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# Pulsed Power Fusion Targets

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in collaboration with our colleagues at Sandia National Laboratories

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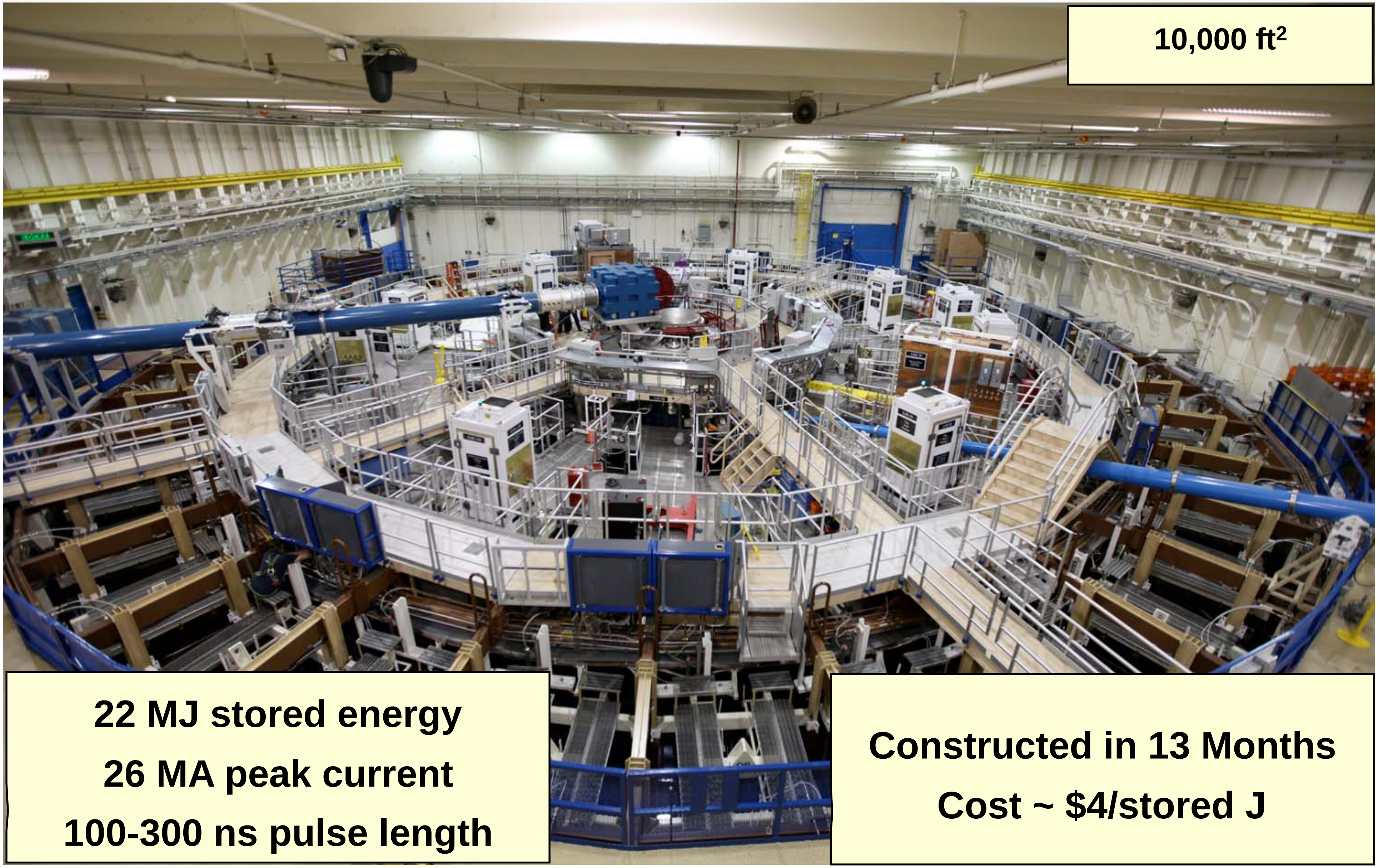
# The Z pulsed power generator provides a compact MJ-class target physics platform



10,000 ft$^2$

22 MJ stored energy

26 MA peak current

100-300 ns pulse length

Constructed in 13 Months

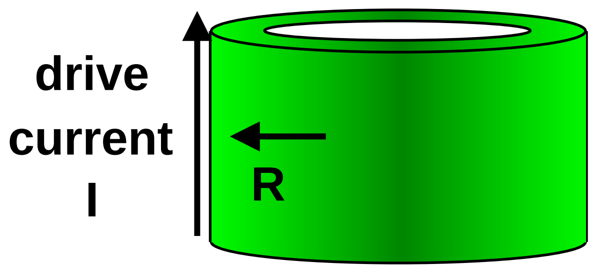
Cost ~ $4/stored J

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

**Magnetic fields and currents can push conductors around:**

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

**Magnetically-Driven Implosion**




$$B \sim \frac{I}{R} \qquad P \sim B^2 \sim \left(\frac{I}{R}\right)^2$$

**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 (no energy wasted on ablation)**

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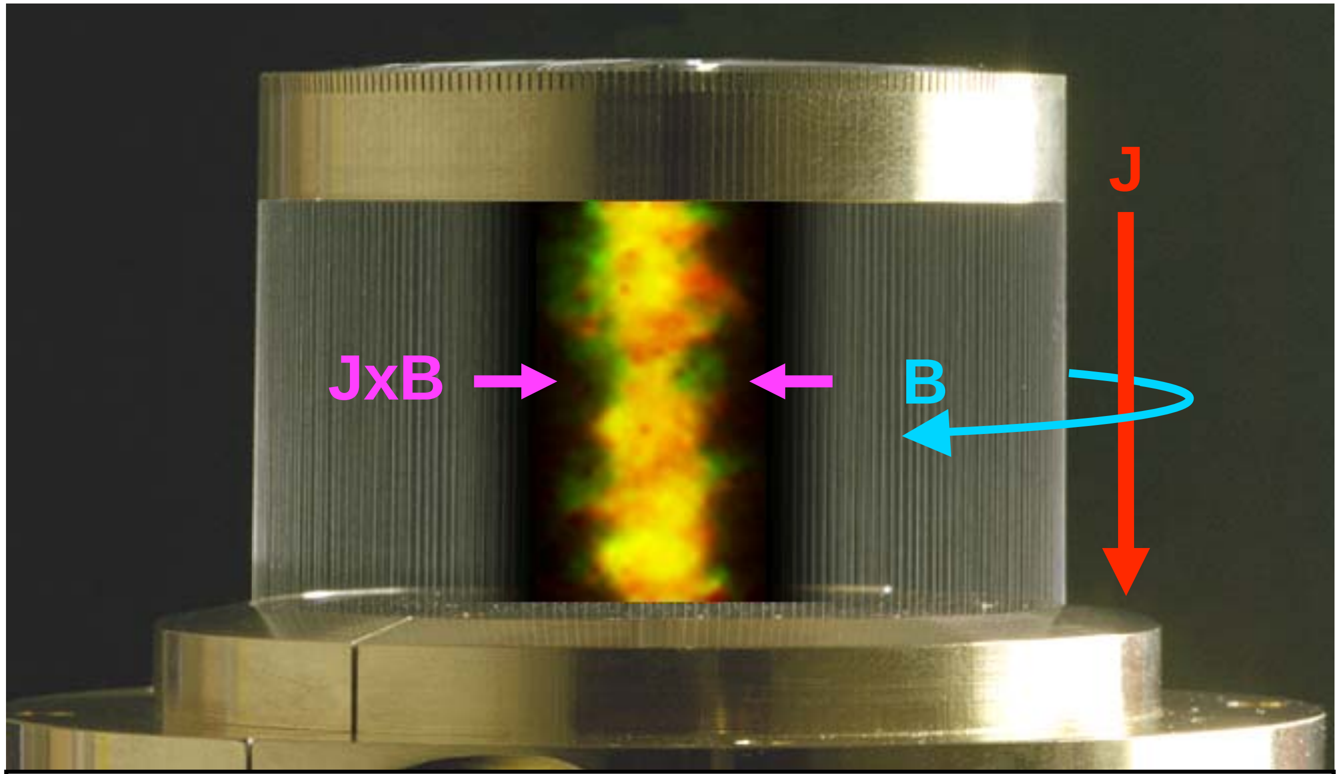
# Wire array Z-pinches efficiently radiate soft x-rays




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

**> 10% wall plug efficiency**

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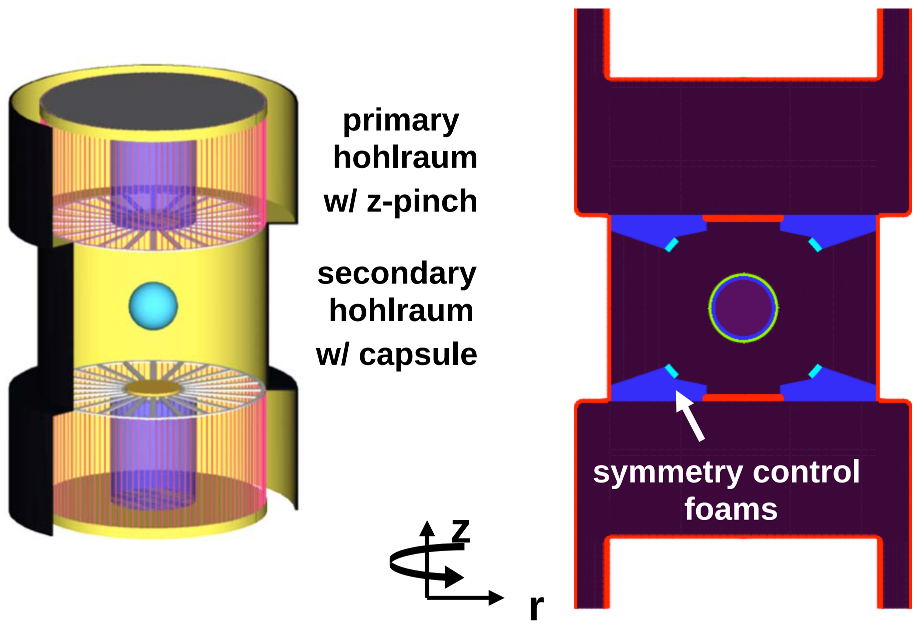
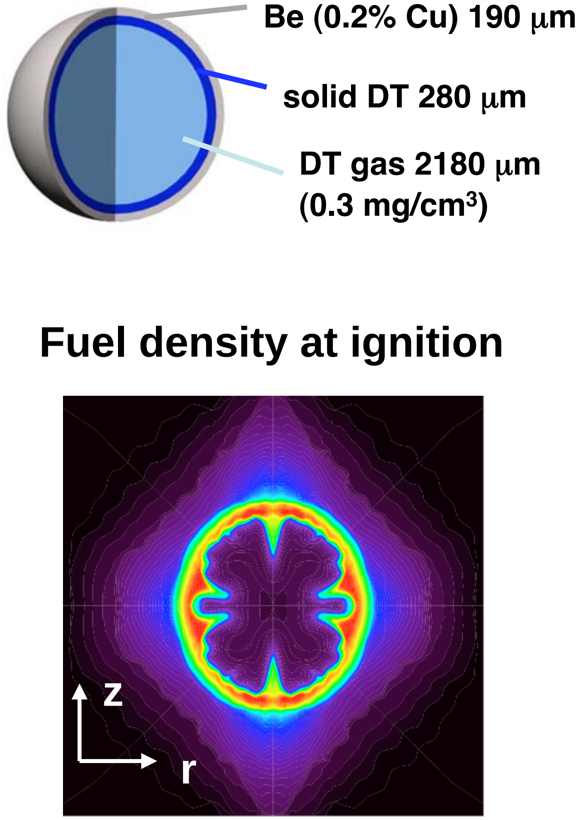
# Integrated LASNEX simulations demonstrate 400+ MJ fusion yield in a pulsed-power z-pinch driven hohlraum

## Double z-pinch hohlraum fusion concept

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



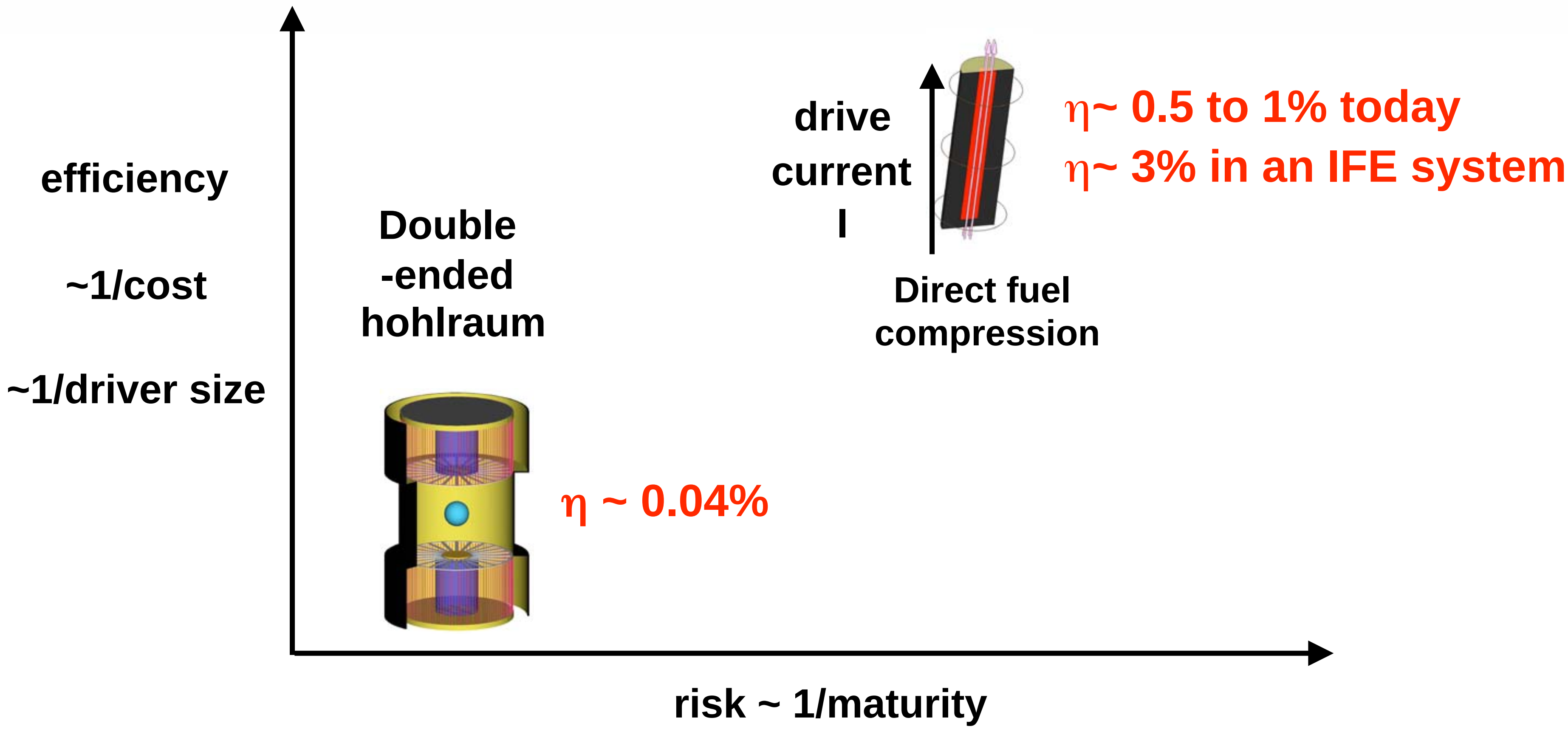

## High yield capsule design




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

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

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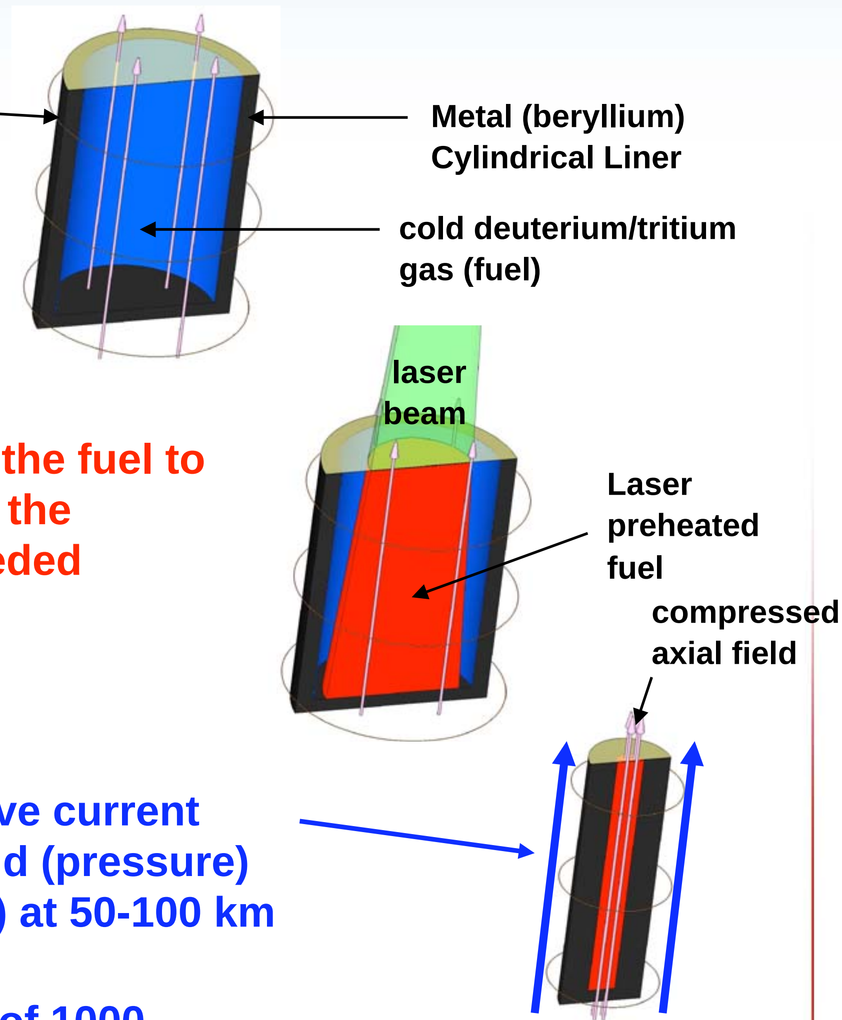
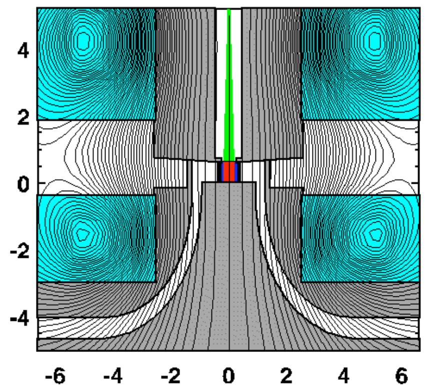
# The Z facility provides a unique opportunity to test the Magnetized Liner Inertial Fusion (MagLIF) concept

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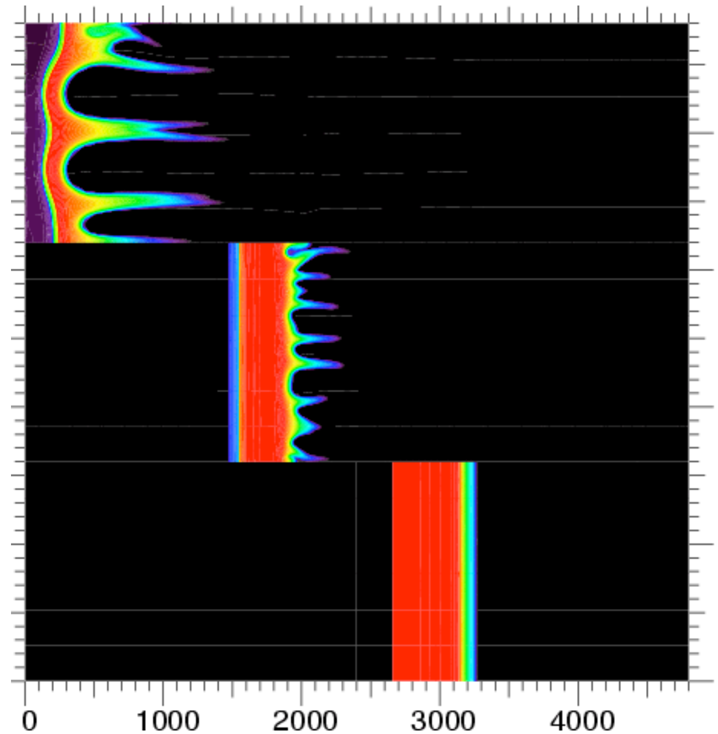
# Simulations indicate scientific breakeven (fusion energy out = energy deposited in fusion fuel) may be possible on Z

| | |
|---|---|
| **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

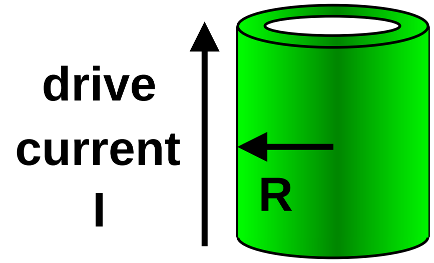
***Stabilization techniques***

***Instability growth***

***Fuel Preheat***

***Convergence ratio***

***Fuel Premagnetization***




***Implosion time and velocity***

***Driver coupling***

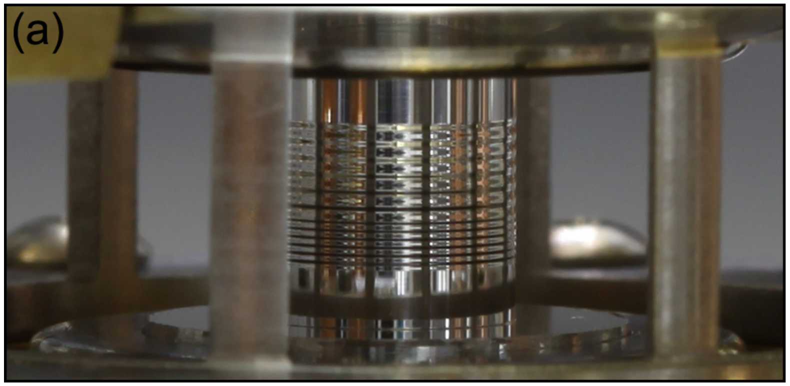
***Pusher adiabat***

***Pusher-fuel mix***

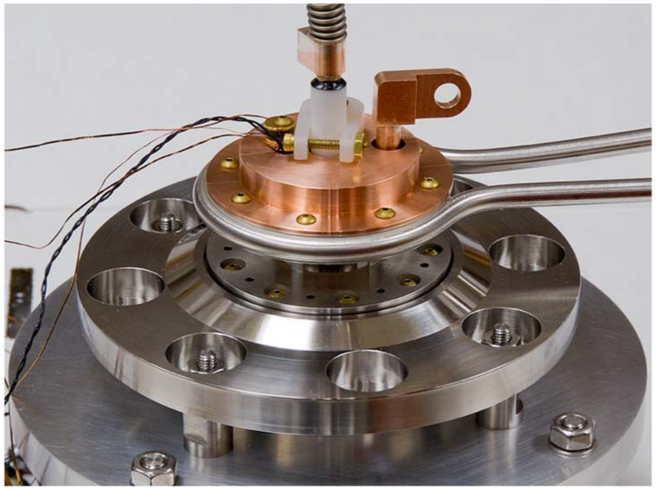
***r-$\theta$ symmetry***

- 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

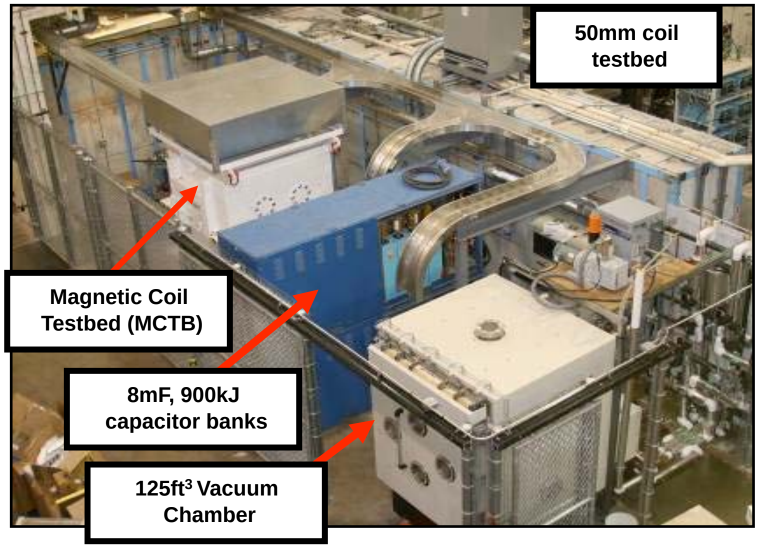
# We have already developed most of the capabilities required to test MagLIF on the Z facility, rest are imminent



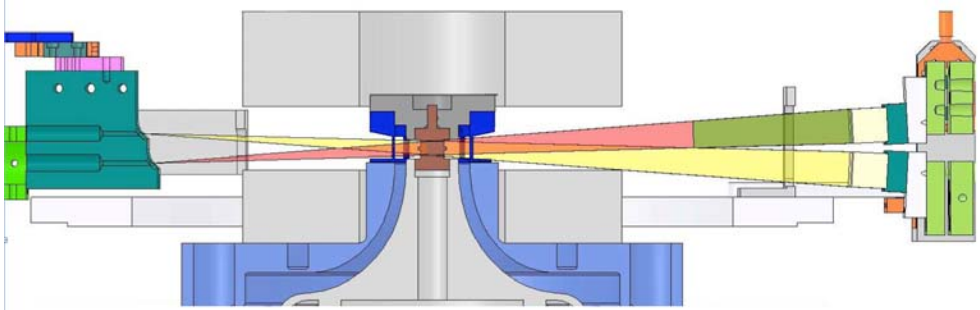

High-quality target fabrication on site



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



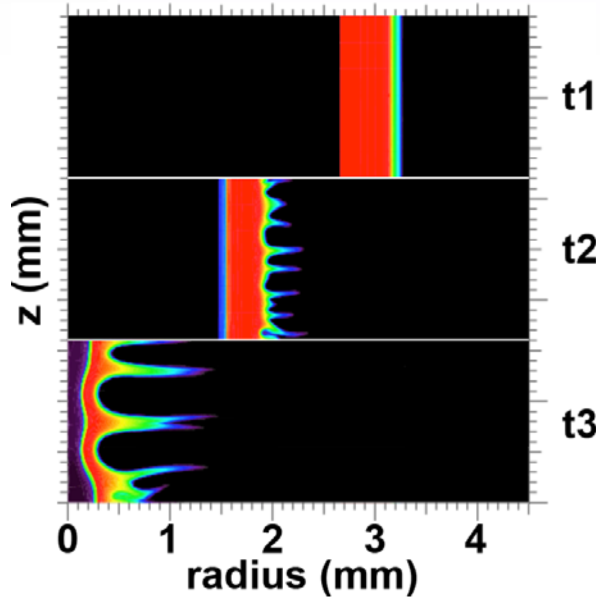

Test facility for coil development on site

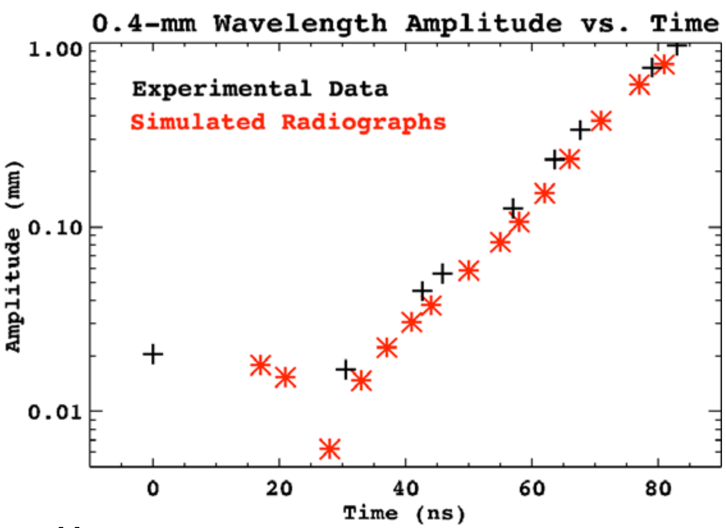


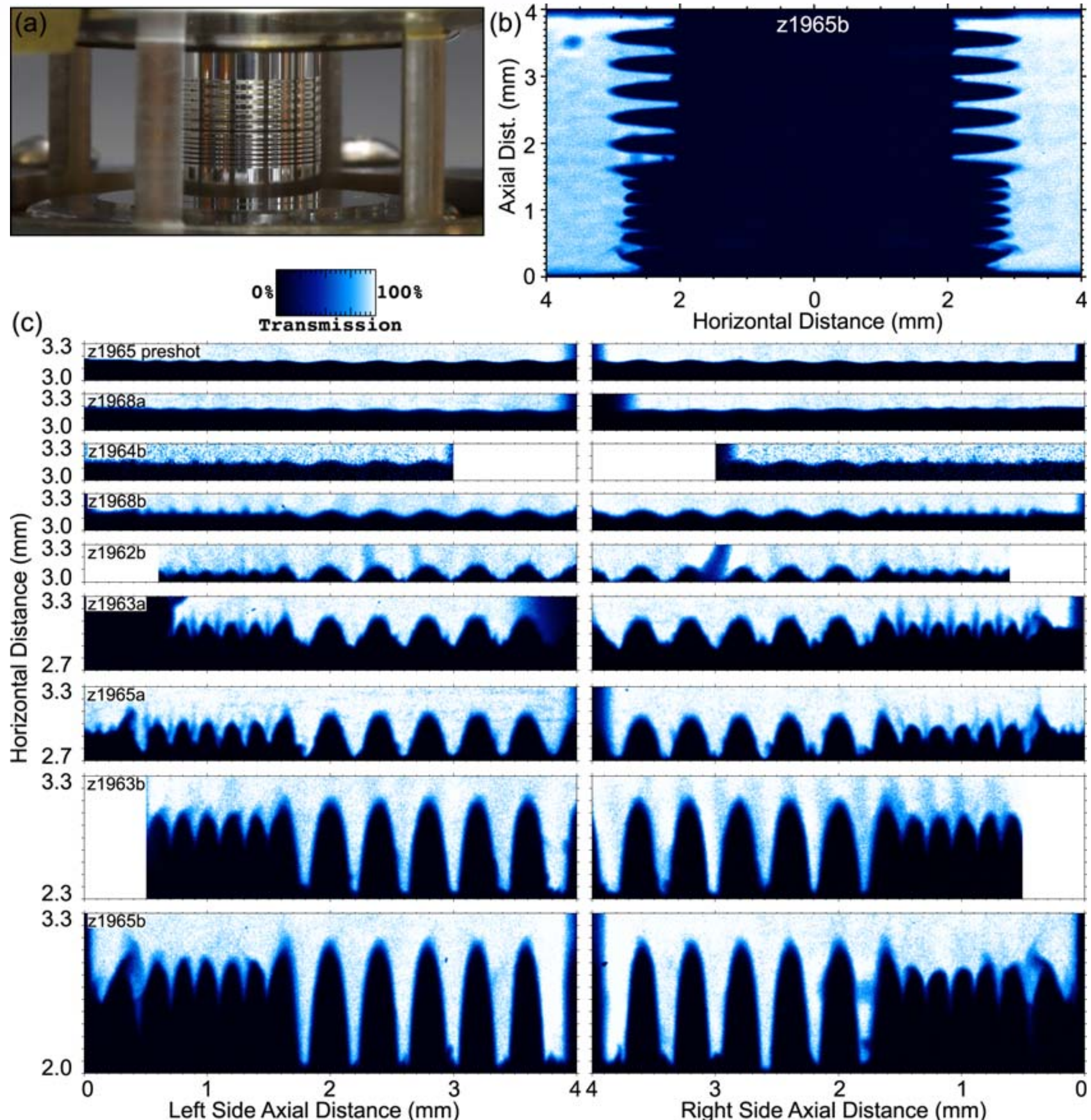
10 T coil designs allowing diagnostic access on Z will be tested

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

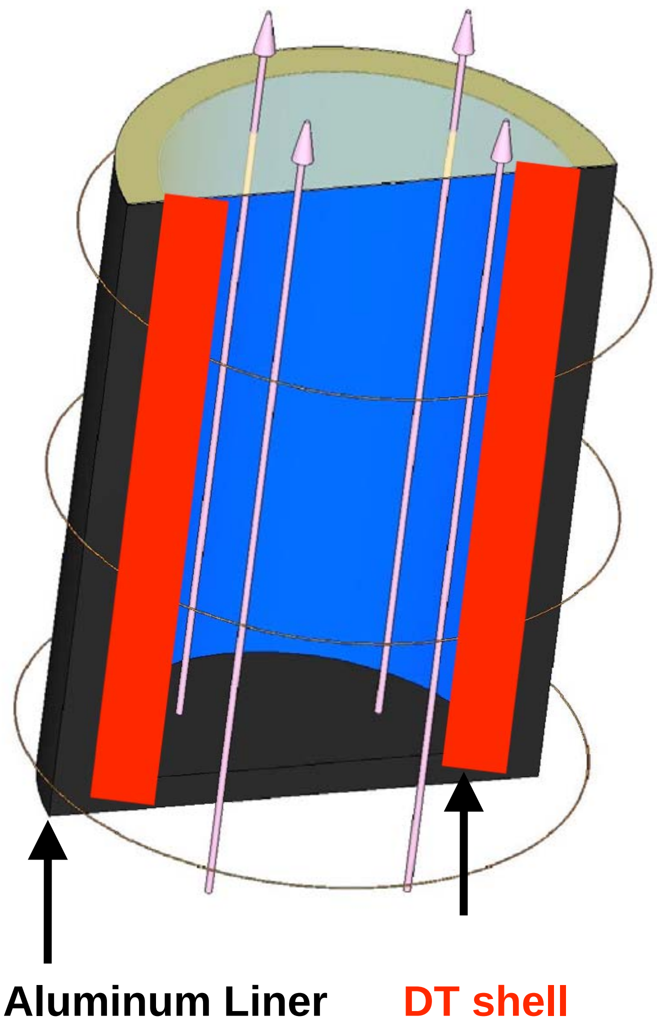
# We observe excellent agreement between theory and experiment for single-mode MRT growth experiments



# 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 |

# 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.

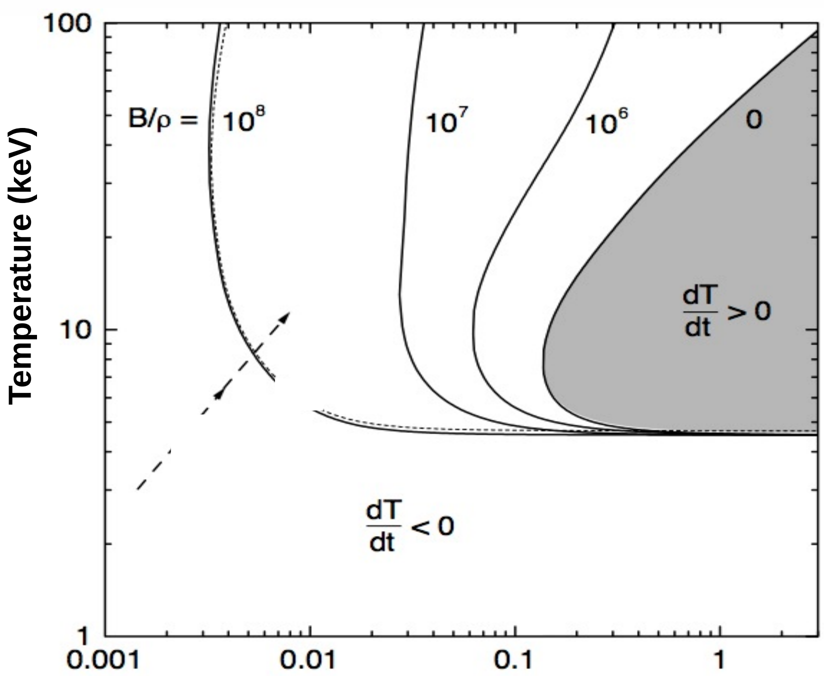
Experimental data on the Magneto-Rayleigh Taylor instability is promising, we hope to do an integrated MagLIF test in 2012.

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

# Backup

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

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




Fuel areal density (g/cm²)

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

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

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