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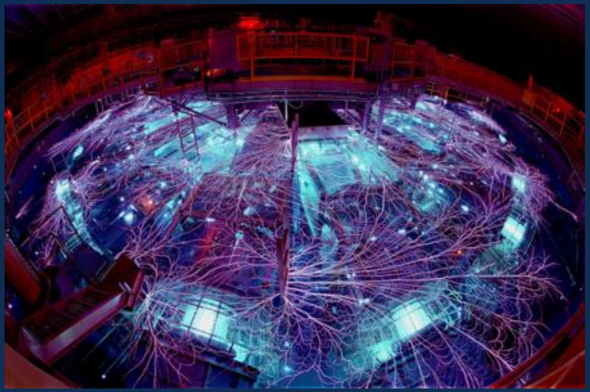

Overview of Fusion Research at Sandia National Laboratories

M. Keith Matzen

Director, Pulsed Power Sciences Center

9/5/2013

U.S. DEPARTMENT OF ENERGY

NNSA National Nuclear Security Administration

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Summary

- **We can use large magnetic fields and high currents to push on matter in different ways, enabling the creation of unique states of HED matter**
- **The refurbished Z facility is being used to explore unique states of matter at high energy densities**
- **Magnetized Liner Inertial Fusion (MagLIF) combines a magnetically driven implosion with a pre-imposed axial magnetic field to enable an interesting approach fusion self heating on the Z facility with relaxed requirements**
- **Initial MagLIF experiments on Z are promising**

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

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

HED Matter P > 1 Mbar, B > 5 Megagauss

- **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**

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

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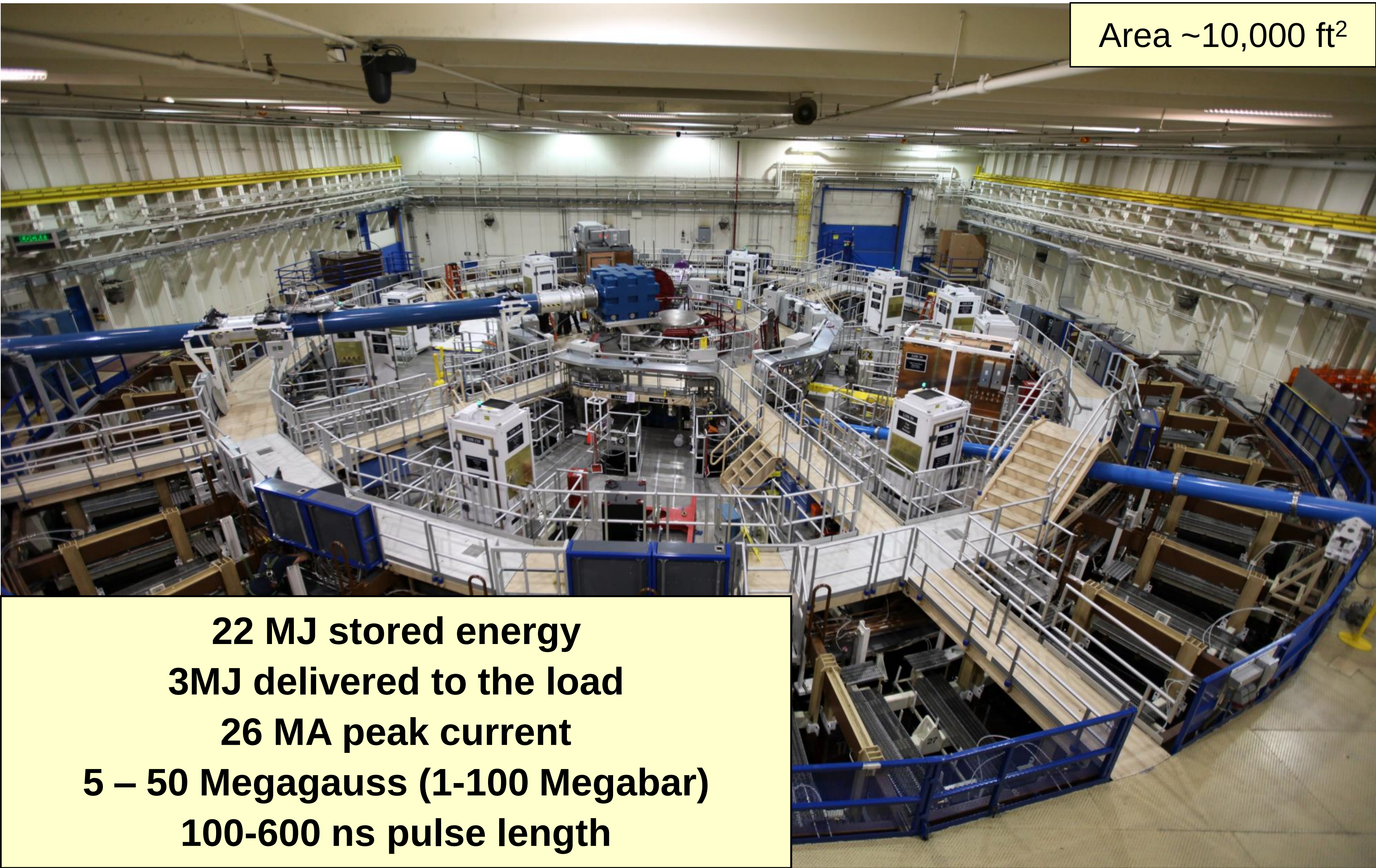
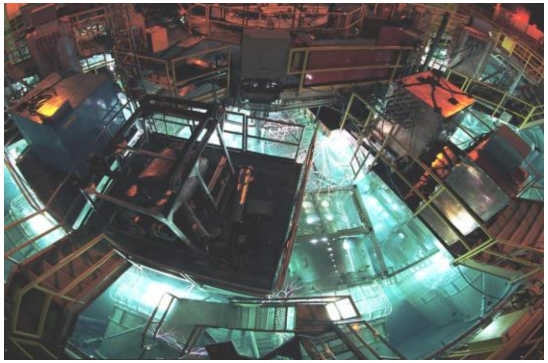


Area ~10,000 ft^2

22 MJ stored energy
3MJ delivered to the load
26 MA peak current
5 – 50 Megagauss (1-100 Megabar)
100-600 ns pulse length

The Z-Refurbishment project was completed in 2007

Last Shot



July '06

Demolition Completed

Sept '06

Tank Modifications Completed

Jan '07

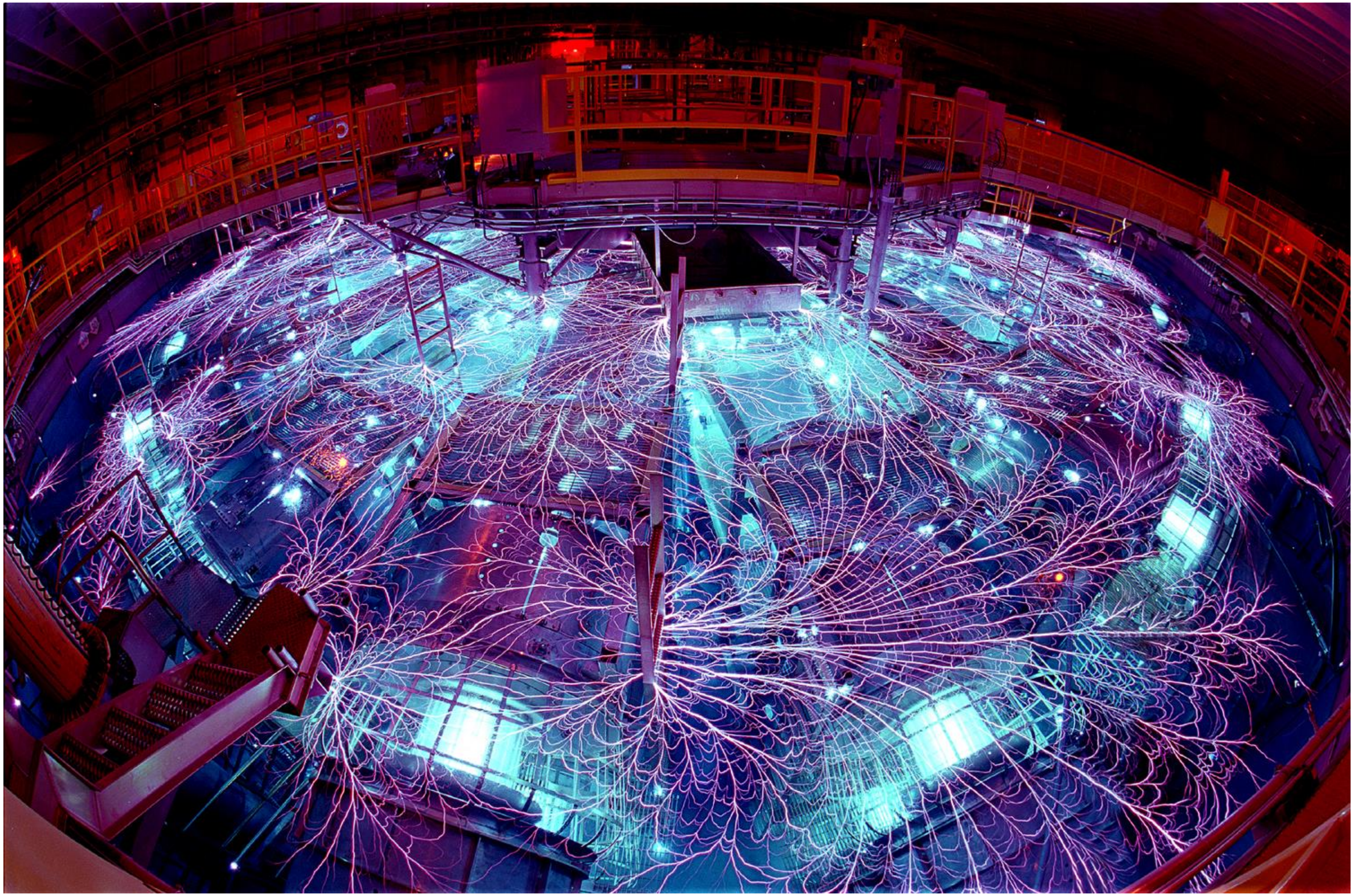
Installation Underway – Multiple Contractors

March '07

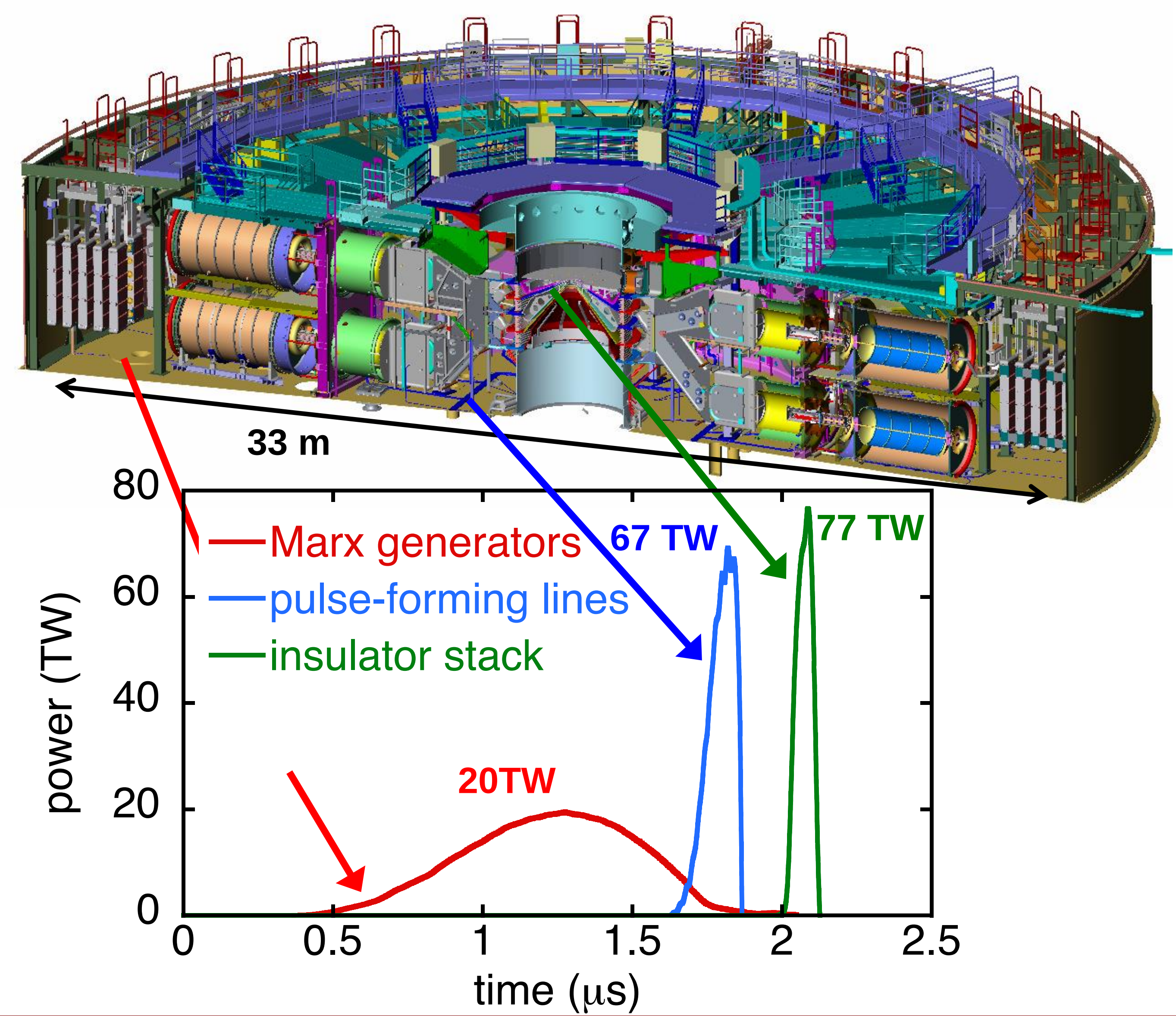
Installation Completed

August '07

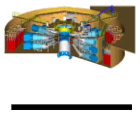
Pictures of Z were more interesting before refurbishment



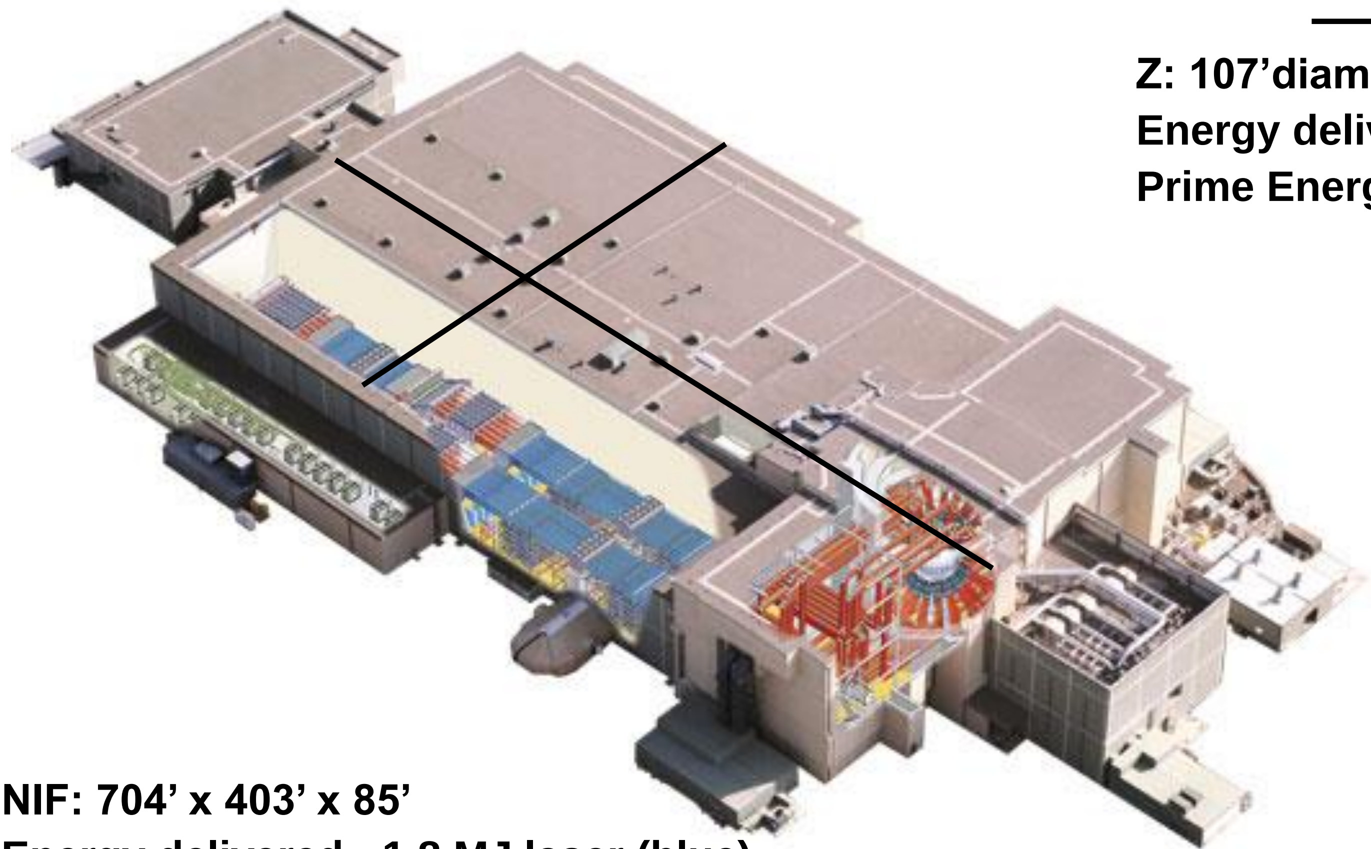
Z works by compressing electromagnetic energy in time and space



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

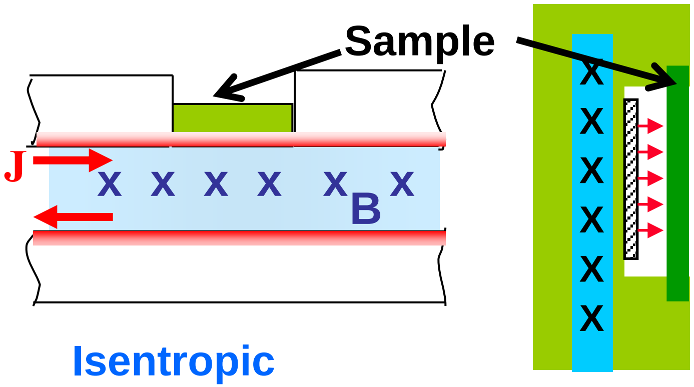


NIF: 704' x 403' x 85'
Energy delivered~ 1.8 MJ laser (blue)
Prime Energy ~ 370 MJ

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

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

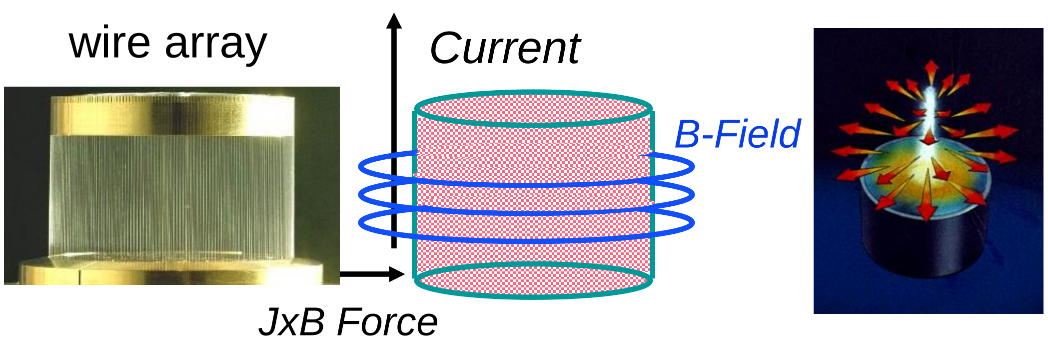
Materials Properties



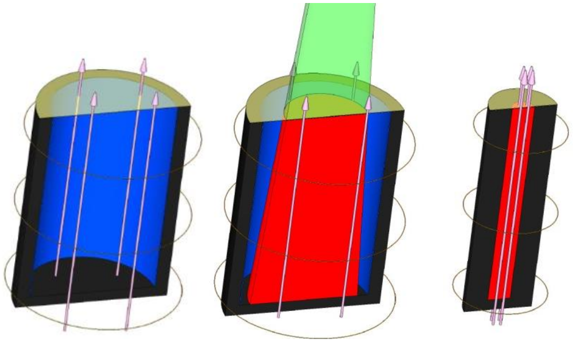
Isentropic Compression

Flyer Plate

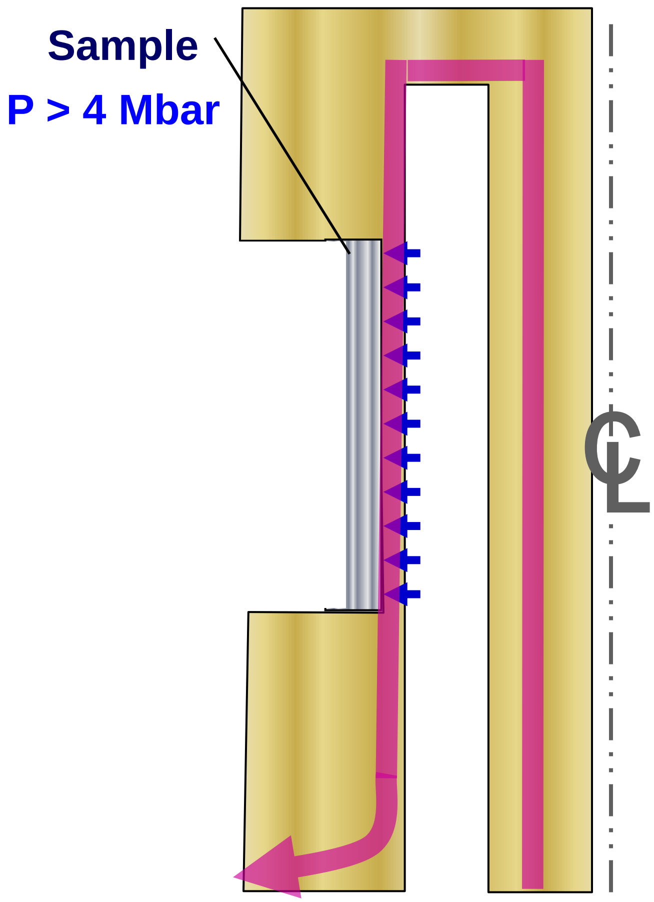
Z-Pinch X-ray Sources

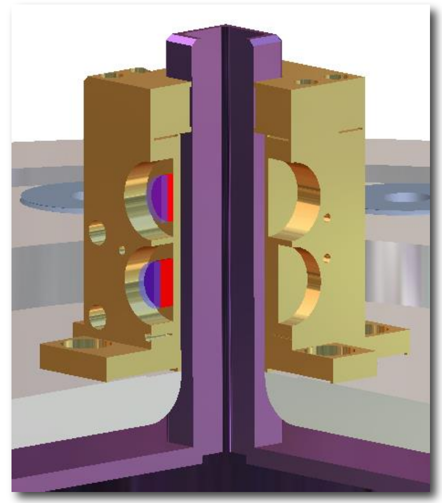


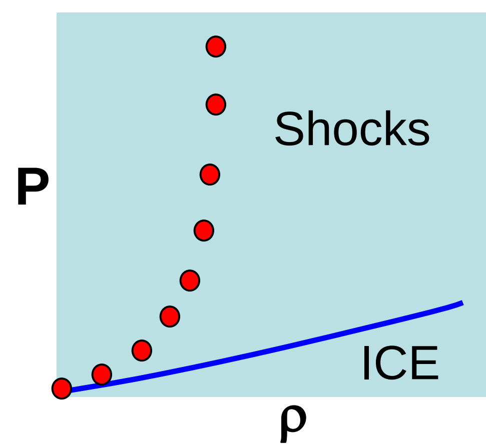
Inertial Confinement Fusion

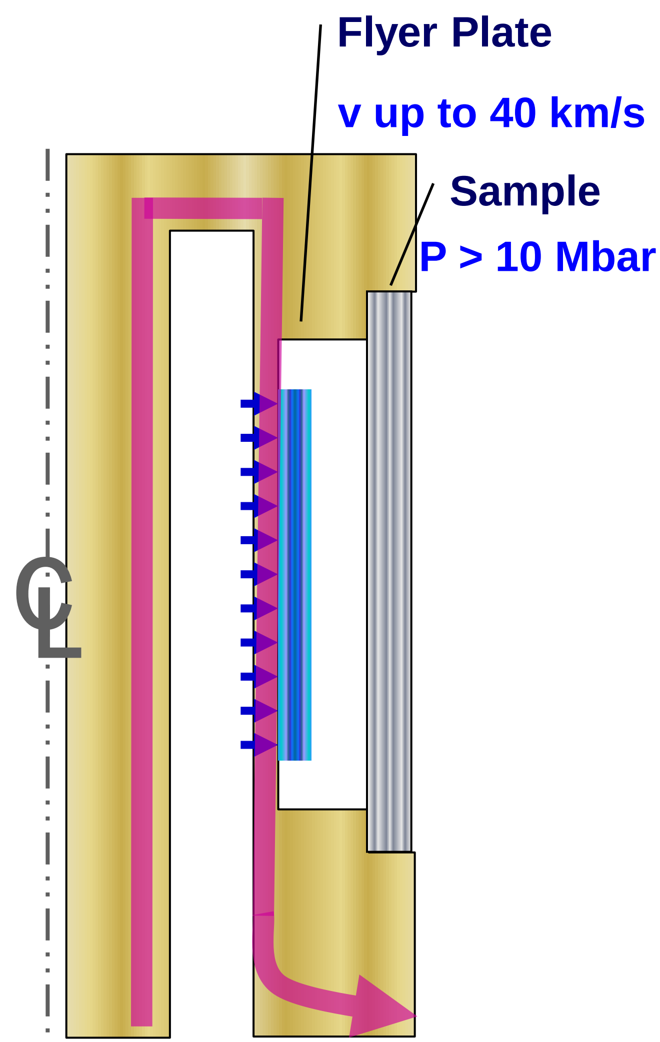


Isentropic compression and shock wave experiments map different regions of phase space









Isentropic Compression Experiments:
gradual pressure rise in sample

Shock Hugoniot Experiments:
shock wave in sample on impact

Z has been used to study material properties in the multi-Mbar regime for many materials

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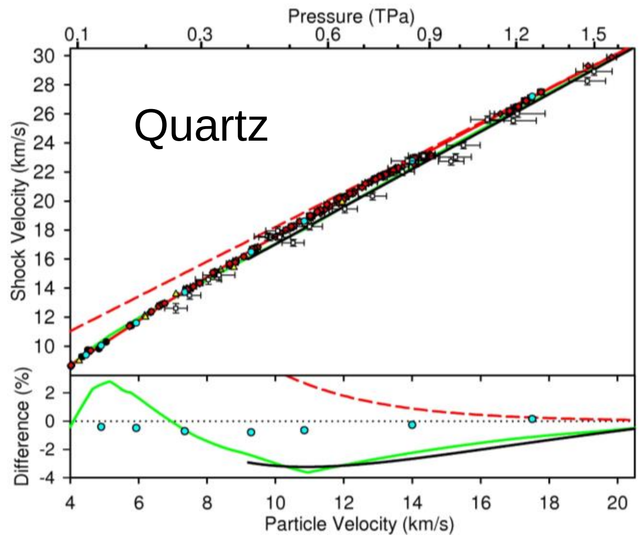

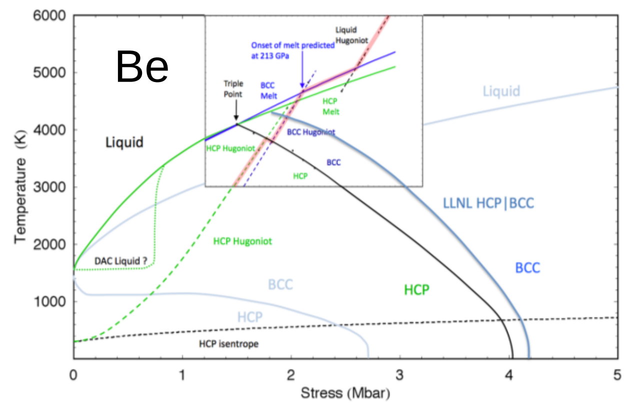

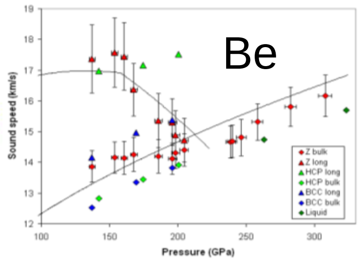

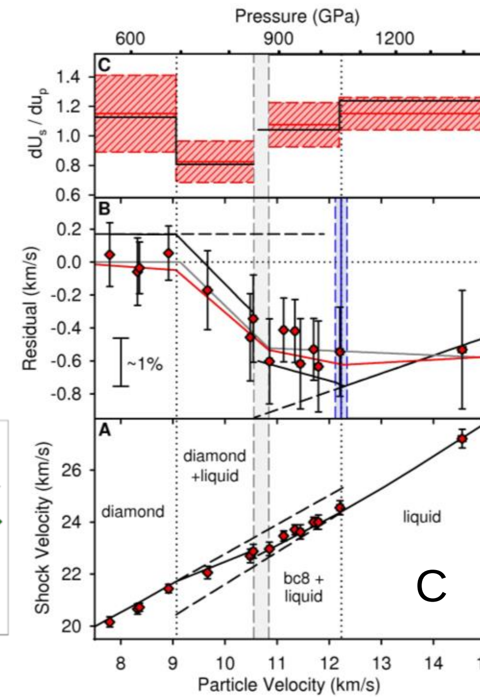

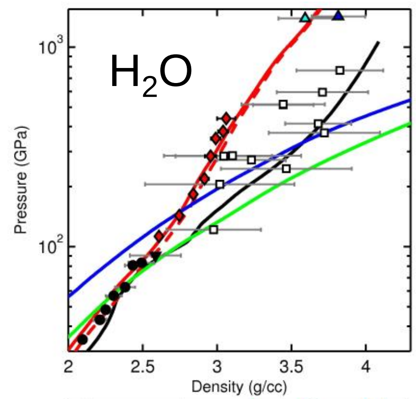

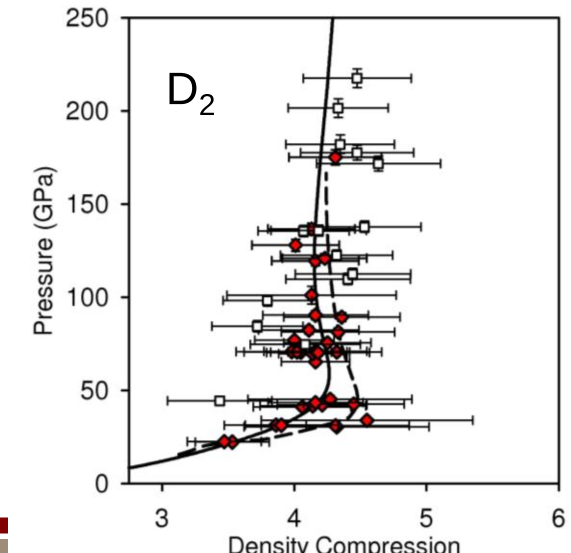

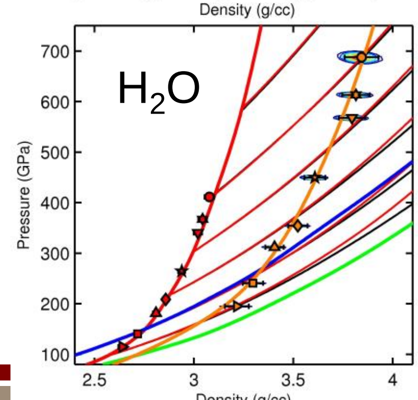

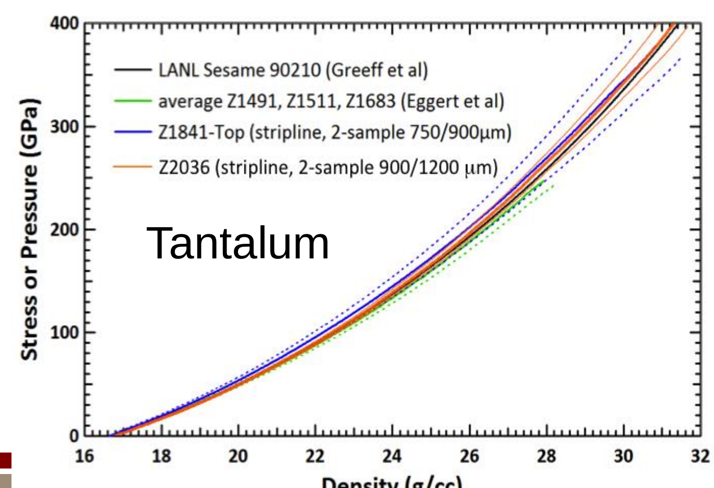

Magnetically driven implosions are efficient, powerful, x-ray sources from 0.1 to 10 keV

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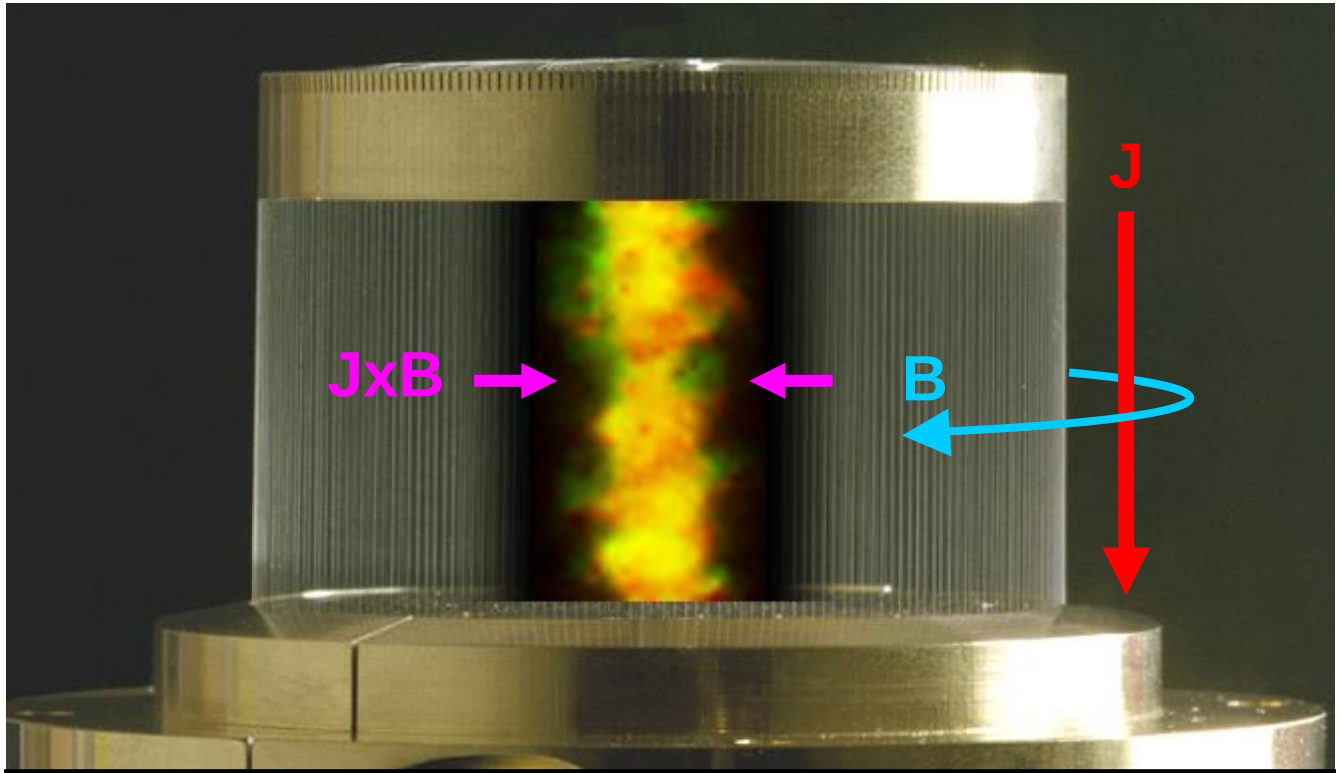
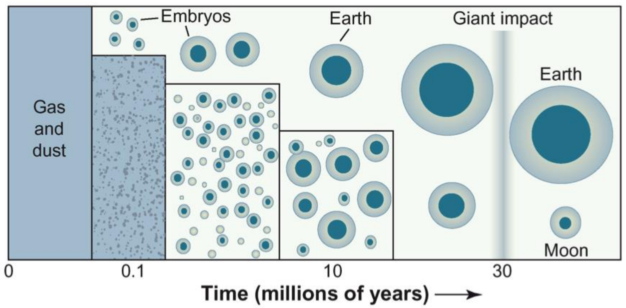


P_{rad} ~ 400 TW, Y_{rad} ~ 2.5 MJ

~ 10-15% wall plug efficiency

We have established a fundamental science program on Z with university collaborators



Earth formation

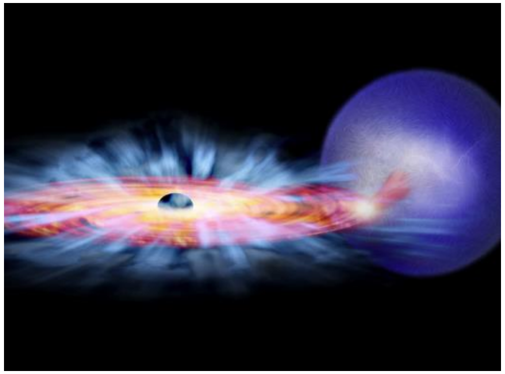
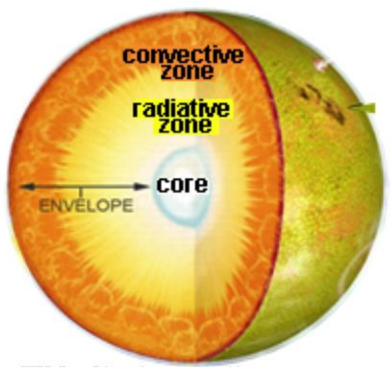
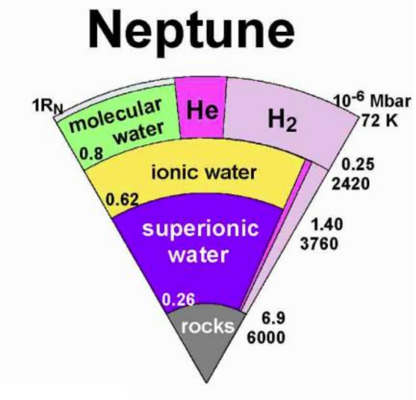


Photo-ionized plasmas



Solar/White Dwarf Opacities



Planetary structure

- **Proposals address exciting scientific issues:**
  - **Do we understand the structure of the sun?**
  - **Can we use white dwarfs as cosmic chronometers?**
  - **How does the accretion disk around a black-hole behave?**
  - **What is the structure of the planets in our solar system (and beyond)?**
  - **How did the Earth and the Moon form?**

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

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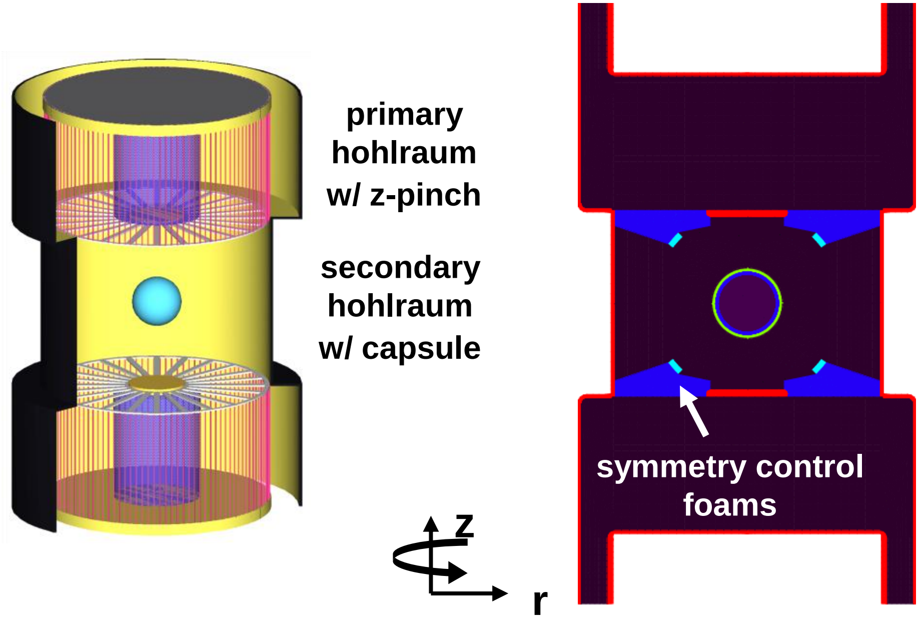
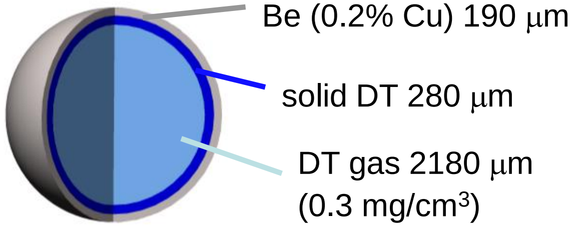
Double z-pinch hohlraum fusion concept

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

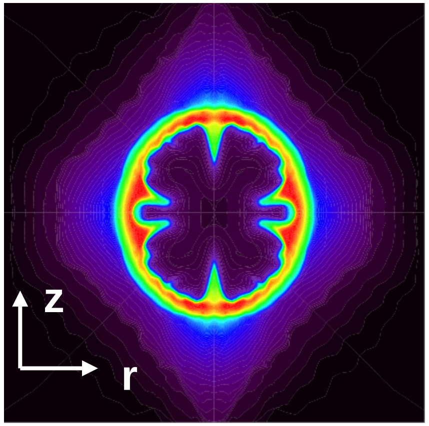


- Two z-pinches, each with 9 MJ x-ray output
- Symmetry control to 1% via geometry, shields
- Capsule absorbs 1.2 MJ, yields 400-500 MJ

High yield capsule design



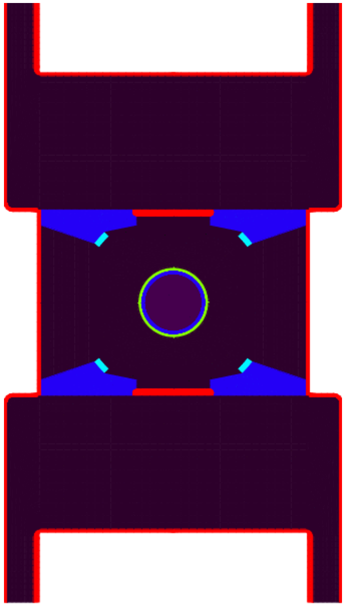
Fuel density at ignition



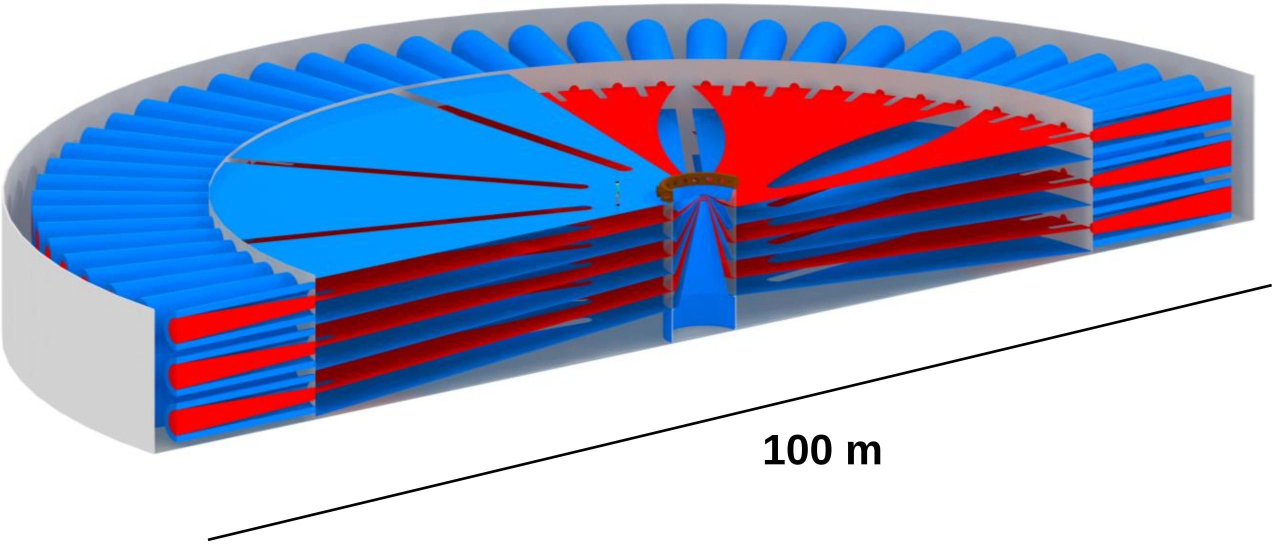
1D capsule yield 520 MJ

2D integrated yield 470 MJ

A large driver (beyond Z) is needed is needed to drive the high-yield double-ended hohlraum



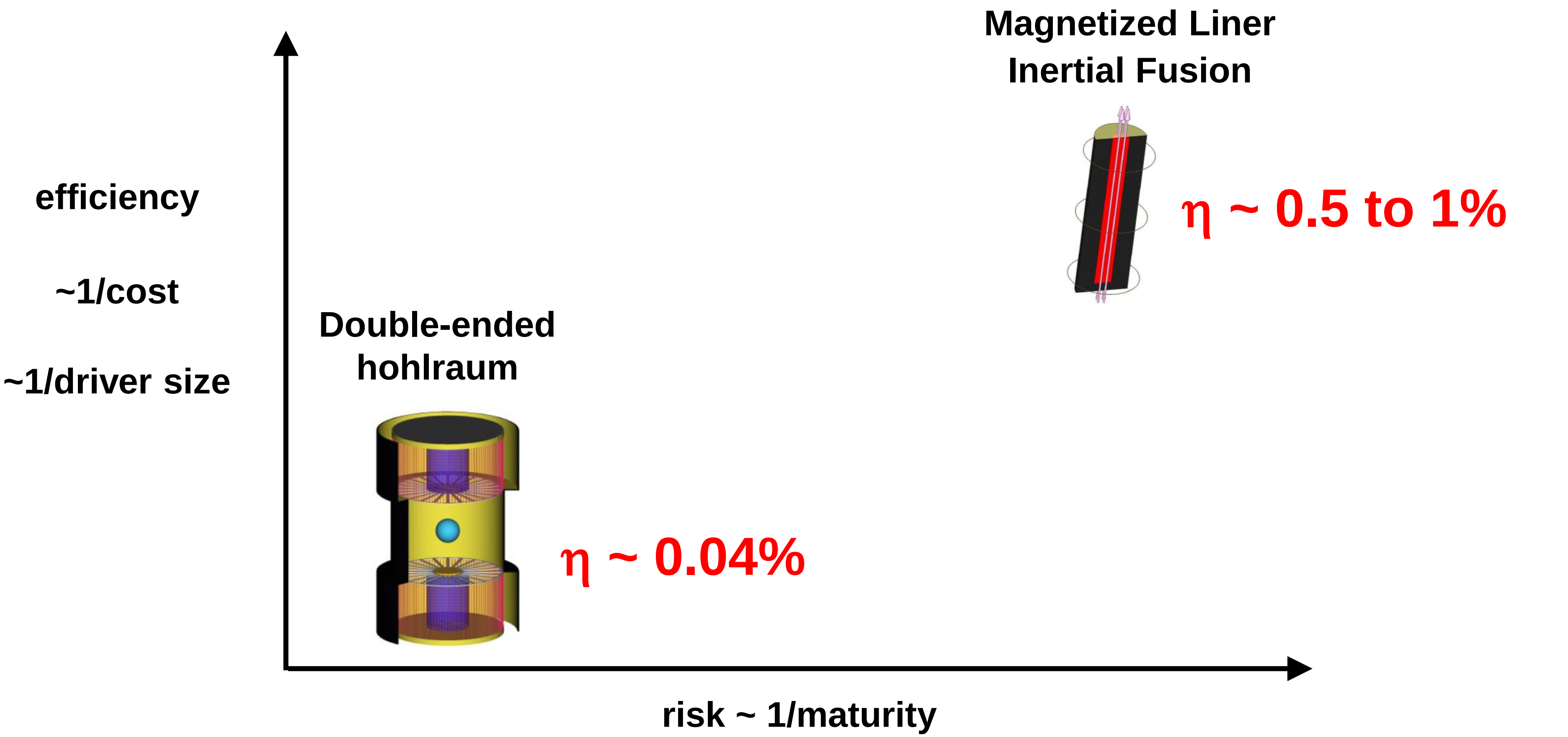
- **Power required (1 PW/pinch @ 20-mm-diameter)**
- **Energy required (8-9 MJ/pinch)**



Because of the inefficiencies in this concept only 0.04% of the driver energy gets to the fusion fuel

Are there more efficient concepts? Is there any way to lower the required pressure?

Magnetic implosions are far more efficient at putting energy into fusion fuel

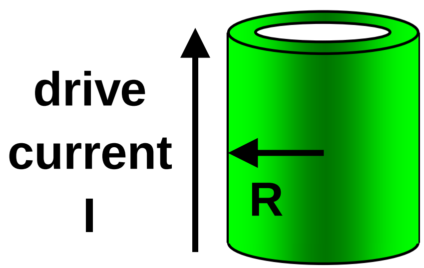


- **Pulsed power can flexibly drive many target types**
- **Direct fuel compression and heating with the magnetic field could be up to 20X more efficient**

Magnetically driven implosions can efficiently couple energy at high drive pressure

Magnetically-Driven Implosion

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



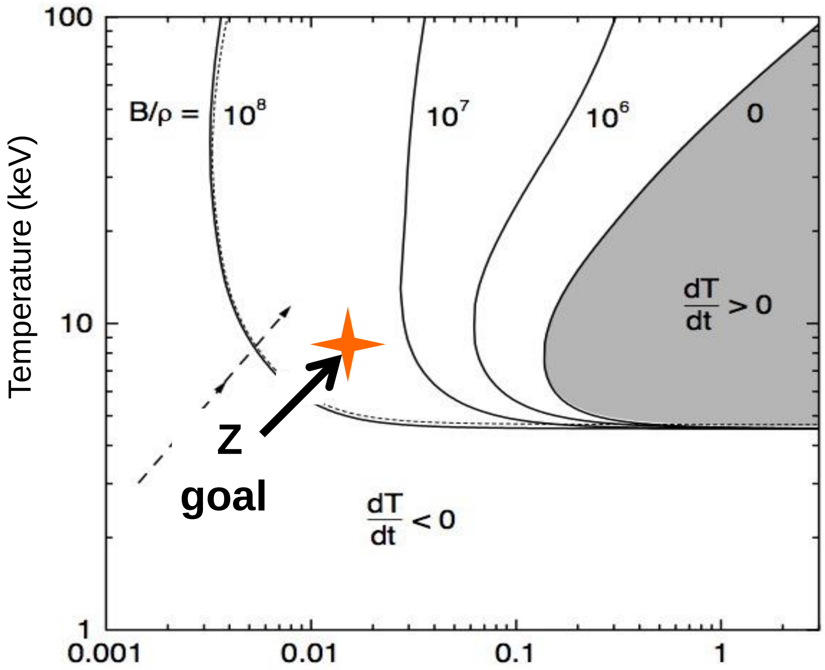
100 MBar at 26 MA and 1 mm

- **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 have nearly as high a pressure multiplier on stagnation**
- **Cylindrical shells must be thick to avoid disruption by instabilities**
- **Thick shells are slow, making the pressure problem harder**

Magnetization significantly reduces the self heating (ignition) requirements for inertial confinement fusion

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



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 alpha particles**

Lower ρr means lower densities are needed (~1 g/cc)

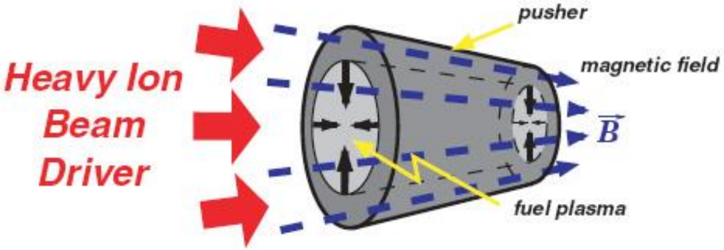
Pressure required for ignition can be significantly reduced to ~5 Gbar (<< 500 Gbar for hotspot ignition)

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

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

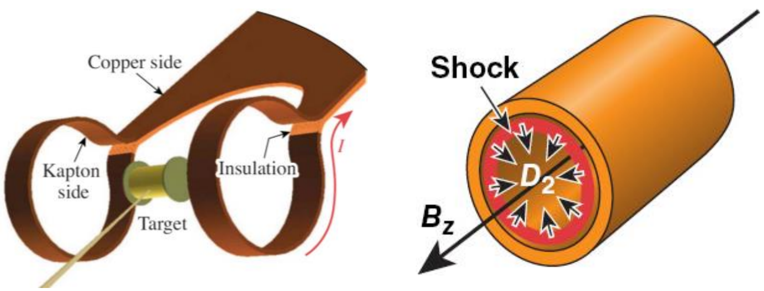
The parameter space for magnetized ICF is large allowing a diverse set of approaches

Max Planck / ITEP



Basko, Kemp, Meyer-ter-Vehn, *Nucl. Fusion* **40**, 59 (2000)
Kemp, Basko, Meyer-ter-Vehn, *Nucl. Fusion* **43**, 16 (2003)

U. Rochester LLE

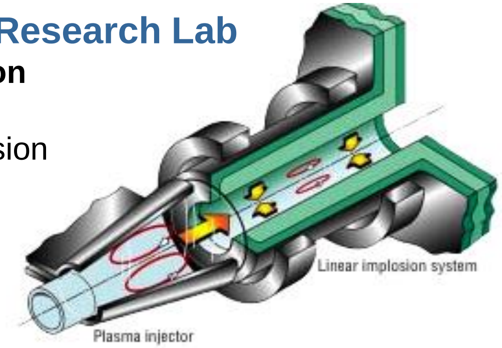


Direct drive laser implosion of cylinders
-- shock pre-heating, high implosion velocity

Gotchev *et al.*, *Bull. Am. Phys. Soc.* **52**, 250 (2007)
Gotchev *et al.*, *Rev. Sci. Instr.* **80**, 043504 (2009)
Gotchev *et al.*, Phys. Rev. Lett. **103**, 215004 (2009)
Knauer *et al.*, *Phys. Plasmas* **17**, 056318 (2010)

Los Alamos / Air Force Research Lab

Field Reversed Configuration
Shiva Star generator
~20 μs, 0.5 cm/μs liner implosion



Taccetti, Intrator, Wurden *et al.*, *Rev. Sci, Instr.* **74**, 4314 (2003)
Degnan *et al.*, *IEEE Trans. Plas. Sci.* **36**, 80 (2008)

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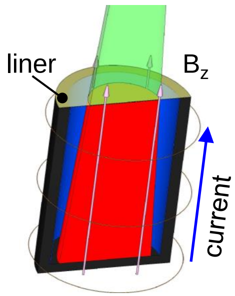
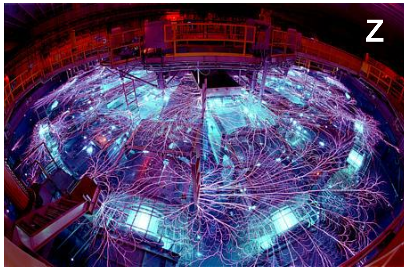
Magnetized Liner Inertial Fusion

Laser preheated magnetized fuel

LASNEX simulations indicate interesting yields





S. A. Slutz *et al.*, *Phys. Plasmas*, 17, 056303 (2010).
D.B. Sinars *et al.*, Phys. Rev. Lett. 105, 185001 (2010)

The Z facility provides an opportunity to test the benefits of fuel magnetization and preheat

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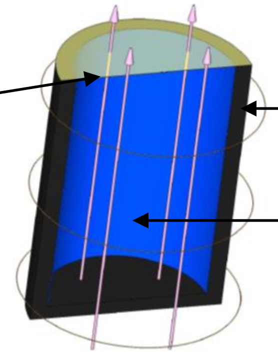
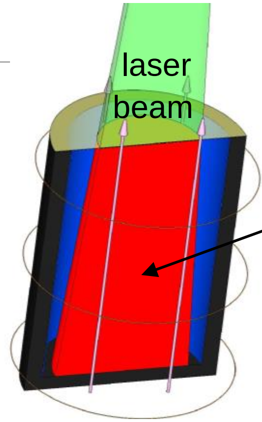
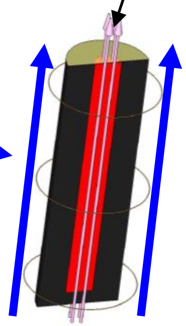
1. A 100-500 kG axial magnetic field is applied before the implosion



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 that scientific breakeven (fusion energy out = energy deposited in fusion fuel) may be possible on Z

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

Simulations indicate that the magneto-Rayleigh Taylor instability may be acceptable in this concept

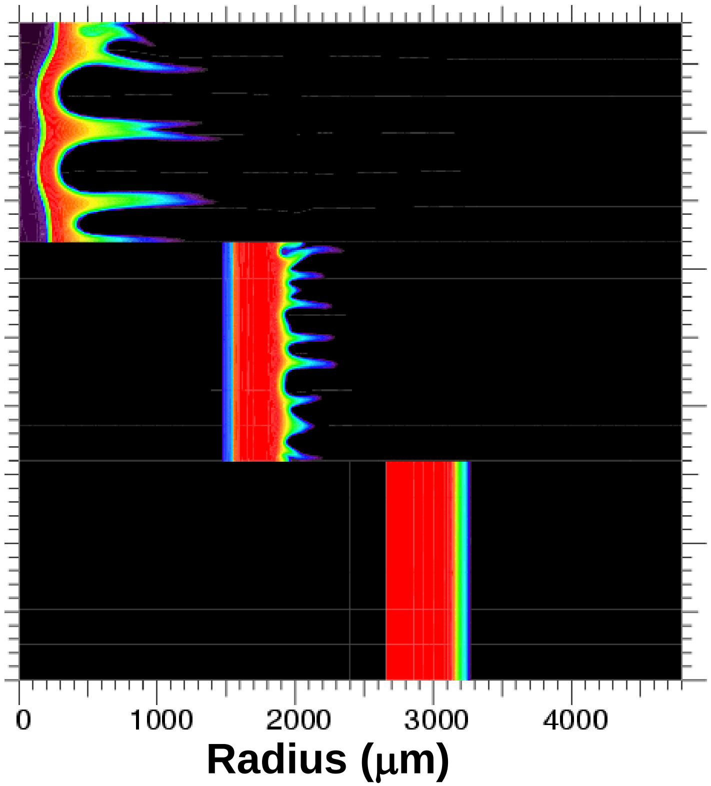
INITIAL CONDITIONS

Peak Current:	27 MA
Be Liner R_0:	2.7 mm
Liner height:	5 mm
Aspect ratio ($R_0/\Delta R$):	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 (R_0/R_f):	23
Final on-axis fuel density:	0.5 g/cc
Peak avg. ion temperature:	8 keV
Final peak B-field:	13,500 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)

A series of experiments were carried out on Z to test the code's predictions of MRT growth

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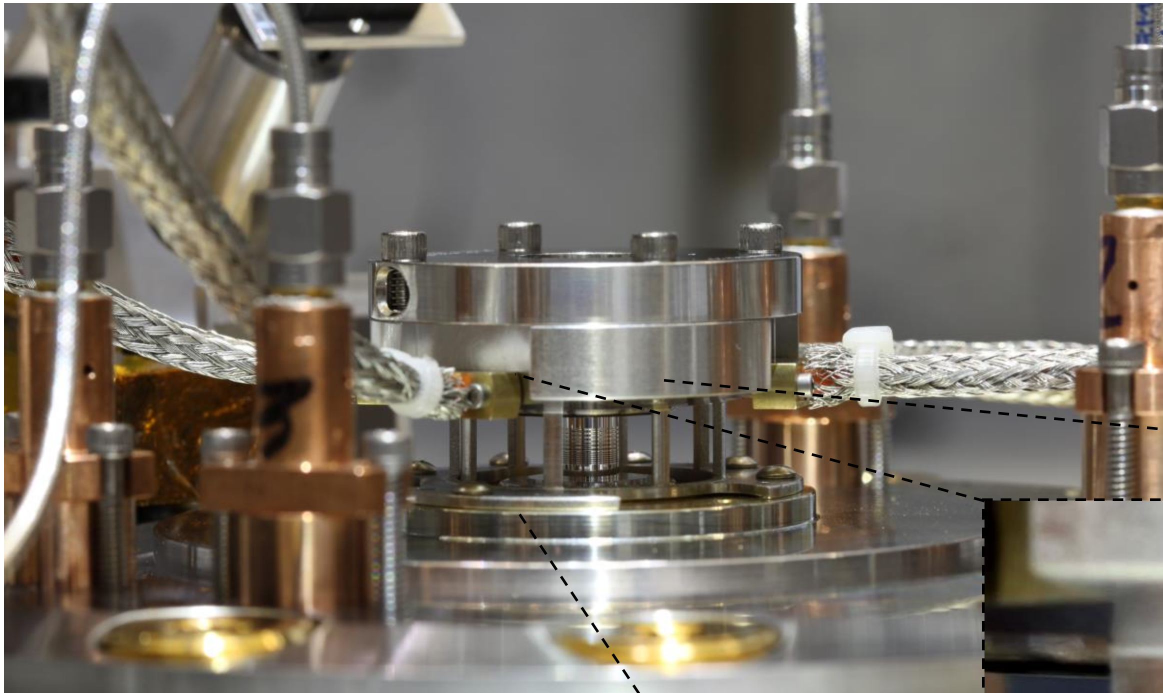
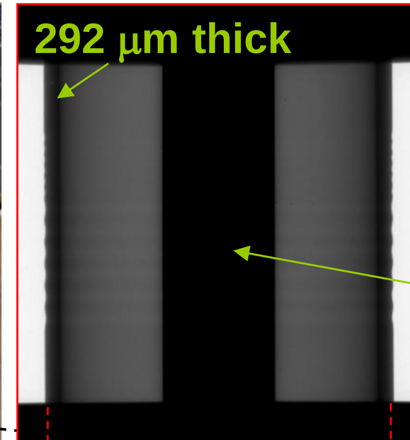
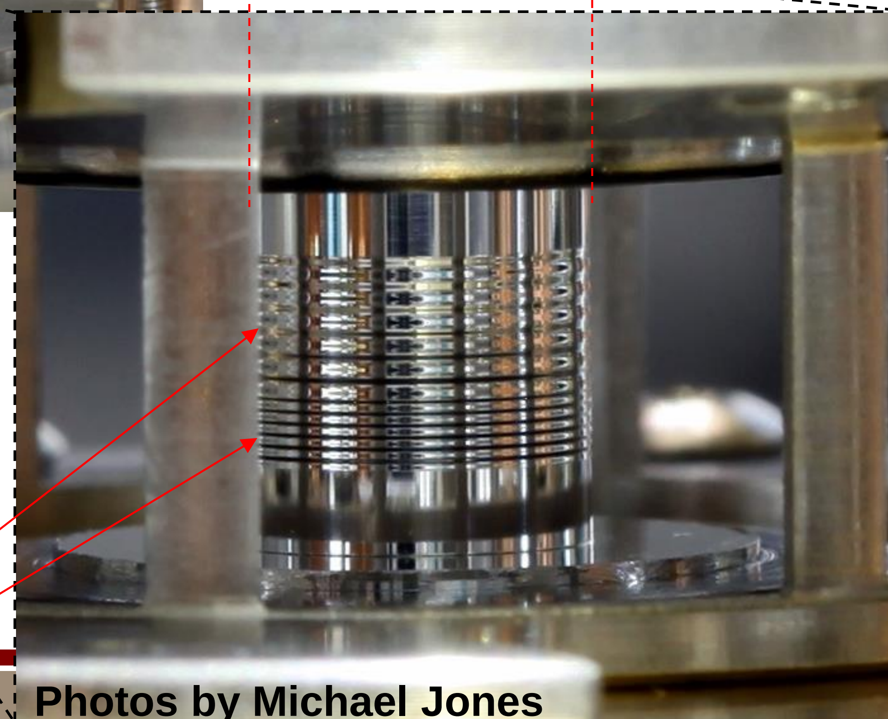




55-60 keV pre-shot radiograph (W Kα source)

2 mm diam. W rod on axis (suppress x rays)

- Solid cylindrical liner (Al 1100 alloy)
- 6.5 mm tall, 6.34 mm diameter, AR=10
- 10 nm surface finish (diamond-turned)
- 12 sinusoidal perturbations:
  six 400-µm wavelength, 20-µm amplitude
  six 200-µm wavelength, 10-µm amplitude

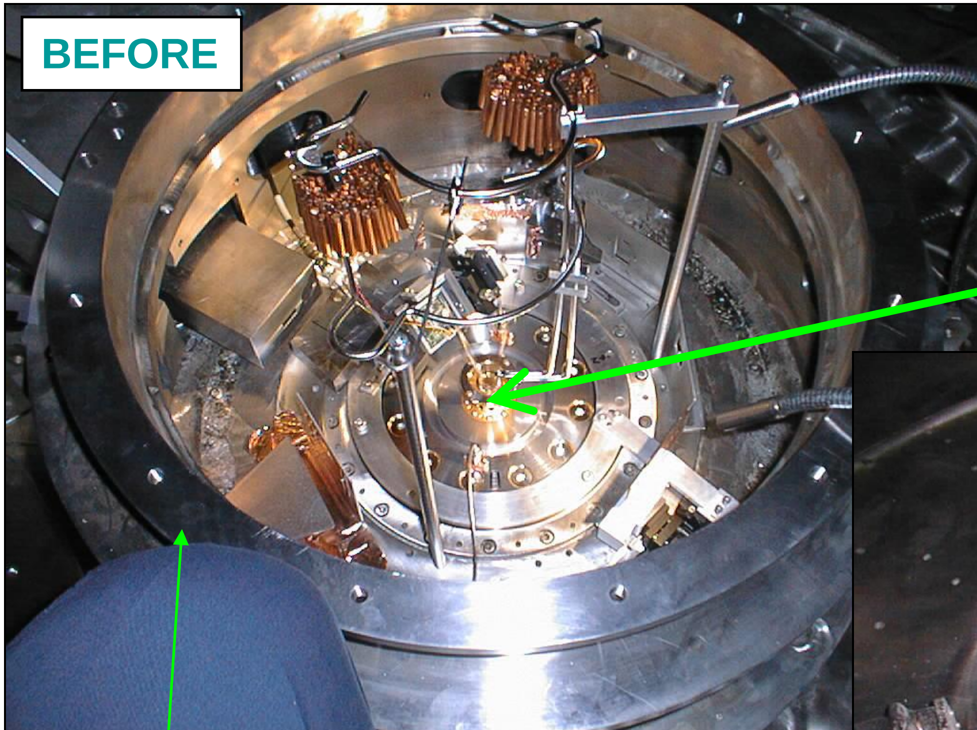


Targets made by General Atomics

The 2-3 MJ of magnetic energy and radiation destroys the experimental hardware

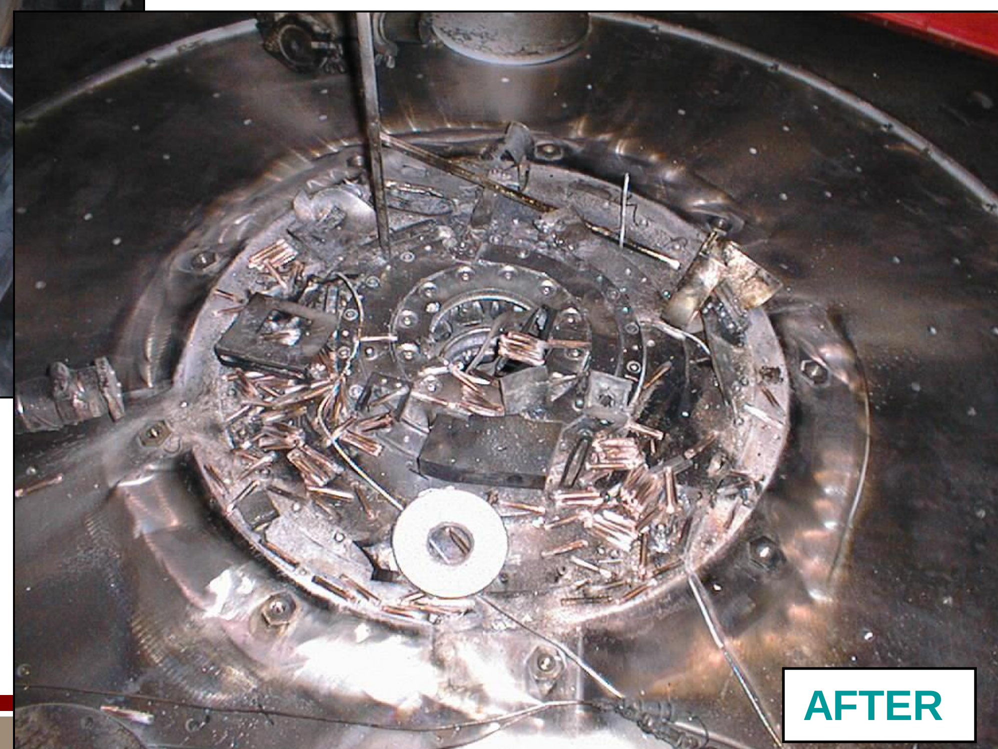
"Hostile" environment

debris, electrical noise, photon background, plasma



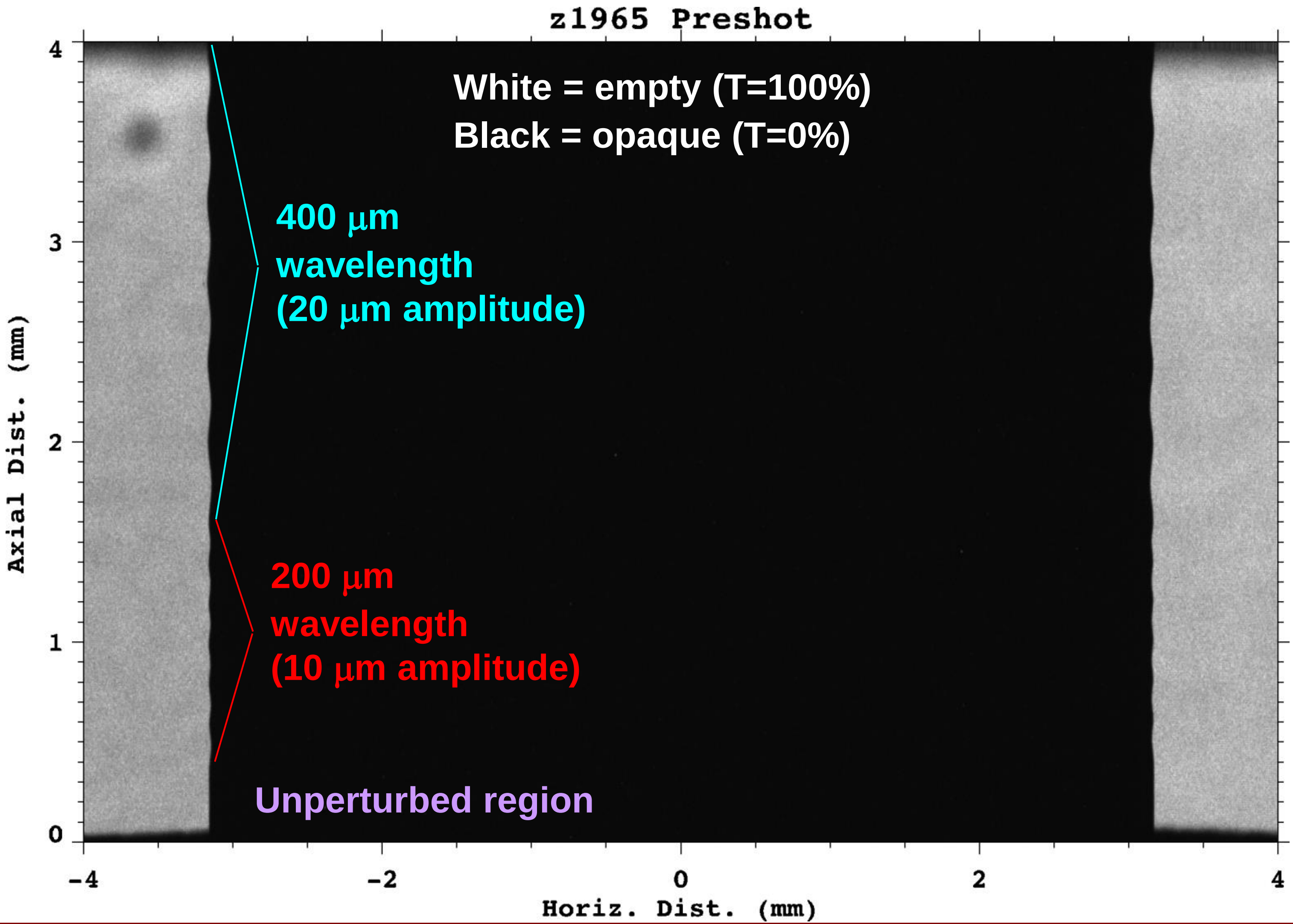
Wire array

Blast shield

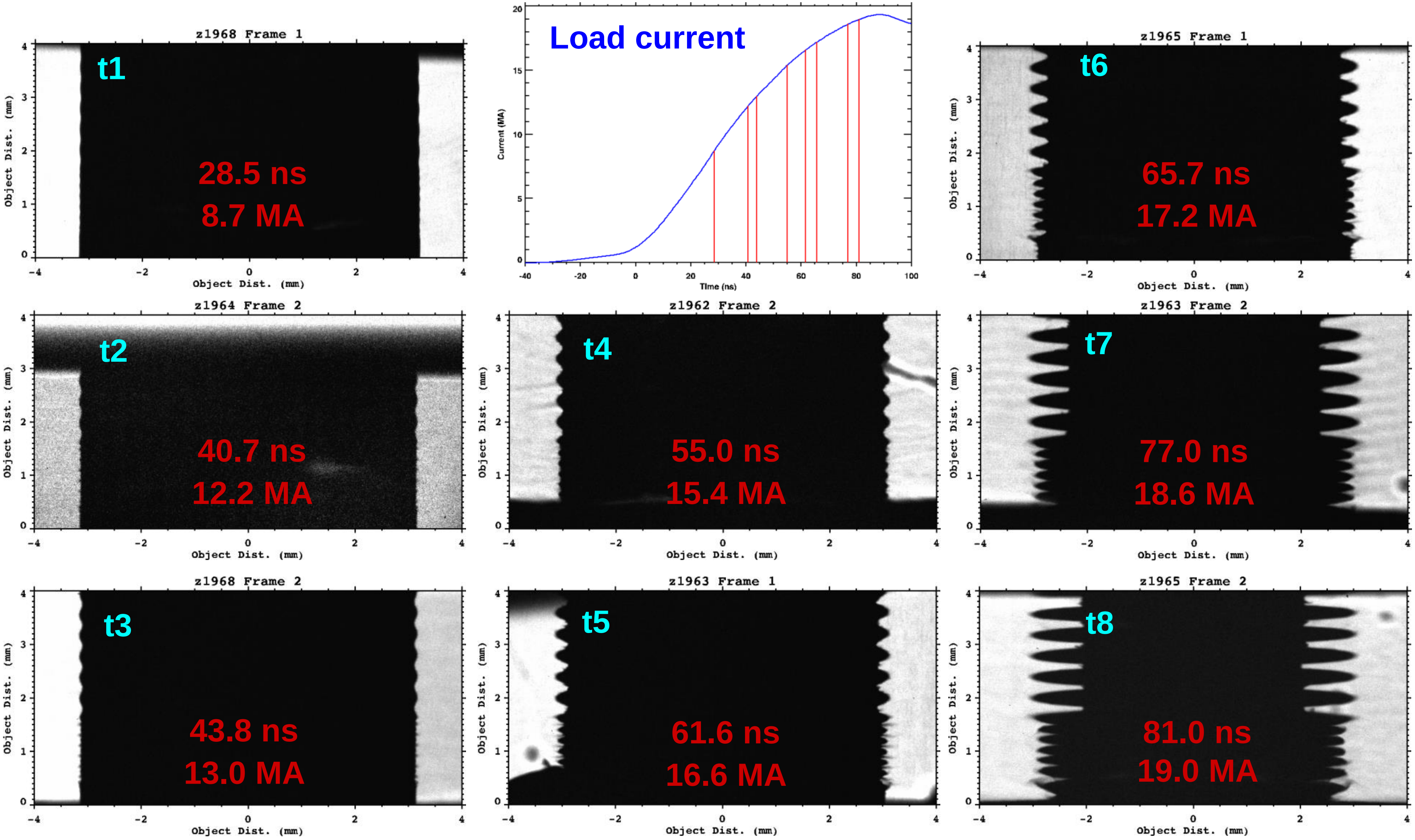


Equivalent to 2 lbs high explosive released in a few ns in <1 cc volume!

A preshot radiograph shows the resolution that can be attained by the bent crystal imaging system



Reproducible machine and liner performance enabled an 8 frame movie over 5 shots



Controlled experiments were a critical test of our understanding of the Magneto-Rayleigh Taylor instability

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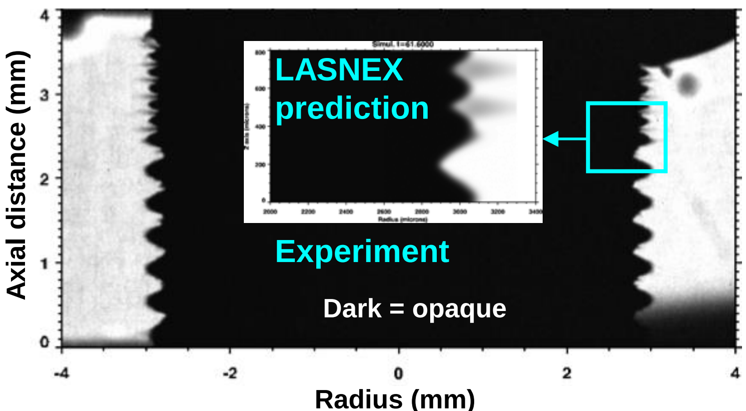
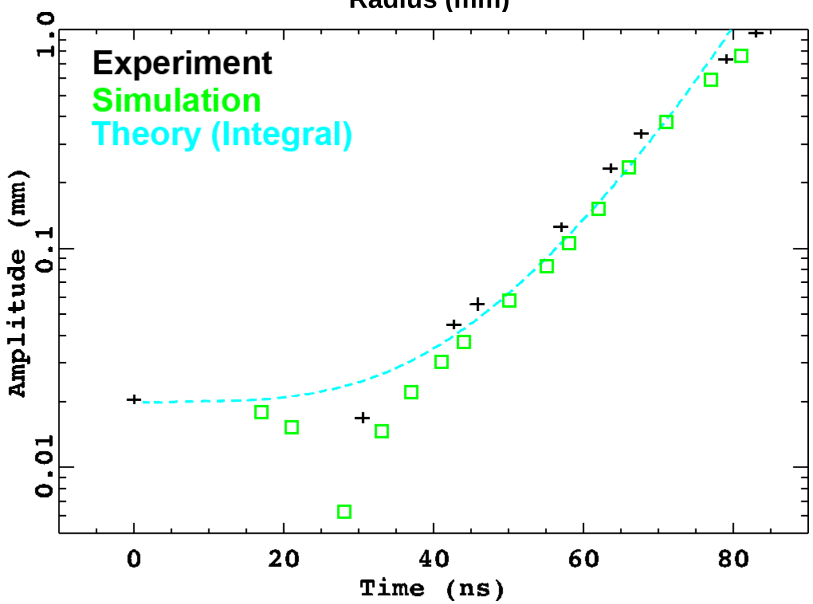
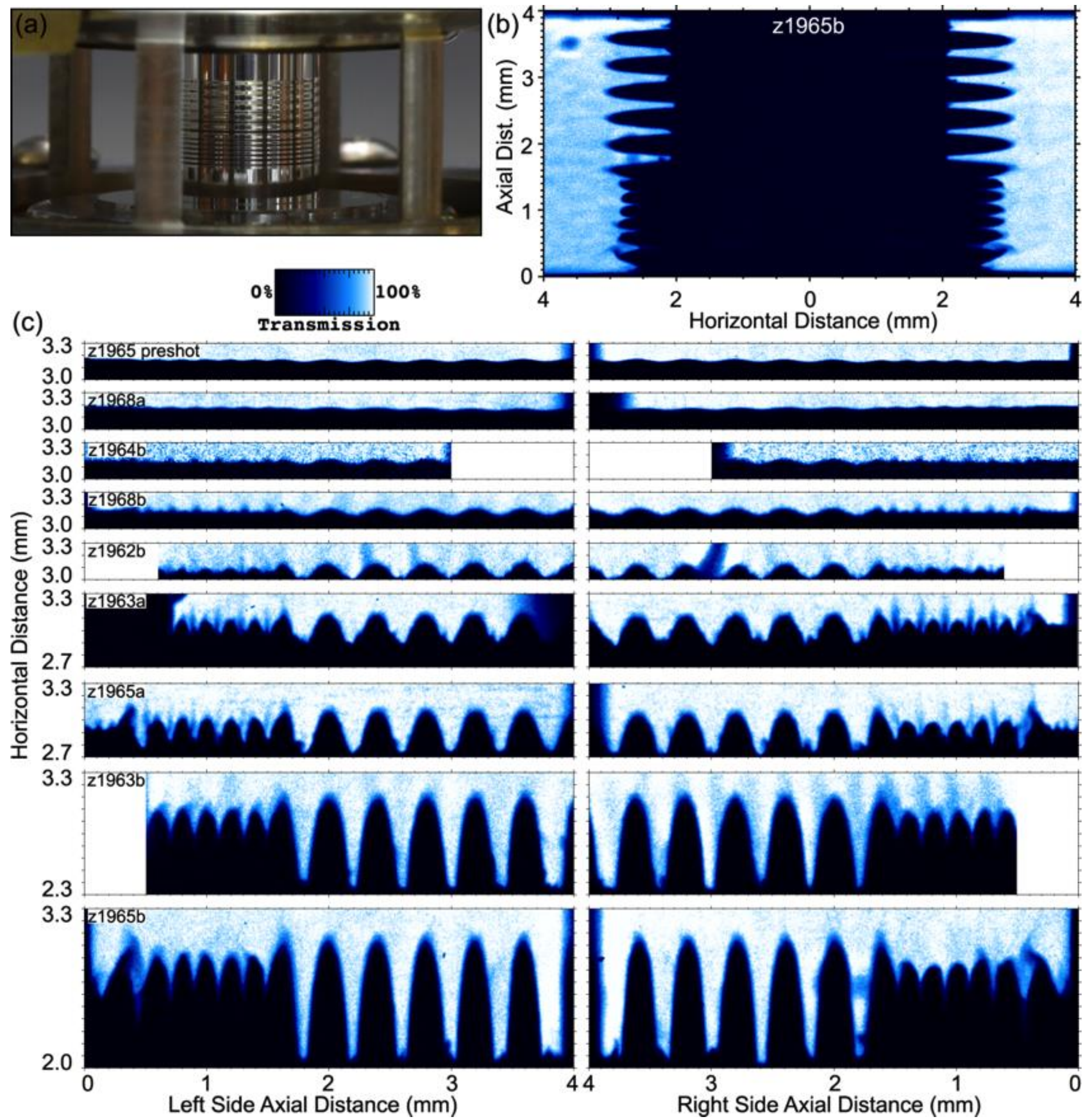
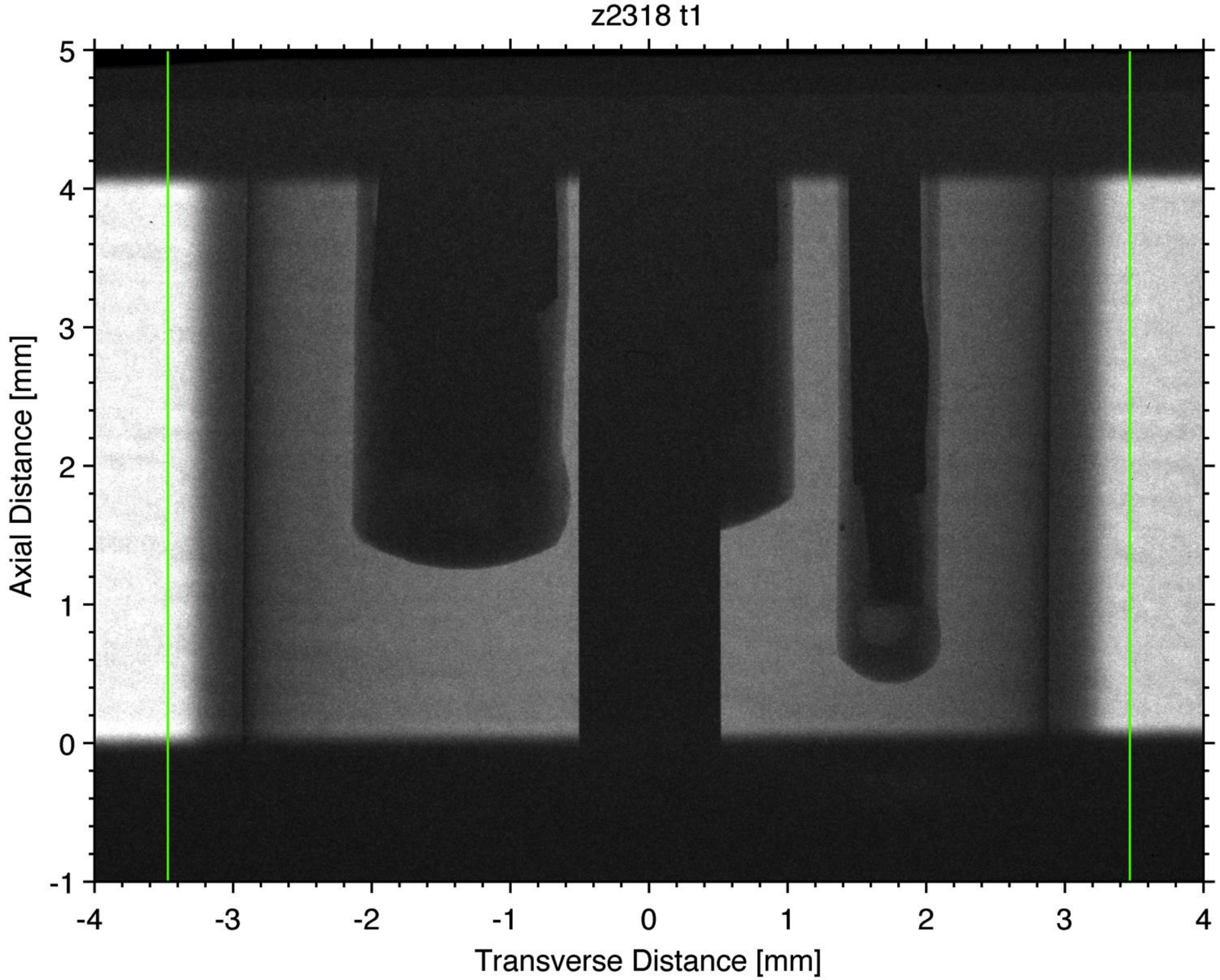
Radiographs captured growth of intentionally-seeded 200, 400-μm wavelength perturbations







Recent studies examined a thin Al sleeve inside a Be liner to study the integrity of the inner surface



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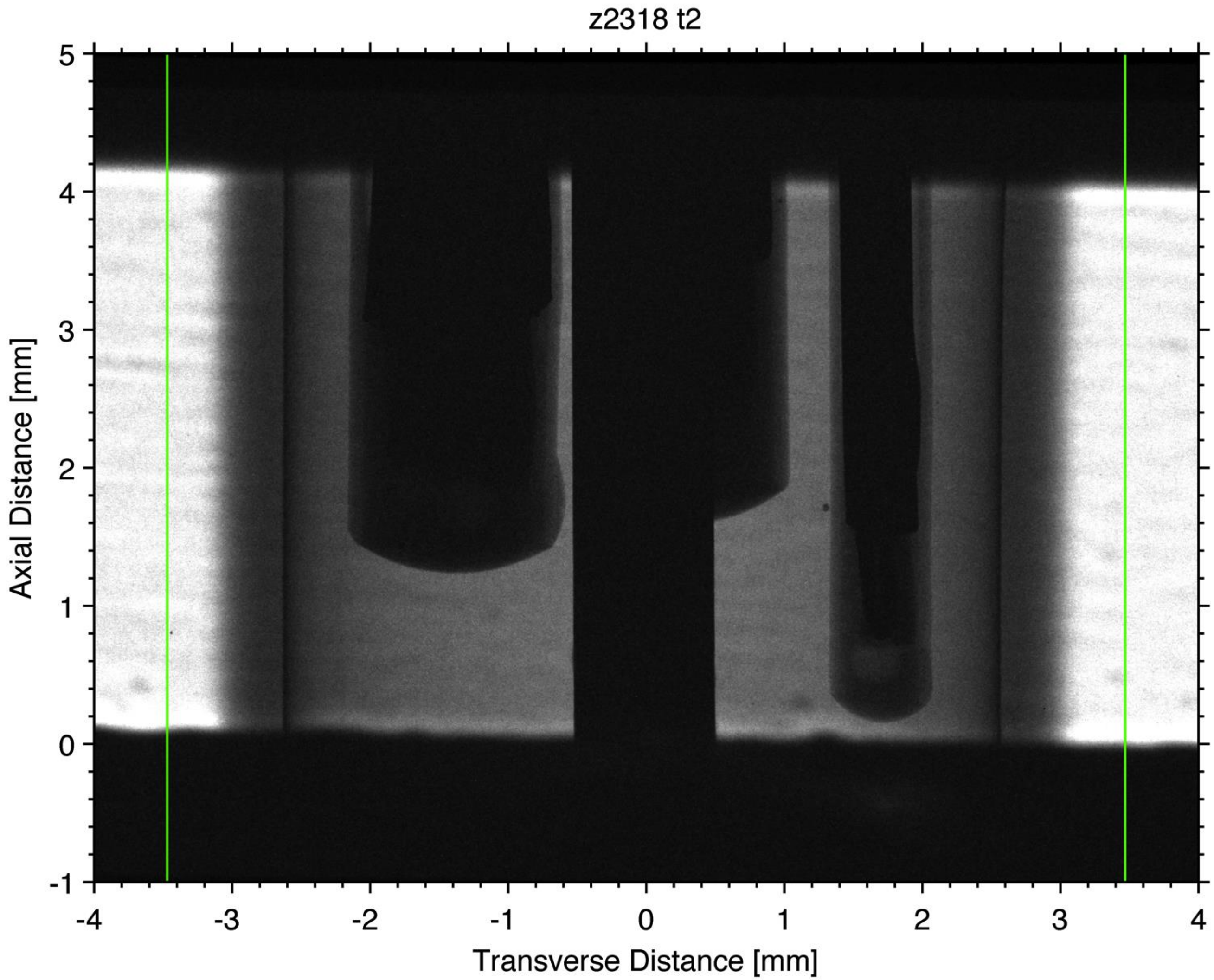

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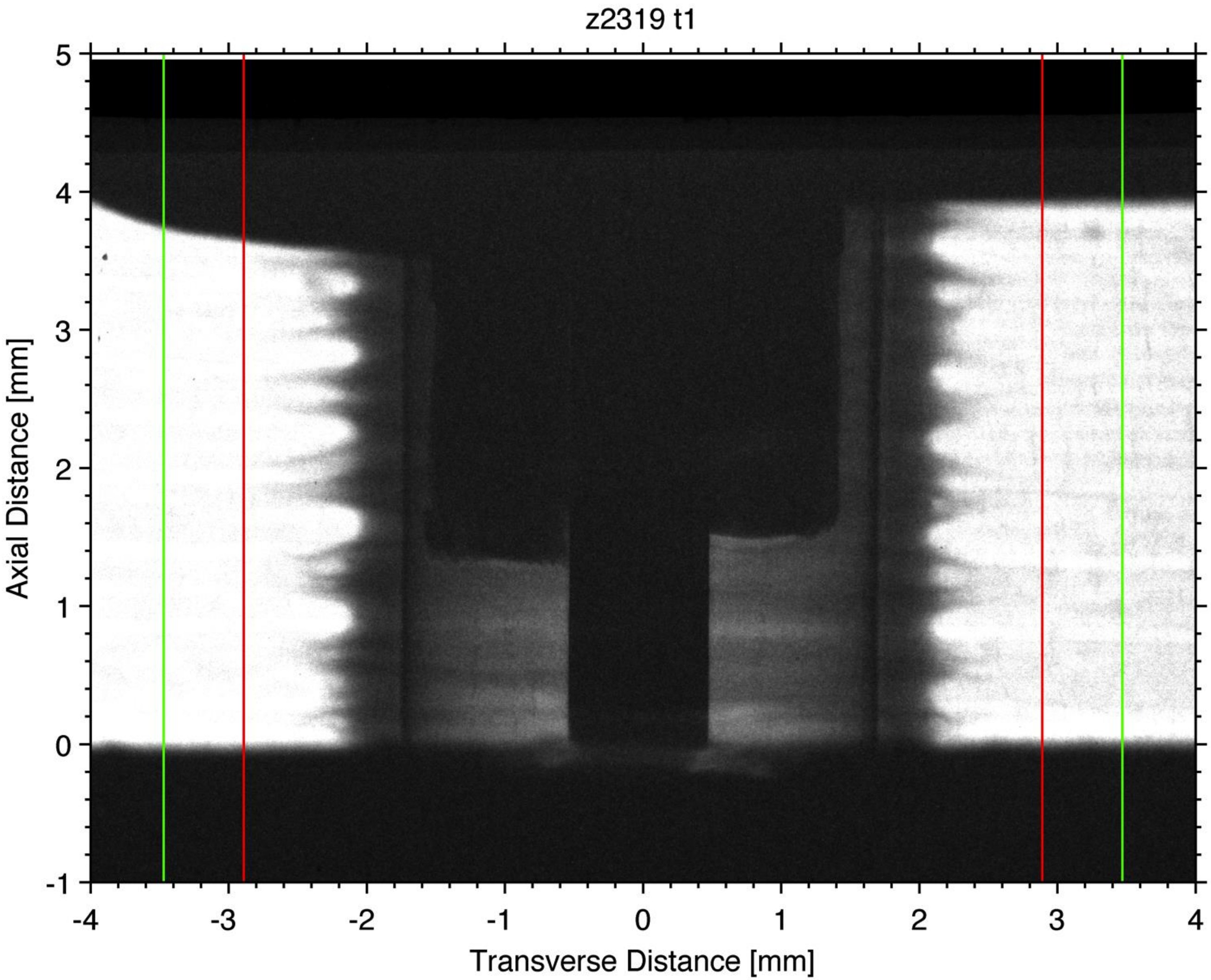

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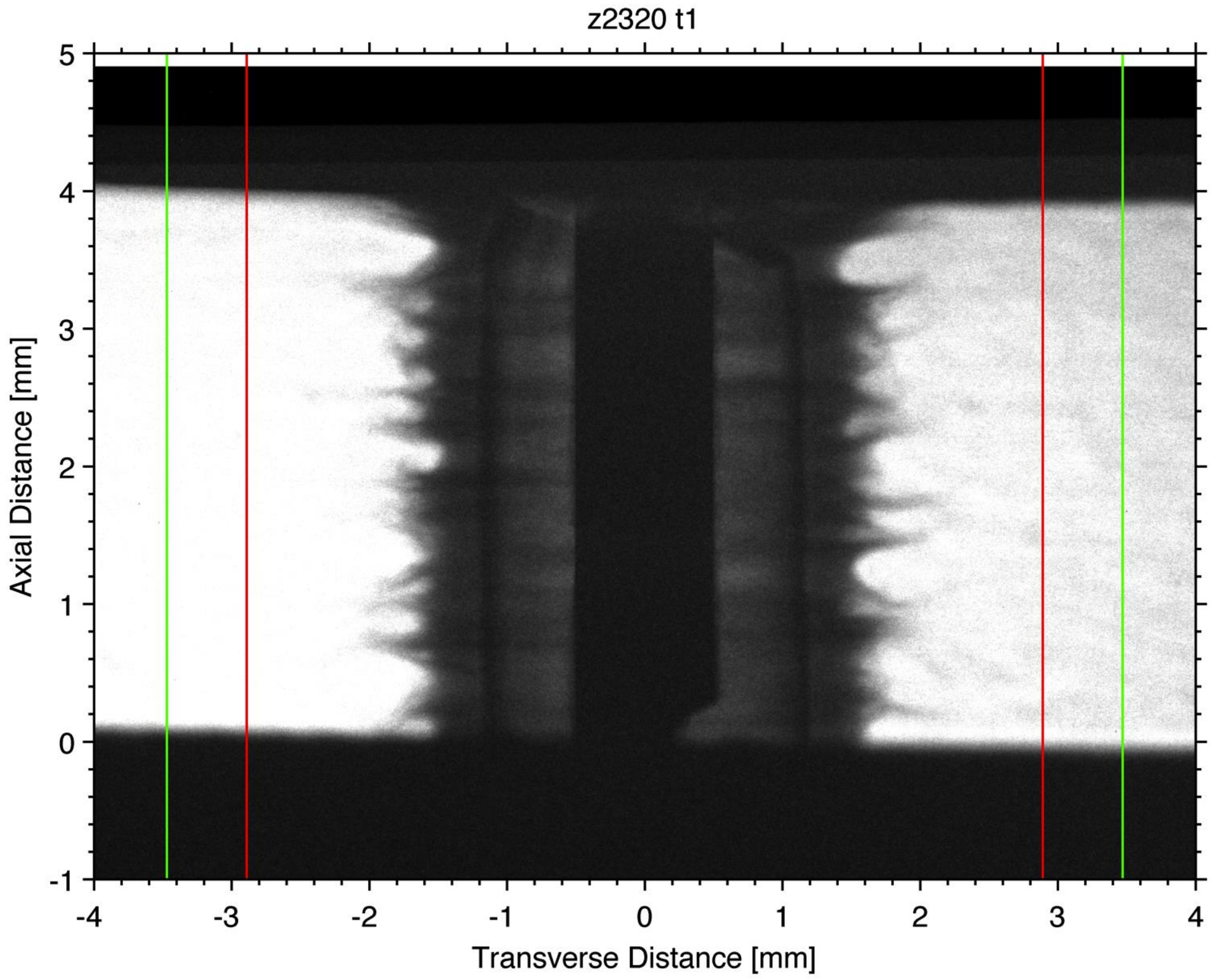

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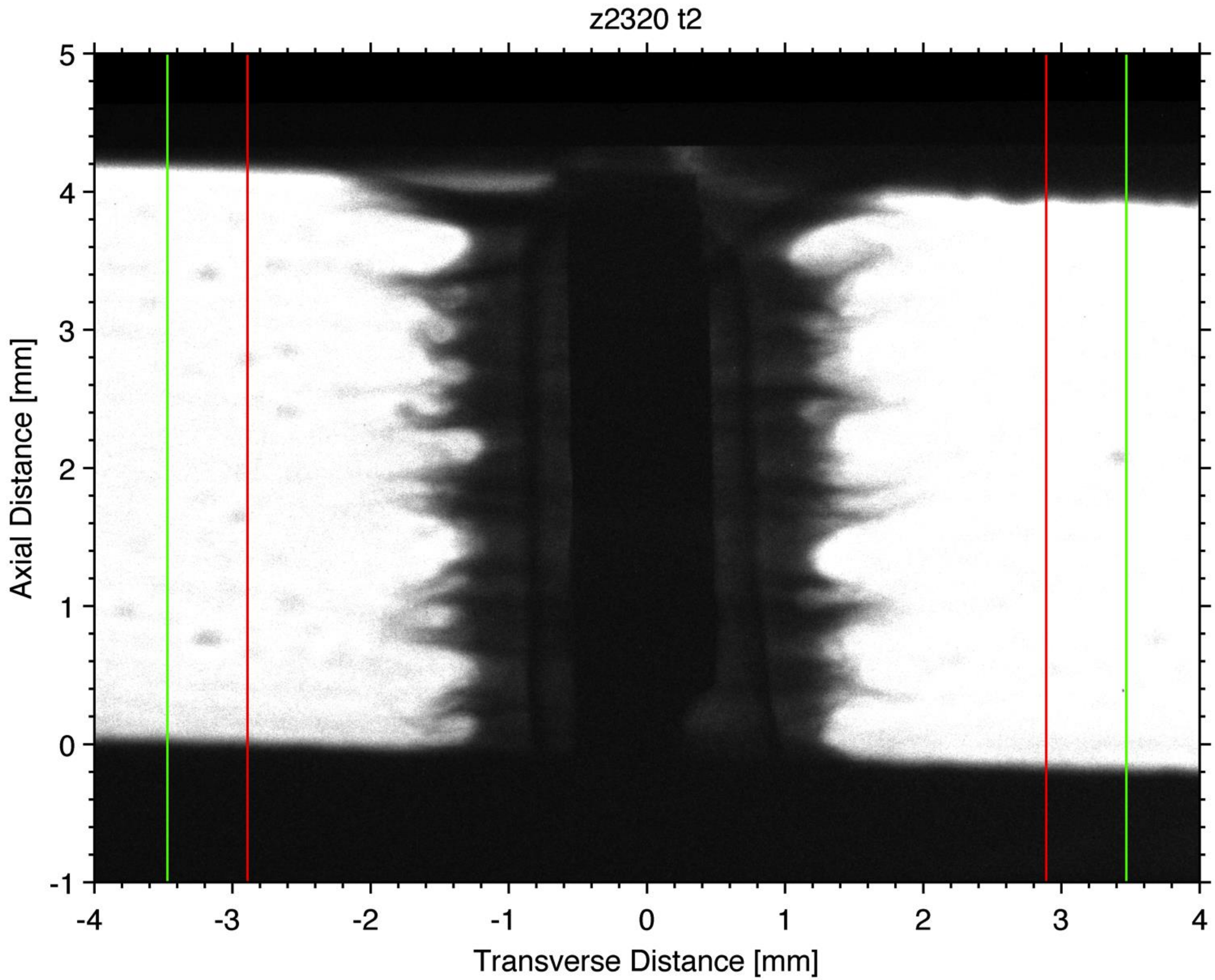


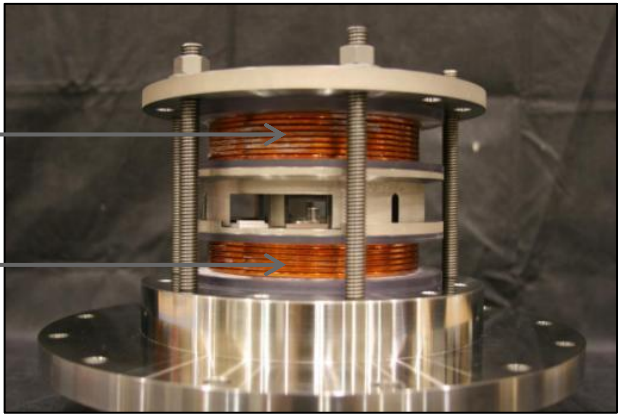
We have installed an 8 mF, 15 kV, 900 kJ capacitor bank on Z to drive 10-30 T axial fields over a several cm^3 volume for MagLIF

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

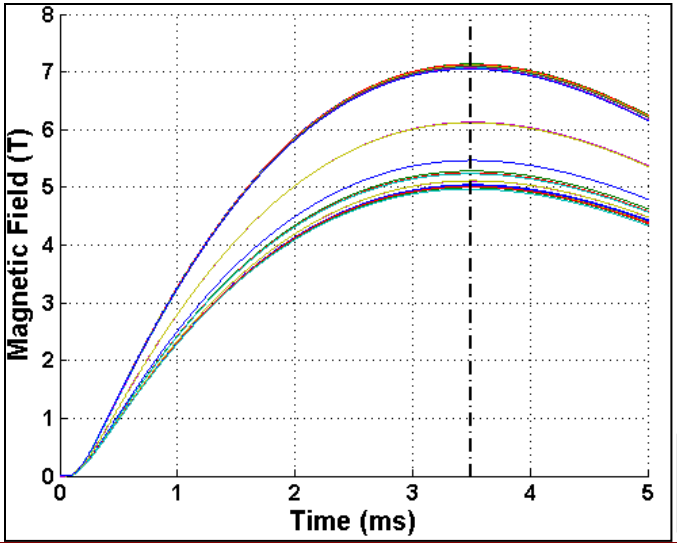
MagLIF prototype assembly with test windings of coils

80-turn coil

60-turn coil



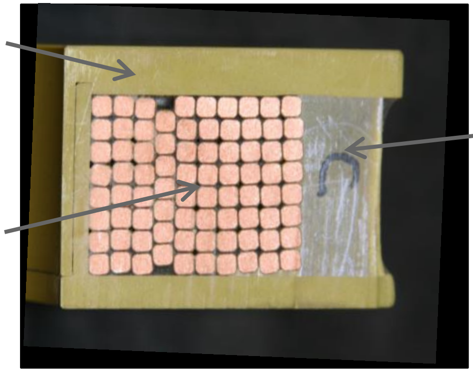
MagLIF on-axis magnetic field data taken at our Systems Integration Test Facility in Bldg. 970



Cross section of 80-turn coil prototype

Torlon housing

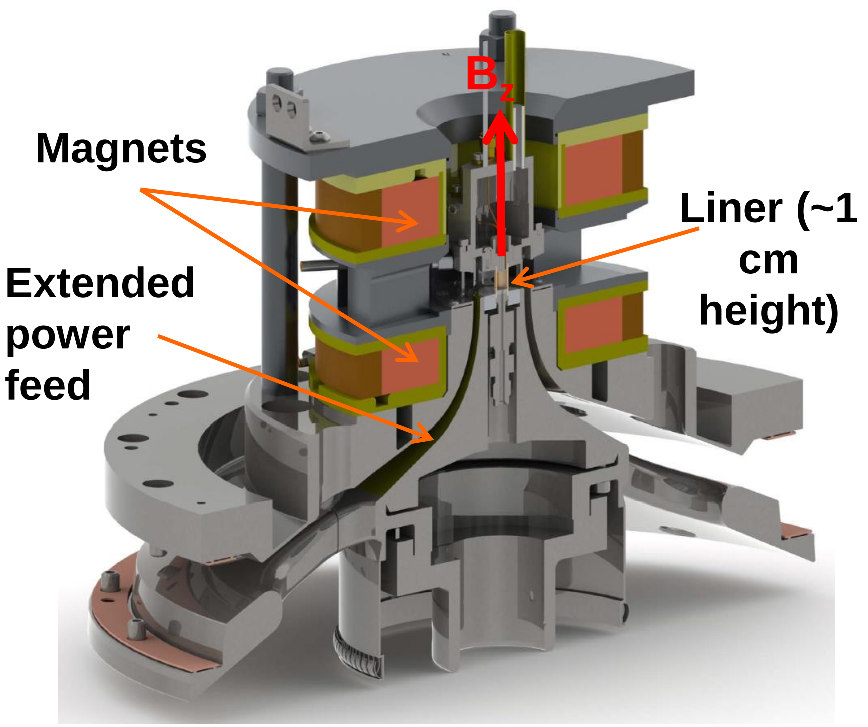
#11 sq. copper wire with double Kapton insulation



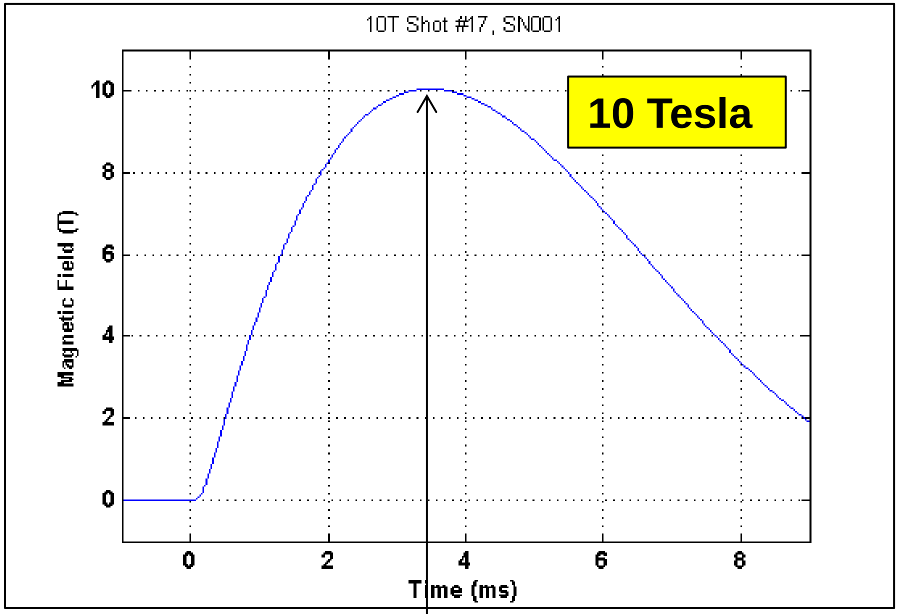
Zylon/epoxy shell provides external reinforcement

Prototype coil development: Jim Puissant, Raytheon-Ktech, Albuquerque
Production coils for Z: Milhous Corporation, Amherst, VA.

Hardware delivers up to 20 MA with no anomalous losses due to axial field. System used on 4 ICF shots on Z to make 7-10 T fields



10 T field coil configuration shown, fields up to 30 T possible by increasing the coil cross section and eliminating the side-on view of liner



Time to peak field = 3.49 ms

Long time scale needed to allow field to diffuse through the liner without deformation

Energy storage is sufficient to meet our long-term goal of a 30 T field

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

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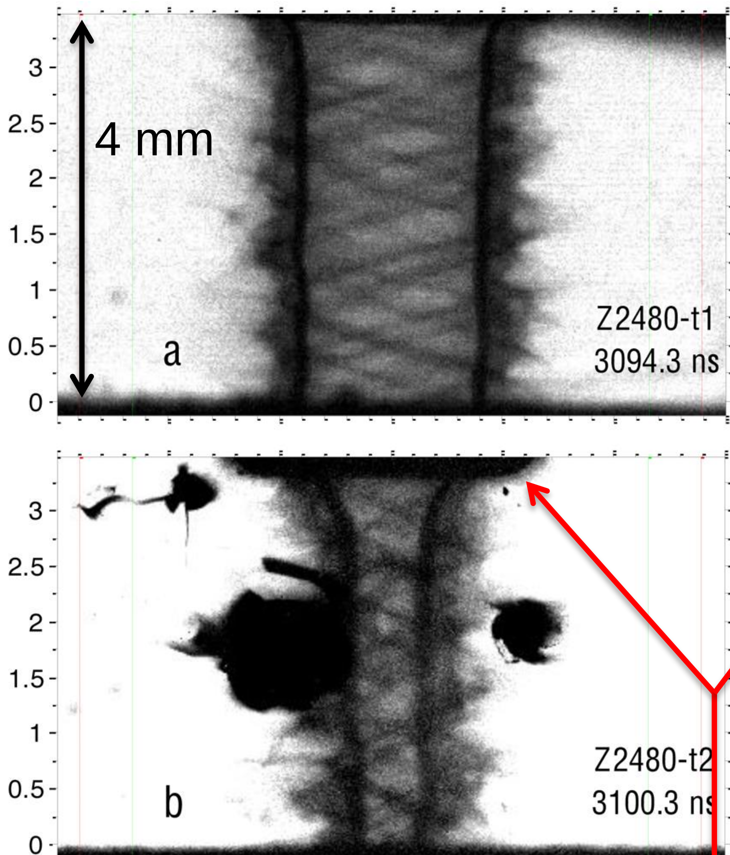
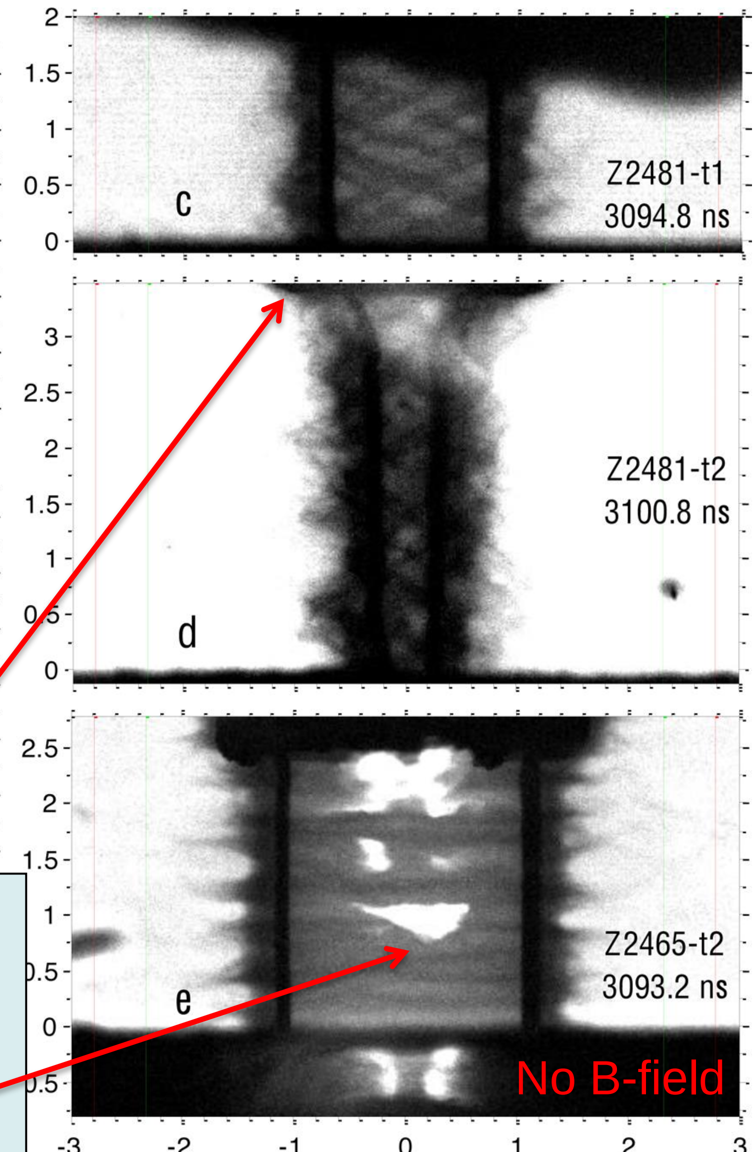


CR =2.7

CR =6.4



CR =2.9

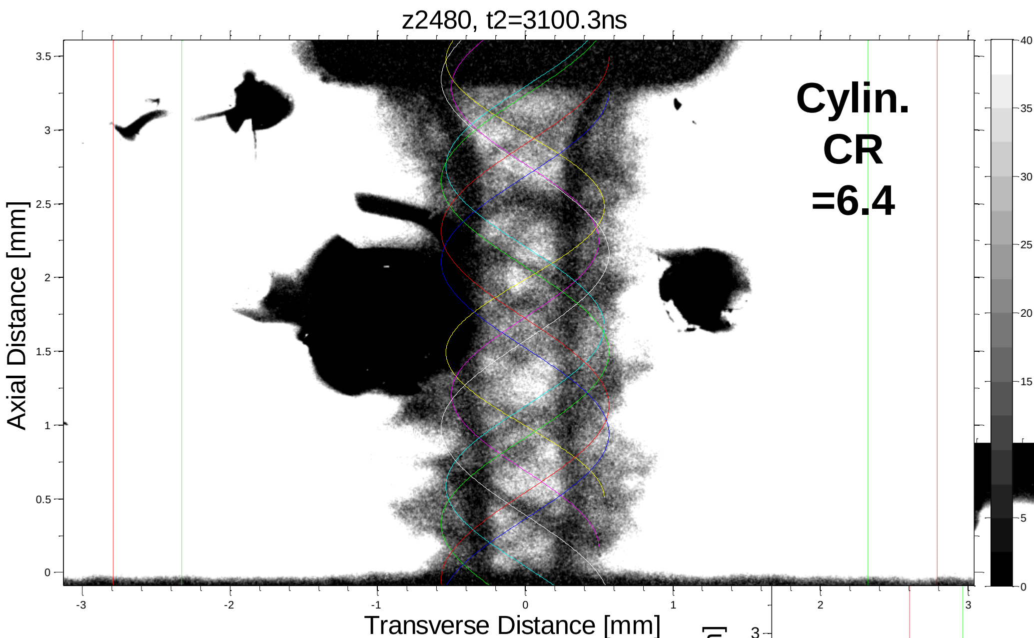
CR =6.9

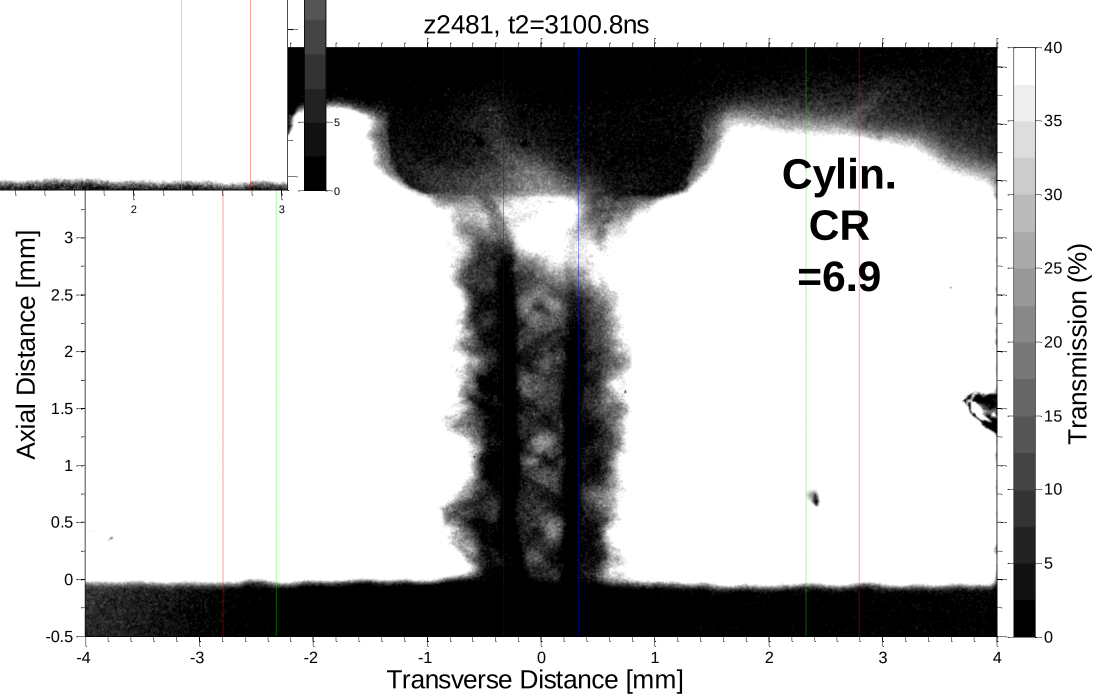
Highest CR imaged to date

CR =2.0

- **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**

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



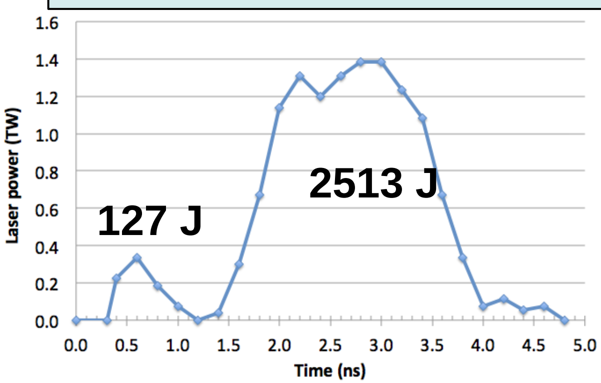


Same images plotted using 0-40% transmission range instead of 0-100%

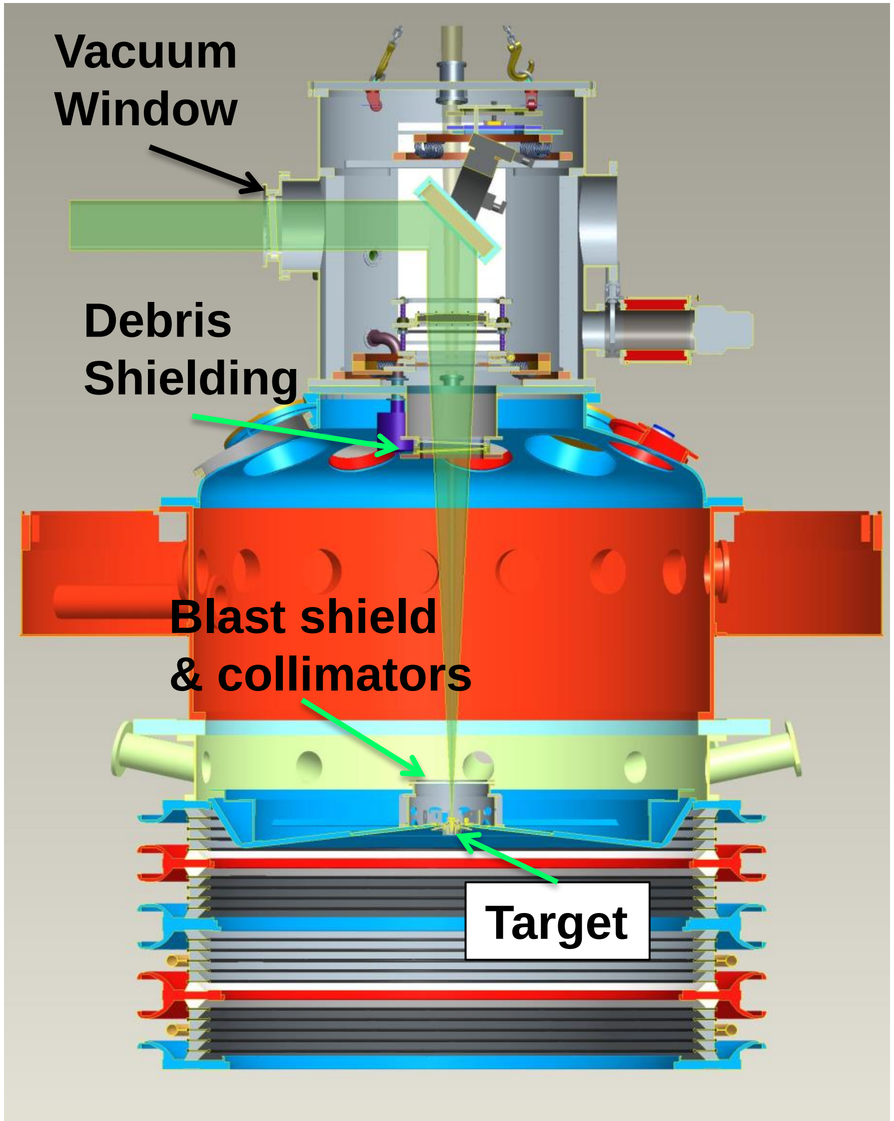
We are integrating 2-2.5 kJ laser preheating into Z MagLIF experiments; 4-6 kJ by 2015

- **A new Final Optics Assembly is optimized for on-axis targeting**
- **Z-Beamlet is capable of delivering 2-2.5 kJ in a two-part pulse**

Example pulse measurement



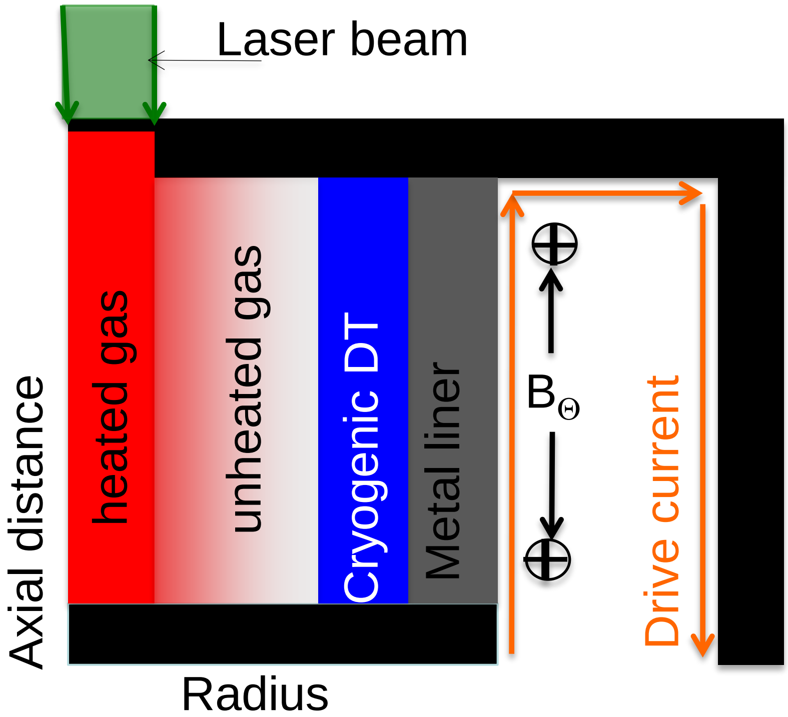
ZBL 2ω light (2.64 kJ)

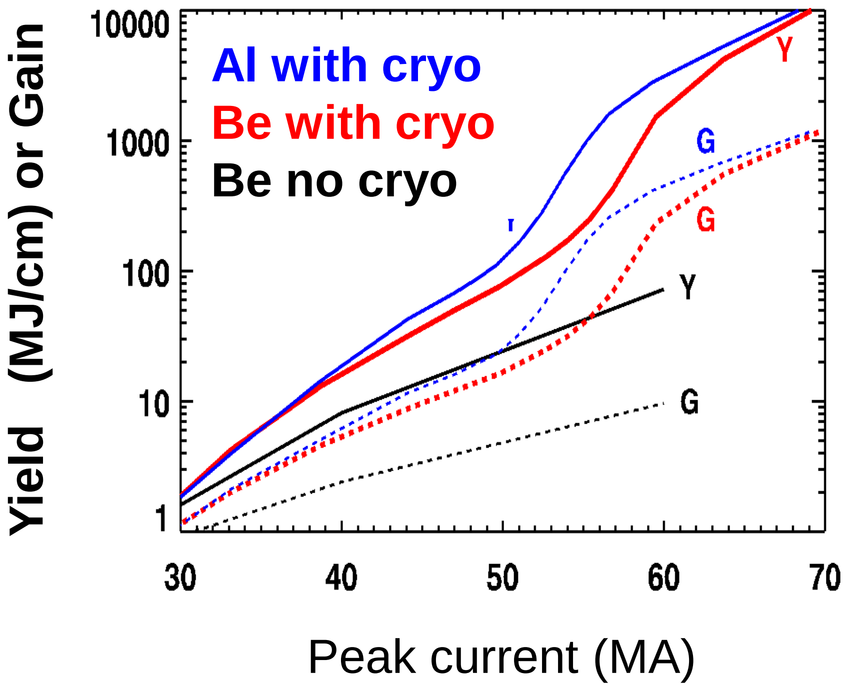


Next Steps for MagLIF concept

- **Initiation of current flow in the liner**
  - **Assess impact of plastic coatings for reducing late-time instabilities**
- **Liner stability and symmetry studies**
  - **Finish testing of predictions for instability growth in fundamental magneto-Rayleigh-Taylor instability studies (multi-mode, helical)**
  - **Deceleration mix studies**
  - **Develop techniques to measure symmetry at CR~20**
- **Preheating in gas-filled targets on Omega-EP (3-ω, ~2.5-5 kJ)**
  - **Measure plasma temperature & lifetime vs. models**
  - **Optimize experiments to infer Braginskii transport coefficients**
  - **Measure impact of preheating on Bfield structure (p radiography)**
- **Preheating in gas-filled targets using Z-Beamlet (2-ω, 2-6 kJ)**
  - **Optimize laser focal quality, foil geometry, energy deposition**
- **Magnetic flux compression**
  - **Continue developing flux compression diagnostics**
- **Measuring stagnation conditions**
  - **Develop neutron and x-ray spectroscopy diagnostics**

Calculations indicate yields > 1GJ are possible with MagLIF targets at currents of 60 MA





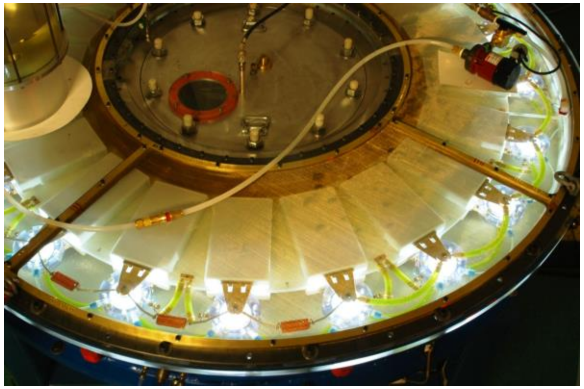
*S.A. Slutz and R.A. Vesey, Physical Review Letters 108, 025003 (2012)

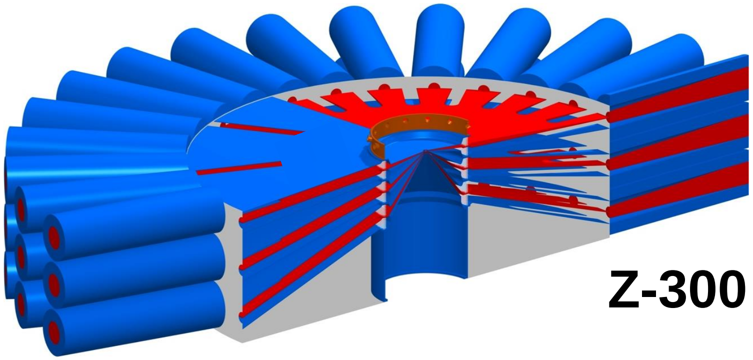
We are exploring the science and technology needed to couple significantly more energy to targets for HED science and ICF

A new pulsed power technology would enable a significant increase in energy coupled to targets

- **4x energy increase within Z footprint**
- **4-16x increase in x-ray yields for radiation effects testing**
- **4-10x increase in dynamic materials pressure**
- **Current understanding suggests significant fusion yields possible on this facility, of course those predictions must be validated!**

LTD Cavity (3-m-diameter)





Z-300

Z-300 is a reasonable step beyond the refurbished Z

E_{stored} = 20 MJ at an 85-kV charge

P_{stack} = 80 TW

V_{stack} = 4.6 MV

L_{vacuum} = 14 nH

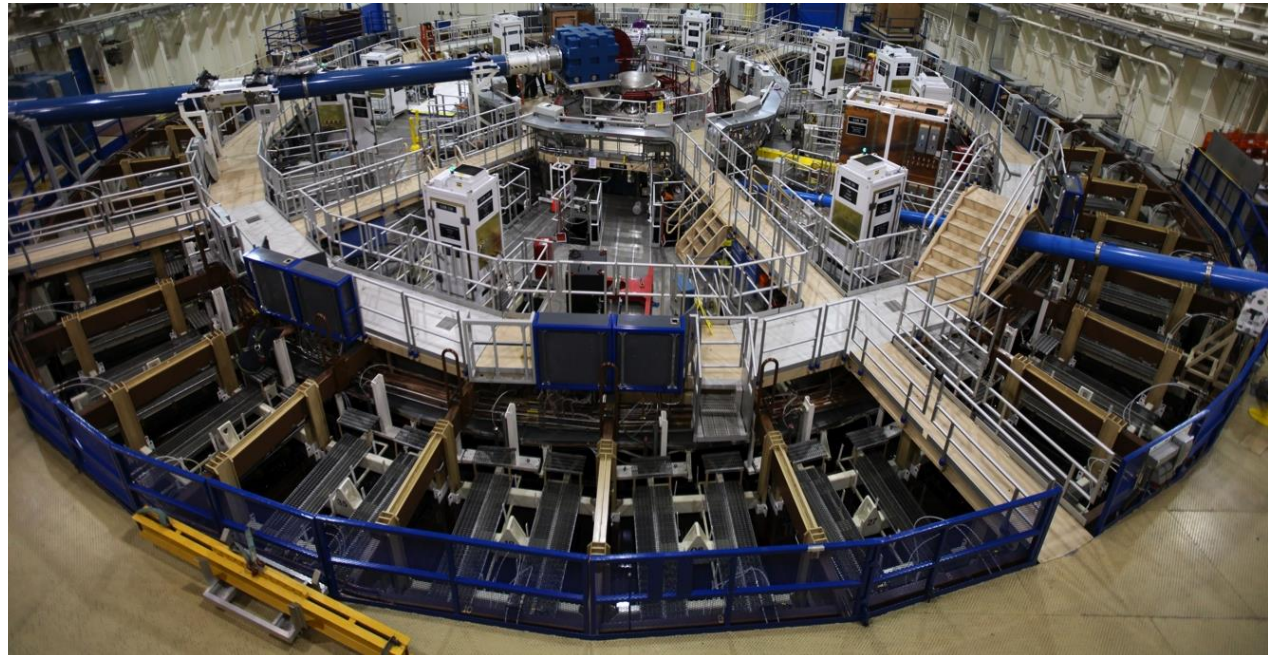
I_{load} = 26 MA

$\tau_{implosion}$ = 130 ns

$E_{radiated}$ = 3 MJ

outer diameter = 33 m

Z



E_{stored} = 48 MJ at a 100-kV charge

P_{LTDs} = 320 TW; P_{stack} = 260 TW

V_{stack} = 8 MV

L_{vacuum} = 14 nH

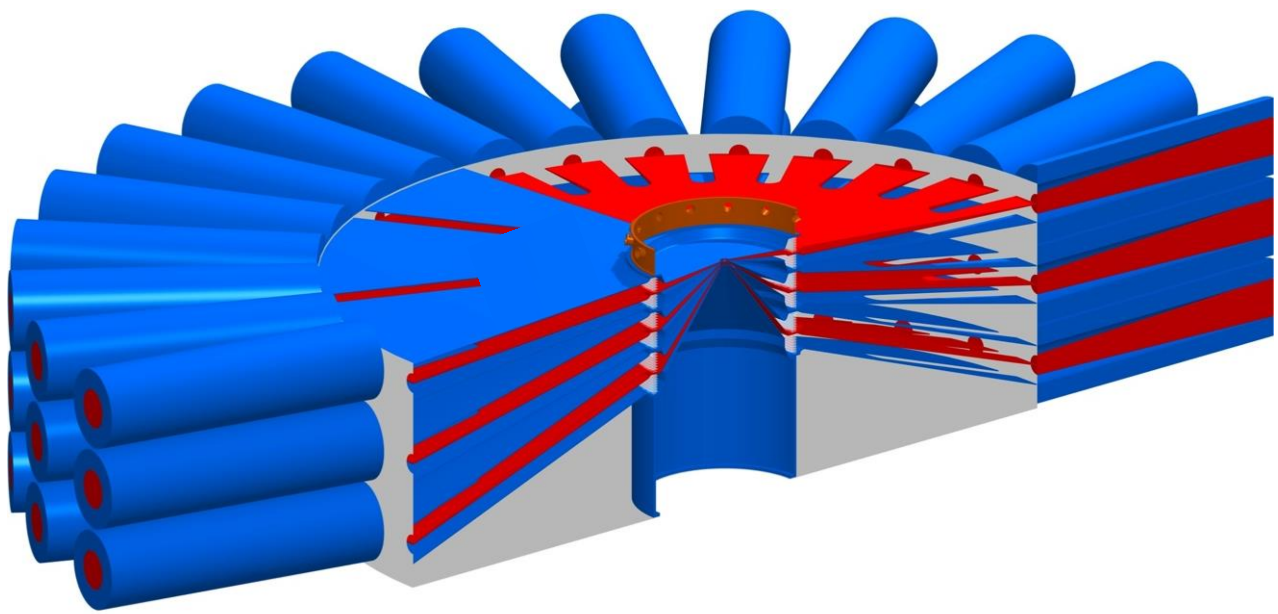
I_{load} = 50 MA

$\tau_{implosion}$ = 130 ns

$E_{radiated}$ = 12 MJ

outer diameter = 35 m

Z-300



Summary

- **We can use large magnetic fields and high currents to push on matter in different ways, enabling the creation of unique states of HED matter**
- **The refurbished Z facility is being used to explore unique states of matter at high energy densities**
- **Magnetized Liner Inertial Fusion (MagLIF) combines a magnetically driven implosion with a pre-imposed axial magnetic field to enable an interesting approach fusion self heating on the Z facility with relaxed requirements**
- **Initial MagLIF experiments on Z are promising**