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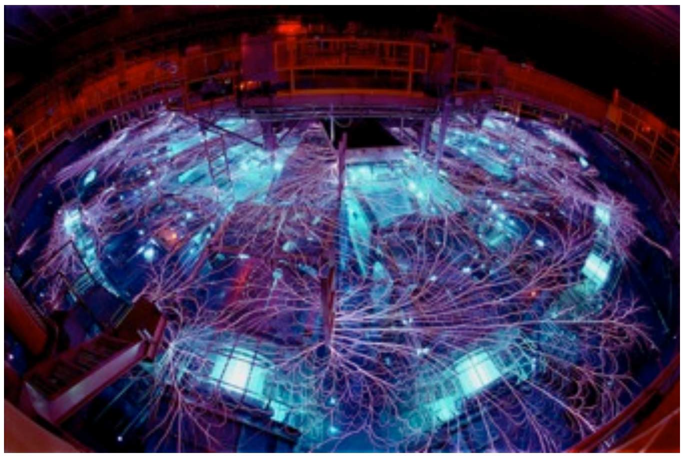
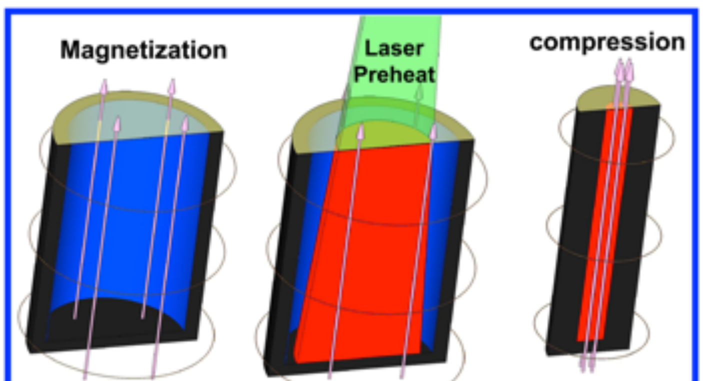


OVERVIEW OF THE HIGH ENERGY DENSITY SCIENCE PROGRAM ON THE Z FACILITY AT SANDIA NATIONAL LABORATORIES



Mark C Herrmann

Pulsed Power Sciences Center

Sandia National Laboratories

Presented at the Eighth International Conference on Inertial Fusion Sciences and Applications

Nara, Japan

September 12, 2013

U.S. DEPARTMENT OF ENERGY NNSA

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Sandia National Laboratories, Albuquerque, NM, USA

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***** General Atomics, San Diego, CA, USA**

Summary

- Large currents and magnetic fields can be used to create and study HED matter in a variety of ways, a recent emphasis is the properties of materials at high pressures
- We are performing state of the art work on the properties of dynamic materials
- Magnetized Liner Inertial Fusion (MagLIF) offers a near term chance for testing our understanding of magnetically driven implosions. If successful, would lead to 100kJ yield with DT.
- We have performed our first integrated MagLIF experiment

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

Magnetic fields and currents can push matter around:

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

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

A 5 Megagauss (500 T) magnetic field applies a pressure of 1 Megabar (MB) to a conductor.
A current of 25 MA at 1cm radius is 5 10^6 G= 1 Mbar of pressure
A current of 25 MA at 1mm radius is 5 10^7 G= 100 Mbar of pressure

The Z facility generates large magnetic fields that can be used to compress and heat matter

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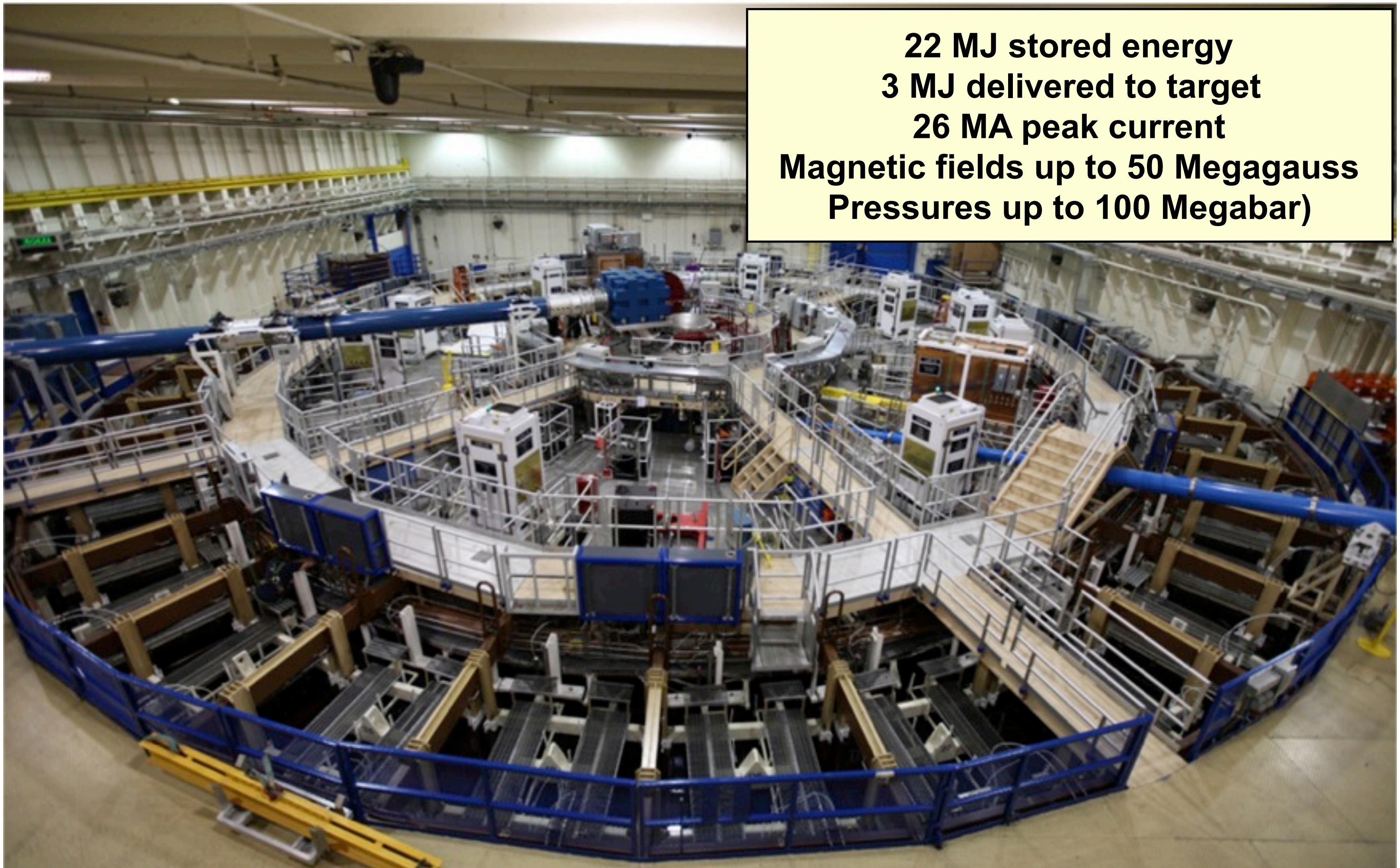
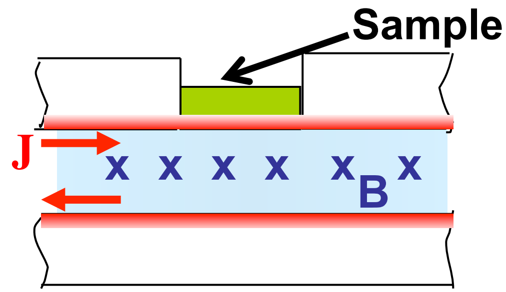


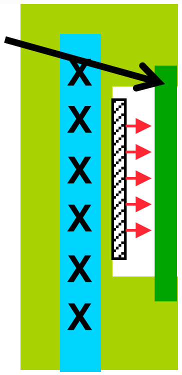
22 MJ stored energy
3 MJ delivered to target
26 MA peak current
Magnetic fields up to 50 Megagauss
Pressures up to 100 Megabar)

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

Materials Properties



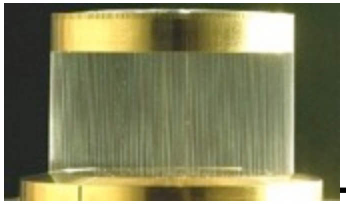
Isentropic Compression

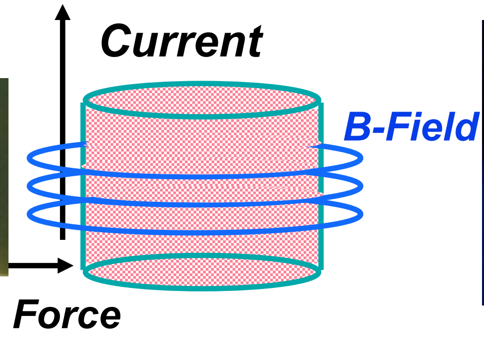


Flyer Plate

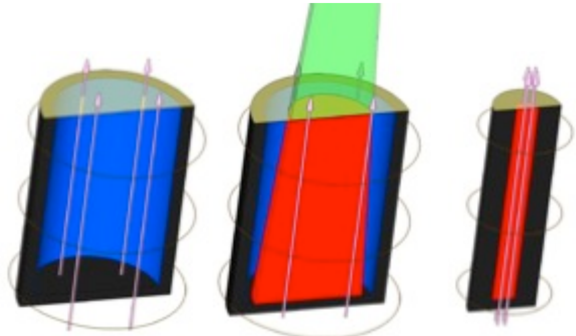
Z-Pinch X-ray Sources

wire array





Inertial Confinement Fusion



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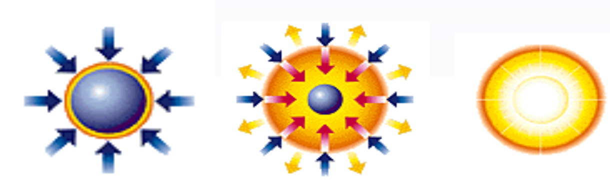
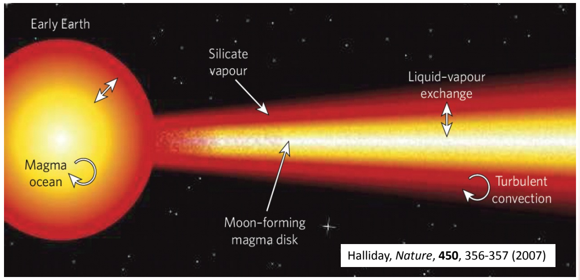
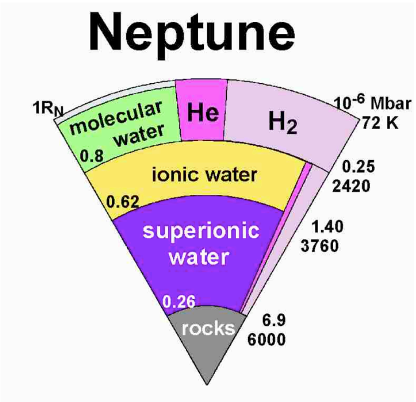
Understanding material properties at high pressure is important for ICF and understanding planets

- Inertial confinement fusion (ICF) materials
  - Behavior of hydrogen, plastics, beryllium, diamond



- Planetary science
  - Earths and super-earths
    - Equation of state of Mg, Fe, Si, C, O and related compounds
  - Giant Planets (e.g. Uranus & Neptune and exo ice-giants)
    - High-pressure mixtures of H, He, C, O, N





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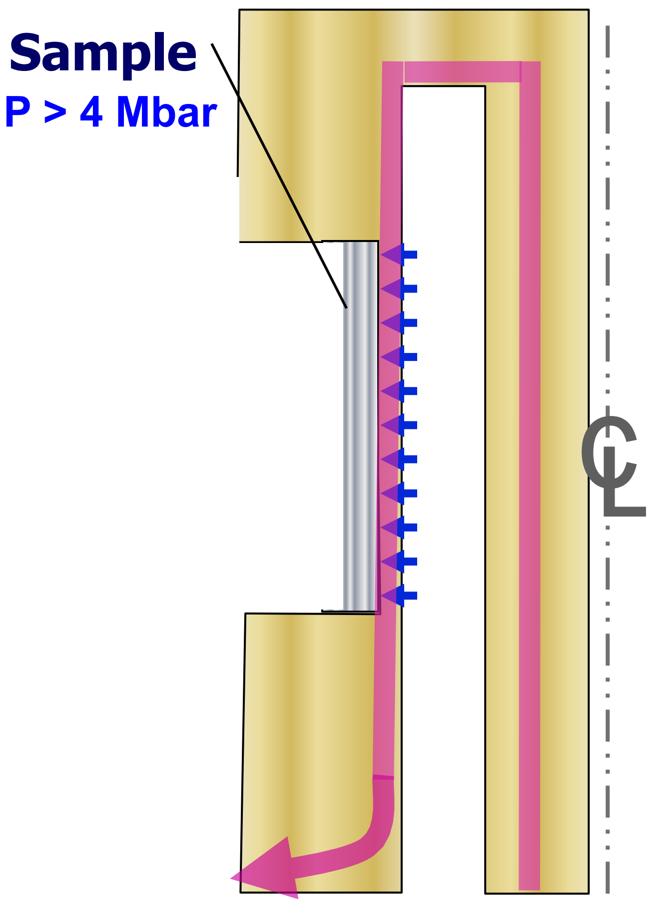
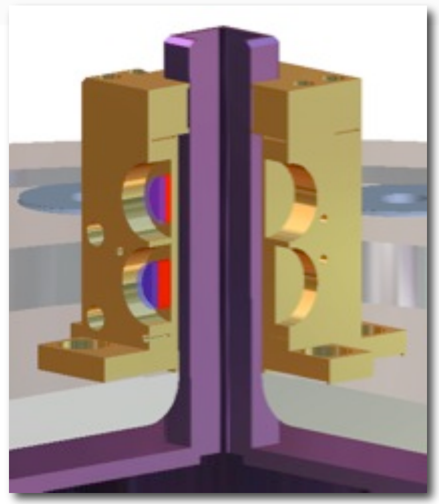
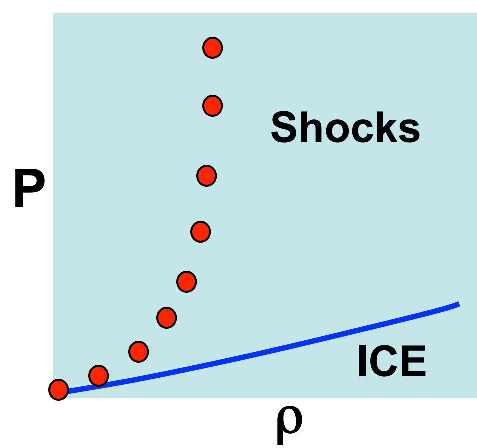
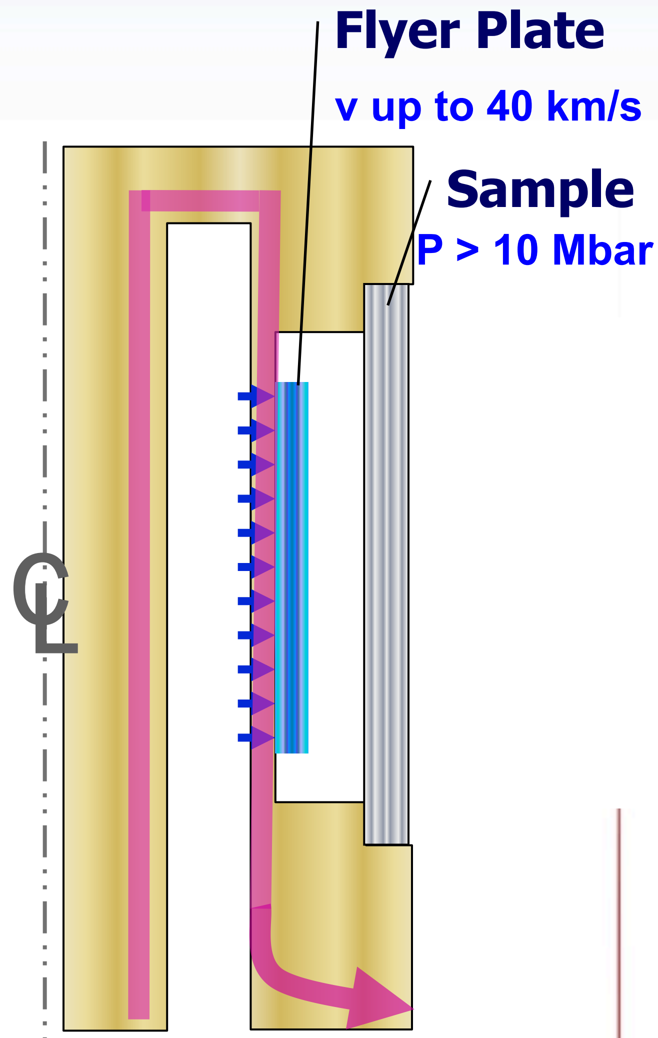
Z can perform both shockless compression and shock wave experiments





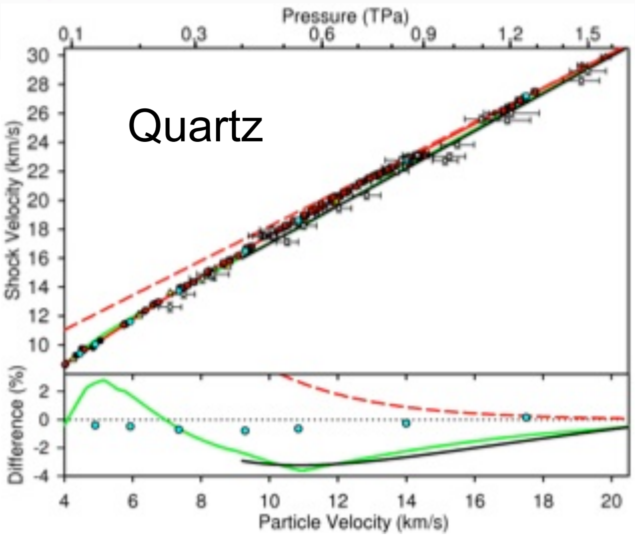


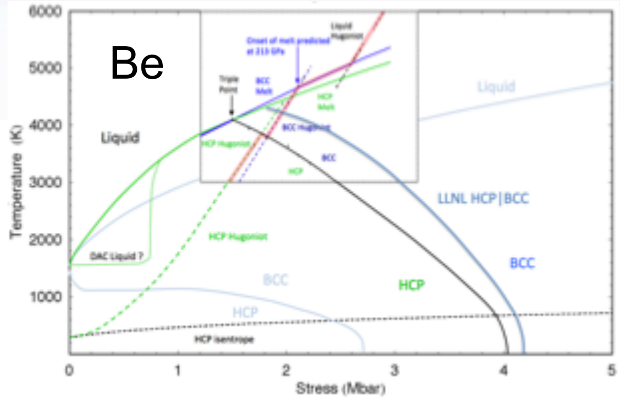


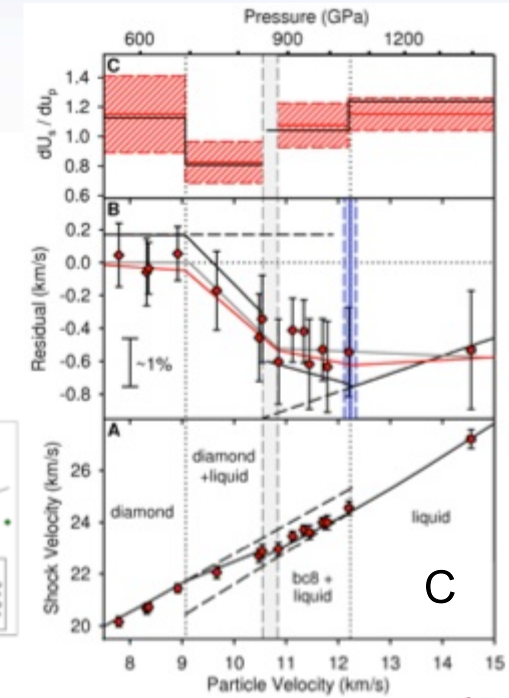
Isentropic Compression Experiments:
gradual pressure rise in sample

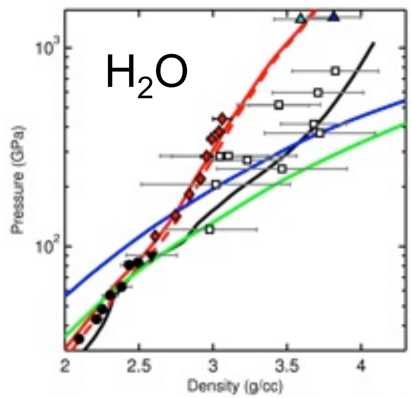
Shock Hugoniot Experiments:
shock wave in sample on impact

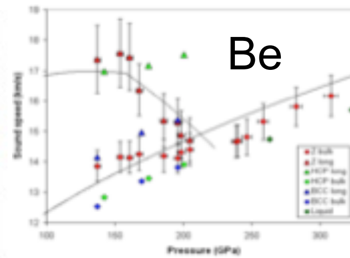
Z has been used to study material properties in the multi-Mbar regime for many materials

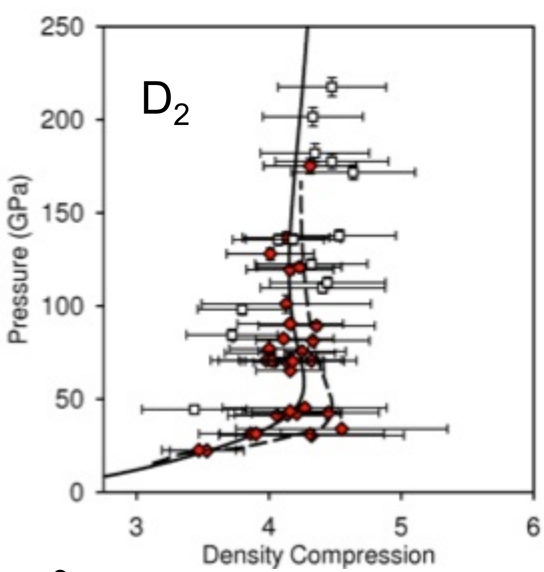


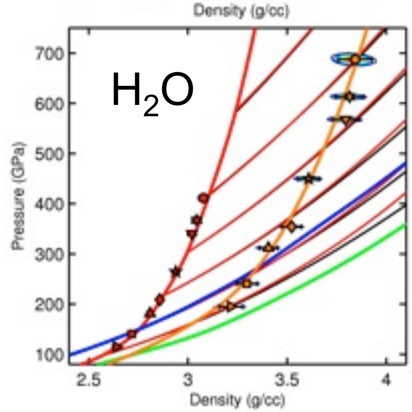


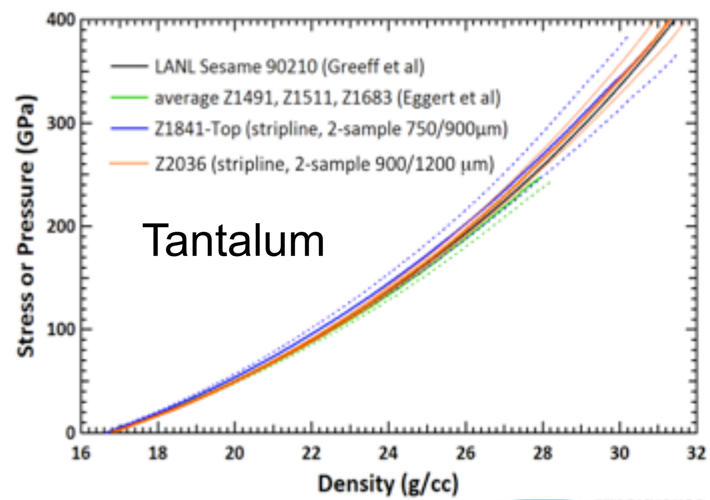




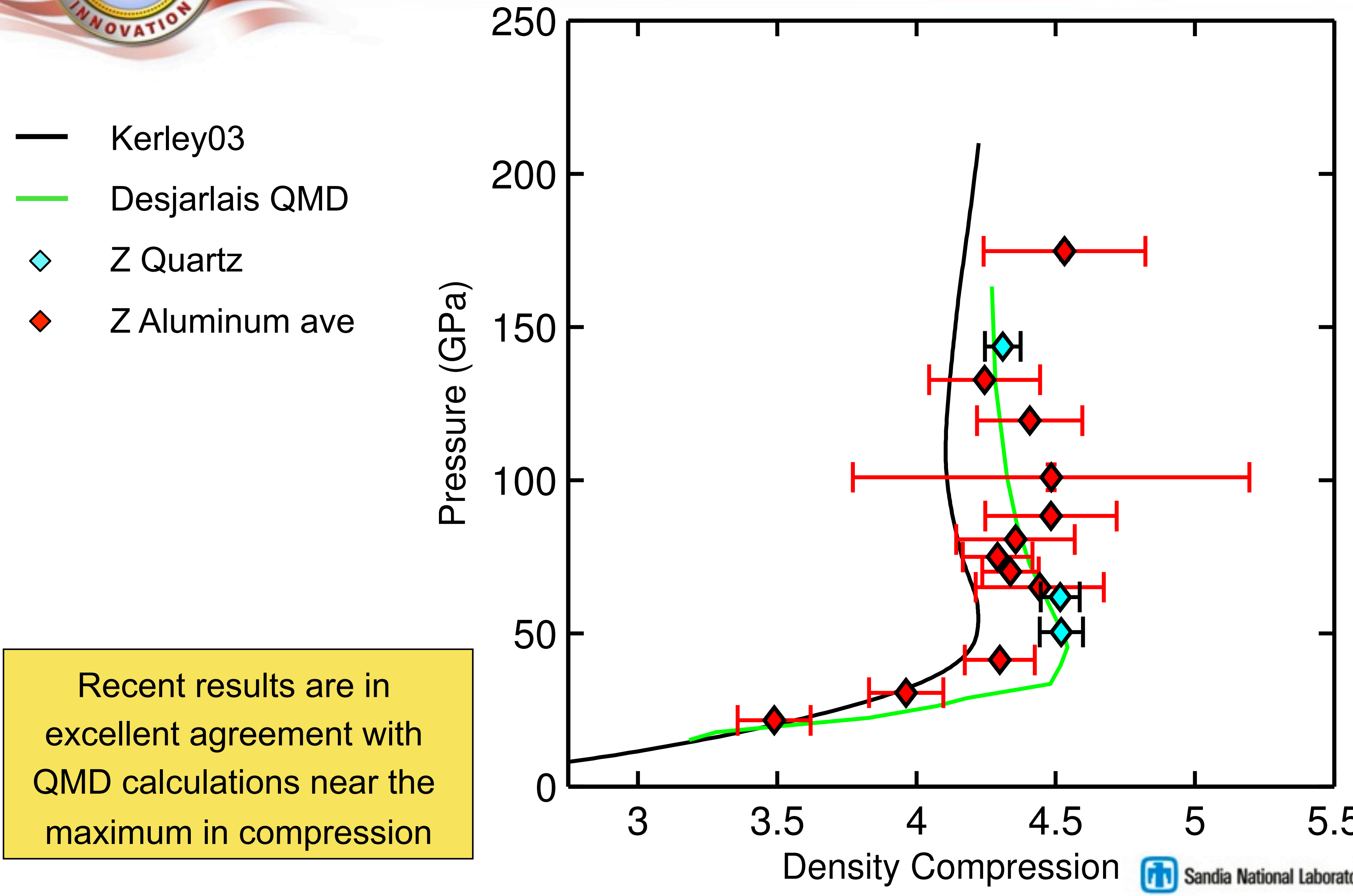








Recent D2 results show significant improvement in precision with respect to previous data



Recent results are in excellent agreement with QMD calculations near the maximum in compression

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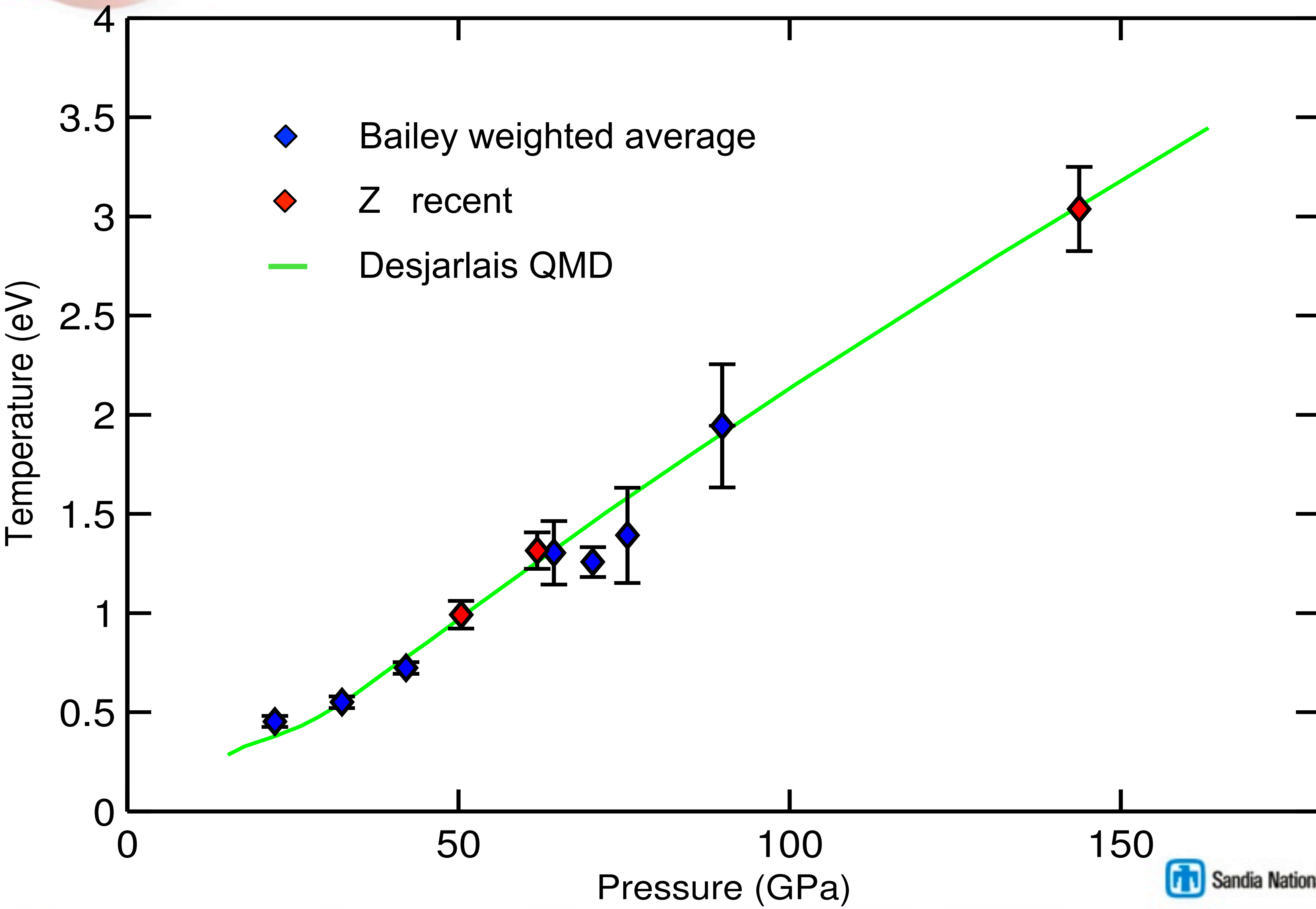
D2 Temperature measurements are in very good agreement with QMD and previous data



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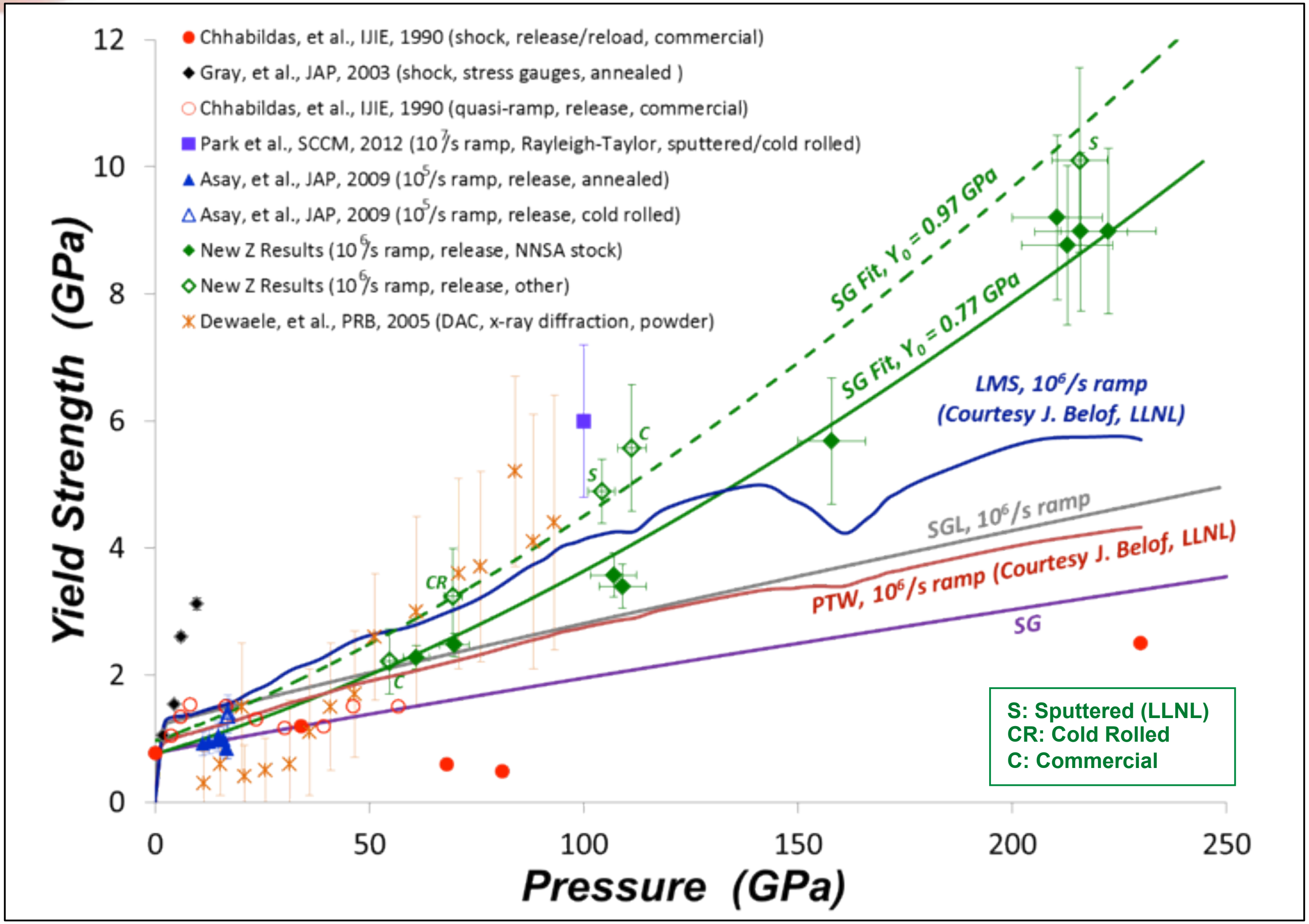
We performed a comprehensive exploration of Ta strength to 2.5MB



Planar loads explode during a shot, divergent geometry limits maximum magnetic pressure

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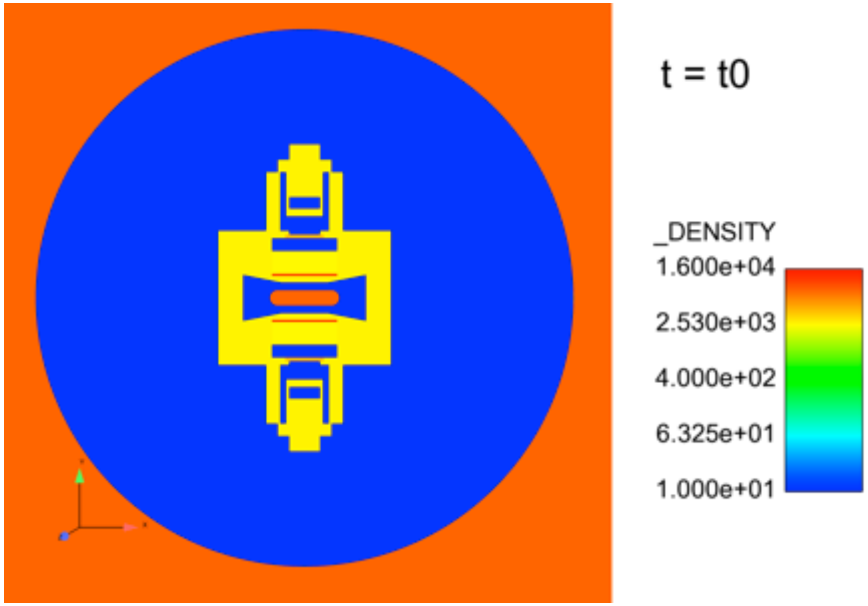

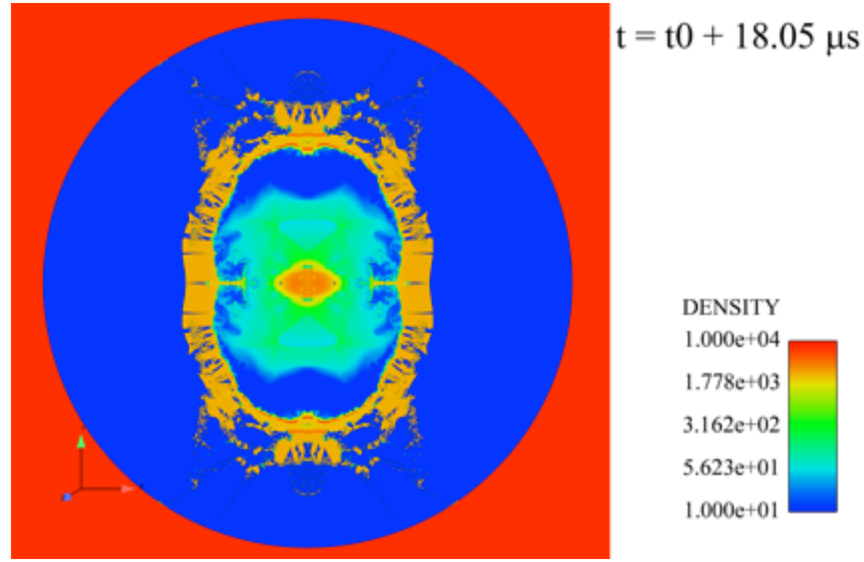

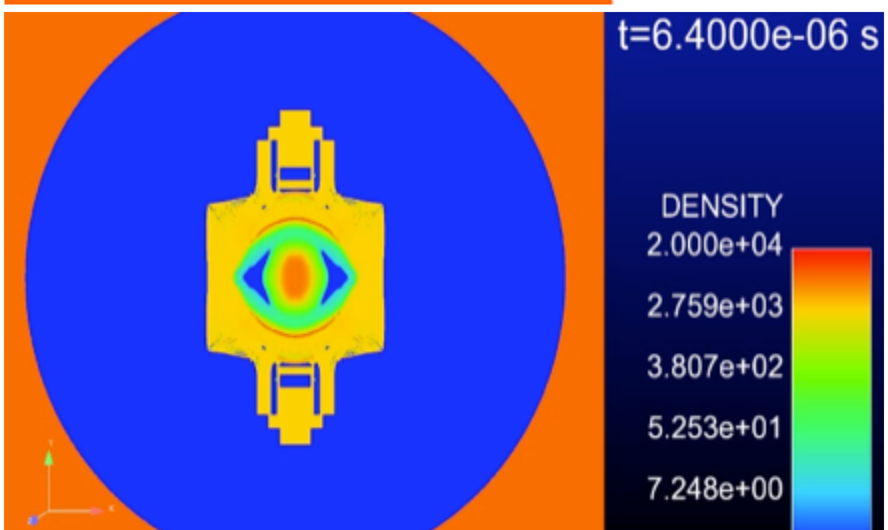

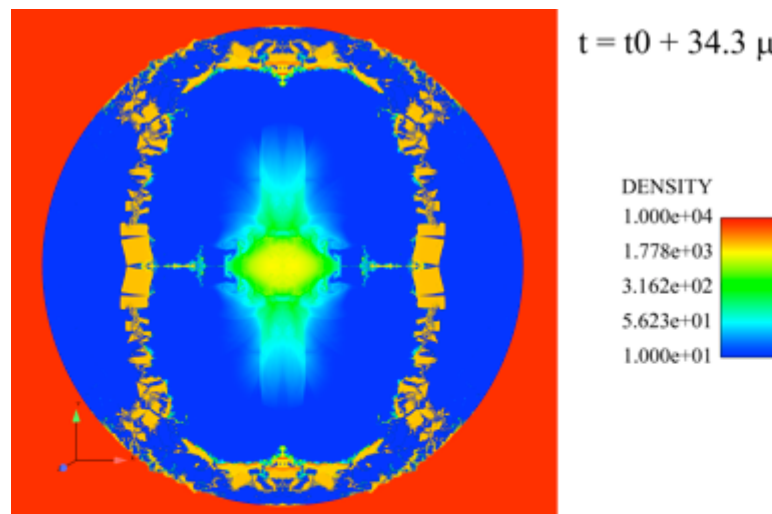

Based on the ICF programs understanding of liner stability we developed a platform to measure the isentrope of Beryllium at 5.5 Mbar

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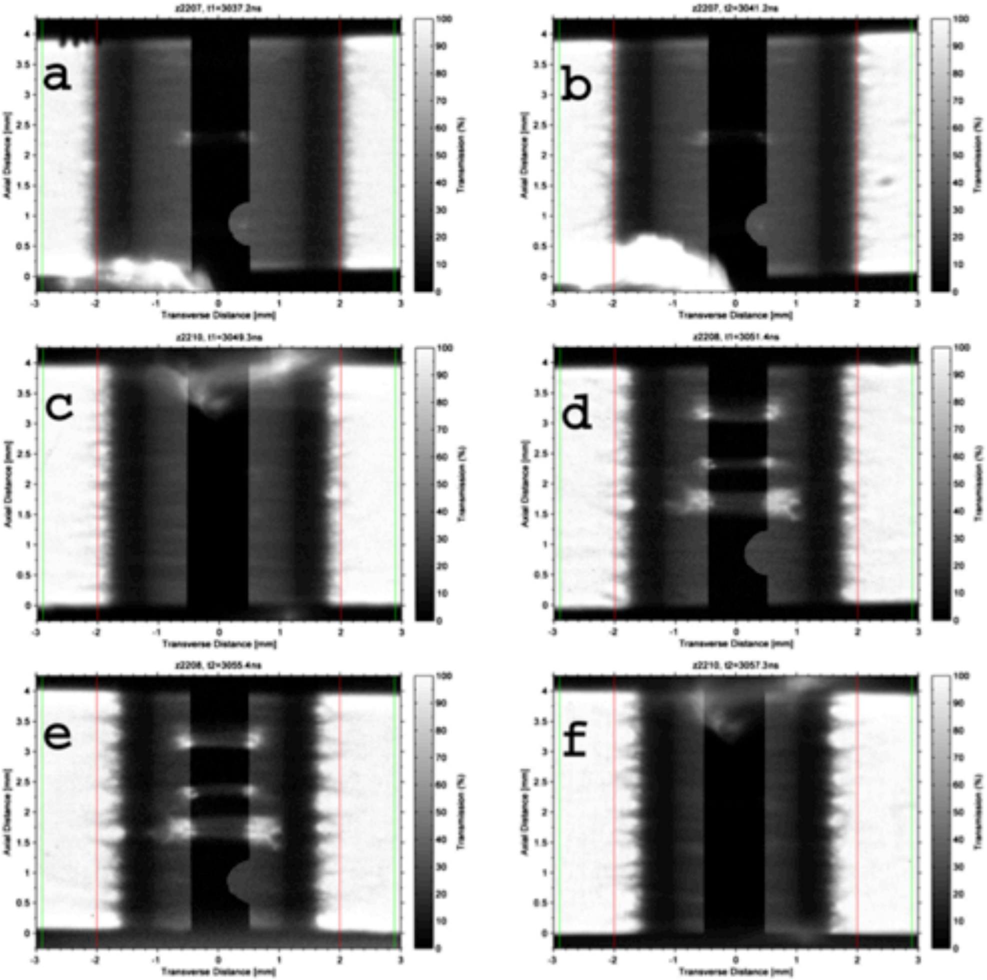
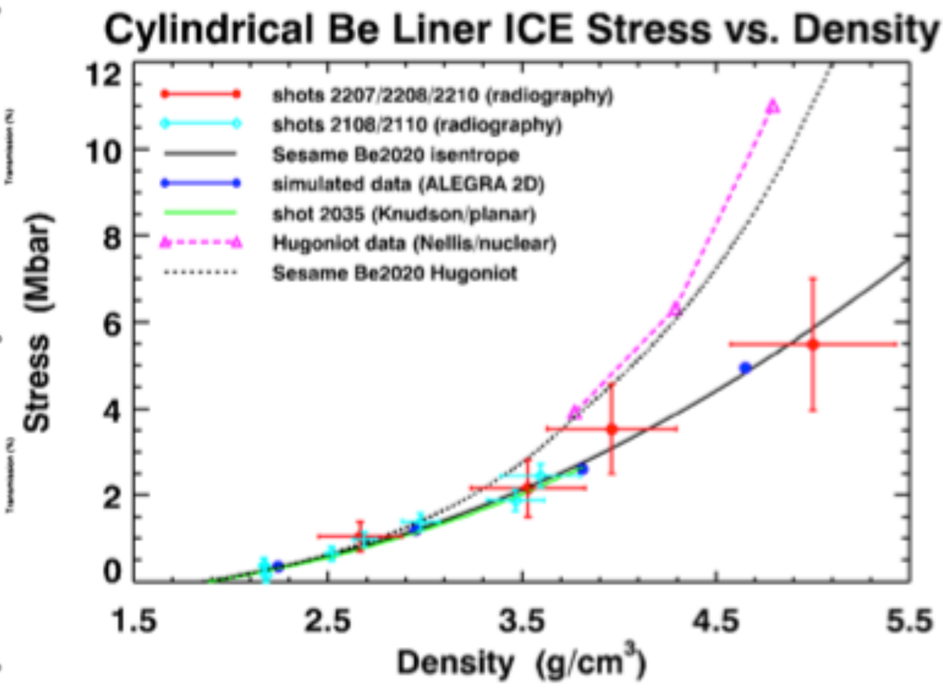
Radiographs of Be liner implosions at different times

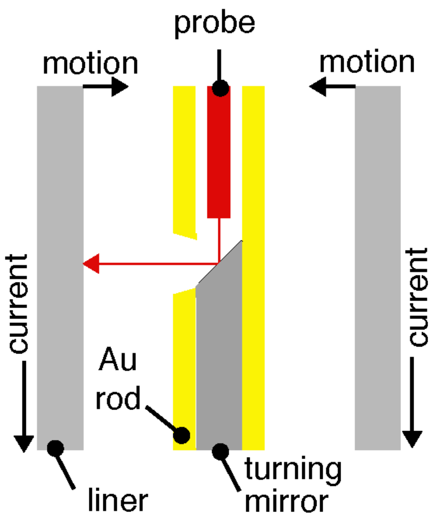


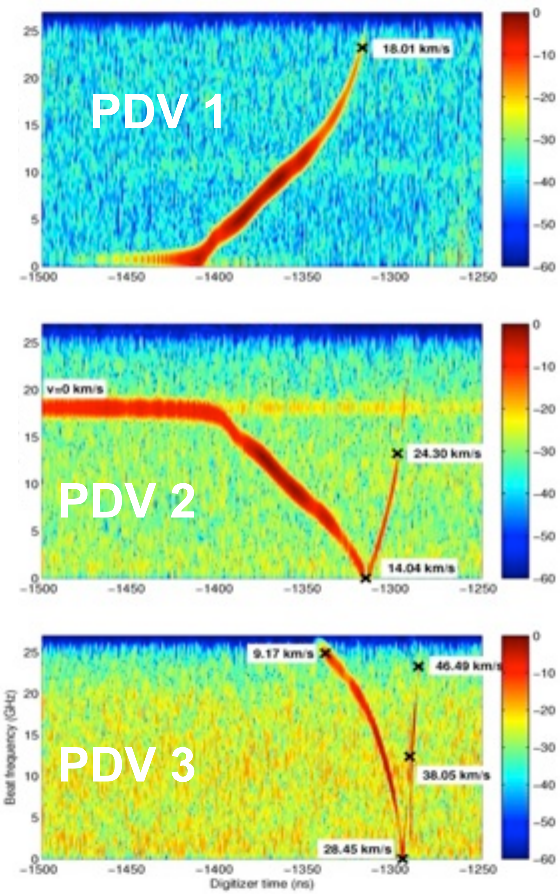


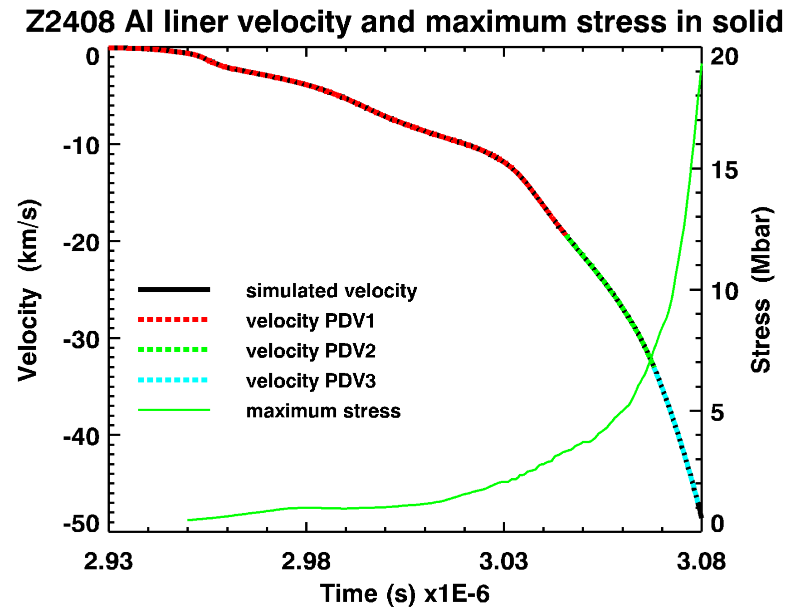
Peak stress is 2x higher than previously studied in planar geometry

Lemke *et al.*, AIP Conf. Proc. (2012); Martin *et al.*, ibid; Martin *et al.*, Phys. Plasmas (2012).

Coupling an internal velocity probe to the cylindrical EOS platform enables shockless compression measurements to 20 Mbar in Al (4 x planar)







GA did a fabulous job building these targets, NNSS helped with diagnostic development

Simulated velocity (black) and approximate ranges for the three PDV frequencies (colors)

Pressure in solid Al (green)

This innovation could significantly broaden Z's ability to obtain data at higher pressures and strain rates

The Harvard/SNL fundamental science project on materials for planetary formation determined the vapor-critical point of iron using a reverse-impact technique on Z

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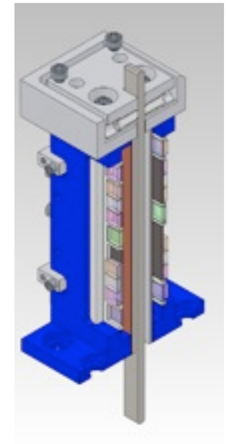
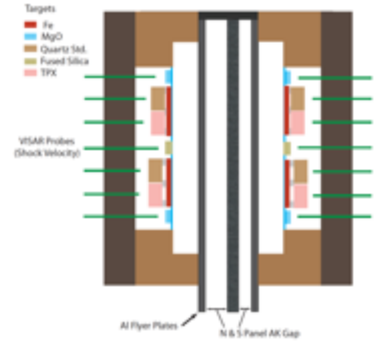
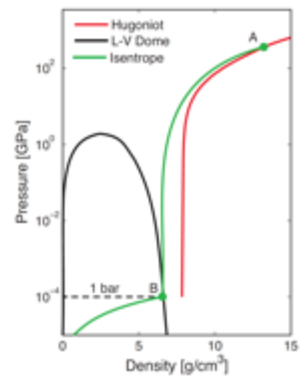
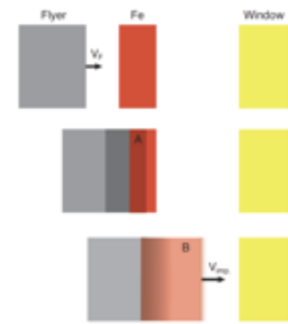
- The team developed a new experimental platform on Z to measure the critical point of a broad range of materials
  - Record number of samples on one experiment
  - Prompted further optimization of flyer design – record thick solid Al flyer at impact
  - Utilizing a broad suite of diagnostics
    - All available VISAR, PDV probes for velocimetry
    - Optical spectroscopy for emission/temperature
- Determined the vapor-liquid critical shock pressure for iron
  - Onset of vaporization at 507(+65,-85) GPa along the Hugoniot
  - *"Most impactors onto the Earth and Moon achieve partial vaporization of their cores"*
  - *The expansion velocities for iron vapor are large enough to gravitationally escape the Moon but not Earth"*

The new 20-sample target assembly



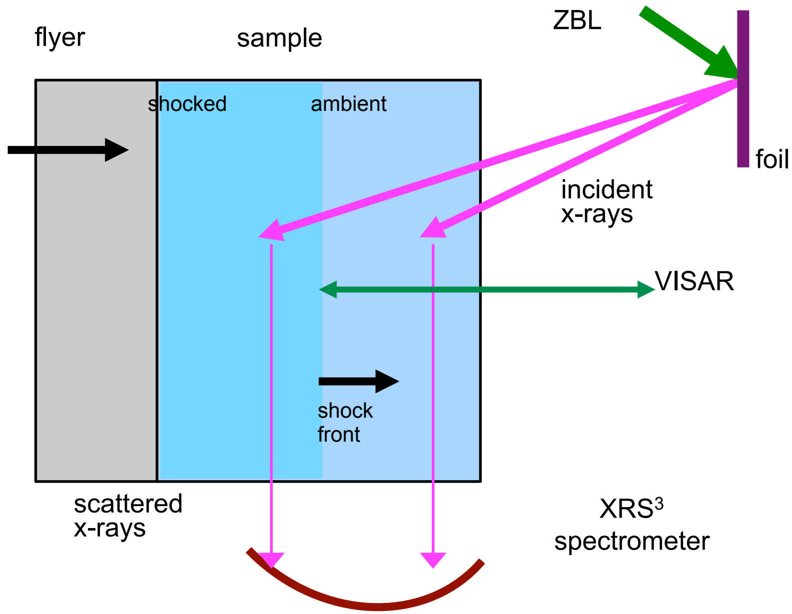


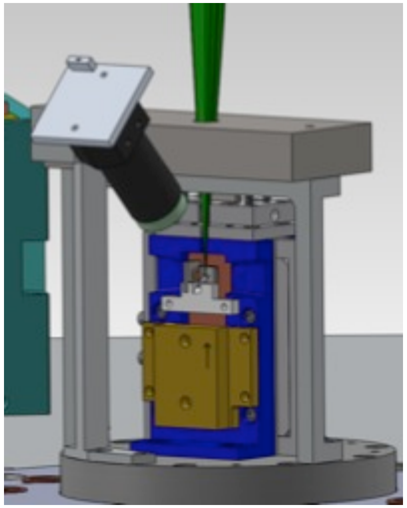




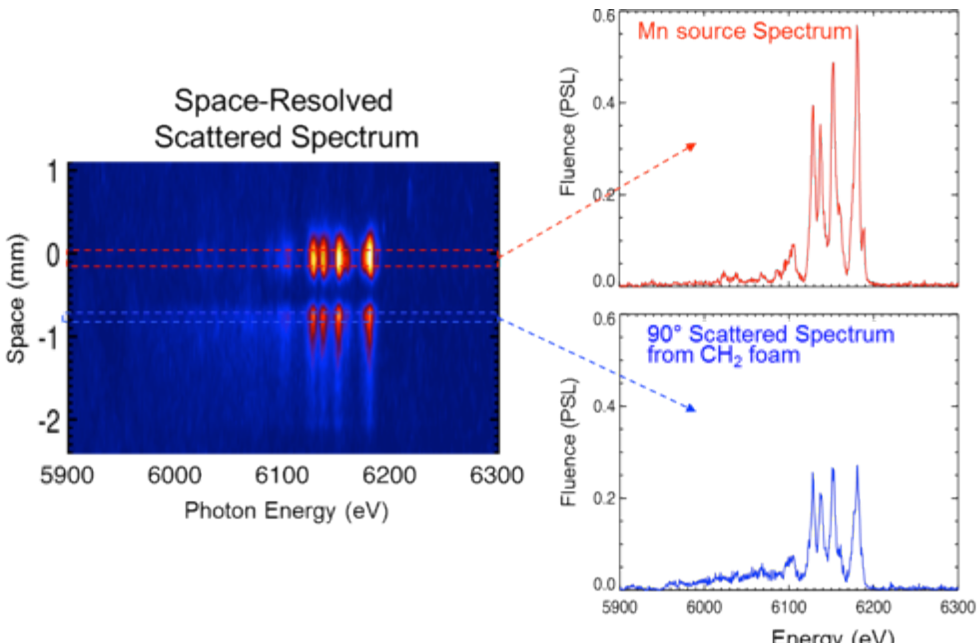
"*Shock Thermodynamics of Iron and Impact Vaporization of Planetesimal Cores*", R. G. Kraus et. al., to be submitted to SCIENCE.

X-ray Thomson scattering enables a new approach to probing the behavior of Warm Dense Matter





An LDRD led by Jim Bailey of SNL researched and developed X-ray Thomson Scattering as an approach to probing Warm Dense Matter



The US has developed a path forward for its ICF program. Magnetically driven implosions are an important part of this path.

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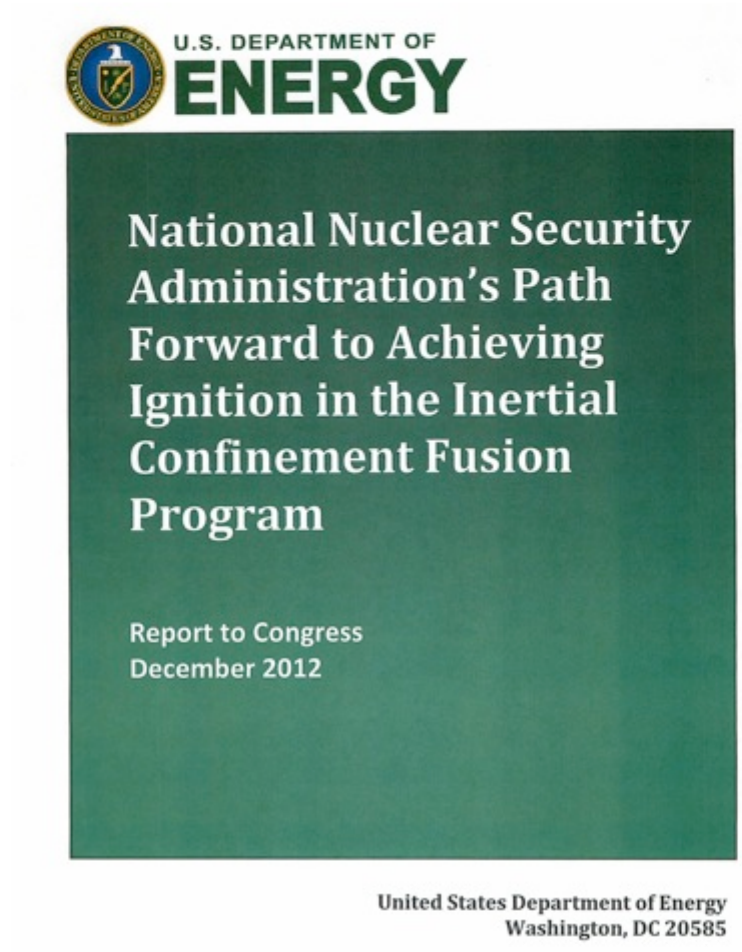

U.S. DEPARTMENT OF
ENERGY

National Nuclear Security Administration's Path Forward to Achieving Ignition in the Inertial Confinement Fusion Program

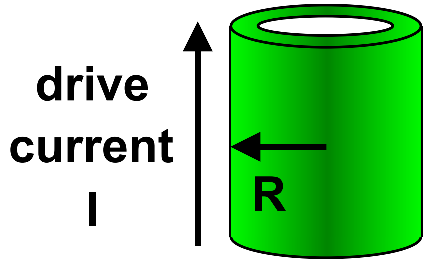
Report to Congress
December 2012

United States Department of Energy
Washington, DC 20585

Magnetically driven implosions can efficiently couple energy to fusion 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

- 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

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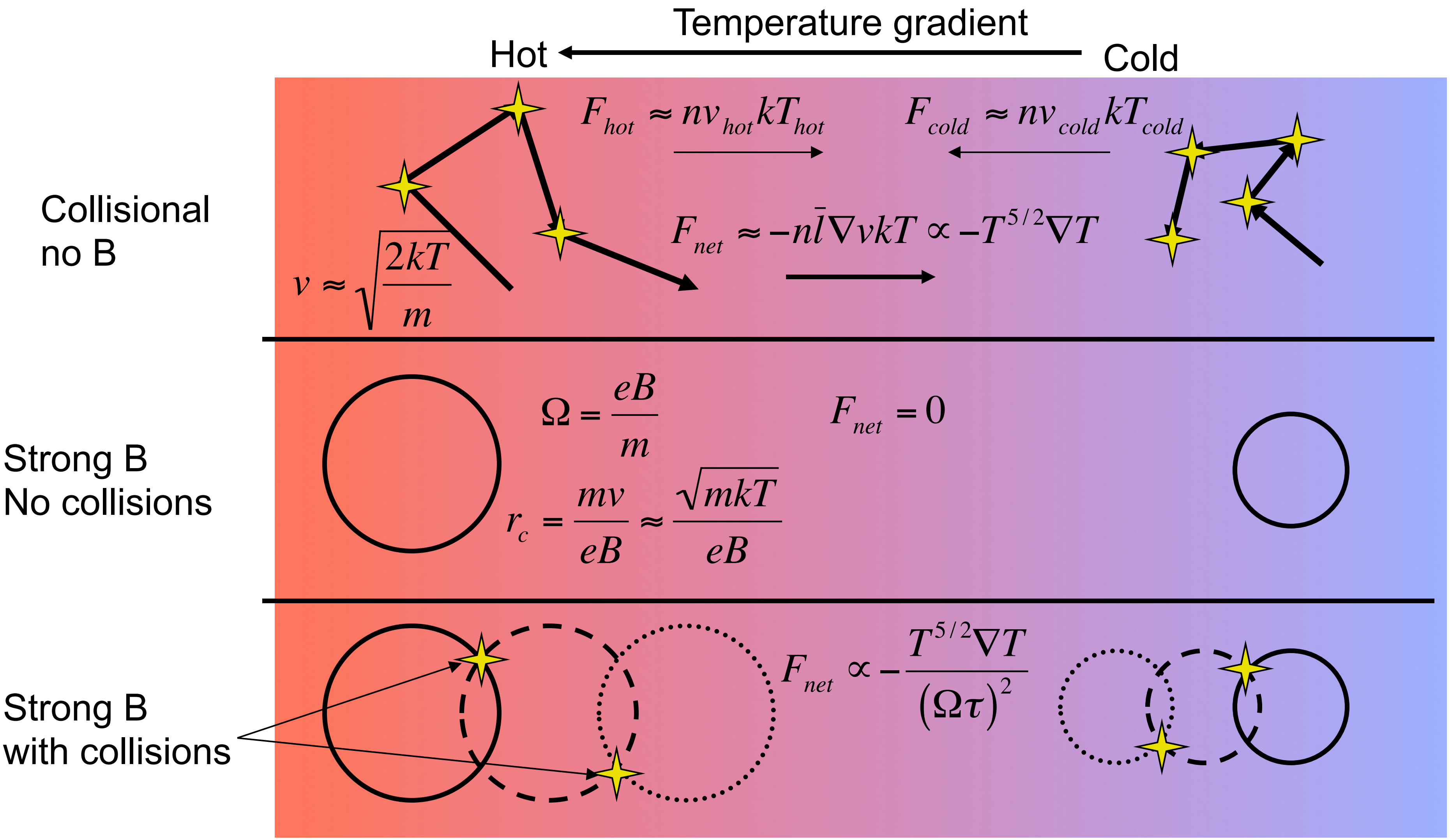
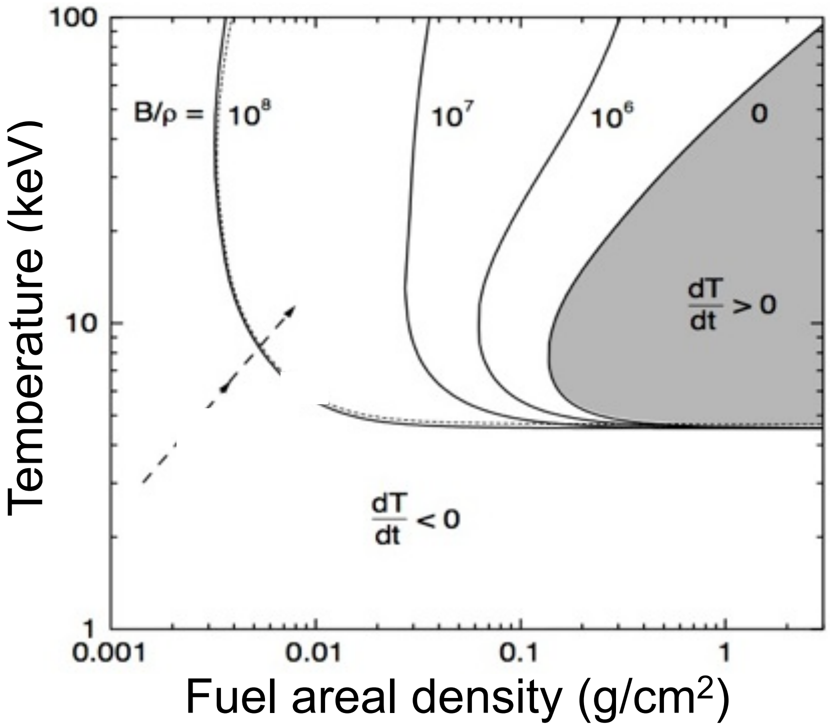
The presence of a magnetic field can strongly reduce the ρr of fusion fuel needed for ignition



Energetic particles (e.g., alpha particles) can also be strongly affected by magnetic fields

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

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



Even in non-optimal field-line geometry magnetic fields have had a positive impact on capsule implosions:
P.-Y. Chang *et al.*, Phys. Rev. Lett. (2011)

The ρr needed for ignition can be significantly reduced by the presence of a strong magnetic field
- Inhibits electron conduction
- Enhances confinement of α particles

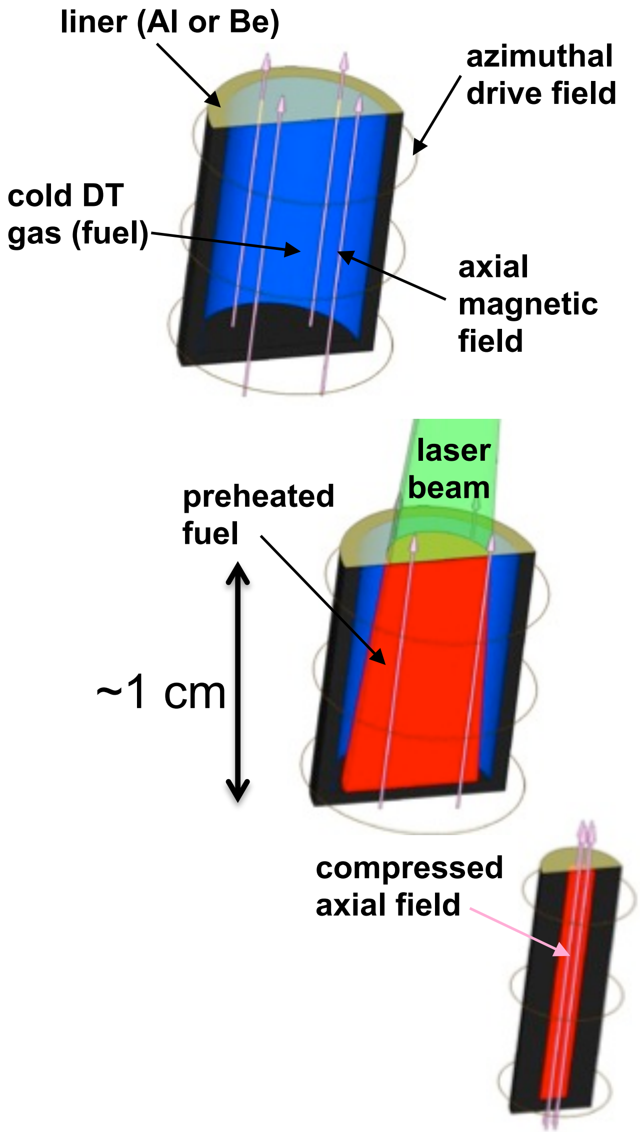
Lower ρr means low densities are needed (~1 g/cc << 100g/cc)

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

Magnetized Liner Inertial Fusion (MagLIF)* concept – to maximize energy coupled to the fuel.



- The magnetic field directly drives a solid liner containing fusion fuel.
- An initial 30 T axial magnetic field is applied
  - Inhibits thermal conduction losses
  - Enhances α-particle energy deposition
- During implosion, the fuel is heated using the Z-Beamlet laser (about 6 kJ)
  - For ignition on Z (with DT), preheating reduces the required compression from 40 to ~25, and the implosion velocity from 350 km/s to ~ 100 km/s.
- ~50-250 kJ energy in fuel; 0.2-1.4% of capacitor bank
- The required stagnation pressure is reduced from 300 Gbar (hot-spot ignition) to ~5 Gbar.
- Scientific breakeven may be possible on Z using DT (fusion yield = energy into fusion fuel)!

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

MDI (Magnetically-Driven-Implosion) milestones in the Path Forward to assess initial MagLIF feasibility

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Fiscal Year	Platform	Milestone	Completion Criterion
2013	All	For all fusion approaches, define the plan and specific goals for scientific and technological activities to be performed in preparation for the FY2015 review.	For all approaches, identify and document the detailed experimental, computational, technology development, and other activities required to be performed in preparation for the FY 2015 review.
2013	MDI	Demonstrate initial capability for magnetized and preheated fusion experiments.	Conduct experiments on Z to simultaneously magnetize and pre-heat cylindrical fusion targets. Determine the impact of the magnetic field on current coupling to the target.
2014	MDI	Complete Initial Integrated Magnetic Liner Inertial Fusion (MagLIF) Experiment.	Determine fusion plasma parameters at initial levels of pre-heat, magnetic fields, and drive currents. Compare results to simulations.
2015	MDI	Evaluate fusion performance and stagnation plasma parameters for MagLIF at enhanced drive conditions and compare results with simulations.	Increase B > 20 T, pre-heat > 4 kJ, current > 22 MA. Conduct experiments to measure the stagnation plasma parameters and fusion target performance for all platforms.

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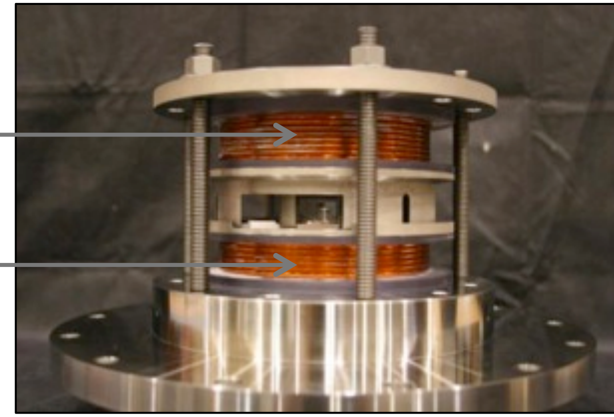
Capacitor bank system on Z
900 kJ, 8 mF, 15 kV

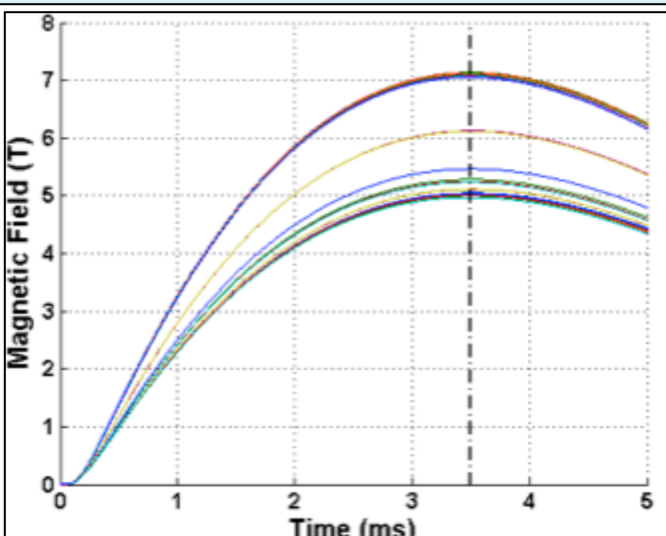
MagLIF prototype assembly with test windings of coils

80-turn coil

60-turn coil



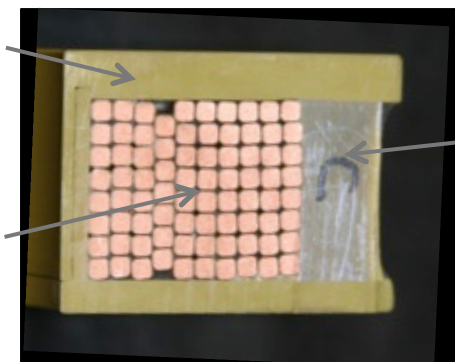
MagLIF on-axis magnetic field data taken at our Systems Integration Test Facility in Bldg. 970



Cross section of 80-turn coil prototype

Torlon housing

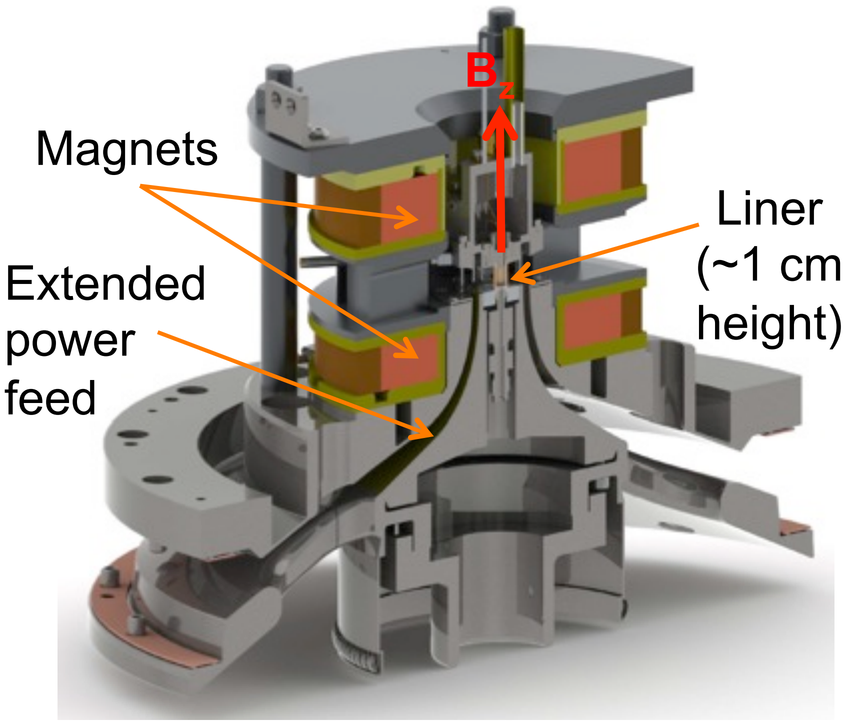
#11 sq. copper wire with double Kapton insulation



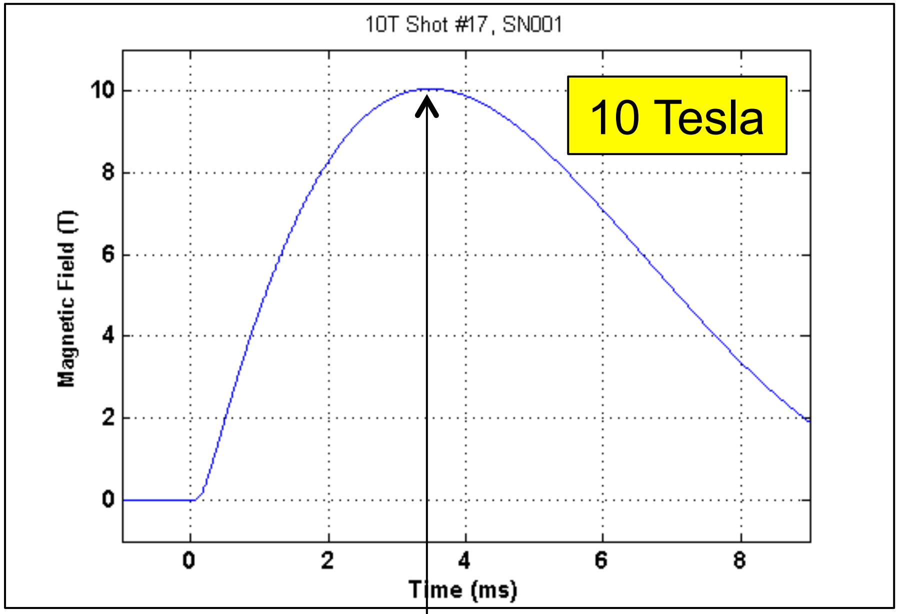
Zylon/epoxy shell provides external reinforcement

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 to make 7-10 T fields on 4 ICF shots



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

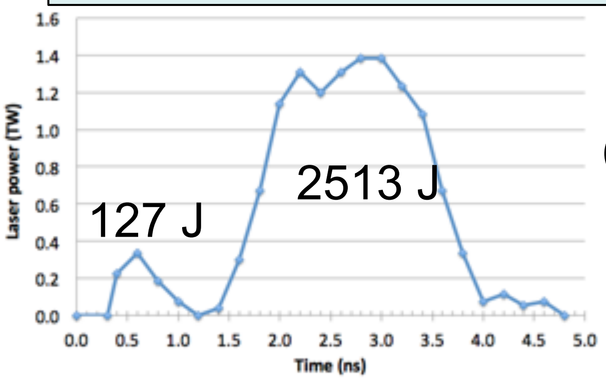
Long time scale needed to allow field to diffuse through the liner without deformation

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

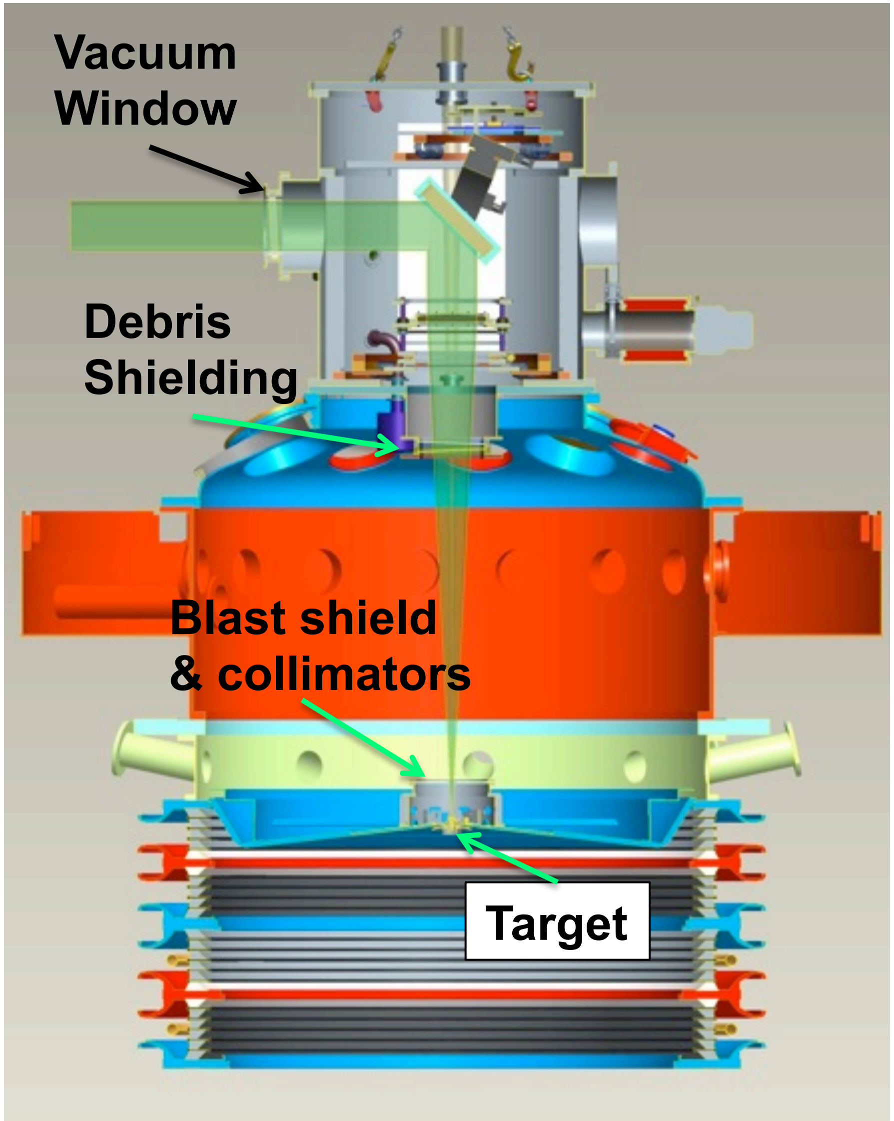
We have begun integration of 2-2.5 kJ laser preheating into Z MagLIF experiments

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

Example pulse measurement



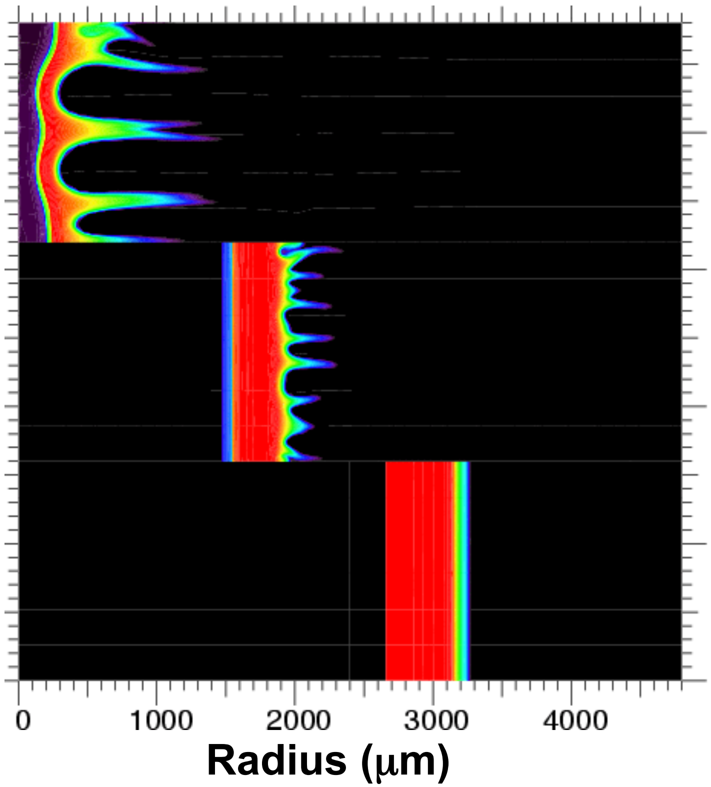
ZBL
2ω light
(2.64 kJ)



Simulations indicate 100kJ fusion yield 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
Preheat Temperature:	250 eV
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

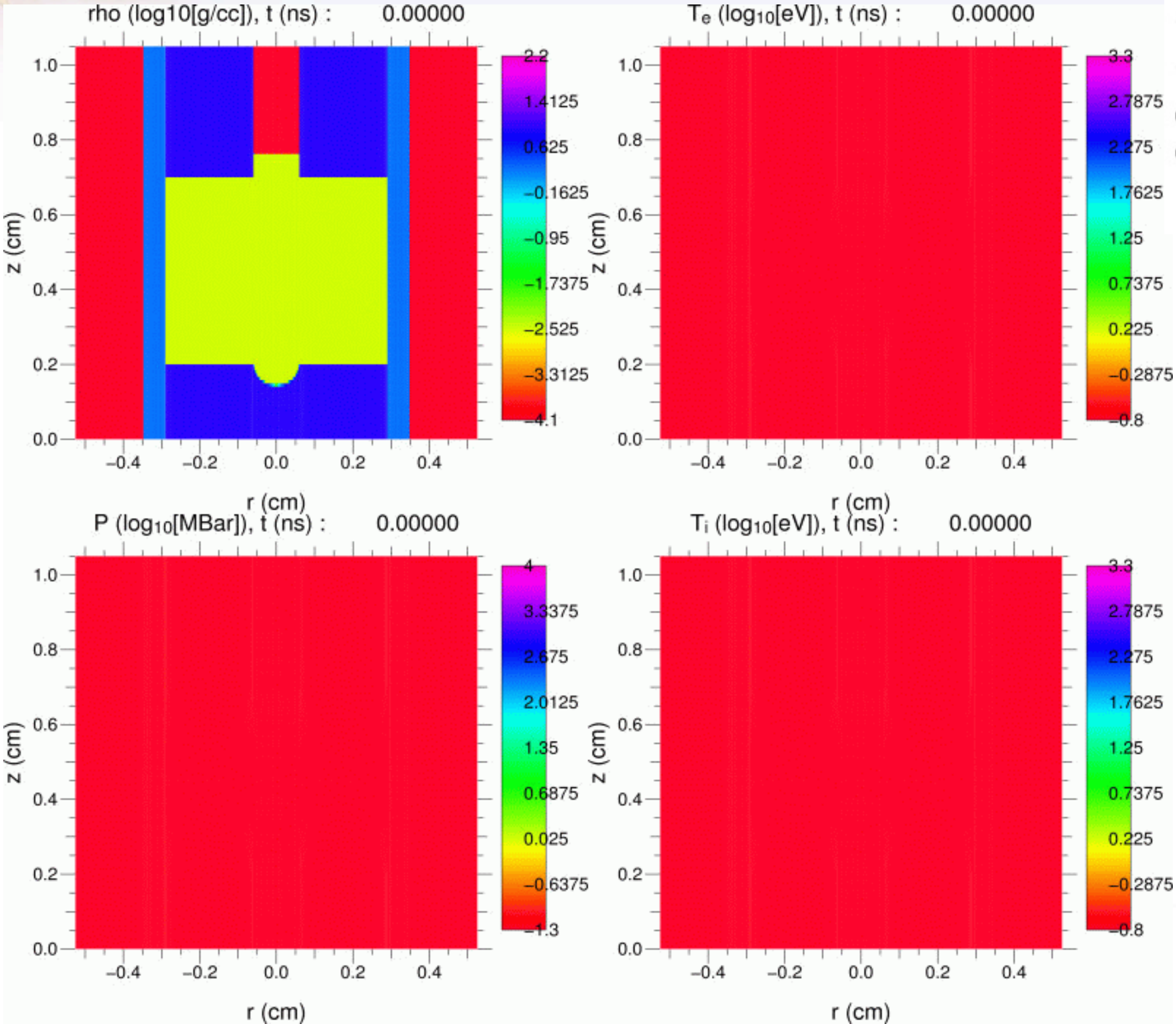
60 nm surface roughness, 80 (μm) waves are resolved

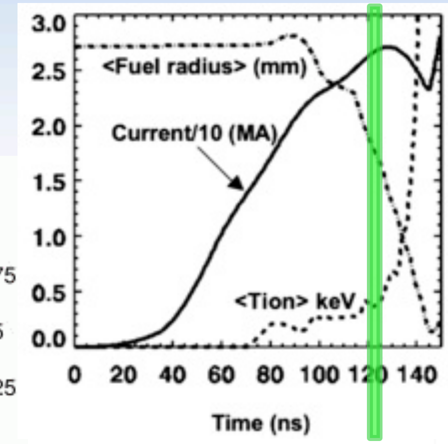


2D yield for a DT target ~ 350 kJ (70% of 1D)

The magneto-Rayleigh Taylor instability is a big concern for this concept

Integrated calculation incorporate "real world" affects



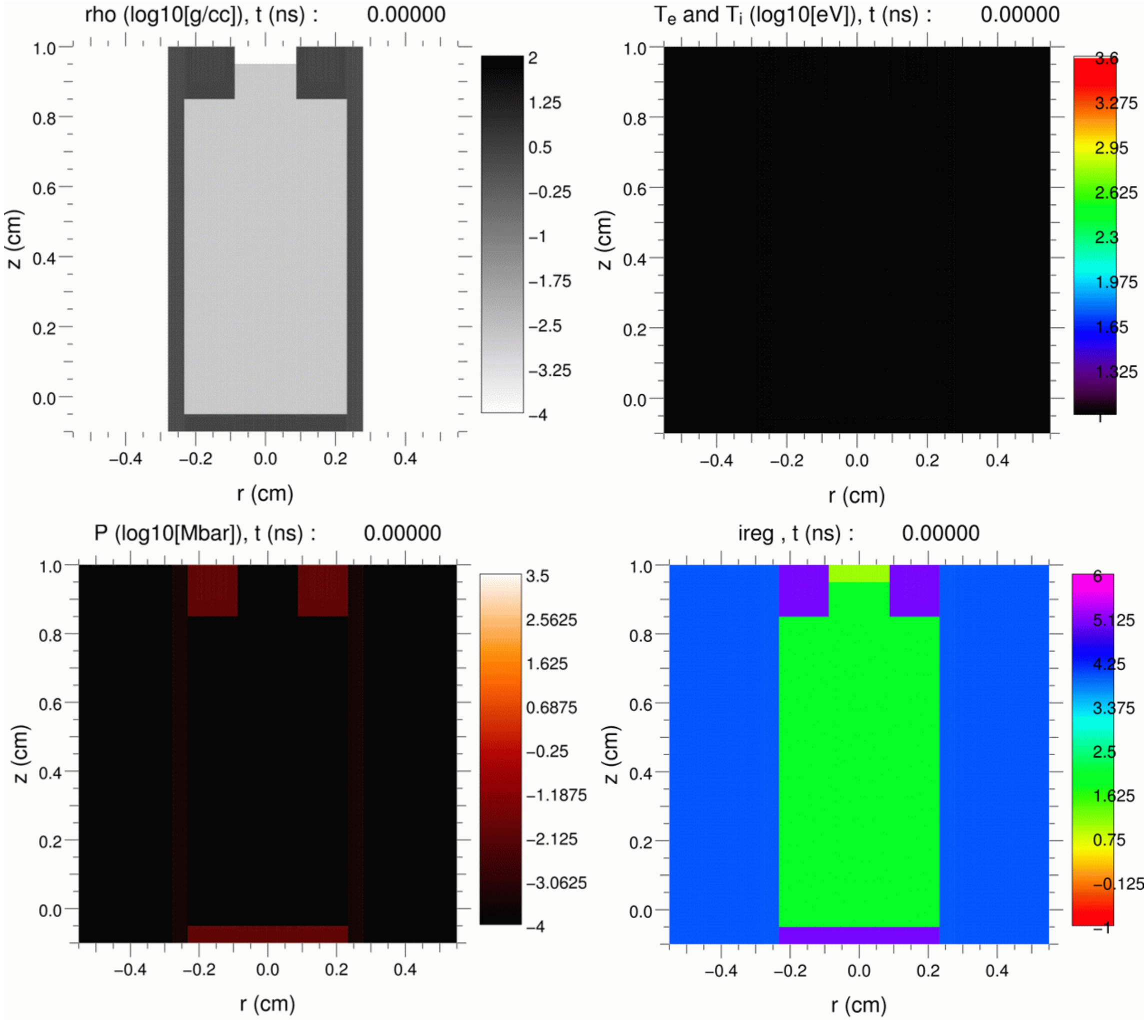


laser heating: 120-124 ns

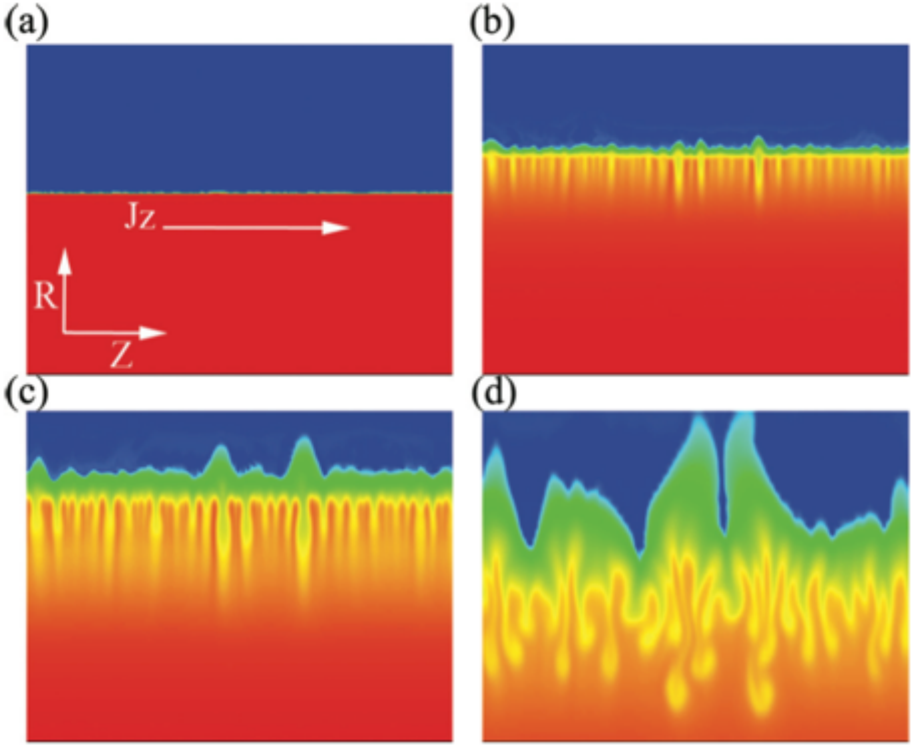
Calculations by
A. Sefkow

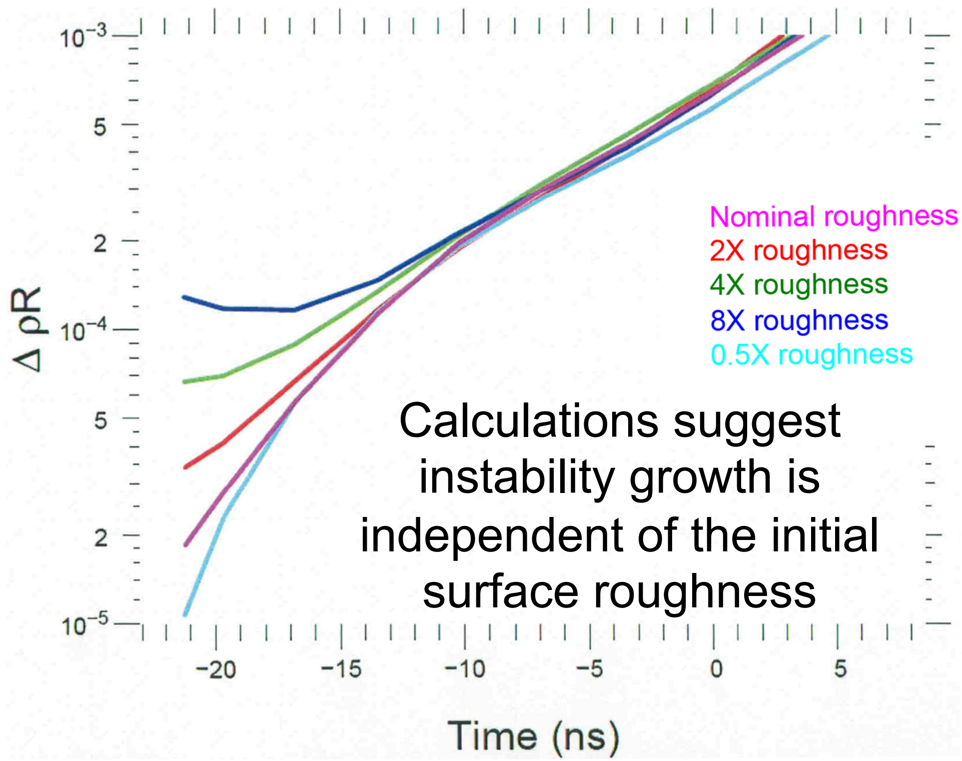
Sandia National Laboratories

A recent simulation of a MagLIF implosion



The electro-thermal instability is an important mechanism that could seed MRT growth*

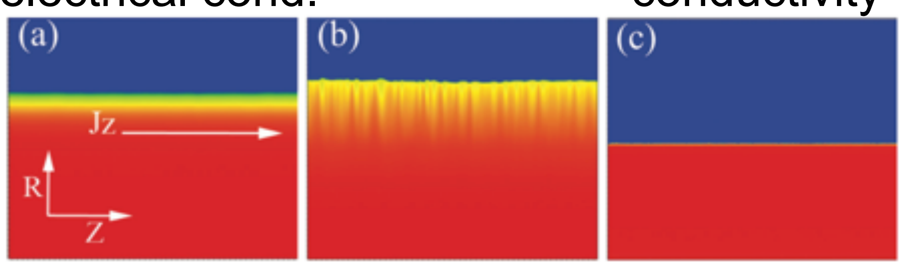




Constant electrical cond.

Nominal

10x thermal conductivity

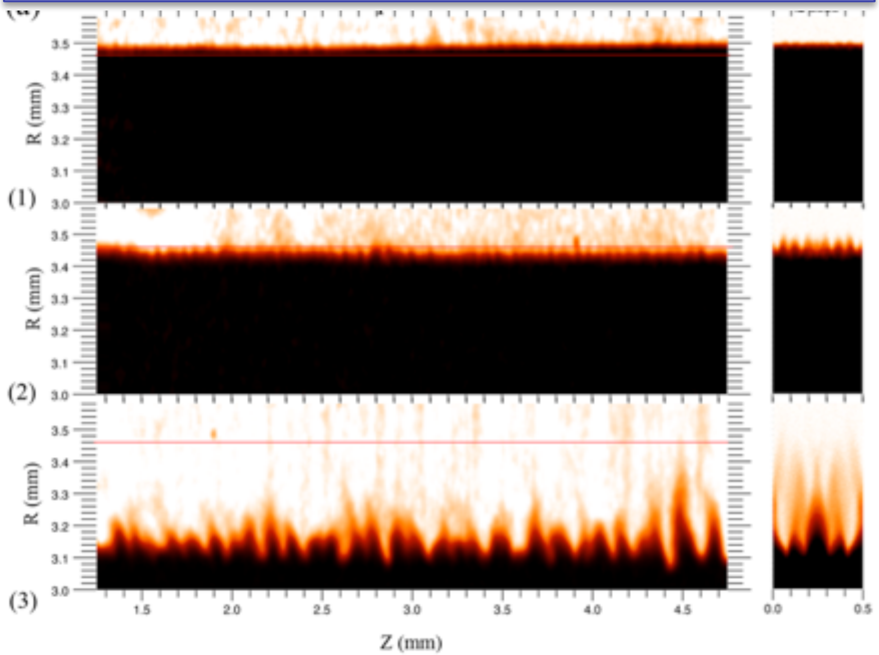


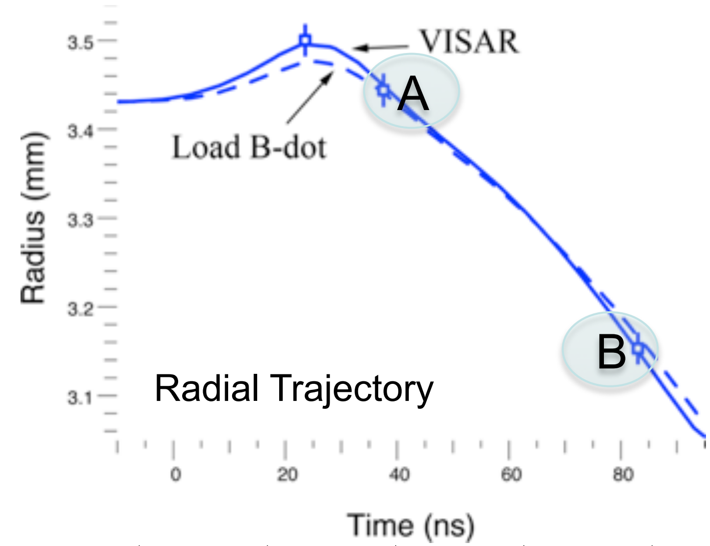
Temperature perturbations give rise to pressure variations which eventually redistribute mass

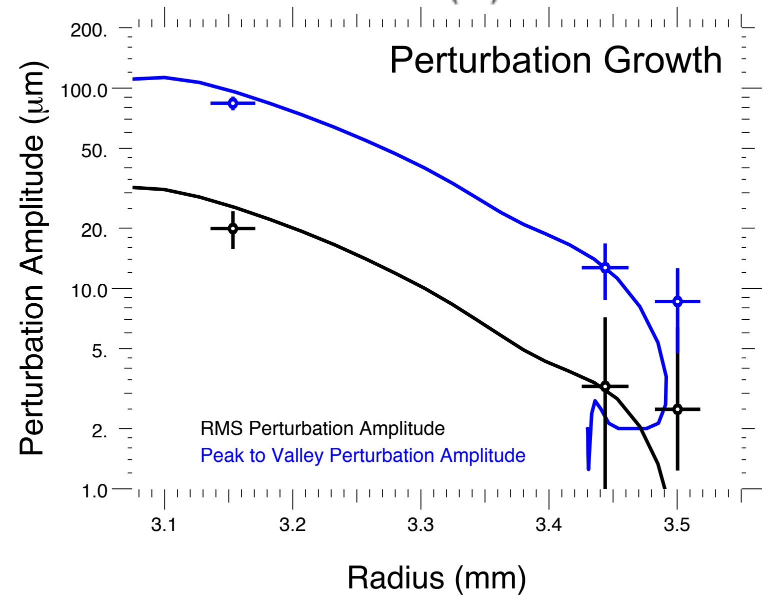
*K.J. Peterson *et al.*, Phys. Plasmas (2012); K.J. Peterson *et al.*, Phys. Plasmas 20, 056305 (2013).

Comparisons between our modeling and experimental instability growth in solid Al liners are promising—the perturbation growth is larger than expected from MRT alone

Experimental (left) & simulated (right) radiographs





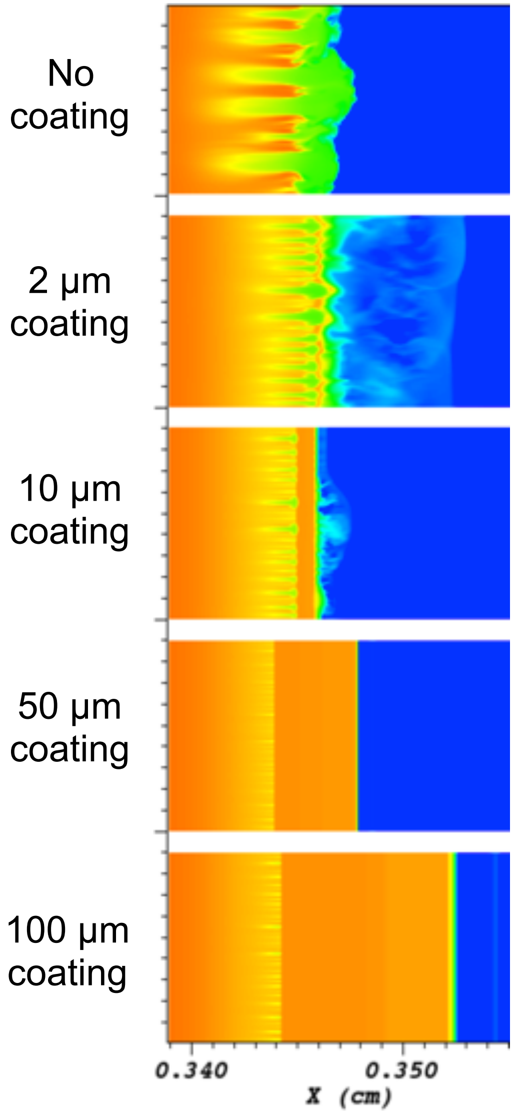


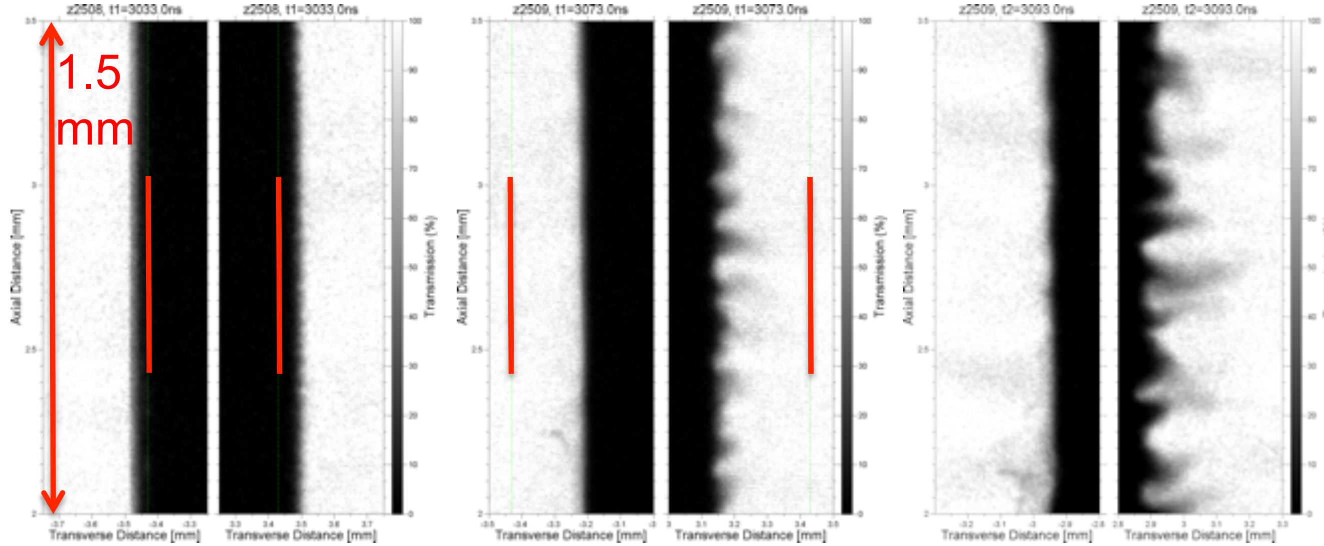
Perturbation Growth Comparison

Time	Est. MRT (λ=100 μm)	$h=0.06Agt^2$	Observed
A	0.36 μm	6.2 μm	13 ± 7 μm
B	24 μm	41 μm	80 ± 7 μm

*K.J. Peterson *et al.*, Phys. Plasmas (2012); K.J. Peterson *et al.*, Phys. Plasmas 20, 056305 (2013).

Simulations predicted that we could mitigate the impact of the electrothermal instability by tamping out the density variations—this was confirmed experimentally



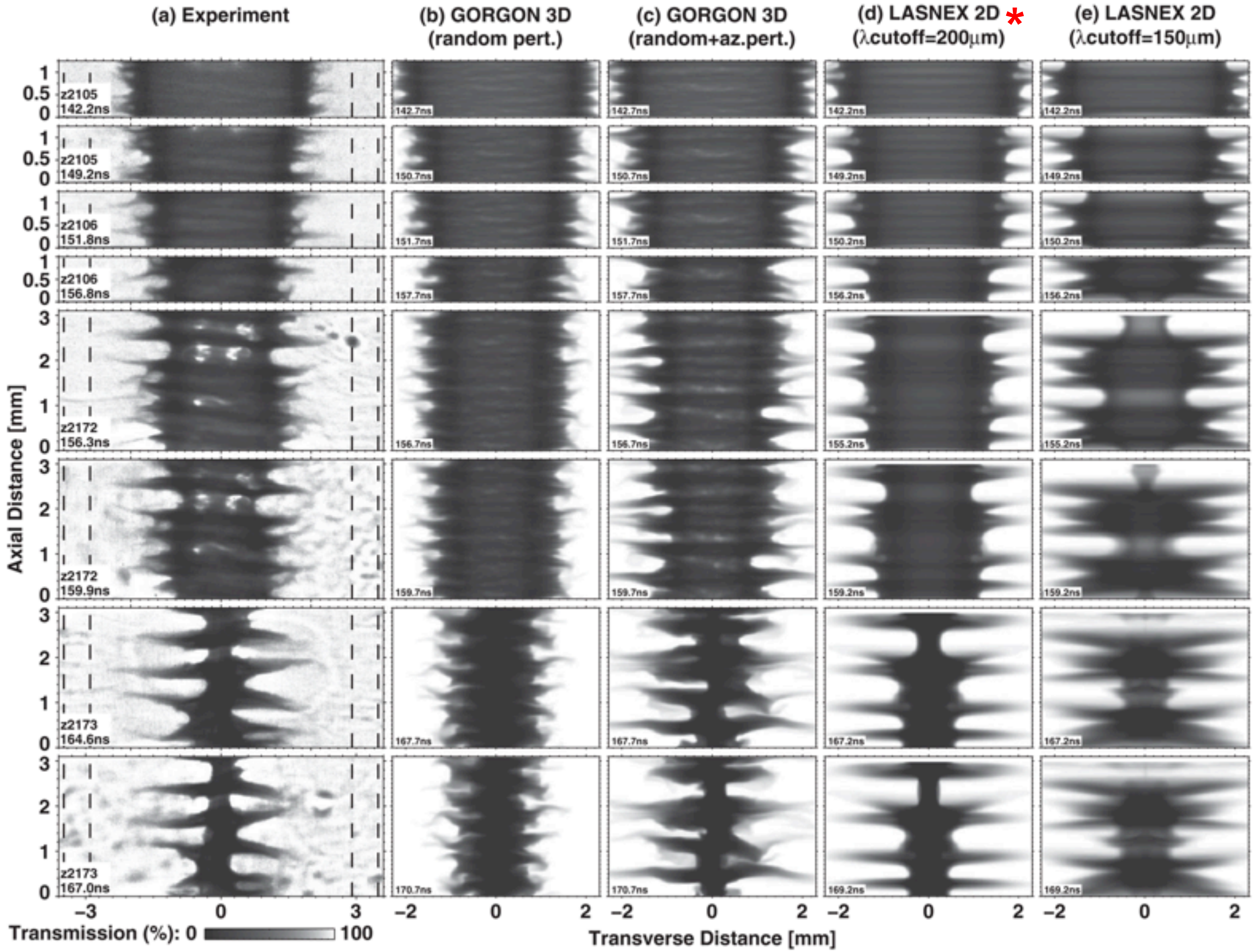


Coated Uncoated

- No ETI growth in plastic coating
  - Carries very little current
  - Theoretically ETI Stable
    (resistivity decreases with increasing temperature)
- Coating does not appear to affect linear ETI growth of temperature perturbations, but it does significantly tamp down the mass redistribution

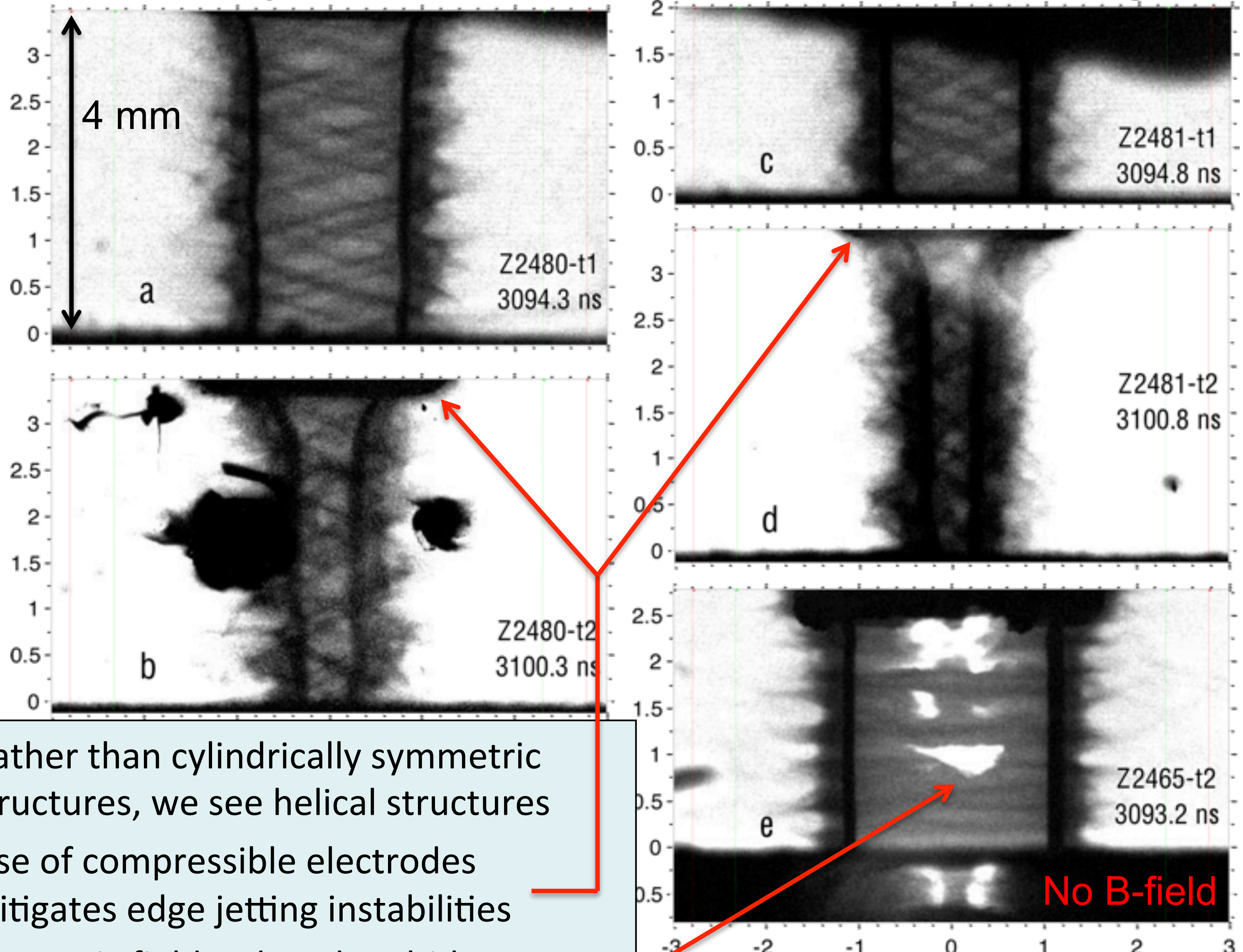
K.J. Peterson *et al.*, manuscript in preparation

Beryllium experiments show surprisingly correlated instability growth at late times that may imply a highly-correlated initial perturbation



R.D. McBride *et al.*, Phys. Rev. Lett. (2012); R.D. McBride *et al.*, Phys. Plasmas 20, 056309 (2013).

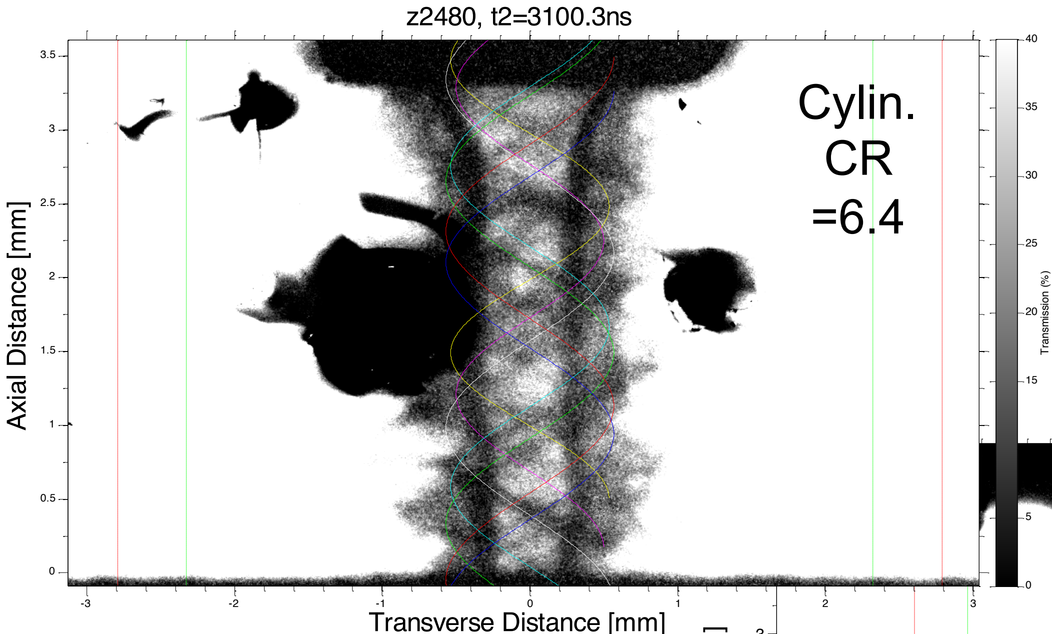
Our first axially-magnetized liner implosion experiments provided us with several new insights

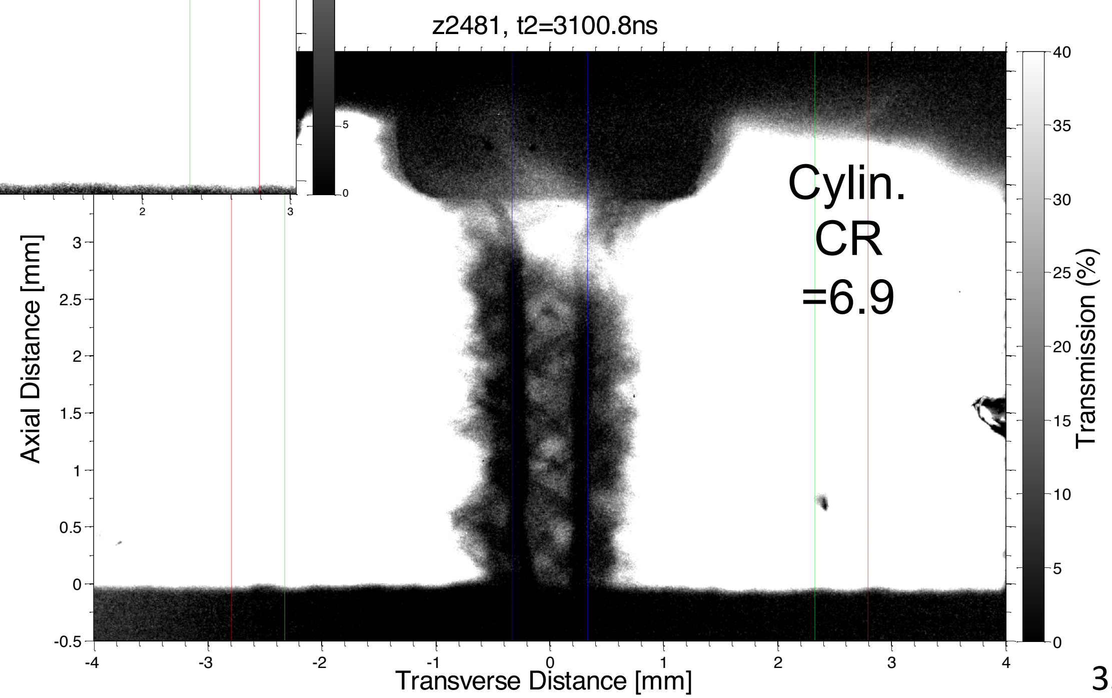


- Rather than cylindrically symmetric structures, we see helical structures
- Use of compressible electrodes mitigates edge jetting instabilities
- Magnetic field reduced multi-keV x rays associated with late-time instabilities

T.J. Awe *et al.*, submitted to Phys. Rev. Lett.

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

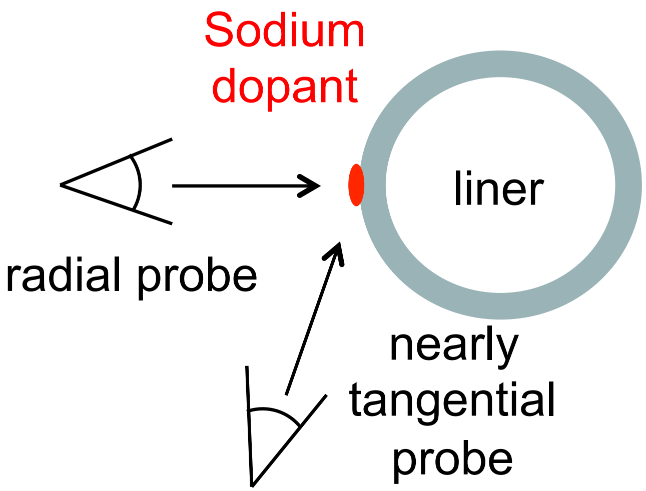


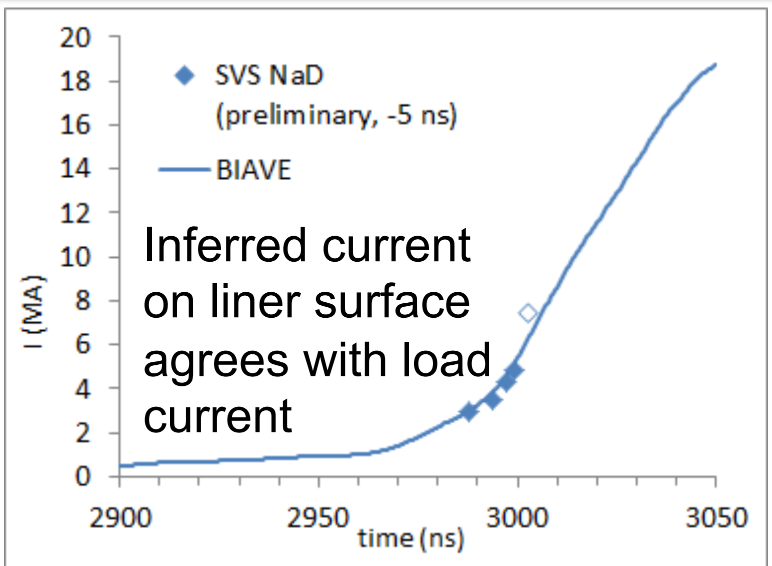


Same images plotted using 0-40% transmission range instead of 0-100%

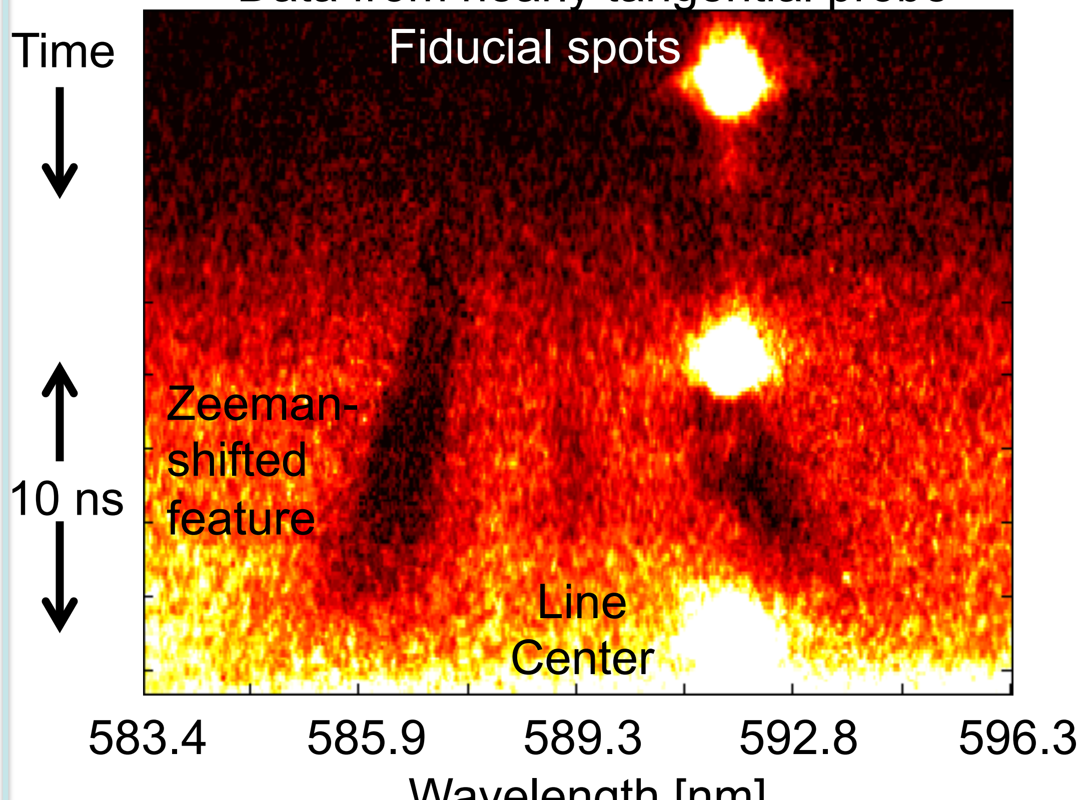
T.J. Awe *et al.*, submitted to Phys. Rev. Lett.

Optical Zeeman splitting is a promising path towards a direct load current measurement and possibly flux compression, though the latter is more challenging





Data from nearly tangential probe



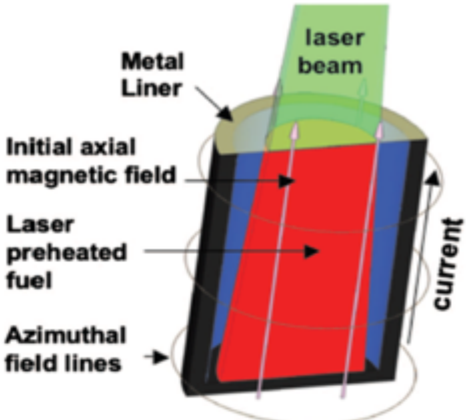
Time-dependent Zeeman splitting of neutral sodium line seen in absorption—splitting is proportional to magnetic field strength

* Data analysis and data from M.R. Gomez, S.B. Hansen

We started testing our preheating model predictions of energy deposition in laser-only experiments

Motivation/aims

We want to ensure that laser preheat energy can be absorbed by MagLIF fuel

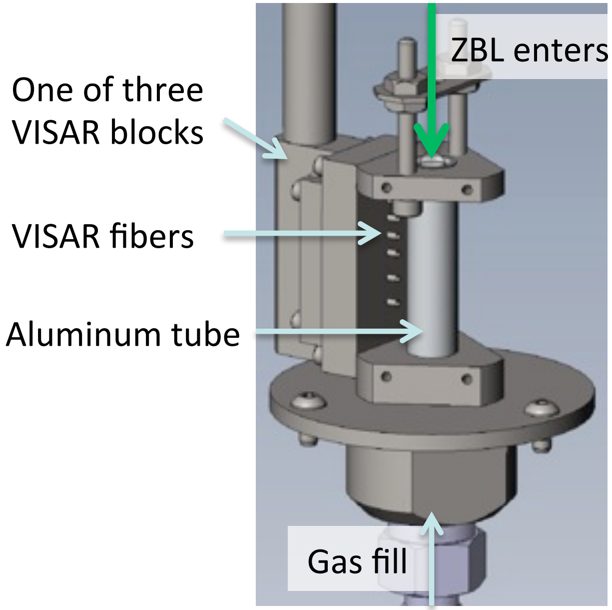


Laser blast wave targets aim to:

1. Reproduce first integrated MagLIF setup as closely as possible
2. Measure laser energy deposition in the fuel by measuring time/velocity of blast wave

Experimental design

ZBL (~2 kJ, 2 ns) enters into thin-walled tube target containing dense D2 gas

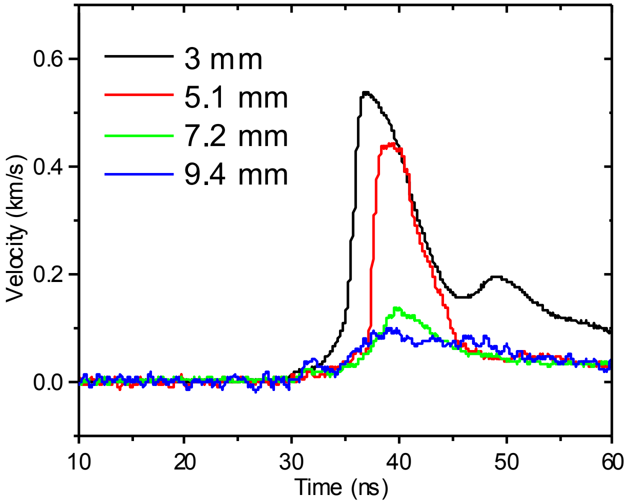


Blast wave in fuel driven by laser energy absorption

Time/velocity of tube wall motion monitored by 21 VISAR probes (3 azimuthal, 7 axial positions)

Results/conclusions

VISAR data shows velocity and time of tube wall motion consistent with laser energy deposition



Data suggests **laser energy is effectively coupled to first ~10 mm of fuel**

Comparisons to HYDRA and LASNEX sims will allow for more detailed, quantitative conclusions

We are designing experiments for Omega-EP to better understand the physics of magnetized & preheated plasma, awarded 2 days on Omega-EP in FY2014 to do this

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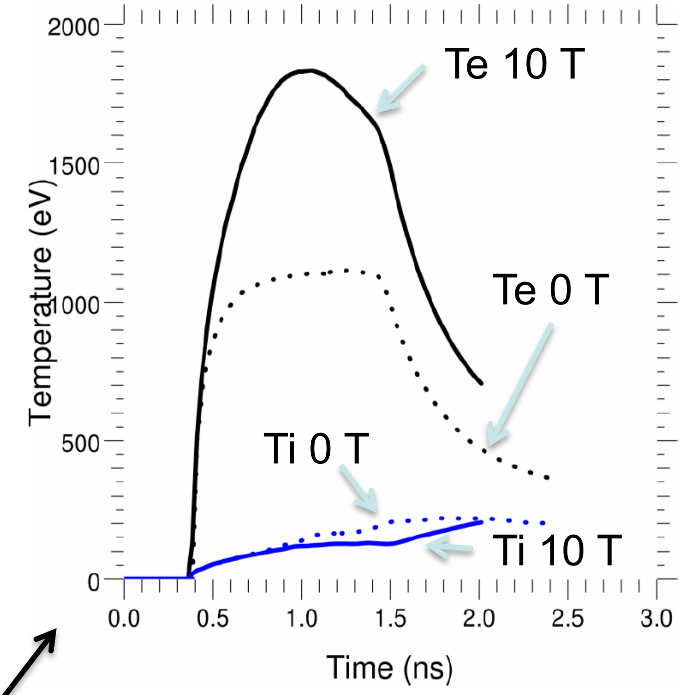
- Previous work used a laser (1ω, 100 J, 1 ns) to heat a magnetized N jet (ne = 1.5e19/cc) with a 12 T peak B field (Froula, PRL 2007)
- Thomson scattering used to determine temperature profile perpendicular to B-field
- They found electron thermal conduction was suppressed according to classic Braginskii models for heat transport

- We propose to extend this in Omega-EP experiments to plasma densities 20x higher, plasma temperatures 5x hotter, using 50x greater laser energy available there
- Effect of 10 T B field on laser-heated plasma dynamics/temperature of laser heated plasma expected to be large/observable
- Near-Braginskii transport under these conditions would be good news for MagLIF!



Ion and electron temperature profiles from HYDRA with and without a 10 T applied B field for a 2mg/cc D2 gas heated with a 3w laser delivering 2.5 kJ in 1 ns

While we plan to test MagLIF using ~6 kJ of laser preheat, we are exploring riskier alternate heating methods that could couple up to 50 kJ and reduce convergence from 23 to ~10

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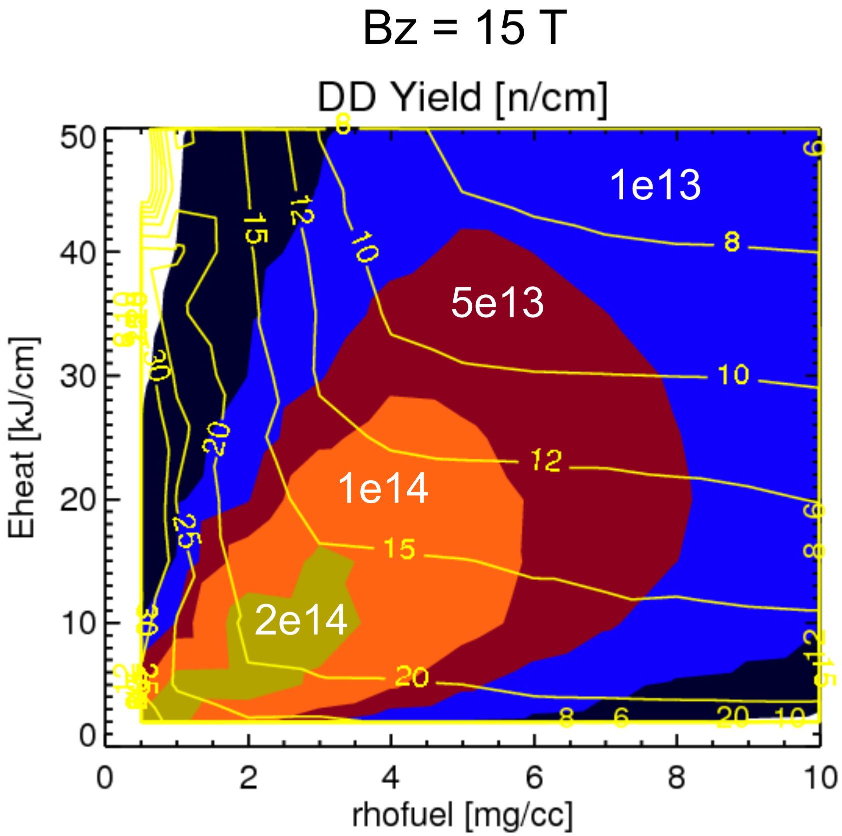
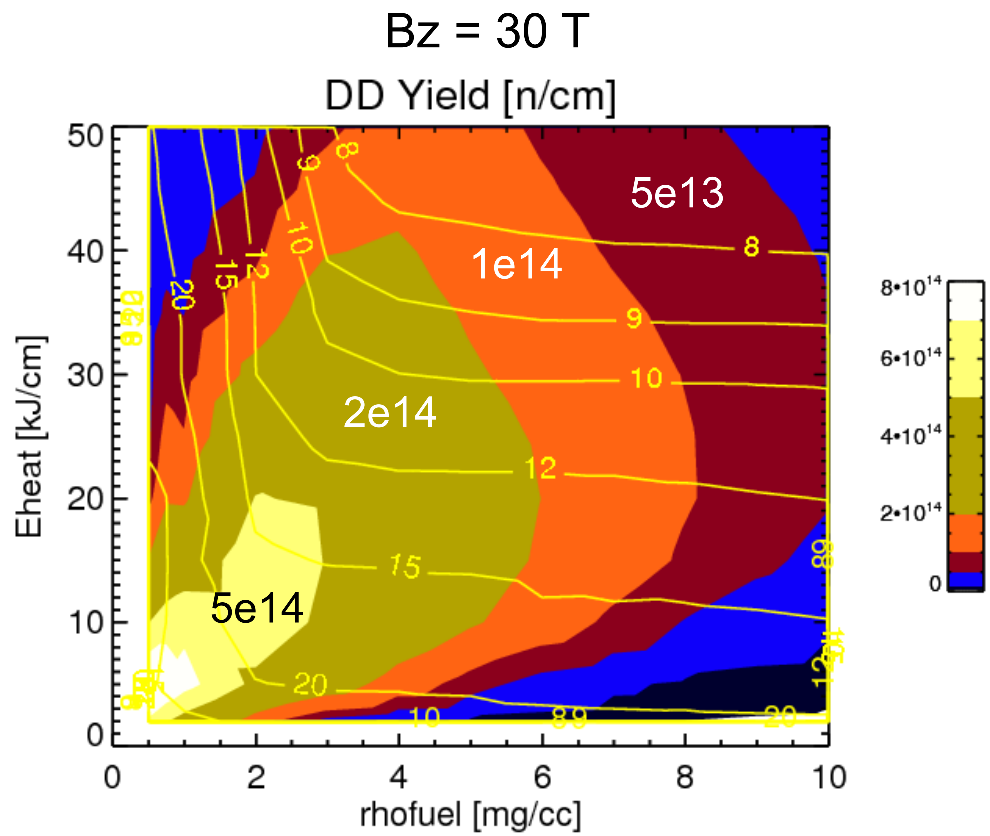
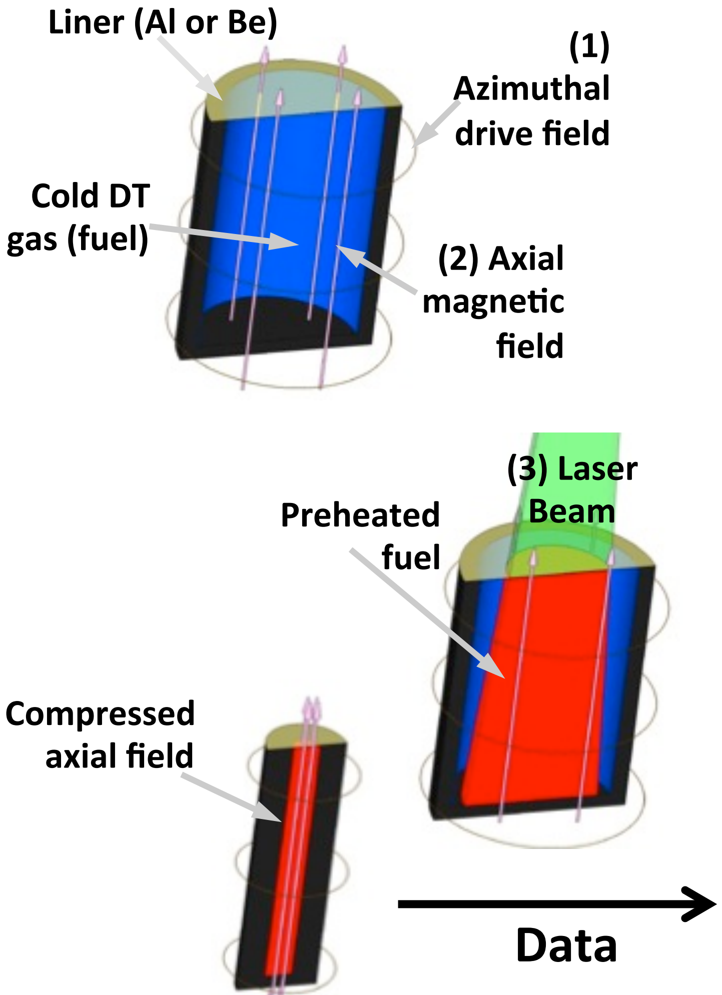


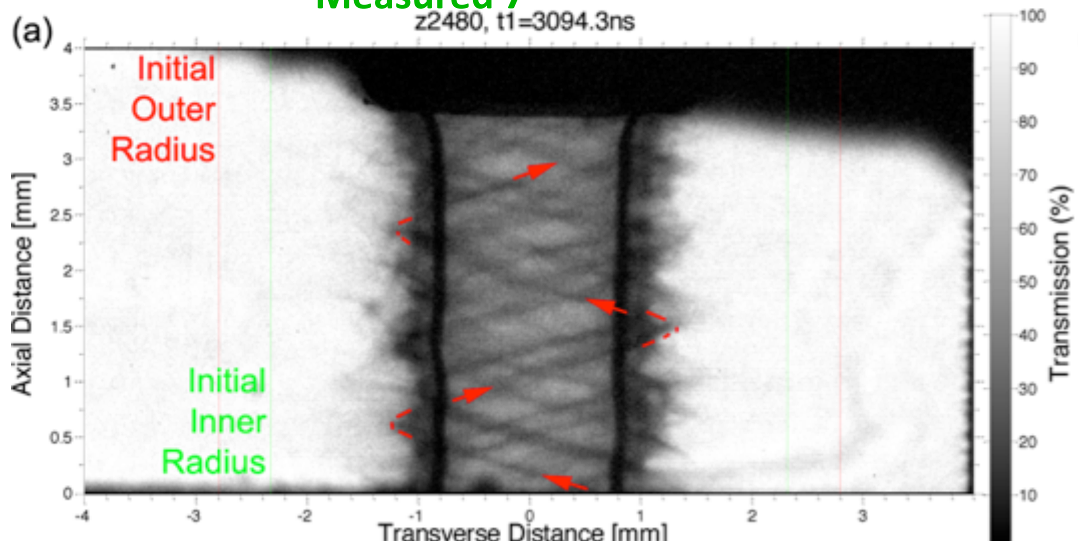


1D contour plots that show how yield (white numbers) and convergence ratio (yellow) vary if significantly more energy (50 kJ) can be coupled to the fuel. Scan done using standard Be MagLIF target, 80 kV marx charge. Values are taken at peak burn.

MagLIF status : Experiments to date are encouraging



- Implosion velocity
  - Required (10^7 cm/sec)
    - Measured (10^7cm/sec)
- Magneto-Rayleigh-Taylor Instability (Acceleration phase)
    - Inner wall liner intact
- Convergence
  - Required ~20
    - Measured 7



Near-term goal: experiments and modeling leading to an integral demonstration of the MagLIF concept with fusion yield of ~100 kJ

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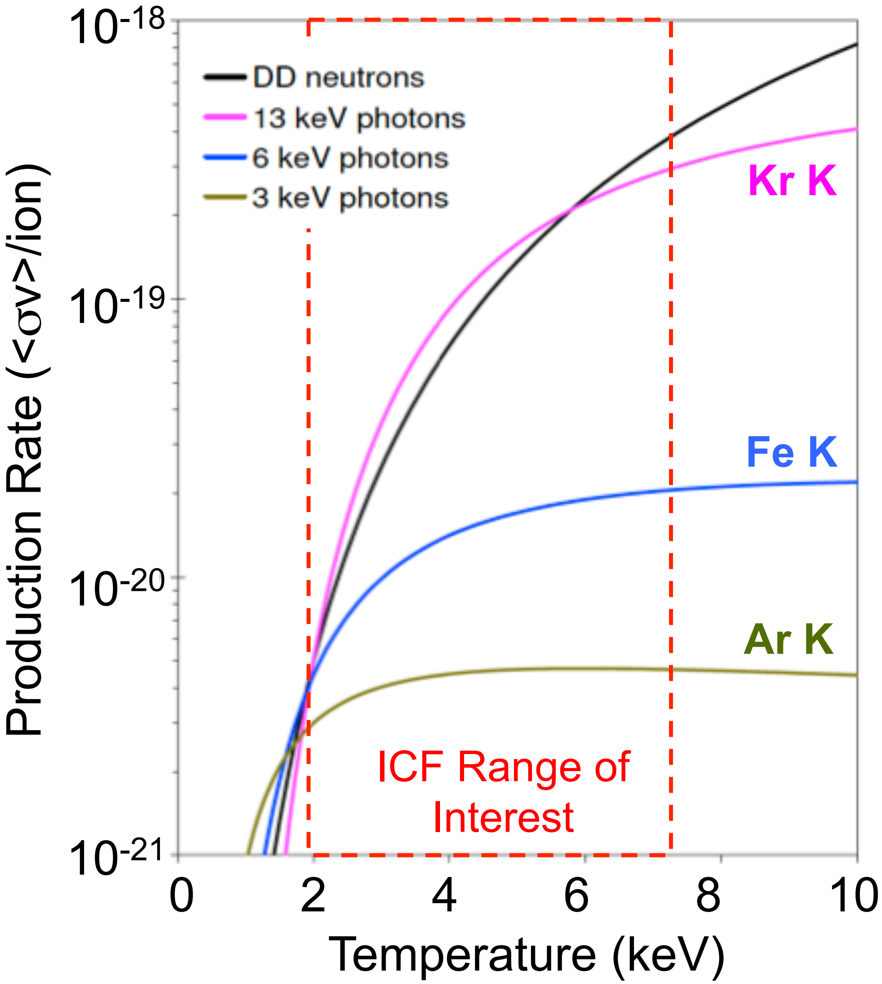
Our draft metrics for progress reflect the need to be able to measure key parameters for MagLIF and to identify obvious failure mechanisms for integrated experiments

- Measure liner stability (Is poor compression an issue?)
  - Use radiography in the short term at CR~10 (limited by opacity)
  - Use spectroscopy and/or monochromatic imaging at CR~20
- Measure flux compression (Is flux leakage an issue?)
  - Use well-established techniques in short term (Bdots, Faraday Rot.)
  - Develop spectroscopic methods for flux near stagnation
- Measure temperature increase from preheating and the temperature at stagnation (Is heating working as expected? Is magnetic suppression of heat loss working as expected?)
  - Standalone laser-only experiments to determine heating issues
  - Neutron and spectroscopy instruments to diagnose stagnation (these mostly exist, but some improvements needed)
- In most cases, we will be relying on focused experiments to guide us in determining issues with integrated experiments

Time-resolved Kr x-ray spectroscopy can serve as a proxy for thermonuclear neutron measurements and will be a key diagnostic for temperature

Photon and Neutron Production Scaling



- Kr K-shell production scales well with DD neutron reactivity
- 13 keV photons easily escape thick liner
- K-α production sensitive to beams
- K-shell production sensitive to thermal conditions

Kr emission approximates the size and duration of the DD fusing plasma

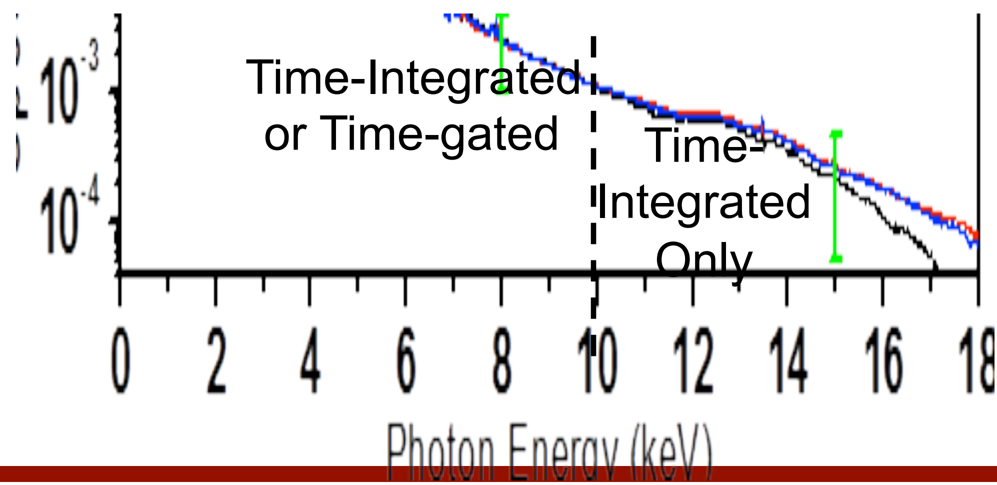
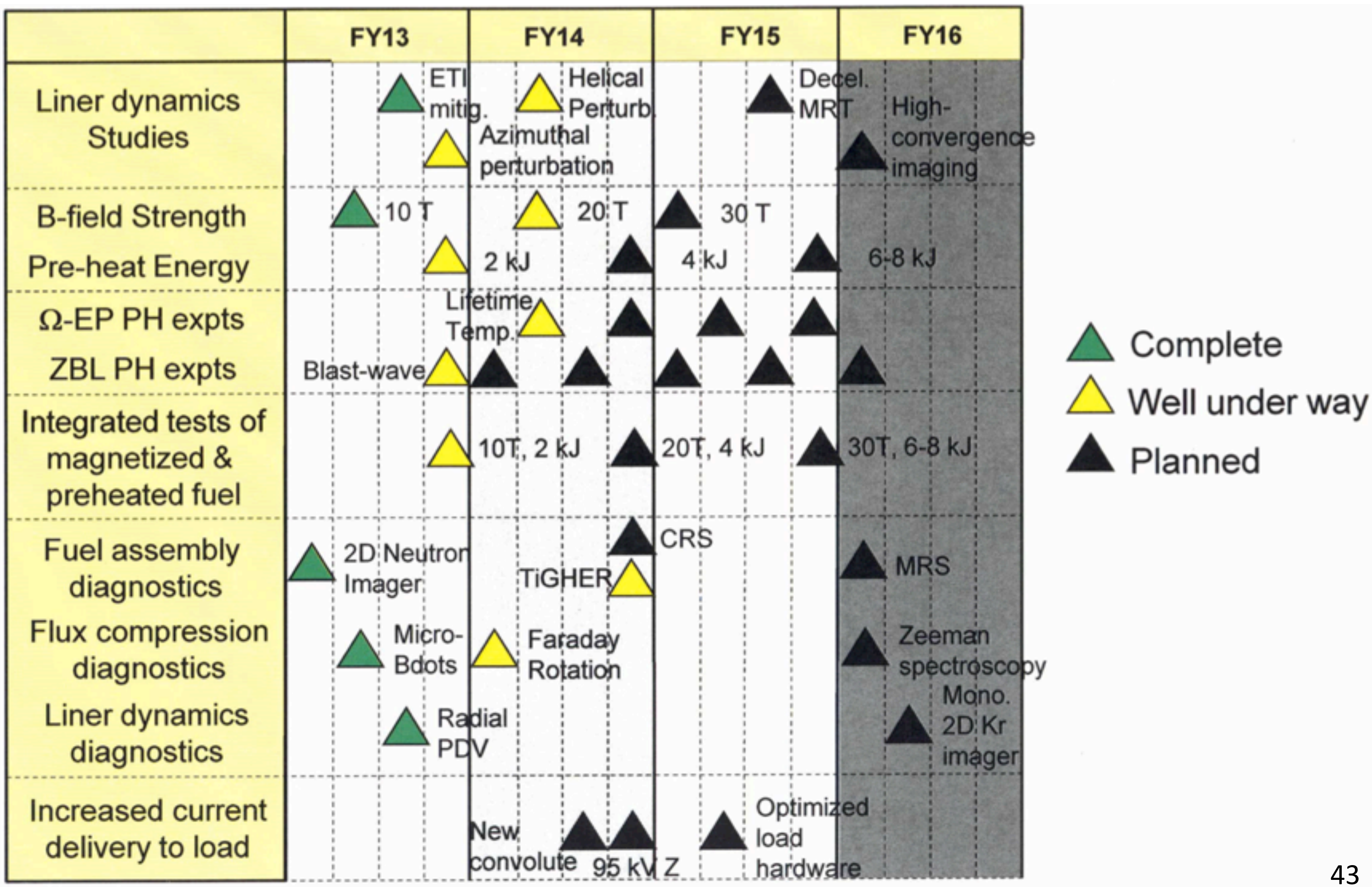
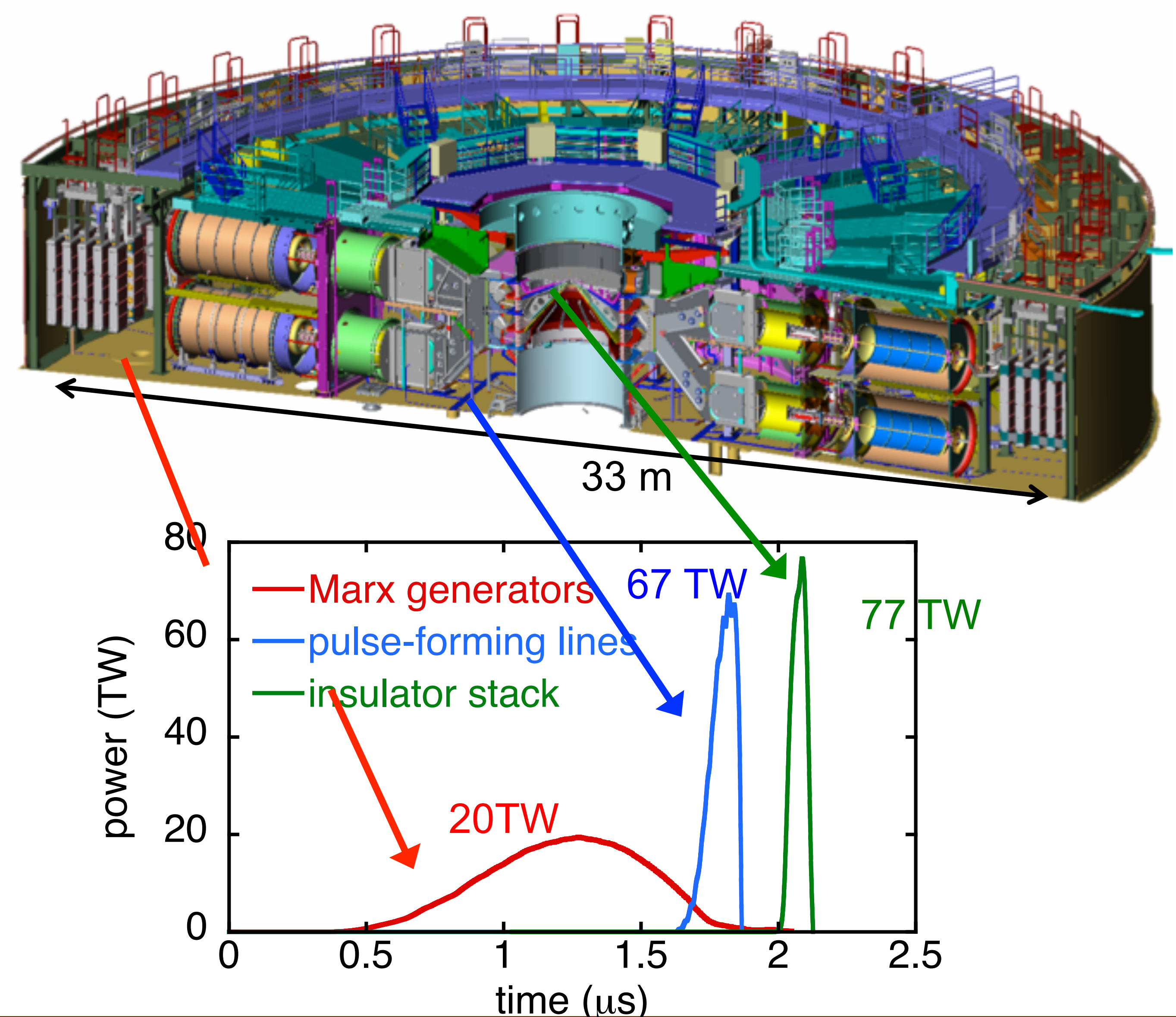


*Figure courtesy S. Hansen, SNL; See also S.B. Hansen, Phys. Plasmas 19, 056312 (2012).

We have developed a 3-year plan that will make significant progress in evaluating Magnetically Driven Implosions by FY15 on a path to 100-kJ equivalent yield



Z works by compressing electromagnetic energy in time and space

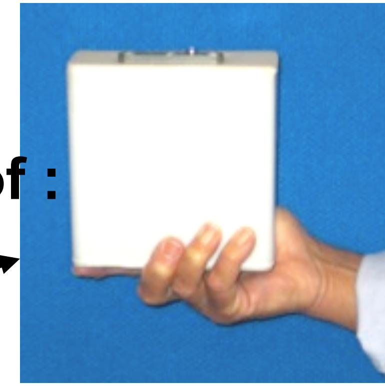


New technologies: The Linear Transformer Driver (LTD) is the most fundamental advance in pulsed power since the invention of the Marx generator in 1924

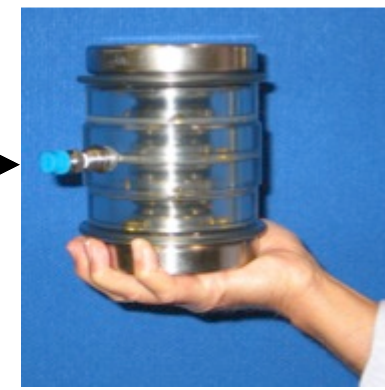
An LTD Cavity is the building block of a future high yield facility

An LTD consists of :

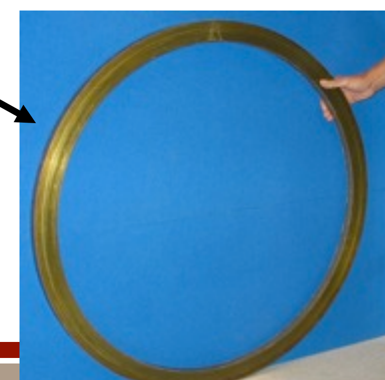
- **Capacitors**



- **Switches**

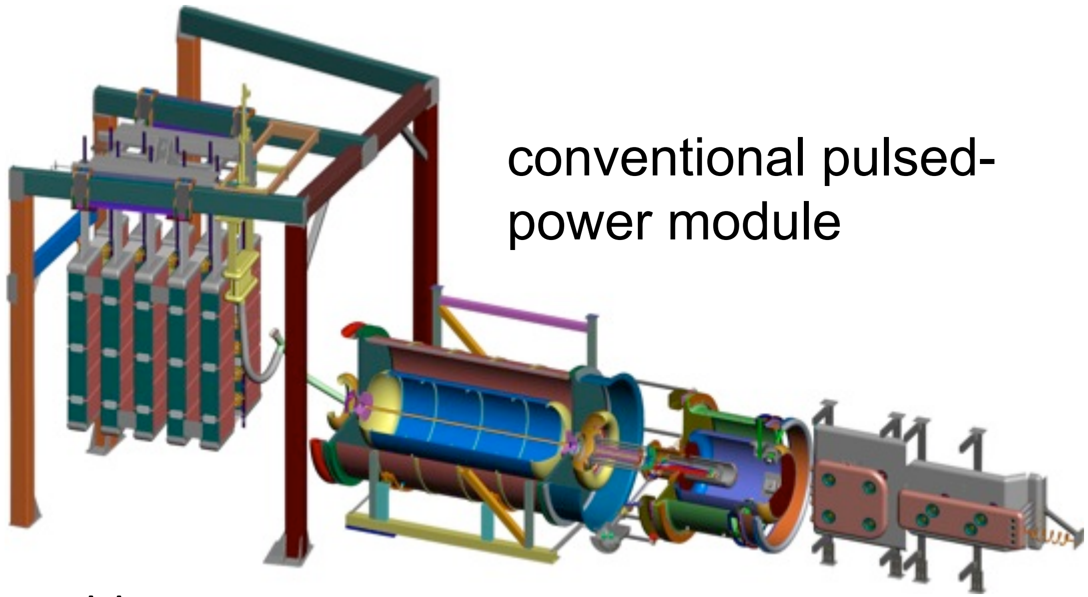


- **Magnetic cores**



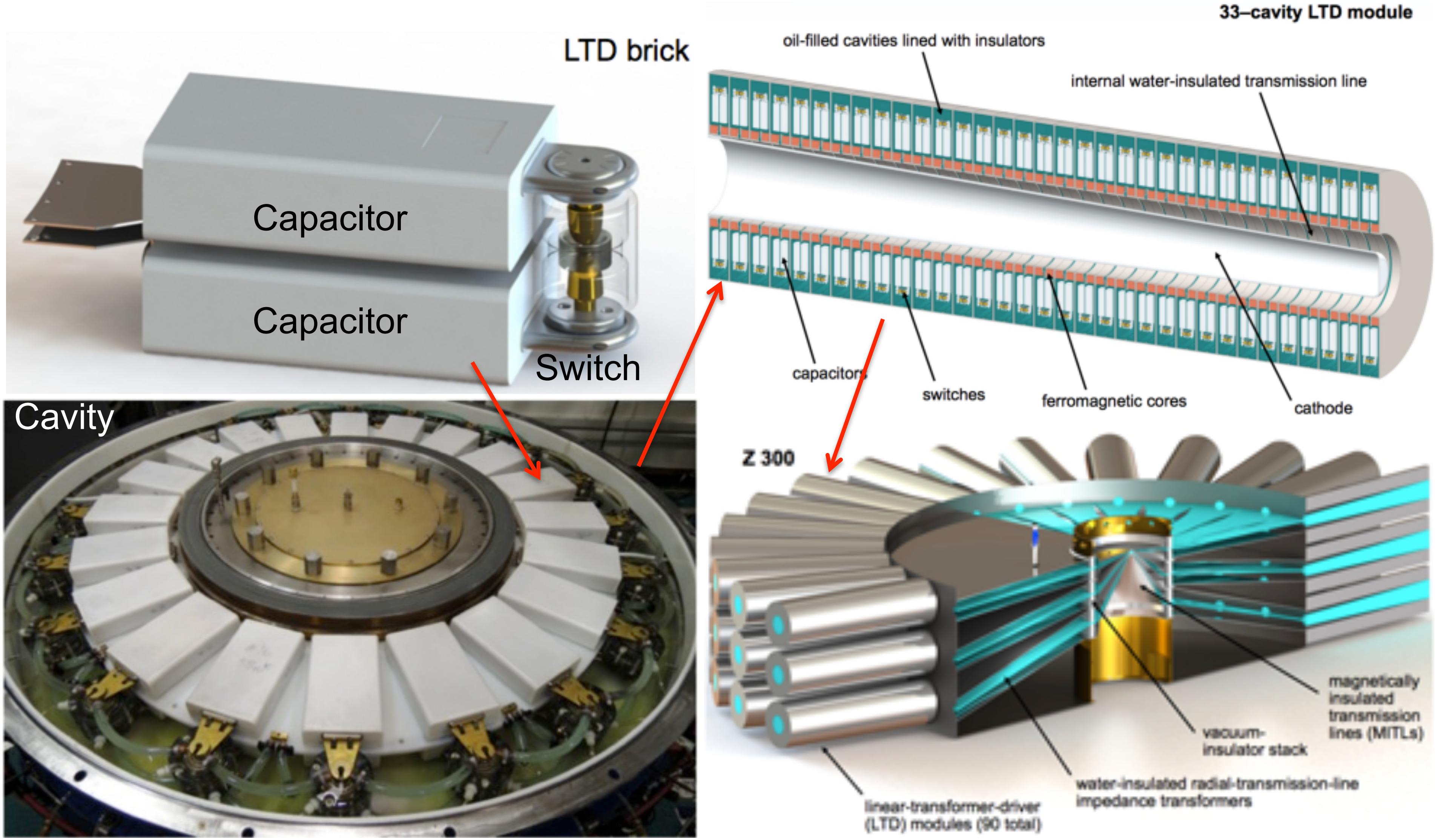
Because an LTD can directly produce a 150-ns pulse, an LTD-driven accelerator requires:

- No Marx generators.
- No intermediate-store capacitors.
- No megavolt gas switches.
- No SF_6 insulating systems.
- No laser-trigger systems.
- No pulse-forming lines.
- No water switches.
- No magnetic switches.
- No transit-time-isolated voltage adders.
- No polarity-reversing cross-over networks.
- No water convolutes.
- No opening switches.
- No vacuum switches.



conventional pulsed-power module

The Linear Transformer Driver (LTD) architecture can scale to very large systems.



Z-300 is a reasonable step beyond the refurbished Z. It could couple over 0.5 megajoules to fusion fuel

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

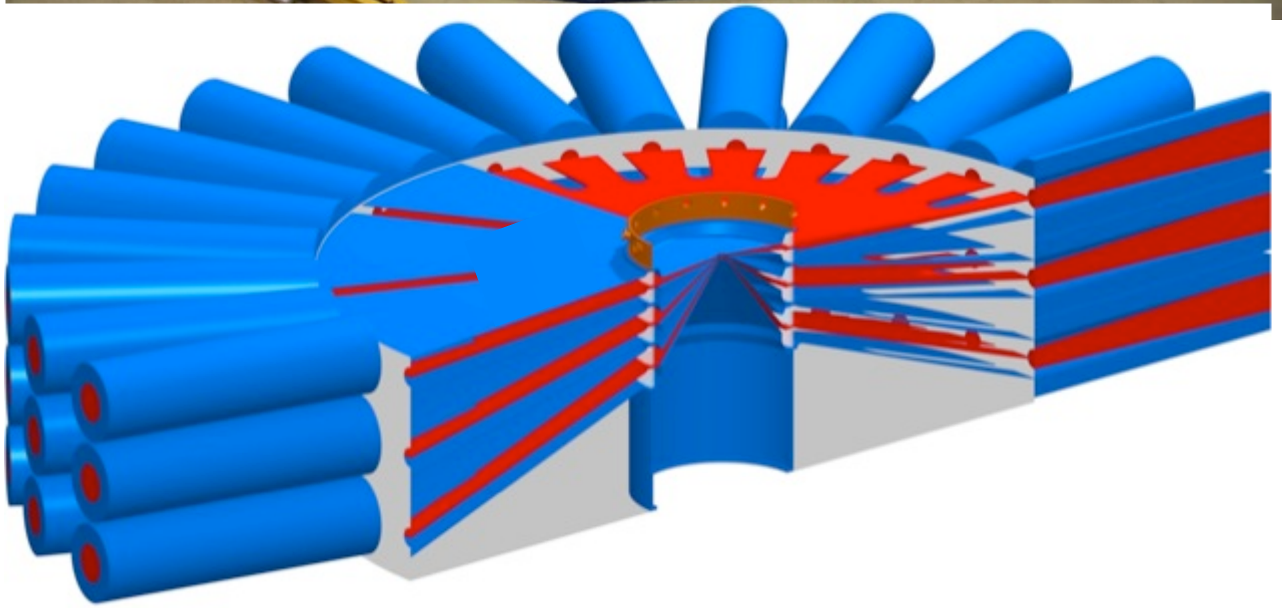
I_{load} = 50 MA

$\tau_{implosion}$ = 130 ns

$E_{radiated}$ = 12 MJ

outer diameter = 35 m

Z-300



Summary

- Large currents and magnetic fields can be used to create and study HED matter in a variety of ways, a recent emphasis is the properties of materials at high pressures
- We are performing state of the art work on the properties of dynamic materials
- Magnetized Liner Inertial Fusion (MagLIF) offers a near term chance for testing our understanding of magnetically driven implosions. If successful, would lead to 100kJ yield with DT.
- We have performed our first integrated MagLIF experiment