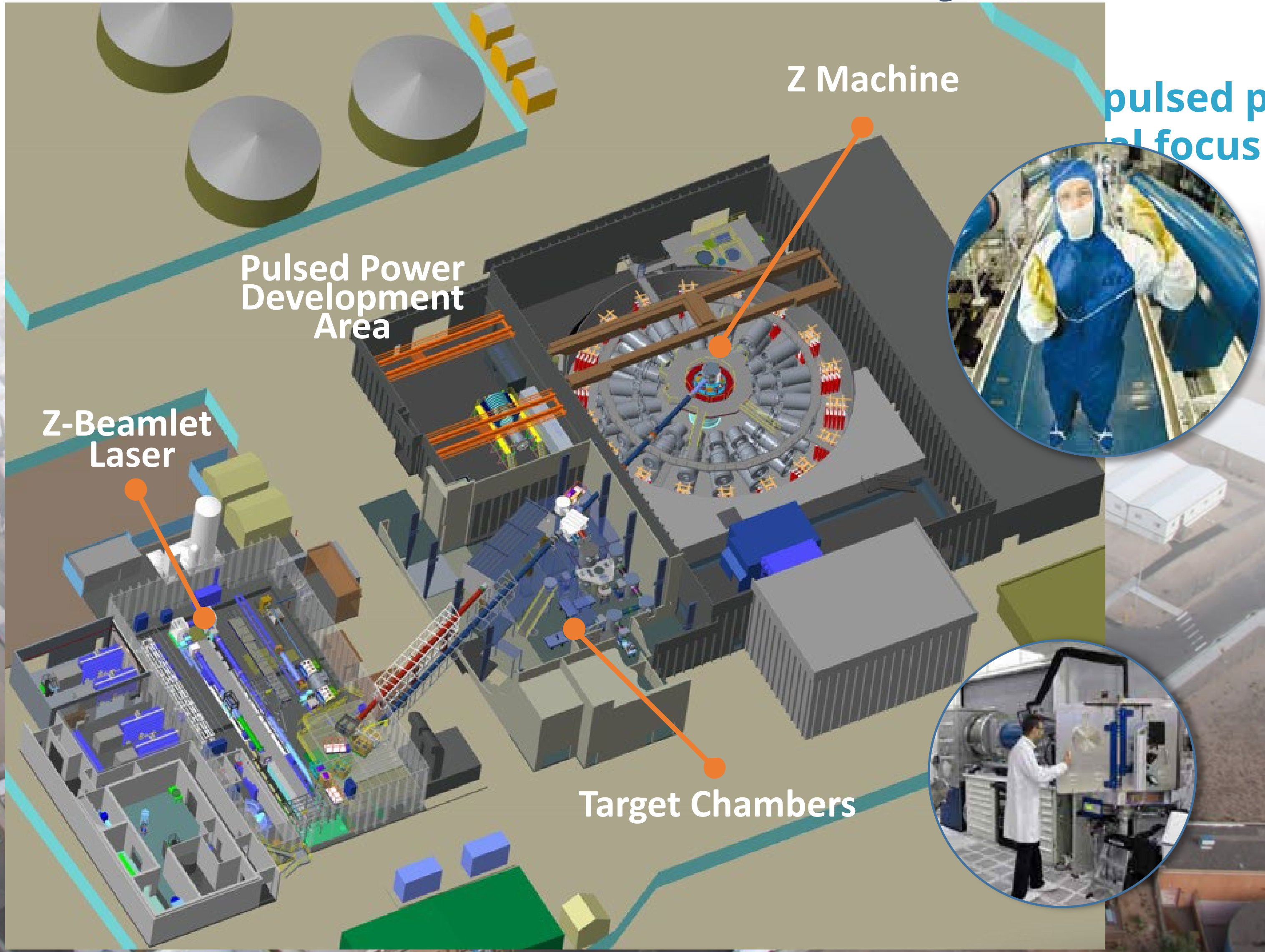
Sandia works on a diverse portfolio of research:

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



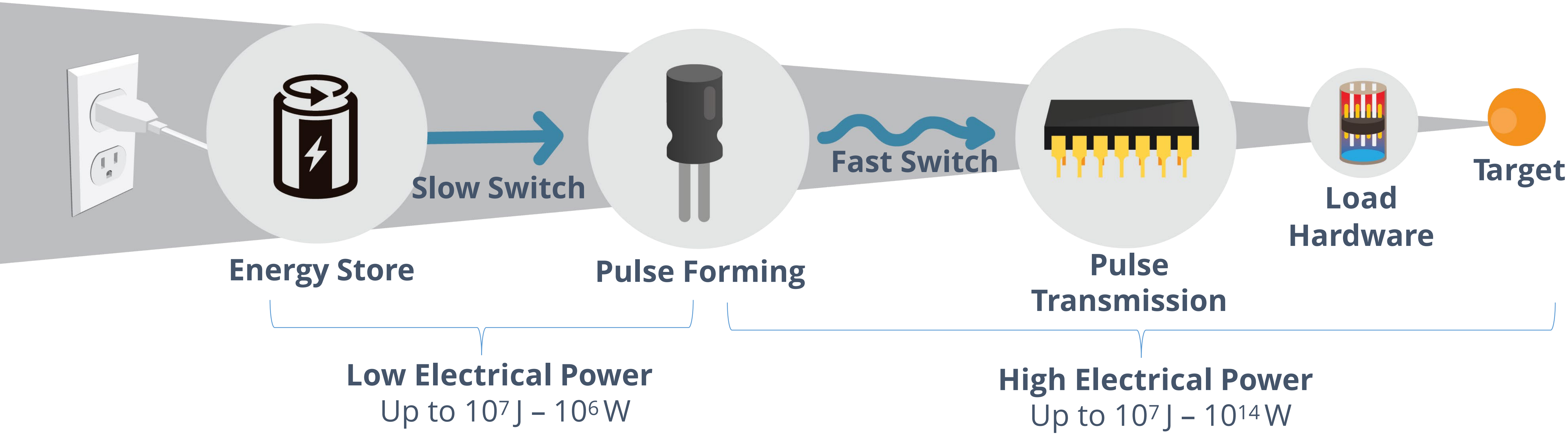
Sandia’s Z Pulsed Power Facility



pulsed power
al focus of today’s

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

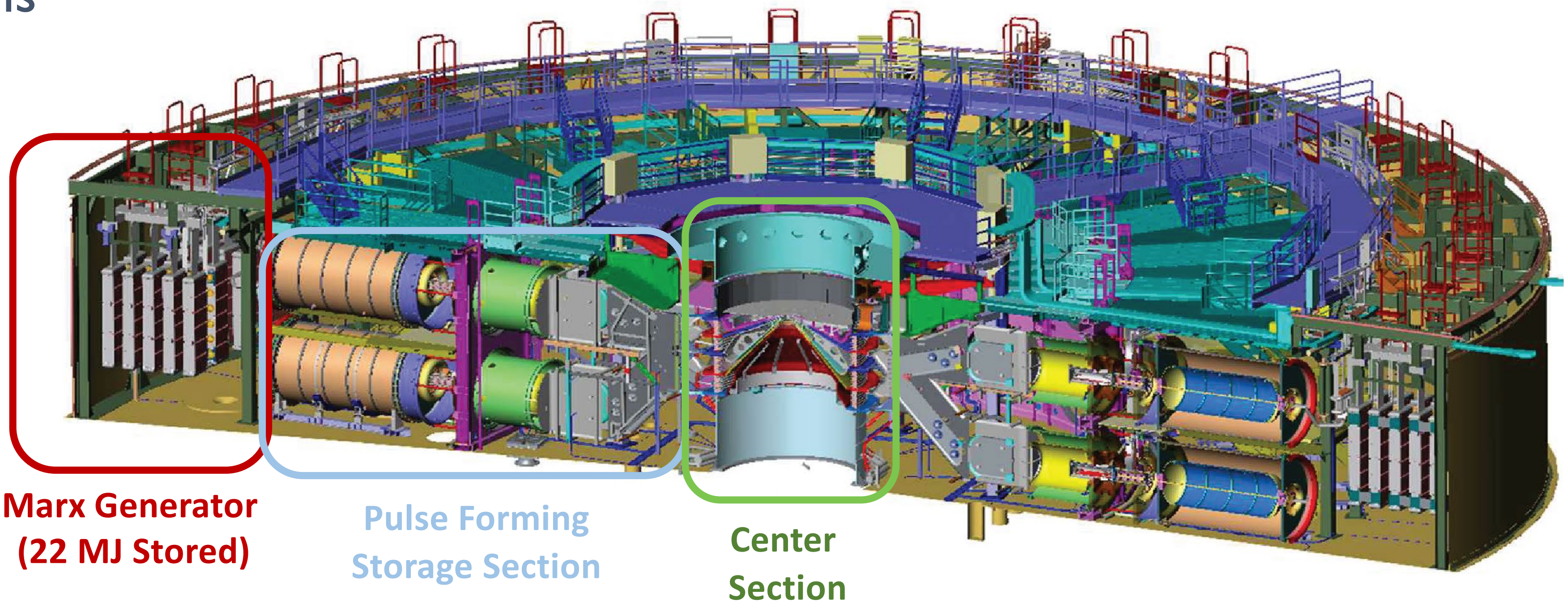
How does pulsed power work?

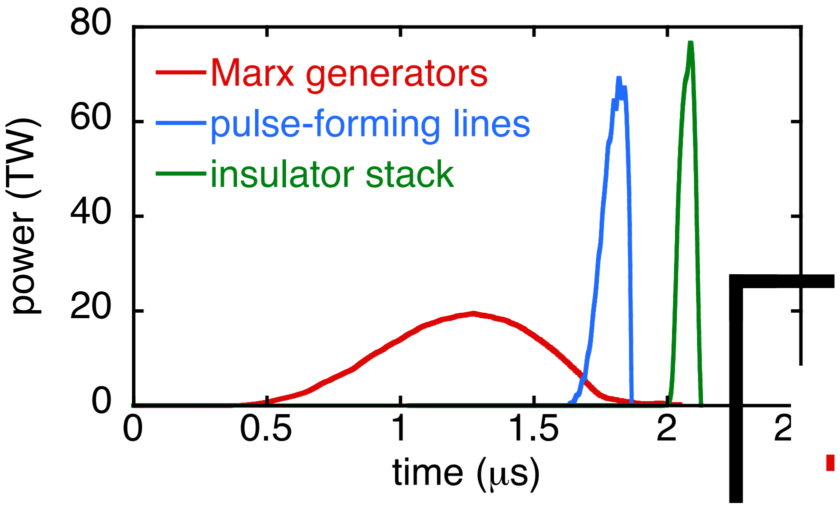


Pulsed power compresses electrical energy in both space and time to produce short bursts of high power.

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

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





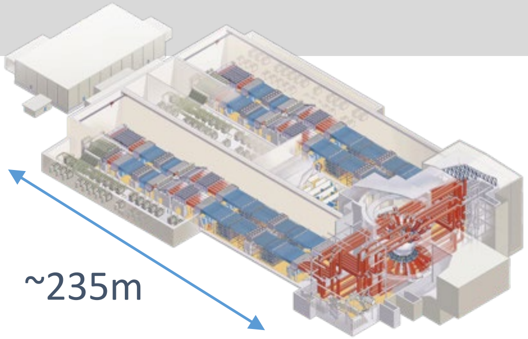
Z today couples several MJ out of 22 MJ stored to the load hardware region at the machine center.

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

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

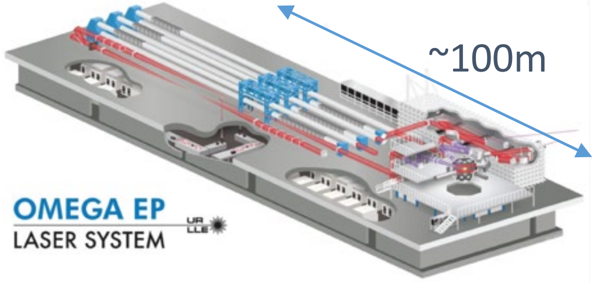
National Ignition Facility (NIF)

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



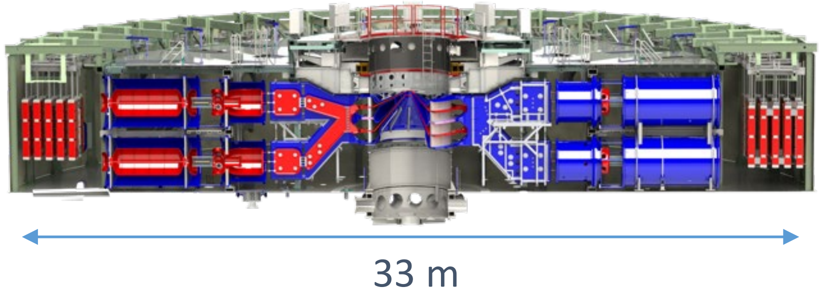
OMEGA Laser Facility

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



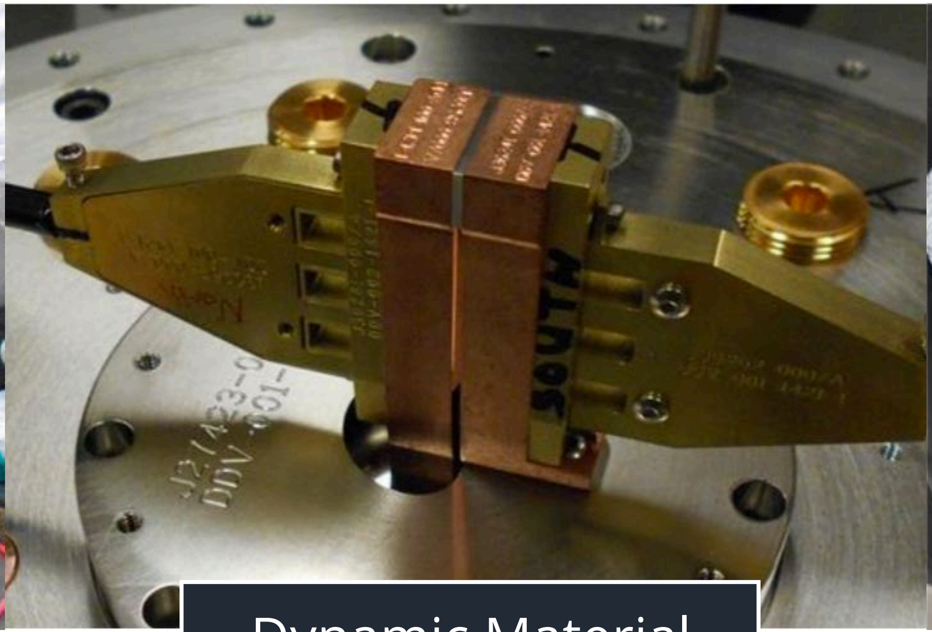
Z Facility

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

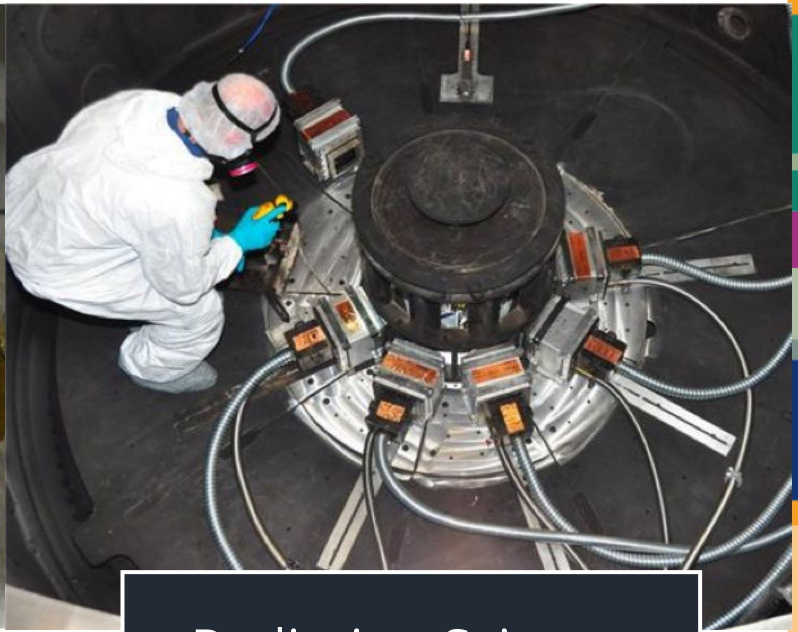


Precision tools for high energy density science

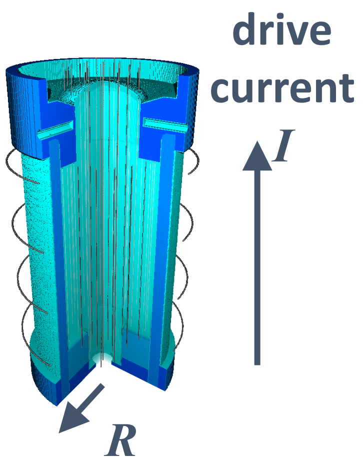
Inertial Confinement Fusion

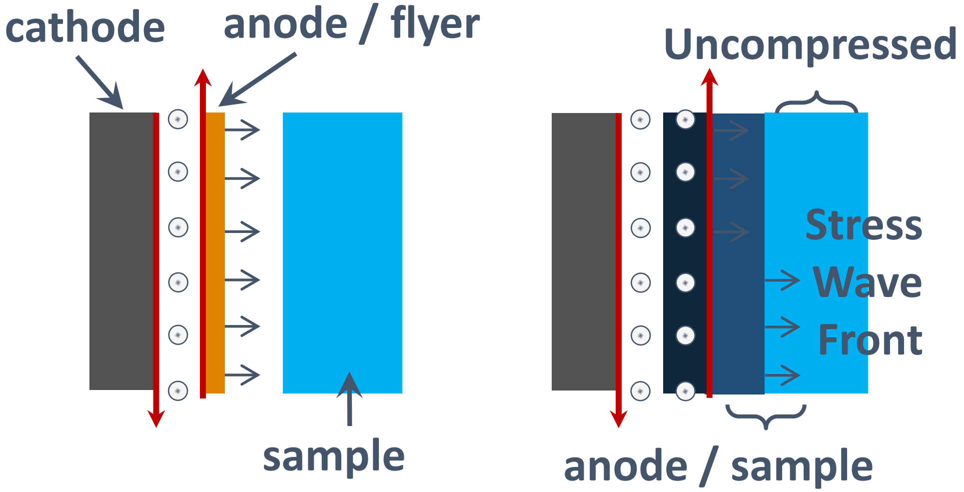


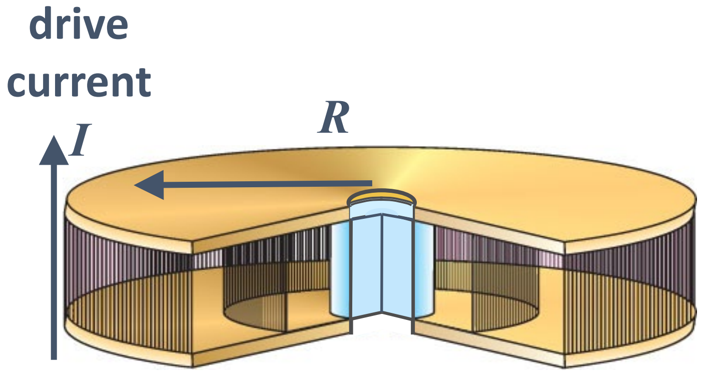
Dynamic Material Properties



Radiation Science

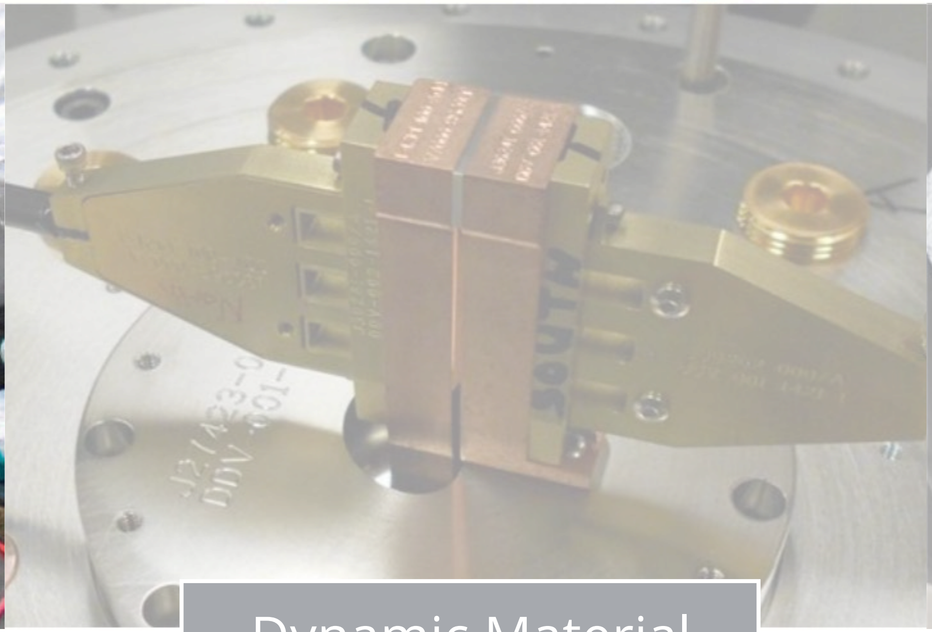






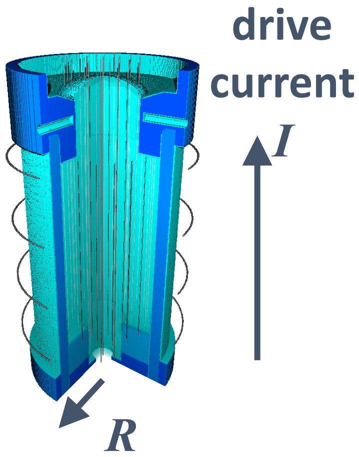
Precision tools for high energy density science

Inertial Confinement Fusion



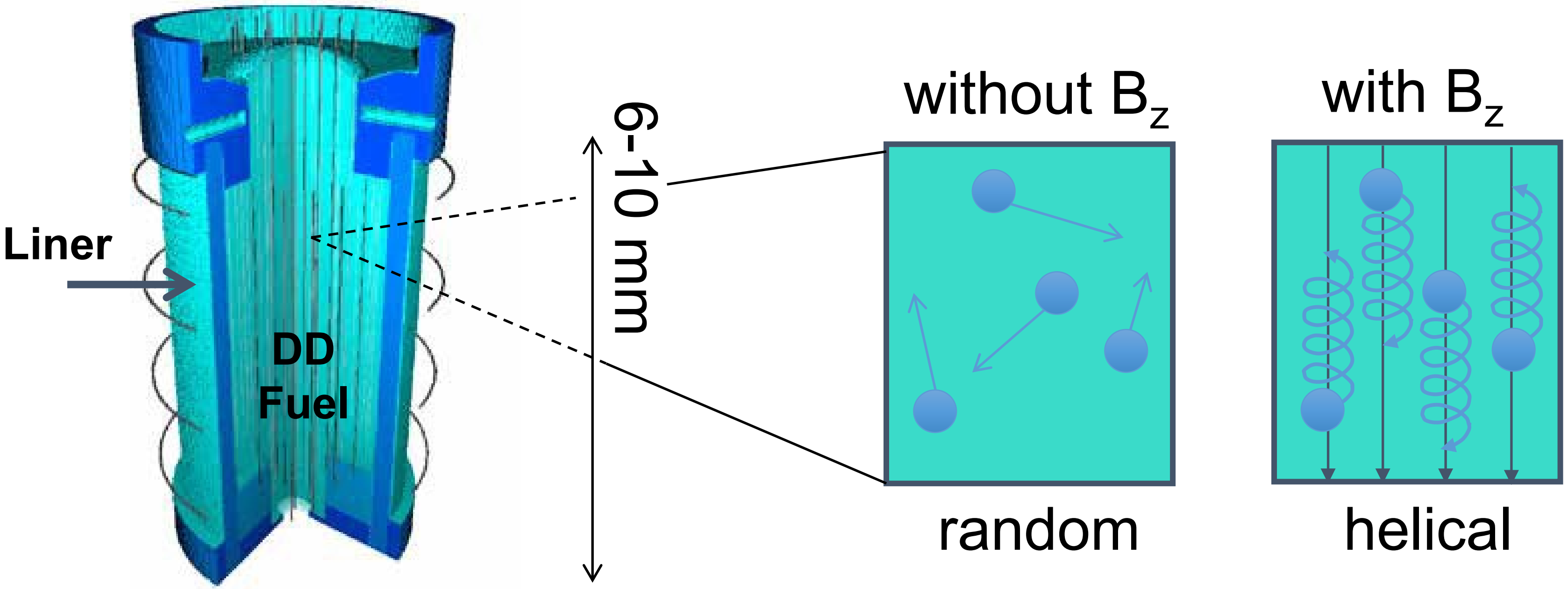
Dynamic Material Properties

Radiation Science



MagLIF is a Magneto-Inertial Fusion (MIF) concept

Relies on three components to produce fusion conditions at stagnation



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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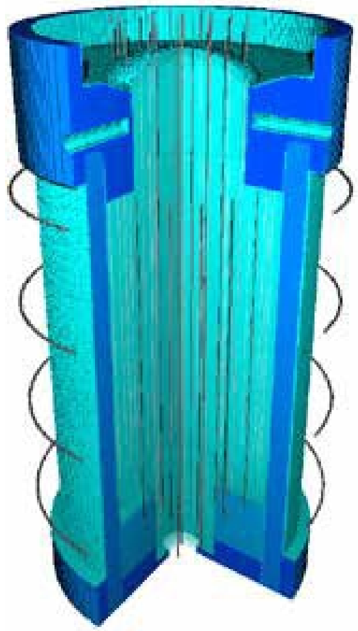

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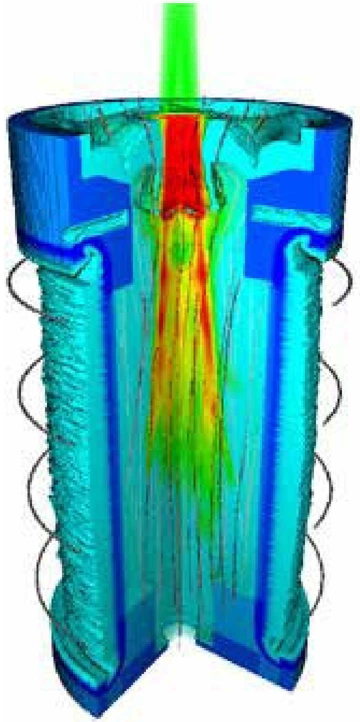

- **Laser preheat: 100-200 eV**
  - **Uses Z-Beamlet Laser (other heating methods possible)**
  - **Relax convergence requirement**
  - **CR=$R_{initial}/R_{final}$= 120 → 20-40**

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

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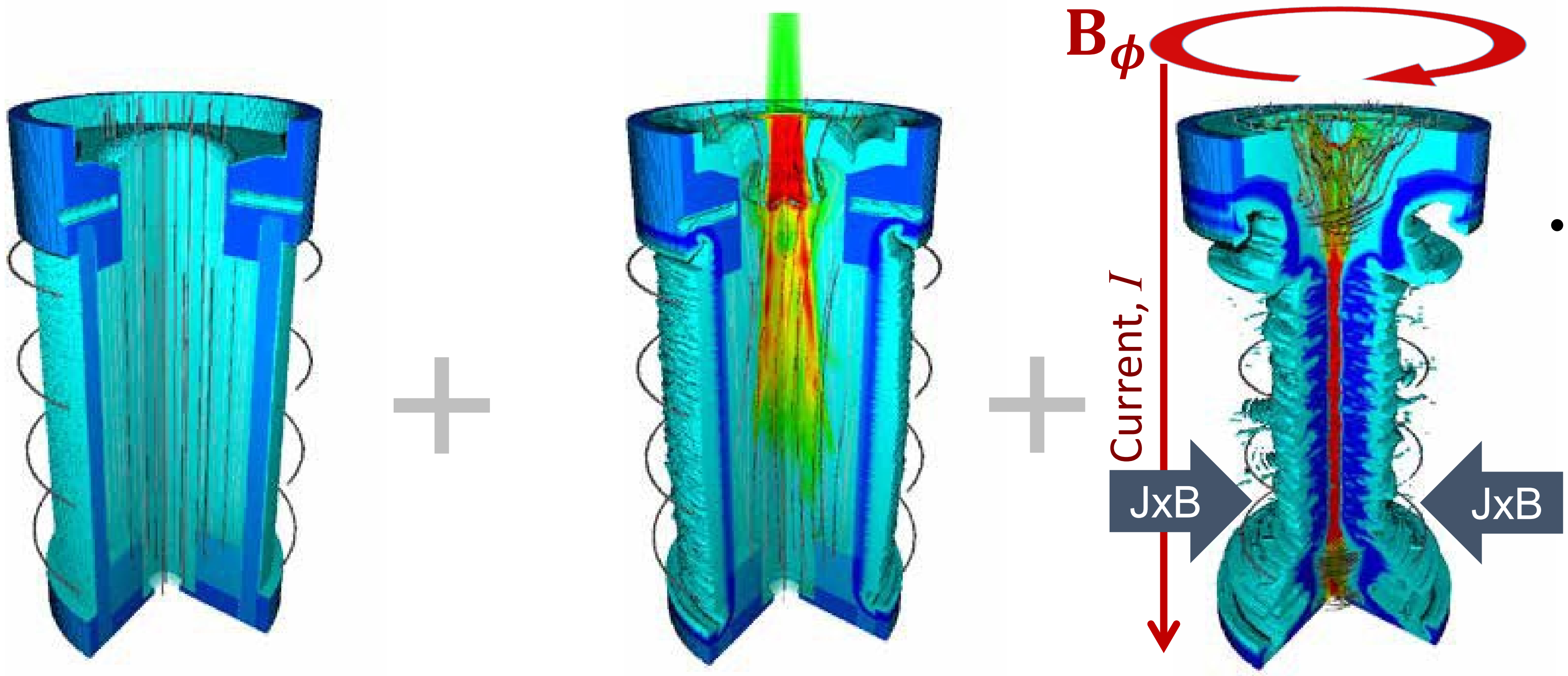

- **Magnetically Driven Implosion**
  - **"Only" ~100 km/s (vs. ~380 km/s on NIF)**
  - **B-field amplified to >10,000 T**

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

Preheat
- Ionize fuel to lock in B-field
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Implosion
- PdV work to heat fuel
- Flux compression to amplify B-field

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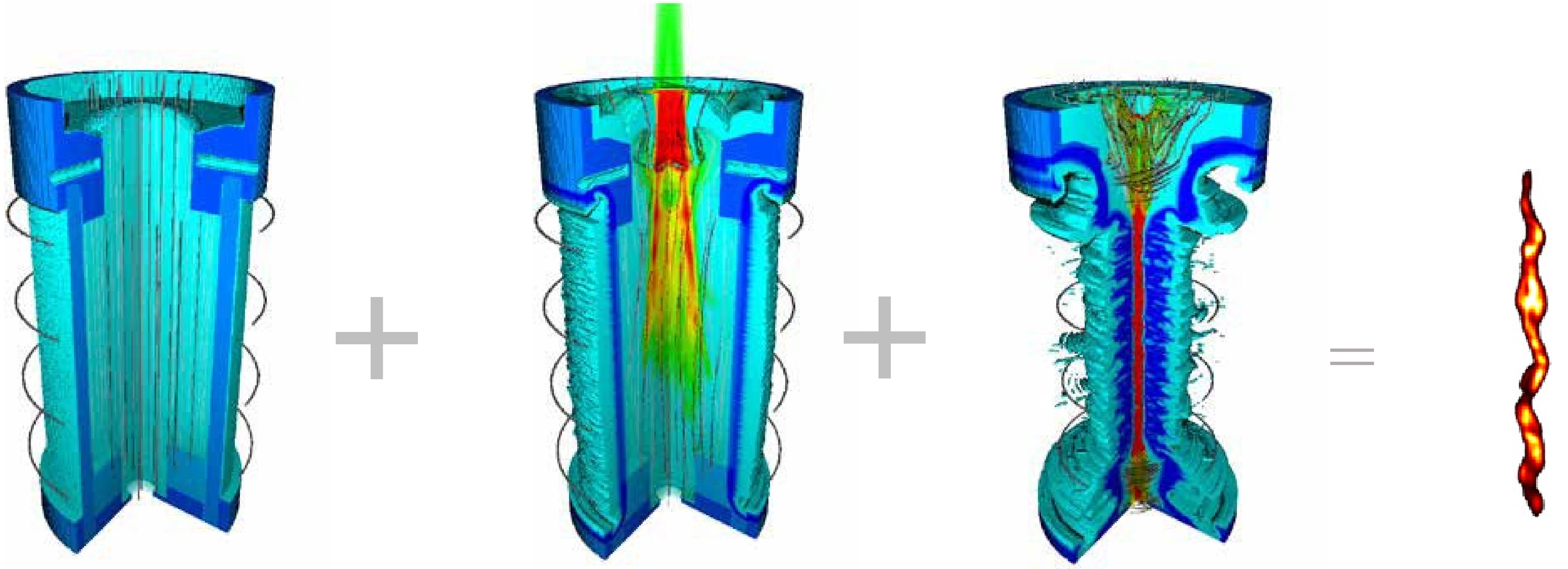

Magnetization

- Suppress radial thermal conduction losses
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Preheat

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Implosion

- PdV work to heat fuel
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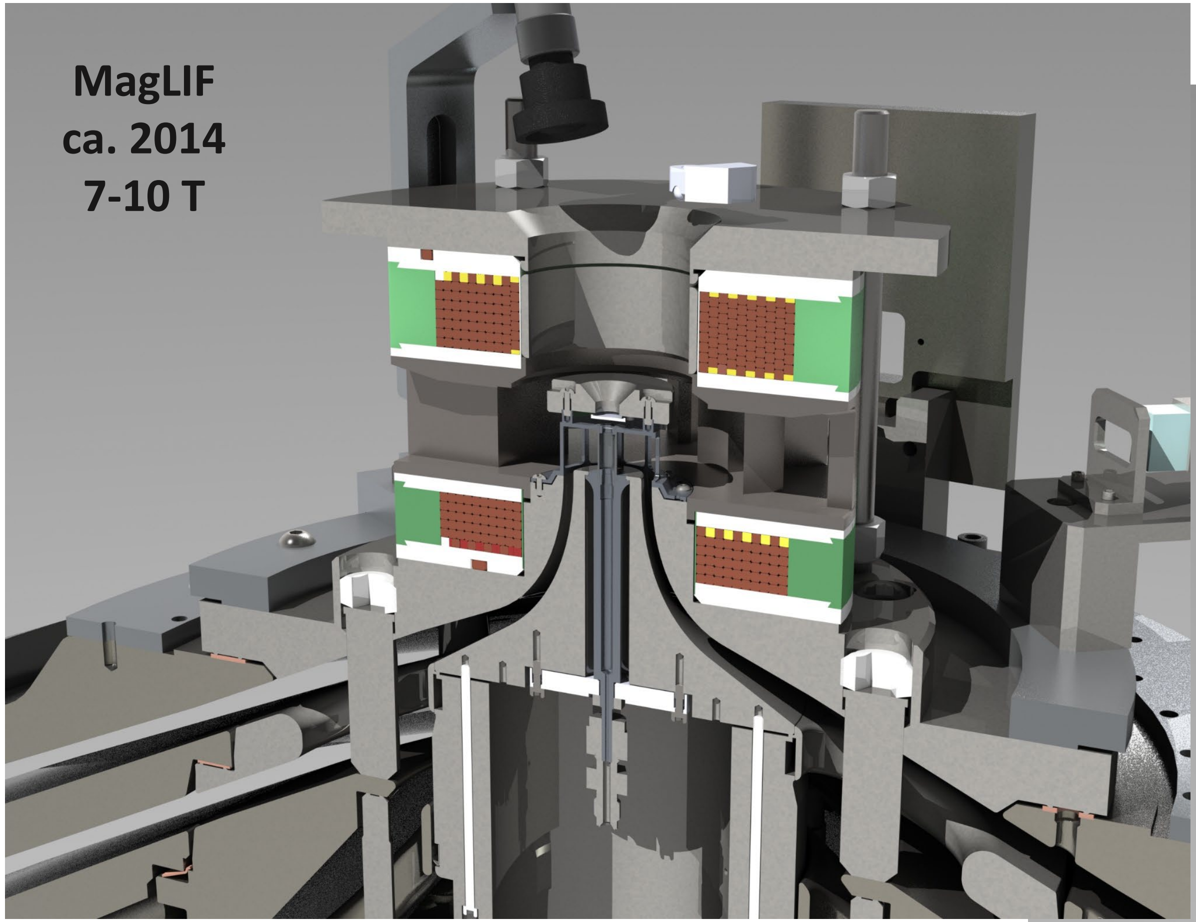
Stagnation

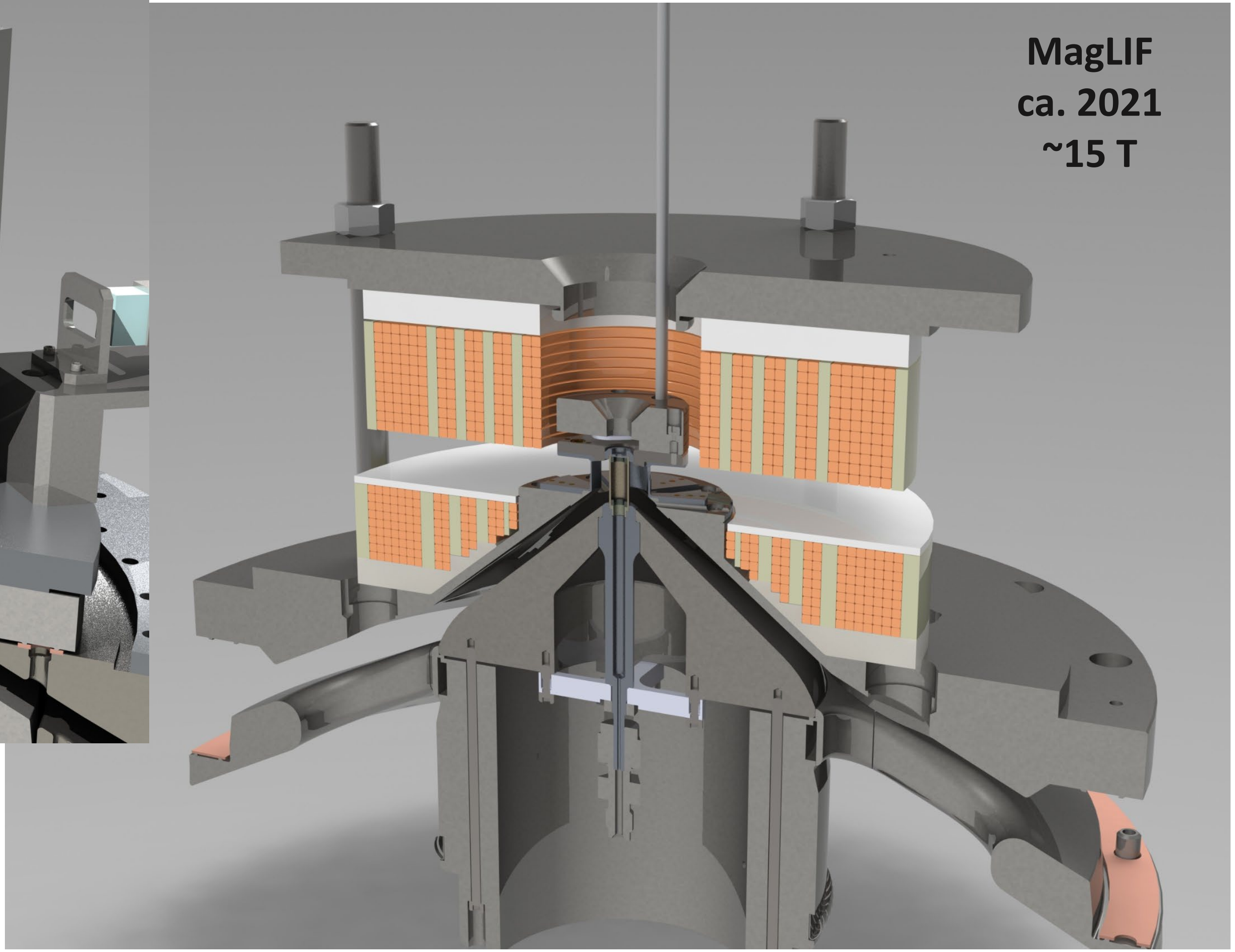
- Several keV temperatures
- Several kT B-field to trap charged fusion products

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

We continue to test MagLIF scaling through further increasing magnetization, preheat, and drive current

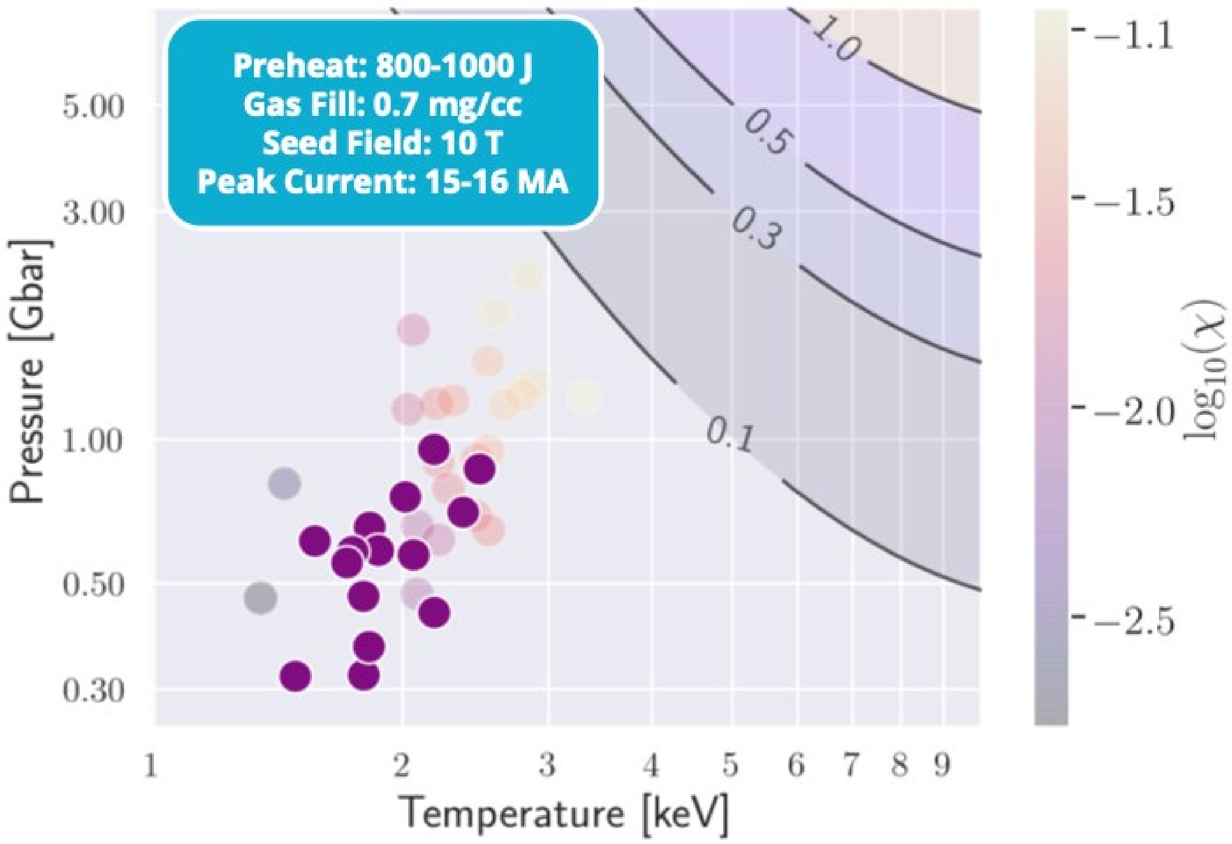
Use-Inspired



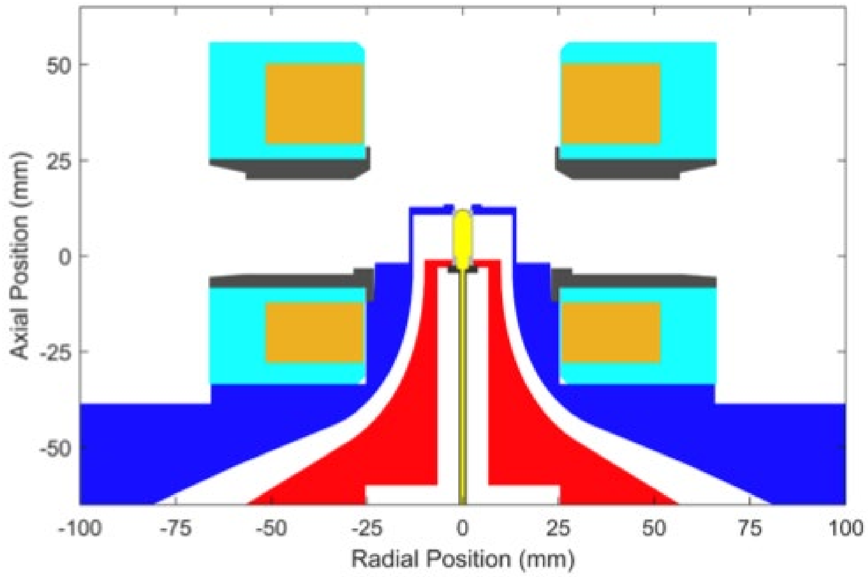


S. A. Slutz, et al., Phys. Plasmas (2018)

Simultaneously increasing all input parameters provides the largest performance improvements



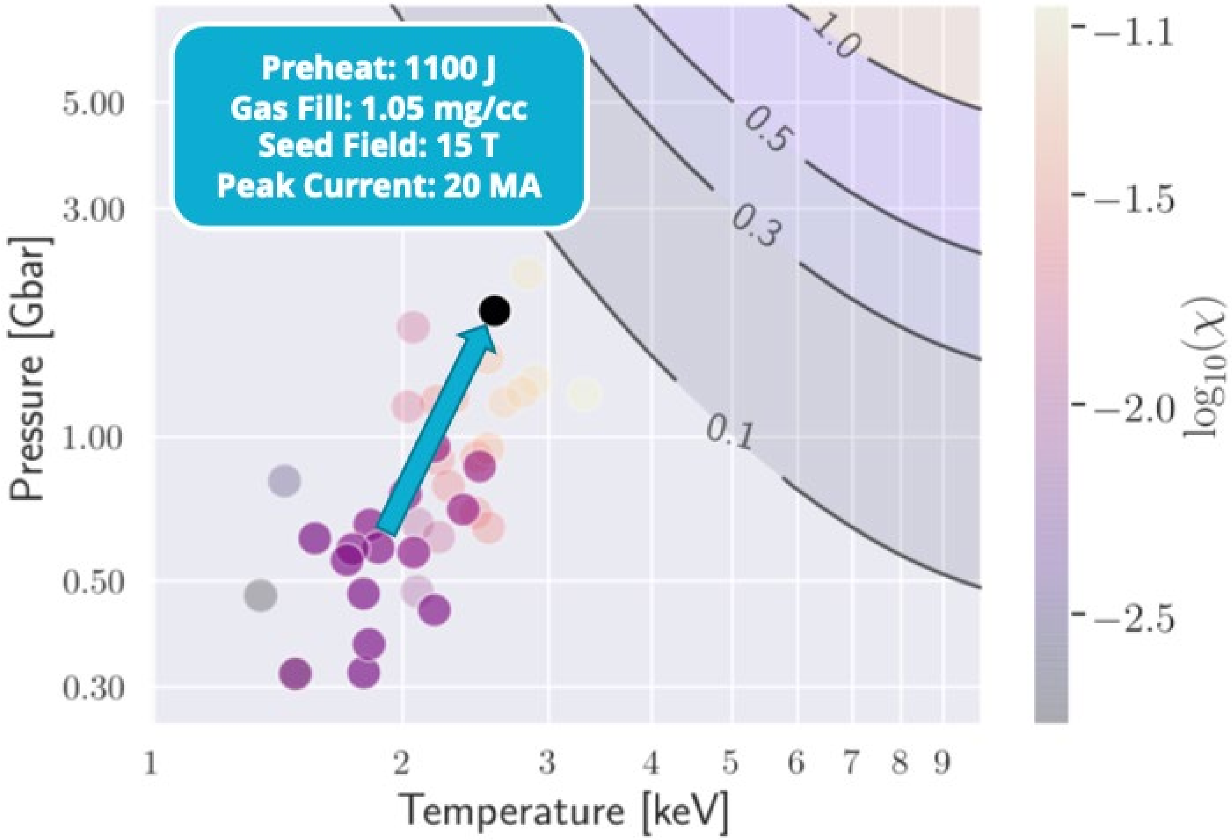
$$\chi = \frac{\varepsilon_\alpha}{24} P_{\mathrm{HS}} \tau_{\mathrm{E}} \frac{\langle \sigma v \rangle_{\mathrm{DT}}}{T^2}$$



- Original MagLIF experiments used an extended power-feed to accommodate coils for a uniform axial field
- This limited feed current delivery to ~16 MA
- Coupling ~1kJ with minimal conditioning led to mix and variability

M R Gomez, et al. PRL (2020)

Simultaneously increasing all input parameters provides the largest performance improvements



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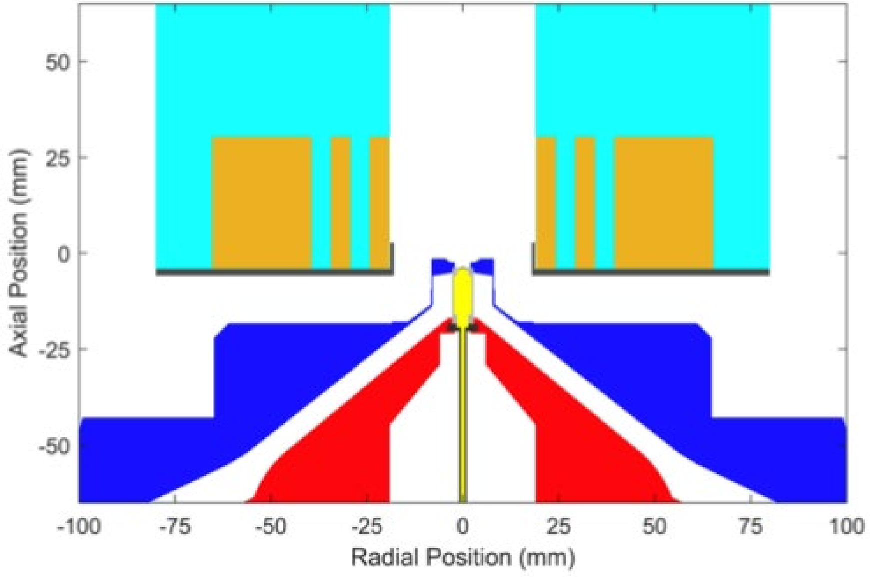
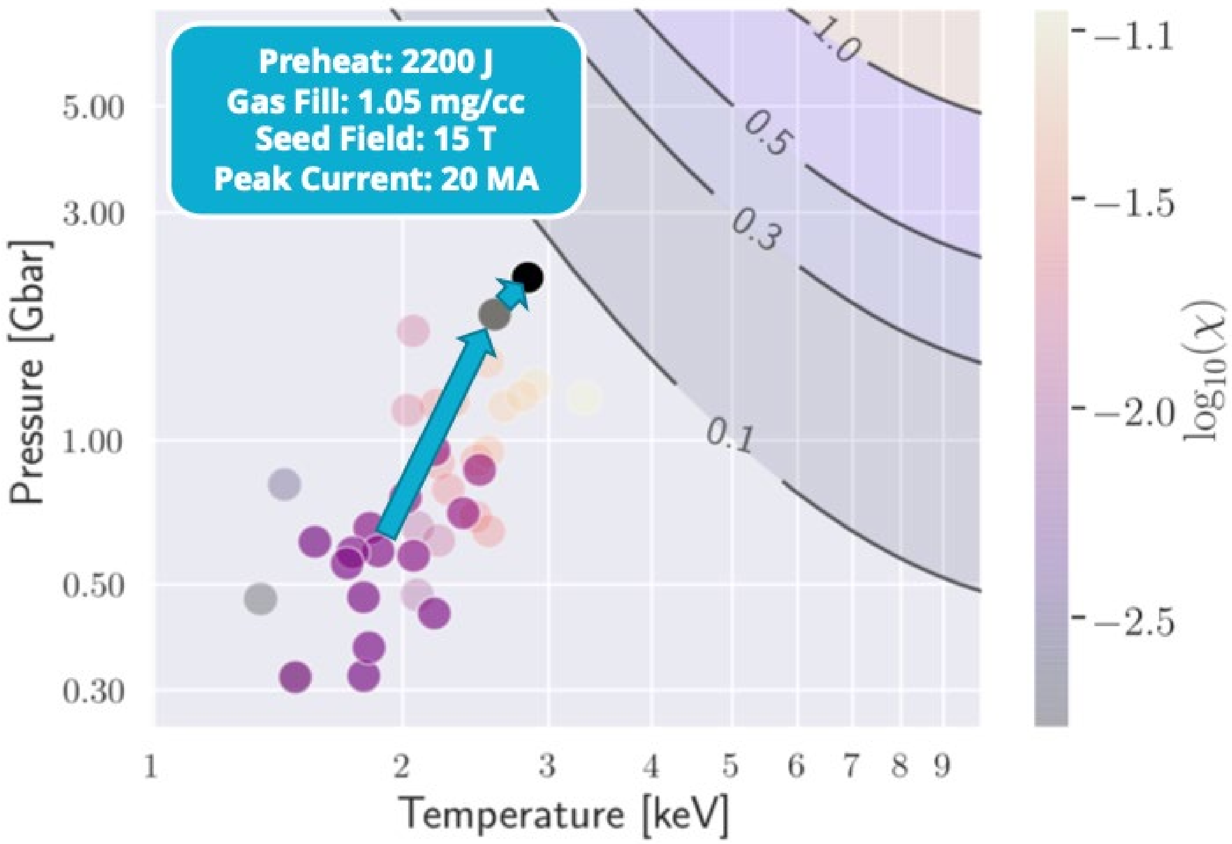


- The power feed and coils were modified to enable higher drive current delivery
- Single-coil design increase the magnetic field to ~15 T
- Improved laser heating protocols and higher fuel density increased coupling

M R Gomez, et al. PRL (2020)

Simultaneously increasing all input parameters provides the largest performance improvements



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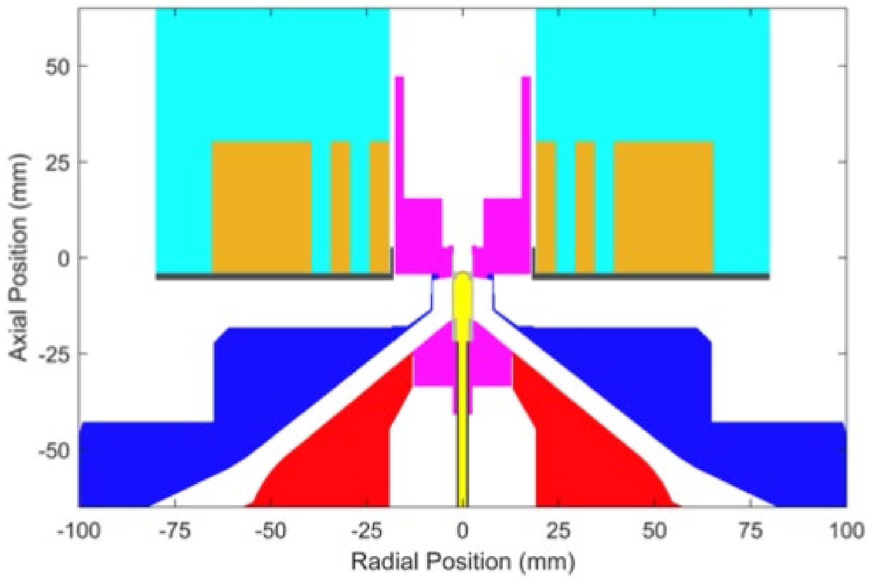
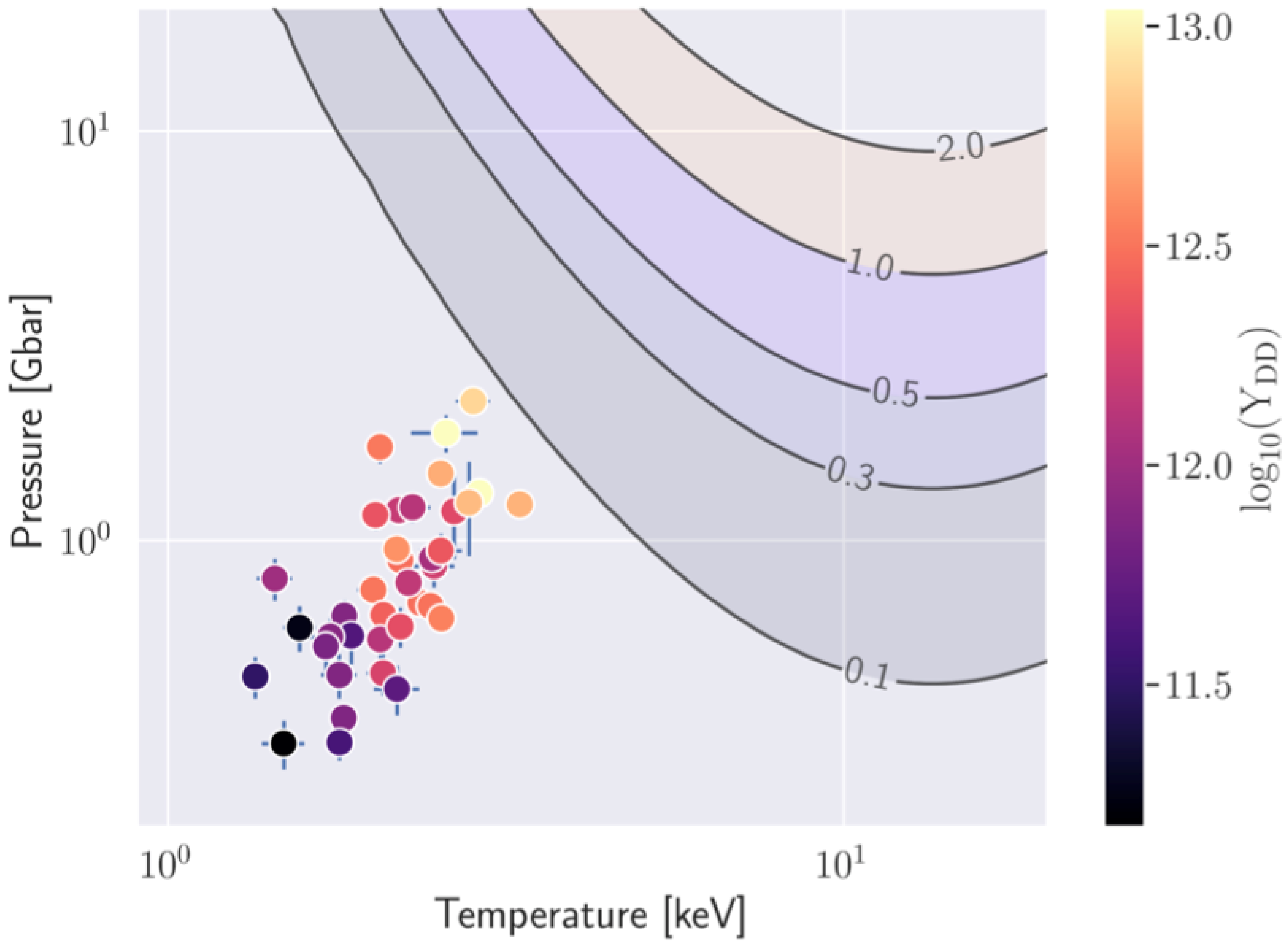


- Further improvements to laser heating were introduced
- Cryogenic cooling enabled thinner LEH windows – improved coupling, less mix
- This target produced the highest coupled preheat to date

M R Gomez, et al. PRL (2020)

Multiple existing data points show the ability to scale to self-heating at realizable drive current



Using analytic scaling theory, we can assess the performance of experimental data points at larger driver energy

We choose a scaling path that preserves implosion time, radiation losses, ion-conduction losses, and end-losses

$$P_{\text{no}-\alpha} \propto I_{\text{peak}}^{1.5}$$

$$T_{\text{no}-\alpha} \propto I_{\text{peak}}$$

$$Y_{\text{no}-\alpha} \propto I_{\text{peak}}^{6.2}$$

P.F. Schmit and D.E. Ruiz., Phys. Plasmas **27**, 062707 (2020)

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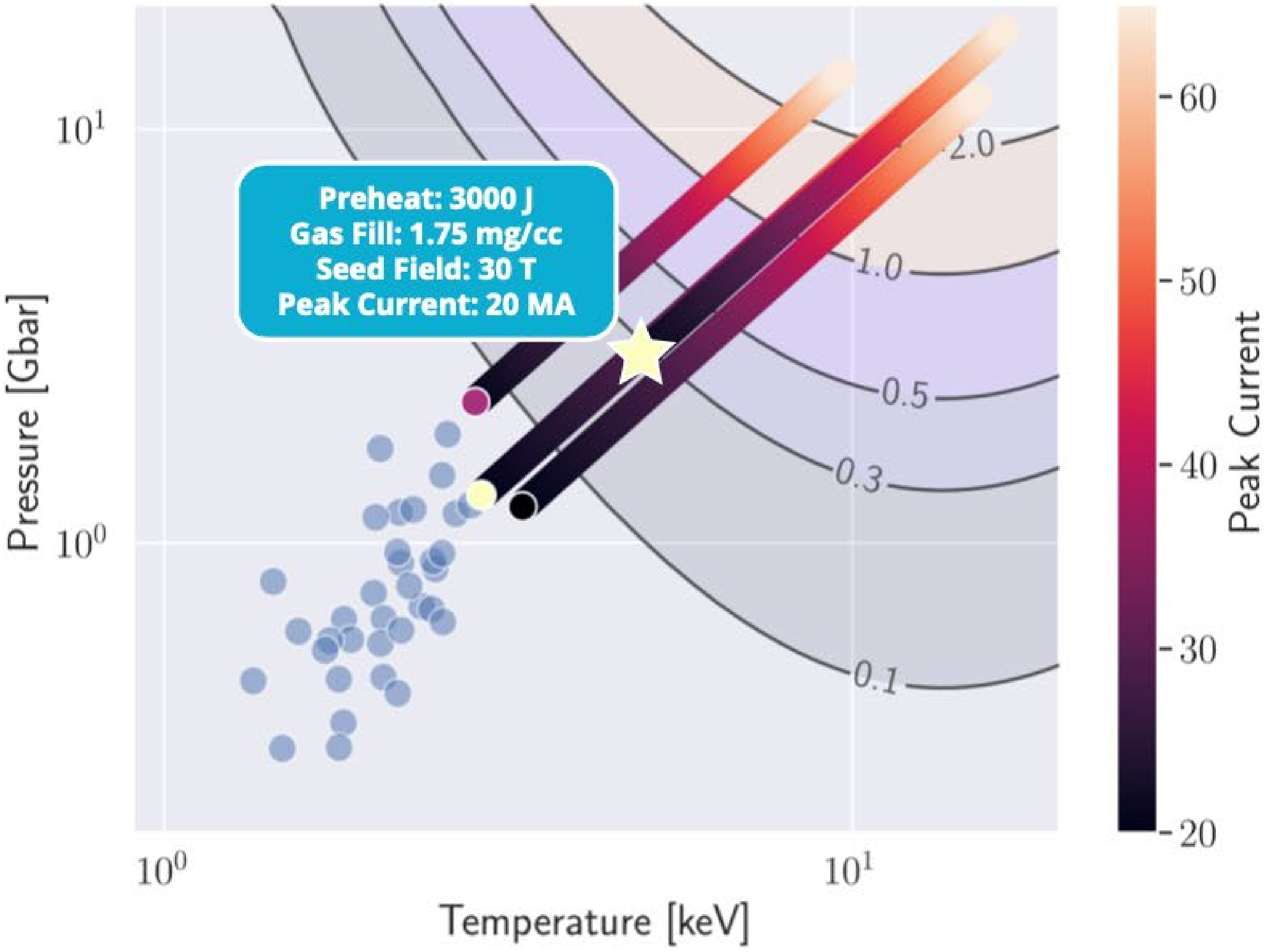


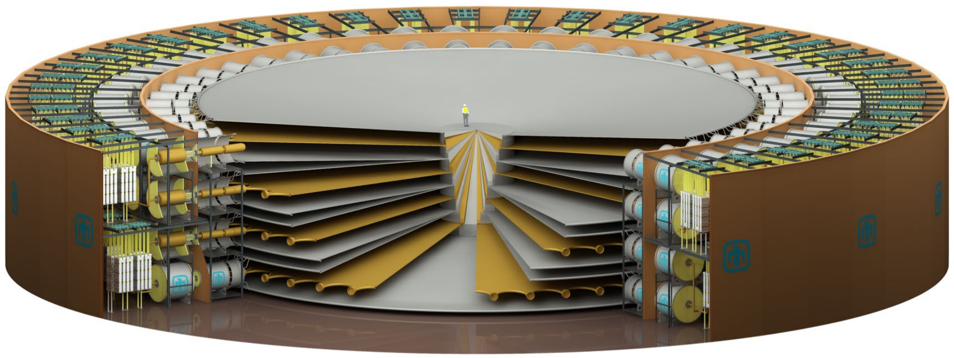
Shot	Y_{DD} [10^{13}]	$\chi_{no\text{-}\alpha}$=1	$Y_{no\text{-}\alpha}$=1 MJ	Y_{α} [MJ]
z3179	0.5	40 MA	49 MA	6-10
z3236	1.1	38 MA	44 MA	5-9
z3576	0.7	45 MA	62 MA	5-10
*Opt.	21	28 MA	41 MA	3-4.2

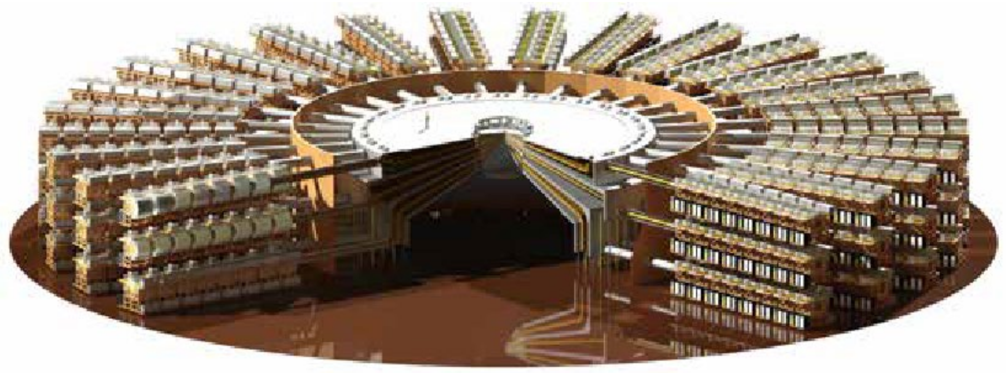
- Existing targets exceed 1 MJ no-α yield at currents > 44 MA
- Yield amplification due to α-heating is >5x
- An optimized target exceeds 1 MJ no-α yield at the lowest drive current
- At 60 MA this target produces >40 MJ

*S.A. Slutz, et al., Physics of Plasmas **23**, 022702 (2016)

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 research**
- **It would provide a venue for scientific and technical innovation for national security**





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

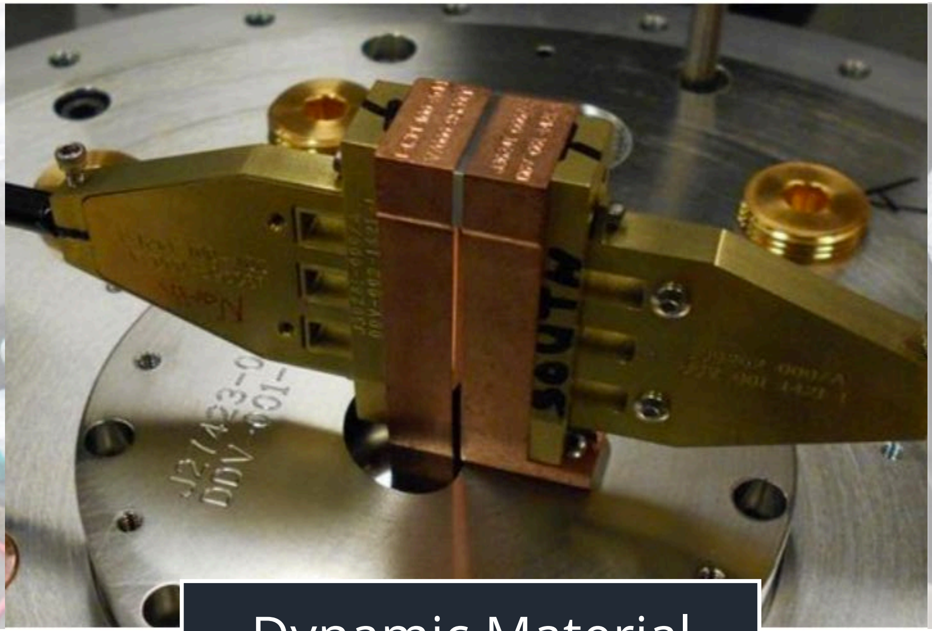
Z will celebrate ~35 years of z-pinch physics in 2030, with some parts of infrastructure ~45 years old.

Sandia is evaluating pulsed power architectures

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

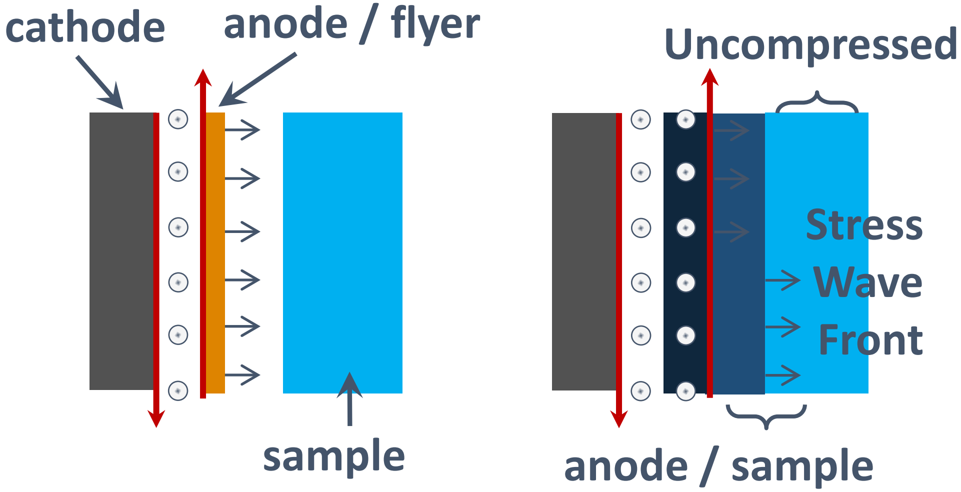
Precision tools for high energy density science

Inertial Confinement Fusion

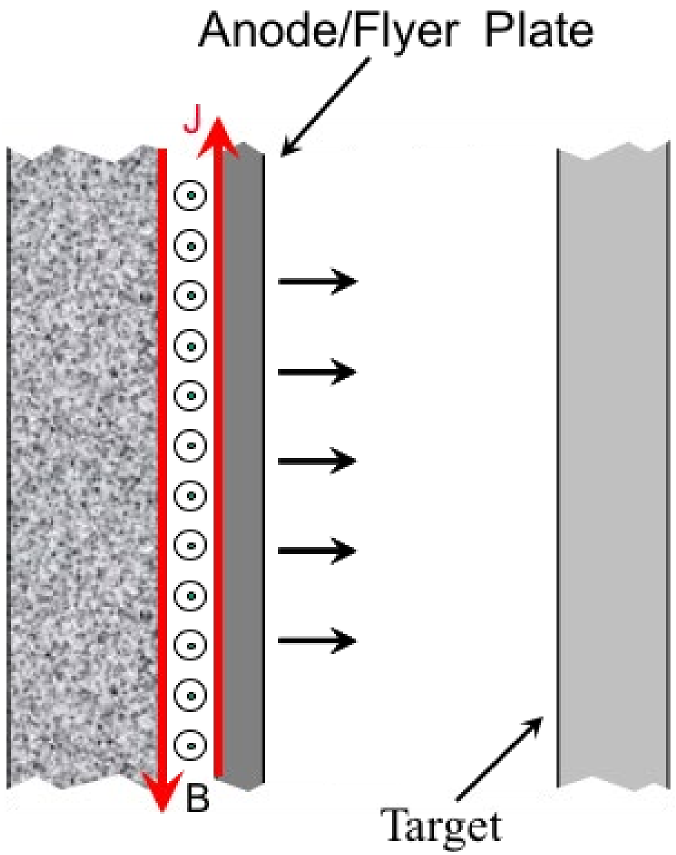


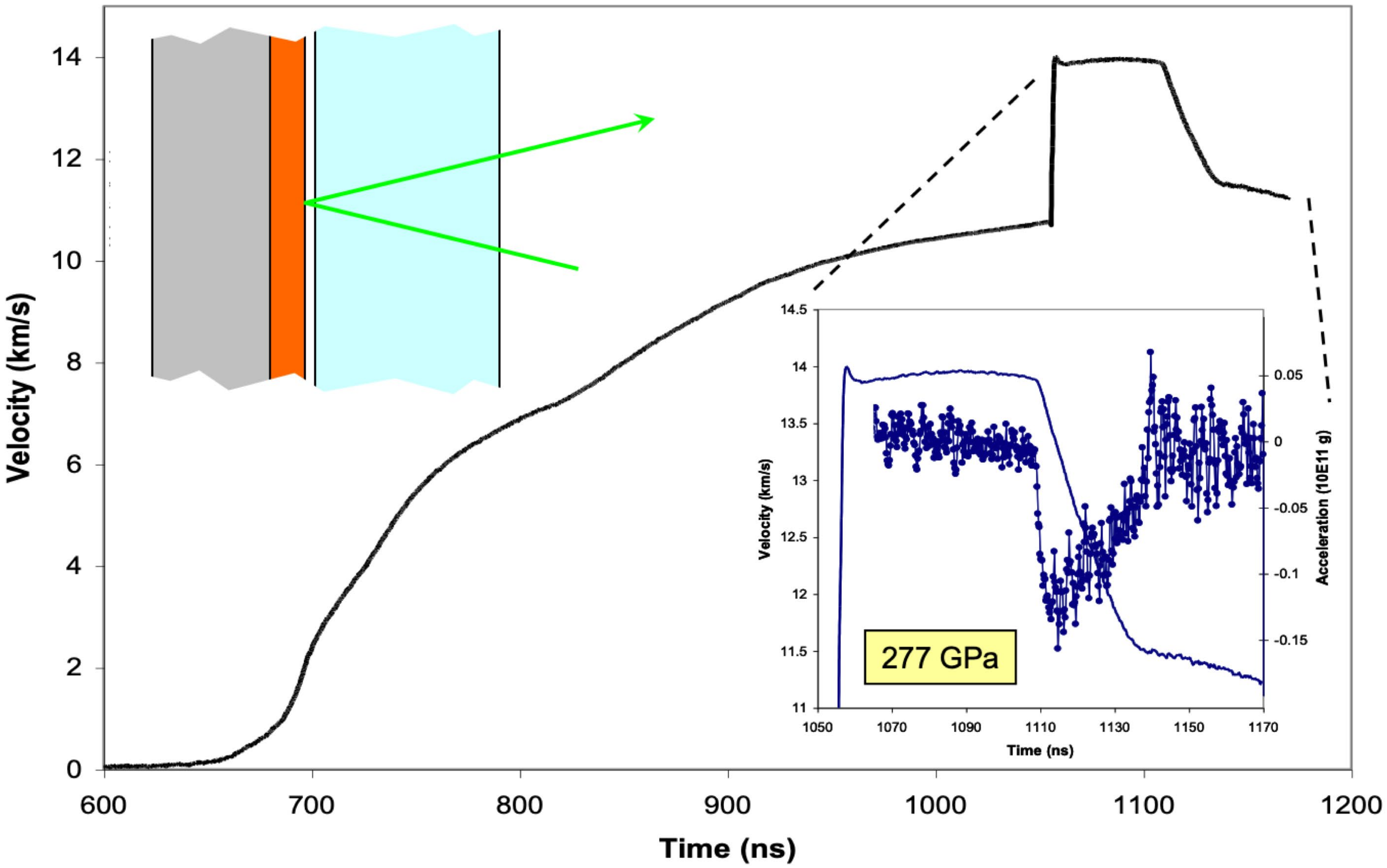
Dynamic Material Properties

Radiation Science



Z uses 26 MA current to create high velocity flyer plates enabling meaurements at multi-Mbar pressures

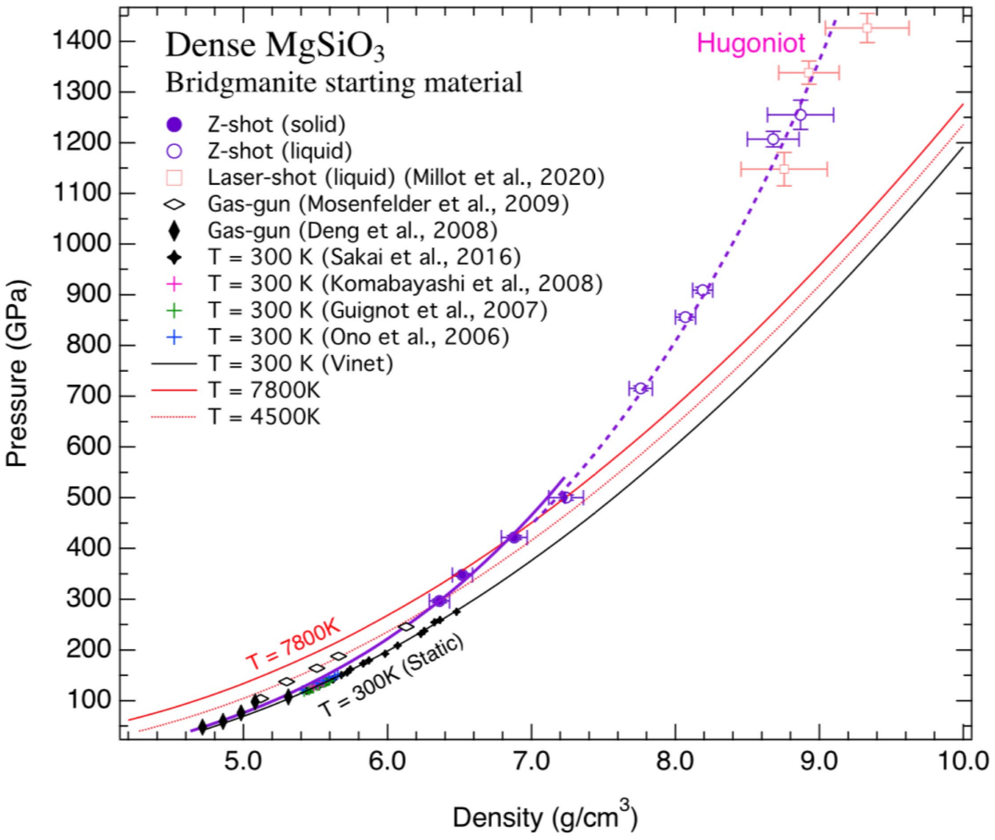


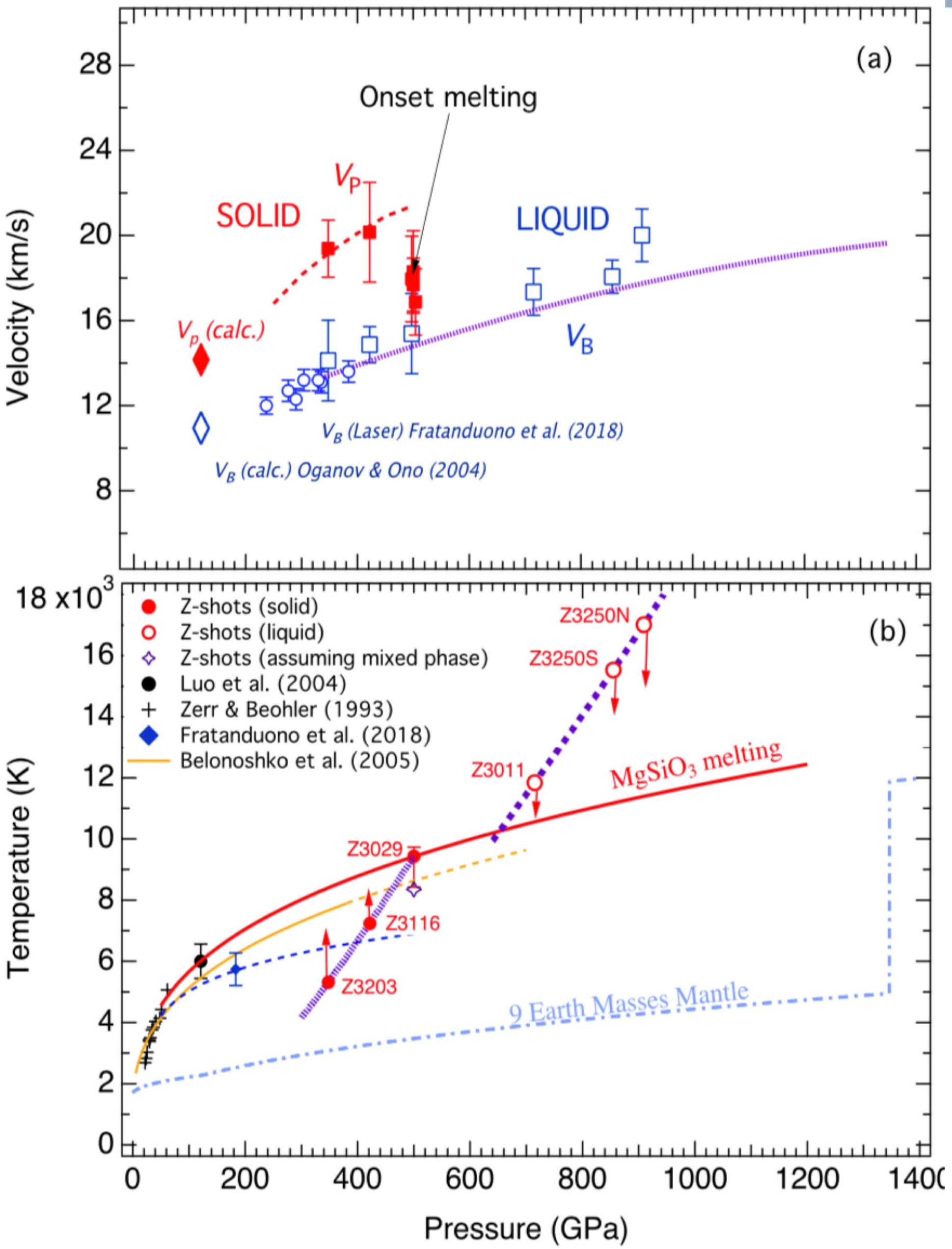


Hypervelocity flyer plate platform on the Sandia Z Machine

Aluminum/copper composite flyer plates provide well-defined complex loading that enables high-precision measurement of both the Hugoniot state and sound speed on the Hugoniot

Bridgmanite: dense high-pressure polymorph of $MgSiO_3$

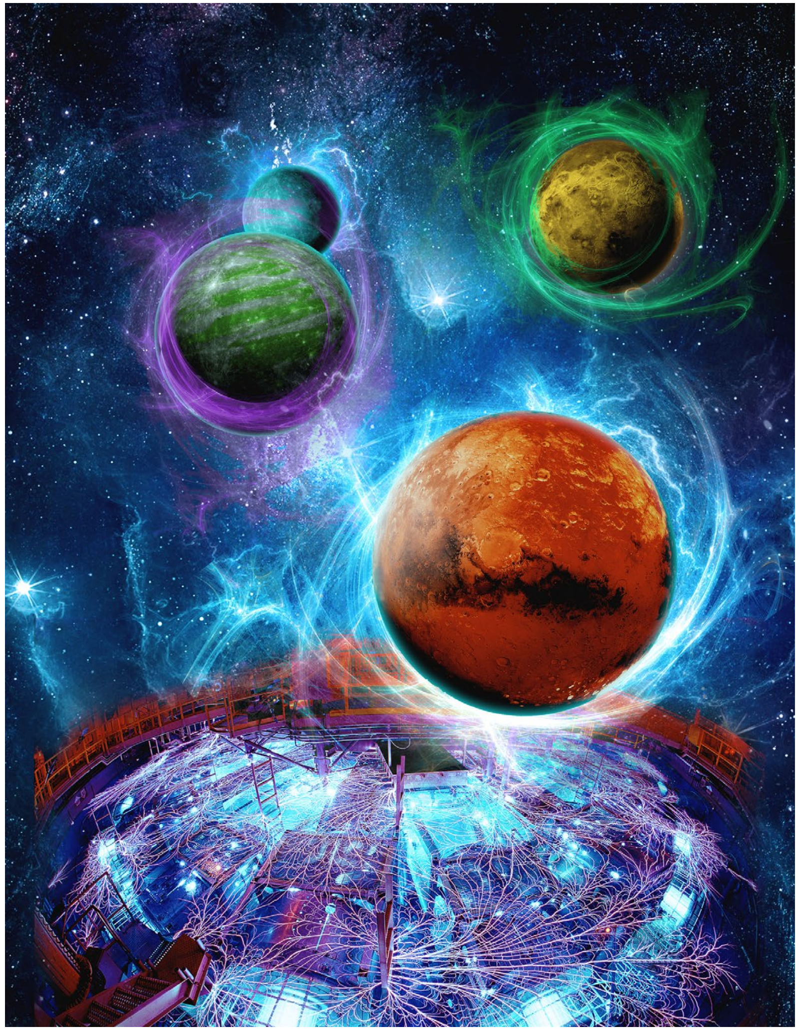


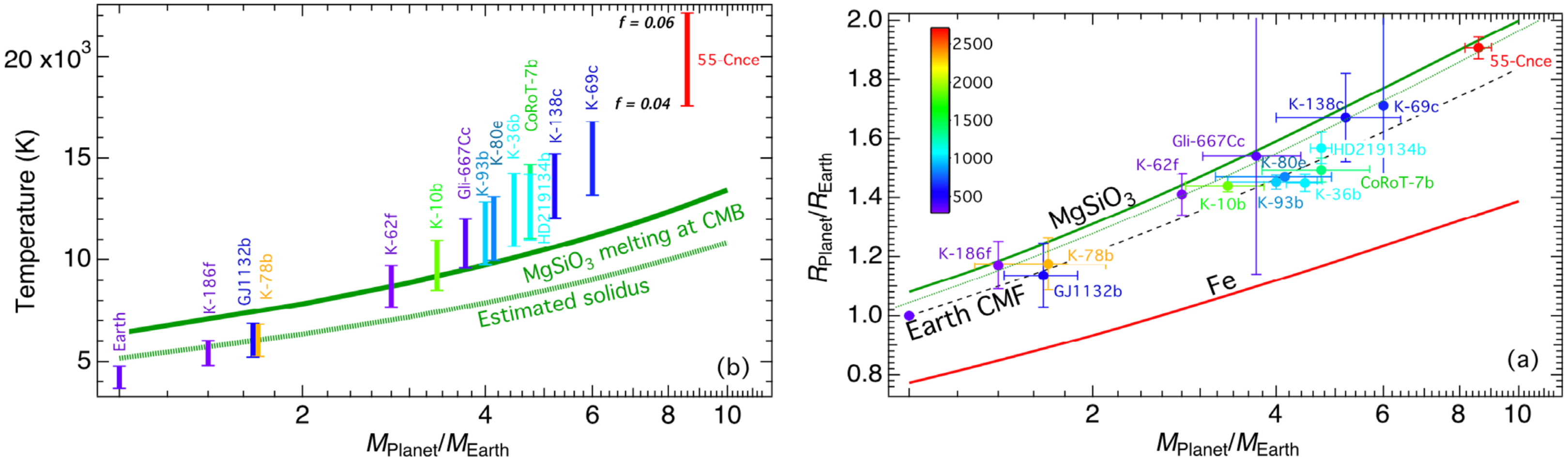


Shock and release measurements in Bridgmanite reveal an extraordinarily high melt temperature at high pressures

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

Implications for super-Earth mantles





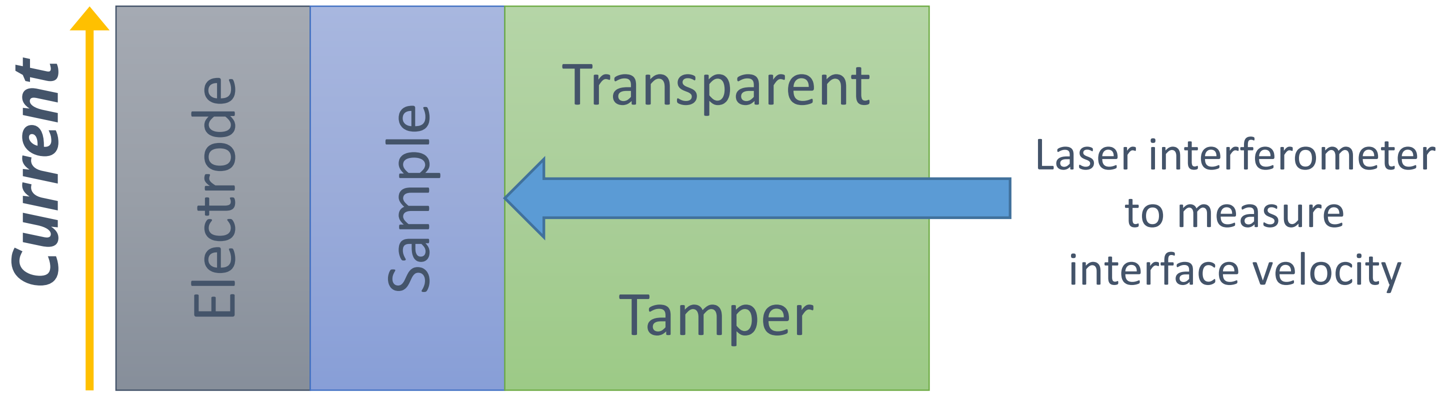
This work has identified a subset of seven super-Earths worthy of further analysis in that they may have similar ratios to Earth in their iron, silicates, and volatile gases in addition to interior temperatures conducive to maintaining magnetic fields

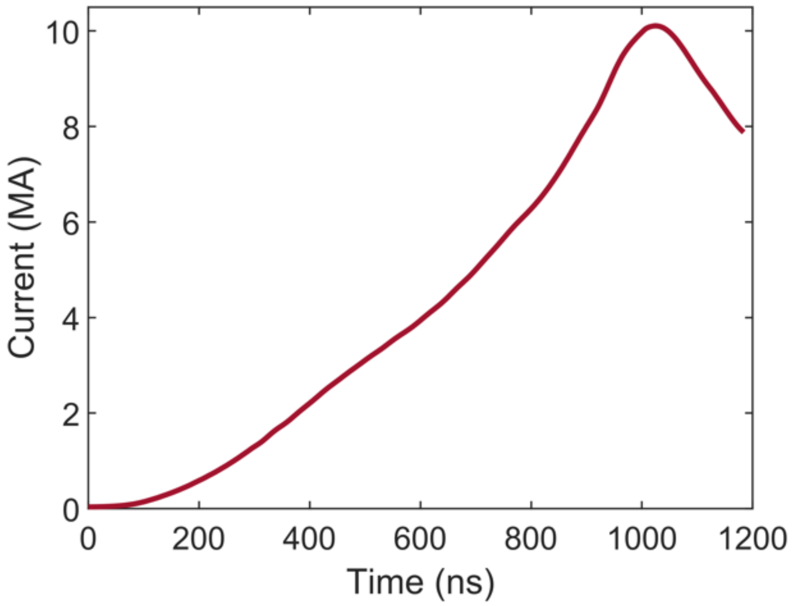
Fei *et al.*, Nature Communications 12, 876 (2021)

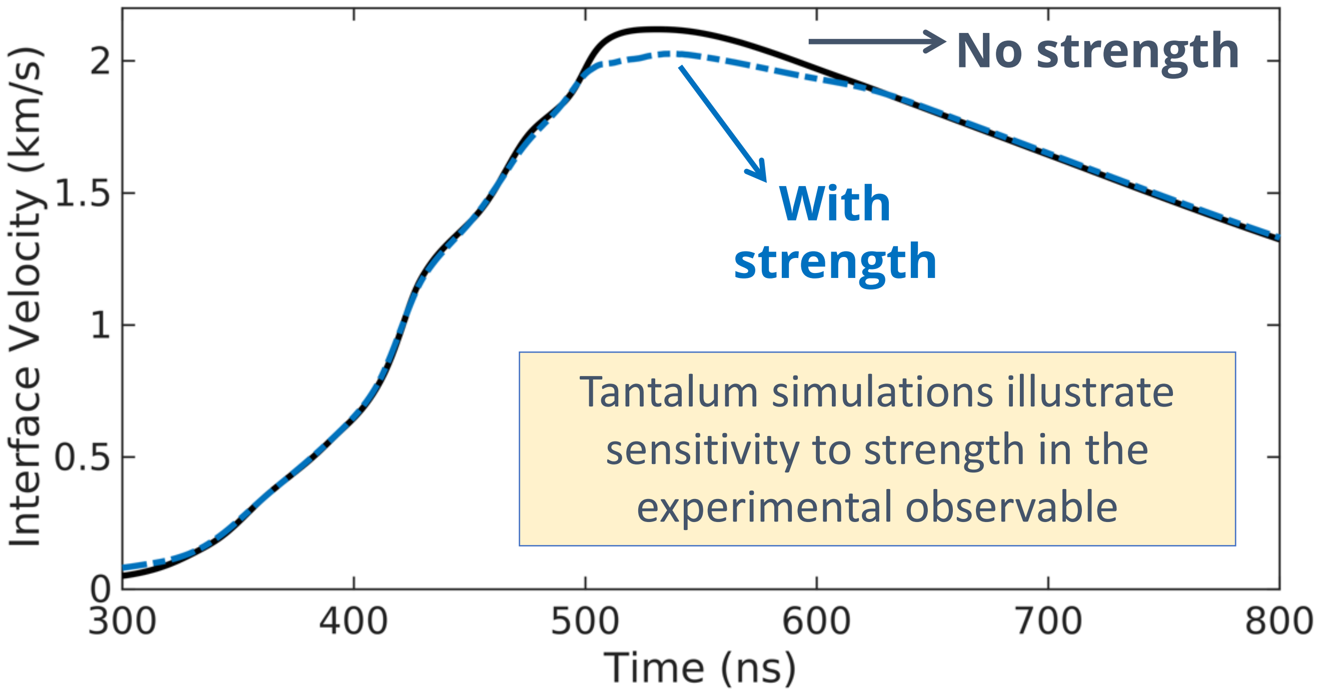
All three NNSA Laboratories are studying tantalum strength using different drivers and strain rates to understand how these affect the strength response

How does data from Z compare to gas gun or NIF data?
How much does the time scale or sample size affect the result?

Current pulse is shaped to result in ramp (shockless) loading of the sample



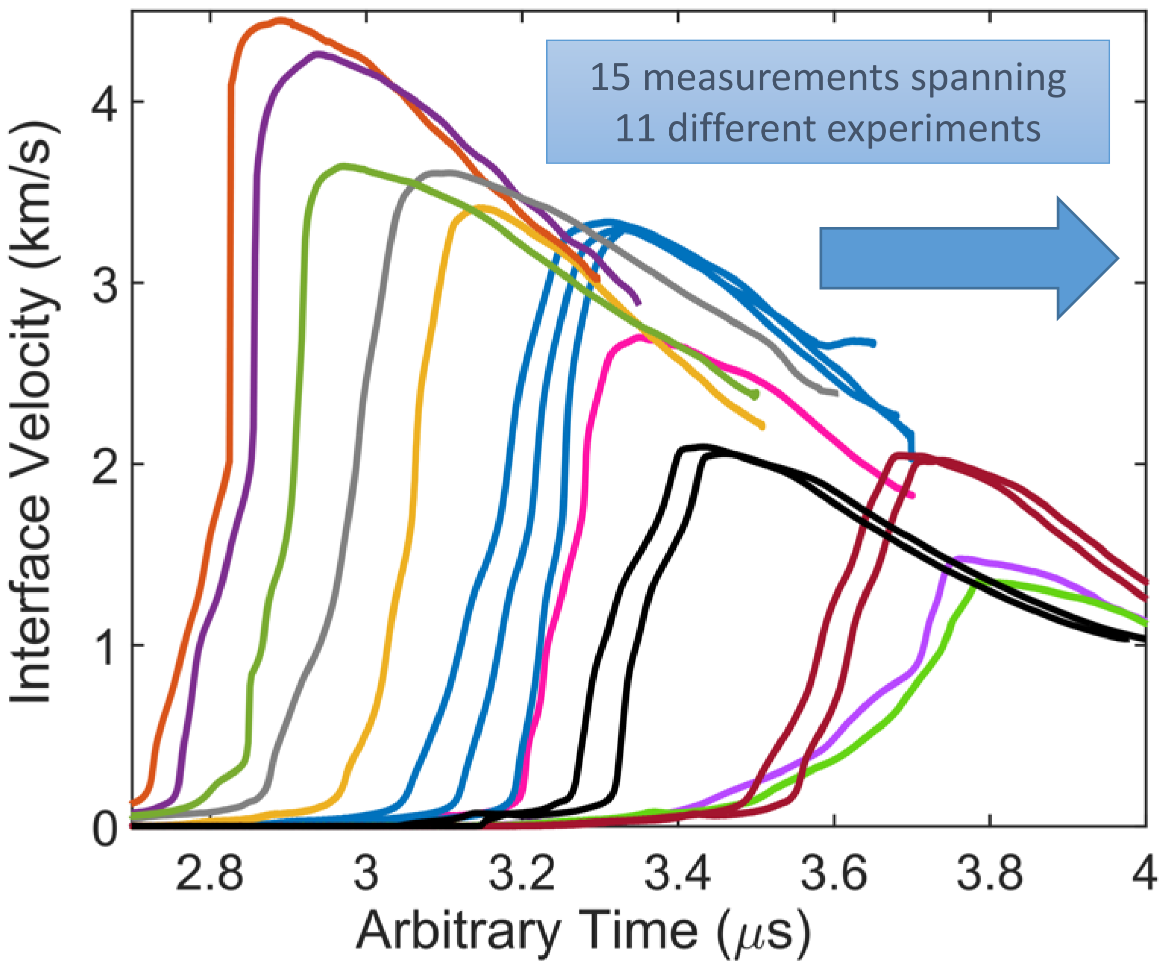


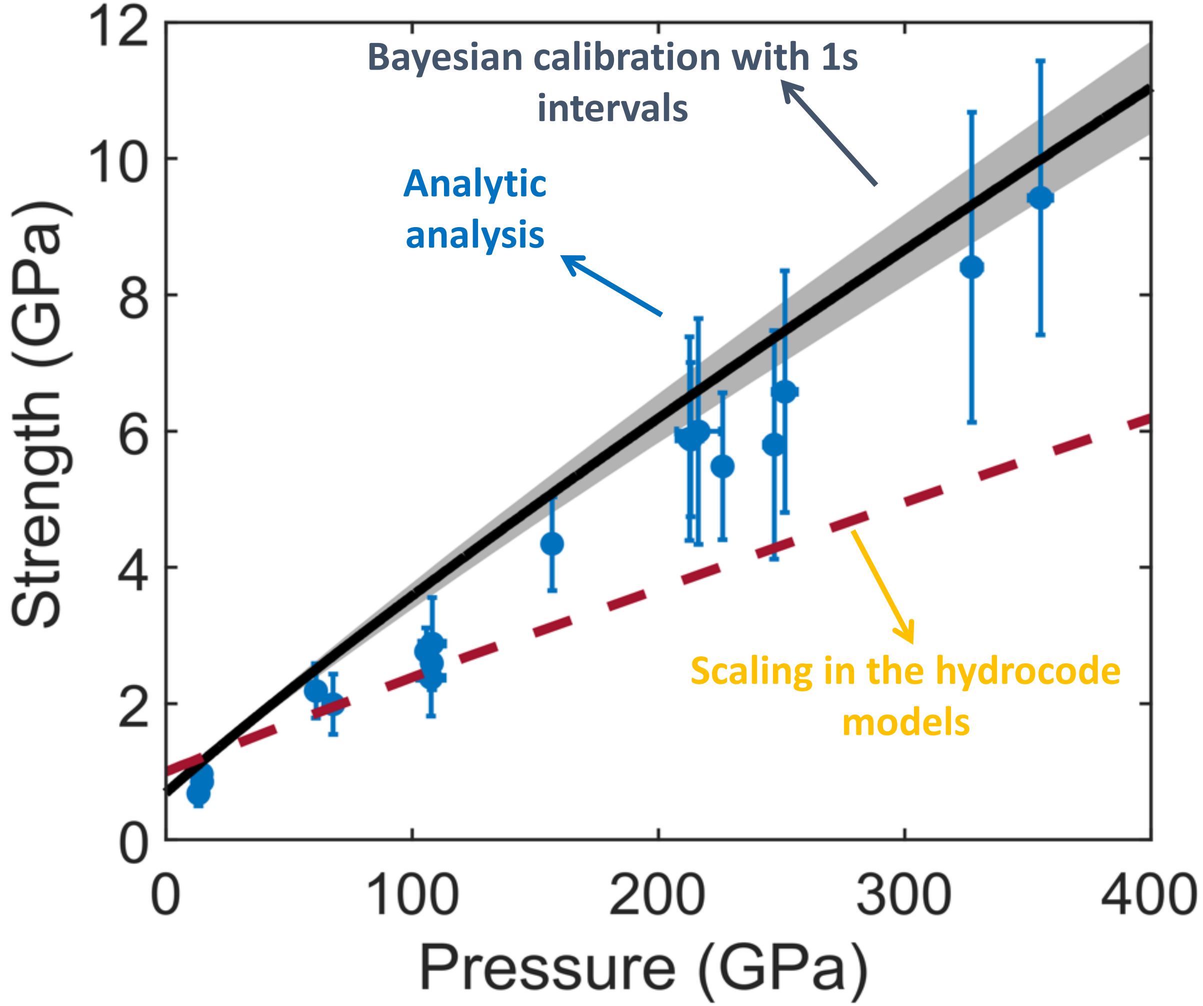


Tantalum simulations illustrate sensitivity to strength in the experimental observable

Partners: LANL, LLNL

Tantalum strength experiments on Z conducted to pressures of 3.5 Mbar (350 GPa) suggest typical pressure hardening in strength models is too low/soft

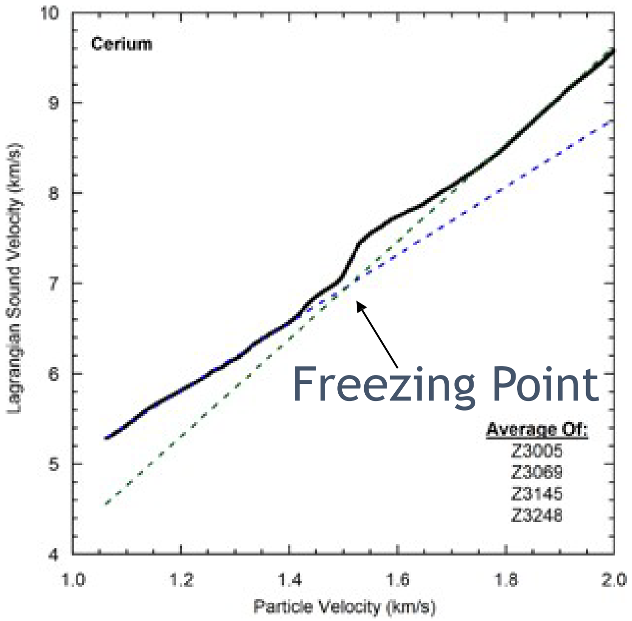




Partners: LANL, LLNL

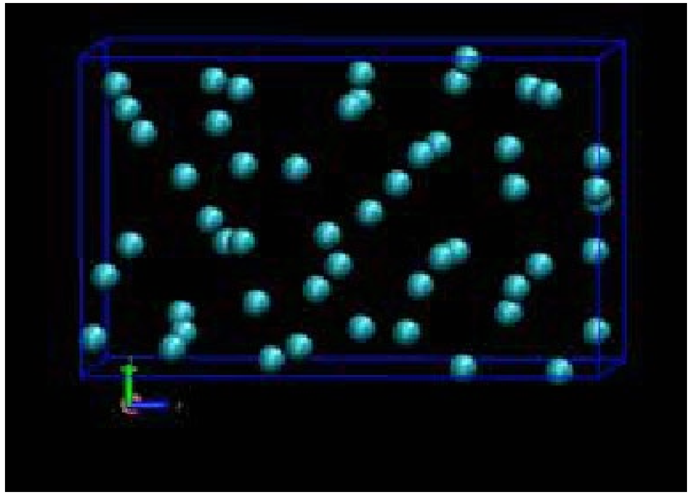
Sandia scientists recently observed dynamic freezing of liquid cerium on Z using a shock-ramp platform

Cerium was shock-melted at 20 GPa and isentropically compressed from this state on several Z experiments



An elastic wave velocity was observed indicating the liquid sample solidified and regained strength

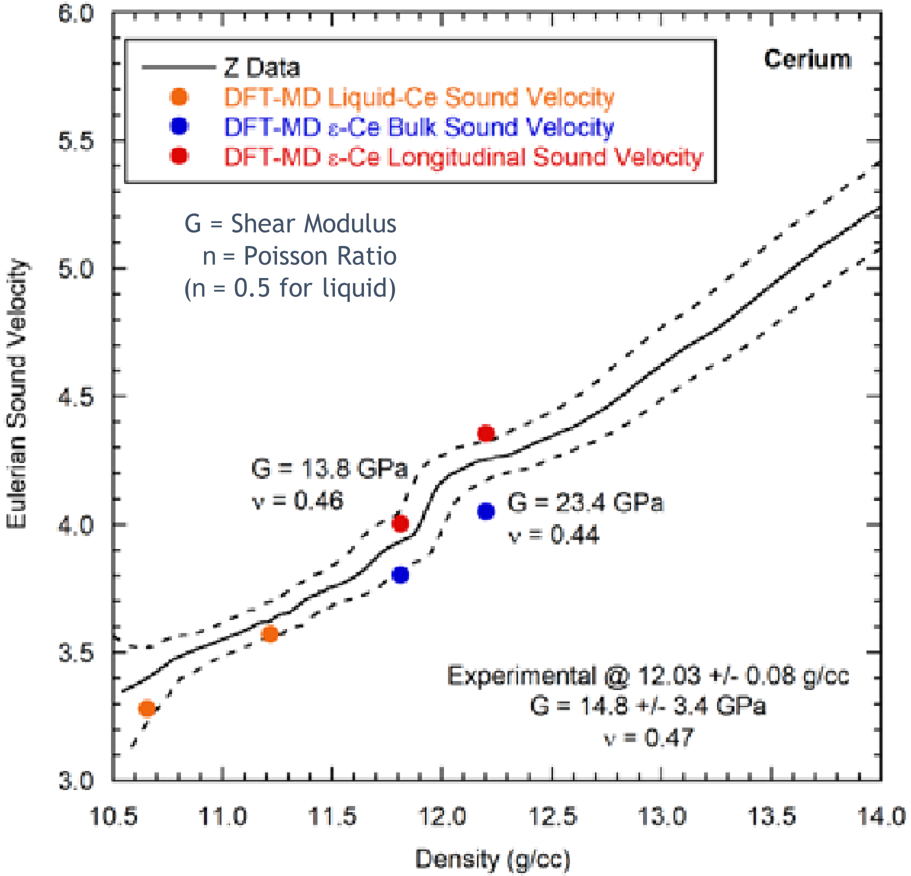
DFT Simulations show spontaneous freezing to the body-centered-tetragonal phase at almost exactly the same pressure (~35 GPa) as experimentally observed



Cerium dynamically freezes on nanosecond timescales during ramp compression at nearly the equilibrium freezing point

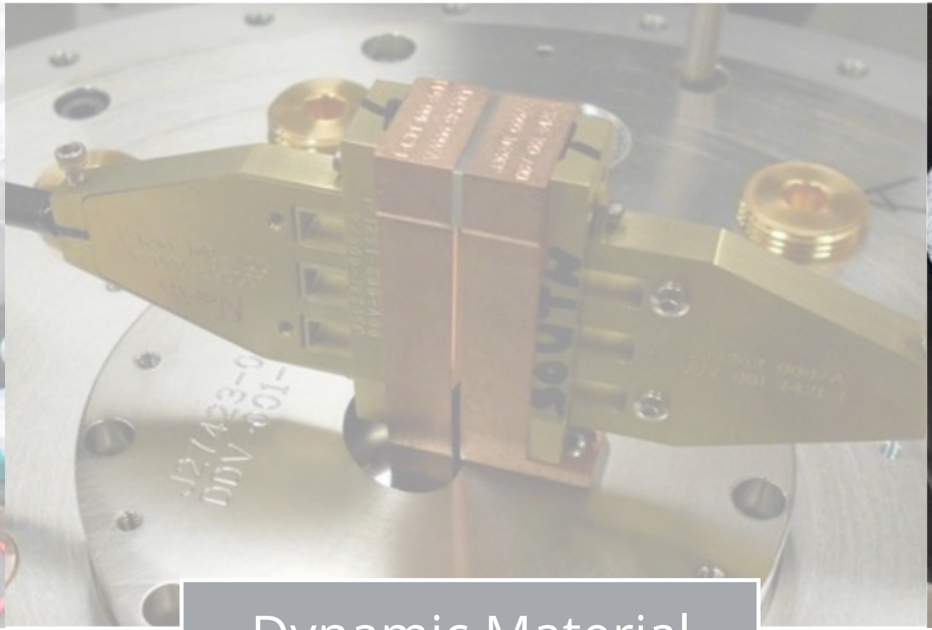
Seagle *et al.*, PRB 102, 054102 (2020)

DFT Simulations were performed to calculate the stress, density, as well as bulk and longitudinal sound velocities for comparison to experiments. Simulation and experiment are in excellent agreement

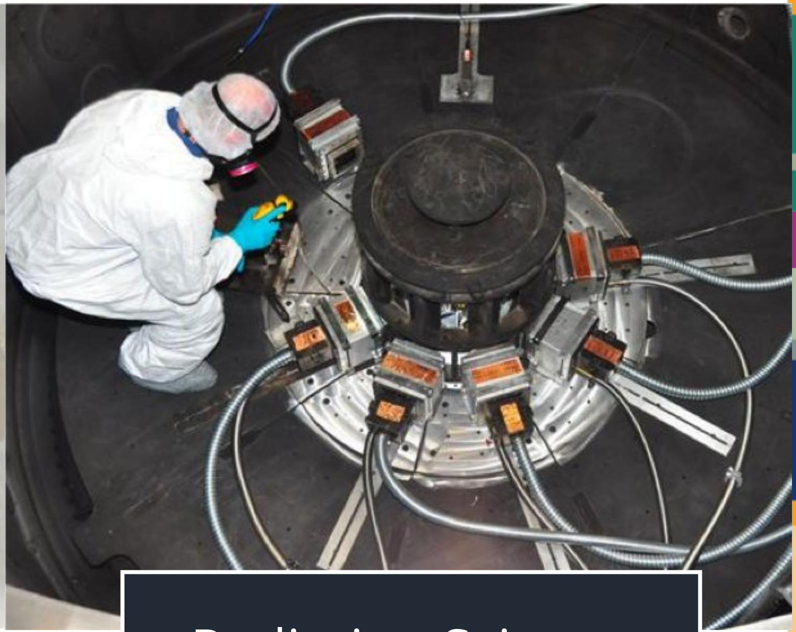


Precision tools for high energy density science

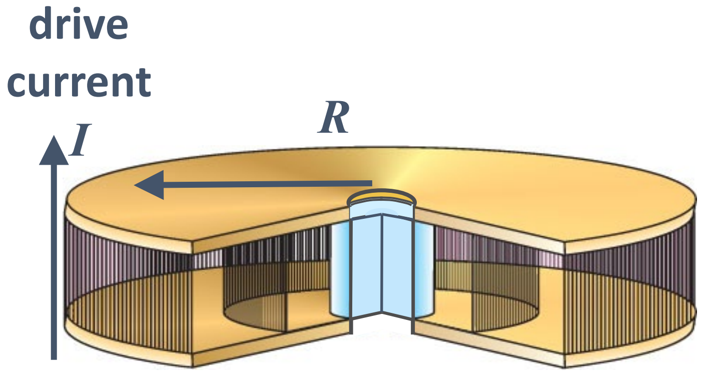
Inertial Confinement Fusion



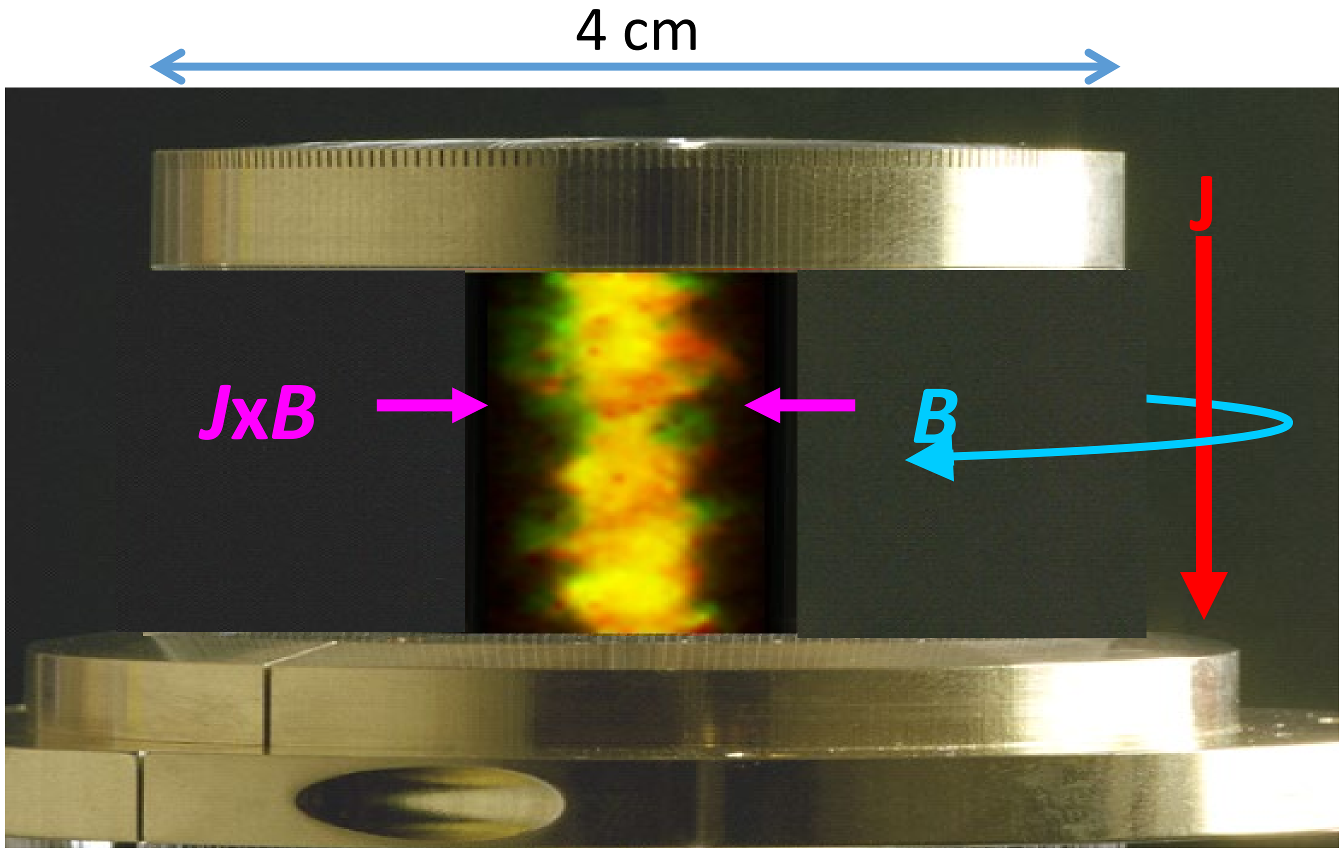
Dynamic Material Properties



Radiation Science



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

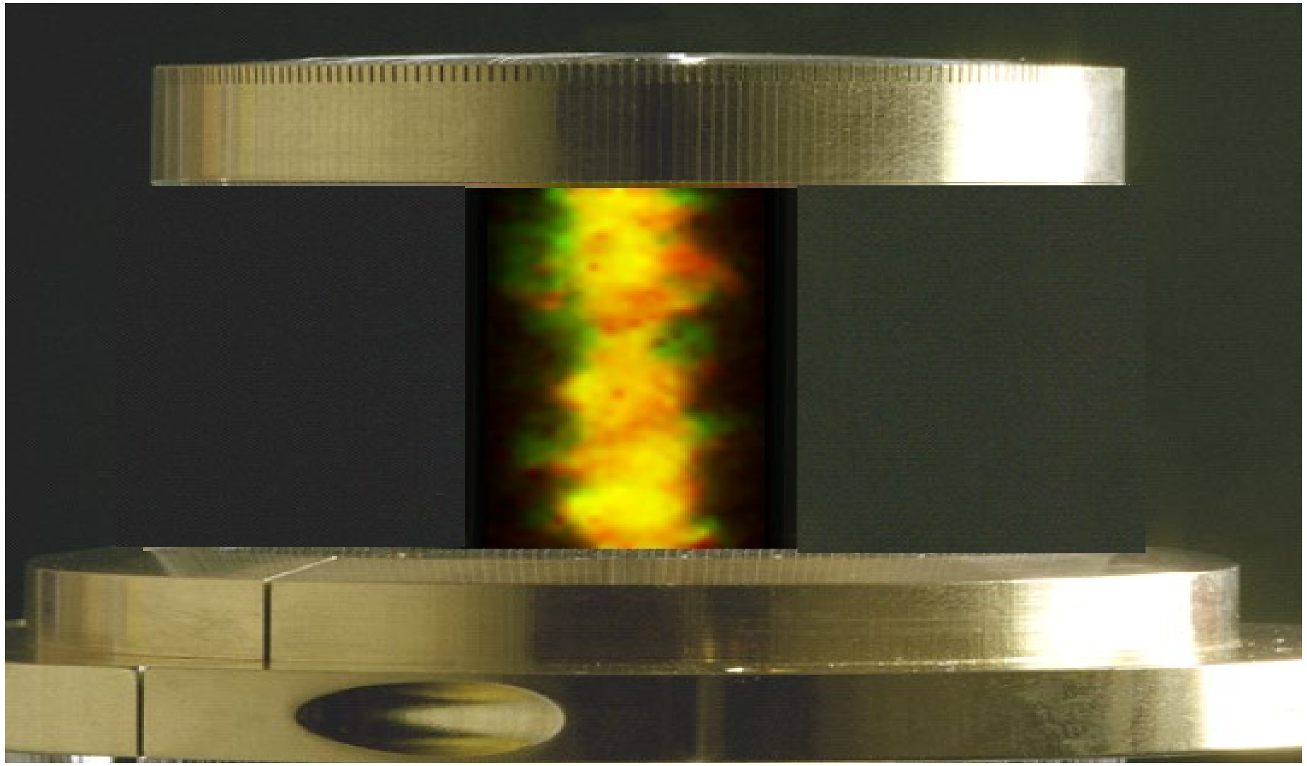


	ZR > 2011	Z < 2007
Marx Energy	20.3 MJ	11.4 MJ
Ipeak	25.8 MA (1.5%)	21.7 MA* (2.1%)
Peak Power	220 TW (10%)	120 TW (14%)
Radiated Energy	1.6 MJ (7%)	0.82 MJ (17%)

* Wagoner *et al.*, PRSTAB 11 (2008)

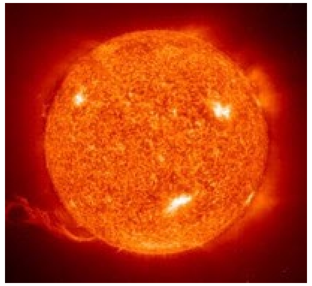
Sanford *et al.*, *PoP* (2002); Bailey *et al.*, *PoP* (2006); Slutz *et al.*, *PoP* (2006); Rochau *et al.*, *PPCF* (2007); Rochau *et al.*, PoP (2014).

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



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}

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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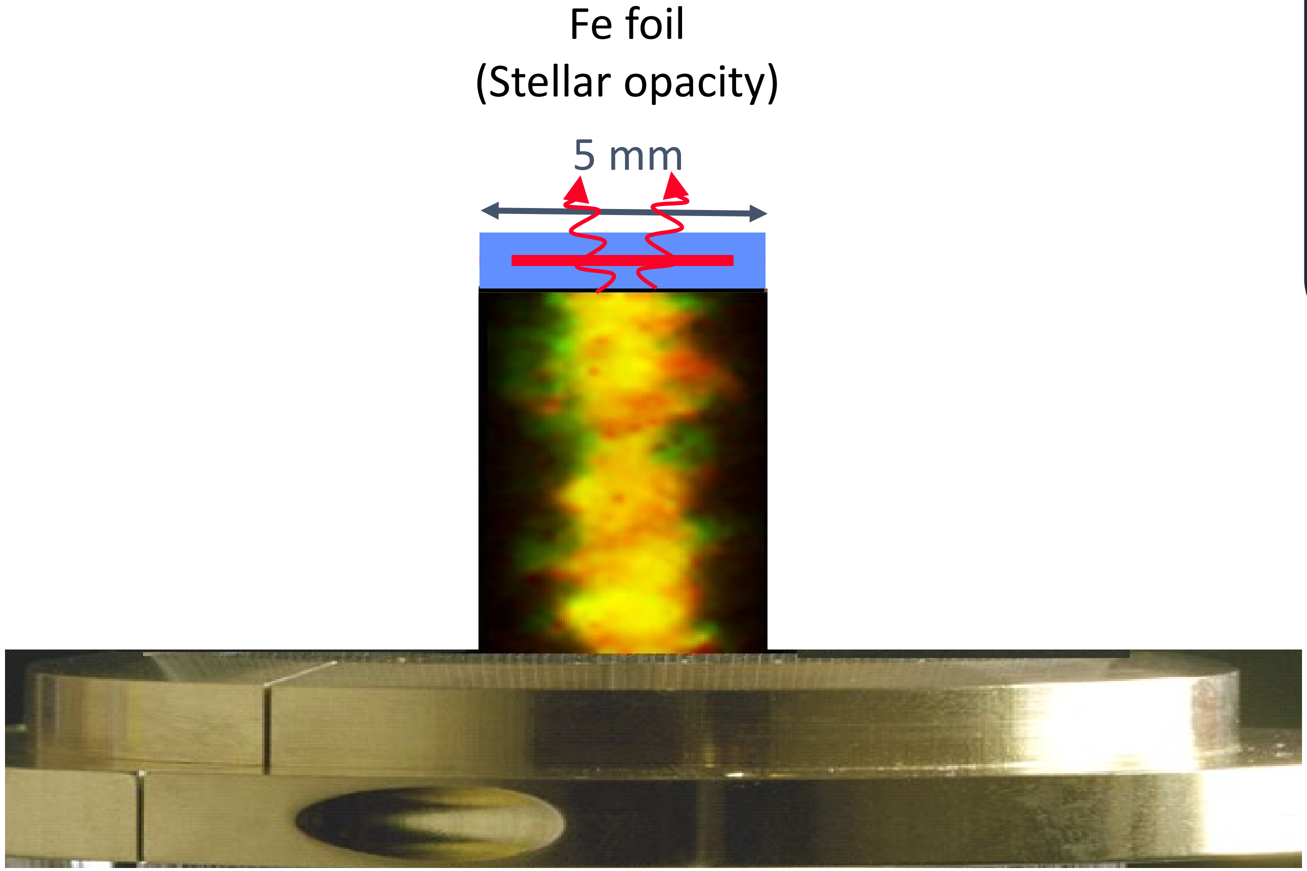

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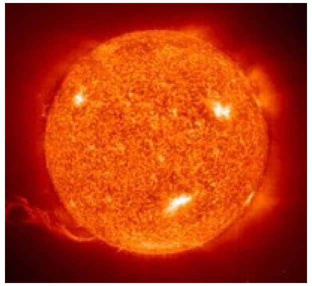
Stellar opacity

2016 Dawson Award



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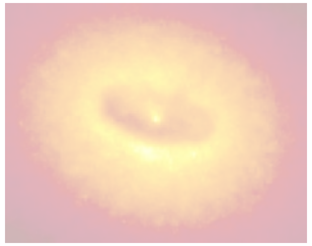

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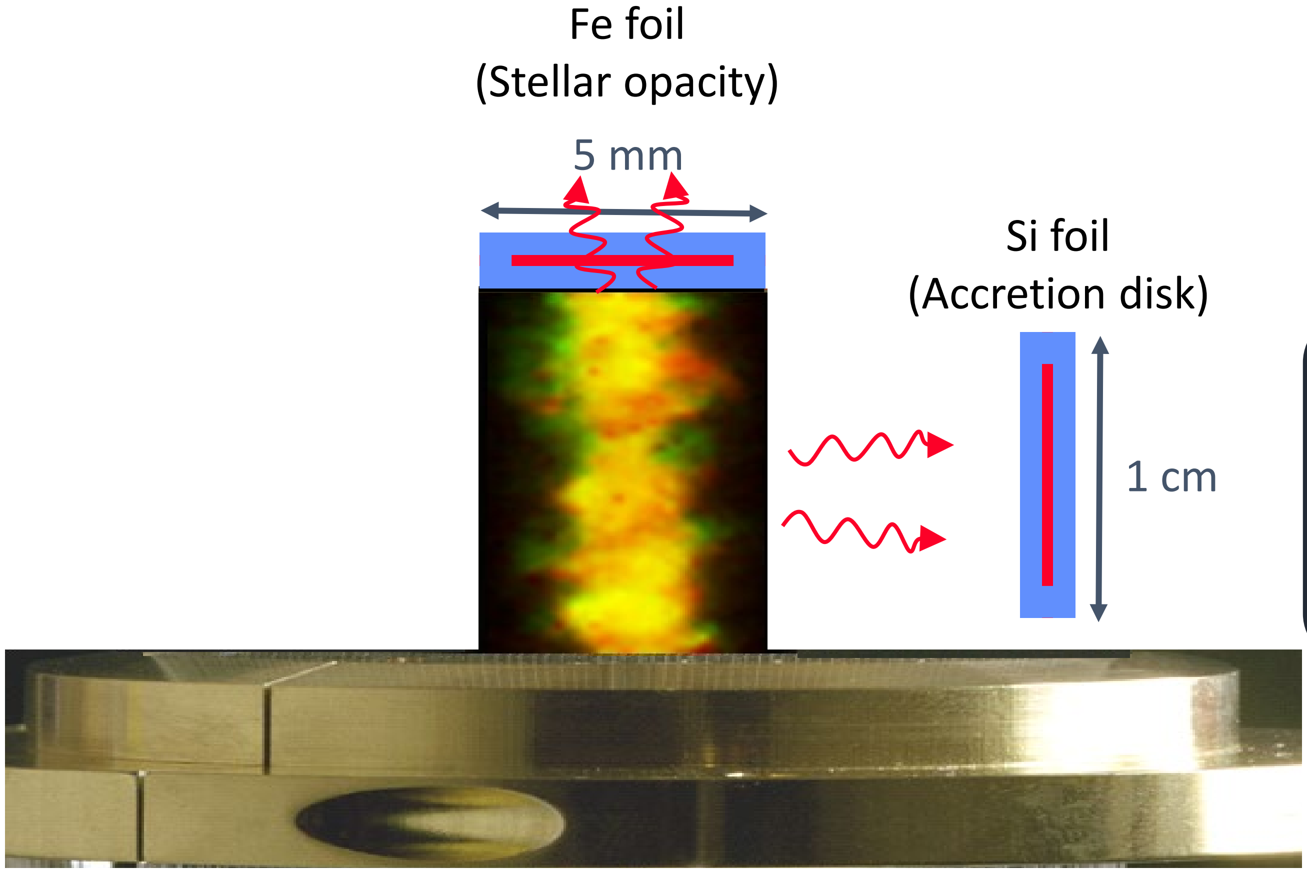

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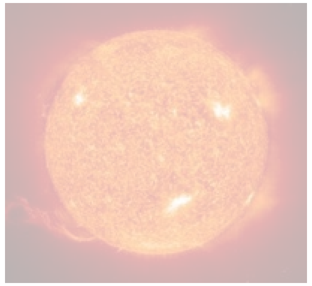
Stellar opacity



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

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

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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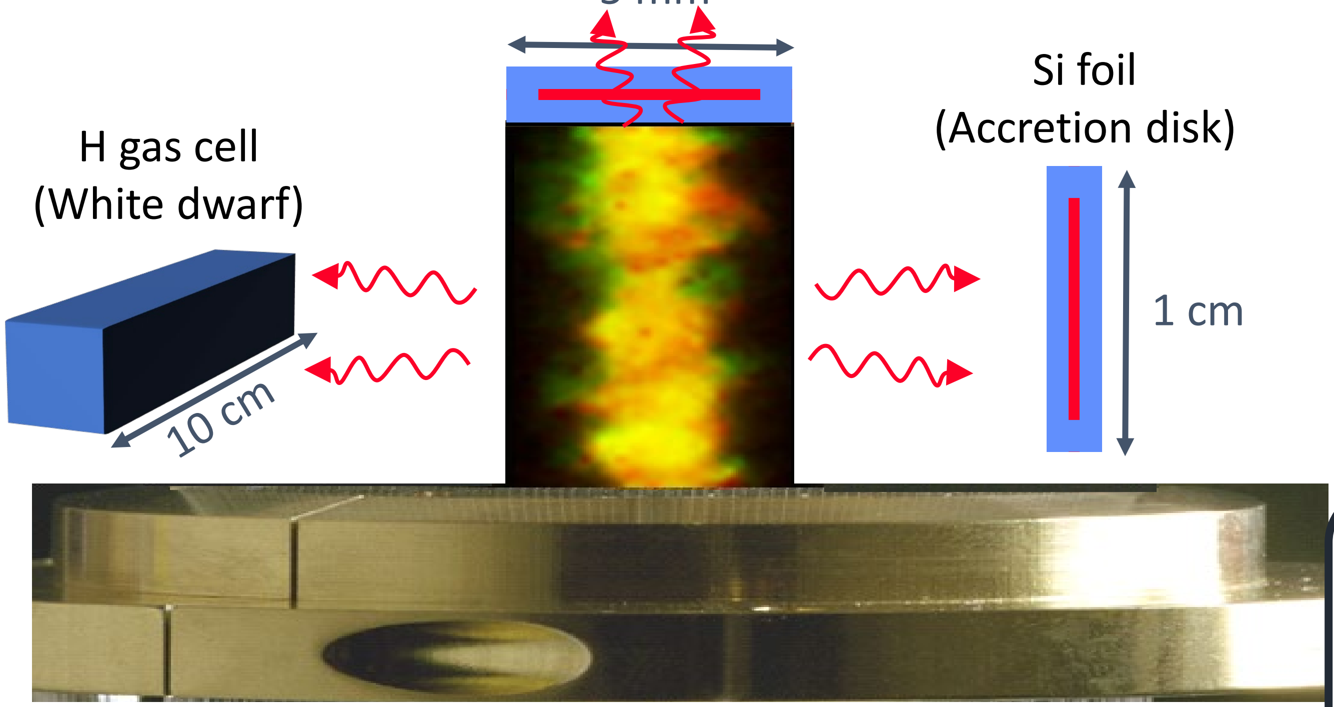

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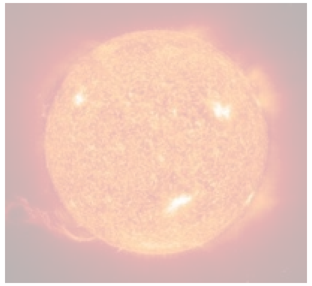

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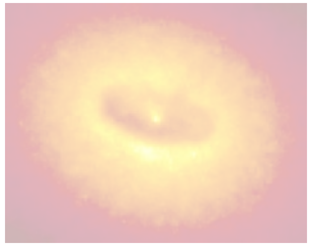

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M-A. Schaeuble PO9.00012

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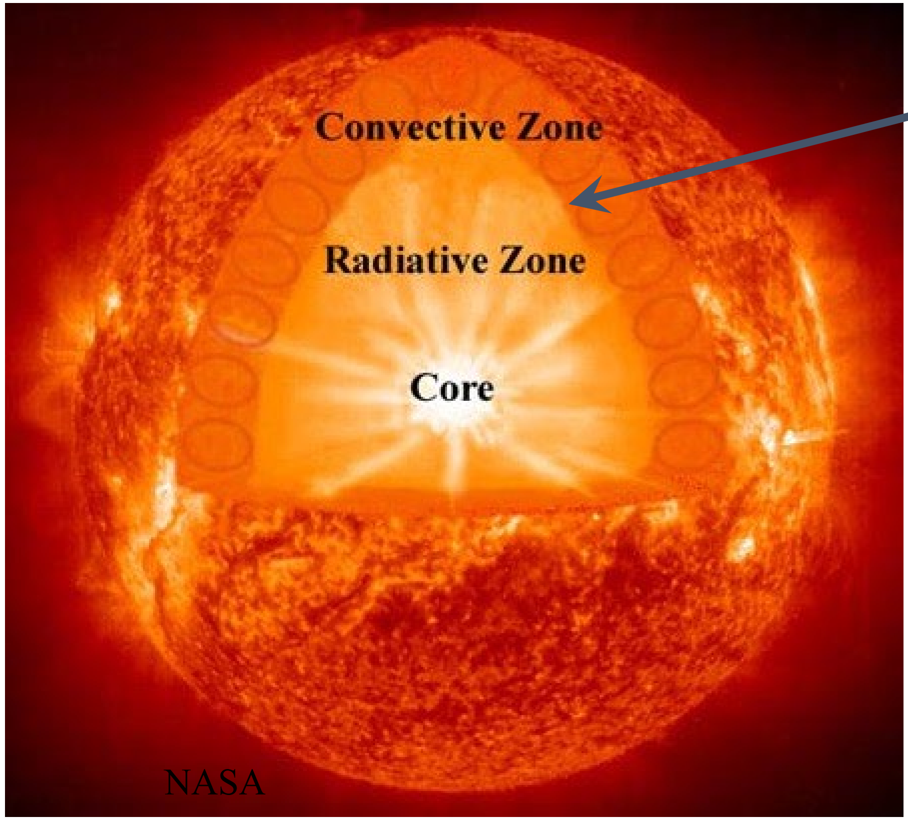
Is opacity-model uncertainty responsible for disagreements between solar interior structure models and helioseismology data?



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

Models depend on:

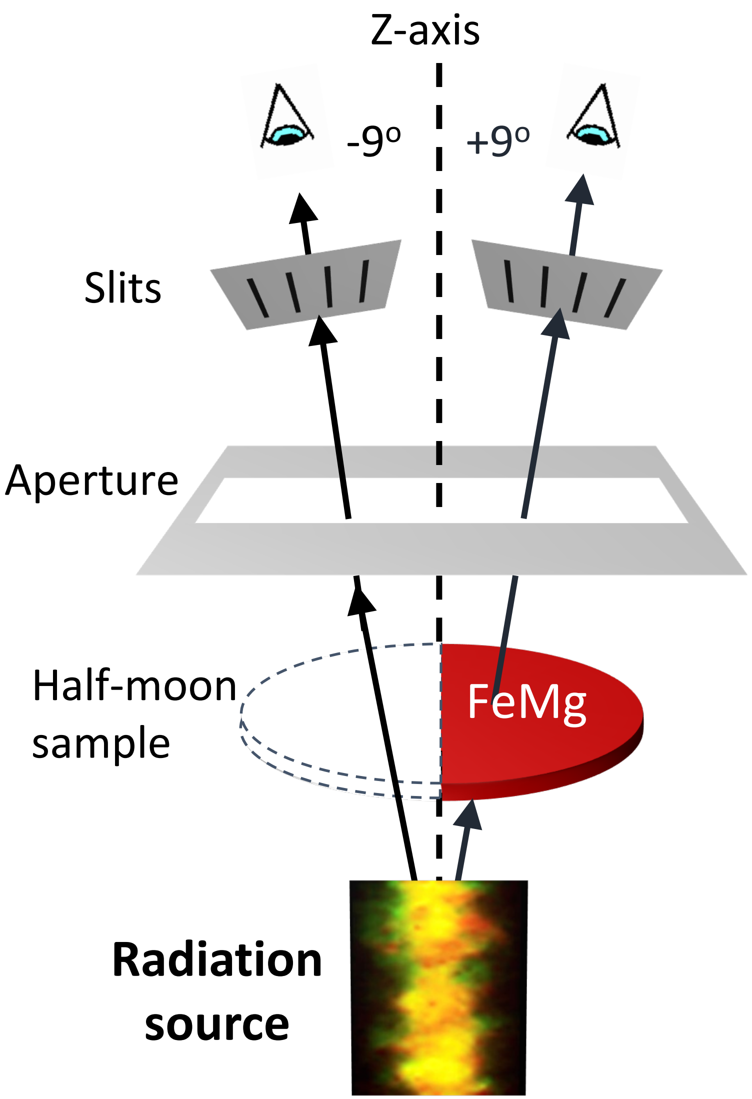
- **Composition (revised in 2005*)**
- **EOS as a function of radius**
- **The solar matter *opacity***
- **Nuclear cross sections**

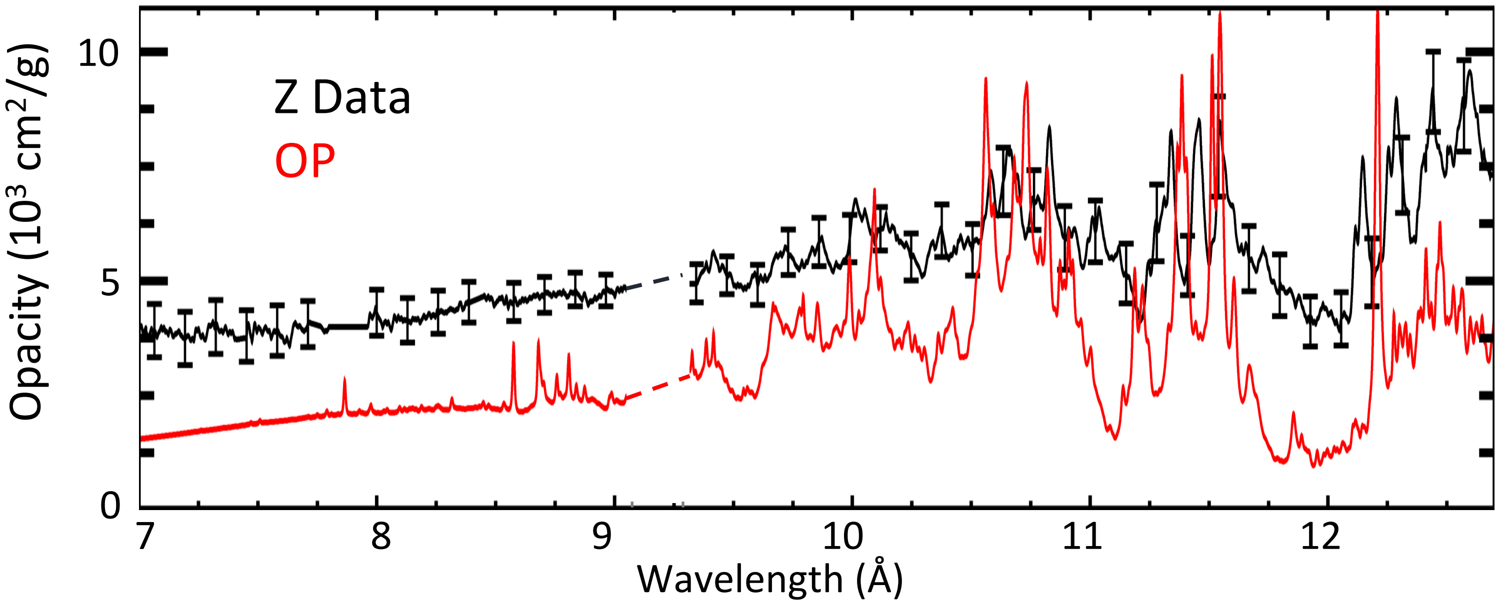
Question: Is opacity uncertainty the cause of the disagreement?

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



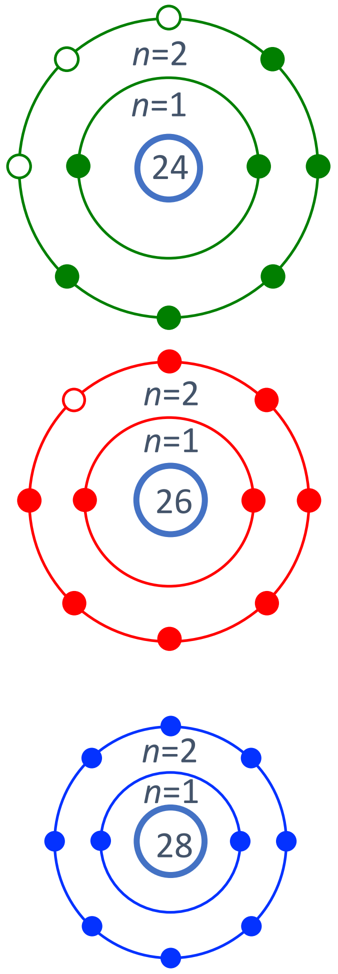


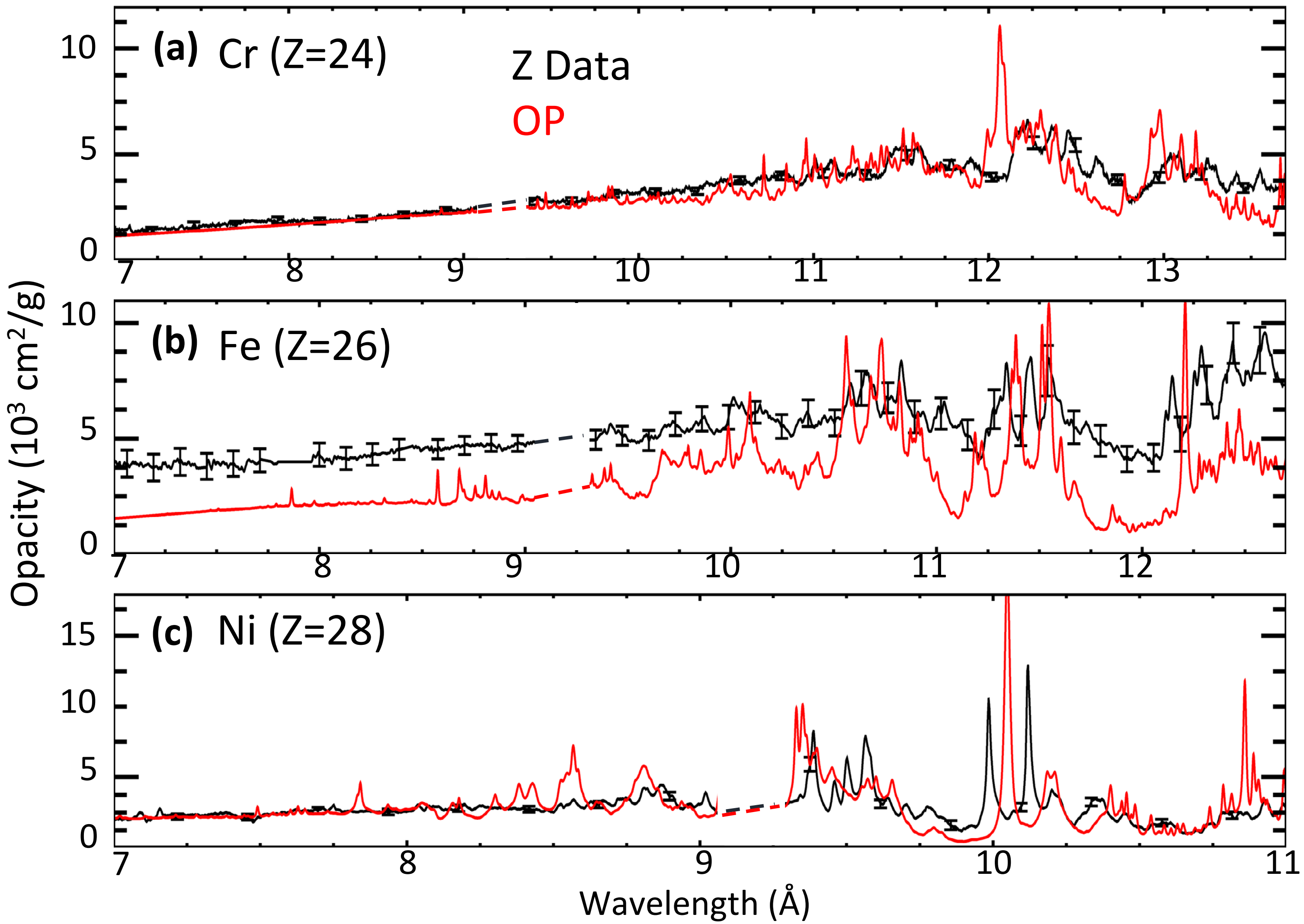
We need to understand what's causing the iron model-data discrepancy
- **Is the experiment flawed?**
- **Do opacity models miss important physics?**

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**

Stellar models using opacity models closer to the Z data* are in closer agreement with helioseismology results

J.E. Bailey *et al.,* A higher-than-predicted measurement of iron opacity at solar interior temperatures, Nature (2015)
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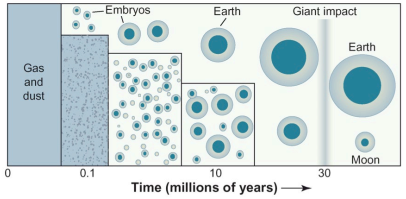
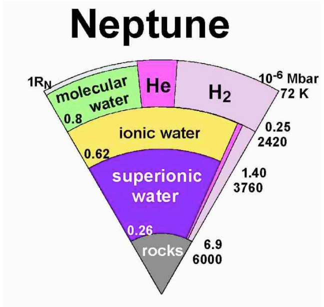
Z Fundamental Science Program

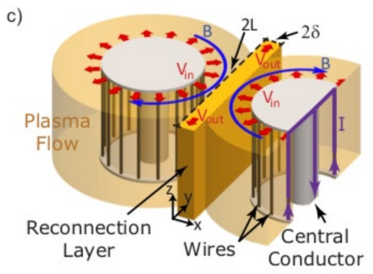
Z Fundamental Science Program is a growing community



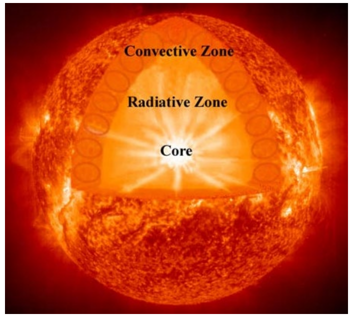
Earth and super earths



Giant Planets



Magnetic reconnection



Stellar physics

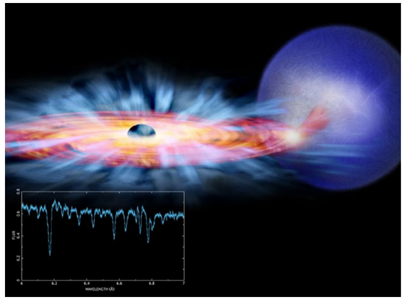
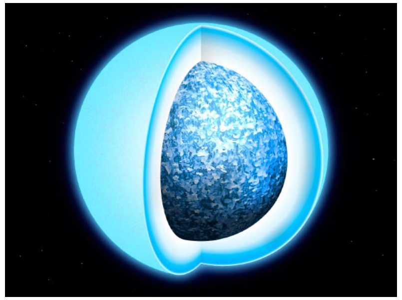


Photo-ionized plasmas



White dwarfs

12+ students are currently involved

Resources over 11 years

- 118 dedicated ZFSP shots (7.5% 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
- 7 Phys. Rev. Lett, 3+ Physics of Plasmas, 6+ Physical Review (A,B,E)
- More than 40 total peer reviewed publications and 10 conference proceedings
- 70+ invited presentations

Popular outreach

- National Public Radio, "All things considered", 2014
- Discover Magazine
  - Reportage 9/16/2012
  - *Iron rain #62 in top 100 Science stories in 2015*
- Albuquerque Journal Front Page 9/2017 and 3/2021
- Twice local TV coverage on planetary science

ZFS Program CY22 Call for Proposals opened on June 15, 2022

- ZFSP call for proposals timeline:
  - –June 15: call for proposals opened
    - Award period: July 1, 2023 through June 30, 2025
  - –August: ZFS Workshop back to in-person!
    - August 2-5, 2022 at the Hotel Andaluz
  - –September 15: call closes
  - –October/November: evaluation and selection
    - Facility review: experimental feasibility, safety, and diagnostics
    - Scientific review of international panel mid-November
    - Distribution of shots mid-December
  - –Notification of Awards on Dec 15, 2022

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
P.O. Box 5800 MS 1195
Albuquerque, NM 87185-1195
(505) 844-1575
mdknuds@sandia.gov

SAND2022-8000 O

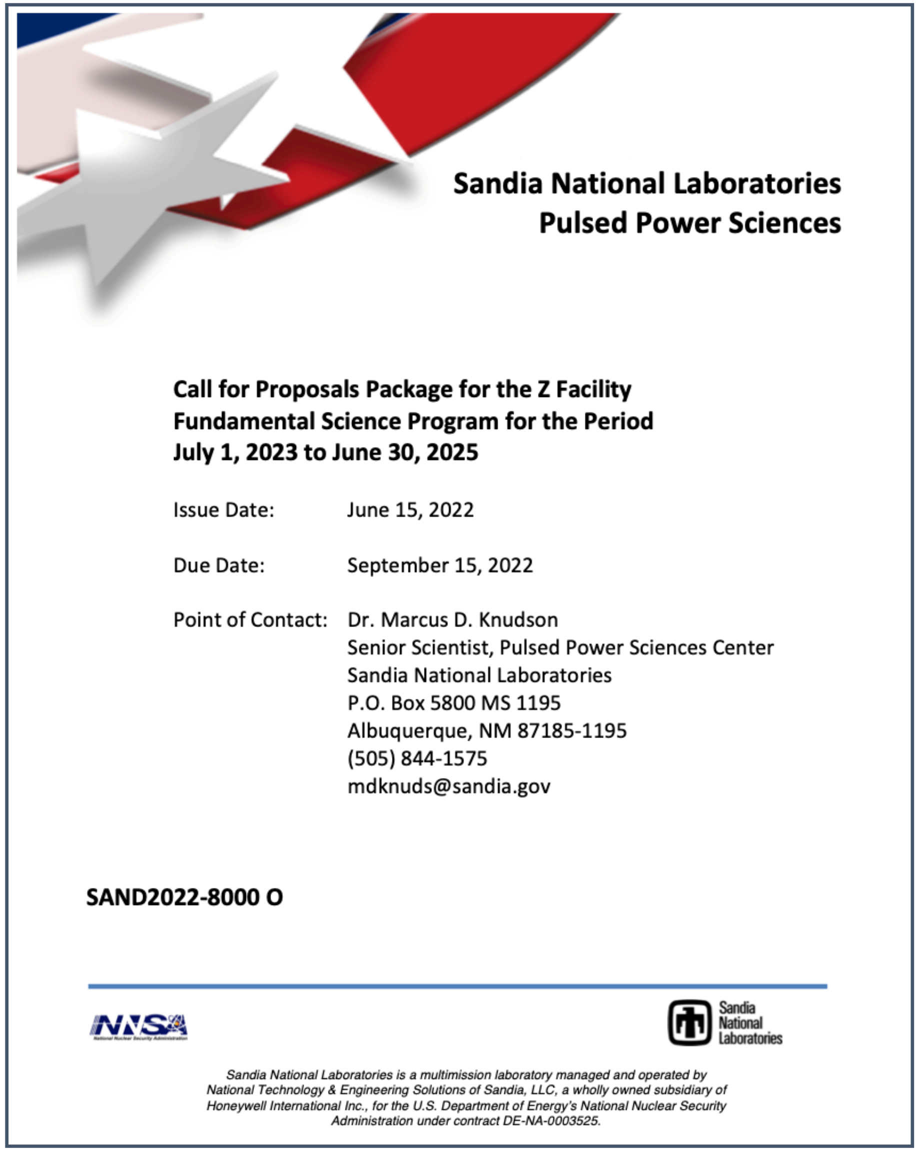
NNSA

Sandia National Laboratories

Proposals reviewed by an external, independent 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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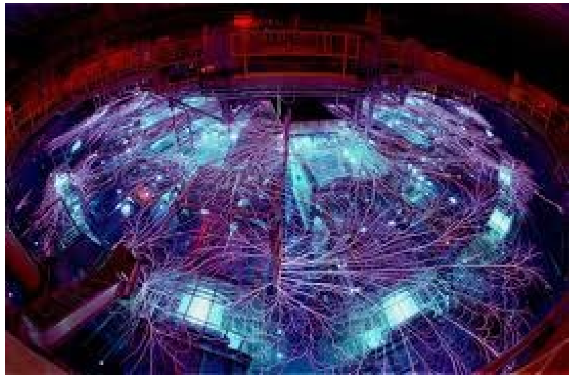
NNSA

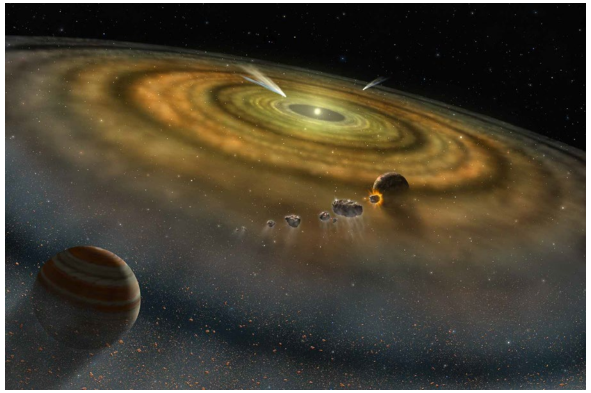
Sandia National Laboratories

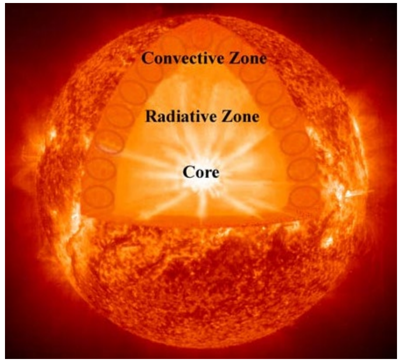
Sandia National Laboratories is a multimission laboratory managed and operated by National Technology & Engineering Solutions of Sandia, LLC, a wholly owned subsidiary of Honeywell International Inc., for the U.S. Department of Energy's National Nuclear Security Administration under contract DE-NA-0003525.

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







Decades of exciting HED Science research lie ahead

Thank you for your attention!

Sandia National Laboratories

Exceptional service in the national interest