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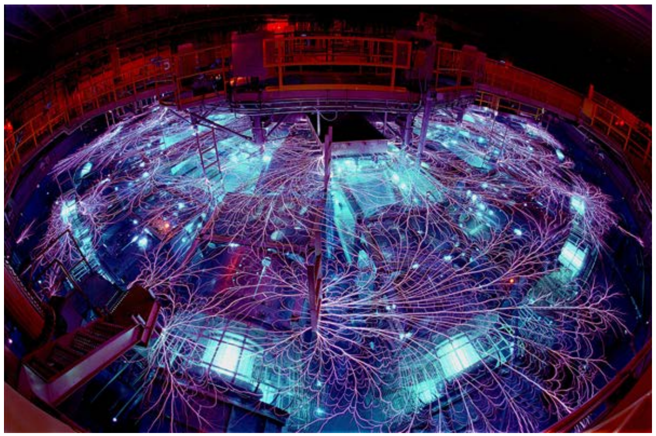

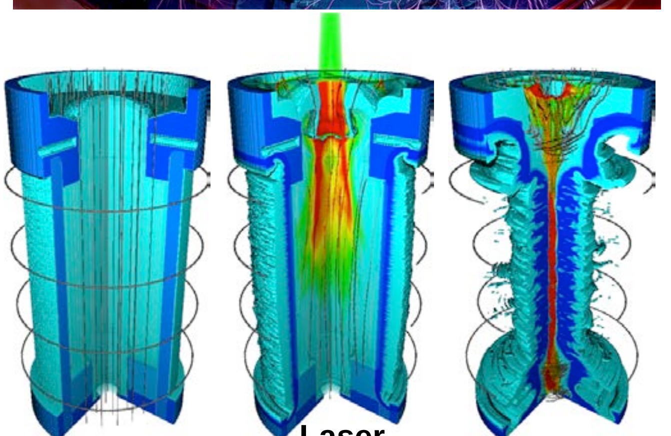

ICF Overview and Z

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Sandia National Laboratories,

Albuquerque, NM, USA

U.S. DEPARTMENT OF ENERGY

NNSA National Nuclear Security Administration

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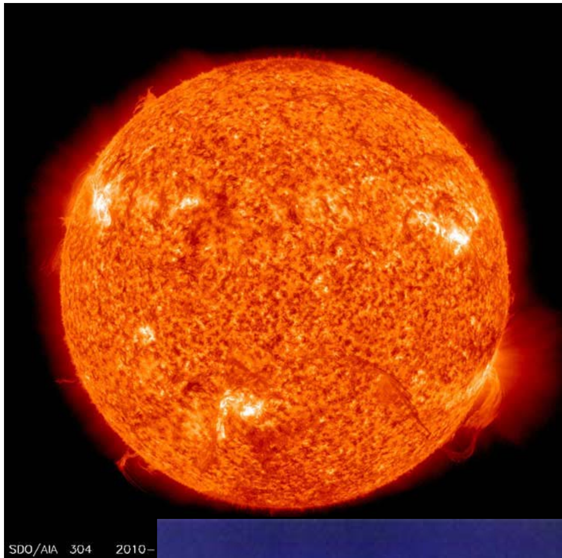
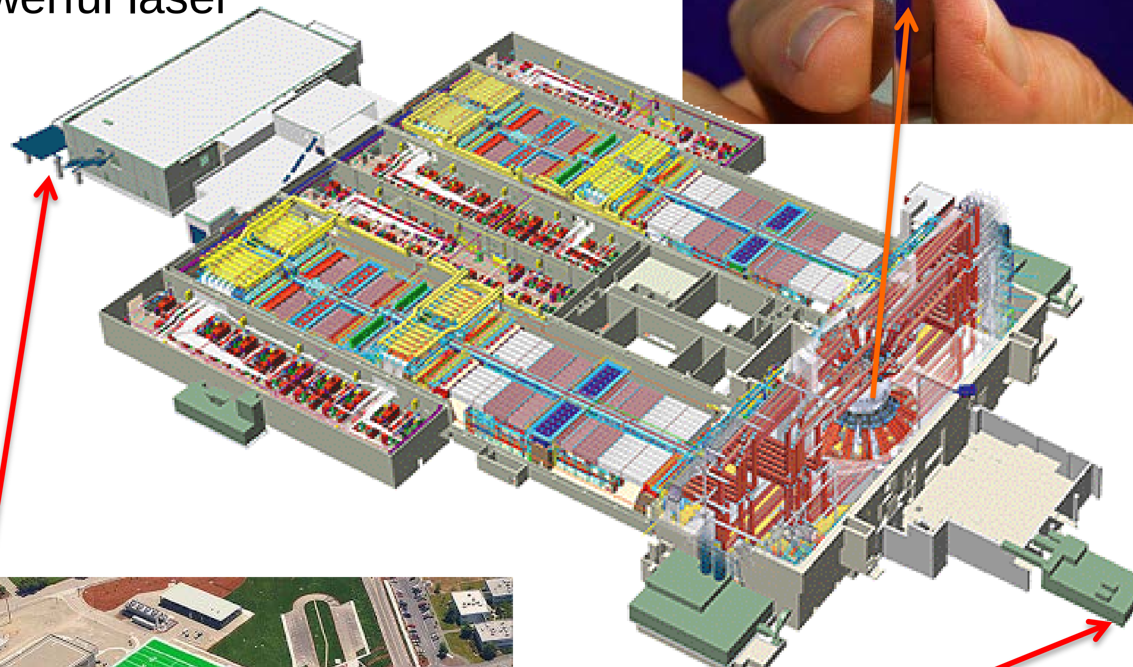
Achieving significant fusion yields has so far required taking extreme measures…



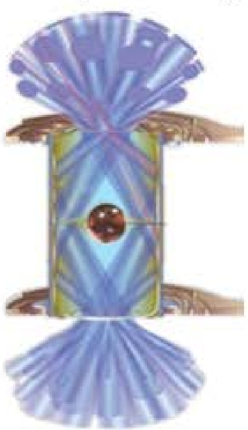
National Ignition Facility:
World's largest and most powerful laser



The U.S. Inertial Confinement Fusion (ICF) Program is pursuing three main approaches to fusion ignition

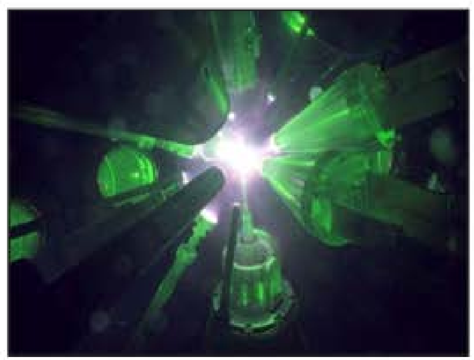
Laser x-ray drive

192 beams, 1.8 MJ, 400 TW

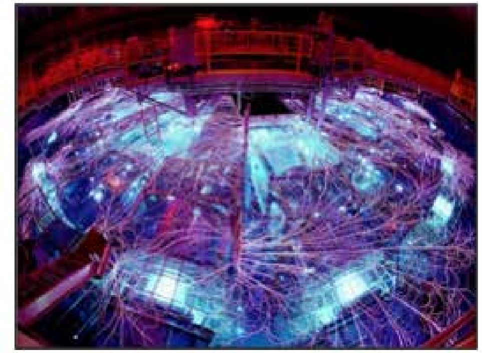


Laser direct drive

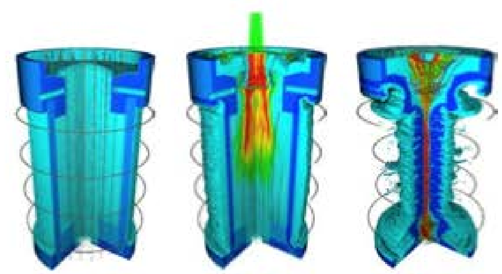
60 beams, 30 kJ, 20 TW



Magnetic direct drive



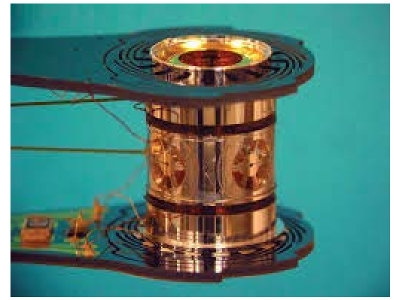
26 MA, 80 TW

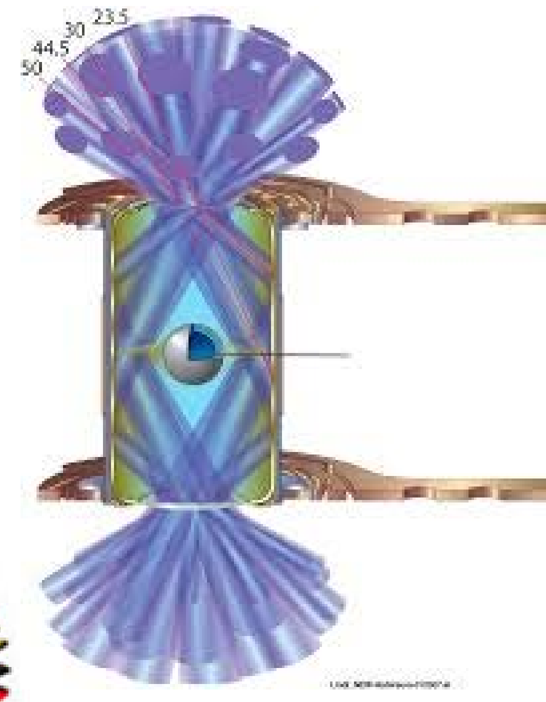


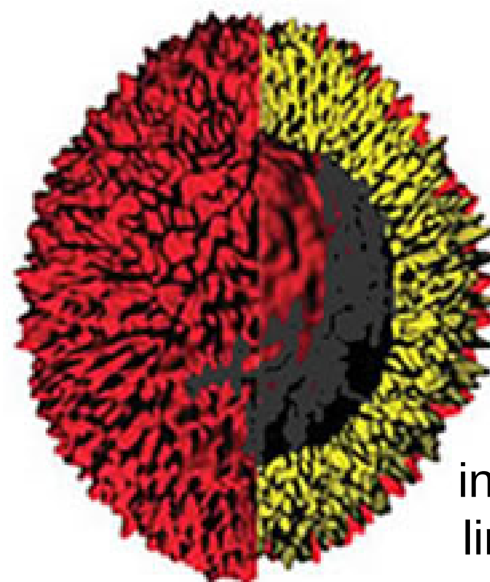
Magnetization Laser heating Compression

X-ray driven implosions on the National Ignition Facility remain the primary approach, but the failure to achieve ignition has encouraged broader thinking in the USA

- Highest yields on the facility to date have been < $1\text{x}10^{16}$ neutrons (35-100x below ignition)
- The highest yield shots do show alpha heating
- The NNSA Lab directors sent a letter last year to Gen. Frank Klotz endorsing the need for “multi-MJ fusion yields”
- Significant uncertainty remains as to whether ignition on NIF is possible, sets the stage for four choices:
  - A bigger laser for x-ray drive
  - Convert NIF to direct drive
  - Pursue a pulsed power driver
  - None of the above







Are 3D instabilities limiting the compression?

The “None of the above” option has risk. The rest of the world may not be content to follow the United States.

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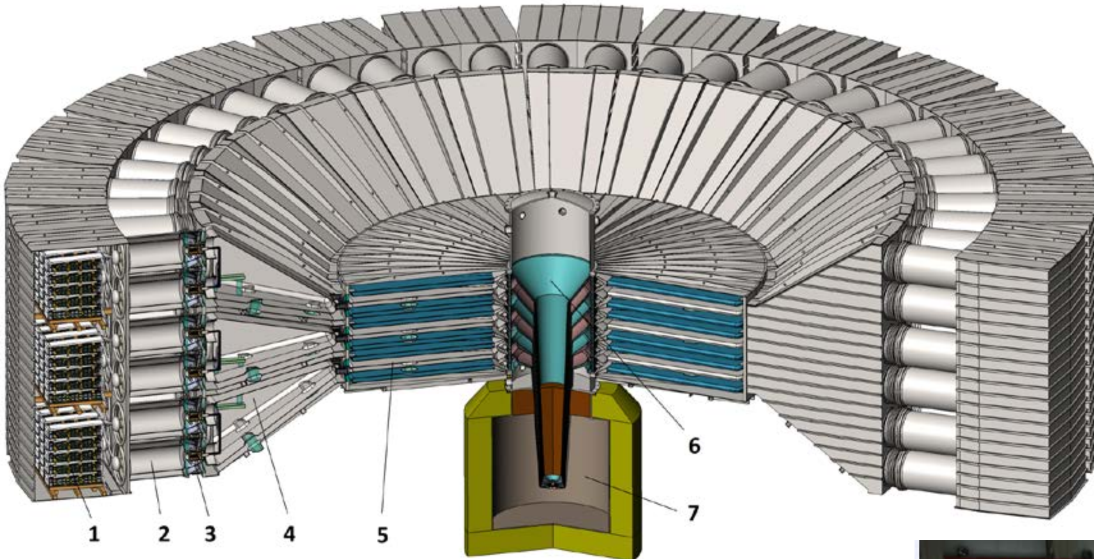


Operating Chinese Facility (PTS)

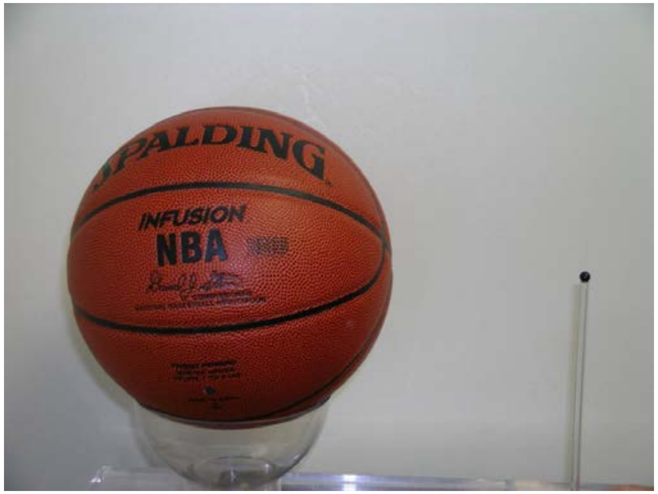
- 8 MA
- 100 ns
- 8 MJ (1/3 x Z)
- Successfully duplicating previous published work worldwide
- They are even building a 1 ns, 1 kJ laser facility like Z-Beamlet!
- They are currently evaluating LTD and Marx-based architectures

Russian Facility (Baikal)

- 50 MA
- 150 ns
- 100 MJ (4 x Z)
- Stated goal: **25 MJ fusion yield**
- Originally scheduled for completion in 2019, delayed due to oil price collapse
- If it works, they could have this capability before the United States

Chinese laser scientist to NIF director: “It is no longer acceptable to just follow the United States, we are considering building a bigger laser to achieve ignition.”

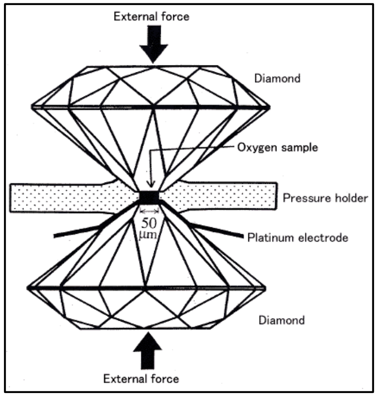
Some context to understand how extreme traditional ICF really is…

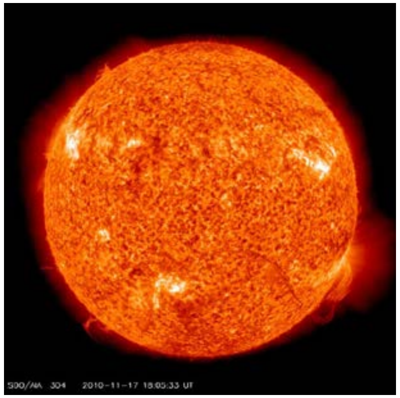


- 35:1 convergence ratio
- Basketball to pea
- Need <1-2% deviation from a perfect sphere
- If an ICF capsule scaled to the size of earth, it would have to be smoother than earth!

- Burn time ~0.2 ns
- Speed of light: 3×10^8 m/s
- Moves 6 cm in 0.2 ns

- 380 km/s implosion
- NY to LA = 3936 km
- Would take about 10 s!
- Faster than a speeding bullet! (~3000 km/h)





- 400 Gbar pressure
- Diamond Anvil Cell reaches ~6 Mbar
- Center of sun is about 250 Gbar!

Anything that we can do to make this less extreme is worth investigating!

The Sandia Z pulsed power facility uses magnetic pressure to efficiently couple MJs of energy to “targets” at its center

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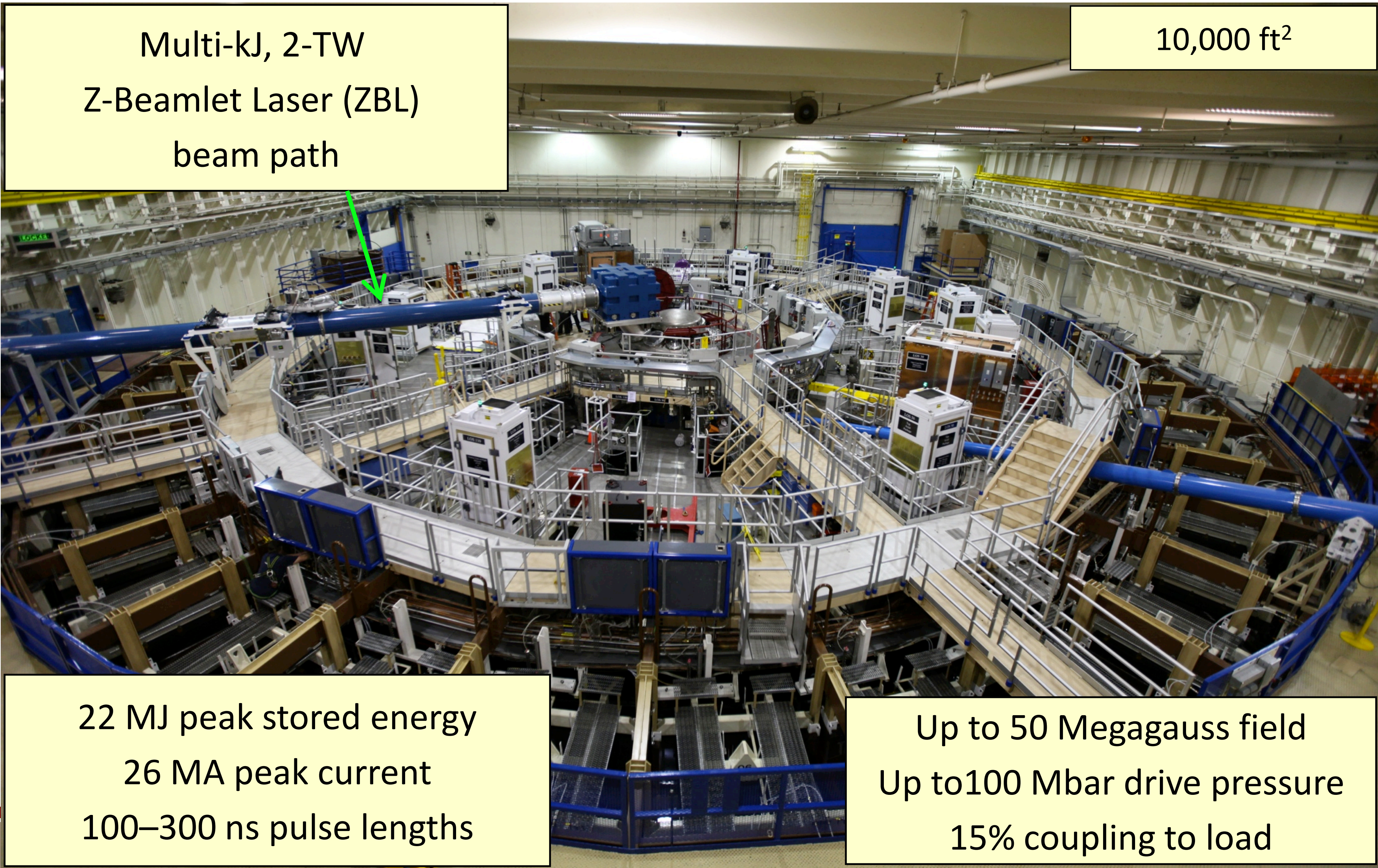
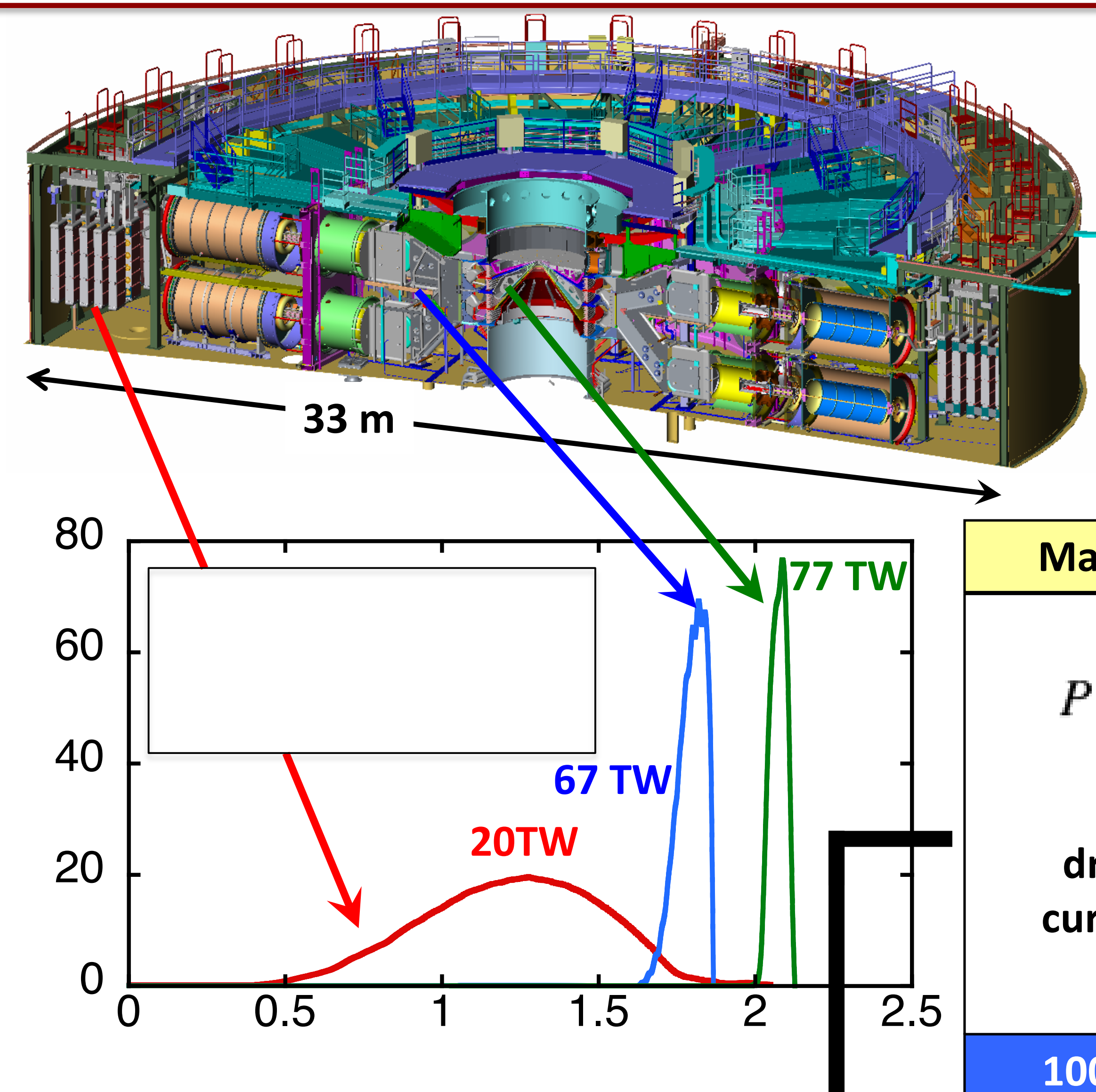


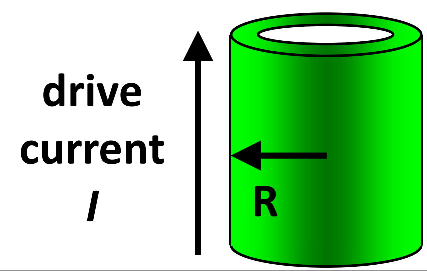
Magnetic direct drive is based on efficient use of large currents to create high pressures



Z today couples ~0.5 MJ out of 20 MJ stored to magnetized liner inertial fusion (MagLIF) target (0.1 MJ in DD fuel).

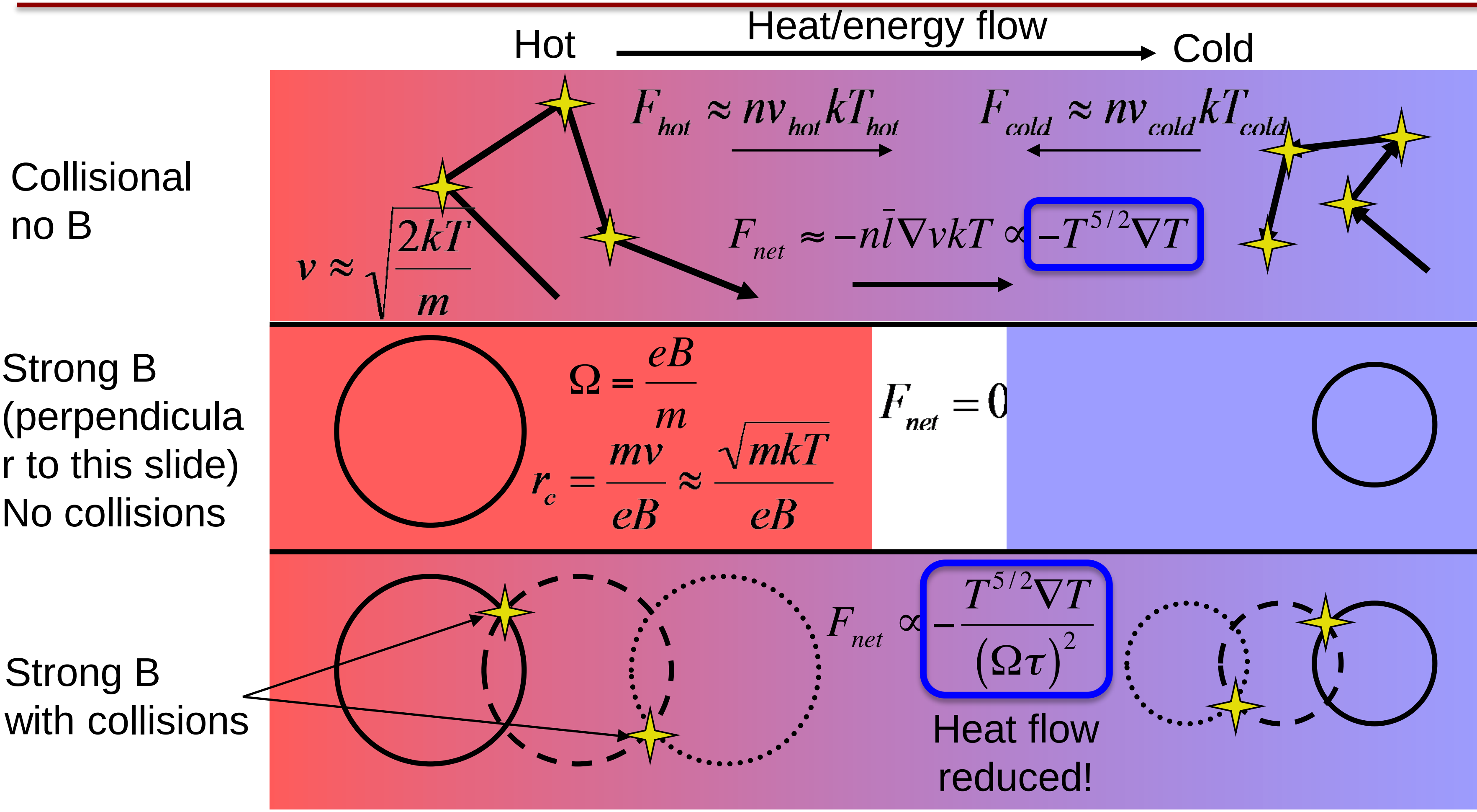
Magnetically Driven Implosion

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



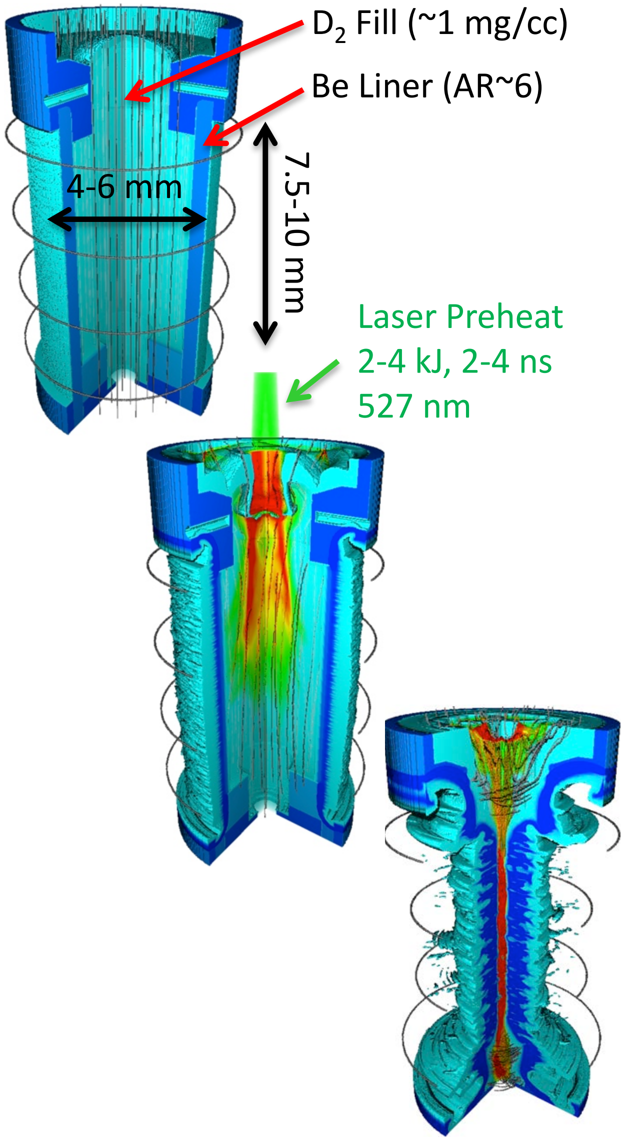
100 MBar at 26 MA and 1 mm

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



"Anomalous" heat transport can reduce the benefit of magnetic fields (e.g., in tokamaks) but there remains a significant benefit

Magnetized Liner Inertial Fusion (MagLIF) is well suited to pulsed power drivers and may reduce fusion requirements



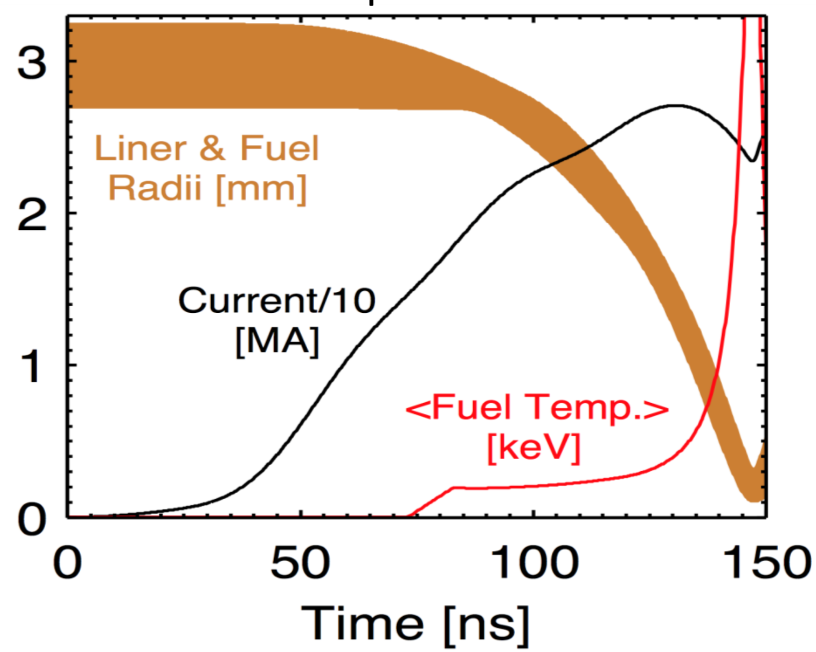
- **Axial magnetization of fuel/liner (B_{z0} = 10-30 T)**
  - Inhibits thermal conduction losses and traps alphas (β: 5~80; $\omega\tau$>200 at stagnation)
- **Laser heating of fuel (2 kJ initially, 6 kJ planned)**
  - Reduces radial fuel compression needed to reach fusion temperatures (R_0/R_f about 25, T_0=150-200 eV)
- **Liner compression of fuel (70-100 km/s, ~100 ns)**
  - Low velocity allows use of thick liners ($R/\Delta R$~6) that are robust to instabilities and have sufficient ρR at stagnation for inertial confinement
- This combination allows fusion at ~100x lower fuel pressure than traditional ICF (~5 Gbar vs. 500 Gbar)
- 2-D Simulations suggest 100 kJ DT yield may be possible on Z in future
  - Requires upgrades from our present system e.g., 10 T → 30 T; 2 kJ → 4 kJ; 19 MA → 24 MA

MagLIF has conservative fuel compression characteristics, but relies on largely untested magneto-inertial fusion principles

Metric	X-ray Drive on NIF	100 kJ MagLIF on Z
Pressure	~140-160 Mbar	26 MA at 1 mm is 100 Mbar
Force vs. Radius	Goes as R^2	Goes as 1/R
Peak velocity	350-380 km/s	70-100 km/s
Peak IFAR	13-15 (high foot) to 17-20	8.5
Hot spot CR	35 (high foot) to 45	25
Volume Change	43000x (high) to 91000x	625x
Fuel rho-R	>0.3 g/cm^2	~0.003 g/cm^2
Liner rho-R	n/a	>0.3 g/cm^2
BR	n/a	>0.5 MG-cm
Burn time	0.15 to 0.2 ns	1 to 2 ns
T_ion	>4 keV	>4 keV

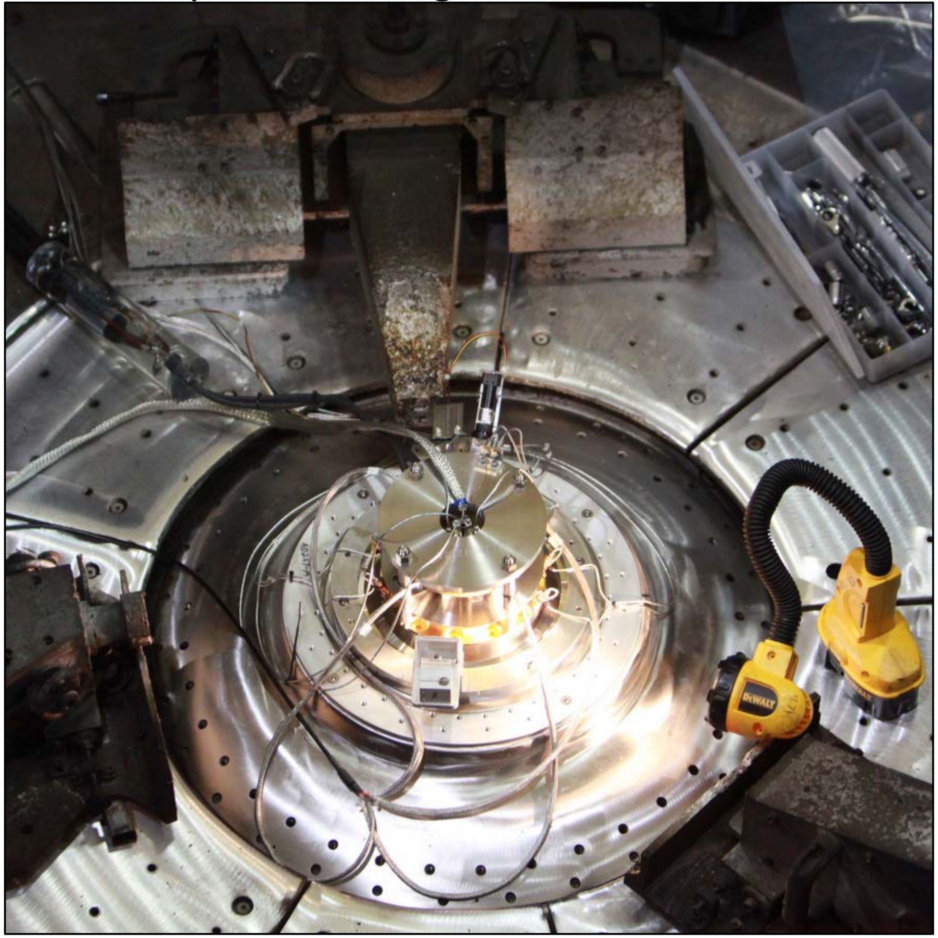
- Low Velocity Implosion
- Low IFAR
- Low convergence ratio / volume compression / fuel ρR

1-D picture*



Z couples several MJ of energy to the load hardware, ~equivalent to a stick of dynamite, making diagnostic measurements and laser coupling challenging

Pre-shot photo of MagLIF load hardware

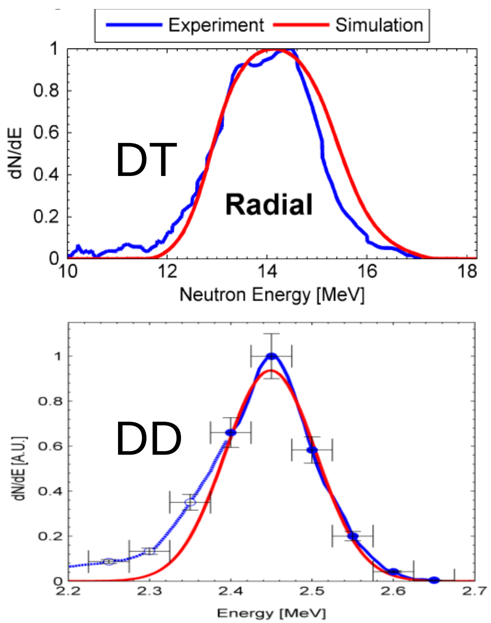


Damage to FOA debris shielding

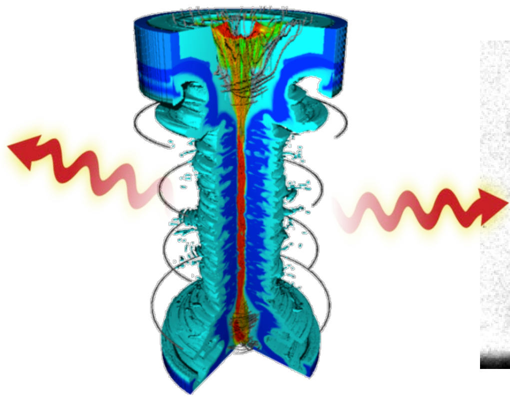
Post-shot photo

We use a combination of current, x-ray, and neutron diagnostics to assess the performance of MagLIF implosions.

Neutron spectra

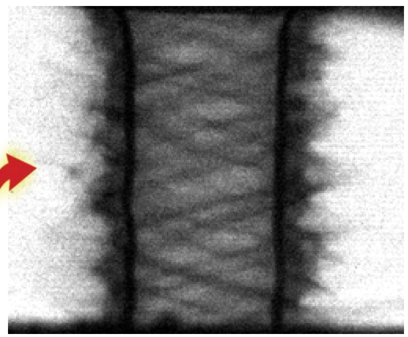


MagLIF Z pinch

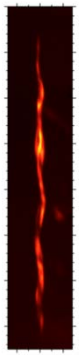


X-ray

Radiography

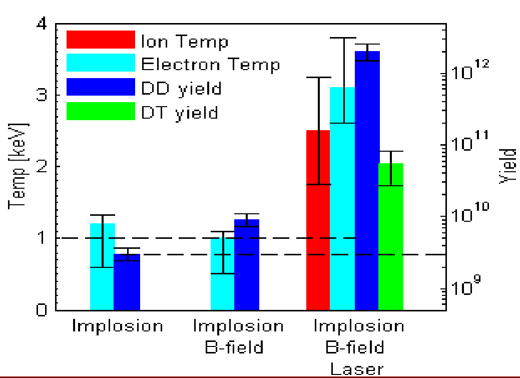


Imaging

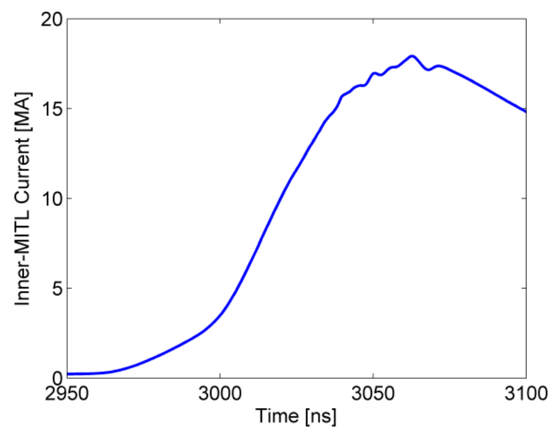


Spectra

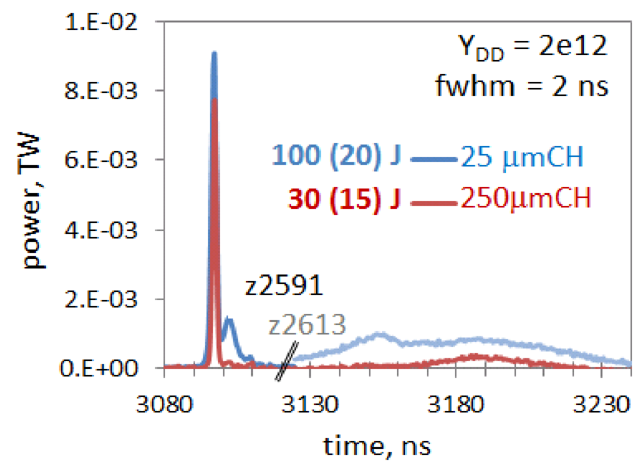
Nuclear Activation



Load Current

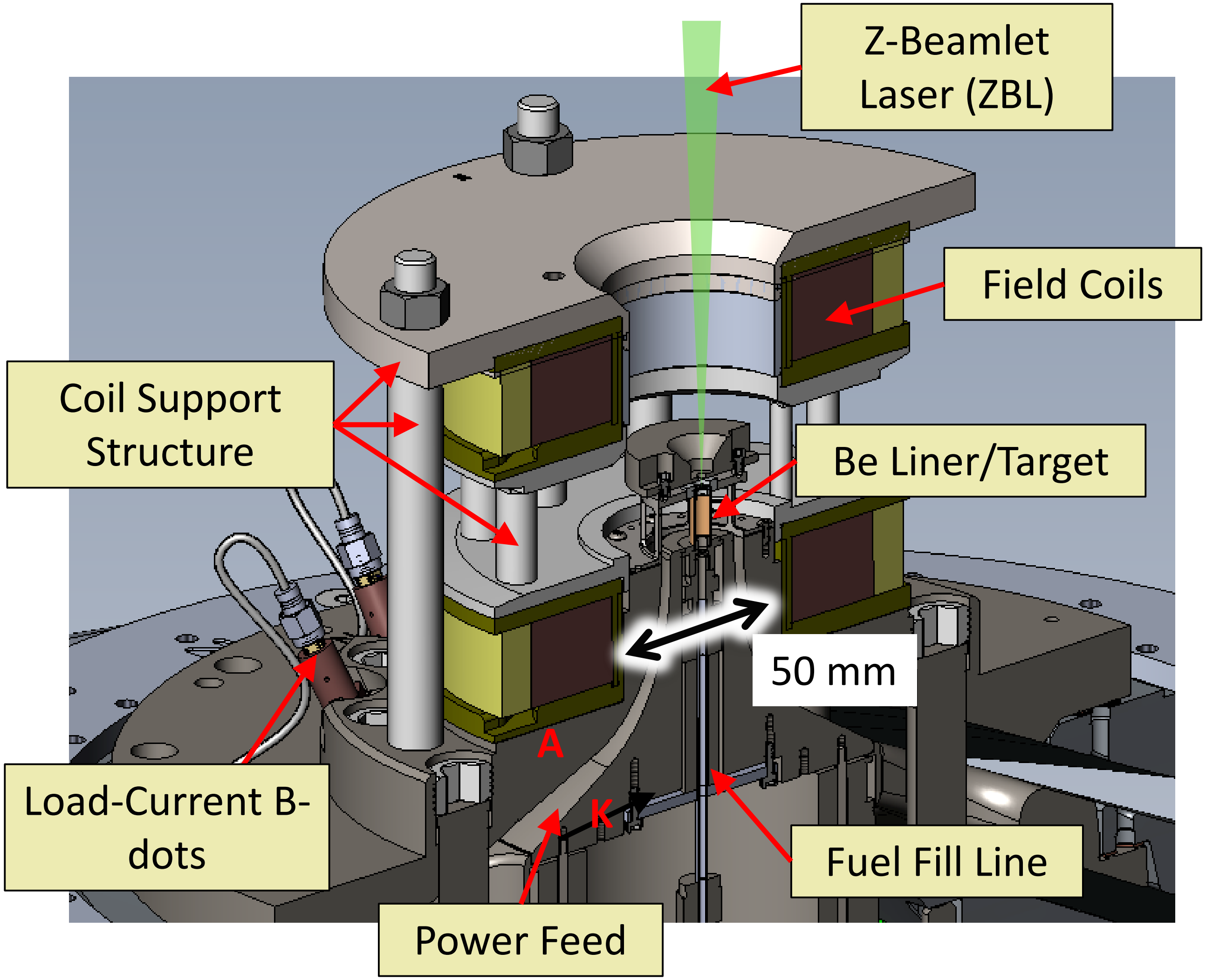


X-ray Power



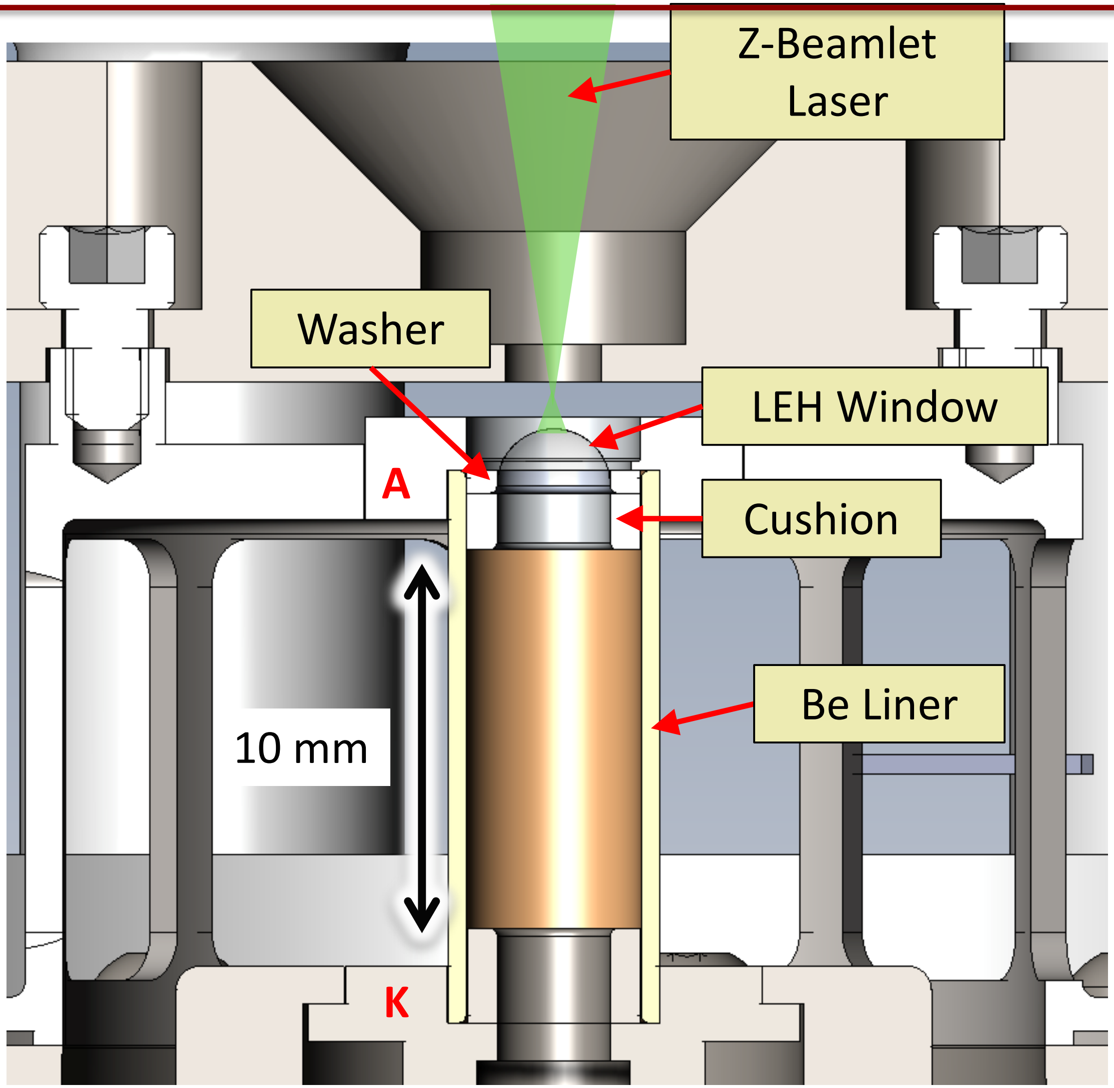
Present 'Baseline' MagLIF Target

- **Field Coils**: Helmholtz-like coil pair produce a 10 T uniform axial field w/ ~3 ms rise time
- **ZBL**: 1-4 kJ green laser, 1-4 ns square pulse w/ adjustable prepulse.
- **Power Feed**: Raised feed with a total inductance of 7.3 nH to allow diagnostic access and uniform B-field



Present 'Baseline' MagLIF Target

- **Be Liner**: OD = 5.58 mm, ID = 4.65 mm, h = 10 mm
- **LEH Window**: 1.5 µm thick Polyimide window.
- **Gas Fill:** D2 at 60 PSI (0.7 mg/cc)
- **Washer**: Be washer supporting LEH window
- **Cushion**: Be structure used to mitigate the wall instability.
- **Return Can:** Slotted for diagnostic access



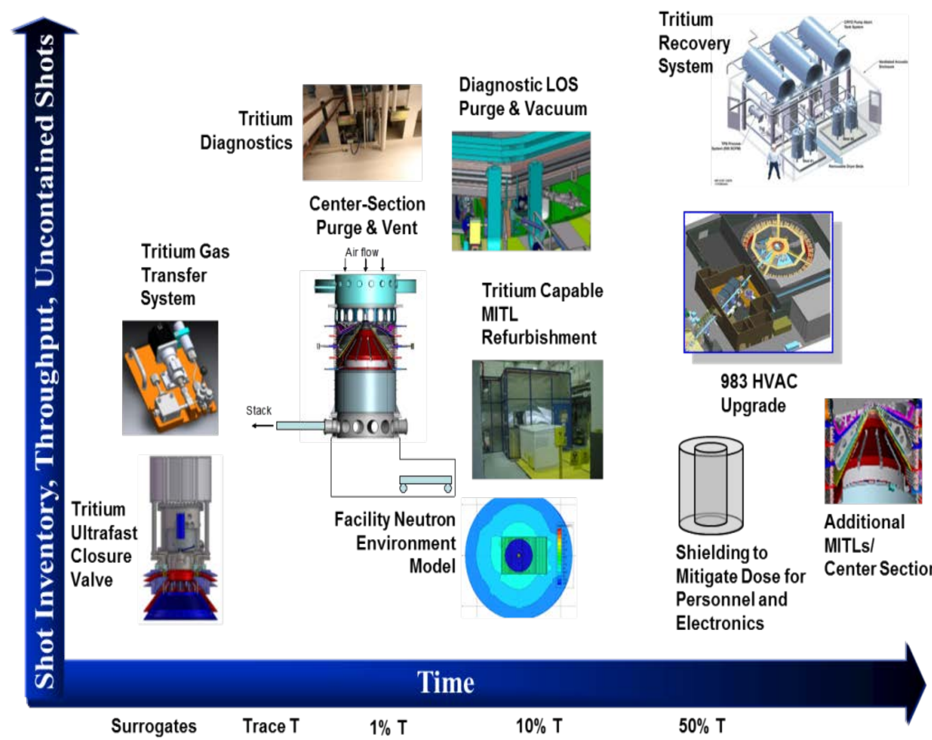
We will invest in tritium capability on Z to enable nuclear diagnostics with a few% T by 2020 and 50-50 DT later.

	2015	2016	2017	2018	2019	2020
Contained	D_2, ^3He	0.1% T	--	1% T	3% T	3% T
Uncontained	D_2, ^3He	D_2, ^3He	0.1% T	0.3% T	1% T	3% T

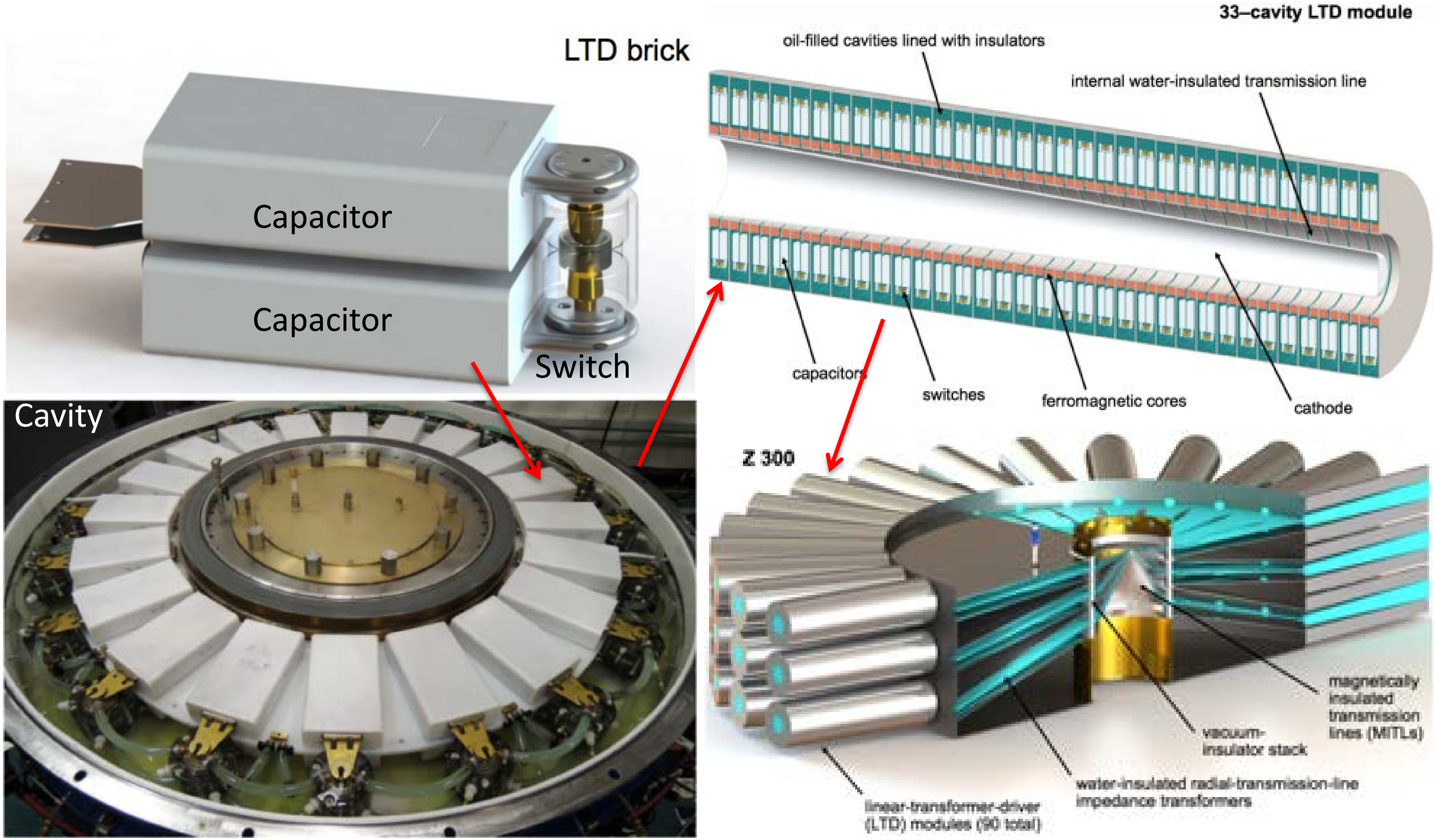
Trace T for thermonuclear, T_{ion} studies
DD and DT nTOF, yield ratio

Advanced nuclear diagnostics
GCD, neutron imaging, MRS

- 0.1% T was shot on Z in 2016 using an containment system.
- Uncontained trace T is desired for ICF.
- Tritium behavior in the Z environment will be studied as we increase quantities.
- Moderate investment will likely be needed for >few% T.

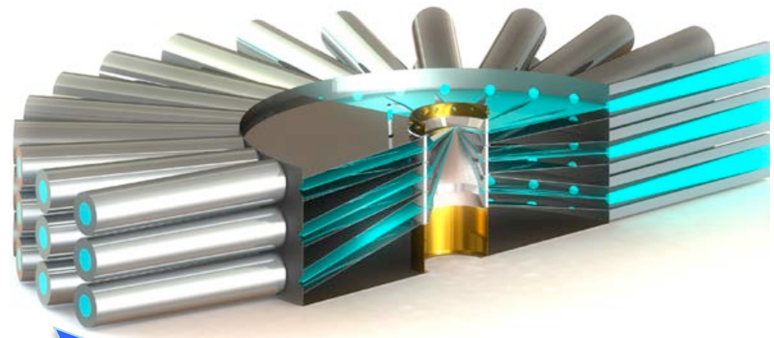


We are exploring a new pulsed power architecture that may scale better to ignition and high-yield



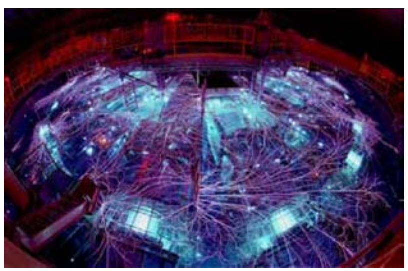
Linear Transformer Driver architecture is 2x as efficient as today's systems and may offer a compelling path forward to reach 0.5-1 GJ yields and meet future Science Program needs

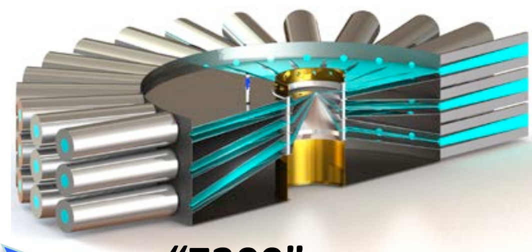
Fusion Yield 0.5-1 GJ?
Burning plasmas



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

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





"Z800"

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

"Z300"

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

Z

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

Note that 1 GJ ~ 0.25 tons TNT and there will be significant radiation and activation issues, so Z800 is "bold"!

The entire laboratory will be needed to successfully develop and execute a Z-Next project

Lab-Wide S & T Engagement
Multi-disciplinary science & technology advances
New simulation codes and high power computing
Materials and Materials Science
Nuclear, Mechanical, Electrical Engineering
HED target science & technology
Pulsed power driver science & technology
Project Management and Systems Engineering
Tritium handling
Nuclear facility design for large fusion yields
Systems design for handling of activated hardware
Siting challenges
Robotics
Licensing, regulations, waste handling, and mitigation

Many unique problems need to be solved

SMEs and teams from around Sandia (and the complex) will be needed to develop the tools, techniques, and capabilities to succeed on a Z-Next project!

Questions?