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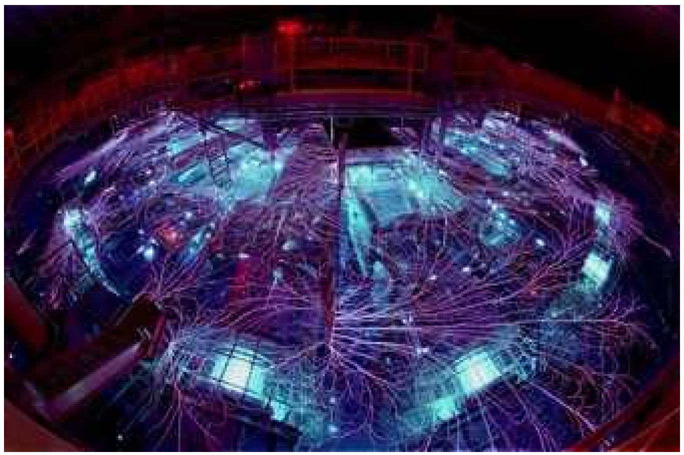
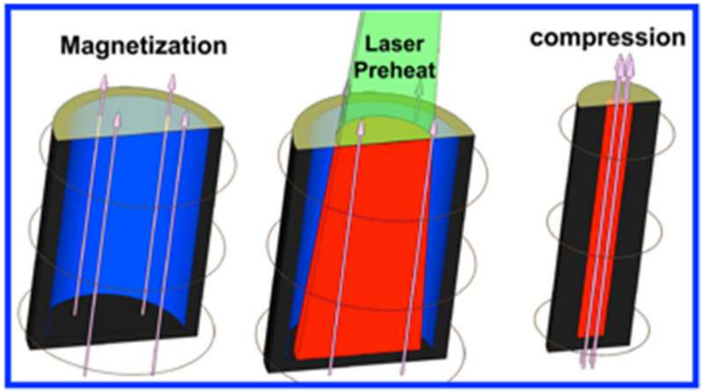


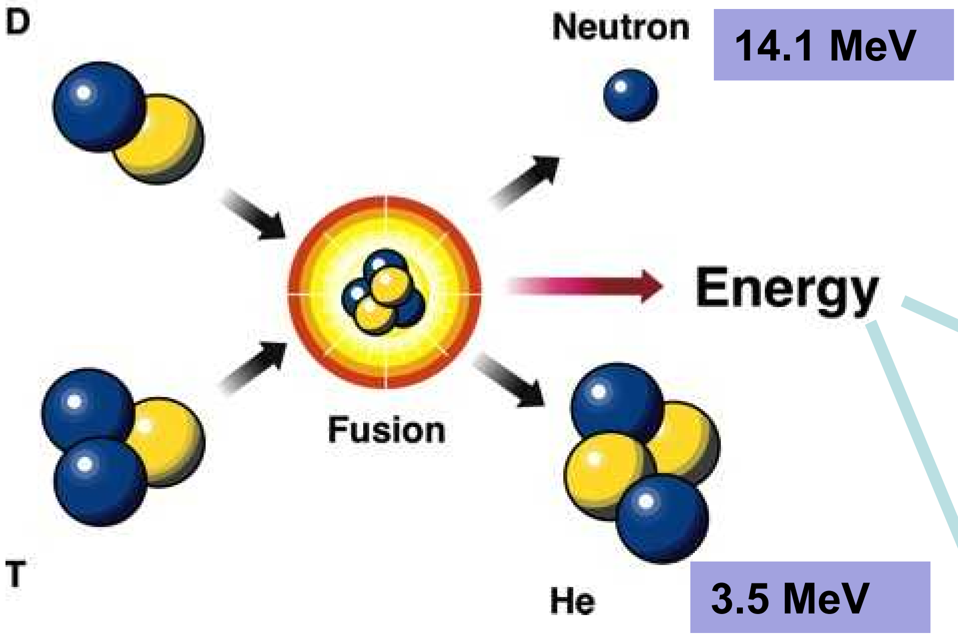


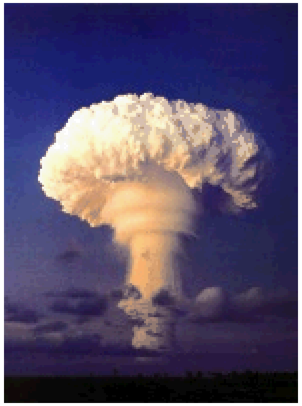
Recent Progress in Inertial Confinement Fusion research

Mark C Herrmann
Pulsed Power Sciences Center
Sandia National Laboratories

March 19, 2014

The Fusion of 1 gram of Deuterium (D) and Tritium (T) results in the release of 340 GJ* of energy





Near term: National Security (Stockpile Stewardship (SSP) and avoid "technology surprise")

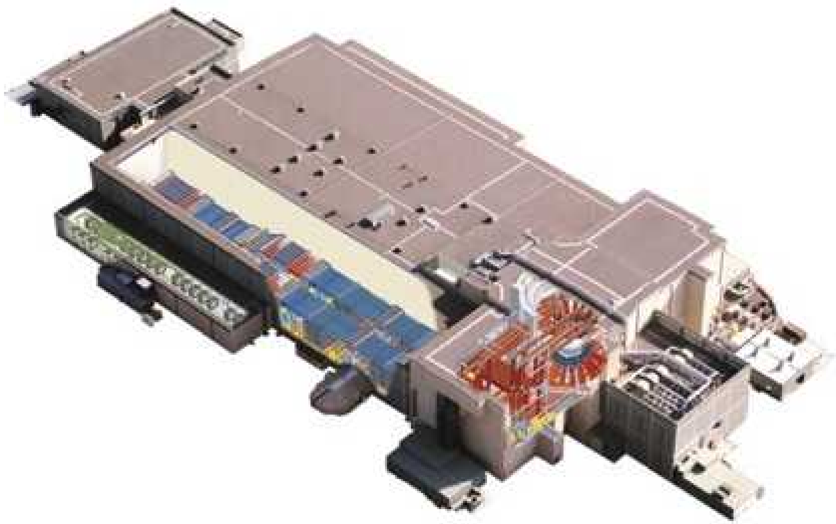
~0.04% of DT mass converted into energy

***340 GJ ~ 80 tons of TNT**

Longer term (~multiple decades) Inexhaustible "environmentally friendly " energy

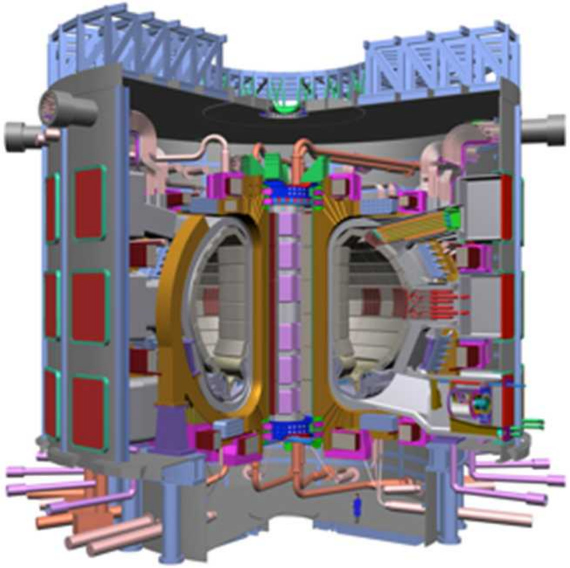
All fusion approaches require ≥ 50,000,000 ° K, and there are two main approaches to plasma confinement

Inertial Confinement Fusion (ICF)
(United States dominant)



- Confinement: Plasma Inertia
  - Confinement time: ~ 10^{-10} sec
- Plasma Pressure: 5-300 Gbars
- Mission : National Security
  - Sponsor: DOE-NNSA
- Experiments: ongoing
- Capital cost: ~$3.5B+
- Operating cost ~$400M/yr

Magnetic Confinement Fusion (MFE)
(Europe and Asia dominant)



- Confinement: Magnetic Fields
  - Confinement time: ~ secs
- Plasma Pressure: ~1-3 Bars
- Mission: Energy
  - Sponsor: International
- Experiments: ~2030 (DT)
- Capital cost: ~$40-60B (US ~ $4.0-6.0B)
- Operating cost (est.) ~$2-3B/yr

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

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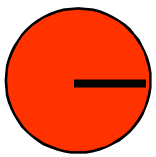
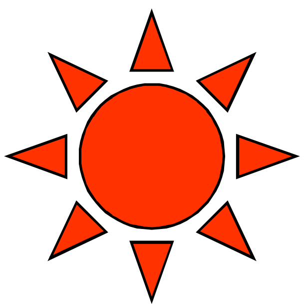


ρ, R, T

- 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?

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



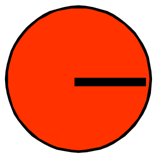
- The fractional burn up of the DT (for small burn up) is:

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

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

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

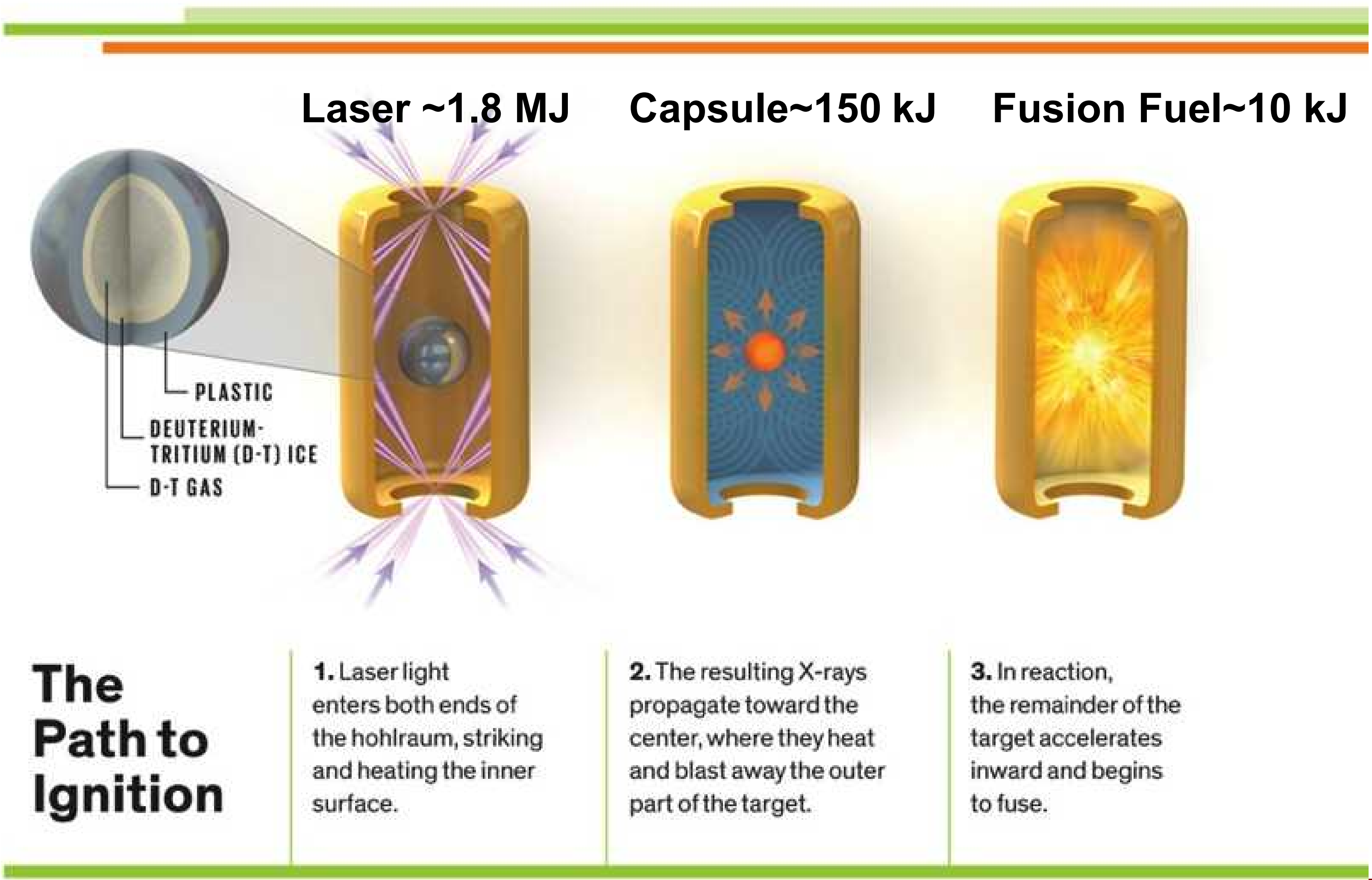
$E_{NIF} \sim 15\,\mathrm{kJ} \Rightarrow P \sim 400\ \mathrm{GBar}$ $\qquad R \sim 30\,\mu\mathrm{m} \Rightarrow$ and $\rho \sim 130\,g/cm^3$

High velocity implosions can achieve these conditions


Cardinal
GOLDEN BEARS
Bruins
Stanford
CALIFORNIA
UCLA
Cal


NIF concentrates all the energy in a football stadium-sized facility into a mm3
Laser Specifications
192 Laser Beams
Energy ⇒ 1.8 MJ
Power ⇒ 500 TW

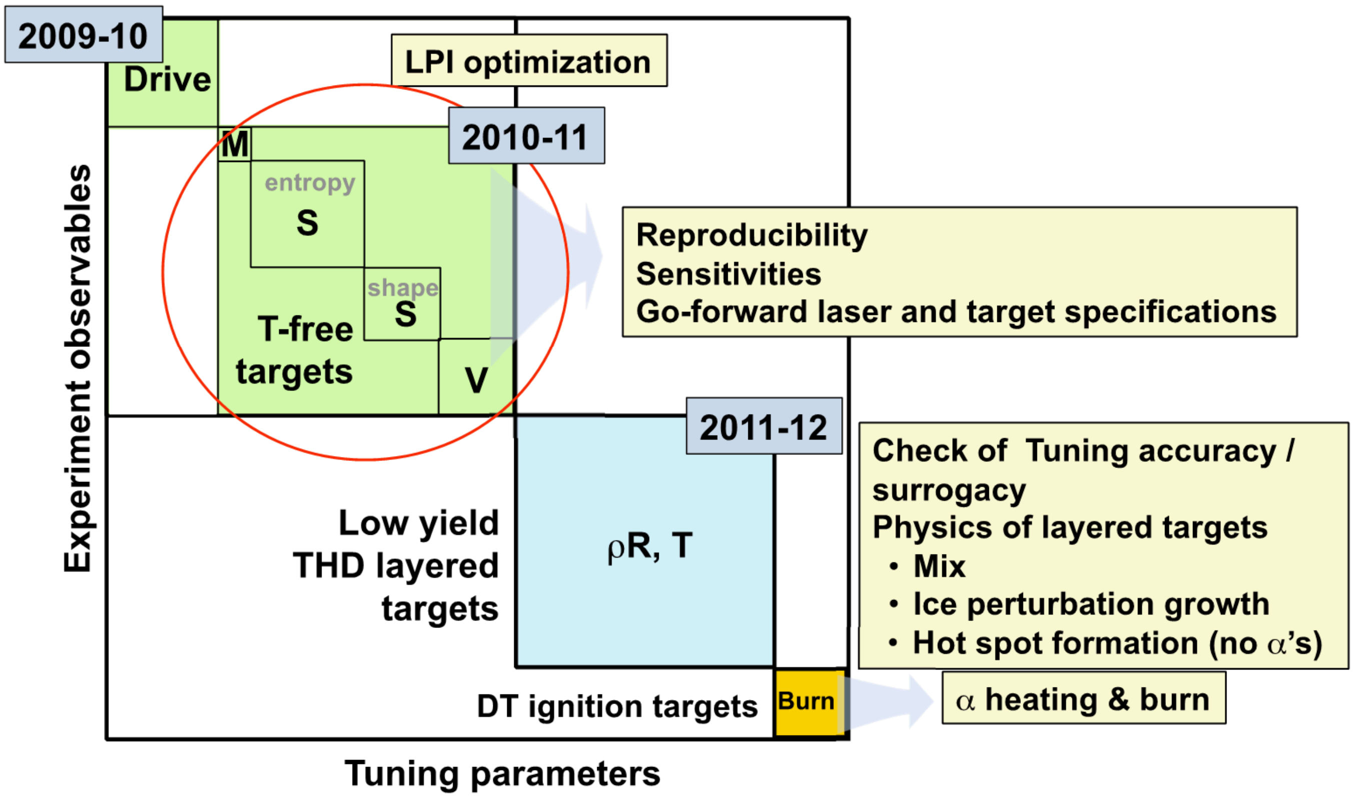
The NIF has focused on the indirect or x-ray driven approach to inertial confinement fusion



IEEE Spectrum (March 2013):

The National Ignition Campaign (2009-2012) pursued a "tuning" approach to achieving ignition

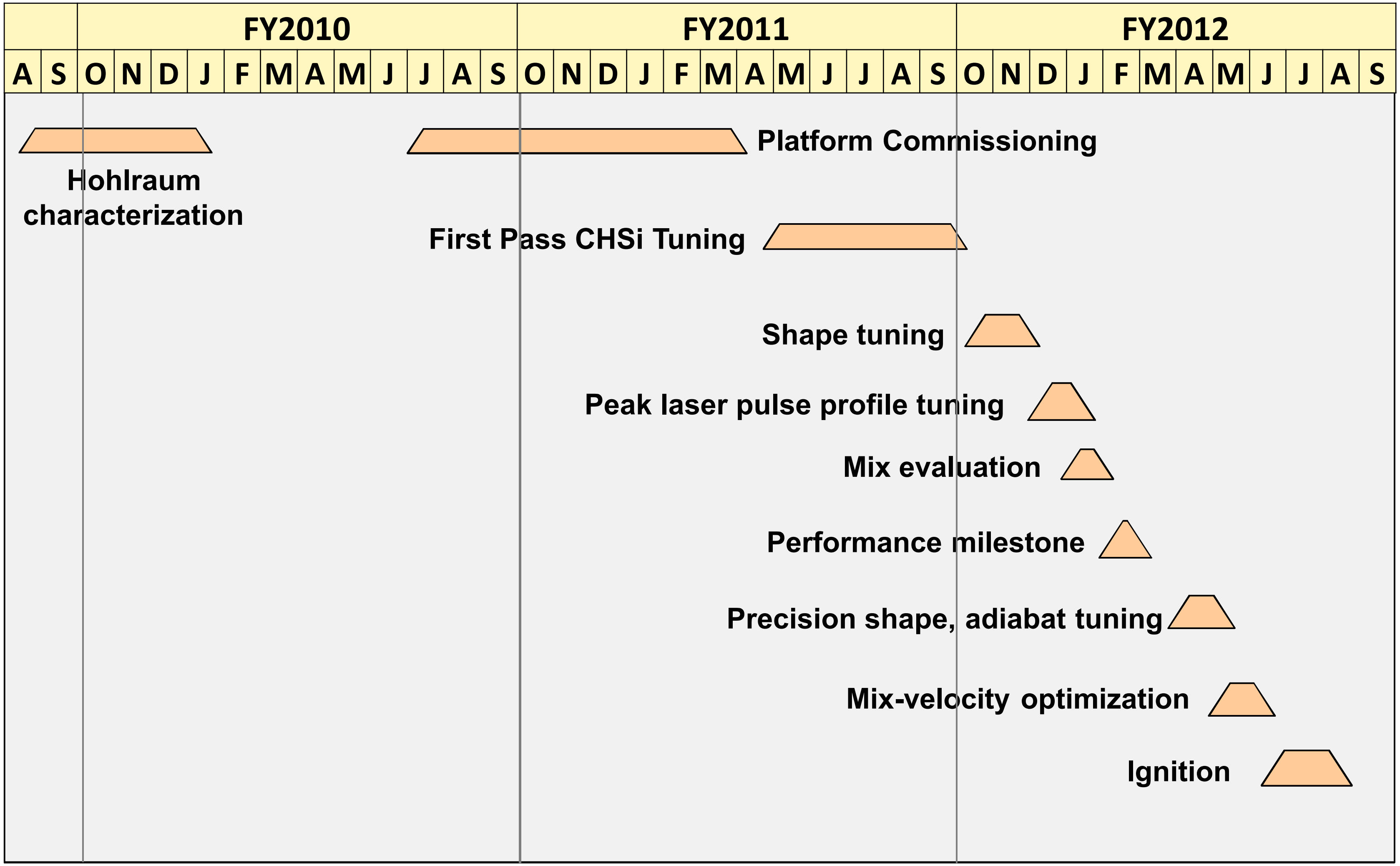
Tuning of mix, entropy, shape and velocity is prerequisite for improving THD/DT implosion performance



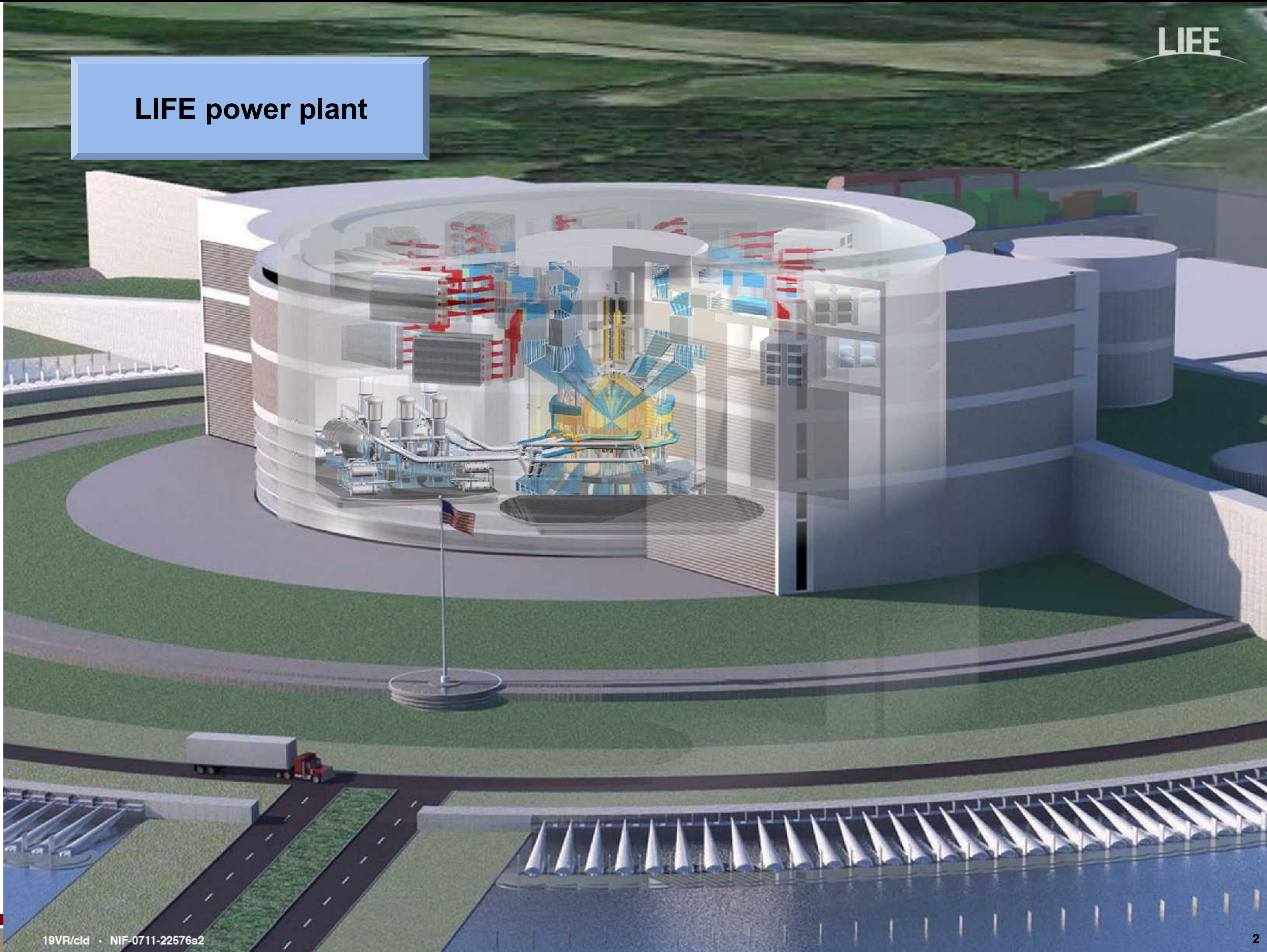
Belief that the codes Were right but could be "offset" from nature.

By "tuning" would be able to empirically achieve ignition

NIC Experimental Plan



LIFE power plant



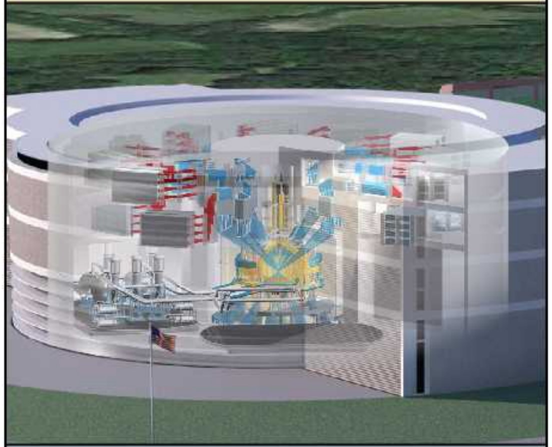
LIFE delivery timescale

National Ignition Facility

2009 - Facility complete
2012 - Ignition

Performance

Market Entry Plants



1,000 MW_{th}

2020's

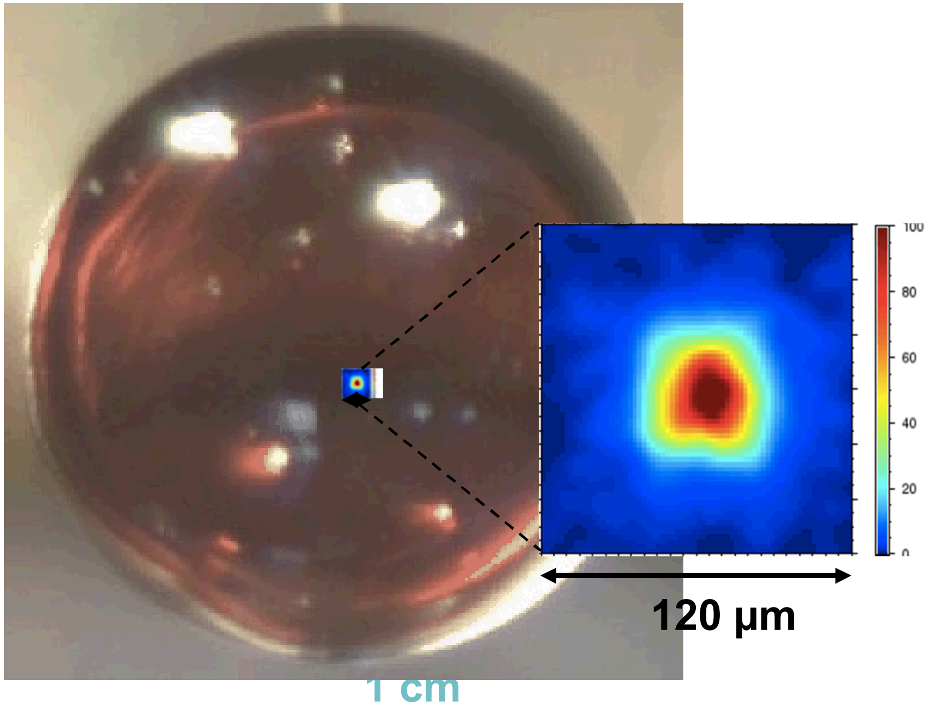
Integration

Mature LIFE Technology

400 MW to 1,600 MW_e

2030's

Achieving fusion ignition at this scale is very challenging



To achieve Fusion conditions with ~200 µg of DT requires:

- **Convergence ~40**
- **Implosion velocity ~3.7 x10^7 cm/sec**
  - **>0.1% speed of light**
- **Control and understanding of Rayleigh-Taylor instabilities**

Several discrepancies emerged between experiment and calculation

- **Lower drive than expected**
- **Greater growth of instabilities**
- **Lack of control over implosion symmetry**

The highest yield NIF experiment remained ~1000x below the yield needed for ignition at the end of the National Ignition Campaign and there was no clear understanding of what the cause was

There was significant fall out from the failure to achieve ignition, including significant program changes and a plan for a major review of the ICF program in FY15

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Nature editorial re: NIC

"The line between optimism and overselling is a thin one that can too easily be crossed."

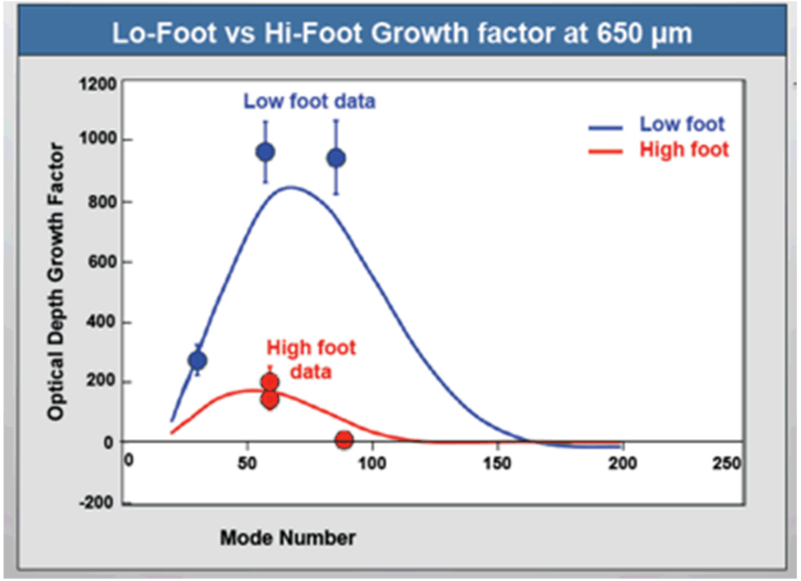
The New York Times | International Herald Tribune

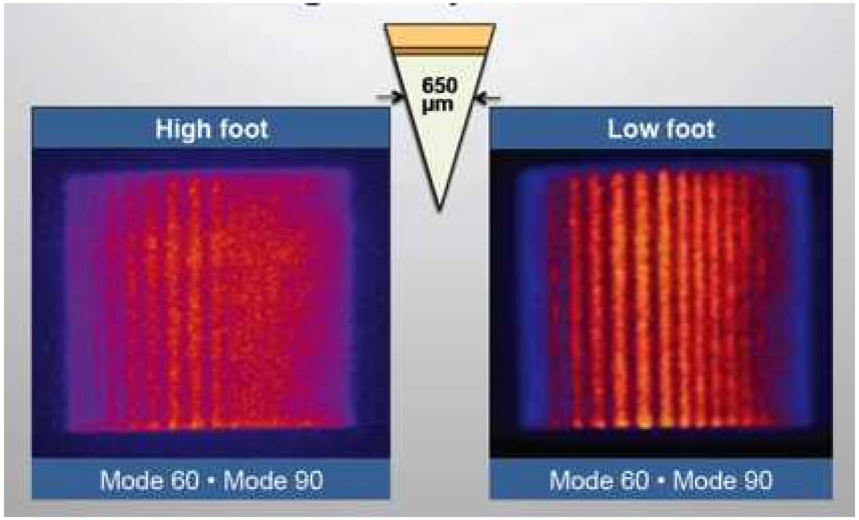
So Far Unfruitful, Fusion Project Faces a Frugal Congress

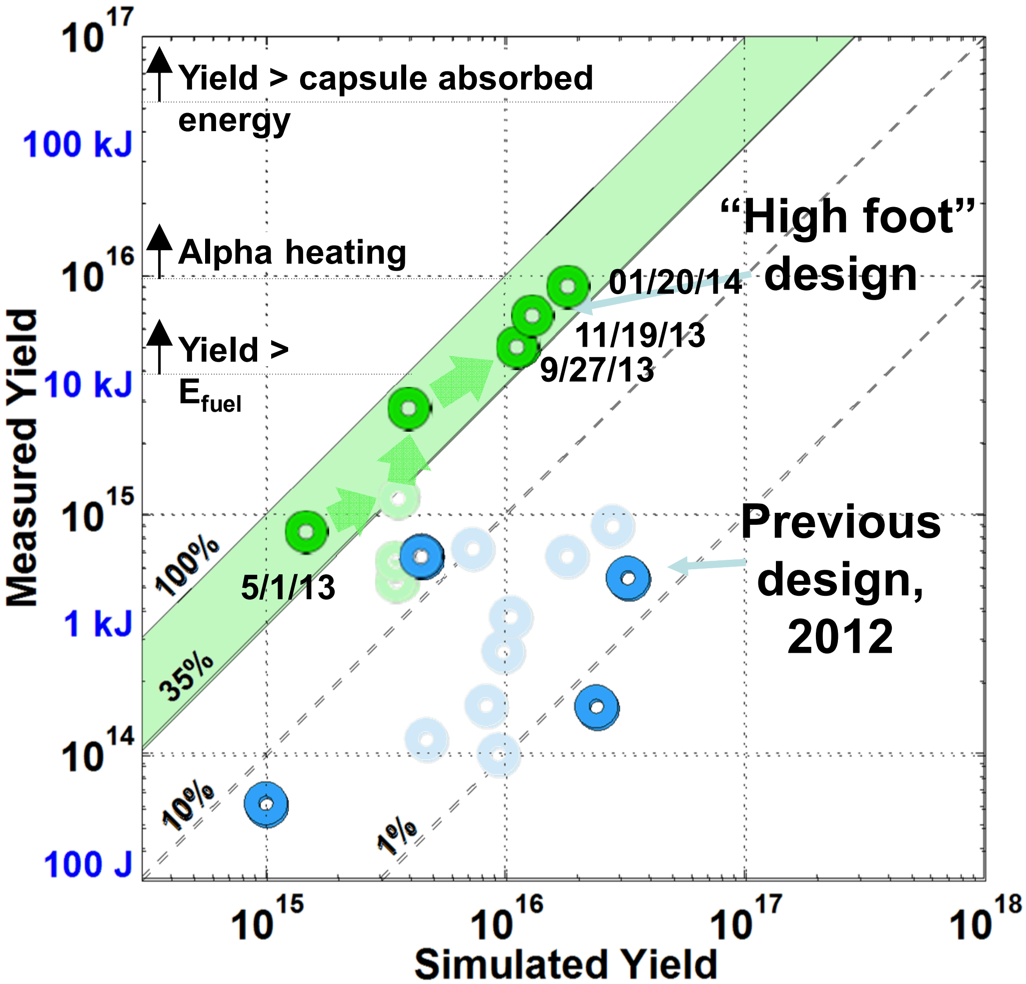
rials, and advanced ignition concepts.

The Committee remains concerned about NIF's ability to achieve ignition—the primary purpose of constructing the facility—by the end of fiscal year 2012 when the National Ignition Campaign ends and the facility is to transition to regular ignition operations and pursue broad scientific applications. The Committee directs NNSA

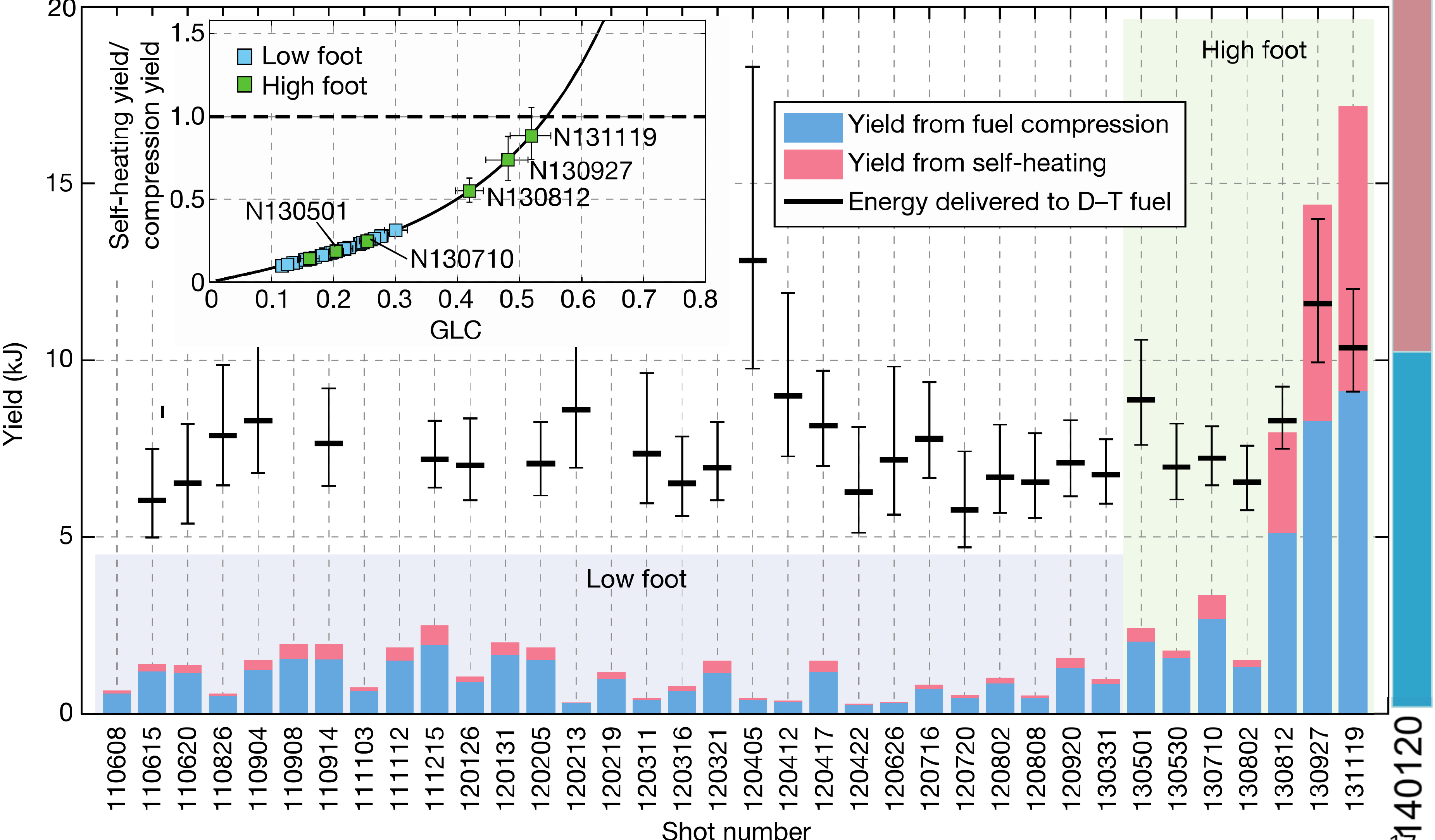
A new approach by a different group of scientists and new leadership have made rapid progress recently







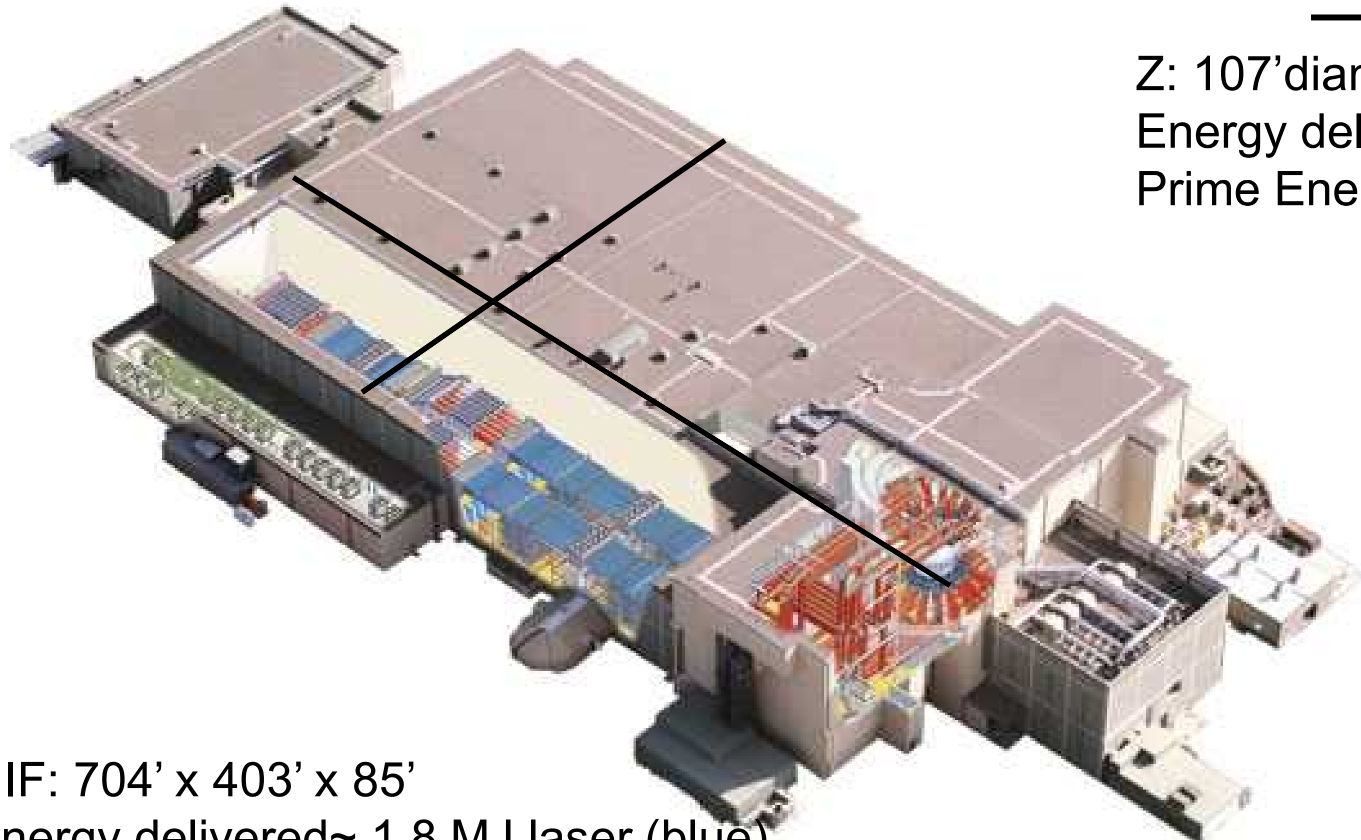
Recent results from NIF are exciting, they obtained more energy from fusion than was invested in the fusion fuel but ignition will require ~100x increase*



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

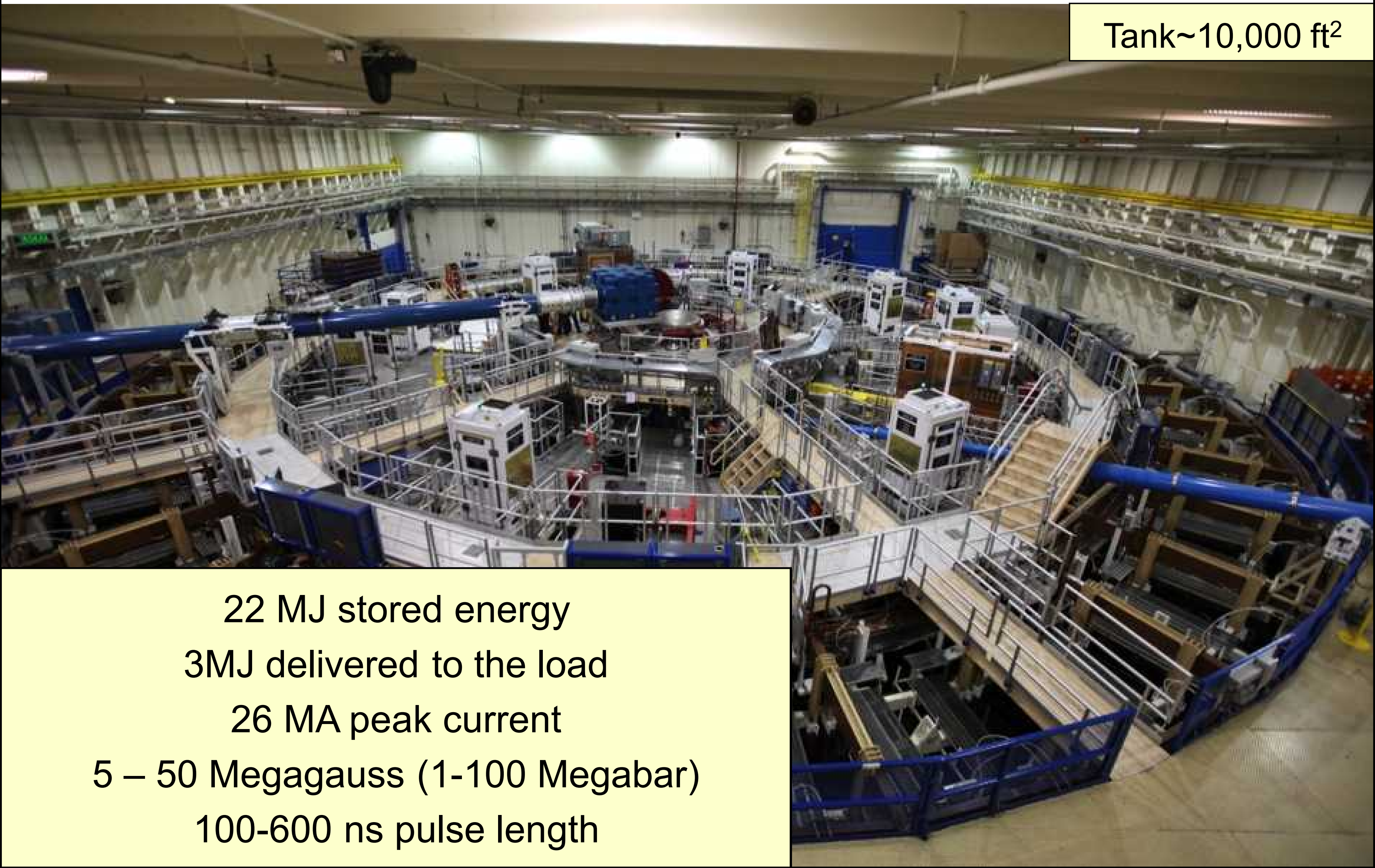


NIF: 704' x 403' x 85'
Energy delivered~ 1.8 MJ laser (blue)
Prime Energy ~ 370 MJ

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

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

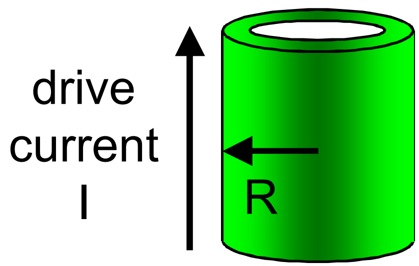
5 – 50 Megagauss (1-100 Megabar)

100-600 ns pulse length

Magnetically driven implosions can efficiently couple energy at high drive pressure

Magnetically-Driven Implosion

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

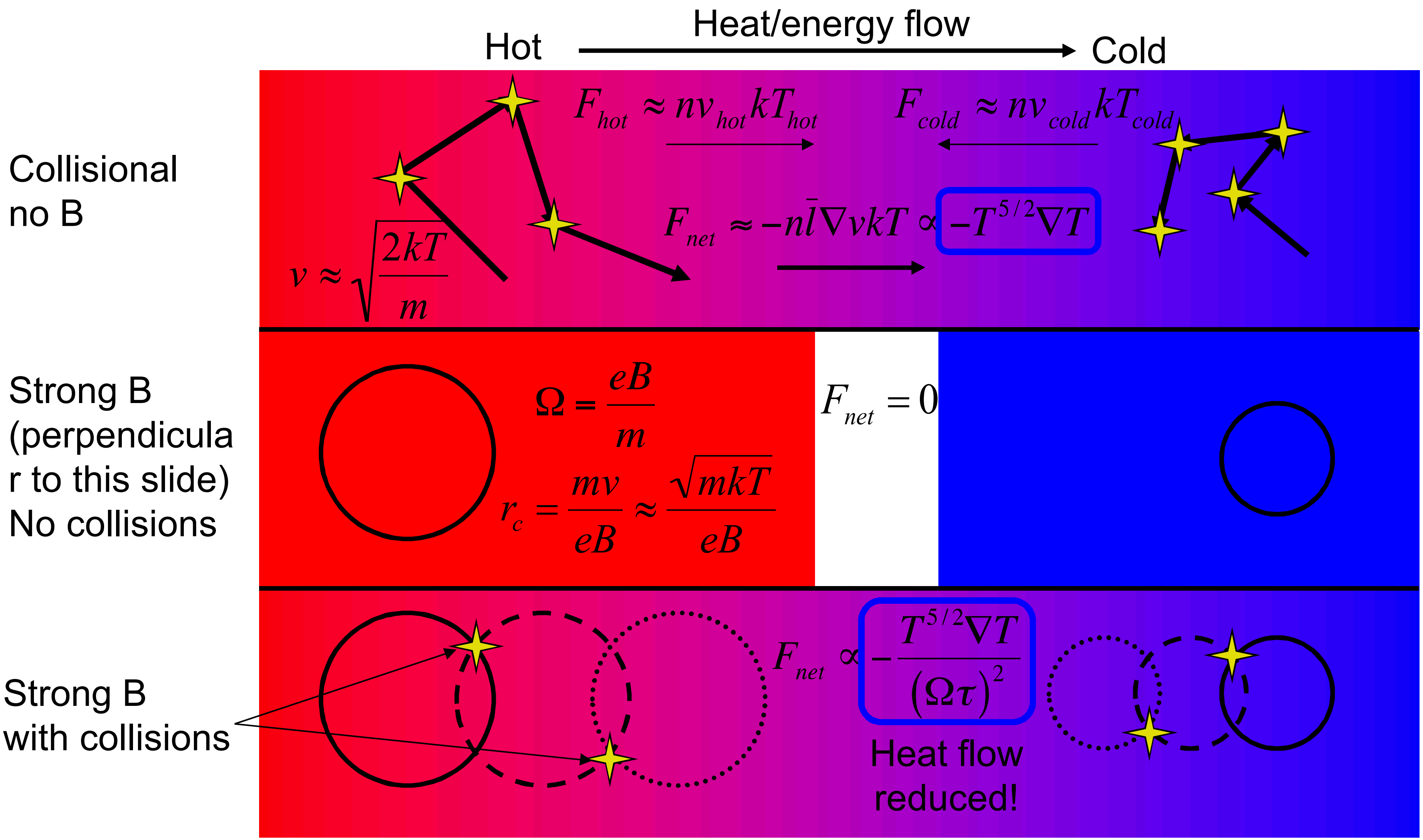


100 MBar at 26 MA and 1 mm

- 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

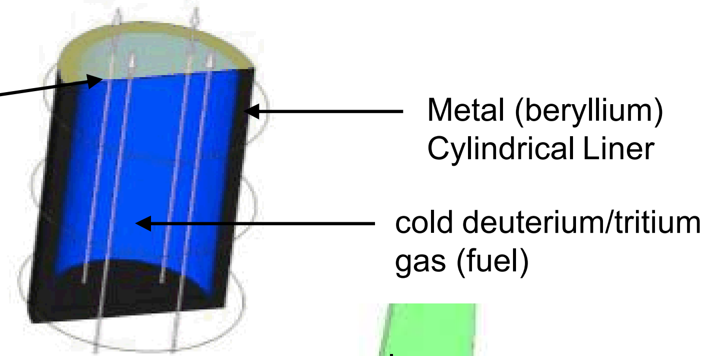
The presence of a strong magnetic field can strongly reduce heat transport and reduce the ρr and pressure needed for ICF



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

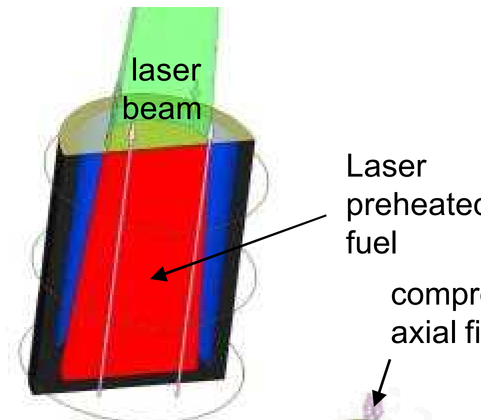
1. A 100-500 kG axial magnetic field

is applied before the implosion

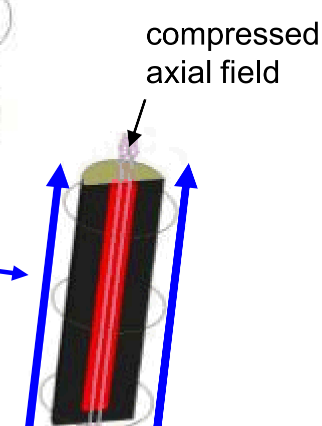


2. Z Beamlet can preheat the fuel to ~100 - 1000 eV

to reduce the compression and velocity needed



3. The Z accelerator can provide the drive current which generates an azimuthal drive field (pressure) to efficiently implode the thick liner at 50-100 km/sec and compress the axial field to 100 MG

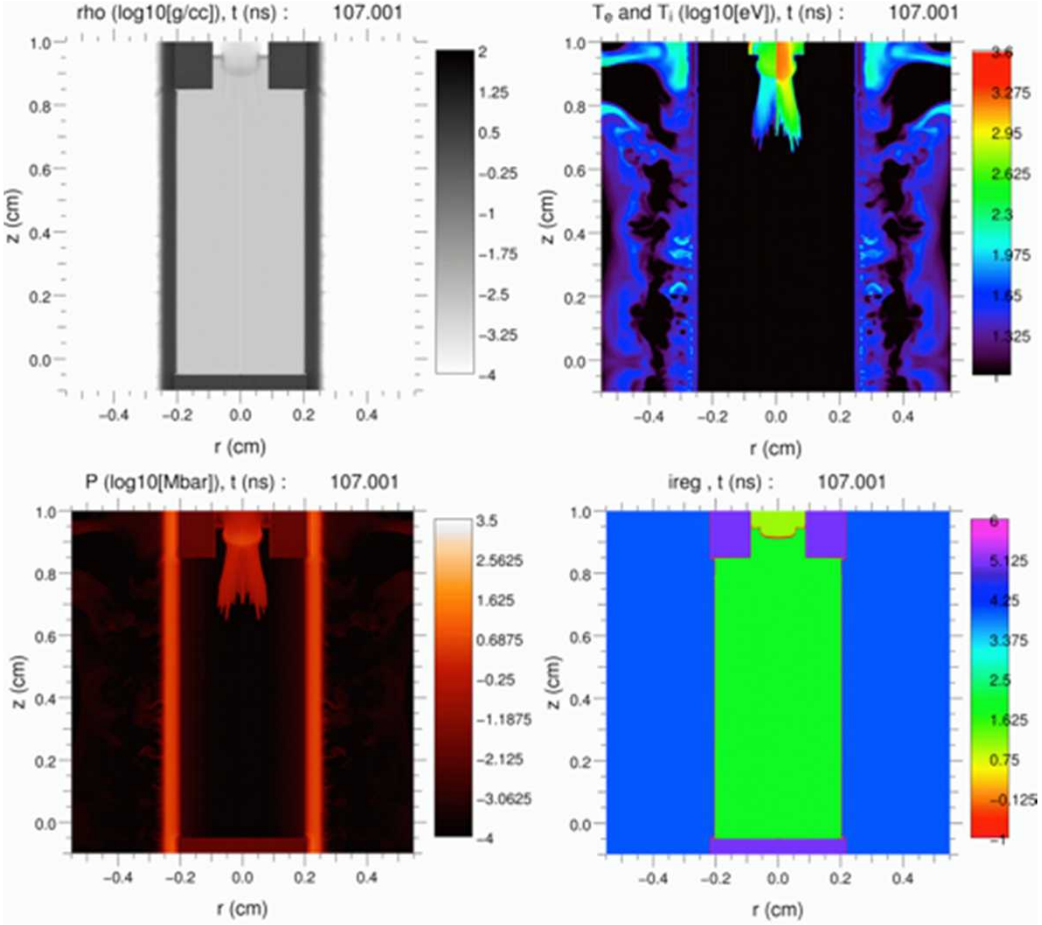


Simulations indicate fuel gain
(fusion energy out = energy deposited in fusion fuel) may be possible on Z

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

A recent HYDRA simulation of a MagLIF implosion illustrates the concept

Log Density Map **Log Temperature Map**



Log Pressure Map **Material Map**

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

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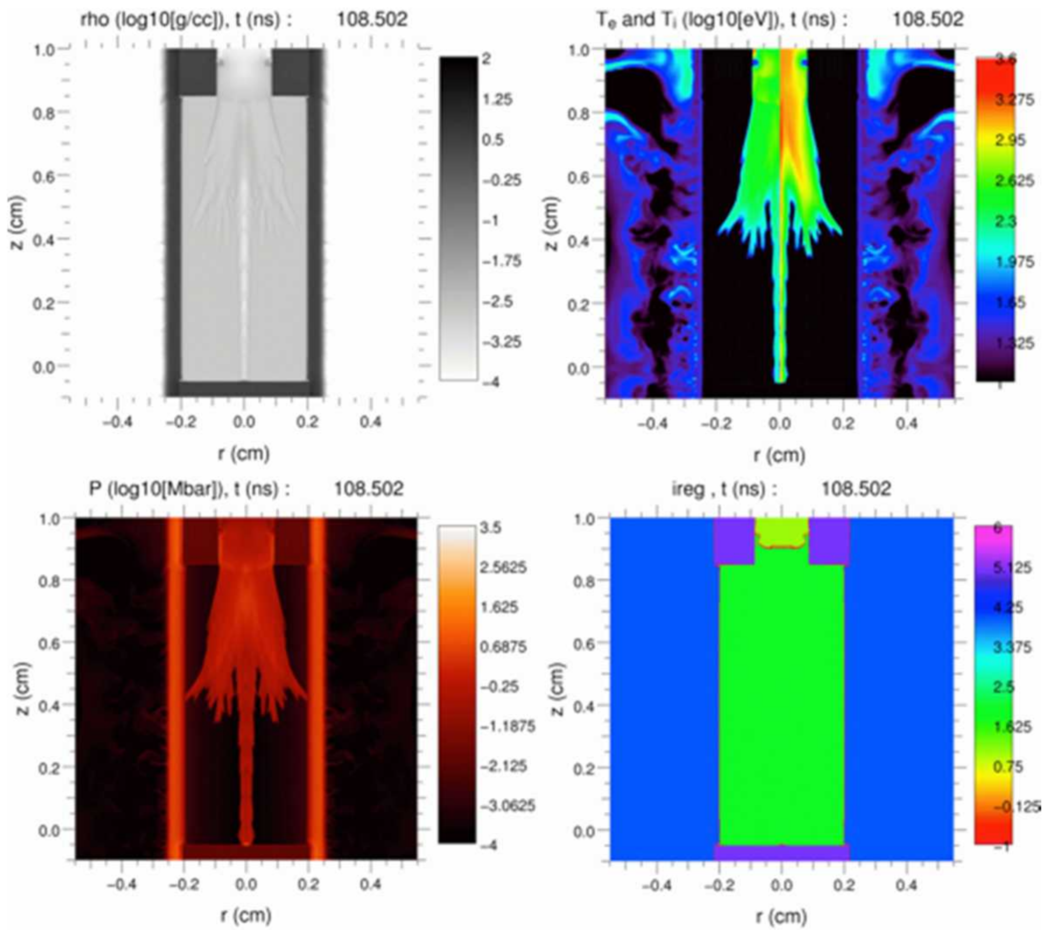
Log Temperature Map



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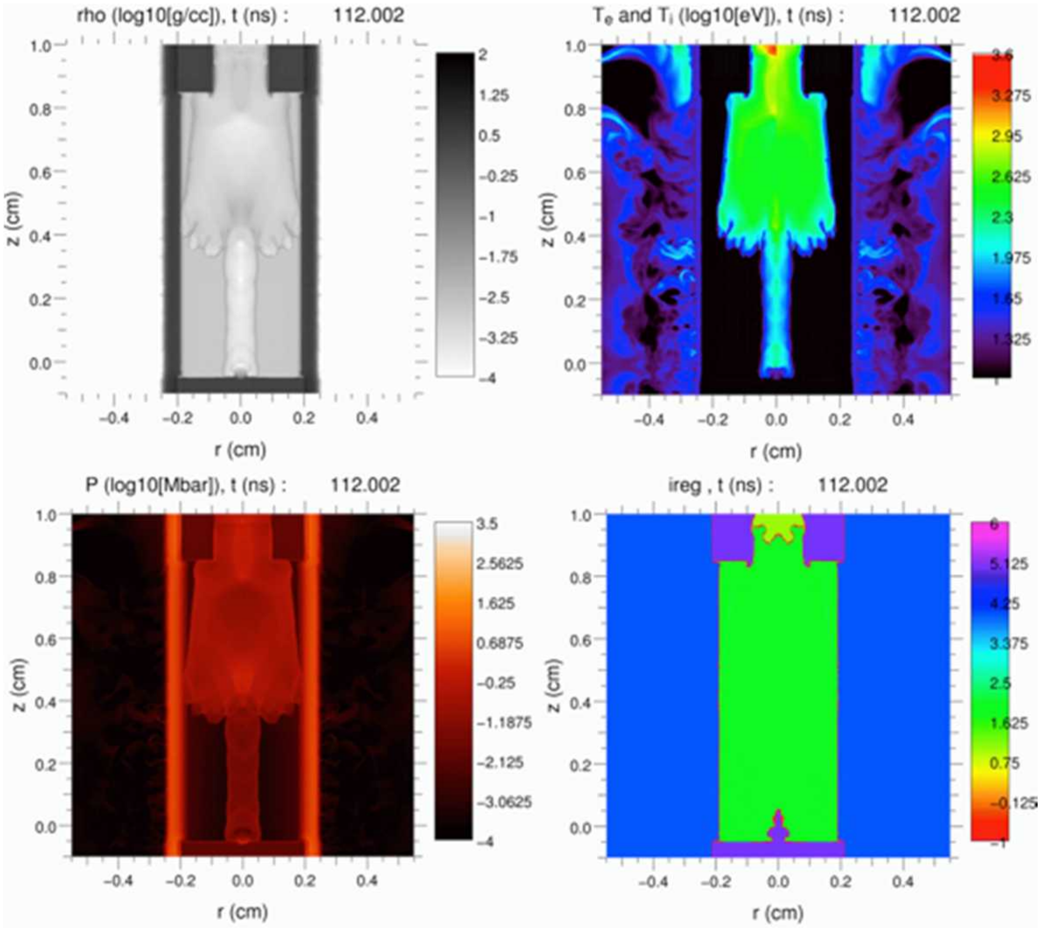

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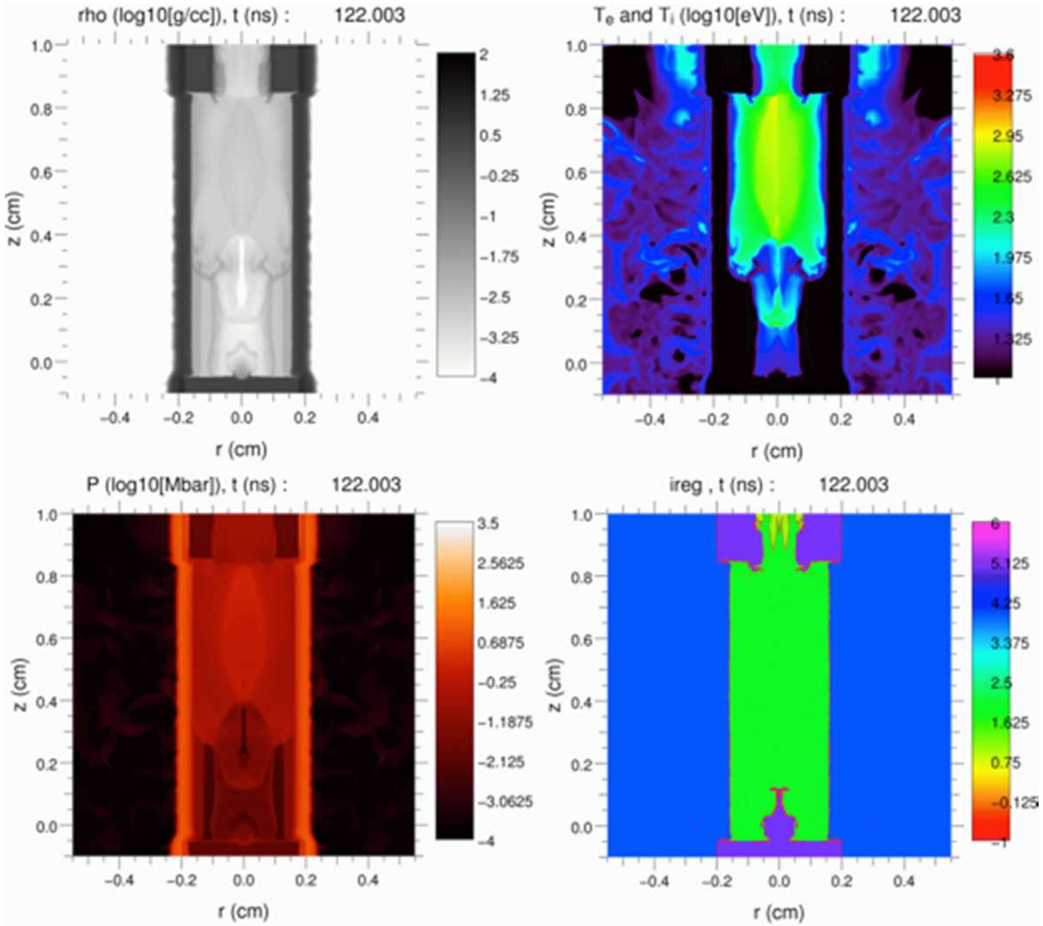

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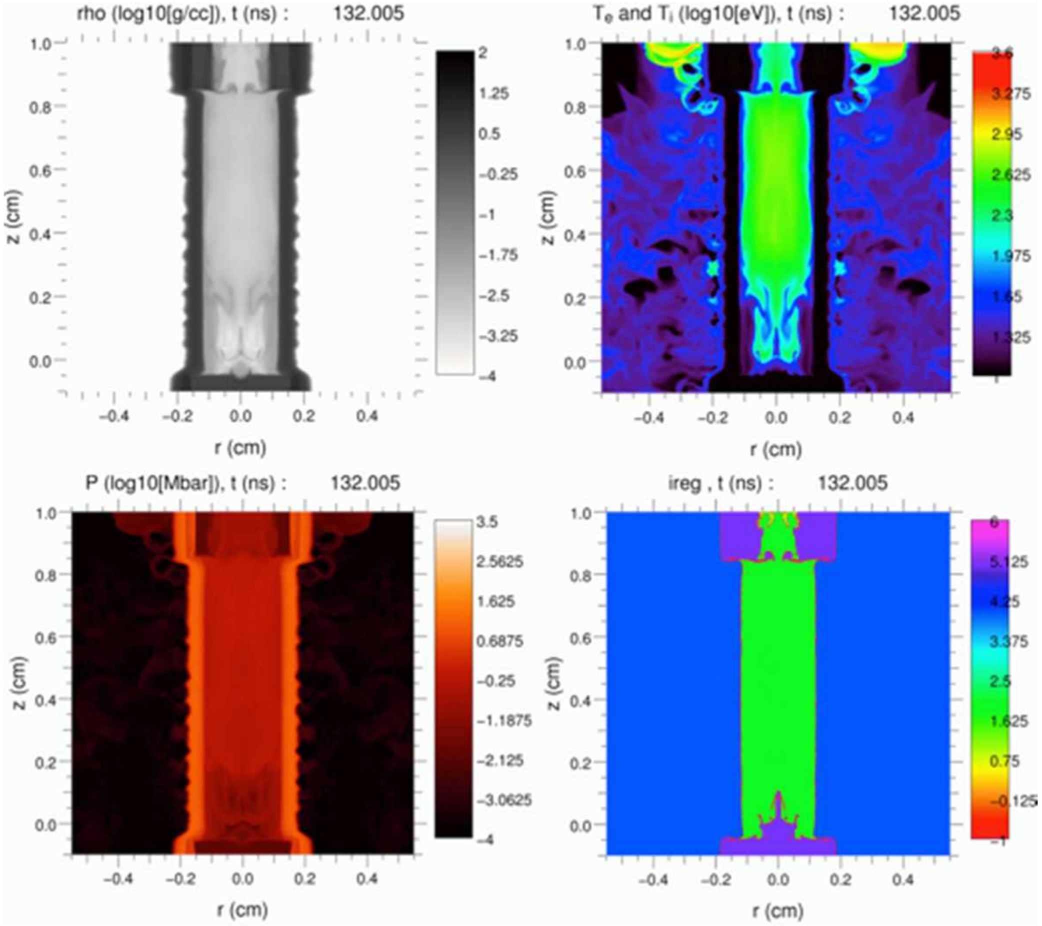

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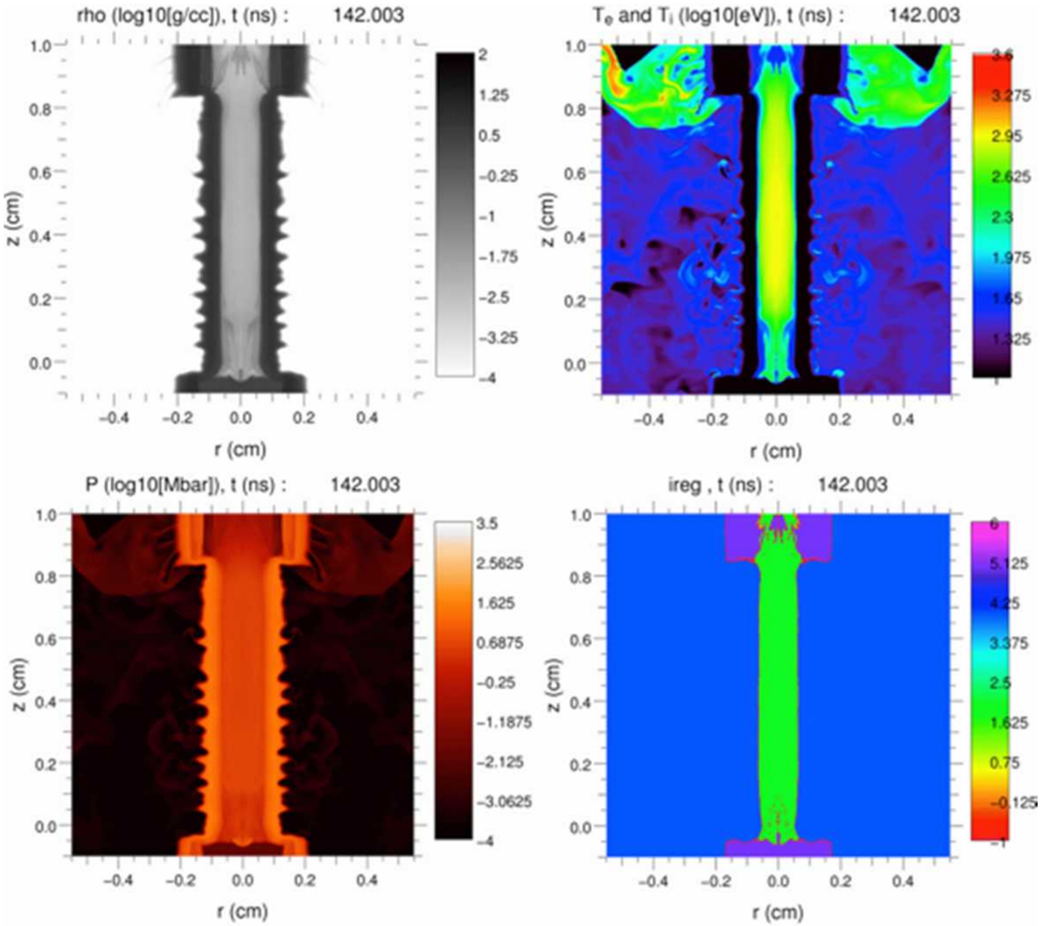

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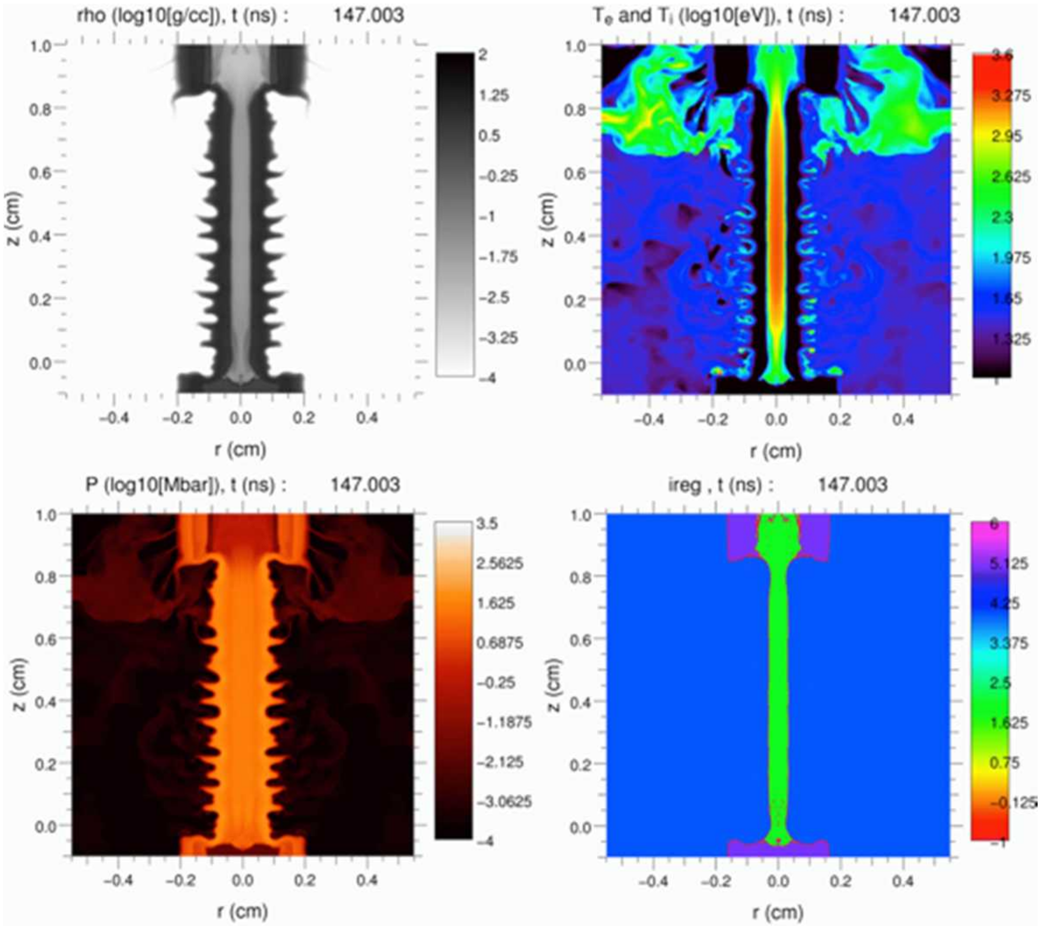

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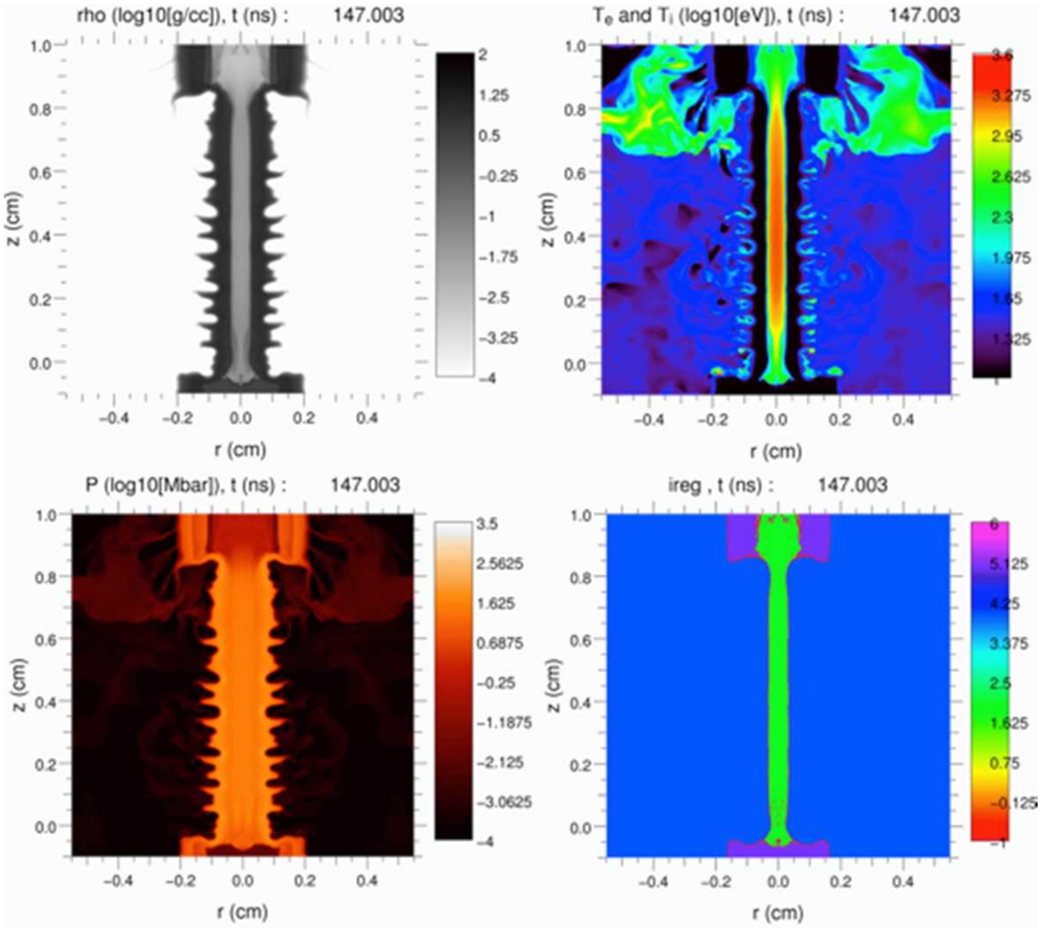

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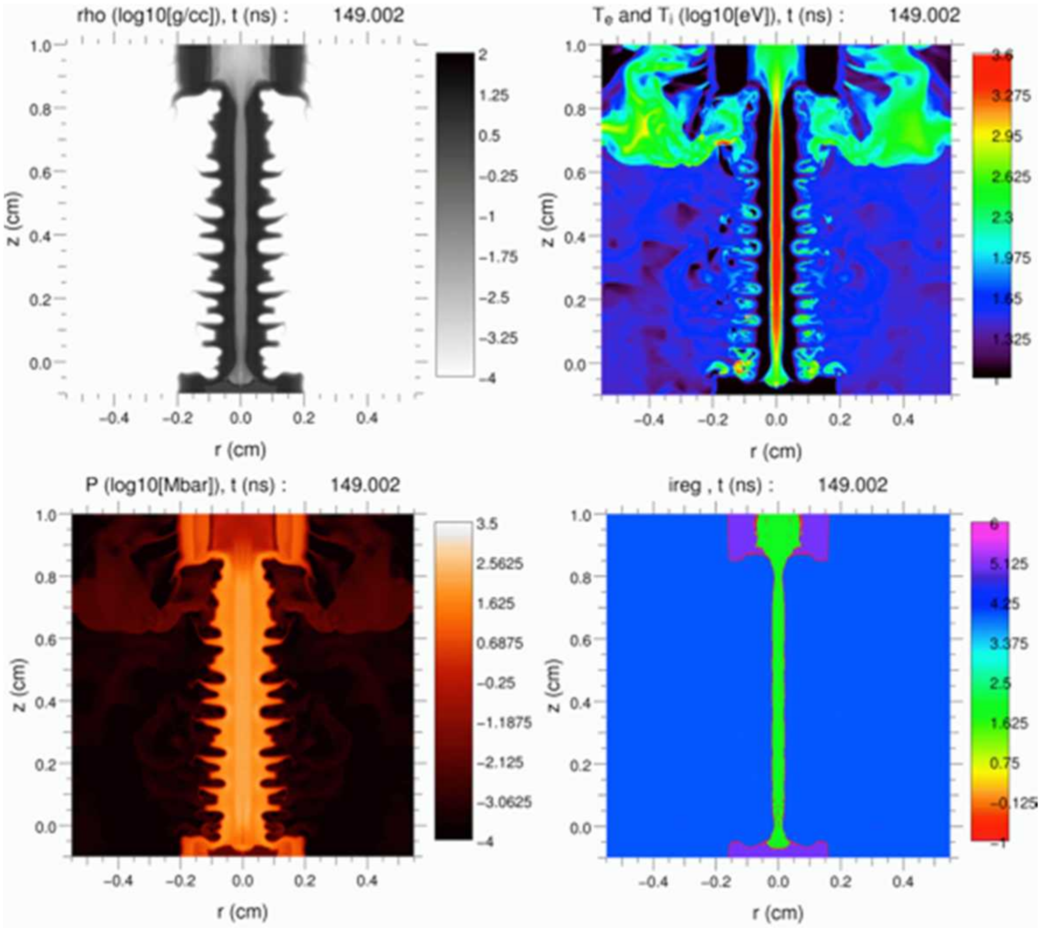

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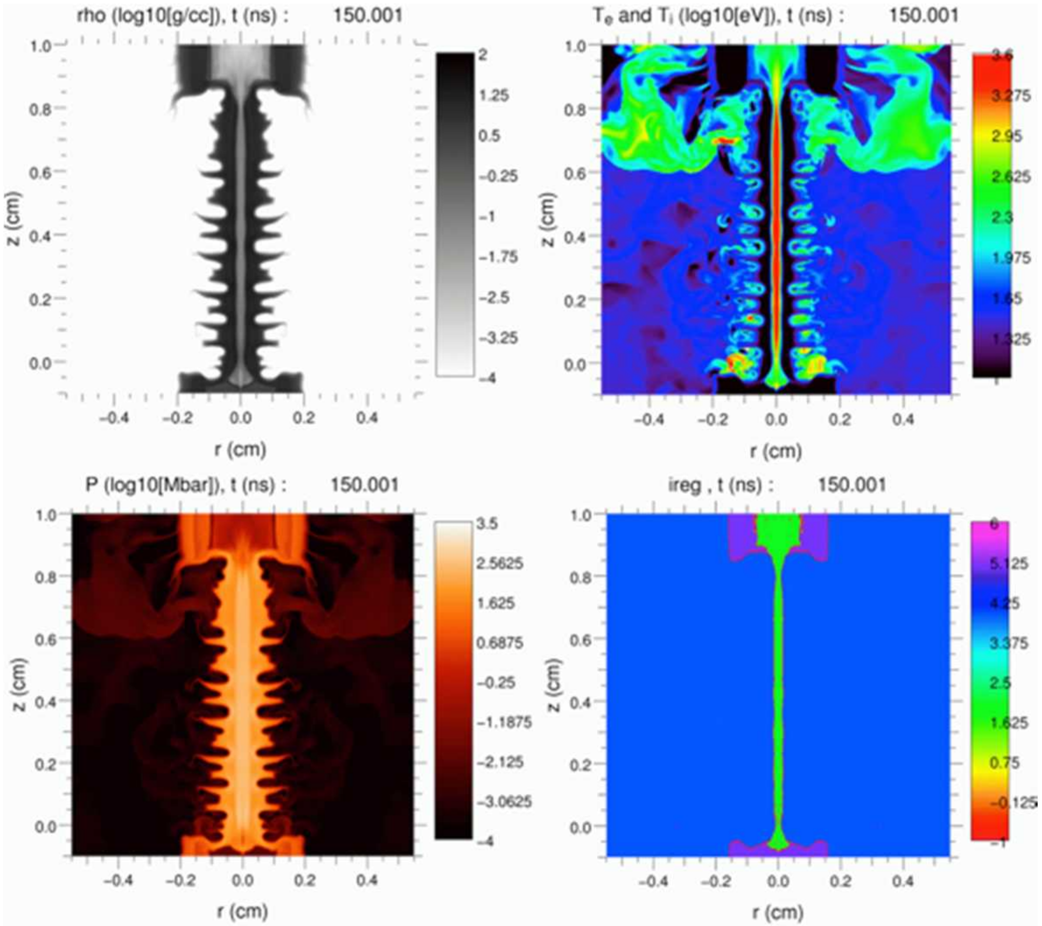

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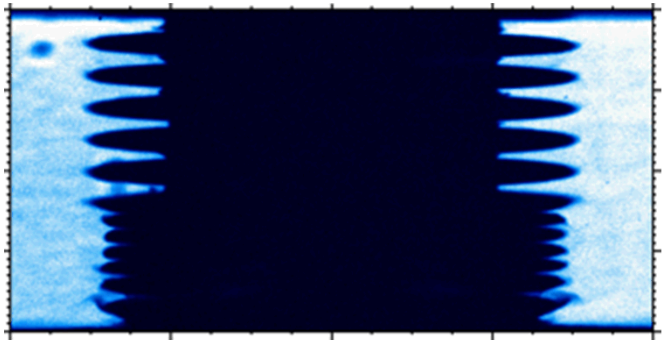
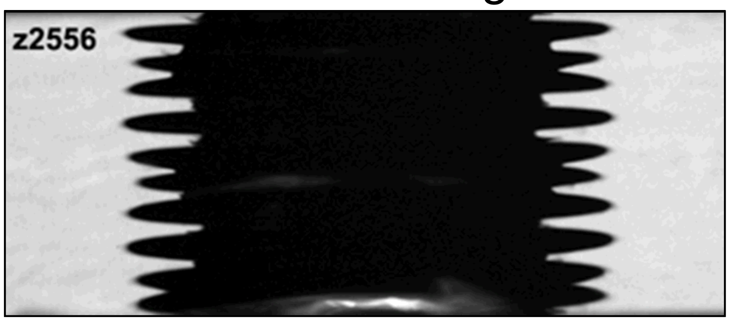
We have been studying numerous aspects of magnetically driven liner implosion dynamics since 2009

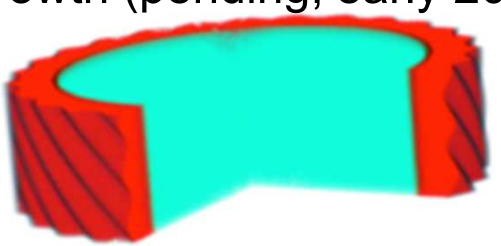
Single-mode magneto-Rayleigh-Taylor growth[1-2]



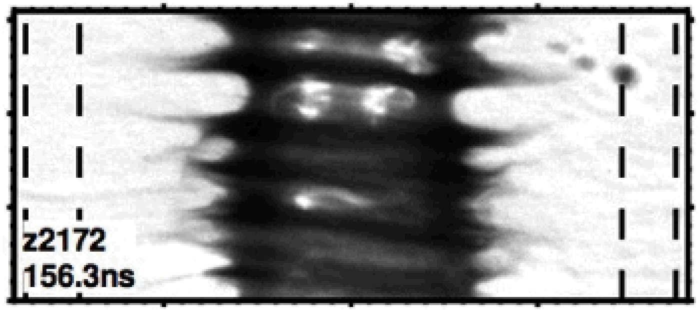
Multi-mode MRT growth[3]



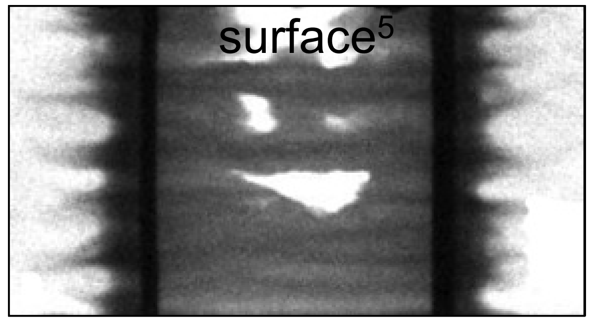
Helical single-mode MRT growth (pending, early 2014)



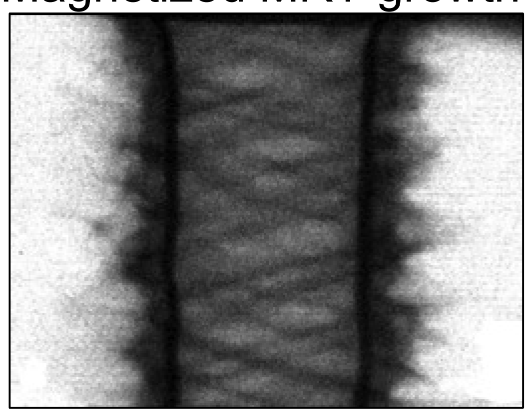
Baseline unseeded MRT[4-5]



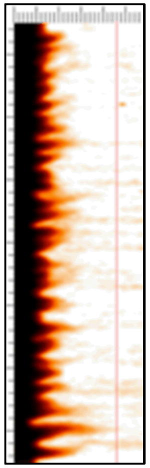
Enhanced contrast inner surface[5]



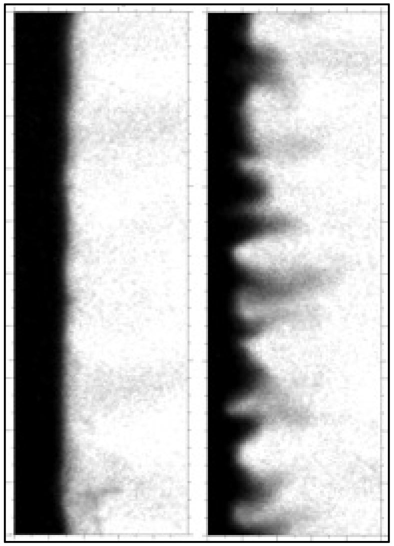
Magnetized MRT growth[6]



Electro-thermal instability growth[7-8]



ETI mitigation[9]



Liner implosion dynamics publications

1. D.B. Sinars *et al.*, Phys. Rev. Lett. 105, 185001 (2010).
2. D.B. Sinars *et al.*, Phys. Plasmas 18, 056301 (2011).
3. D.B. Sinars *et al.*, manuscript in progress.
4. R.D. McBride *et al.*, Phys. Rev. Lett. 109, 135004 (2012).
5. R.D. McBride *et al.*, Phys. Plasmas 20, 056309 (2013).
6. T.J. Awe *et al.*, Phys. Rev. Lett. 111, 235005 (2013).
7. K.J. Peterson *et al.*, Phys. Plasmas 19, 092701 (2012).
8. K.J. Peterson *et al.*, Phys. Plasmas 20, 056305 (2013).
9. K.J. Peterson *et al.*, Phys. Rev. Lett. Accepted (2014)

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

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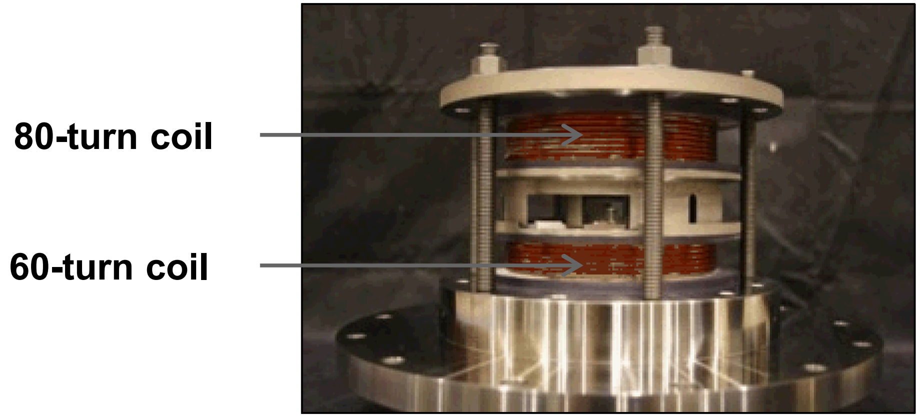
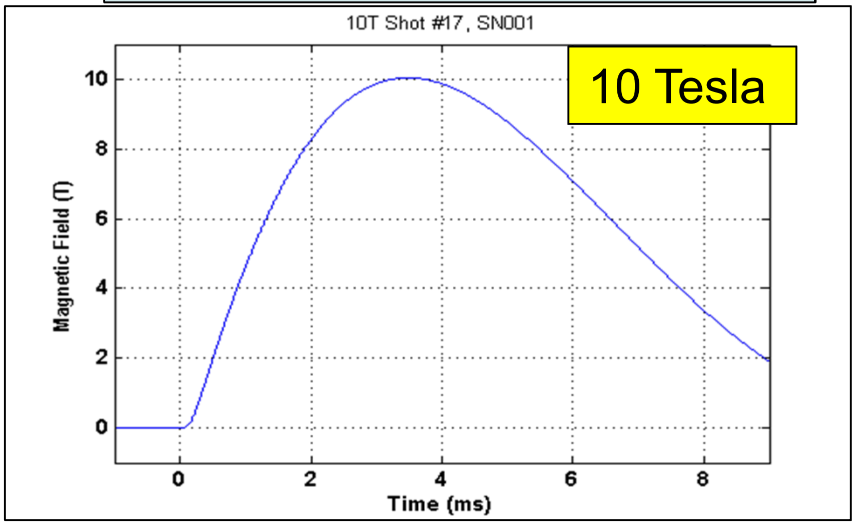
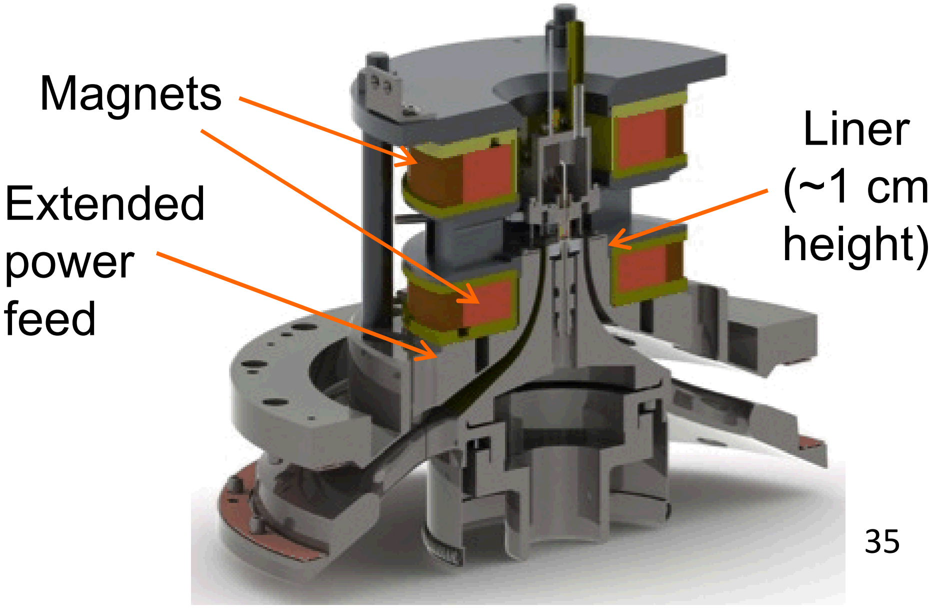
Capacitor bank system on Z
900 kJ, 8 mF, 15 kV

MagLIF assembly with coil



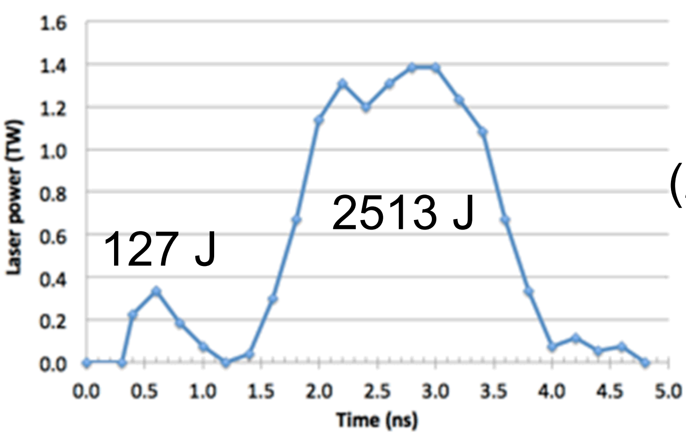
MagLIF on-axis magnetic field data





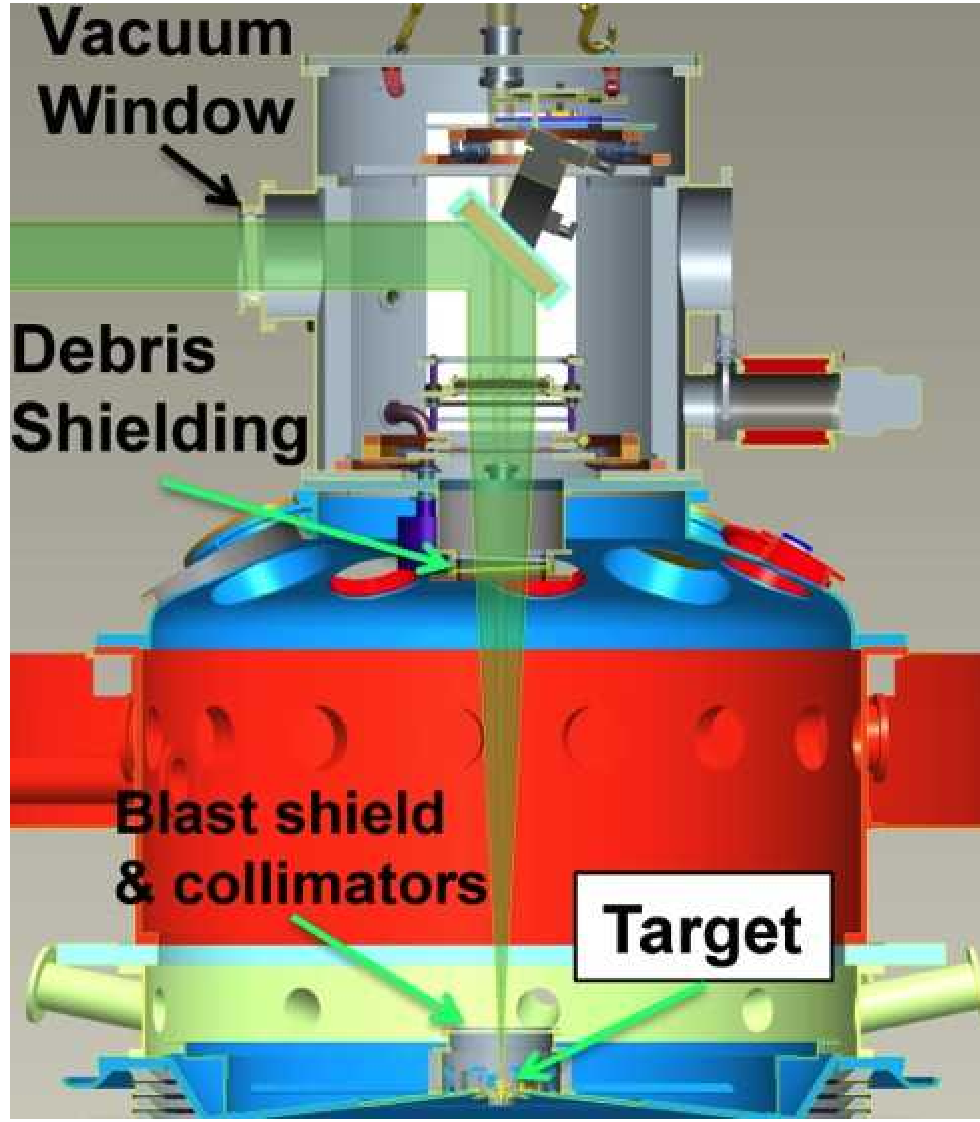
In August 2013 we commissioned a new vacuum final optics assembly to safely enable 2 kJ of laser preheating of fuel

Example pulse measurement



ZBL
2ω light
(2.64 kJ)

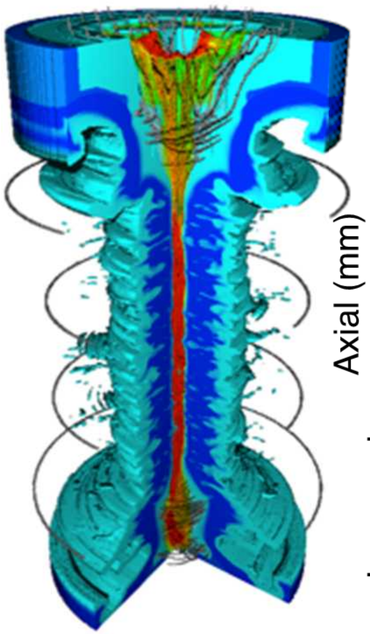
Prepulse vaporizes gas-containing foil; main pulse couples to DD fuel

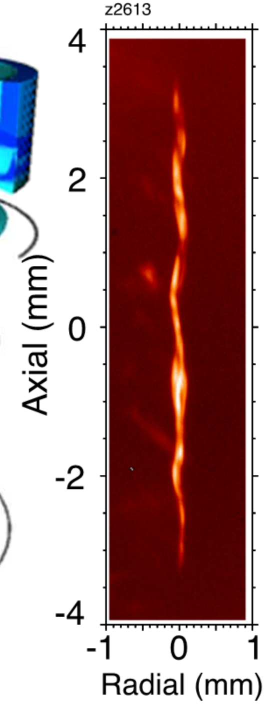


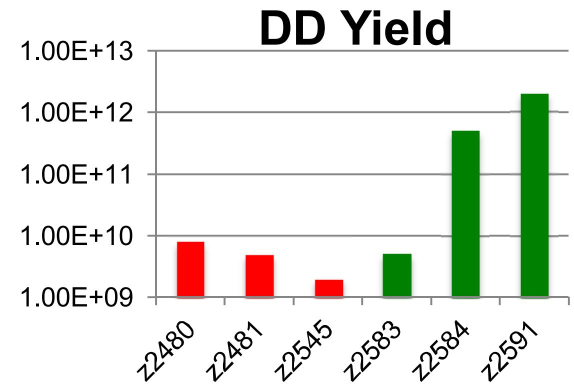
We obtained promising results in our ICF program in late 2013 and expect significant progress before the National ICF Path Forward Review in FY15

Sandia National Laboratories

- We achieved DD yields up to 2e12 (~0.3 kJ DT equivalent) in our first four shots testing novel Magnetized Liner Inertial Fusion (MagLIF) targets
- These experiments confirm the idea that fuel magnetization can help reduce fusion requirements—the same target without magnetization and laser heating produced >200x fewer DD neutrons!
- A variety of data were collected that appear to show a <150 μm diameter, ~3.5 keV, highly magnetized plasma was produced—a remarkable achievement for a ~100 km/s liner target implosion!
- We are continuing to build on these results with a balanced combination of focused and integrated experiments in 2014-2015 to tackle the physics
- In parallel we are improving capabilities to put us closer to the regime where ~100 kJ yields are possible







Our results attracted significant external attention as well

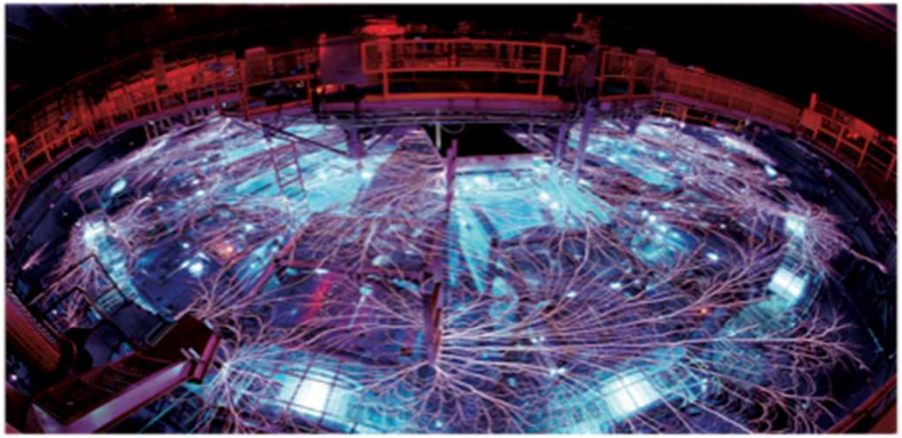
NEWS IN FOCUS

CLIMATE Water will be scarce in warmer world, huge study says **p.10**

PHYSICS With $50 million spent, X-ray source is now out in the cold **p.11**

2014 Transgenic monkeys, comets and more will make the news this year **p.13**

EPIGENETICS A scientist's bid to track down the roots of aggression **p.14**



The intense electrical discharge of the Z machine at Sandia National Laboratories in New Mexico is used in attempts to trigger nuclear fusion.

PLASMA PHYSICS

Triple-threat method sparks hope for fusion

The secrets to its success are lasers, magnets and a big pinch.

BY W. WAYT GIBBS

The Z machine at Sandia National Laboratories in New Mexico discharges the most intense pulses of electrical current on Earth. Millions of amperes can be sent towards a metallic cylinder the size of a pencil eraser, inducing a magnetic field that creates a force — called a Z pinch — that crushes the cylinder in a fraction of a second.

Since 2012, scientists have used the Z pinch to implode cylinders filled with hydrogen isotopes in the hope of achieving the extreme temperatures and pressures needed for energy-generating nuclear fusion. Despite their efforts, they have never succeeded in reaching ignition — the point at which the energy gained from fusion is greater than the energy put in.

But after tacking on two more components, physicists think they are at last on the right path. Researchers working on Sandia's Magnetized Liner Inertial Fusion (MagLIF) experiment added a secondary magnetic field to thermally insulate the hydrogen fuel, and a laser to pre-heat it (see 'Feeling the pinch'). In late November, they tested the system for the first time, using 16 million amperes of current, a 10-tesla magnetic field and 2 kilojoules of energy from a green laser.

"We were excited by the results," says ▸

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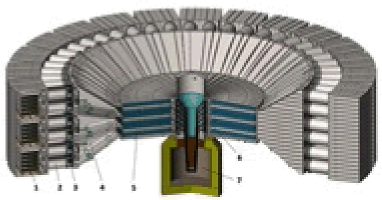
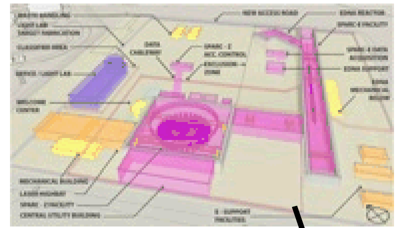
Our long-term vision is to establish a compelling argument that pulsed power ICF can achieve 1 GJ/shot



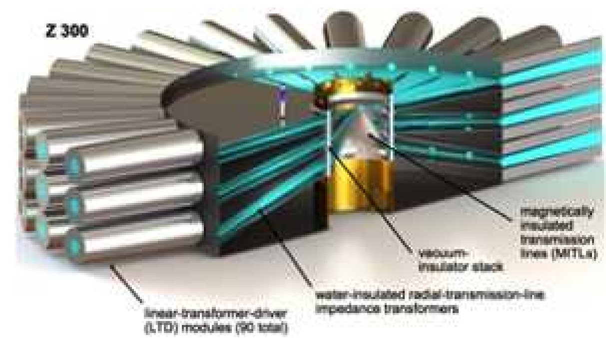


1 GJ

2019: Baikal operations begin

SPARC-Z operations begin

CD-0 for SPARC-Z High-Yield Facility



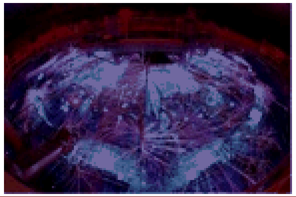
Z-300 demonstrates ignition

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