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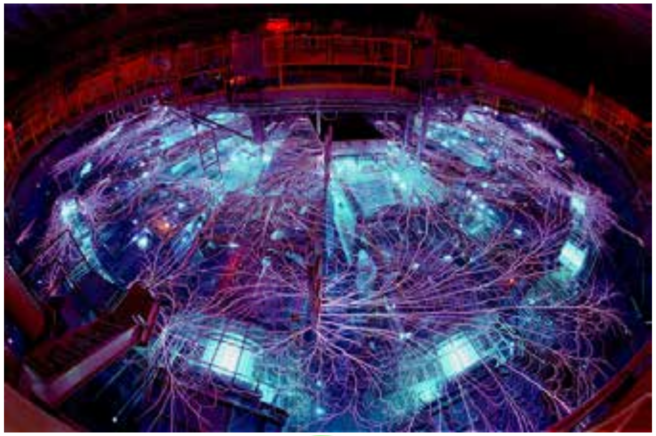

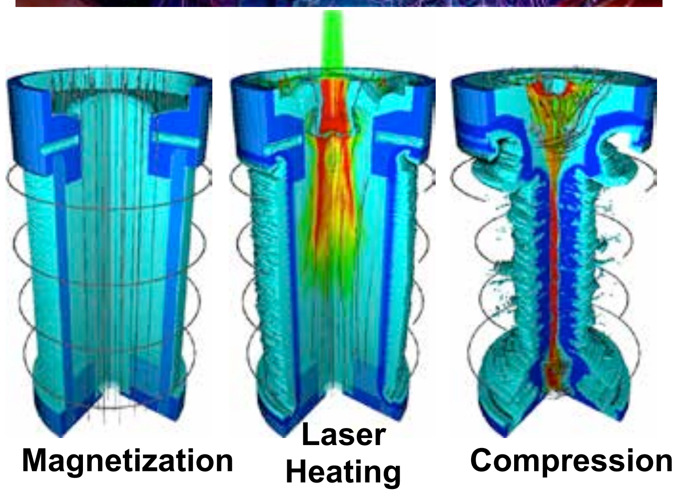

Overview of the Magnetically Driven Implosions approach to Inertial Confinement Fusion

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FY15 Overview Meeting,
May 18-20, 2015

U.S. DEPARTMENT OF ENERGY

NNSA National Nuclear Security Administration

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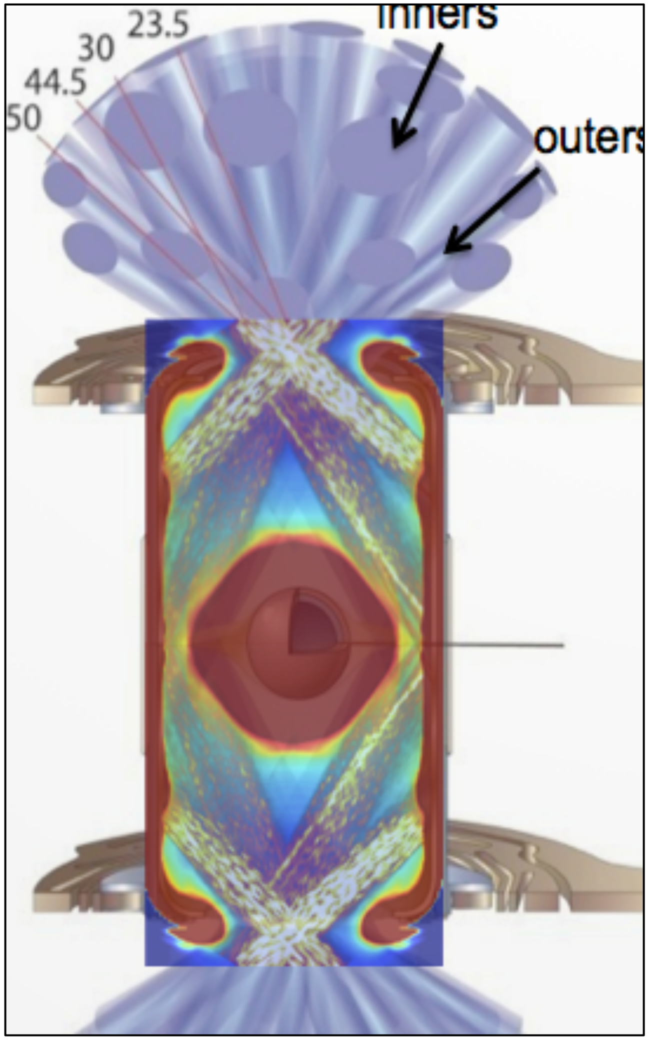
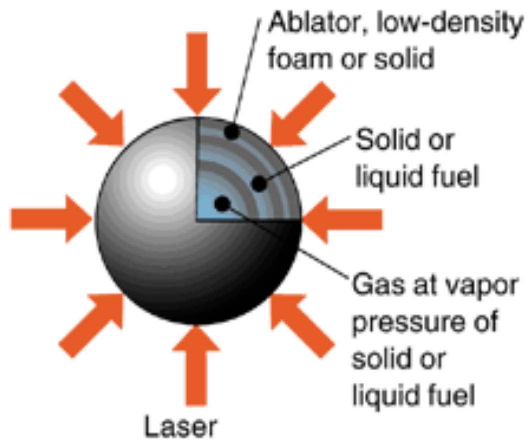
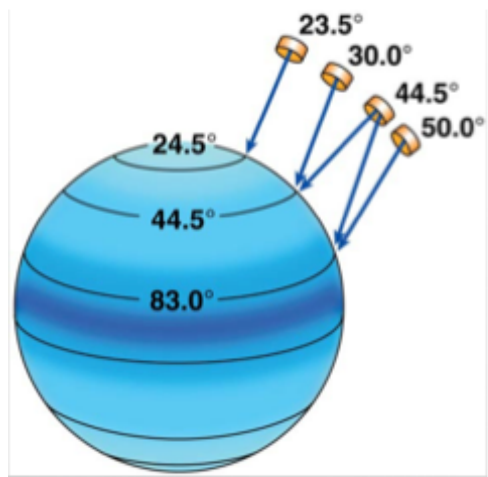
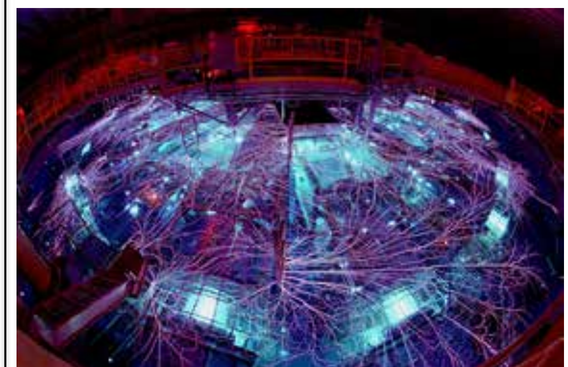
The United States ICF program has focused on three main approaches to ignition dating back to the 2012 Path Forward report to Congress

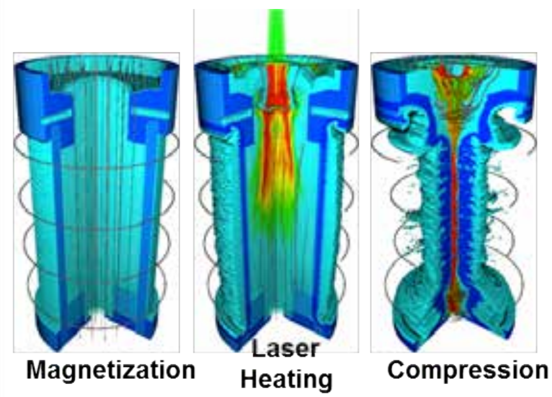
Radiation-driven implosions	Laser-driven implosions	Magnetically-driven implosions











Focus of today's talk

"Magnetic direct drive" is based on the idea that we can efficiently use large currents to create high pressures

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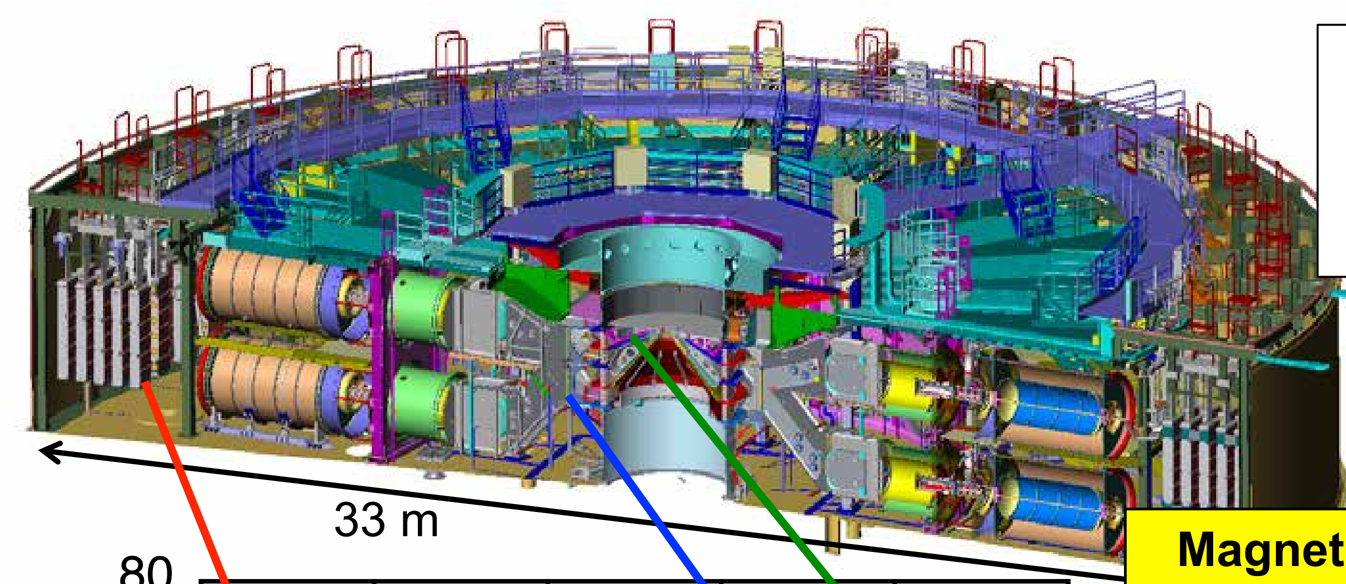
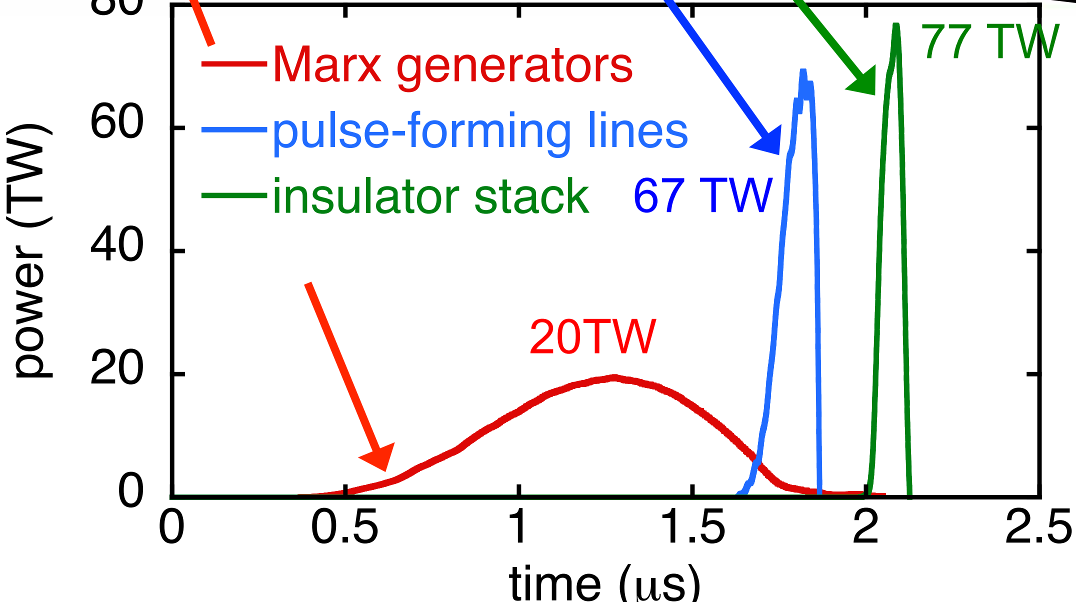
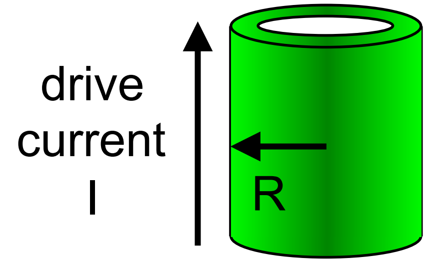


Z today couples ~0.5 MJ out of 20 MJ stored to MagLIF target (0.1 MJ in DD fuel).



Magnetically-Driven Implosion

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



100 MBar at 26 MA and 1 mm

Implosion time ~50 ns; stagnation ~0.1-1 ns

(1 atm = 1 bar = 10^5 Pascals)

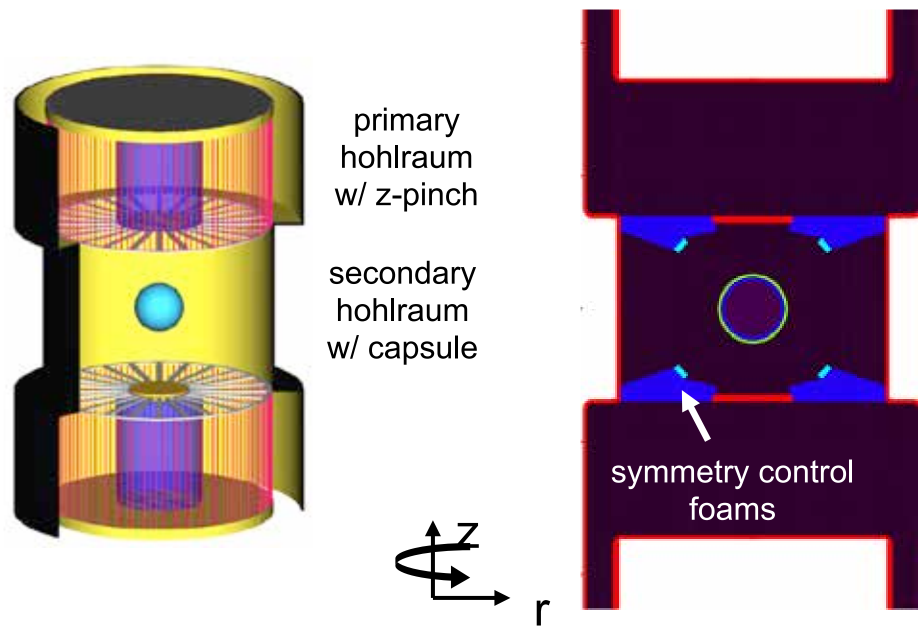
Since 1996, magnetic direct drive has focused on four main areas with the long-term goal of achieving high single-shot yields (0.5-1 GJ)

- Can x-ray sources created using magnetic drive be used to drive traditional ICF targets capable of 0.5-1 GJ single-shot laboratory yields? (1996-2007)
- Can magnetically driven target implosions directly compress and heat fusion fuel to reach standard ICF ignition criteria and ultimately generate 0.5-1 GJ yields?
- Can magnetically driven targets achieve fusion ignition and 0.5-1 GJ yields under relaxed conditions by using magneto-inertial fusion principles?
- Can we build an 800-1000 TW pulsed power driver that is efficient, cost-effective, and can handle 0.5-1 GJ yields?

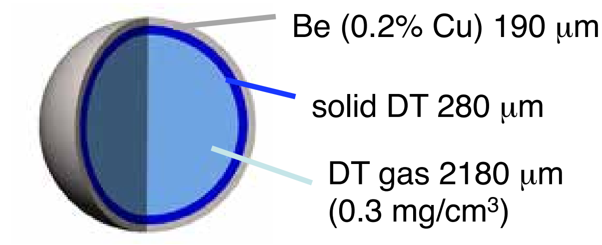
From 1996-2007 Sandia studied x-ray driven capsules with magnetic-driven radiation sources. Integrated LASNEX simulations showed 400+ MJ yield in a gold hohlraum

Double z-pinch hohlraum fusion concept

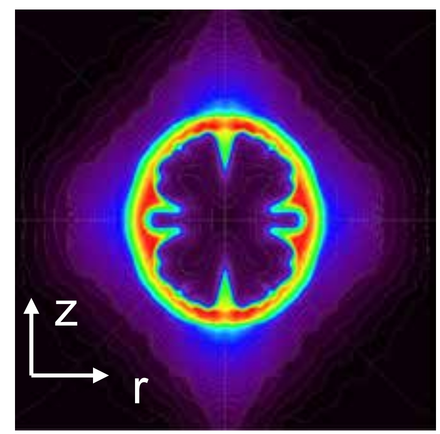
R. A. Vesey, M. C. Herrmann, R. W. Lemke *et al.*,
Phys. Plasmas (2007)



High yield capsule design



Fuel density at ignition



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

- Two PW-class Z-pinches, each with 9 MJ output
- Symmetry control to 1% via geometry, shields
- Capsule absorbs 1.2 MJ, CR~35, yields 400-500 MJ
- Needs large driver (~100 m diam.; 1000 TW; 400 MJ)

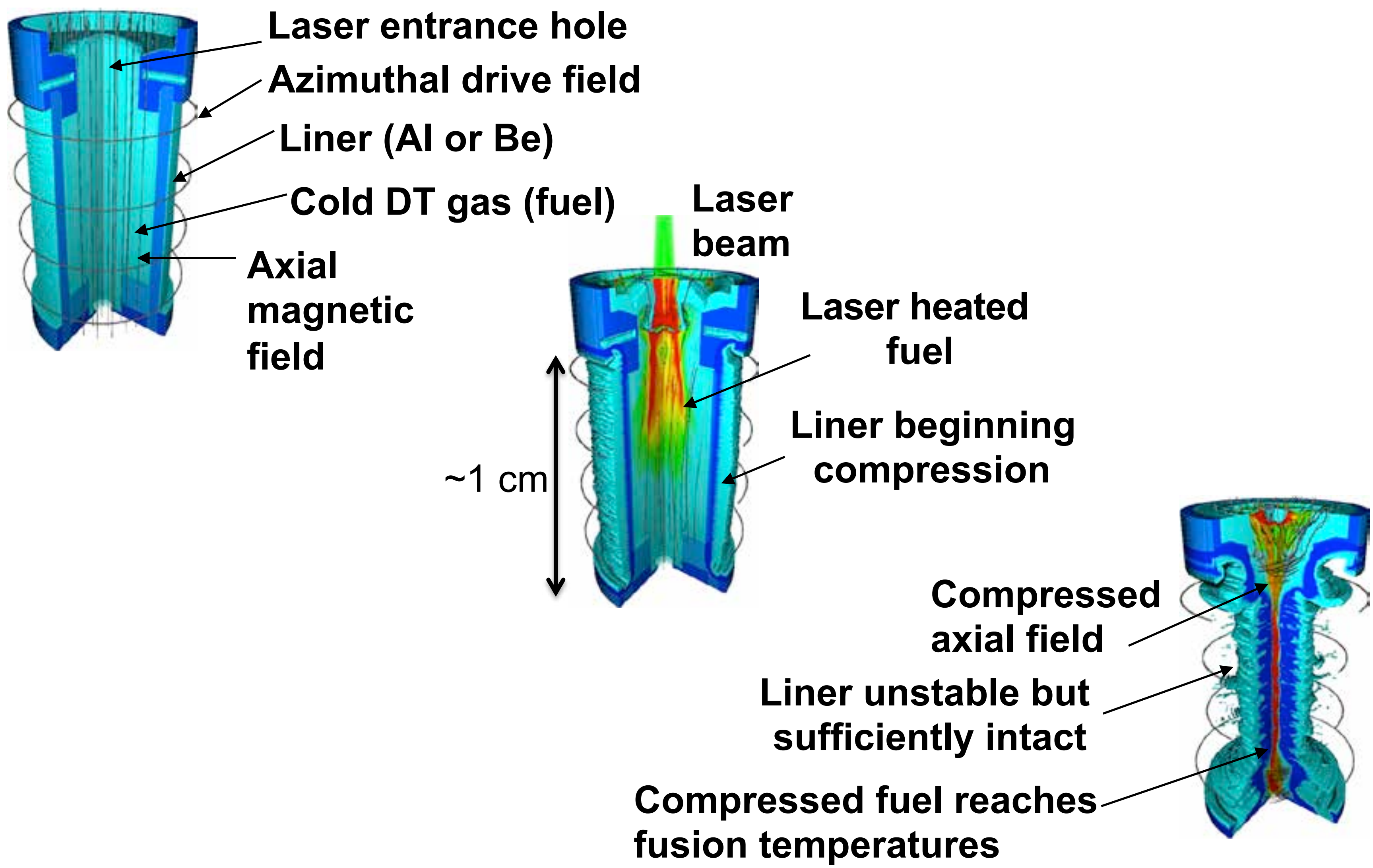
Would be more compelling with a NIF understanding of hohlraum/capsule physics

Place holder 1

Place holder 2

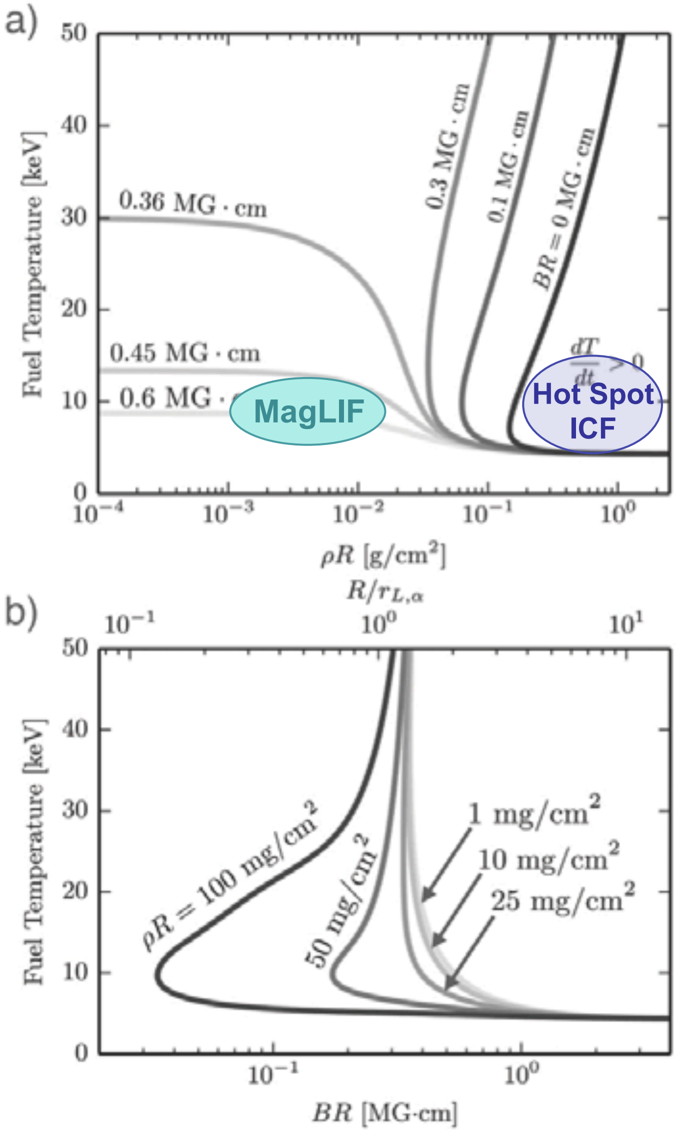
Place holder 3

We are evaluating a Magnetized Liner Inertial Fusion (MagLIF)* concept that is well suited to pulsed power drivers and that may reduce fusion requirements



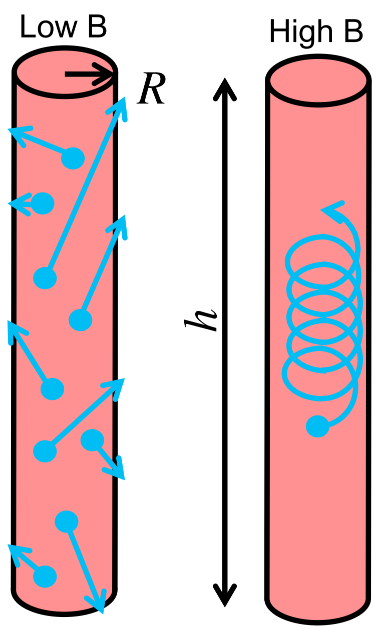
*S.A. Slutz *et al.*, Phys Plasmas (2010); S.A. Slutz and R.A. Vesey, Phys Rev Lett (2012); A.B. Sefkow *et al.*, Phys Plasmas (2014).

Magnetization ("BR") can be used to reduce rho-R requirements and reduce electron heat losses, lower density also reduces bremsstrahlung losses



- <u>Axial magnetization</u> of fuel/liner (B_{z0} = 10-30 T)
  - **Inhibits thermal conduction losses, may help stabilize liner compression, ions magnetized too (β: 5~80; ωτ>200)**

$$\frac{R}{r_\alpha} = \frac{BR\,[T\cdot \mathrm{cm}]}{26.5} = \frac{BR\,[G\cdot \mathrm{cm}]}{2.65e5} \approx 4BR\,[MG\cdot \mathrm{cm}]$$

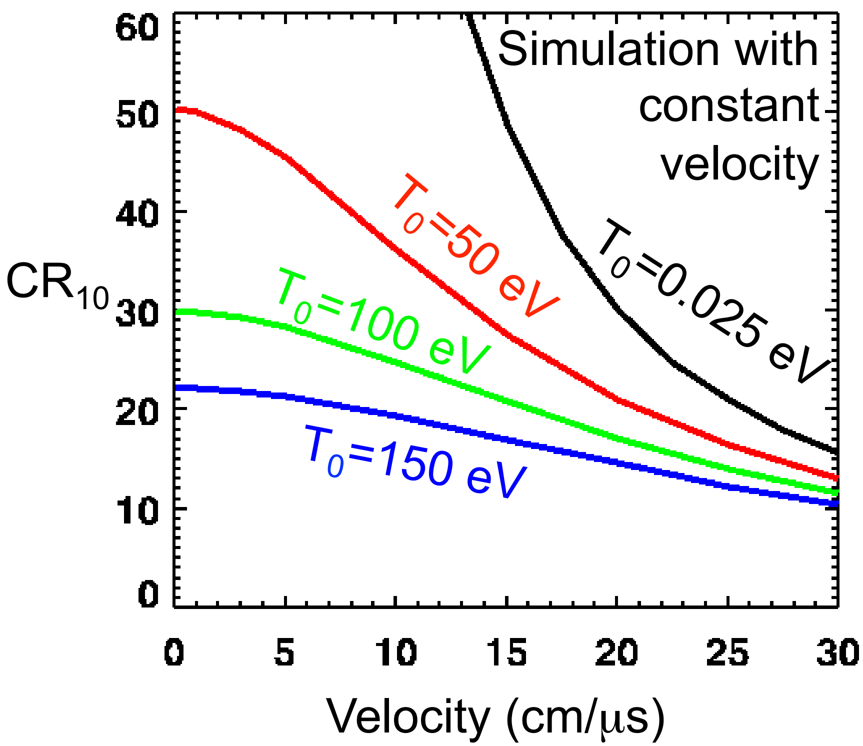


Fraction of trapped α's (tritons) is a function of ***BR*** only

At BR>0.5 MG-cm the effects saturate. Measurements to date suggest 0.4 MG-cm!

*S.A. Slutz *et al.*, Phys Plasmas (2010); S.A. Slutz and R.A. Vesey, Phys Rev Lett (2012); A.B. Sefkow *et al.*, Phys Plasmas (2014).

Typical ICF implosions need high velocities to reach fusion temperatures—starting the implosion with heated fuel potentially reduces requirements



CR_{10} = Convergence Ratio (R_0/R_f) needed to obtain 10 keV (ignition) with no radiation losses or conductivity

- **Laser heating of fuel (6-10 kJ) offers one way to reach pre-compression temperatures of ~200 eV**
- **Detailed simulations suggest we can reach fusion temperatures at R_0/R_f of 25**

*S.A. Slutz *et al.*, Phys Plasmas (2010); S.A. Slutz and R.A. Vesey, Phys Rev Lett (2012); A.B. Sefkow *et al.*, Phys Plasmas (2014).

Relative to the primary ICF approach, MagLIF uses a very different (conservative?) fuel compression method and largely untested magneto-inertial fusion principles

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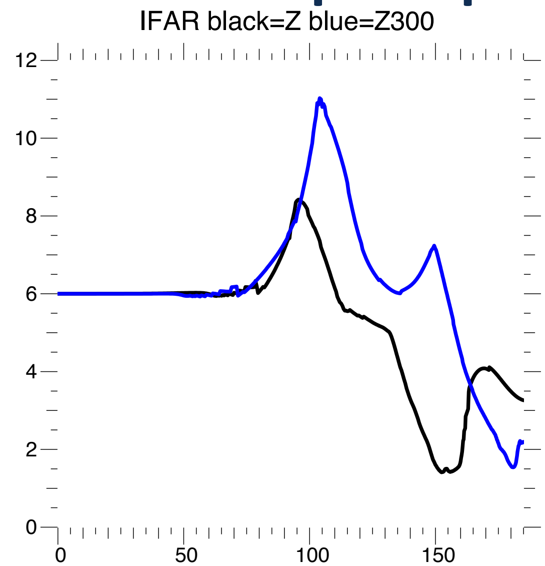
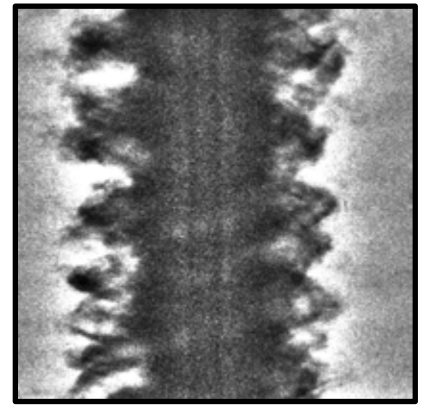
Metric	X-ray Drive on NIF	100 kJ MagLIF on Z
Pressure	~140-160 Mbar	26 MA at 1 mm is 100 Mbar
Force vs. Radius	Goes as R^2	Goes as 1/R^2
Peak velocity	350-380 km/s	70-100 km/s
Peak IFAR	13-15 (high foot) to 17-20 (low foot)	8.5
Hot spot CR	35 (high foot) to 45 (low foot)	25
Volume Change	43000x to 91000x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

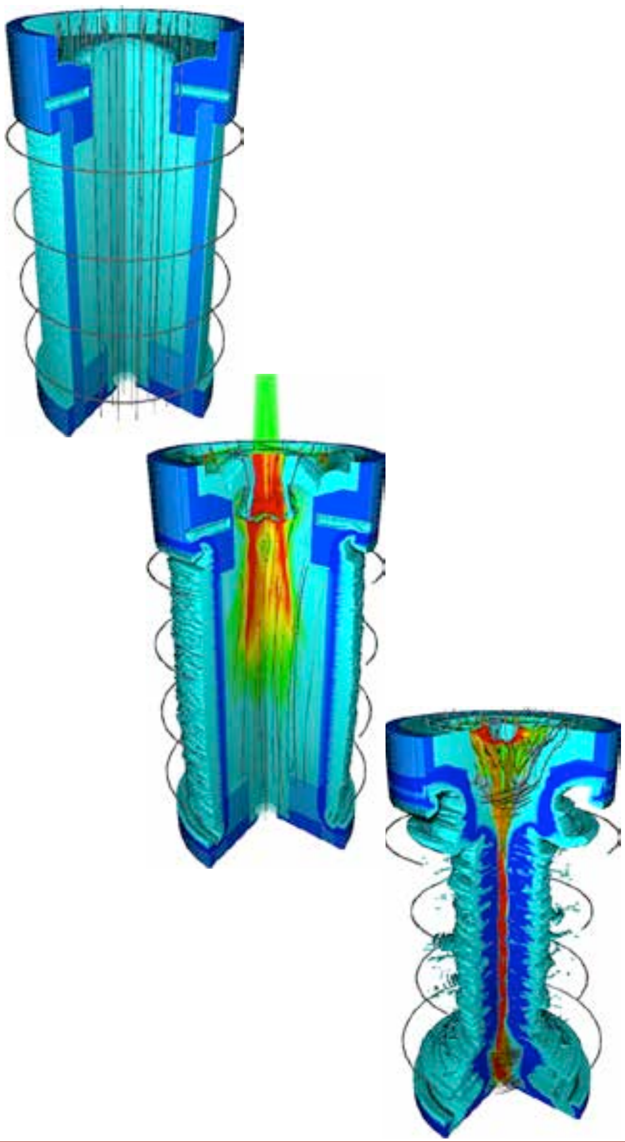




Plastic-coated, magnetized Be liner at CR of 13 to 25

- Magnetic drive is fundamentally different than x-ray or laser-driven ablation
- By traditional ICF implosion metrics MagLIF is very conservative, though different physics
- Reaching fusion conditions relies on largely untested MIF principles
  - Long stagnation time (2 ns) → more susceptible to high-Z contamination
  - Magnetic suppression of heat transport

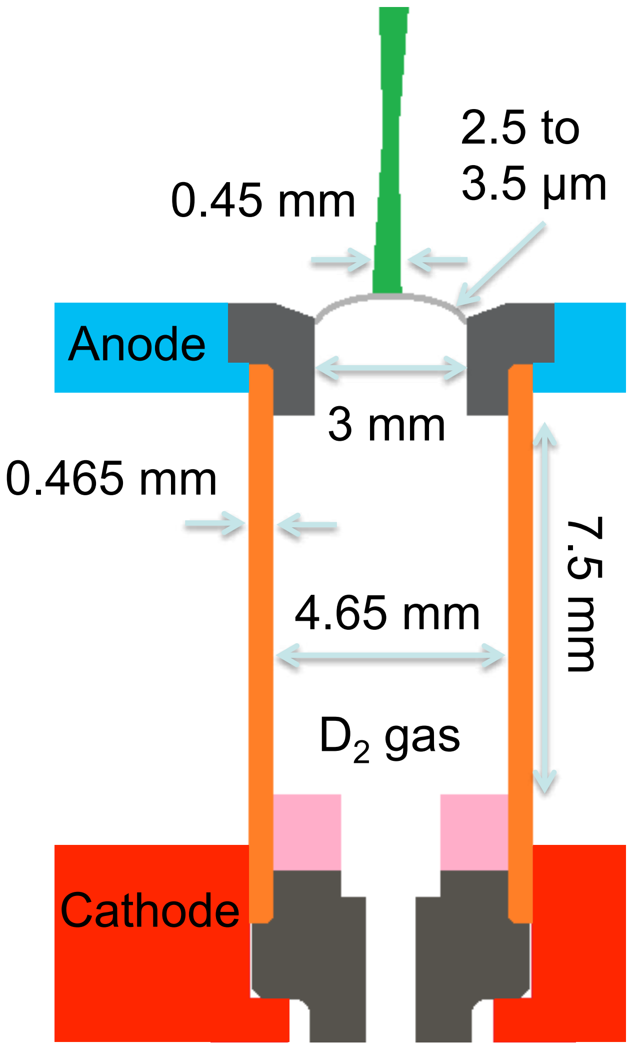
We are evaluating a Magnetized Liner Inertial Fusion (MagLIF)* concept that is well suited to pulsed power drivers and that may reduce fusion requirements

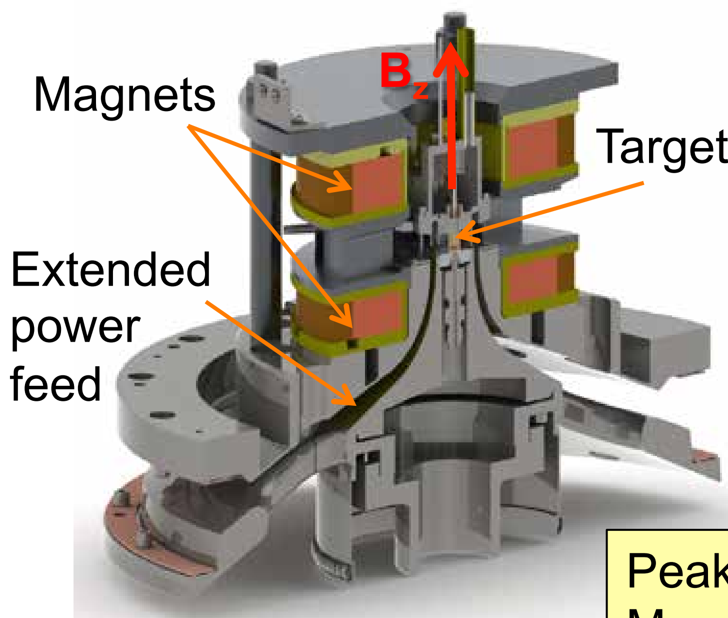


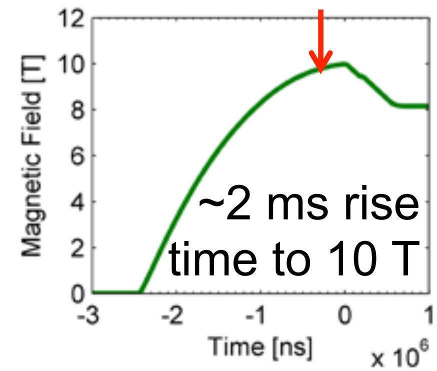
- Axial magnetization of fuel/liner (B_{z0} = 10-30 T)
  - Inhibits thermal conduction losses, may help stabilize liner compression, ions magnetized too (β: 5~80; $\omega\tau$>200)
- Laser heating of fuel (2-10 kJ)
  - Reduces amount of radial fuel compression needed to reach fusion temperatures (R_0/R_f = 23-35)
- Liner compression of fuel (70-100 km/s, ~100 ns)
  - "Slow", quasi-adiabatic compression of fuel
  - Low velocity requirements allow use of thick liners ($R/\Delta R$~6) that are robust to instabilities (need sufficient ρR at stagnation to inertially confine fuel)
- Combination allows fusion at ~100x lower fuel density than traditional ICF (~5 Gbar vs. 500 Gbar)
- DD equivalent of 100 kJ DT yield may be possible on Z in future—requires upgrades from our initial setup e.g., 10 T → 30 T; 2 kJ → >6 kJ; 19 MA → >24 MA

*S.A. Slutz *et al.*, Phys Plasmas (2010); S.A. Slutz and R.A. Vesey, Phys Rev Lett (2012); A.B. Sefkow *et al.*, Phys Plasmas (2014).

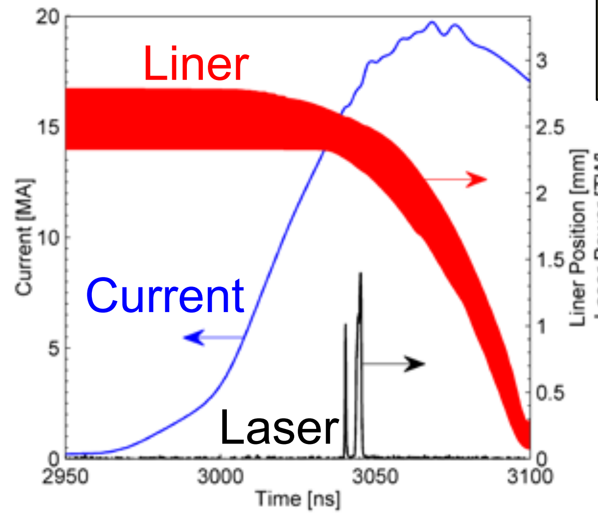
The initial experiments used 10 T, 2.5 kJ laser energy, and 19-20 MA current to drive a D_2 filled (0.7 mg/cc) Be liner

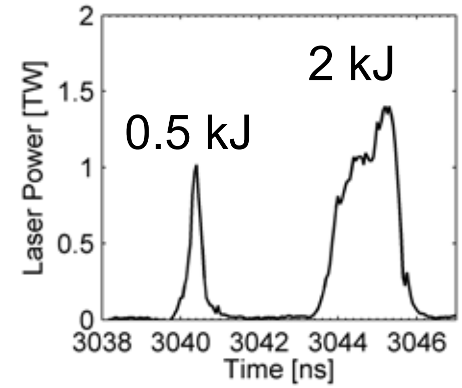






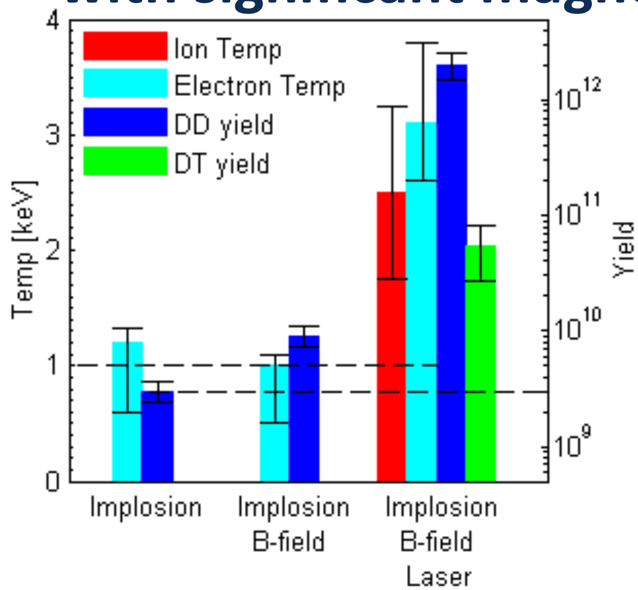
Peak current is 19 MA
Magnetic field is 10 T
Total laser energy is 2.5 kJ

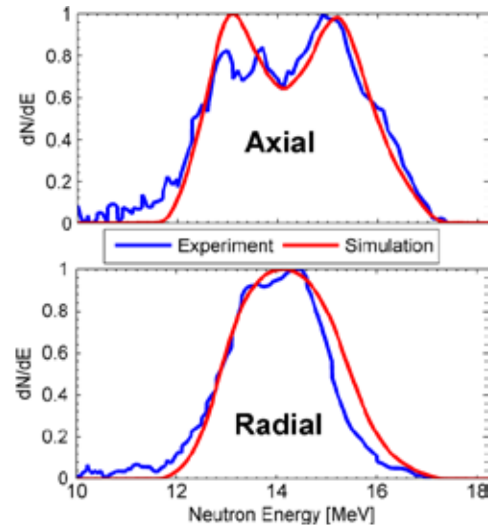


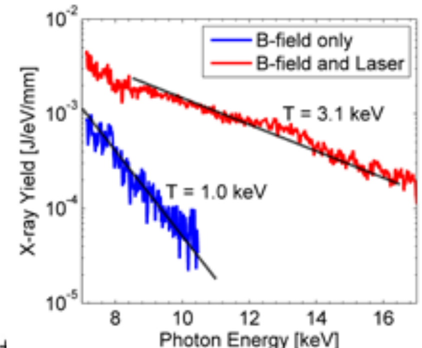


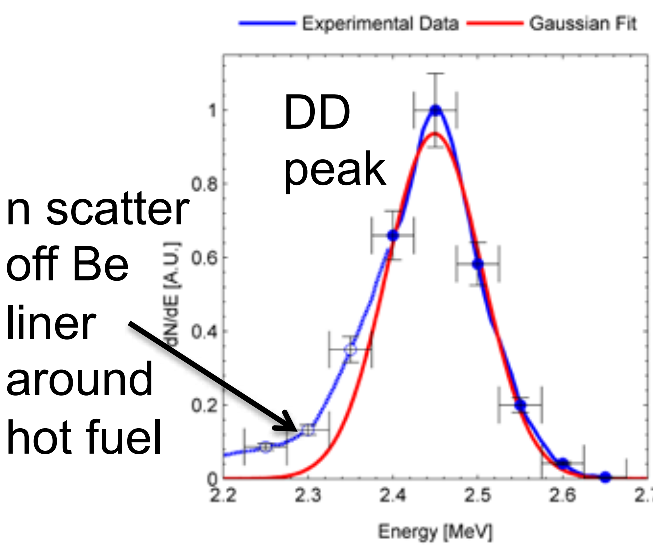
M.R. Gomez *et al.*, Phys. Rev. Lett. 113, 155003 (2014).

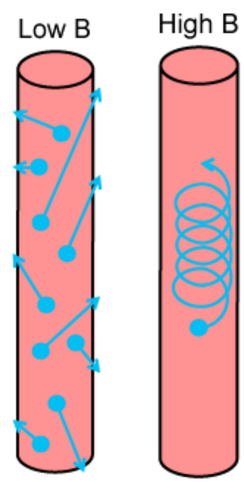
Our initial MagLIF experiments successfully demonstrated fusion yield consistent with a thermonuclear origin and with significant magnetization of the fusing plasma

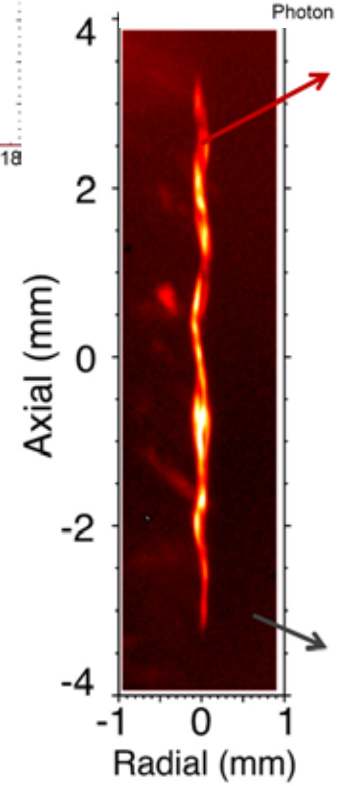












Stagnating plasma

$\langle T \rangle = 3 \pm 0.5$ keV

$T(r) = T_0[1 - (r/R)^2]$

$t_{burn} = 1.5 \pm 0.5$ ns

$f_{Be} = 5 \pm 3$ %

$z = 5 \pm 2$ mm

$R = 50 \pm 20$ μm

$\rho_D = 0.3 \pm 0.1$ g/cm³

$P(z) = 1 \pm 0.2$ Gbar

ρR ~ 1.5 mg/cm²

BR ~ 0.4 MG·cm

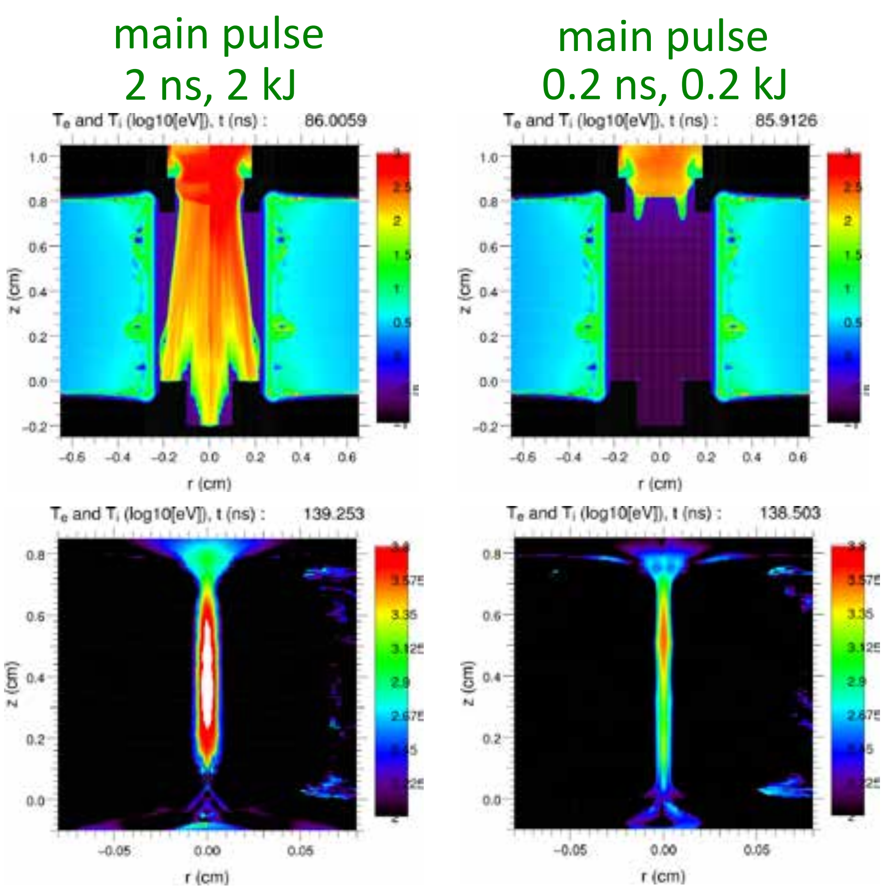
Confining liner

$\rho r_{liner} = 0.9$ g/cm²

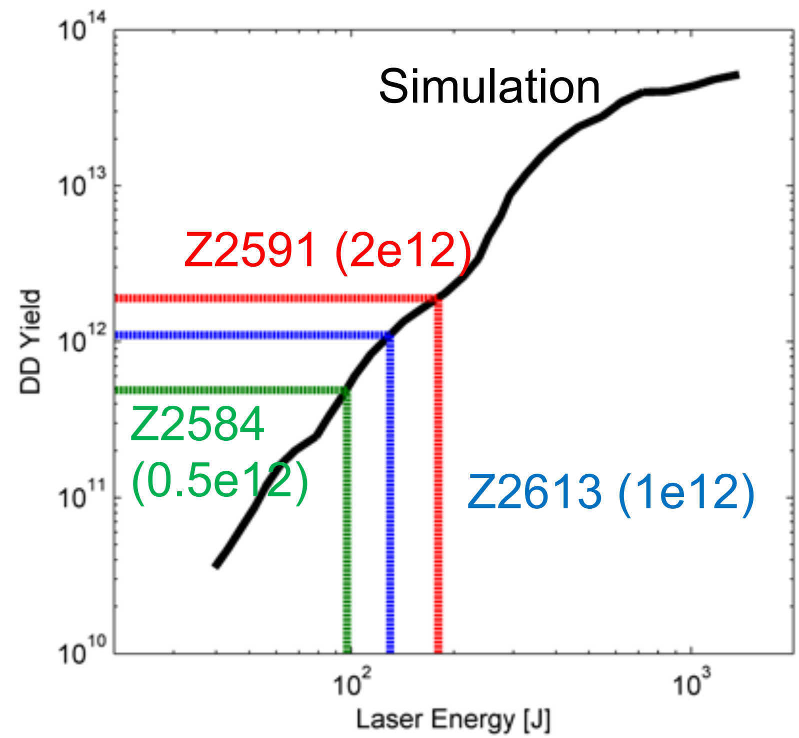
M.R. Gomez *et al.*, Phys Rev Lett 113, 155003 (2014); P.F. Schmit *et al.*, Phys Rev Lett 113, 155004 (2014).

Lower than predicted coupling of laser energy to the fusion fuel was a leading hypothesis: Original MagLIF data can be modeled by assuming no mix and 200-300 J in fuel

HYDRA Simulations*

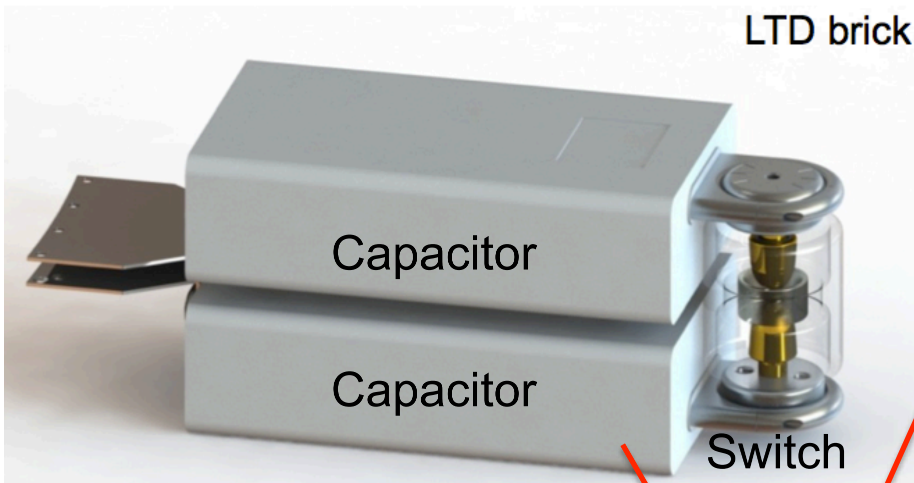


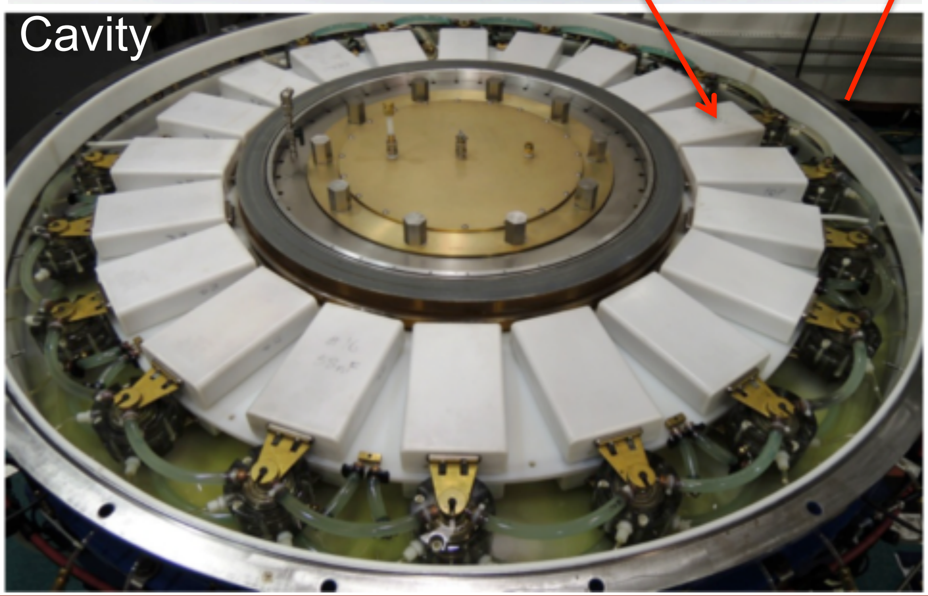
e.g., A.B. Sefkow *et al.*, Phys. Plasmas (2014).

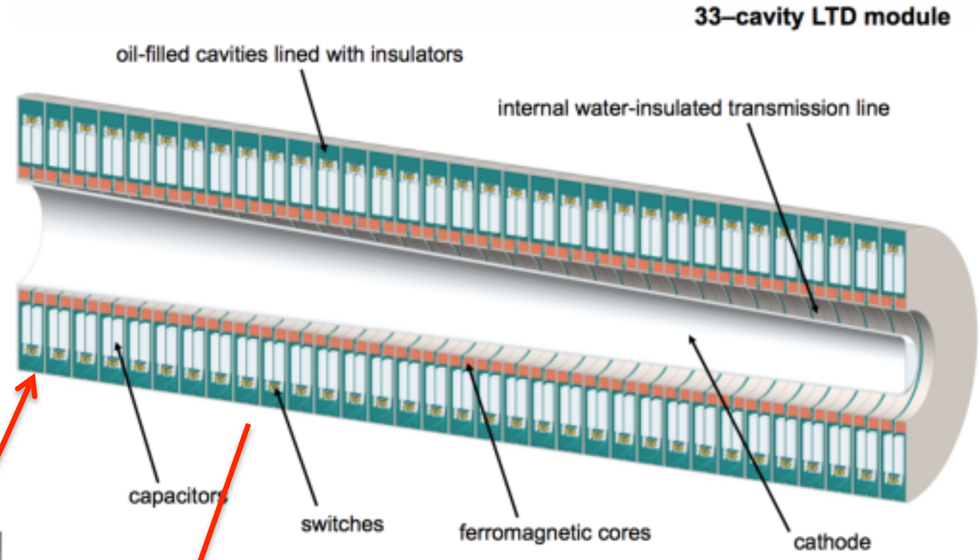


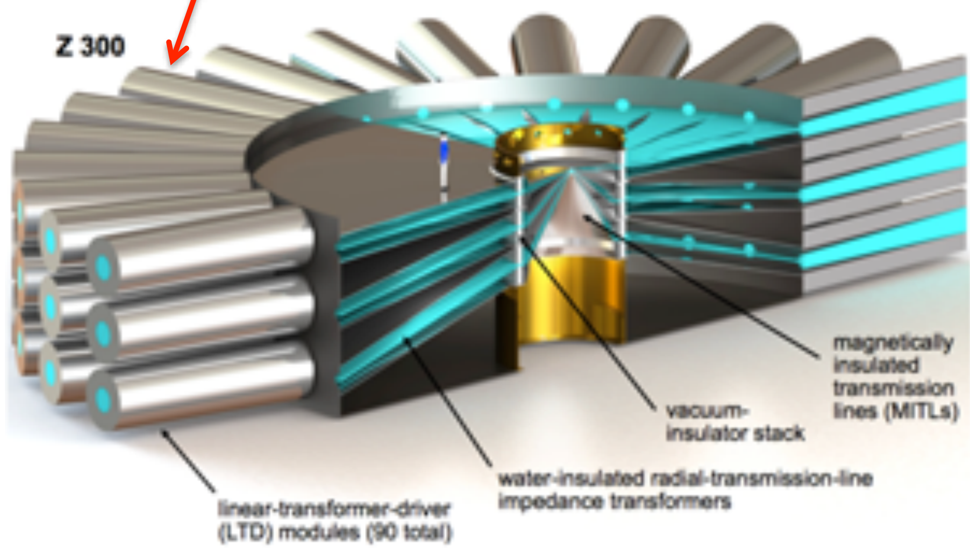
Simulations with 200 J match not only the yield, but other parameters measured in the experiments (temperature, shape, BR, etc.)

We have developed a Linear Transformer Driver (LTD) architecture that can scale to 800-1000 TW about twice as efficiently as Z and can be optimized for several applications.

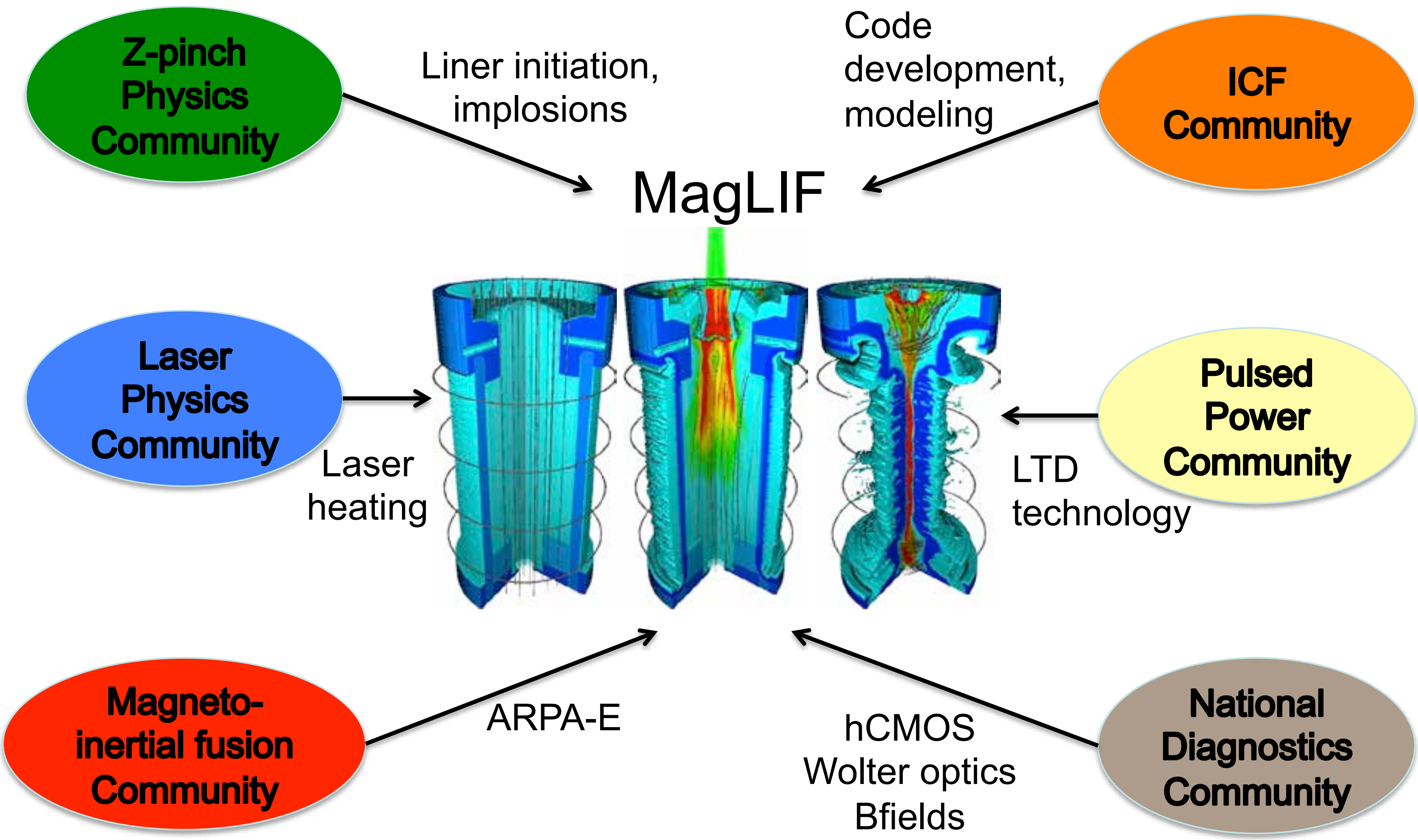








Many people from diverse communities have shown interest in MagLIF—our program should build on this



We have developed a science-based plan and structure for Magnetically Driven Implosions for the next 5 years that is increasingly national in scope

~85% of effort

- **Study the underlying science, emphasizing MagLIF**
  - Requires research in several areas identified by national ICF program:
    - Driver-target coupling, Target Pre-conditioning, Implosion, Stagnation & Burn, Modeling, Approximations, and Scaling
  - Both "focused" and "integrated" experiments on multiple facilities (e.g., Z, Z-Beamlet, Omega, Omega-EP, universities, NIF)
  - Development of new diagnostics, simulation tools and methods

~10% of effort

- **Demonstrate desired conditions and target scaling**
  - 100 kJ DT yields (or DD equivalent); P-tau > 5 Gbar-ns + BR > 0.5 MG-cm
  - Demonstrate scaling on Z (and OMEGA) with varying drive conditions

~5% of effort

- **Develop a path to ignition and beyond**
  - Define credible gas (~5 MJ) and ice burning (~ 1GJ) ignition designs for magnetically driven implosions
  - Demonstrate "at-scale" fuel heating on NIF relevant to MagLIF

~1% of effort

- **Motivate a future beyond ignition** by developing a compelling basis for why the nation needs a facility capable of ~1 GJ/shot

We are organizing the scientific aspects of our ICF program to better couple to the national program

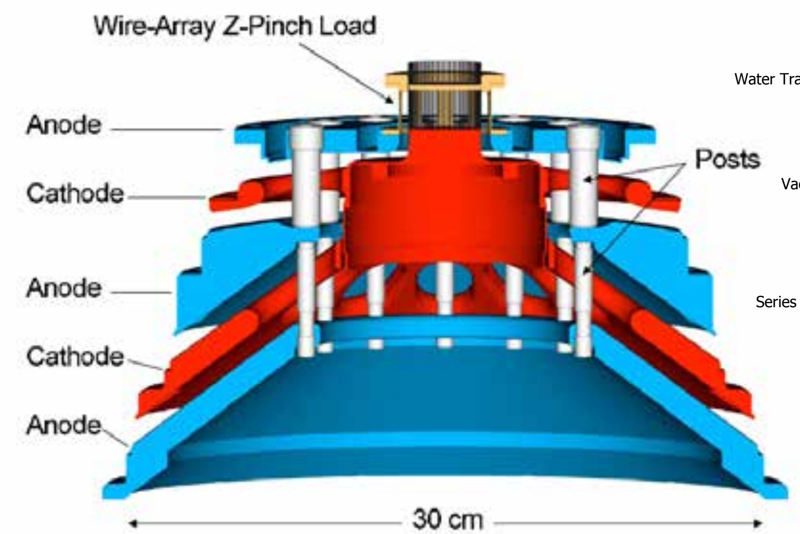
Research Group	Team Leaders
Driver-Target Coupling	Bill Stygar, Mike Cuneo
Target Pre-conditioning	Kyle Peterson
Implosion	Ryan McBride
Stagnation & Burn	Greg Rochau and Brent Jones
Intrinsic & Transport Properties	(treated as subset of next category)
Modeling, Approximations, & Scaling	Kyle Peterson and Thomas Mattsson

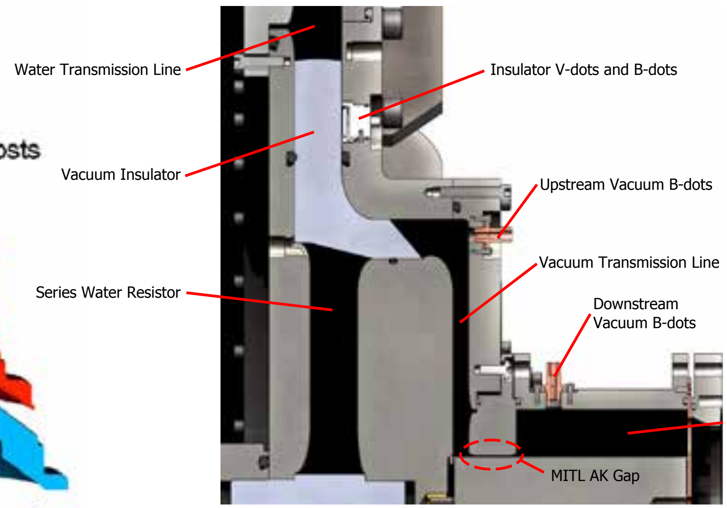
- Team leaders responsible for organizing the program of work for each of the research groups, including coordinating national research in each area

- The following slides summarize our progress to date and our key goals for the next five years in these areas
- We are working on detailed plans and schedules to meet those goals, but those are too detailed for this presentation

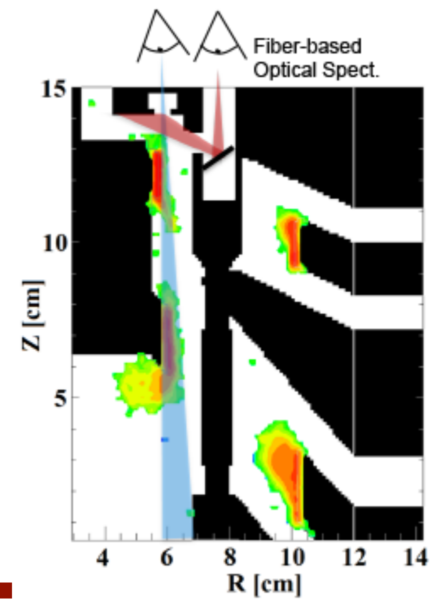
Some improvements in our understanding of the coupling between the pulsed power driver and ICF targets have been made, more are needed

- **Based on our Z experience, we have developed conceptual convolute & load designs for next-step accelerators that are optimized to achieve about 2% current loss**
- **Power-flow modeling using LSP suggests low-impedance loads and clean MITL surfaces are essential. In the presence of contamination, 3D PIC simulations needed**
- **To validate convolute models, we are using optical spectroscopy to quantitatively assess plasma formation and B field strength in the Z current feed**
- **To improve our vacuum power flow models, we are conducting focused experiments on the 0.2-TW Mykonos accelerator**





LSP simulation of plasma formation in the Z Convolute*

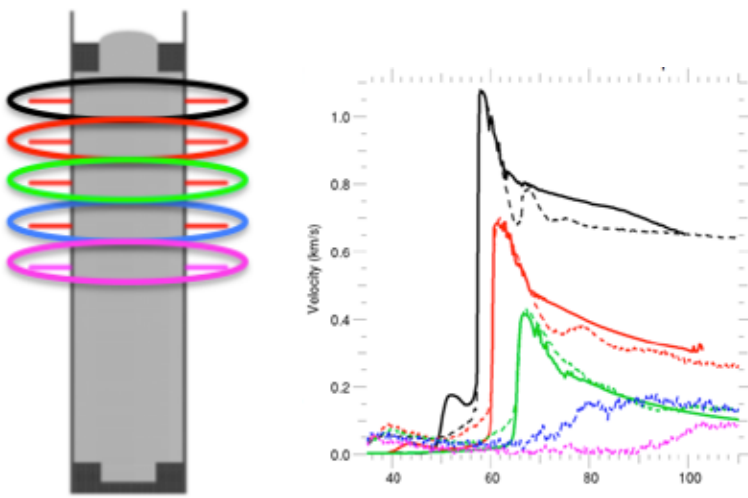


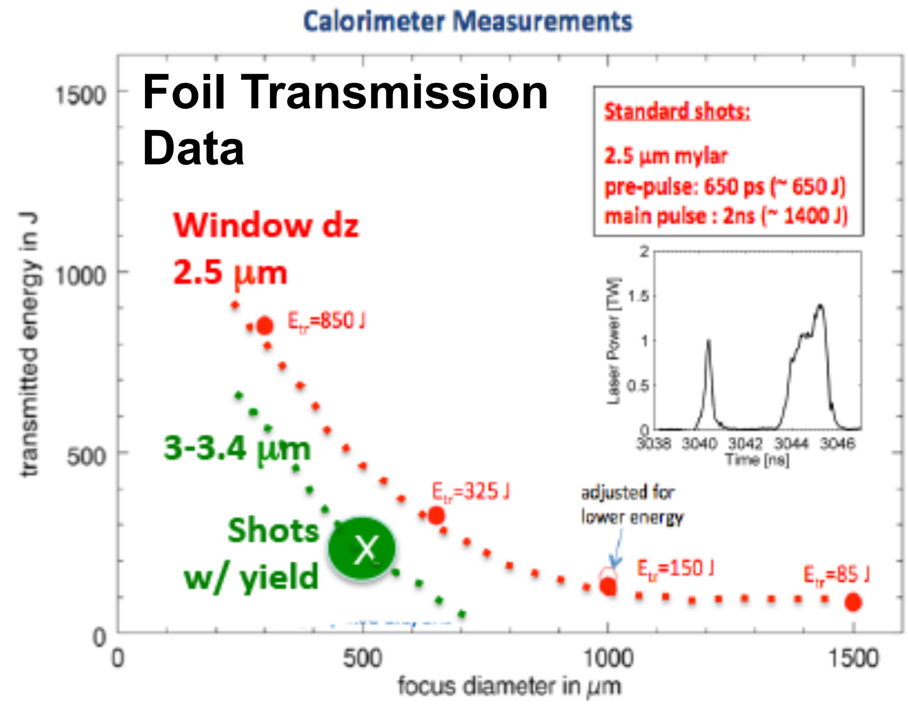
Over the next five years, we seek to accomplish the following goals related to driver-target coupling:

- **Deliver 25 MA to a MagLIF target on Z.**
  - To offer the potential of achieving Yield ~ E_{fuel} ~ 100 kJ.
- **Quantify the benefits to ICF loads of current-pulse shaping (affects current loss).**
  - To explore the performance space between low-adiabat implosions and stability.
- **Quantify the benefits of longer implosions (such as might be achieved by an LCM).**
  - To explore the performance space between peak current and pulse length.
- **Develop a point *pulsed-power* design of a MagLIF target for Z Next that achieves a net target gain of 1 (Likely, Yield ~ E_{target} ~ 3-5 MJ) .**
  - Gain=1 is a potential goal for Z Next that would define the driver requirements.
- **Conduct scaled power-flow experiments under conditions similar to those of Z Next.**
  - To demonstrate that Z Next will perform as expected.
- **Develop predictive (~5%) circuit and PIC models of an accelerator coupled to a variety of loads (possibly including a single integrated simulation of power flow + target?).**
  - To facilitate the design of MagLIF experiments on Z, and the design of Z Next.

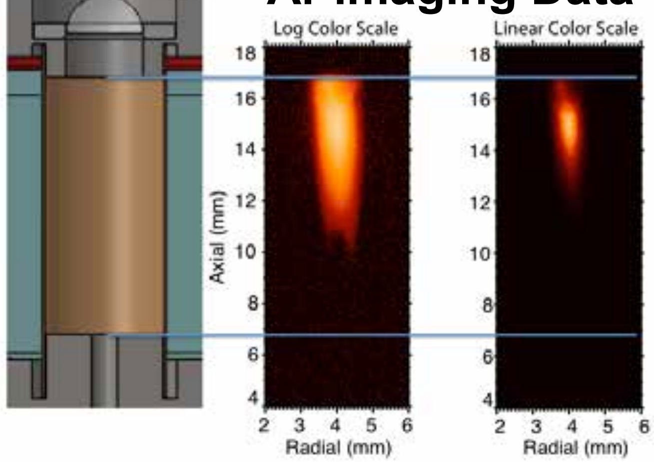
Laser-only experiments appear to confirm that laser-fuel coupling is a concern: Multiple measurements are consistent with 200-600 J in heated gas out of >2000 J

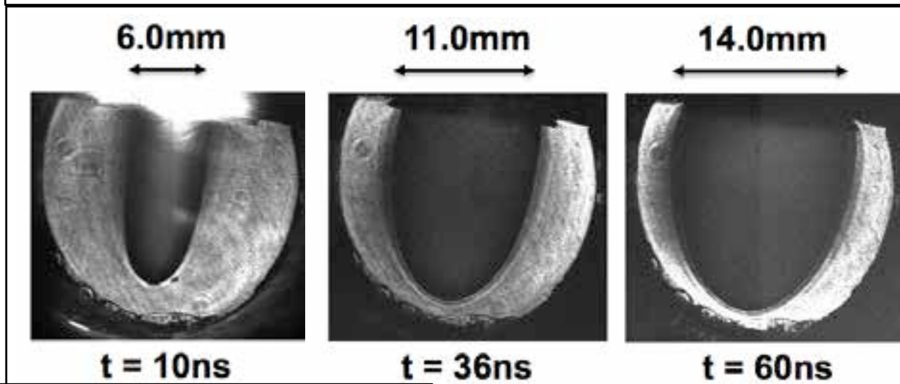
Blast Wave Data





Ar imaging Data

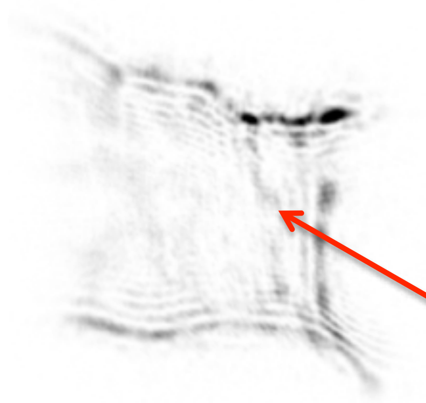




Shadowgraphy Data

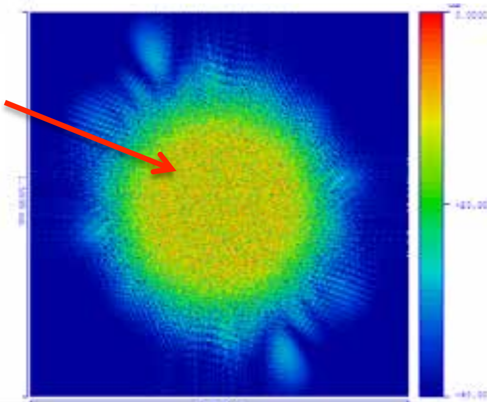
The Z-Beamlet beam spot quality may be one reason that we are struggling to couple well to the fusion fuel

Z-Beamlet currently does not use any beam smoothing techniques adopted by the laser community

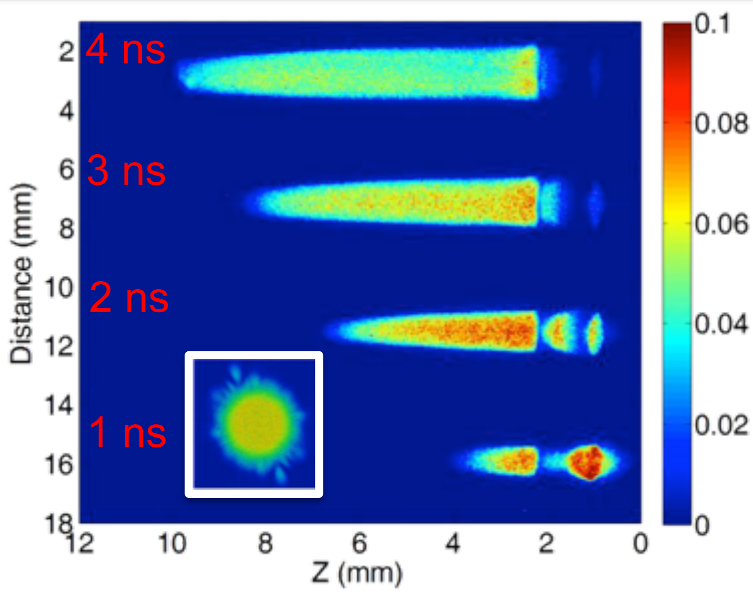


ZBL: No DPP (representative)

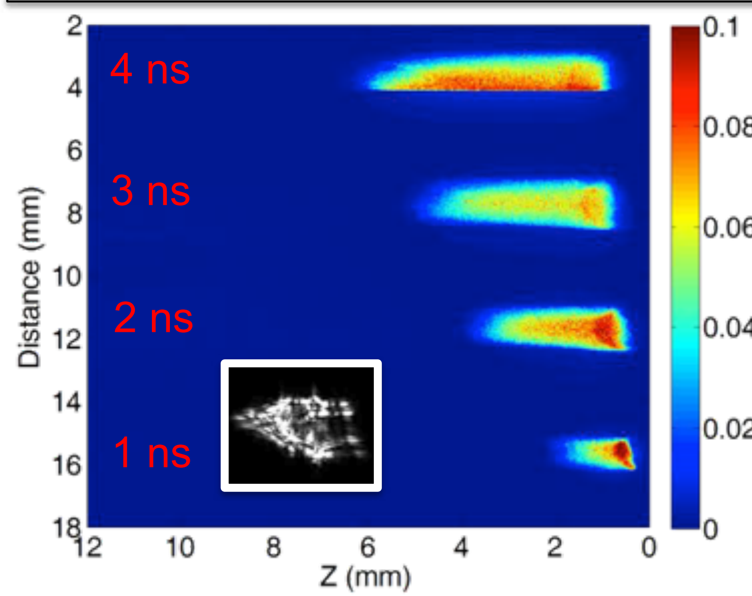
OMEGA-EP 750um DPP



4 ns/3.1 kJ, 2 μm LEH, no prepulse with DPP (SNL Omega-EP data)



4 ns/2.93 kJ, 2 μm LEH, no prepulse without DPP (SNL Omega-EP data)



Over the next five years, we seek to accomplish the following goals related to target pre-conditioning:

- **Demonstrate a method for reproducibly coupling >2 kJ into magnetized fuel**
  - To achieve our stagnation & burn goals in integrated tests
  - This includes measuring conditions created in situ on the Z facility
- **Improve Z-Beamlet to be capable of a multi-ns, >6 kJ, well-characterized "smoothed" beam profile (including an optimized pulse shape)**
  - As the primary path to achieve the previous goal during the next 5 years
- **Minimize the likelihood and impact of laser-plasma interactions**
  - To maximize our chances of predicting performance and scaling
  - Is sensitive to fuel density, window thickness, laser intensity, wavelength
- **Characterize & mitigate any fuel contamination as a result of the heating method**
  - To minimize radiation losses throughout the implosion
  - Understand over a range of coupled energy (1-30 kJ) to predict scaling
- **Demonstrate 30 kJ heating on the NIF**
  - To help lay the foundation for a next-step facility, where >20 kJ is needed

We have started investigating laser preheating on a number of different facilities, each of which offers unique capabilities and opportunities to learn

Facility	ZBL (Pecos)	ZBL (in Z)	OMEGA-EP	OMEGA	NIF
Collaborator	none	Some w/ LLNL	GA & LLE	LLE	LLNL
Shots/day	Up to 3	Up to 2	Up to 9	Up to 12	Up to 4
Shots/year	>150	15-20 (FY15)	18 to 27	18 to 36	TBD
Energy (1-beam)	4.5 kJ	4.5 kJ	2-2.5 kJ	0.4-0.6	8-10 kJ
Wavelength	2ω	2ω	3ω	3ω	3ω
Beam Smoothing	None yet	None yet	Very good	Excellent	Very good
Spectroscopy diagnostics	Limited, time-integrated	Extensive	Streaked	Limited	TBD
Imaging diagnostics	Shadowgraphy	Monochromatic & Gated MLM	Gated pinhole	Gated pinhole	TBD
Back scatter diagnostics	Diodes	None	None	Excellent	Excellent
B field capability	30 T single-coil May 2015	30 T ABZ System	30 T MIFEDS	30 T MIFEDS	Conceptual LDRD
Pre-pulse options	8 ns window, soon arbitrary	8 ns window, soon arbitrary	Limited (2nd beam)	None	TBD
Cryogenics?	Development	Development	None yet	None yet	TBD

A key challenge for the team is to coordinate this national effort!

We have built up a collection of data for testing and validating 2D and 3D magneto-hydrodynamics codes, but we are struggling to keep up with the modeling effort

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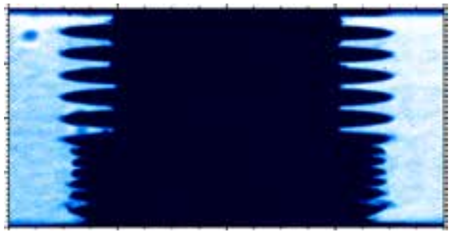
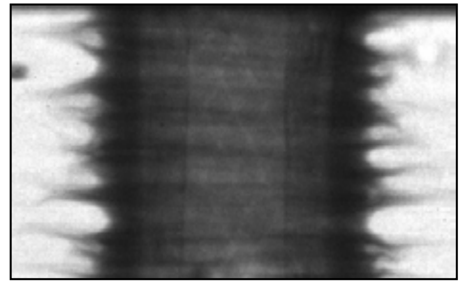
Single-mode magneto-Rayleigh-Taylor growth

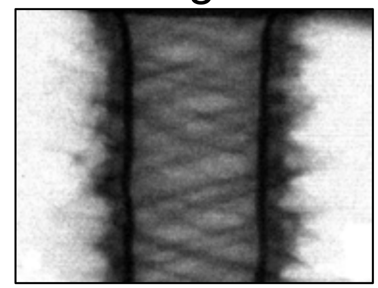


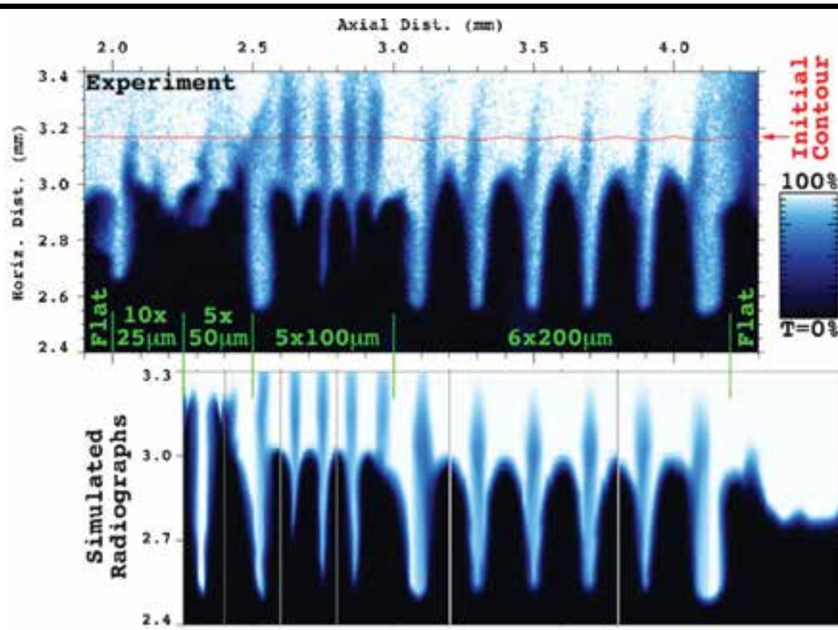
Multi-mode MRT growth

Helically perturbed growth



Magnetized MRT growth

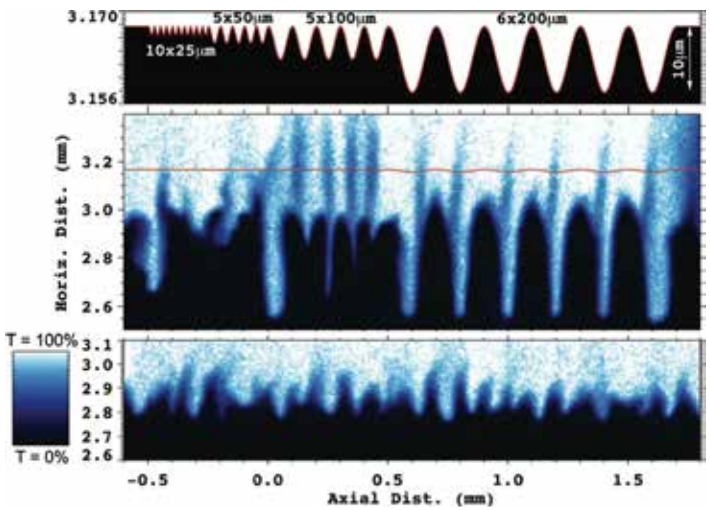




High-resolution 2D modeling can capture early growth down to the ~50-micron scale

Complex HYDRA (or HYDRA+LSP) simulations can capture details but the harvest is plentiful and the workers are few!

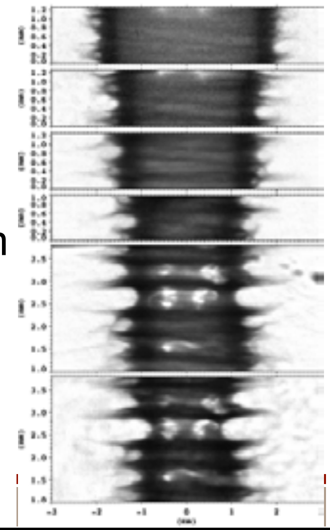
We have made progress in understanding the seed for liner instability growth and in mitigating this growth, which may open up design space for MagLIF



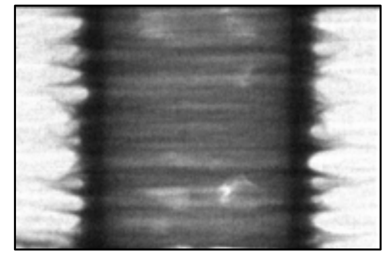
A_0 = 25,000 to 200,000 nm

A_0 = 60 nm

McBride PRL data

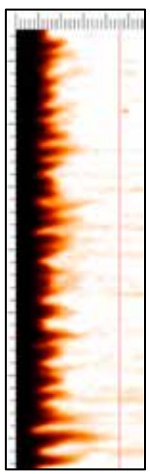


Axially-polished liner growth

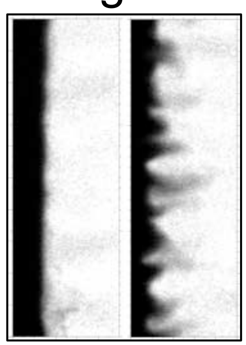


Changing the character of the surface did not change the observations

Based on a hypothesis that instabilities seeded by electro-thermal instability, we have developed a mitigation strategy

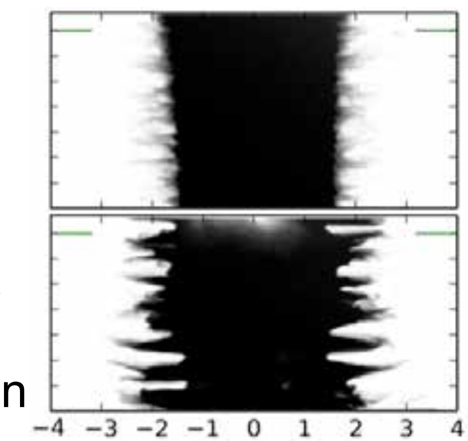


Suppressed growth using CH overcoat



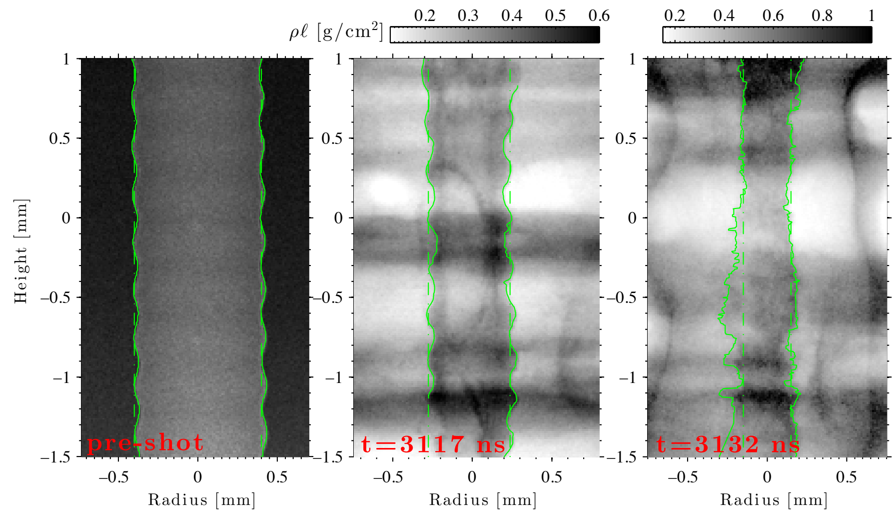
Rod

Liner implosion



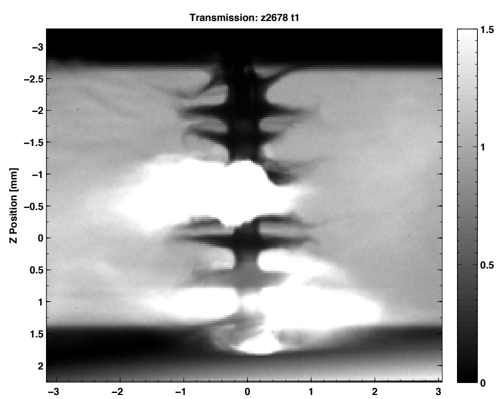
Data collected during past year appears to support the mitigation idea

In the last year we began studying deceleration instabilities, high-density compression, and high CR compression



- A Be, liquid D2 filled liner is imploded onto an on-axis rod with a sinusoidal perturbation
- The liner launches a shock in the D2 which strikes the rod/fuel interface (1st image after shock)
- Shock reflects off the axis and re-shocks the Be/D2 interface (2nd)

Current pulse shaping to compress liquid D2 to extreme densities



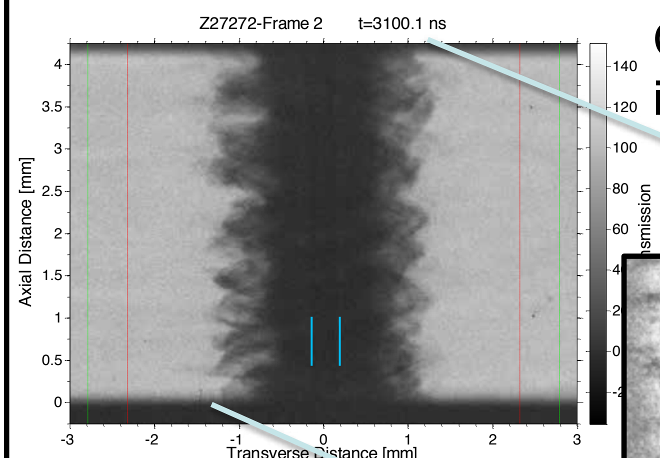
$$CR \approx 19$$

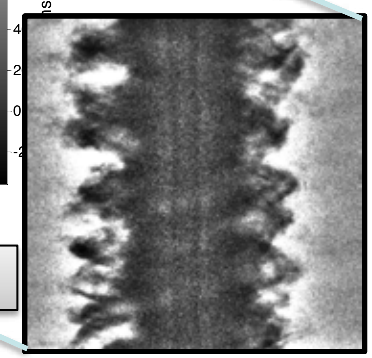
$$\langle \rho \rangle = 60 \text{ g/cm}^3$$

$$\langle \rho R \rangle = 0.5 \text{ g/cm}^2$$

$$r_{stag} = 110 - 170 \ \mu\text{m}$$

Magnetized & CH-coated Be implosion (CR is 13-21)



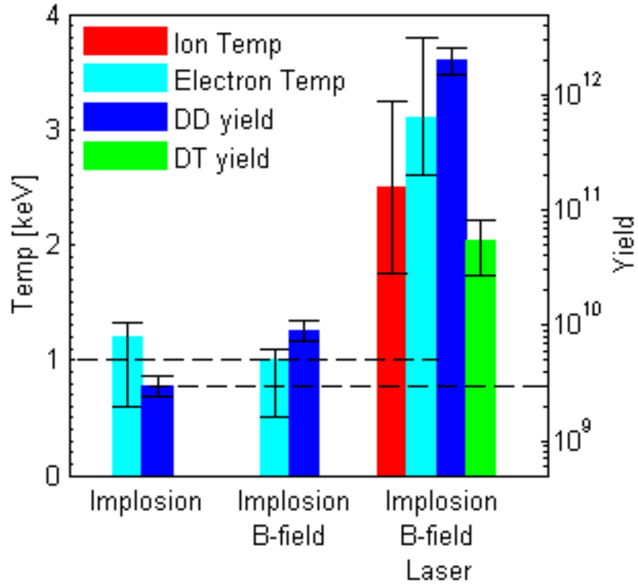


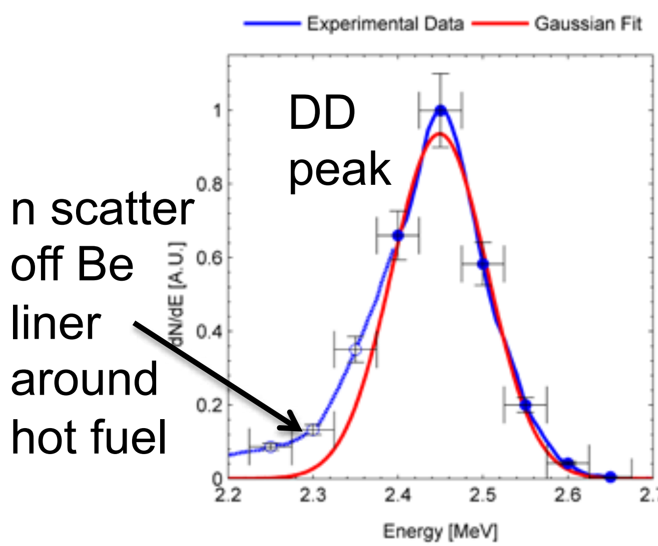
Inner liner radius ~ 120 microns!

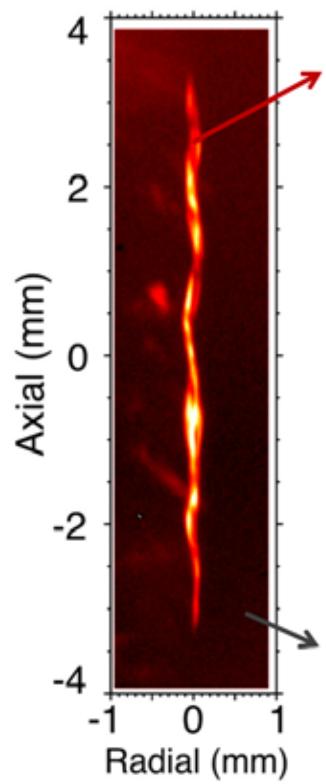
Over the next five years, we seek to accomplish the following goals related to magnetic implosions:

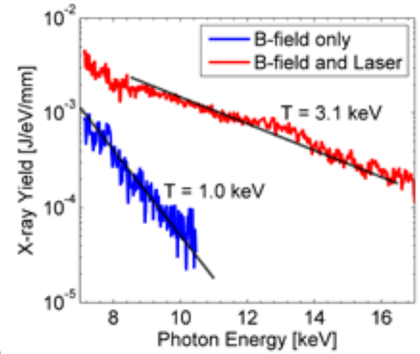
- **Determine the dominant seeds for observed acceleration and deceleration instabilities, and strategies to mitigate against them (creates more design flexibility)**
  - Accel seeds may include surface roughness, electro-thermal, or electro-choric effects
  - Decel seeds may include surface roughness, heating (blast and/or beams), or kinetics
- **Demonstrate the ability to model the evolution of 2D & 3D instability structures in codes used to predict the integrated target performance**
  - Over a range of drive conditions (18-25 MA, 100-300 ns), magnetization (0-30 T), and relevant target designs (including Li, Be, Al liners and end cap geometries)
  - Accurate drive (current) measurements are needed for code comparisons
- **Measure the spatial distributions for temperature, density, B_z, and any contaminants in the fuel after heating and through at least CR=5**
  - Radiation and heat conduction losses are expected to be sensitive to distributions; needed to estimate energy transport out of the imploding region (radial and axial)
  - Over a range of laser preheat (1-4 kJ), magnetization (0-30 T), and target geometries
- **Experimental demonstration of a magnetized liner implosion resulting in a diagnosable, ignition-relevant stagnation pressure-tau product of > 5 Gbar ns**
  - Can be achieved in a low-temperature, high-density surrogate platform

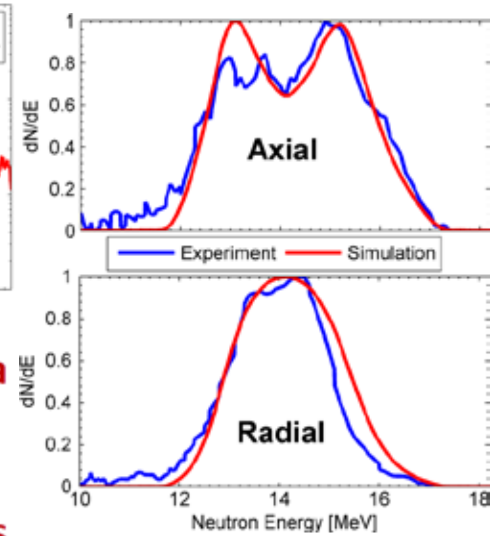
We have a number of diagnostics today for measuring conditions at stagnation, but most are time-integrated and others are needed











Stagnating plasma

$\langle T \rangle = 3 \pm 0.5$ keV

$T(r) = T_0[1 - (r/R)^2]$

$t_{burn} = 1.5 \pm 0.5$ ns

$f_{Be} = 5 \pm 3$ %

$z = 5 \pm 2$ mm

$R = 50 \pm 20$ μm

$\rho_D = 0.3 \pm 0.1$ g/cm³

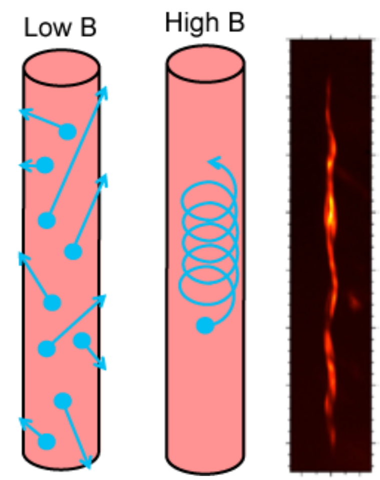
$P(z) = 1 \pm 0.2$ Gbar

$\rho R \sim 1.5$ mg/cm²

BR ~ 0.4 MG·cm

Confining liner

$\rho r_{liner} = 0.9$ g/cm²



Over the next five years, we seek to accomplish the following goals related to stagnation and burn:

- **Achieve a burn-averaged ion temperature of >4 keV (robust burn threshold)**
  - T_i should increase with increasing preheat energy and decrease with increasing high-Z contamination (due to radiation loss)
- **Achieve a BR > 0.5 MG-cm (R/r_α > 2)**
  - Above this level the benefits of magnetization saturate
- **Achieve fuel pressure > 5 Gbar and $P\tau$ > 5 Gbar-ns**
  - Achieving Y ~ E_{fuel} ~ 100 kJ requires P ~ 5-10 Gbar and $P\tau$ ~ 10 Gbar-ns
  - Need to understand scaling with preheat & driver energy
- **Minimize and mitigate against radiation loss from high-Z contamination**
  - Known to vary with target geometry and character of laser heating
  - Improving liner stability and use of anti-mix layers can mitigate dynamic mix
- **Demonstrate a continuous, nearly uniform stagnation column at CR>20**
  - Discontinuous plasma assembly loses benefit of ρz and increases losses
  - Achieving Y ~ E_{fuel} ~ 100 kJ requires CR of 25, but lower stagnation fuel pressures (e.g., due to low preheat) will actually result in higher convergence
- **Determine the non-thermal component of the fusion yield.**
  - A significant portion of the yield for many z-pinches is not thermonuclear

To understand stagnation and burn stage will require a large focus on improving our measurement capabilities on Z

Measured Quantity	Measurement Method	5-year Development Activities and Goals
Ion Temperature	• DD spectra	• Improve nTOF to provide ±15% accuracy in T_i at Y_{DD}>5E10
Electron Temperature	• Continuum slope • Emission line ratios	• Develop diagnostics to measure $T_e(r,z,t)$ to ±20% with δr < 50 um, δz < 500 um, and δt < 0.5 ns
BR	• DT/DD yield ratio • DT spectra	• Improve nTOF DT spectra to achieve ~0.15 MeV resolution at Y_{DT}>5E9 • Improve DT/DD yield ratio to ±30% at Y_{DT}>5E9 and increase the angular coverage
Mix Fraction & Electron Density	• Spectral signatures and emission amplitude	• Develop targets with tracer layers • Develop diagnostics to measure absolute x-ray emission to ±50% with δz < 500 um and δt < 0.5 ns
Fuel Morphology	• X-ray imaging	• Develop an x-ray imager with δr < 50 um, δz < 500 um, and δt < 0.5 ns with sensitivity to >1 GW
Burn Duration	• 10-15 keV x-ray history • Inferred from Te(t)	• Leverage electron temperature activities and goals

Over the next five years, we seek to accomplish the following goals related to modeling, simulation, & scaling:

- **Improve our existing codes capable of fully-integrated simulations by upgrading the MHD-based models in them**
  - All of the codes benchmarked to date as being useful for simulating all aspects of magneto-inertial fusion are based on fluid-like MHD approximations
  - Additions to the models are needed to capture more of the relevant physics, including magnetic flux loss (Nernst, Ettinghausen) and current flow in low-density plasma (“extended MHD”)
- **Investigate hybrid particle-in-cell codes as an alternative approach to fully-integrated simulations**
  - Traditional particle-in-cell codes do not scale well to the high particle densities typical of inertial confinement fusion
  - Hybrid fluid/particle calculation techniques may allow some codes to bridge the gap into this area (e.g., LSP or other ASC codes)
- **Develop tools and experiments for validating our simulations**
  - Can be theoretical test problems (e.g., magnetic Noh problem)
  - Can be simple, highly-specialized test codes with better physics models
  - Each of the previous four areas shall generate validation data for our tools
- **We will not invest significant effort in modeling laser-plasma interactions**

Our modeling and simulation strategy for magnetically driven implosions is currently under revision—a key challenge is the small user base for this application

- **Our main fully integrated scaling and design tools for magnetic drive are codes developed and supported by LLNL, based on MHD**
  - E.g., LASNEX (2D MHD), HYDRA (3D MHD), ARES (3D MHD)
  - “Workhorse” codes that allow design and scaling studies
  - Large user base for non-MHD aspects of these codes helps “break in the code” so that they are robust and at least partially validated over a wide range of problems and scales
- **Additional tools being used to do some problems because they offer unique physics advantages**
  - E.g., GORGON (3D MHD), ALEGRA (3D MHD), LSP (hybrid-PIC)
  - Each does some things particularly well, but unproven in others
  - Small user base for each
- **A relatively small number of FTEs across the laboratories are currently using MHD-based code tools. New collaborations may help improve these tools.**

We have developed a science-based plan and structure for Magnetically Driven Implosions for the next 5 years that is increasingly national in scope

~85% of effort

- **Study the underlying science, emphasizing MagLIF**
  - Requires research in several areas identified by national ICF program:
    - Driver-target coupling, Target Pre-conditioning, Implosion, Stagnation & Burn, Modeling, Approximations, and Scaling
  - Both "focused" and "integrated" experiments on multiple facilities (e.g., Z, Z-Beamlet, Omega, Omega-EP, universities, NIF)
  - Development of new diagnostics, simulation tools and methods

~10% of effort

- **Demonstrate desired conditions and target scaling**
  - 100 kJ DT yields (or DD equivalent); P-tau > 5 Gbar-ns + BR > 0.5 MG-cm
  - Demonstrate scaling on Z (and OMEGA) with varying drive conditions

~5% of effort

- **Develop a path to ignition and beyond**
  - Define credible gas (~5 MJ) and ice burning (~ 1GJ) ignition designs for magnetically driven implosions
  - Demonstrate "at-scale" fuel heating on NIF relevant to MagLIF

~1% of effort

- **Motivate a future beyond ignition** by developing a compelling basis for why the nation needs a facility capable of ~1 GJ/shot

Achieving alpha heating and ignition is possible on a future facility using a cryogenic DT layer and substantial preheat—we will test most of the physics of these targets on Z today

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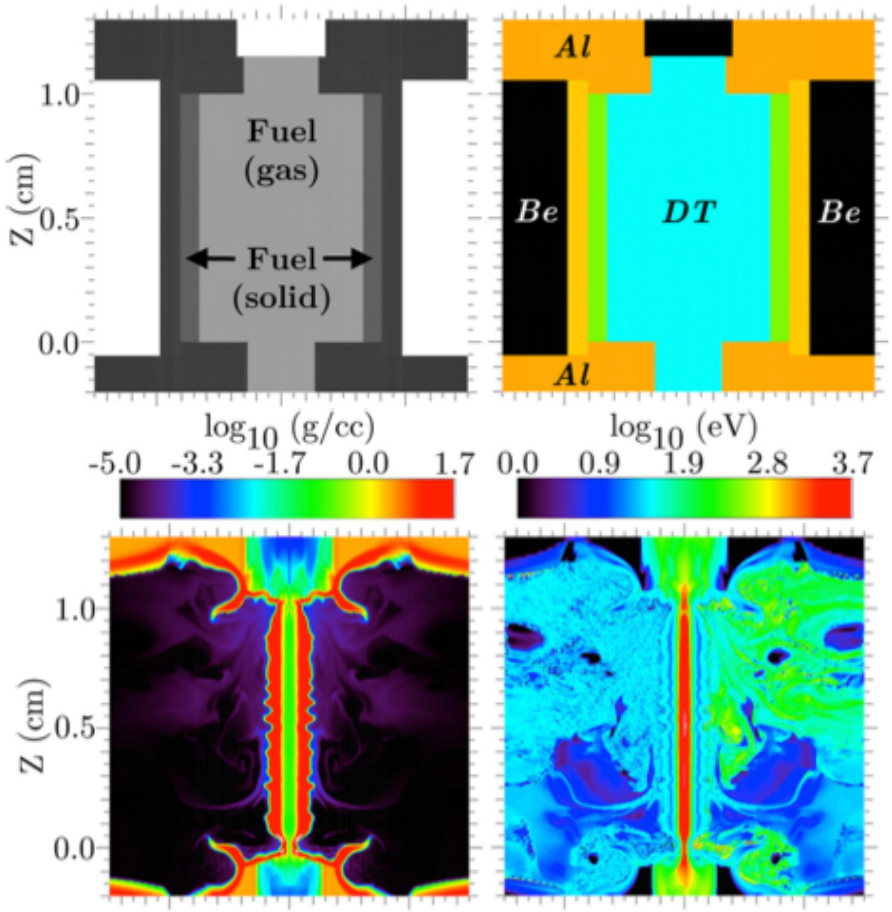
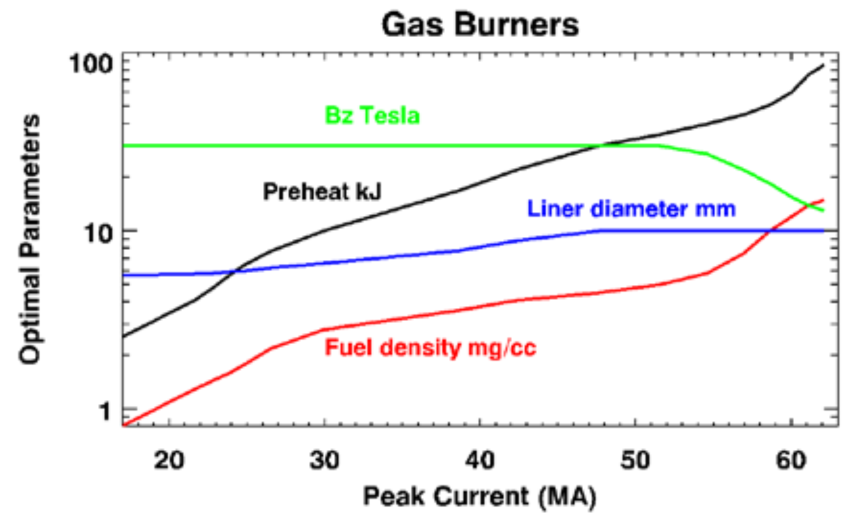
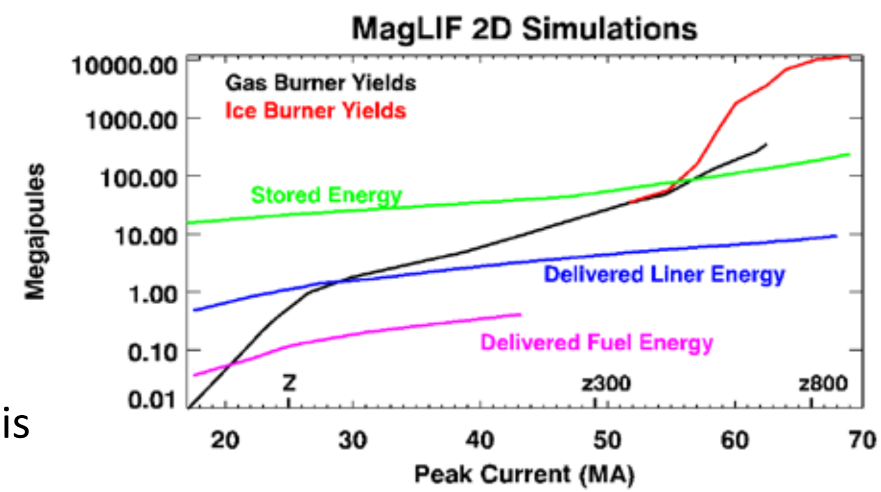






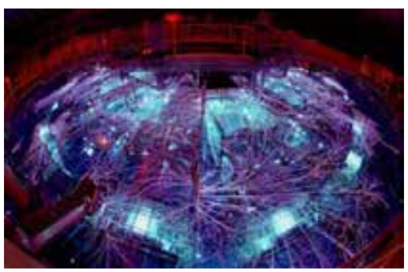
An intermediate regime exists wherein the B_z field is

- *strong enough* to reduce conduction losses, but
- *weak enough* not to inhibit the α deflagration wave

S.A. Slutz and R.A. Vesey, Phys Rev Lett (2012); A.B. Sefkow *et al.*, Phys Plasmas (2014).

We are currently exploring target designs and pulsed power architectures that may be on the path to 0.5-1 GJ yields and that also meet the needs of the science campaigns

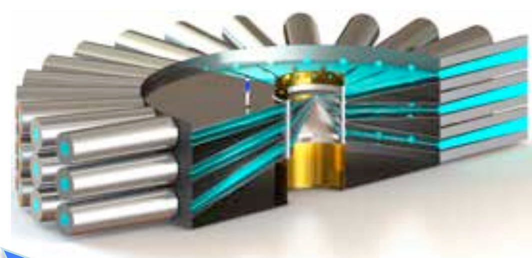
Yield = E_{fuel}?
(~100kJ$_{DT\ eq}$)
Physics Basis for Z300



Z

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

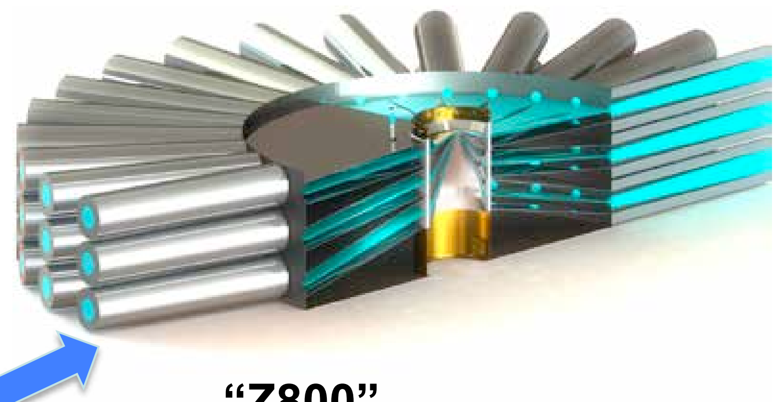
Yield = Etarget?
(About 3-4 MJ)
α-dominated plasmas



"Z300"

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

Fusion Yield 0.5-1 GJ?
Burning plasmas

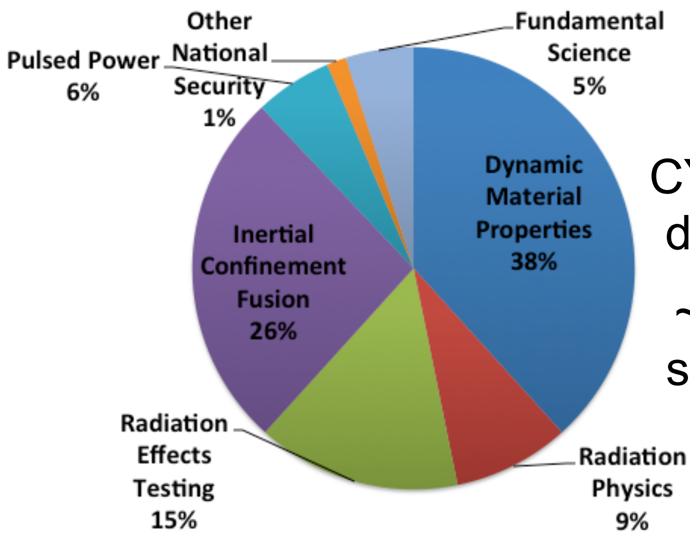


"Z800"

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

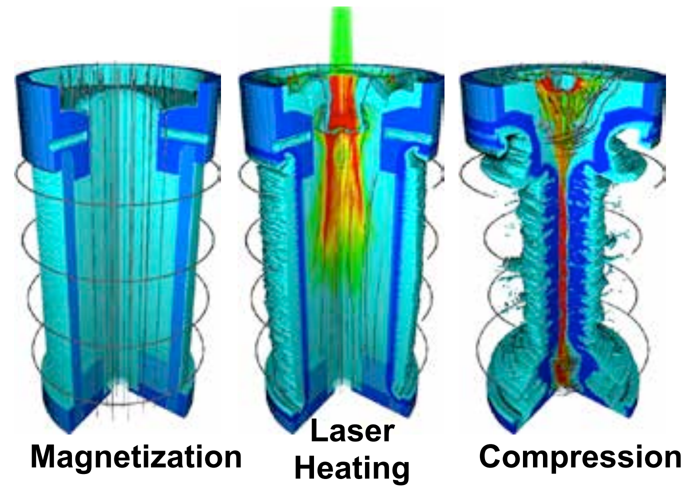
The "bold outcome" of the First to High Yield Fusion Research Challenge

About 25% of the Z shots each year have been available to the ICF program (60 days, 40-45 shots). The ICF effort on Z will emphasize MagLIF in particular for the next 5 years.



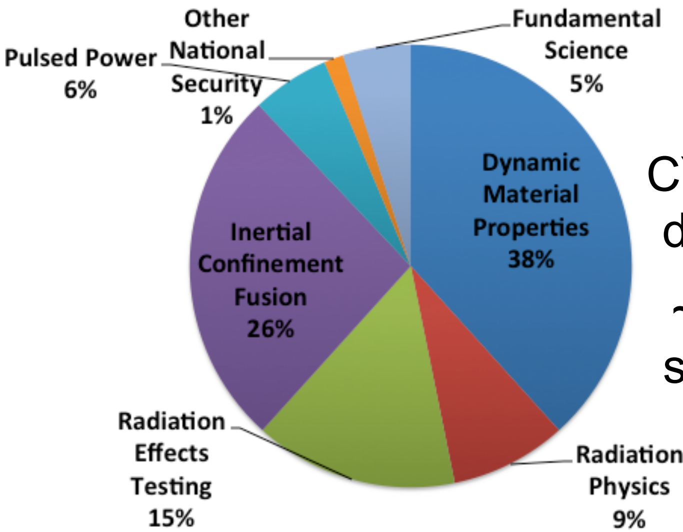
CY13 Z shot distribution

~150-200 shots/year



- 2015 Z shot time (60 days) divided into 14 unique campaigns (~4 shots/campaign), most campaigns will span several years with an iteration cycle of 1-2 times/year
- In the first 15 months of studies on MagLIF, we did 15 integrated (Z+ZBL+B_z) experiments
- Due to the importance of laser heating and the lack of diagnostics on Z-Beamlet target chambers, at least 10 shot days on Z in 2015 will be laser-only experiments
- Z shot time must be used carefully—any work that can be done elsewhere should be

Increasing the Z shot rate for at least some program areas would help meet the growing demand for time



CY13 Z shot distribution

~150-200 shots/year

New demands on Z shot schedule

- **Increased time for DSW needs in radiation effects**
- **Increased time for studying high-hazard materials**
- **Increased time for ICF, including requests from LLNL**

- Increasing the overall Z shot rate would enable increased time for each of these areas
- Construction of a separate "capacity" generator facility ("Neptune") would help offload high-hazard experiments from Z, but realistically not ready until 2020+.
  - CY2015: ~65 planned days of DMP experiments would be good candidates for Neptune, plus 8-10 Fundamental Science DMP-like days, and possibly another 9 days of cylindrical DMP. Only 23 days are not good candidates due to unique capabilities for Z (e.g., MAPS, diagnostics)
- Redistributing the shot fractions amongst ICF and Science possible, but relative efforts are roughly consistent with current funding portfolio

While this is a national effort, increased operations and staff funding at Sandia beginning in FY17 is needed to form a critical mass to support progress in magnetic drive

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- FY15 PBR Sandia funding in ICF is split into:
  Z/ZBL Operations ($36M), Diagnostics ($2M), and staff ($5M)

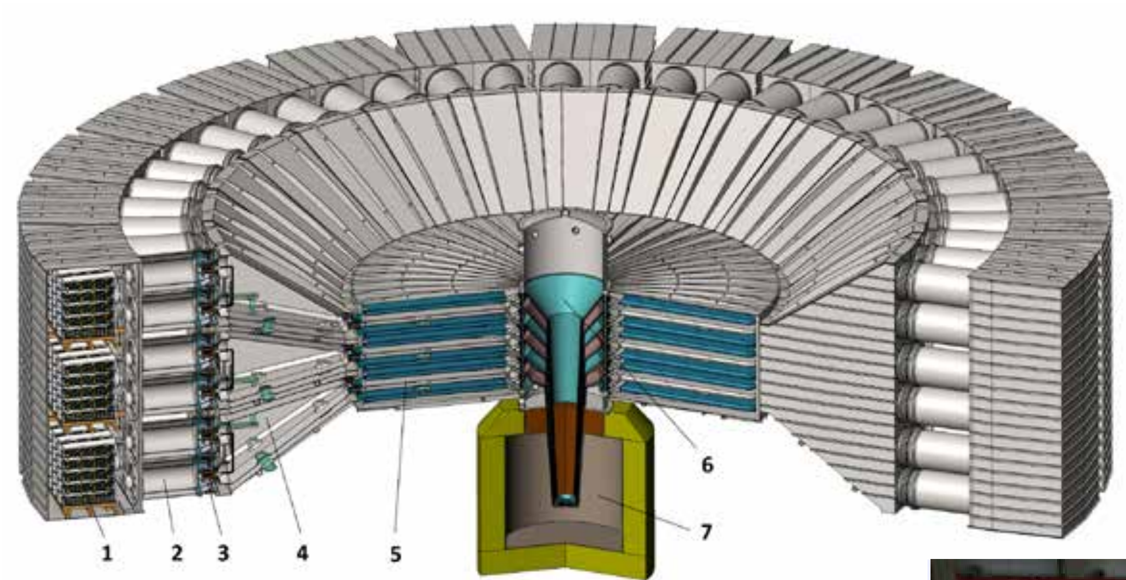
- Nominally 13-15 FTEs in ICF, in practice between 22-25 people at part-time; roughly twice this number is needed to coordinate a healthy national effort

- Z facility upgrades to address safety, aging, and shot rate: 200 shots/year requires $5M/year for labor, hardware, targets, consumables

- 95 kV Operation on Z (Supports higher current for ~100 kJ): $3M, 2 years

- Use of tritium on the Z facility (diagnostics, thermonuclear demonstration): $10M over 5 years to use few % tritium fills

There is also growing international interest in pulsed power ICF—our world leadership position is not assured



Operating Chinese Facility (PTS)

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

Russian Facility (Baikal)

- 50 MA
- 150 ns
- 100 MJ (4 x Z)
- Stated goal: **25 MJ fusion yield**
- Scheduled for completion in 2019, funding is secured and there is activity
- If it works, they will have this capability before any realistic scenario for Z-300

ICOPS meeting in Turkey at end of May is opportunity to learn more

We have developed a science-based plan and structure for Magnetically Driven Implosions for the next 5 years that is increasingly national in scope

~85% of effort	**Study the underlying science, emphasizing MagLIF**
~10% of effort	**Demonstrate desired conditions and target scaling**
~5% of effort	**Develop a path to ignition and beyond**
~1% of effort	**Motivate a future beyond ignition**

- **Study the underlying science, emphasizing MagLIF** (~85% of effort)
  - Requires research in several areas identified by national ICF program:
    - Driver-target coupling, Target Pre-conditioning, Implosion, Stagnation & Burn, Modeling, Approximations, and Scaling
  - Both "focused" and "integrated" experiments on multiple facilities (e.g., Z, Z-Beamlet, Omega, Omega-EP, universities, NIF)
  - Development of new diagnostics, simulation tools and methods
- **Demonstrate desired conditions and target scaling** (~10% of effort)
  - 100 kJ DT yields (or DD equivalent); P-tau > 5 Gbar-ns + BR > 0.5 MG-cm
  - Demonstrate scaling on Z (and OMEGA) with varying drive conditions
- **Develop a path to ignition and beyond** (~5% of effort)
  - Define credible gas (~5 MJ) and ice burning (~ 1GJ) ignition designs for magnetically driven implosions
  - Demonstrate "at-scale" fuel heating on NIF relevant to MagLIF
- **Motivate a future beyond ignition** by developing a compelling basis for why the nation needs a facility capable of ~1 GJ/shot (~1% of effort)

Questions?

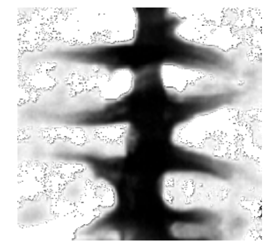
At the national level, there is broad and increasing support for magnetically driven implosion research, building on the momentum from the Klotz letter

- **ARPA-E ($3.8M, 2-year award) collaboration with Sandia & U. Rochester**
  - SNL-led laser-heating experiments on Omega-EP
  - LLE-led "mini-MagLIF" experiments on Omega
- **Substantial collaboration between Sandia and LLNL**
  - LLNL-led magnetic drive experiments on Z
  - Joint LLNL/SNL code workshop scheduled for June—magnetic drive effort is largely based on LLNL-developed simulation tools
  - LLNL interest in engaging and leading laser-heating experiments on NIF and possibly Z-Beamlet
  - Collaboration expected to grow with time (e.g., peer review of designs, diagnostic development for Z/Z-Beamlet).

Several of the transformative capabilities being developed by the National Diagnostics Plan will enable critical measurements for magnetic drive

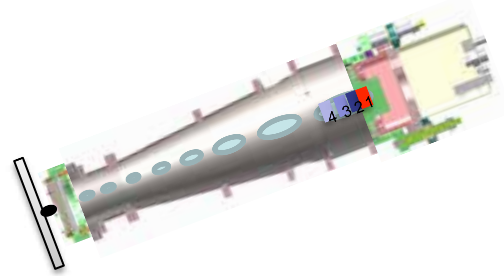
- **hCMOS single line-of-sight imaging/ spectroscopy (0-3 years)**
  - High convergence multi-frame radiography
  - Preconditioning temperature history

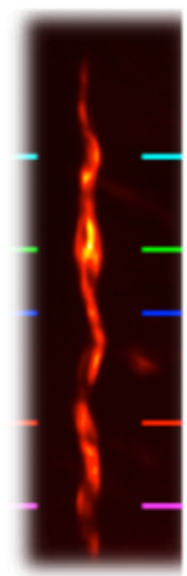
hybrid CMOS sensor



- **Pulse-dilation imaging/spectroscopy (5+ years)**
  - High resolution stagnated plasma morphology
  - Mix evolution at stagnation

Pulse-dilation + hCMOS





- **Full aperture short-pulse beam propagation (2-3 years)**
  - Simultaneous radiography and preconditioning

There are known deficiencies in the way that widely-adopted MHD models treat low density plasmas

- **All of the codes demonstrated today to be capable of fully-integrated calculations are based on fluid-based MHD models**
  - Necessitates use of density and conductivity "floors"
  - In some cases, the results are shown to be sensitive to the choices of the values for these floors
  - Accounting for magnetic flux loss in liner implosions requires higher-order corrections to the standard MHD models (e.g., "Nernst" and "Ettinghausen" terms) that have seldom, if ever, been validated
- **We are looking at a two-pronged strategy to address this**
  - Incorporation of "extended MHD" models that include electron terms in generalized Ohm's Law that are usually neglected*, potentially allowing us to push MHD-based codes down to lower plasma densities
  - Improvement & testing of hybrid particle-in-cell codes that model the particle kinetics directly, allowing us to push these codes to the high plasma densities typical of magneto-inertial fusion (e.g., LSP)
  - "Test codes" and good test problems will be needed to justify these

* e.g., Seyler & Martin, Phys. Plasmas (2011).

We are engaging with multiple collaborators to help us improve our codes for magnetically driven implosions

- **Improving MHD modeling:**
  - **U. Rochester**: Collaboration on "mini-MagLIF" is expected to examine MHD modeling of magnetic flux loss
  - **LLNL**: A "code workshop" at LLNL planned for June to understand the issues with our LLNL-based workhorse codes and develop a path forward
  - **Universities** (e.g., Cornell): Actively developing extended MHD models and doing validation experiments to understand the importance of including this new physics
- **Improving PIC/Hybrid-PIC modeling:**
  - **Universities**: We are trying to get more groups involved in this effort, e.g., Princeton University, through our Fundamental Science program
  - **Voss Scientific**: Sandia is engaging with Voss Scientific to develop robust hybrid PIC models for MagLIF
  - **ASC Program**: Sandia will be engaging with ASC program to develop robust hybrid PIC models for MagLIF
- **Validation**:
  - **NRL**: Is working on theoretical validation problems (e.g., MHD Noh, Nernst)
  - Concurrently collect data that can be used to validate the new models

Sandia sent 4 participants to a workshop in Chengdu in April to learn more about the Chinese pulsed power program

Sandia National Laboratories

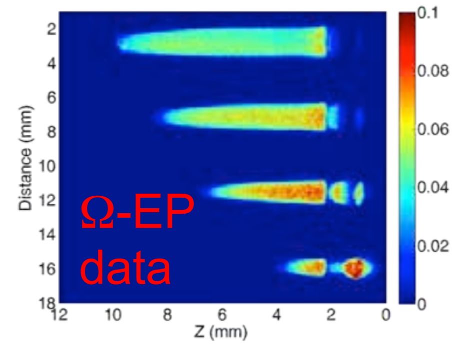
- **Their program appears to be as large or larger than effort in US**
  - CAEP: "About 200 in Institute for Fluid Physics, another 80 in a 2nd Institute"
- **Main emphasis is demonstrating that China can do what others have done**
  - Majority of 160 shots on 8-10 MA PTS facility are duplicative in nature
  - No clearly stated long-term goals for fusion or dynamic materials
  - Diagnostic set impressive
- **Dynamic Materials research a large emphasis**
  - About 1/3 of 160 shots devoted to this, starting very early
  - PTS has laser-triggered pulse shaping capability like Z
  - Supported by work on many smaller facilities (e.g., CQ-4)
- **Connections to Russia**
  - Showed research done on Russian facilities, mentioned a recent visit to Russia
- **Pulsed power technology research includes extensive LTD activity**
  - Discussed plans for 0.1 Hz LTD, working up from 40 kA to 1 MA
  - On "4th generation" of LTD gas switches
  - Conceptual models shown: (60 MA, 80 ns; 50 MA, 150 ns; 60 MA, 200 ns)

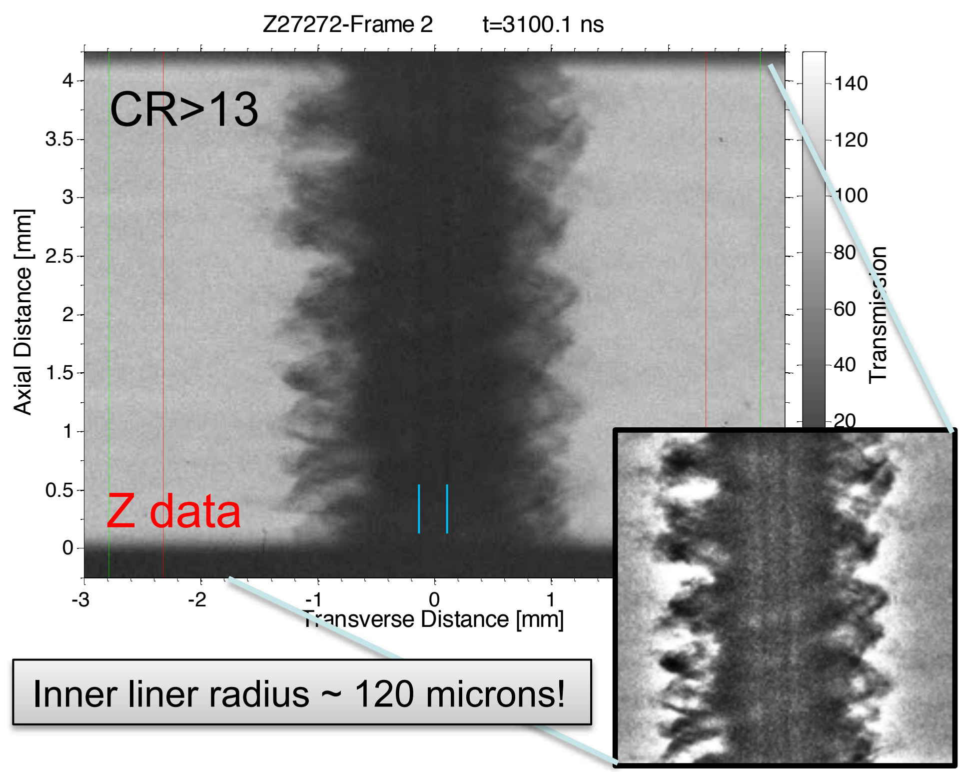
The 2015 Klotz letter from the Lab directors reaffirms the three approaches and the goals of ignition and high yield

- "The USA must continue to strive to be the first nation to demonstrate ignition and high yield in the laboratory."
- "NNSA currently has three credible approaches to demonstrating laboratory ignition and high fusion yield…"
- "We…will be meeting regularly in 2015 to ensure progress toward this integrated and coordinate National HED effort…"
- "In the absence of new nuclear tests and the attrition of test experience, looking forward the nuclear weapons laboratories will need the ability to:"
  - Test nuclear designers in HED experimental design
  - Access material pressure and density regimes that are presently inaccessible to other experimental techniques
  - <u>Generate and utilize thermonuclear burning plasmas</u>
  - Develop commensurate high-fidelity diagnostics and experimental platforms that help to assure our weapons are safe, secure, and effective
  - <u>Created and apply multi-megajoule fusion yields to enable enduring stockpile stewardship</u>

We are excited by advances in our ICF program and are restructuring the effort to take advantage

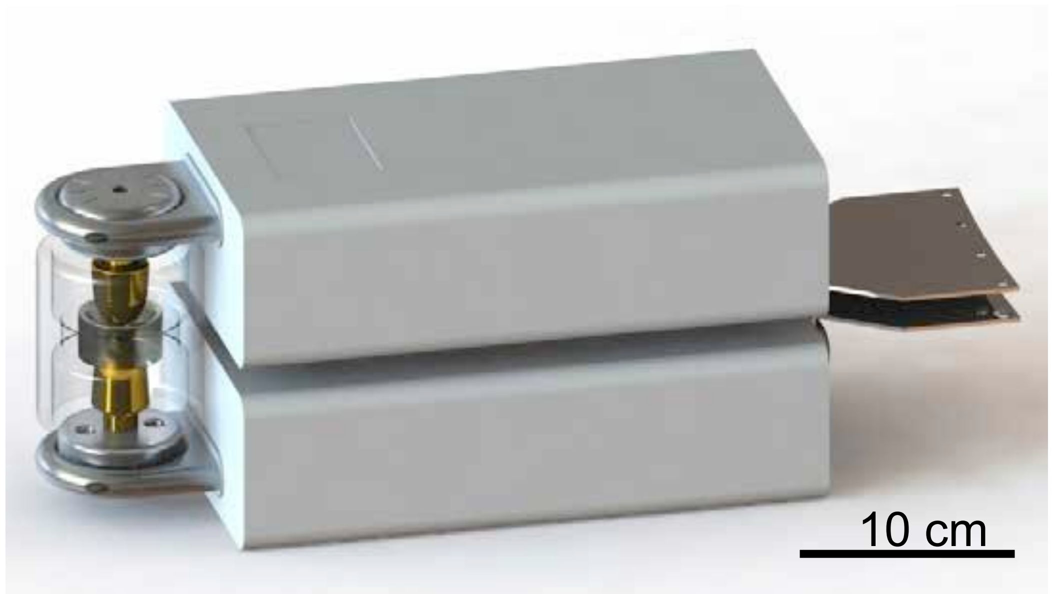
- Reproduced initial MagLIF results, clarified that laser heating is indeed an issue using laser-only experiments
- Magnetic drive approach has grown into a truly national program
  - Executing work on every major ICF facility (Z, ZBL, OMEGA, OMEGA-EP, & now NIF in FY16)
  - Strong collaboration with LLE including joint ARPA-E proposal, phase plate loans, “mini-MagLIF”
  - Strengthening our collaboration with LLNL on Z, NIF, codes
- Advances in fuel compression on Z
  - Instability mitigation demonstrated
  - Imaged magnetized liner at CR>13
  - Compressed D2 to ~60 g/cm^3, ρR~0.5 g/cm^2 using pulse shaping
  - First deceleration studies





Sandia has developed the first 100-ns LTD brick that generates 5 GW, and cavity tests are underway

- The brick exceeds all requirements for an 800-TW driver architecture.
- To date, the brick has survived 20,000 shots without a single switch prefire, switch no-fire, switch failure, or capacitor failure.
- A full-scale facility would have $>10^5$ of these bricks in it!

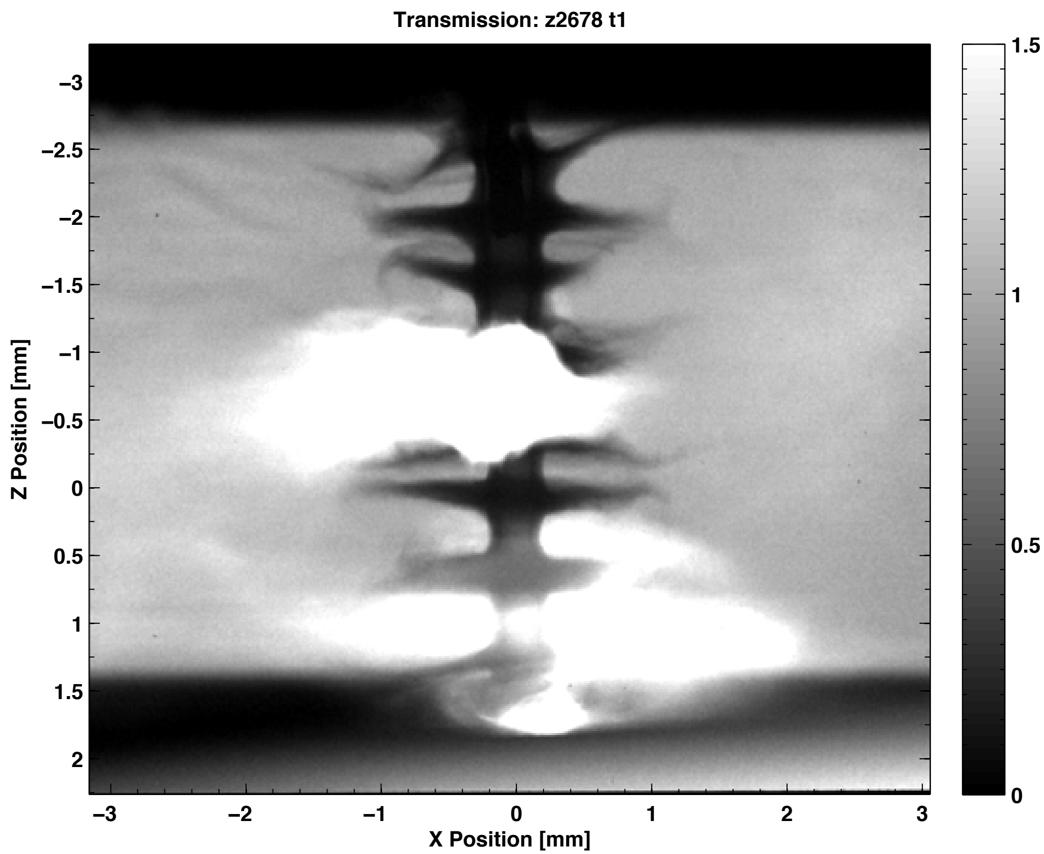


Woodworth et al., PRSTAB 12, 060401 (2009).
Woodworth et al., PRSTAB 13, 080401 (2010).
Gruner et al., IEEE PPC (2013).
* Stygar et al., PRSTAB 10, 030401 (2007).

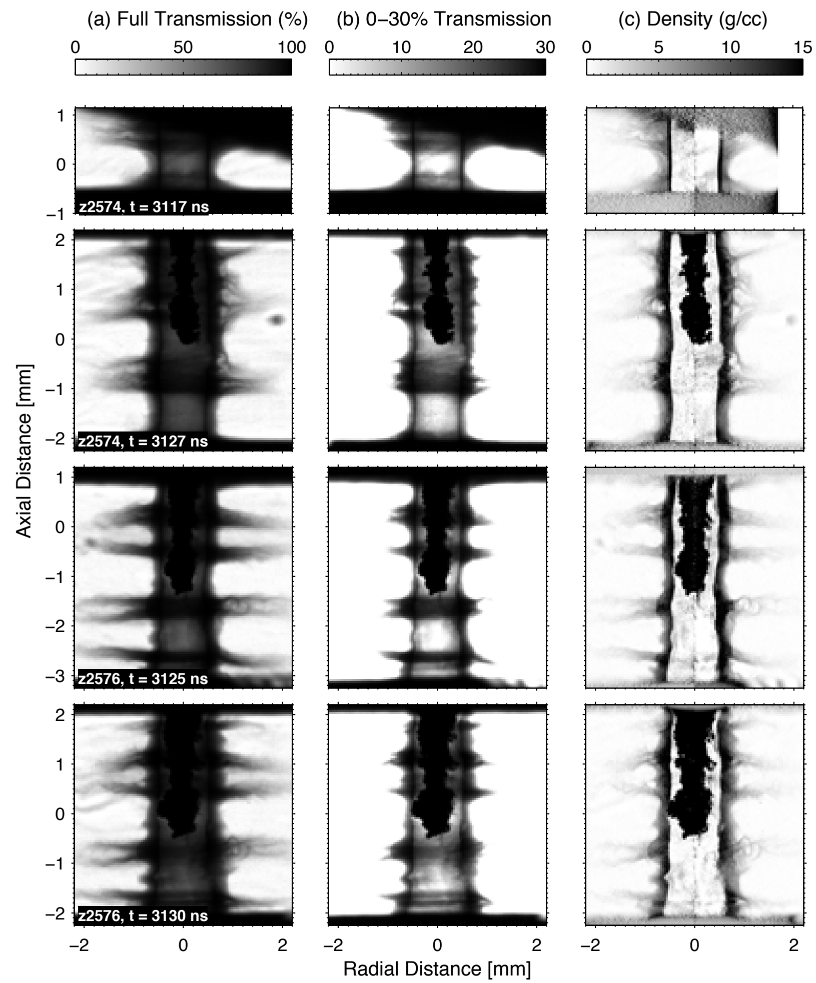
parameter	brick requirement*	achieved
peak electrical power	≥ 5 GW	5.6 GW
output power variation	≤ 26% (1σ)	3% (1σ)
timing jitter	≤ 2 ns (1σ)	1.6 ns (1σ)
switch prefire rate	≤ 0.1%	< 0.005%
lifetime	≥ 5000 shots	> 20,000 shots

We are studying our predictive capability to symmetrically compress fuel in high convergence implosions

Sandia National Laboratories



Cylindrical DD EOS Experiment



$$\langle\rho\rangle = 60 \text{ g/cm}^3 \qquad CR \approx 19$$

$$r_{stag} = 110 - 170 \ \mu\text{m} \qquad \langle\rho R\rangle = 0.5 \text{ g/cm}^2$$

Data are consistent with pre-shot simulations; current pulse shaping important

We are still improving power-flow in experiments on Z each year—we have developed a large convolute (31-cm) that performs better than the present baseline design (15-cm)

- **The 31-cm convolute has been used for 19 experiments on Z and enables large diameter loads (gas puffs, containment)**
- **It has outperformed the baseline design in A/B comparisons**
- **LDRD is investigating in-situ MITL cleaning techniques to reduce surface contamination**

Comparison of currents and losses for z2369 and z2515