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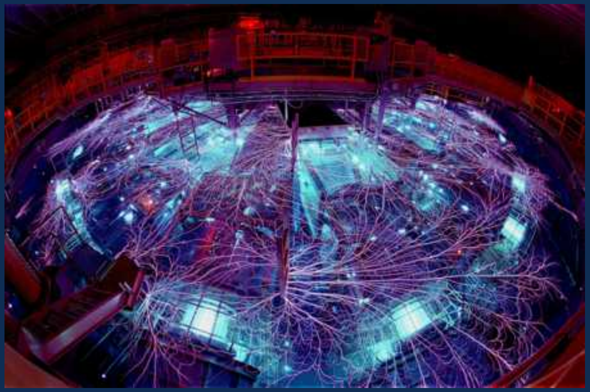

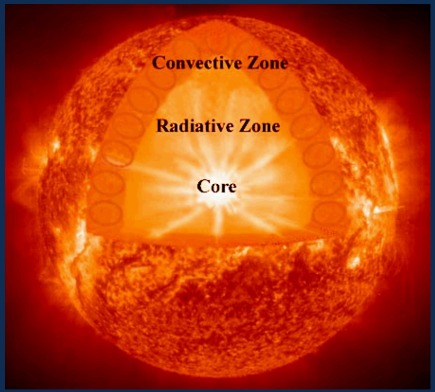

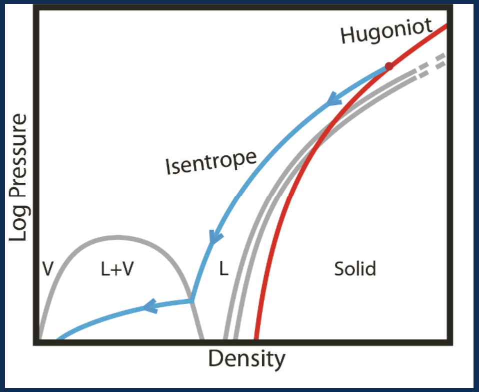

HED Science at Sandia: planets, stars, fusion, and the future

Thomas Mattsson

Manager, HEDP Theory

Workshop on High Energy Density Physics
University of California, San Diego, December 3-4, 2015.

U.S. DEPARTMENT OF ENERGY NNSA National Nuclear Security Administration

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MHD: currents and the corresponding magnetic fields can create high energy density matter

Current x magnetic field

$$\rho\left(\frac{\partial \mathbf{u}}{\partial t}+(\mathbf{u}\cdot\nabla)\mathbf{u}\right)=\frac{\mathbf{J}\times\mathbf{B}}{c}-\nabla P\approx\frac{1}{4\pi}\mathbf{B}\bullet\nabla\mathbf{B}-\nabla\left(P+\frac{B^2}{8\pi}\right)$$

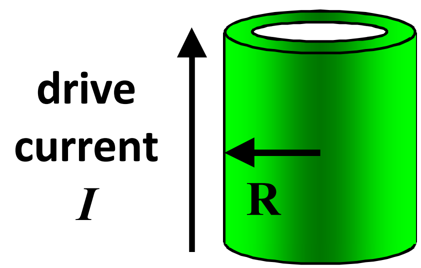
velocity field

Pressure

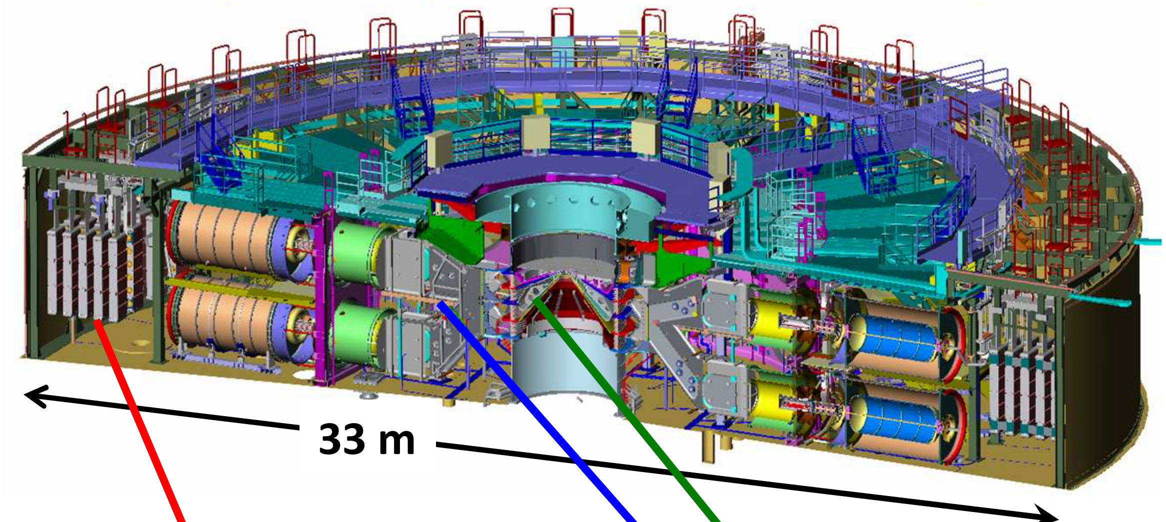
Magnetic field as scalar pressure

- Using pulsed power (current) as a source has advantages
  - *Can create high pressures without making material hot*
  - Generated over long time scales with control over the time history
  - Large samples and energetic sources (2 MJ to load of 20 MJ stored)
  - Low price - $4/Joule stored for refurbishment in 2007
- Integrated projects with theory/simulations/experiment
  - Develop, design, analyze, and optimize experiments

- 25 MA at 1cm radius is 1 Mbar
- 25 MA at 1mm radius is 100 Mbar

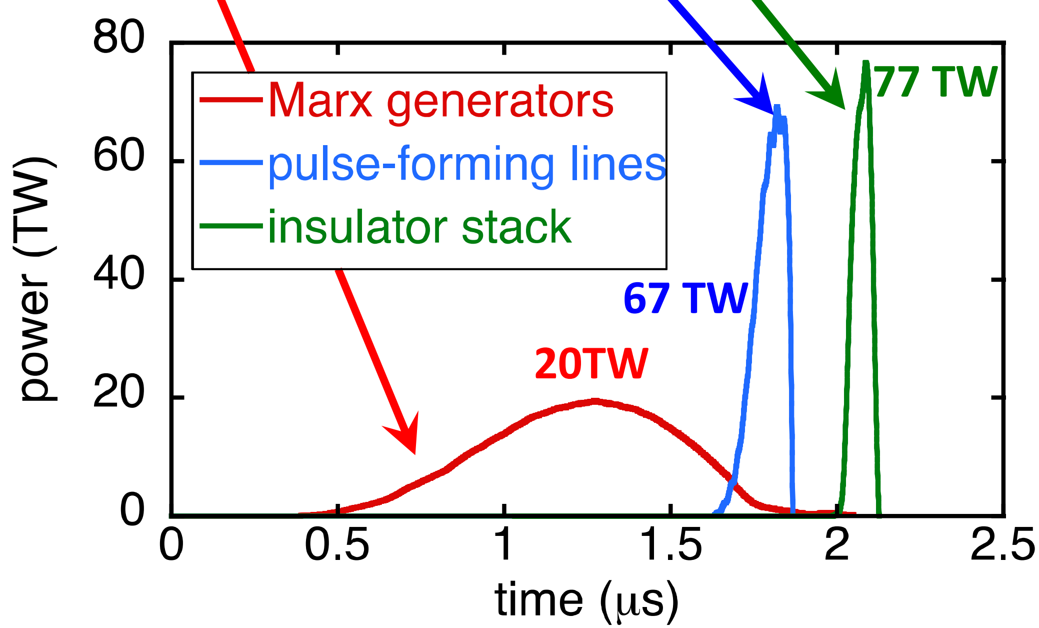


The current pulse on Z is tenfold compressed and then shaped depending on the experimental objective



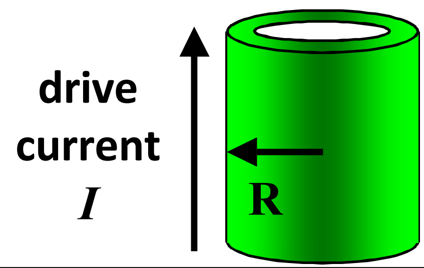
20 MJ stored on Z to:

0.5 MJ in MagLIF targets
0.1 MJ in DD fuel
1.5 MJ broad band x-ray
0.4 MJ Al K-shell x-ray



Magnetically Driven Implosion

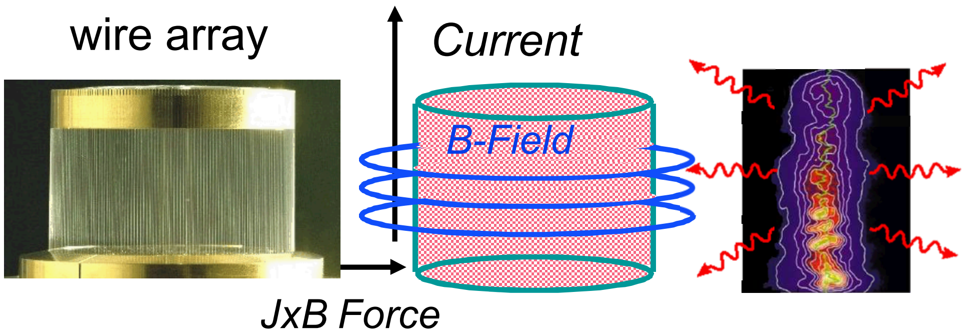
$$P = \frac{B^2}{8\pi} = 105\left(\frac{I_{MA}/26}{R_{mm}}\right)^2 \text{ MBar}$$



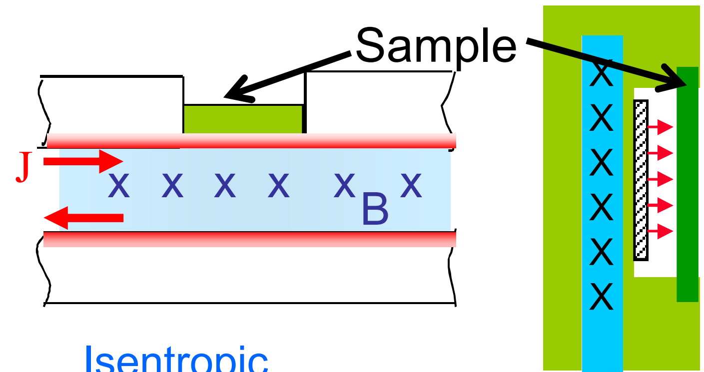
100 MBar at 25 MA and 1 mm

We use magnetic fields to create HED matter in different ways for different applications

Radiation physics using Z-Pinch X-ray Sources



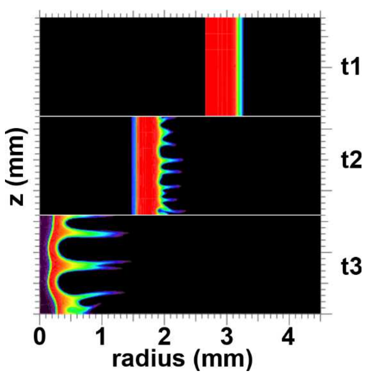
Materials Properties: EOS



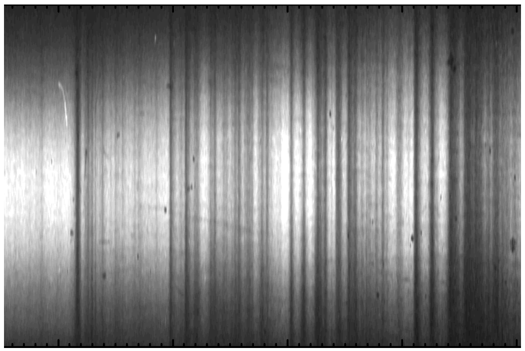
Isentropic Compression

Flyer Plate

Atomic- and plasma physics

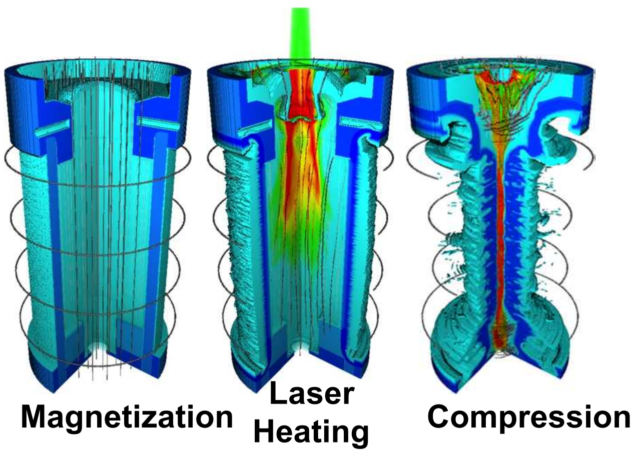


MRT instabilities



Iron spectrum

Inertial confinement fusion



The Z Fundamental Science Program has grown over the last few years

Sandia National Laboratories

ZFSP past and present

- IHEDS 2009-2010 workshops in SF
- 2010 – call for proposals and review
- 2011 – 15 dedicated shots on Z
- 2012 – 20 dedicated shots on Z
- 2013 – NNSA/NA-11 pause
- 2014 – Restart of ZFSP
- 2014 – External review of the program and extension for CY15 shots
- 2015 – 18 shots on the schedule
- 2016 – 12 shots planned (FY16 is tight)
- 2017 – TBD with a goal of 20 shots

- **Workshops**
  - 2009 Hilton, Santa Fe
  - 2010 Eldorado, Santa Fe
  - 2011 Eldorado, Santa Fe
  - 2012 Andaluz, Albuquerque
  - 2014 Andaluz, Albuquerque
  - 2015 Hyatt, Albuquerque
- **Liner Fusion workshop**
  - 2012 Marriott, Albuquerque

2016 ZFSP workshop

Sunday 7/31/16 (eve.) to Wednesday 8/3/16, Albuquerque, NM.

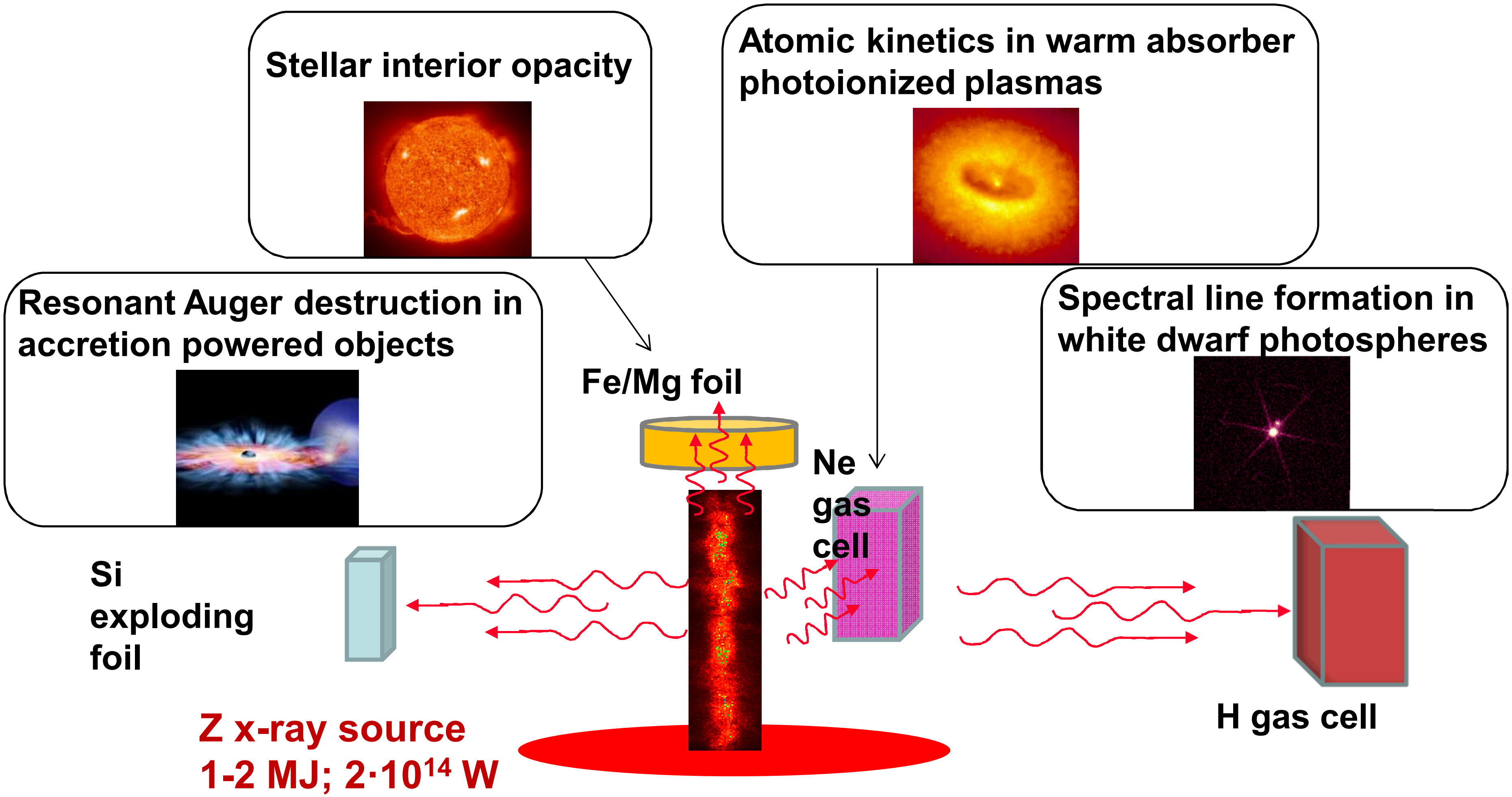
The Z Fundamental Science Program engages a broad international community and has advanced HED science

Sandia National Laboratories

- **Resources/shots on Z over 5 years**
  - 50+ dedicated ZFSP shots (~5% of all Z shots)
  - Ride-along experiments on program shots
- **Science with far-reaching impact**
  - 1 Nature, 1 Nature Geoscience, 1 SCIENCE
  - 1 Phys. Rev. Lett, 3 Physics of Plasmas, 2 Physical Review (A,B) , 9 others

- **Popular outreach**
  - National Public Radio, “All things considered”, Joe Palca 3/6/2014
  - MIT Technology review, 10/4/2012
  - Discover Magazine
    - Reportage 9/16/2012
    - *Iron rain #62 in top 100 Science stories in 2015*
  - Local TV coverage (7-KOAT, 13-KRQE) in early 2015
- **New external funding won**
  - DOE/OFES/HEDLP
- **Students and postdocs**
  - 4 M.Sc. Exam, 2 Ph.D. exams
  - 5 postdocs

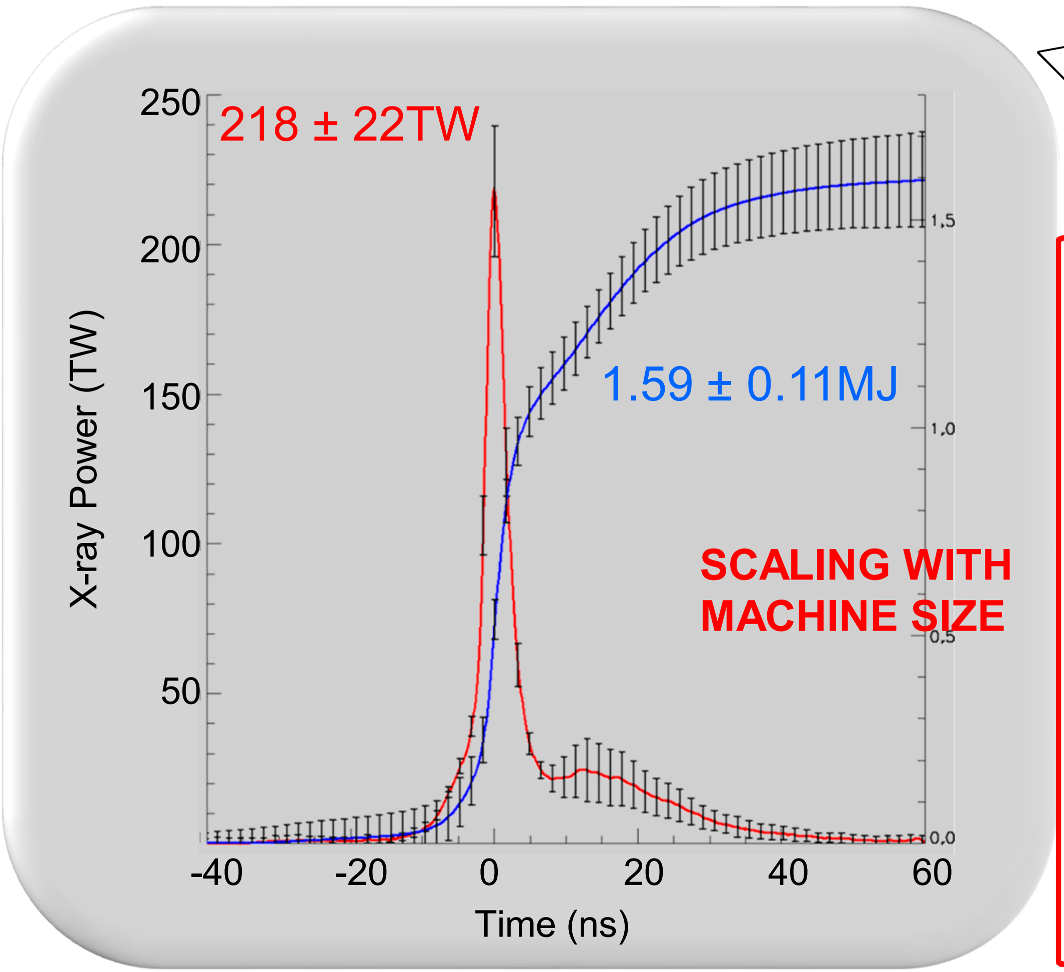
Z Astrophysical Plasma Properties (ZAPP) collaboration uses one source to simultaneously address 4 astrophysics topics



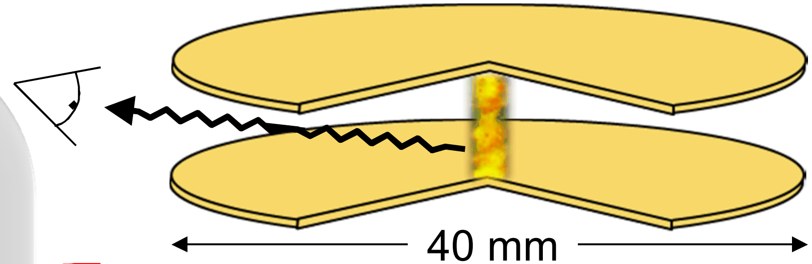
- Multiple samples are exposed to Z x-rays on each shot
- Highly efficient use of the facility

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

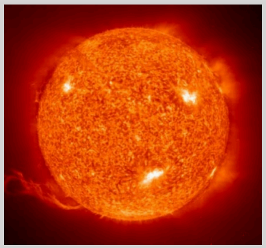


	ZR >2011	Z <2007
Marx Energy	20.3 MJ	11.4 MJ
Ipeak	25.8 MA (1.5%)	21.7 MA* (2.1%)
Mass	8.5 mg	3.8 mg
Peak Power	220 TW (10%)	120 TW (14%)
Radiated Energy	1.6 MJ (7%)	0.82 MJ (17%)

*Wagoner, PRSTAB 11 (2008)

ZAPP campaigns simultaneously study multiple issues spanning 200x in temperature and 10^6x in density

Solar Opacity



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

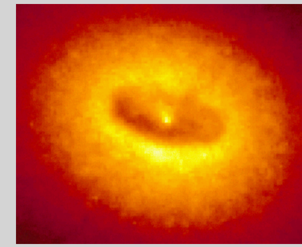
Achieved Conditions:
T_e ~ 200 eV, n_e ~ 10^{23} cm^{-3}

White Dwarf Line-Shapes

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

Acheived Conditions:
T_e ~ 1 eV, n_e ~ 10^{17} cm^{-3}

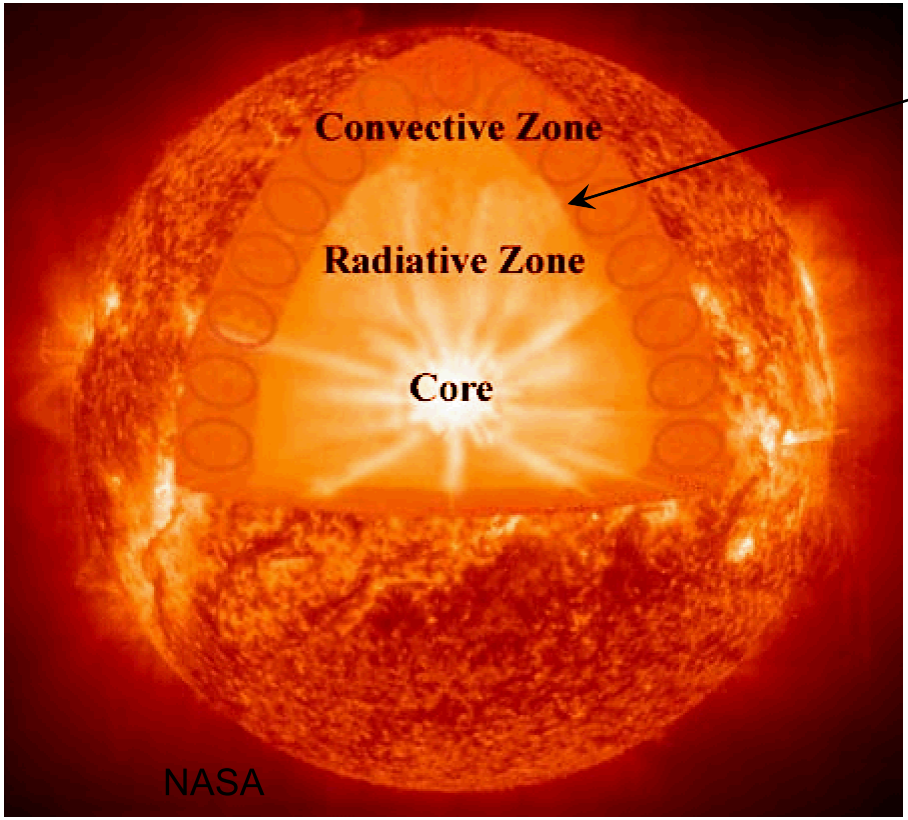
Photoionized Plasmas



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

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

Does opacity uncertainty cause the disagreement between solar interior models and helioseismology?



Discrepancies in CZ boundary location, C_s (r), and ρ(r)

Models depend on:
- element abundances
- EOS
- opacity

focus: iron at convection zone base {187 eV, 9e22 e/cc}

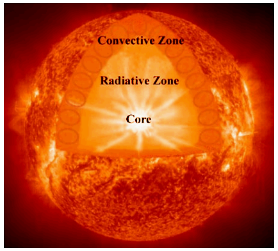
Disagreement could be resolved if the true mean opacity for solar matter is 10-30% higher than predicted

S. Basu *et al*, Physics Reports (2008). M. Asplund *et al*, Annu. Rev. Astro. Astrophys (2005)

Z iron opacity experiments imply that photon absorption in high energy density matter may be different than our models

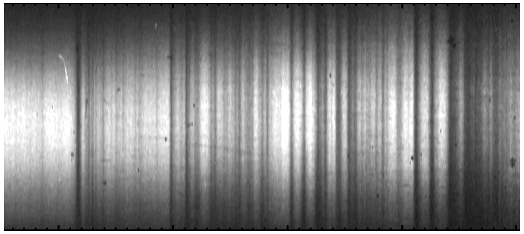
- **Solar interior predictions don't match helioseismology**

  → Arbitrary 10-20% opacity increase would fix the problem, but is this the correct explanation?



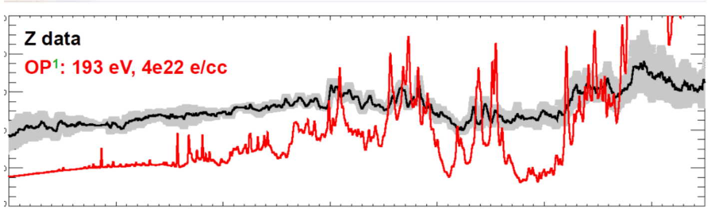
- **Z experiments have measured iron plasma opacity at nearly solar convection zone base conditions**

  → Experiment temperature is the same as in sun, density within a factor of 2



- **Opacity models disagree with measurements at near-solar-interior conditions**

  → The solar Rosseland mean opacity is ~ 7% higher using Z iron data instead of OP calculations

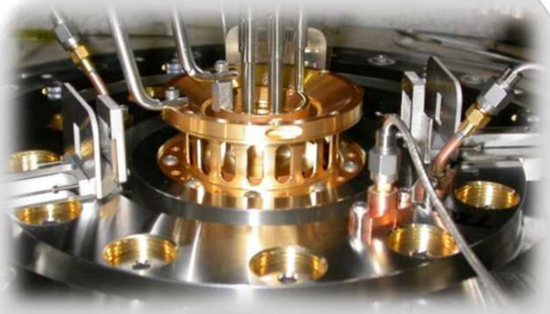


The measurements imply that some of the disagreement between modeling and measurements may indeed be due to incorrect opacity models.

J.E. Bailey et al., *Nature* 517, 56–59 (2015).

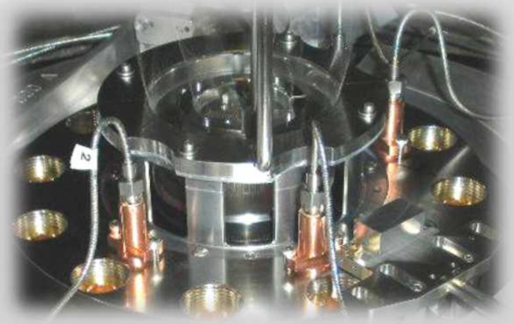
Three types of routine, established z-pinch x-ray sources

Z-pinch Dynamic Hohlraum



- Tungsten Wires
- Near-Planckian Emission Spectrum
- Broadband Energy Emission: 1.5 MJ
- Peak Power: 200 TW
- Power FWHM: 3 ns

K-shell Wire-Array Sources



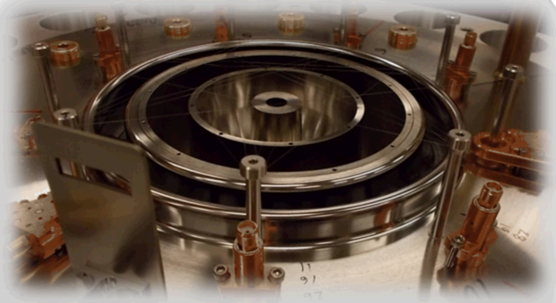
- Optimized for K-shell emission
- Spectrum/Power/Energy depends on wire material:

  Al (400 kJ @ 1-2.5 keV)

  SS (80 kJ @ 5-8 keV)

  Cu (25 kJ @ 8-10 keV)

K-shell Gas Puff Sources



- Supersonic gas nozzle with 2 concentric shells & 1 central jet
- Spectrum/Power/Energy depends on gas:

  Ar (350 kJ @ 3-5 keV)

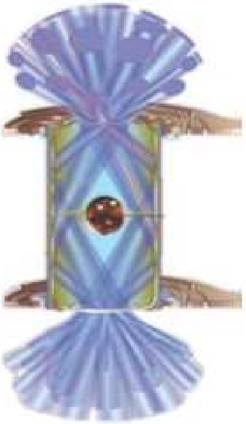
  Kr (8 kJ @ >13 keV)

The U.S. ICF Program is pursuing three main approaches to fusion ignition to manage the scientific risk

Sandia National Laboratories

Laser x-ray drive

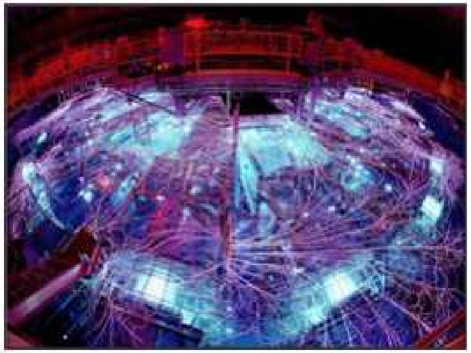
192 beams, 1.8 MJ, 400 TW



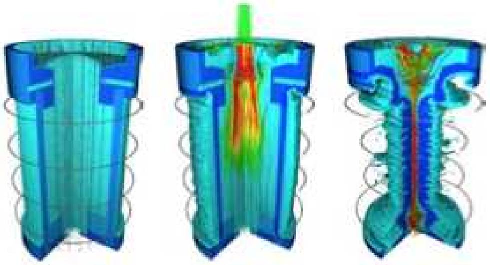
Laser direct drive

60 beams, 30 kJ, 20 TW

Magnetic direct drive

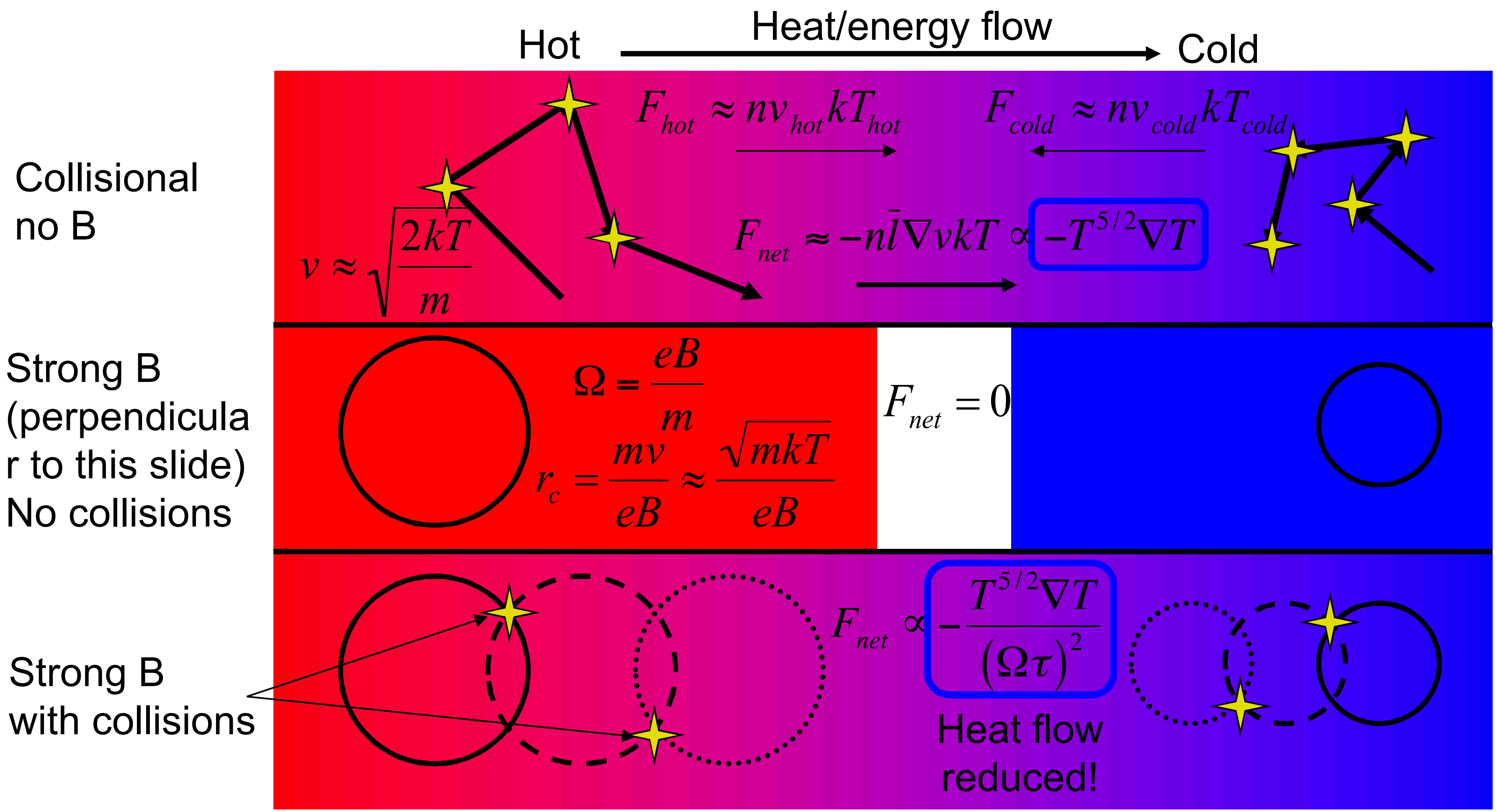


26 MA, 80 TW



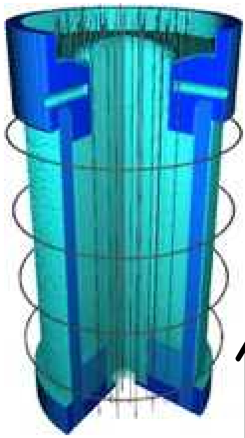
Magnetization | Laser heating | Compression

Magneto-inertial fusion is based on the idea that energy and particle transport can be reduced by strong magnetic fields, even in collisional plasmas



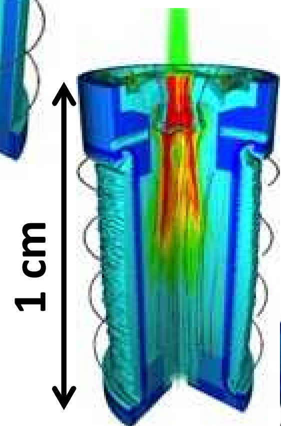
*The magnetic field also confines α-particles – beneficial beyond ignition

The Magnetized Liner Inertial Fusion (MagLIF) target design for Z is well suited to pulsed power



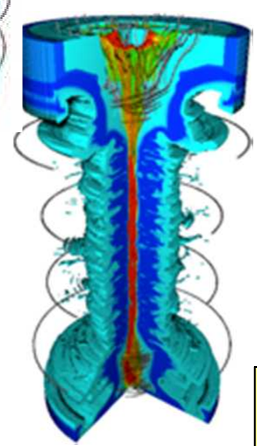
Axial Magnetic Field (10 T initially; 30 T available)

- Inhibits thermal losses from fuel to liner
- May help stabilize liner during compression
- Fusion products magnetized



Laser heated fuel (2 kJ initially; 6-10 kJ planned)

- Initial average fuel temperature 150-200 eV
- Reduces compression requirements (R_0/R_f ~ 25)
- Coupling of laser to plasma in an important science issue



Magnetic compression of fuel (~100 kJ into fuel)

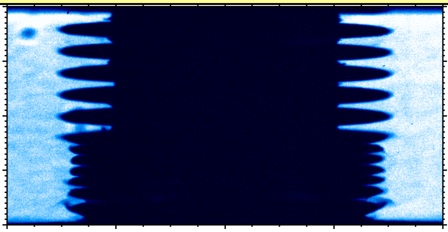
- ~70-100 km/s, quasi-adiabatic fuel compression
- Low Aspect liners ($R/\Delta R$~6) are robust to hydrodynamic (MRT) instabilities
- Significantly lower pressure/density than ICF

Goal is to demonstrate scaling: *Y* (B_{z0}, E_{laser}, I)
DD equivalent of 100 kJ DT yield possible on Z

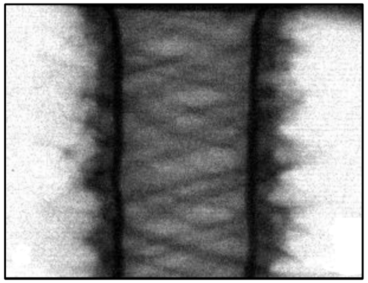
S.A. Slutz *et al.*, Phys Plasmas (2010); S.A. Slutz & R.A. Vesey, Phys Rev Lett (2012); A.B. Sefkow *et al.*, Phys Plasmas (2014).

We have systematically investigated liner implosion modeling, and have made interesting discoveries and innovations

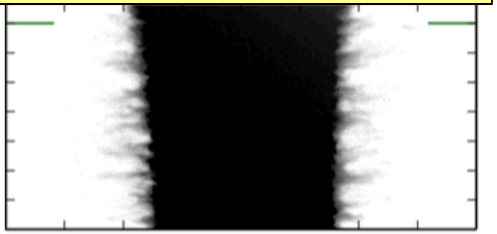
Single-mode magneto-Rayleigh-Taylor growth

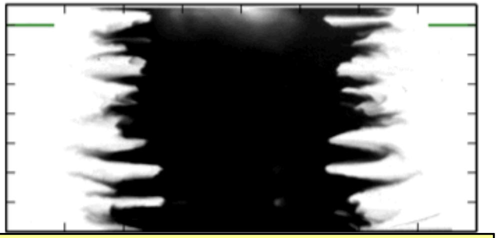


Magnetized MRT growth



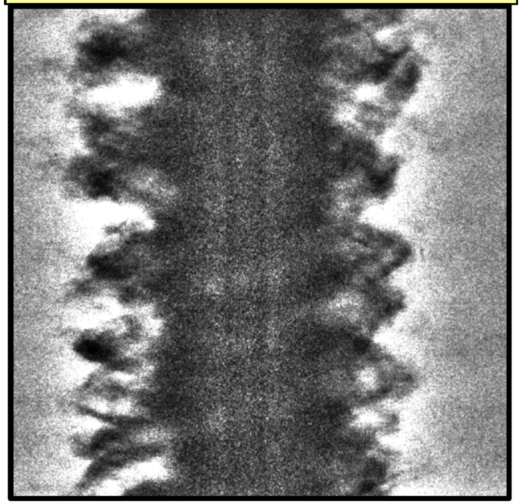
Dielectric-coated Al liner implosion



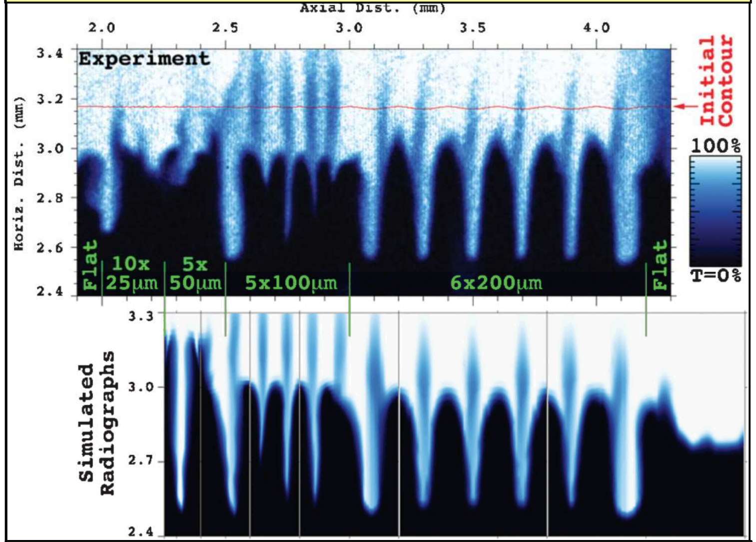


Uncoated

Magnetized & dielectric-coated Be (R_0/R_f~17)



Experimental Data



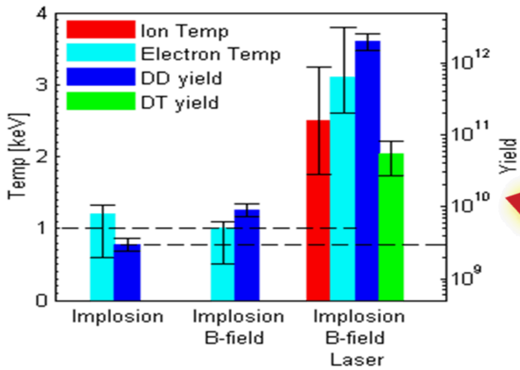
Simulations

High-resolution 2D modeling can capture early growth down to the ~50-micron scale

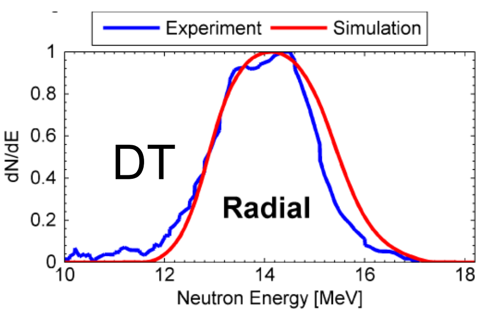
D.B. Sinars *et al.*, Phys. Rev. Lett. (2010).
R.D. McBride *et al.*, Phys. Rev. Lett. (2012).
T.J. Awe *et al.*, Phys. Rev. Lett. (2013).
K.J. Peterson *et al.*, Phys. Rev. Lett. (2014).
T.J. Awe *et al.*, submitted (2015).

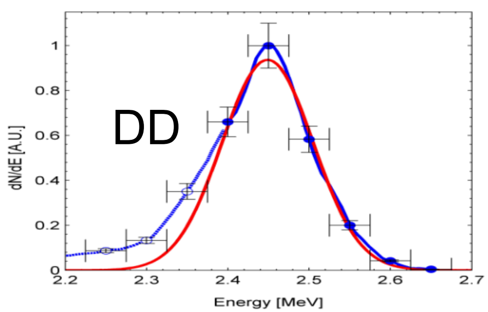
An ensemble of measurements from our first MagLIF experiments are consistent with a magnetized, thermonuclear plasma!

Nuclear Activation (yield)

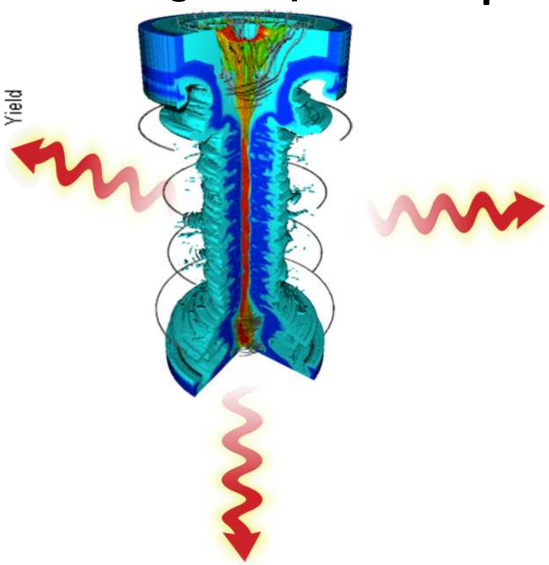


Neutron spectra (Tion)

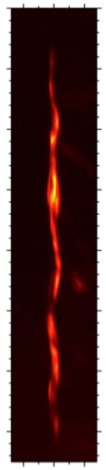




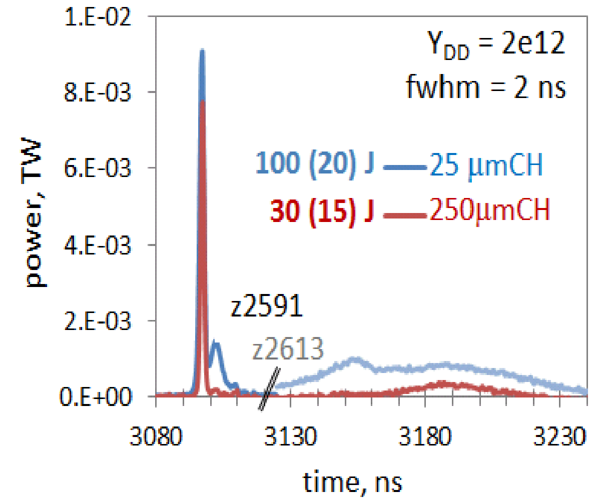
MagLIF Z pinch



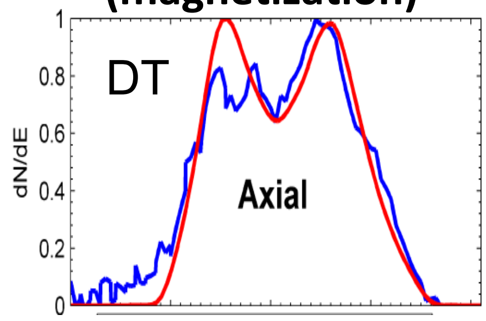
X-ray Imaging (hot plasma shape)



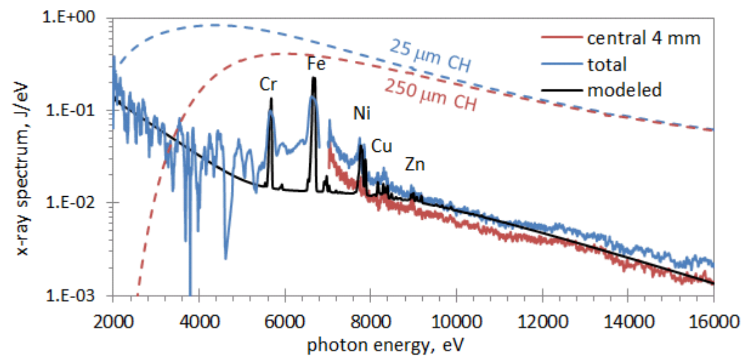
X-ray Power (duration)



DT Neutron spectra (magnetization)



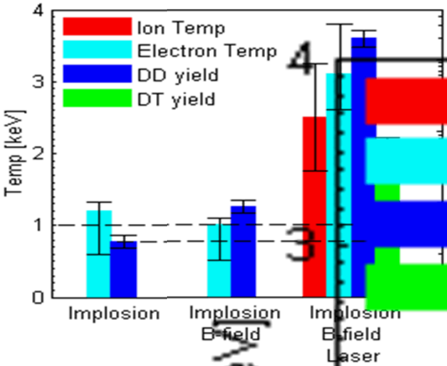
X-ray Spectra (T_e, mix)



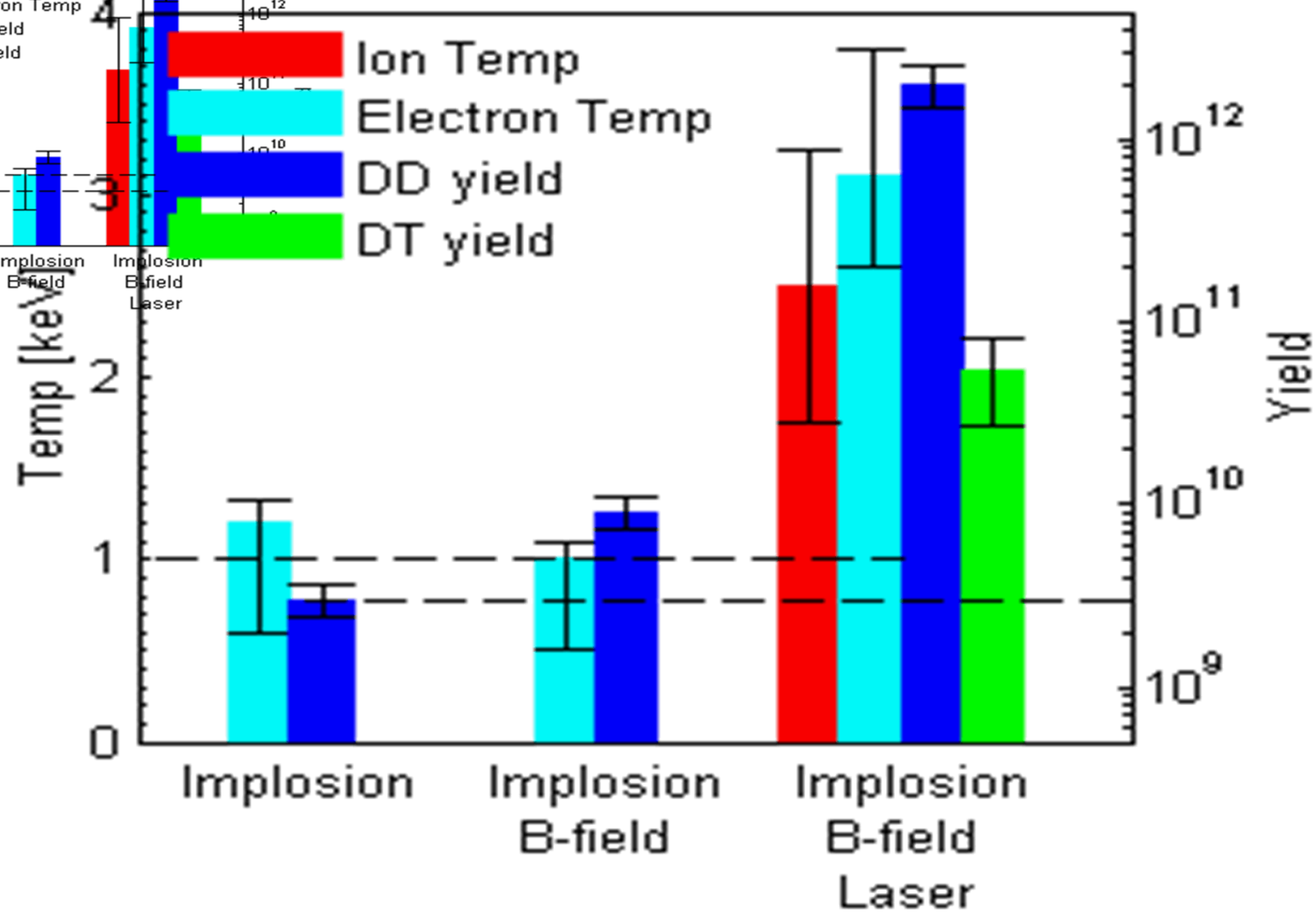
Each of these measurement techniques involves unique & rich physics!

An ensemble of measurements from our first MagLIF experiments are consistent with a magnetized, thermonuclear plasma!

Nuclear Activation (yield)

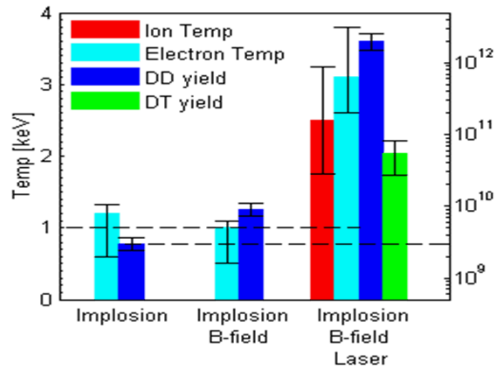


Nuclear Activation (yield)

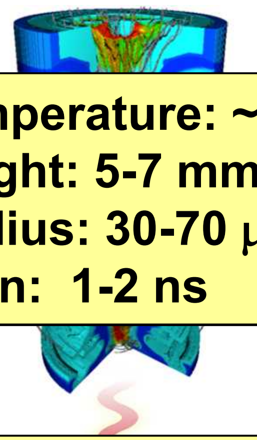


An ensemble of measurements from our first MagLIF experiments are consistent with a magnetized, thermonuclear plasma!

Nuclear Activation (yield)

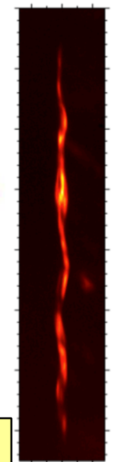


MagLIF Z pinch

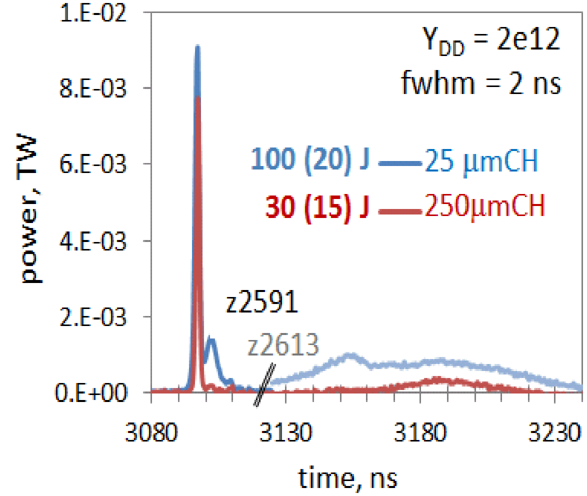


Temperature: ~3 keV
Height: 5-7 mm
Radius: 30-70 μm
Burn: 1-2 ns

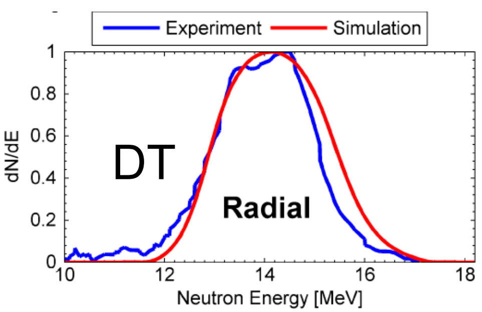
X-ray Imaging (hot plasma shape)

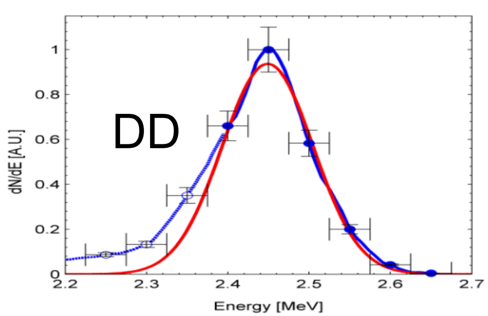


X-ray Power (duration)

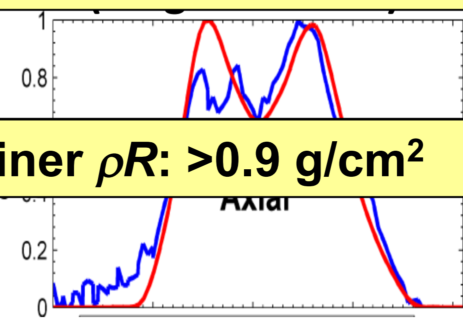


Neutron spectra (Tion)



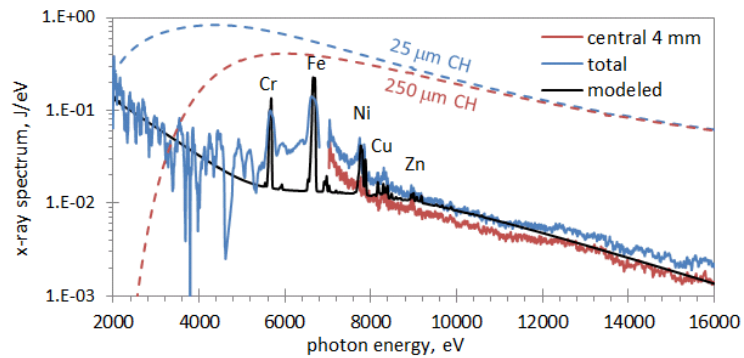


Fuel ρ: 0.2-0.4 g/cm^3
Fuel ρR: ~1.5 mg/cm^2
Fuel ρz: ~150 mg/cm^2
Pressure: ~1 Gbar

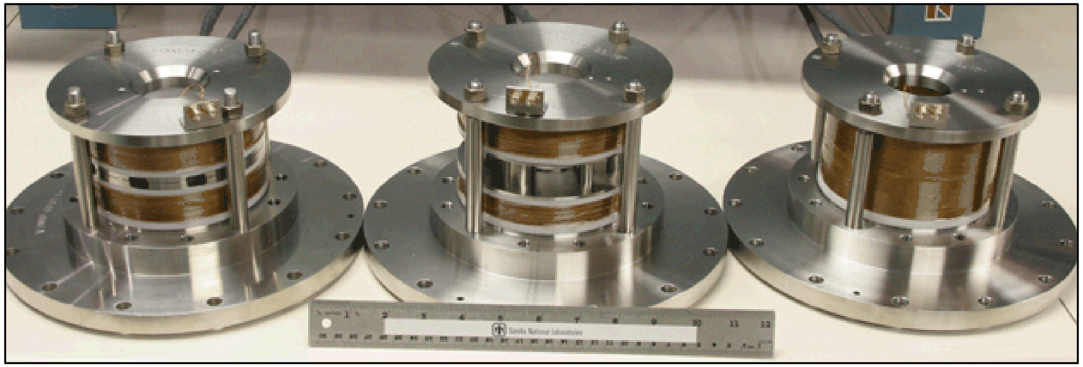


Liner ρR: >0.9 g/cm^2

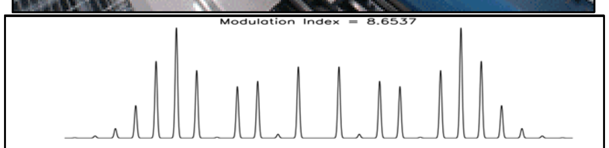
X-ray Spectra (Te, mix)



We are working to increase the available drive conditions over the next five years in order to understand scaling



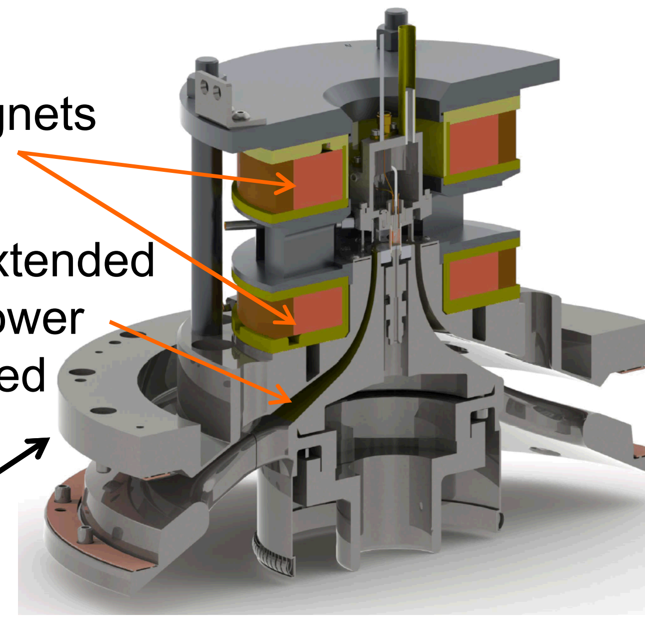
Increase B-field from 10 T to 30 T



Increase laser energy from 2 kJ to 6-10 kJ; Install phase plates

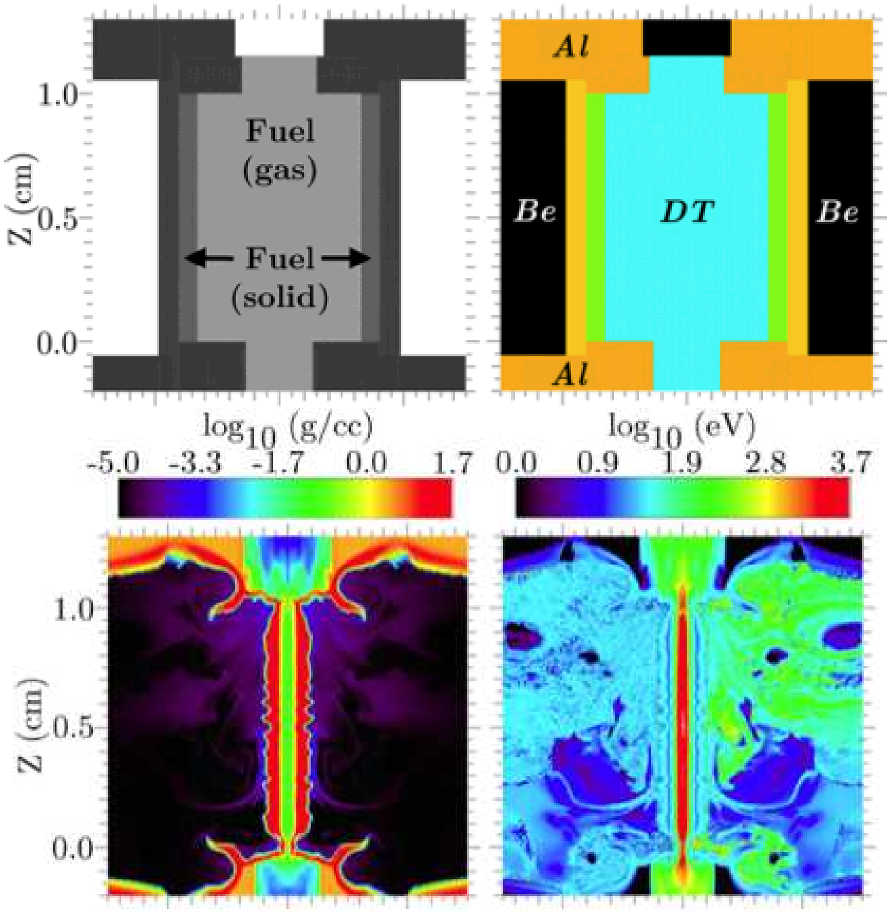
Magnets

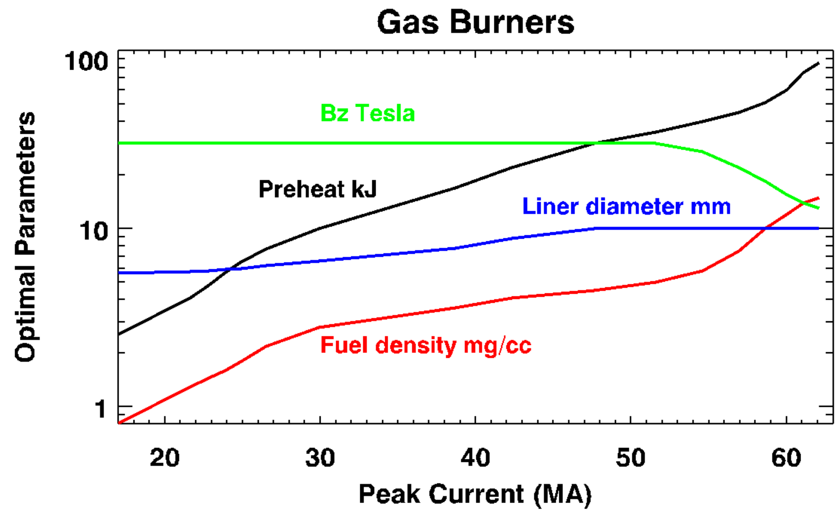
Extended power feed

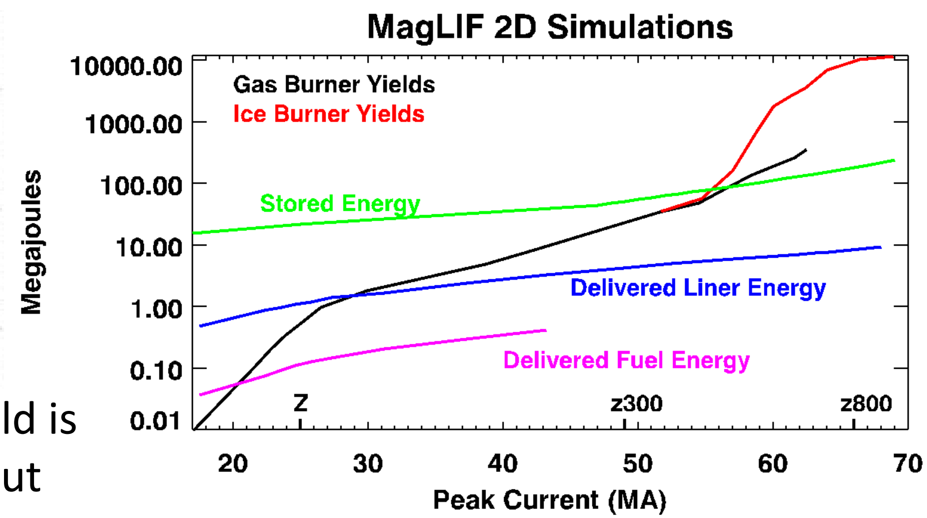


Increase current from 19 MA to ~25 MA (Z facility upgrades; load hardware optimization)

It may be possible to achieve ~100 kJ yields on Z. Achieving alpha heating and ignition may be possible on a future facility. A cryogenic DT layer could enable up to ~1 GJ yield.







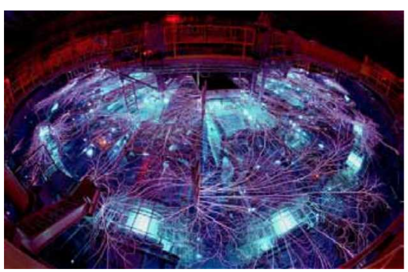
An intermediate regime exists wherein the B_z field is

- *strong enough* to reduce conduction losses, but
- *weak enough* not to inhibit the α deflagration wave

S.A. Slutz and R.A. Vesey, Phys Rev Lett (2012); A.B. Sefkow *et al.*, Phys Plasmas (2014).

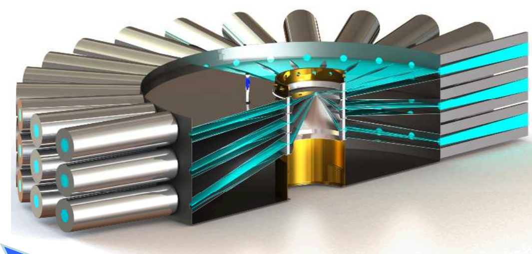
Improvements in pulsed power technology since Z was refurbished in 2007 make the step from Z to a facility with MJ fusion yields practical

Yield = E_{fuel}?
(~100$kJ_{DT\ eq}$)
Physics Basis for Z300



Z
- 80 TW
- 33 Meter diameter
- 26 MA
- 22 MJ Stored Energy

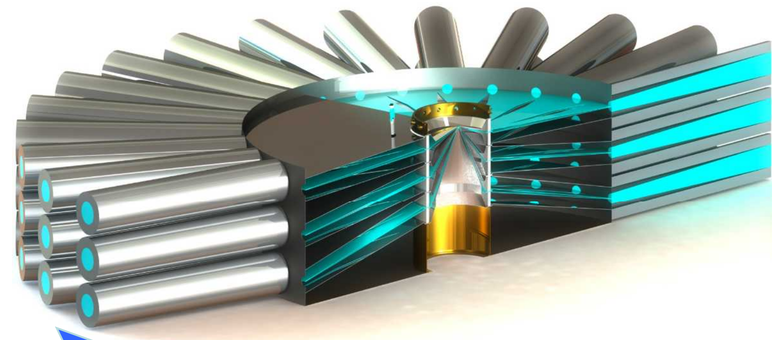
Yield = E_{target}?
(About 3-4 MJ)
α-dominated plasmas



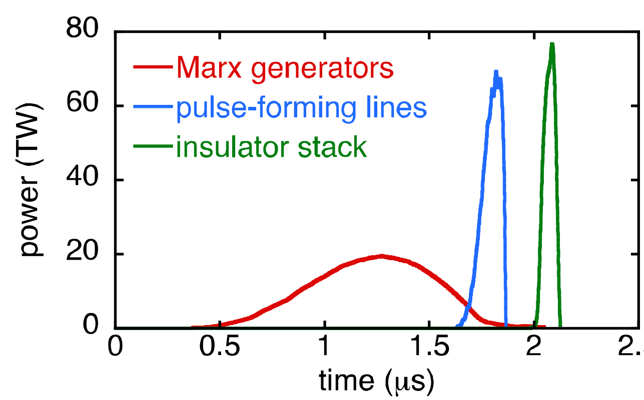
"Z300"
- 300 TW
- 35 Meter diameter
- 47 MA
- 47 MJ Stored Energy

Improvements in power flow pay big dividends

Fusion Yield 0.5-1 GJ?
Burning plasmas

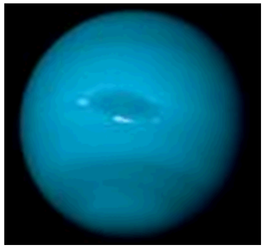


"Z800"
- 800 TW
- 52 Meter diameter
- 61 MA
- 130 MJ Stored Energy

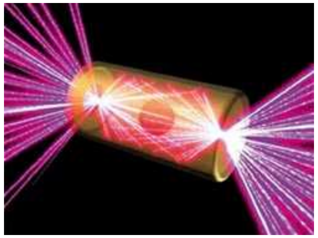


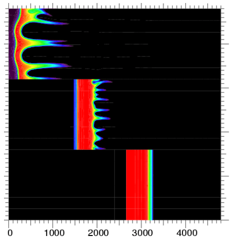
Properties of matter under HED (High Energy Density) conditions are important to many geophysical problems

- **Planetary science – Jupiter, Saturn, Uranus, Neptune, and exo planets [e.g. hot Neptunes]**
  - Water in 2005-2012: 2 Phys Rev Letts and 2 Phys Rev B
  - Metallization of hydrogen/deuterium: Science 2015
- **Planetary science – earths and super-earths**
  - Silicates, MgO (Phys. Rev. Lett. 2015), and iron/iron alloys
  - Determining the vaporization threshold for iron – and implications for planetary formation, Nature Geoscience 2015.
- **Materials for Stockpile Stewardship, HED and inertial confinement fusion (ICF)**
  - Investigating the periodic table from Aluminum to Zirconium: a broad range of materials are of interest - a talk in itself
  - *The programmatic work drives precision – we rely on the data!*



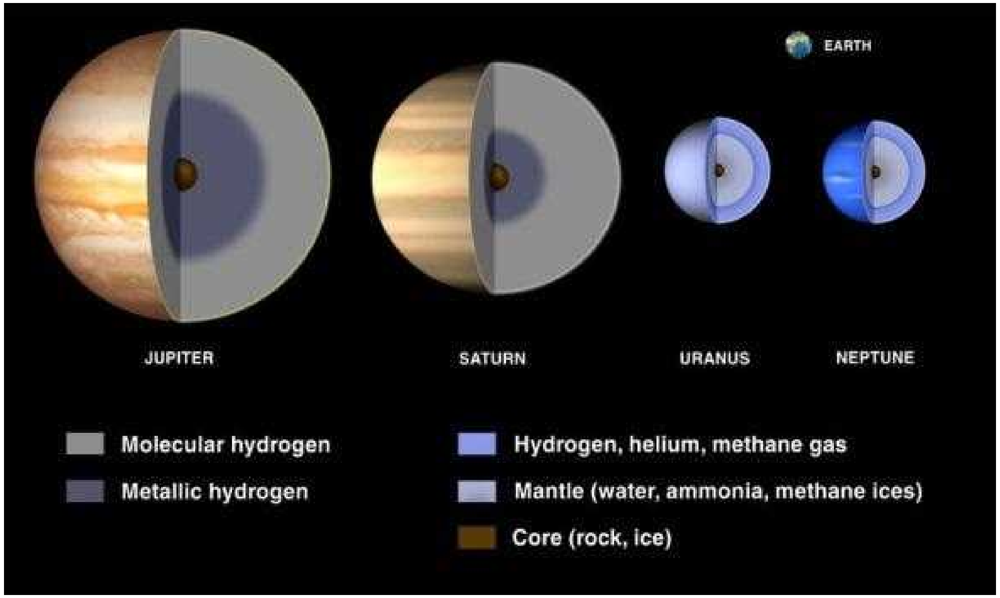
We have turned planetary science *quantitative* by high fidelity modeling and high-precision experiments





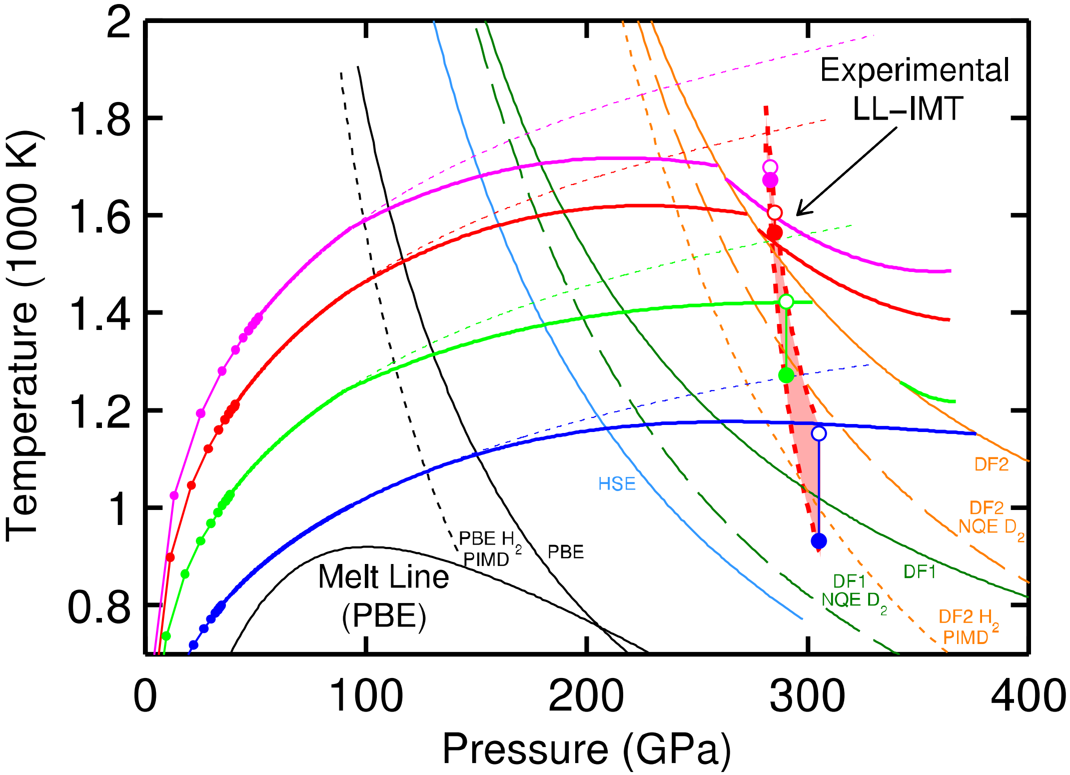
ICF concepts: laser driven Hohlraum and MagLIF

Understanding the properties of hydrogen is crucial for understanding giant planets



- **Present structure**
  - Layers of different composition while fulfilling observational constraints
- **Evolution**
  - Discrepancies in modeling the evolution of Jupiter and Saturn – the “Saturn age problem”
  - Why is Saturn so luminous?
- **Magnetic fields**
  - Origin of multi-polar fields in Neptune and Uranus

We have located the Liquid-Liquid Insulator-to-Metal Transition in deuterium to be a steep curve at 300 GPa



M.D. Knudson, M.P. Desjarlais, A. Becker, R.W. Lemke, K.R. Cochrane, M.E. Savage, D.E. Bliss, T.R. Mattsson, and R. Redmer, Science **348** 1455, 26 June 2015.

- **Experiments used a new shock + ramp drive to scan this space**
- ***Insensitivity to T suggests this is a ρ-driven transition***
  - ρ at the transition is inferred to be ~2-2.1 g/cc in deuterium
  - Qualitatively different transition than in shock experiments (T driven)
- **Broad team with expertise in diagnostics, pulse-shaping, experimental design, and first-principles simulations**
- **A project within the Z Fundamental Science Program**
  - Professor Ronald Redmer's group at University of Rostock

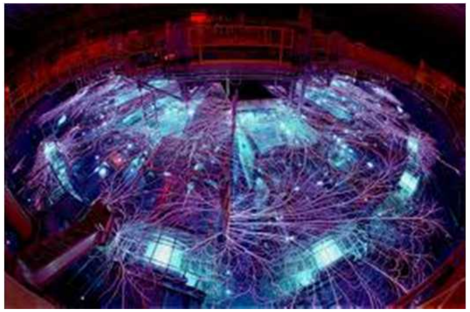
The ZFSP and collaborations with academic groups greatly benefits Sandia's and NNSA's mission on both short- and long term

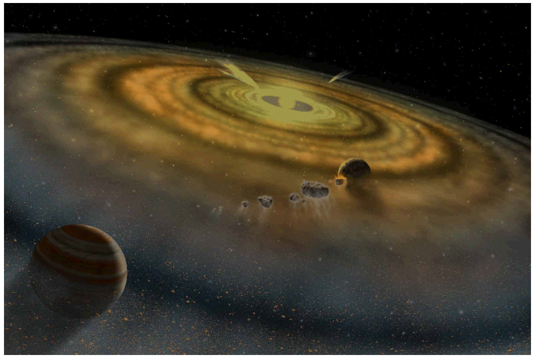
- **Supporting HED science**
  - Students and groups active in topics of importance to the national laboratories
- **Growth in the HED science community**
  - New funding won by teams
  - Active participation in the academic community of HED science – attracting new academic partners
  - Scientific discoveries make the field attractive
- **Direct methods development**
  - The platform for shock- and vaporization experiments developed jointly with Harvard/UC Davis is now our standard load for science campaign experiments
  - The work on Fe opacity has served an important role for platform development and provides international peer review
- **Development of technical staff**
  - An opportunity for Sandia staff to do leading research and participate fully in the international research community

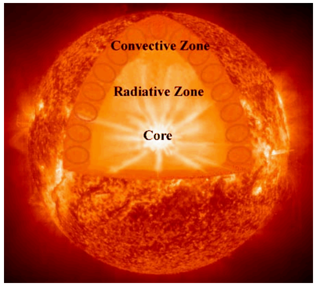
A future Sandia machine at 40-50 MA creates a capability gap - an opportunity for mid-scale facilities

Pulsed power is exquisitely suited for HED science

- **Sandia's Z machine is ideal for Mbar material experiments**
  - Compression of solids and liquids
  - Obtain conditions of the interiors of gas giants and the Earth/ super earths, other exoplanets
- **The Z machine produces MJs of x-rays**
  - Radiation effects on materials
  - Fundamental properties of matter
- **Fundamental plasma physics**
  - Spectroscopy and plasma conditions: line broadening and opacity
- **Promising fusion concept**
  - Direct cylindrical drive
  - Pre-magnetized and –heated fuel
  - *Systematic studies of the underlying physics*
- **Strong integration between experiments, theory, and simulations**
  - From quantum mechanics to MHD and beyond
- ***Well-defined path for the future – decades of exciting HED Science research lies ahead***

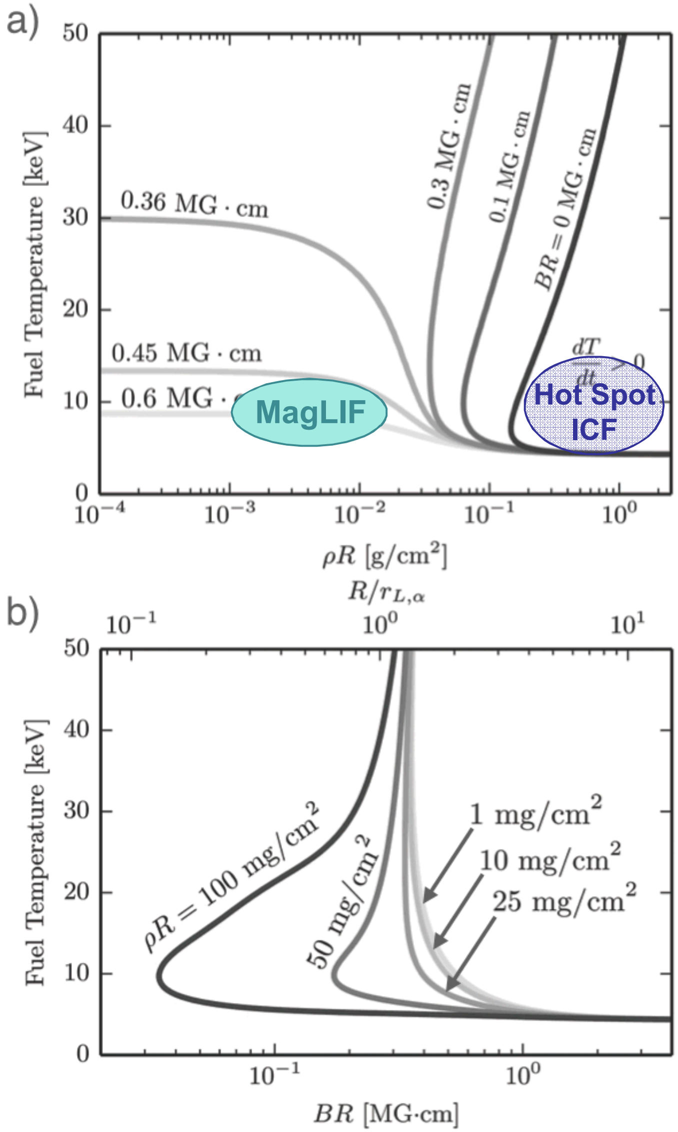




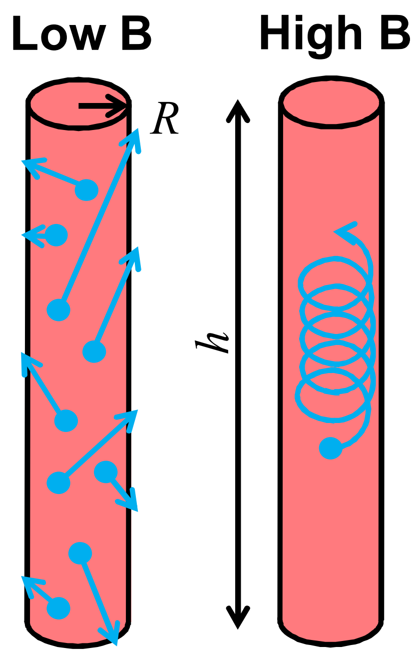


Backup slides

Magnetization (*BR*) can be used to reduce electron heat losses and to reduce ρR requirements; lower density also reduces bremsstrahlung radiation losses



- **Initial 10-30 T field greatly amplified during the implosion through *flux compression***
- **Too much field is inefficient—want to stagnate on plasma pressure, not magnetic pressure**



$$\frac{R}{r_\alpha} \approx 4BR\ [MG \cdot \mathrm{cm}]$$

- **Fraction of trapped tritons (or α's) a function of *BR***
- **Effects saturate at *BR* > 0.6 MG-cm**
- **Measurements to date suggest *BR* of 0.4 MG-cm**

Basko *et al*. Nuclear Fusion 40, 59 (2000); P.F. Knapp *et al*., Phys. Plasmas (2015).