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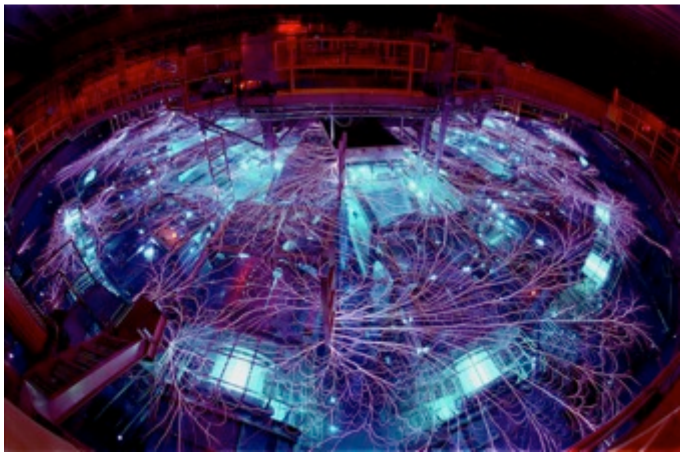
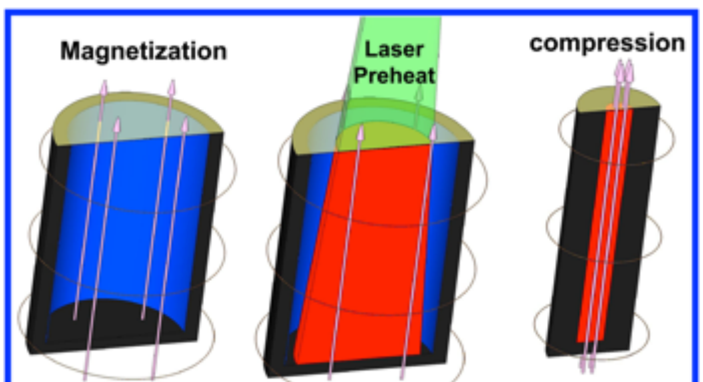


Using Magnetic Fields to Create and Control High Energy Density Matter



Mark C Herrmann

Pulsed Power Sciences Center

Sandia National Laboratories

University of Wisconsin Plasma Physics Seminar

February 17, 2014

U.S. DEPARTMENT OF ENERGY NNSA

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Sandia National Laboratories, Albuquerque, NM, USA

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***General Atomics, San Diego, CA, USA**

It is an exciting time to be working in High Energy Density Science

- Large currents and magnetic fields can be used to create and study high energy density matter

- We are applying the Z facility to better understanding material properties relevant to planetary science and astrophysics

- Various approaches to inertial confinement fusion are showing progress.

- We have performed our first test of Magnetized Liner Inertial Fusion (MagLIF) on the Z facility. Initial results are promising.

What is high energy density science?

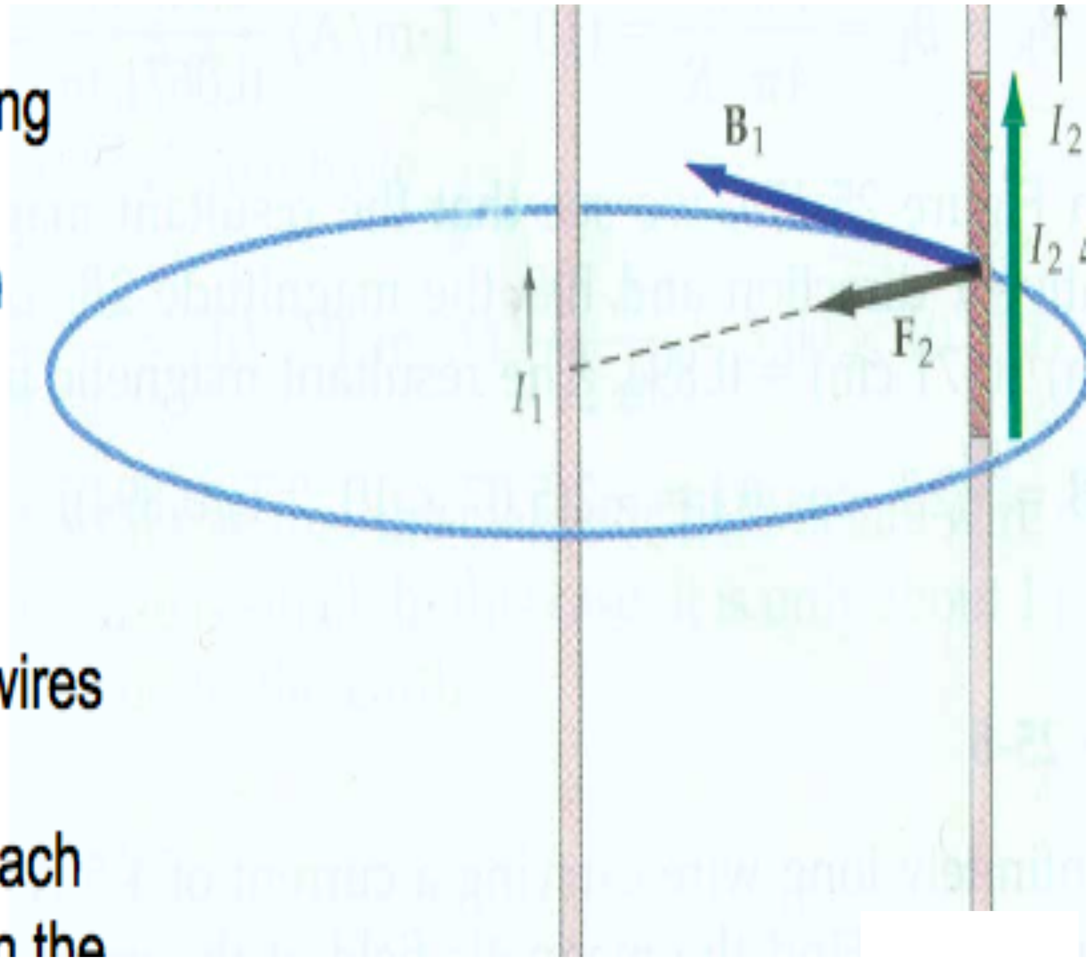
- **Pressure (Pascals, bars) is equivalent to Energy Density (J/m^3)**
  - **1 Mbar = 10^6 atm = 10^{11} Pascals = 10^{11} J/m^3**
- **HED threshold is pressures >1 Mbar, which exceeds the internal energy density of molecules/atoms (solids become compressible, etc.)**

Object	Pressure (Mbar)
Atmosphere at sea level	1e-6
High pressure gas cylinder	1e-4
TNT	0.07
Internal energy of H atom	1.00
Pressure at the center of the Earth	3.5
Pressure at the center of Jupiter	30.00
Center of the sun	250,000.00

Currents create magnetic fields that in turn apply forces on other currents

Two parallel wires carrying current along the same direction will attract each other (Biot-Savart Law, “JxB force”)

Definition of an Ampere:
If two very long parallel wires 1 m apart carry equal currents, the current in each is defined to be 1 A when the



Large currents and the corresponding magnetic fields can create and manipulate high energy density(HED) matter

Magnetic fields and currents can push matter around:

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

Magnetic fields have some unique advantages when creating HED plasmas:

- **Magnetic fields are very efficient at creating HED matter enabling large samples and energetic sources**
- **Magnetic fields have very interesting properties in converging geometry**

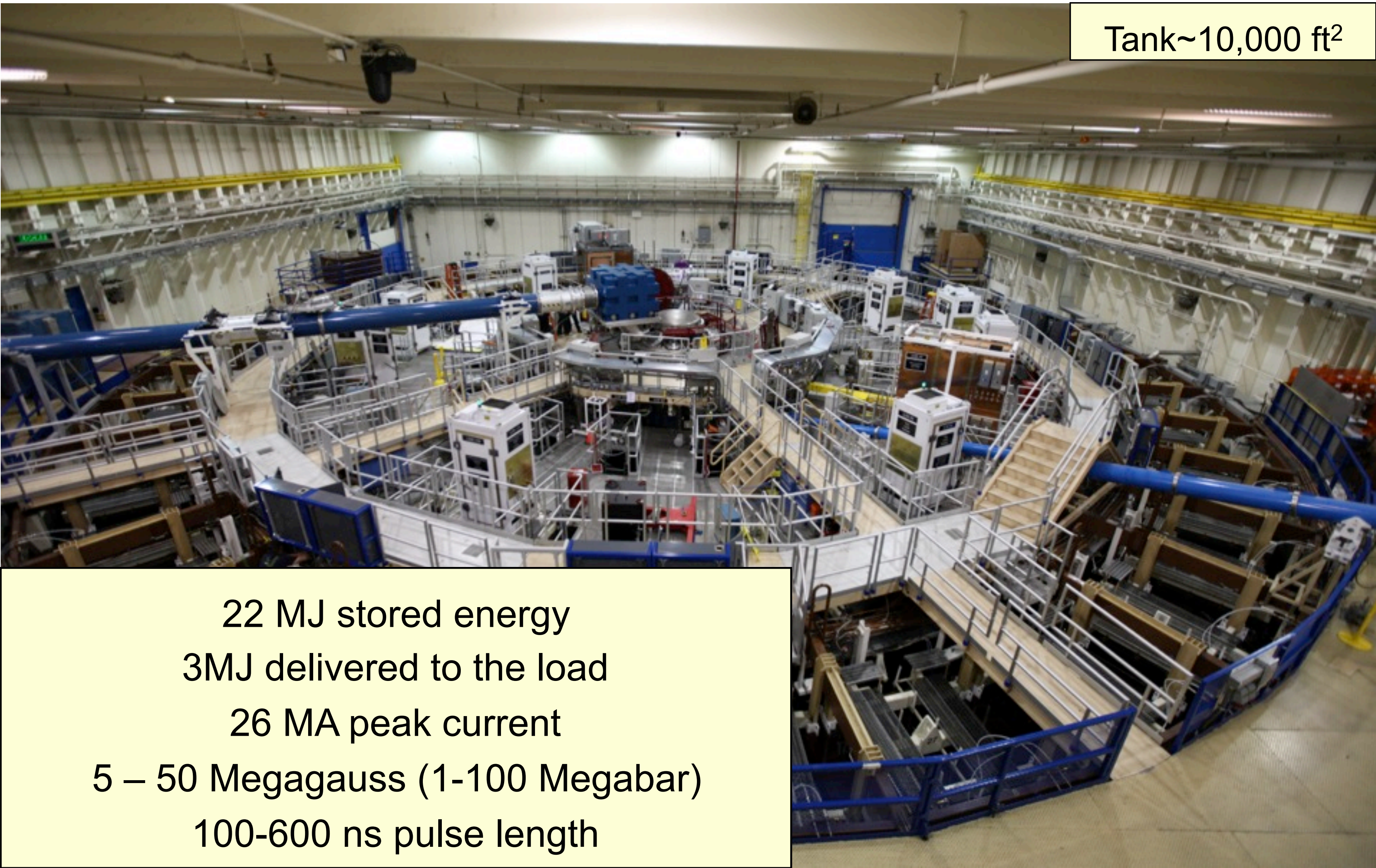
Magnetic fields have interesting contrasts with other ways of generating HED:

- **Magnetic fields can create high pressures without making material hot**
- **Magnetic fields can be generated over long time scales with significant control over the time history**

Magnetic fields change the way particles and energy are transported in a plasma

A 5 Megagauss (500 T) magnetic field applies a pressure of 1 Megabar (MB) to a conductor.
A current of 25 MA at 1cm radius is 5 10^6 G= 1 Mbar of pressure
A current of 25 MA at 1mm radius is 5 10^7 G= 100 Mbar of pressure

We use the Z pulsed power facility to generate large currents and large magnetic fields



Tank~10,000 ft^2

22 MJ stored energy

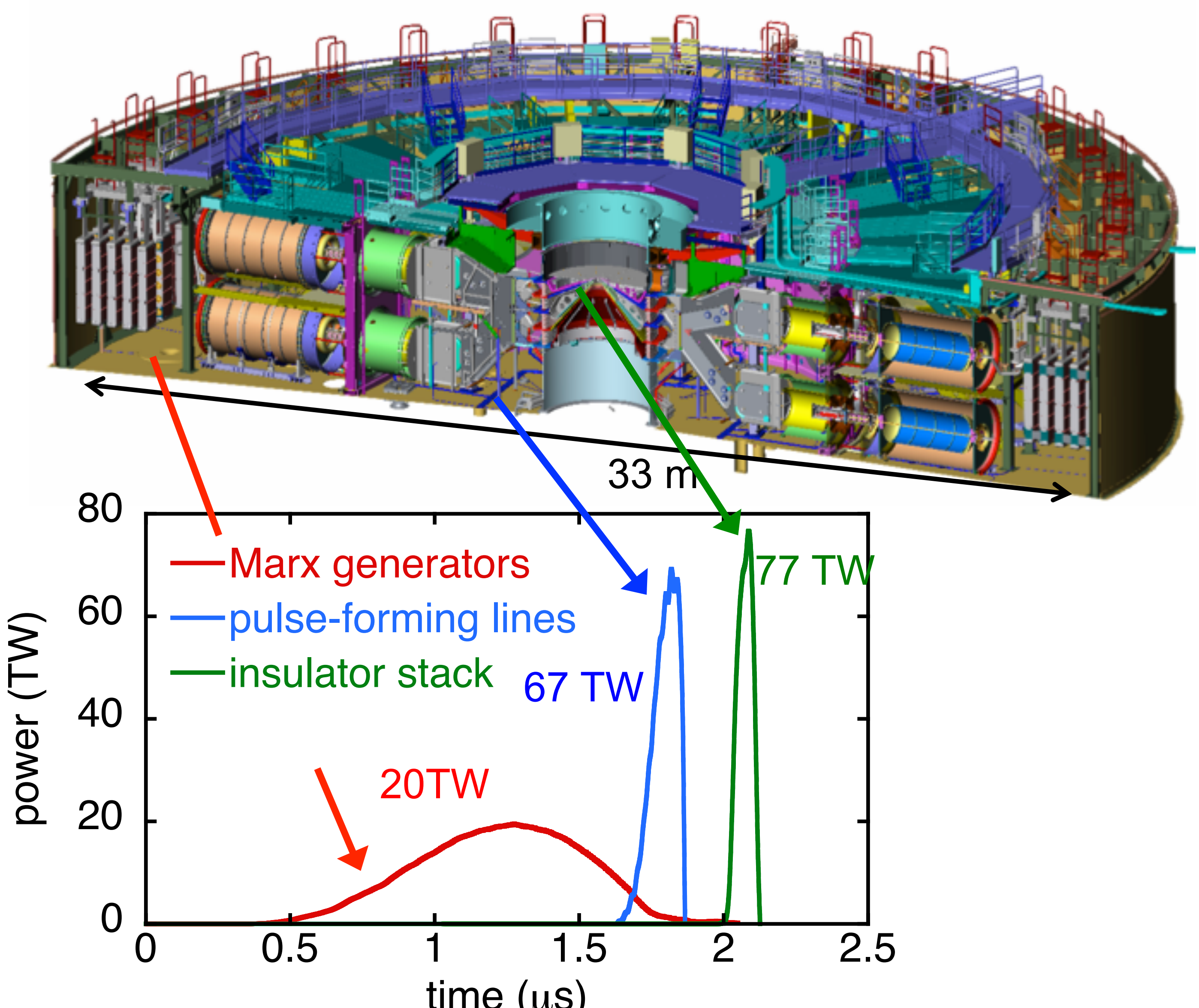
3MJ delivered to the load

26 MA peak current

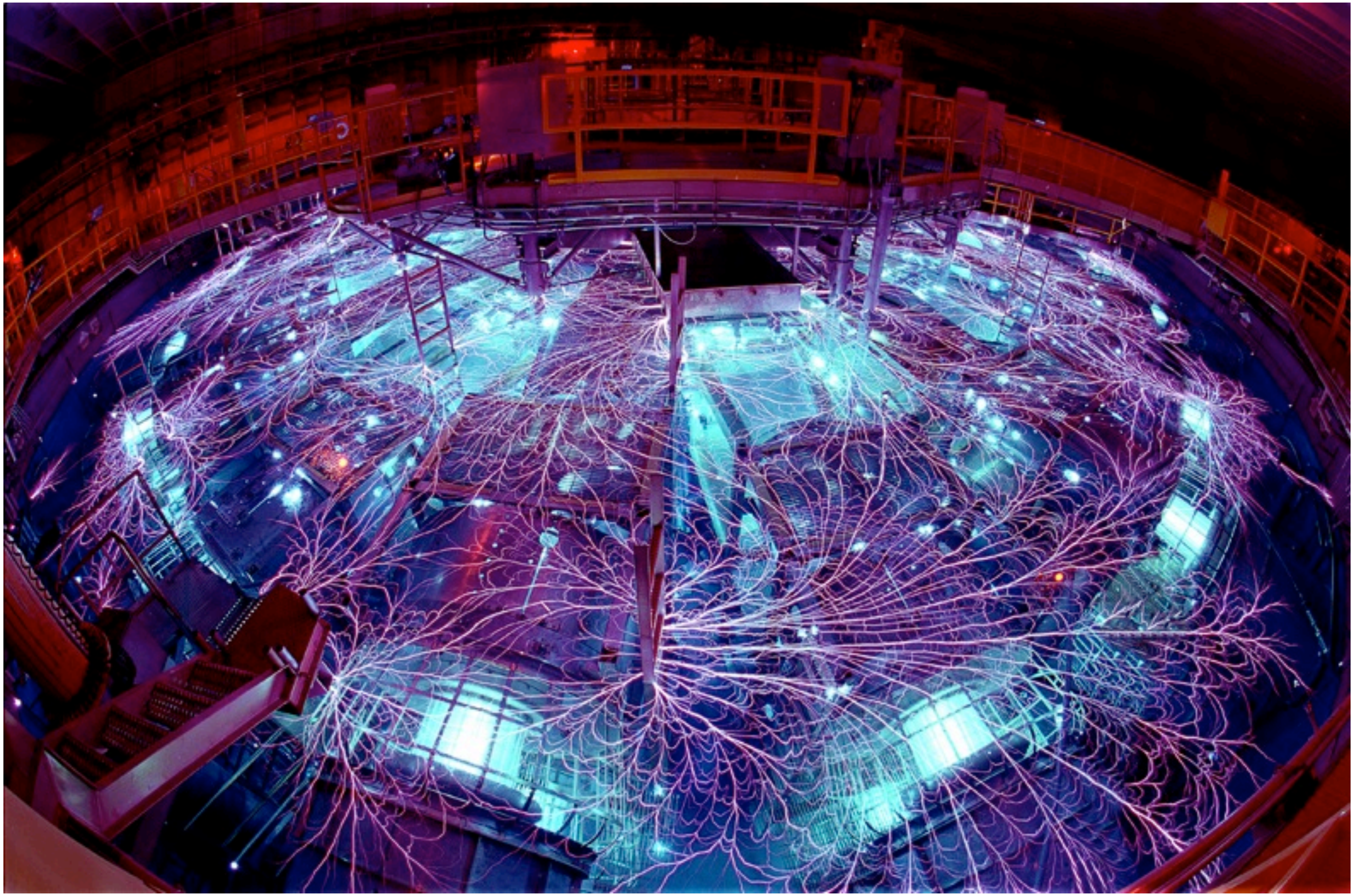
5 – 50 Megagauss (1-100 Megabar)

100-600 ns pulse length

Z works by compressing electromagnetic energy in time and space



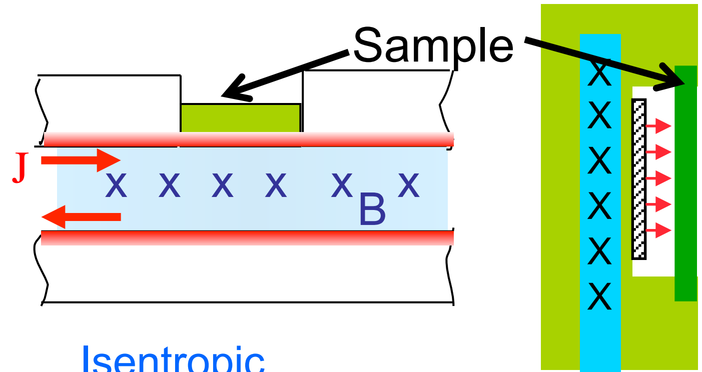
Not all of the electrical energy in the Z facility makes it to the load




Z West High Bay Camera
CAUTION
2009/11/03 13:39:33.91
11-03-2009 13:39:33

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

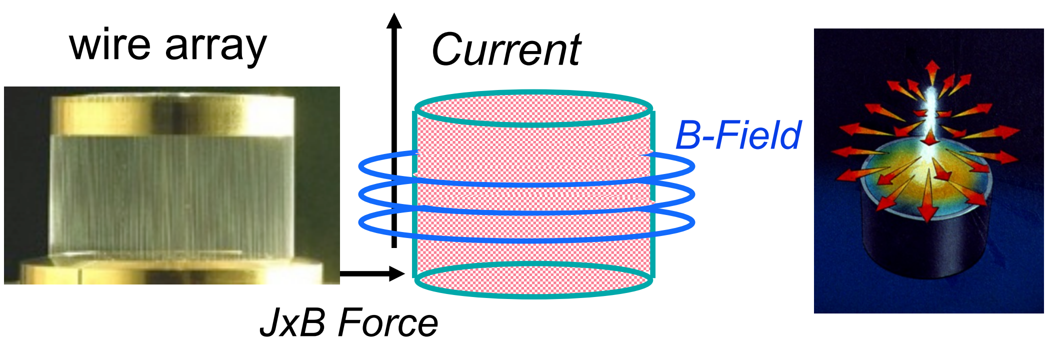
Materials Properties



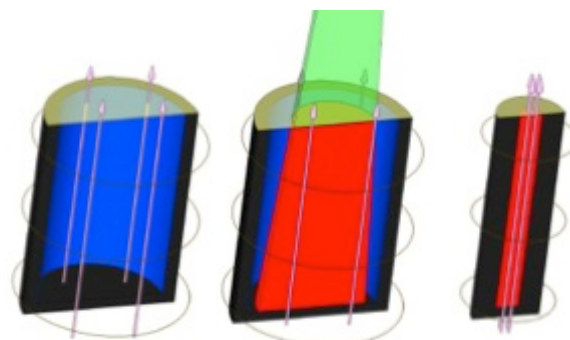
Isentropic Compression

Flyer Plate

Z-Pinch X-ray Sources

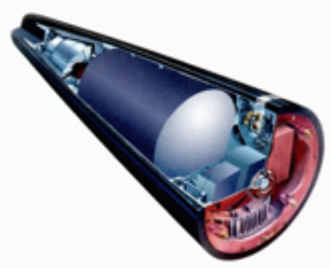


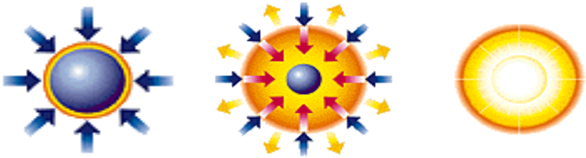
Inertial Confinement Fusion

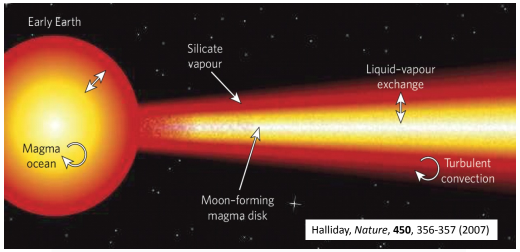


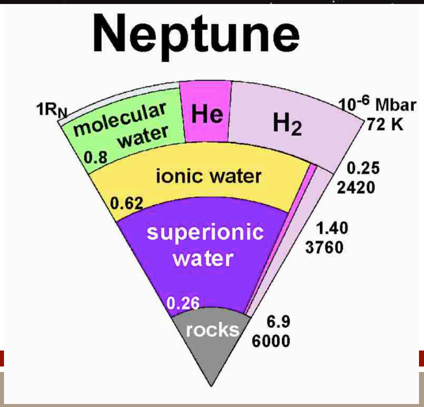
Understanding material properties at high pressure is important for Stockpile Stewardship, ICF, and understanding planets

- Nuclear Weapons materials
  - In the absence of underground testing we need a predictive capability
  - Material properties are a key input to nuclear weapons simulations
- Inertial confinement fusion (ICF) materials
  - Behavior of hydrogen, plastics, beryllium, diamond
- Planetary science
  - Giant impacts (e.g. Moon Forming Event)
  - Earths and super-earths
    - Equation of state of Mg, Fe, Si, C, O and related compounds
  - Giant Planets (e.g. Uranus & Neptune and exo ice-giants)
    - High-pressure mixtures of H, He, C, O, N

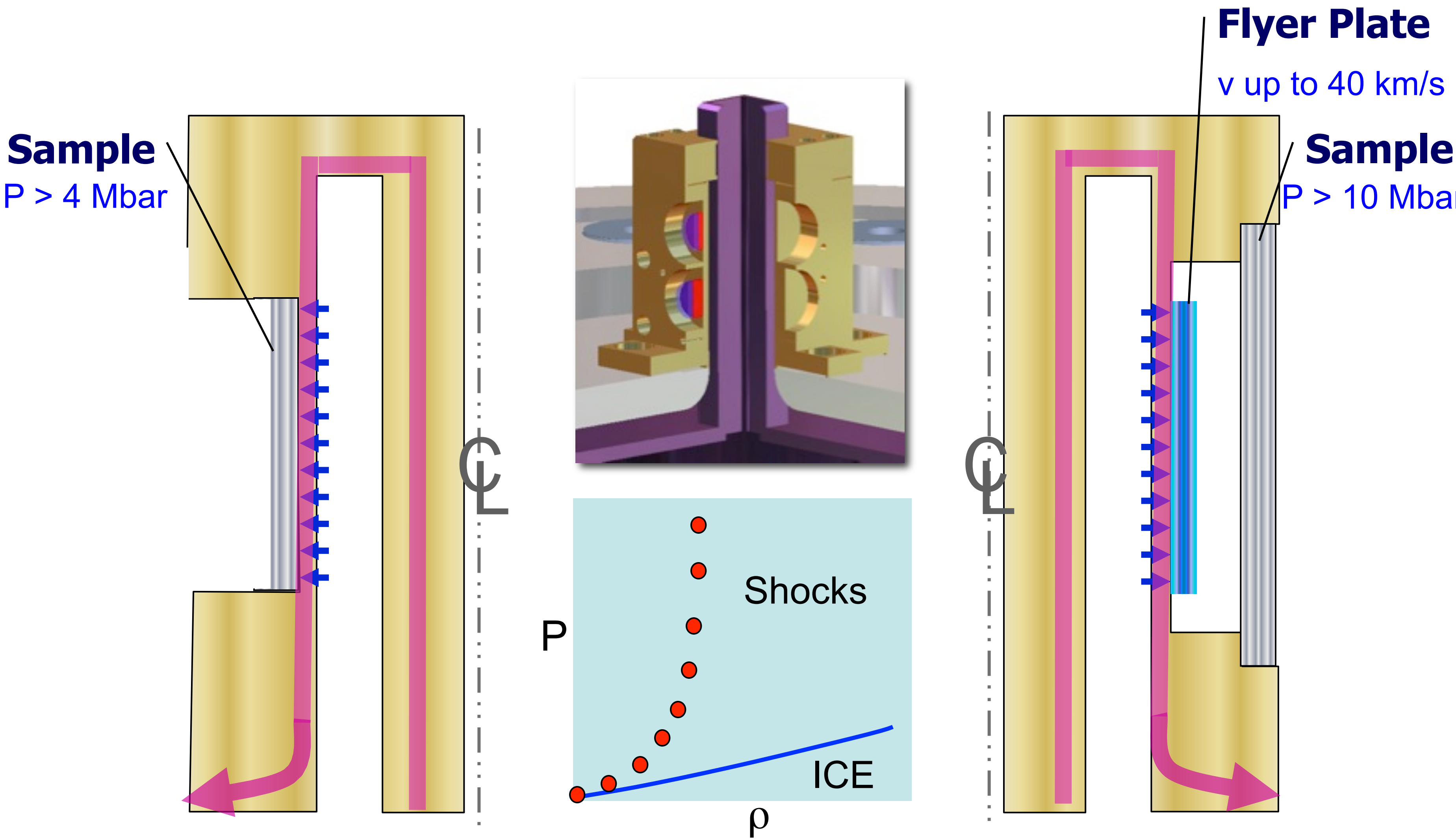








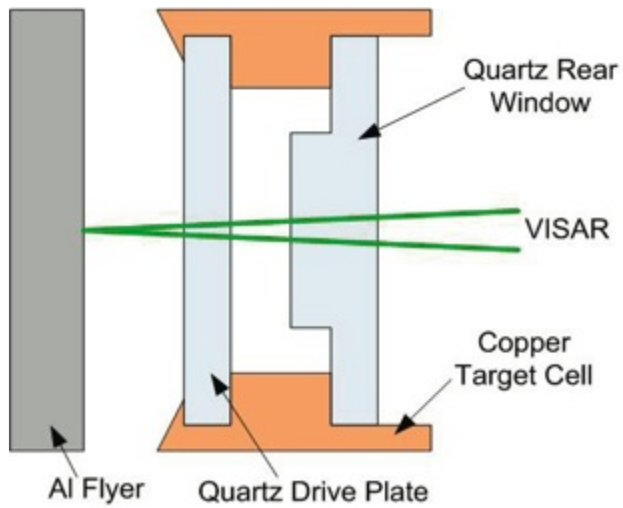
Isentropic compression and shock wave experiments map different regions of a material's phase space

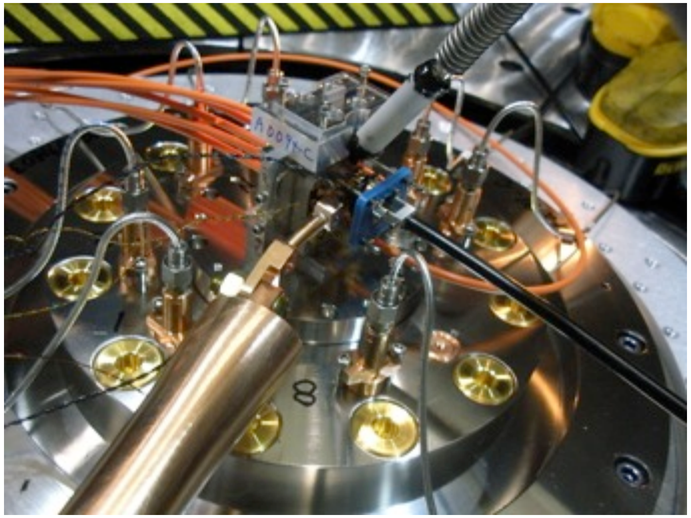


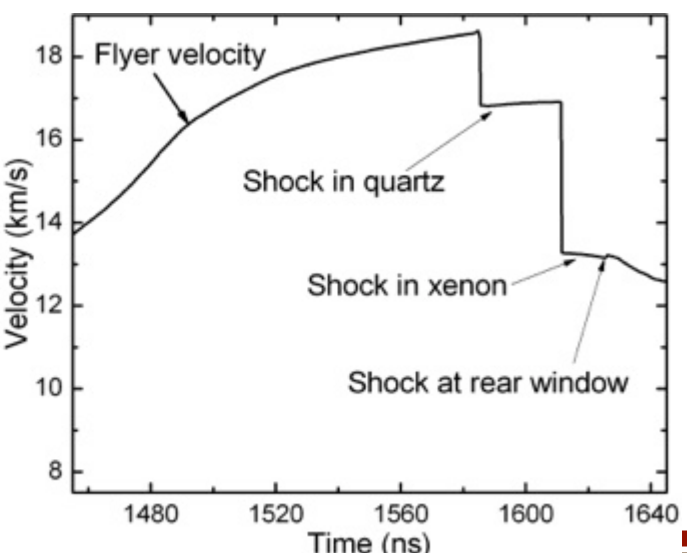
Isentropic Compression Experiments:
gradual pressure rise in sample

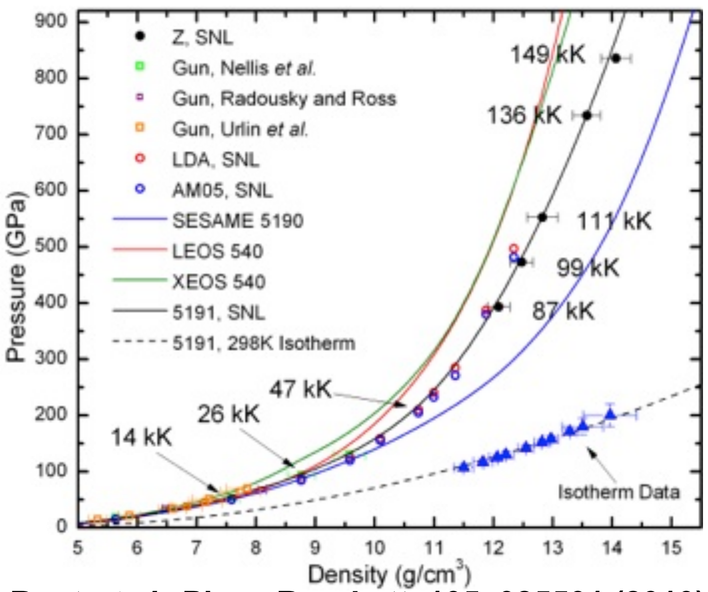
Shock Hugoniot Experiments:
shock wave in sample on impact

Large sample sizes and "long" time scales enable sub-percent accuracy at record pressures









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

VISAR trace from a xenon experiment with 18.5 km/s impact velocity

The structure of planets is determined by properties of elements and compounds at very high pressure

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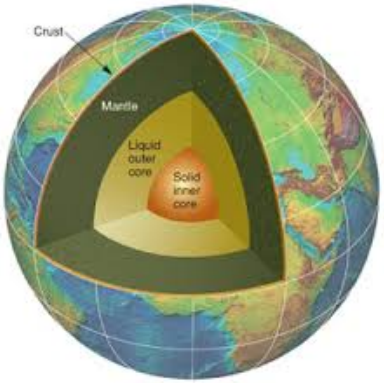
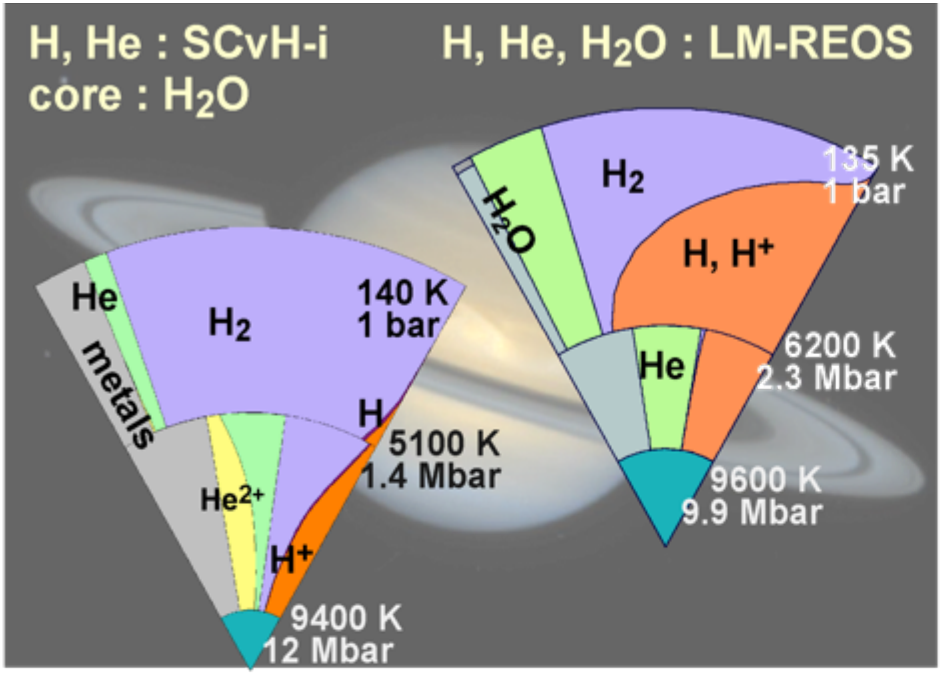




1 Mbar is 1 million atmosphere pressure:

Core of the Earth 3.5 Mbar

Core of Saturn 10 Mbar

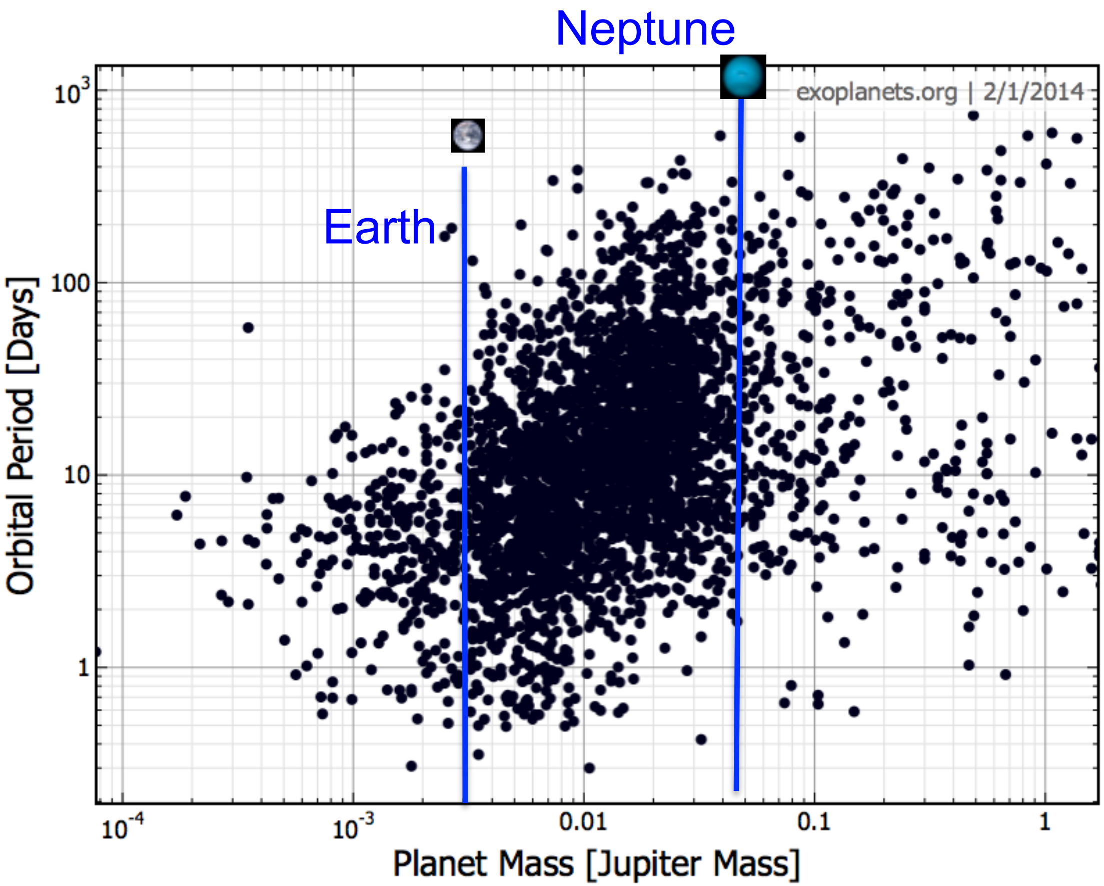
Core of Jupiter 40 Mbar

Structural models of Saturn using different equation of state (pressure/density/temperature) relationships

Notice the differences in core temperature and pressure from the competing models

Using the Z-machine, we can create and diagnose matter at these conditions

The field of planetary science has seen a rapid growth in terms of planets and complexity

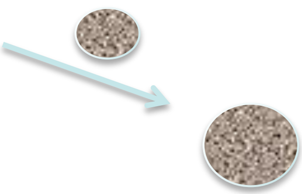


The solar system we know is not the only one – so formations theories need to be applicable elsewhere too

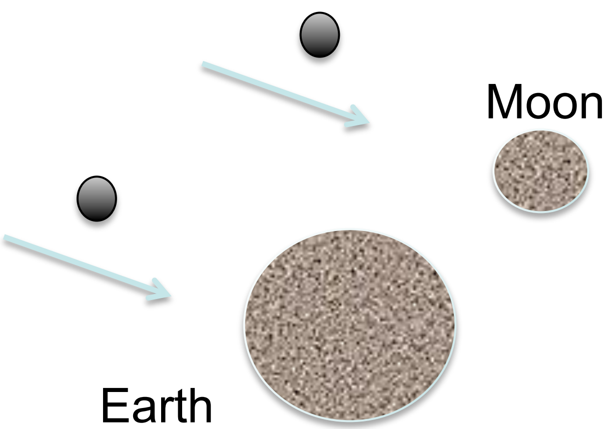
Kepler candidates and confirmed exo-planets on February 1, 2014

The plethora of newly discovered planets raises profound questions about the formation of solar systems (planetesimal collisions, giant impacts, moon formation) and structure of planets (magnetic fields, layering, plate tectonics, etc.)

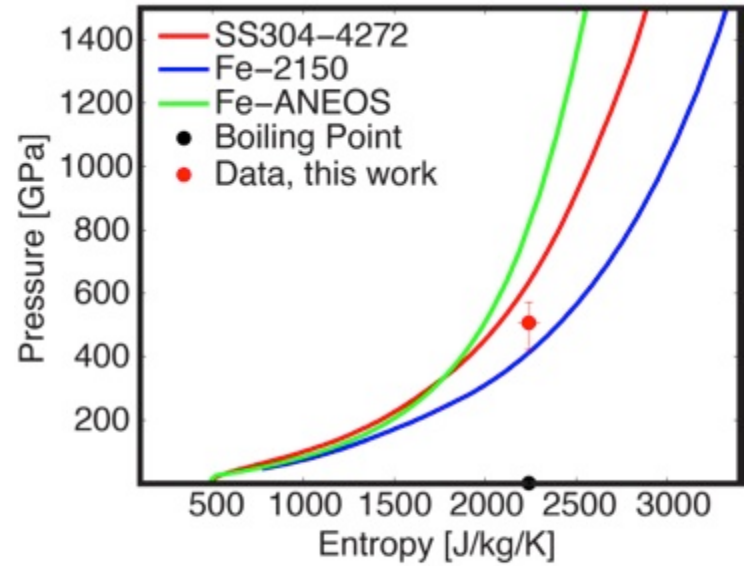
We have determined the shock pressure (impact velocity) at which iron is vaporized



Collisions between planetesimals in the early solar system



Meteor impacts on the earth/moon system



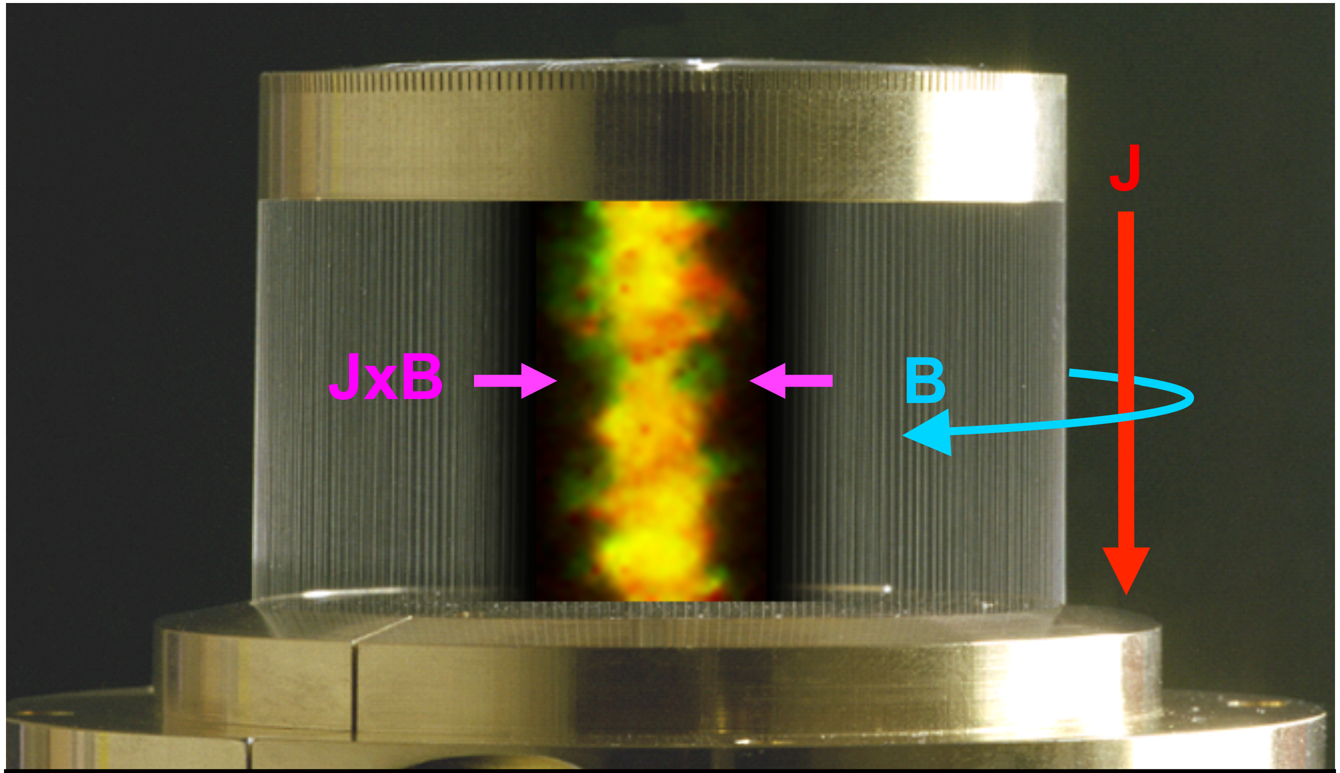
By knowing the vaporization pressure of iron we can eliminate significant uncertainties in simulations of solar system formation

Shock Thermodynamics of Iron and Impact Vaporization of Planetesimal Cores

Kraus, Root, Lemke, Stewart, Jacobsen, and Mattsson. Harvard University and Sandia National Laboratories

Submitted to Nature Geoscience (2013).

Magnetically driven implosions are efficient, powerful, x-ray sources from 0.1 to 10 keV



P_{rad} ~ 400 TW, Y_{rad} ~ 2.5 MJ
~ 10-15% wall plug efficiency

We are using the intense x-ray bursts from Z to create unique plasmas that can help address astrophysical questions

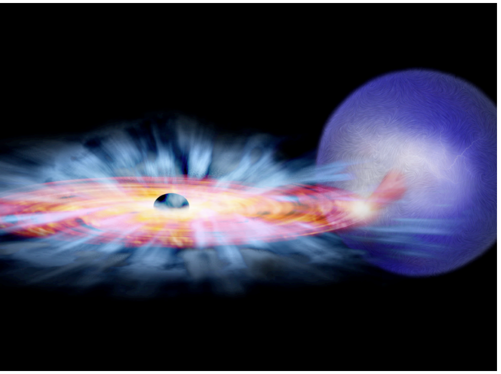
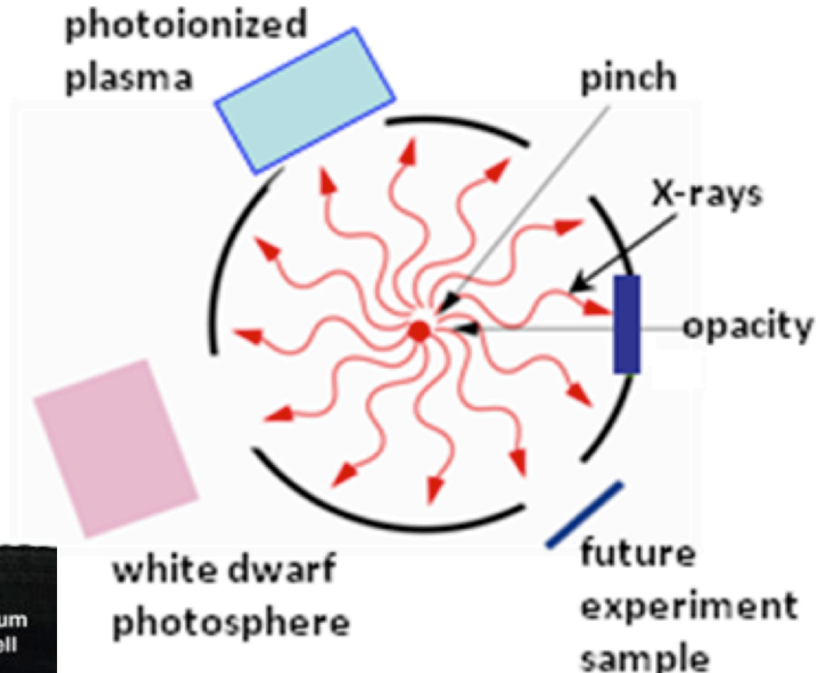


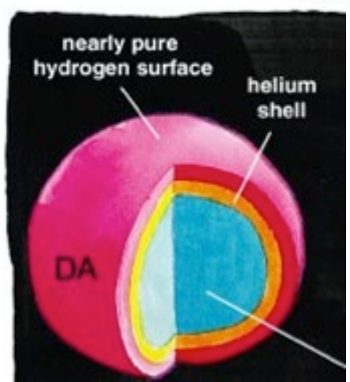
Photo-ionized plasmas

How does the accretion disk around a black-hole behave?



Solar Opacities

Do we understand the structure of the sun?



White Dwarfs

Can we use white dwarfs as cosmic chronometers?

The Z Astrophysical Plasma Properties (ZAPP) collaboration studies the behavior of atoms in plasmas

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Los Alamos National Laboratory

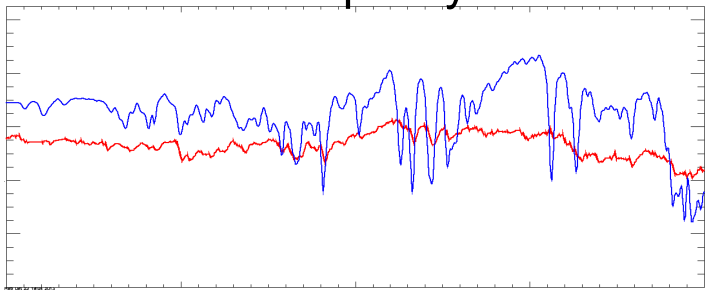
cea

- Why can't we predict the location of the convection zone boundary in the Sun?
  - ➢ Opacity of Fe at ~200 eV

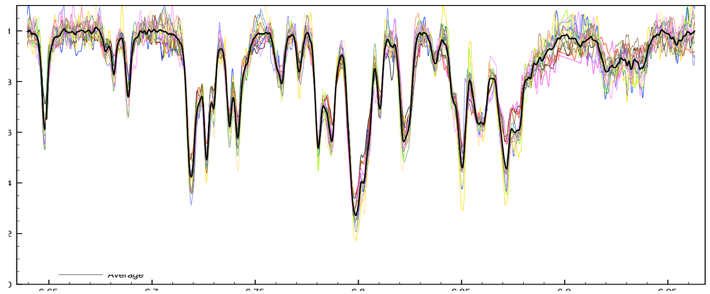
- How does ionization and line formation occur in accreting objects and warm absorbers?
  - ➢ Ionization distribution and spectral properties of photoionized Ne and Si

- Why doesn't spectral fitting provide the correct properties for White Dwarf stars?
  - ➢ Stark-broadened H-Balmer line profiles

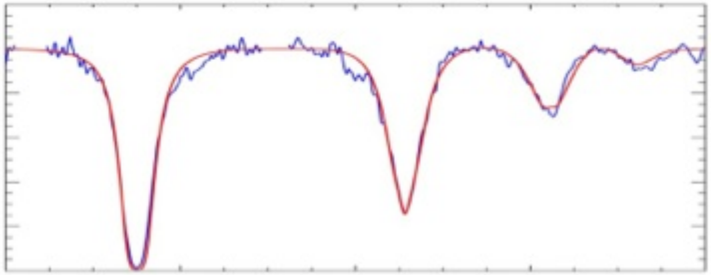
Fe Opacity



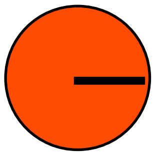
Si Photoionization



H-Balmer Line shapes



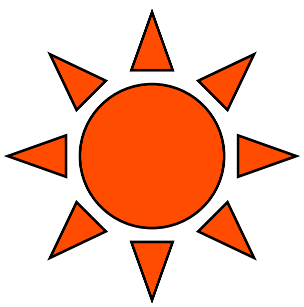
Under extreme conditions a mass of DT can undergo significant thermonuclear fusion before falling apart



ρ, R, T

- Consider a mass of DT with radius R, density ρ, and temperature T
- How does the disassembly time compare with the time for thermonuclear burn?

$$\tau_{disassembly} \sim \frac{R}{c_s} \sim \frac{R}{\sqrt{T}} \qquad \tau_{burn} \sim \frac{1}{n_i\langle \sigma v\rangle} \sim \frac{1}{\rho\langle \sigma v\rangle}$$



- The fractional burn up of the DT (for small burn up) is:

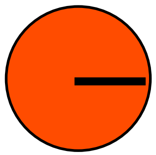
$$f_{burn} \approx \frac{\tau_{disassembly}}{\tau_{burn}} \sim \rho R \frac{\langle \sigma v\rangle}{\sqrt{T}}$$

- At sufficiently high ρR and T the fractional burn up becomes significant and the energy deposited by alpha particles greatly exceeds the initial energy in the fusion fuel ("ignition")

- Typical conditions are:

$$\rho R \approx 0.4\,\mathrm{g/cm^2}$$
$$T \approx 5\,\mathrm{keV}$$

For hot spot ignition fusion fuel must be brought to a pressure of a few hundred billion atmospheres



ρ, R, T

For ignition conditions: $\left\{ \begin{array}{l} \rho R \approx 0.4\,\mathrm{g/cm^2} \\ T \approx 5\,\mathrm{keV} \end{array} \right\}$

$$E_{HS} \propto m_{HS} T_{HS} \propto \rho_{HS} R_{HS}^3 T_{HS} \propto \frac{\left(\rho_{HS} R_{HS}\right)^3 T_{HS}^3}{P_{HS}^2}$$

$E_{NIF} \sim 15\,\mathrm{kJ} \Rightarrow P \sim 400\,\mathrm{GBar}$ $\quad R \sim 30\,\mu\mathrm{m} \Rightarrow$ and $\rho \sim 130\, g/cm^3$

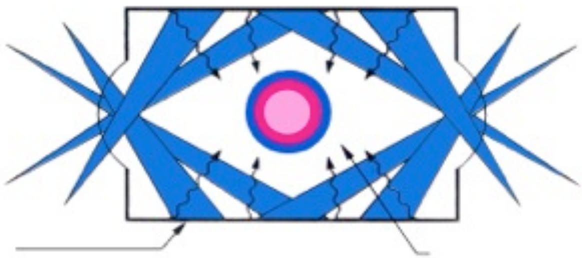
This is consistent with detailed calculations

Note for magnetic confinement fusion ignition

$P \sim \mathrm{few\ Bars} \quad \rho \sim \mathrm{few}\ 10^{-10}\, g/cm^3$

Imploding thin shells at high velocities is the most common approach to reaching these conditions

Indirect Drive (X-ray)



In either direct or indirect drive, peak drive pressures are of order ~ 50-150 MBars

We need to get pressures to > 1000X that for ignition!

Spherical implosions enable us to store energy in the fusion fuel in the form of kinetic energy, which is converted to pressure at stagnation

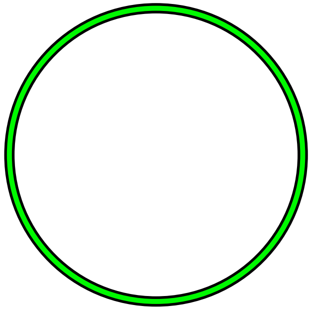
$$P_{stag} \sim \alpha \rho_{stag}^{5/3} \quad \alpha \rho_{stag}^{2/3} \sim \mathrm{v}^2 \Rightarrow P_{stag} \sim \mathrm{v}^5 / \alpha^{3/2}$$

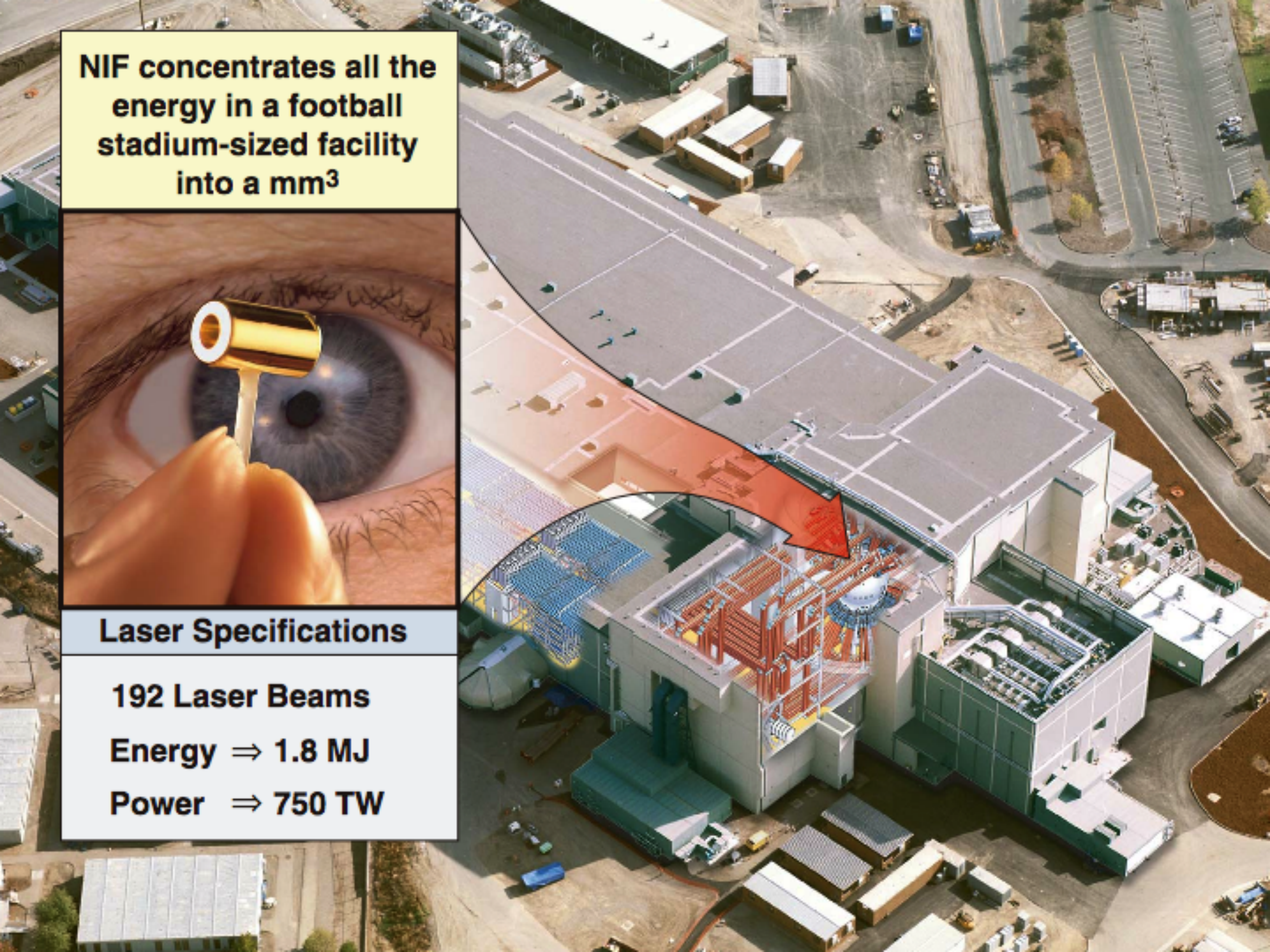
$$\alpha \equiv P / P_{Fermi}$$

Thin shell implosions can reach the 200-400 km/sec needed for ICF

$$\int P_{drive} d\mathrm{V} = \frac{1}{2} m \mathrm{v}^2 \quad m \sim 4\pi R^2 \rho \delta R$$

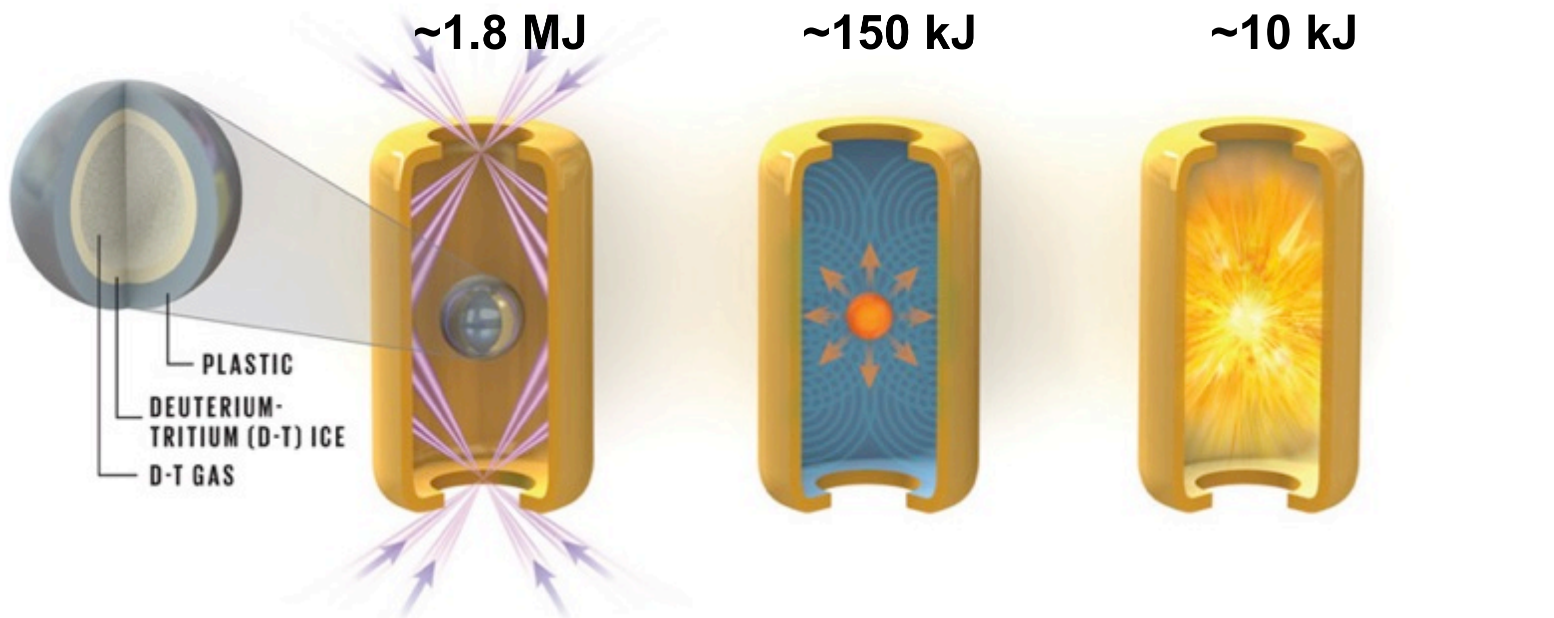
$$P_{drive} R^3 \sim R^2 \rho \delta R \, \mathrm{v}^2 \Rightarrow \mathrm{v}^2 \sim \frac{P_{drive}}{\rho} \frac{R}{\delta R}$$




NIF concentrates all the energy in a football stadium-sized facility into a mm3
Laser Specifications
192 Laser Beams
Energy ⇒ 1.8 MJ
Power ⇒ 750 TW


Cardinal
Stanford
GOLDEN BEARS
CALIFORNIA
Cal
Bruins
UCLA
UCLA BRUINS

The NIF has focused on the indirect or x-ray driven approach to inertial confinement fusion



The Path to Ignition

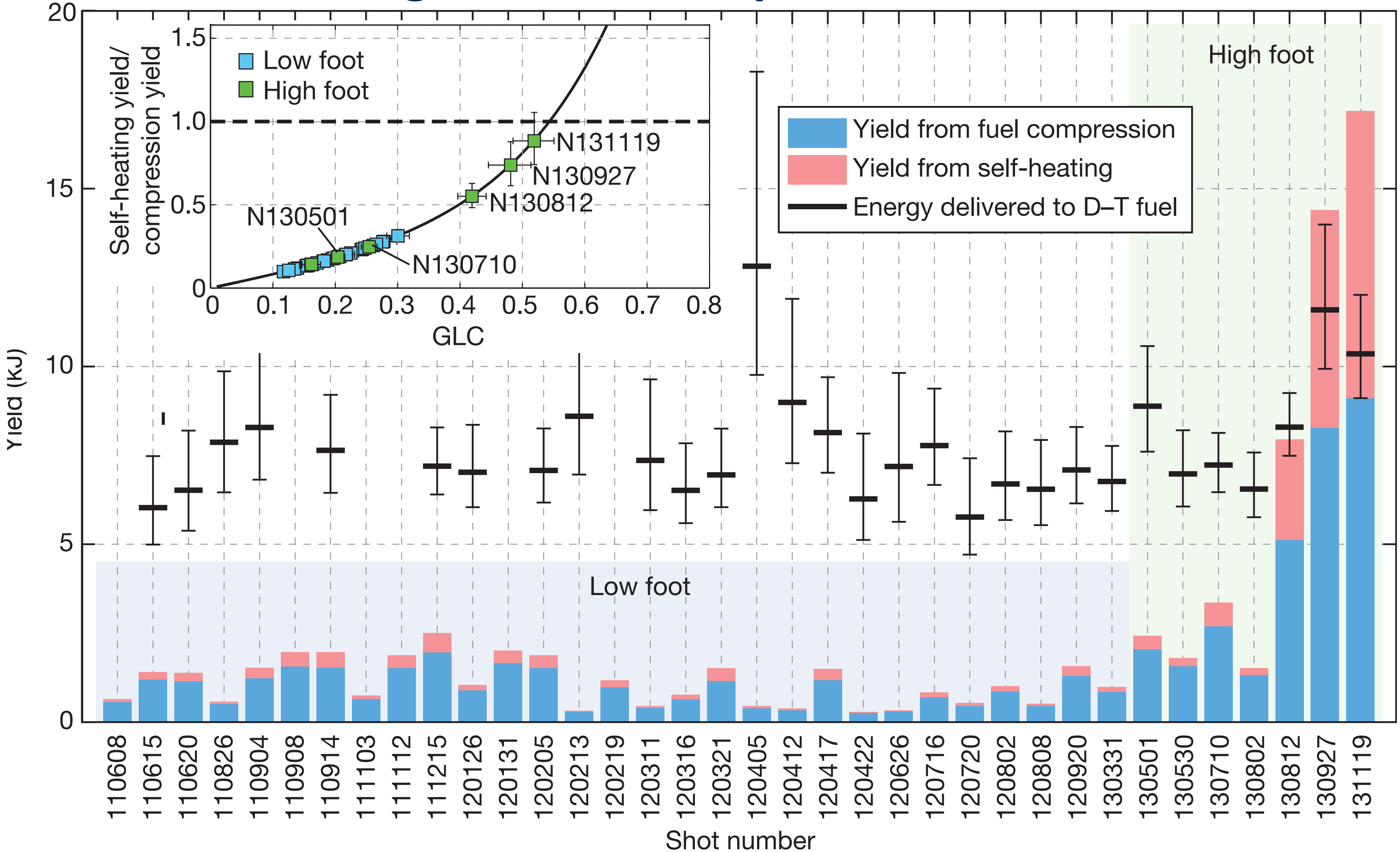
1. Laser light enters both ends of the hohlraum, striking and heating the inner surface.

2. The resulting X-rays propagate toward the center, where they heat and blast away the outer part of the target.

3. In reaction, the remainder of the target accelerates inward and begins to fuse.

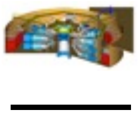
IEEE Spectrum (March 2013):

Recent results from NIF are exciting, they obtained more energy from fusion than was invested in the fusion fuel but ignition will require 100x increase*

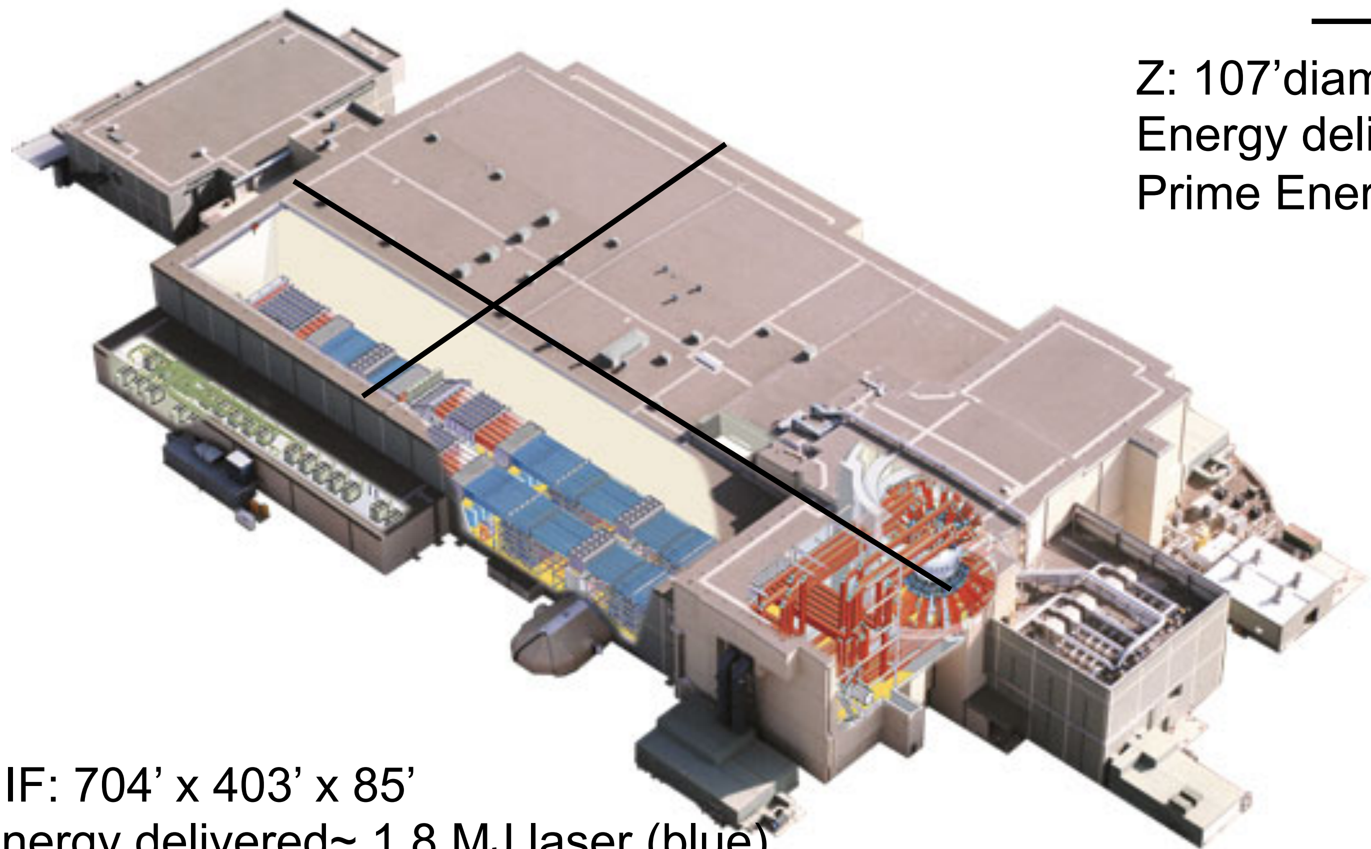


Hurricane,O.A.*et al. Nature* http://dx.doi.org/10.1038/nature13008 (2014).

Pulsed power is a compact and efficient driver for high energy density experiments



Z: 107’diam x 20’ high
Energy delivered ~3 MJ
Prime Energy ~ 22 MJ



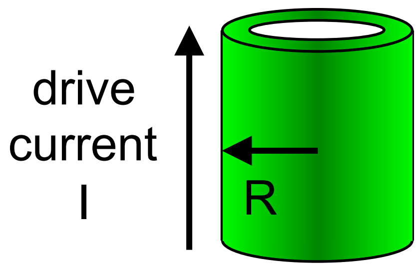
NIF: 704’ x 403’ x 85’
Energy delivered~ 1.8 MJ laser (blue)
Prime Energy ~ 370 MJ

Of course, high energy lasers have tremendous control over where and when energy is delivered.

Magnetically driven implosions can efficiently couple energy at high drive pressure

Magnetically-Driven Implosion

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



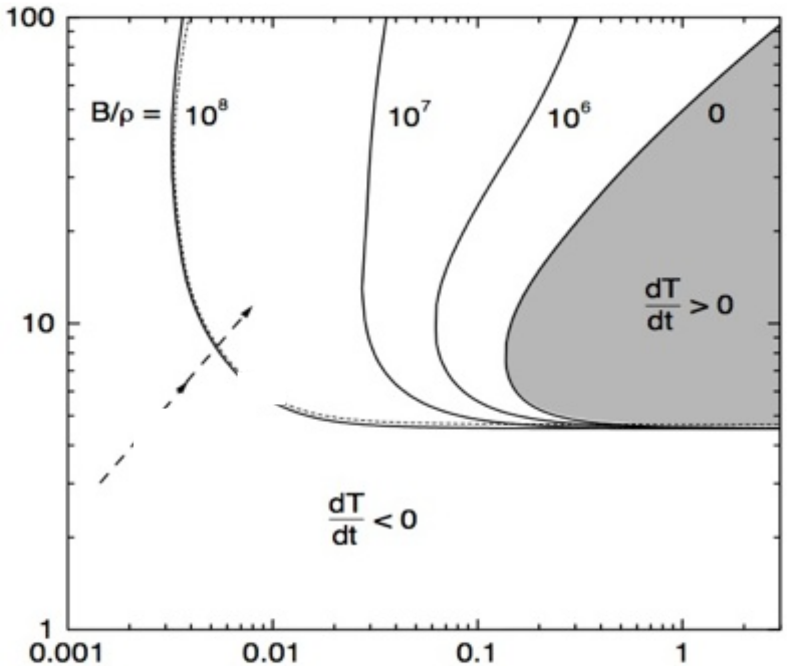
100 MBar at 26 MA and 1 mm

- Magnetic drive can reach very high drive pressures if current reaches small radius
- Magnetic drive is very efficient at coupling energy to the load (no energy wasted on ablation)
- 100 MBar is comparable to drive pressure on a NIF capsule

- However cylindrical implosions do not achieve the same compression that spherical implosions do
- Cylindrical shells must be thick to avoid disruption by instabilities
- Thick shells are slow, meaning they won’t obtain high pressures at stagnation

A large, embedded magnetic field significantly expands the space for fusion self heating

*Basko et al. *Nuc. Fusion* 40, 59 (2000)



Temperature (keV)

Fuel areal density (g/cm^2)

The ρr needed for ignition can be significantly reduced by the presence of a strong magnetic field

- Inhibits electron conduction
- Enhances confinement of α particles

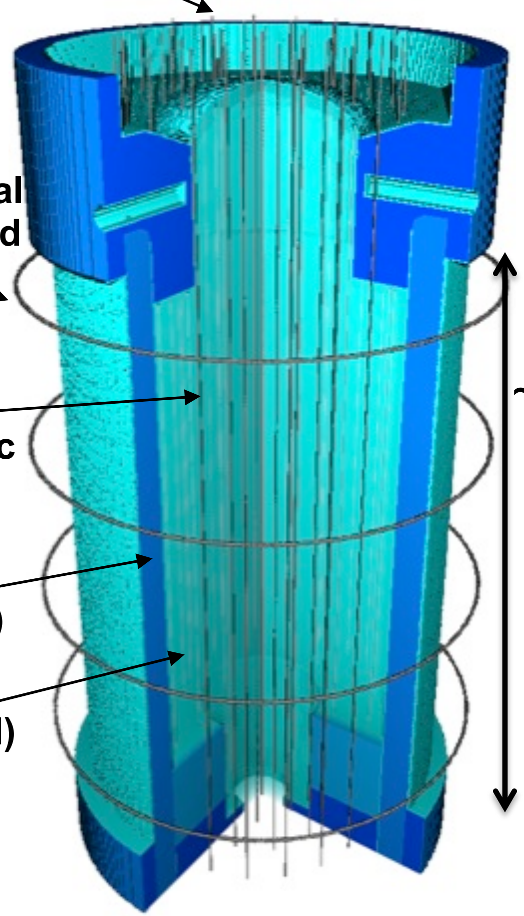
Lower ρr means low densities are needed (~1 g/cc << 100g/cc)

Pressure required for ignition can be significantly reduced to ~5 Gbar (<< 500 Gbar for hotspot ignition)

Large values of B/ρ are needed and therefore large values of B are needed.

B~ 50-150 Megagauss >> B_0 -> flux compression is needed

We are evaluating a Magnetized Liner Inertial Fusion (MagLIF)* concept that may reduce fusion requirements



- An initial 30 T axial magnetic field is applied
  - Inhibits thermal conduction losses
  - May help stabilize implosion at late times
- During the ~100 ns implosion, the fuel is heated using the Z-Beamlet laser (about 6 kJ in designs)
  - Preheating to ~300 eV reduces the compression needed to obtain fusion temperatures to 23 on Z
  - Preheating reduces the implosion velocity needed to ~100 km/s, allowing us to use thick liners that are more robust against instabilities
- ~50-250 kJ energy in fuel; 0.2-1.4% of capacitor bank (Pulsed power is very energy efficient!)
- Stagnation pressure required is ~5 Gbar
- 100 kJ yield may be possible on Z using DT Early experiments would use DD fuel

*S.A. Slutz *et al.*, Phys. Plasmas 17, 056303 (2010). S.A. Slutz and R.A. Vesey, Phys. Rev. Lett. (2012).

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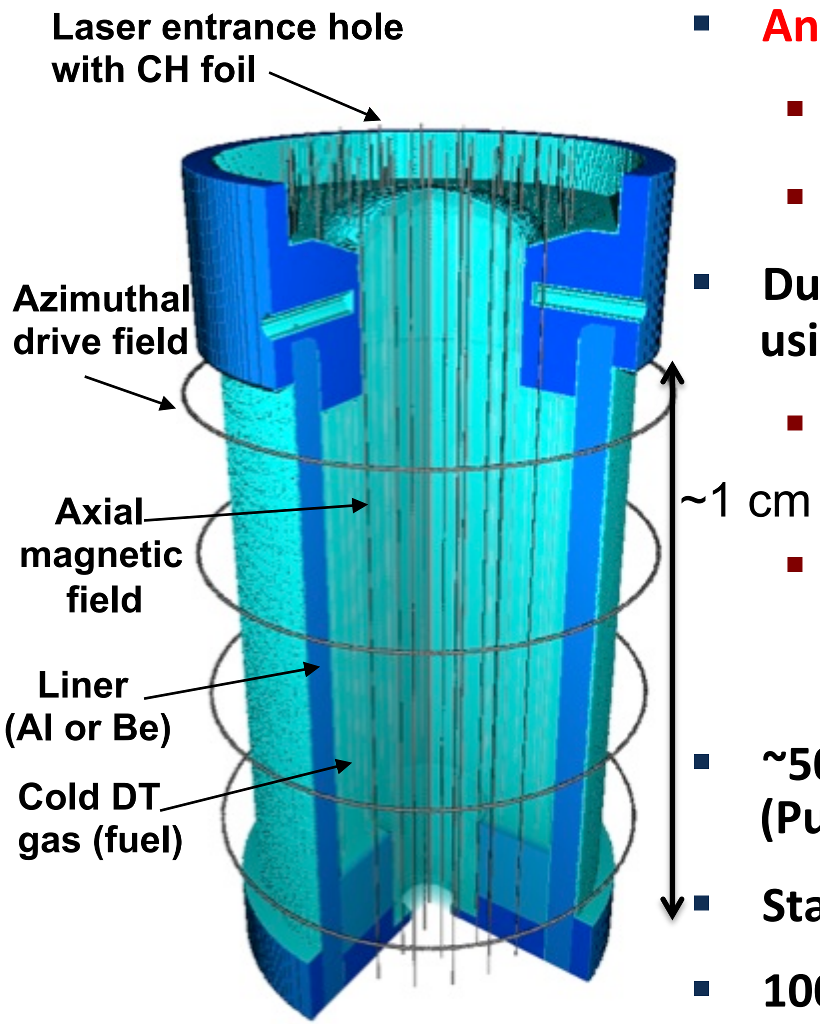

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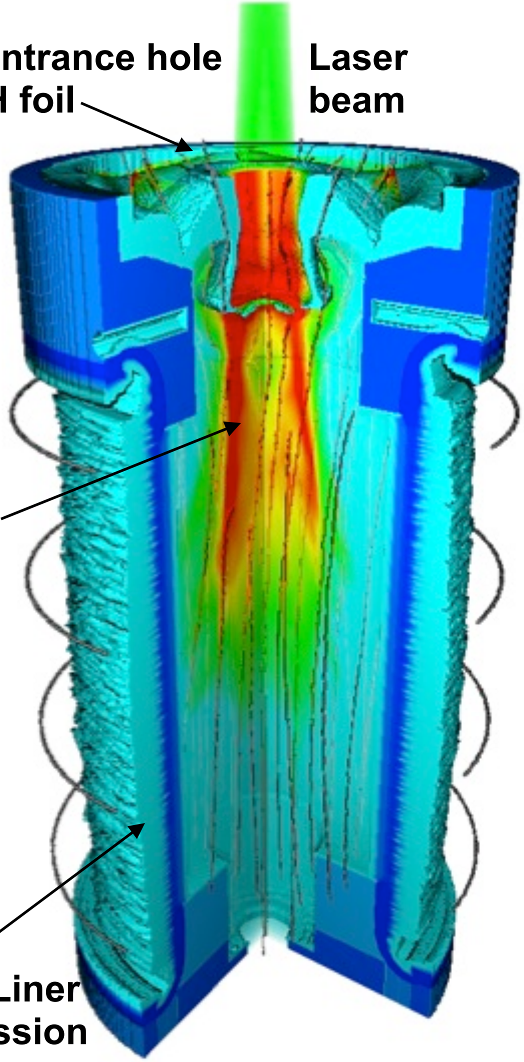

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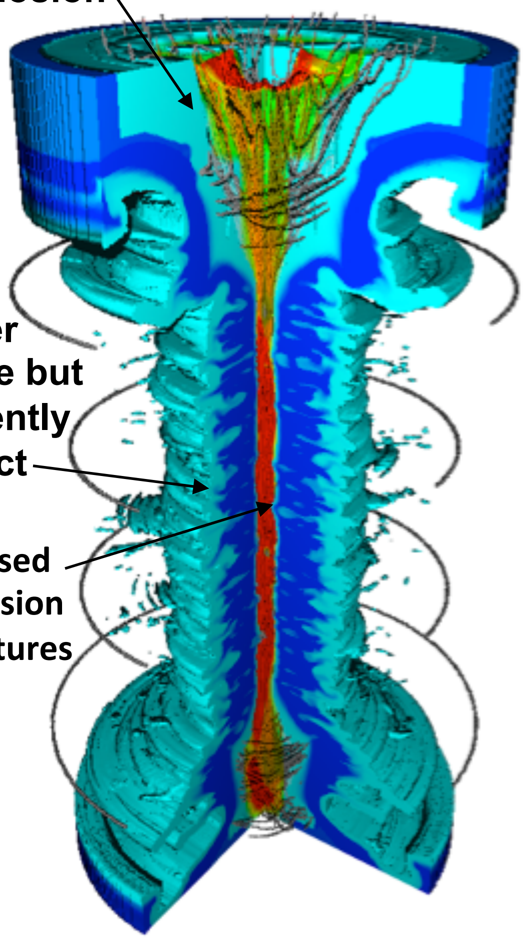

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Simple scalings for a cylindrical implosion apply

Let $R_0 / R_f \equiv CR$ then for high magnetic Reynolds number

$B_{Zf} R_f^2 \sim B_{Z0} R_0^2 \Rightarrow B_{Zf} \sim CR^2 B_{Z0}$ Implies convergences of ~ 20-30 for desired B's

For an implosion slow compared to the sound speed in the preheated gas (but fast enough that radiative losses are negligible) :

$$T \sim T_0 \left(\frac{\rho}{\rho_0} \right)^{2/3} \sim T_0 CR^{4/3}$$

Implies T_0 of a few hundred eV for fusion temperatures

Axial α-trapping with open field lines requires $\rho \Delta z > 0.5 g/cm^2$

Implies a final density of ~ 1g/cc

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Simulations indicate interesting conditions may be possible on Z with DT fuel

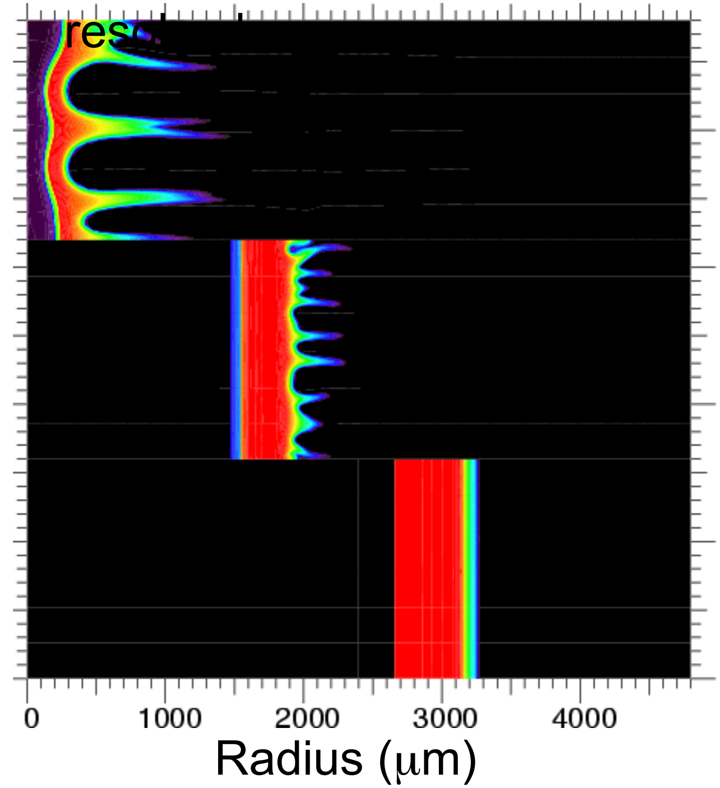
INITIAL CONDITIONS

Peak Current: 27 MA
Be Liner R0: 2.7 mm
Liner height: 5 mm
Aspect ratio (R0/ΔR): 6
Initial gas fuel density: 3 mg/cc
Initial B-field: 30 T
Preheat Temperature: 250 eV

FINAL CONDITIONS

Energy in Fusion Fuel ~200 kJ
Target Yield: 500 kJ
Convergence ratio (R0/Rf): 23
Final on-axis fuel density: 0.5 g/cc
Peak avg. ion temperature: 8 keV
Final peak B-field: 13500 T
Peak pressure: 3 Gbar

60 nm surface roughness, 80 (μm) waves are
res



2D yield for a DT target ~ 350 kJ (70% of 1D)

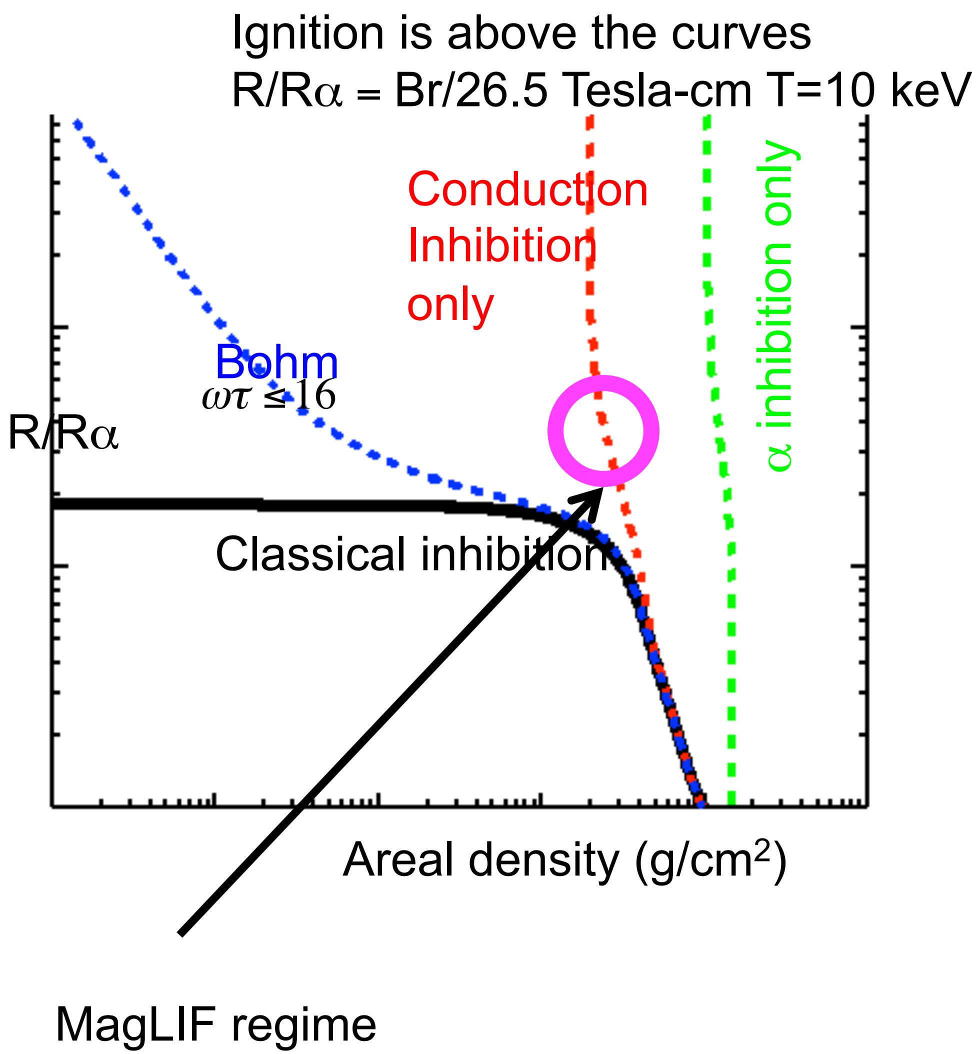
The MagLIF plasmas transitions through interesting regimes

	n, 10^{21}cm^{-3}	T(keV)	B(MG)	a(mm)	L(mm)	ρ_i(μm)	λ(μm)	W(kJ)
T preheat	**0.3**	**0.3**	**0.3**	**3**	**6**	**132**	**9**	**7.34**
T stagnation	**120**	**8**	**130**	**0.12**	**6**	**1.57**	**16**	**125**

	$\frac{a}{\rho_i}$	$\frac{a}{\lambda}$	β	$\frac{L}{a}$
T preheat	**22.7**	**333**	**80.5**	**2**
T stagnation	**76.4**	**7.50**	**4.57**	**50**

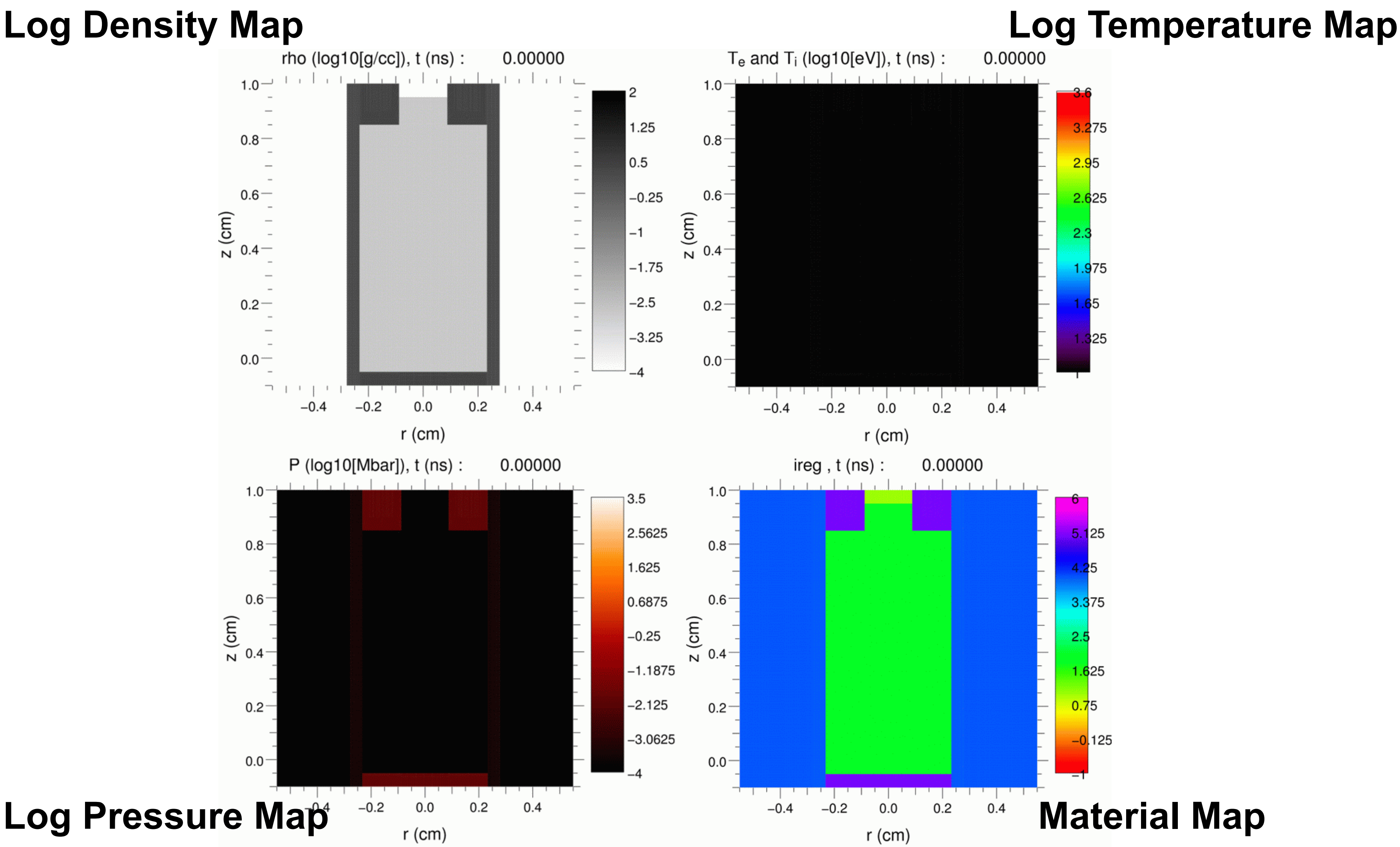
* D.D Ryutov *et al.*, Physics of Plasmas 2012

There are a number of interesting plasma physics questions raised by MagLIF



- What role might anomalous transport play in these plasmas?
- How will self generated magnetic fields (grad n X grad T) compare to our preimposed magnetic field?
- How will flows of the very high beta plasma tangle the magnetic field lines and what effect will that have?
- Will plasma rotation play a significant role?
- How will laser heat the gas in the presence of a large magnetic field?

A recent HYDRA simulation of a MagLIF implosion illustrates the concept



Example calculations by A. Sefkow, DD fuel, I=18MA, B_Z=10T, E_{LASER}=2.6 kJ

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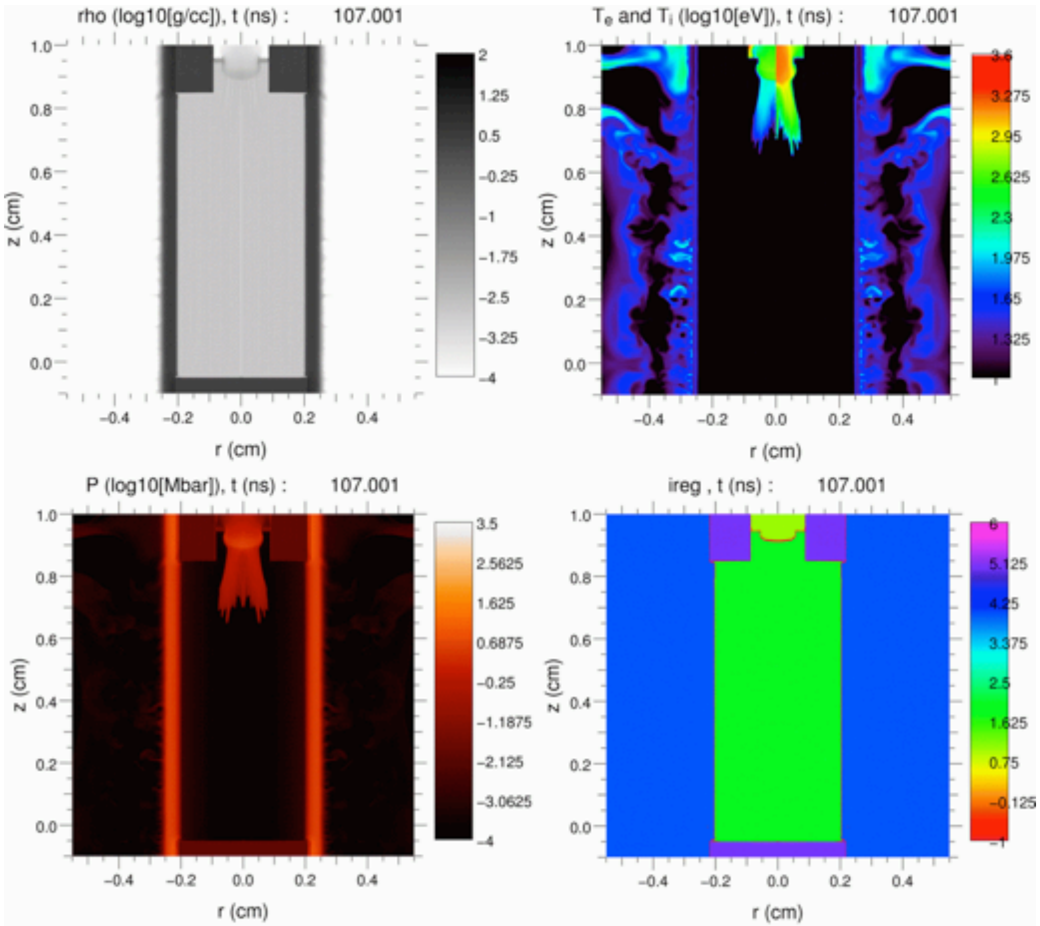
Log Density Map **Log Temperature Map**



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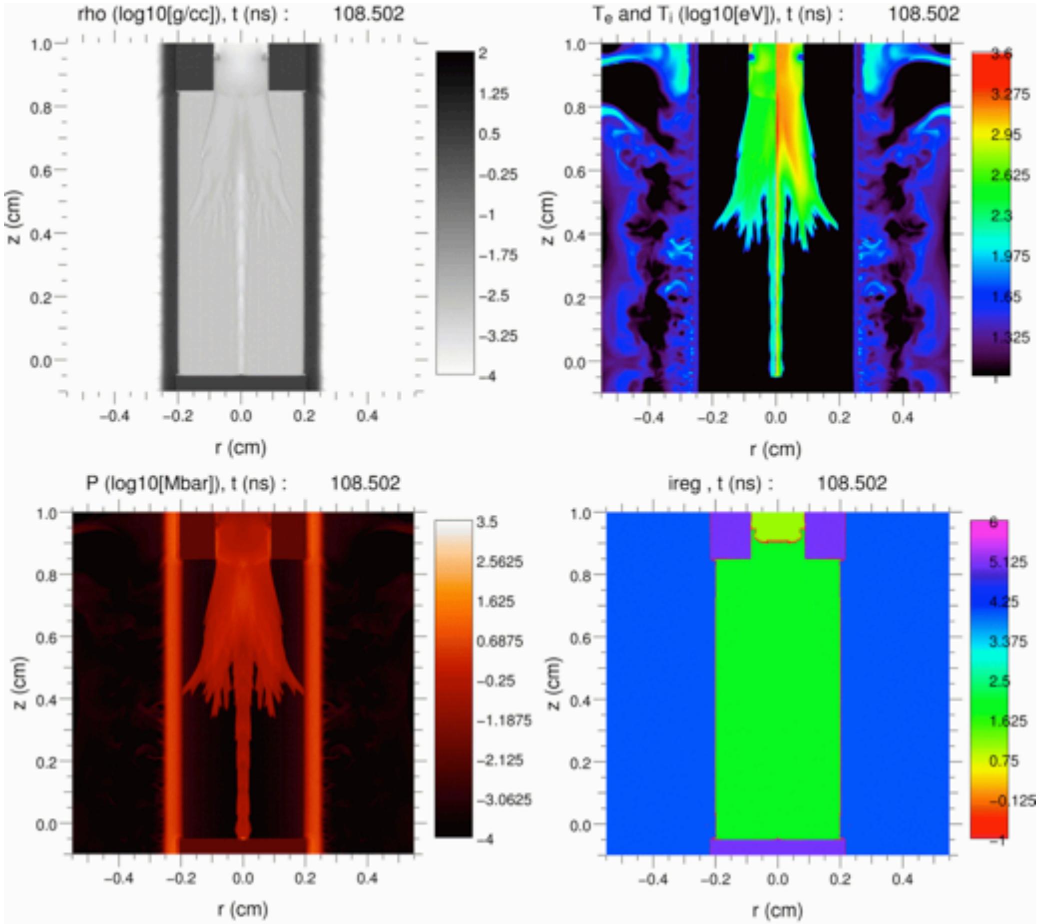

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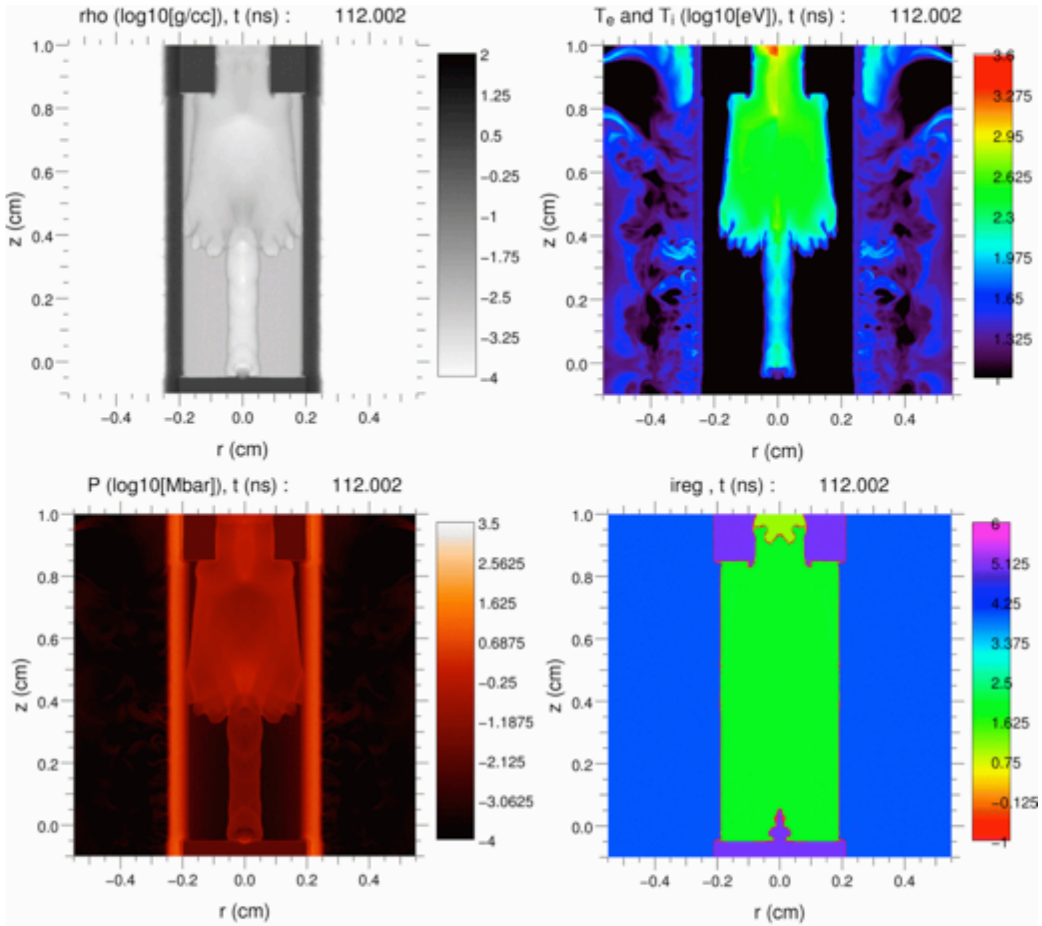

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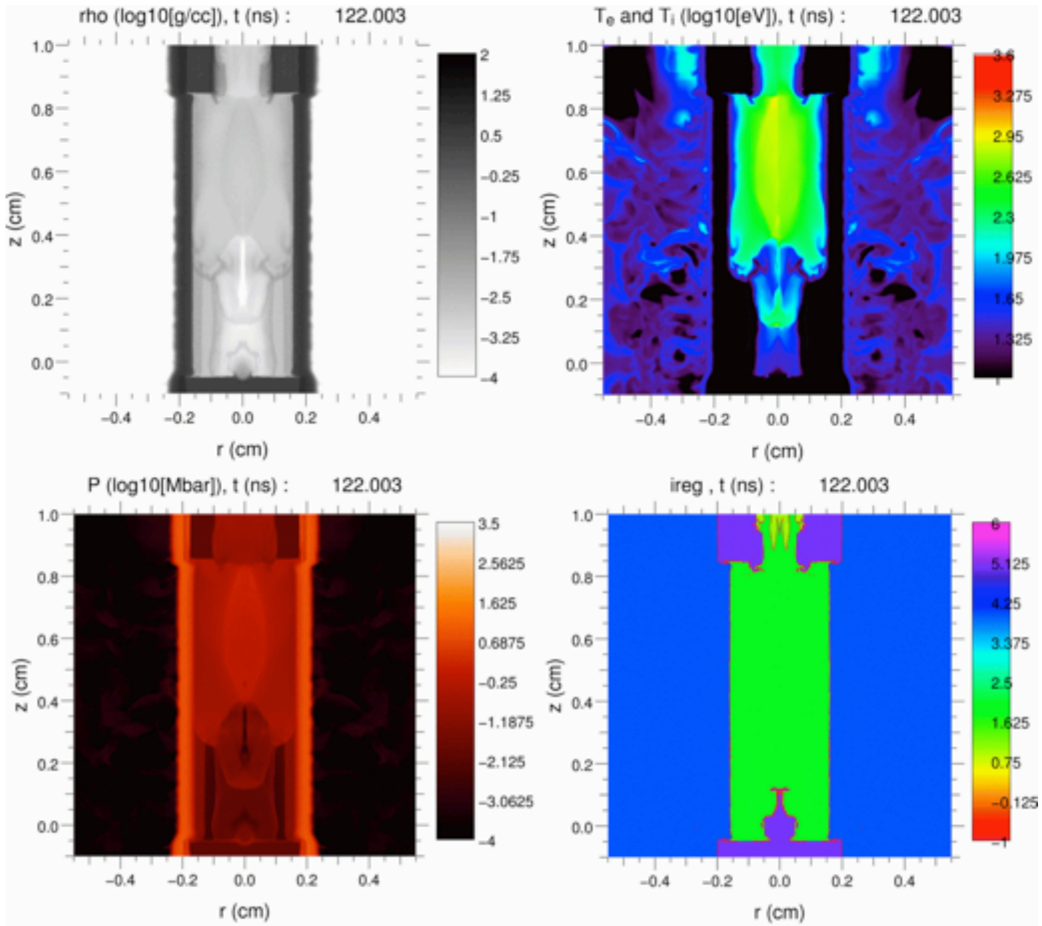

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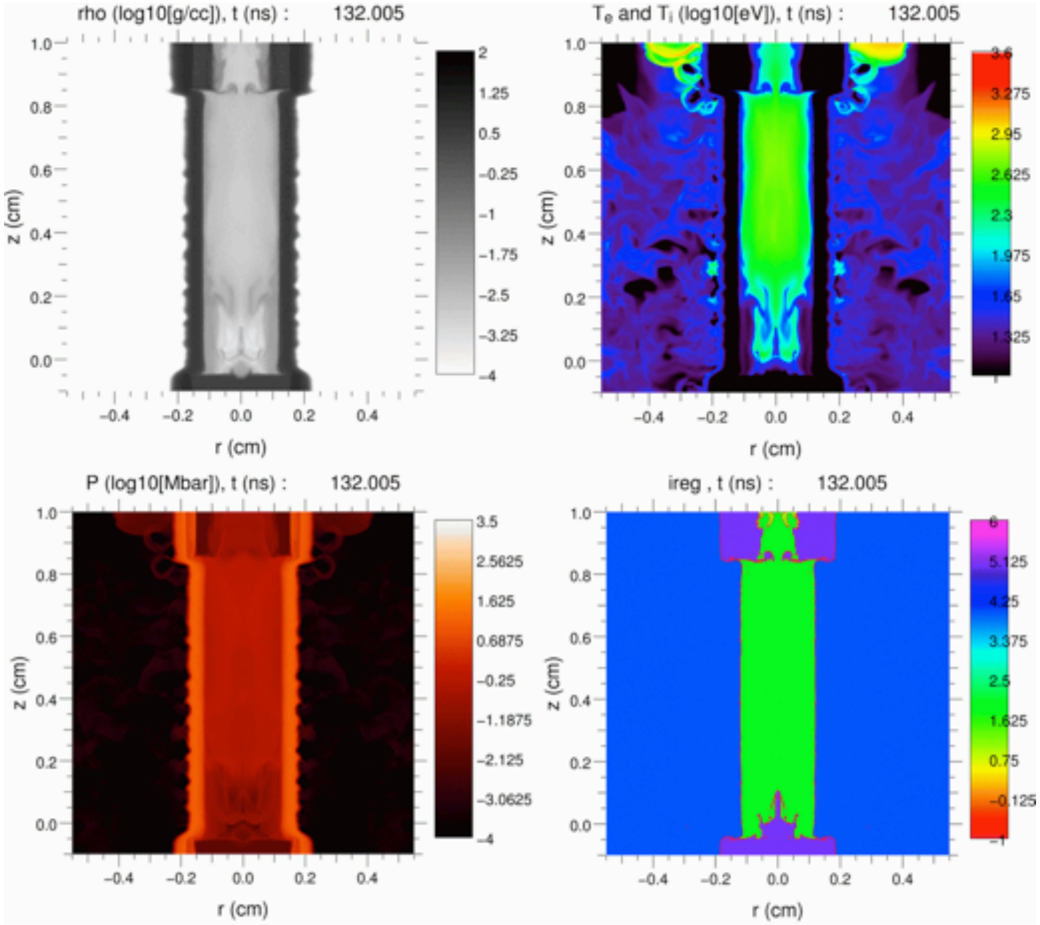

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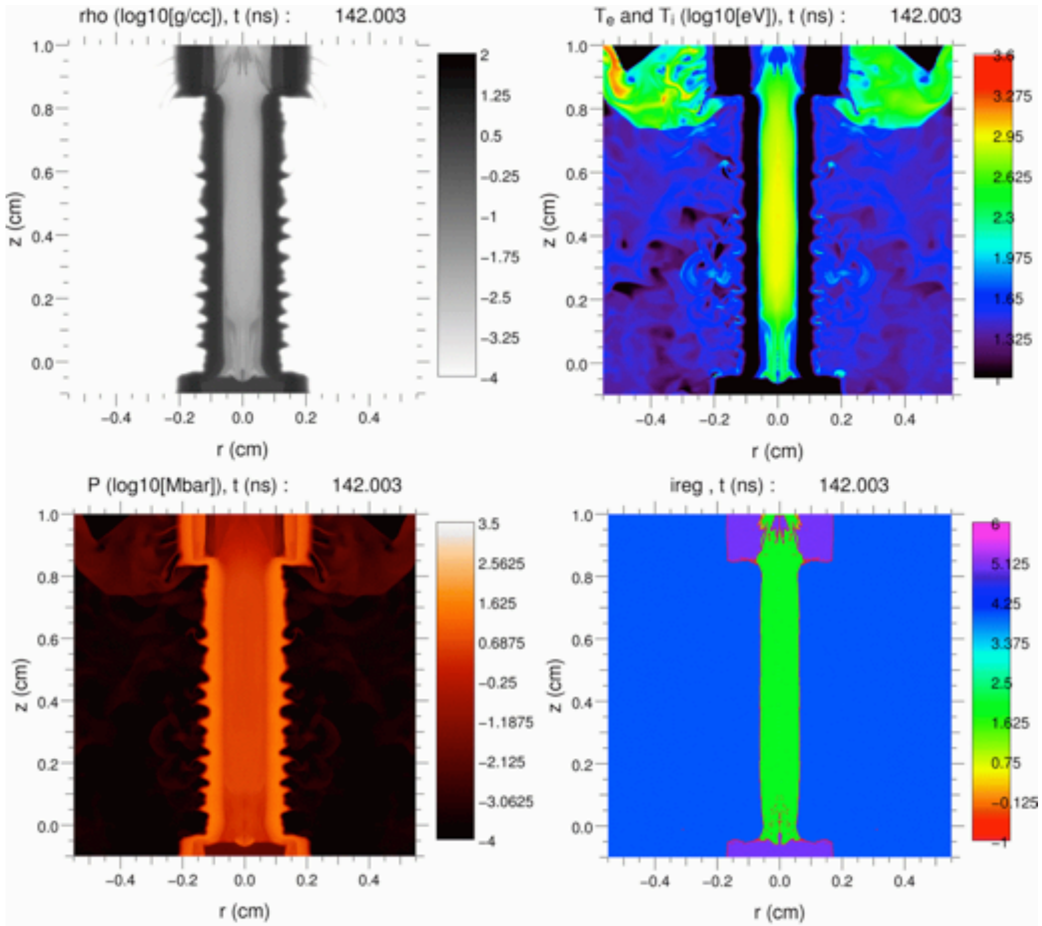

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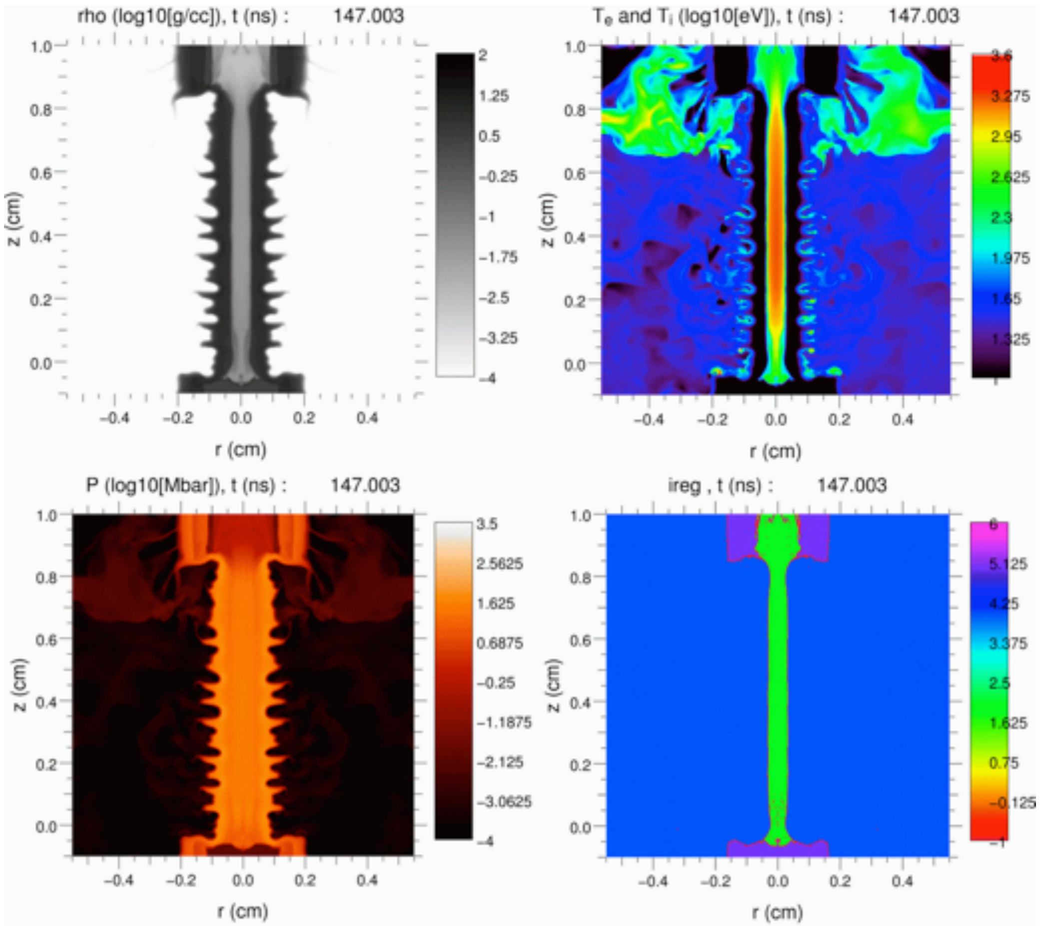

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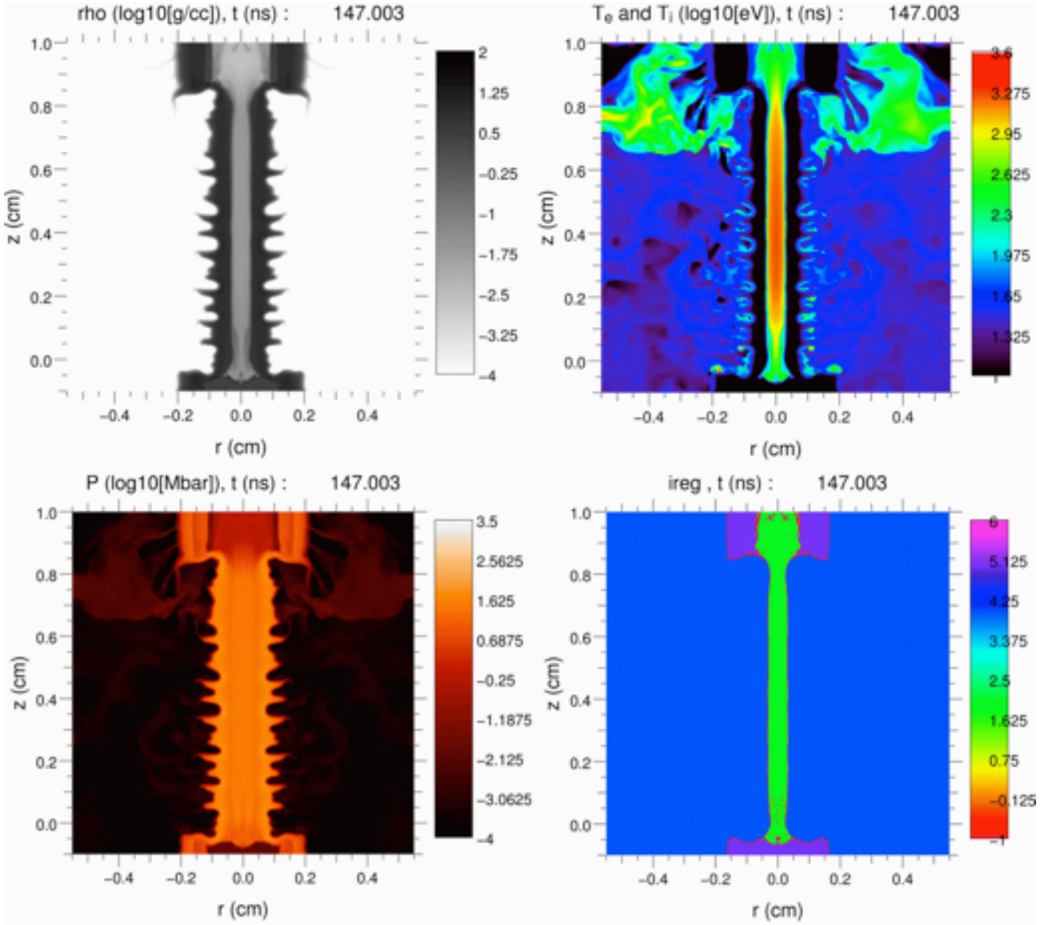

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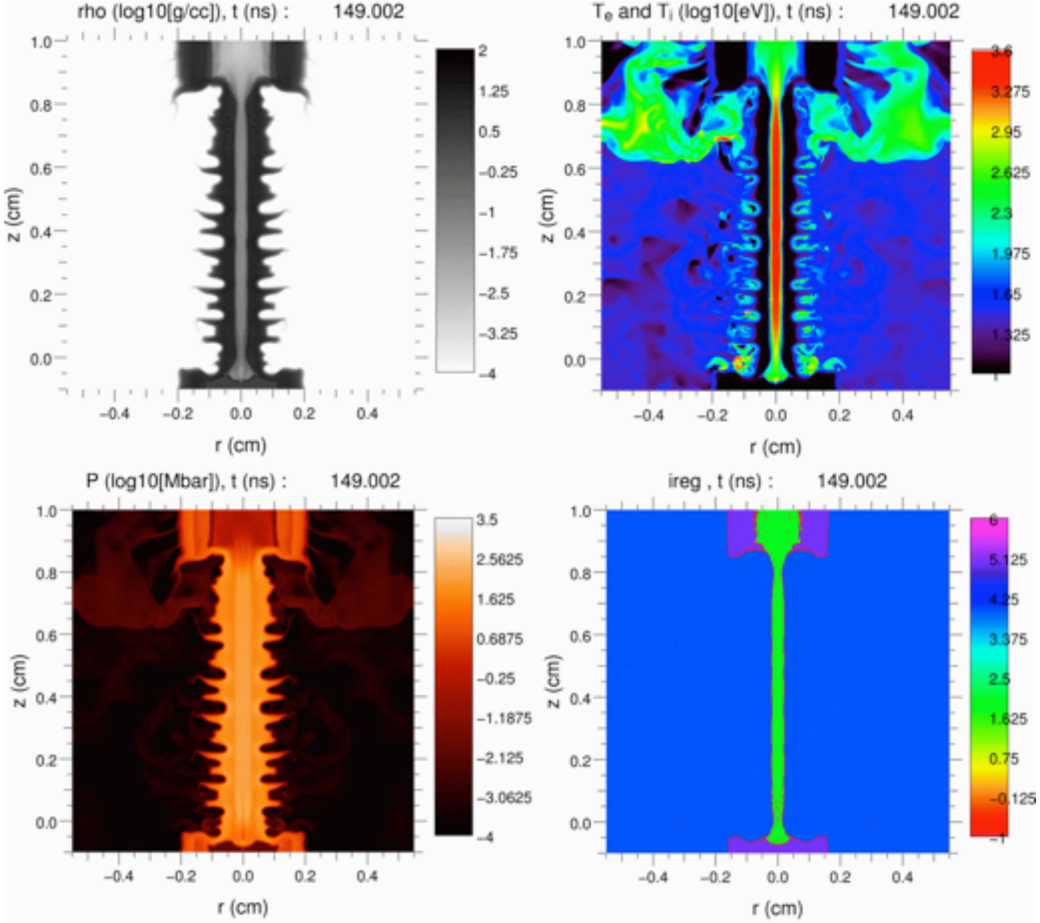

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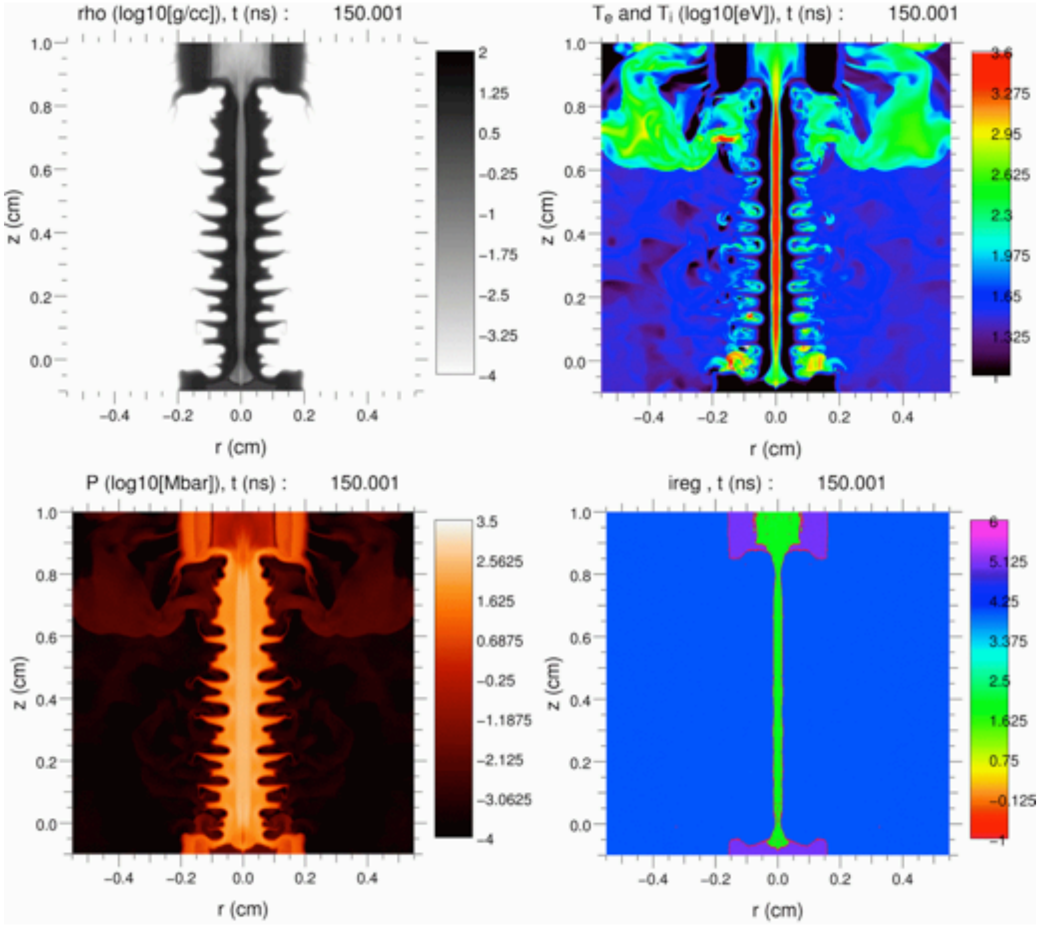

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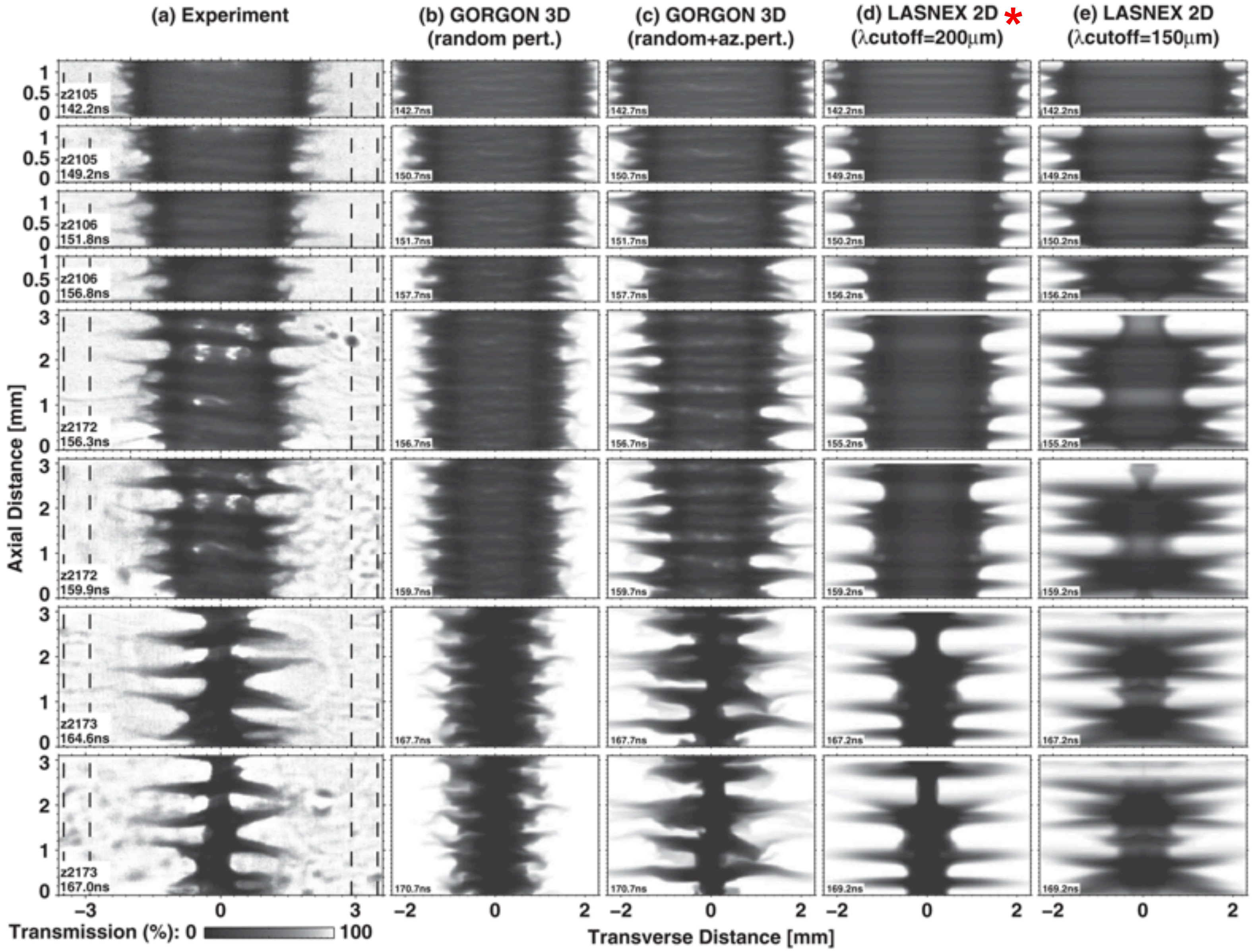
Beryllium experiments show strong azimuthal correlation of the instability growth at late times, informing calculations

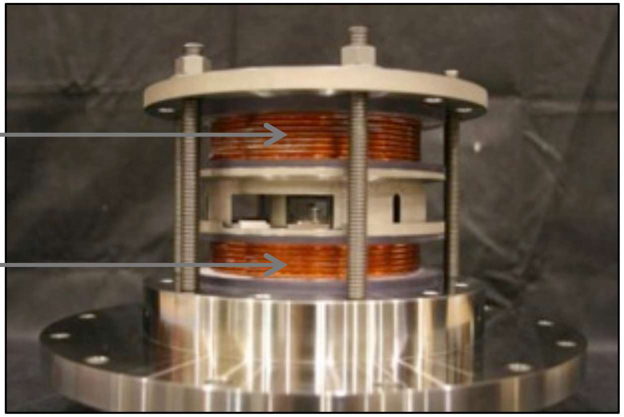


R.D. McBride *et al.*, Phys. Rev. Lett. (2012); R.D. McBride *et al.*, Phys. Plasmas 20, 056309 (2013).

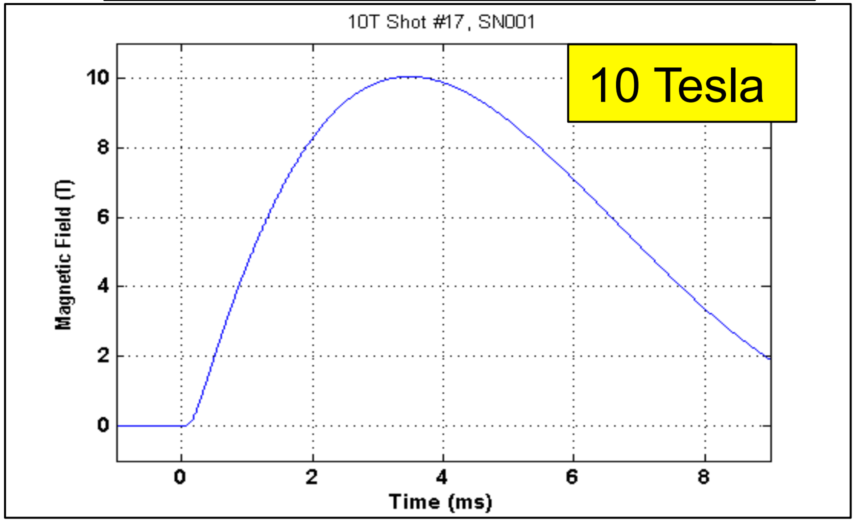
We have installed an 8 mF, 15 kV, 900 kJ capacitor bank on Z to drive 10-30 T axial fields over a several cm^3 volume for MagLIF

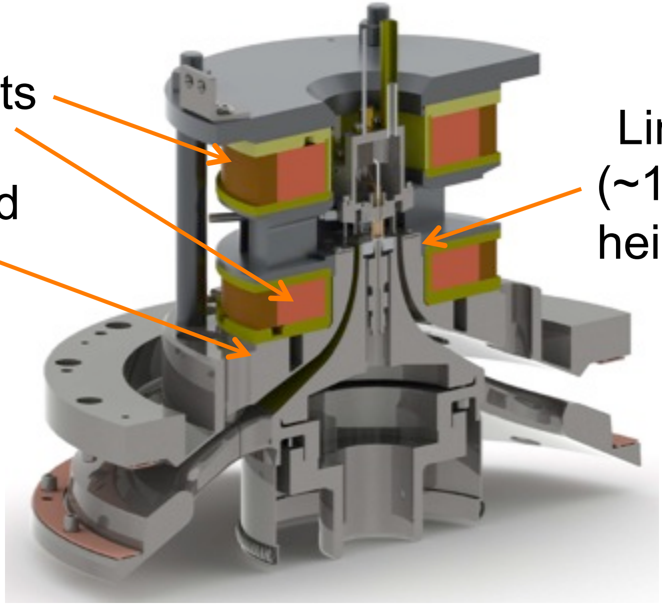
Capacitor bank system on Z
900 kJ, 8 mF, 15 kV

MagLIF assembly with coil



MagLIF on-axis magnetic field data





Our first axially-magnetized liner implosion experiments provided us with several new insights

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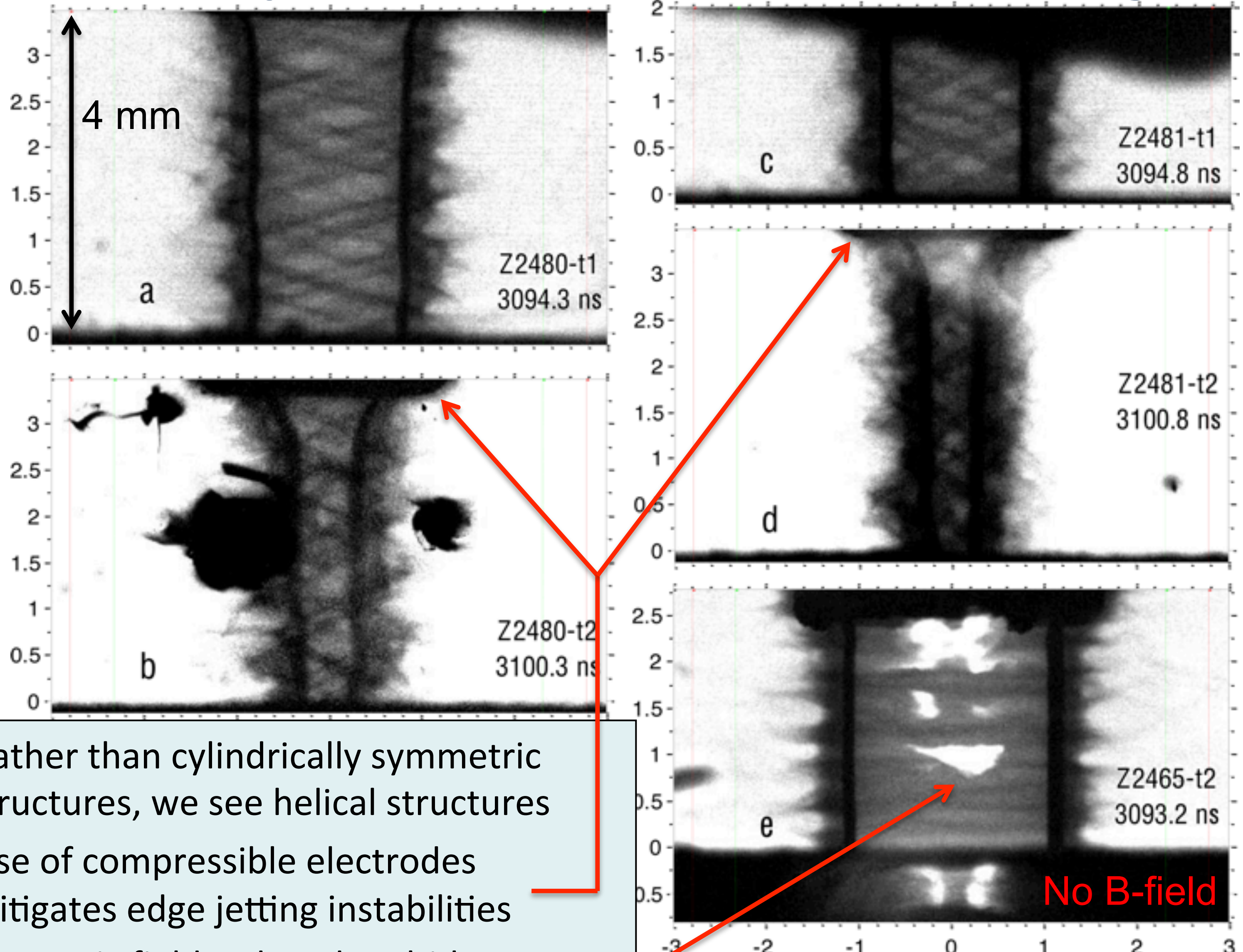
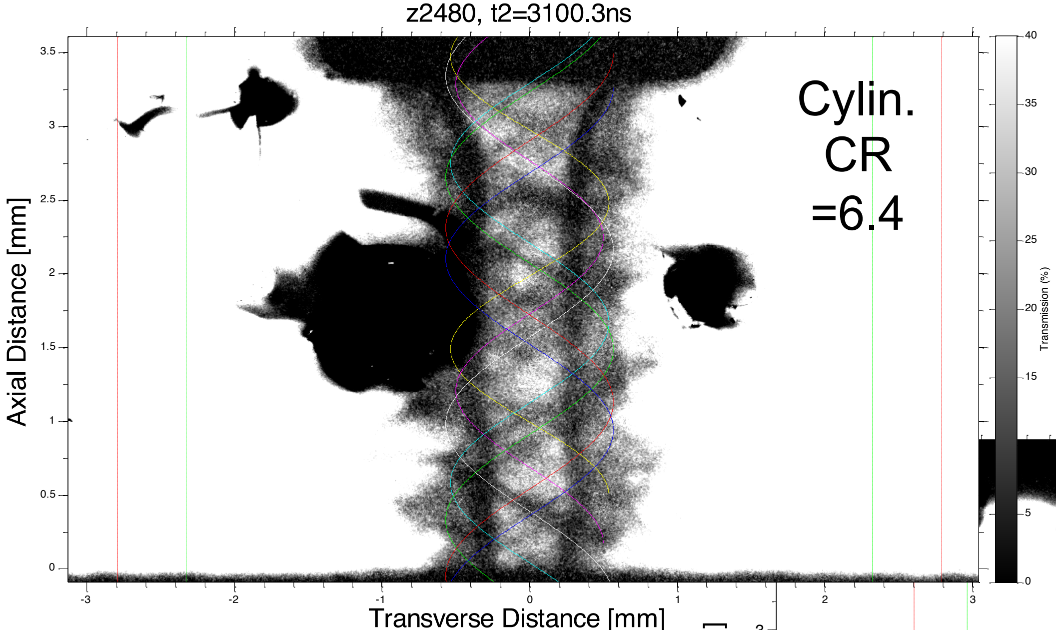
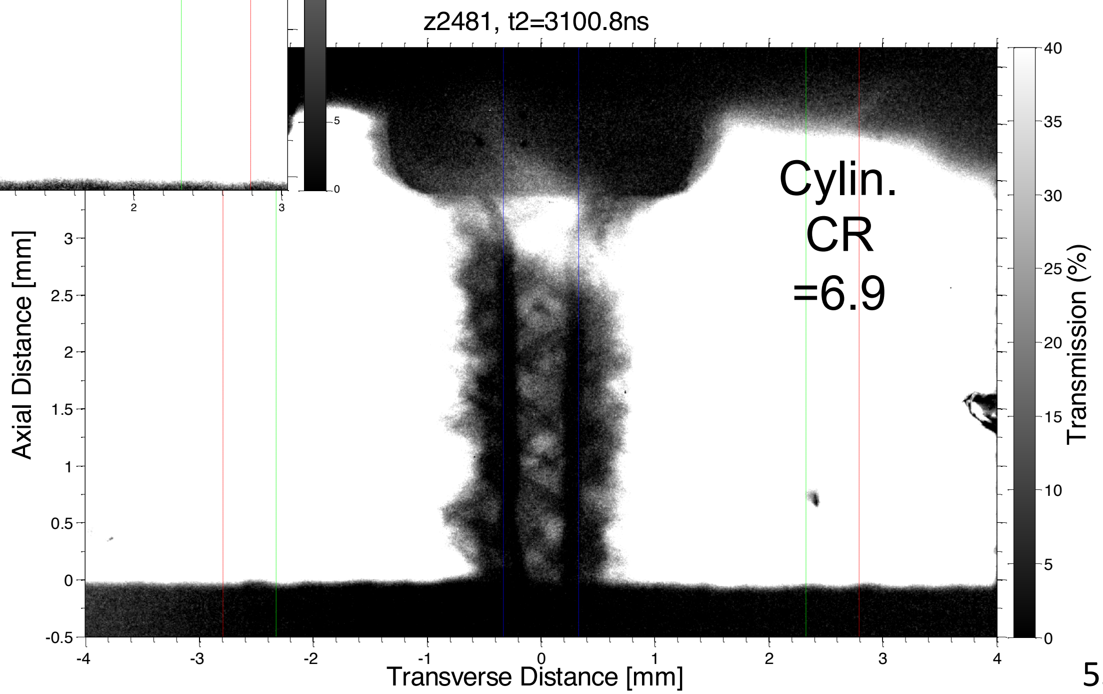


- Rather than cylindrically symmetric structures, we see helical structures
- Use of compressible electrodes mitigates edge jetting instabilities
- Magnetic field reduced multi-keV x rays associated with late-time instabilities

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

Though the opacity of the converging liners is significant, it is possible to see the inner boundary adjacent to the fuel, which looks reasonably good



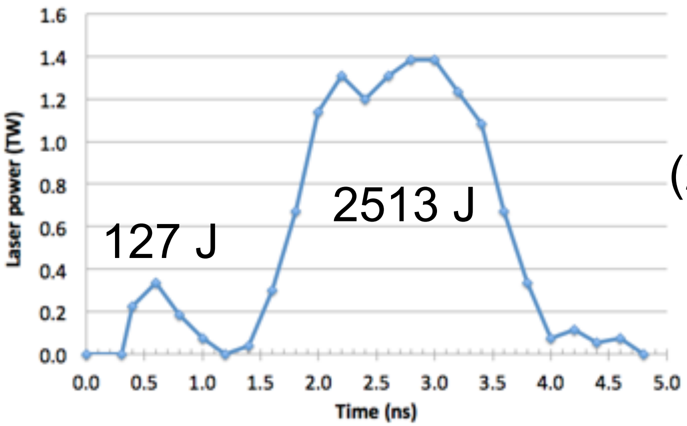


Same images plotted using 0-40% transmission range instead of 0-100%

T.J. Awe *et al.*, submitted to Phys. Rev. Lett.

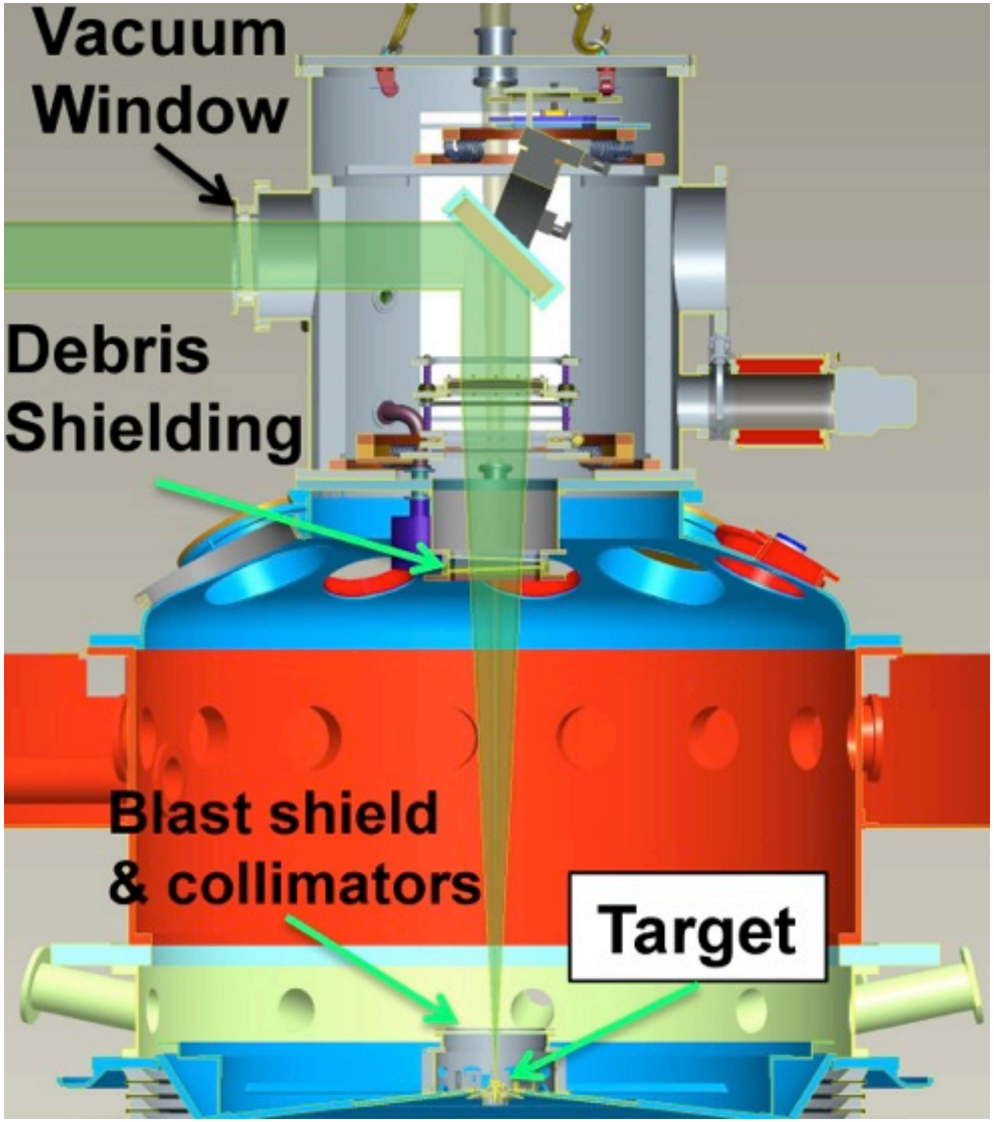
In August 2013 we commissioned a new vacuum final optics assembly to safely enable 2 kJ of laser preheating of fuel

Example pulse measurement



ZBL
2ω light
(2.64 kJ)

Prepulse vaporizes gas-containing foil; main pulse couples to DD fuel



Integrated shots on Z with both magnetization and preheat dramatically outperformed shots using the same target without both of these design elements

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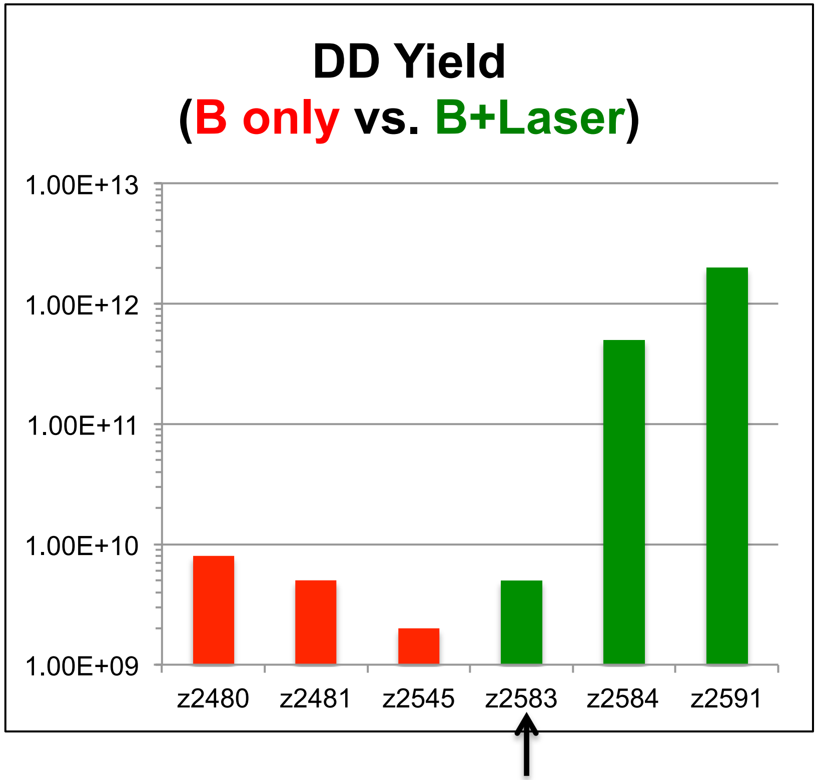
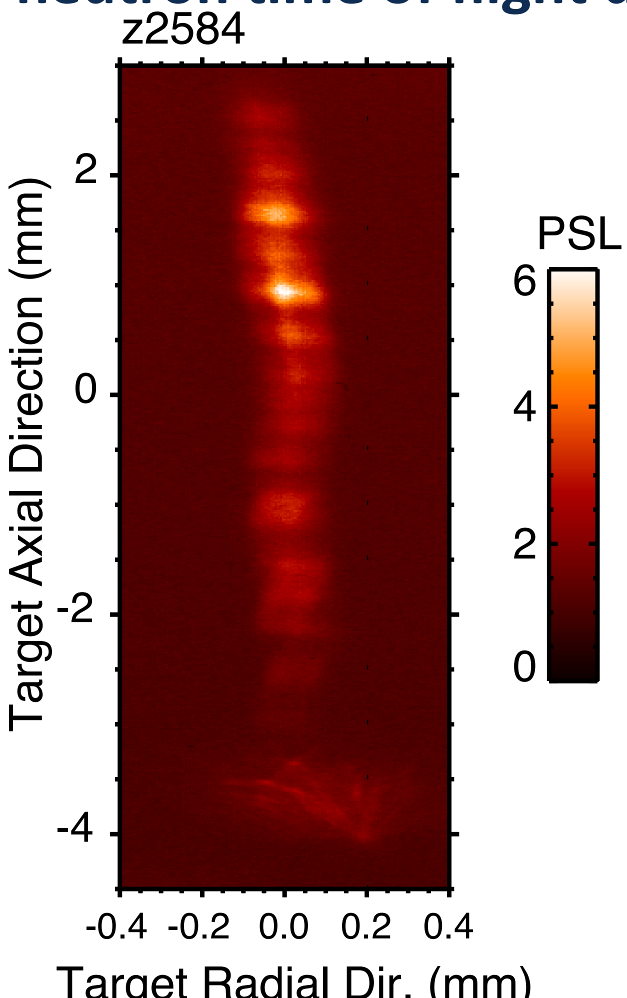
- Targets without magnetization or laser-heated fuel produced <1e9 DD yield (these shots included high-Z dopants that contributed to reduced yield)
- Targets that were magnetized but not laser-heated produced ~5e9 DD yield
- High yields were obtained in our first four tests using both magnetization and laser heating of the fuel
  - Z2584: 5e11 DD (2.45 MeV) +1.2e10 DT (14 MeV) neutron yield
  - Z2591: 2e12 DD (2.45 MeV) +5.4e10 DT (14 MeV) neutron yield

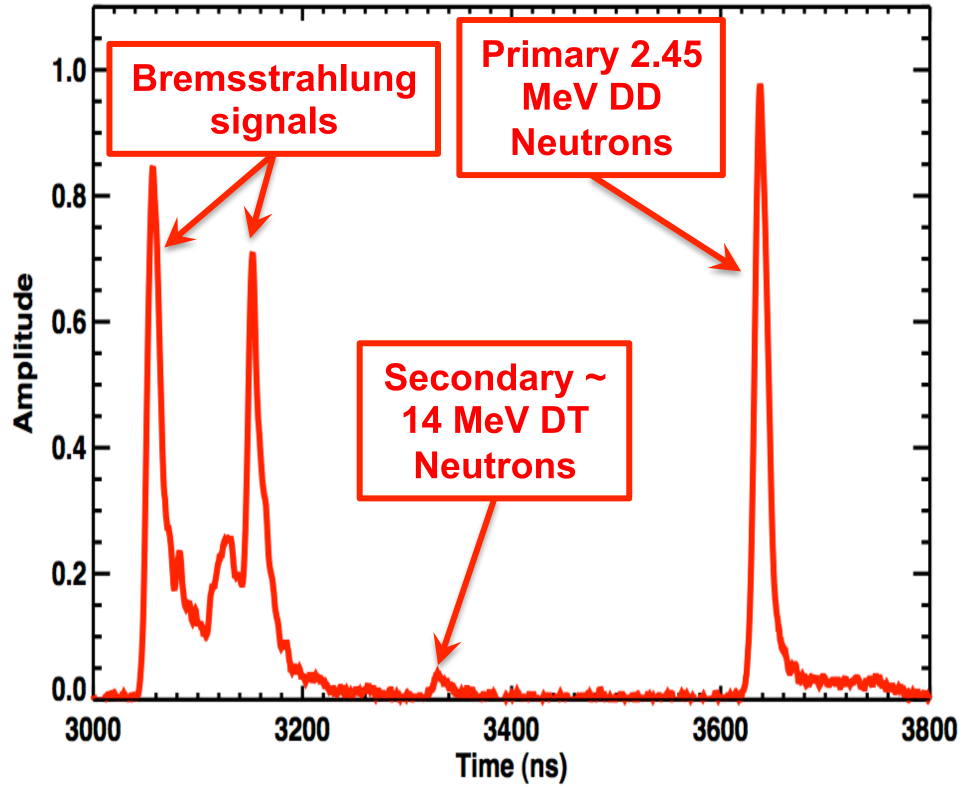


Z2583 result not fully understood. An additional shot (z2585) used fuel dopants for diagnostic purposes that were predicted to reduce the yield —it gave 2e9 DD

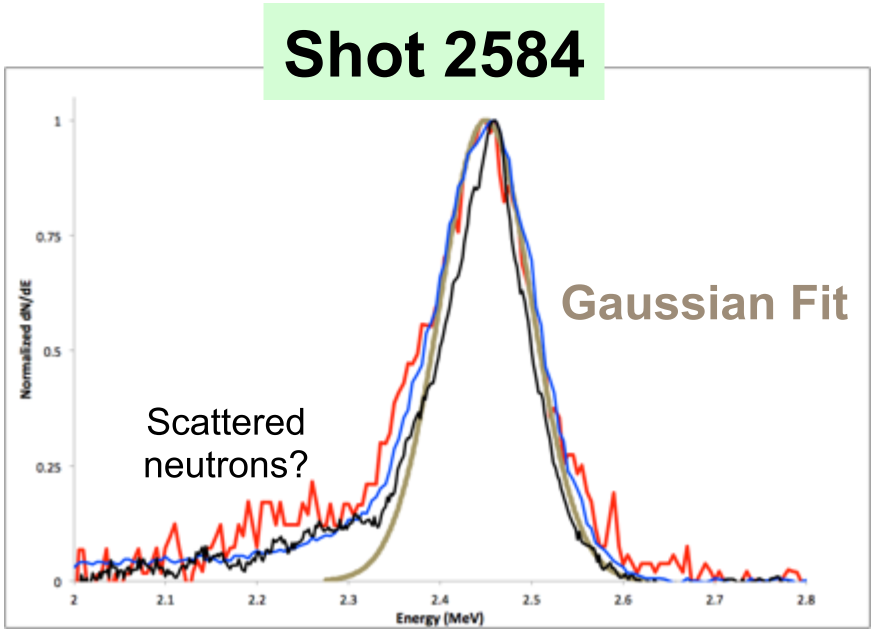
For z2584 (5e11 yield shot) we obtained x-ray imaging and neutron time of flight data

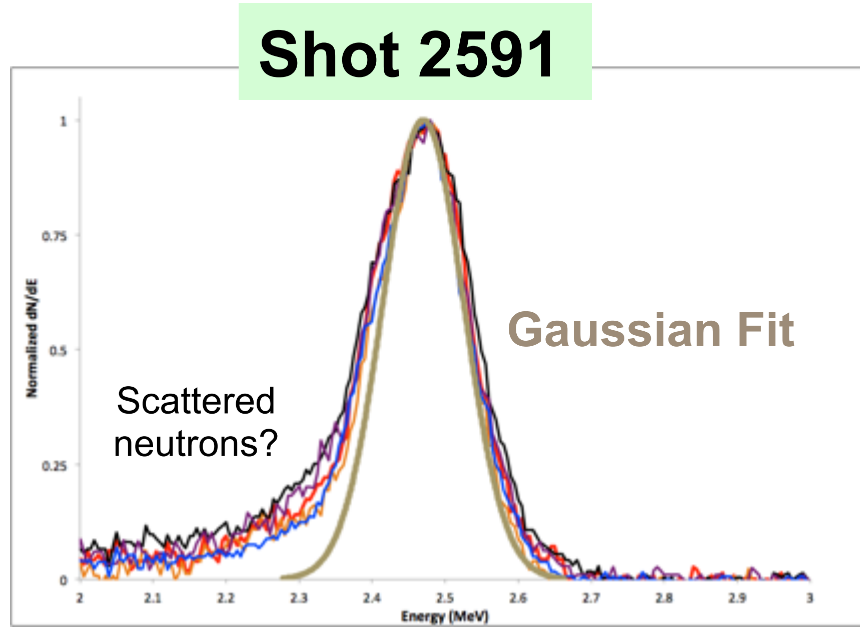


X-ray Image @3.1 and 6.2 keV is ~140 microns wide



The DD peaks on the nTOF instruments can be used to infer ion temperatures. Fits to the spectra from the high-yield shots suggest 2.5 keV (z2584) and 3.5 keV (z2591) ion temperatures.





Normalized neutron energy spectra from detectors at 3-5 different distances and 2 different pinch viewing angles are overlaid

Ion temperatures of 3.5 keV on z2591 agree with electron temperatures from x-ray spectroscopy

Our path forward for the next few years involves increasing our understanding and enhancing capabilities

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Improve experimental capabilities to support ~100 kJ DT yield experiments on Z

- Increase current from 20 MA to 25 MA
- Increase Bfield from 10 T to 30 T
- Increase laser energy from 2 kJ to >6 kJ
- Begin designs for DT capabilities on Z

Understand the physics of target magnetization and fuel preheating (on Z, Ω, Z-Beamlet)

- Understand and measure efficacy of magnetic flux compression by the liner implosion (e.g., Nernst effect)
- Understand the efficacy of heat loss suppression (Braginskii transport valid?)
- Understand laser-plasma coupling efficiency and dynamics

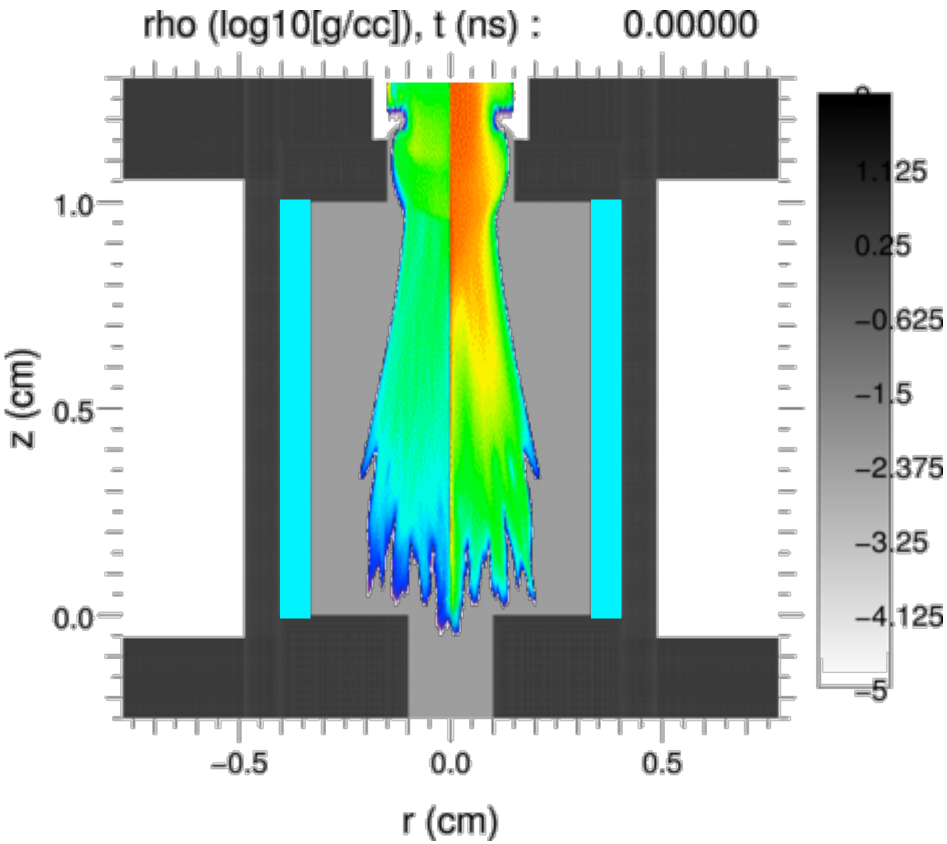
Continue to advance our understanding of liner implosions

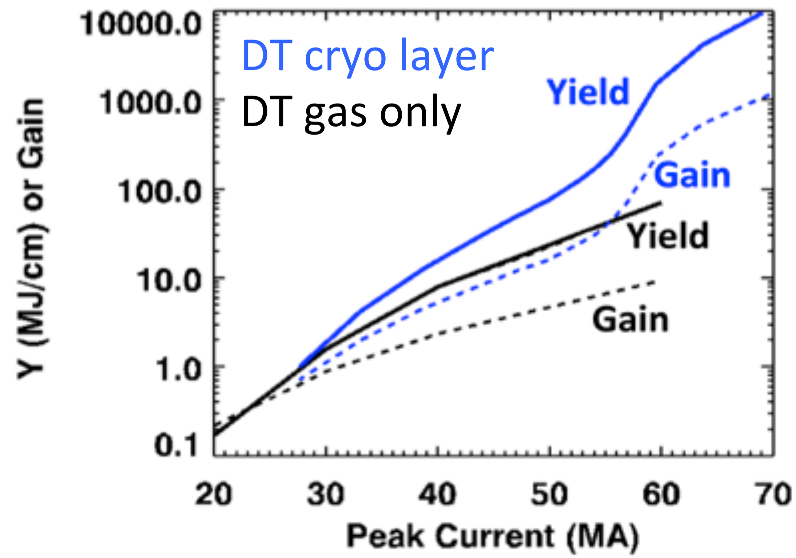
- Have a large database of radiography-based instability studies with images up to convergence ratio of 8
- Will begin working on deceleration instability studies in 2014
- Developing methods to measure liner implosion symmetry

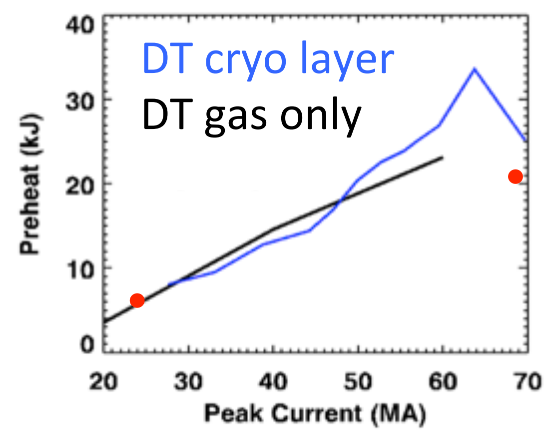
Performing and diagnosing integrated implosions

- Apply diagnostics to understand stagnation conditions
- Study the implosion performance with changing inputs
- Begin exploring non-laser-based methods for preheating to couple >10 kJ

Calculations suggest there is a path to much larger yields with more current



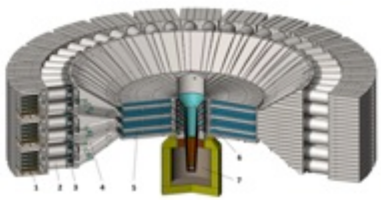


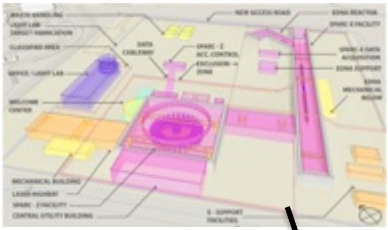


An intermediate regime exists where the B_z field is

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

Our long-term vision is to establish a compelling argument that pulsed power ICF can achieve 1 GJ/shot



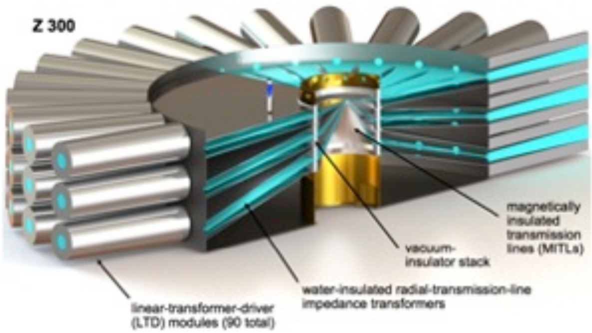


2019: Baikal operations begin

SPARC-Z operations begin

CD-0 for SPARC-Z High-Yield Facility

Z-300 demonstrates ignition



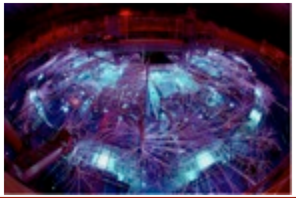
Z-300 operations begin

Review of Ignition on Z-300; CD-0 for Z300

Demonstrate LTD module prototypes (e.g., radiography)

2015: National ICF program review

2013: First integrated tests of new MagLIF idea on Z



Backup

Precision, early-time data allows detailed analysis of perturbation growth from electrothermal instabilities

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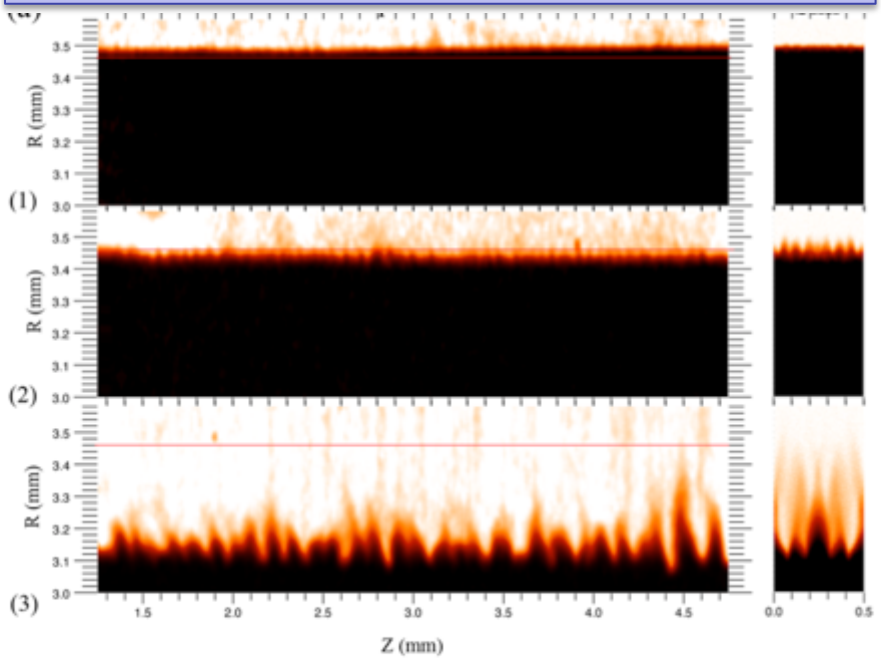
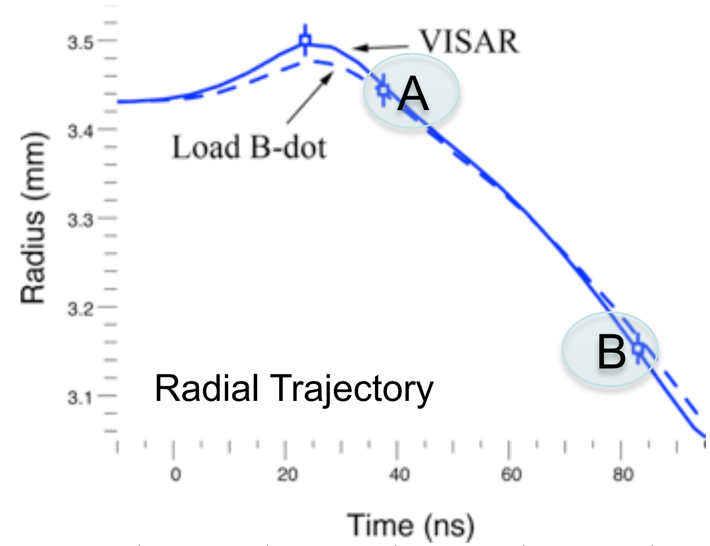
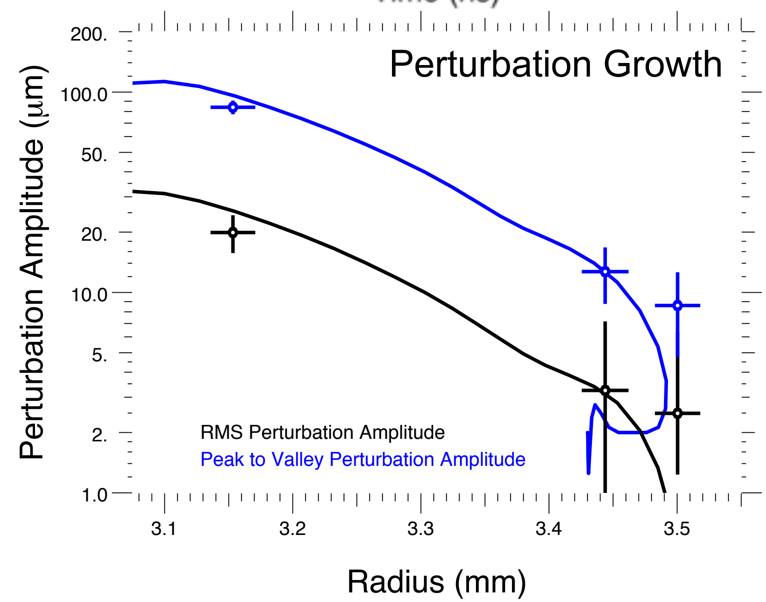
Experimental (left) & simulated (right) radiographs







Perturbation Growth Comparison

Time	Est. MRT (λ=100 μm)	$h=0.06Agt^2$	Observed
A	0.36 μm	6.2 μm	13 ± 7 μm
B	24 μm	41 μm	80 ± 7 μm

*K.J. Peterson *et al.*, Phys. Plasmas (2012); K.J. Peterson *et al.*, Phys. Plasmas 20, 056305 (2013).

Simulations predicted that we could mitigate the impact of the electrothermal instability by tamping out the density variations—this was confirmed experimentally

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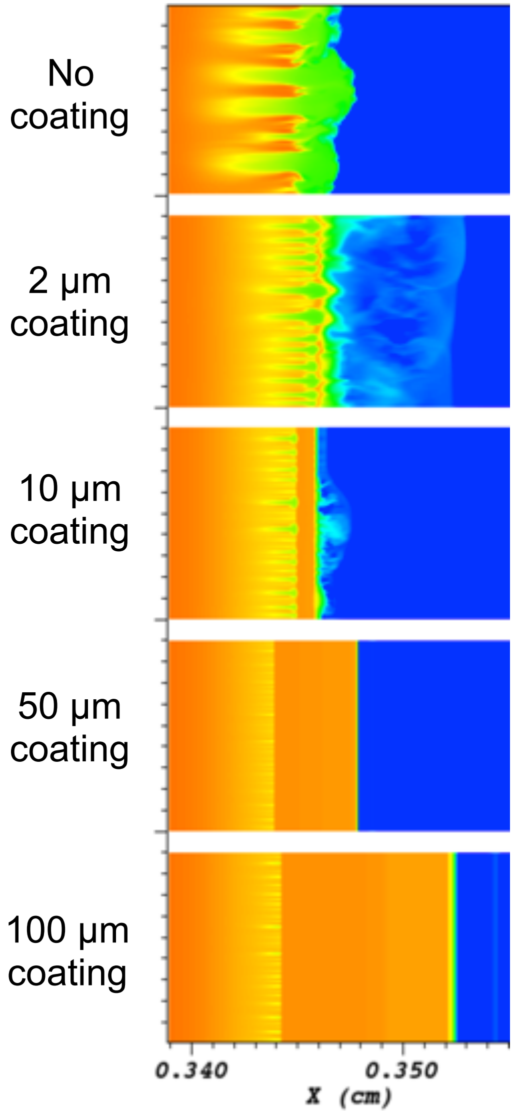

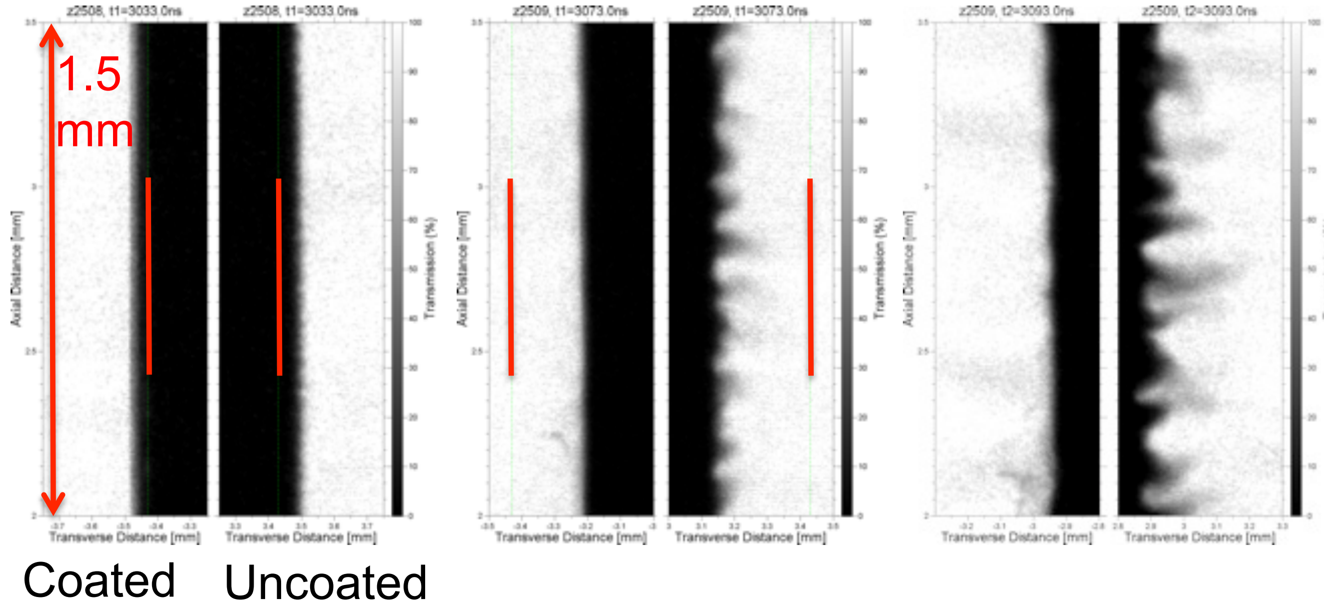

- No ETI growth in plastic coating
  - Carries very little current
  - Theoretically ETI Stable (resistivity decreases with increasing temperature)
- Coating does not appear to affect linear ETI growth of temperature perturbations, but it does significantly tamp down the mass redistribution

K.J. Peterson *et al.*, submitted to Phys. Rev. Lett.