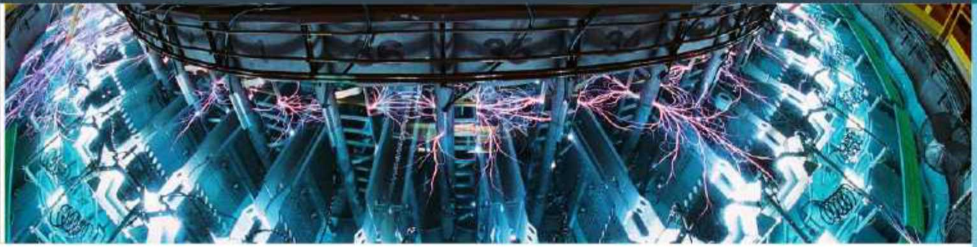
Sandia National Laboratories

SAND2019-12842C

From Astrophysics to Z-Pinches, High Energy Density Science with Pulsed Power



PRESENTED BY

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

APS Division of Plasma Physics Talk | October 22, 2019

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SAND2019-XXXX

These are exciting times to be working in pulsed power

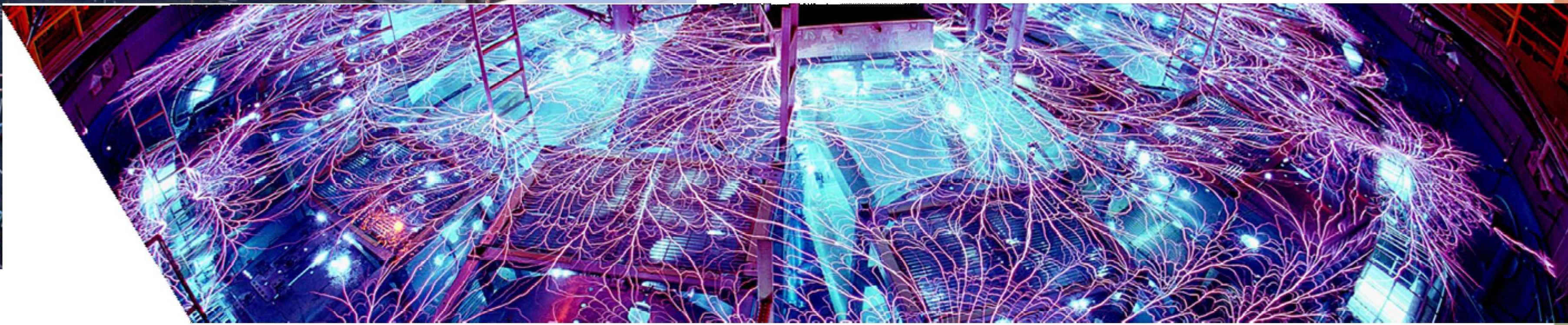
1. The world's largest pulsed power facility, Z, is used for a spectrum of research spanning:
   - Fundamental/Basic Science
   - Use-inspired Science
   - Applied/Mission Science
2. Pulsed power has matured into a precision tool for high energy density science encompassing:
   - **Dynamic Material Properties**
   - **Radiation Science**
   - **Inertial Confinement Fusion**
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

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

Sandia works on a diverse portfolio of research:

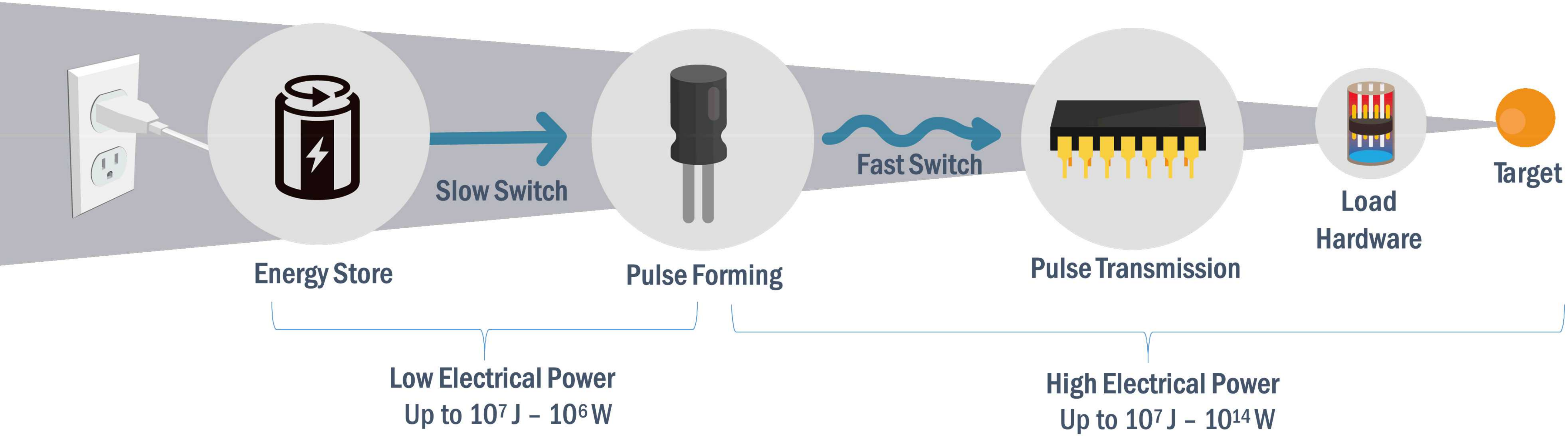
- Advanced Science & Technology
- Nuclear Deterrence
- National Security Programs
- Energy & Homeland Security
- Global Security



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.

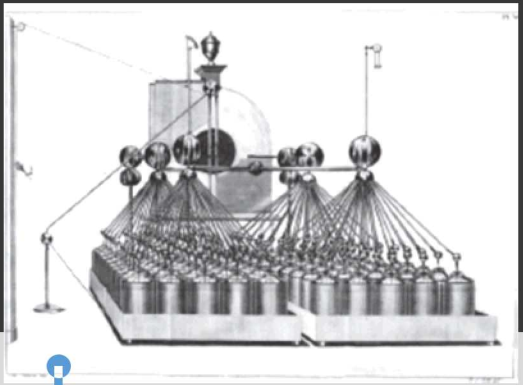
Pulsed power can be used to create conditions similar to those found in or caused by the detonation of nuclear weapons.

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

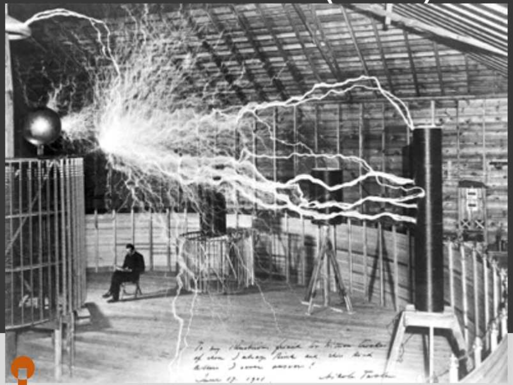
1790-2019

SANDIA PULSED POWER HISTORY

Martinus van Marum



Tesla's Lab (GW)



PBFA-II (20 TW)

Sandia's Z Facility (80 TW)

1790

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

1900

Invention of the Marx Generator

1920

Today 36 Marx generators are used on Z

1971

Gerold Yonas initiated the particle-beam fusion program at Sandia

1985

Sandia PBFA-II Light Ion Beams

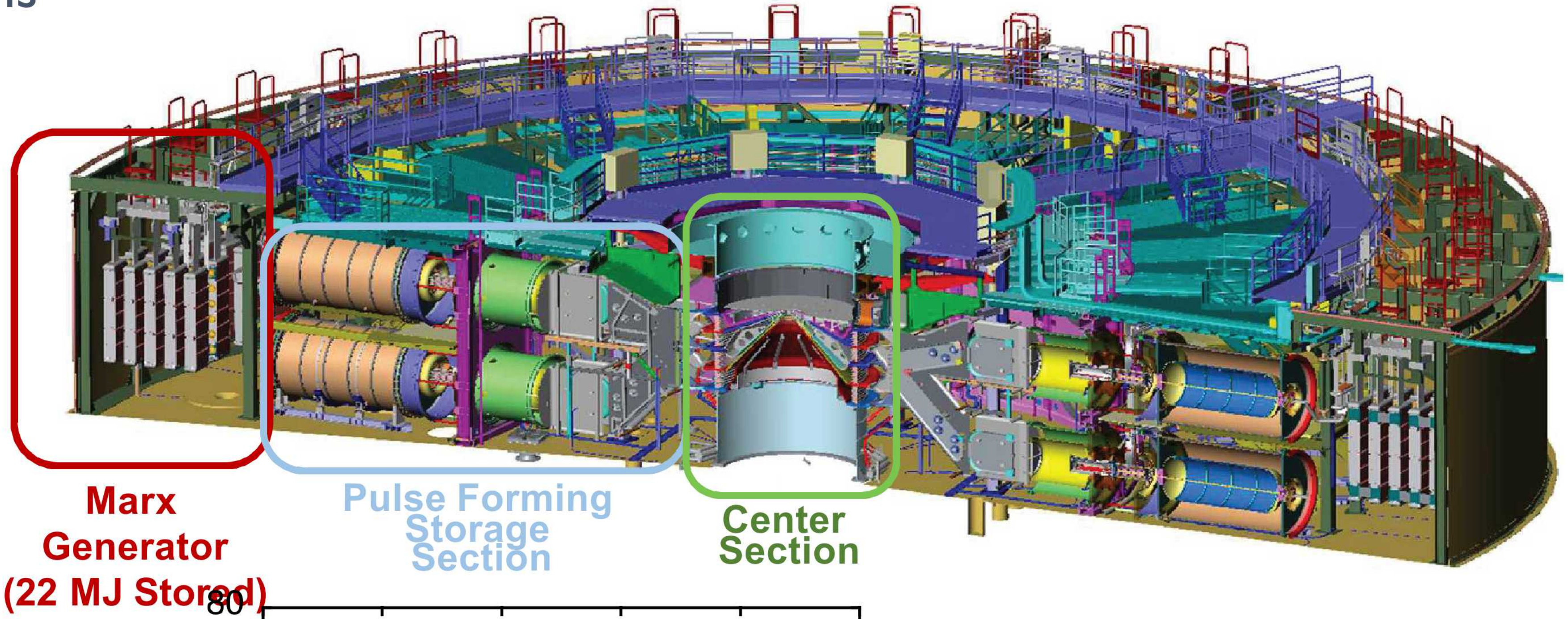
1996

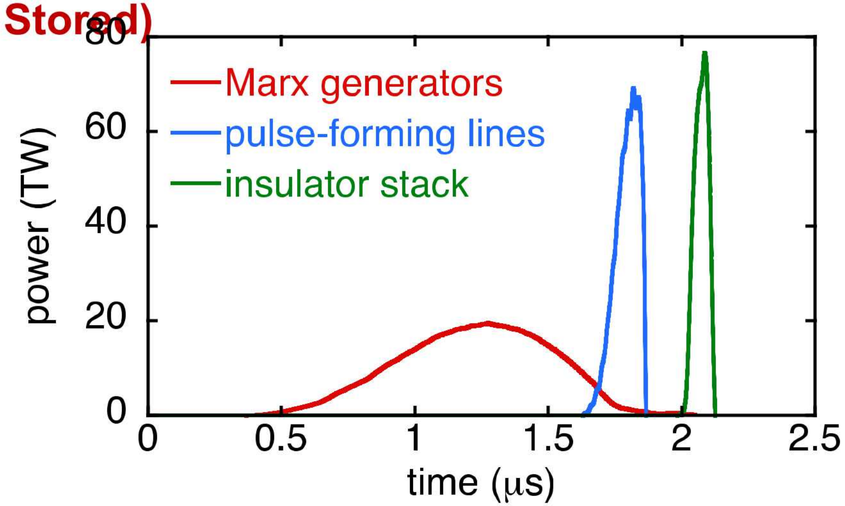
PBFA-II converted to Z; 11 MJ stored

2007

Z Refurb
22 MJ stored

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





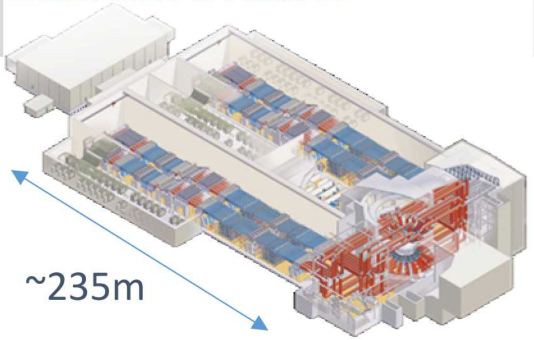
Z today couples several MJ out of 22 MJ stored to the load hardware region at the machine center.

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

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

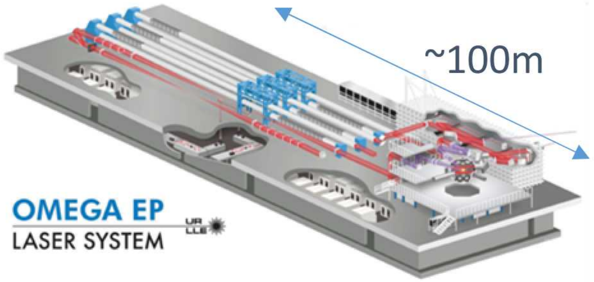
National Ignition Facility (NIF)

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



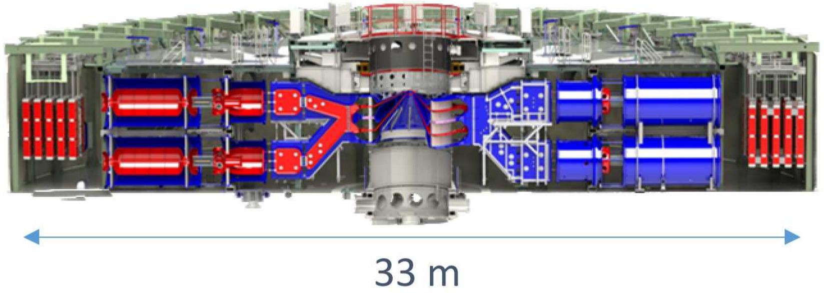
OMEGA Laser Facility

- 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)

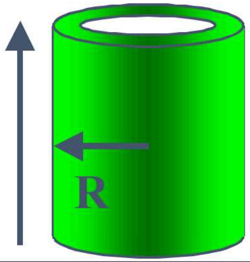


Pulsed power can generate ~100 Mbar drive pressures, which can be used to obtain even higher pressures such as those in inertial fusion

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/m³)

1 Mbar = 10^{11} J/m³

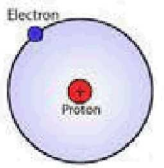
Z Storage capacitor

2e-6 Mbar

TNT

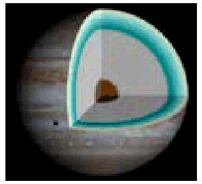
0.07 Mbar

Internal Energy of H atom



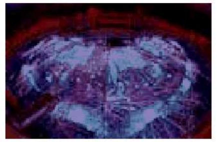
1 Mbar

Metallic H in Jupiter's core



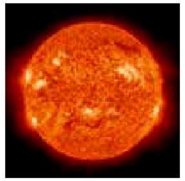
30 Mbar

Z Magnetic Drive Pressure



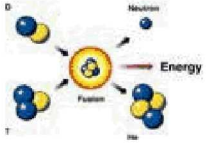
~100 Mbar

Center of Sun



250,000 Mbar

Burning ICF plasma



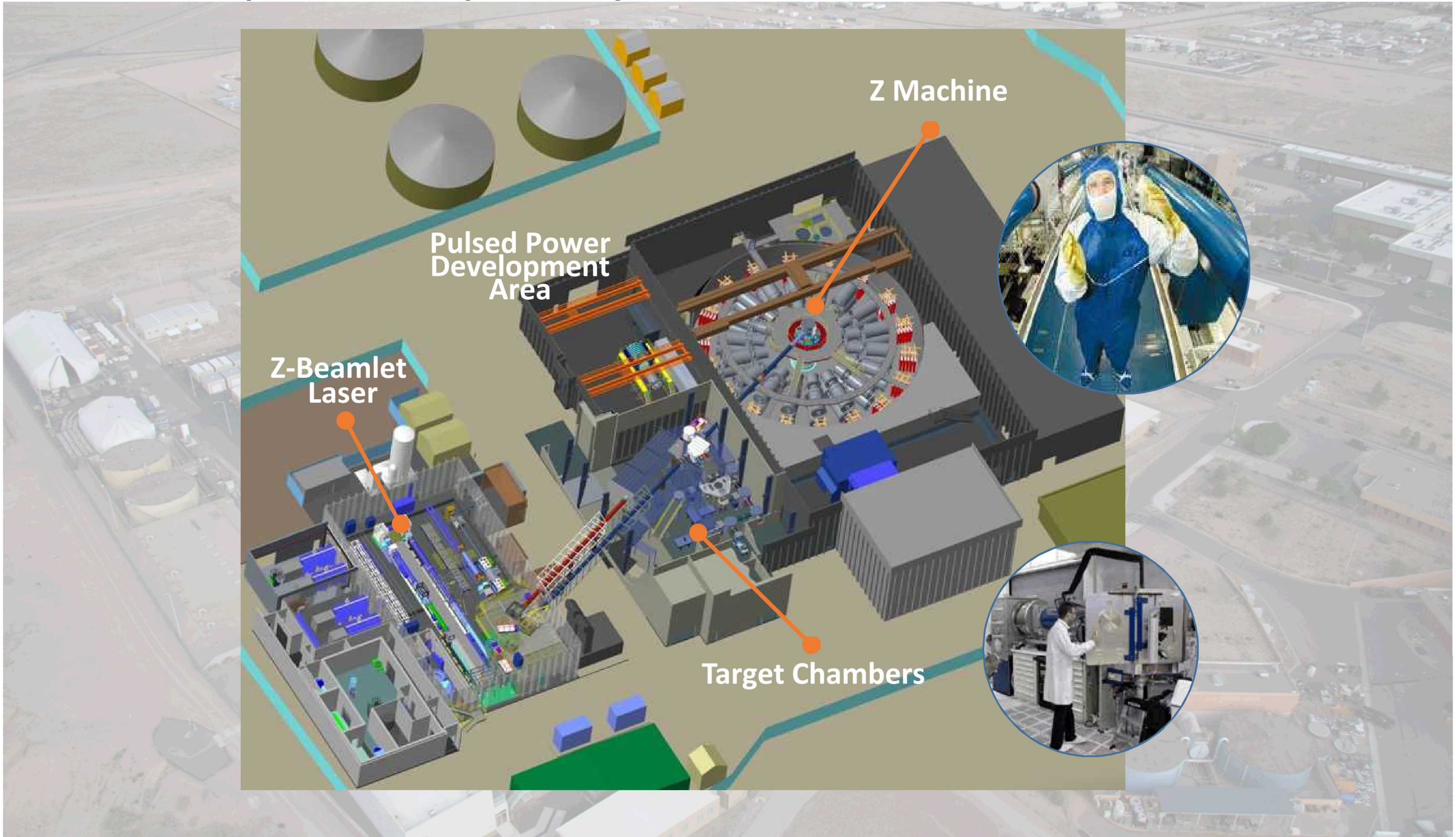
800,000 Mbar

Push on samples

Compress fuel at high velocity

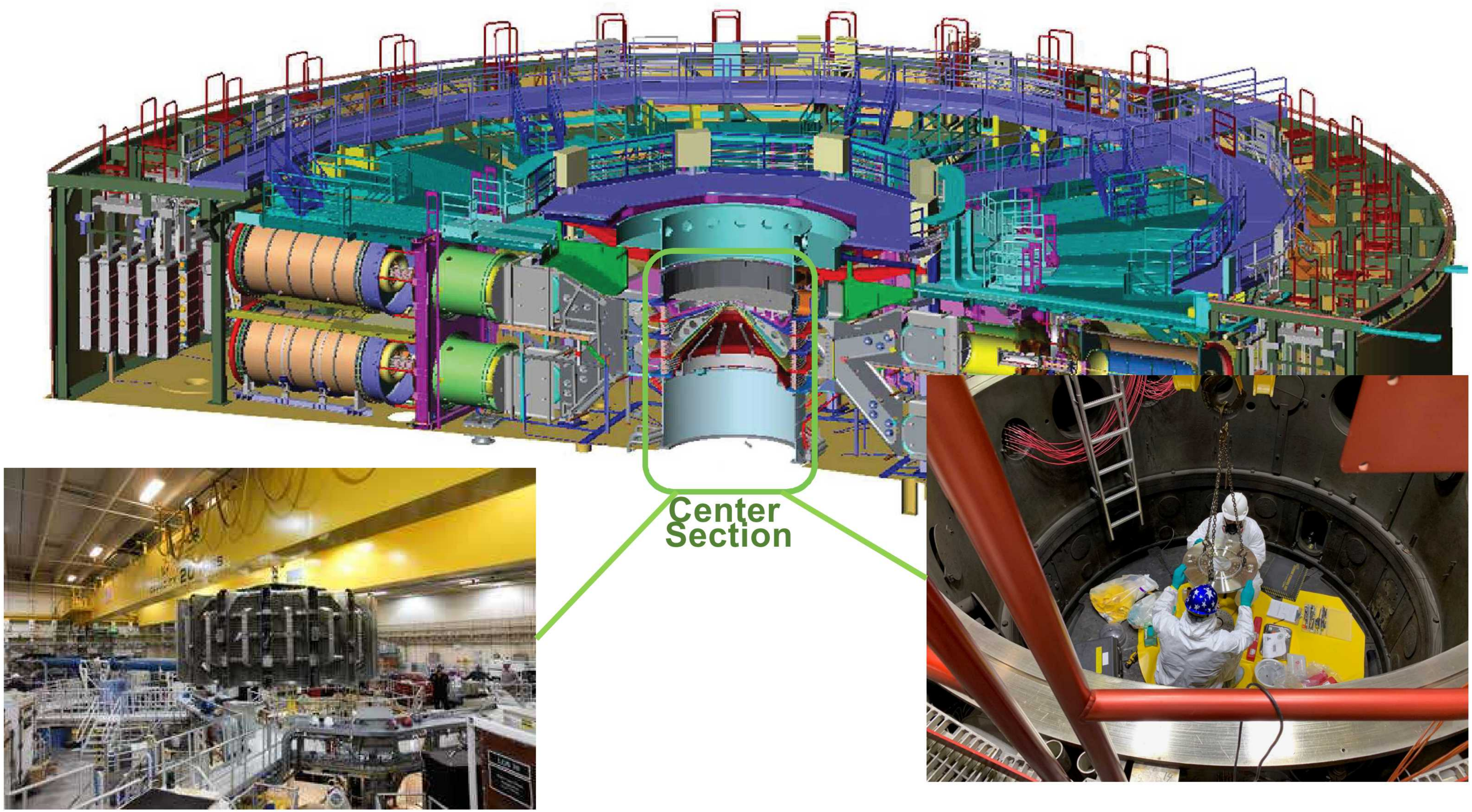
The Z facility is supported by the multi-kJ Z-Beamlet & Z-Petawatt lasers, which can also be operated independently

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

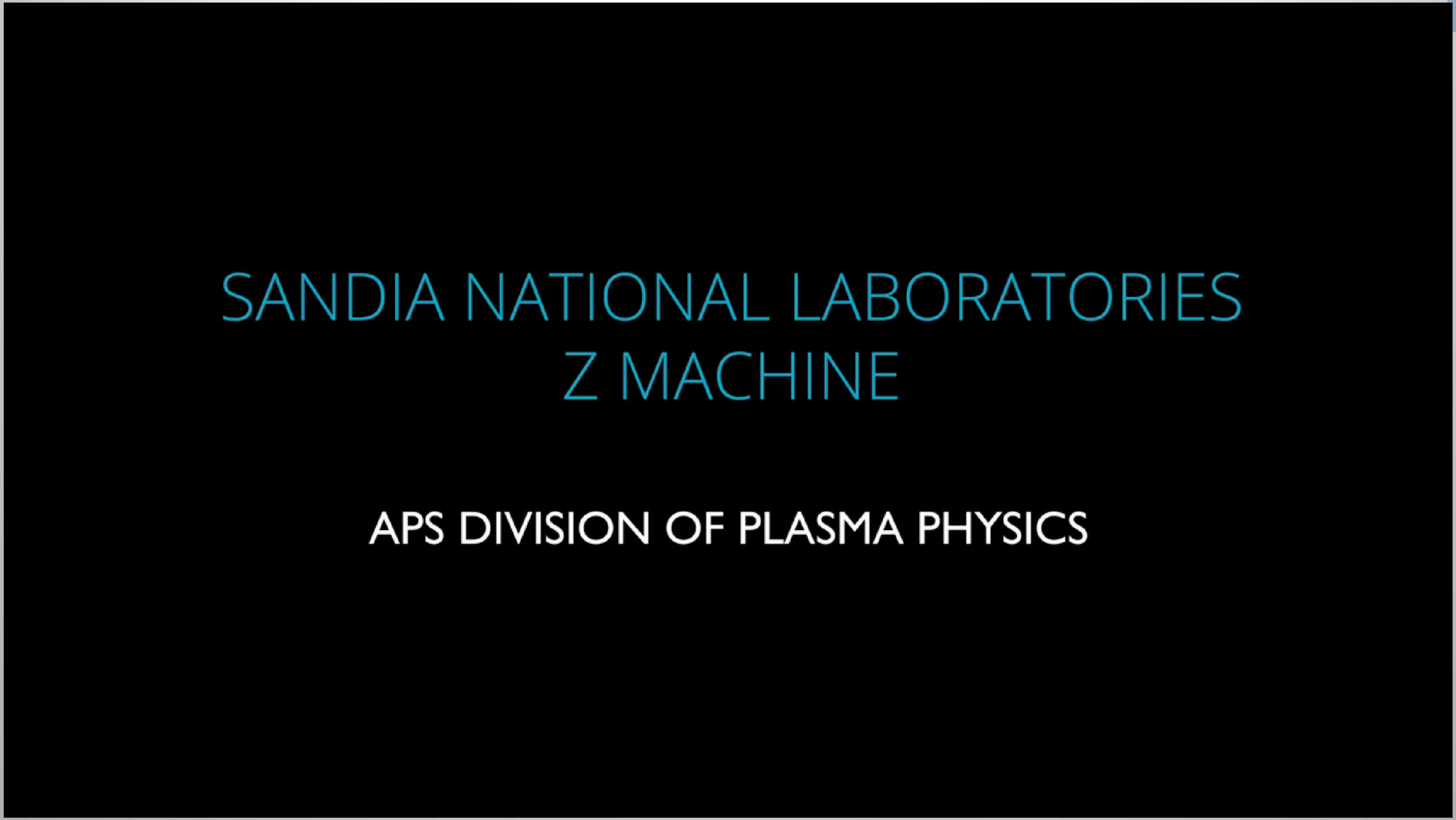


P.K. Rambo *et al.*, Applied Optics 44 (2005); P. Rambo *et al.*, Proc. SPIE 10014 (2016).

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



A day in the life at Z

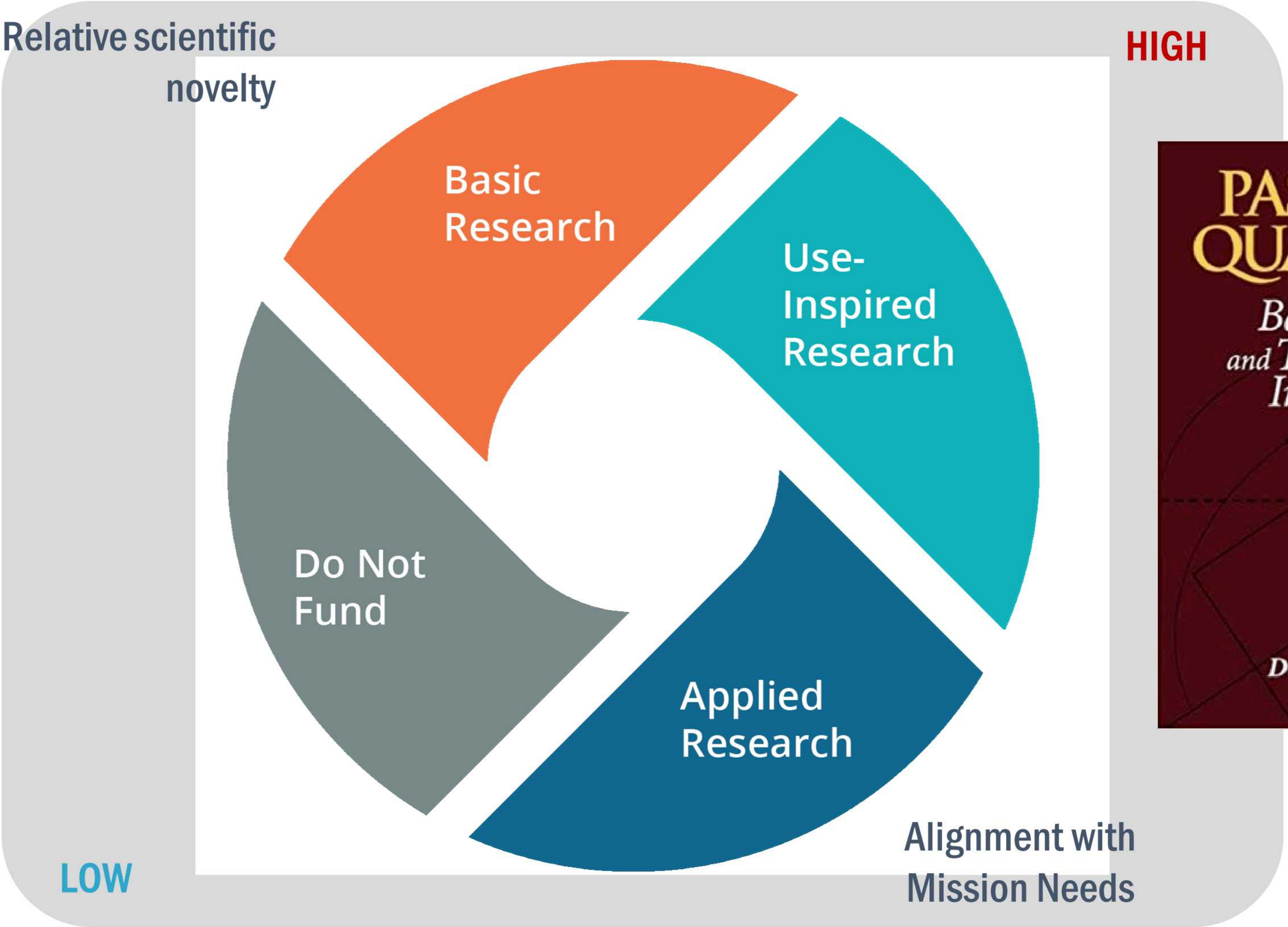


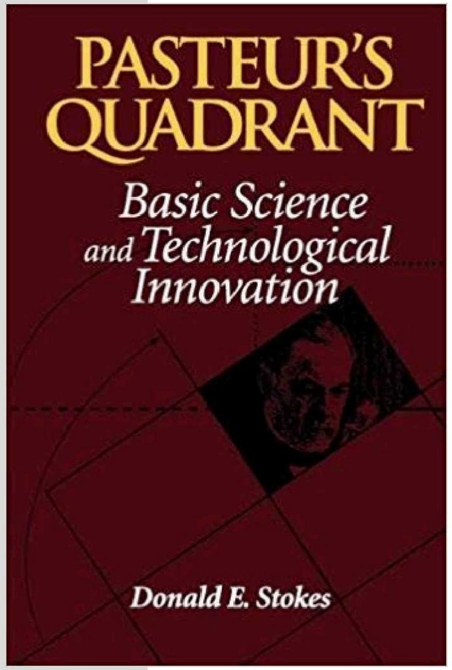
Z experiments release the energy of a few sticks of dynamite

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

Majority of Z research is "use-inspired"

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





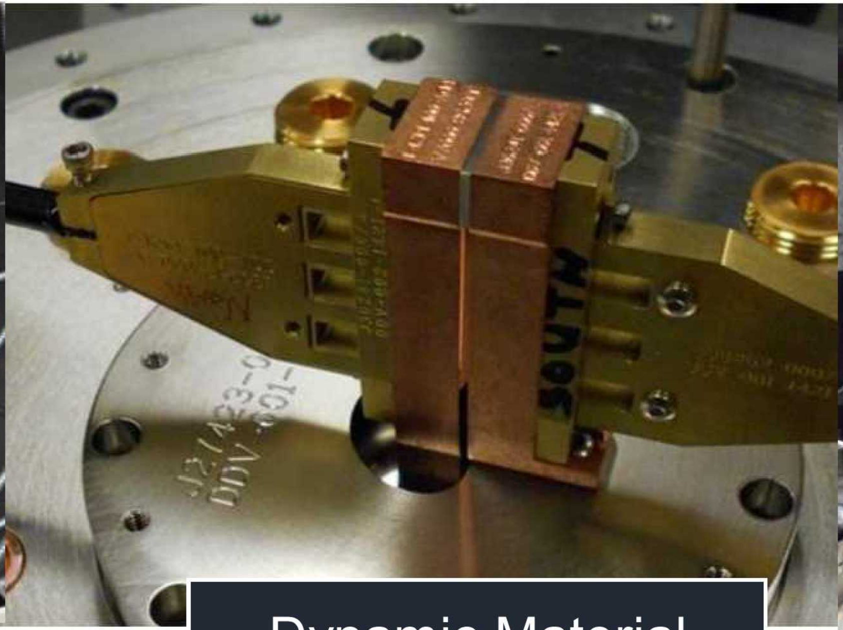
Basic

Use-Inspired

Applied

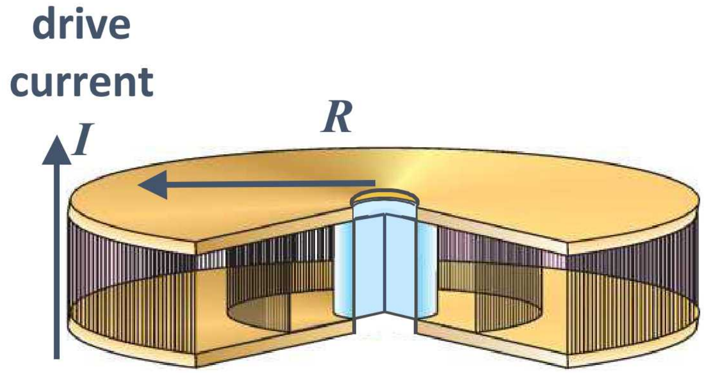
Precision tools for high energy density science

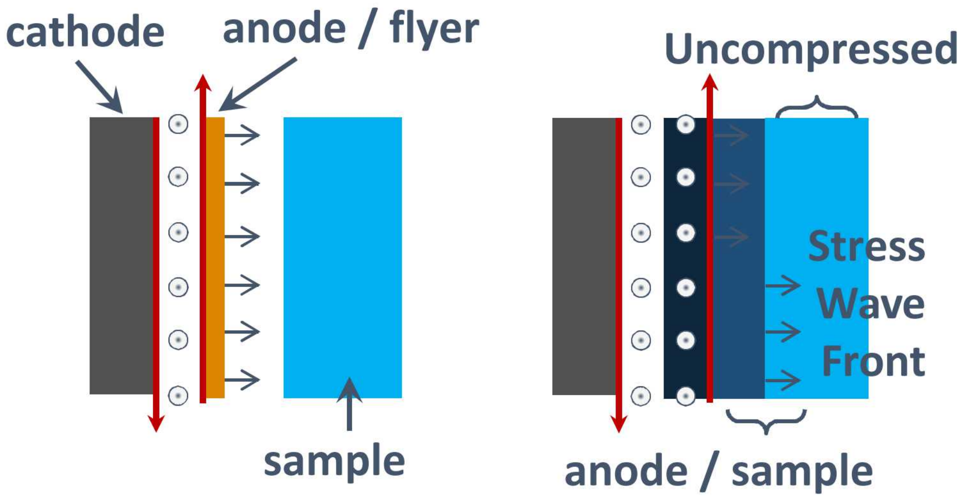
Radiation Science

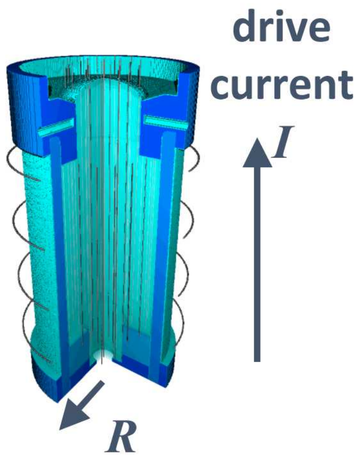


Dynamic Material Properties

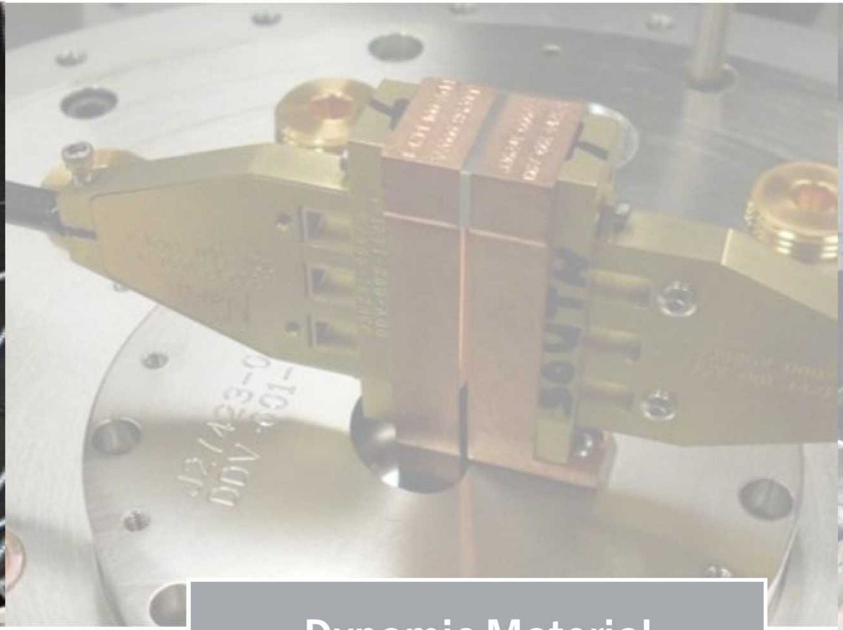
Inertial Confinement Fusion







Radiation Science

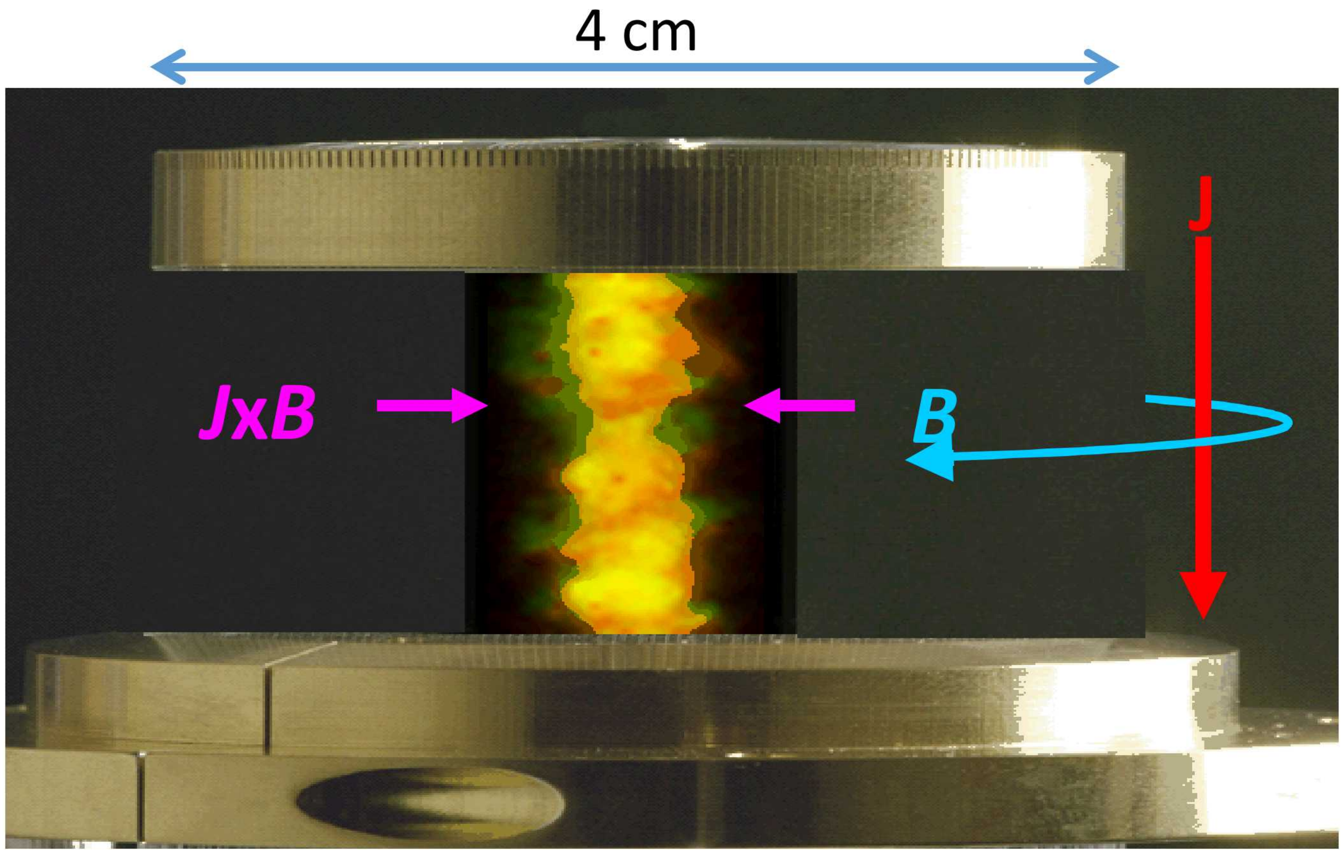


Dynamic Material Properties

Inertial Confinement Fusion

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

Basic



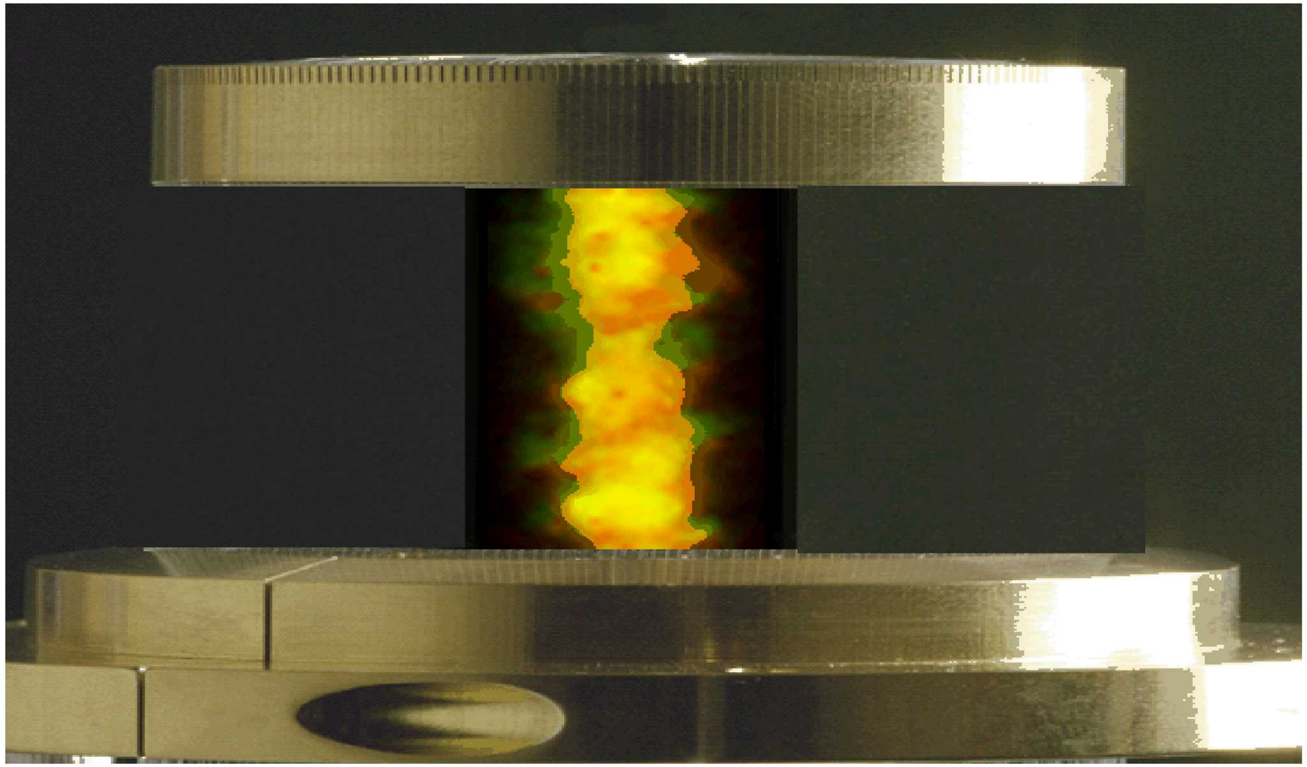
	ZR > 2011	Z < 2007
Marx Energy	20.3 MJ	11.4 MJ
Ipeak	25.8 MA (1.5%)	21.7 MA* (2.1%)
Peak Power	220 TW (10%)	120 TW (14%)
Radiated Energy	1.6 MJ (7%)	0.82 MJ (17%)

* 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).

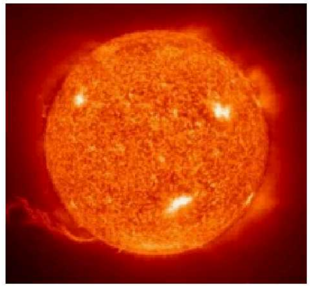
We collaborate with several institutions to do multiple radiation-driven basic science experiments on a single Z shot

Basic



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

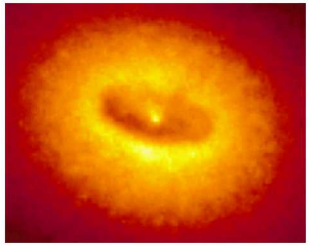
Stellar opacity



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

Achieved Conditions:
$T_e \sim 200$ 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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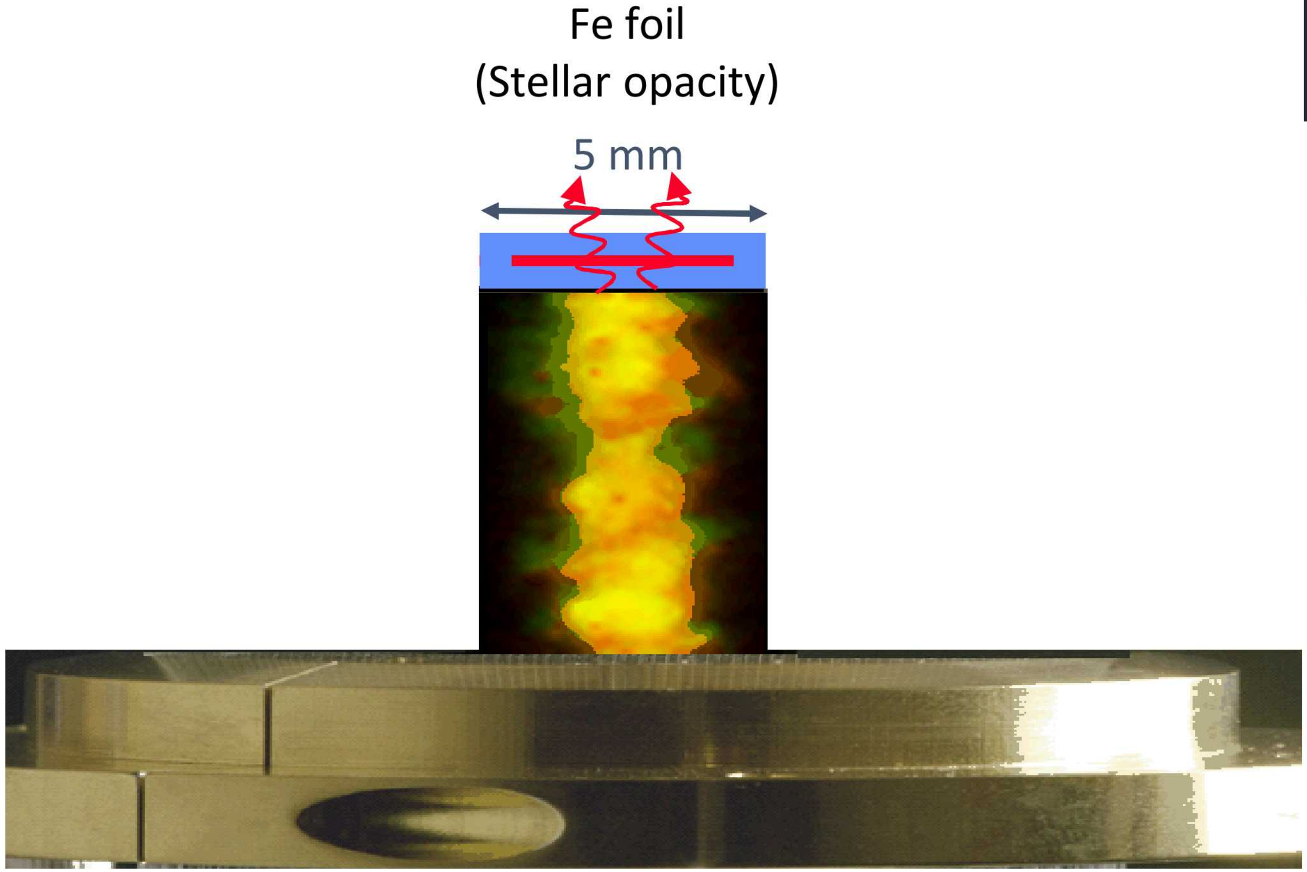

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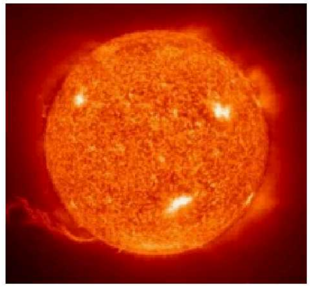
Basic

Stellar opacity

2016 Dawson Award



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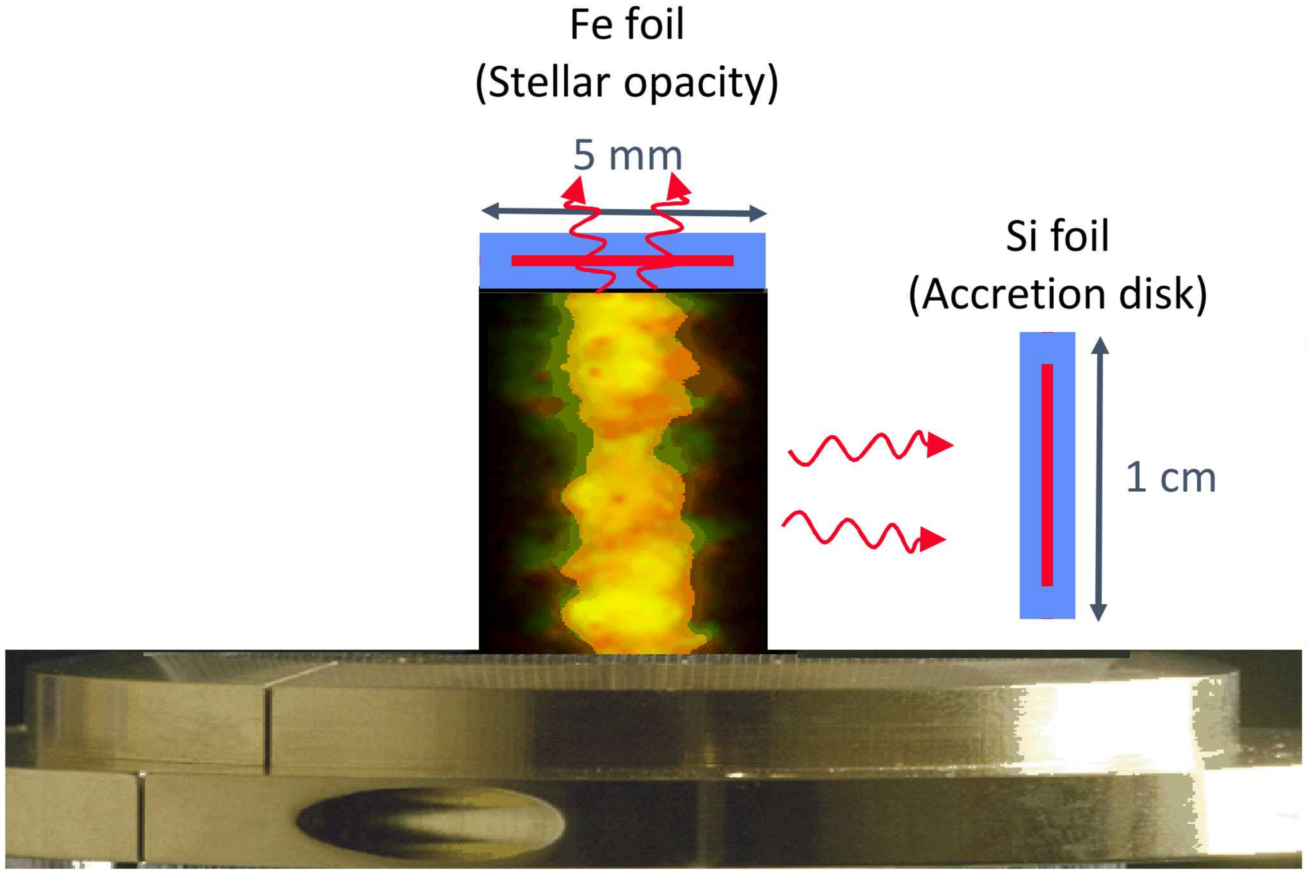

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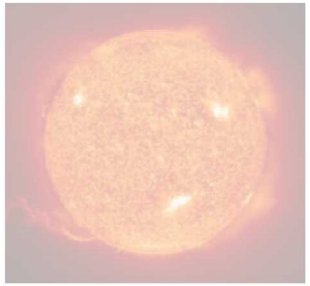
Stellar opacity



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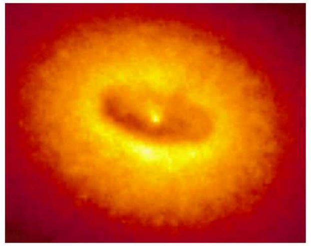
Achieved Conditions:
T_e ~ 200 eV, n_e ~ 10^{23} cm^{-3}

Accretion disk

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



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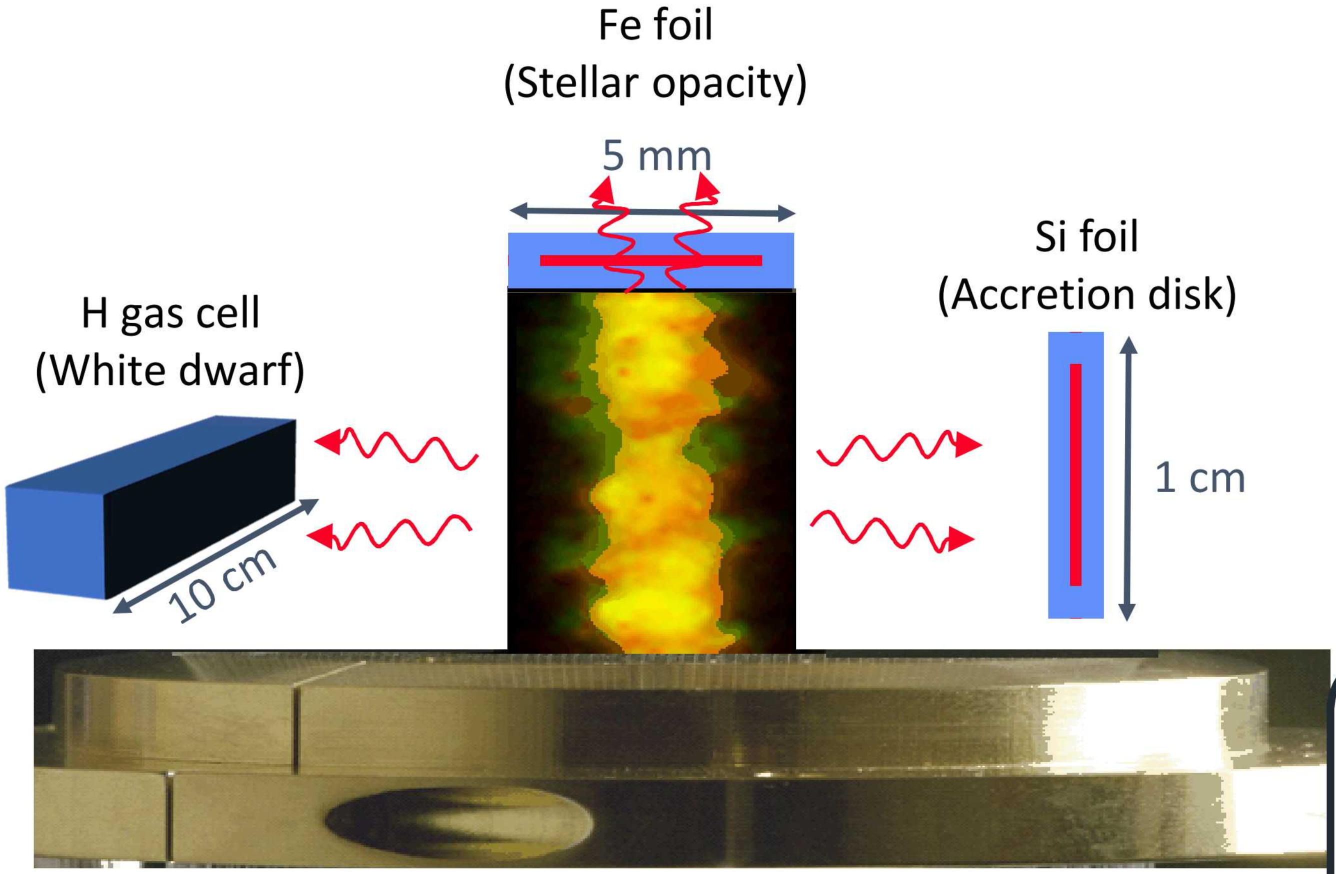

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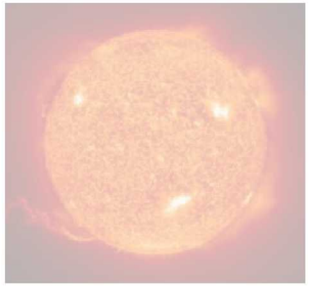

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M-A. Schaeuble PO9.00012

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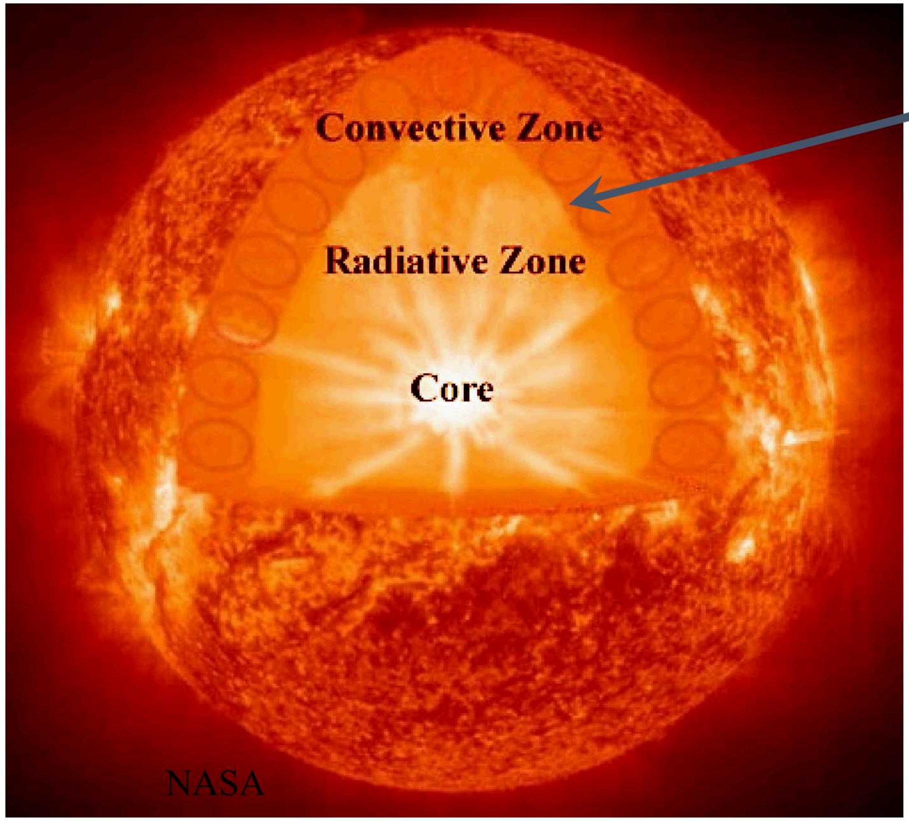
Sanford *et al.*, *PoP* (2002); Bailey *et al.*, *PoP* (2006); Slutz *et al.*, *PoP* (2006); Rochau *et al.*, *PPCF* (2007); Rochau *et al.*, PoP (2014).

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**

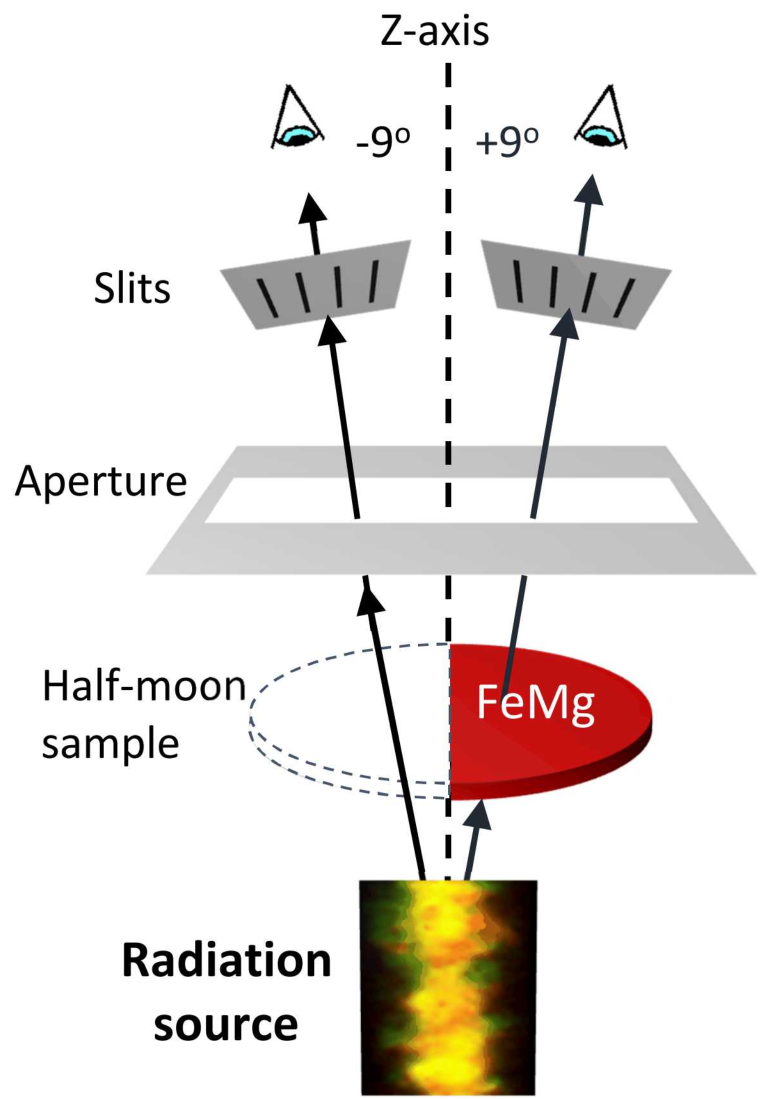
Question: Is opacity uncertainty the cause of the disagreement?

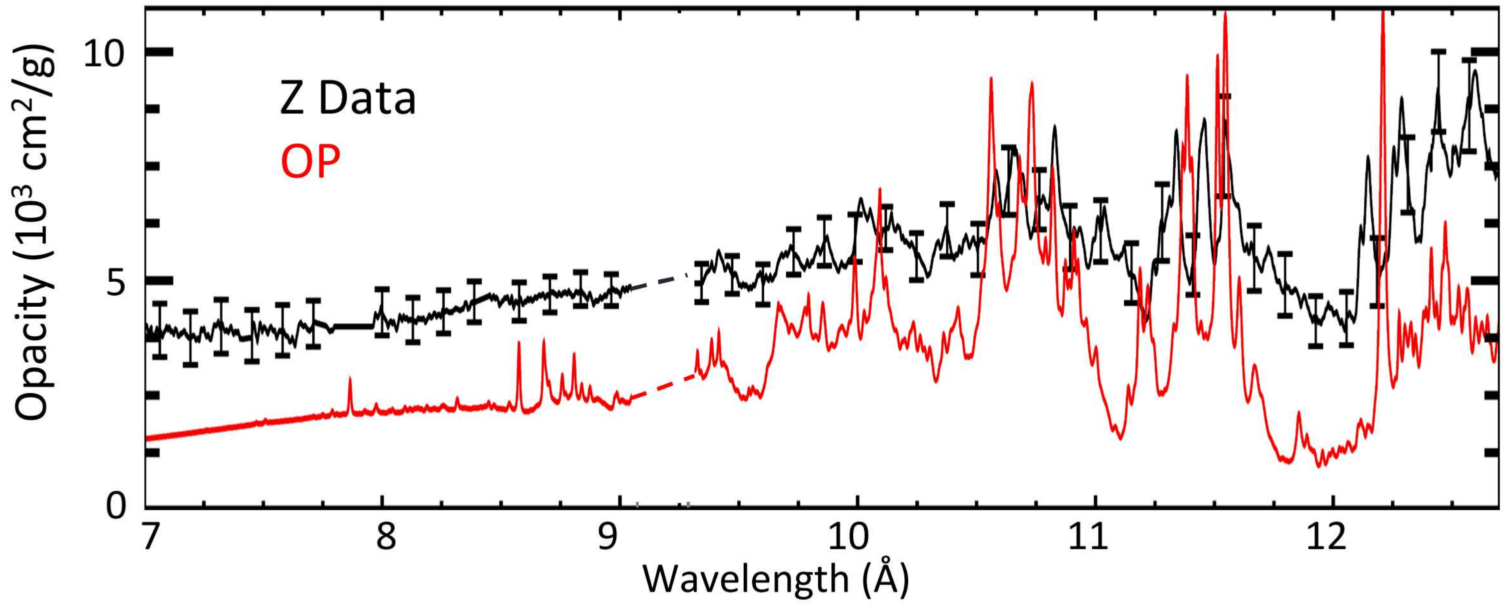
Objective: Measure Fe opacity at CZ base conditions.

*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





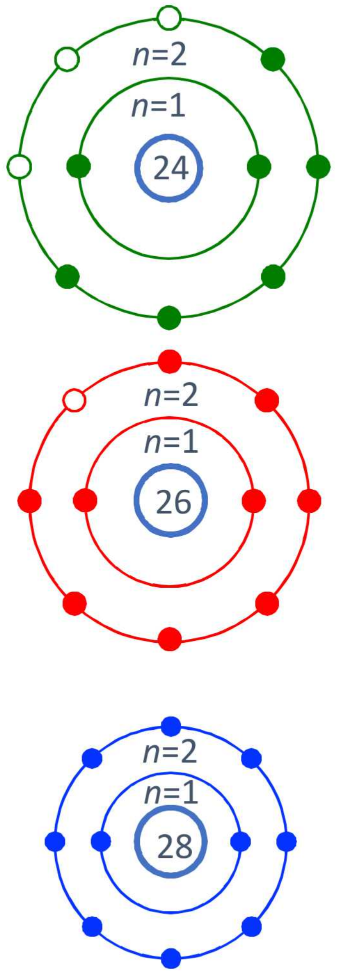
We need to understand what's causing the iron model-data discrepancy

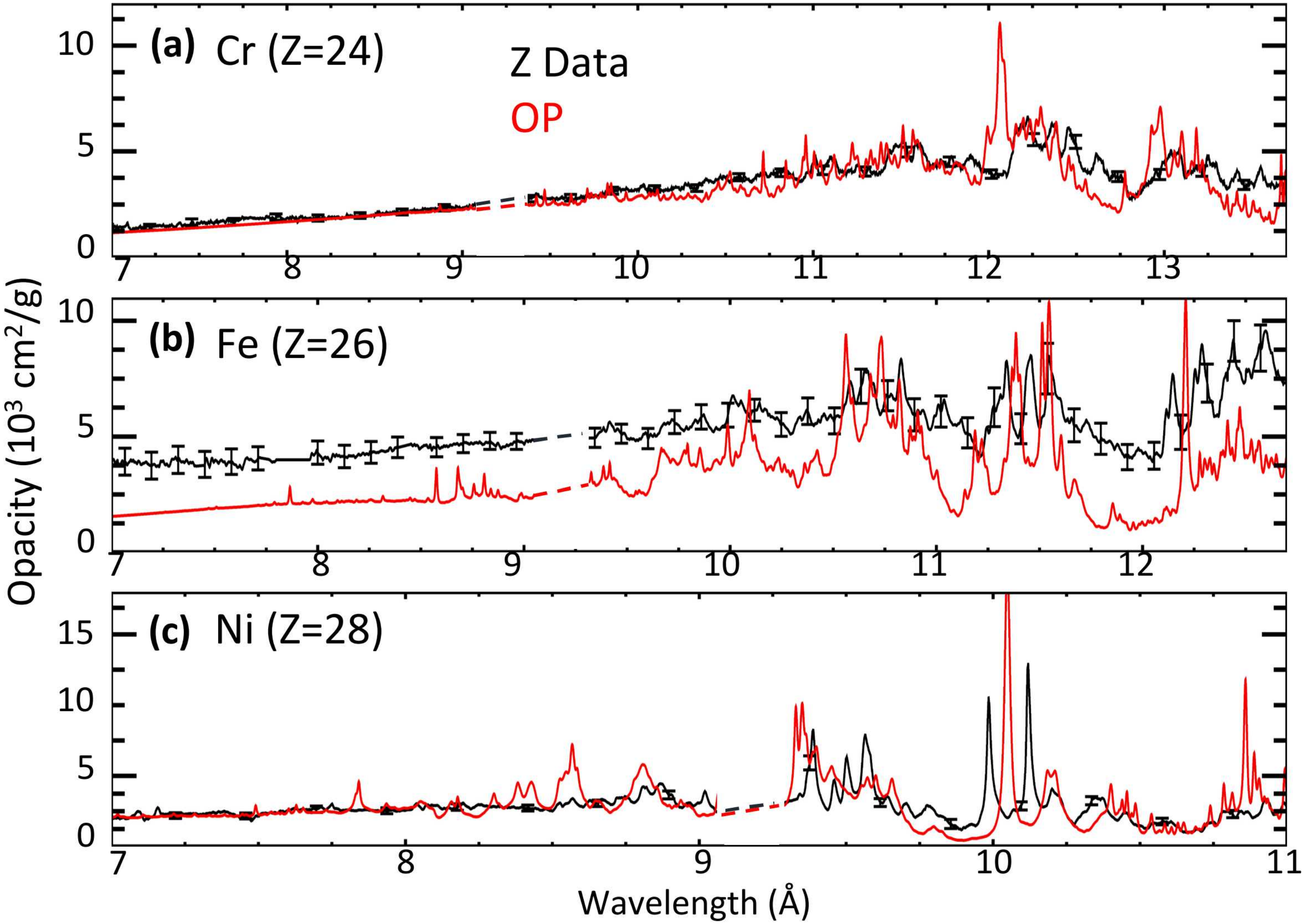
- **Is the experiment flawed?**
- **Do opacity models miss important physics?**

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**

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

*Talk by S. Hansen (BO7.00011)

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

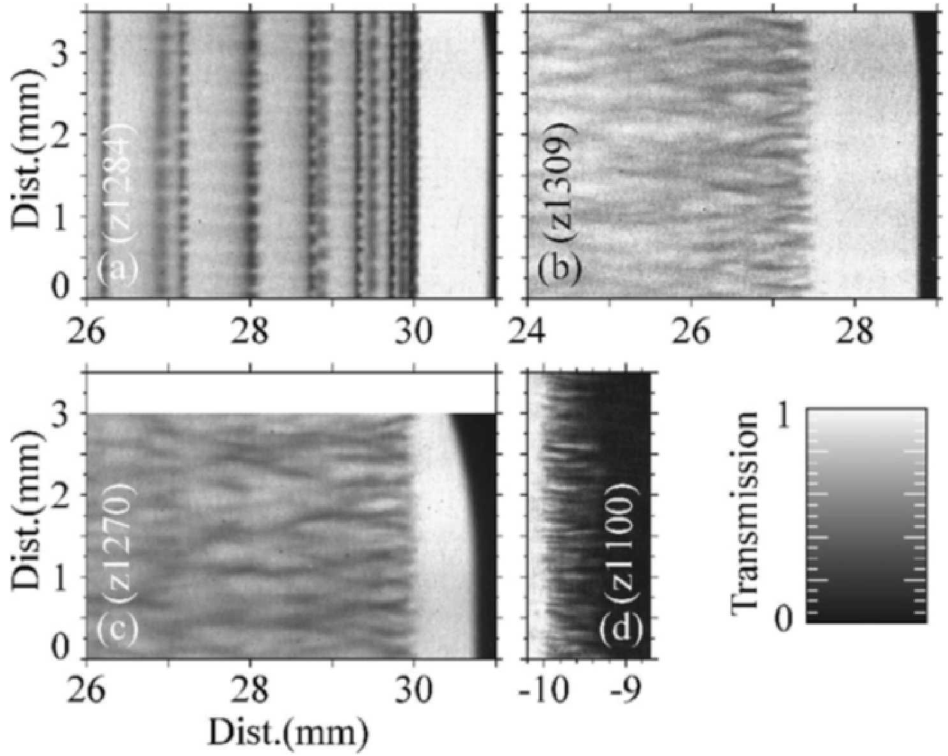
T. Nagayama *et al*., Systematic Study of L-shell Opacity at Stellar Interior Temperatures, Phys. Rev. Lett. (2019)

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

Use-Inspired

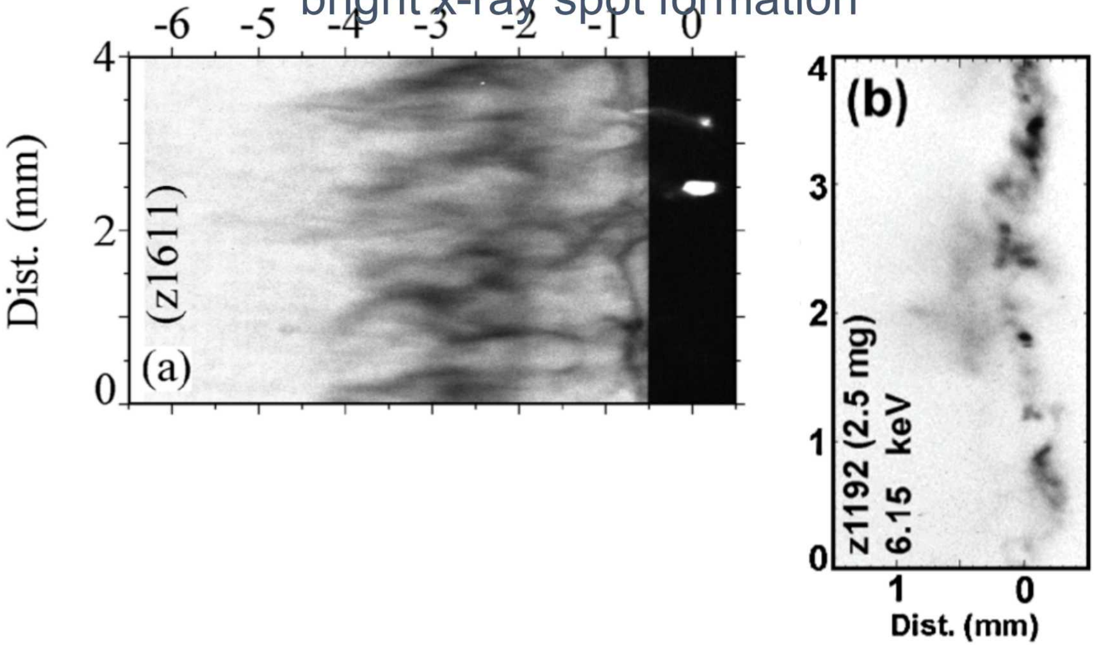
How do wire arrays turn into plasma?
Can we model wire array implosion instabilities?
What are the conditions at stagnation?

Examples of complex wire array ablation dynamics



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

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



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

Sandia has an extensive history of x-ray spectroscopy measurements to both measure x-ray output and diagnose stagnation conditions

Use-Inspired

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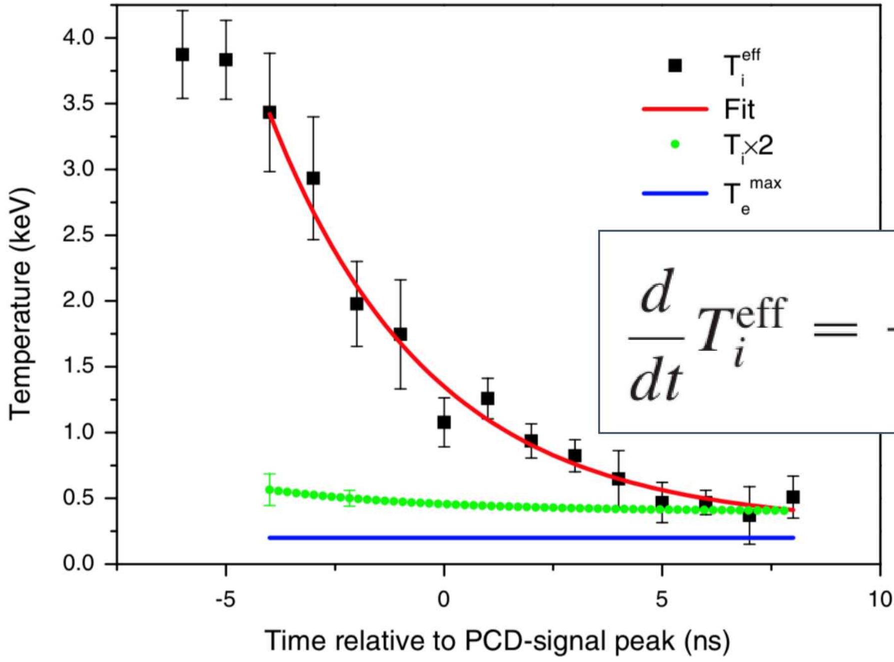
מכון ויצמן למדע
WEIZMANN INSTITUTE OF SCIENCE

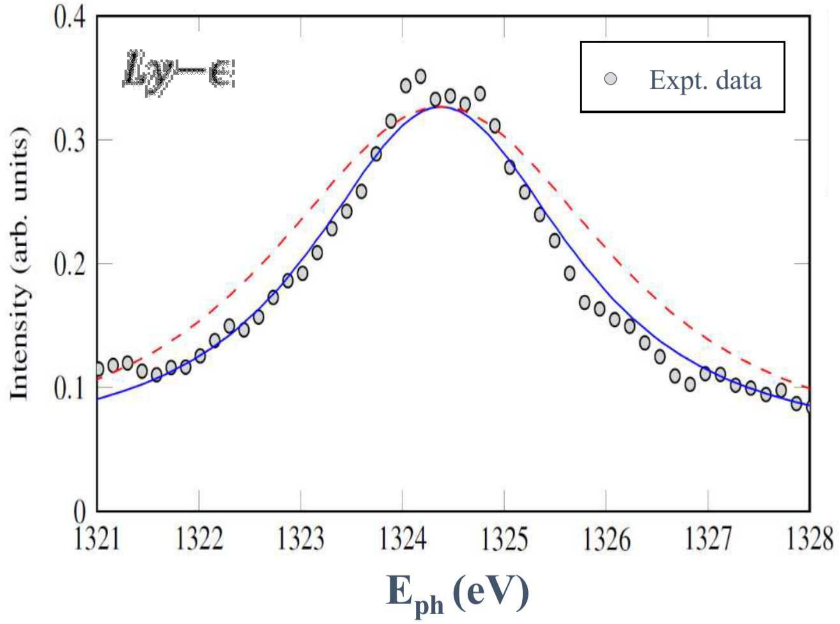
Doppler measurements demonstrated that the energy of the ions remains bound in hydrodynamic motion with an energy transfer time scale to ele...

Weizmann Institute developed a new measurement technique based on Stark effect to demonstrate this more directly



$$\frac{d}{dt}T_i^{\mathrm{eff}} = -\frac{T_i - T_e}{\tau_{\mathrm{ie}}}$$

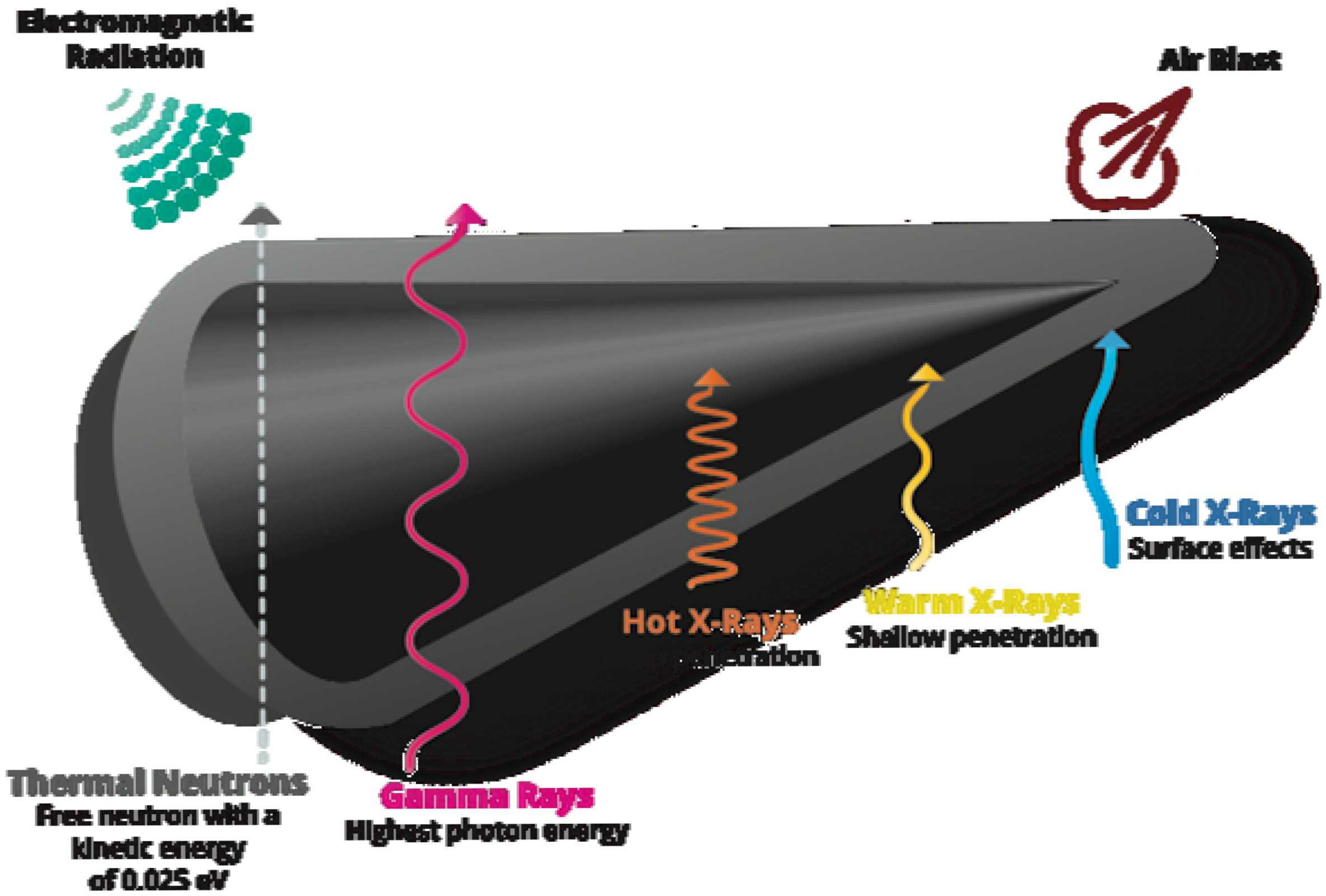
E. Kroupp *et al.*, PRL (2011); Y. Maron tutorial PT3.00001



D. Alumot *et al.*, PRL (2011); Y. Maron tutorial PT3.00001

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

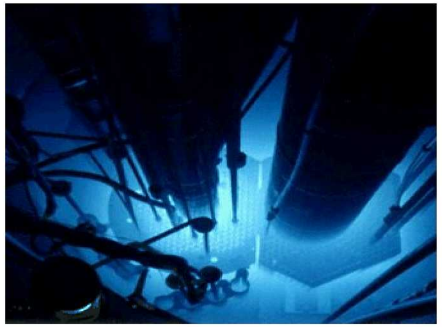
Applied



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

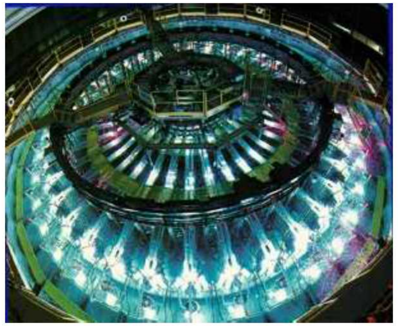
Applied

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



Annular Core Research Reactor
Fission neutrons

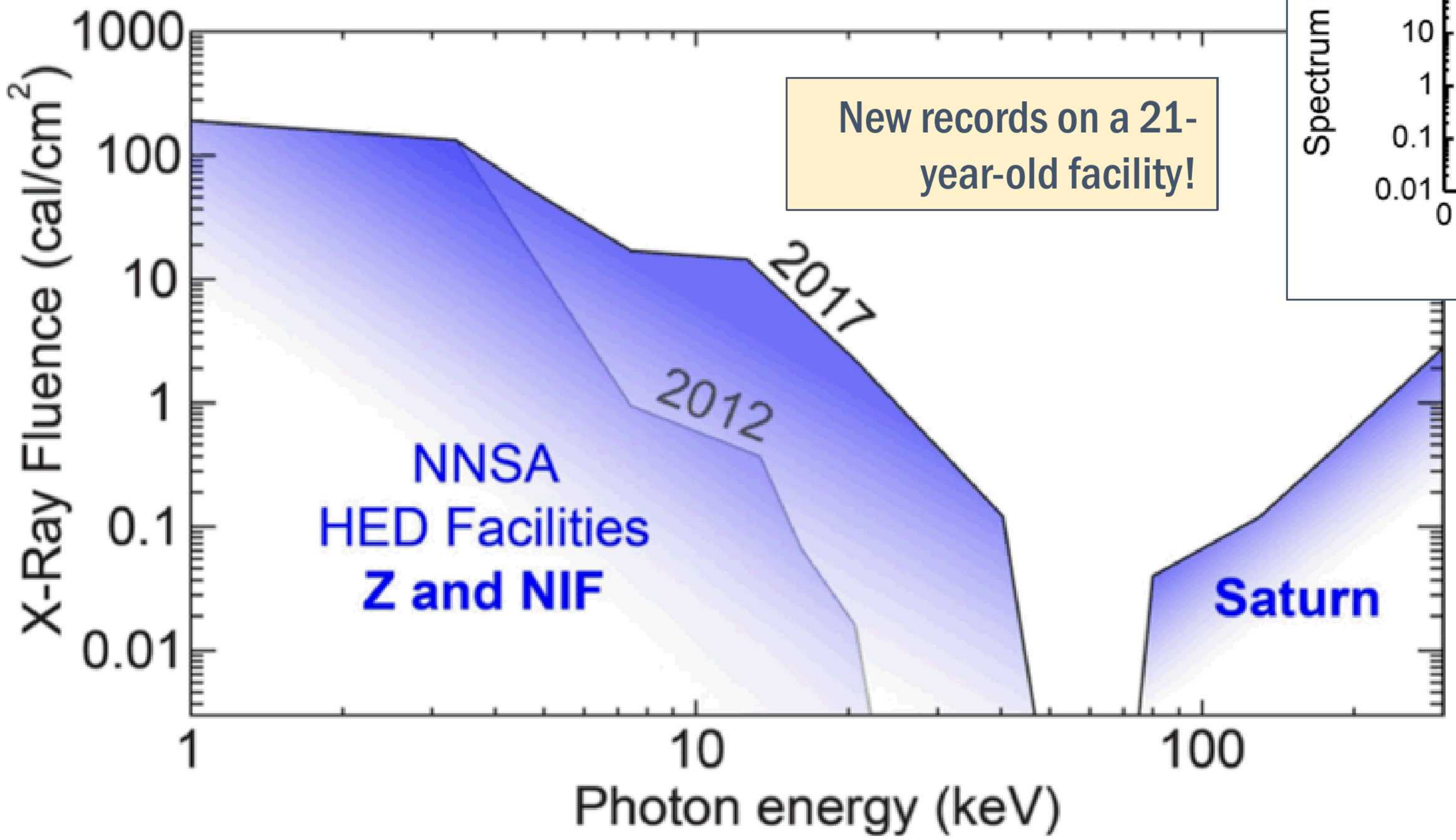
HERMES III
Gamma rays



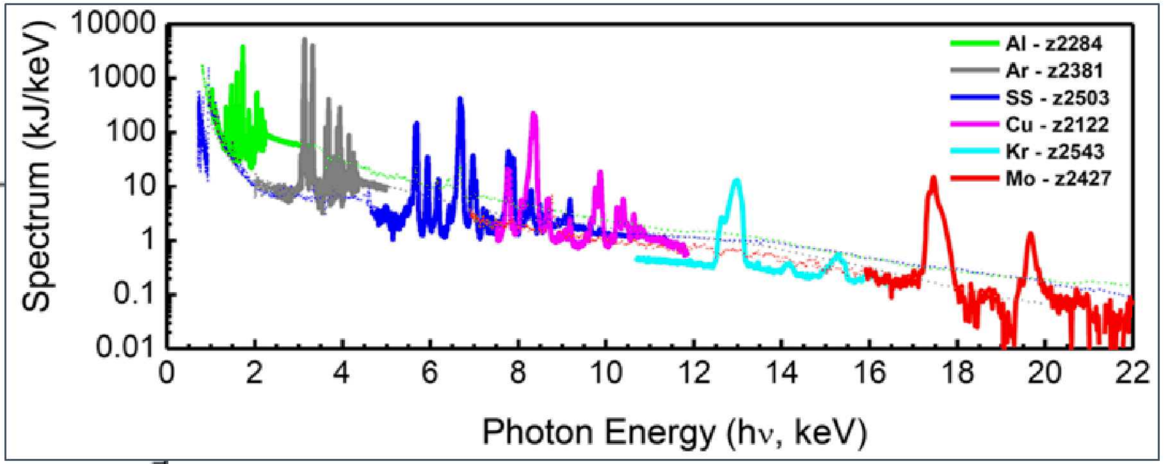
Saturn
Hot X-rays

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

Applied



New records on a 21-year-old facility!

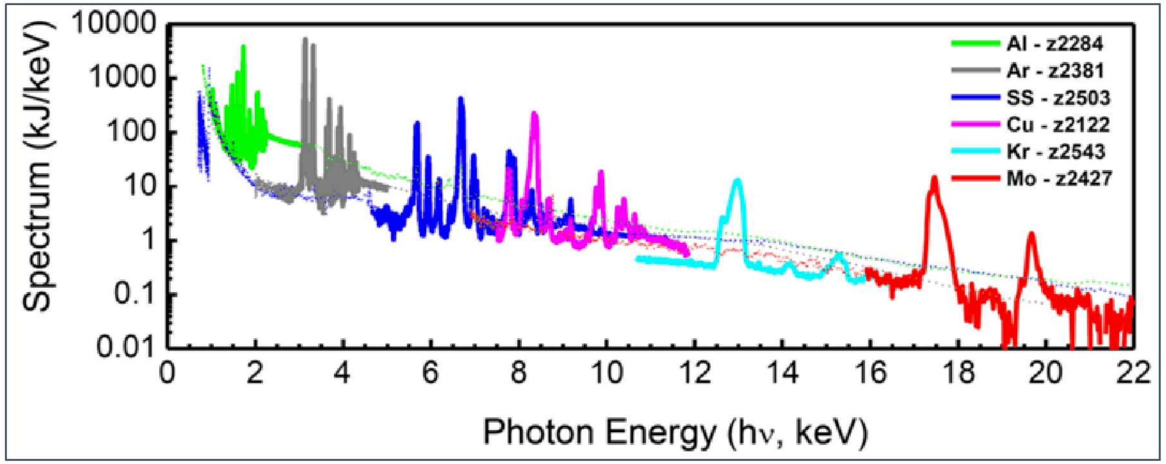


Z and NIF are developing advanced x-ray sources that provide unprecedented >10 keV yields

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

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

Applied

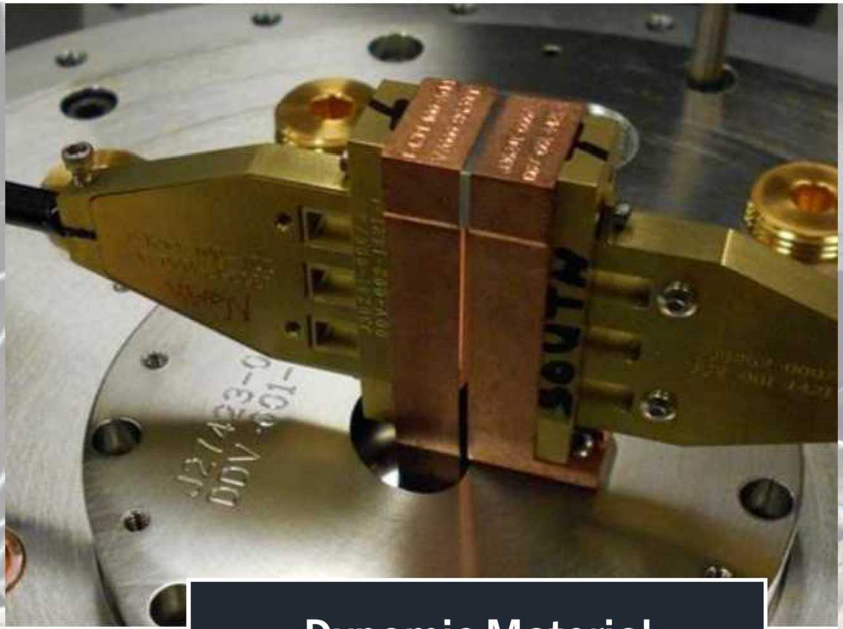


These x-ray sources are being used to study physics models for matter exposed to rapid, intense doses of x rays

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

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

Radiation Science



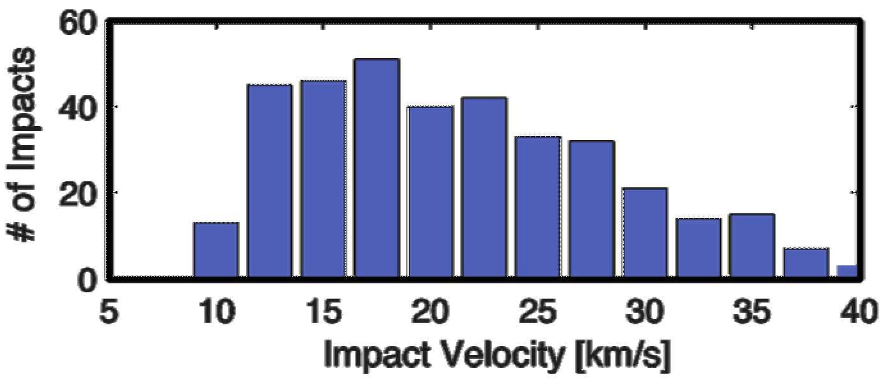
Dynamic Material Properties

Inertial Confinement Fusion

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

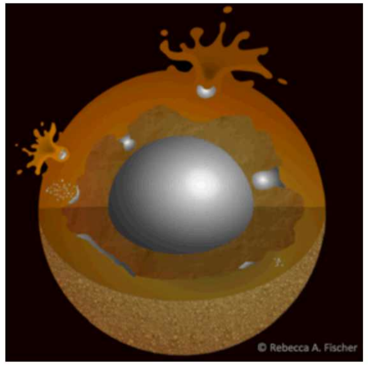
Basic

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



Simulations of planetary dynamics suggest high impact velocities

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

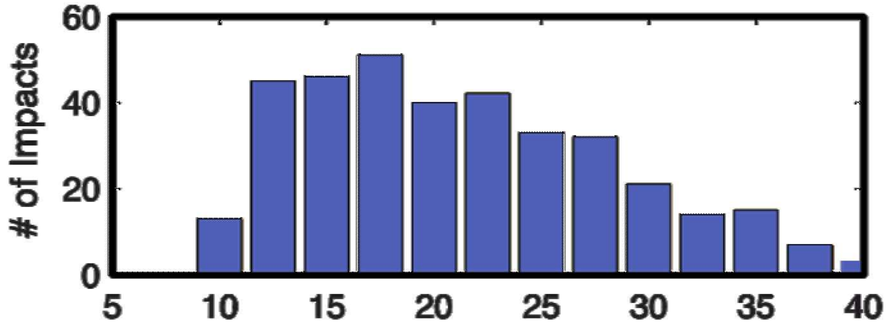


Partners: Harvard, UC Davis, LLNL

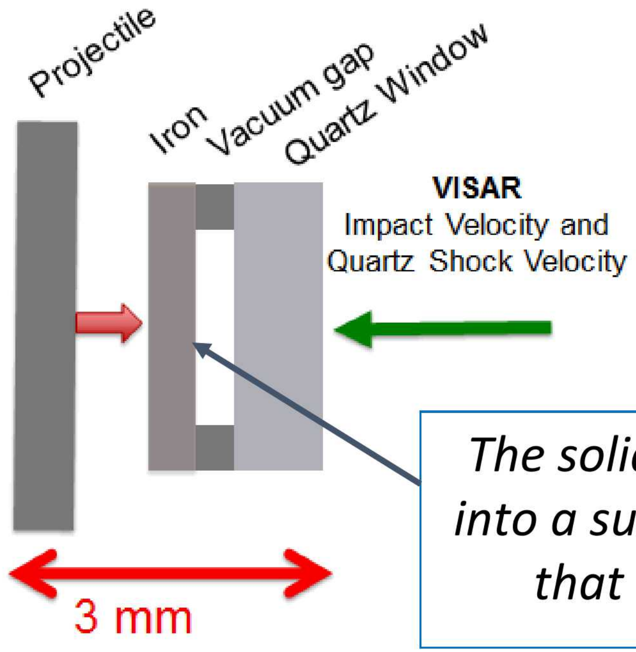
*N-body simulations from Raymond et al. 2009

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

Basic

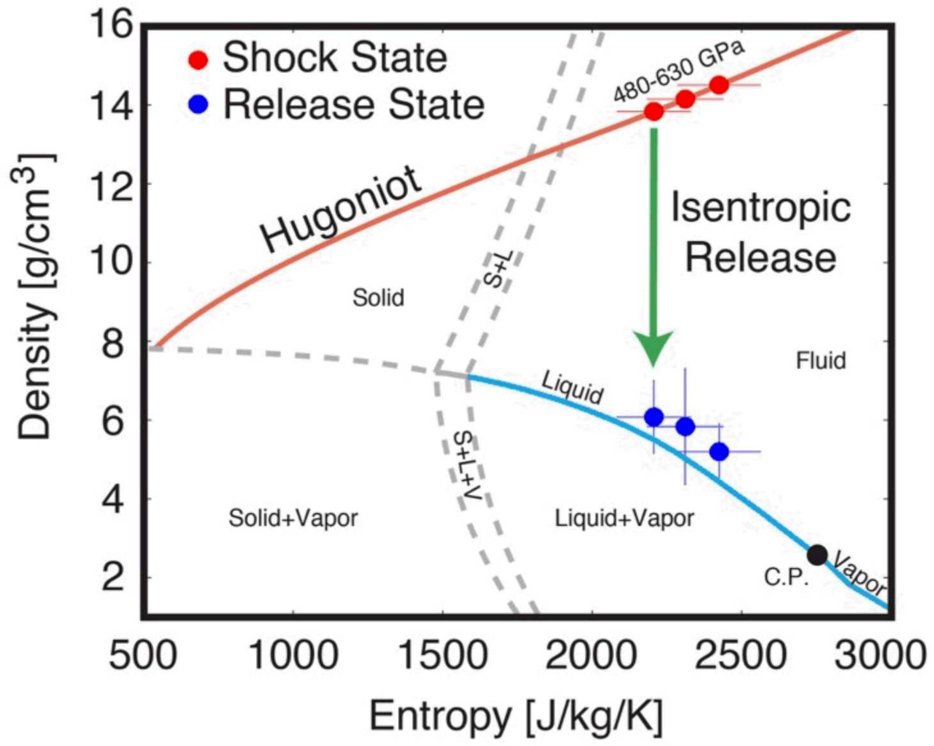


- On Z, we can launch flyer plates up to 40 km/s
- It is possible to directly probe the full range of planetary impact conditions



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

Iron Shock and Release Data

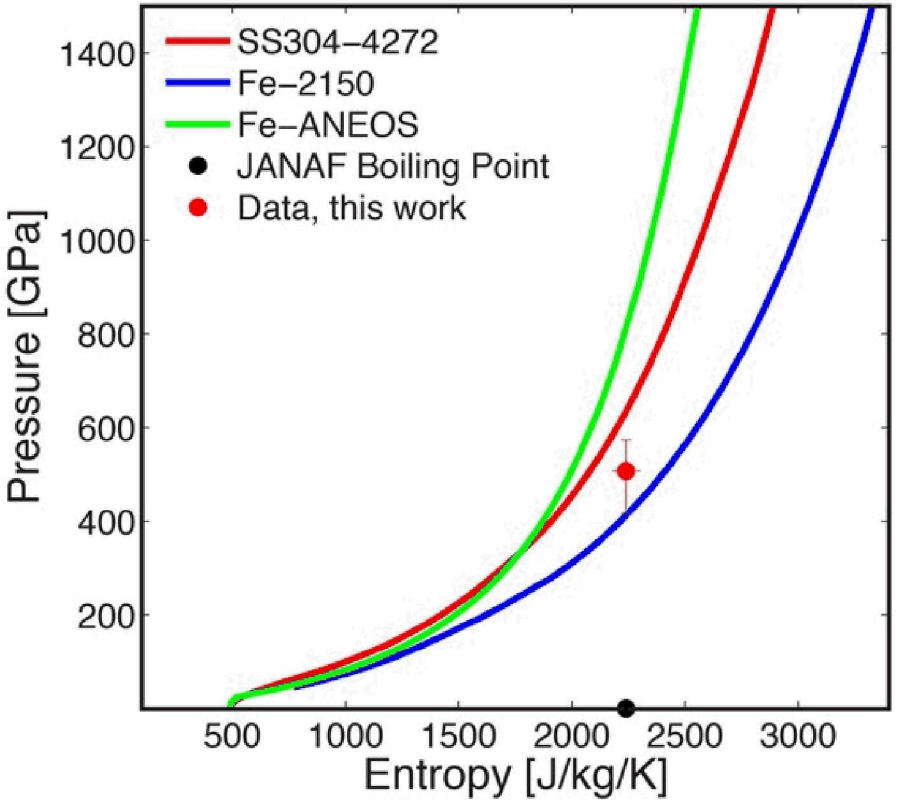


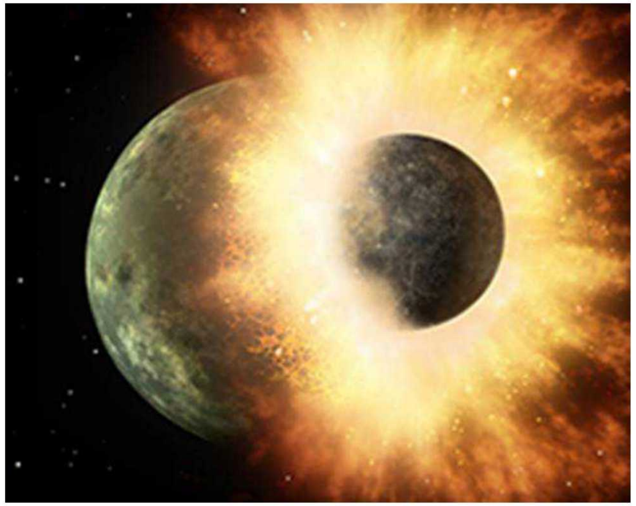
Partners: Harvard, UC Davis, LLNL

One of the first determinations of the thermal state of an opaque material on the Hugoniot*

Basic

Z data shows that iron vaporization occurs at significantly lower pressures than ANEOS suggests (the most broadly used model)





Team* concluded 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

Quantitative knowledge of the behavior of matter under extreme conditions is crucial for improving our understanding of planetary physics

Partners: Harvard, UC Davis, LLNL

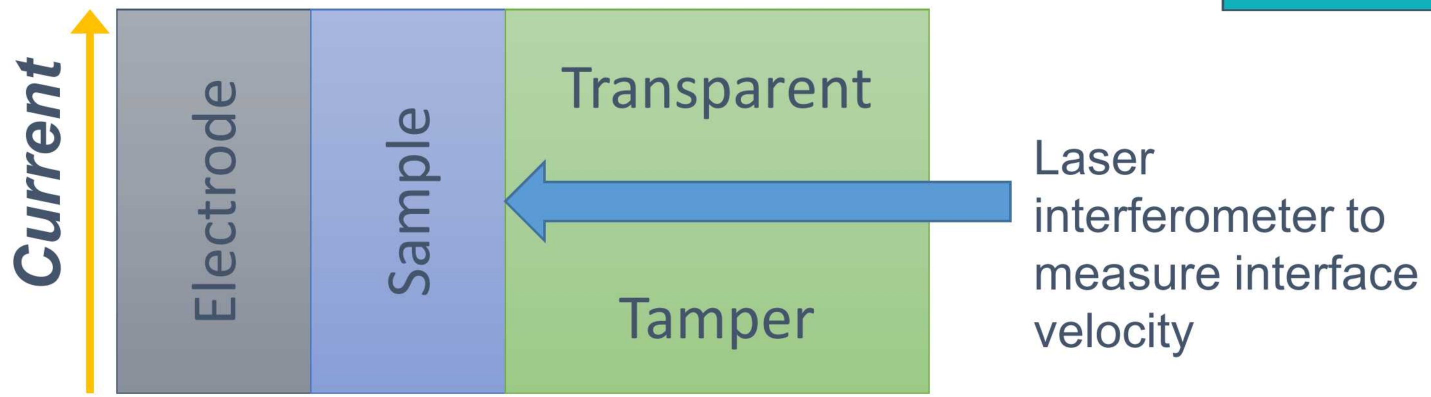
* *Impact vaporization of planetesimal cores in the late stages of planet formation*, R.G. Kraus et al., Nature Geoscience 2015

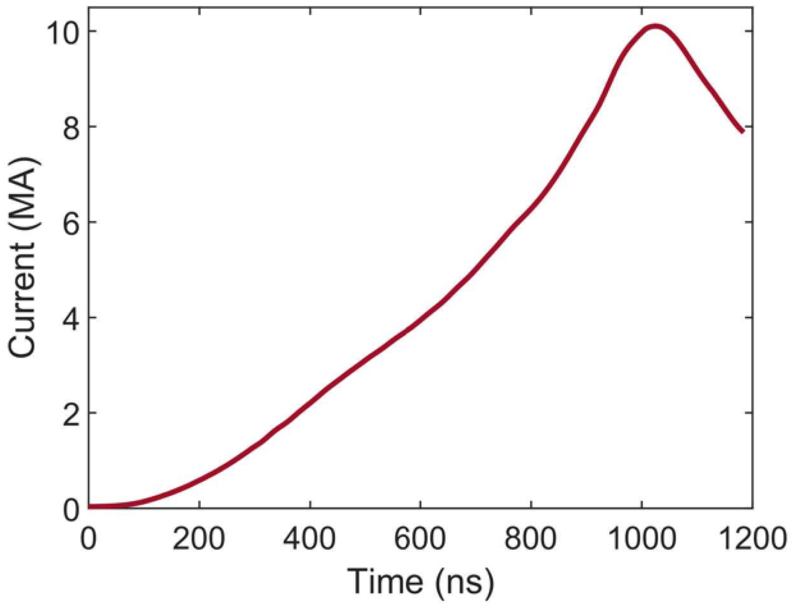
All three NNSA Laboratories are studying tantalum strength using different drivers and strain rates to understand how these affect the data

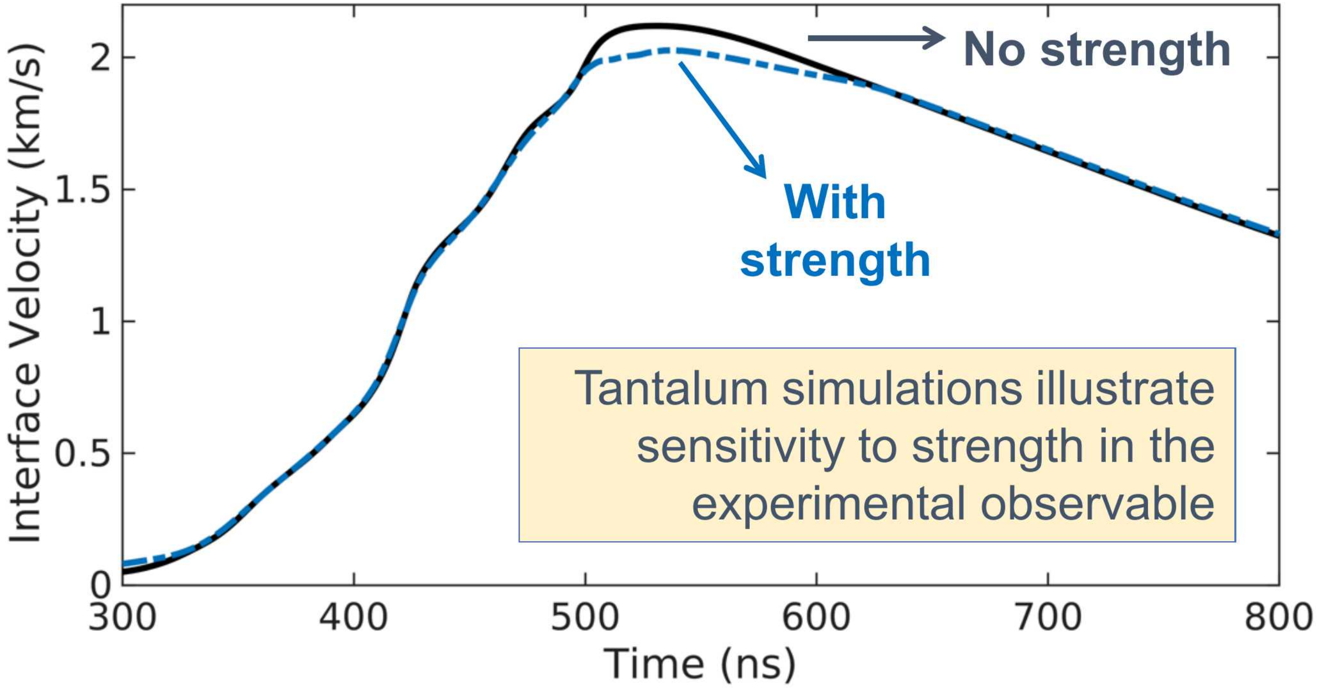
Use-Inspired

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





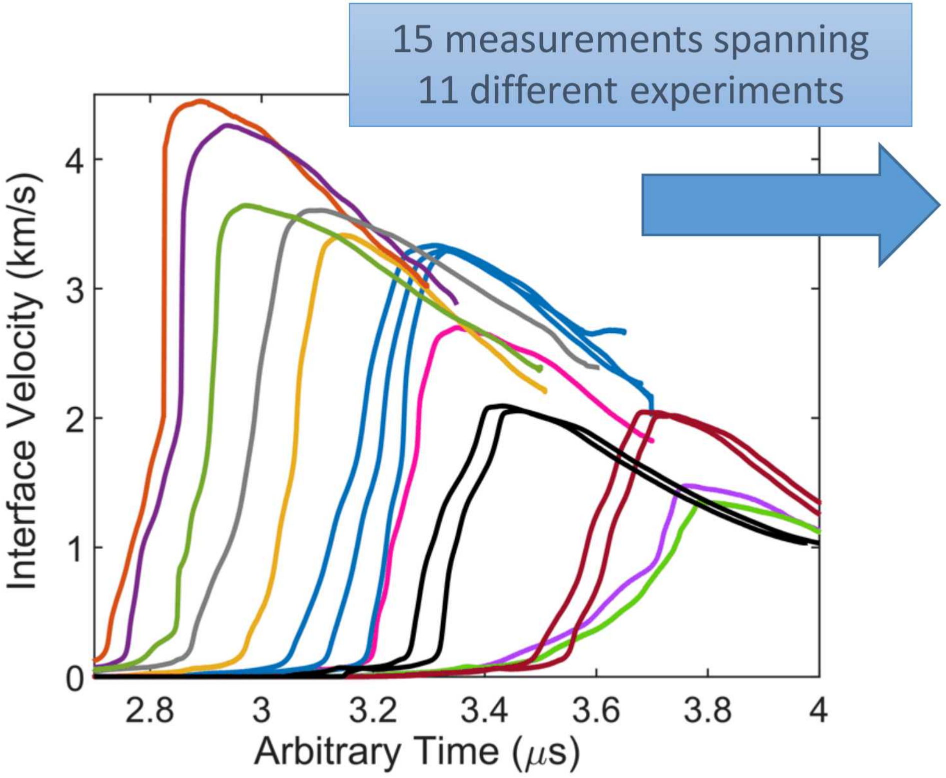


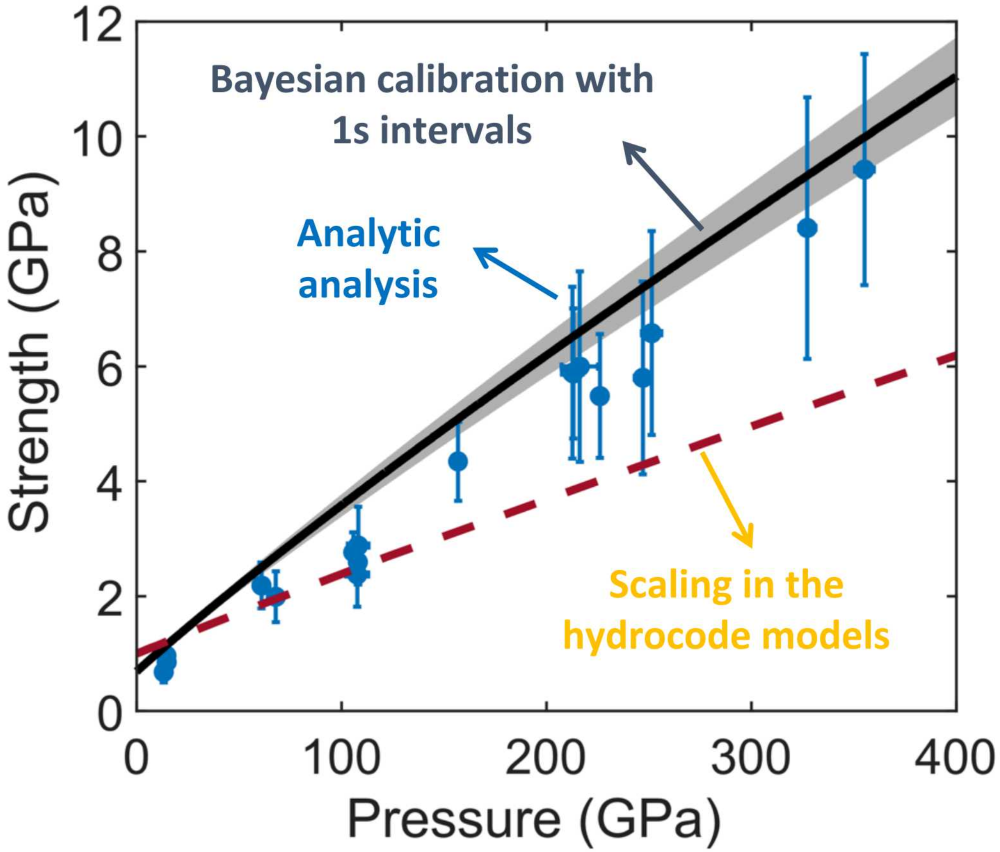
Partners: LANL, LLNL

Los Alamos NATIONAL LABORATORY EST.1943

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

Use-Inspired





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 dynamic materials research

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

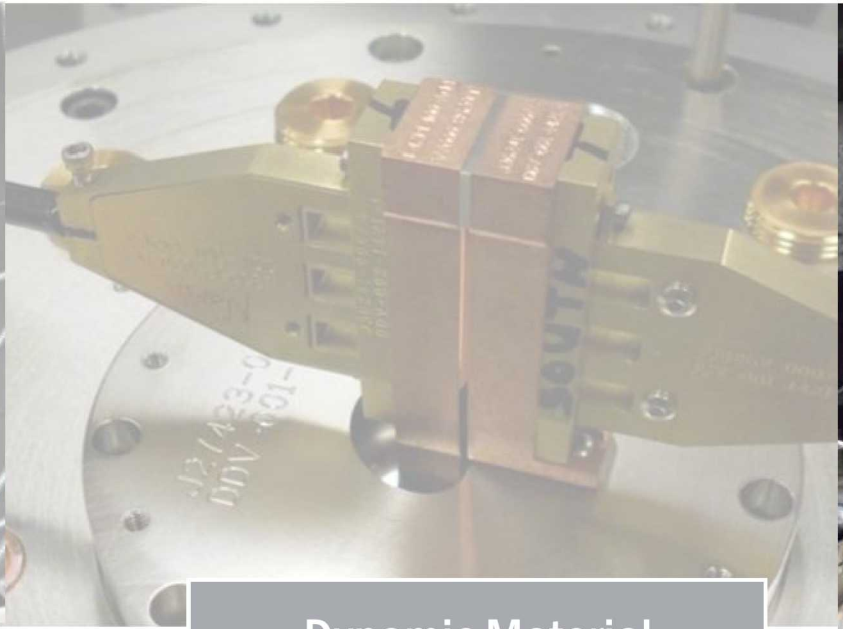
Compared response of 5- and 52-year-old Pu samples to improve pit aging analysis for certification models

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

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

Partners: LANL, LLNL

Radiation Science

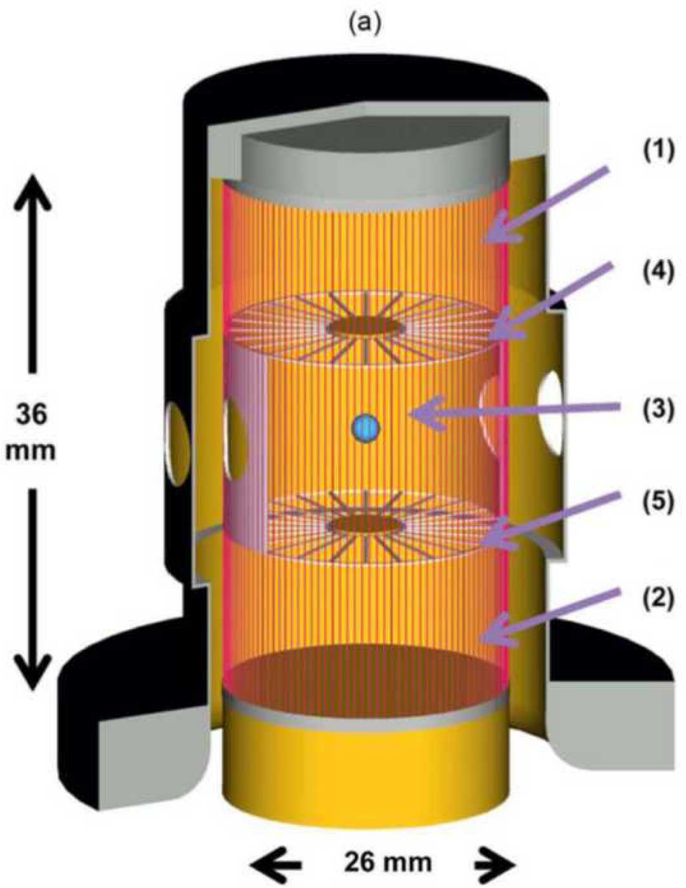


Dynamic Material Properties

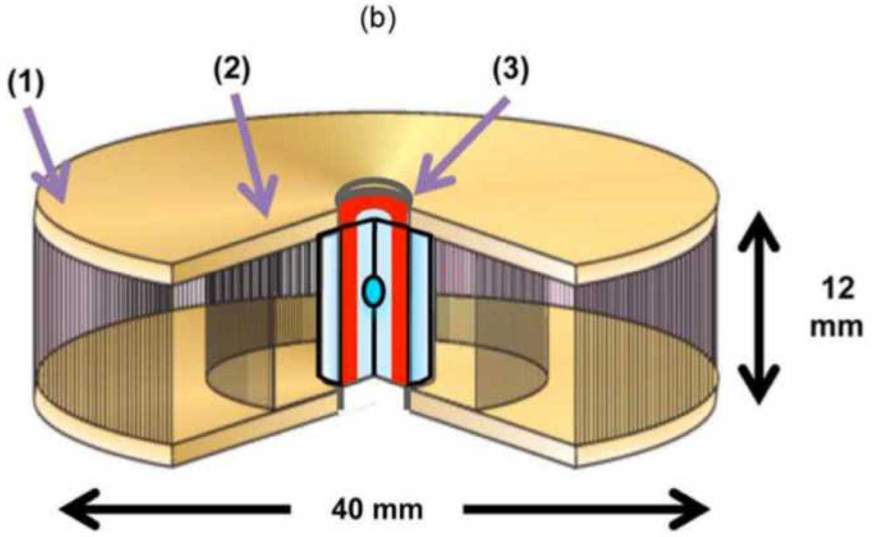
Inertial Confinement Fusion

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



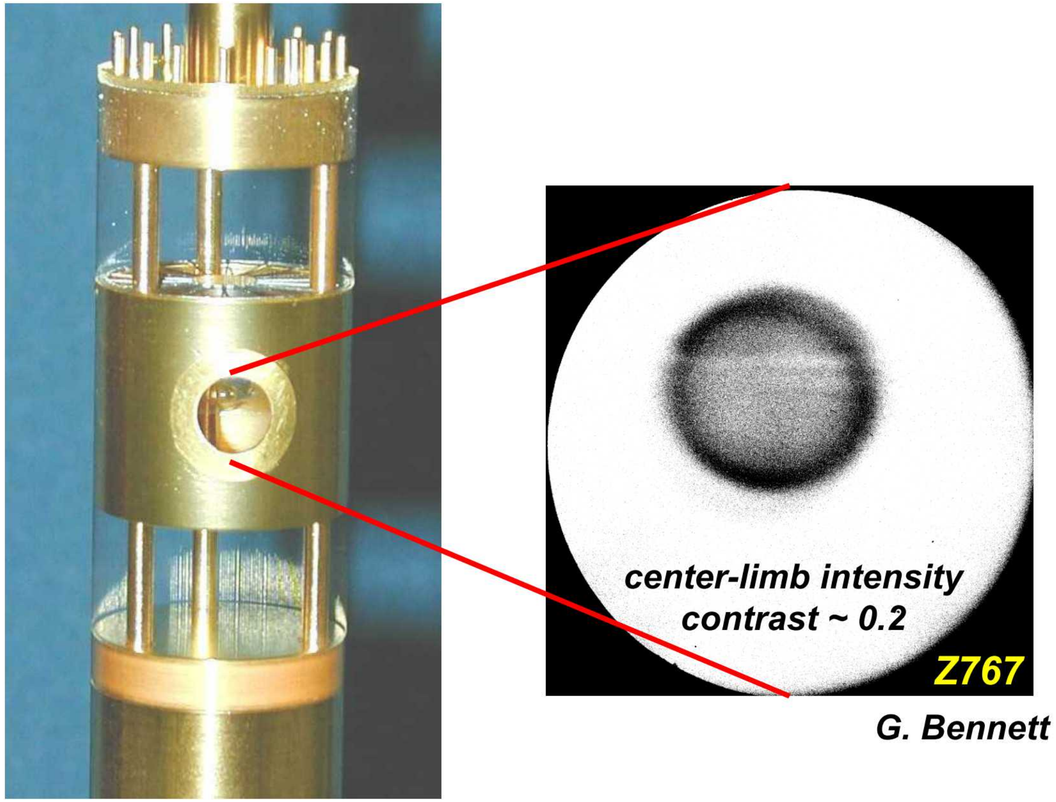
Z-pinch Dynamic Hohlraum (with capsule!)

Today there is renewed interest from LANL and LLNL in studying magnetic indirect drive e.g., See U07.000111, UP10.00040

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

Prior to 2007, Sandia scientists collaborated with LLNL scientists to evaluate capsule physics relevant to NIF today

Basic

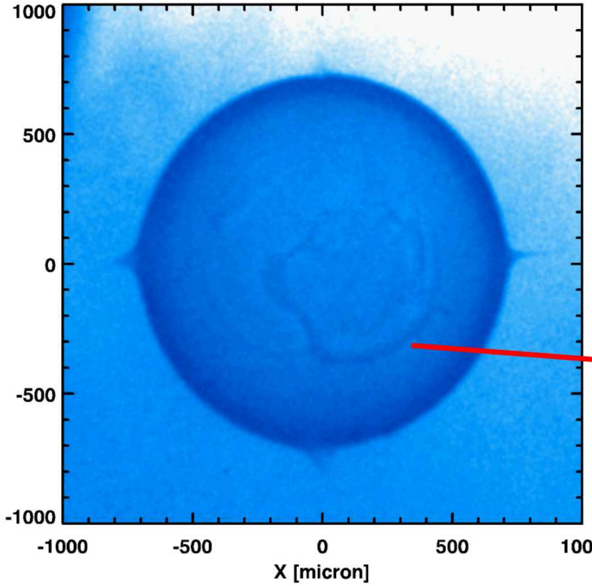


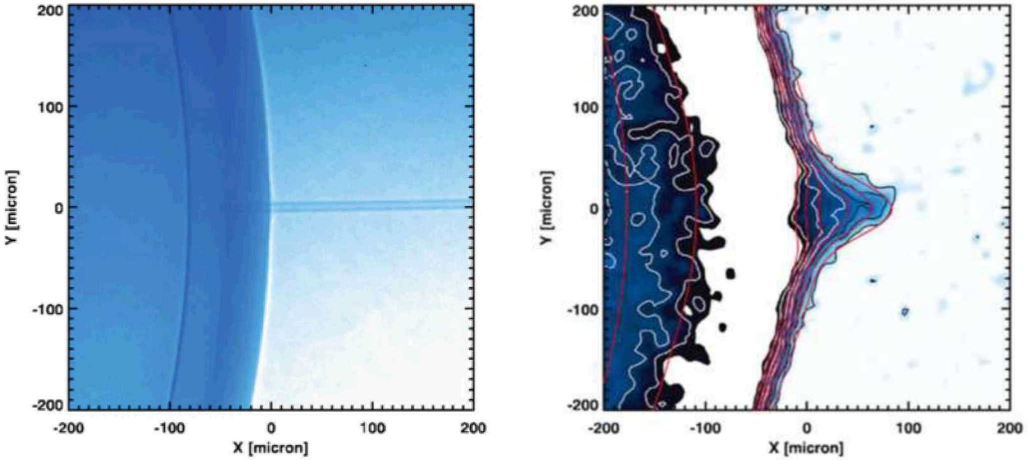
G. Bennett

Early radiographs from Z showed capsule perturbations resulting from the plastic tent used to hold the capsule in place. No one appreciated that it would still have such an impact under NIF conditions.

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

Up to four fill tubes studied per Z shot





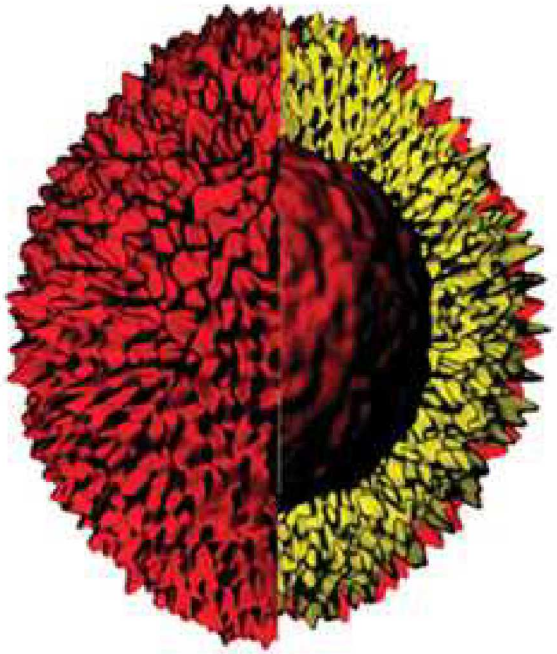
Later experiments provided benchmark data relevant to NIF simulations of the fill tube

G.R. Bennett *et al.*, Phys. Rev. Lett. (2007).

When we switched to directly using the magnetic field to compress solid liner targets containing fusion fuel, the biggest question was whether we could model implosion instabilities

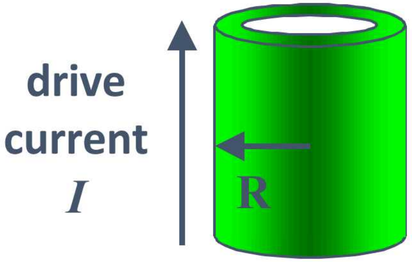
Basic

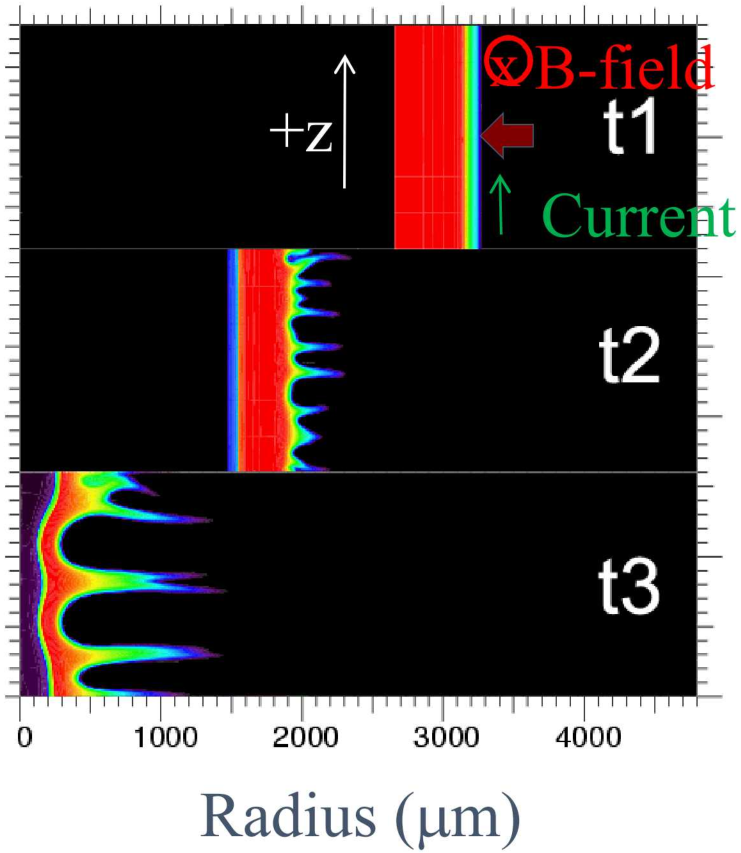
Classical Rayleigh-Taylor Boundary Instability



Magneto-Rayleigh-Taylor (MRT) Instability

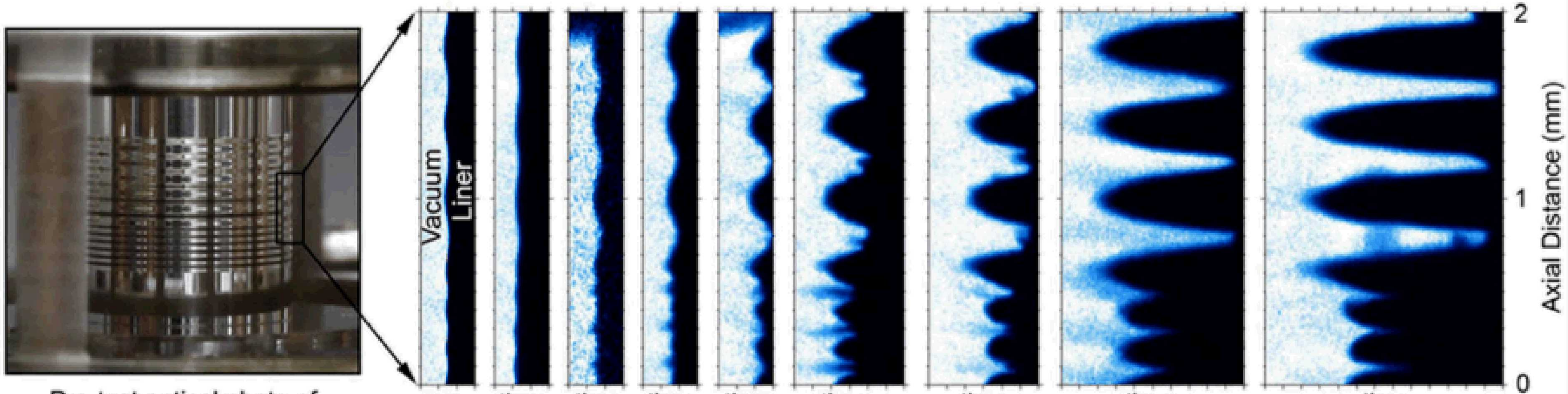
* E.G. Harris, Phys. Fluids 5, 1057 (1962).





To address this question, we did a number of fundamental implosion instability studies over several years

Basic

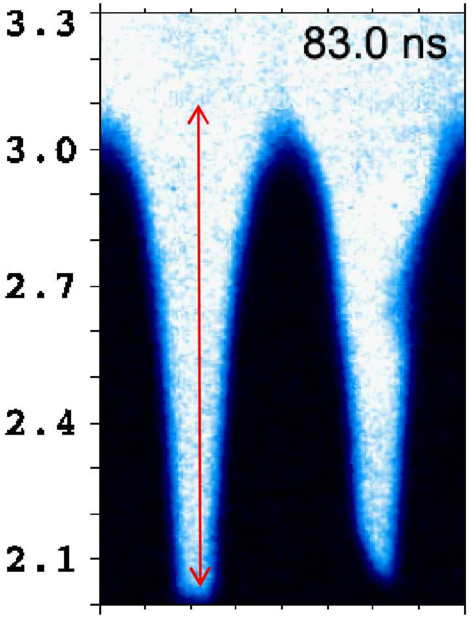


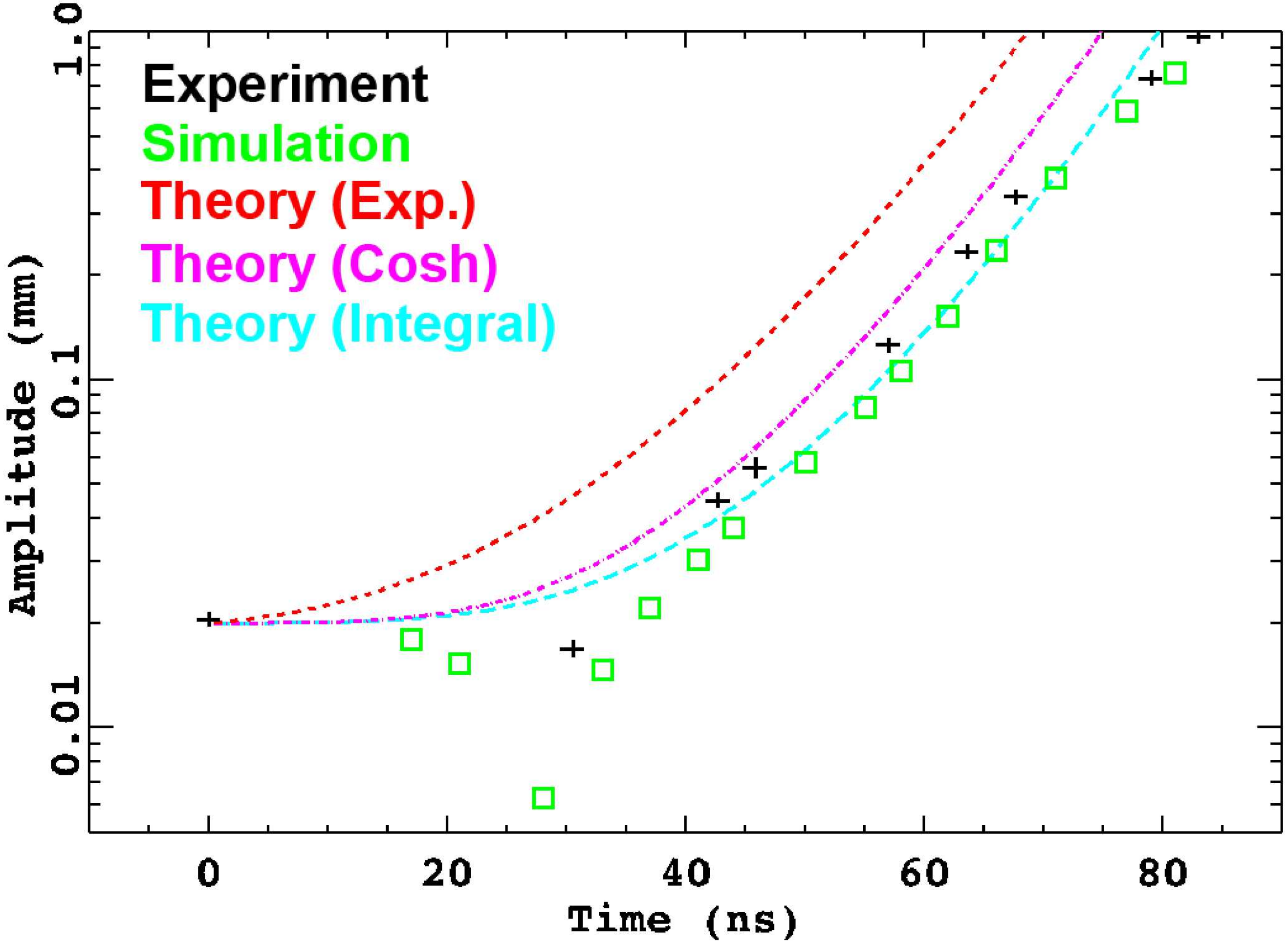
Pre-test optical photo of perturbed Al liner target

D.B. Sinars *et al.*, Phys. Rev. Lett. (2010).
D.B. Sinars *et al.*, Phys. Plasmas (2011).

To our pleasant surprise, the simulation tools were accurately able to predict the growth of the perturbation amplitude

Basic

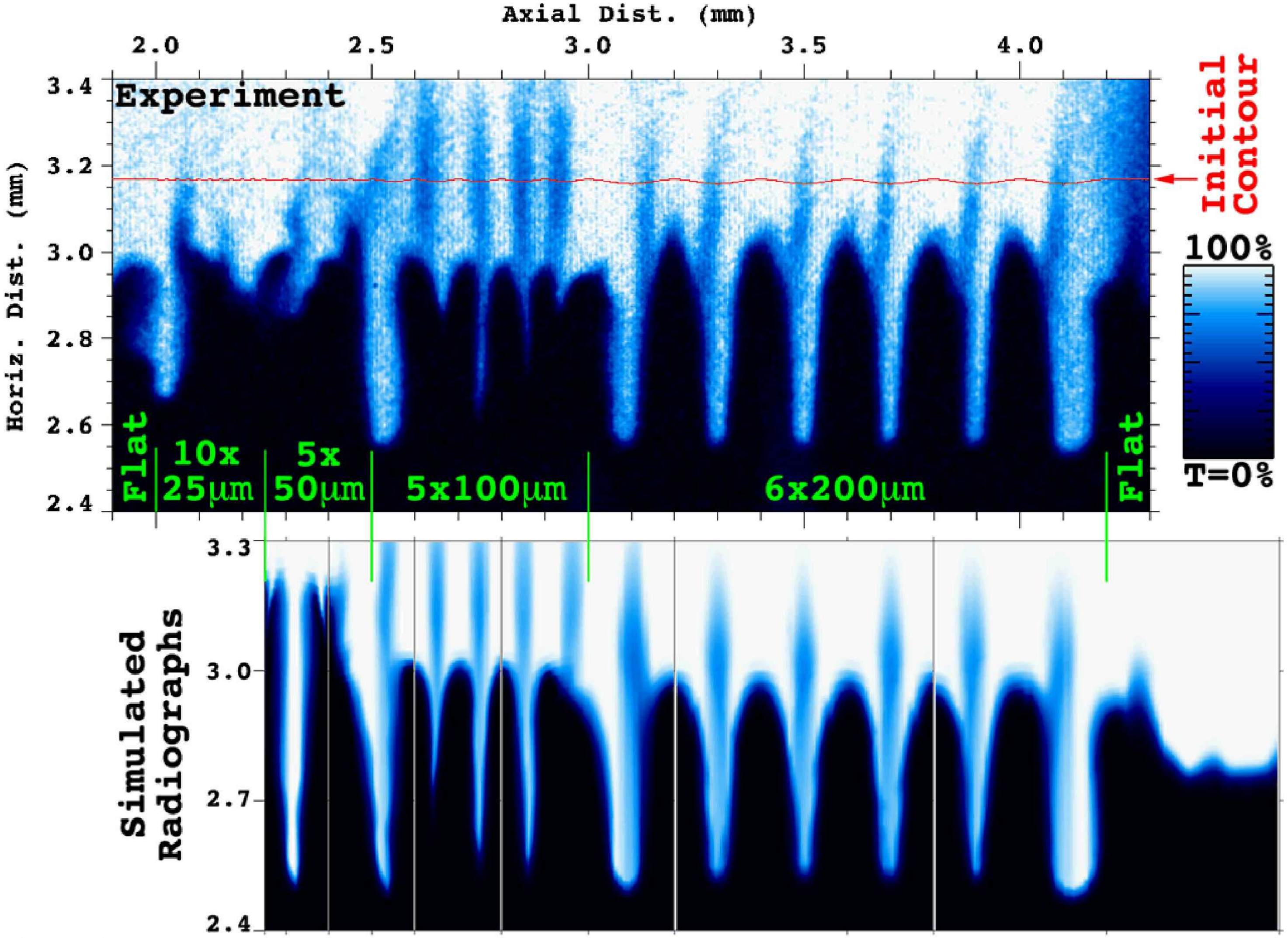




D.B. Sinars *et al.*, Phys. Rev. Lett. (2010).
D.B. Sinars *et al.*, Phys. Plasmas (2011).

Our pre-shot simulations were able to predict not only amplitude growth, but also small-scale features such as ablation and jetting

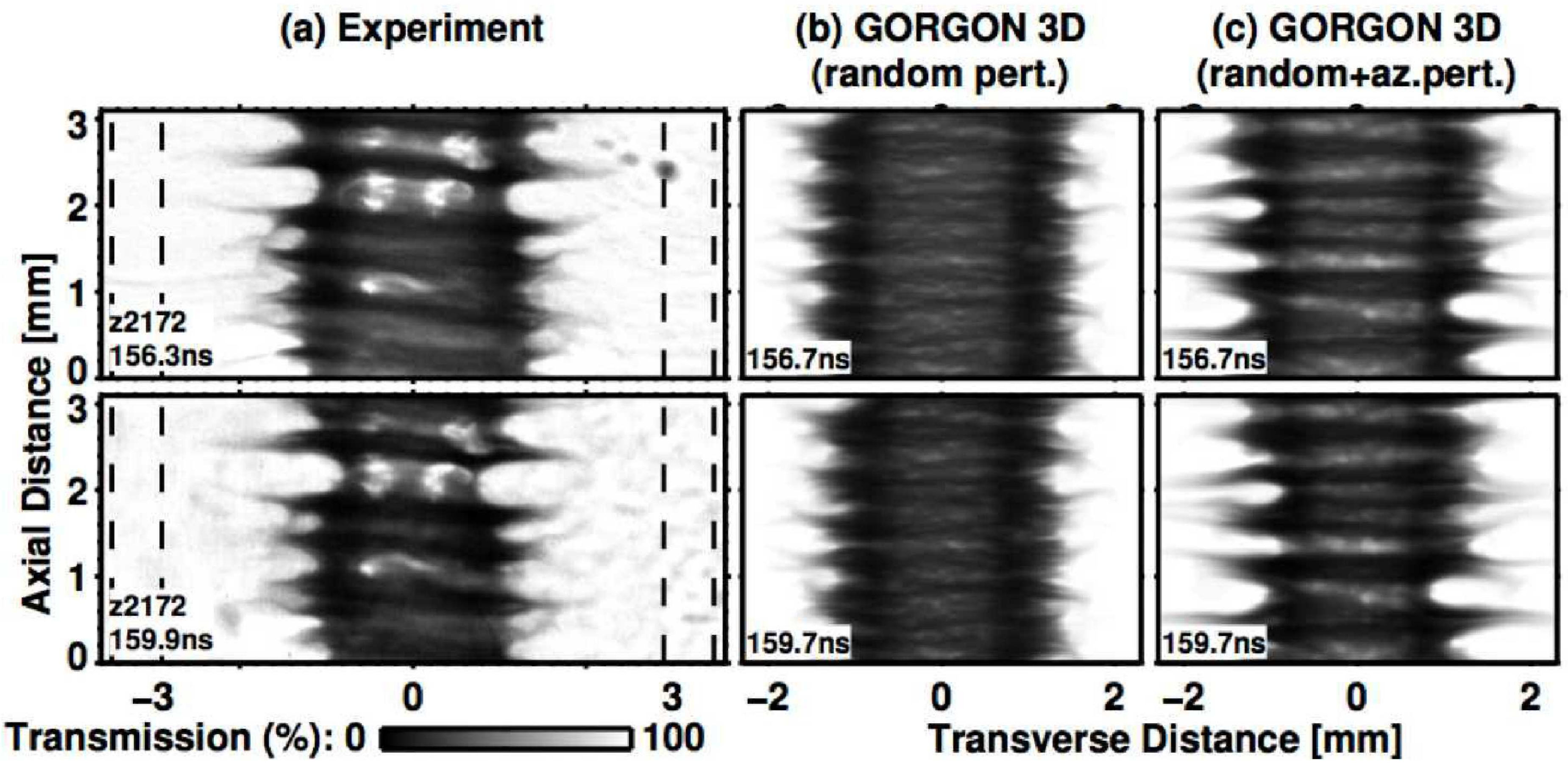
Basic



D.B. Sinars *et al.*, Phys. Rev. Lett. (2010).
D.B. Sinars *et al.*, Phys. Plasmas (2011).

An early mystery was why unperturbed liner implosions exhibited highly correlated, cylindrical instabilities

Basic



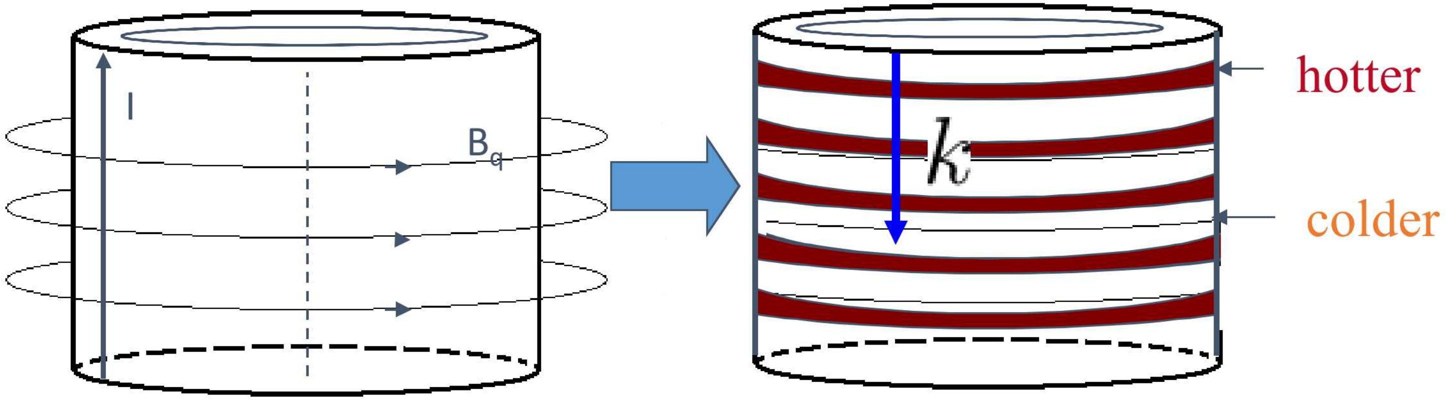
Achieving the observed structure in 3D simulations required seeding azimuthally-correlated perturbations early in time

R.D. McBride *et al.*, Phys. Rev. Lett. (2012). See also posters by D.E. Ruiz UP10.00045; D. Yager-Elorriaga UP10.00047

We hypothesized that the correlation was seeded at early times by electro-thermal instabilities that arise when resistivity depends on temperature

Basic

Predominant energy deposition mechanism in the metallic phase is Ohmic/resistive heating



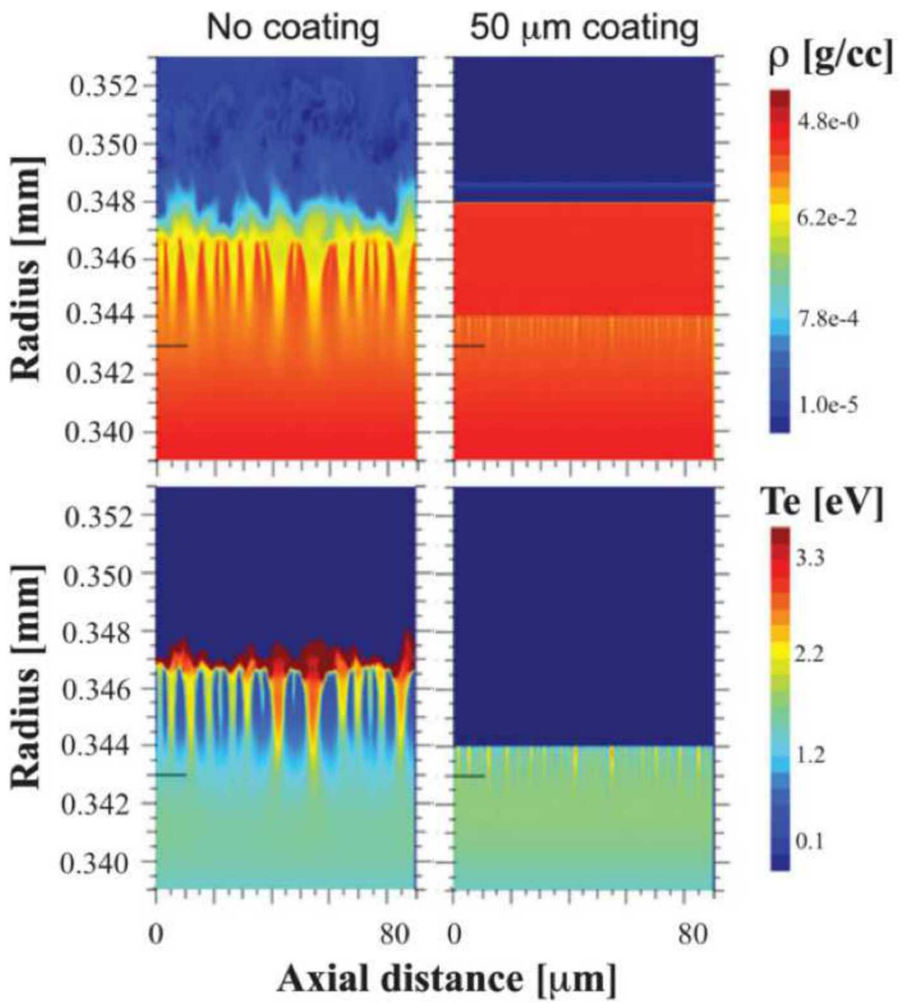
Since resistivity increases with temperature in metals ($d\eta/dT>0$), striation form of the electro-thermal instability can occur.

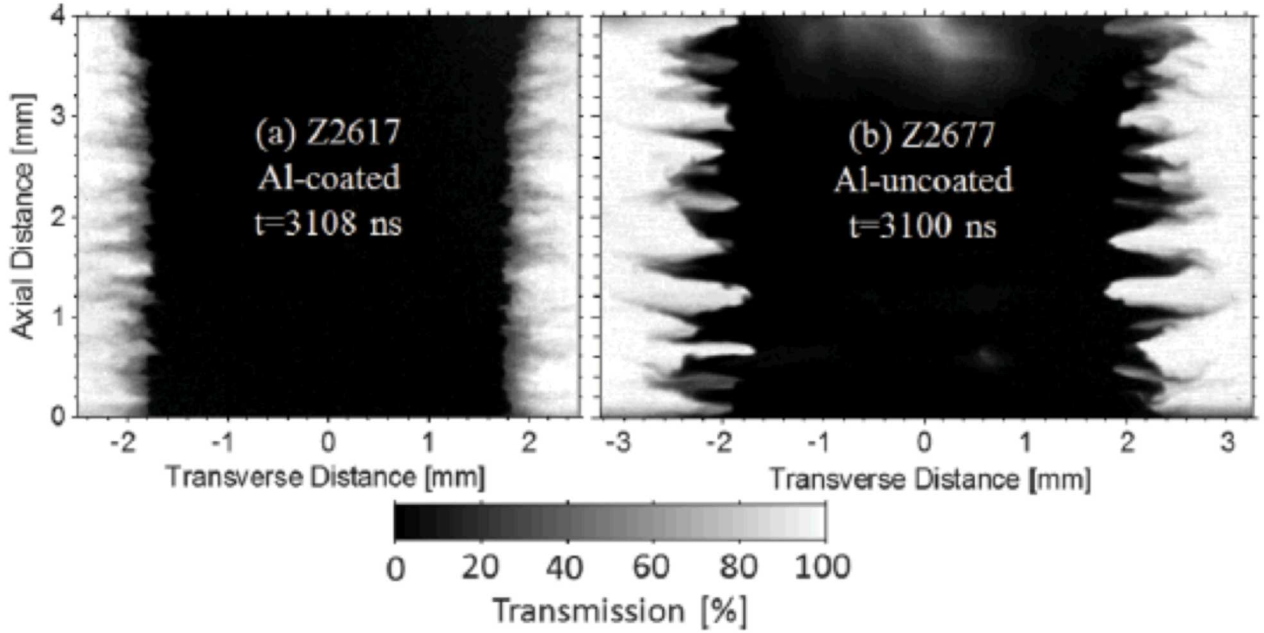
Eventually, hot plasma expands, creating density perturbations that readily couple to magneto-Rayleigh-Taylor instability

See talk by E.P. Yu later today (PI2.00006); Other related ETI work by U. Nevada-Reno includes CP10.00051; CO4.00004; JP10.00090

Simulations suggested that the effect of ETI could be mitigated

Basic





Thick dielectric coatings suppress ETI and the resulting density perturbations

K.J. Peterson *et al.*, Phys. Rev. Lett. (2014).

Liner implosion experiments show a dramatic difference with and without coatings

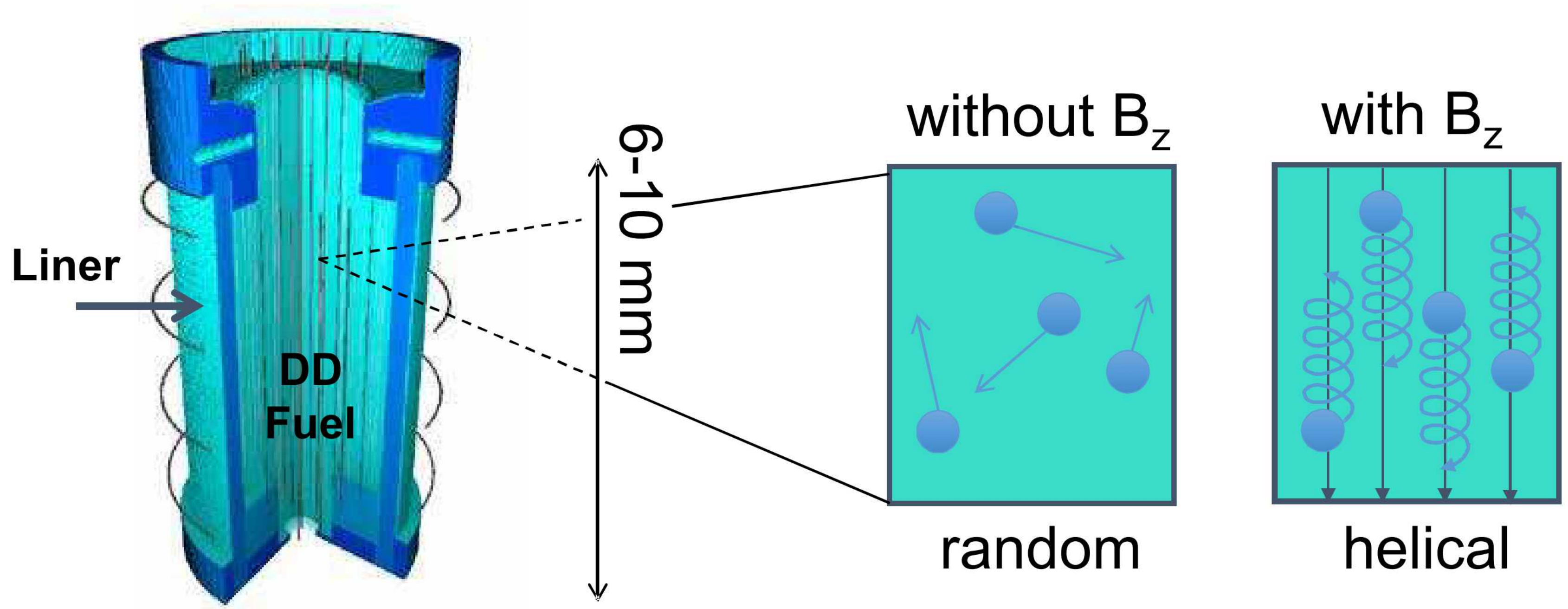
T.J. Awe *et al.*, Phys. Rev. Lett. (2016).

See talk by E.P. Yu later today (PI2.00006)

MagLIF is a Magneto-Inertial Fusion (MIF) concept

Use-Inspired

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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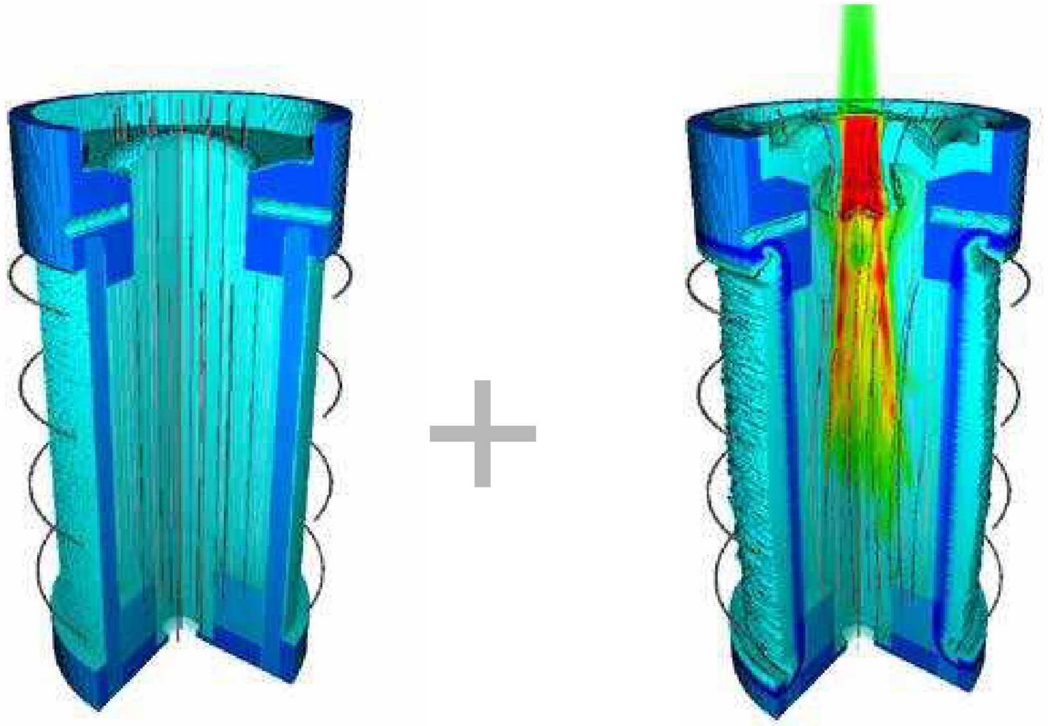
Use-Inspired



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

Magnetization

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

Preheat

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

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

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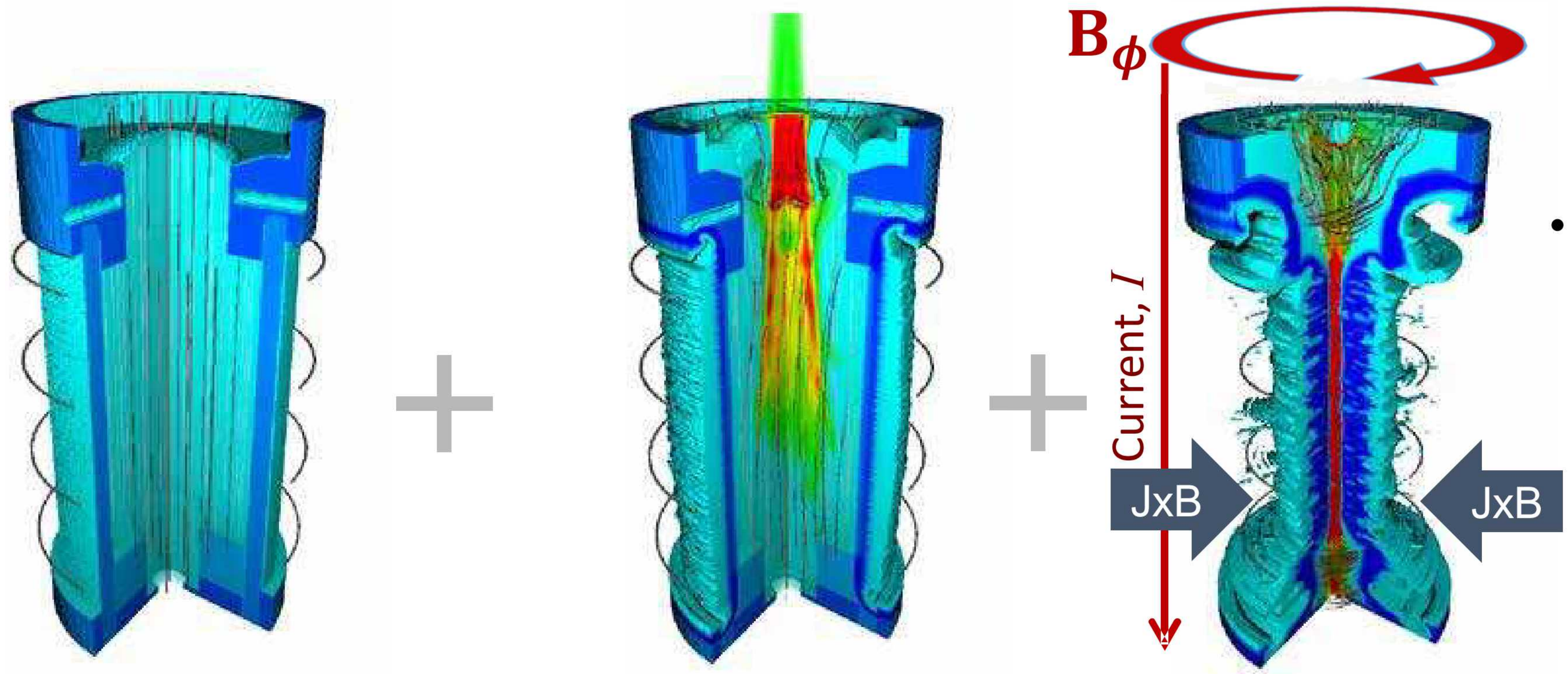


- **Magnetically Driven Implosion**
  - **"Only" ~100 km/s (vs. ~380 km/s on NIF)**
  - **B-field amplified to >10,000 T**

Magnetization

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

Preheat

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

Implosion

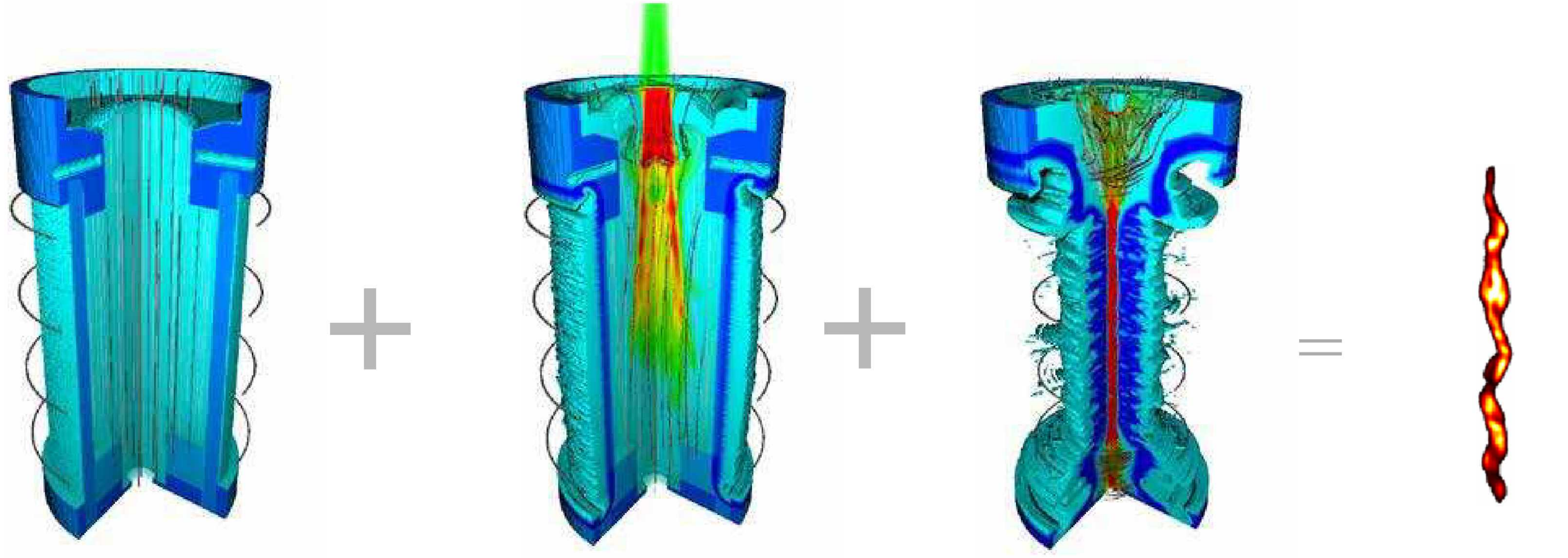
- PdV work to heat fuel
- Flux compression to amplify B-field

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

MagLIF is a Magneto-Inertial Fusion (MIF) concept

Use-Inspired

Relies on three components to produce fusion conditions at stagnation



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

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

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

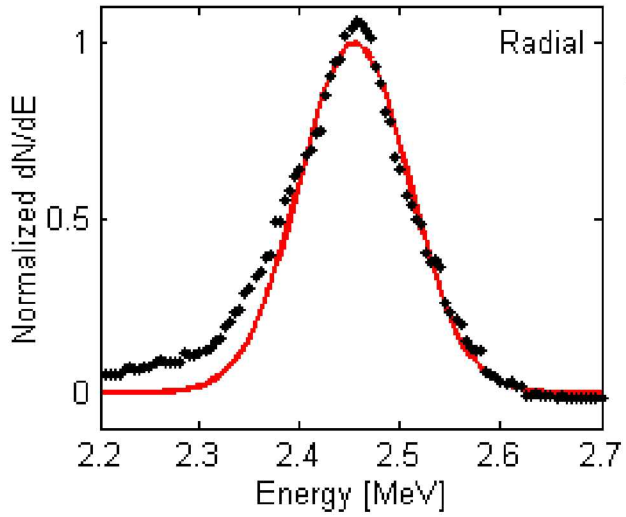
Stagnation
- Several keV temperatures
- Several kT B-field to trap charged fusion products

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

MagLIF allowed us to demonstrate the key tenets of magneto-inertial fusion

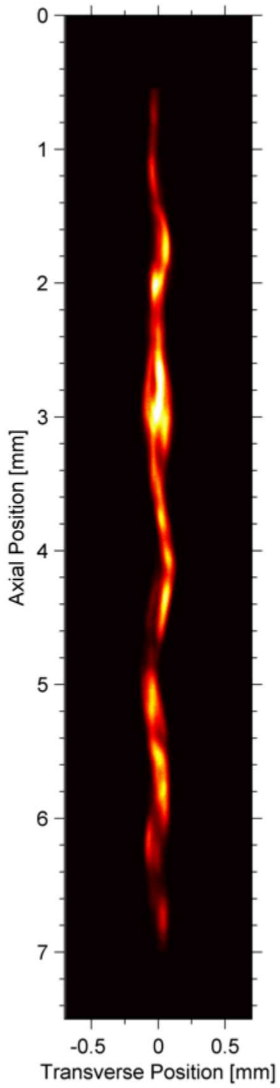
In a target that would not produce significant yield without both heating and magnetization

Use-Inspired

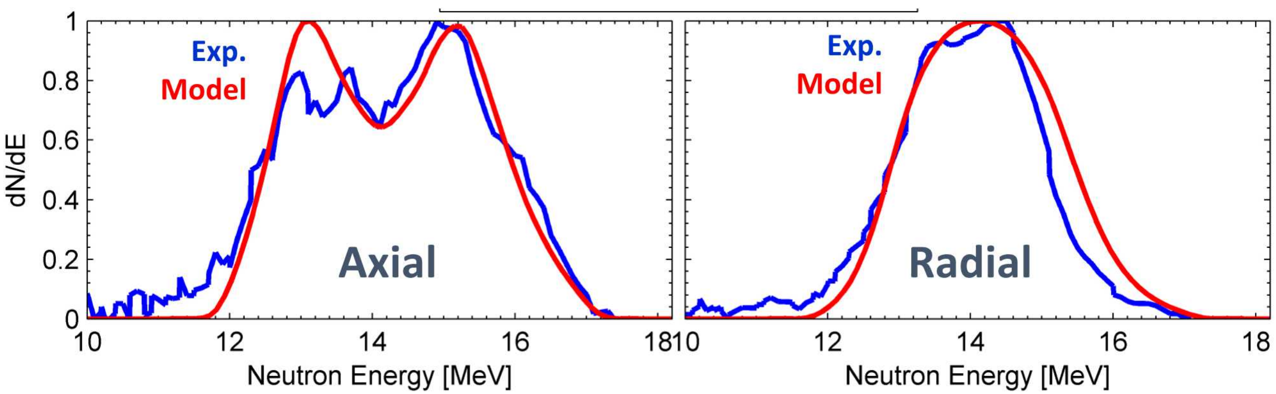


Thermonuclear neutron generation with fusion-relevant ion temperatures (2-3 keV)

High aspect ratio fuel column at CR > 30



Highly magnetized fuel at stagnation (>0.3 MG-cm)

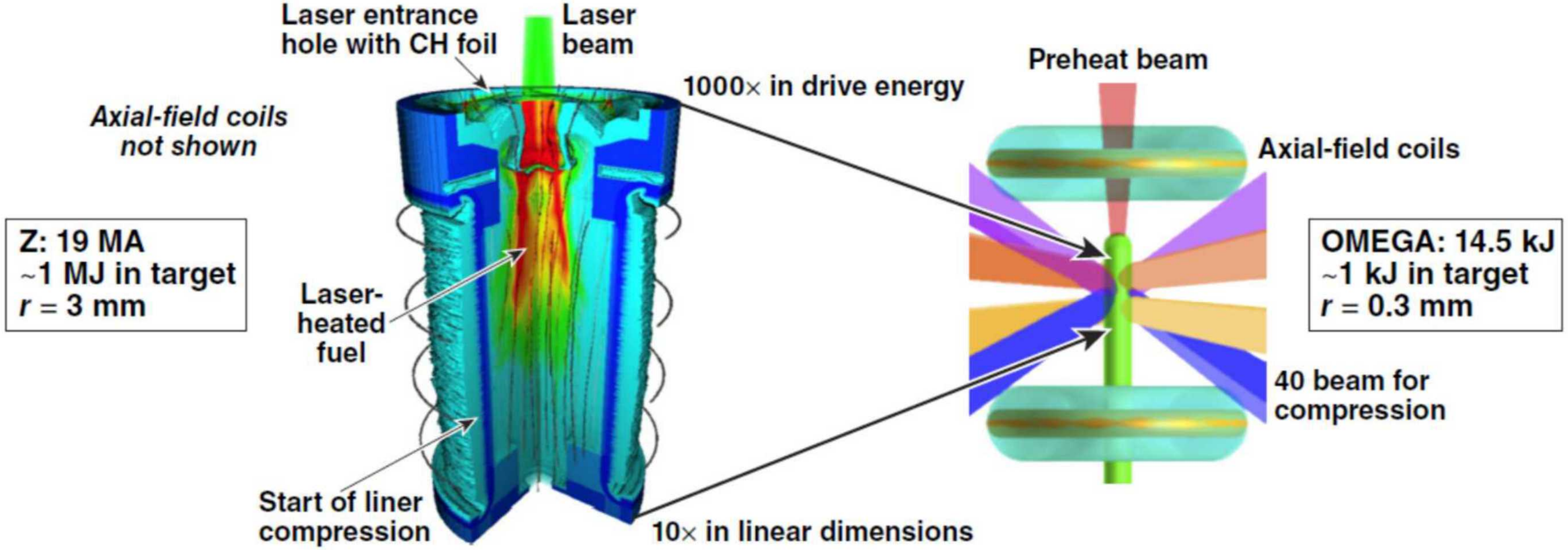


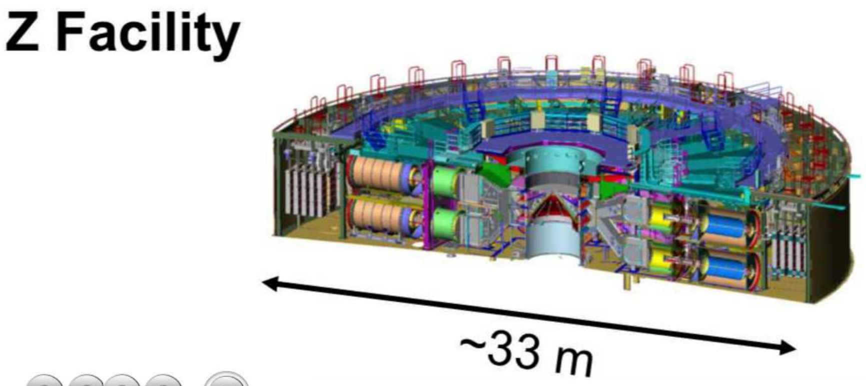
Secondary DT Neutron Spectra

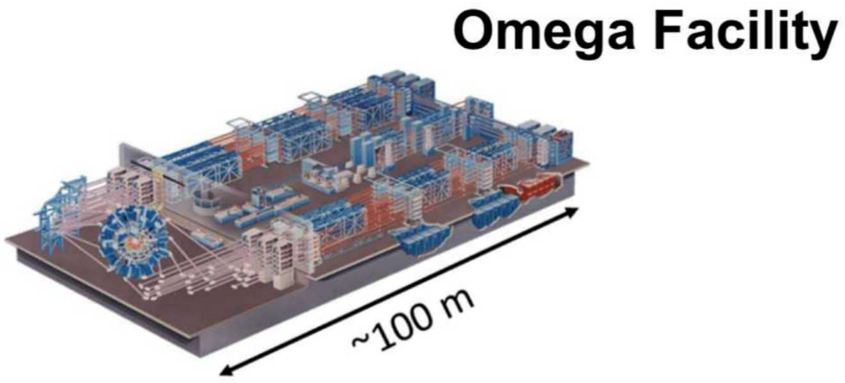
M.R. Gomez *et al.*, Phys Rev Lett (2014); P.F. Schmit *et al.*, Phys Rev Lett (2014).

We then demonstrated that MagLIF can be scaled down 1000x in energy

Use-Inspired





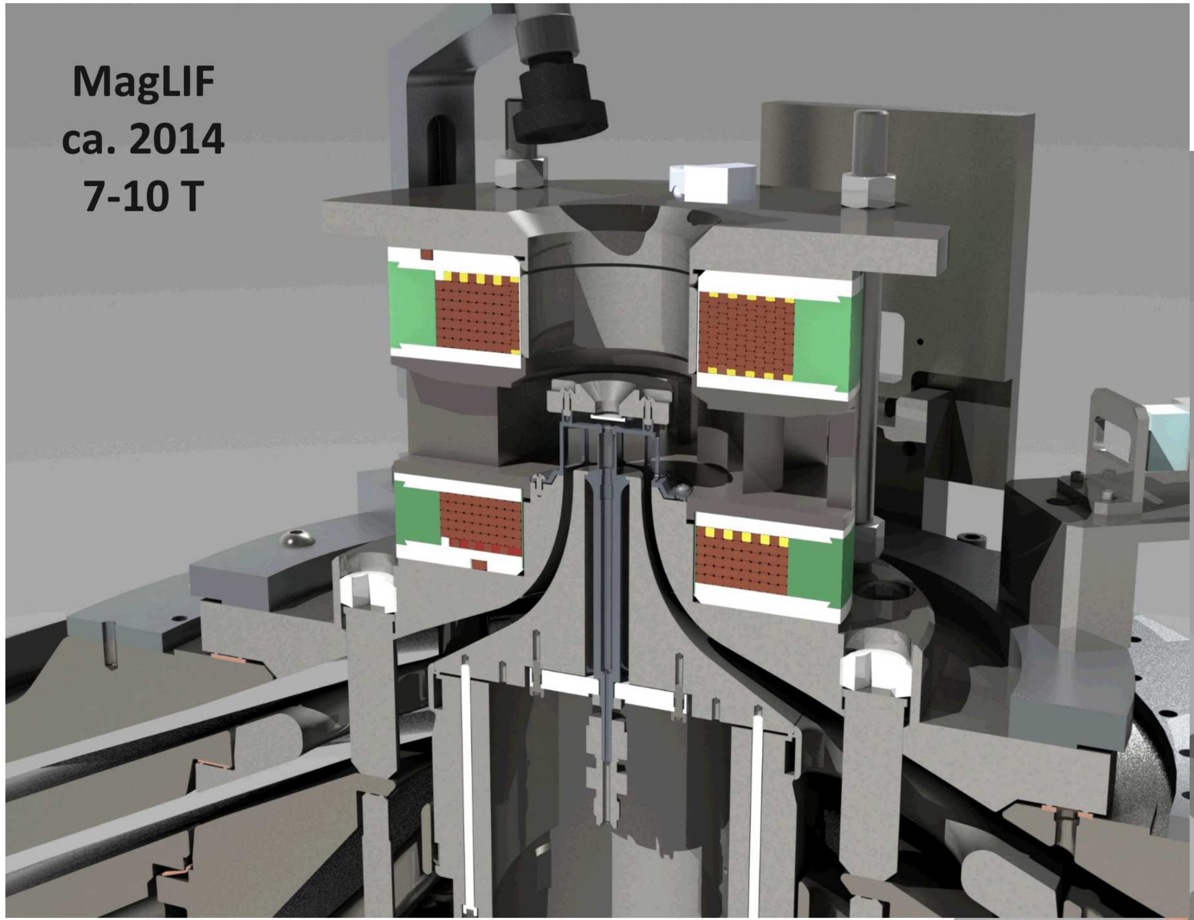


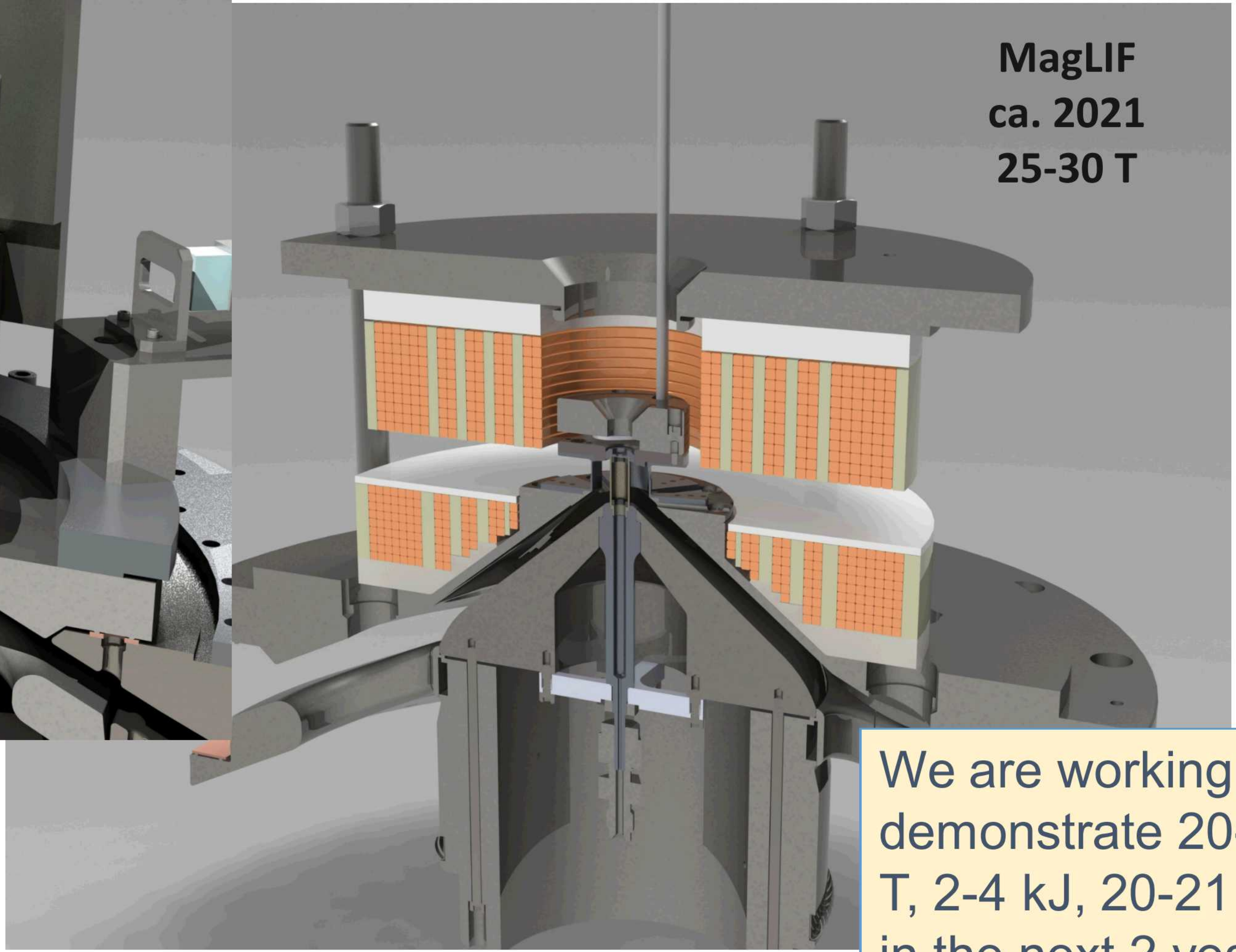
CHANGING WHAT'S POSSIBLE

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

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

Use-Inspired



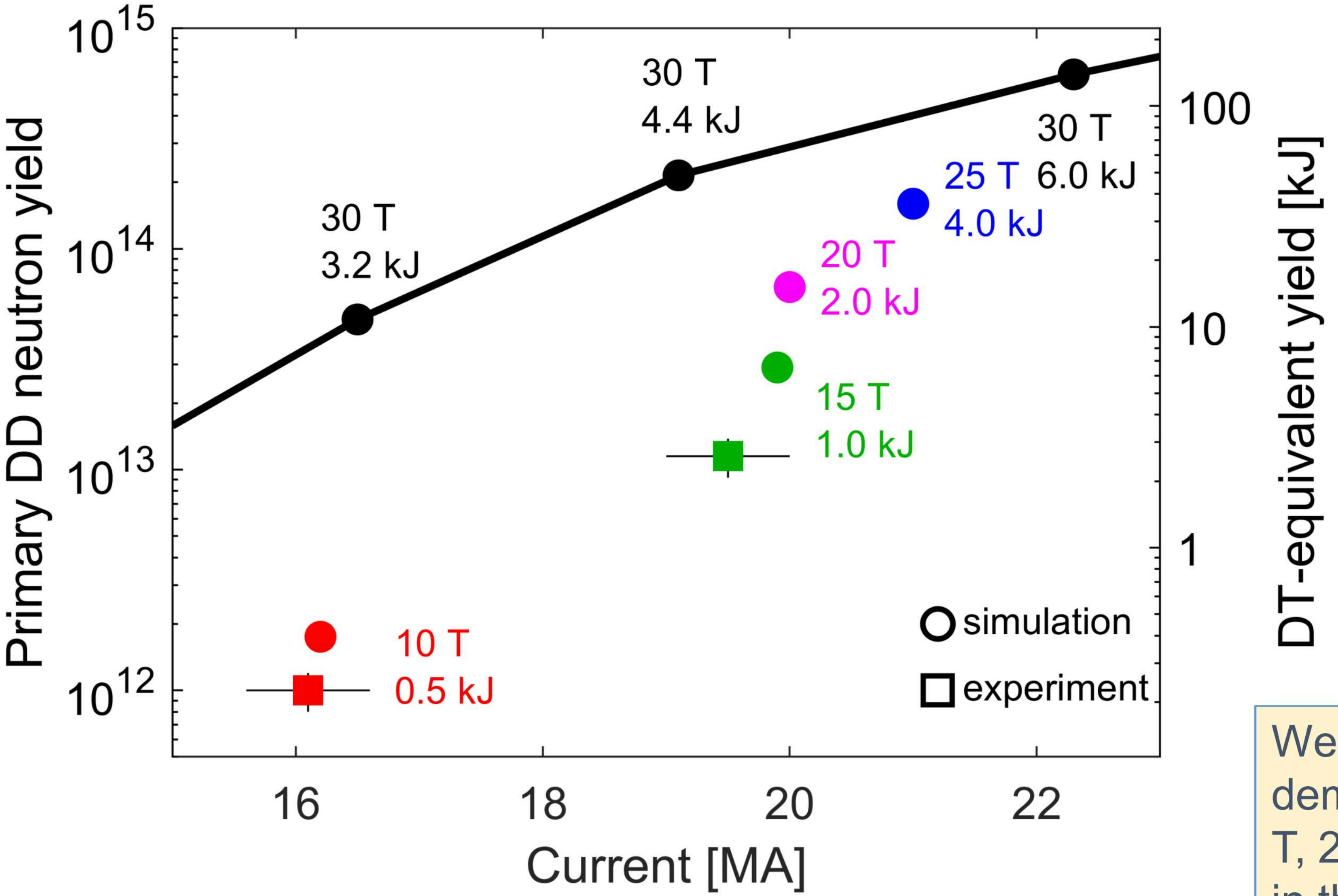


We are working to demonstrate 20-25 T, 2-4 kJ, 20-21 MA in the next 2 years

S. A. Slutz, et al., Phys. Plasmas (2018); Invited talk by M. Gomez GI3.00004; see also P. Schmit TO6.00001; M. Weis TO6.00002

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

Use-Inspired



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

Applied

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

Excerpt from NNSA 2018 ICF Framework Document

Future Science Opportunities

A number of exciting scientific challenges and opportunities lie ahead on Z

Basic

Use-Inspired

Applied

Examples Include:

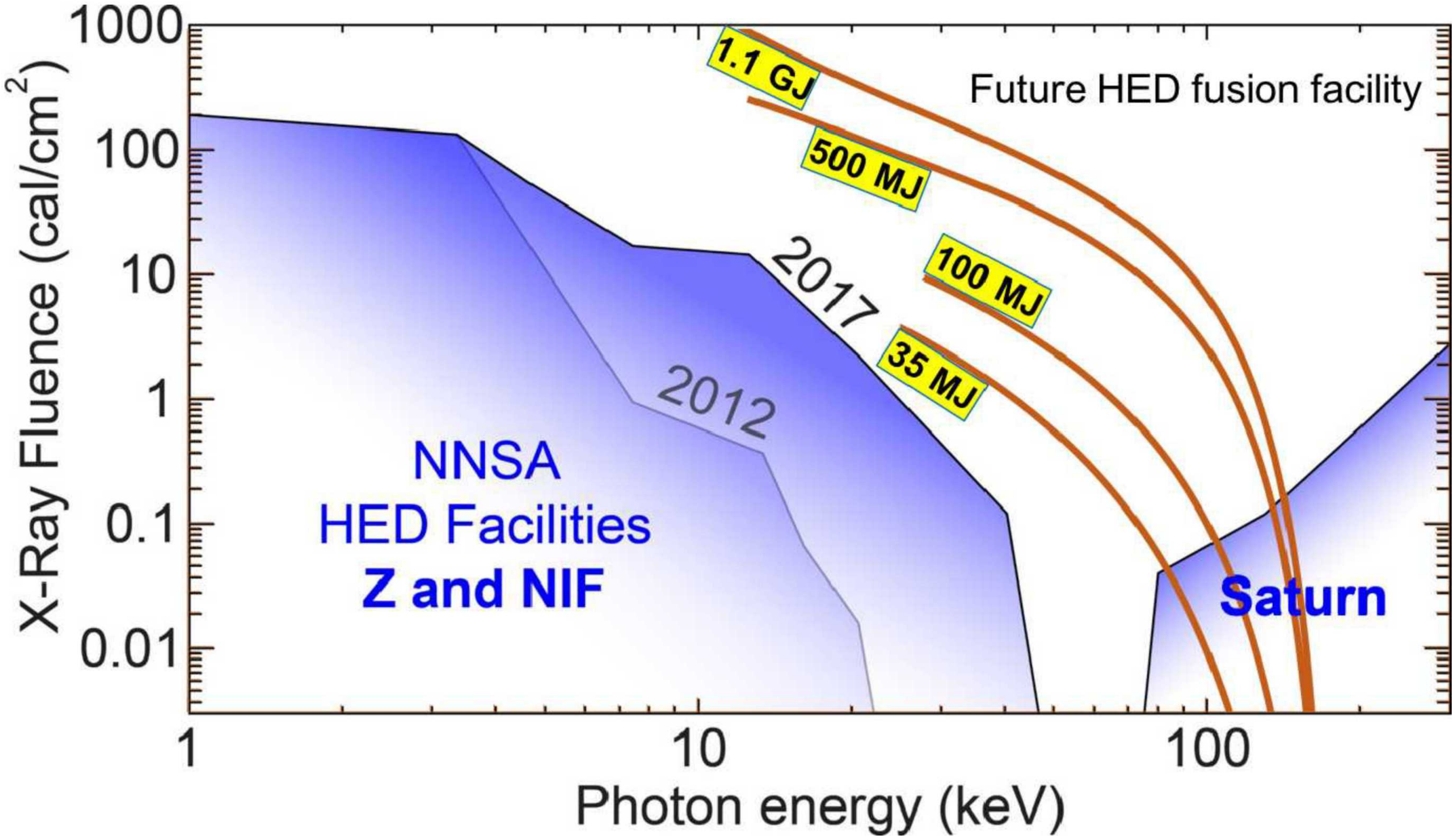
- **Dynamic Material Properties**:
  We will observe dynamic freezing of liquid cerium with unprecedented precision
  We will quantify the importance of phase transition kinetics in macroscopic samples
- **Radiation Science**:
  We will model energetic electron beams in z-pinches and predict non-thermal, multi-keV x-ray production
- **Fusion Science**:
  We will demonstrate 30-100 kJ DT-equivalent yields on the existing Z machine
  Can we achieve multi-MJ fusion yields in the laboratory on a future machine?
- **Power Flow Physics:**
  We will model the behavior of plasmas carrying 80 TW of electrical current in gaps spanning several millimeters
  Can we model plasmas carrying >800 TW of electrical current on a future

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

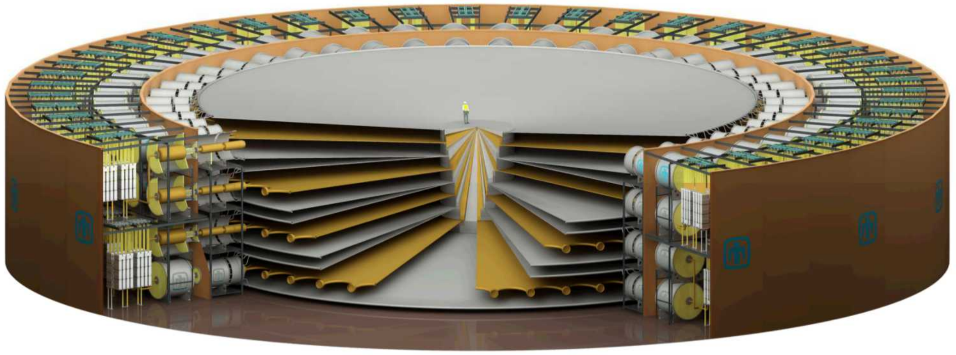
Applied

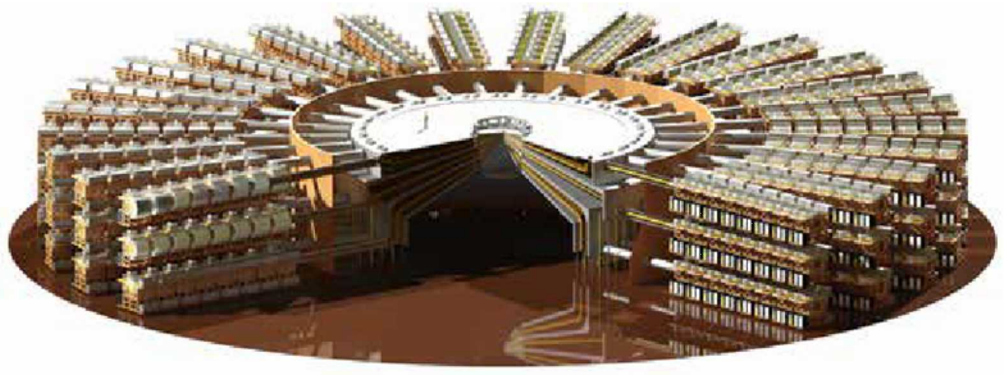


Such a Z-pinch driver would also be capable of powerful radiation-only x-ray sources.

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

- **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

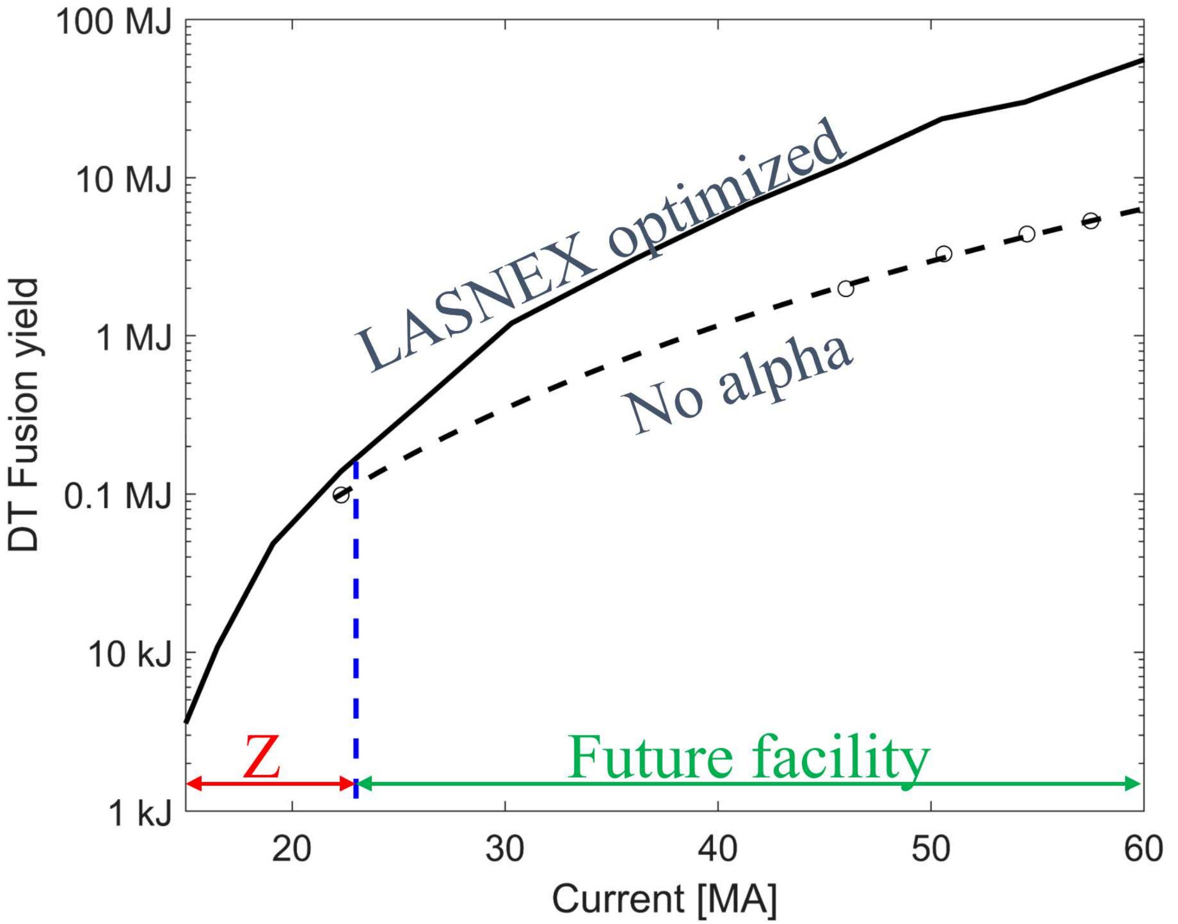
Z will celebrate ~35 years of z-pinch physics in 2030, with some parts of infrastructure ~45 years old.

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

Achieving close to 100 kJ yield on Z with MagLIF would improve the credibility of scaling to multi-MJ fusion yields on a future facility

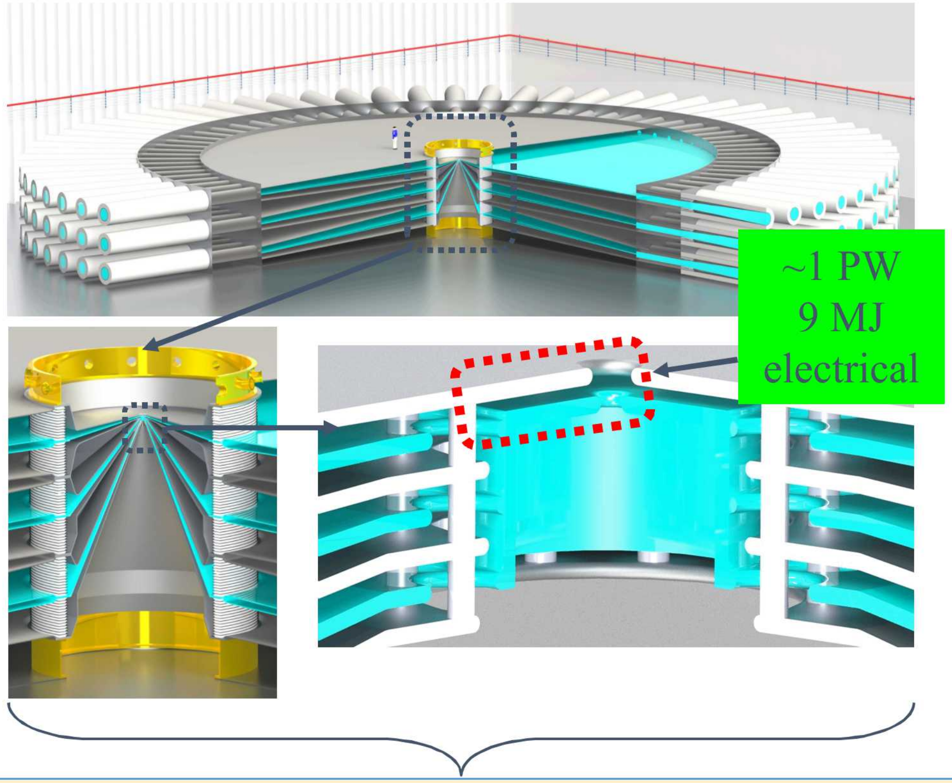
2D clean simulated MagLIF performance



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

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

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



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

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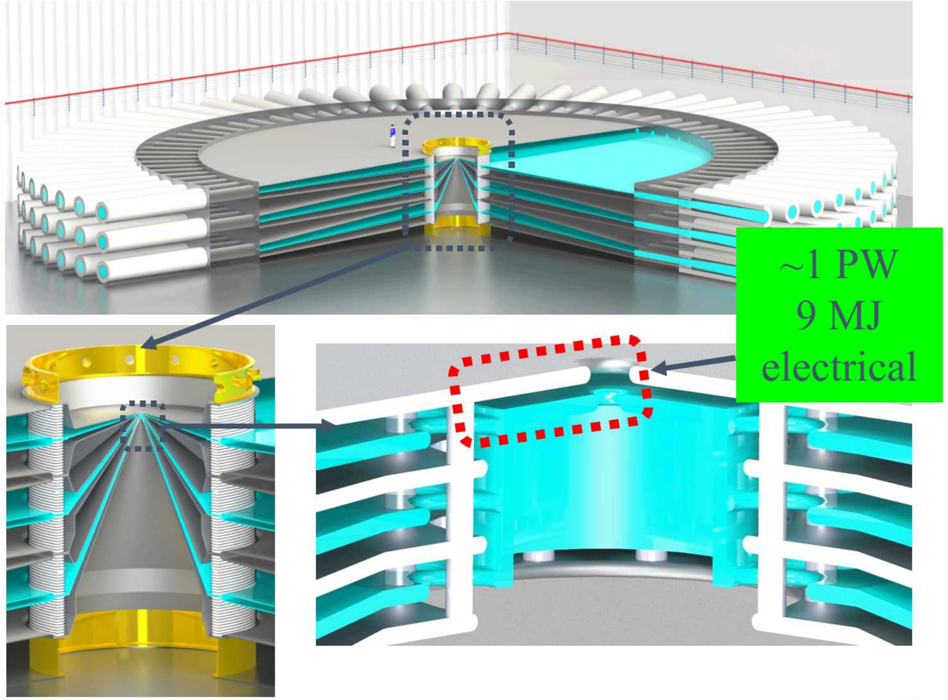
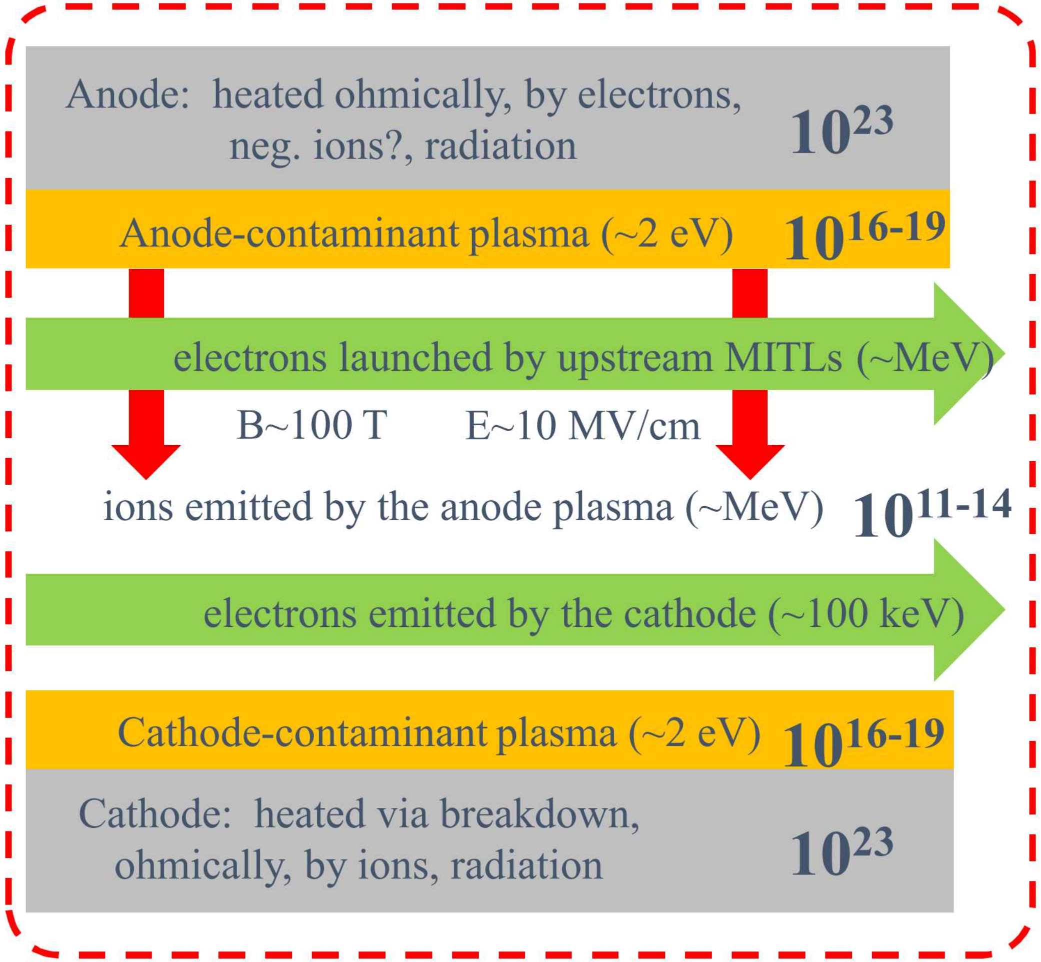


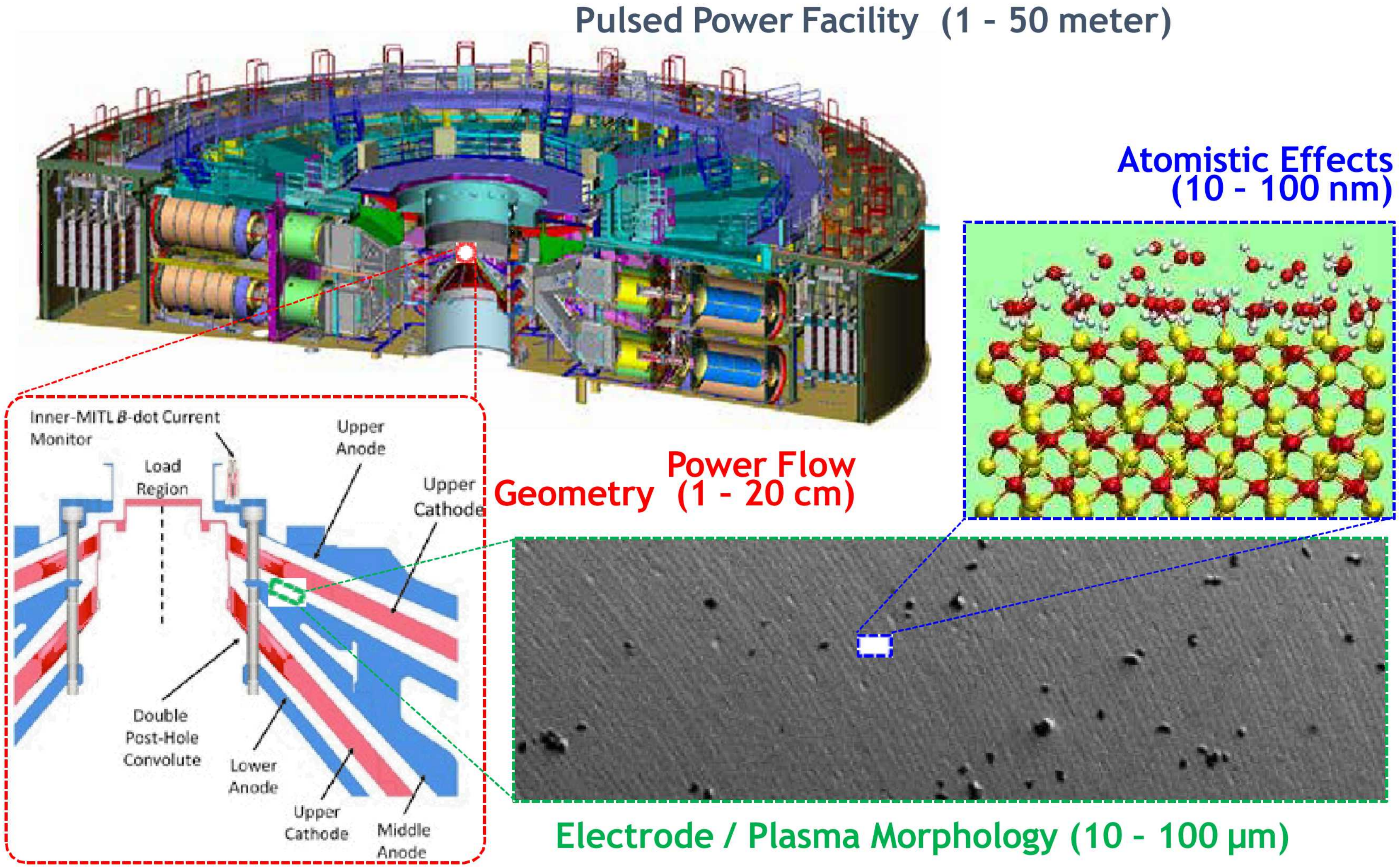
- How do plasmas form from surfaces?
- How well insulated are the gaps during the current pulse?

Section of a "vacuum" transmission line



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

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



Basic

e:

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

Use-Inspired

Use-inspired:

- Hybrid fluid/particle-in-cell algorithm development

Applied

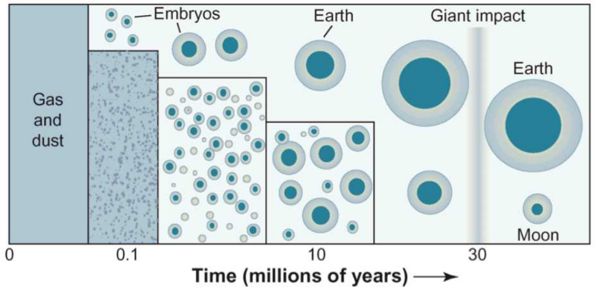
Applied:

- 3D double post hole Z convolute simulation
- Combined power flow and target simulations

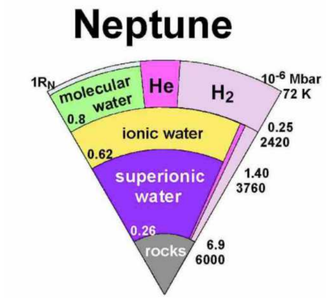
Invited talk by N. Bennett GI3.00006; Oral talk by N. Hamlin JO4.00010; Posters: Patel CP10.00060; Shields TP10.0083; Johnston YP10.00060

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

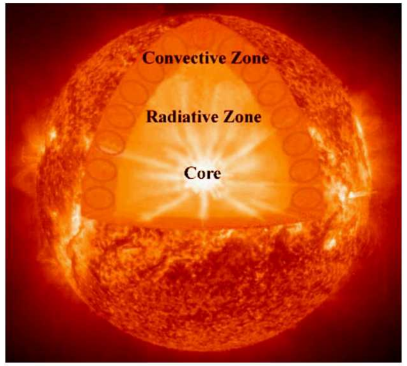
Z Fundamental Science Program



Earth and super earths
Properties of minerals and metals



Jovian Planets
Water and hydrogen



Stellar physics
Fe opacity and H spectra

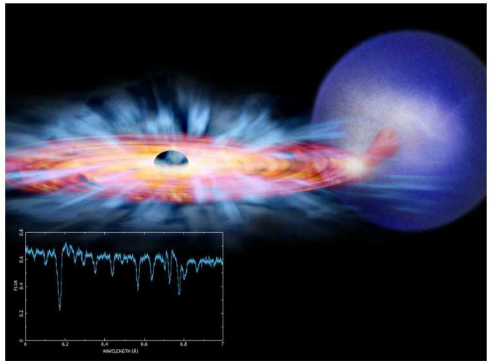


Photo-ionized plasmas
Range of ionization param. ξ

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

First ZnetUS Workshop

- Intended to build upon success of the LaserNetUS consortium
- January 6-8, 2020 at La Jolla Shores Hotel
- Hosted by Center for Energy Research at UCSD (Prof. Farhat Beg)
- Organizing Commmittee includes UCSD, Sandia, U.Michigan, LLE, LLNL, and Cornell
- Topics include
  - Pulsed power technology
  - Magneto-inertial fusion
  - Astrophysical plasmas and planetary science
  - MHD and hybrid code development
  - Magnetized HED

https://cer.ucsd.edu/_news-events-articles/2020/ZNetUS_Workshop_2020.html

These are exciting times to be working in pulsed power

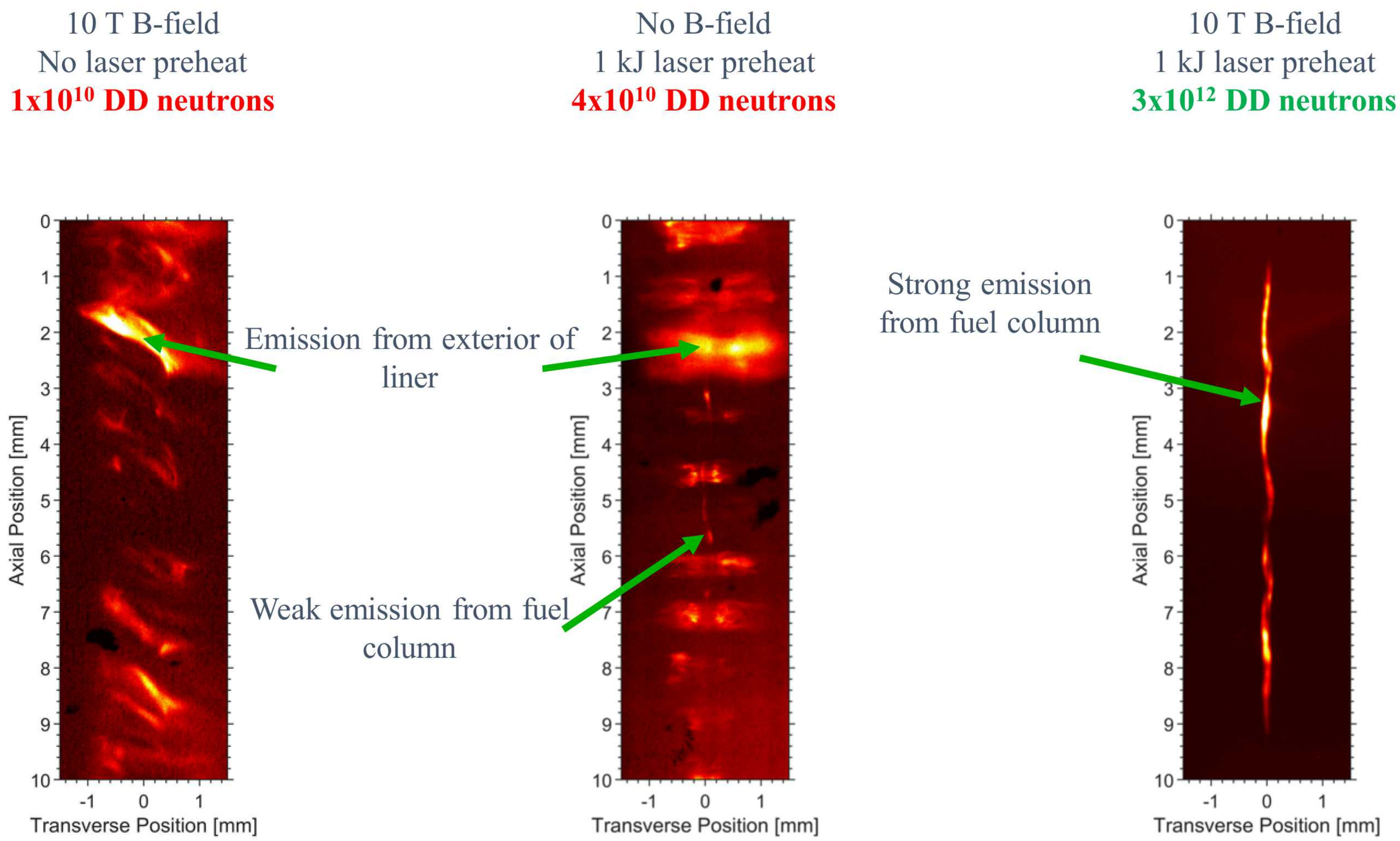
1. The world's largest pulsed power facility, Z, is used for a spectrum of research spanning:
   - Fundamental/Basic Science
   - Use-inspired Science
   - Applied/Mission Science
2. Pulsed power has matured into a precision tool for high energy density science encompassing:
   - **Dynamic Material Properties**
   - **Radiation Science**
   - **Inertial Confinement Fusion**
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

Thank you for your attention!

Exceptional service in the national interest

Maglif Allowed us to demonstrate the key tenets of magneto-inertial fusion

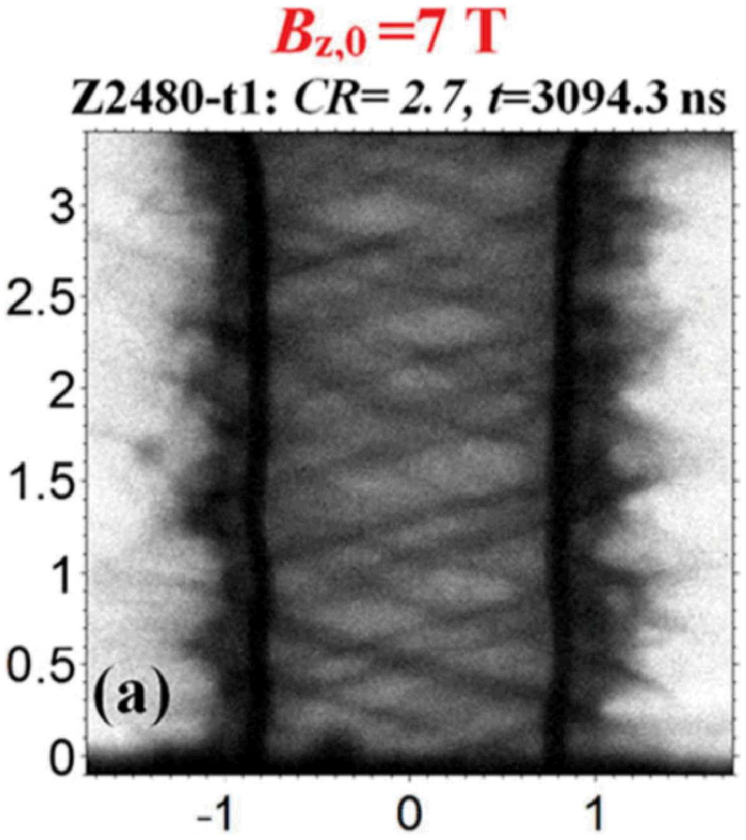
In a target that would not produce significant yield without both heating and magnetizations



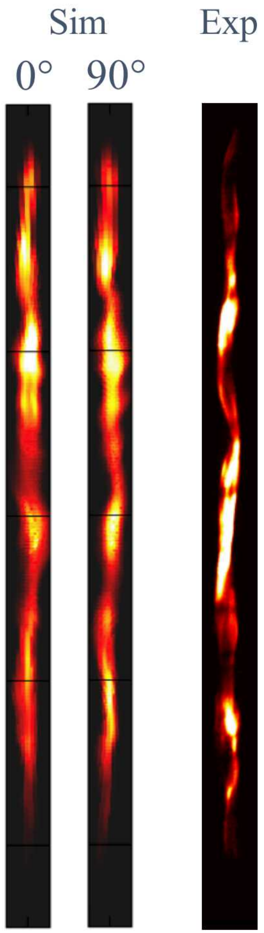
M.R. Gomez *et al.*, Phys Rev Lett 113, 155003 (2014); P.F. Schmit *et al.*, Phys Rev Lett 113, 155004 (2014).

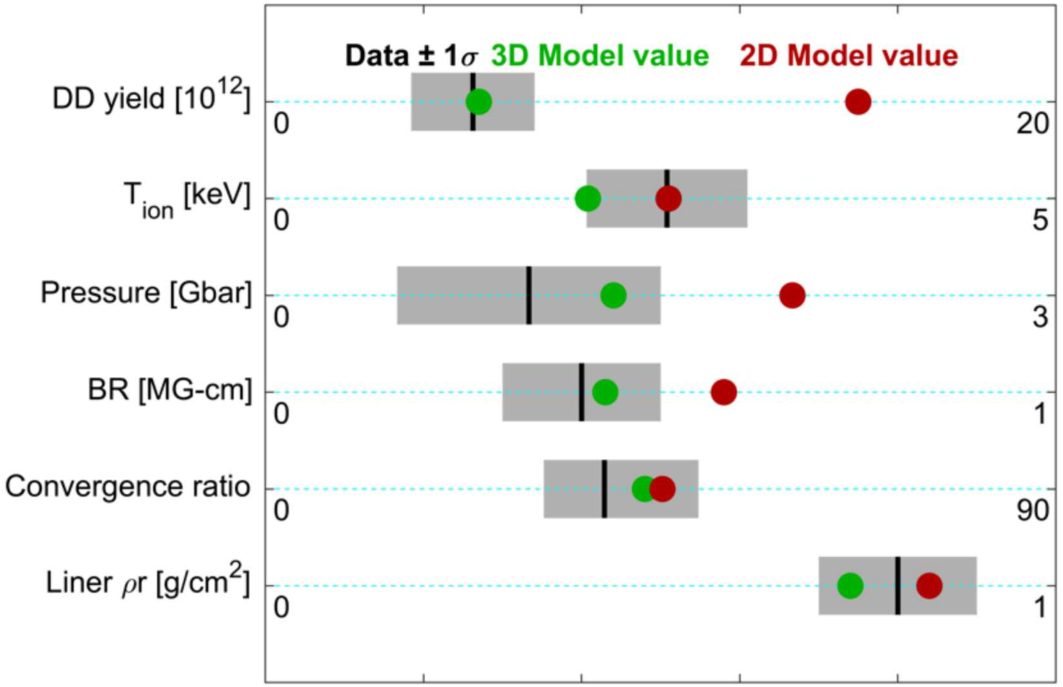
The addition of the axial magnetic field results in a helical MRT instability structure during implosion and a helical stagnation

Use-Inspired



T.J. Awe *et al.*, Phys. Rev. Lett. (2013).





3D HYDRA simulations appear to do a better job of matching the key observables than 2D

see M. Weis TO6.00002

We believe that nuclear weapons are used every day; we also don't want to see them used in practice ever again

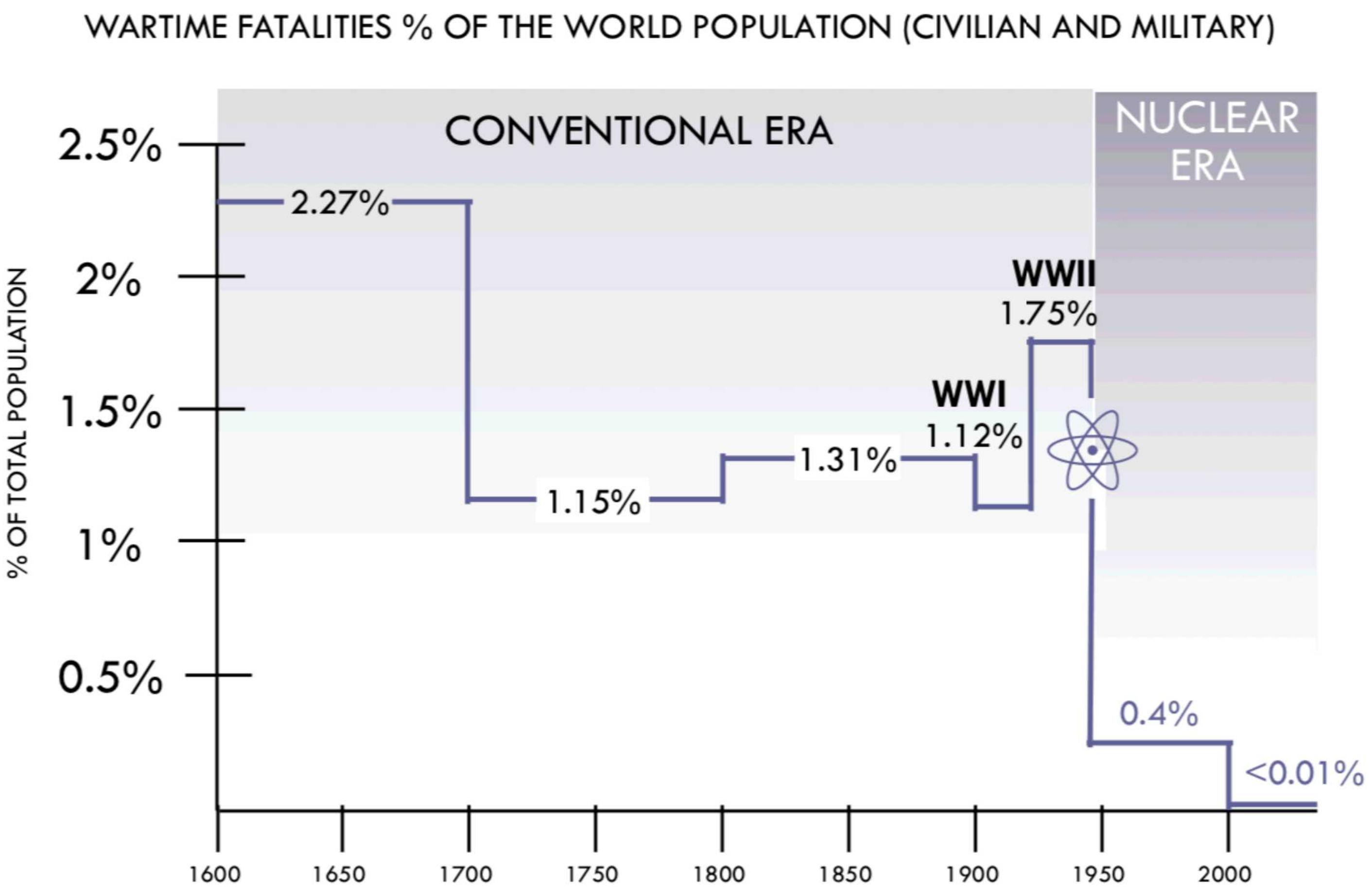


Figure 2. Wartime Fatalities Percentage of World Population

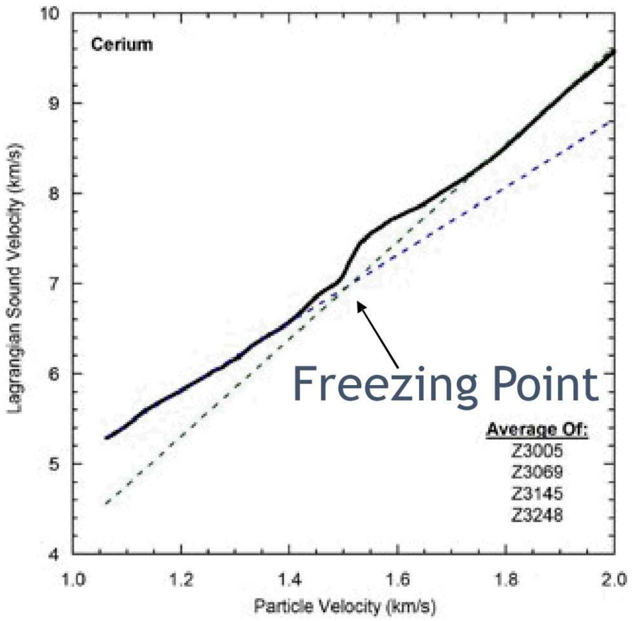
Data from the DoD Historical Office

Plot excerpted from 2018 Nuclear Posture Review

Photo from Hiroshima Peace Memorial

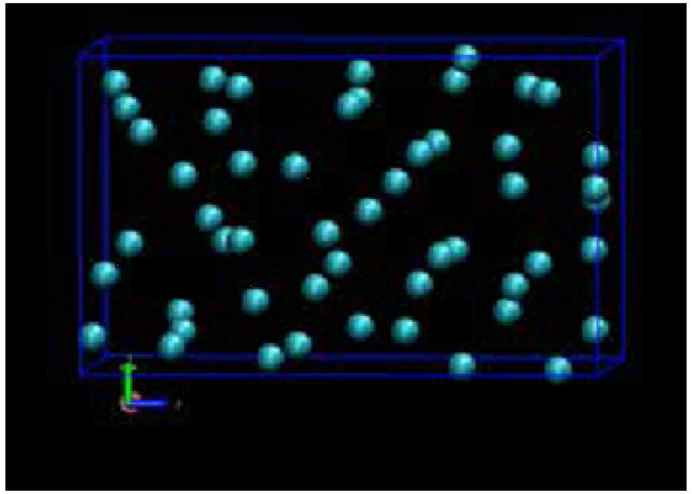
Sandia scientists recently observed dynamic freezing of liquid cerium on Z using isentropic compression

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



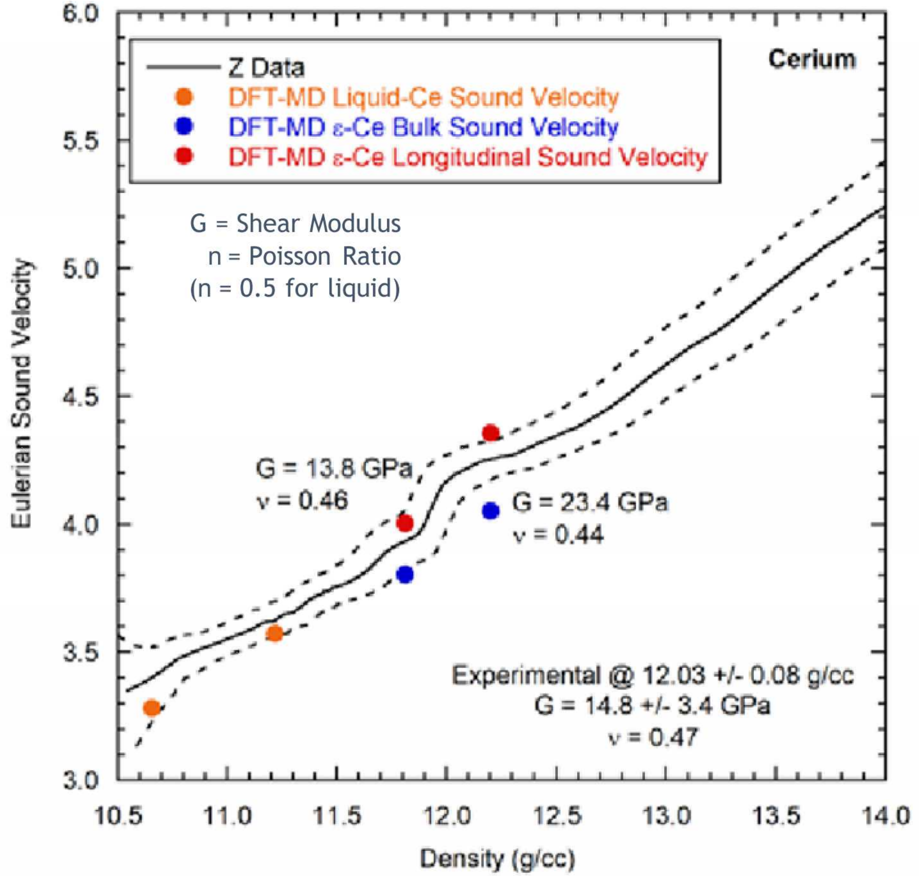
An elastic wave velocity was observed indicating the liquid sample solidified and regained strength.

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



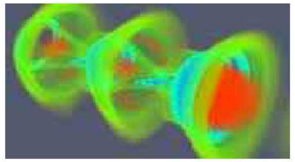
Cerium dynamically freezes on nanosecond timescales during ramp compression at nearly the equilibrium freezing point.

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.

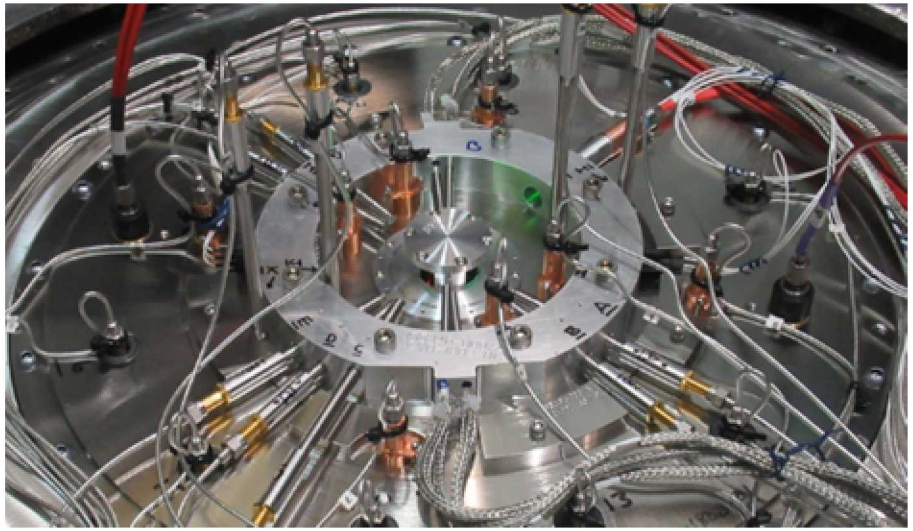


The multi-scale physics models / codes established by this GC LDRD will be impactful to several areas of plasma reviews over the past decade have noted that improved “multi-scale / hybrid” models/codes are desired:

- Magnetic Confinement (plasma/wall interactions, kinetic beam heating with MHD plasma, etc.)
- 2010 NAS Report, “Plasma Science: Advancing Knowledge in the National Interest” üLaser – Plasma Interactions (kinetic beam electrons with solid material / HED plasma, etc.)
- 2009 DOE OFES Advisory Committee Report, “Advancing HED Laboratory Plasmas”
- Low Temperature Plasmas (arc physics, industrial plasma processing, non-equilibrium plasmas, etc.)
- 2012 J. Phys. D, “2012 Plasma Roadmap” (Review)
- 2018 Plasma Sources Sci. Tech., “Foundations of Modelling Non-Equilibrium Plasmas” (Review)
- Accelerator Technology, High Voltage Switching, etc.



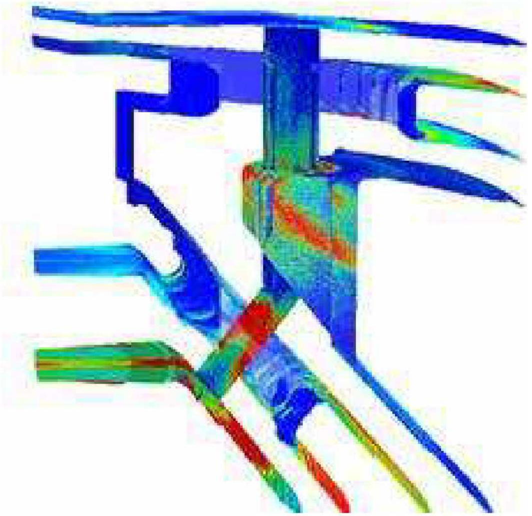
Sandia is also making experimental investments in plasma physics relevant to power flow in order to validate these computations



5-10 Z experiments/year devoted to power-flow measurements in 2018 and 2019; >12 new diagnostics developed and fielded specifically for power flow physics;

Plan to continue developing platforms and advanced diagnostics going forward

Project Integration Plan and Deliverables

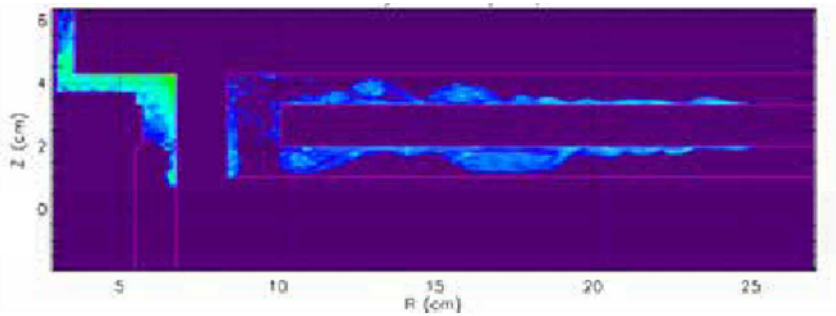


3D Z Double-Post Hole Convolute Demonstration

- Actual Z experimental design geometry (CAD engineering model)
- Deliver via EMPIRE and CHICAGO à Kinetic
- Z-relevant circuit coupling, simple desorption model
- Current loss metrics for ICF-relevant pulse (110ns)
- Demonstrate ability to complete at-scale simulation <200 hours

3D Ideal Half-o-Lute Performance Benchmark

- Deliver via EMPIRE and CHICAGO à Kinetic / Fluid / Hybrid
- Z-relevant circuit coupling, simple desorption model
- Current loss metrics for ICF-relevant pulse (110ns)
- Demonstrate EMPIRE-Hybrid (δf) in relevant environment (TRL5)
- Demonstrate >100x speed-up compared to pre-LDRD performance



2D Planar MITL Study with Improved Desorption Model

- Stainless Steel 304L model validated against experiments
- Confirmed desorption mechanisms against multi-scale theory (MD)
- Uncertainty Qualified metrics of desorption sensitivity
- Deliver via EMPIRE and CHICAGO à Kinetic