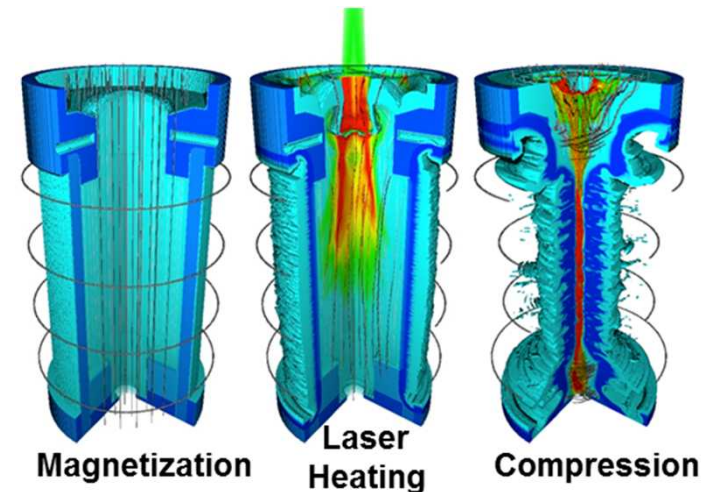
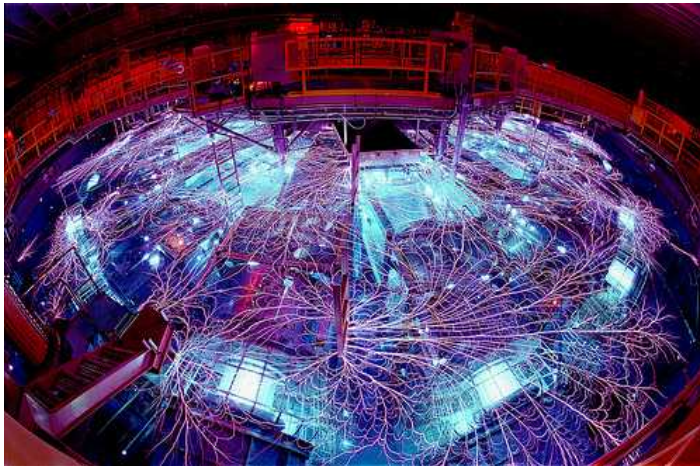


*Exceptional service in the national interest*

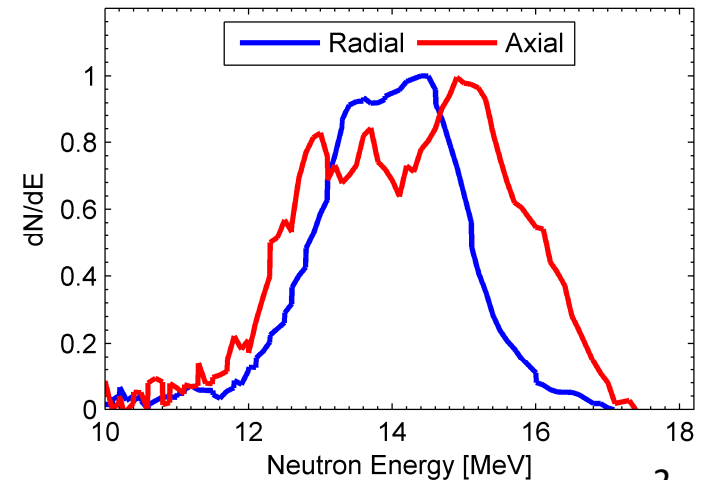
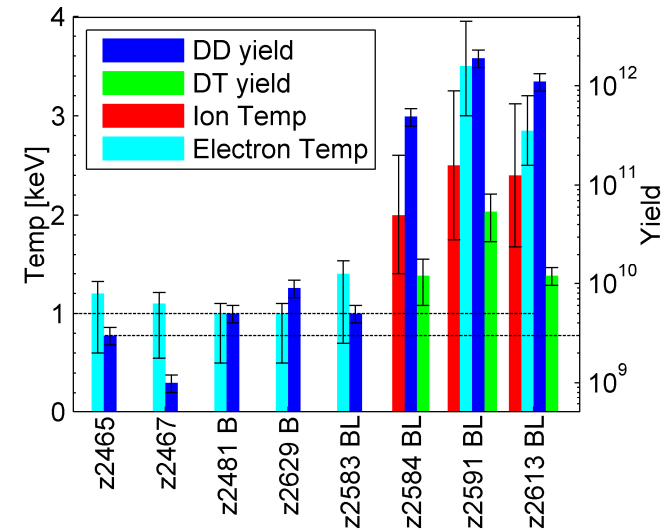
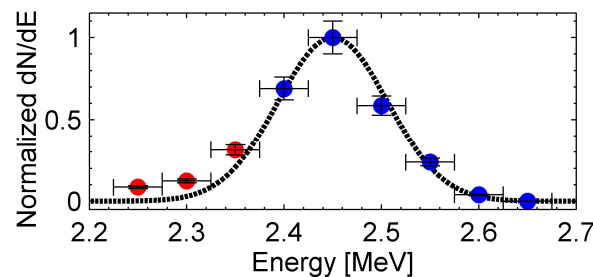
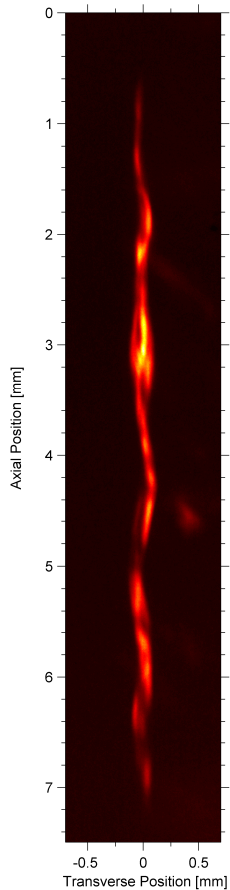


# Experimental Verification of the Magnetized Liner Inertial Fusion (MagLIF) Concept

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

# First integrated MagLIF experiments successfully demonstrated the concept

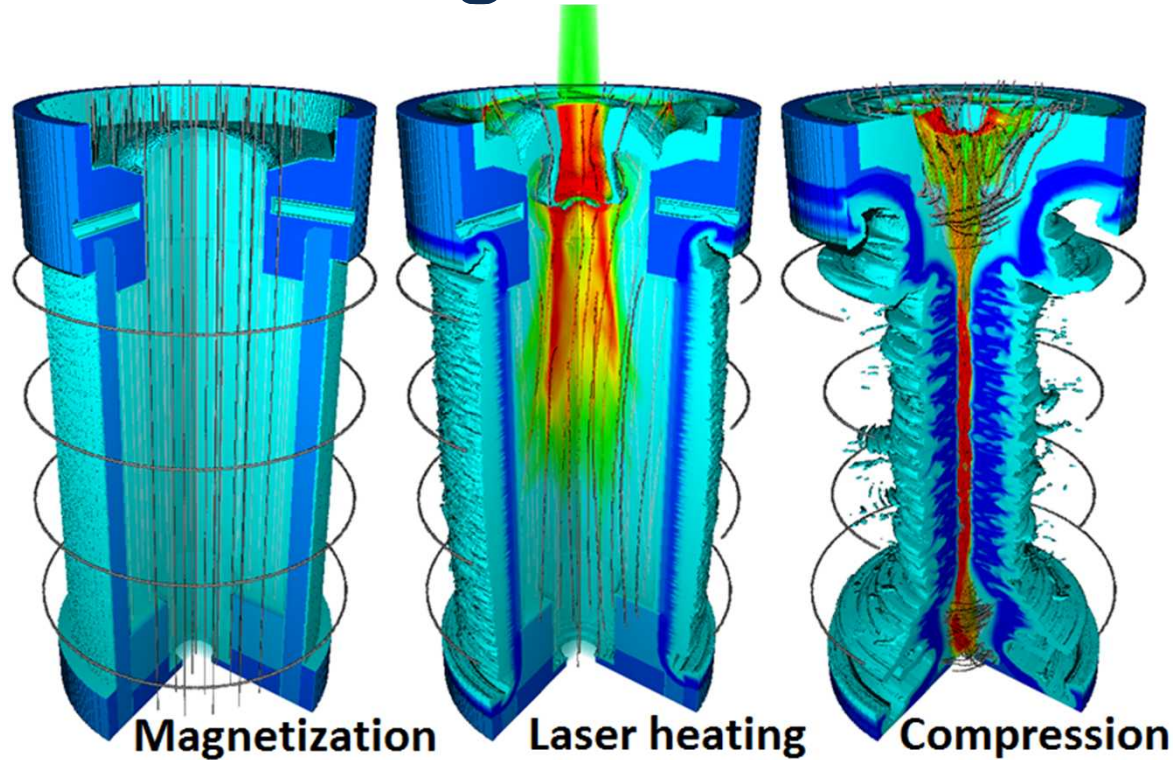
- Thermonuclear neutron generation up to  $2 \times 10^{12}$  DD
- Fusion-relevant stagnation temperatures
- Stable pinch with narrow emission column at stagnation
- Successful flux compression



# Outline

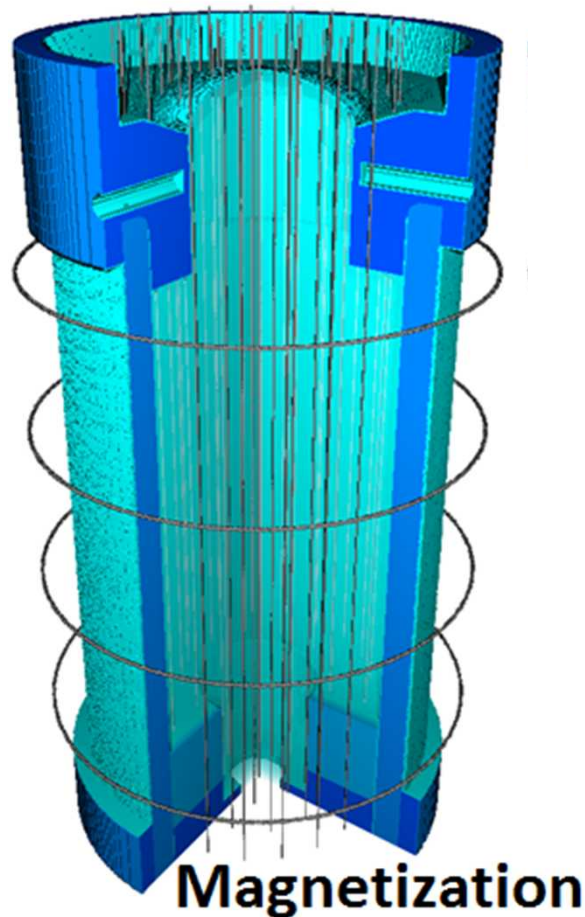
- Summary of experimental results
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# Magnetized Liner Inertial Fusion is a Magneto-Inertial Fusion concept that we are evaluating on Z



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

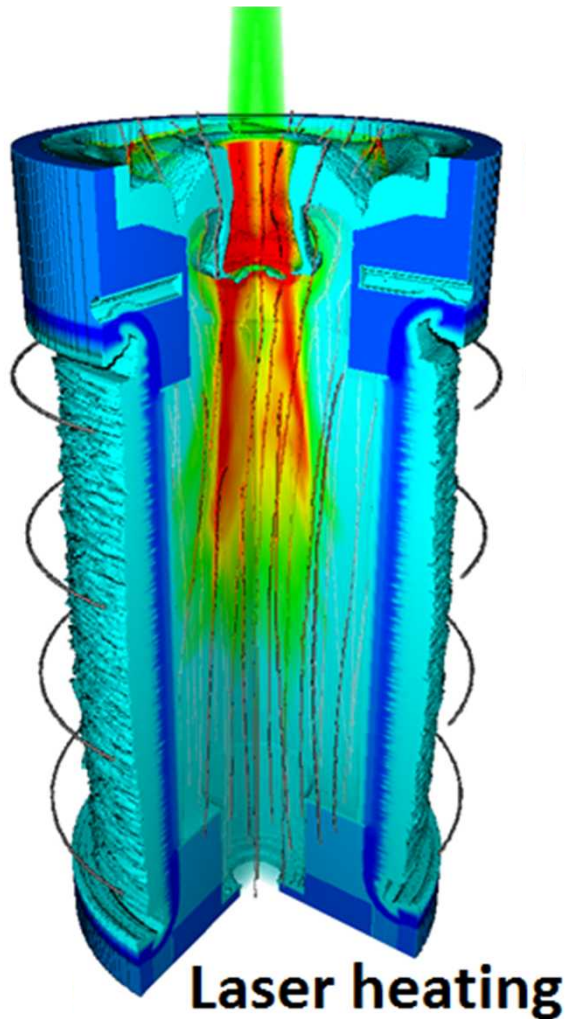
# Stage 1: Magnetization



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

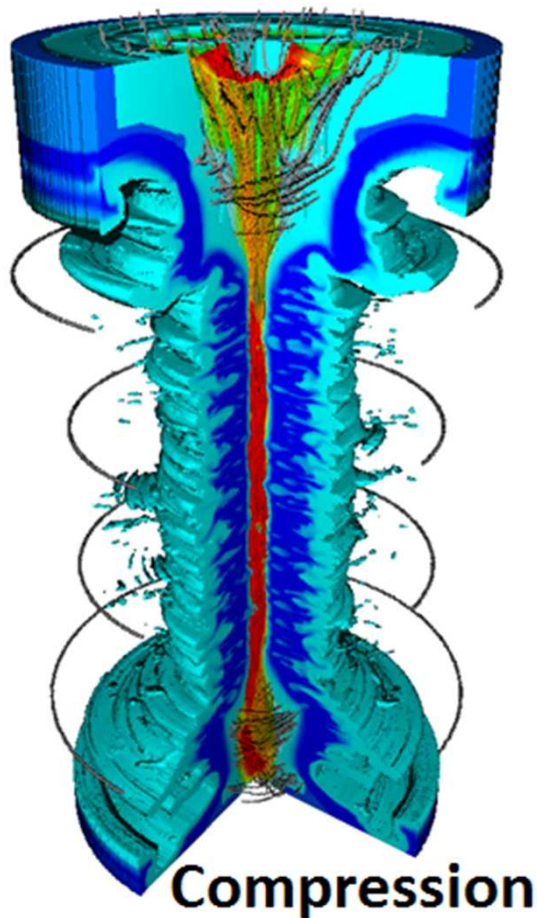


# Stage 2: Laser Heating



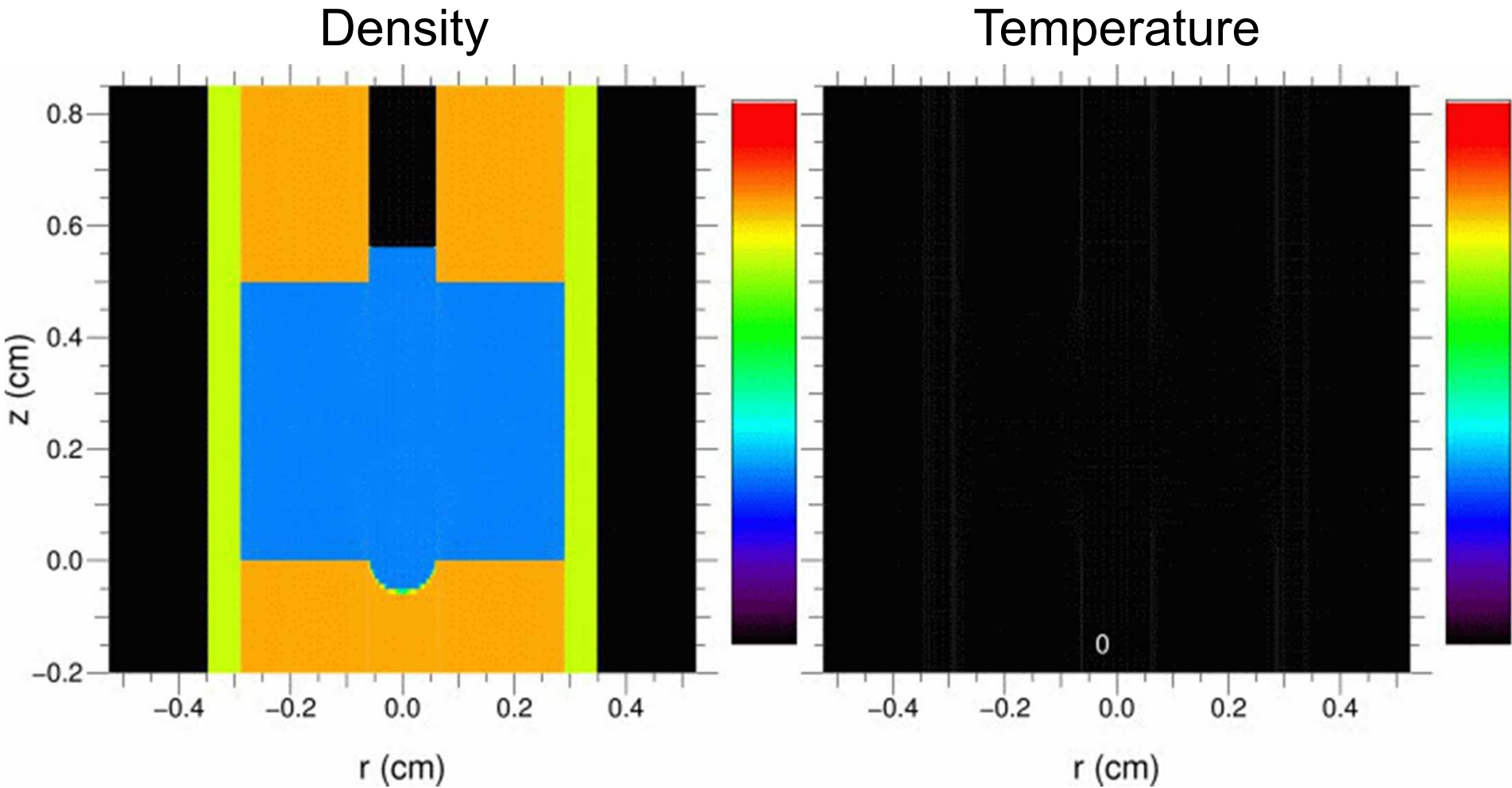
- **Liner begins to compress**
  - OD is moving but ID is stationary
- **Laser heats the fuel**
  - $T_e \sim 100\text{s of eV}$
- **Liner ID begins to implode**
- **Fuel conditions isotropize over the 10s of ns of the implosion**

# Stage 3: Compression



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

# Putting it all together...



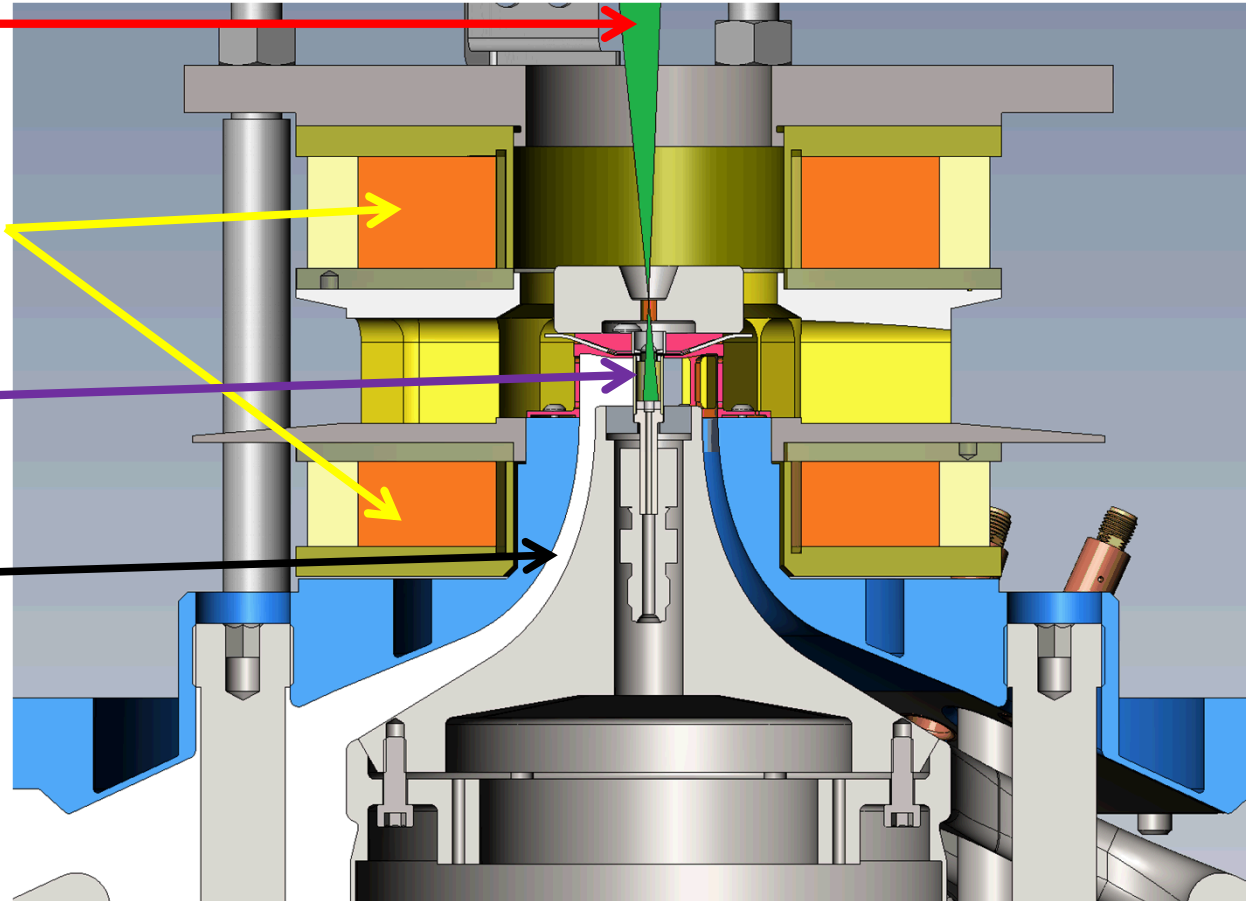


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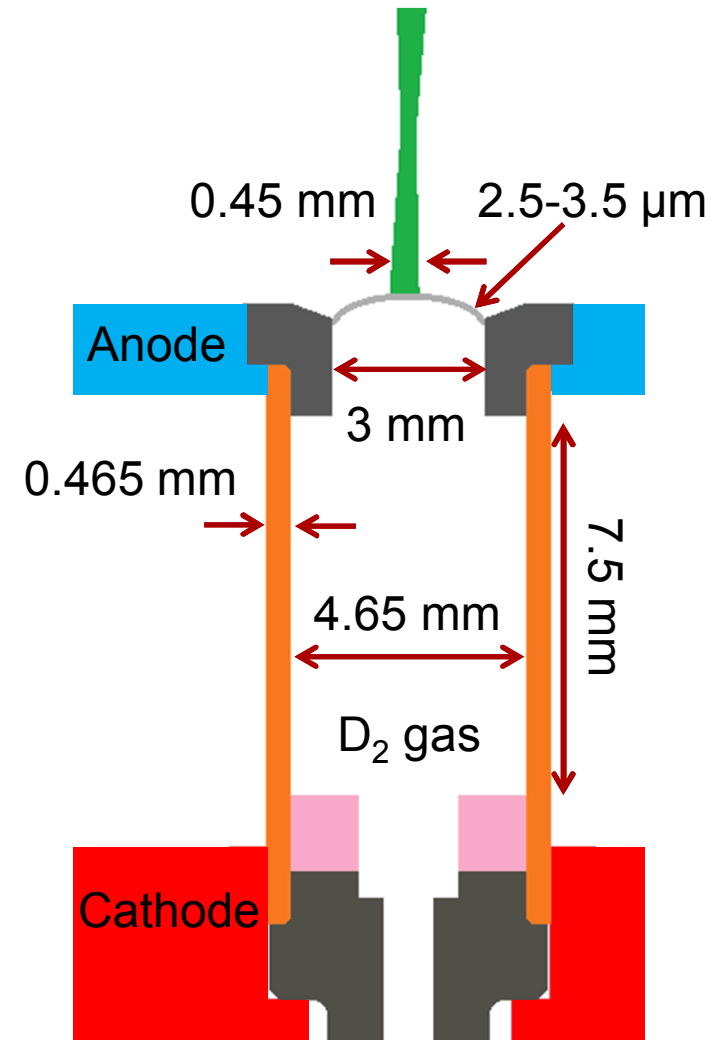
# Prior to the integrated experiments, a series of focused experiments were conducted to test all of the critical components of MagLIF

- **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



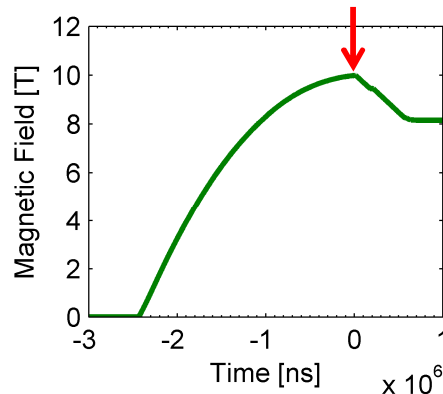
# The target design for these initial experiments incorporates the knowledge gained from focused experiments and extensive simulations

- 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



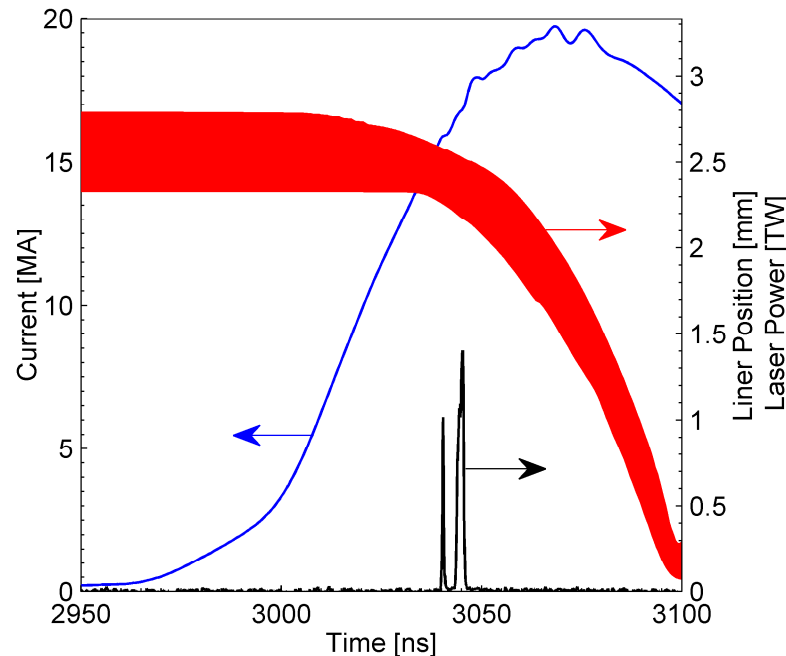
# Initial experiments were conducted at $I = 19$ MA, $B = 10$ T, and Laser = 2.5 kJ

Time of  
experiment



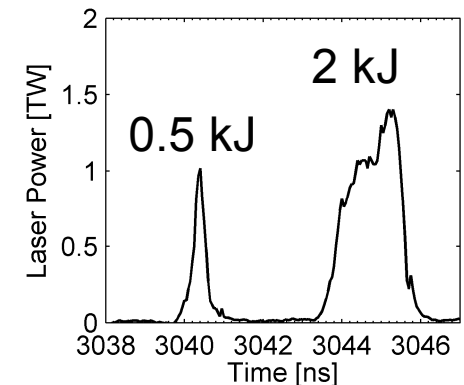
Magnetic field risetime  
is approximately 2 ms

$B$  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:  
1<sup>st</sup> pulse intended to  
destroy LEH  
2<sup>nd</sup> pulse intended to  
heat fuel

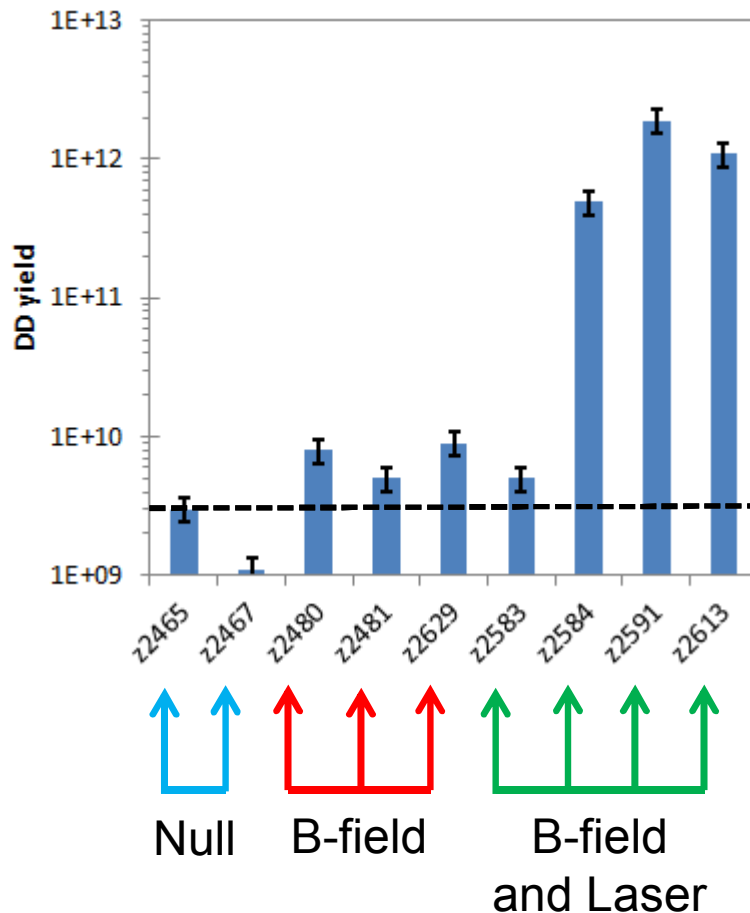


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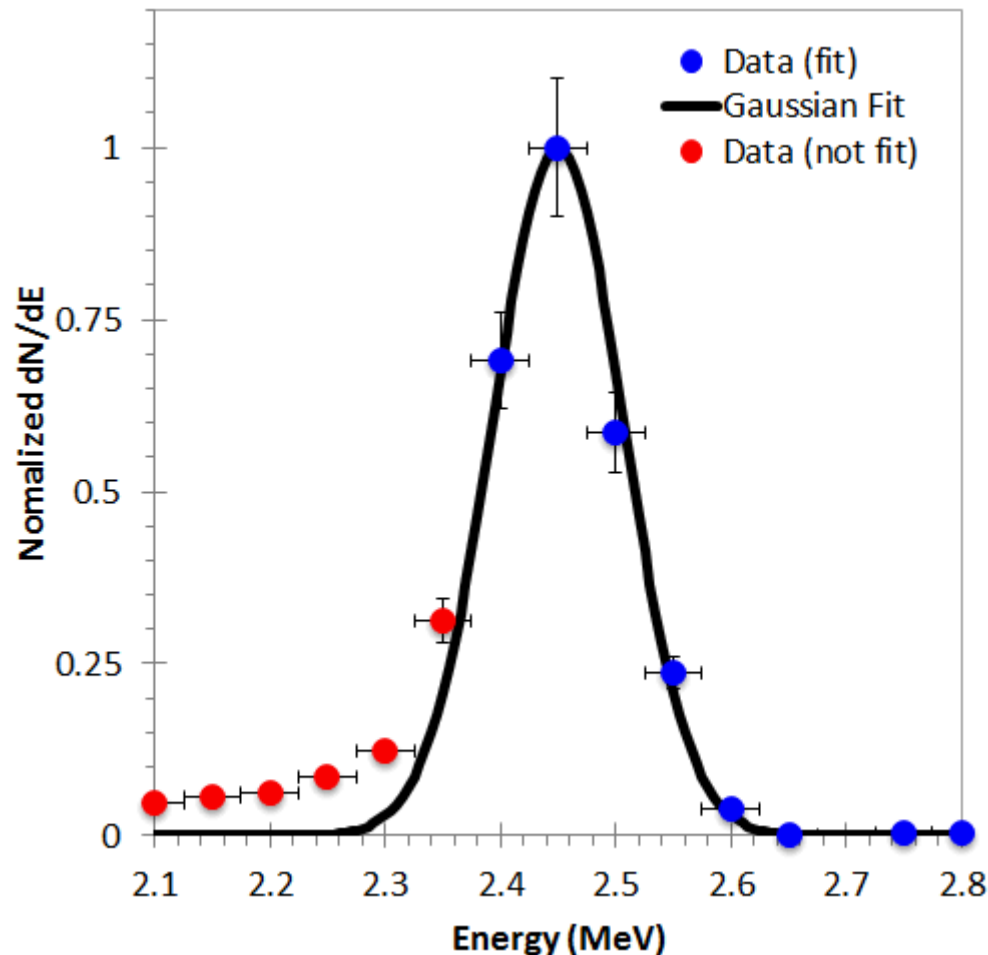


# Thermonuclear DD yields in excess of $10^{12}$ were observed in experiments with laser and B-field



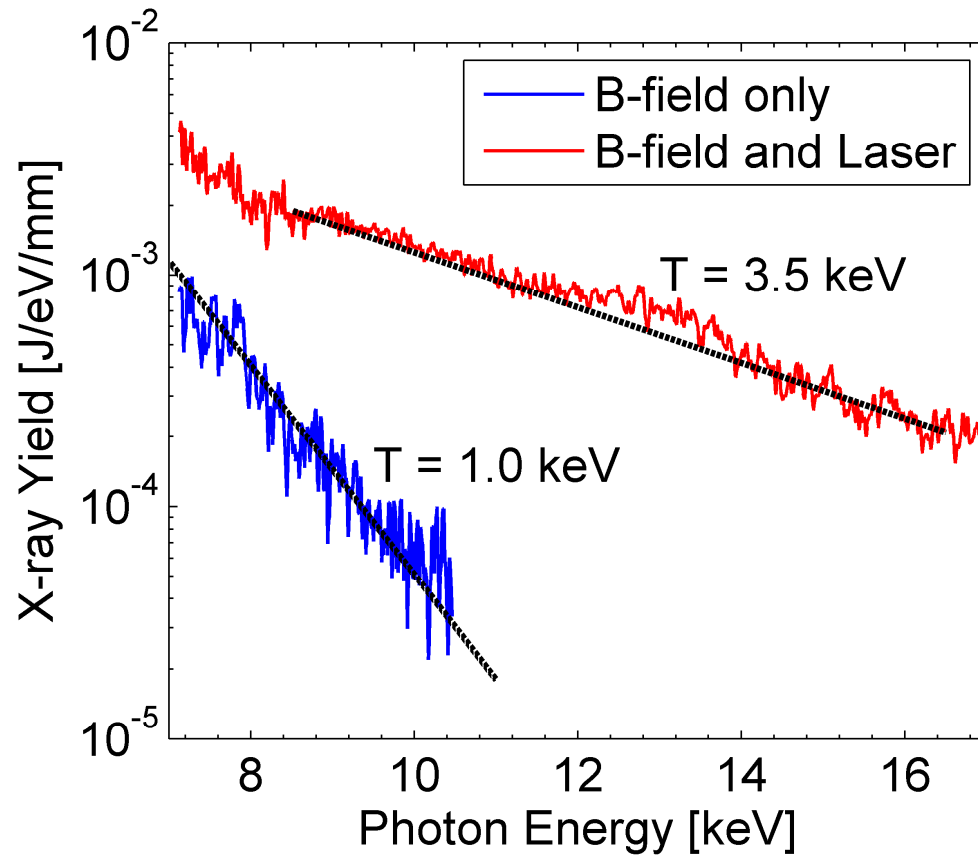
- High yields were only observed on experiments incorporating both applied magnetic field and laser heating
- A series of experiments without laser and/or B-field produced yields at the background level of the measurement
- Result of z2583 is not well understood nor reproduced at this time

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



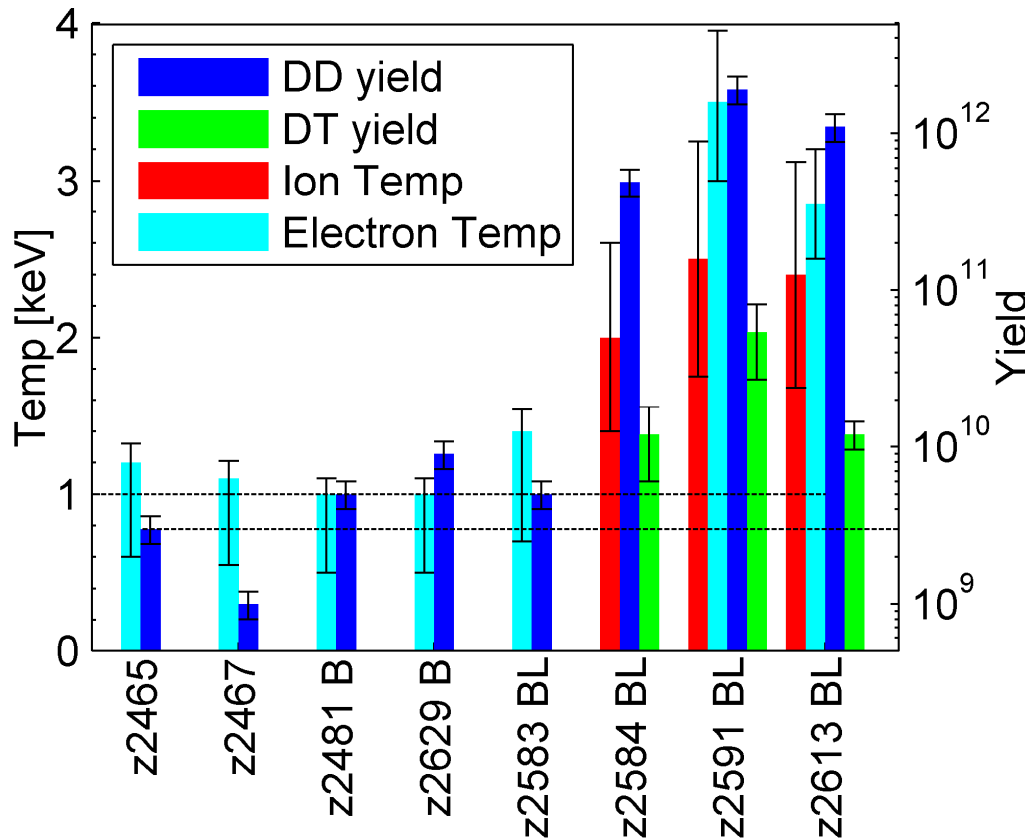
- DD neutron peak observed in experiments with significant yield ( $>1e10$ )
- Gaussian profile fit to high energy side of peak to determine ion temp
- Ion temperatures were between 2 and 2.5 keV for high yield experiments

# High energy x-ray spectra indicate electron temperatures = 2.9-3.5 keV in experiments with laser and B-field



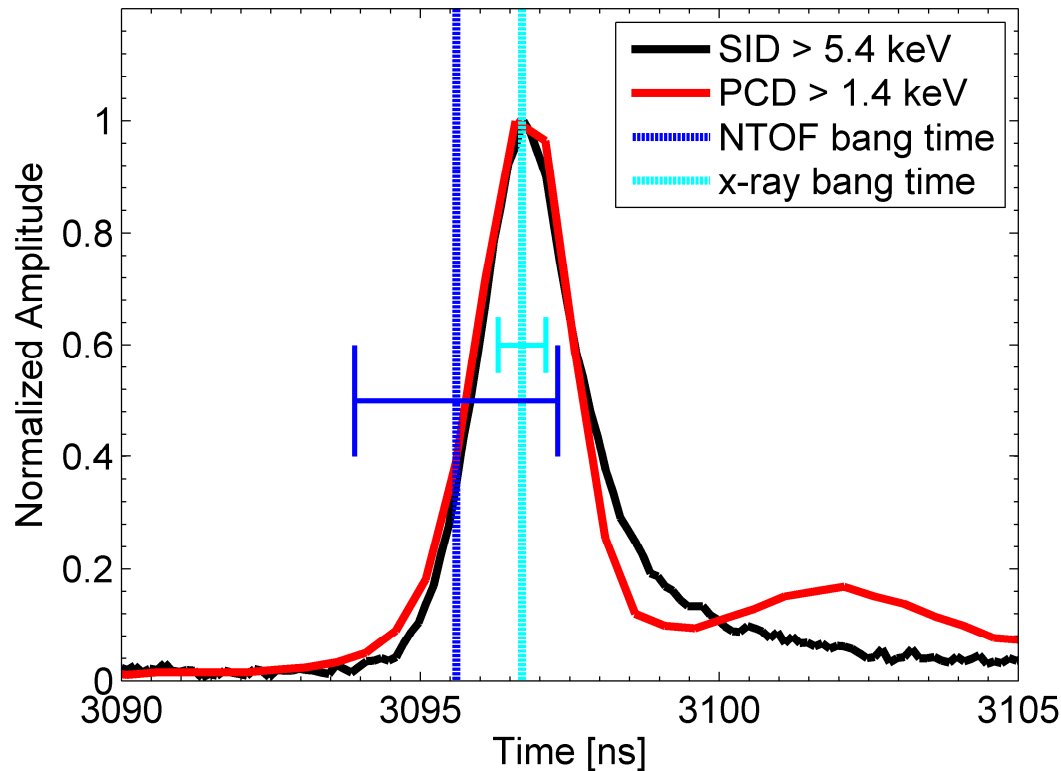
- Electron temperatures inferred from continuum emission
- > 2 keV observed on shots with yield
- Approximately 1 keV observed on shots without yield
- Lower bound on measurement capability is around 1 keV

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



- Experiments with  $T_{\text{electron}} \approx 1$  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)

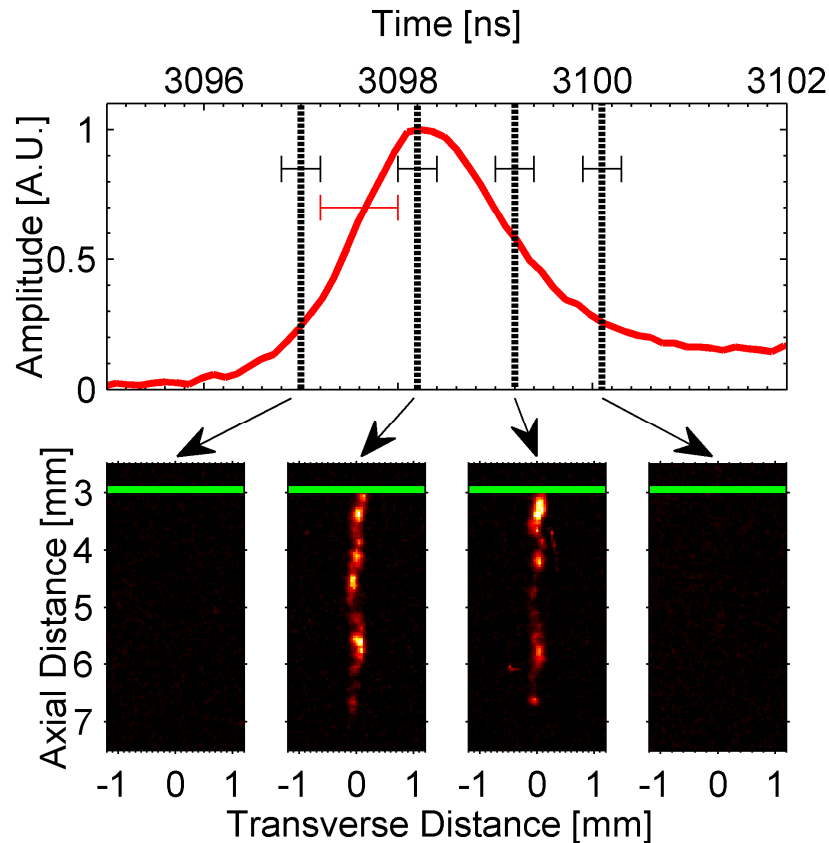
# Narrow (<2 ns FWHM) peak on PCD and Si Diode signals is consistent with NTOF bang time estimate



- Narrow x-ray signature only observed on experiments with significant neutron yield
- X-ray burst has high energy components
- X-ray bang time and NTOF bang time agree within the uncertainty of the measurements



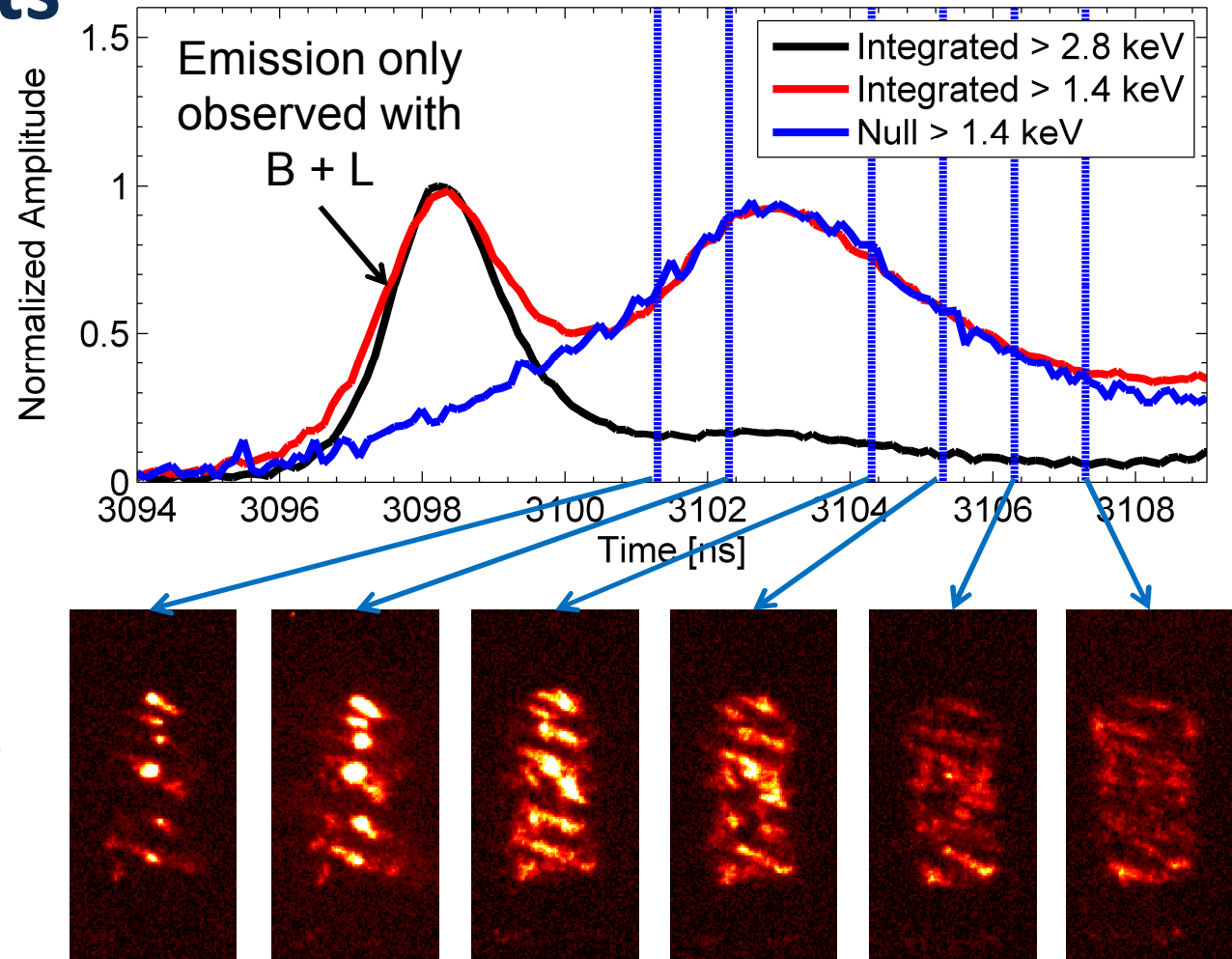
# Time-resolved x-ray pinhole imaging ( $h\nu > 2.8$ keV) shows a narrow emission column during peak in X-ray signal



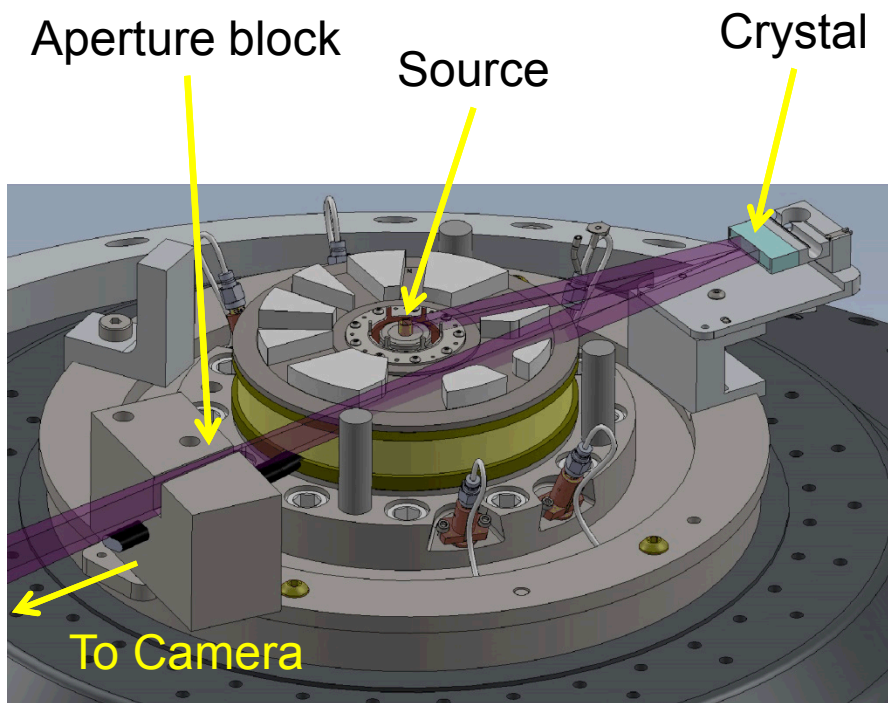
- Emission column is observed only during the peak in the x-ray signal
- Emission column is only observed on experiments with high neutron yield
- Stagnation column width is at the resolution limit of the instrument ( $\sim 150$  microns)

# High energy x-ray signal and narrow emission region are absent in null experiments

- Liner emission is observed in all experiments
- Liner emission is at a lower photon energy ( $< 2.8$  keV)
- Liner emission is getting larger at late times



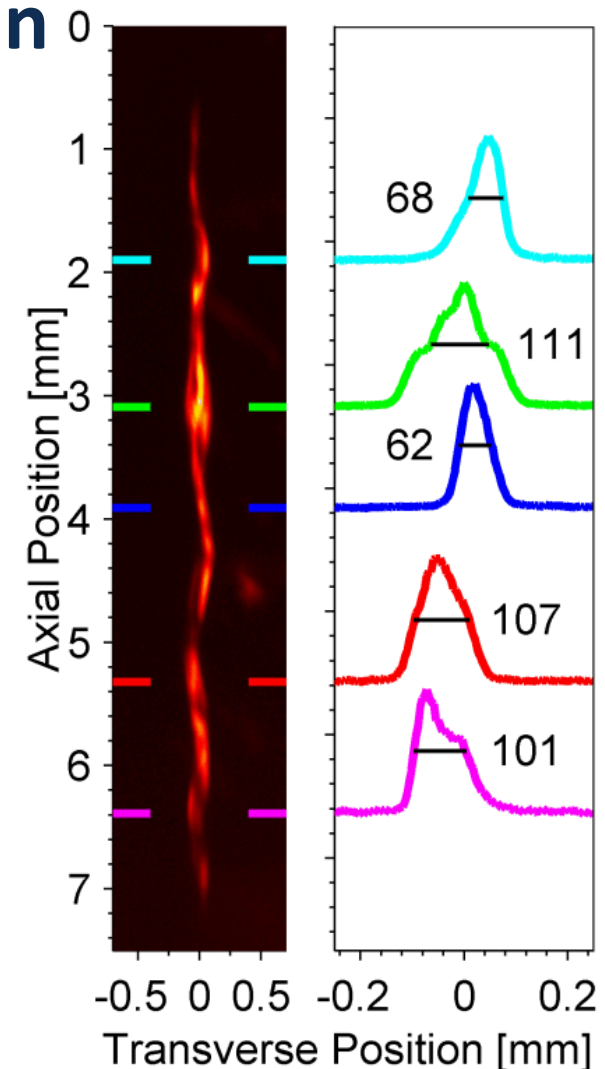
# A new self-emission diagnostic was developed, which helps diagnose the stagnation column with high resolution



- **Bent crystal imager, similar to backlighter system, but in self emission with a Ge 220 crystal**
- **Imaging continuum emission from stagnation column**
- **Given the instrument response and the liner opacity, the signal should primarily consist of 6 and 9 keV photons**

# 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  $\mu\text{m}$  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



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

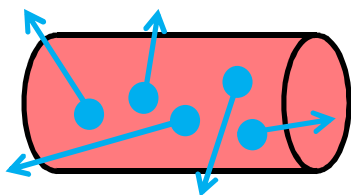
- Hot fuel:  $r = 40\text{-}50\text{ }\mu\text{m}$ ,  $h = 4\text{-}6\text{ mm}$ 
  - $V \approx 2.0\text{-}4.7 \times 10^{-5}\text{ cm}^3$
- $\tau \approx 1\text{-}2\text{ ns}$
- Stagnation density =  $0.2\text{-}0.6\text{ g/cm}^3$ 
  - $n \approx 0.66\text{-}2.0 \times 10^{23}/\text{cm}^3$
- Stagnation temperature =  $2\text{-}3.5\text{ keV}$ 
  - $\langle\sigma v\rangle \approx 0.5\text{-}4.4 \times 10^{-20}$
- $f = 0.5n^2\langle\sigma v\rangle \approx 1.1\text{-}88 \times 10^{25}/\text{cm}^3\text{s}$
- Calculated Yield =  $\tau Vf \approx \text{2e11-8e13}$  DD neutrons
- Measured yield =  $\text{5e11-2e12}$  DD neutrons



# Yield<sub>DT</sub>/Yield<sub>DD</sub> and NTOF spectra indicate significant magnetic flux compression

$$B \cdot r = 0$$

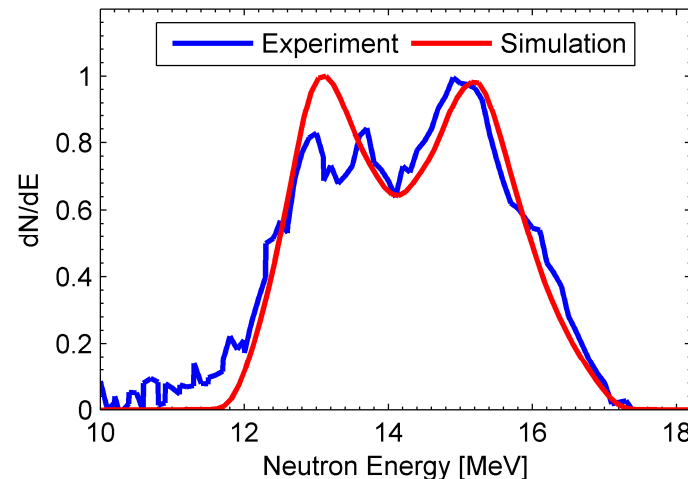
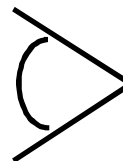
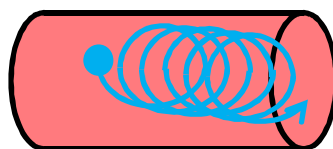
$$Y_{DT}/Y_{DD} \sim 10^{-4}$$



Relatively low estimated  $\mu r$  for these experiments (2.0 mg/cm<sup>2</sup>)

$$B \cdot r > 40 \text{ T-cm}$$

$$Y_{DT}/Y_{DD} \sim 10^{-2}$$



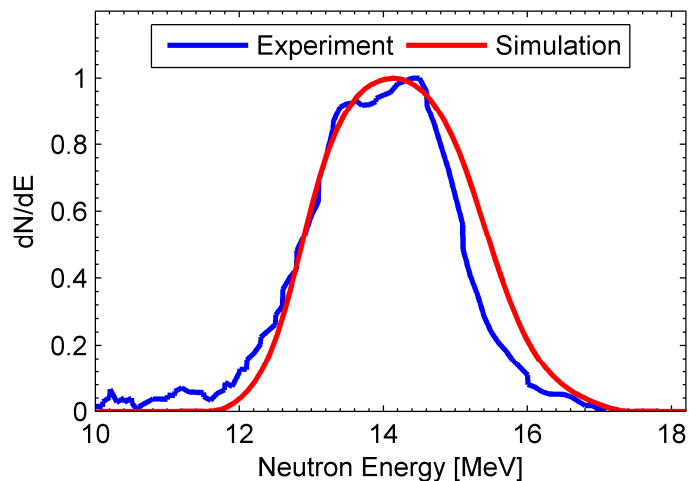
$$Y_{DT}/Y_{DD} = 1.3-4.3 \times 10^{-2}$$

is consistent with

$B \cdot r = 40-110 \text{ T-cm}$

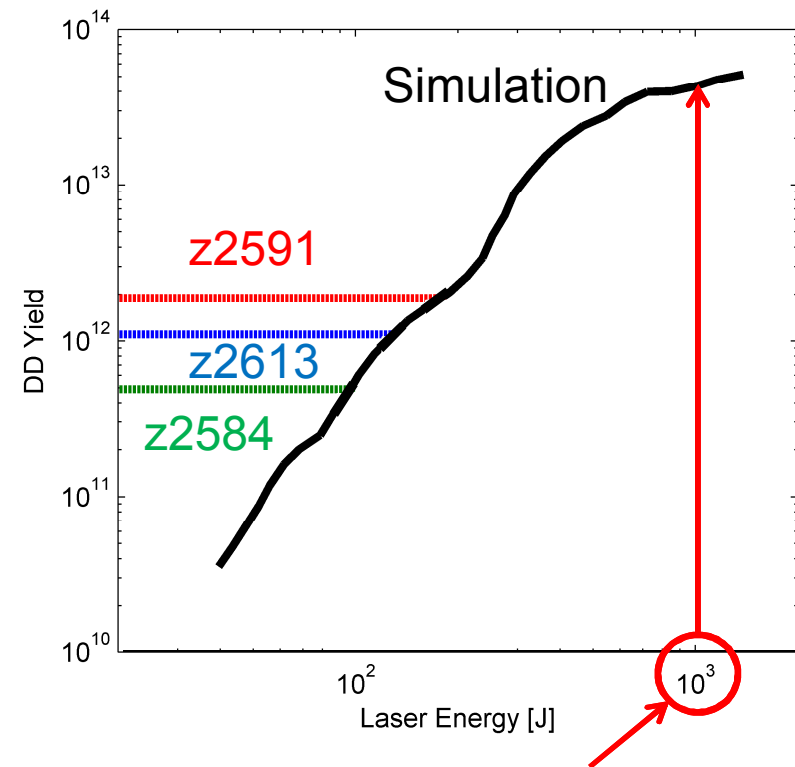
NTOF spectra are consistent with

$B \cdot r \approx 45 \text{ T-cm}$



# 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

# Experimental observables are well matched by 2D simulations

Parameter	Experimental	Simulation
Current	$19 \pm 1.5$ MA	19 MA
Implosion time	$90 \pm 1$ ns	90 ns
Energy absorbed in gas	Less than 600 J	$150 \pm 50$ J
$R_{\text{stag}}$ hot plasma	$44 \pm 13$ $\mu\text{m}$	40 $\mu\text{m}$
$T_{\text{ion}}, T_{\text{elec}}$	2.0-2.5 keV, 2.8-3.5 keV	$3.0 \pm 0.5$ keV, $2.7 \pm 0.5$ keV
Density <sub>stag</sub>	$0.4 \pm 0.2$ g/cm <sup>3</sup>	$0.4 \pm 0.2$ g/cm <sup>3</sup>
$\rho R_{\text{liner}}$	$0.9 \pm 0.3$ g/cm <sup>2</sup>	0.9 g/cm <sup>2</sup>
$B^*r_{\text{stag}}$	40-110 T-cm	48 T-cm
DD yield	$2.0 \pm 0.4 \times 10^{12}$	$4.4 \pm 0.9 \times 10^{12}$ (no Nernst term)
DD/DT yield ratio	$40 \pm 20$	41-57
DD, DT spectra	Isotropic, asymmetric	Isotropic, asymmetric
Burn duration	1.5-2.3 ns (x-rays)	$1.6 \pm 0.2$ ns (neutrons)

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# Significant upgrades to key components of MagLIF are planned for the near future to test our understanding

- **Laser energy upgrade in progress**
  - Expect 4 kJ early this summer
  - 6+ kJ is expected in early 2015
- **Laser beam smoothing is under investigation**
- **Magnetic field upgrade available**
  - 15 T is 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 by the end of 2015



# First integrated MagLIF experiments successfully demonstrated the concept

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- Fusion-relevant stagnation temperatures
- Stable pinch with narrow emission column at stagnation
- Successful flux compression

