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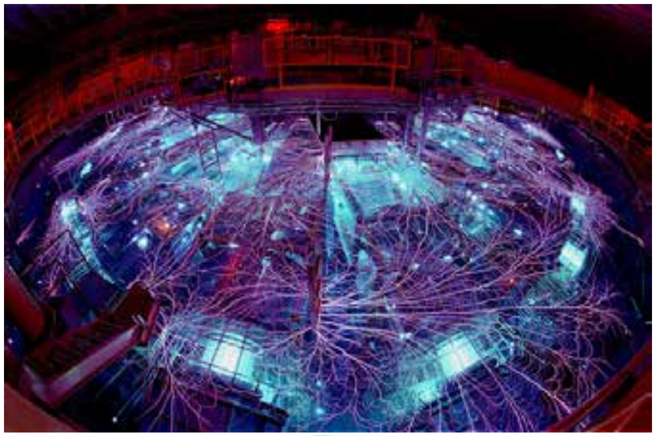

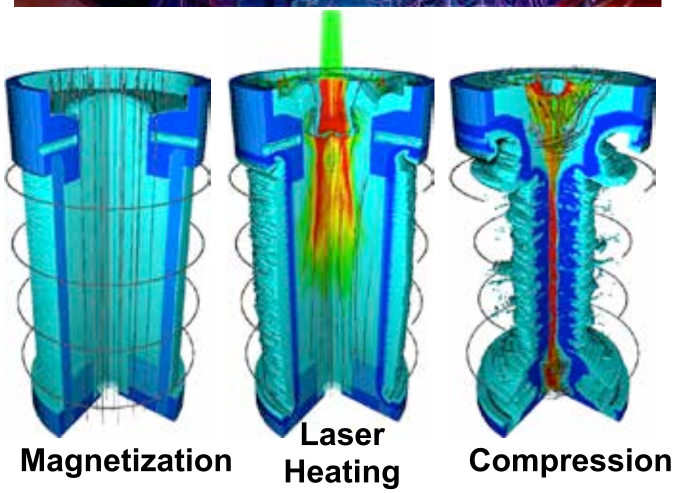

Magnetized Liner Inertial Fusion (MagLIF) research at Sandia National Laboratories

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Sandia National Laboratories

1st Chinese Pulsed Power Society Workshop,
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Chengdu, China

U.S. DEPARTMENT OF ENERGY   NNSA National Nuclear Security Administration

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We have a great team of scientists and engineers contributing to the work being shown today

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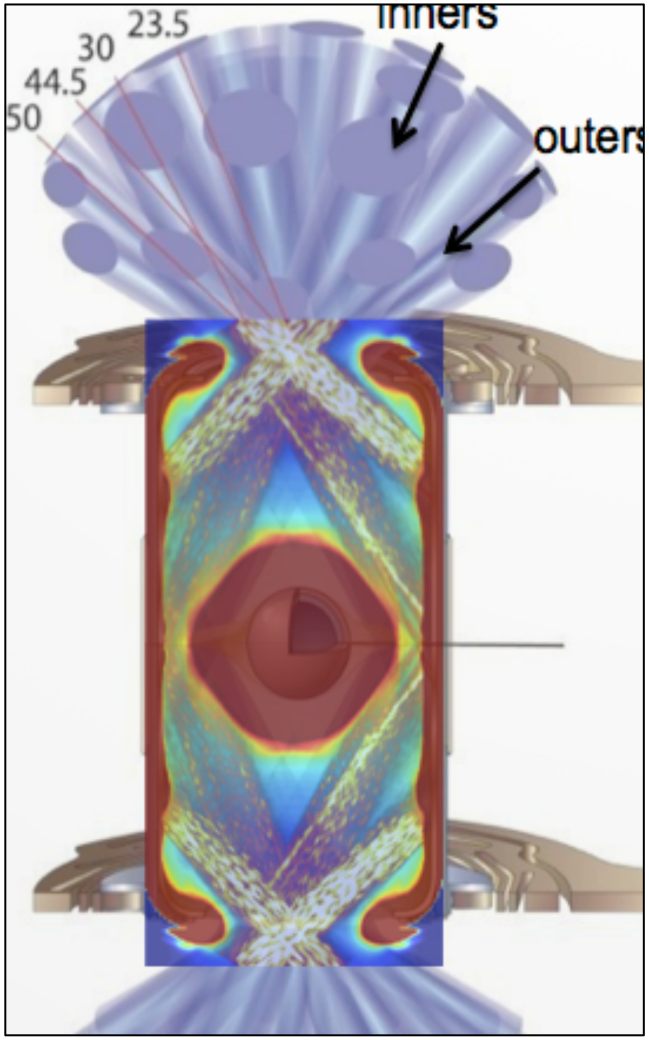
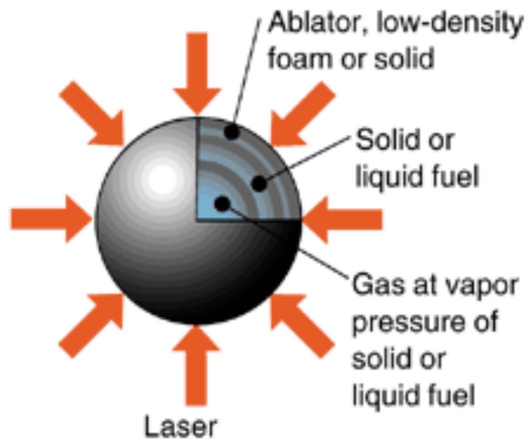
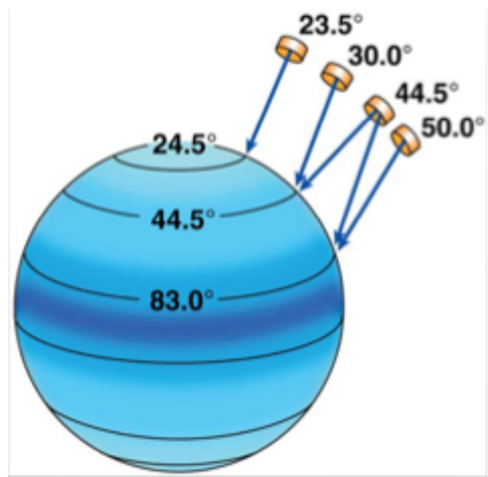
The United States ICF program is pursuing three main approaches to ignition

Radiation-driven implosions

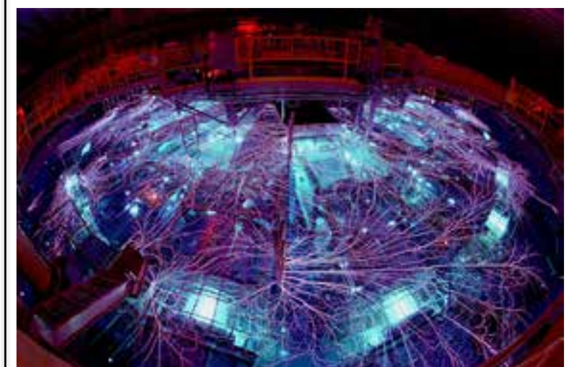


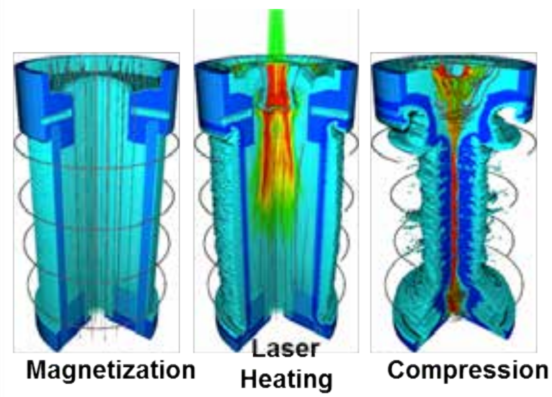
Laser-driven implosions





Magnetically-driven implosions





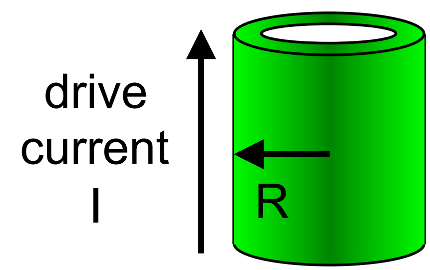
Focus of today's talk

Magnetically driven implosions may be a compelling path to high pressure and significant fusion yields (>100 MJ) per shot

- Magnetic fields created by pulsed power can create the large drive pressures (high energy density) needed for fusion
- Approach is fundamentally different than laser-driven target compression with unique physics, risks, and benefits
- Magnetic fields can also make laboratory fusion easier, e.g., strong fields can affect charged particles (electrons, alphas) and thus plasma heat transport and confinement properties

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

- Magnetically-driven targets driven by pulsed power drivers are energy efficient and could be a practical and cost-effective path to achieving significant fusion yields (>100 MJ). Z today couples ~0.5 MJ out of 20 MJ stored to MagLIF target (0.1 MJ in DD fuel).

Much work is needed to make the target physics credible!

The "Z" pulsed power facility at Sandia is being used for ICF research and has a large diagnostic suite to support our research program

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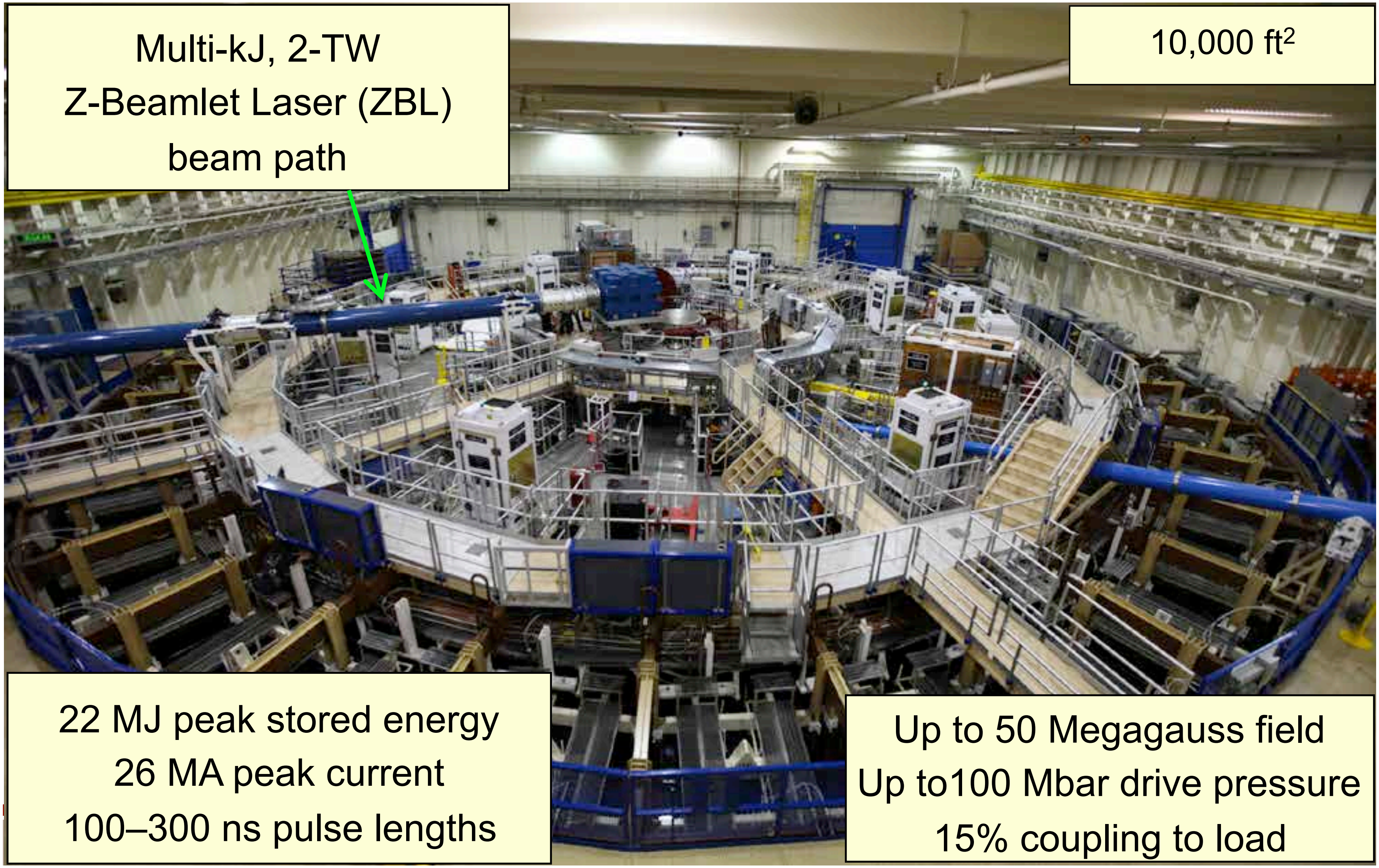
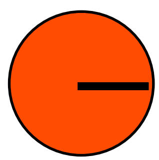


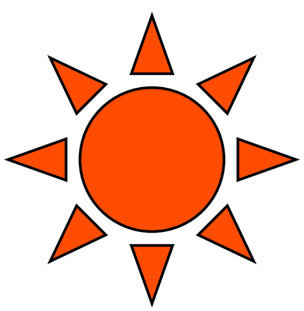
Under extreme conditions a mass of DT can undergo significant thermonuclear fusion before falling apart



ρ, R, T

- Consider a mass of DT with radius R, density ρ, and temperature T
- How does the disassembly time compare with the time for thermonuclear burn?

$$\tau_{disassembly} \sim \frac{R}{c_s} \sim \frac{R}{\sqrt{T}} \qquad \tau_{burn} \sim \frac{1}{n_i\langle \sigma v\rangle} \sim \frac{1}{\rho\langle \sigma v\rangle}$$



- **The fractional burn up of the DT (for small burn up) is:**

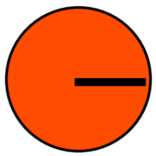
$$f_{burn} \approx \frac{\tau_{disassembly}}{\tau_{burn}} \sim \rho R \frac{\langle \sigma v\rangle}{\sqrt{T}}$$

- **At sufficiently high ρR and T the fractional burn up becomes significant and the energy deposited by alpha particles greatly exceeds the initial energy in the fusion fuel ("ignition")**

- **Typical conditions are:** $\rho R \approx 0.4\,\mathrm{g/cm^2}$

  $T \approx 5\,\mathrm{keV}$ (>50,000,000 K)

For hot spot ignition fusion fuel must be brought to a pressure of a few hundred billion atmospheres



ρ, R, T

For ignition conditions:

$$\left\{ \begin{array}{l} \rho R \approx 0.4\,\mathrm{g/cm^2} \\ T \approx 5\,\mathrm{keV} \end{array} \right\}$$

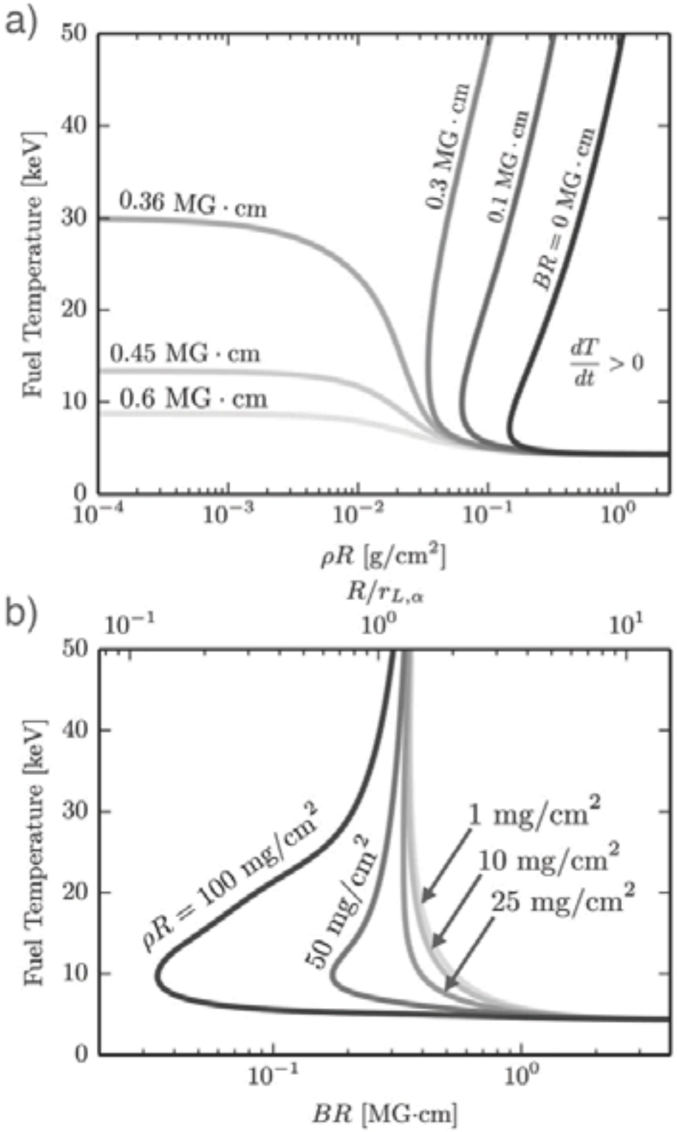
$$E_{HS} \propto m_{HS} T_{HS} \propto \rho_{HS} R_{HS}^3 T_{HS} \propto \frac{(\rho_{HS} R_{HS})^3 T_{HS}^3}{P_{HS}^2}$$

$E_{NIF} \sim 15\,\mathrm{kJ} \Rightarrow P \sim 400\,\mathrm{GBar}$ $\quad$ $R \sim 30\,\mu\mathrm{m} \Rightarrow$ and $\rho \sim 130\,g/cm^3$

This is consistent with detailed calculations

Note: The key challenge for ICF is to make the fuel both ***dense*** and ***hot***. This leads to extreme compression requirements—a NIF capsule has a radial convergence of 35-40x, for a volume compression of ~50,000! Likewise, the temperature in a NIF hot spot scales roughly with (implosion velocity)^8

Magneto-inertial fusion seeks to compress heated fuel, using low fuel density and magnetization to minimize radiation and electron thermal conduction losses, respectively



The ρr needed for ignition can be significantly reduced by the presence of a strong magnetic field largely through inhibiting electron conduction

Lower ρr reduces the required final fuel density (e.g., ~1 g/cc << 100g/cc), reducing radiation loss

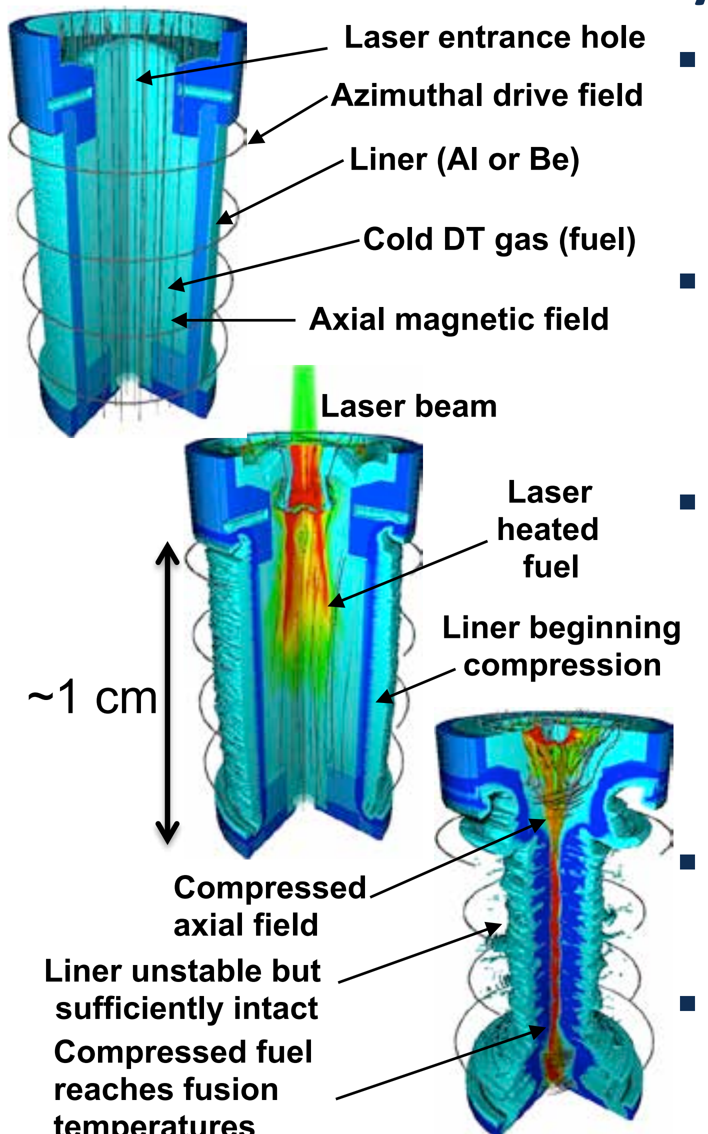
This means the stagnation plasma pressure at ignition temperatures is significantly reduced (e.g., ~5 Gbar << ~500 Gbar for hot spot ignition)

Large values of BR are needed and therefore large values of B are needed, B ~ 10,000 Tesla (Earth's B-field is ~0.00003 Tesla)

This field significantly exceeds pulsed coil technology (B_0 ~10-30 T), therefore flux compression is needed

* Basko *et al.,* Nucl. Fusion (2000); S.A. Slutz *et al.*, Phys Plasmas (2010); P.F. Knapp *et al.*, Phys. Plasmas (2015).

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

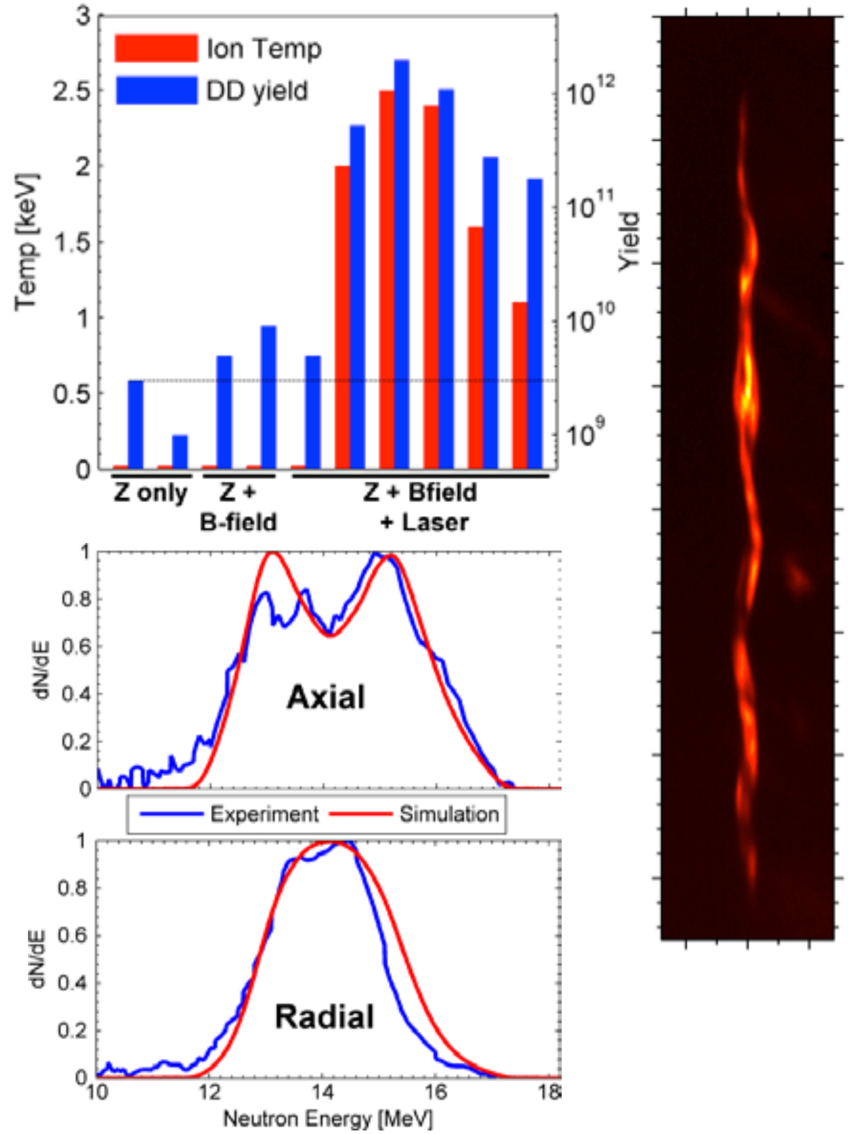


- **<u>Axial magnetization</u> of fuel/liner (B_{z0} = 10-30 T)**
  - **Inhibits thermal conduction losses, may help stabilize liner compression (Nominal β: 5~80)**
- **<u>Laser heating</u> of fuel (2-10 kJ)**
  - **Reduces amount of radial fuel compression needed to reach fusion temperatures (R_0/R_f = 23-35)**
- **<u>Liner compression</u> 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**

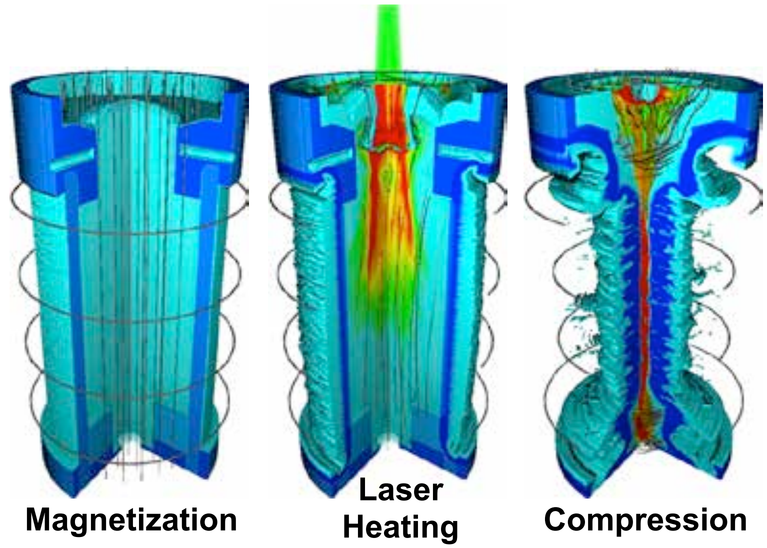
*S.A. Slutz *et al.*, Phys Plasmas (2010); S.A. Slutz and R.A. Vesey, Phys Rev Lett (2012); A.B. Sefkow *et al.*, Phys Plasmas (2014).

Today we will discuss exciting new fusion results obtained on Sandia's "Z" pulsed power facility

- Magnetized (10 T) and laser-heated (2 kJ) cylindrical targets reached ~3 keV (30,000,000 K) temperatures and produced fusion yield (up to $2x10^{12}$ DD) at 70 km/s implosion velocity
  M.R. Gomez *et al.*, Phys Rev Lett (2014);
- Secondary neutron yield (>10^{10} 14 MeV) and spectra demonstrate that the fusing plasma was highly magnetized
  P.F. Schmit *et al.*, Phys Rev Lett (2014);
- Detailed analysis of stagnation conditions consistent with thermonuclear yield, though less energy in fusing plasma than predicted
- Additional experiments on multiple facilities focused on specific physics issues (laser-gas coupling, liner dynamics, flux compression)
- We are working toward the conditions needed to demonstrate ~$3x10^{14}$ DD yields on our current facility (~100 kJ DT equiv.)



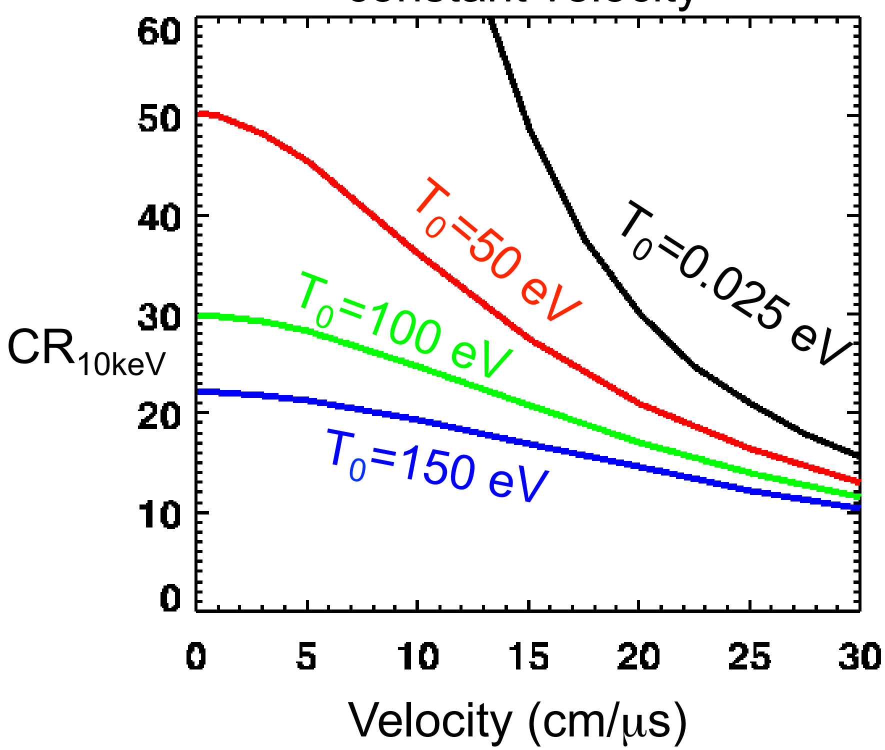
MagLIF combines three complementary design elements into a single target design—we will now go through them in a little more detail



- Key target design elements
  - Magnetization
  - Laser heating
  - Liner compression

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

Simulation with constant velocity



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

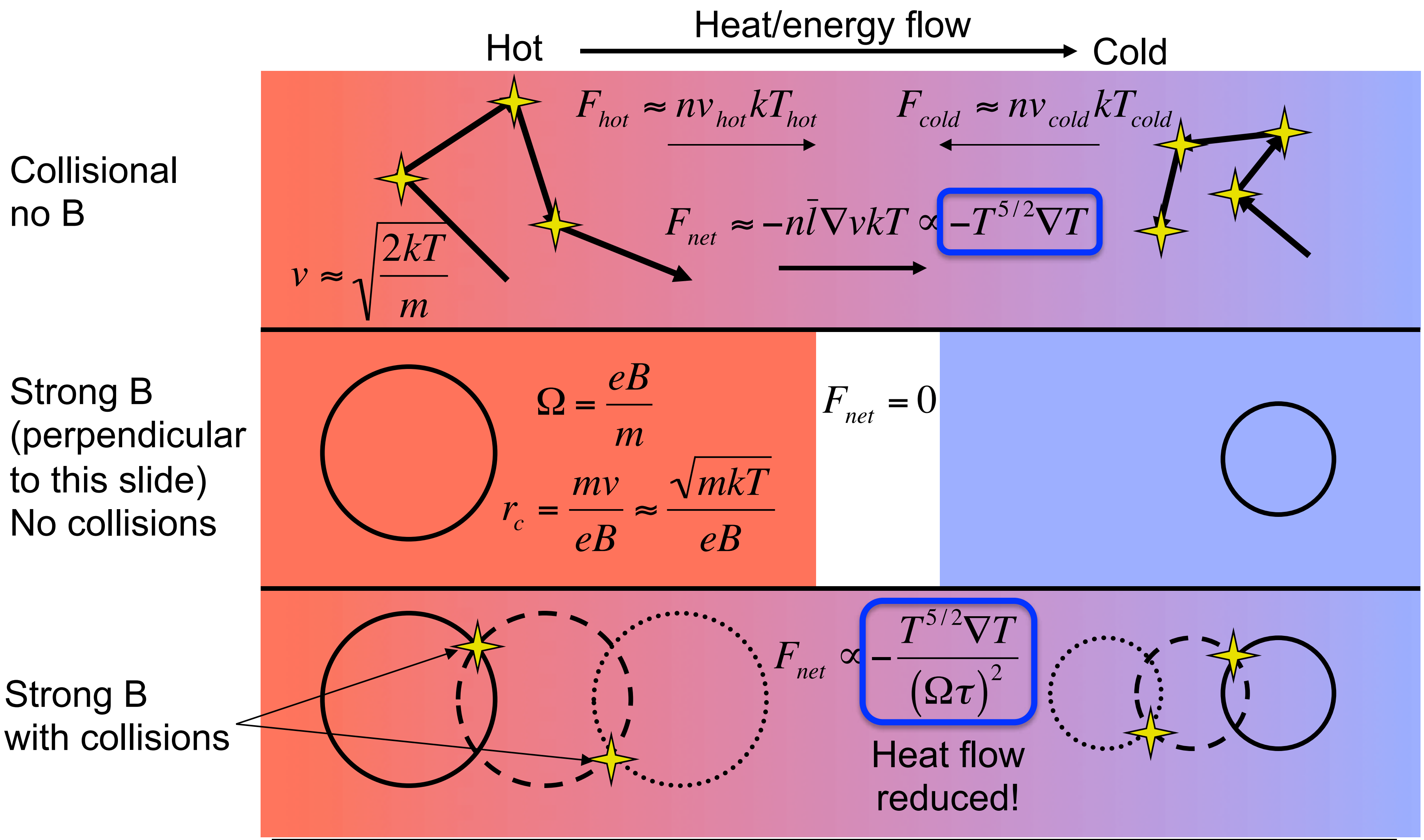
Heating fuel to ignition temperatures is typically done with a high-velocity shock (or series of shocks)

High velocities make it easier to reach fusion temperatures and also reduce the time available for losses (e.g., electron heat conduction or radiation)

Heating the fuel prior to the implosion *in the absence of losses* can allow low-velocity, low-convergence implosions to reach ignition temperatures

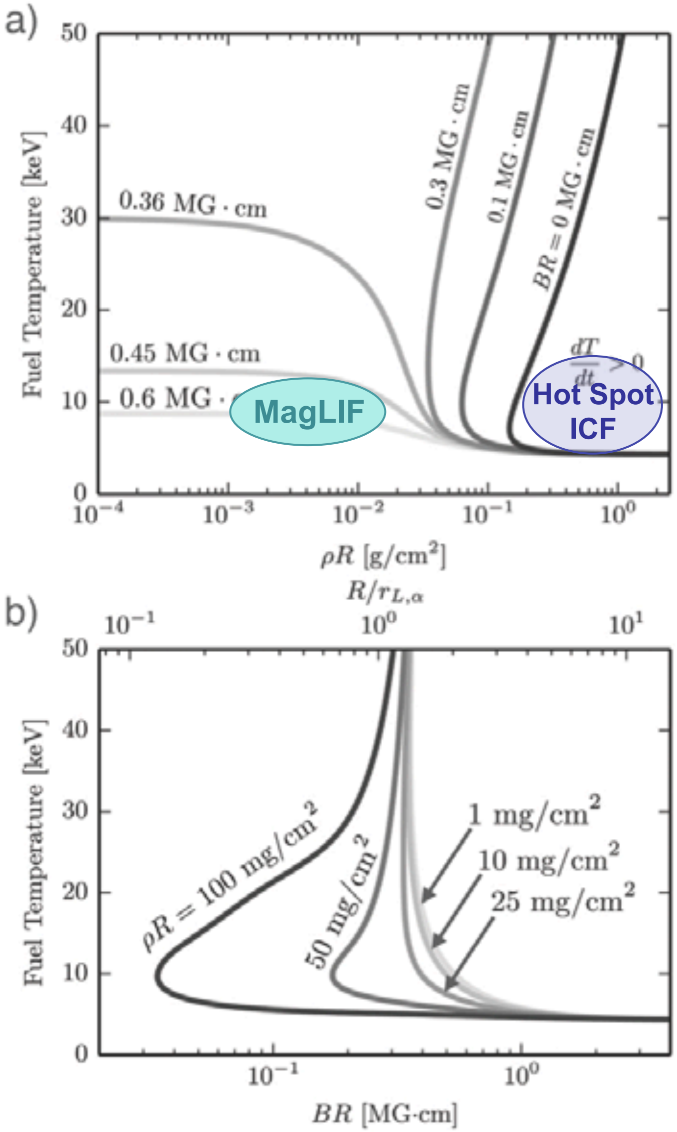
Is there a way to reduce losses?

The presence of a magnetic field can strongly affect transport properties, e.g. electron heat conduction

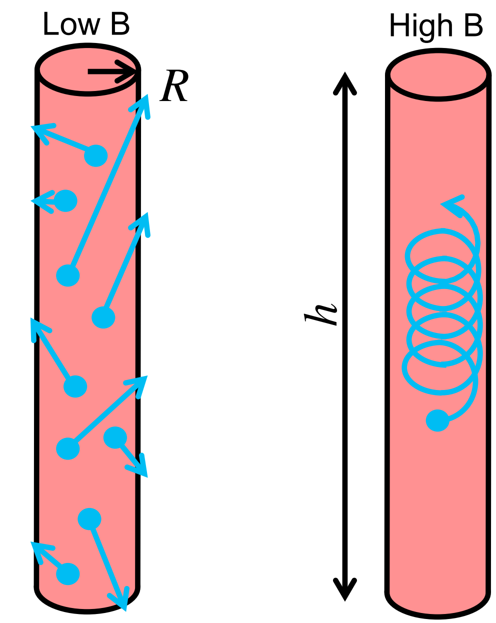


"Anomalous" heat transport can reduce the benefit of magnetic fields (e.g., in tokamaks) but there remains a significant benefit

Magnetization ("BR") can be used to reduce rho-R requirements and reduce electron heat losses

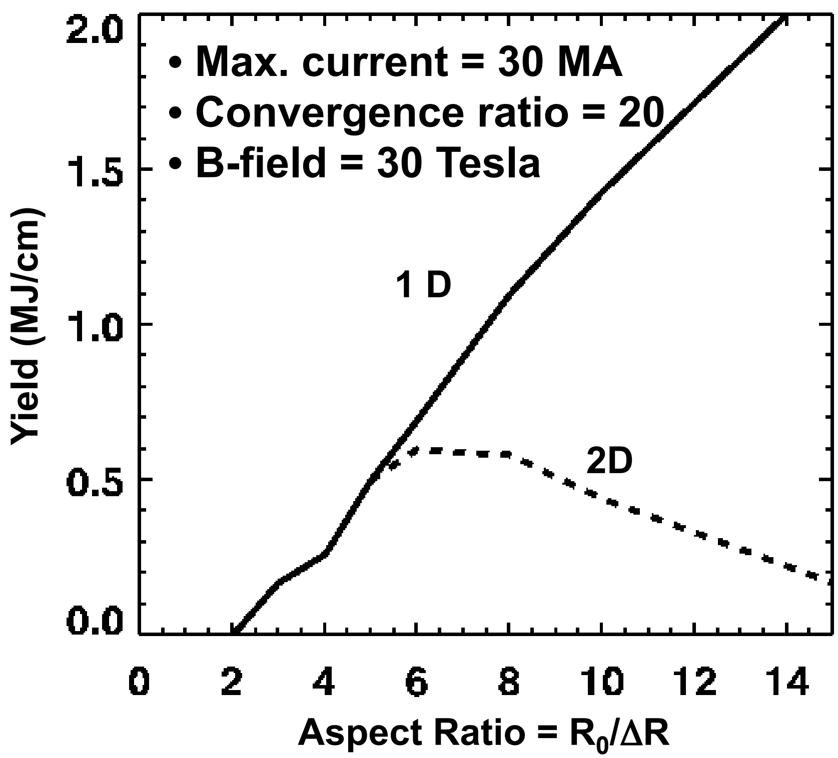


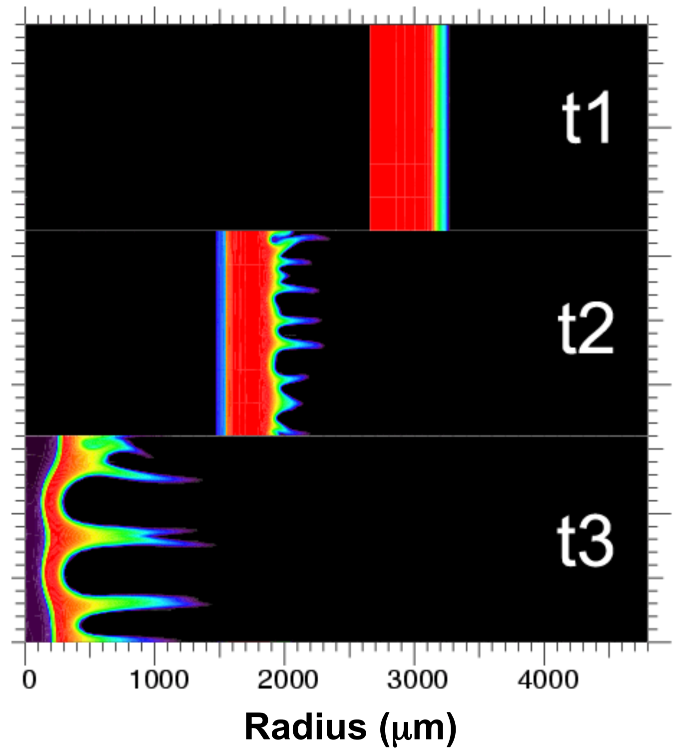
$$\frac{R}{r_\alpha} = \frac{BR\ [T \cdot \mathrm{cm}]}{26.5} = \frac{BR\ [G \cdot \mathrm{cm}]}{2.65e5} \approx 4BR\ [MG \cdot \mathrm{cm}]$$



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

Reducing the implosion velocity requirements through fuel heating and magnetization allows us to use thicker, more massive liners to compress the fuel that are more stable



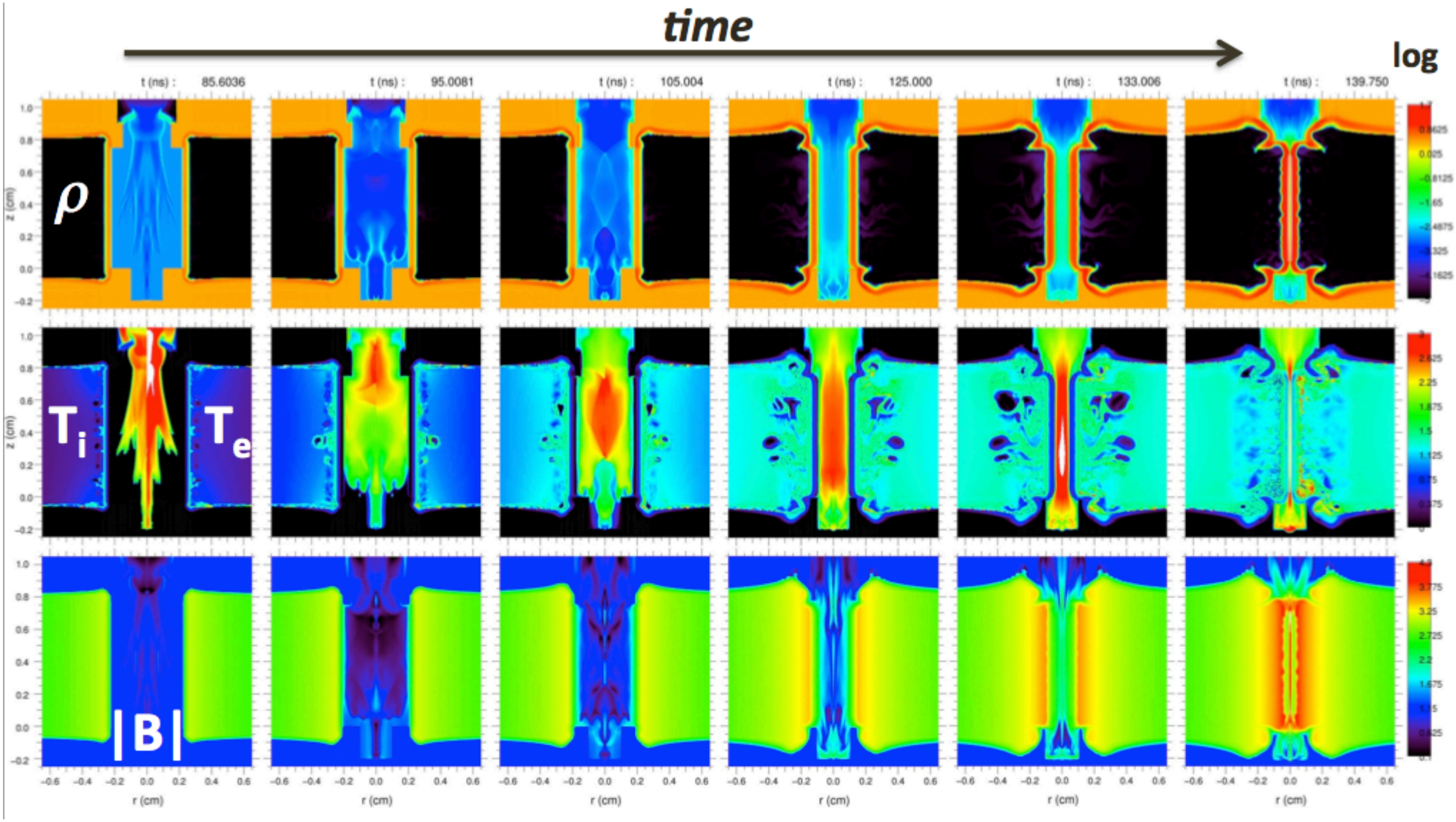


• The Magneto-Rayleigh-Taylor instability degrades the yield as the aspect ratio is increased (due to decreased liner ρR)

• Simulations of AR=6 Be liner show reasonably uniform fuel compression and sufficient liner ρR at stagnation to inertially confine the fuel—important because fuel density is low!

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

Example fully-integrated HYDRA calculations of near-term Z experiments (19 MA, 10 T, 2 kJ) illustrate the stages of a MagLIF implosion



A.B. Sefkow, S.A. Slutz *et al.*, Phys. Plasmas 21, 072711 (2014).

Fully-integrated HYDRA calculations of near-term Z experiments (19 MA, 10 T, 2 kJ)

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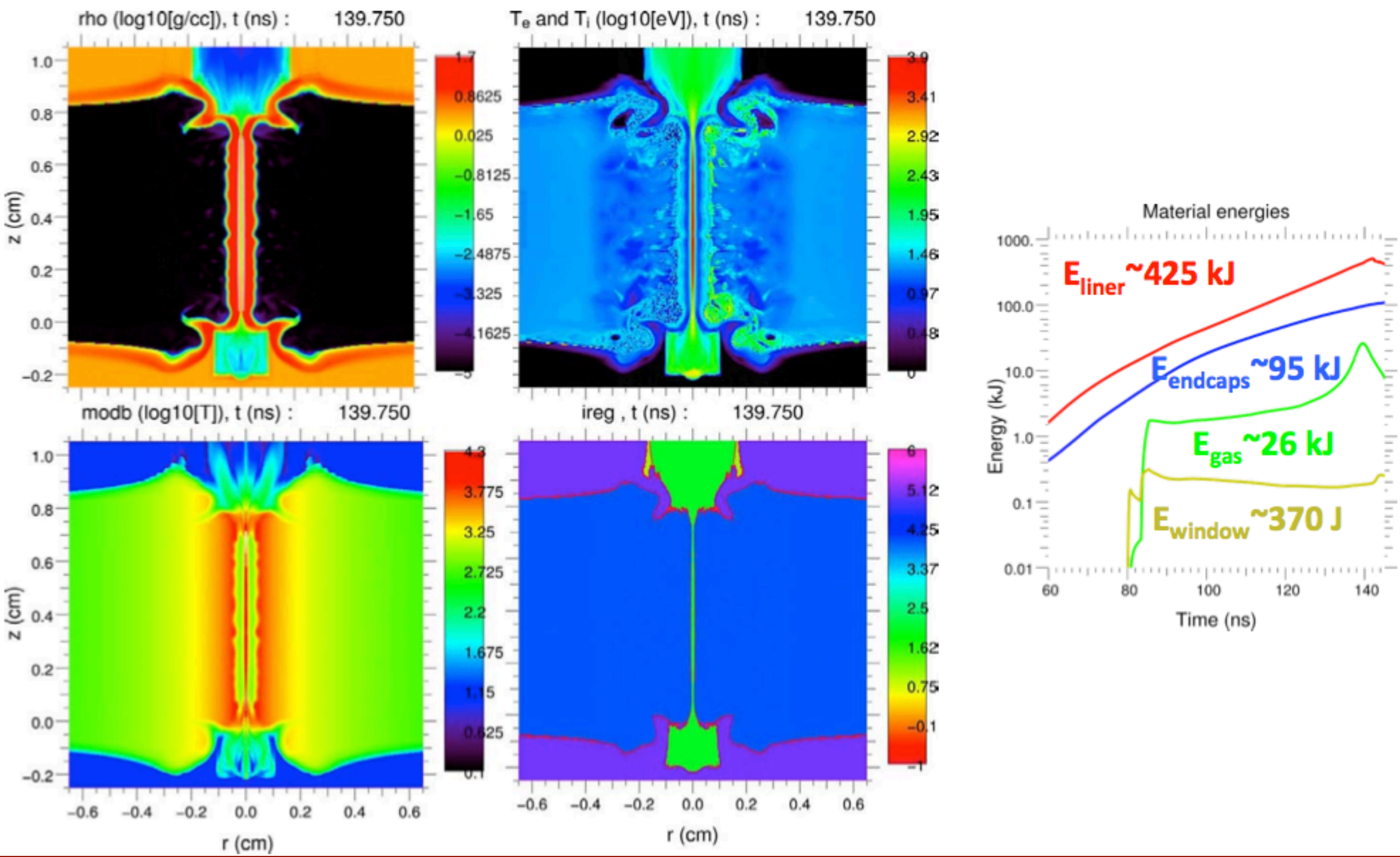

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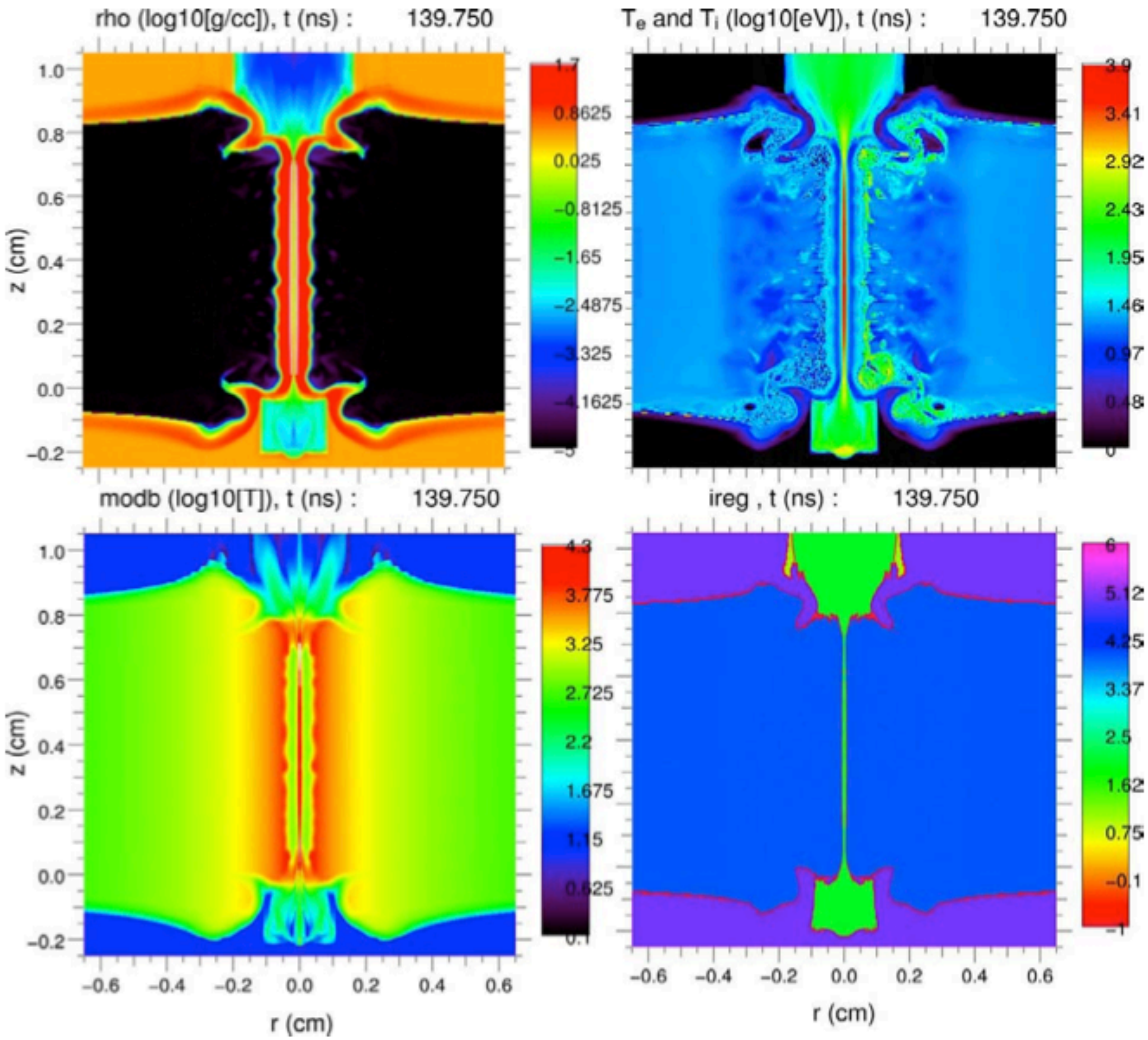
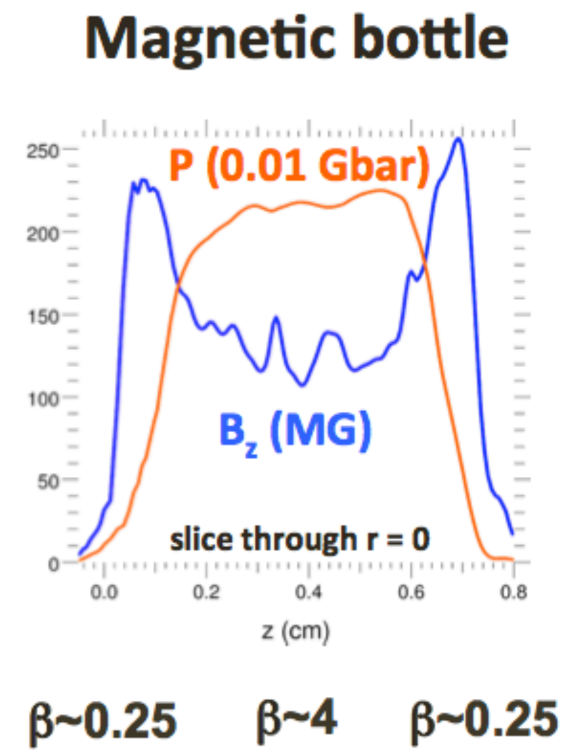
Fully-integrated HYDRA calculations of near-term Z experiments (19 MA, 10 T, 2 kJ)





A.B. Sefkow, S.A. Slutz *et al.*, Phys. Plasmas 21, 072711 (2014).

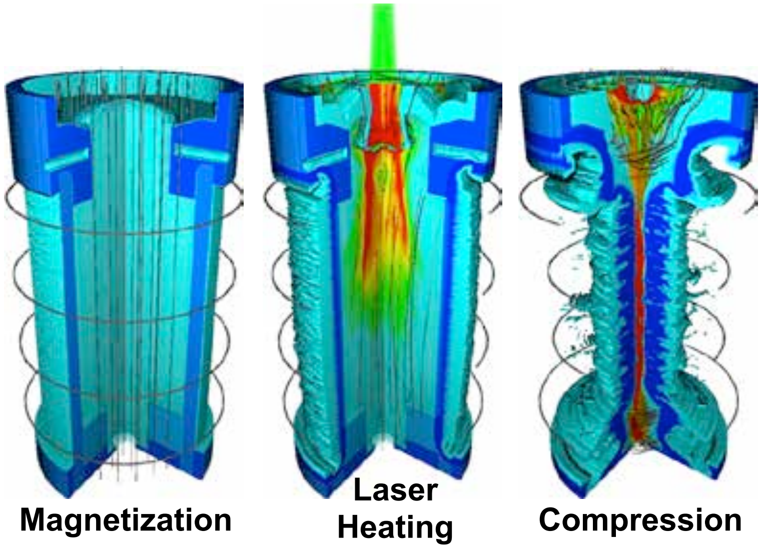
Comparison of 1D and 2D HYDRA calculations of near-term Z experiments (19 MA, 10 T, 2 kJ)

Parameter	1D ideal	2D integrated
• E_{gas}^{abs}	2.20 kJ	1.74 kJ
• m_{loss}	0%	43%
• Φ_{loss}	36%	38%
• CR_{2D}	28 (r_{stag} 84 μm)	37 (r_{stag} 63 μm)
• T_i^{peak}	5.0 keV	6.5 keV
• $<T_i>^{DD}$	2.9 keV	3.2 keV
• ρ_{gas}^{stag}	0.6 g cm^{-3}	0.5 g cm^{-3}
• ρR_{liner}^{stag}	1.0 g cm^{-2}	0.9 g cm^{-2}
• P^{stag}	2.5 Gbar	2.2 Gbar (peak in bottle)
• $B_z^f r_{stag}$	4.1e5 G cm (r_{stag}/r_α 1.5)	5.3e5 G cm (r_{stag}/r_α 2.0)
• Y_n^{DD}	2.6e14 (in 7.5mm)	6.1e13 (24% of 1D)
• Y_n^{DD}/Y_n^{DT}	23	44
• t_{burn}^{FWHM}	3.2 ns	2.1 ns

Note: A unique property of magnetic drive is increasing pressure with decreasing radius. If less energy is coupled to fuel, target converges farther in simulations until plasma pressure is sufficient to stop the implosion.

A.B. Sefkow, S.A. Slutz *et al.*, Phys. Plasmas 21, 072711 (2014).

Our path to studying the underlying science is a mixture of focused and integrated experiments to address key physics



- Key target design elements
  - Liner compression
  - Magnetization
  - Laser heating

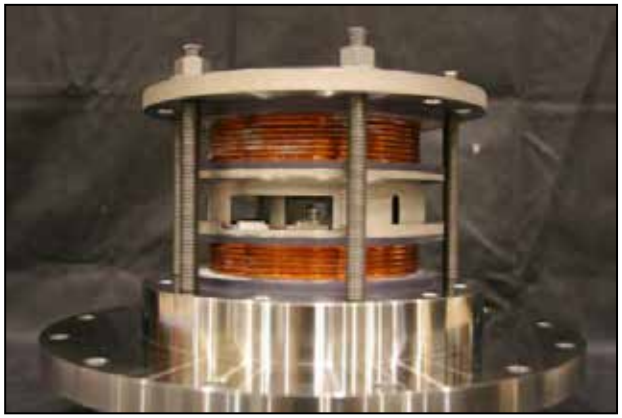
- Key physics uncertainties
  - Liner instabilities
    - Electro-thermal
    - Magneto-Rayleigh-Taylor
    - Deceleration RT
    - Impact of 3D fuel assembly
  - Liner/fuel interactions & mix
  - Laser-window and laser-fuel scattering, absorption, uniformity
  - Suppression of electron heat transport in dense plasma by magnetic fields
  - Magnetic flux compression

Experiments to address the key physics are planned for the Z pulsed power facility and the Z-Beamlet, Omega, and Omega-EP lasers.

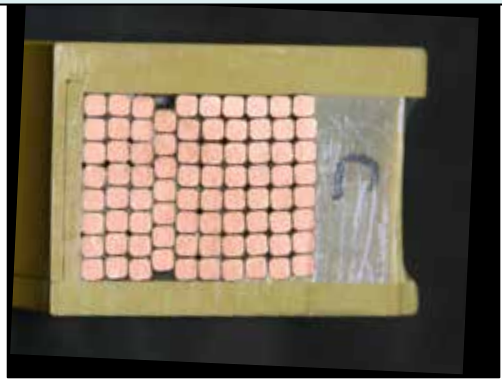
We have successfully implemented 10 T axial fields over a several cm^3 volume for MagLIF and the capacitor bank is capable of driving 30 T field coils under development

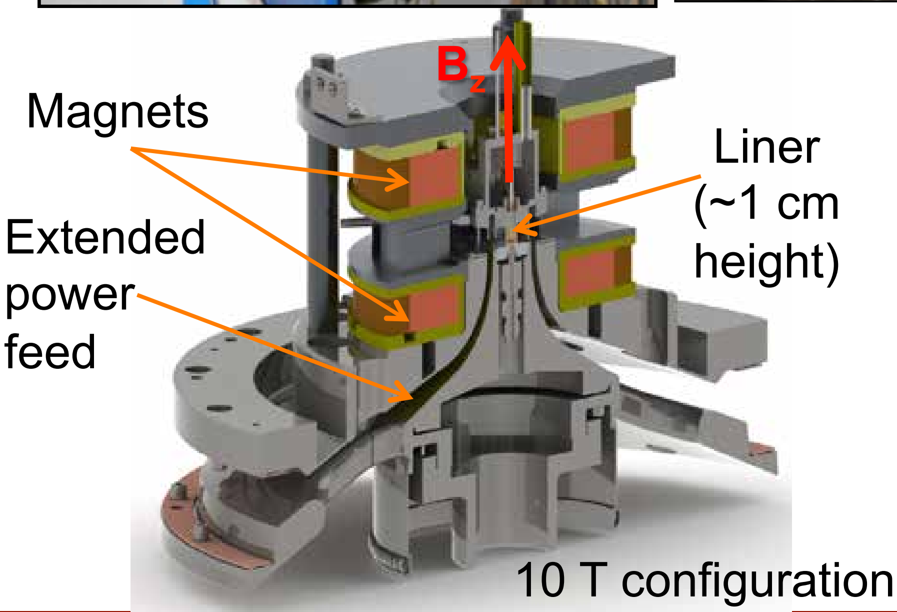
Capacitor bank system on Z
900 kJ, 8 mF, 15 kV (Feb. 2013)

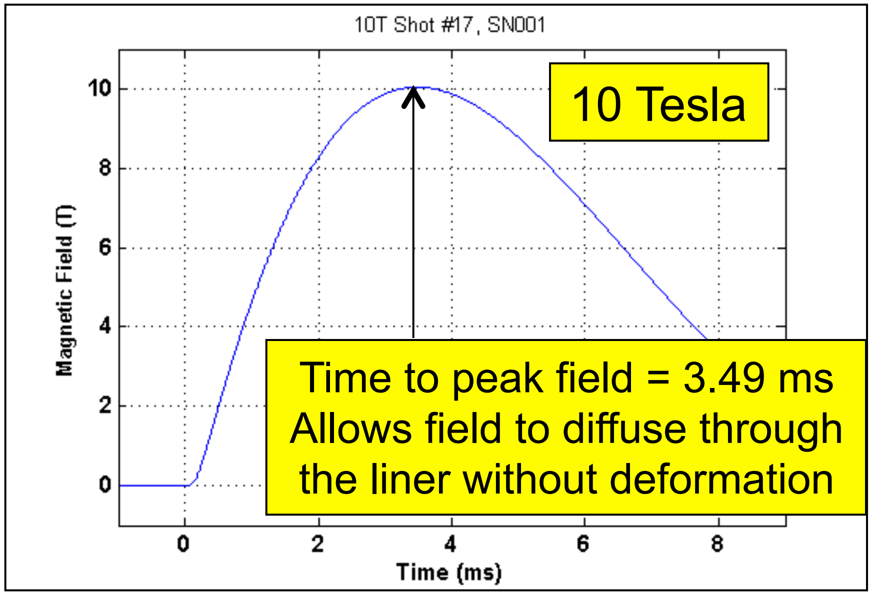
Example MagLIF coil assembly with copper windings visible



Cross section of coil showing Cu wire, Torlon housing, and Zylon/epoxy reinforcement

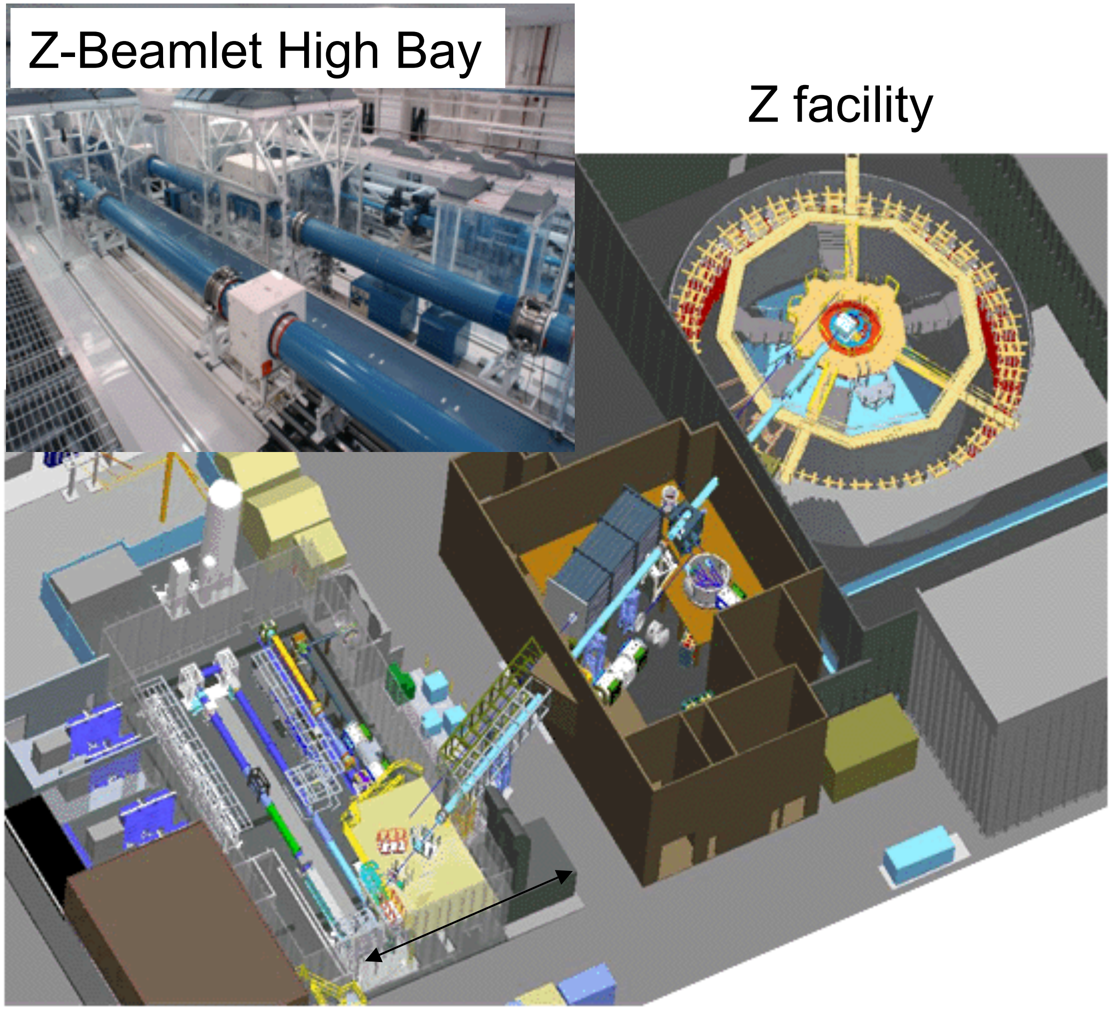






D.C. Rovang, D. Lamppa *et al.*, Rev. Sci. Instrum. (2014).

The Z-Beamlet laser at Sandia* can be used to radiograph liner targets and heat fusion fuel



Z-Beamlet and Z-Petawatt lasers

Z-Beamlet (ZBL) is routinely used to deliver ~ 2.4 kJ of 2ω light in 2 pulses for backlighting experiments on Z

Modifications adding bandwidth to the laser enable us to reach 4-4.5 kJ in 4 ns today

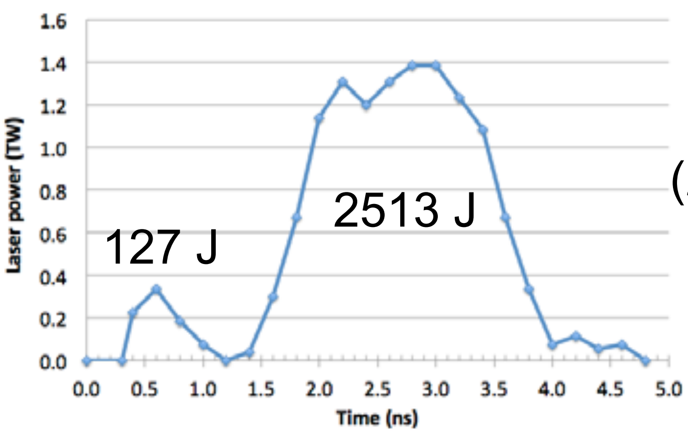
Filling out the booster amps would enable longer pulses (5-7 ns) which would extract up to 6 kJ of 1ω, for 4.2 kJ of 2ω.

Typical MagLIF initial fuel densities correspond to 0.10 to 0.30 x critical density for 2ω

* P. K. Rambo *et al.*, Applied Optics 44, 2421 (2005).

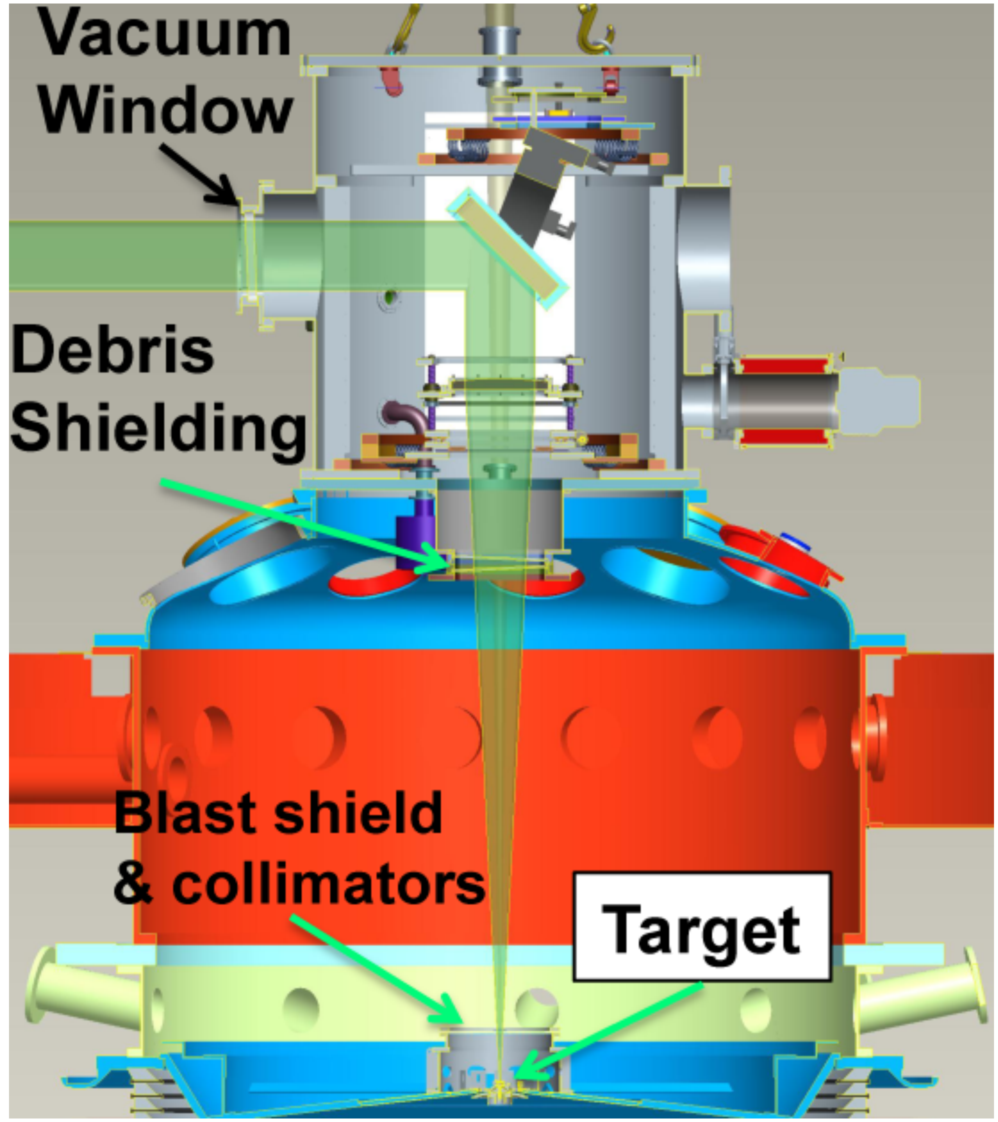
In August 2013 we commissioned a new vacuum final optics assembly to safely enable 2 kJ of on-axis laser heating of fuel

Example pulse measurement



ZBL
2ω light
(2.64 kJ)

Prepulse vaporizes gas-containing foil; main pulse couples to DD fuel



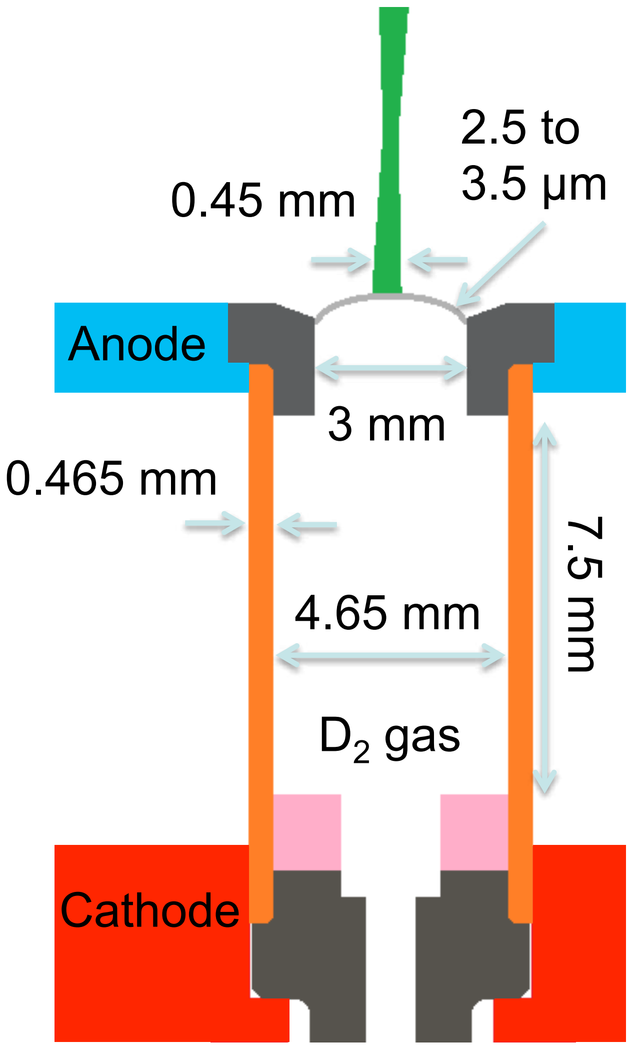
Z couples several MJ of energy to the load hardware, ~equivalent to a stick of dynamite, making diagnostic measurements and laser coupling challenging

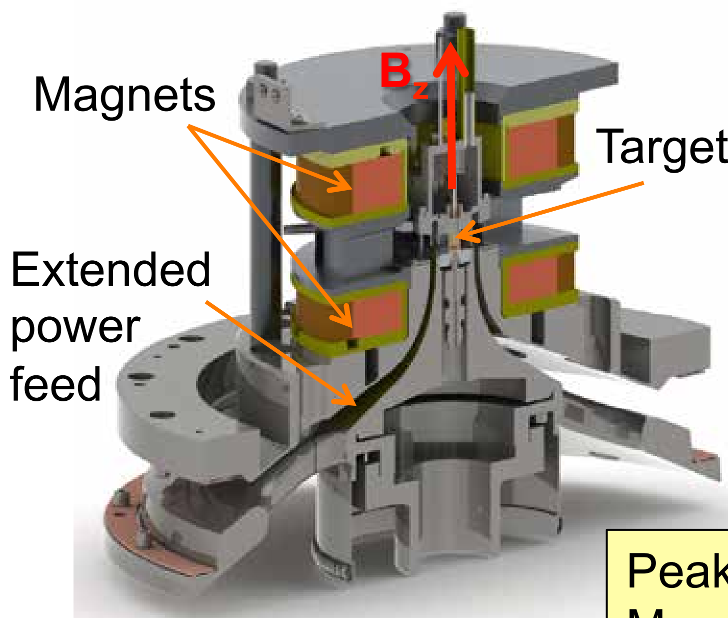
Pre-shot photo of MagLIF load hardware

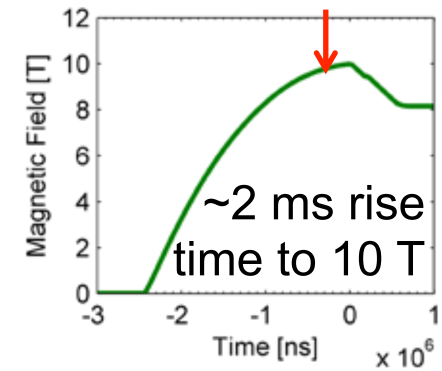
Damage to FOA debris shielding

Post-shot photo

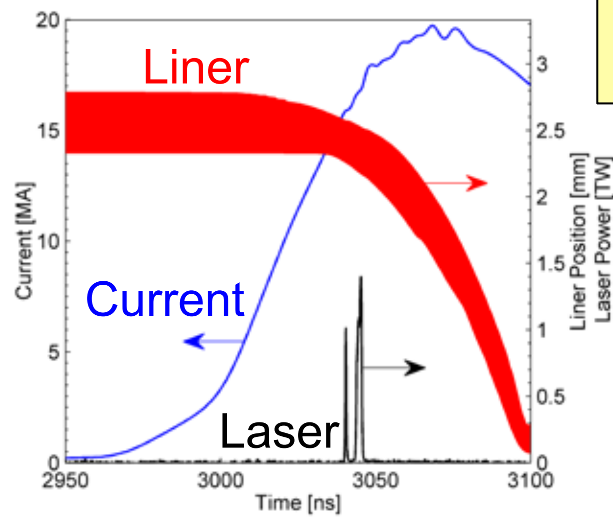
The initial experiments used 10 T, 2.5 kJ laser energy, and 19-20 MA current to drive a D_2 filled (0.7 mg/cc) Be liner

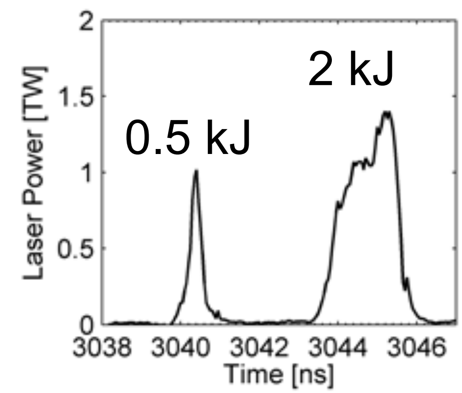






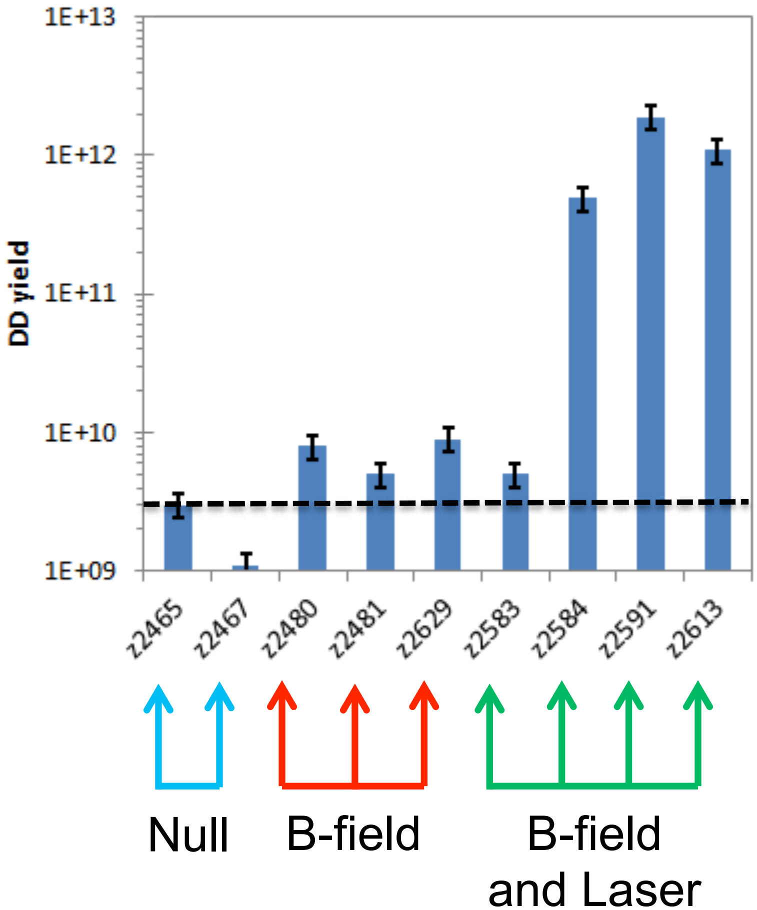
Peak current is 19 MA
Magnetic field is 10 T
Total laser energy is 2.5 kJ





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

Z shots producing DD yields in excess of 10^{12} were only observed in experiments with laser and B-field

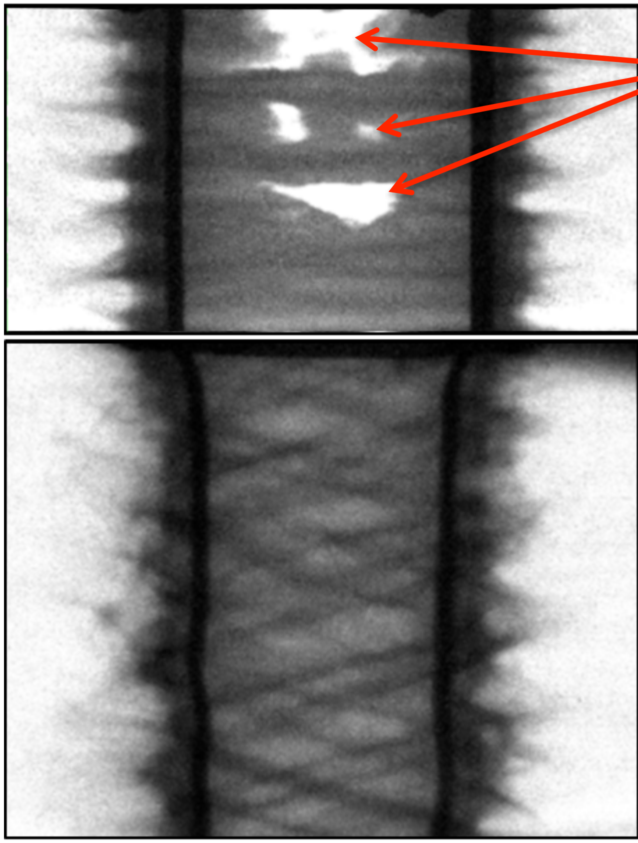


- **High yields were only observed on experiments incorporating both applied magnetic field and laser heating**
- **A series of experiments without laser and/or B-field produced yields at the background level of the measurement**
- **Result of z2583 is not well understood nor reproduced at this time**

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

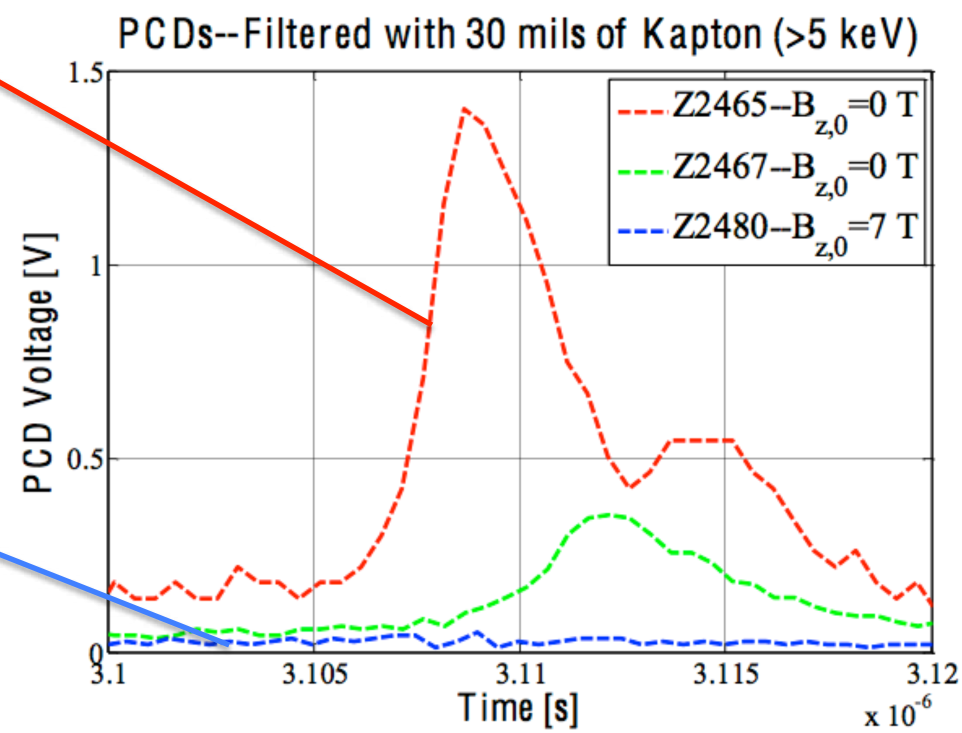
Adding an axial magnetic field reduces hard x rays and hot spots, and changes the liner instability structure from cylindrical to helical—evidence it is doing something!

Without Magnetic Field



With Magnetic Field

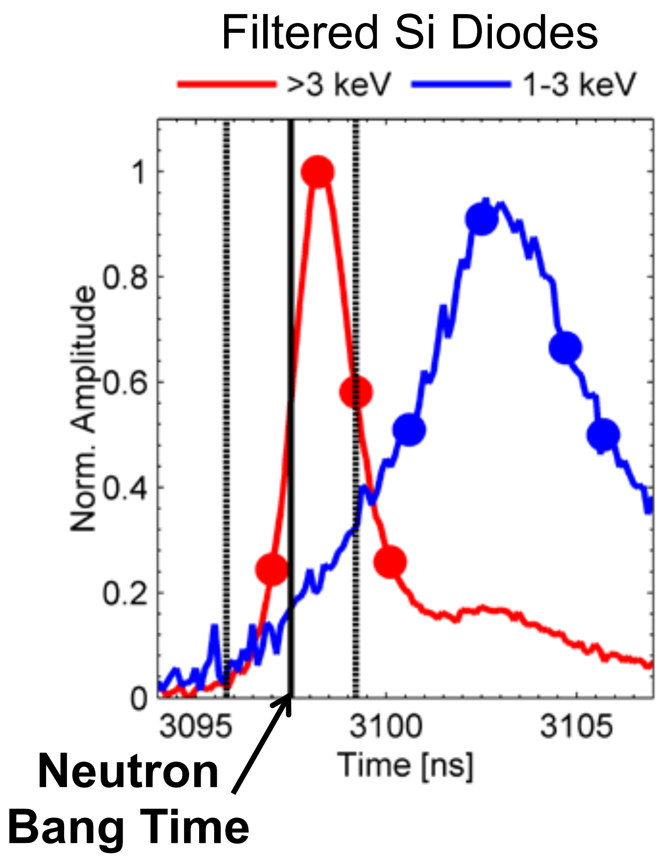
Time-integrated self-emission from liner implosion at 6151 eV; missing in shots with axial field

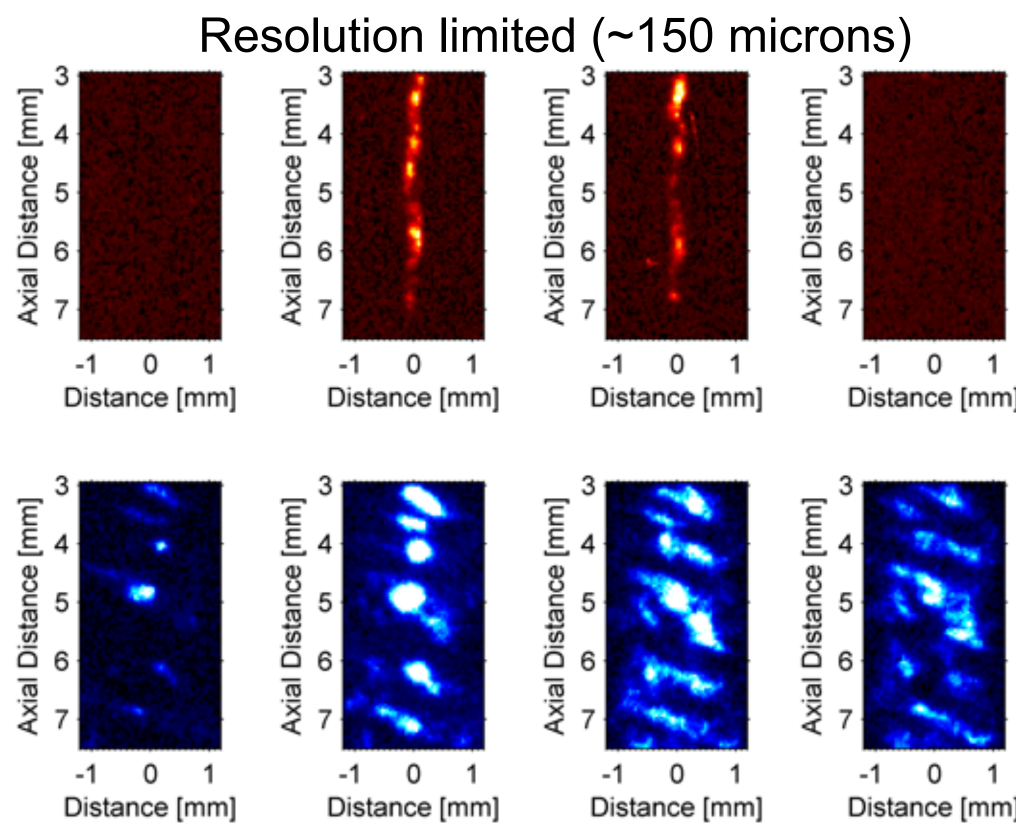


If magnetic flux roughly conserved the additional magnetic pressure from the axial field will suppress micro-pinching—this is indirect evidence for flux compression

T.J. Awe *et al.*, Phys. Rev. Lett. (2013); *ibid.*, Phys. Plasmas (2014).

High energy x-ray emission is only present in magnetized and laser-heated experiments, and its timing is consistent with neutron bang time estimates from nTOF

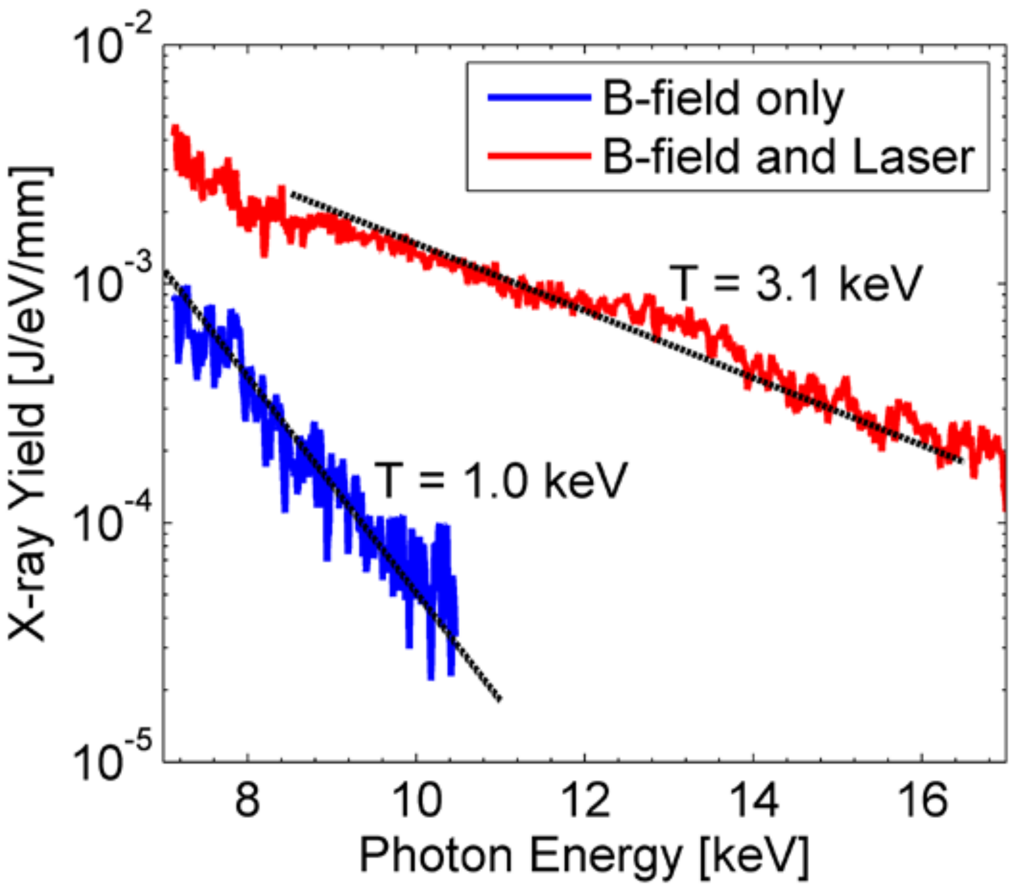




High energy emission from fuel is only observed in experiments with laser and B-field

Emission from exterior of liner is observed with and without laser and B-field

High energy x-ray spectra indicate electron temperatures = 2.5-3.1 keV in experiments with laser and B-field

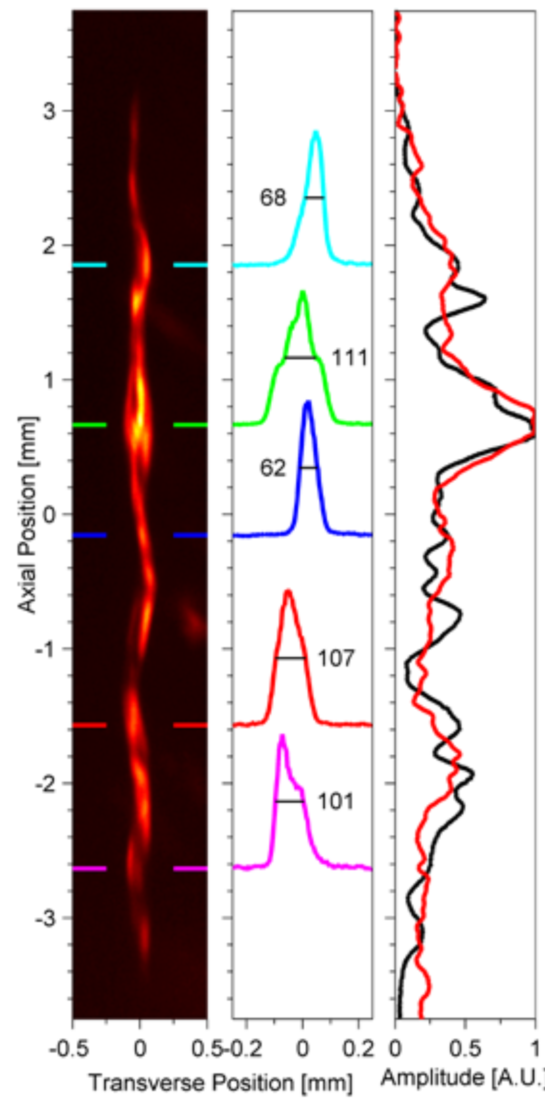


- **Electron temperatures inferred from continuum emission**
- **> 2.5 keV observed on shots with yield**
- **Approximately 1 keV observed on shots without yield**
- **Lower bound on measurement with this method is around 1 keV**

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

High-resolution monochromatic imaging of the x-ray emission shows a narrow, hot plasma column with weakly helical structure

- **Lineouts of stagnation column vary from 60 to 120 μm FWHM (resolution about 60 μm)**
- **Emission is observed from about 6 mm of the 7.5 mm axial extent**
- **Note that the emission doesn't necessarily define the fuel-liner boundary, but only the hot fuel region**
- **The stagnation column is weakly helical with a wavelength of about 1.3 mm and a 0.05 mm horizontal offset**
- **Axial lineouts of image (black) agree with 9.3 keV 1D spectrometer lineouts (red), suggesting features are due to emission and not liner opacity (Be opacity >9 keV small).**



M.R. Gomez *et al.*, Phys. Rev. Lett. 113, 155003 (2014); E.C. Harding *et al.*, in progress.

These experiments produced both primary (2.45 MeV) and secondary (14 MeV) neutrons recorded by neutron time-of-flight and activation sample diagnostics

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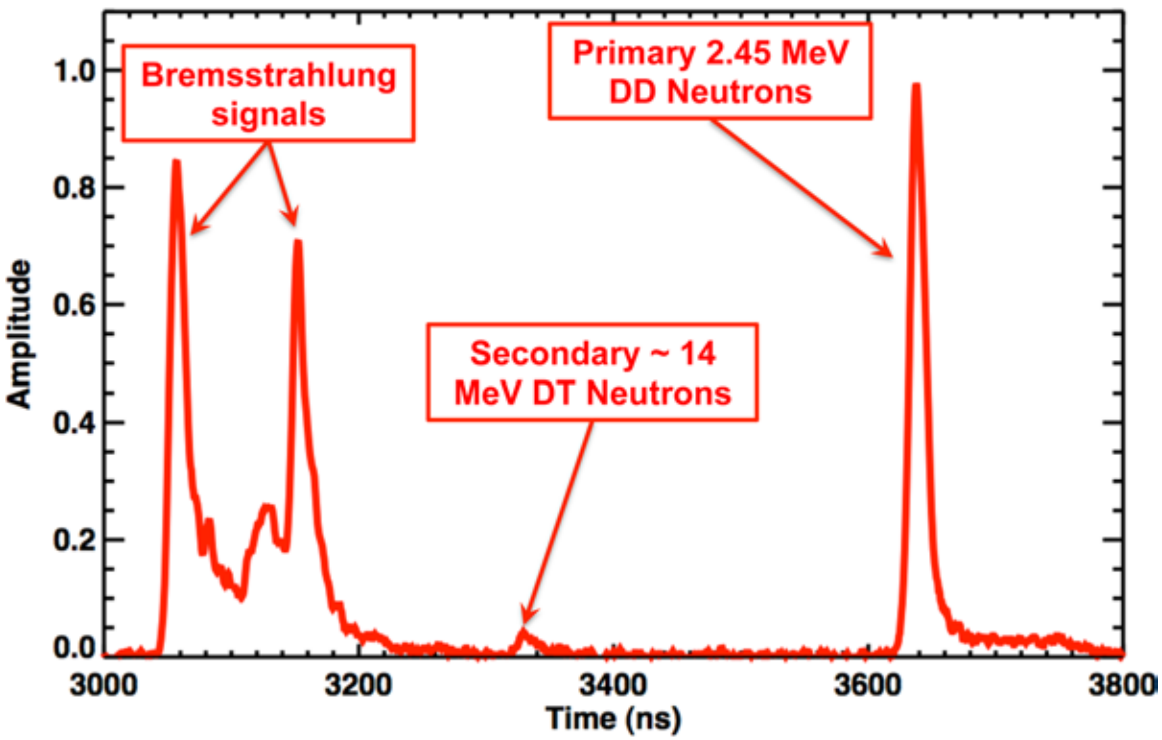
"Secondary" 14 MeV neutrons can be produced by 1 MeV tritons interacting with D fuel

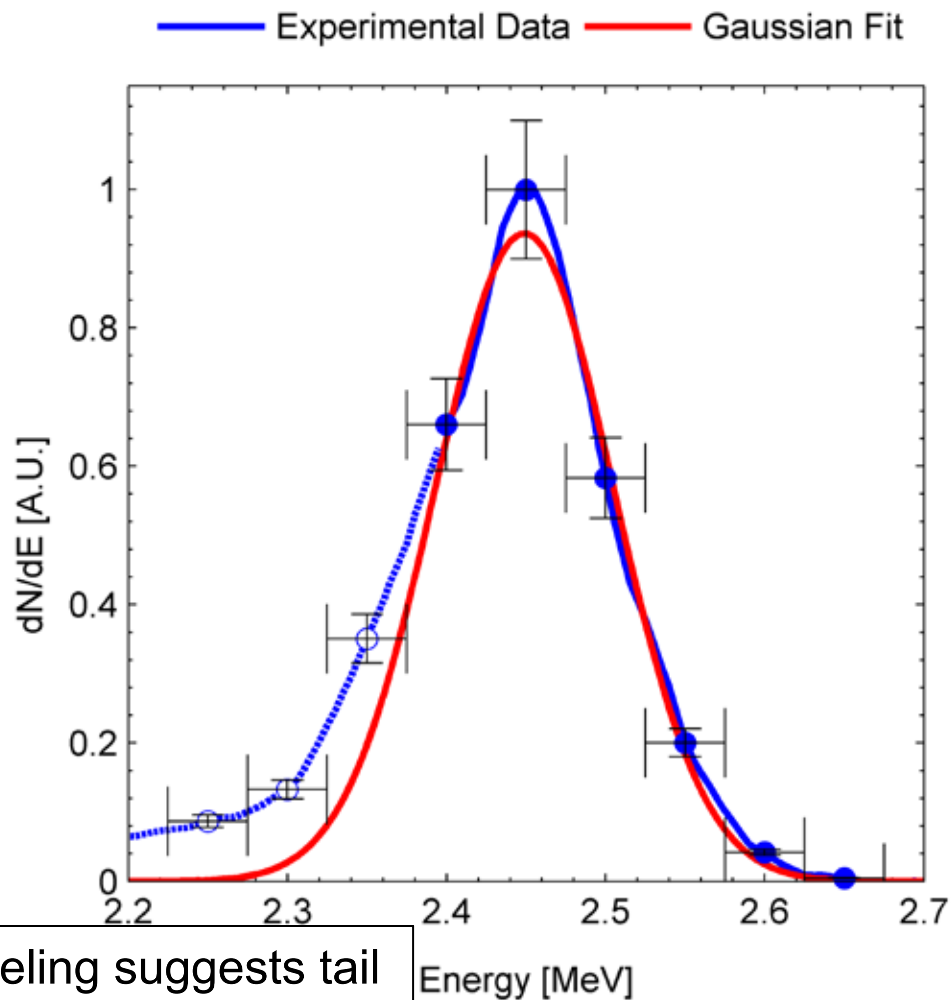
$$D + D \xrightarrow{50\%} 0.8\ \text{MeV}\ He^3 + 2.5\ \text{MeV}\ n$$
$$D + D \xrightarrow{50\%} 1.0\ \text{MeV}\ T + 3.0\ \text{MeV}\ p$$

So one triton is produced for every 2.45 MeV neutron that is produced



Note: Significant ~0.1-10 MeV bremsstrahlung produced by facility induces a background activation "yield"—e.g., shots with no fusion fuel produce ~5e9 "DD yield"

Neutron Time of Flight spectra indicate ion temperatures greater than 2 keV at stagnation



Modeling suggests tail due to nBe scattering from liner

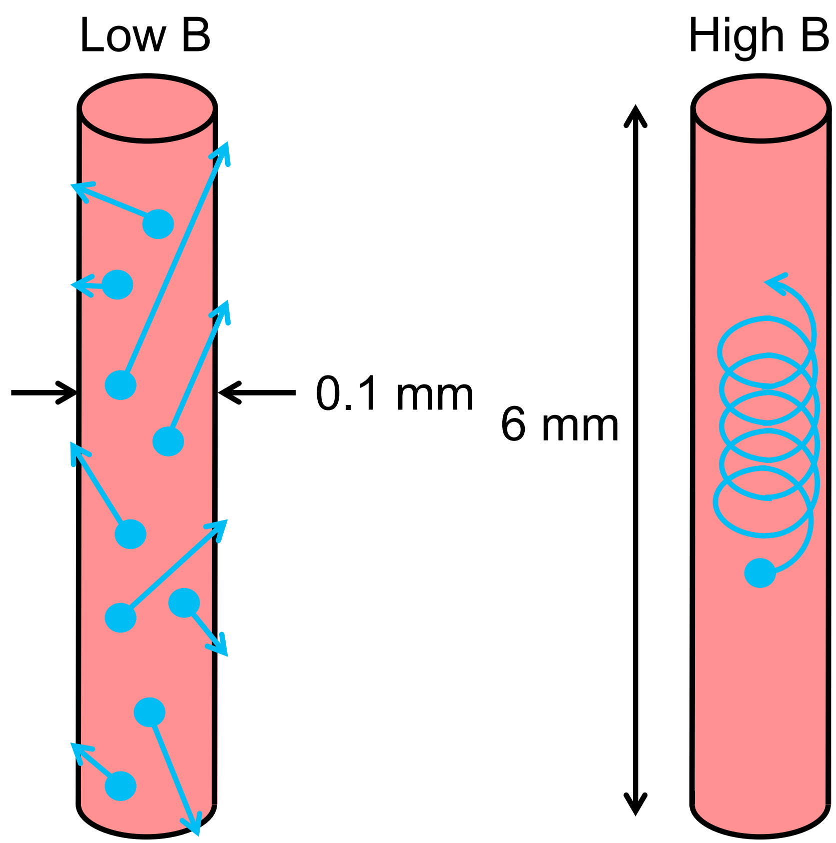
- DD neutron peak observed in experiments with significant yield (>1e10)
- Gaussian profile fit to high energy side of peak to determine ion temp
- Ion temperatures were between 2 and 2.5 keV for high yield experiments

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

$Yield_{DT}/Yield_{DD}$ can be used to infer magnetization at stagnation

High aspect ratio cylinder

Most tritons born with trajectory that exits the fuel radially



ρ ~ 0.4 g/cm^3

R ~ 0.005 cm

Z ~ 0.6 cm

ρR ~ 0.002 g/cm^2

ρZ ~ 0.2 g/cm^2

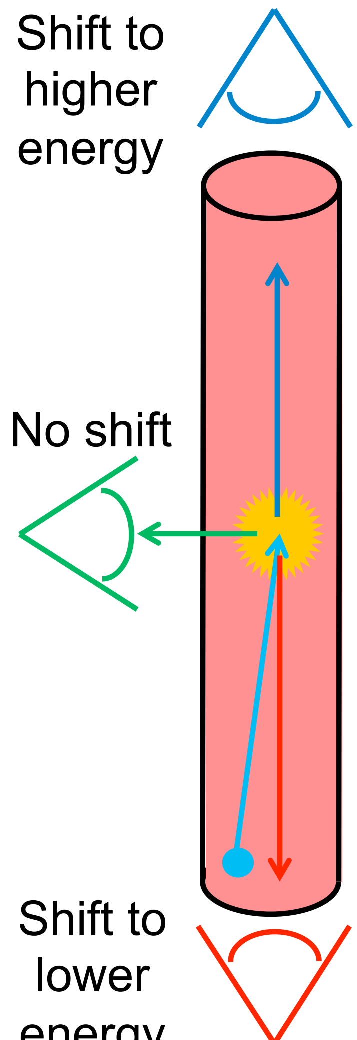
Tritons sample small ρr when B-field is low so DT/DD is low

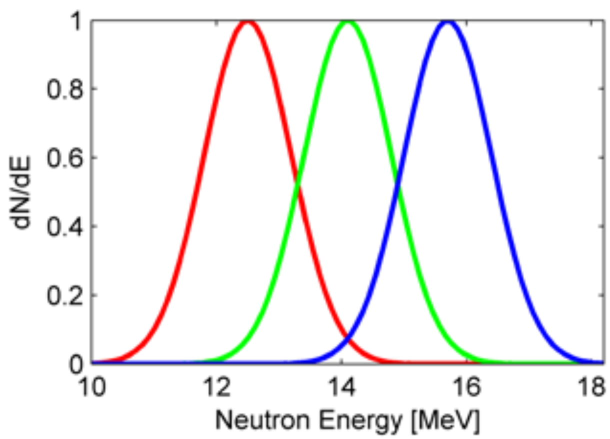
High B-field traps tritons increasing the effective ρr so DT/DD increases

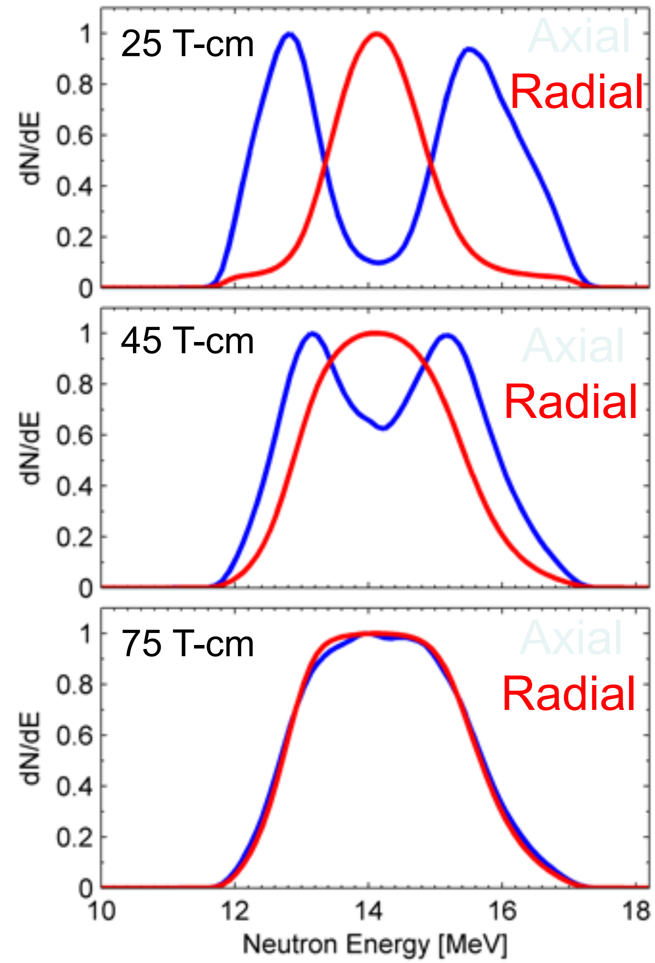
P.F. Schmit *et al.*, Phys Rev Lett 113, 155004 (2014); P.F. Knapp *et al.*, Phys. Plasmas (2015).

DT NTOF spectrum can also be used to infer magnetization at stagnation

DT reactions primarily occur for tritons traveling along the Z axis







P.F. Schmit *et al.*, Phys Rev Lett 113, 155004 (2014); P.F. Knapp *et al.*, Phys. Plasmas (2015).

$Yield_{DT}/Yield_{DD}$ and NTOF spectra indicate significant magnetic flux compression in MagLIF experiments

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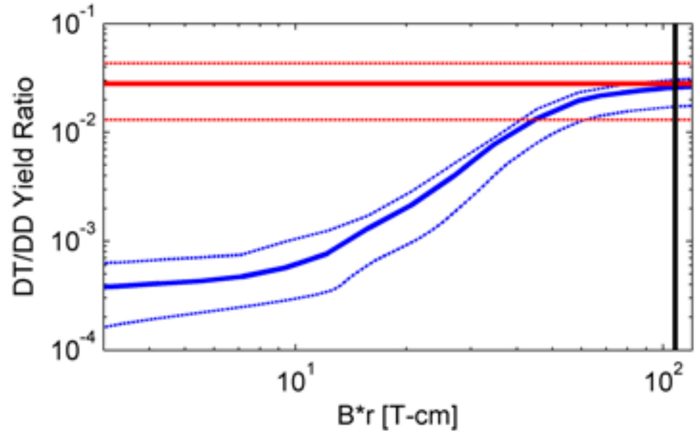
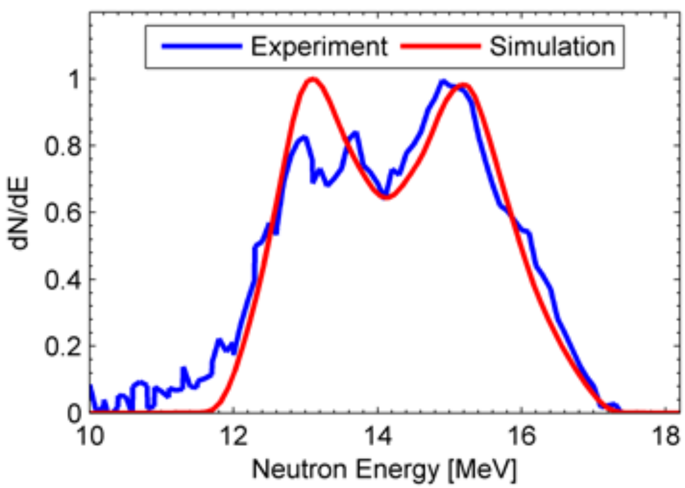
Measured

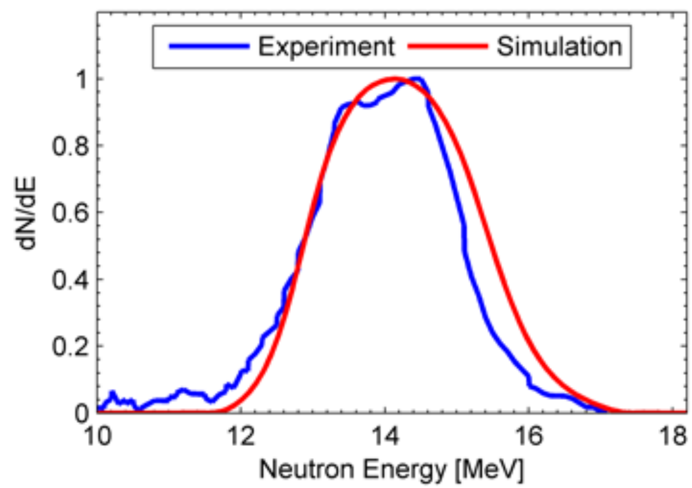
Calculated



$Y_{DT}/Y_{DD} = 1.3\text{-}4.3 \times 10^{-2}$
is consistent with
B*r > 40 T-cm

For ideal flux compression and 0.1 mm diameter at stagnation B^*r_{max} = 108 T-cm





NTOF spectra are consistent with
B*r ≈ 45 T-cm

P.F. Schmit *et al.*, Phys Rev Lett 113, 155004 (2014); P.F. Knapp *et al.*, Phys. Plasmas (2015).

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

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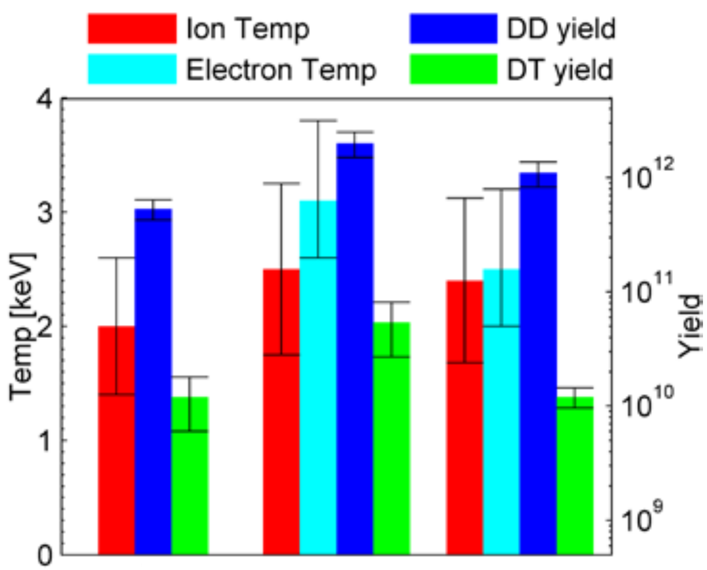
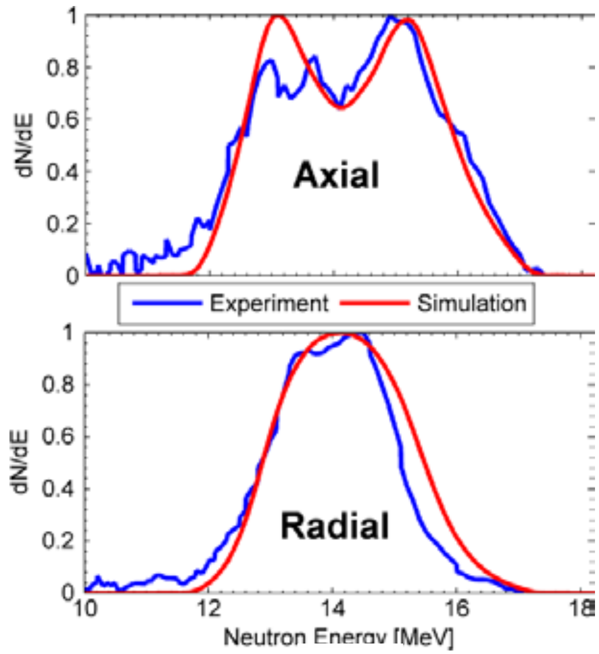
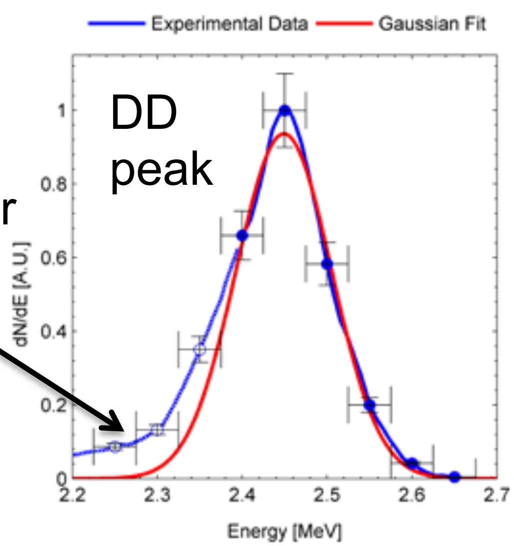


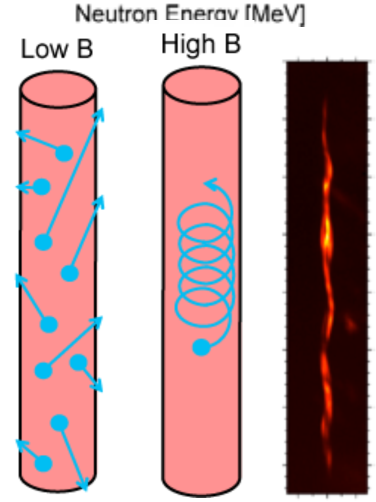


Inferred Stagnation Conditions

Volume = 2-5 $\times10^{-5}$ cm^3
Duration = 1-2 ns
ρ_{fuel} = 0.7-2 $\times10^{23}$ cm^{-3}
= 0.2-0.6 g/cm^3
Temp. = 2.5-3.1 keV
$<\sigma v>$ = 1.3-2.8 $\times10^{-20}$

n scatter off Be liner around hot fuel





Calculated Yield =
6 $\times10^{11}$ to 3 $\times10^{13}$ DD

Measured Yield =
2 $\times10^{12}$ DD

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

Laser heating of fusion fuel has emerged as a leading hypothesis for why the yields are lower than predicted

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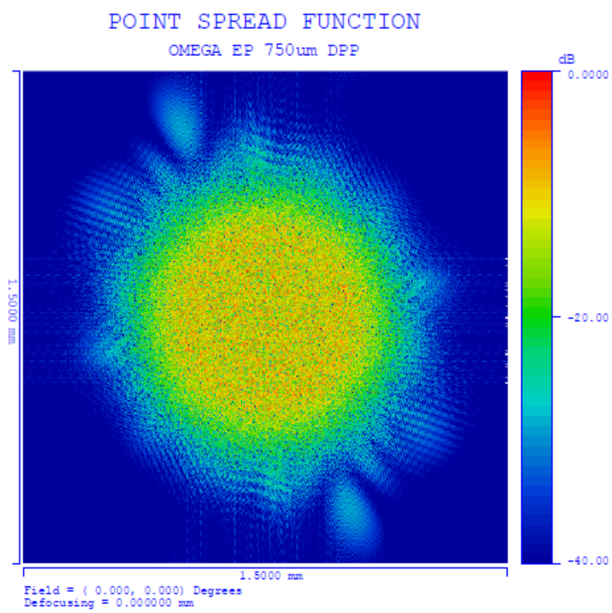
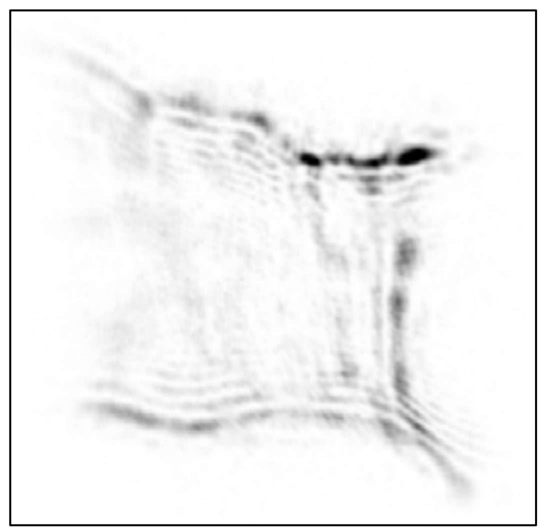
- Use of deuterium at relatively high gas densities → >1 micron foils
  - Typically avoided by ICF community, which uses higher-Z gas fills that allow lower pressures (e.g., neo-pentane in hohlraums)
  - Cryogenically-cooled gas a good option but needs time to implement

OMEGA-EP
750um DPP

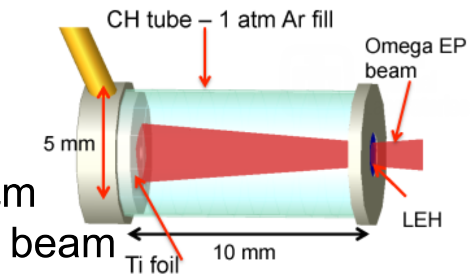


ZBL (Z-Beamlet)
No DPP (representative)



- Other U.S. laser facilities use “beam smoothing” technology that was never installed on Z-Beamlet (not needed for radiography diagnostics)

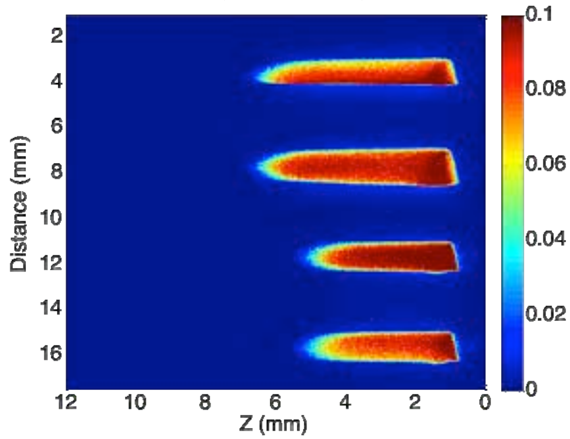
We are working on laser facilities across the USA to improve our modeling of laser heating



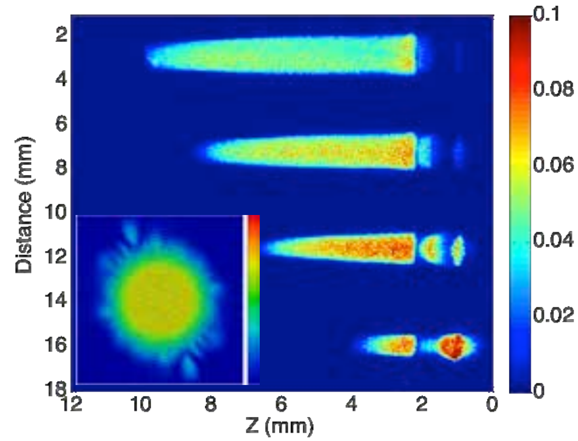
750 µm diam. beam

Omega-EP (Harvey-Thompson, Sefkow)

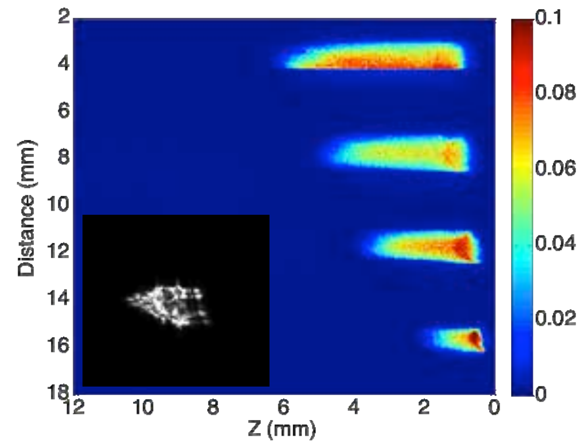
2 ns beam, 2.2 kJ, 1um LEH



4 ns beam, 3.1 kJ, 2um LEH



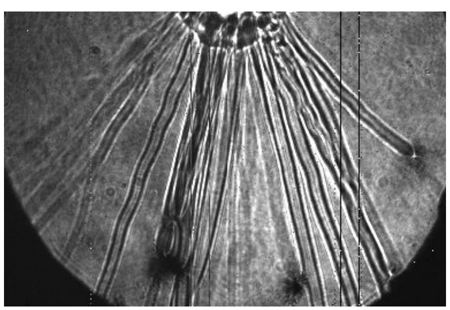
4 ns beam, 2.9 kJ, 2um LEH, No DPP



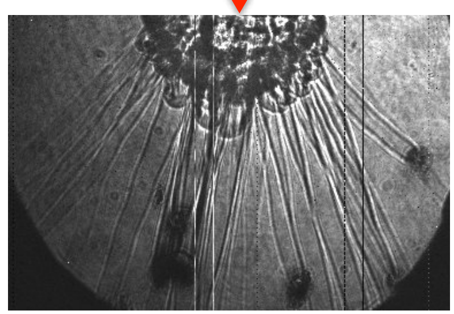
Z-Beamlet (Geissel, Porter, Lewis)

High Intensity, thick foil

Laser

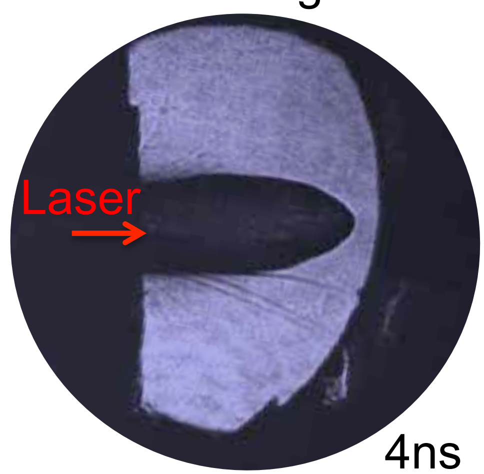


t = 10ns

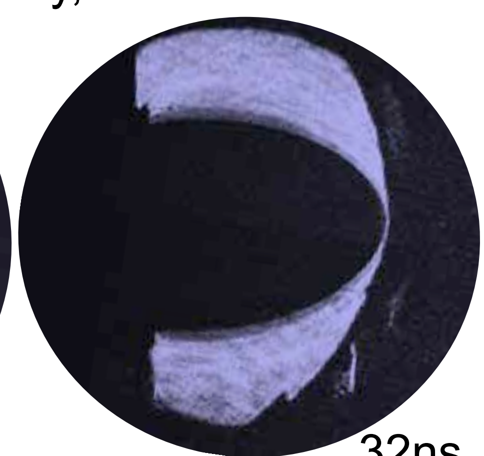


t = 36ns

High Intensity, thin foil

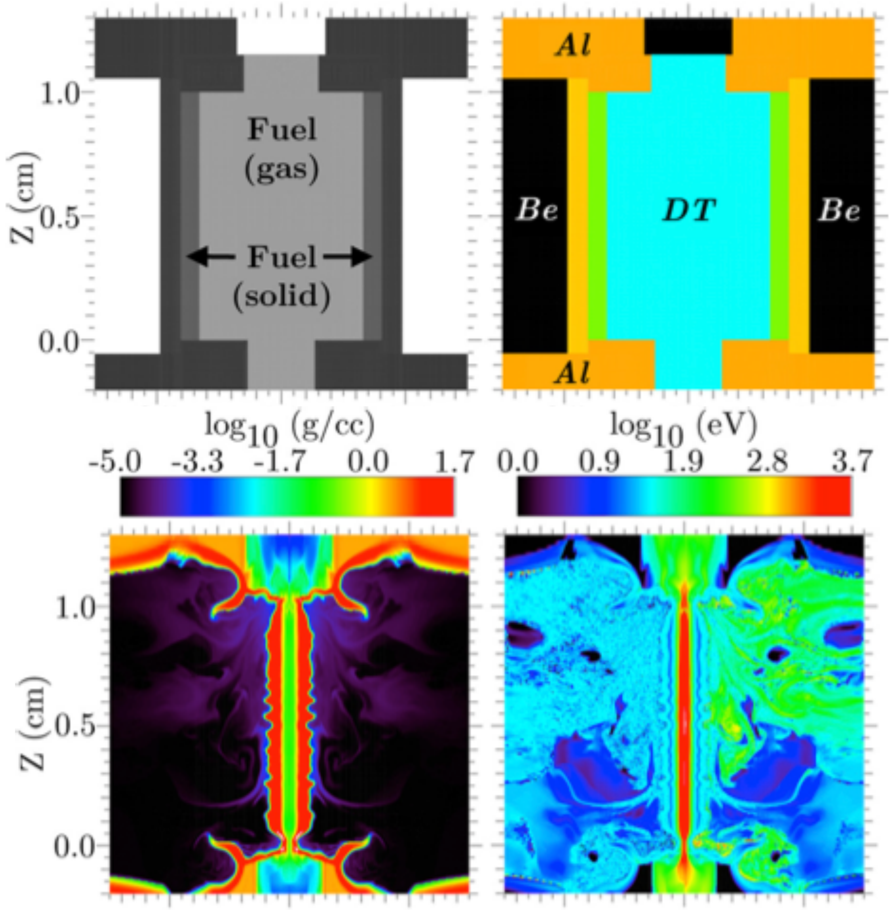


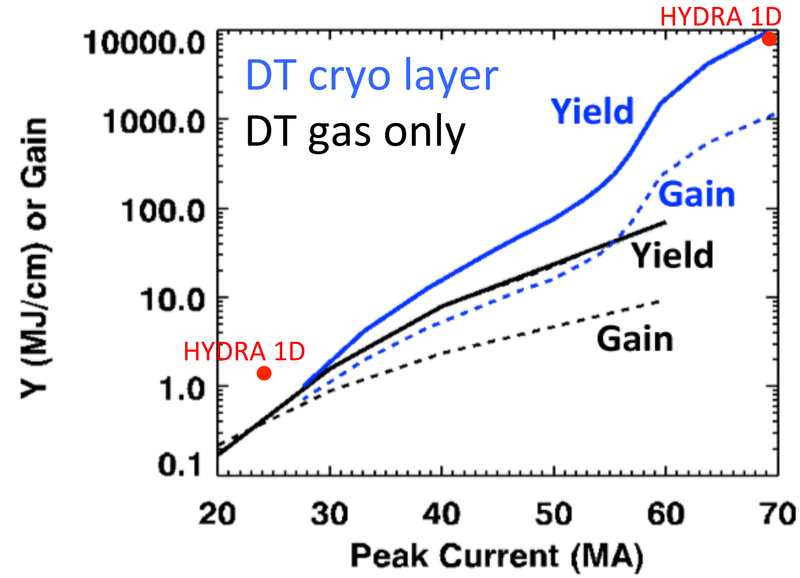
4ns

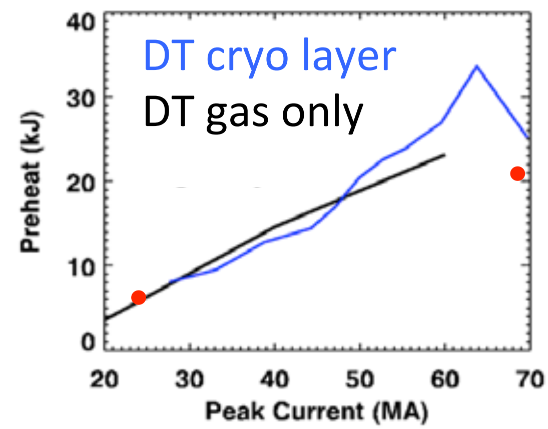


32ns

In principle, MagLIF designs achieve higher yields on future facilities using a cryogenic DT layer and substantial preheat—we can test most of the physics of these targets on Z today





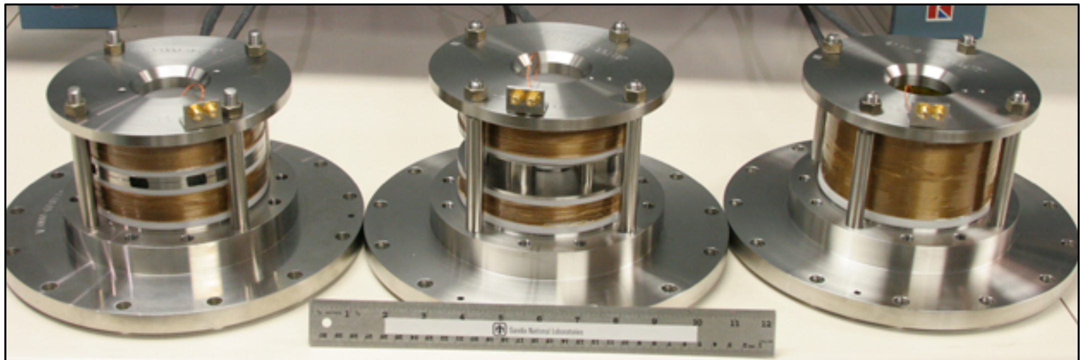


An intermediate regime exists wherein the B_z field is

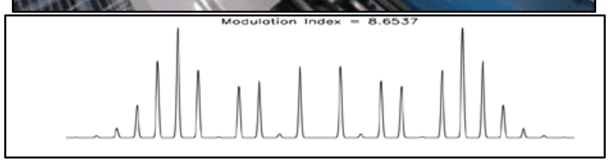
- *strong enough* to reduce conduction losses, but
- *weak enough* not to inhibit the α deflagration wave

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

Over the next few years we are working to increase the drive conditions on Z to help understand how MagLIF scales

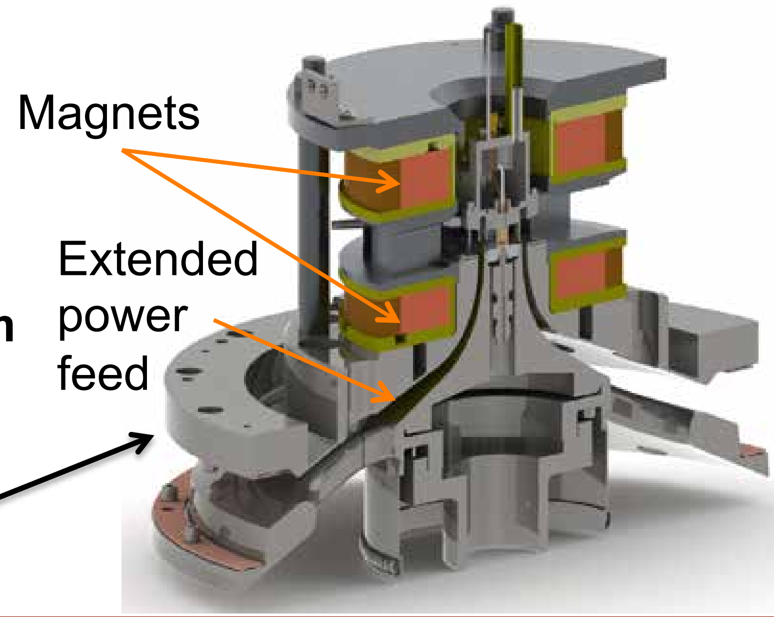


Increase B-field from 10 T to 30 T



Increase laser energy from 2 kJ to >6 kJ

Increase current from 19 MA to >20 MA (Z facility upgrades; load hardware optimization)



Today we will discuss exciting new fusion results obtained on Sandia's "Z" pulsed power facility

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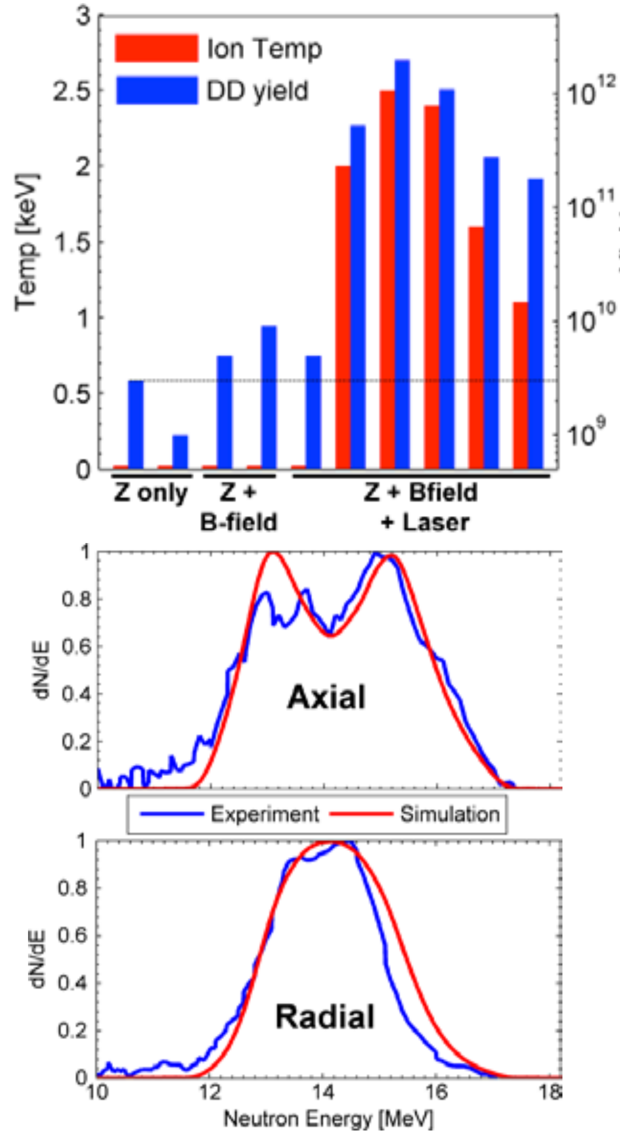
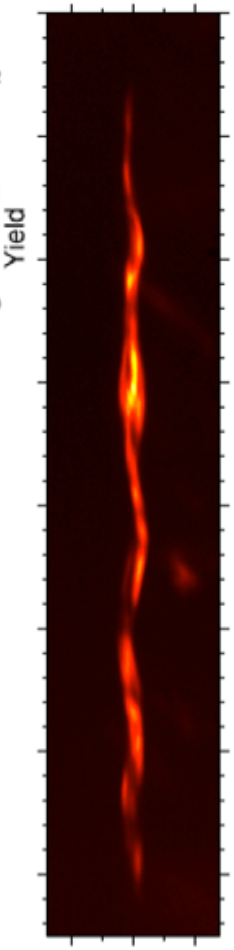
- Magnetized (10 T) and laser-heated (2 kJ) cylindrical targets reached ~3 keV (30,000,000 K) temperatures and produced fusion yield (up to 2×10^{12} DD) at 70 km/s implosion velocity
  M.R. Gomez *et al.*, Phys Rev Lett (2014);
- Secondary neutron yield ($>10^{10}$ 14 MeV) and spectra demonstrate that the fusing plasma was highly magnetized
  P.F. Schmit *et al.*, Phys Rev Lett (2014);
- Detailed analysis of stagnation conditions consistent with thermonuclear yield, though less energy in fusing plasma than predicted
- Additional experiments on multiple facilities focused on specific physics issues (laser-gas coupling, liner dynamics, flux compression)
- We are working toward the conditions needed to demonstrate $\sim 3 \times 10^{14}$ DD yields on our current facility (~100 kJ DT equiv.)





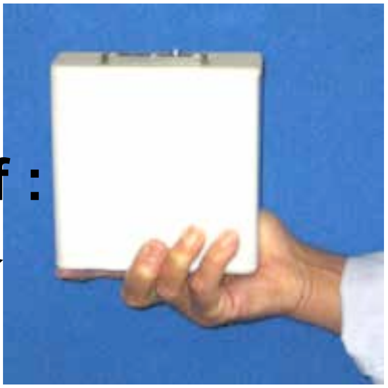
Thank you for your attention!

New driver technology: The Linear Transformer Driver (LTD) is the biggest advance in pulsed power since the invention of the Marx generator in 1924

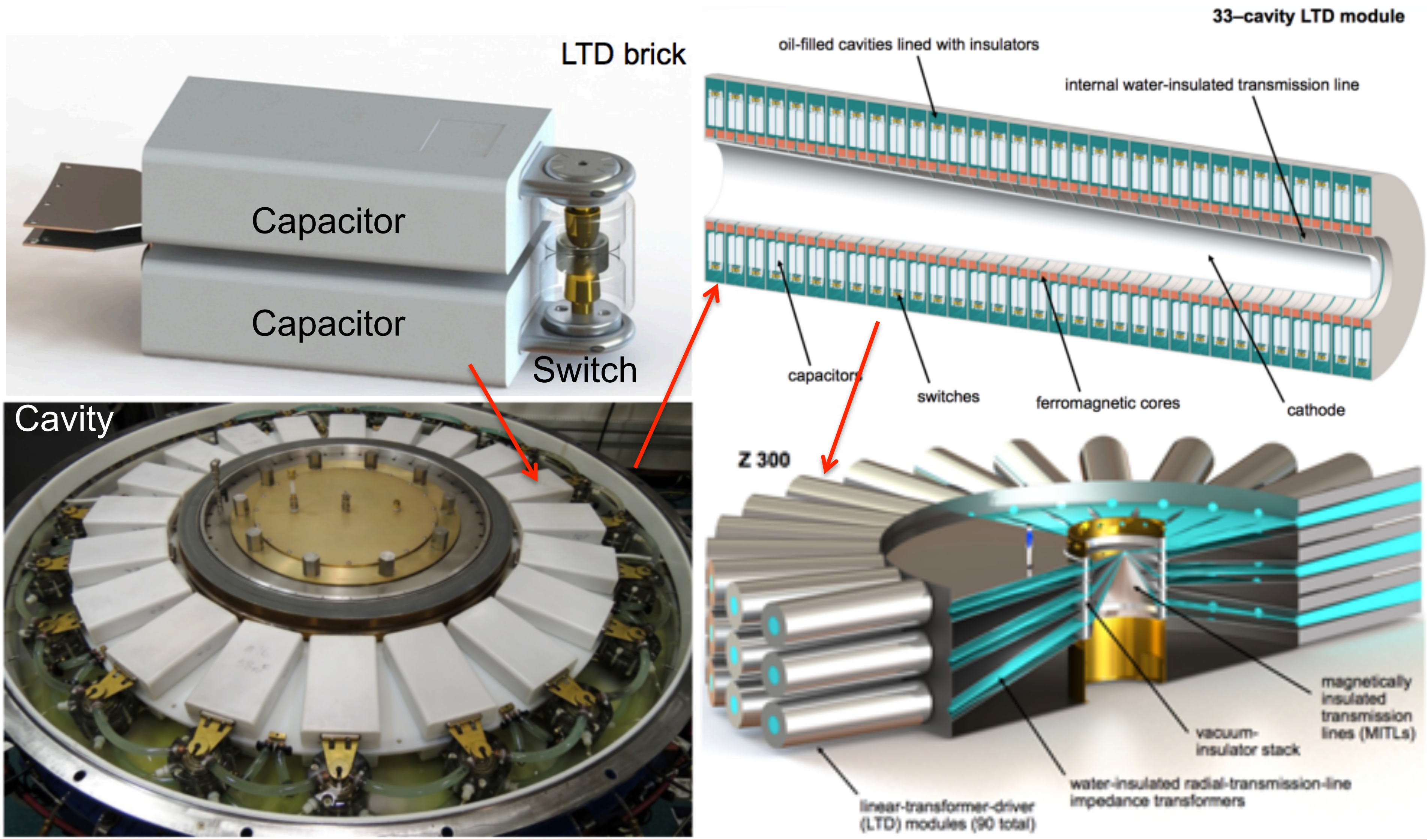
An LTD Cavity is the building block of a future high yield facility

An LTD consists of :

- **Capacitors**
- **Switches**
- **Magnetic cores**



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



This technology can generate about 47 MA, 300 TW in a machine the same size as Z (26 MA, 85 TW)

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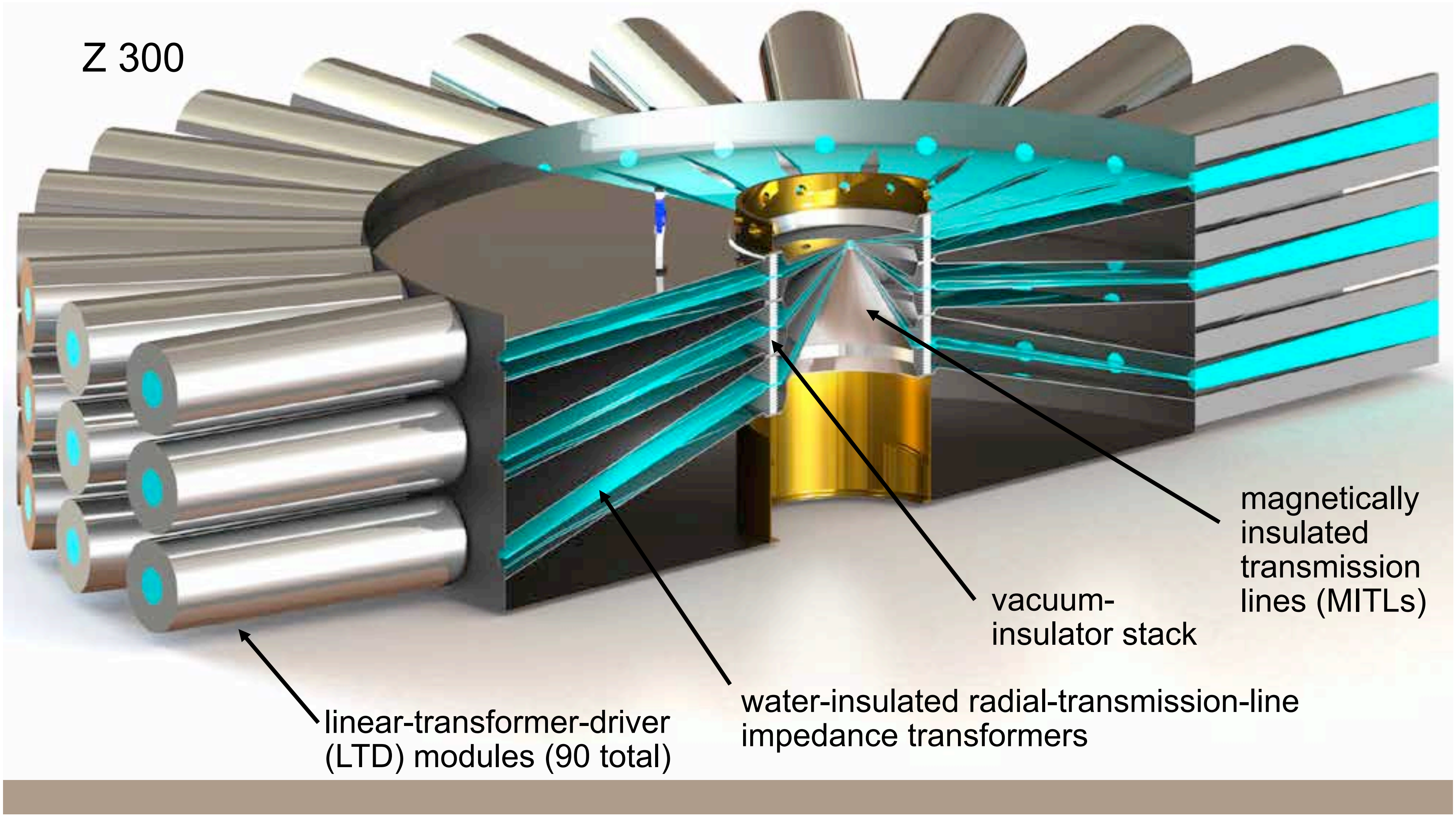
P_{LTDs} = 300 TW
E_{LTDs} = 47 MJ

V_{stack} = 7.5 MV
L_{vacuum} = 14 nH

I_{load} = 50 MA
$\tau_{implosion}$ = 130 ns

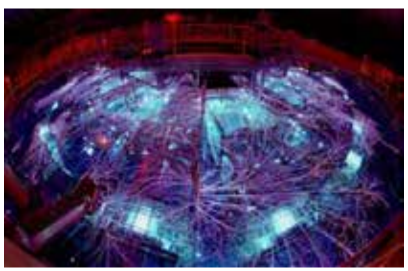
$E_{radiated}$ = 11 MJ
diameter = 35 m

η_{x-ray} = 23%



We are collectively developing a facility and fusion target scaling strategy that if successful will result in >1 GJ single-shot yields in the laboratory

Fusion Yield ~100kJ$_{DT\ eq}$
Physics Basis for Z300

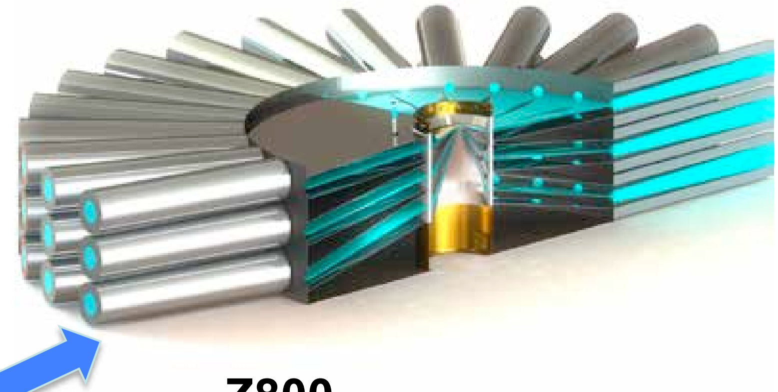


Z
- 80 TW
- 33 Meter diameter
- 26 MA
- 22 MJ Stored Energy

Fusion Yield ~5 MJ
Physics Basis for Z800

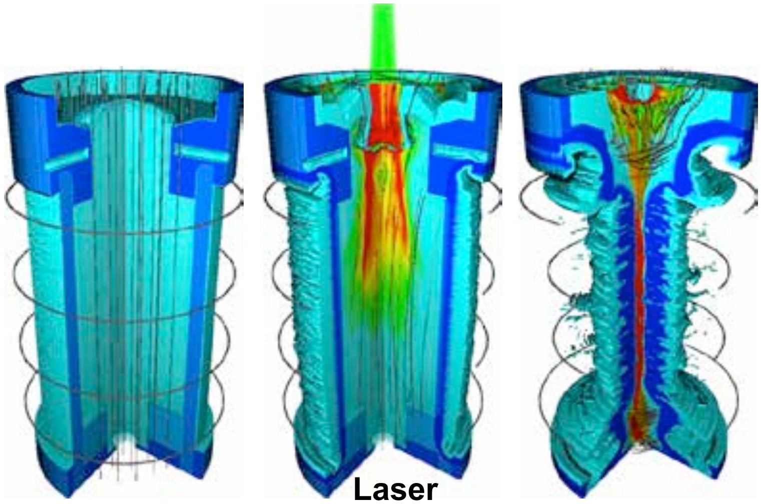
Z300
- 300 TW
- 35 Meter diameter
- 47 MA
- 47 MJ Stored Energy

Fusion Yield ~1 GJ



Z800
- 800 TW
- 52 Meter diameter
- 61 MA
- 130 MJ Stored Energy

Our path to studying the underlying science is a mixture of focused and integrated experiments to address key physics

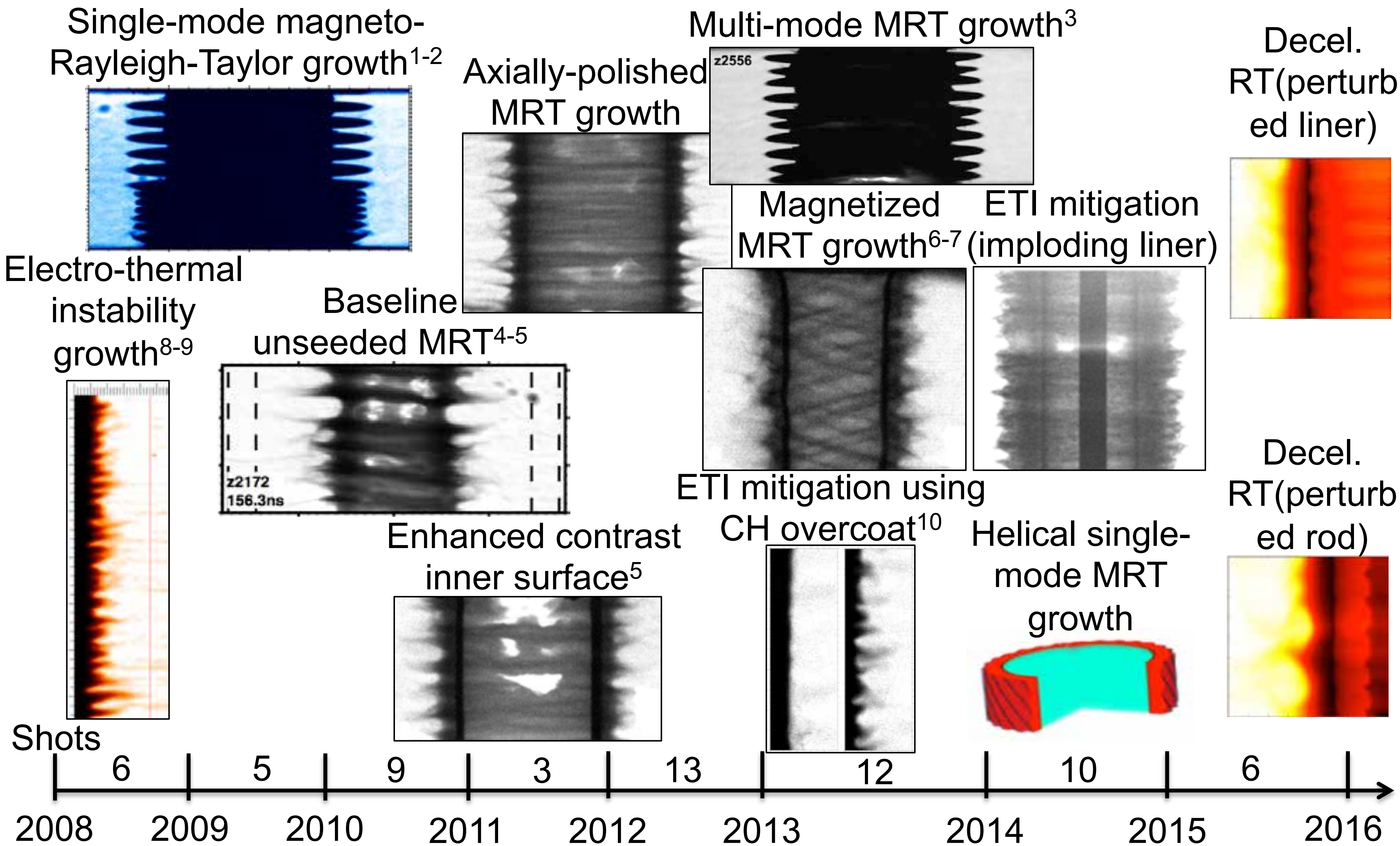


- Key target design elements
  - Liner compression
  - Magnetization
  - Laser heating

- Key physics uncertainties
  - Liner instabilities
    - Electro-thermal
    - Magneto-Rayleigh-Taylor
    - Deceleration RT
    - Impact of 3D fuel assembly
  - Liner/fuel interactions & mix
  - Laser-window and laser-fuel scattering, absorption, uniformity
  - Suppression of electron heat transport in dense plasma by magnetic fields
  - Magnetic flux compression

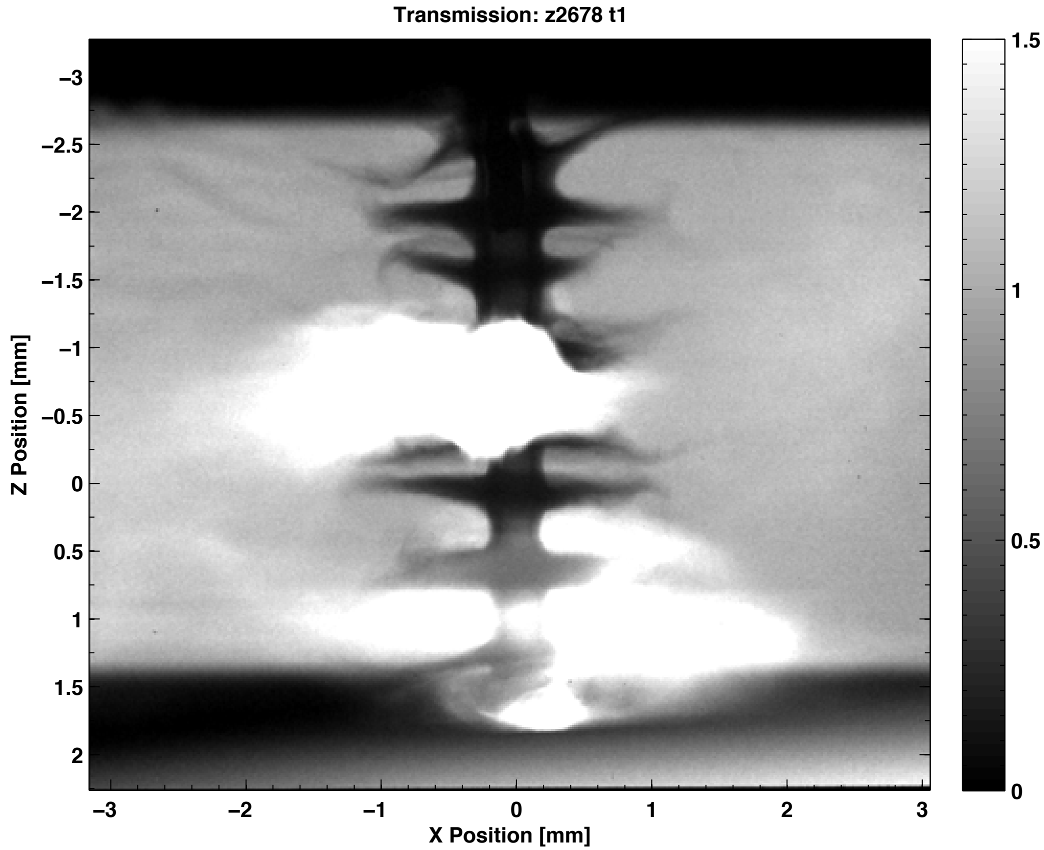
Experiments to address the key physics are planned for the Z pulsed power facility and the Z-Beamlet and Omega (and -EP) lasers.

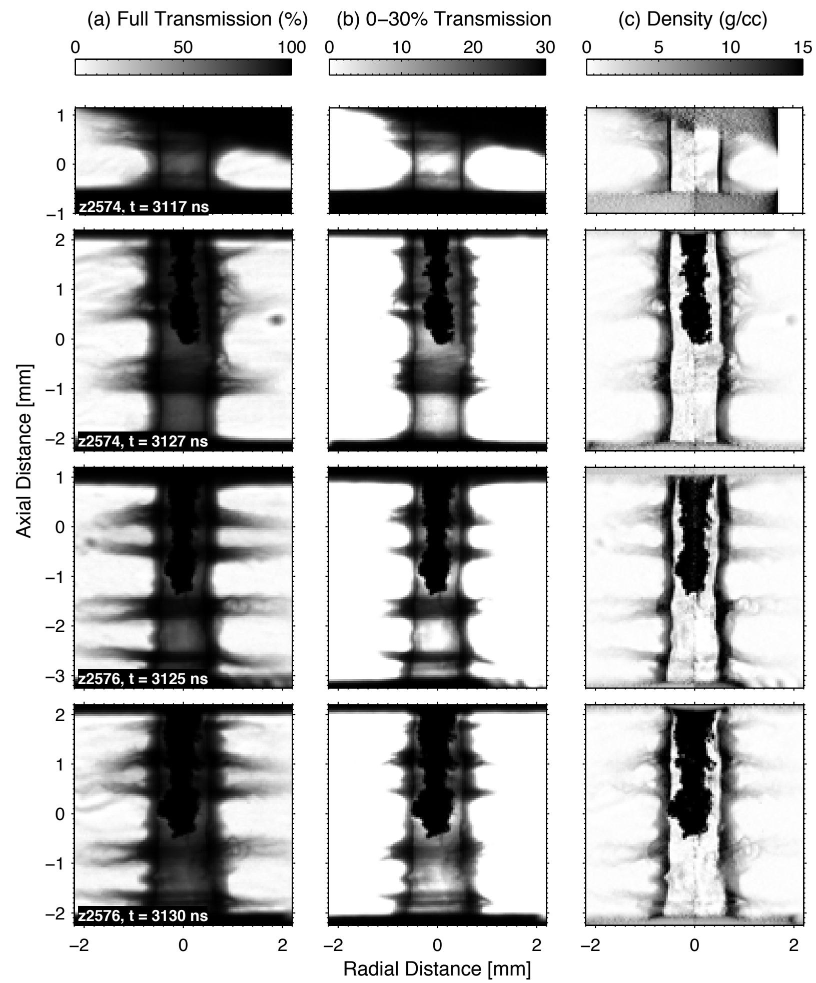
Fundamental liner instability experiments represent an important example of a sustained focused science effort—we are transitioning from experiments on initiation/acceleration stages to deceleration stage



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

Cylindrical DD EOS Experiment





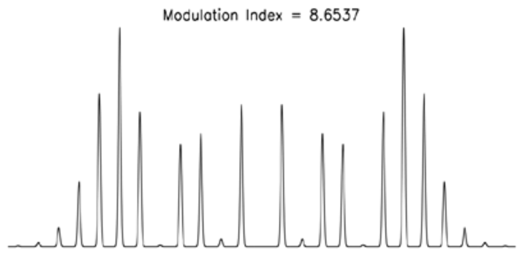
$\langle\rho\rangle = 60\ \mathrm{g/cm^3}$ $\quad CR \approx 19$

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

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

We recently upgraded Z-Beamlet from 2 kJ to 4 kJ to support MagLIF/DMP experiments—we have started working on upgrades to eventually take us to >6 kJ

- Upgrade to 4 kJ to be completed by June 2014. This upgrade increases the bandwidth of the laser to suppress SBS and allows us to go from 2 ns pulses to 4 ns pulses at existing ~1 TW power levels. (Note: NOVA lost lens to SBS in 1990s—want to avoid!)

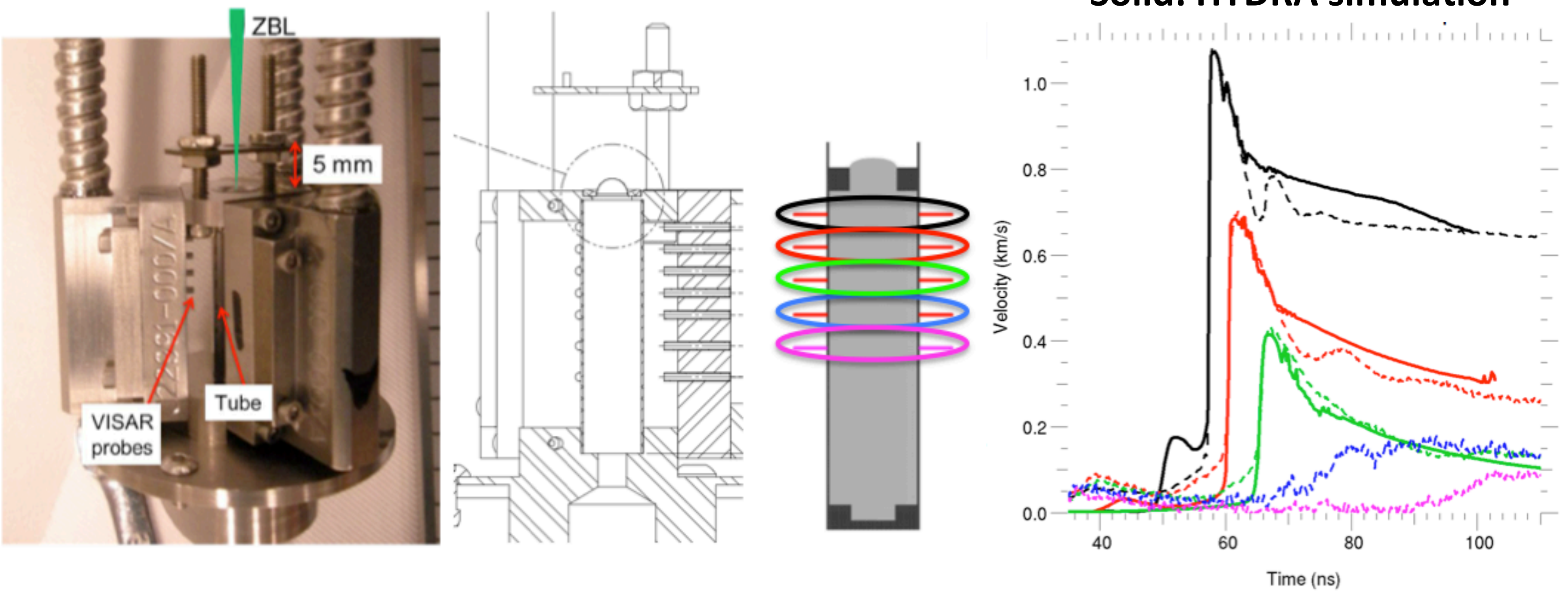


- Upgrading to 6-8 kJ to be completed by the end of 2014. Some of the long-lead time components exist from the original "Beamlet" system Sandia inherited from LLNL in late 1990s, but were never installed. Other components have to be purchased or modernized.
  - Install and optimize adaptive optic for improved beam wave front
  - Procure/replace some damaged optics in beam transport system (related to improving beam wave front)
  - Install booster amplifiers and associated pulsed power

Four sets of data imply low levels of preheat.

Data set #1: Blastwave measurements via VISAR

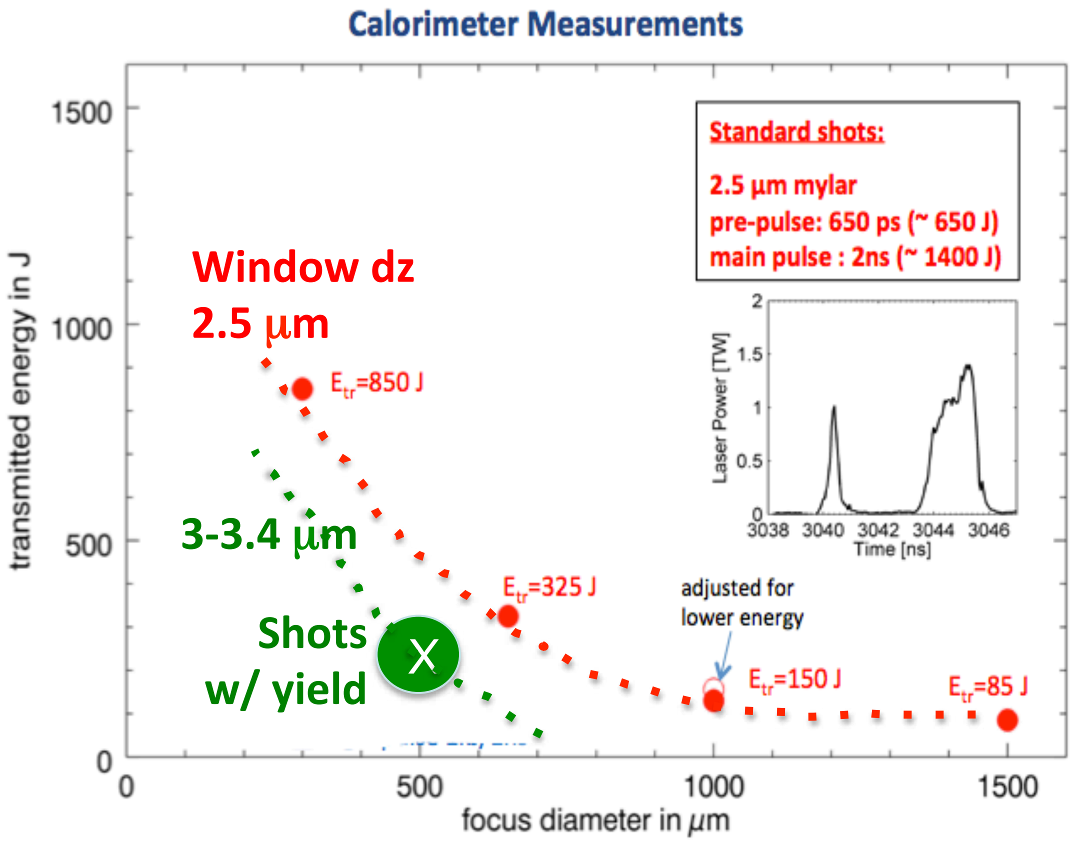
Dashed: Data
Solid: HYDRA simulation

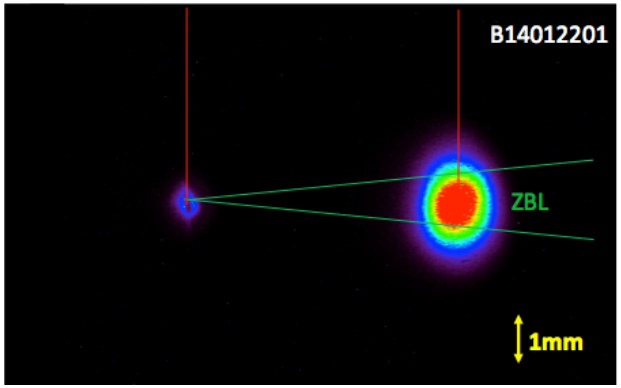


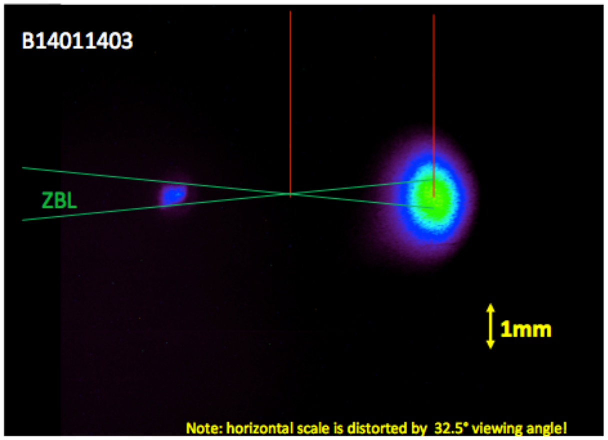
Inferred: 330 J or less coupled to the gas (of ~2.8 kJ)

Four sets of data imply low levels of preheat.

Data set #2: Calorimeter measurements in foil-only tests







Inferred: ~200-300 J coupled through 3-3.4 µm foils

Four sets of data imply low levels of preheat.

Data set #3: Shadowgraphy of blastwave (~600 J*)

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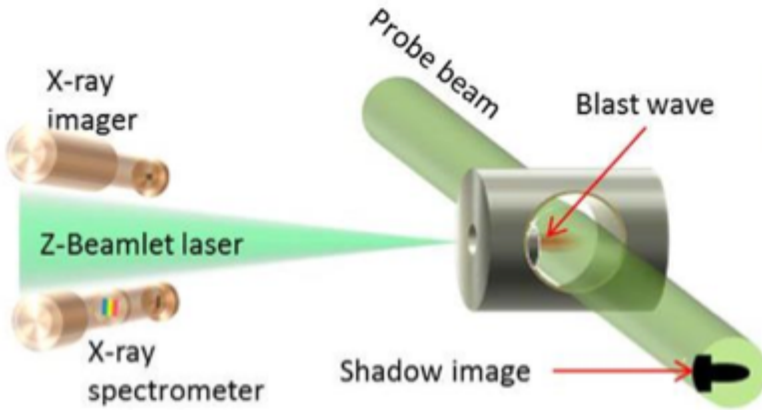
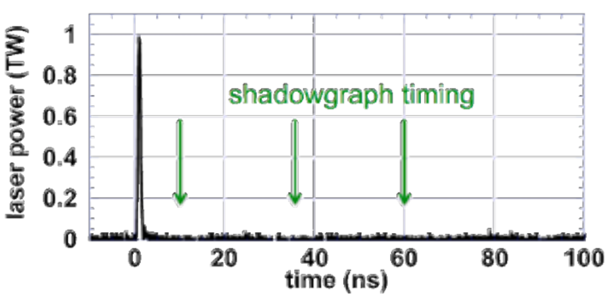
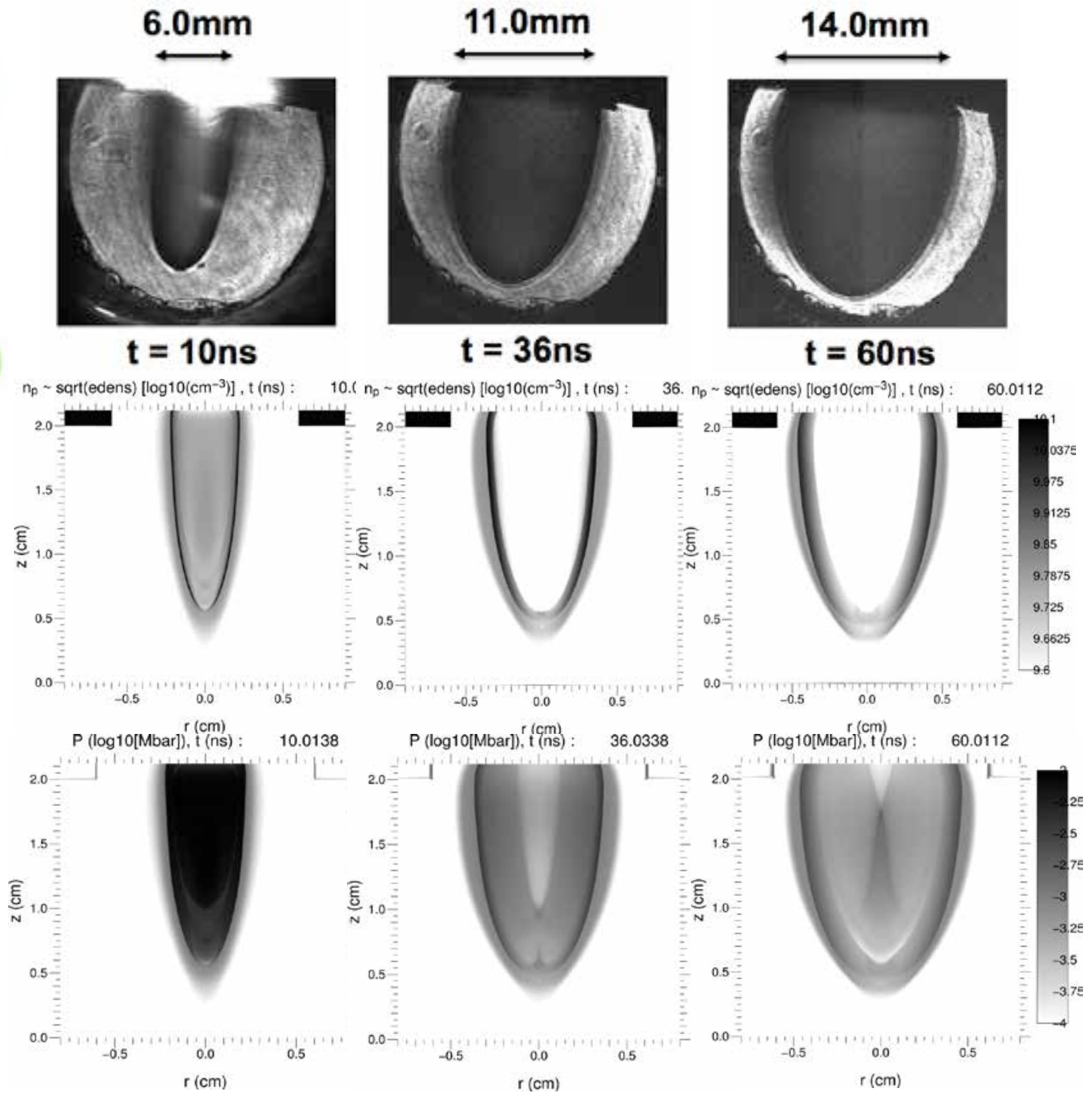


Shadowgraph measurements
Ne 250 Torr gas-cell shot, 10/6/2014

ZBL: 1.8kJ/2ns, 300J prepulse, 1mm dia. focus
Target: scale-2 gas cell, 1μm-thick Mylar LEH, 250 Torr neon gas fill



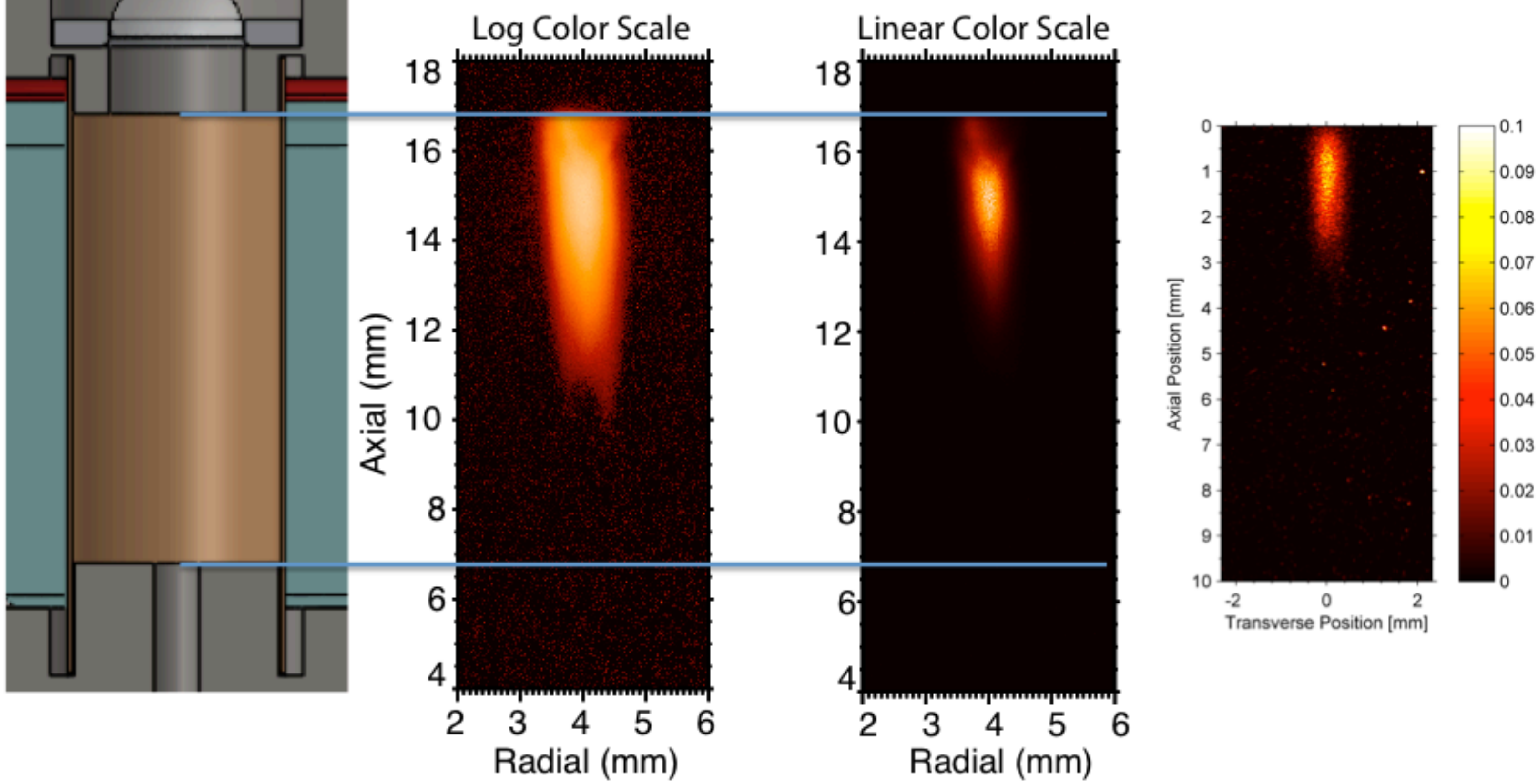
Shadowgraphs sensitive to density gradients and are compared to the simulated plasma's index of refraction $n \sim n_e^{0.5}$



Four sets of data imply low levels of preheat.

Data set #4: Laser-only with B_z shots in Z chamber

Two separate diagnostics confirmed heating.
Inferred peak T_e~500 eV (equilibration value lower)



Inferred: ~200 J coupled through 1.5* μm foils (of ~2.5 kJ)

We have started a campaign of 2 shot days/year (~20 shots) on OMEGA-EP to study laser heating and magnetized target physics, which we want to continue for the next 3-5 years

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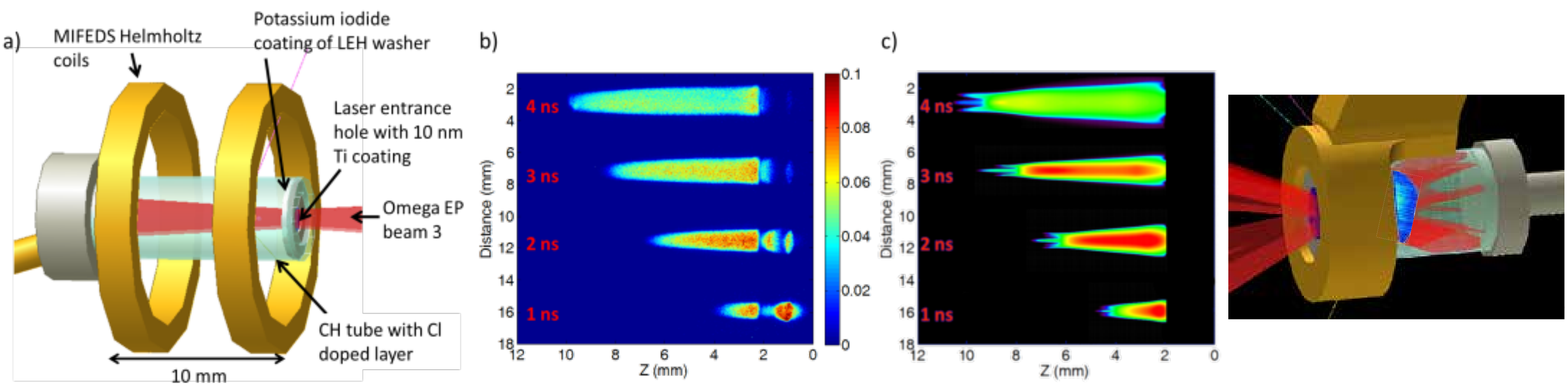
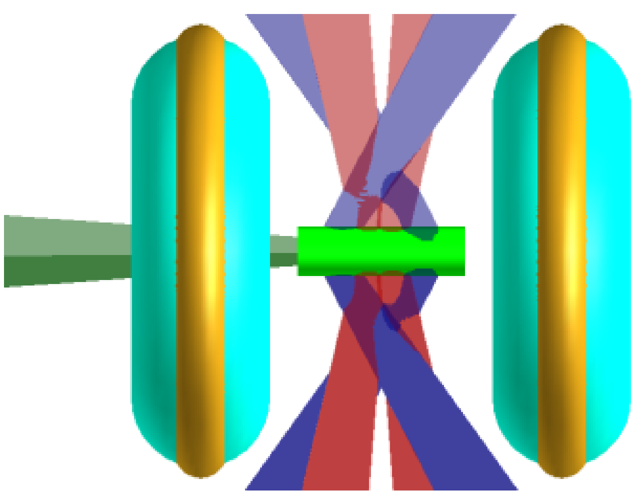
- Our first experiments in 2014 successfully started two different thrusts
  - Investigating the effects of an applied magnetic field: Measure temperature several ns after the end of the main laser pulse under various conditions
  - Heating optimization experiments: Plan is to look for impact of effects of spot size, window thickness, pre-pulse separation from main pulse, pre-pulse energy, effects of wavelength, and the effect of temporal smoothing (Smoothing by Spectral Dispersion, SSD).



We started working with Riccardo Betti's group at the Laboratory for Laser Energetics to study "mini-MagLIF" to understand how the physics scales

- Calculations suggest it is possible to scale the MagLIF concept from Z (~1MJ/cm) down to OMEGA (~0.01 MJ/cm) and still create the same stagnation pressures—can we demonstrate this? May be able to do >100 shots in 3 years on OMEGA!
- 3 shot days in 2015



Metric	State of the Art	Proposed (OMEGA)	Proposed (Z)
Coupled Energy	200-300 J	> 2 kJ	> 2 kJ
Stagnation Pressure	~1 Gbar	> 1 Gbar	> 5 Gbar
Fusion Yield	2×10^{12}	$> 10^{9}$	$> 10^{14}$