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Sandia National Laboratories

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Z-pinch Target Physics

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in collaboration with

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

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

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**

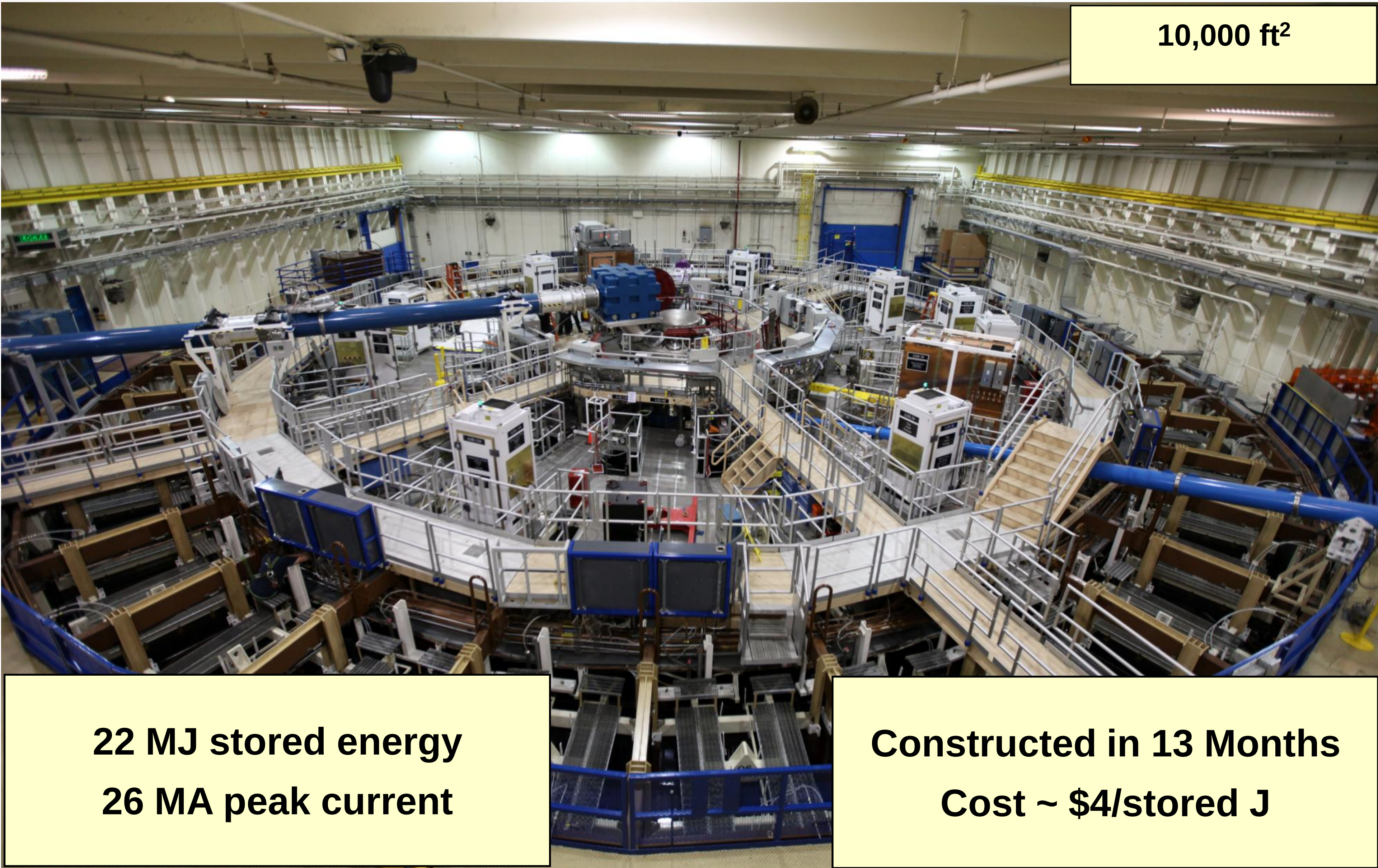
Magnetic fields change the way particles and energy are transported in a plasma

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**

The Z pulsed power generator provides a large current for MJ-class high energy density physics



10,000 ft^2

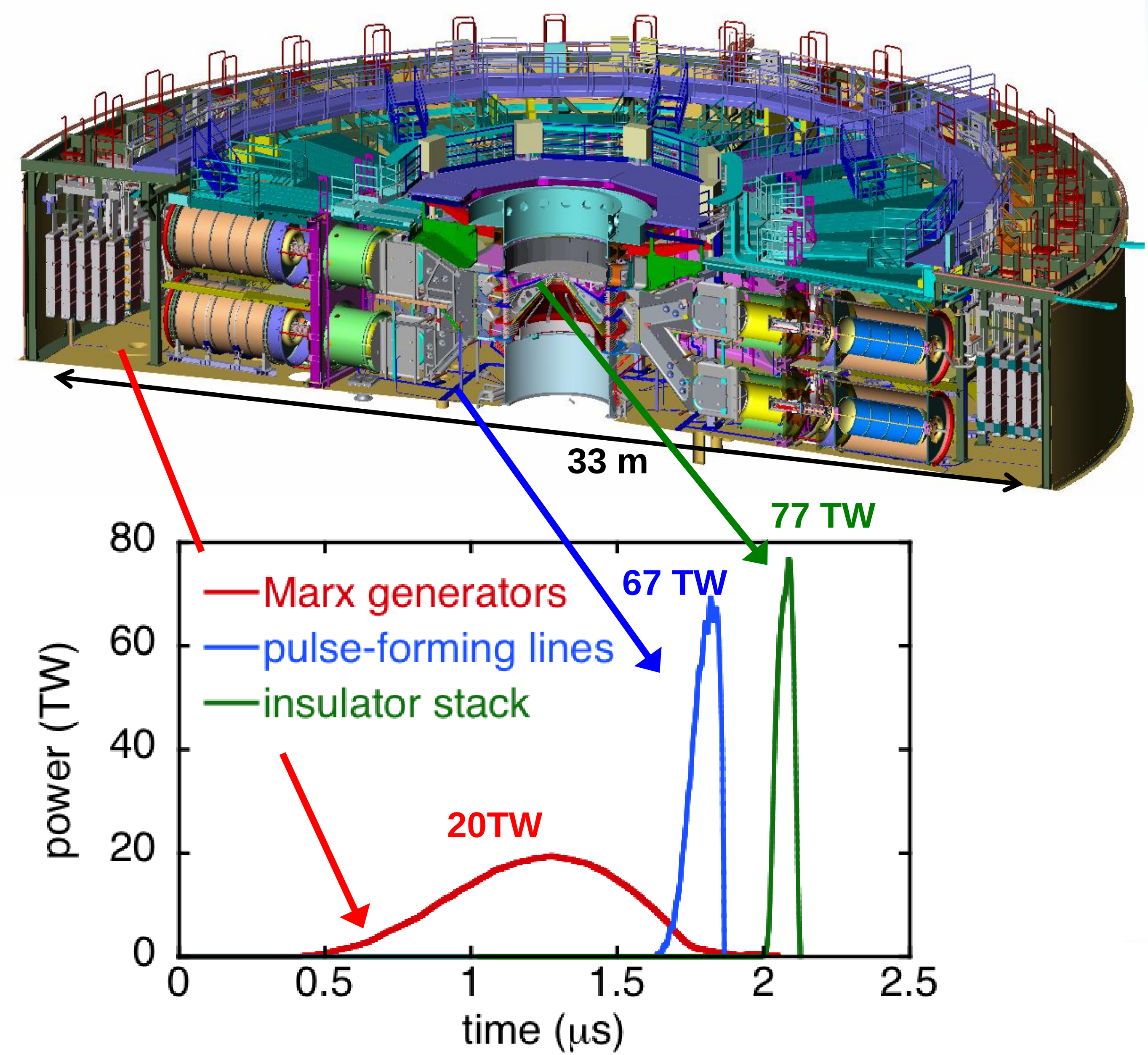
22 MJ stored energy

26 MA peak current

Constructed in 13 Months

Cost ~ $4/stored J

Z works by compressing electromagnetic energy in time and space



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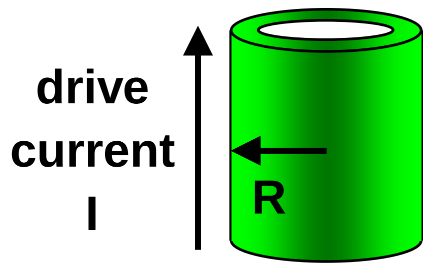
Magnetically driven implosions can efficiently couple energy at high drive pressure

Magnetically-Driven Implosion

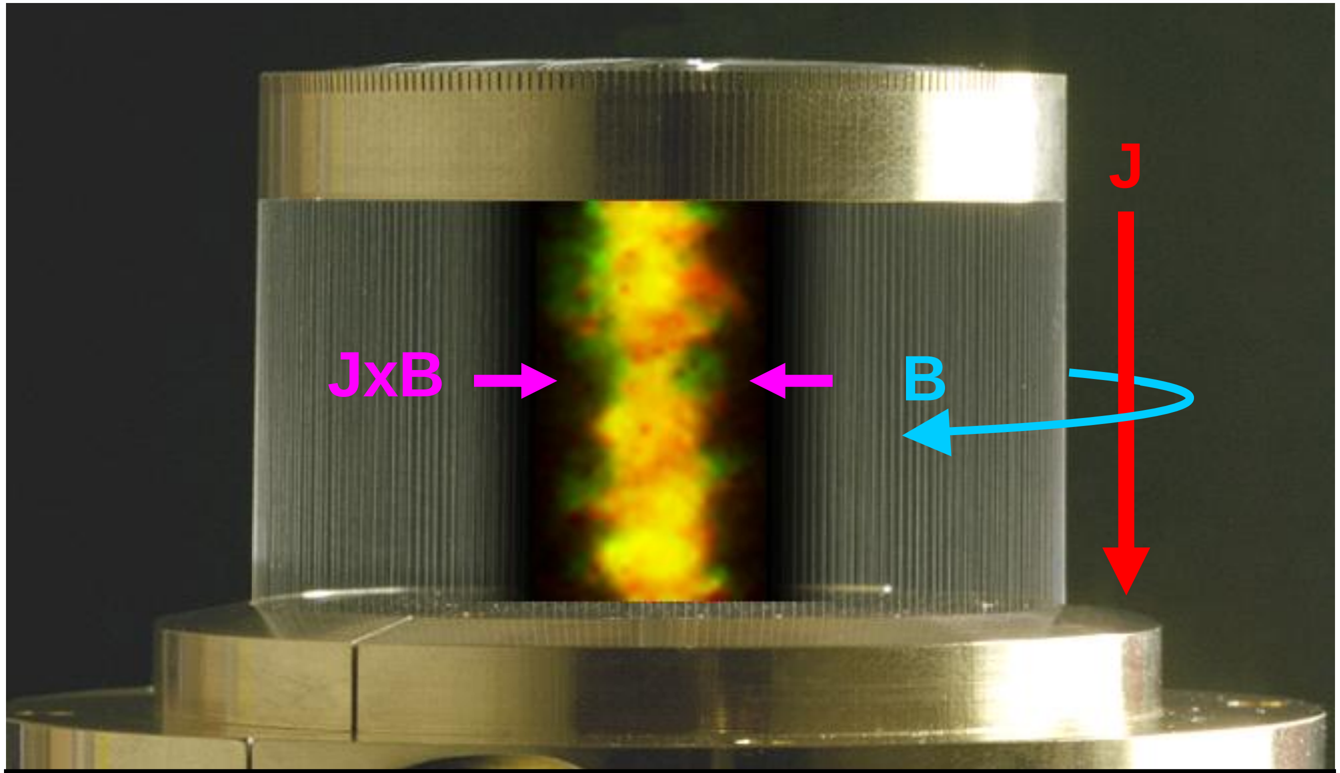
$$P = \frac{B^2}{8\pi} = 105\left(\frac{I_{MA}/26}{R_{mm}}\right)^2 \text{ MBar}$$



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)
- At high yield scale (60 MA)
  - Deliver up to 10 MJ to targets
  - GBar peak drive pressures

Wire array Z-pinches efficiently radiate soft x-rays



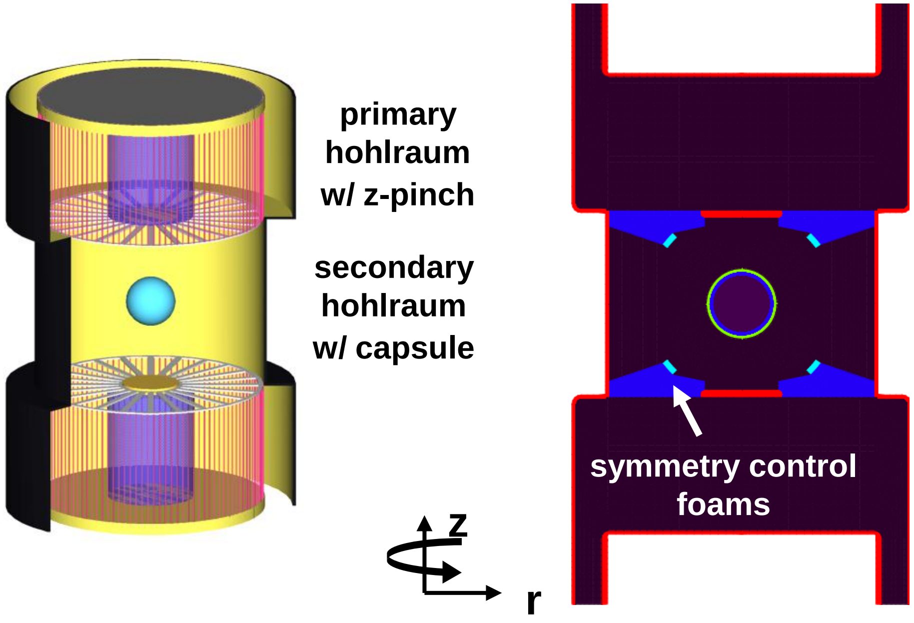
P_{rad} ~ 330 TW, Y_{rad} ~ 2 MJ

> 10% wall plug efficiency

Indirect drive with pulsed power has been studied

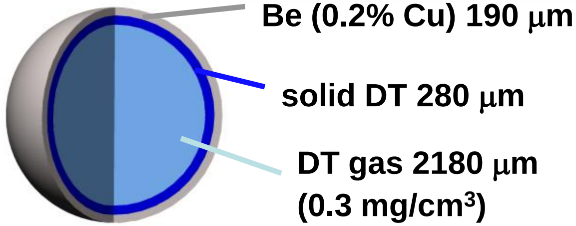
Double z-pinch hohlraum fusion concept

R. A. Vesey, M. C. Herrmann, R. W. Lemke *et al.*,
Phys. Plasmas (2007)

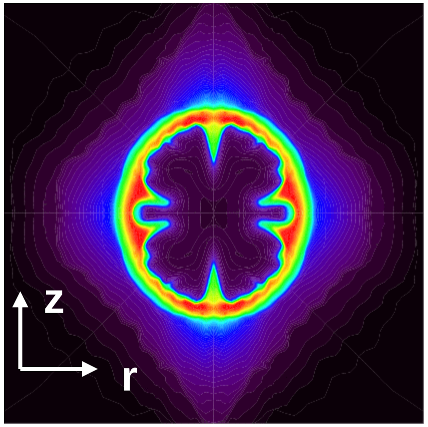


Inefficiencies lead to only 0.04% of the driver wall plug energy in the fusion fuel

High yield capsule design

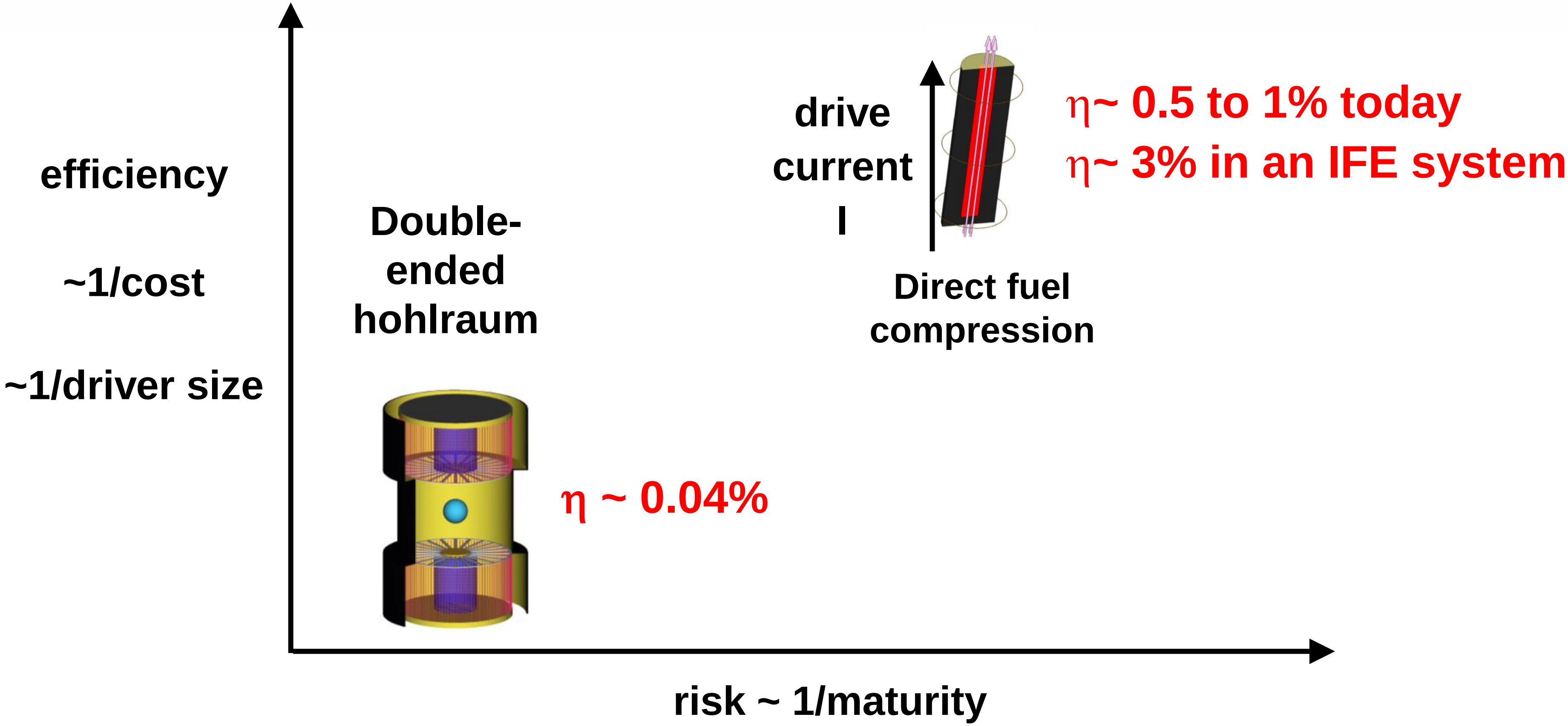


Fuel density at ignition



1D capsule yield 520 MJ
2D integrated yield 470 MJ

Direct fuel compression and heating with the magnetic field could be 25X more efficient than indirect-drive



- A near term directly driven concept we can test is Magnetized Liner Inertial Fusion
- Other High Yield/ High Gain concepts are also being explored

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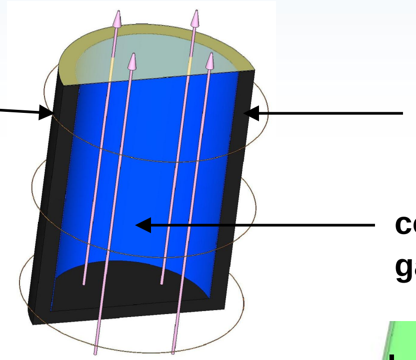
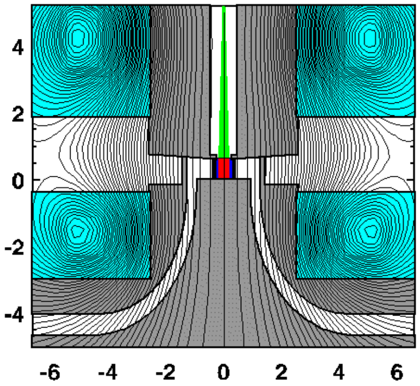
The Z facility provides a unique opportunity to test the Magnetized Liner Inertial Fusion (MagLIF) concept

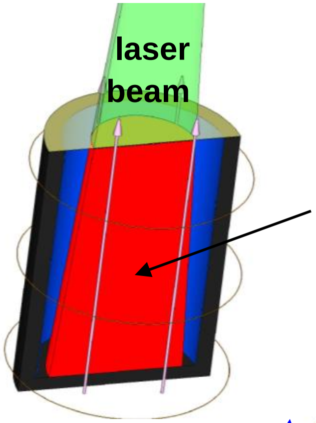
1. A 10-30T axial magnetic field

is applied to inhibit thermal conduction and enhance alpha particle deposition before the implosion begins

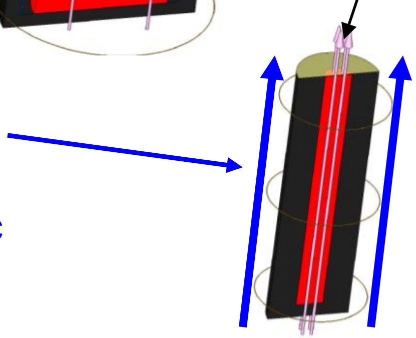




2. Z Beamlet can preheat the fuel to ~100 - 1000 eV to reduce the require compression needed



3. The Z accelerator can provide the drive current which generates an azimuthal drive field (pressure) to efficiently implode the liner (Z pinch) at 50-100 km/sec and compress the axial field by factors of 1000



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

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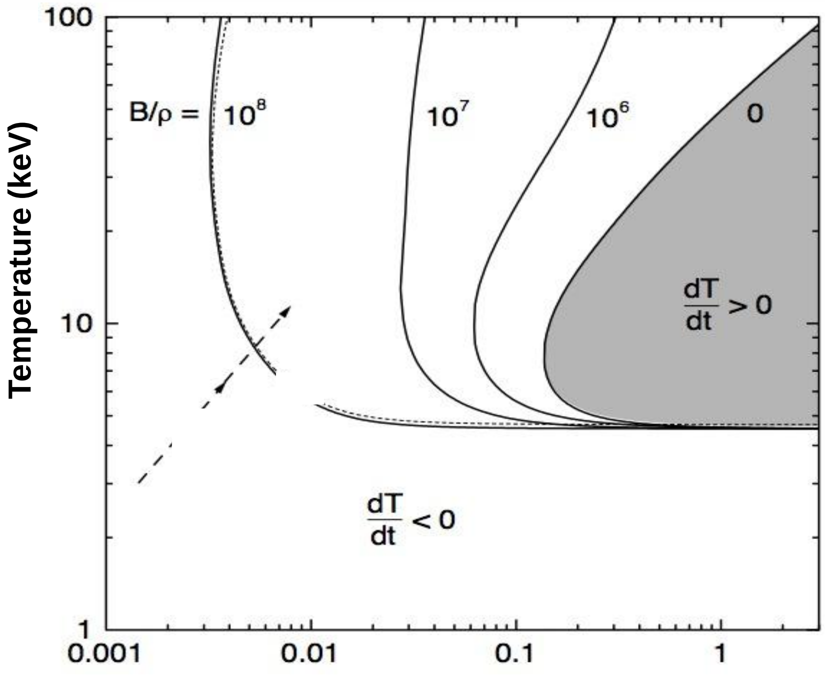
A large, embedded magnetic field significantly expands the space for fusion self heating

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



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

- **inhibits electron conduction**
- **enhances confinement of alpha particles**

Lower r 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/ are needed and therefore large values of B are needed.

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

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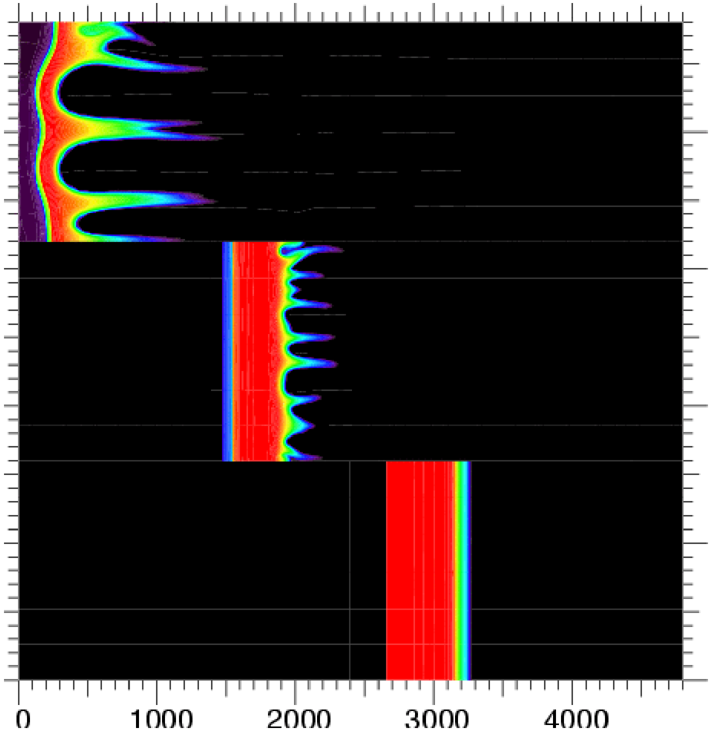
Simulations indicate scientific breakeven (fusion energy out = energy deposited in fusion fuel) may be possible on Z with DT fuel

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
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 resolved



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

The magneto-Rayleigh Taylor instability is the biggest concern for this concept

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The physics issues for direct magnetic-drive targets are similar to those for other inertial fusion concepts

Stabilization techniques

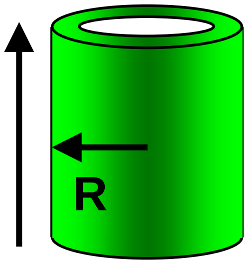
Instability growth

Fuel Preheat

Convergence ratio

Fuel Premagnetization

drive current I



Implosion time and velocity

Driver coupling

Pusher adiabat

Pusher-fuel mix

r-θ symmetry

- We are conducting a vigorous research program to validate the general class of magnetically-driven targets on the Z facility at the MJ target scale

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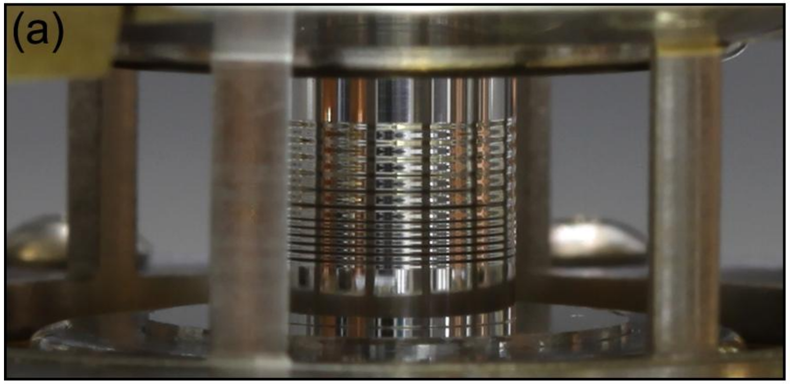
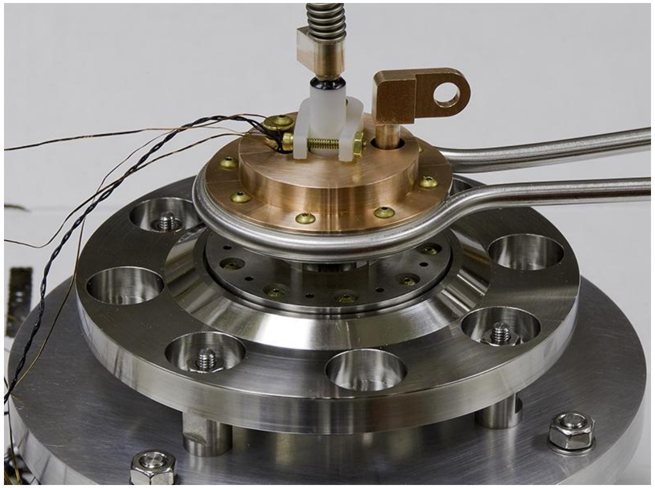
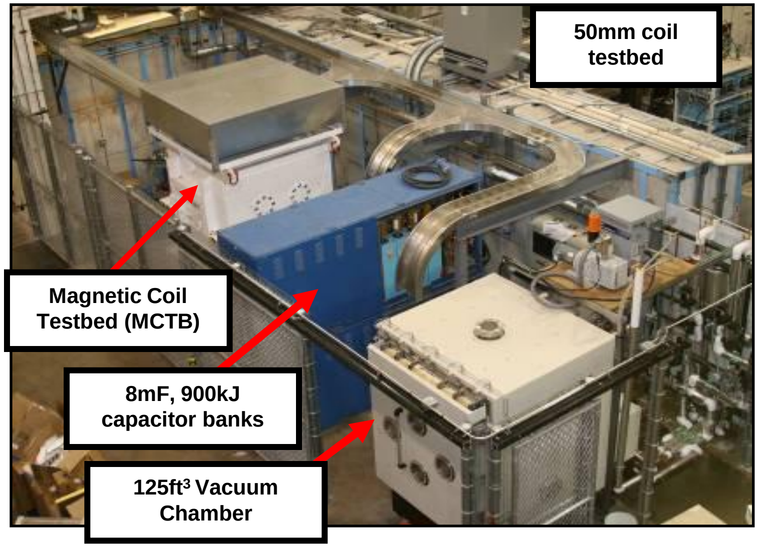
We have already developed most of the capabilities required to test MagLIF on the Z facility



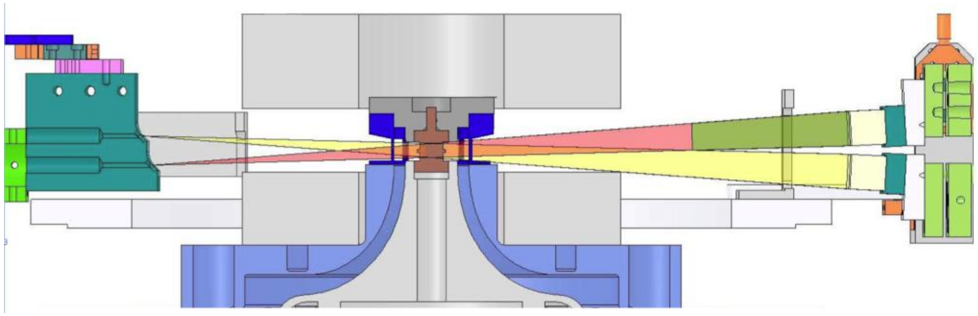
Precision target fabrication



Cryogenic cooling of liner targets has been demonstrated (liquid D2)



Test facility for coil development on site



10 T coil designs allowing diagnostic access will be tested

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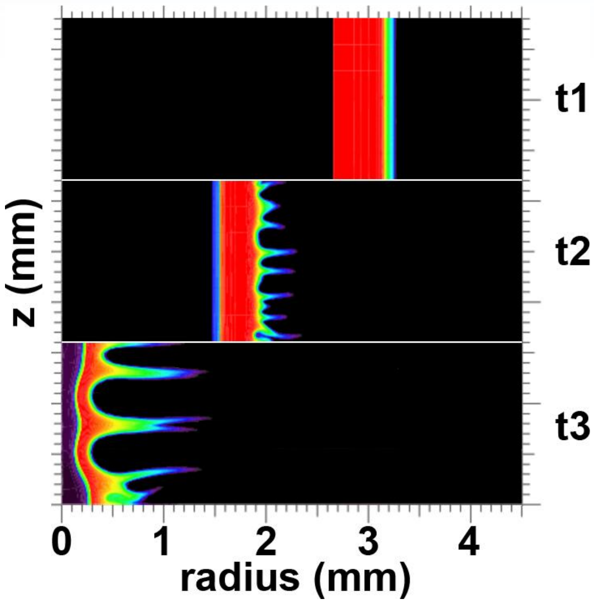
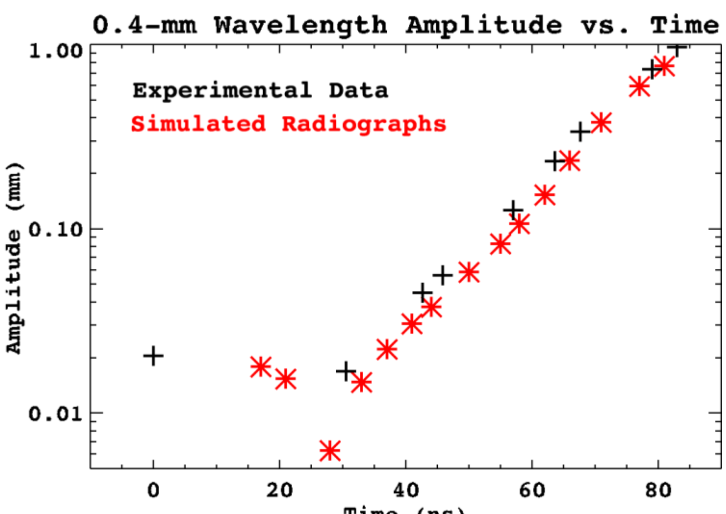
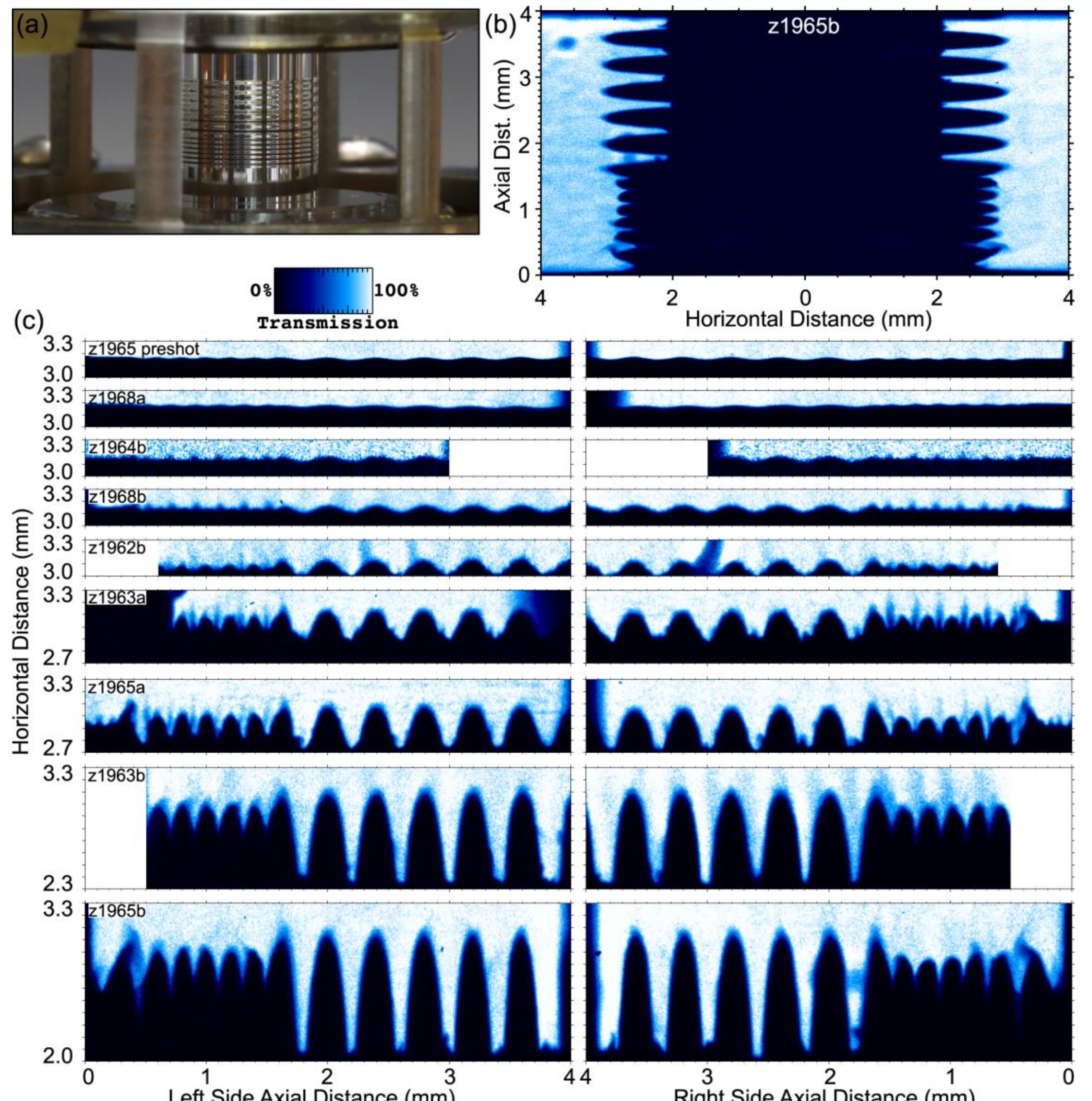
D. Sinars, S. Slutz *et al.*, Phys. Rev. Lett. (2010)

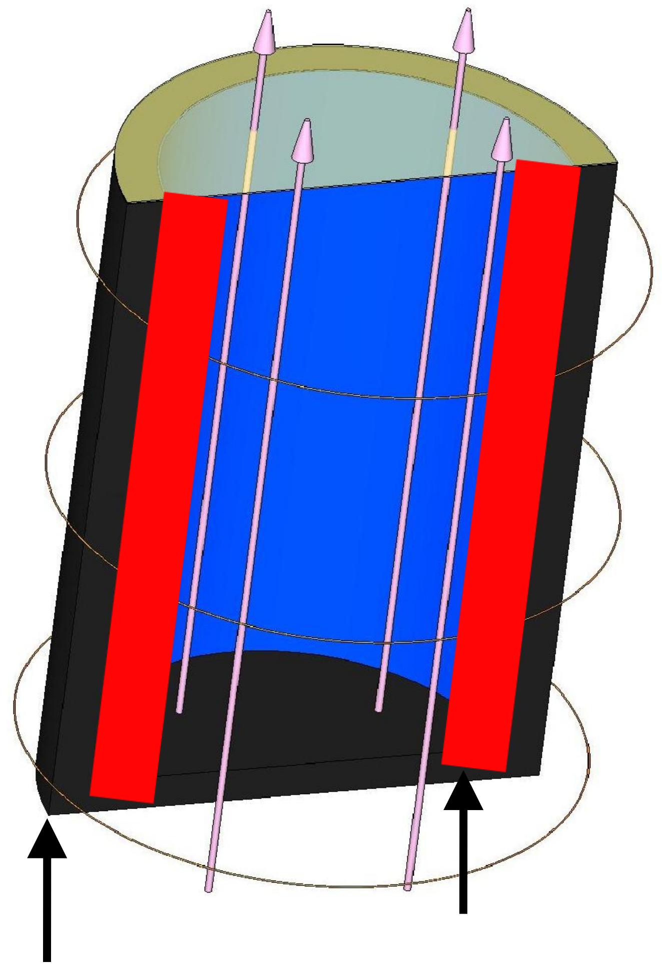
We observe excellent agreement between simulation and experiment for single-mode MRT growth experiments







A levitated shell version of MagLIF could give high yield and high gain on a larger facility



INITIAL CONDITIONS	
Peak Current:	**61 MA**
Al Liner R0:	**4.4 mm**
Liner height:	**10 mm**
Aspect ratio (R0/ΔR):	**6**
Initial gas fuel density:	**10 mg/cc**
Initial B-field:	**10 T**
FINAL CONDITIONS	
Target Yield:	**4.8 GJ**
Target Gain:	**700**
Convergence ratio (R0/Rf):	**22**
Final on-axis fuel density:	**9.3 g/cc**
Final peak B-field:	**12500 T**

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Summary

Pulsed power is an efficient, inexpensive way to create matter at high energy densities

Magnetically driven implosions offer a path to coupling much higher fractions of the driver stored energy to fusion fuel

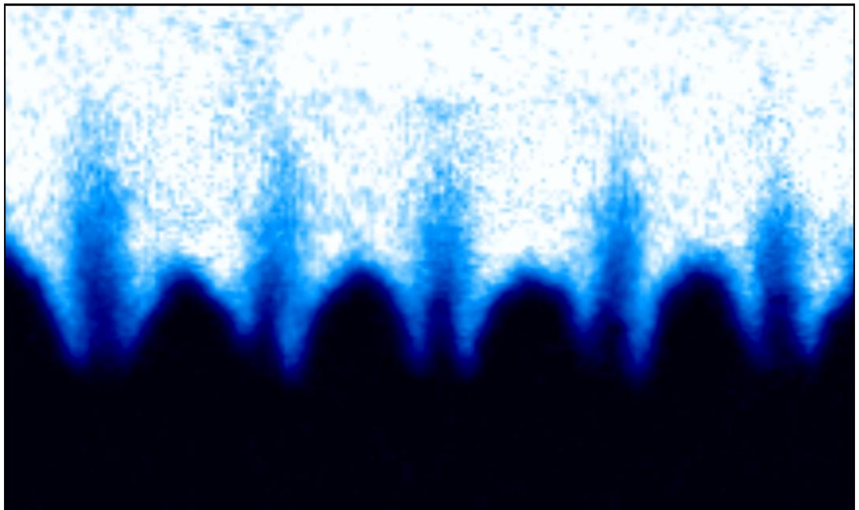
Magnetized Liner Inertial Fusion (MagLIF) offers a near term chance for testing our understanding of magnetically driven implosions. If successful, would lead to breakeven with DT.

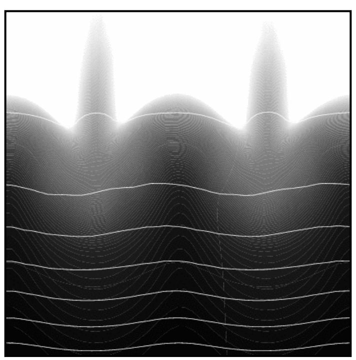
Experimental data on the Magneto-Rayleigh Taylor instability is promising, we hope to begin integrated MagLIF testing in 2012.

A high-yield (GJs), high-gain (>500) MagLIF design is under development. Much of the relevant physics can be tested on Z.

Backups

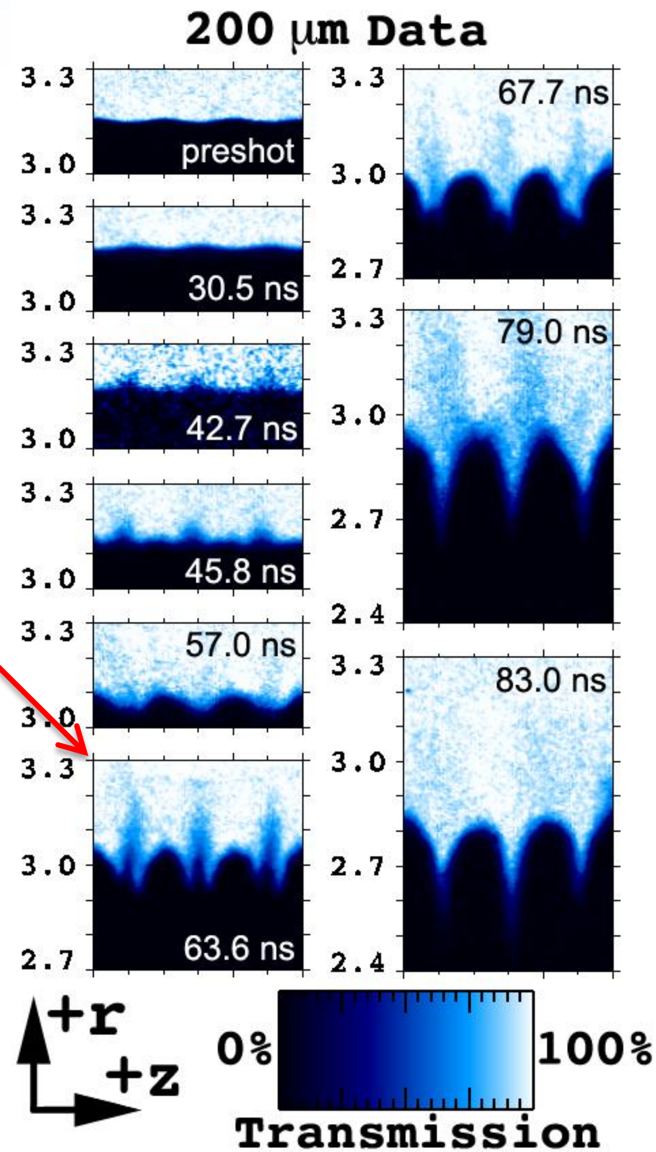
At shorter wavelengths we see very different behavior, but still get good agreement



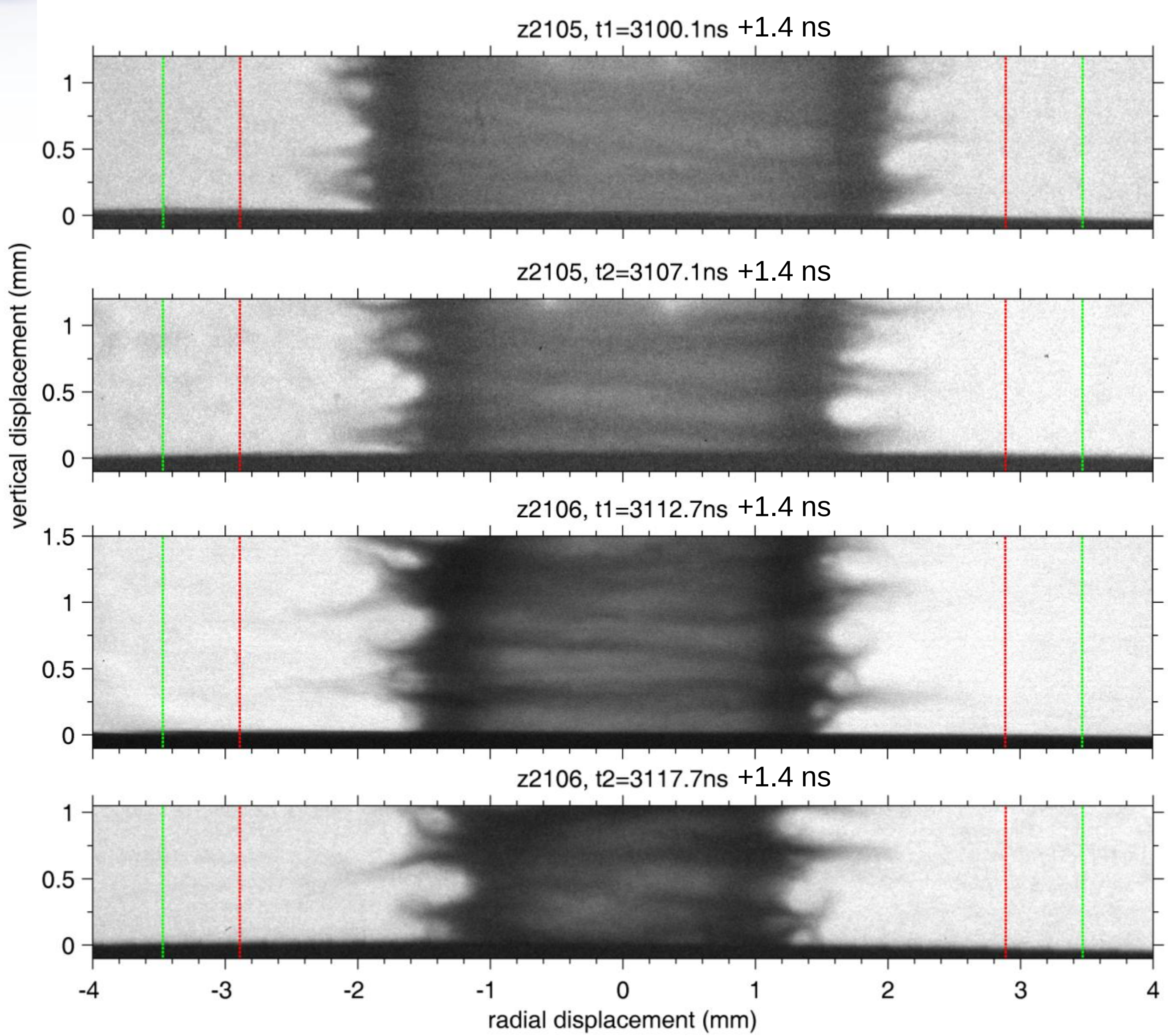


Simulated density map with rB_θ contours

Ablated material coalesces in valleys to form jets visible in the radiographs



Radiographs of several rough Be liners imploding have been obtained



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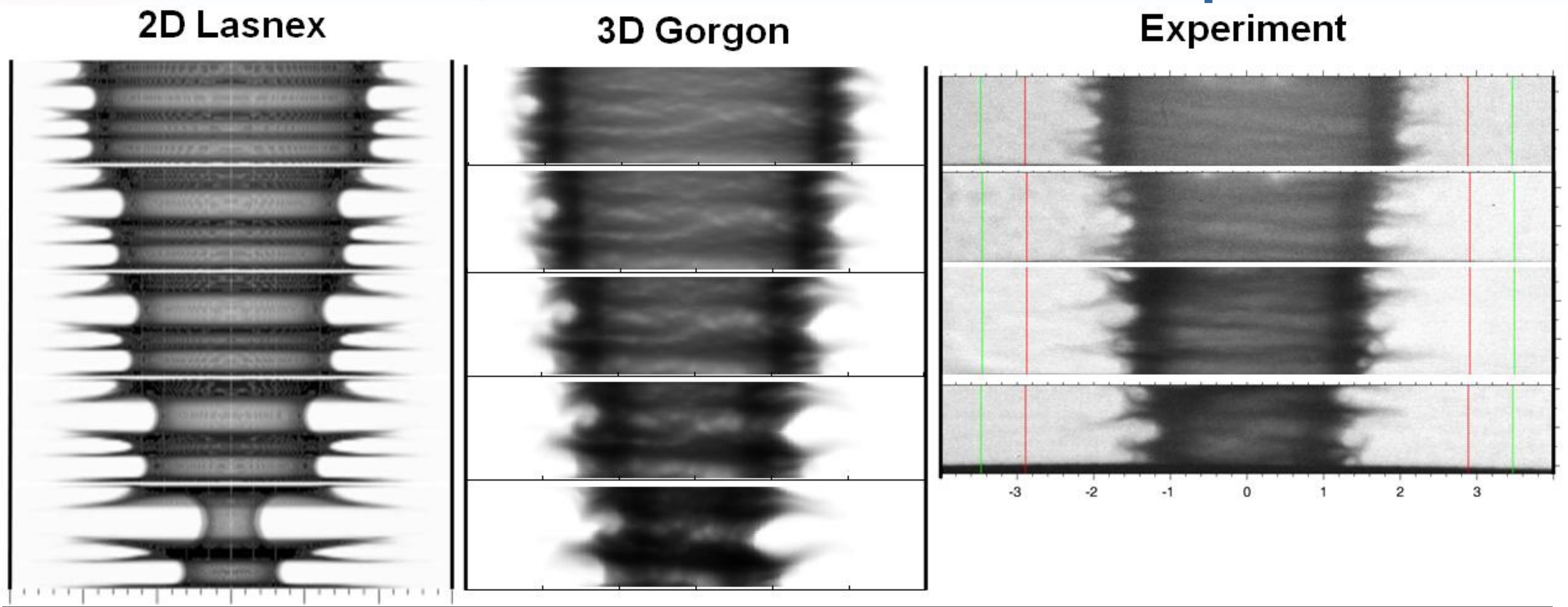
Based on our experience with 2D vs. 3D z-pinch simulations, 3D calculations will be important



- **2D calculations of wire-array z-pinch implosions overestimate growth rates for MRT instability not seen in 3D calculations and experiments [e.g., Yu *et al.*, Phys. Plasmas 15, 056301 (2008).]**
- **2D calculations of liner z-pinch implosions likewise overestimate MRT growth compared to 3D simulations and experiments**
- **2D calculations tend to predict extreme on-axis conditions (as in 1D)**

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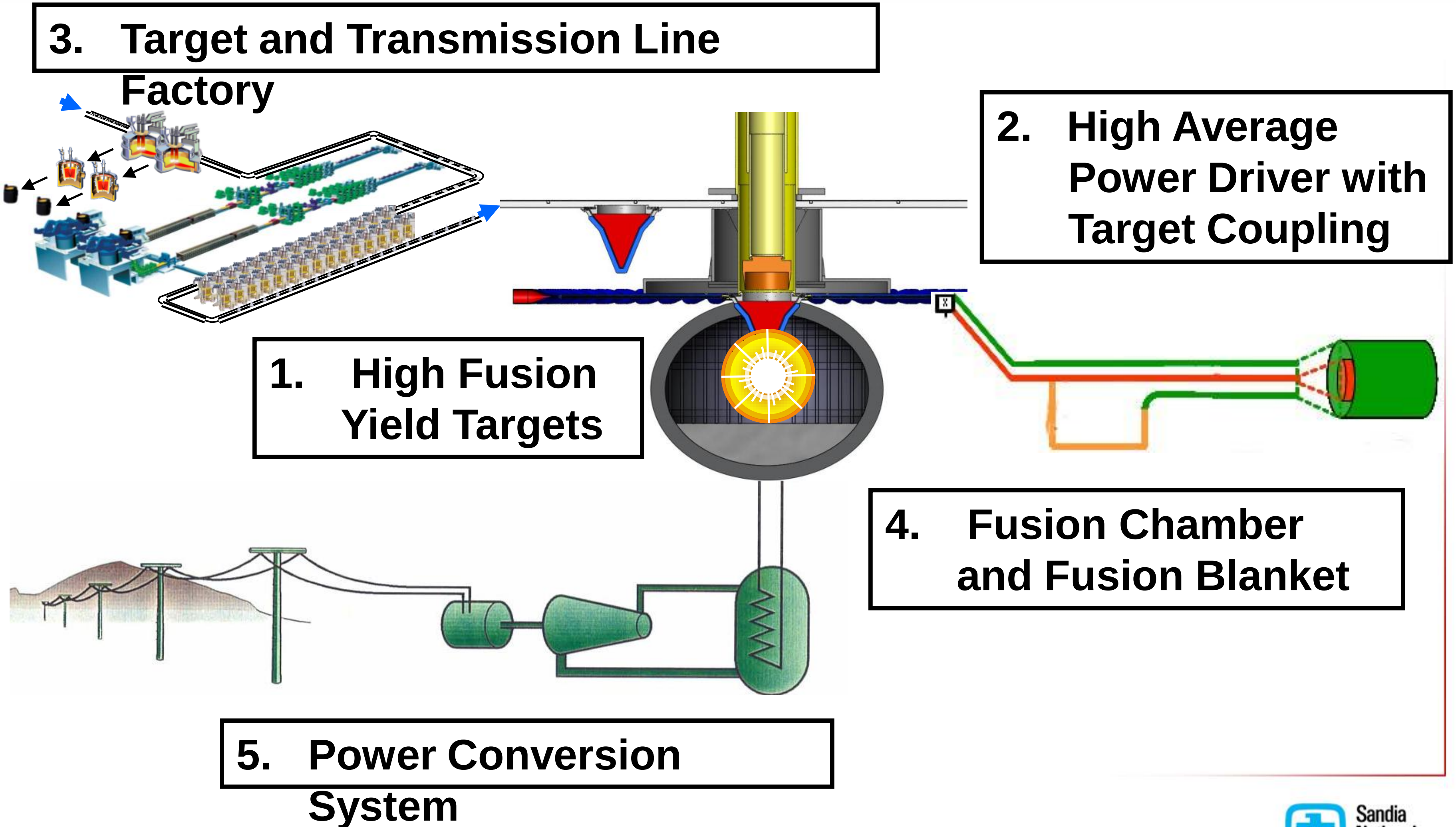
At a high level, all IFE power sources have five major elements



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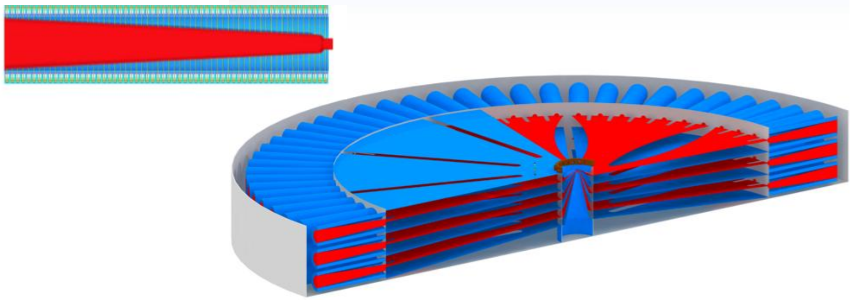
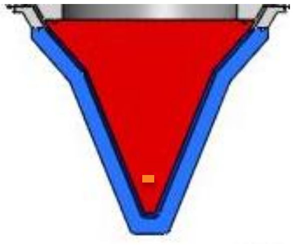
4 challenges for Pulsed Power IFE

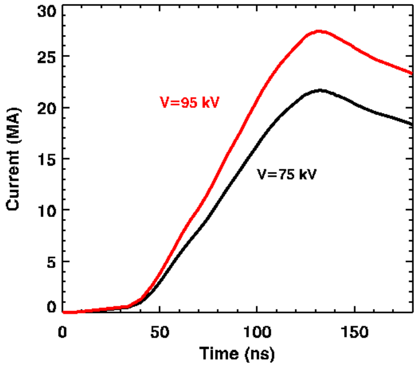
Rep-rate Linear Transformer Drivers (LTD)

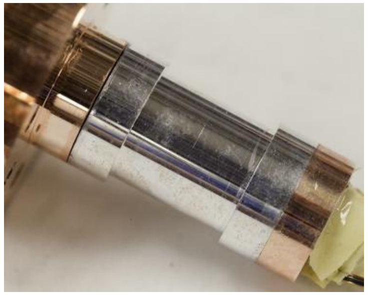


Coupling
Recyclable Transmission Lines (RTLs)

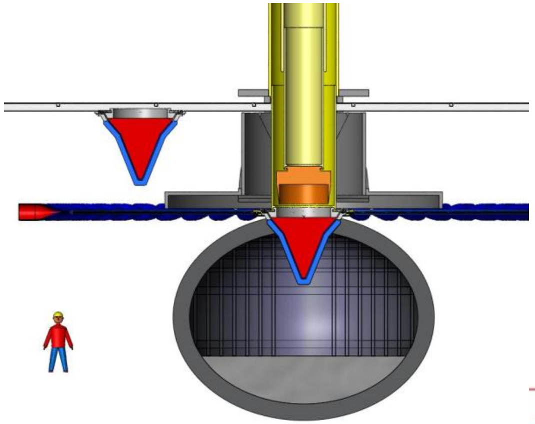


Direct Drive Target Physics





Thick Liquid Wall (TLW)
Fusion Chambers



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Large yields and low rep-rate may be an attractive path for Inertial Fusion Energy

The logic of the integrated system is compelling

- Compact, efficient, low cost, long-lifetime, repetitive driver
- Advanced, efficient, low cost, robust targets that are simple to fabricate
- ⟹ Very large absorbed target energies
- ⟹ Very large fusion yields
- ⟹ Allows low rep-rate
- ⟹ RTL coupling is feasible, engineering development required
- ⟹ RTL provides vacuum for power flow, clears chamber debris
- ⟹ RTL permits a thick-liquid-wall chamber
- ⟹ Thick-liquid-wall & vaporizing blanket provide long lifetime chamber
- ⟹ Long inter-pulse interval clears chamber
- ⟹ RTL can shield line of sight to the driver

Key enabling physics: magnetically-driven-targets
Key enabling technologies: LTD's and RTL's

What are the unique aspects of pulsed power IFE?

- Z can efficiently couple 2 MJ's of energy to fusion targets
- Refurbished Z was inexpensive (~$4/Joule)
- New pulsed power architectures based on Linear Transformer Drivers (LTD's) are rep-rateable, efficient, and low cost
- Targets directly driven by magnetic fields are a new idea we are exploring
- Our pulsed power IFE concept uses large yields, low rep-rates, and thick liquid walls

- 1)Overview of the status of Z-pinch target technology (level of maturity)
- We are making rapid progress applying the understanding of inertial confinement fusion science developed over decades in the ICF program to our approaches to pulsed power driven ICF. We are excited by our rate of progress and believe we can continue.
- 2)Important distinctions between targets for Z-pinch fusion and for laser or heavy ion drivers
- Z-pinch targets have fundamentally different coupling to the driver than either lasers or heavy ion beams. This coupling requires an electrical connection, which presents both challenges (large mass per shot, cost of fabrication, ensuring connection between driver and target) and advantages (direct connection, can protect target from chamber environment, enables liquid walls) over other schemes. These targets while building on ICF foundations, do introduce new physics that must be understood. Large driver energies and drives are possible since pulsed power is inexpensive. This enables large yields. Large yields are desirable because of low repetition rates.

- 3) Key engineering, scientific, and economic challenges associated with Z-pinch target development
- Scientific challenges include understanding magnetically driven implosions. Lots of science there. That understanding is key to understanding many of the engineering challenges, although some, like building a driver capable of coupling significantly more energy than Z, and devising a scheme for repetitive recyclable transmission lines could be addressed today. Both of these in turn lead to what is the overall system reliability and cost which is the economic challenge for IFE.

- 4) How these challenges are currently being addressed

- Target physics research is modestly funded by NNSA. Driver research is proceeding at a low level consistent with our stewardship of pulsed power science and technology. A program is needed to address these challenges for IFE.

- 5) How Z-pinch targets could fit into an overall program for IFE (e.g., gain, rep rate)

- Z-pinch targets occupy a relatively unique niche in the space of IFE targets as the overall system is likely to optimize at very high yields and low repetition rates. This is consistent with both the driver costs (inexpensive) and the coupling scheme (recyclable transmission lines).