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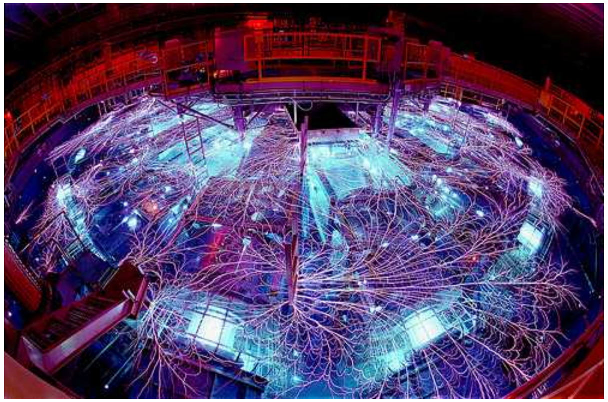

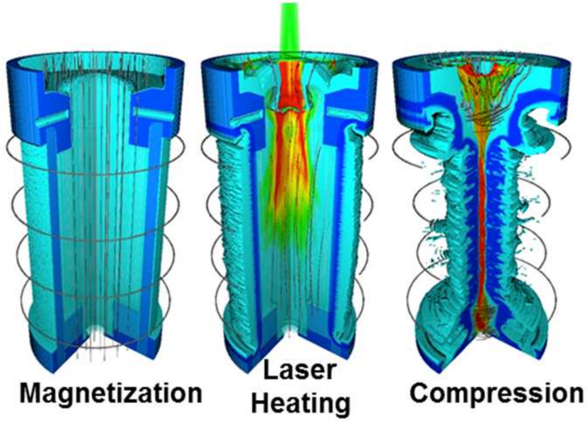

Demonstration of fusion relevant conditions in Magnetized Liner Inertial Fusion experiments on the Z facility

M. R. Gomez, S. A. Slutz, A. B. Sefkow, D. B. Sinars, K. D. Hahn, S. B. Hansen, E. C. Harding, P. F. Knapp, P. F. Schmit, C. A. Jennings, T. J. Awe, M. Geissel, D. C. Rovang, G. A. Chandler, M. E. Cuneo, A. J. Harvey-Thompson, M. C. Herrmann, D. C. Lamppa, M. R. Martin, R. D. McBride, K. J. Peterson, J. L. Porter, G. A. Rochau, C. L. Ruiz, M. E. Savage, I. C. Smith, and R. A. Vesey

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

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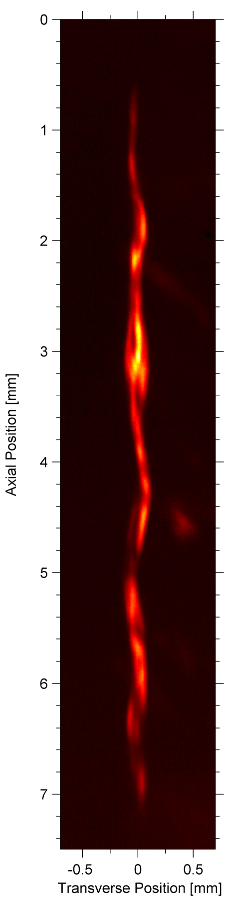
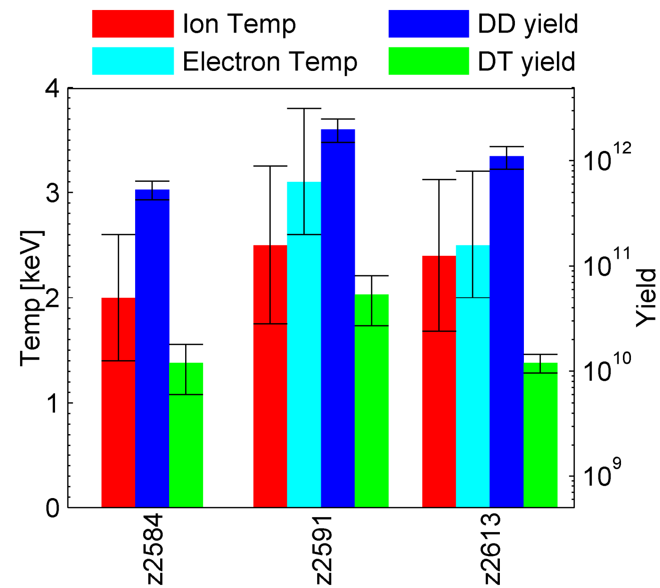
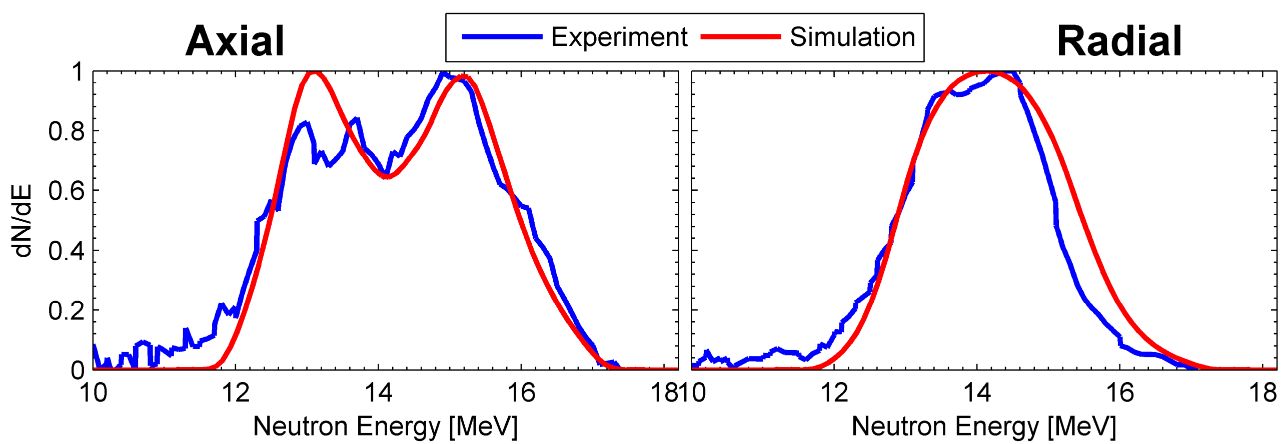
The Magnetized Liner Inertial Fusion concept has been successfully demonstrated



- **Thermonuclear neutron generation up to 2e12 DD**
- **Temp approximately 3 keV**
- **Stable pinch at stagnation**
  - **approximately 6 x 0.1 mm**
- **Successful flux compression**
  - **$R_{Larmor} < R_{stagnation}$**





Outline

- Summary of experimental results
- Define Magnetized Liner Inertial Fusion (MagLIF)
- Experimental setup
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  - Fusion yields and temperatures
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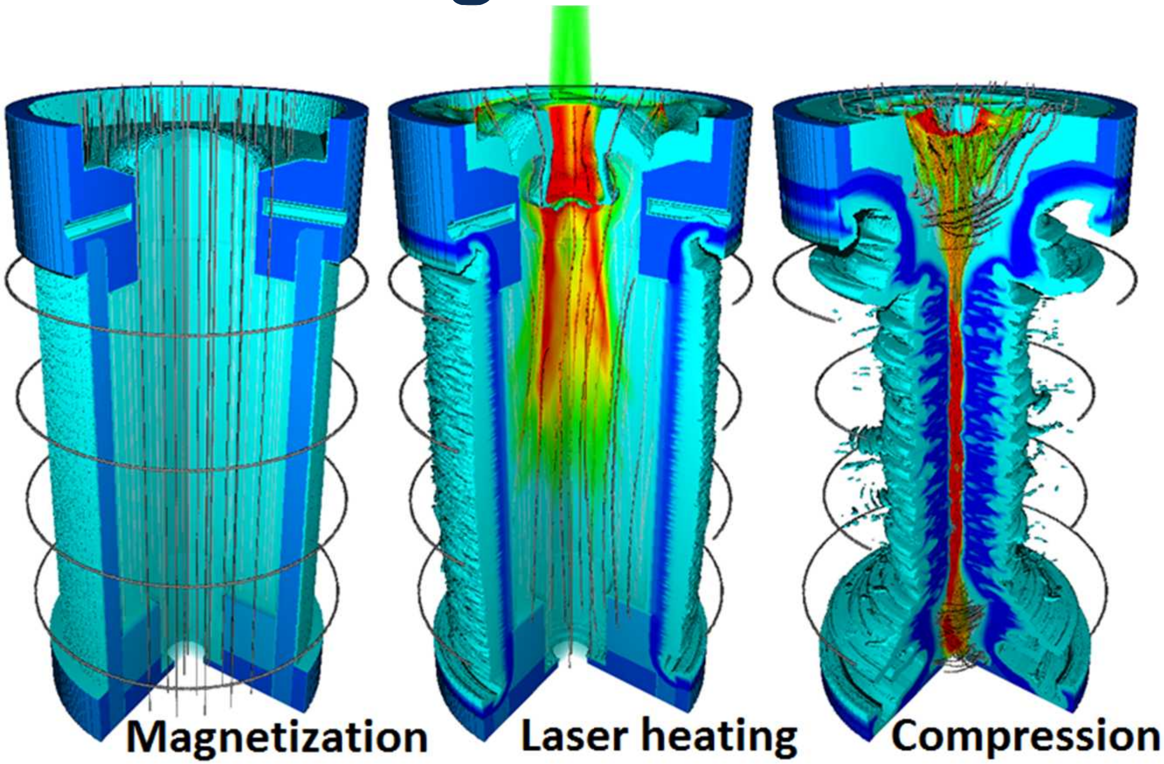
- The future

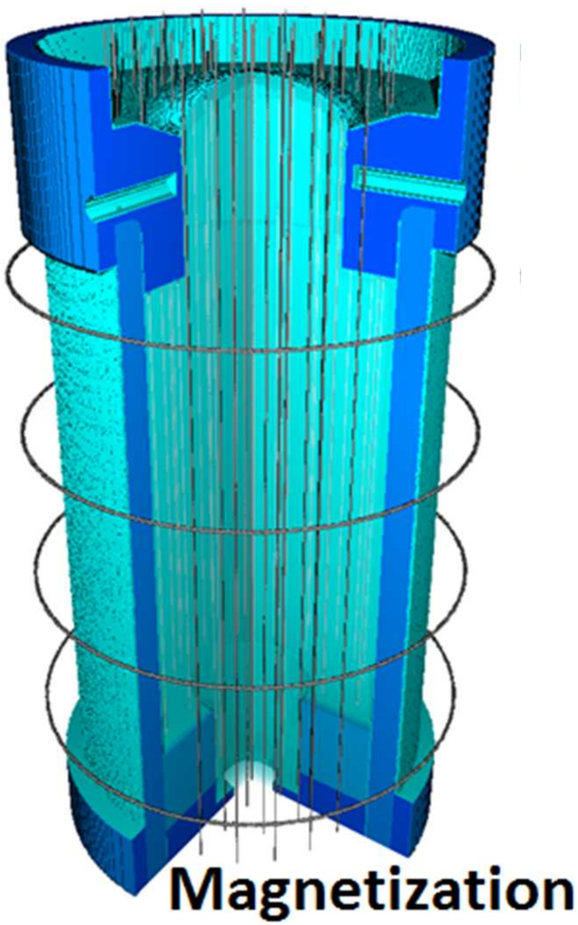
Magnetized Liner Inertial Fusion is a Magneto-Inertial Fusion concept that we are evaluating on Z



Magnetization and laser heating relax the implosion velocity, areal density, and convergence requirements of inertial confinement fusion

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

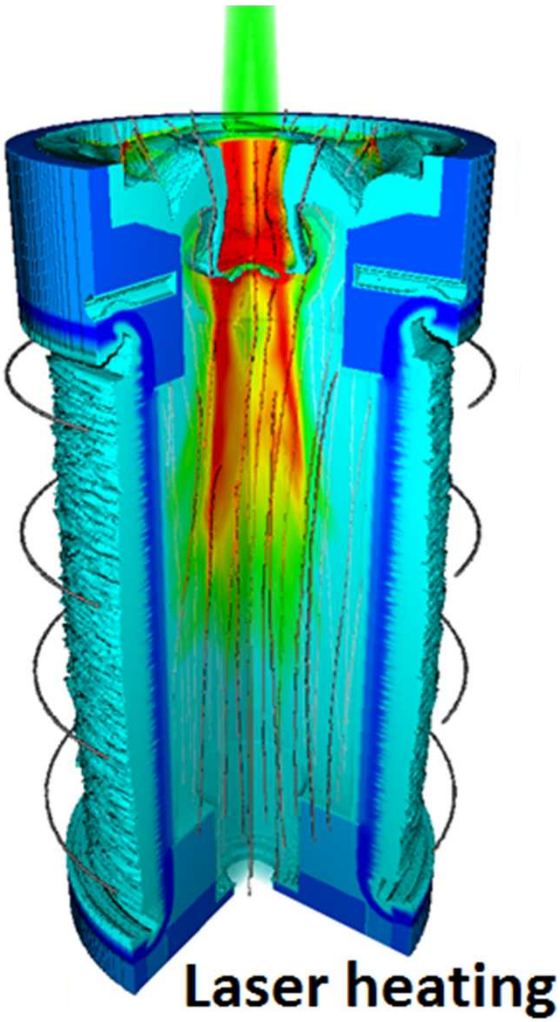
Stage 1: Magnetization



- **Be liner containing fusion fuel**
  - **D2 gas ~ mg/cc (n_e/n_{crit} < 0.1)**
- **Axial magnetic field is applied to target**
  - **10-30 T**
  - **~ ms risetime**
- **Z current starts creating an azimuthal drive field**

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

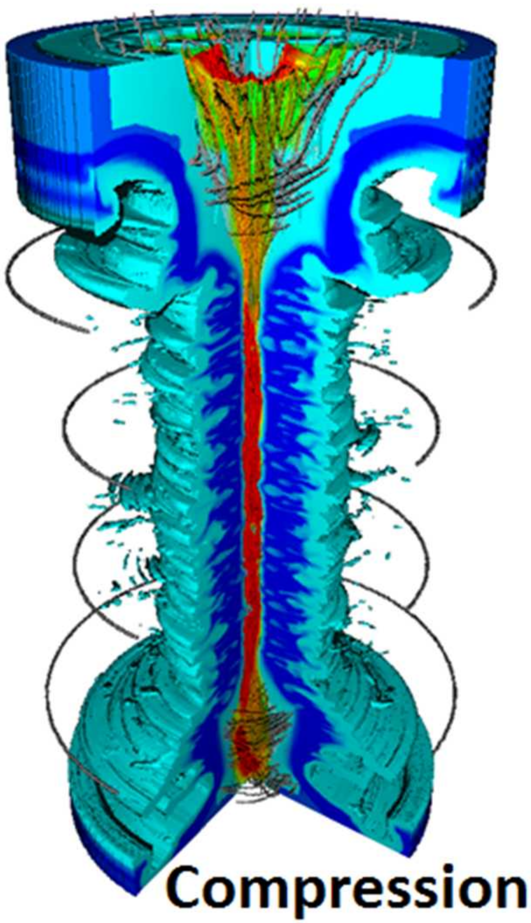
Stage 2: Laser Heating



- **Liner begins to compress**
  - **OD is moving but ID is stationary**
- **Laser heats the fuel**
  - **T_e ~ 100s of eV**
- **Liner ID begins to implode**
- **Simulations indicate that fuel conditions isotropize over the 10s of ns of the implosion**

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

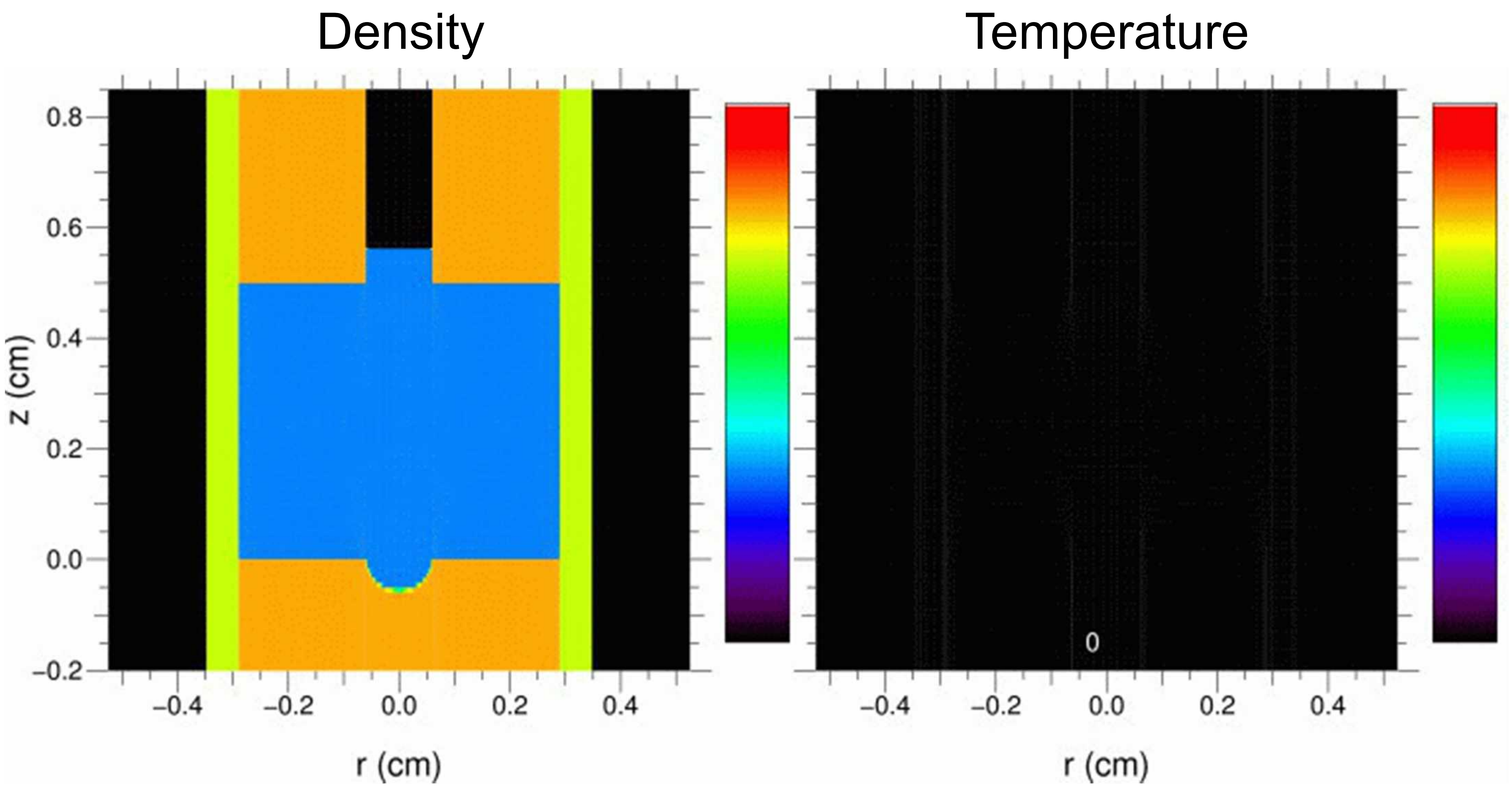
Stage 3: Compression



- **Axial magnetic field insulates fuel from liner throughout implosion**
  - **Field increases substantially through magnetic flux compression**
- **Fuel is heated though PdV work to keV temperatures**
  - **Near adiabatic compression**
- **Liner stagnates**
  - **Plasma pressure exceeds drive pressure**

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

Putting it all together…



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

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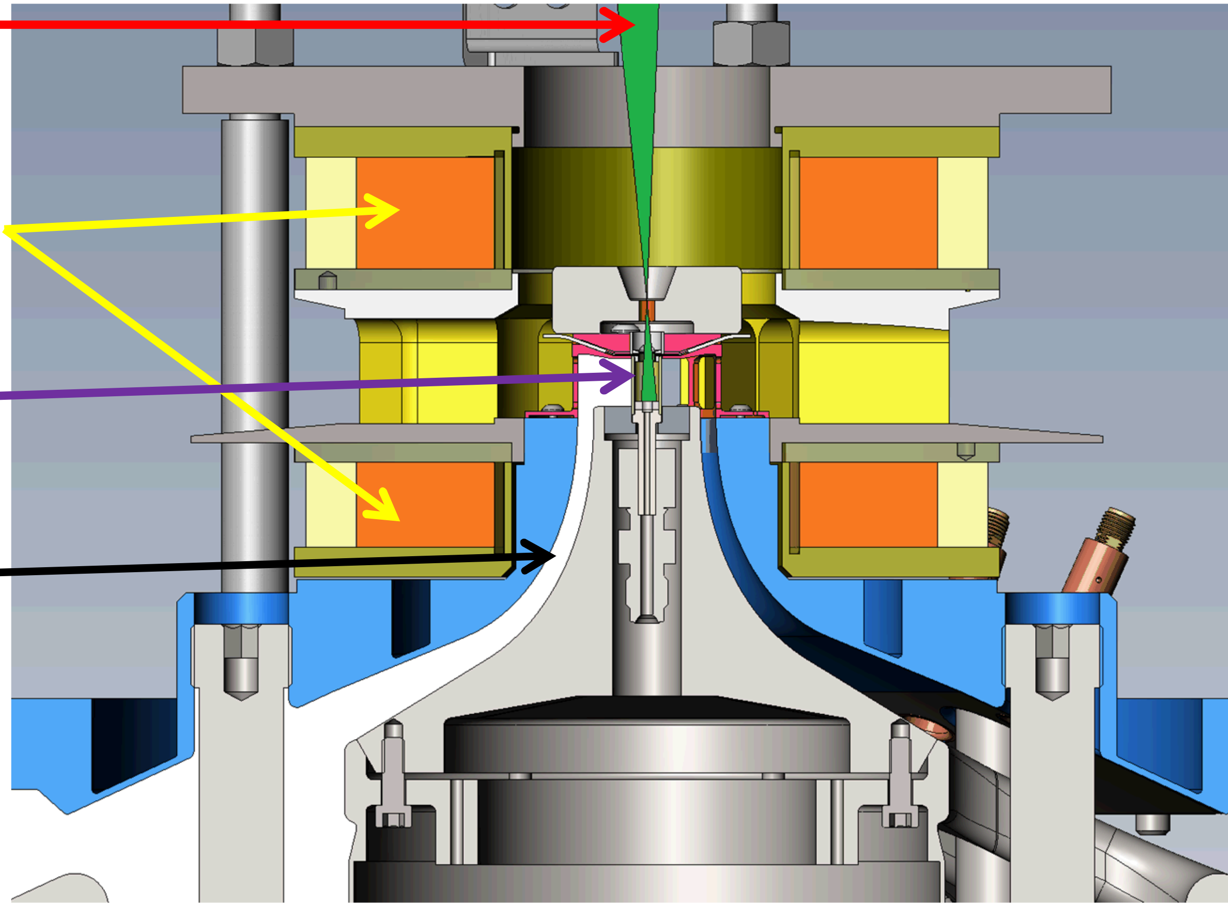
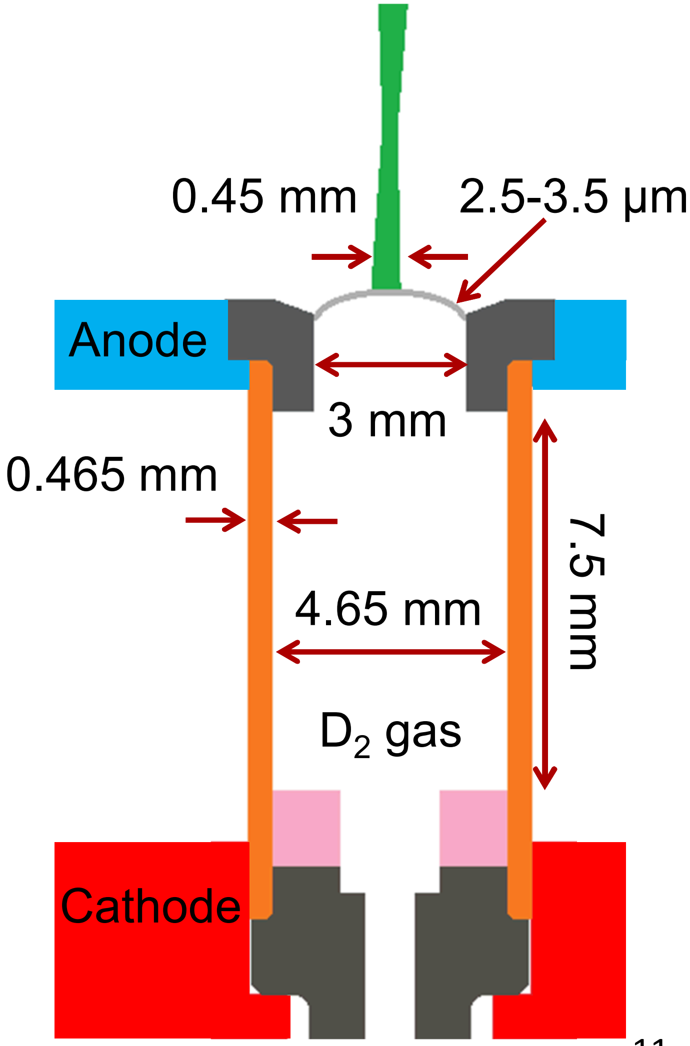
Prior to the integrated experiments, a series of focused experiments were conducted to test all of the critical components of MagLIF

- **Laser preheat**
  - **>20 laser-only experiments**
- **Applied magnetic field**
  - **>10 experiments**
- **Liner Stability**
  - **>30 experiments**
- **Modified power flow**
  - **Geometry scan to minimize losses**
  - **>20 experiments**
- **Fully integrated shots**
  - **5 Z + ZBL shots**



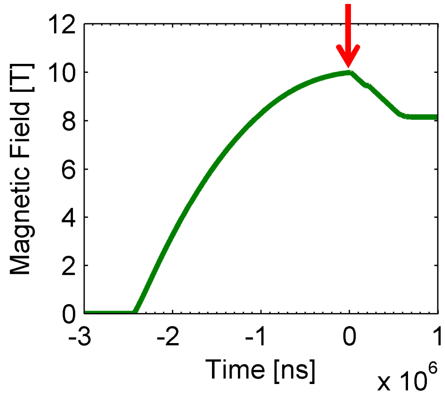
The target design for these initial experiments incorporates the knowledge gained from focused experiments and extensive simulations

- **Beryllium liner with aspect ratio 6**
  - **Thick liner is more robust to instabilities**
  - **Still allows diagnostic access > 5 keV**
- **Top and bottom implosion cushions**
  - **Mitigates wall instability**
- **Standoff between LEH and imploding region**
  - **Avoid window material mixing with fuel**
- **Exit hole at bottom of target**
  - **Avoid interaction with bottom of target**



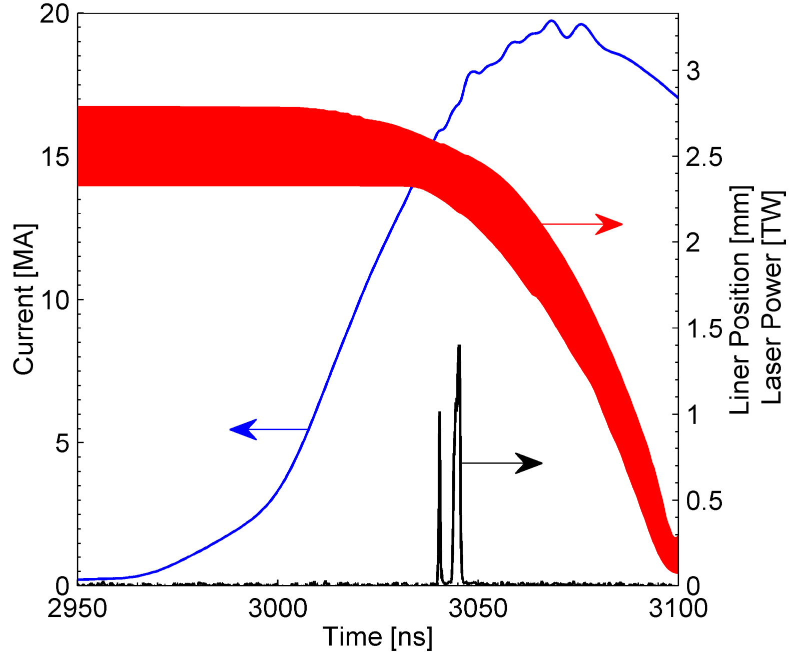
Experiments were conducted at B = 10 T, I = 19 MA, and Laser = 2.5 kJ

Time of experiment



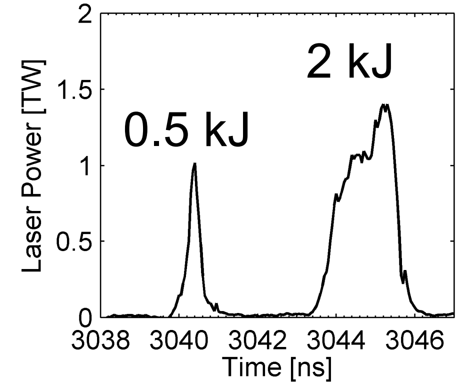
Magnetic field risetime is approximately 2 ms

B is constant over the timescale of the experiment



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

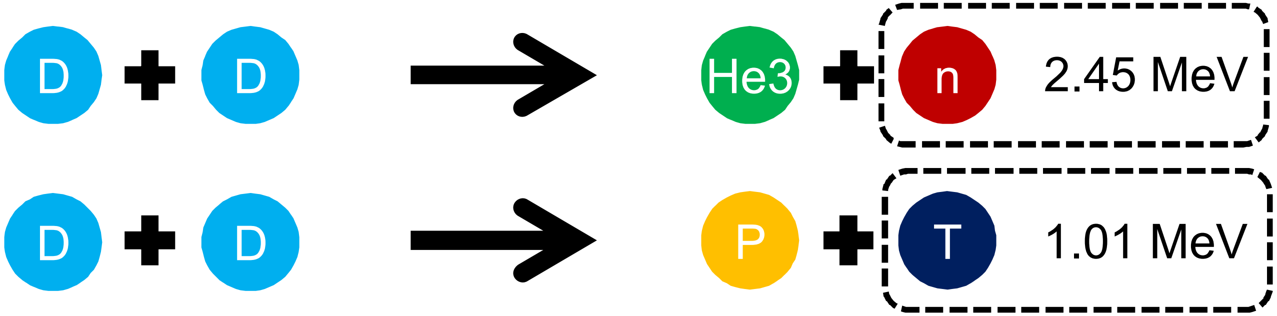
Laser energy is split into 2 pulses:
1st pulse intended to destroy LEH
2nd pulse intended to heat fuel



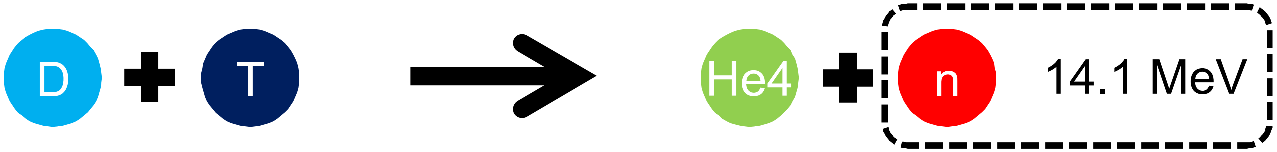
M. R. Gomez, et al., submitted to Phys. Rev. Lett. (2014).

Experiments utilize D2 gas fill at approximately 0.7 mg/cc (60 PSI)

- Primary reactions



- Secondary reactions



- Triton may still retain fraction of birth energy when reacting

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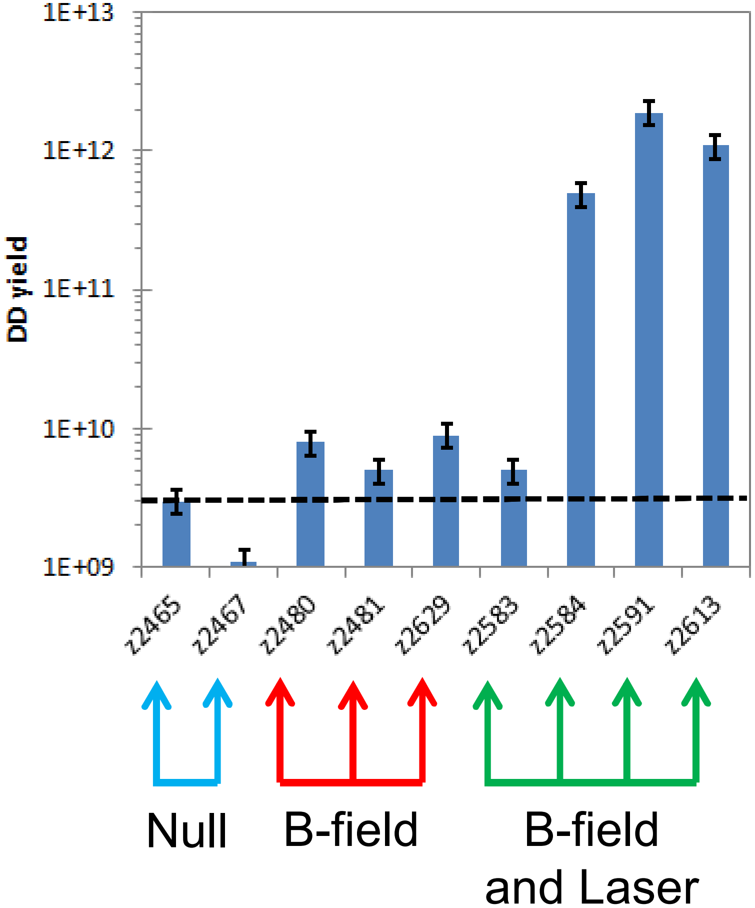
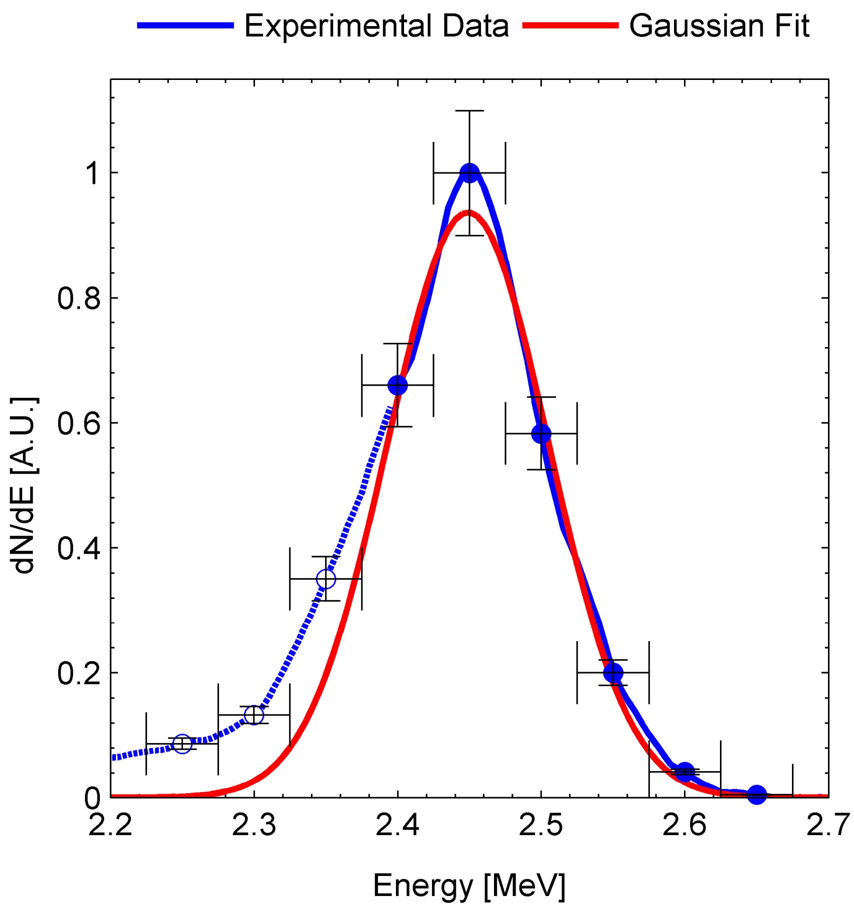
Thermonuclear DD yields in excess of 10^{12} were observed in experiments with laser and B-field



- 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 at this time

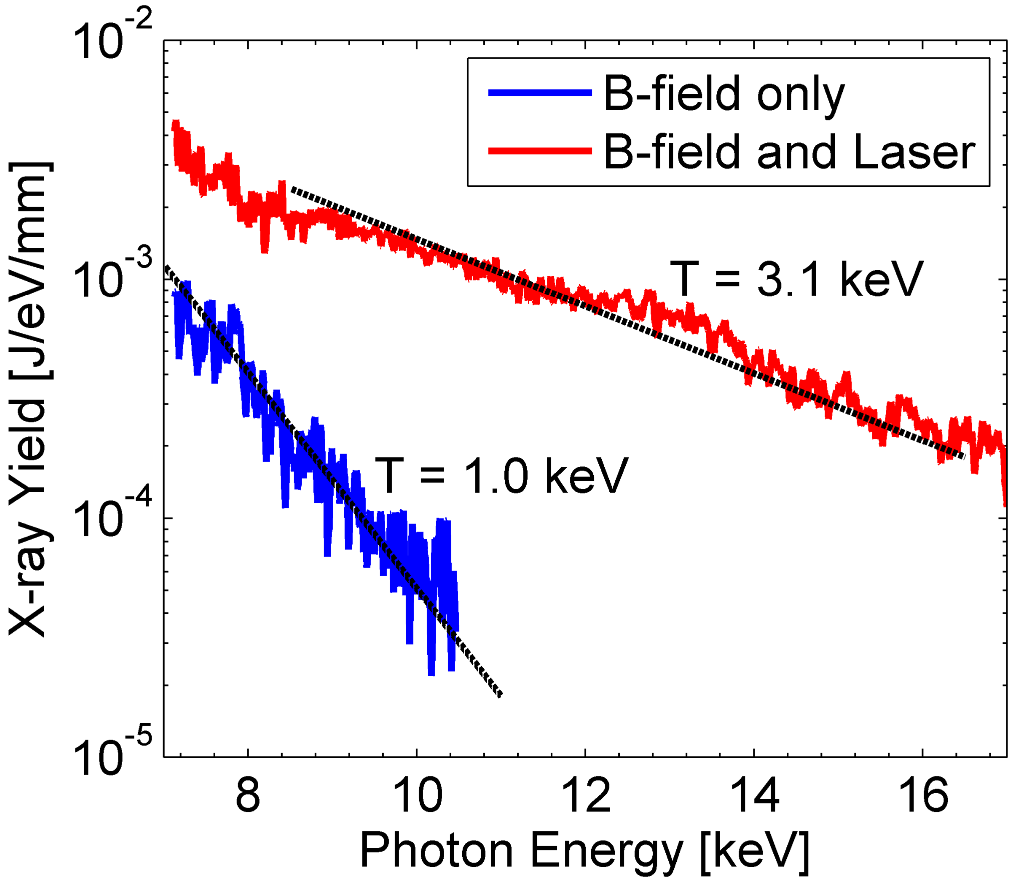
Neutron Time of Flight spectra indicate ion temperatures greater than 2 keV at stagnation



- **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**

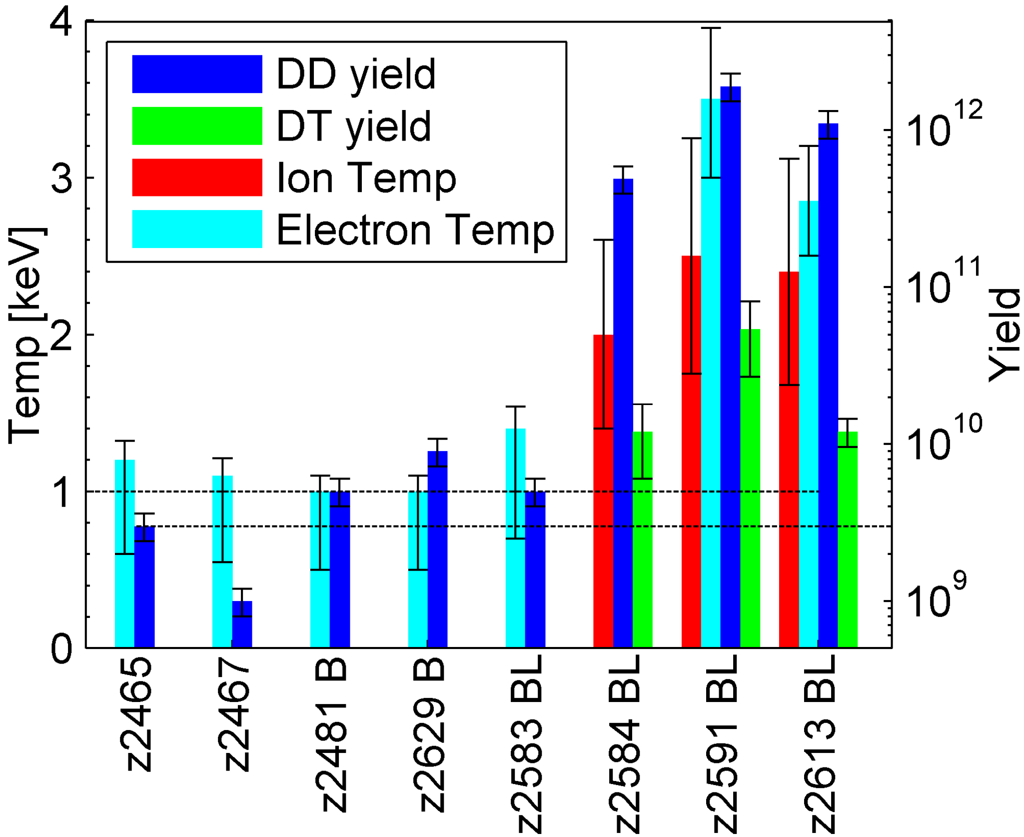
M. R. Gomez, et al., submitted to Phys. Rev. Lett. (2014).

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 keV observed on shots with yield
- Approximately 1 keV observed on shots without yield
- Lower bound on measurement capability is around 1 keV

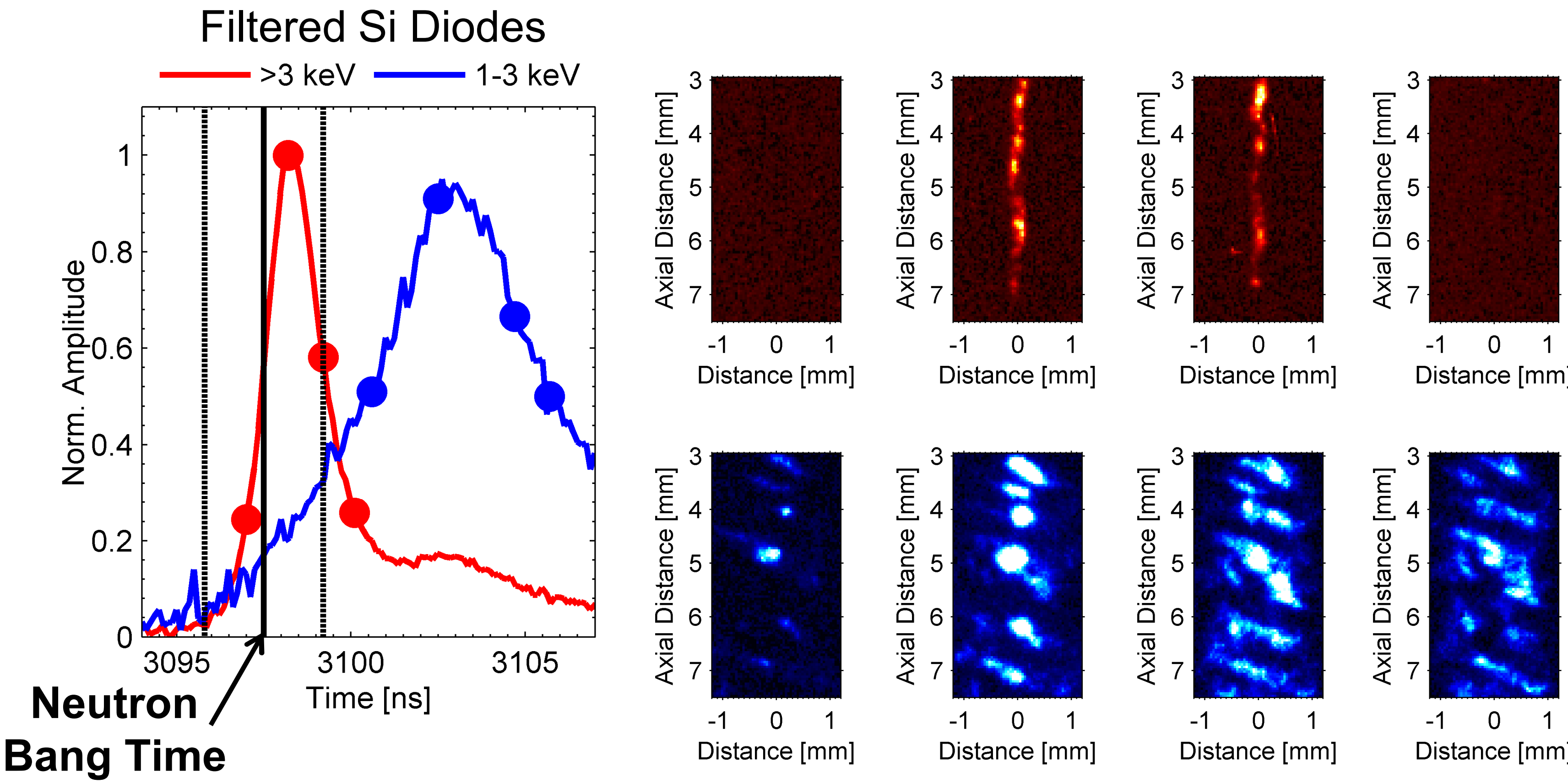
Neutron yield, ion temperature, and electron temperature all trend as expected



- **Experiments with $T_{electron} \approx 1$ keV have negligible DD yield**
- **For $T_i \approx T_e > 2$ keV, significant yield is observed**
- **Measurable DT yield is observed on experiments with high DD yield (more on this later)**

M. R. Gomez, et al., submitted to Phys. Rev. Lett. (2014).

High energy x-ray emission timing is consistent with neutron bang time



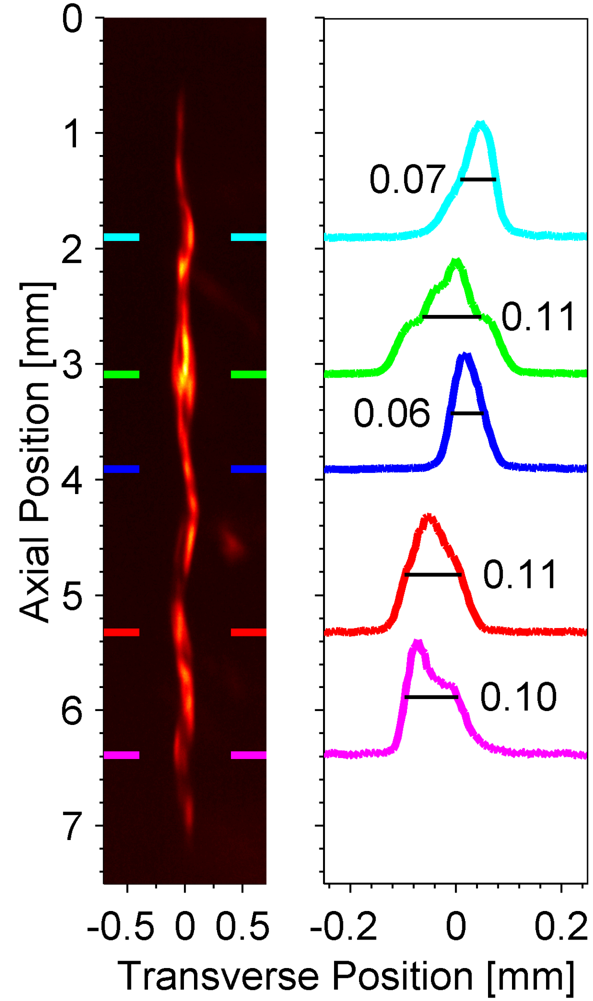
High energy emission from fuel is only observed in experiments with laser and B-field

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

M. R. Gomez, et al., submitted to Phys. Rev. Lett. (2014).

High resolution images of the x-ray emission from the hottest part of the fuel show a relatively stable stagnation column

- **Lineouts of stagnation column vary from 60 to 120 µm FWHM (resolution is about 60 microns)**
- **Emission is observed from about 6 mm of the 7.5 mm axial extent**
- **Emission region does not define the fuel-liner boundary, but defines the hottest region of the fuel**
- **Stagnation column is weakly helical with 1.3 mm wavelength and 0.05 mm offset**



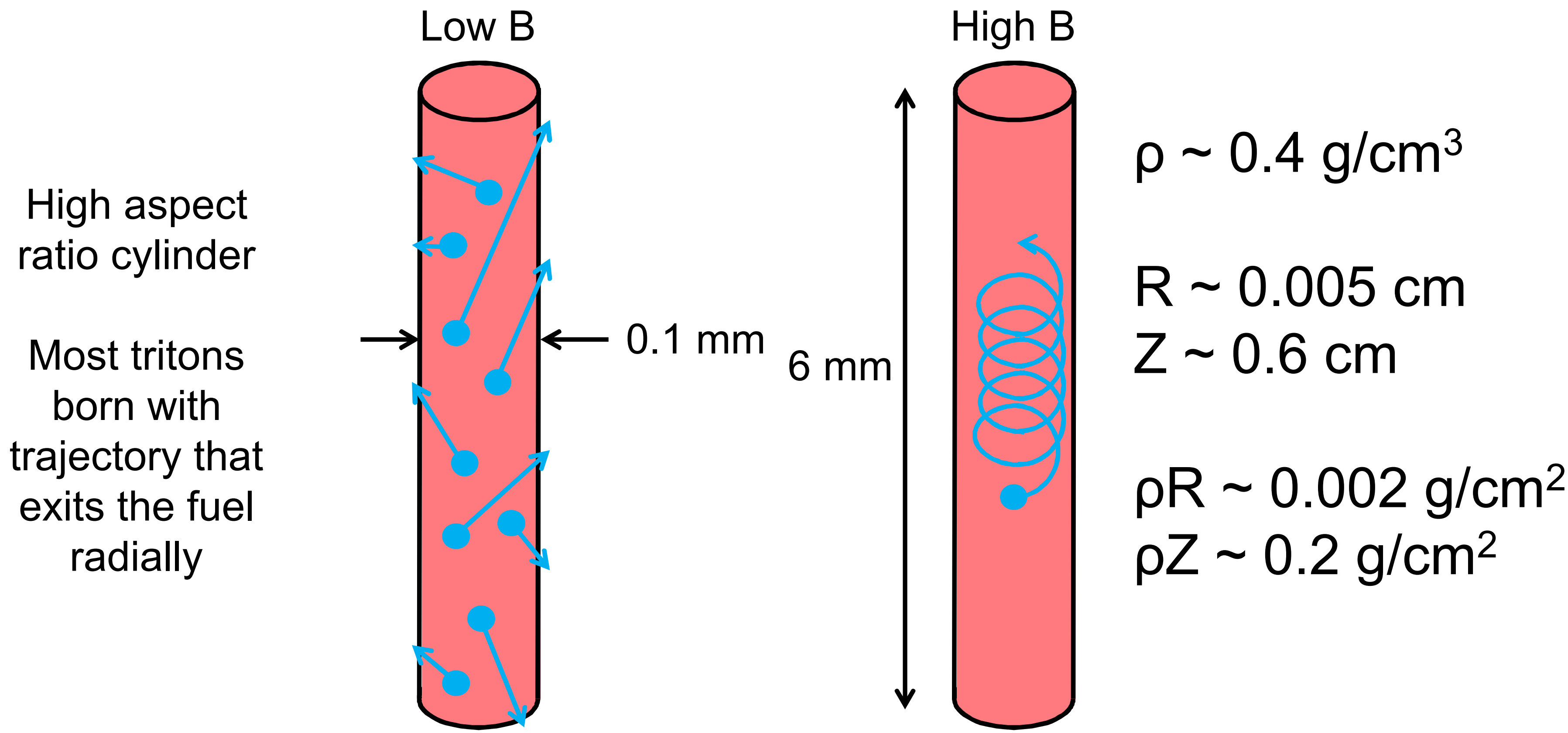
M. R. Gomez, et al., submitted to Phys. Rev. Lett. (2014).

Measured and inferred stagnation parameters are consistent with the measured DD yield

- Hot fuel: r = 40-50 µm, h = 4-6 mm
  - $V \approx 2\text{-}5 \times 10^{-5}$ cm^3
- $\tau \approx$ 1-2 ns
- Stagnation density = 0.2-0.6 g/cm^3
  - $n \approx 0.66\text{-}2.0 \times 10^{23}$/cm^3
- Stagnation temperature = 2-3.1 keV
  - $\langle\sigma v\rangle \approx 0.5\text{-}2.8 \times 10^{-20}$
- $f = 0.5n^2\langle\sigma v\rangle \approx 1.1\text{-}56 \times 10^{25}$/cm^{3}s
- Calculated Yield = $\tau V f \approx$ 2e11-6e13 DD neutrons
- Measured yield = 5e11-2e12 DD neutrons

M. R. Gomez, et al., submitted to Phys. Rev. Lett. (2014).

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



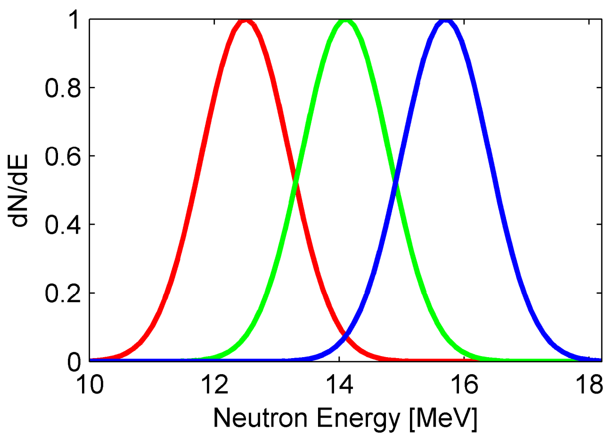
Tritons sample small ρr when B-field is low so DT/DD is low

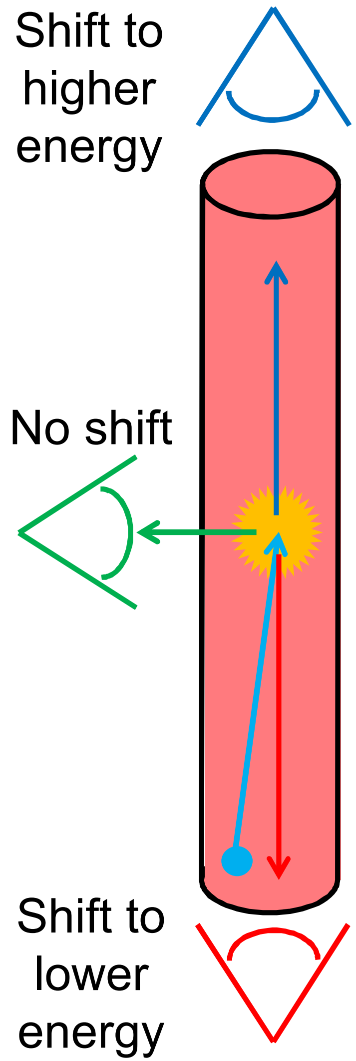
High B-field traps tritons increasing the effective ρr so DT/DD increases

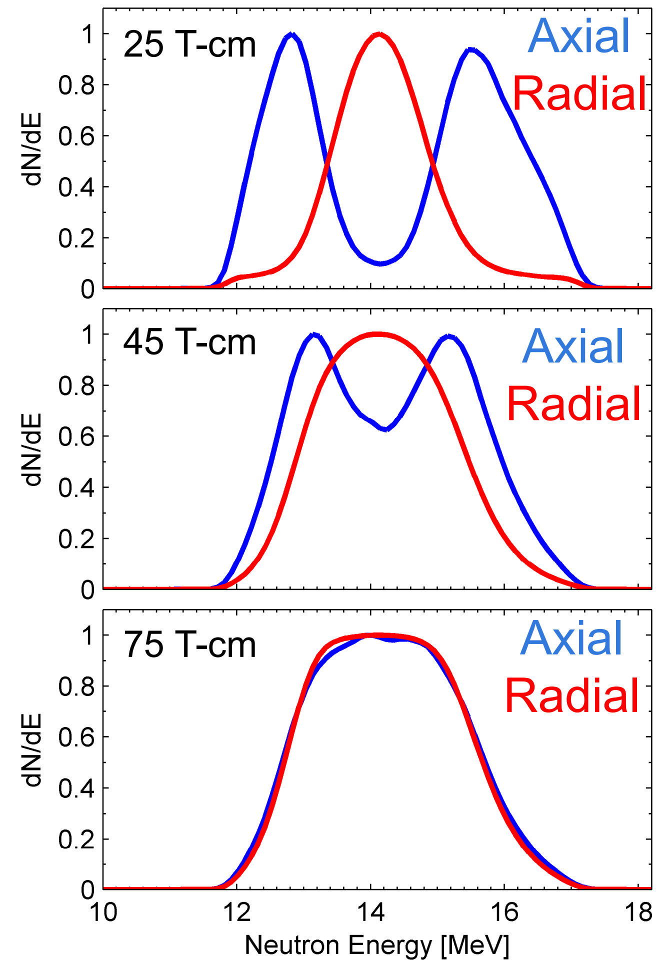
P. F. Schmit, P. F. Knapp, et al., submitted to Phys. Rev. Lett. (2014).

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

DT reactions primarily occur for tritons traveling along the Z axis





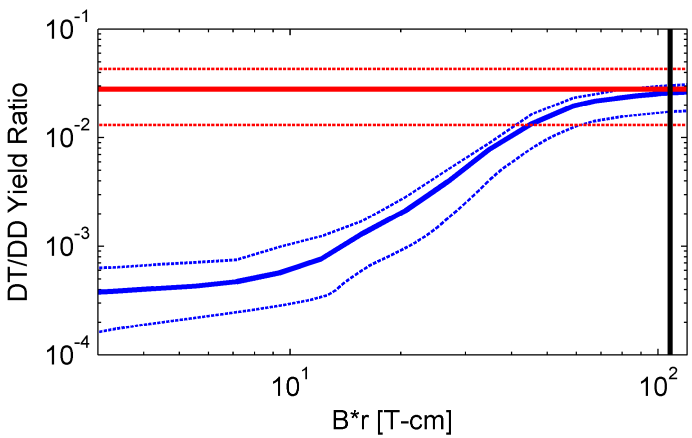


P. F. Schmit, P. F. Knapp, et al., submitted to Phys. Rev. Lett. (2014).

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

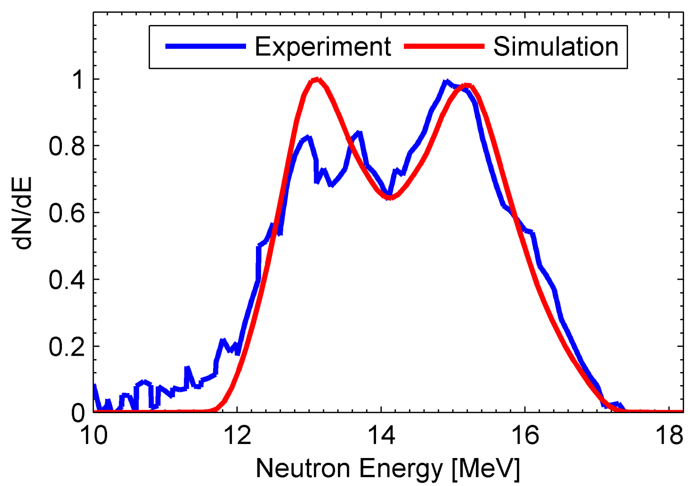
Measured

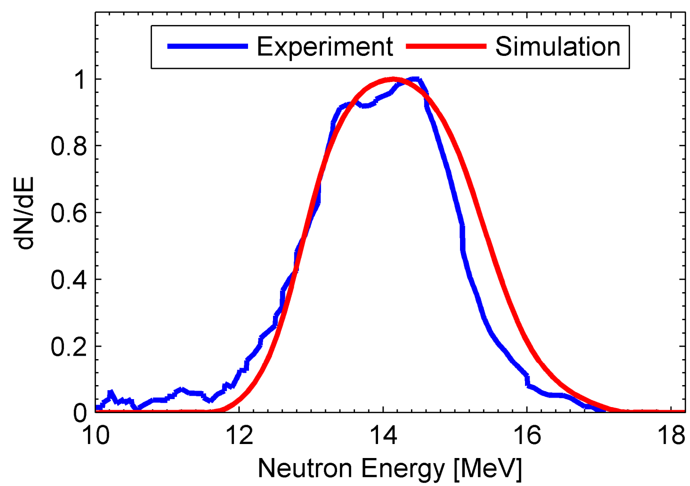
Calculated



$Y_{DT}/Y_{DD} = 1.3\text{-}4.3 \times 10^{-2}$
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, P. F. Knapp, et al., submitted to Phys. Rev. Lett. (2014).

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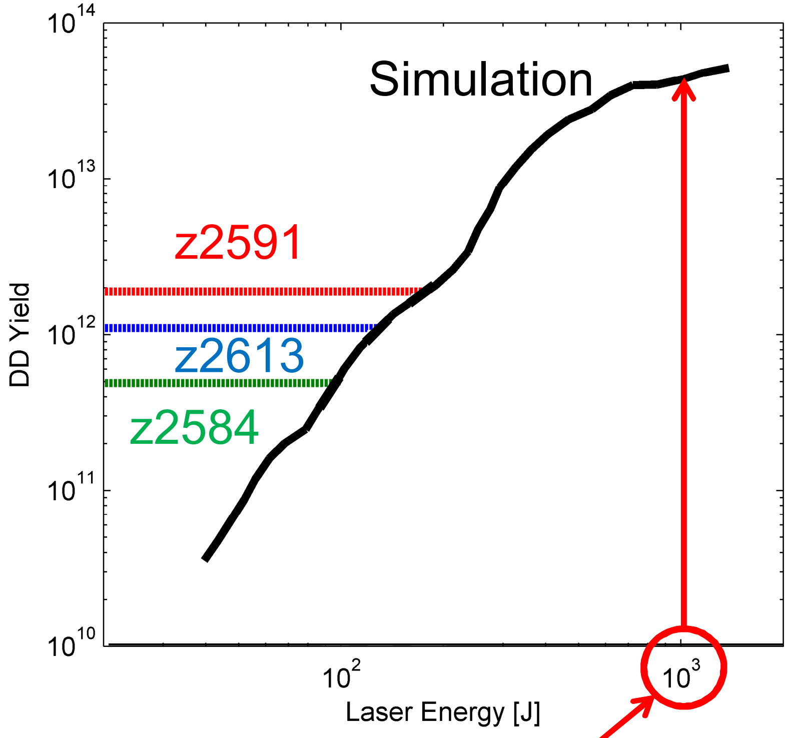
Experimental observables are well matched by 2D simulations

Parameter	Experimental	Simulation[1]
Current	19 ± 1.5 MA	19 MA
Implosion time	90 ± 1 ns	90 ns
Energy absorbed in gas	Unknown, < 600 J	150 ± 50 J
R_{stag} hot plasma	44 ± 13 μm	40 μm
T_{ion}, T_{elec}	2.0-2.5 keV, 2.5-3.1 keV	3.0 ± 0.5 keV, 2.7 ± 0.5 keV
$Density_{stag}$	0.4 ± 0.2 g/cm^3	0.4 ± 0.2 g/cm^3
ρR_{liner}	0.9 ± 0.3 g/cm^2	0.9 g/cm^2
B^*r_{stag}	40-110 T-cm	48 T-cm
DD yield	2.0 ± 0.4 x 10^{12}	4.4 ± 0.9 x 10^{12} (no Nernst term)
DD/DT yield ratio	40 ± 20	41-57
DD, DT spectra	Isotropic, asymmetric	Isotropic, asymmetric
Burn duration	1.5-2.3 ns (x-rays)	1.6 ± 0.2 ns (neutrons)

[1]A. B. Sefkow, et al., Phys. Plasmas, 21 072711 (2014).

Laser heating was not optimized for these experiments

- **Offline laser transmission measurements indicate that the majority of the laser energy does not make it through the foil**
- **Simulations show the efficiency of laser-energy coupling in these targets is a critical factor**
- **Recent laser transmission experiments with smoothed beam show significantly improved foil transmission**



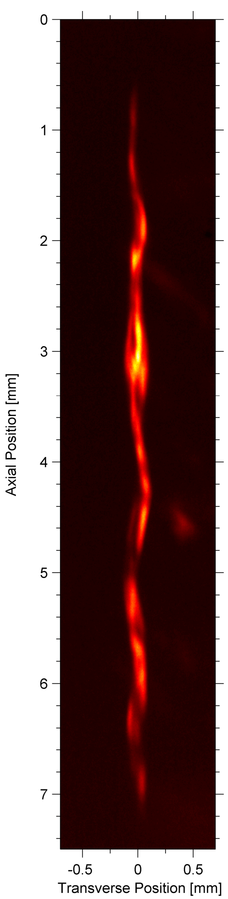
Experiments will be conducted in near future to test improvements in laser coupling with smoothed beams

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

Significant upgrades to key components of MagLIF are planned for the near future

- **Laser energy upgrade in progress**
  - **4 kJ now available**
  - **6+ kJ is expected in early 2015**
- **Laser beam smoothing is under investigation**
- **Magnetic field upgrade available**
  - **15 T now available**
  - **Up to 25 T is expected in early 2015**
  - **30+ T is possible by the end of 2015**
- **> 20 MA drive current expected by early 2015**
  - **Up to 25 MA may be possible on Z**

The Magnetized Liner Inertial Fusion concept has been successfully demonstrated



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