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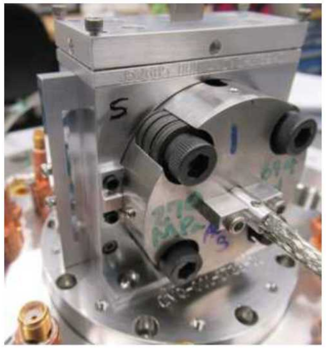
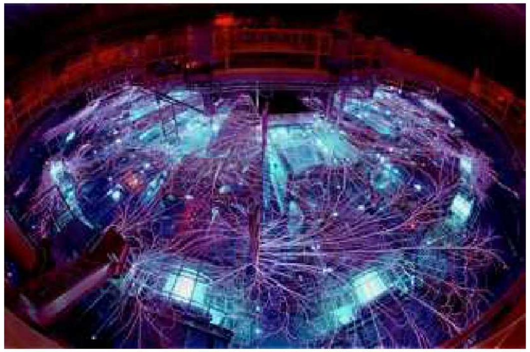




Pulsed Power Science and Applications on Sandia's Z Machine

Daniel Sinars, Sandia National Laboratories

Euro-Asian Pulsed Power Conference, Changsha, China

September 16-20, 2018

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-NA-0003525.

Outline

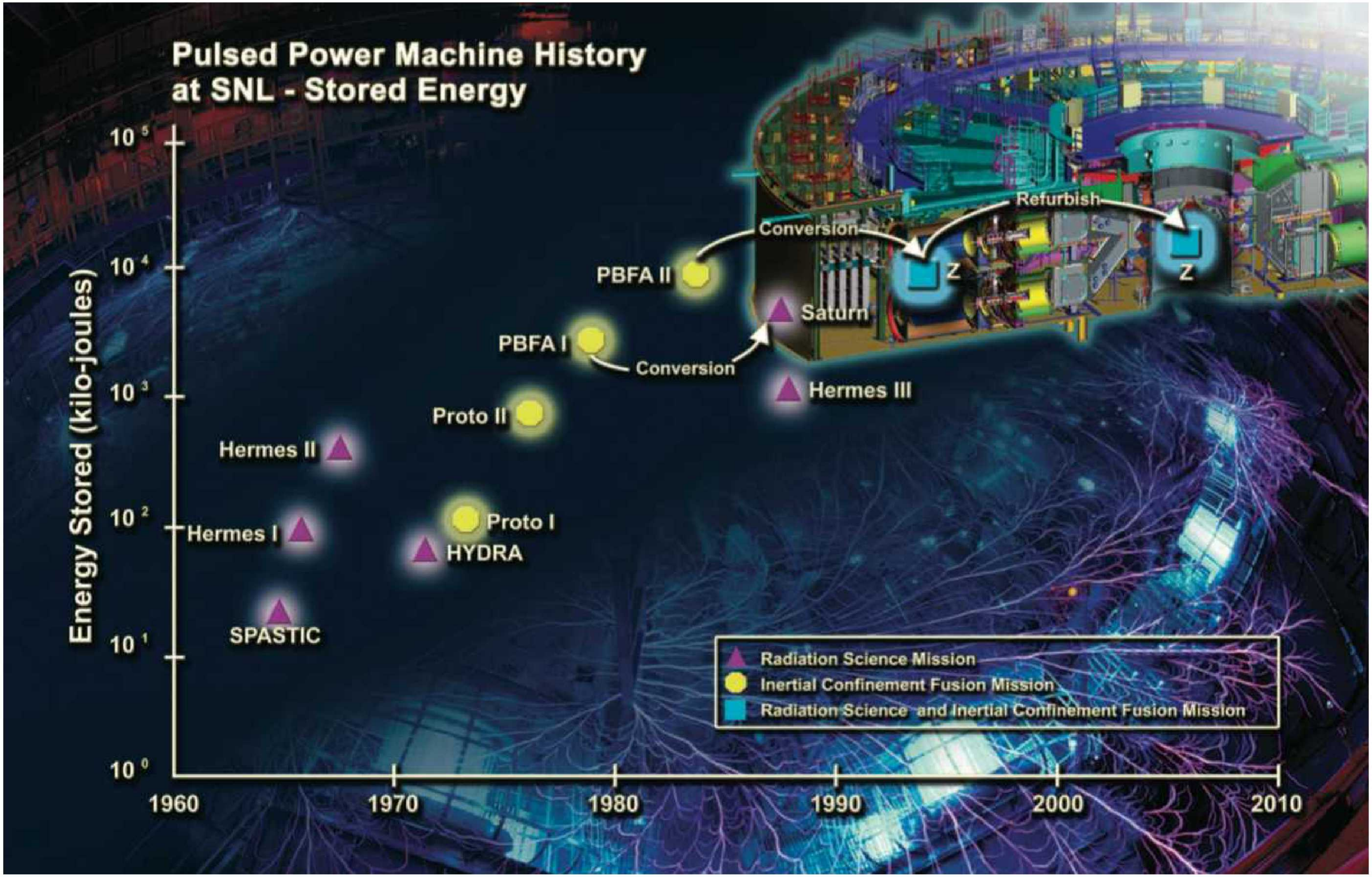
- Pulsed power at Sandia: The Z Machine
- Applications of pulsed power to High Energy Density (HED) Science
- The future? Pulsed power technology development at Sandia

The Z pulsed power facility is located at Sandia National Laboratories in Albuquerque, New Mexico, USA

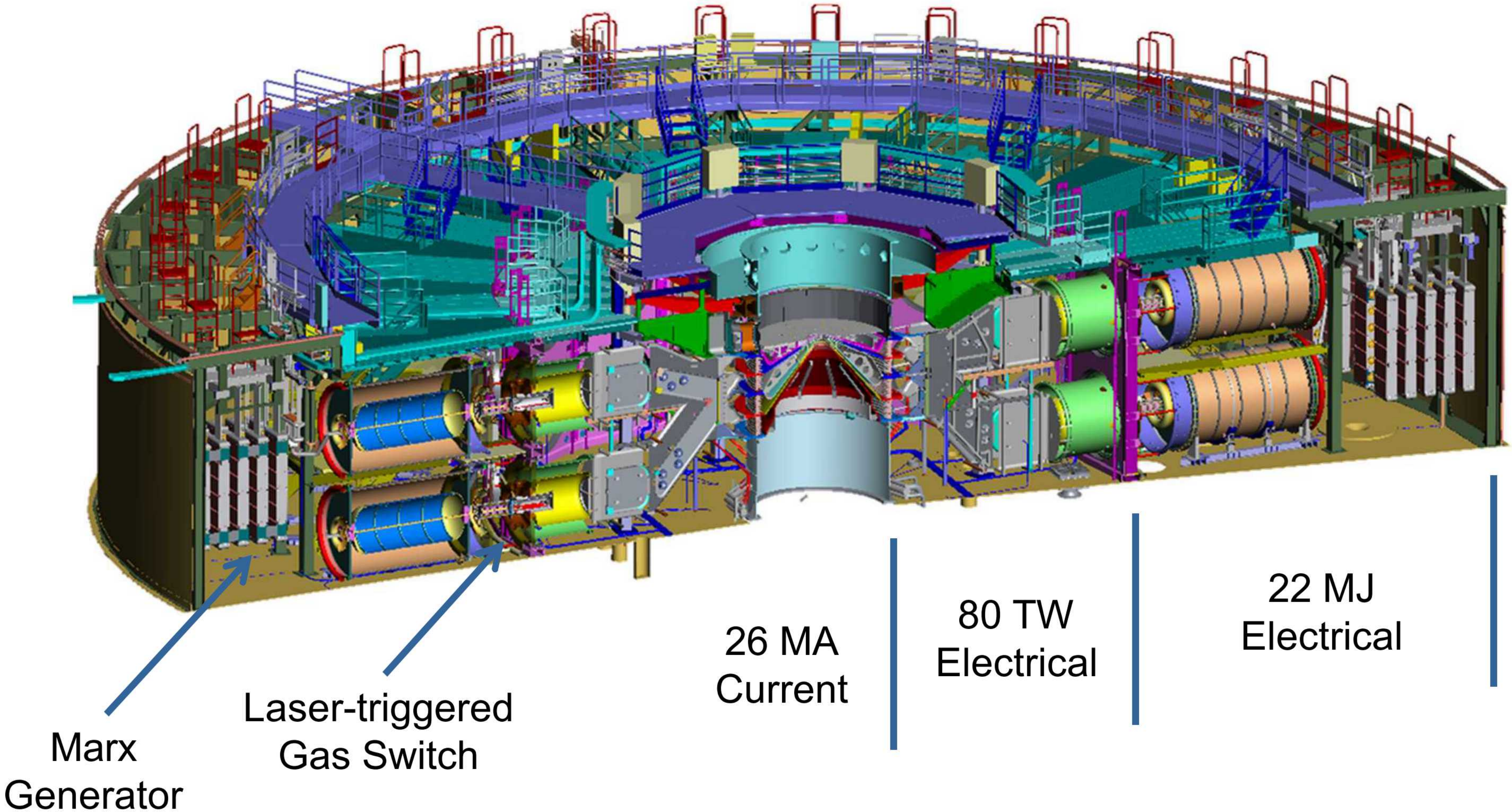
Sandia National Laboratories

- Albuquerque, New Mexico
- Sandia is presently the largest of the 17 U.S. Department of Energy National Laboratories, at >12,000 employees

Sandia National Laboratories has been using pulsed power for Radiation, Fusion, and Materials Science for decades



Z is the world's largest pulsed power machine, and compresses energy in space (>10^9 x) and time (>10^9 x) to generate high energy density conditions

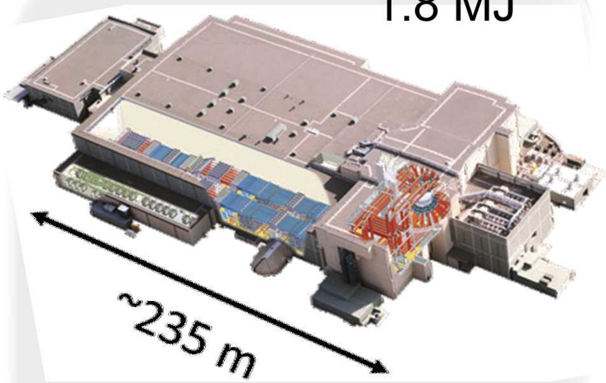


Z is an "engine of discovery" for stewardship and fundamental HED science

Z is one of three major facilities in the United States Inertial Confinement Fusion program used for high energy density science

National Ignition Facility

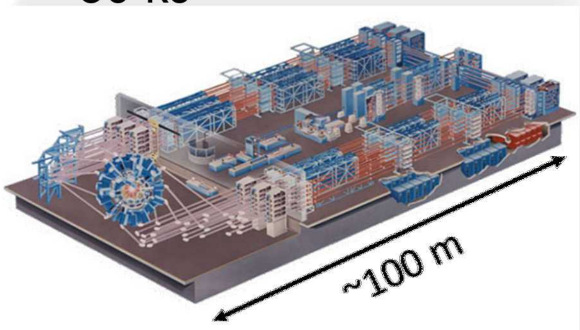
1.8 MJ



- Hottest temperatures and highest pressures on Earth
- **Largest Laser on Earth**
- **400 TW / 1.8 MJ (Max Power & Energy)**

Omega Facility

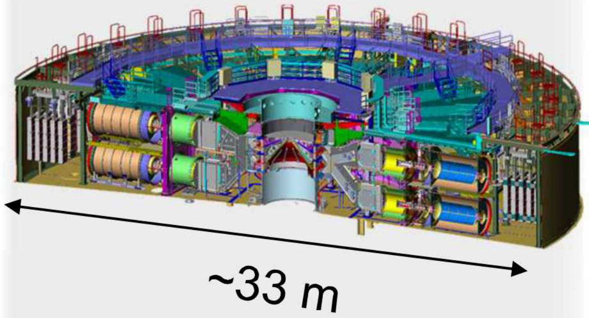
30 kJ



- High shot-rate academic laser facility
- Platform and diagnostic development
- **20 TW / .03 MJ (Max Power & Energy)**

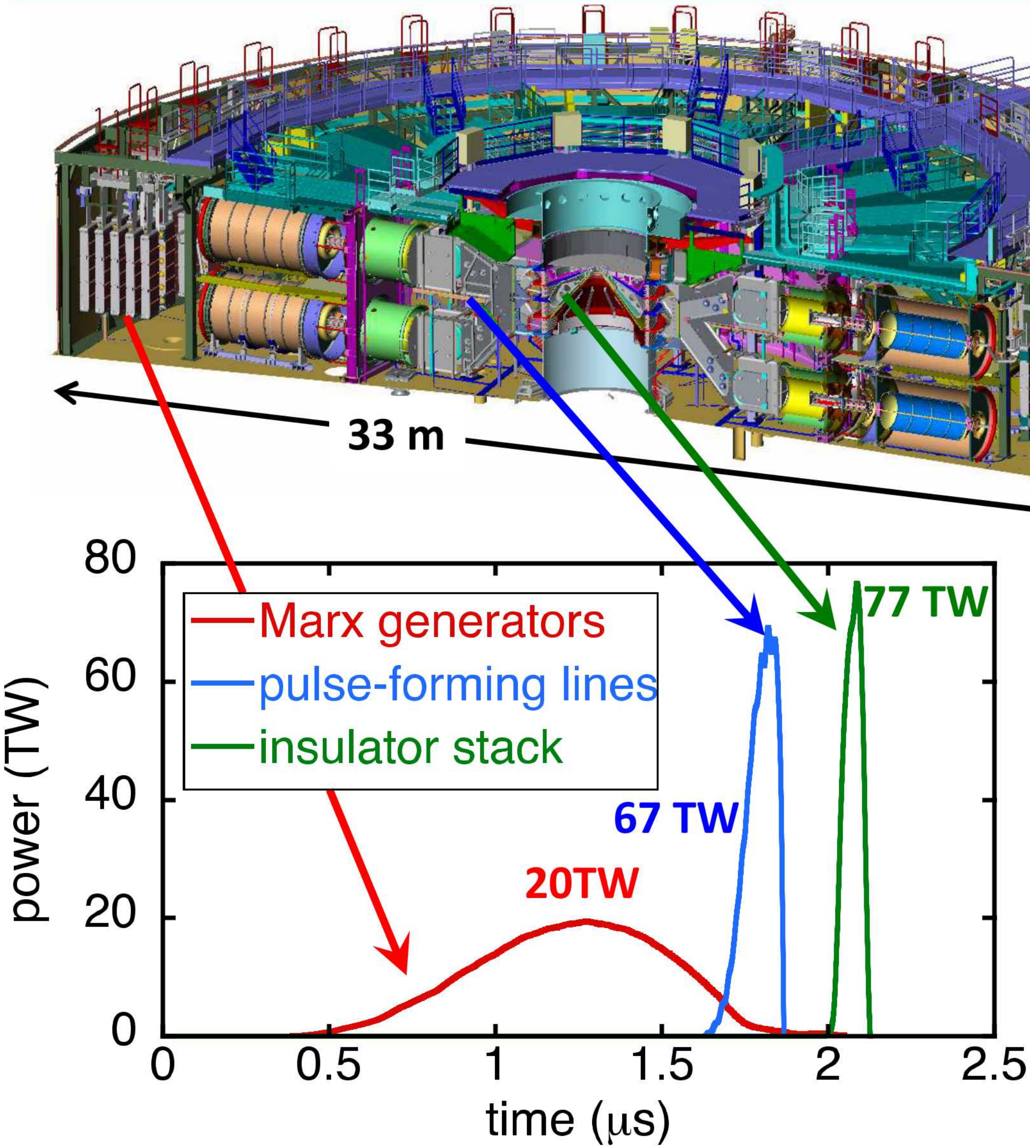
Z Facility

2-3 MJ



- Larger samples & time scales than NIF
- **Largest Pulsed Power Facility on Earth**
- **80 TW / 3 MJ (Max Power & Energy)**

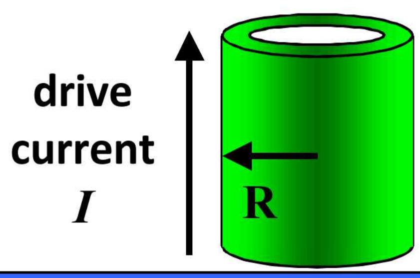
Very high pressures can be obtained using the large currents on Z



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

Magnetically Driven Implosion

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



100 MBar at 26 MA and 1 mm

100 GPa = 1 Mbar ≈ 10^6 atmospheres

Pulsed power can be used to obtain even higher pressures such as those in inertial fusion

- Pressure equivalent to Energy Density (J/m^3)
- 1 Mbar = 10^6 atm = 10^{11} J/m^3

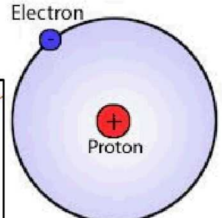
Z Storage capacitor

2e-6 Mbar

TNT

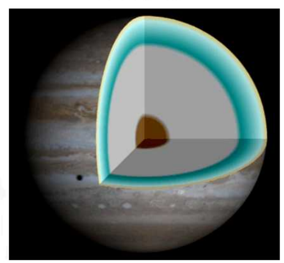
0.07 Mbar

Internal Energy of H atom



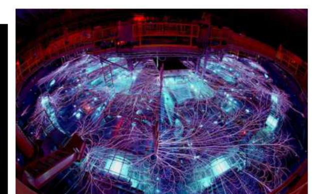
1 Mbar

Metallic H in Jupiter's core



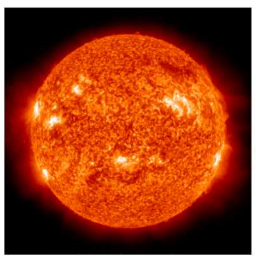
30 Mbar

Z Magnetic Drive Pressure



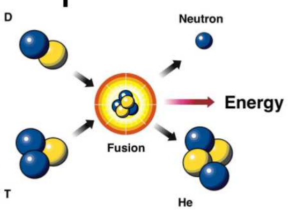
~100 Mbar

Center of Sun



250,000 Mbar

Burning ICF plasma



800,000 Mbar

Push on samples

Compress fuel at high velocity

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

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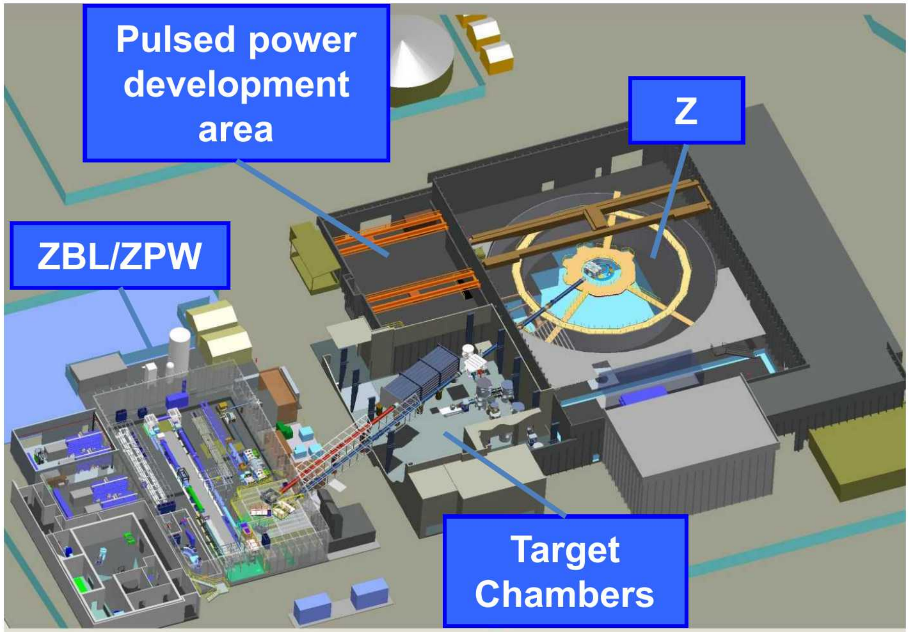
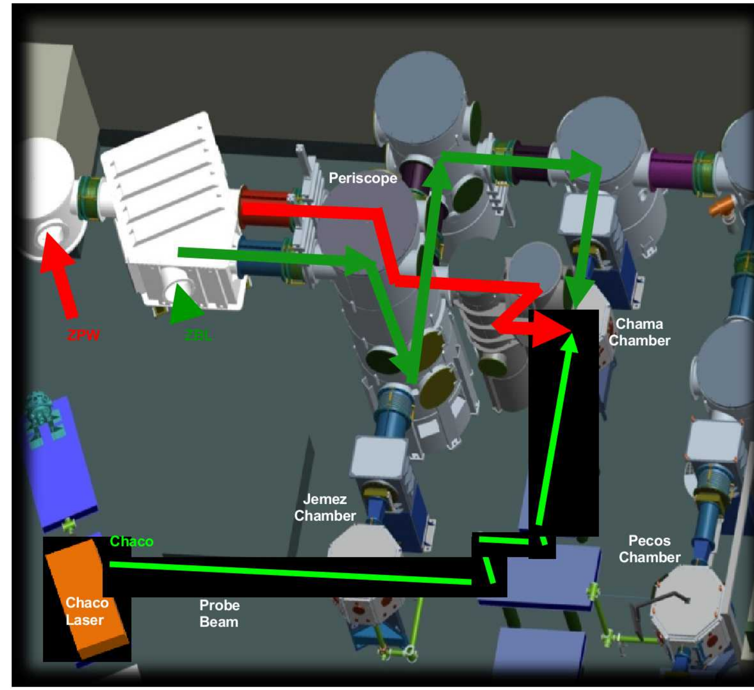
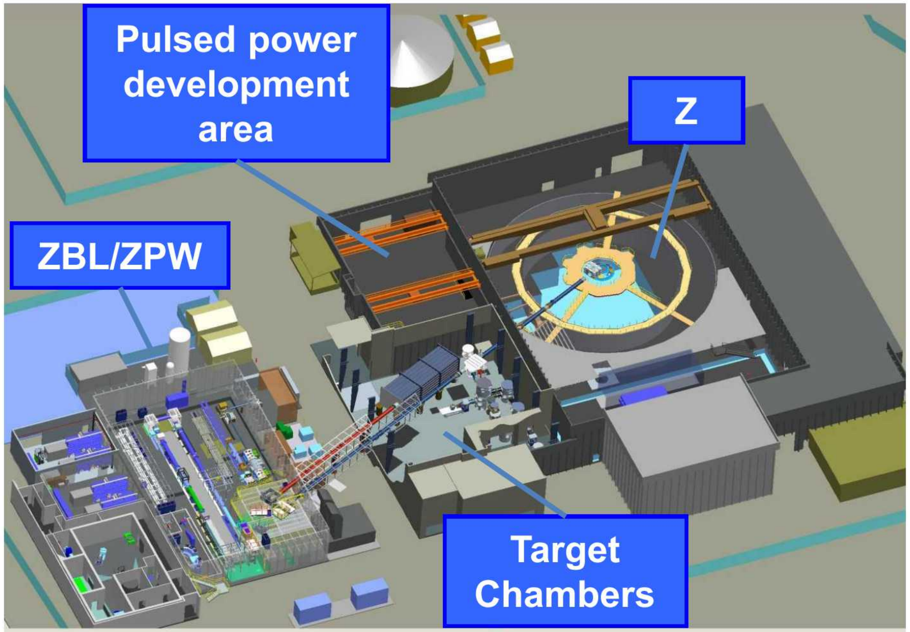
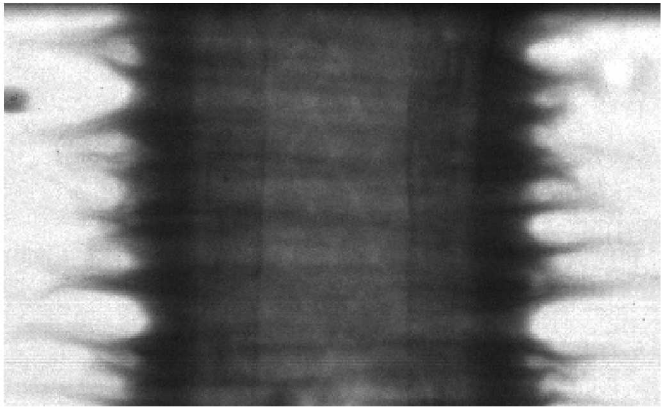


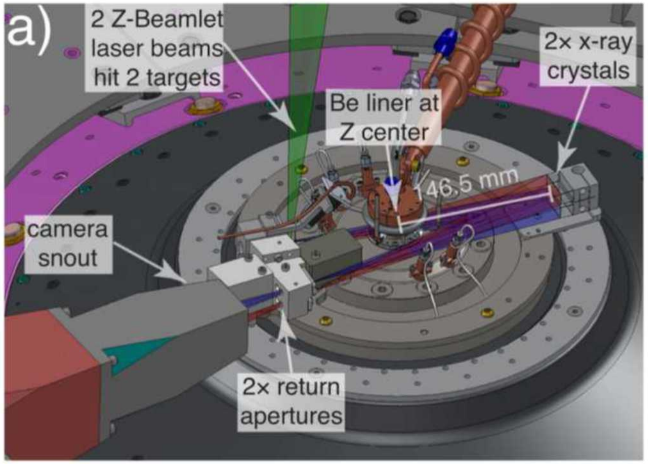


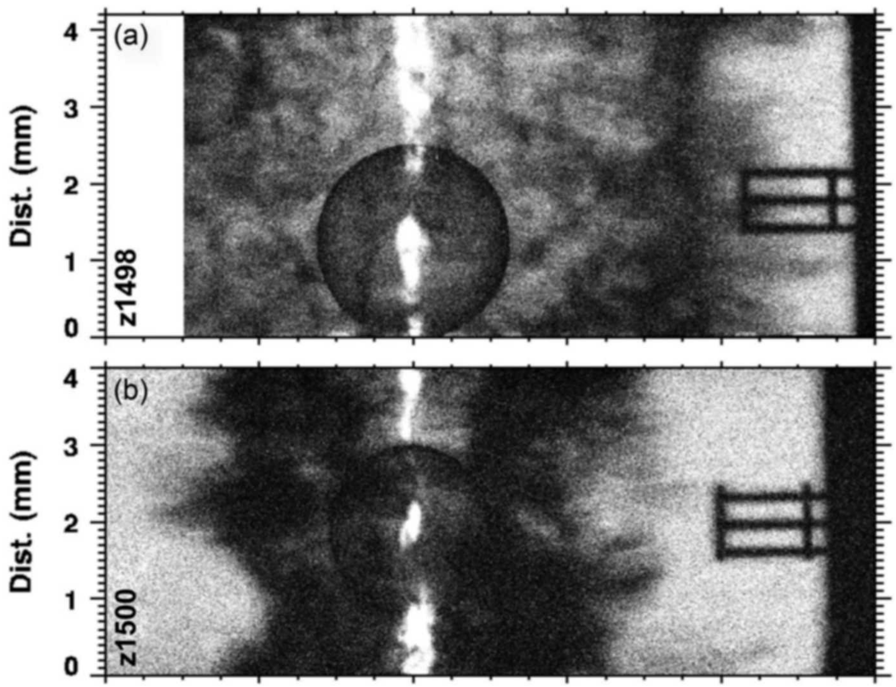
P.K. Rambo *et al.*, Applied Optics 44 (2005); P. Rambo *et al.*, Proc. SPIE 10014 (2016).

The co-location of ZBL/ZPW with Z enables us to pursue unique scientific opportunities (e.g., Radiography, diffraction, MagLIF)



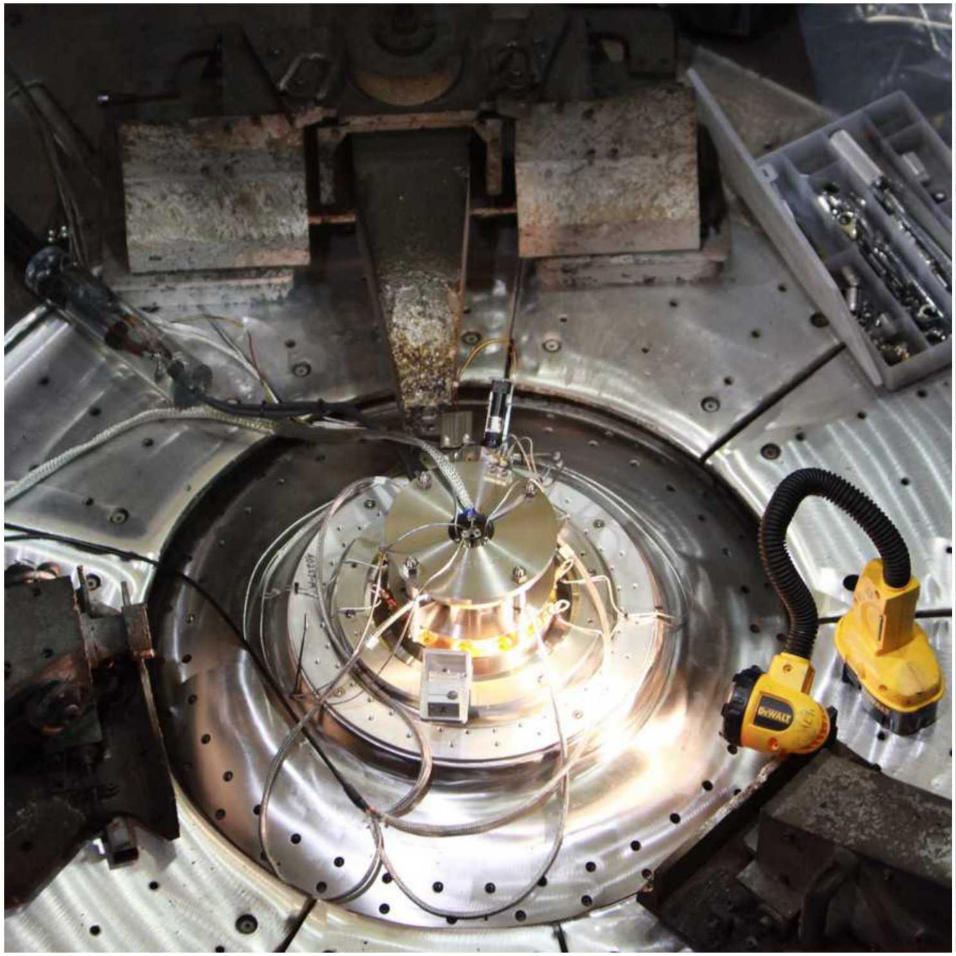






Sinars *et al.*, RSI (2004); Bennett *et al.*, RSI (2008); Schollmeier *et al.*, RSI (2017).

A challenge for Z experiments is that they release the energy of a few sticks of dynamite



Pre-shot photo of coils & target hardware

Post-shot photo

- Harsh debris, shock, and radiation environment make fielding experiments unique and challenging

Outline

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There are multiple ways to use the current on Z

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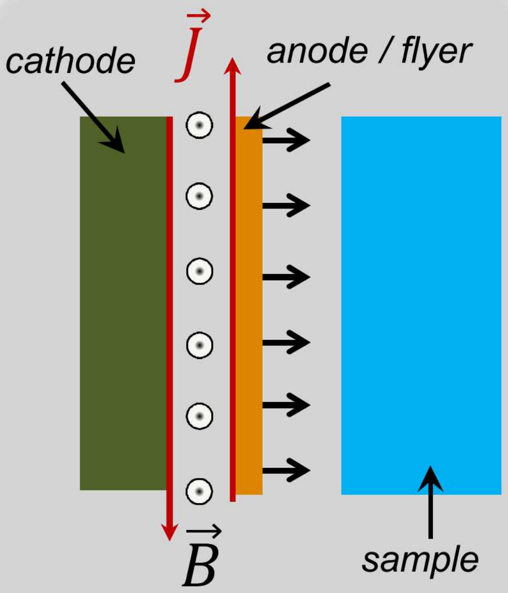
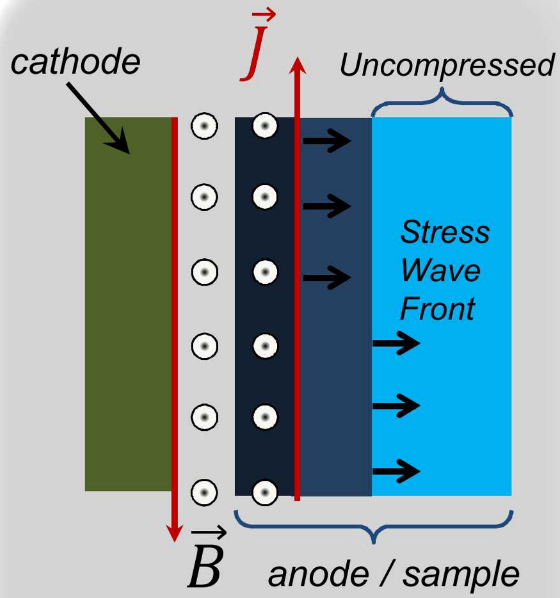
Planar Shock Compression



Shock Hugoniot

Flyer Velocity > 40 km/s
Pressure > 10 Mbar

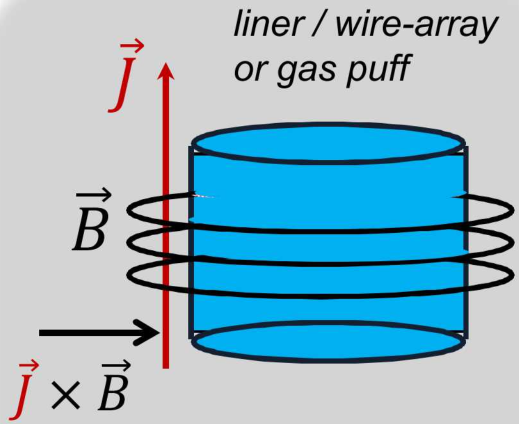
Planar Shockless Compression



~Isentropic Compression

Pressure up to 5 Mbar

Cylindrical Implosion

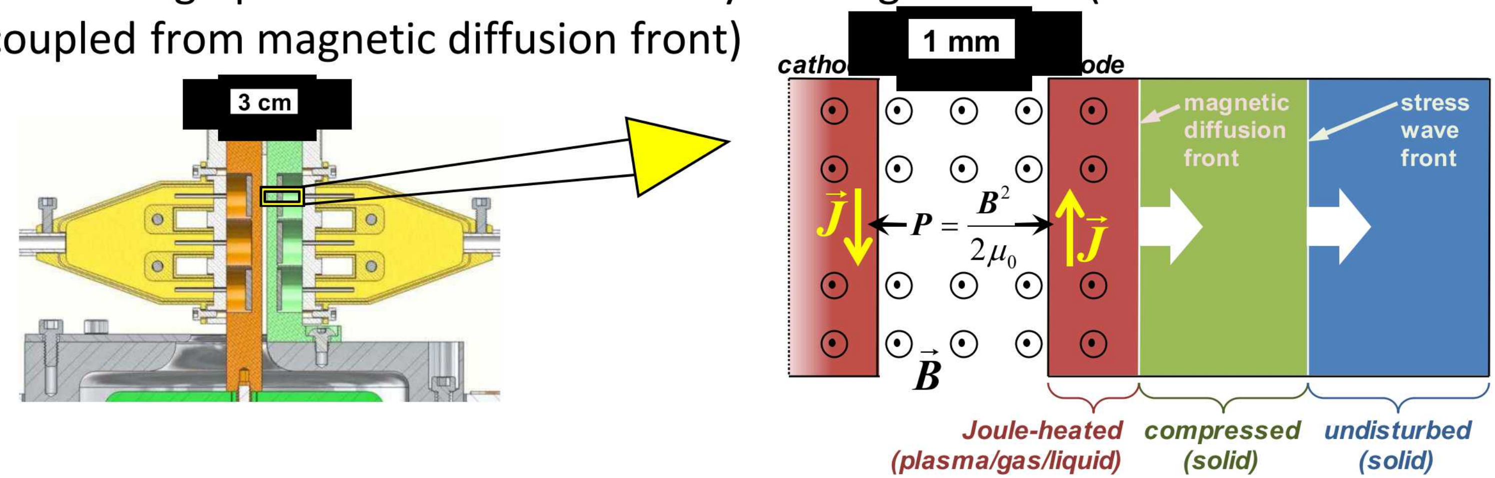


- ~Isentropic Compression
  Pressure >10 Mbar
- X-rays
  E > 2 MJ
  P > 330 TW
- Fusion
  $>10^{13}$ DD (MagLIF)

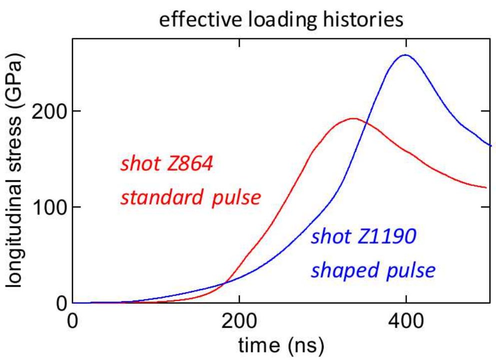
Improving the precision and reproducible delivery of 2-3 MJ electrical energy enabled the invention of new platforms over the last 20 years

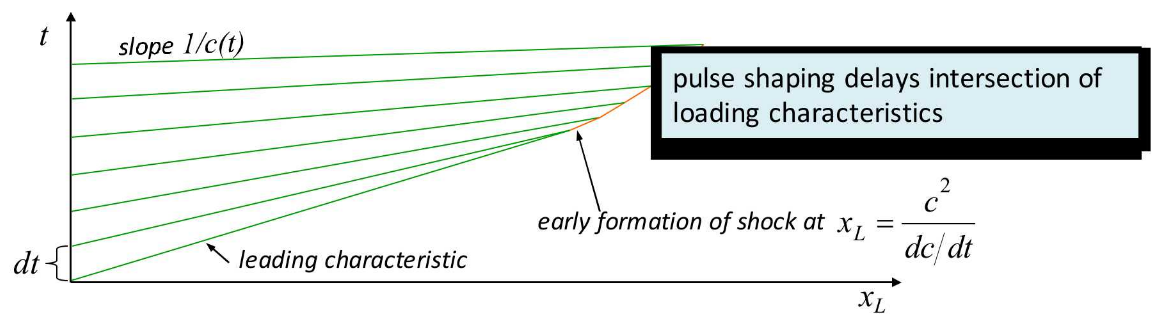
Using magnetic pressure as a source has some unique advantages

- Can create high pressures without directly heating material (stress wave de-coupled from magnetic diffusion front)



- Generated over long time scales (100-1200 ns) with control over the time history





- Large samples (mm to cm) and energetic sources (2 MJ to load of 20 MJ stored)
  - Allows HED conditions in sample sizes >> sample grain boundary dimensions
  - One Z experiment can field 6-20 samples all experiencing identical drive

An ongoing research area at Sandia is using the shock-ramp technique to probe between the principal Hugoniot and isentrope

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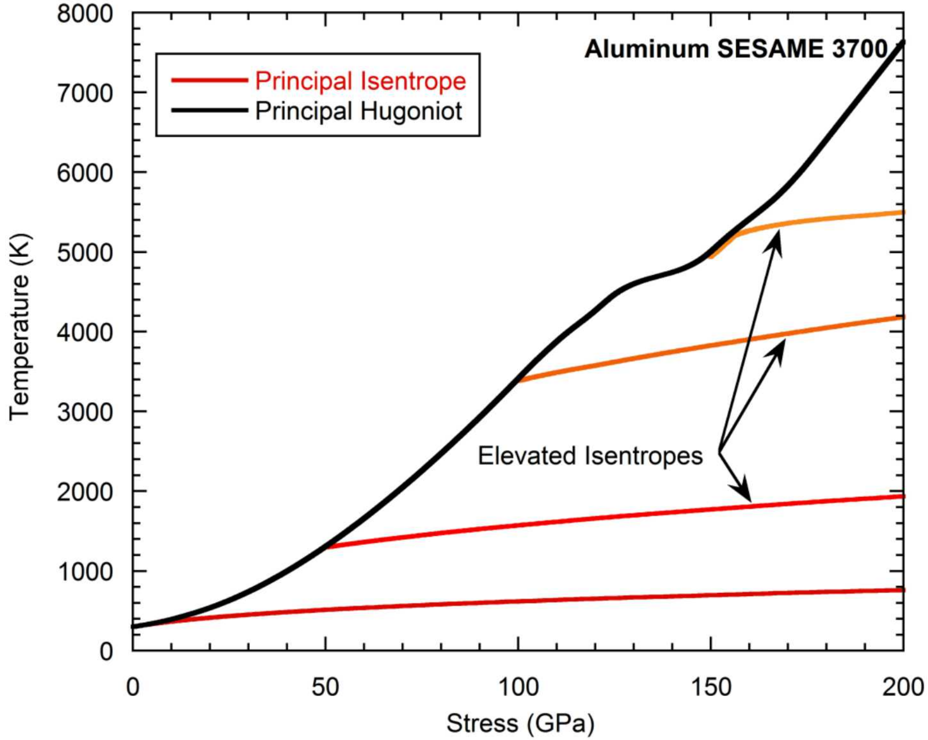

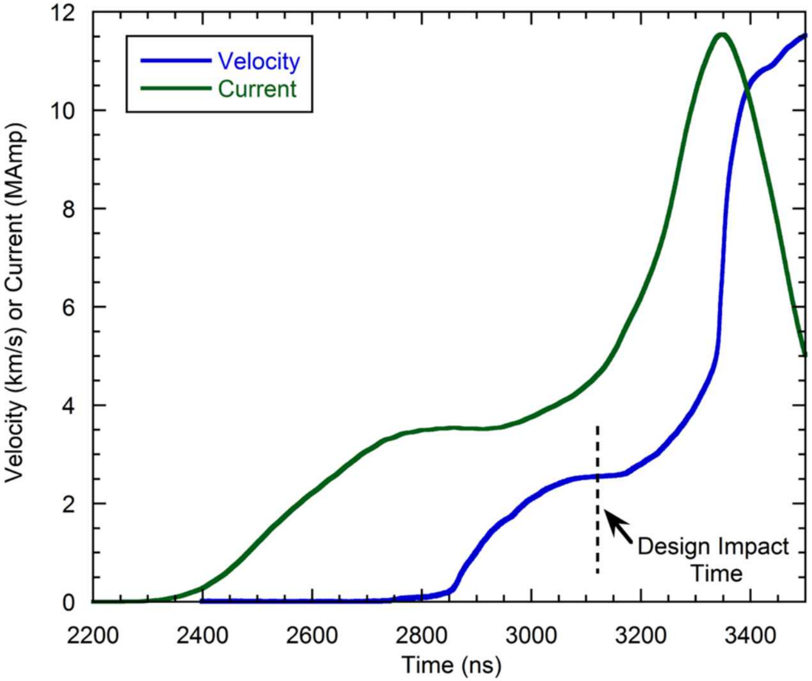

Ramp compression from a Hugoniot state results in intermediate temperatures at high compression.

Flight gaps and pulse shape designed to enable impact at nearly constant velocity

This velocity plateau also generates a "hold" in the shock state

Collectively, we have a wide range of tools on Z allowing dynamic compression experiments to probe large regions of a material's equation-of-state surface

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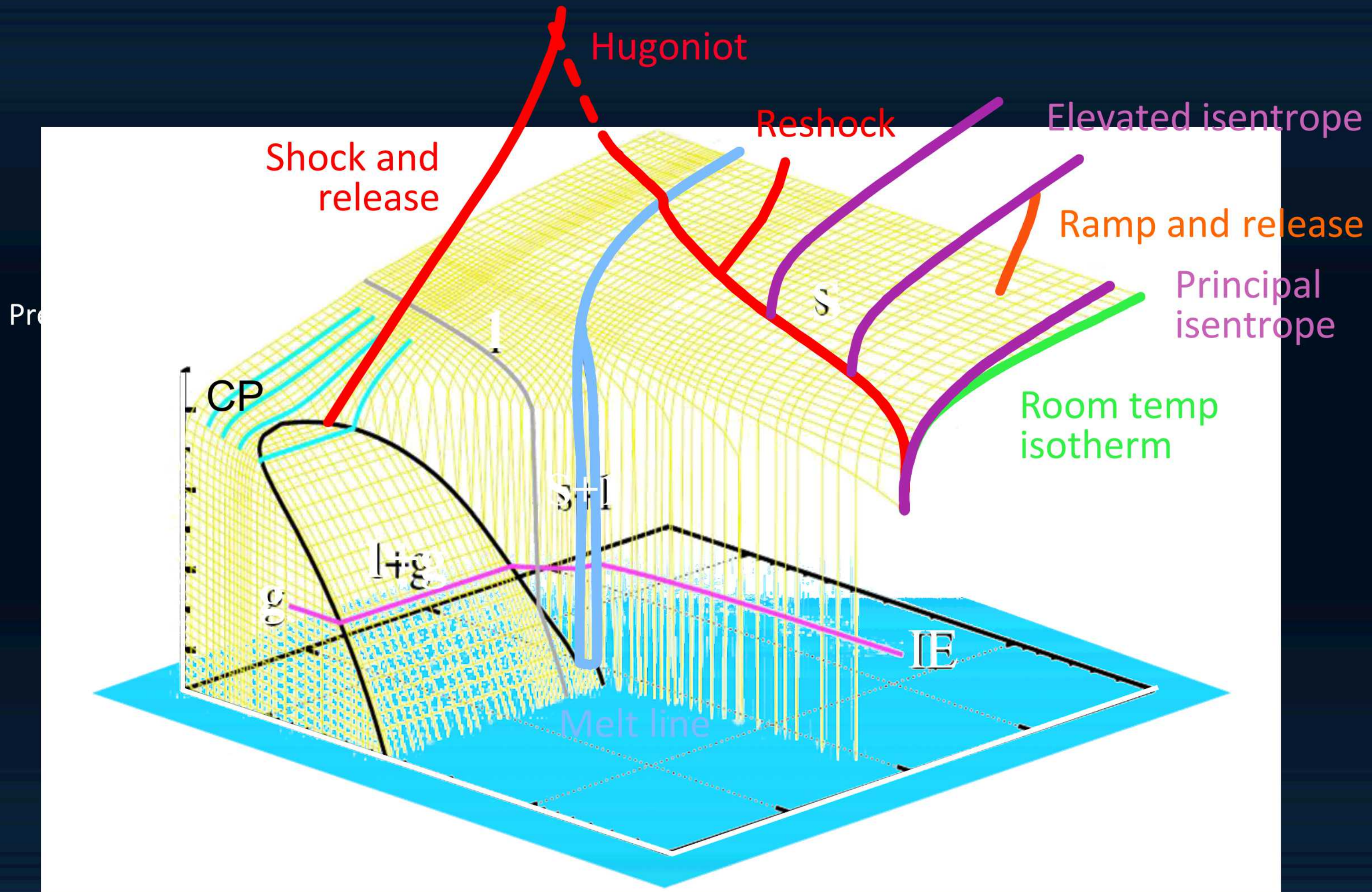
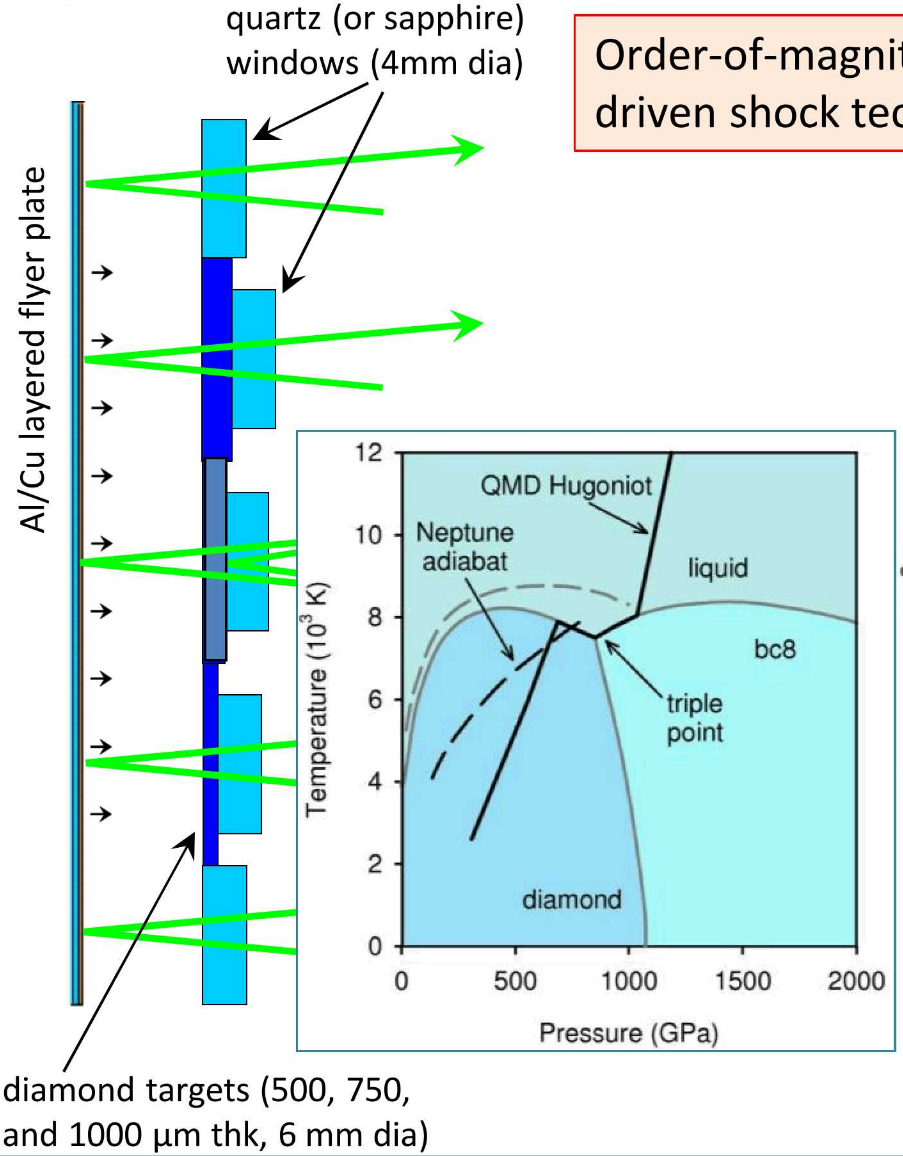
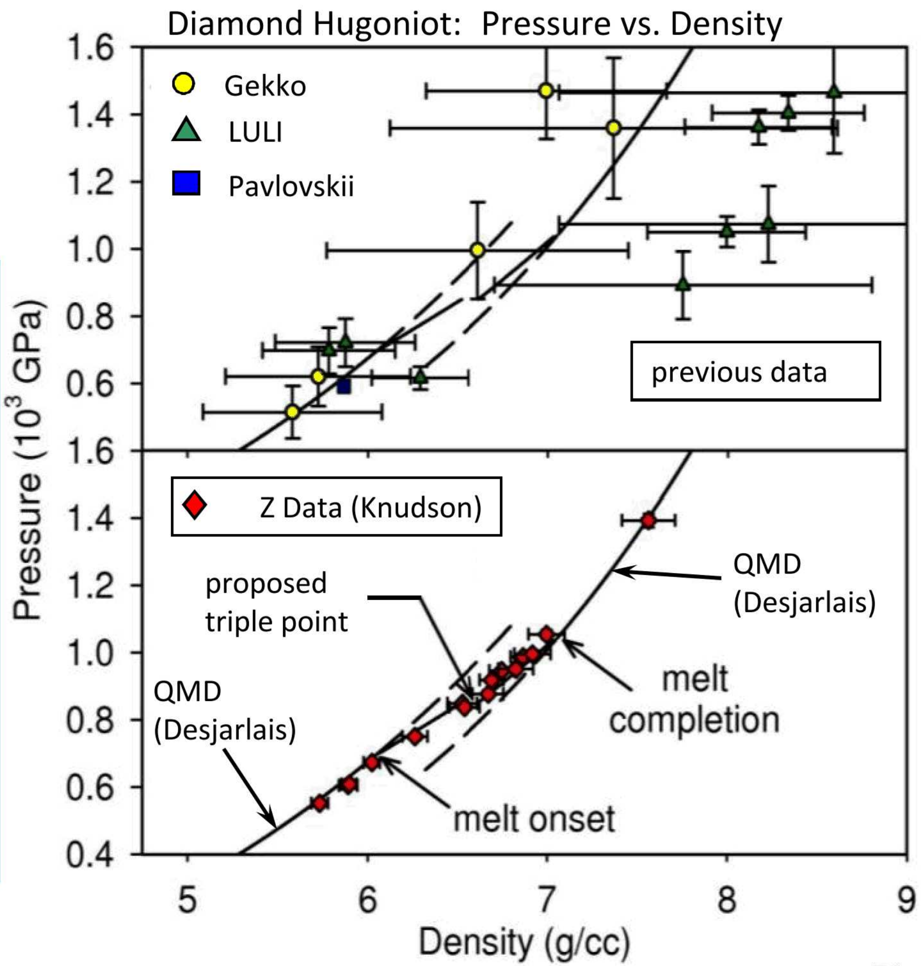


Z flyers provided first experimental evidence of diamond-liquid-BC8 triple point in carbon, important for determining at what shock pressure diamond ICF capsule ablators on NIF would melt

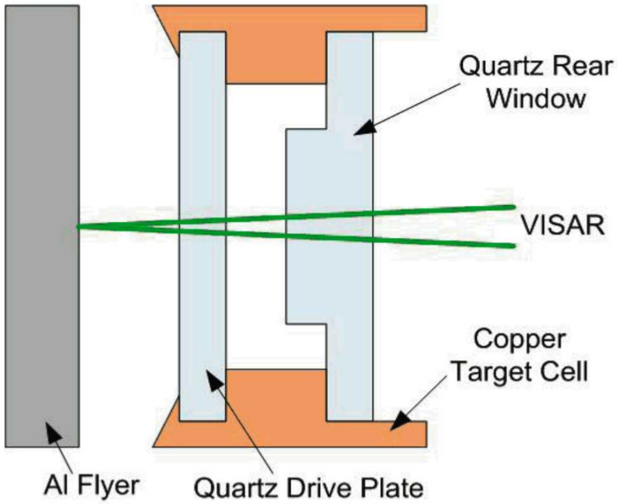
Order-of-magnitude improvement in precision over laser-driven shock techniques (larger spatial/temporal scales)

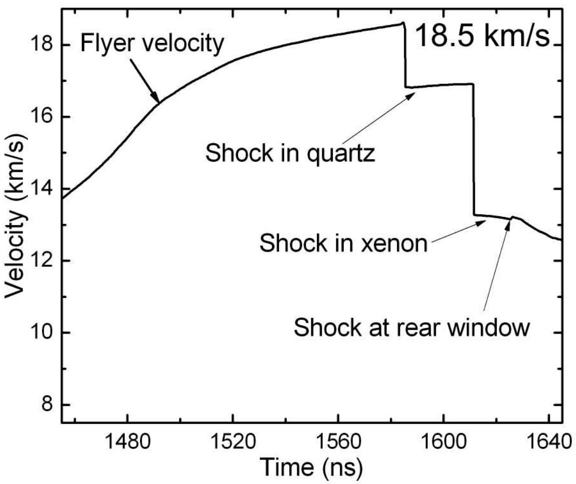




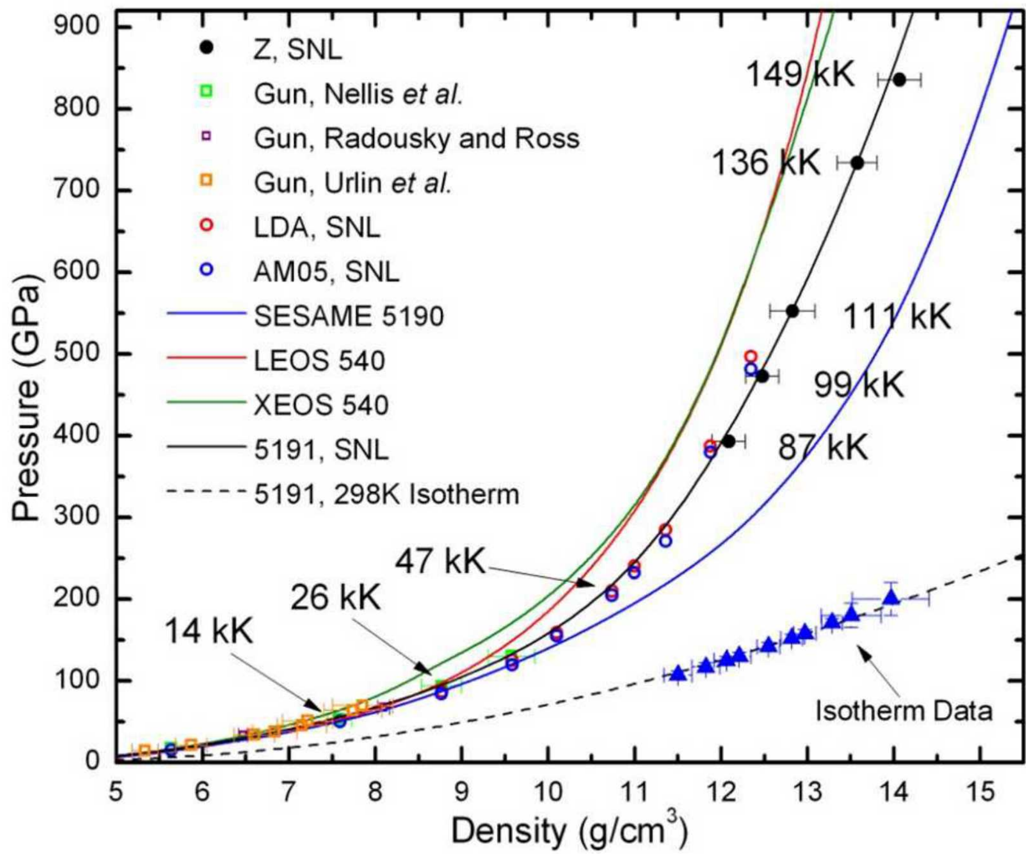
M.D. Knudson, M. P. Desjarlais and D. H. Dolan, *Science* **322**, 1822 (2008)

Z flyer experiments and theory provided new understanding of high pressure Xenon





Shock velocities in transparent materials measured with sub-percent accuracy

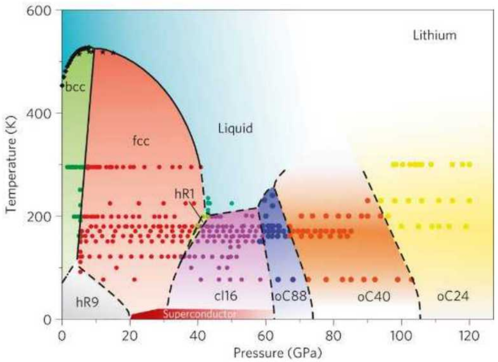


Theory & data almost always diverge in previously unreachable regimes

S. Root *et al*., Phys. Rev. Lett. 105, 085501 (2010).

Today Z is routinely used to study a wide range of multi-Mbar material science questions

- Key physics questions
  - Role of microstructure
  - Kinetics and phase transitions
  - Strength
  - Transport properties
  - Radiation shock

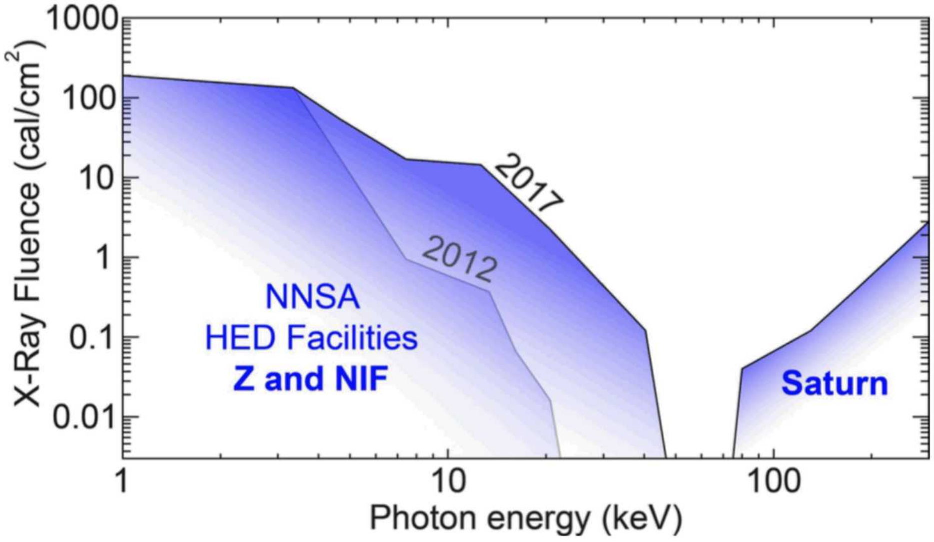


Phase diagram of lithium showing a number of solid phases with a large degree of uncertainty

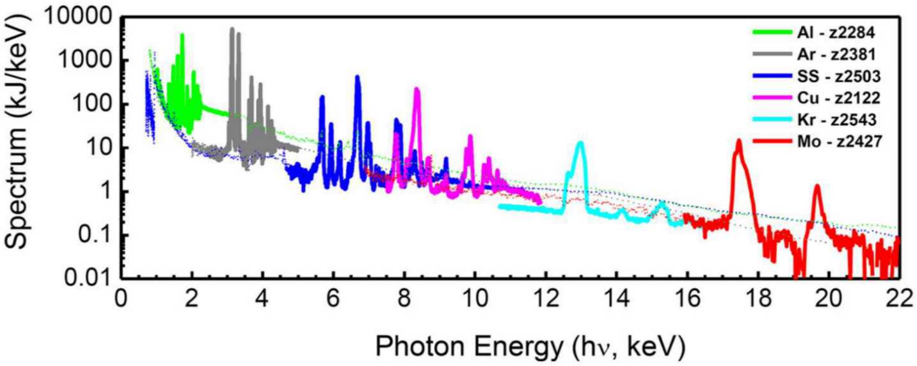
Image from electron backscattering diagnostic of grains in an additively-manufactured stainless steel. The different colors represent different grain orientations.

Image of Z explosive containment system used to contain debris from experiments with hazardous materials such as plutonium

Sandia and Lawrence Livermore National Laboratories are collaborating to produce record levels of >10 keV x rays



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



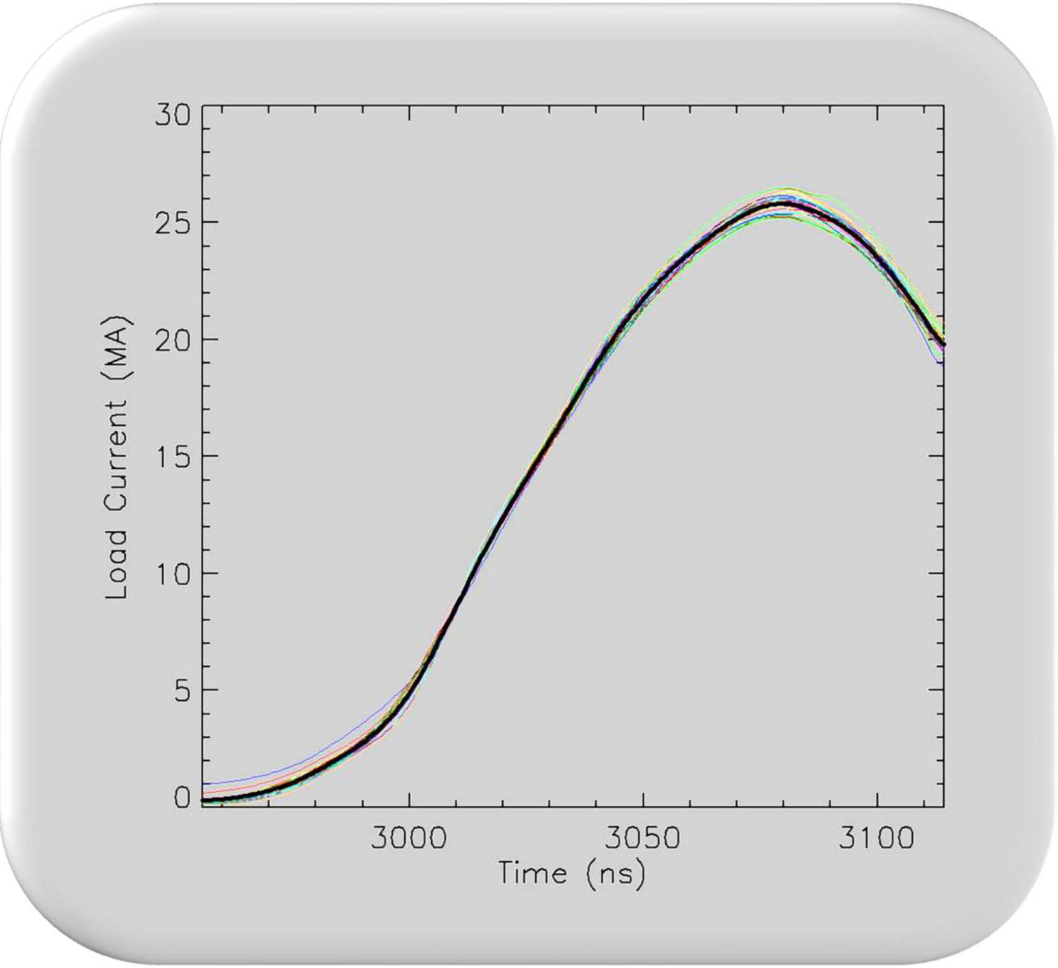
These x-ray sources are being used to study physics models for matter exposed to rapid, intense doses of x rays

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).

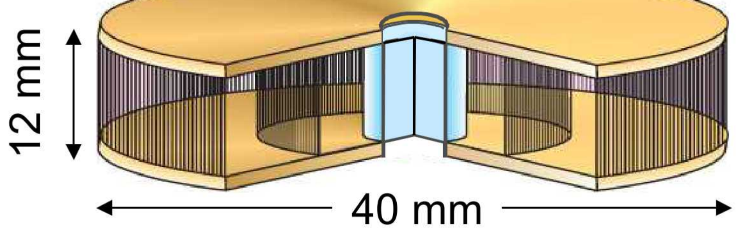
D.J. Ampleford *et al.*, Phys. Plasmas 21, 056708 (2014).

The z-pinch dynamic hohlraum (ZPDH) produces record currents of 25.8 MA with 1.5% reproducibility

Load Currents (20 shot average)



Z-pinch Dynamic Hohlraum



Standard ZPDH Characteristics

360 W wires – 11.4 μm diameter

m = 8.5 mg W total

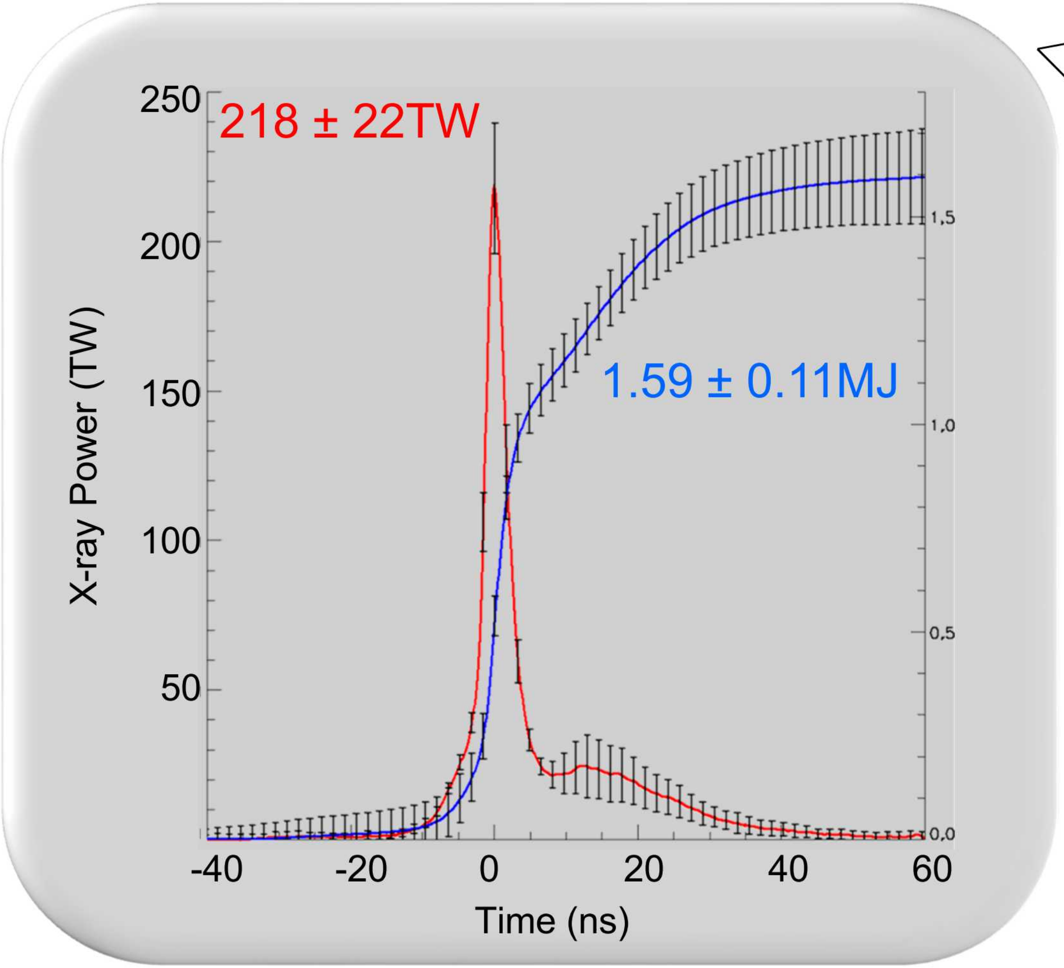
V_{marx} = 85 kV (20.3 MJ)

I_p = 25.8 ± 0.4 MA [20 shots]

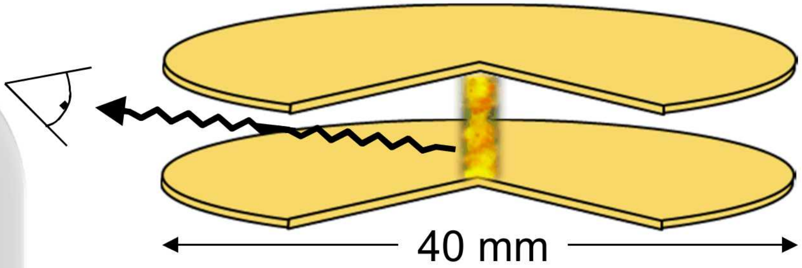
Sanford et al., POP 9 (2002)
Lemke et al., POP 12 (2004)
Bailey et al., POP 13 (2006)
Slutz et al., POP 13 (2006)
Rochau et al., PRL 100 (2008)

The ZPDH x-ray emission is reproducible to ± 10% in peak power and ± 7% in energy

Radial X-ray Power and Energy (20 shot average)



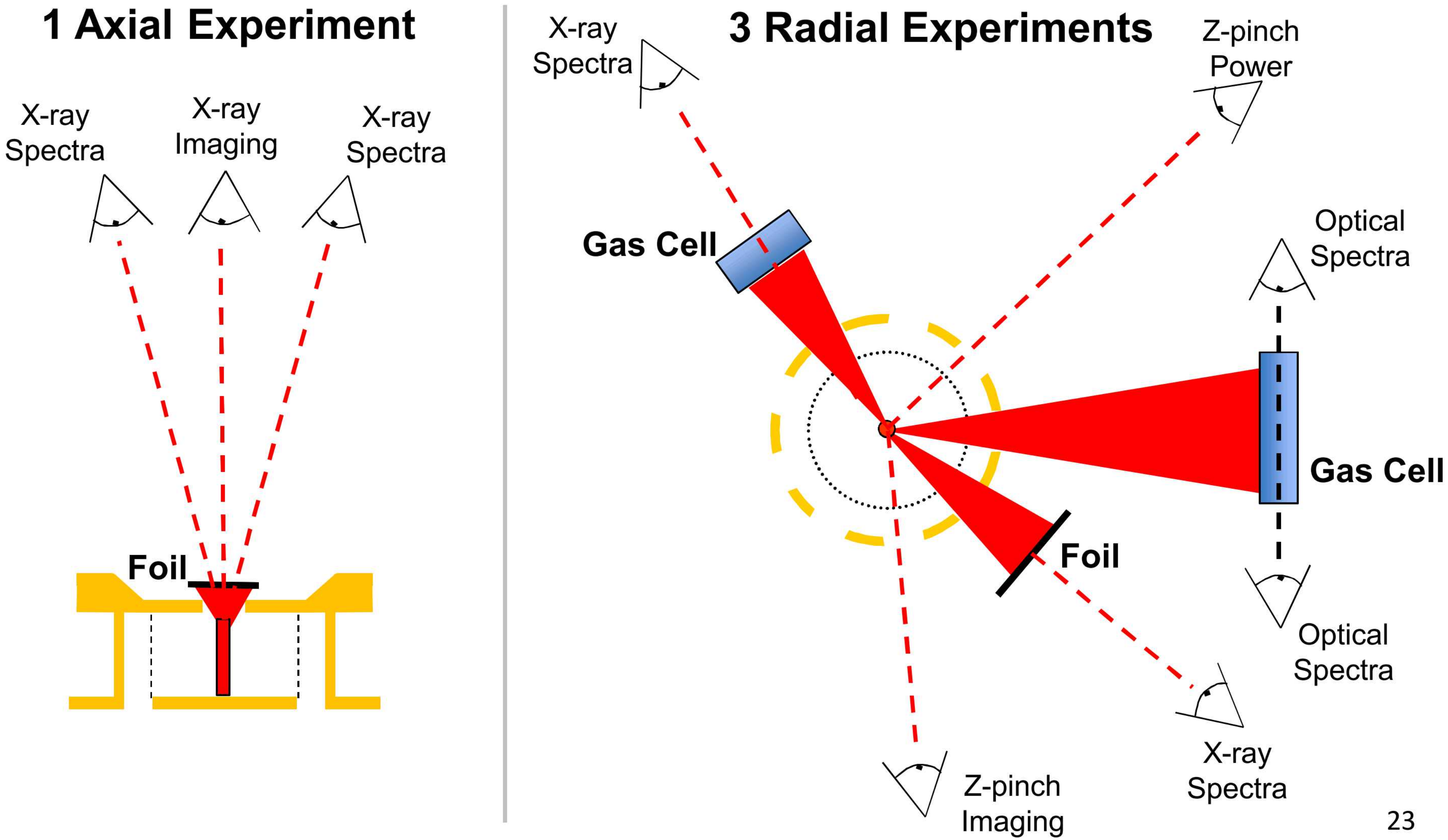
Z-pinch Dynamic Hohlraum



	ZR >2011	Z <2007
Marx Energy	20.3 MJ	11.4 MJ
Ipeak	25.8 MA (1.5%)	21.7 MA* (2.1%)
Mass	8.5 mg	3.8 mg
Peak Power	220 TW (10%)	120 TW (14%)
Radiated Energy	1.6 MJ (7%)	0.82 MJ (17%)

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

The ZPDH can also radiatively heat samples placed above the z-pinch to T_e~200 eV, allowing multiple simultaneous experiments on a single Z shot



Our radiation and materials platforms are heavily used by academic partners as part of Sandia's Z Fundamental Science Program

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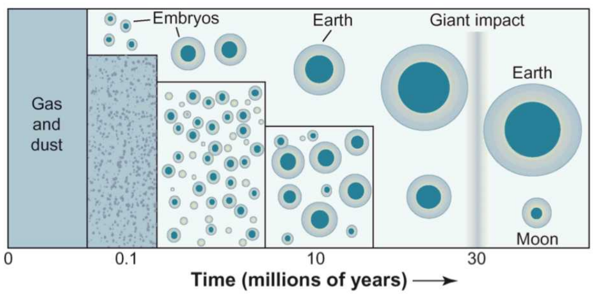
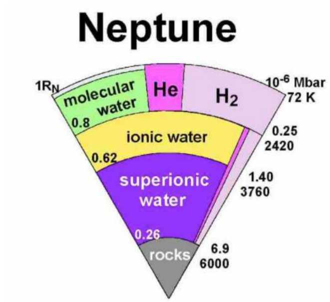
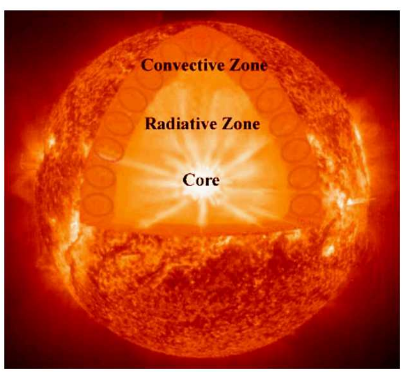


Earth and super earths
Properties of minerals and metals



Jovian Planets
Water and hydrogen



Stellar physics
Fe opacity and H spectra

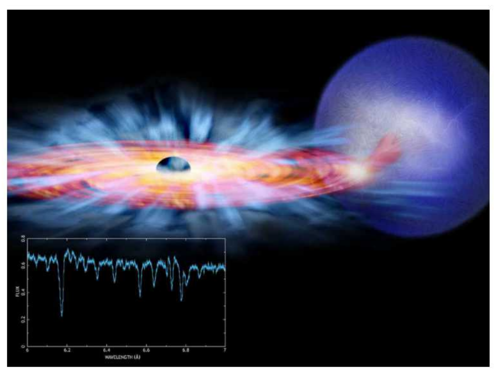


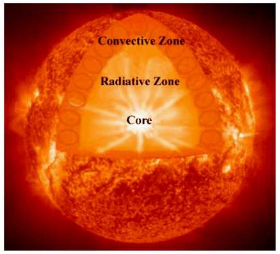
Photo-ionized plasmas
Range of ionization param. ξ

- Scientists at Sandia partner with academic researchers to study cutting-edge high energy density science
- Competitive proposal process
- NNSA provides experimental time on Z, academic partners provide their own support and some equipment
- Has resulted in great science that benefits both academic and applied research efforts on Z!

Five major discoveries in Astrophysics and Planetary Science within the Z Fundamental Science Program

Sandia National Laboratories

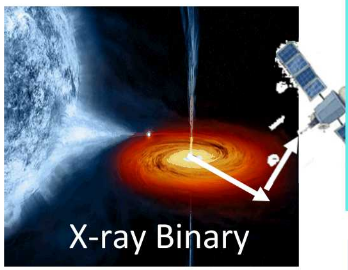
Solar Model



1 μg of stellar interior at R ~ 0.7Rsol

A higher-than-predicted measurement of iron opacity at solar interior temperatures
Jim Bailey, et. al., Nature **517**, 14048 (2015)

Black hole accretion



10^{-3} liters of accretion disk at R ~ 100 – 1000 km from black hole

Benchmark Experiment for Photoionized Plasma Emission from Accretion-Powered X-Ray Sources
G. P. Loisel, J. E. Bailey, et. al., Physical Review Letters **119**, 075001 (2017)

White dwarf photosphere

~0.1 liters of white dwarf photosphere

Laboratory Measurements of White Dwarf Photospheric Lines: HB
Ross Falcon, et. al., The Astrophysical Journal **806** (2015)

1.3 mg (0.8 μL) of metallic hydrogen

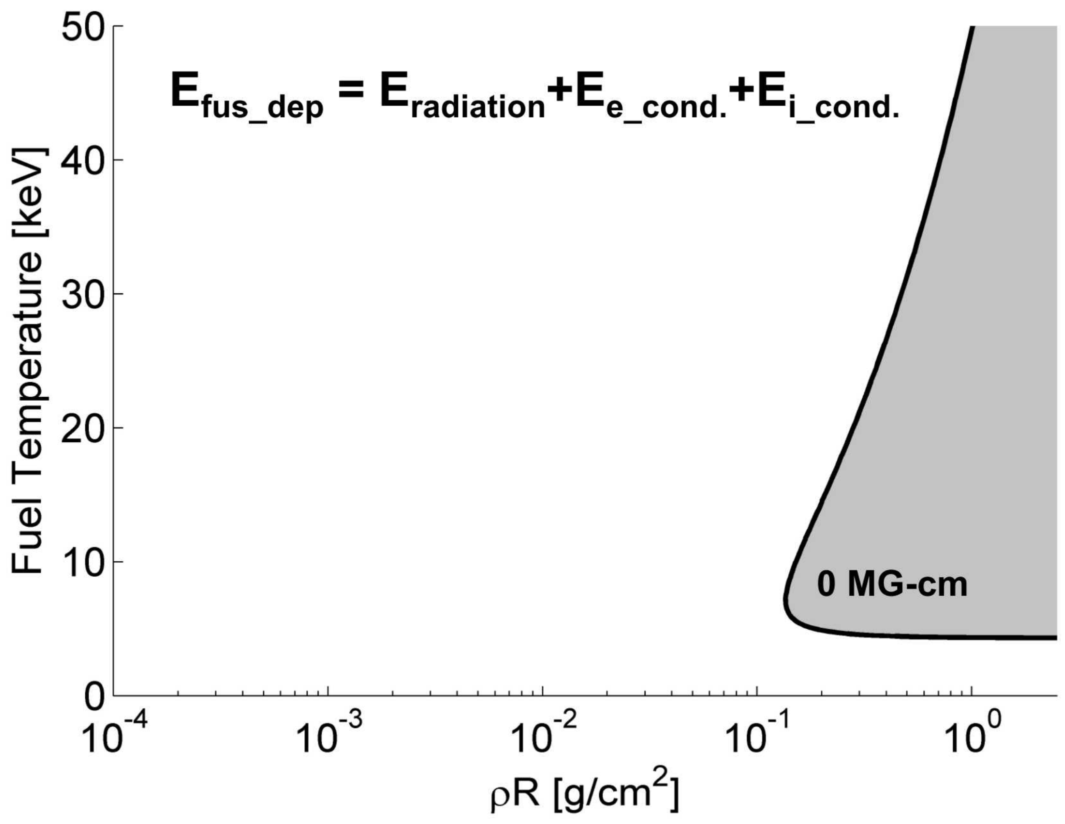
Direct observation of an abrupt insulator-to-metal transition in dense liquid deuterium
Marcus D. Knudson, Michael Desjarlais, et. al., Science **348**, 1455 (2015).

Planetary physics

20 mg (2.5 μL) shocked iron

Impact vaporization of planetesimal cores in the late stages of planet formation
Richard D. Kraus, Seth Root, et. al., Nature Geoscience, DOI:10.1038/NGEO2369 (2015)

ICF has requirements on stagnation conditions to produce and stop alpha particles in order to propagate a burn wave (for high yield)



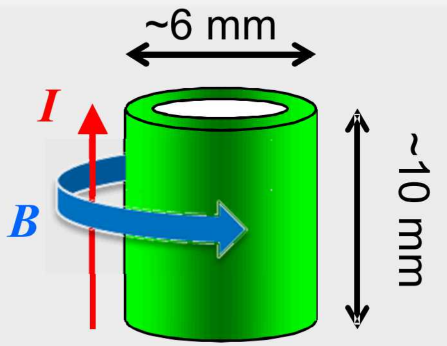
- There is a minimum fuel temperature of about 4.5 keV
  - This is where fusion heating outpaces radiation losses
- The minimum fuel areal density is around 0.2 g/cm^2
- Traditional ICF concepts attempt to operate in this minimum

Room temperature ~0.025 eV

P. F. Knapp *et al.*, Phys. Plasmas 22, 056312 (2015).

Magnetic direct drive provides an alternative way to do ICF using an axial B-field to reduce ρr requirements

Magnetic Direct Drive (MDD)



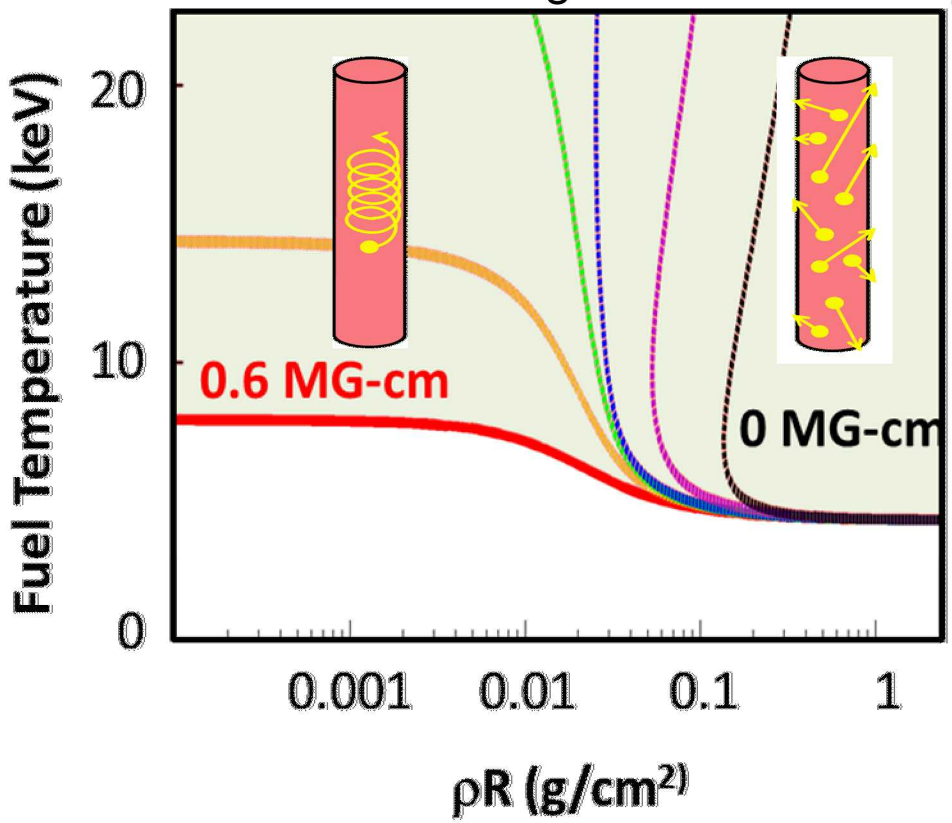
Drive Pressure

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

- Cylindrical convergence
  - Harder to achieve high ρr
- Thick liners (~500 μm)
  - Harder to achieve high velocity

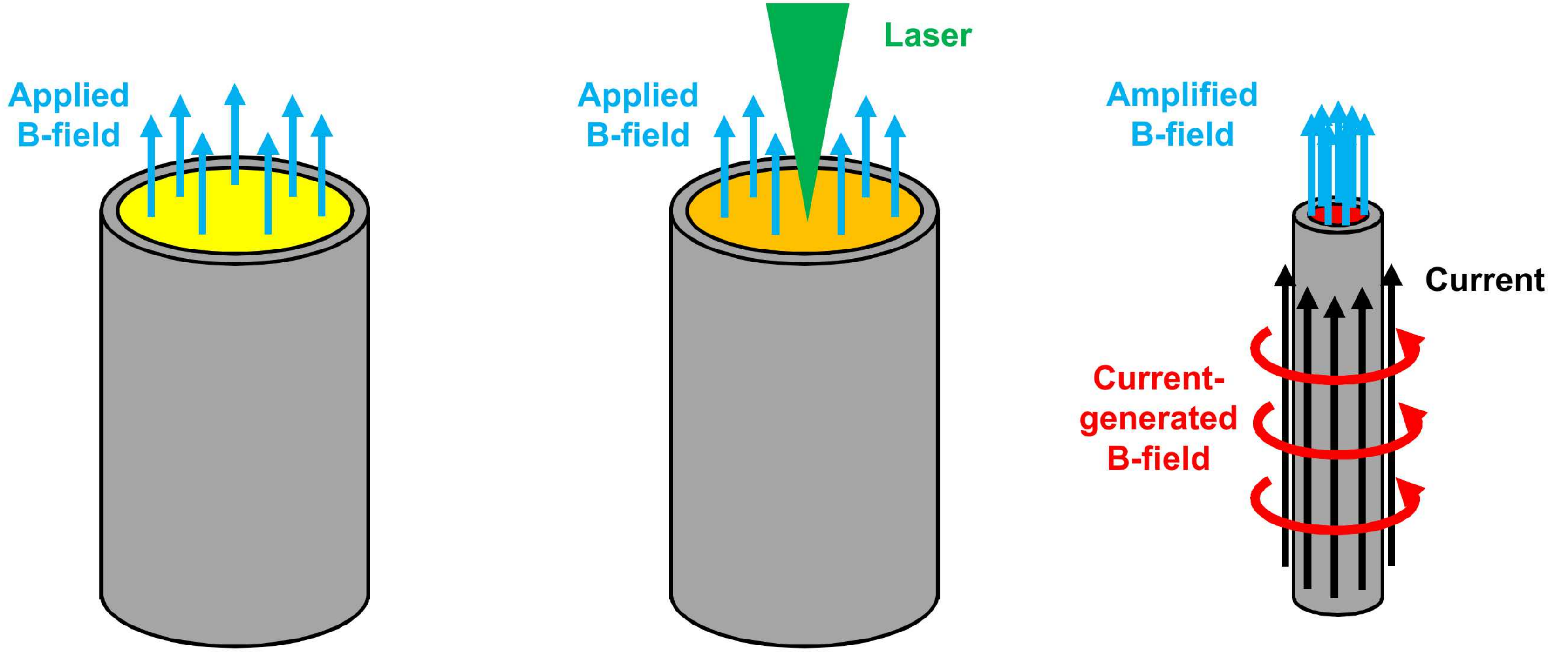
Imposing an axial B-field relaxes ρr requirements

Curves of self-heating from DT fusion alphas



P. F. Knapp *et al.*, Phys. Plasmas 22, 056312 (2015).

Magnetized Liner Inertial Fusion (MagLIF) relies on three stages to produce fusion relevant conditions



Apply axial magnetic field

Heat the magnetized fuel (e.g., with a laser)

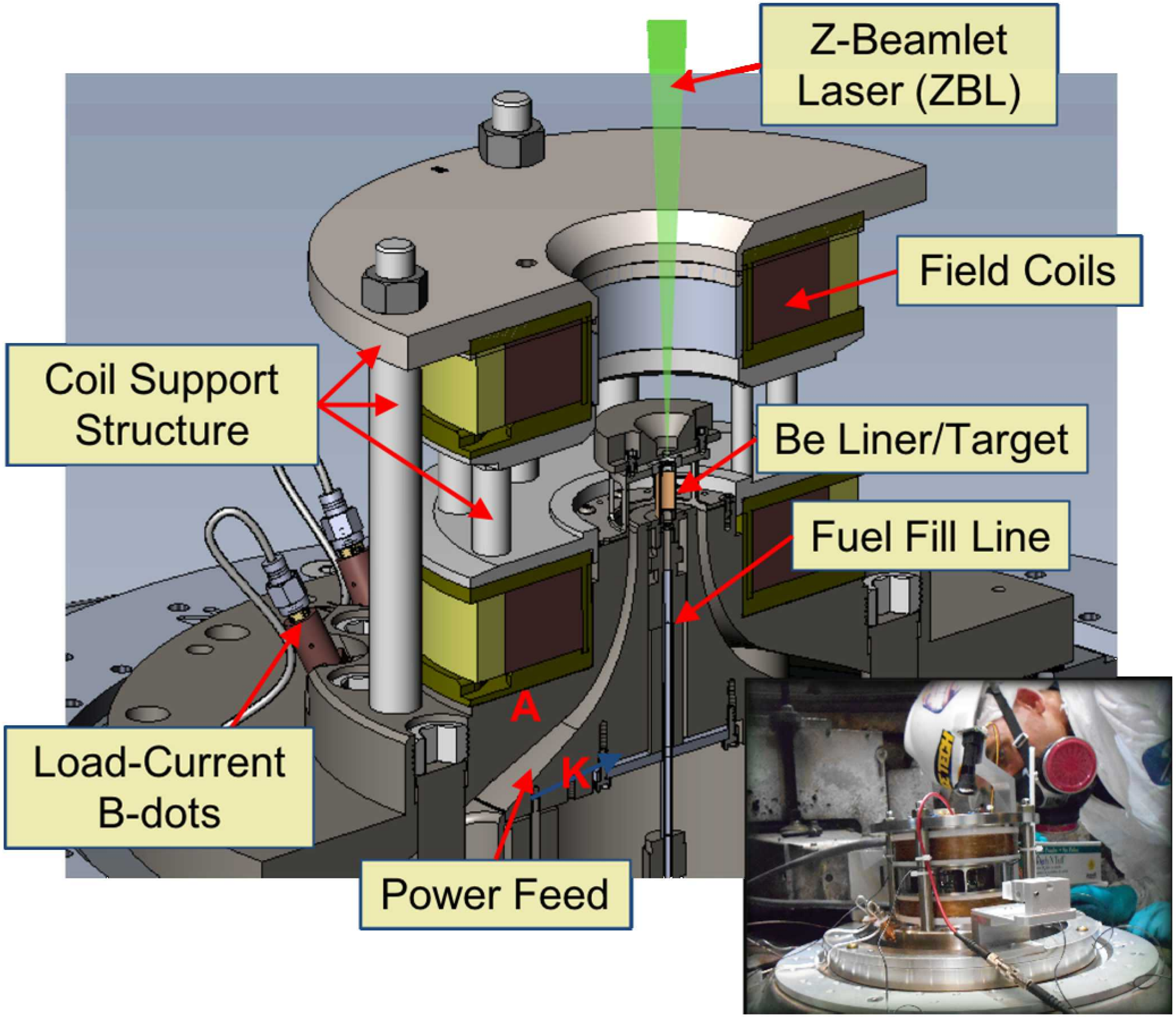
Compress the heated and magnetized fuel

S. A. Slutz *et al.*, Phys. Plasmas 17, 056303 (2010).

Configuration of initial MagLIF Experiments (ca. ~2014)

- **Field Coils**:
  Helmholtz-like coil
  10-30 T axial field
  ~3 ms rise time

- **ZBL**: 1-4 kJ green laser, 1-4 ns square pulse w/ adjustable prepulse (prepulse used to help disassemble laser entrance window)



M.R. Gomez *et al.*, Phys. Rev. Lett. (2014); D.C. Rovang *et al.*, RSI (2014).

We have demonstrated key aspects of magneto-inertial fusion on Sandia's Z facility

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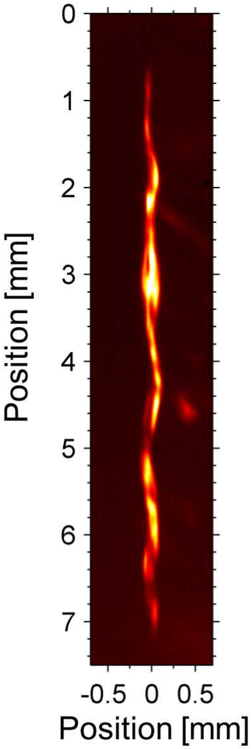
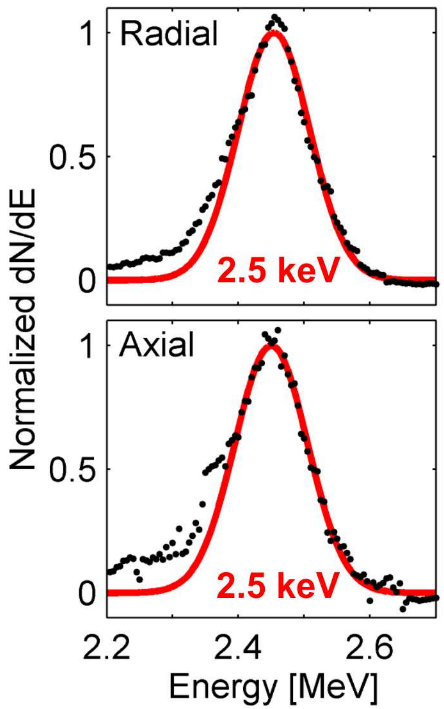
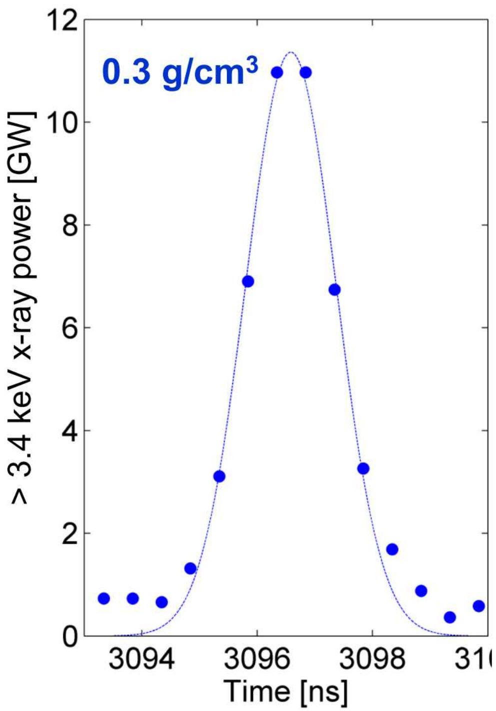
Well-behaved stagnation volume



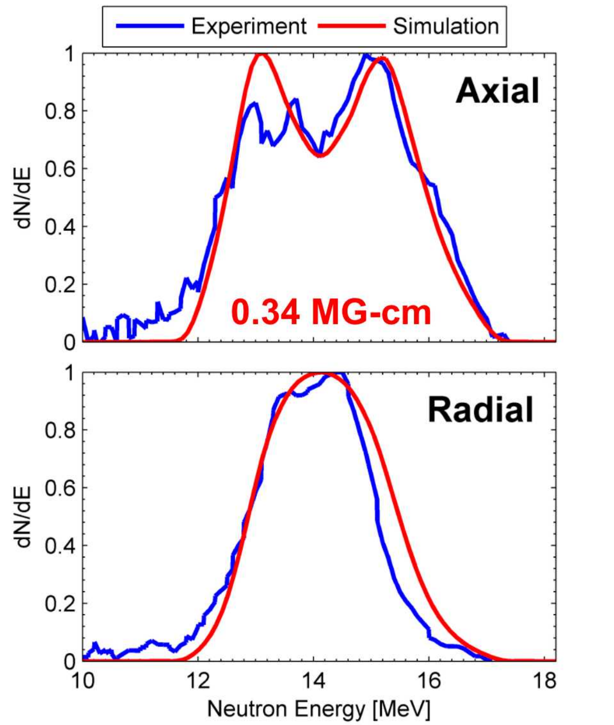
Relevant temperatures



Relevant densities



Relevant fuel magnetization

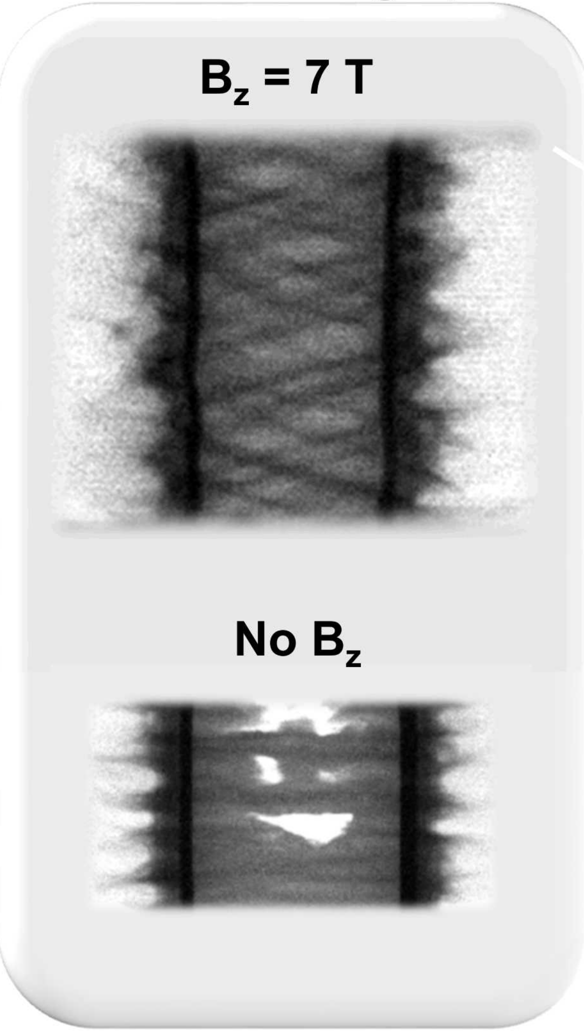


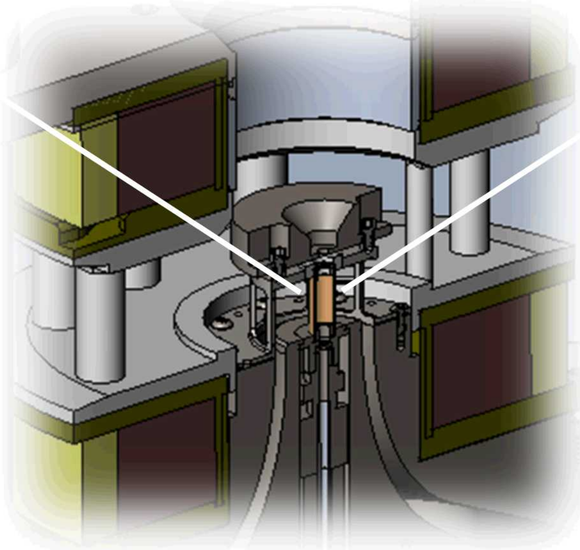
Differences in nTOF shape of secondary DT peak due to magnetization of tritons

M.R. Gomez *et al*., Phys. Rev. Lett. 113, 155003 (2014);
K.D. Hahn *et al.,* RSI 85 (2014);
S.B. Hansen *et al*., Phys. Plasmas 22, 056313 (2015);
P.F. Schmit *et al*., Phys. Rev. Lett. 113, 155004 (2014).

In MagLIF, the applied B-field induces 3-D liner features that imprint on the stagnation column at CR > 40.

Backlit Radiographs

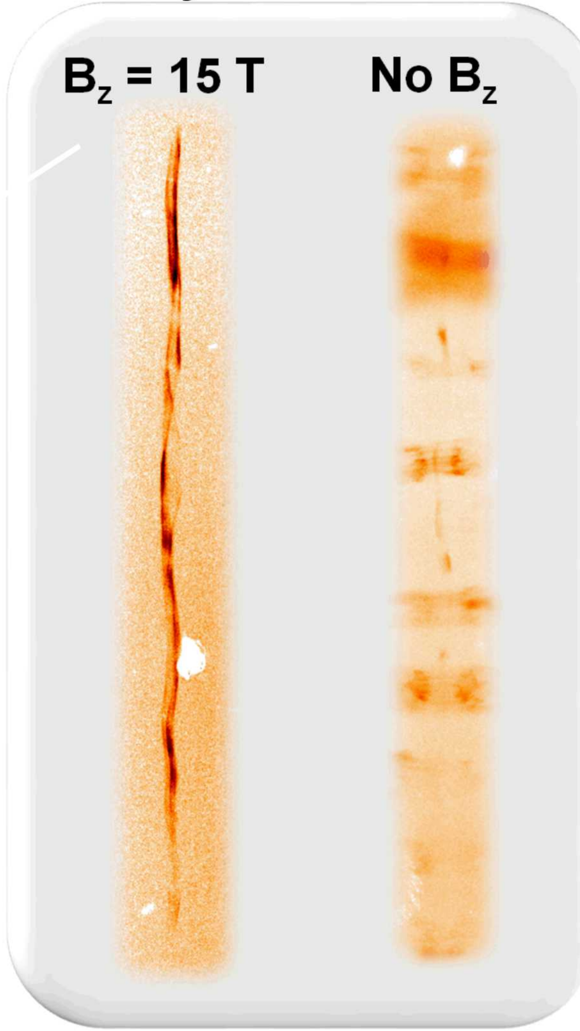




Helmholtz Coil Provides Axial Magnetic Field (B_z)

- Thermal insulation
- Trap fusion particles

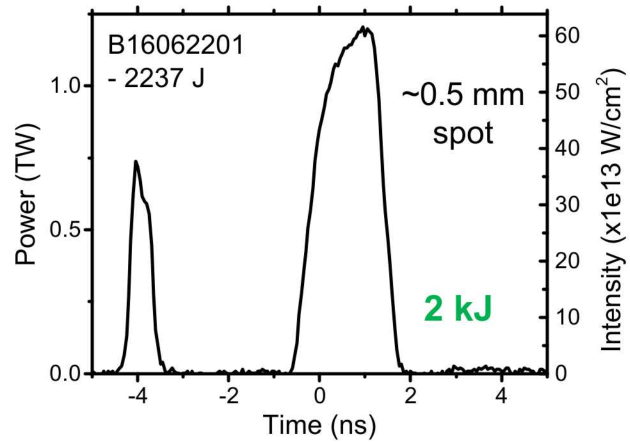
X-ray Self Emission



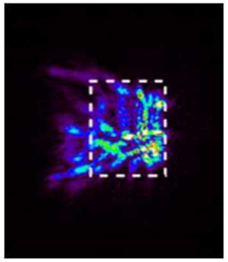
Our initial experiments had significant uncertainty in the coupled laser energy due to poor beam quality

- No beam smoothing was employed (Z-Beamlet only used for radiography before MagLIF)
- Laser configuration produced significant laser plasma interactions (LPI) not modeled in our codes
- Several independent laser heating experiments suggested low (200-600J) preheat coupling
  - Window transmission
  - X-ray emission
  - VISAR blastwave analysis

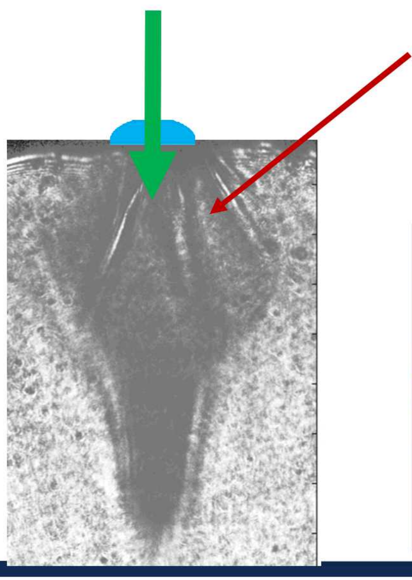
Original MagLIF laser pulse



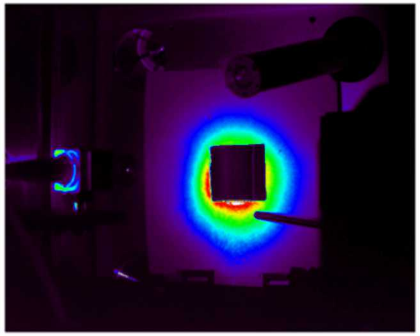
Beam Profile



filamentation



Stimulated Brillouin Scattering: 900J !



M. Geissel *et al.,* Proc. SPIE 9731 (2016); M. Geisel *et al.*, Phys. Plasmas 22 (2018).

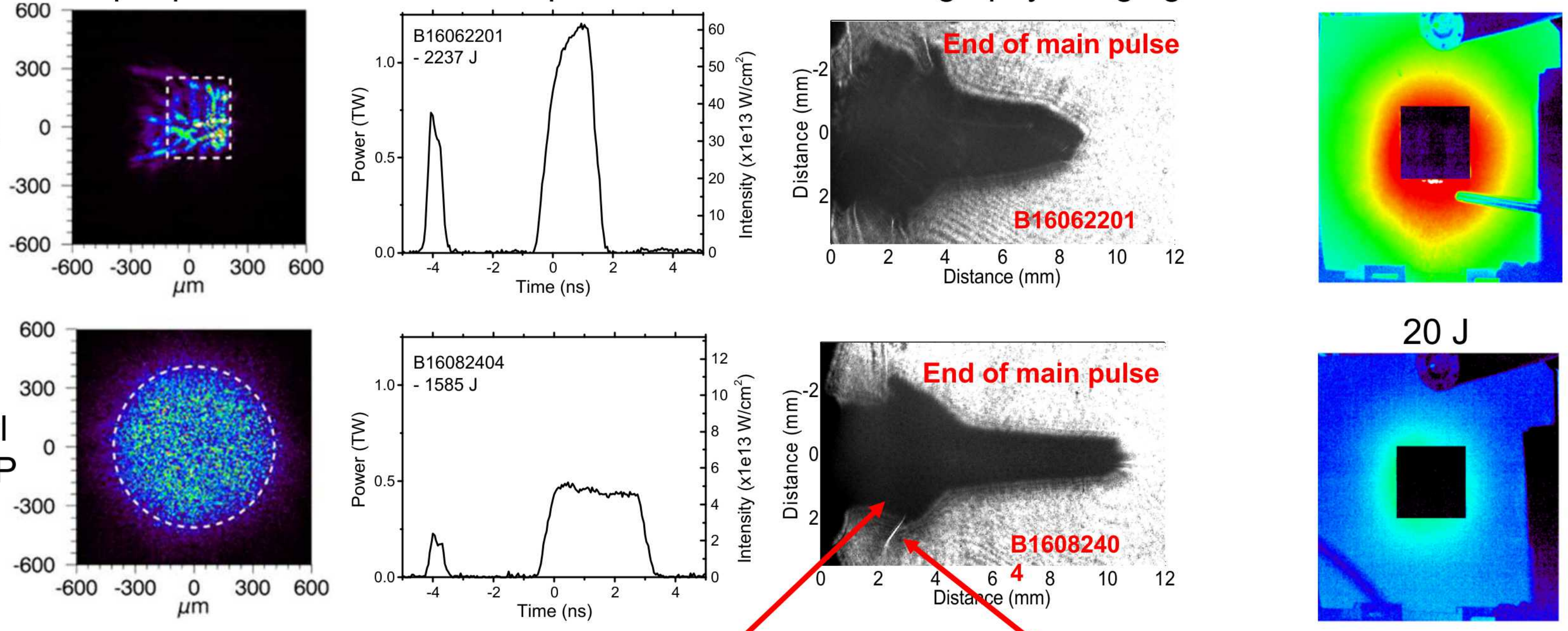
A laser protocol was developed for Z-Beamlet that used phase plate smoothing & lower laser intensity to reduce LPI and modeling uncertainties

SBS backscatter

Spot profile | Laser power | Shadowgraphy imaging | 900 J

Old protocol
No DPP

New protocol
1100 μm DPP

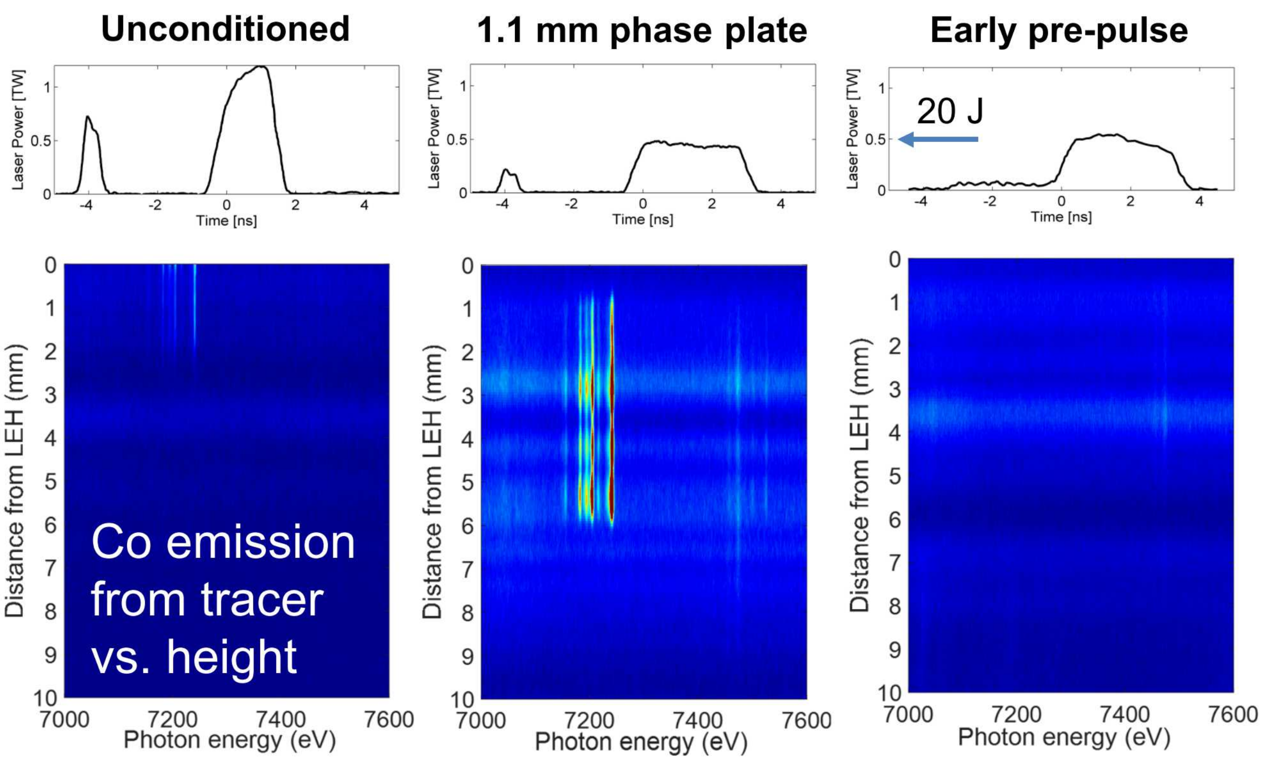


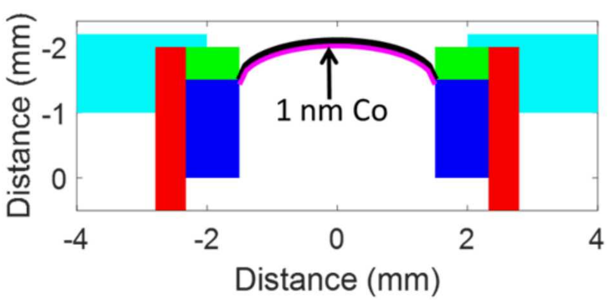
Bulbous features could be beam spray/filamentation or SRS sidescatter or ???

Filament

M. Geissel *et al.*, Proc. SPIE 9731 (2016); M. Geisel *et al.*, Phys. Plasmas 22 (2018).

Spectroscopic diagnostics demonstrated that the phase-plate configuration drove more window material (mix) into the fuel, which was solved by moving the prepulse earlier

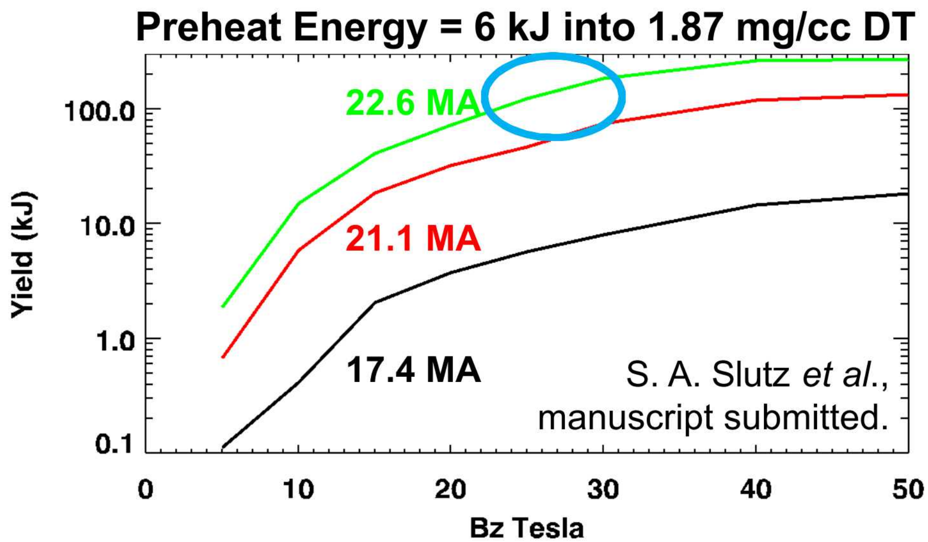




- April Z experiments using a similar early prepulse configuration resulted in improved performance
  - ~1200 J coupled out of 2500 J total laser energy
  - DD neutron yield of 1.1e13 (~2 kJ DT-equivalent)

Our goal on Z is to produce a fusion yield of ~100 kJ DT-equivalent

- 2D simulations indicate a 22+ MA and 25+ T with 6 kJ of preheat could produce ~100 kJ
- Presently, we cannot produce these inputs simultaneously.
- We are making progress in demonstrating scaling



Date	Liner	Fill (D2)	Current	Bfield	Preheat	Yield (DT-eq.)
2014	AR=6	0.7 mg/cc	17-18 MA	10 T	~0.3 kJ?	0.2-0.4 kJ
April 2018*	Coated AR=9	1.1 mg/cc	15-16 MA	10 T	~1.2 kJ*	2.4 kJ*
Aug. 2018**	AR=6	1.1 mg/cc	20 MA	15 T	~1.2 kJ**	~2.4 kJ**
2020 Goal	TBD	~1.5 mg/cc	20-22 MA	20-30 T	2-4 kJ	~10 kJ
Final Goal	TBD	1.5 mg/cc	22 MA	25-30 T	6 kJ	100 kJ

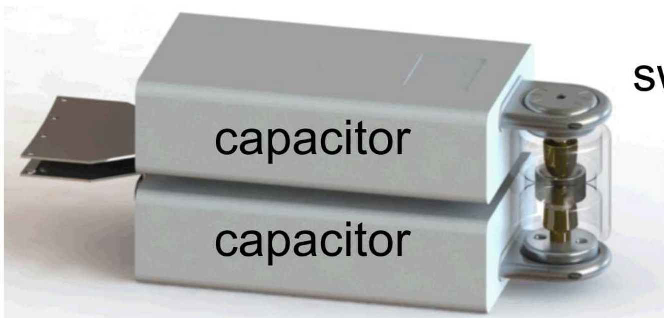
* A.J. Harvey-Thompson *et al.*, preliminary analysis; ** M.R. Gomez *et al.*, preliminary analysis

Outline

- Pulsed power at Sandia: The Z Machine
- Applications of pulsed power to High Energy Density (HED) Science
- The future? Pulsed power technology development at Sandia

We are exploring a modular architecture that can scale to 300-1000 TW and is twice as electrically efficient as Z

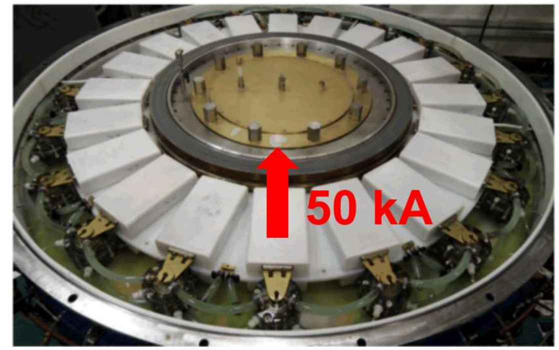
Brick – "quantum" of the next gen systems
Single step pulse compression to 100 ns



switch

5.2 GW/800 J per brick

Cavity – multiple bricks in parallel



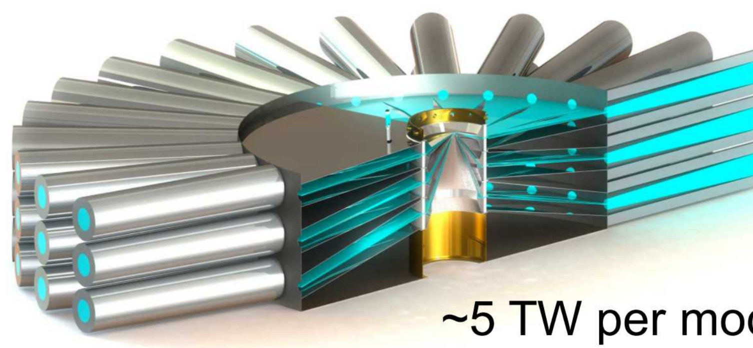
50 kA per brick

Module – multiple cavities in series

Linear Transformer Driver (LTD)

100 kV per cavity

Machine – multiple modules and levels in parallel



~5 TW per module

Next-gen machines: 20,000-200,000 bricks, 33-60 cavities/module, and 65-800 modules!

W.A. Stygar *et al.*, PRSTAB (2007); W.A. Stygar *et al.*, PRSTAB (2015); W.A. Stygar *et al.*, Proc. IEEE PPC (2017).

Bricks are a basis for other driver architectures, e.g., multi-MA arbitrary waveform generators for material science

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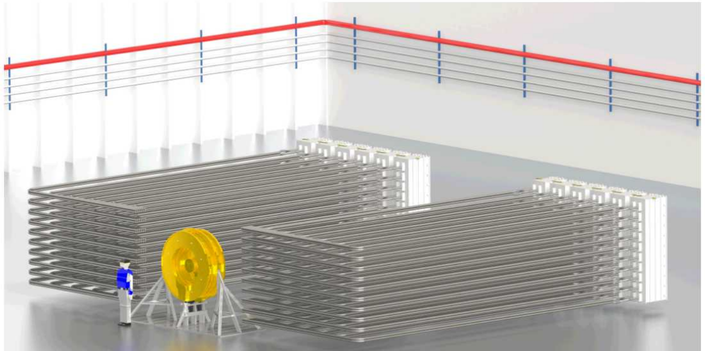
Brick

Thor-72 (0.5 Mbar)

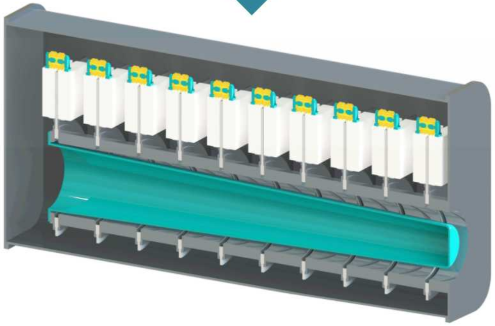
4 MA, 200 ns

Thor-240 (1.2 TW, 2 Mbar)



Reisman *et al.*, PRSTAB 18 (2015).

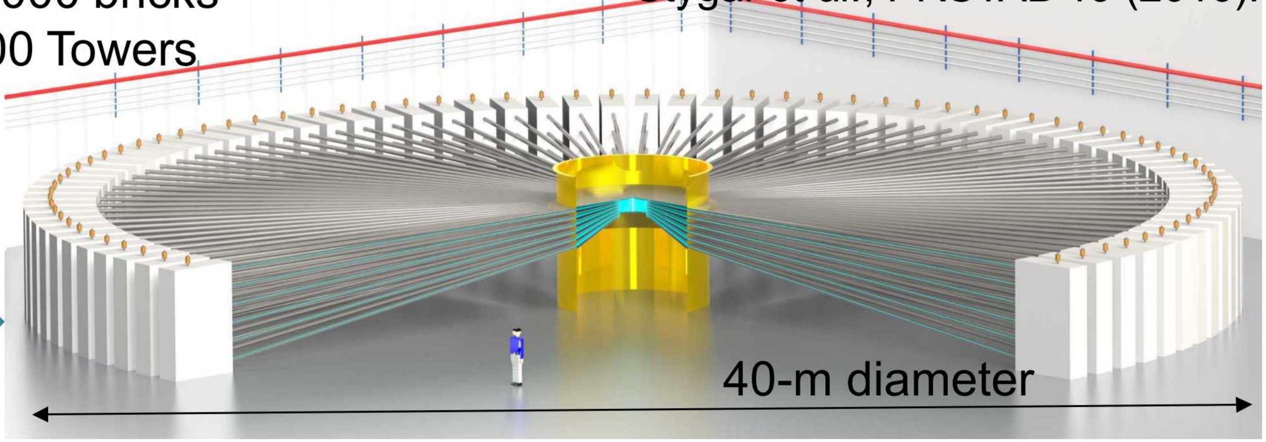
7 MA, 200 ns



4,800 IMGs
48,000 bricks
800 Towers

10-stage Impedance Matched Marx Generator (IMG)

Neptune (50 TW, 20 MBar)

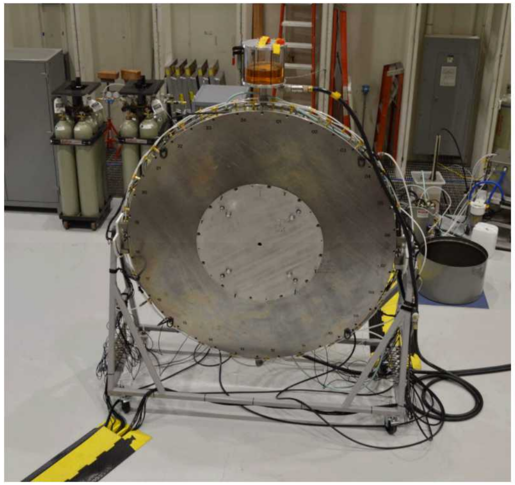


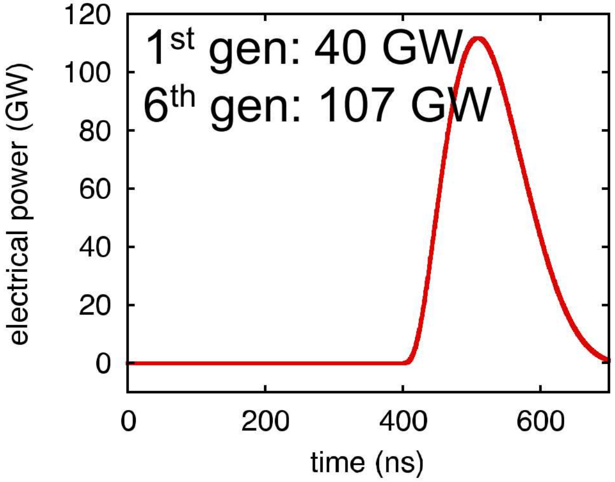
Stygar *et al.*, PRSTAB 19 (2016).

23 MA, 750 ns

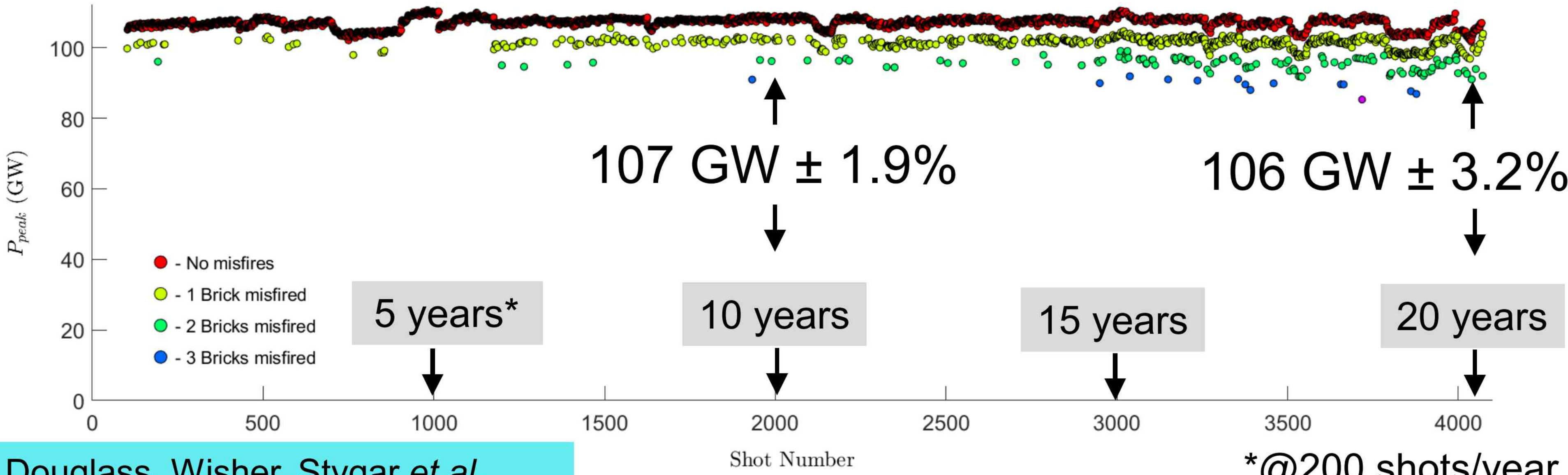
LTD Cavity: We demonstrated 4750 shots over 6 months at full voltage (100 kV) with no major configuration change or component failure

6th generation cavity





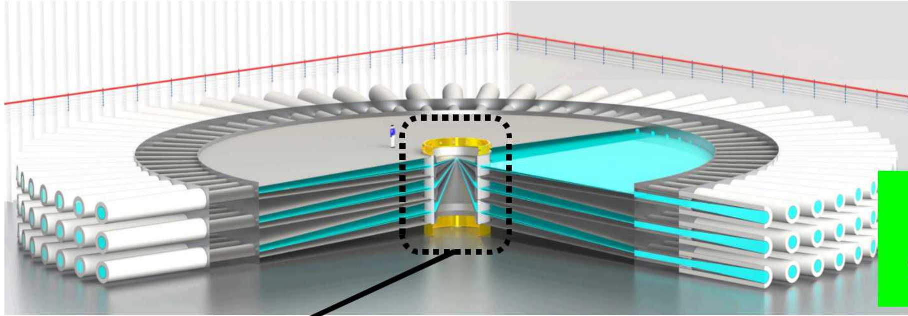
Shots	Cavity Power	Module variation (42 cavities)	Variation per 100 modules (460 TW)
2000	107 ± 1.9%	±0.3%	±0.03%
3970	106 ± 3.2%	±0.5%	±0.05%

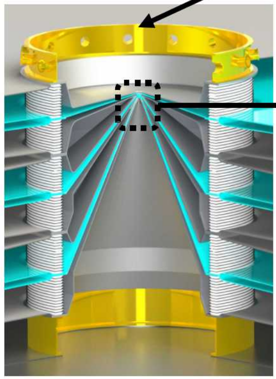


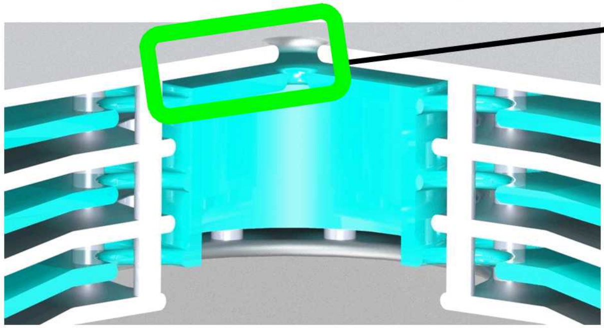
Douglass, Wisher, Stygar *et al.*

*@200 shots/year

We are also starting to investigate driver-target coupling physics, which is an uncertainty in going to larger machines

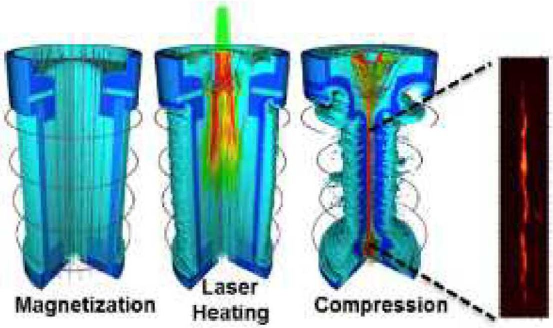






~3-5 PW
9 MJ electrical

Inertial Confinement Fusion Ignition



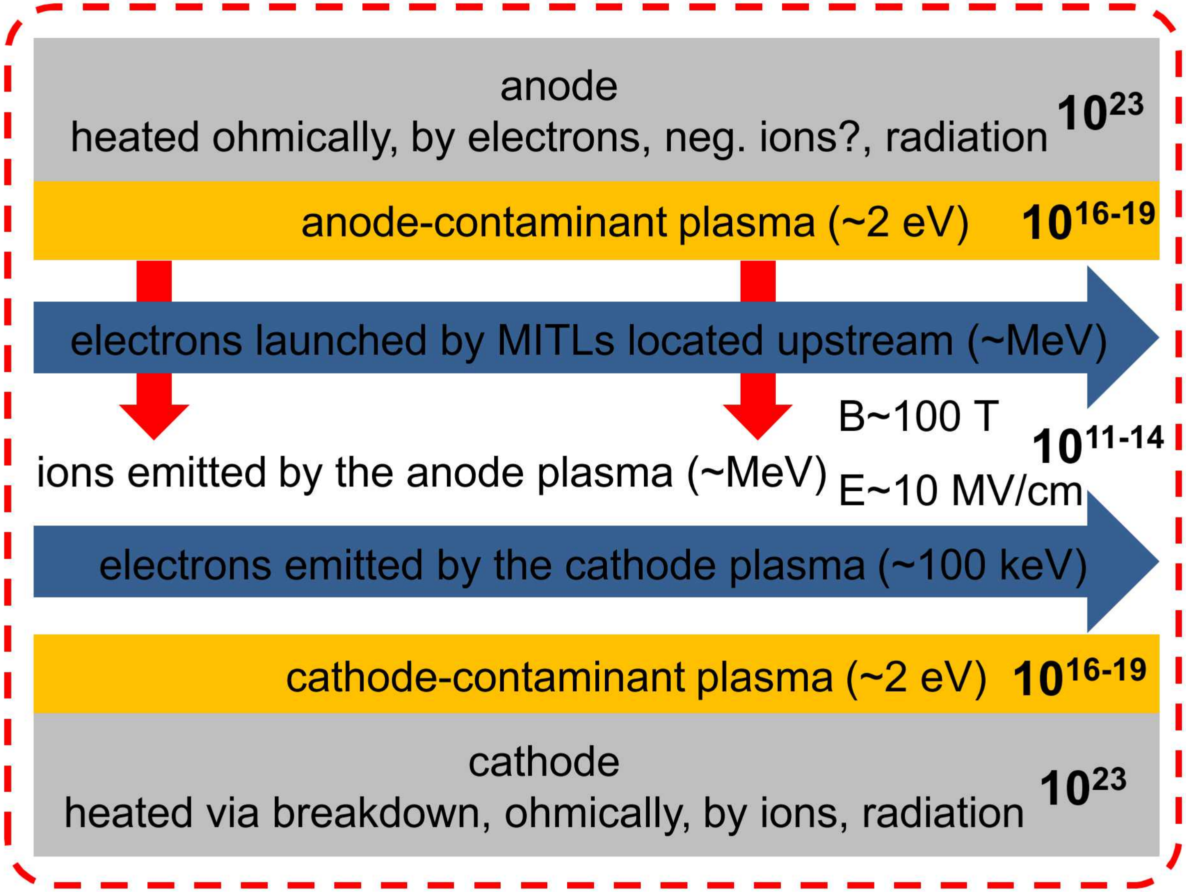
1-30 PW DT neutrons
4-5 PW soft x-rays

Discovery Science Experiments

<u>Example driver uncertainties</u>
Electrode plasma formation/expansion
Current loss

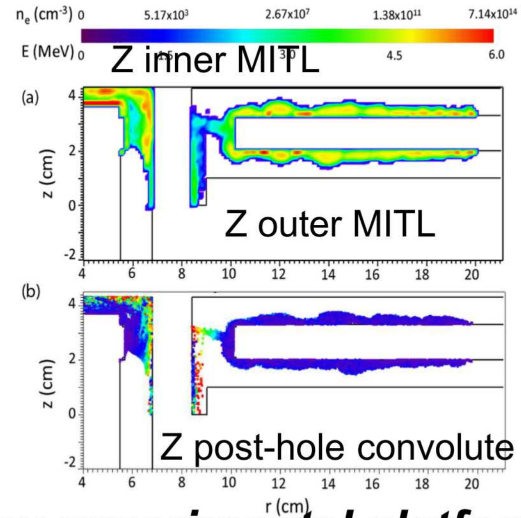
A terawatt-class power pulse generates plasmas within a vacuum transmission line

section of a “vacuum” transmission line at small radius

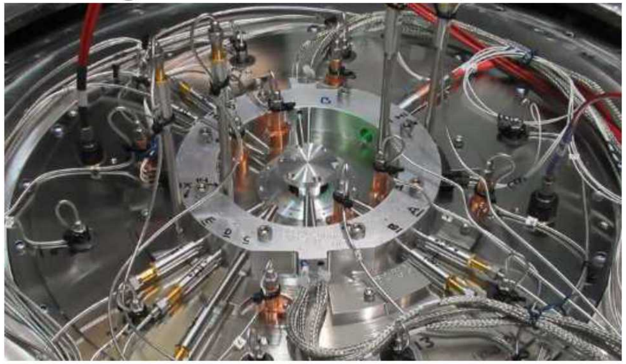


Multi-scale and non-neutral plasmas crossing PIC and Continuum regimes

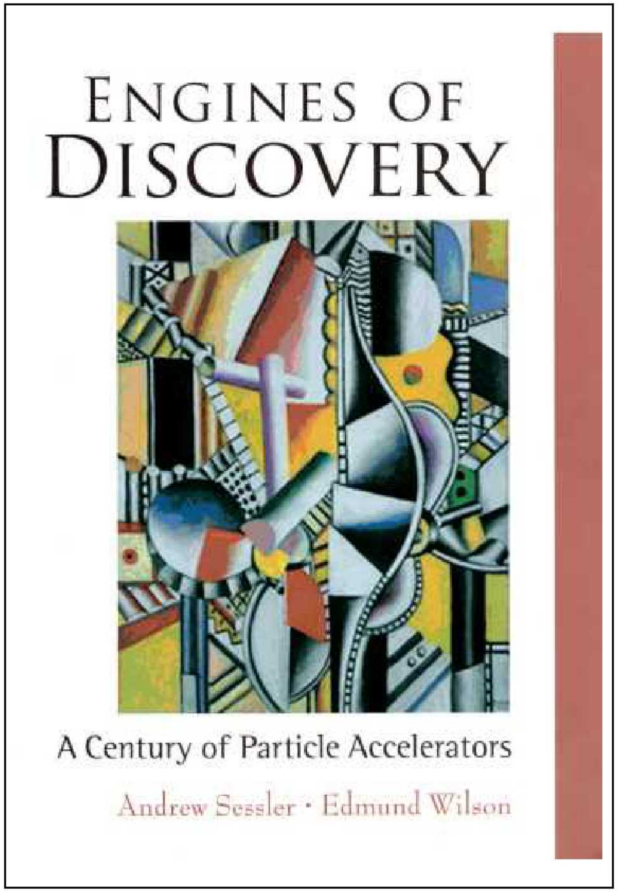
Improvements to modeling



New experimental platforms & diagnostic developments



It is our job as a community to demonstrate that pulsed power machines can be "engines of discovery" for HED science, just as particle accelerators have been



- Classical particle accelerators have numerous applications to fundamental understanding of the universe and structure of matter, to probing of matter, and to industrial and medical applications.
  - Induced radioactivity, Isotope enrichment, antiproton, nuclear structure, J/ψ (quarks), tau lepton, W, Z particles, top quark, Higgs boson
  - Industrial (hardening, sterilization)
  - Medical use (imaging, therapy)
  - Research (x-ray and particle probes)
  - 14 Nobel prizes for accelerators or using accelerators
- Pulsed power accelerators are engines of discovery for HED science
  - Intrinsic material properties (EOS, conductivity, strength, structure of materials)
  - Radiation transport, atomic physics, opacity
  - Magnetized plasma physics
  - Fusion ignition ("chief unsolved problem in plasma physics")

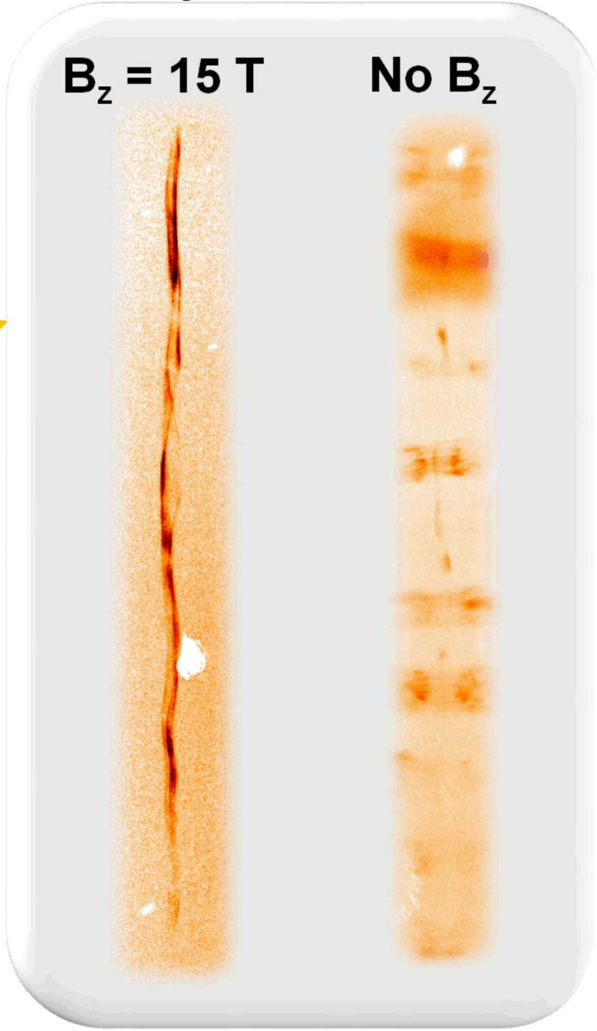
END

We have verified that good performance requires both applied B-field and laser heating, though the No B-field case is not really the same experiment

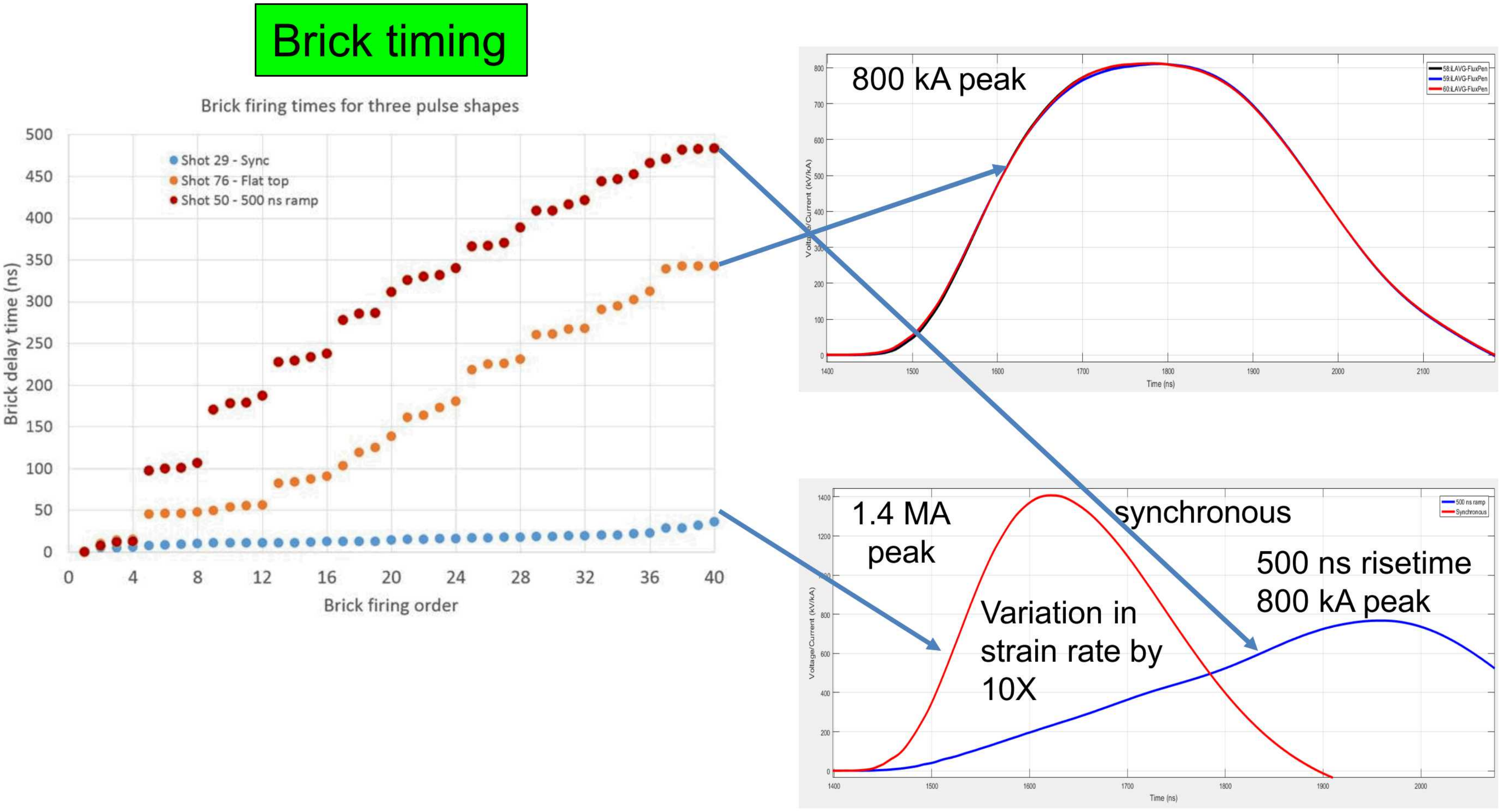
	No B-field	B-field
No Laser Heating	**3×10^{9}** **(near-background)**	**1×10^{10}**
Laser Heating	**4×10^{10}**	**3×10^{12}**

3×10^{12} is a DT-equivalent yield of ~0.6 kJ

X-ray Self Emission



Thor provides a multi-MA arbitrary waveform generator with unprecedented precision in achieving a desired loading history



Thor is capable of many different loading histories which allows greater flexibility in accessing the materials temperature-density phase space

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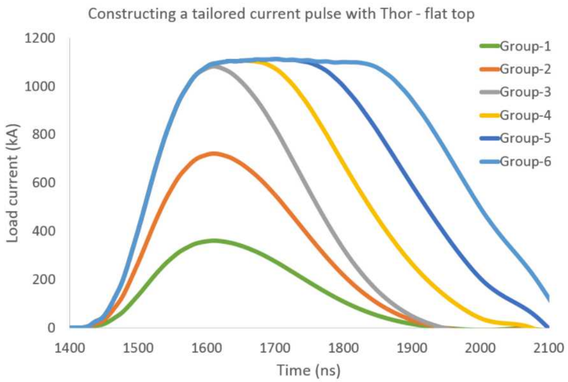
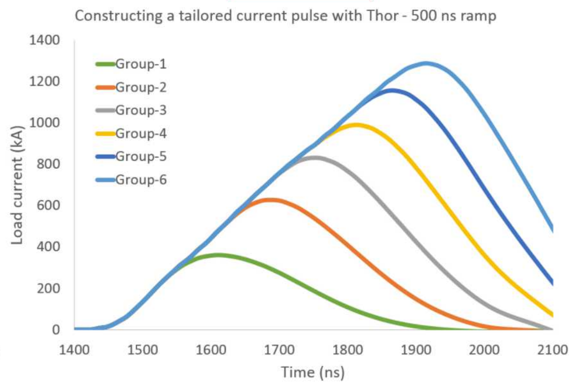
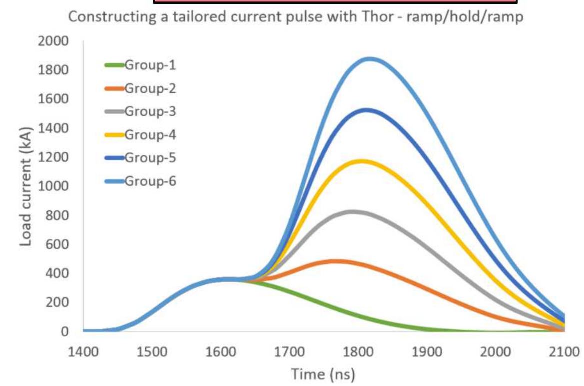
ramp-hold-release



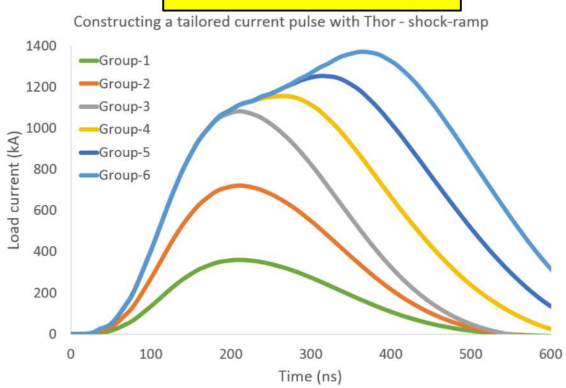
ramp



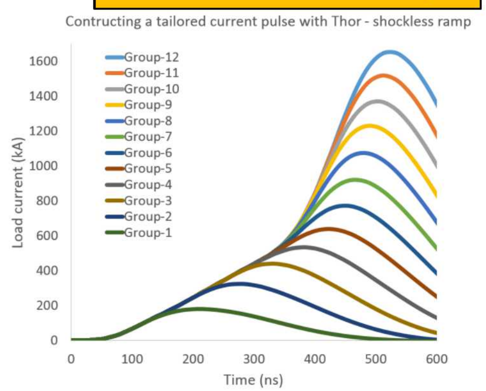
ramp-hold-ramp



shock-ramp



shockless ramp



ramp-hold-ramp