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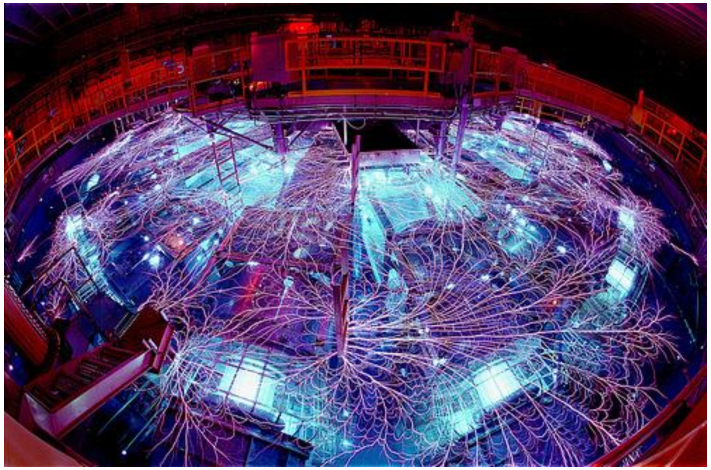

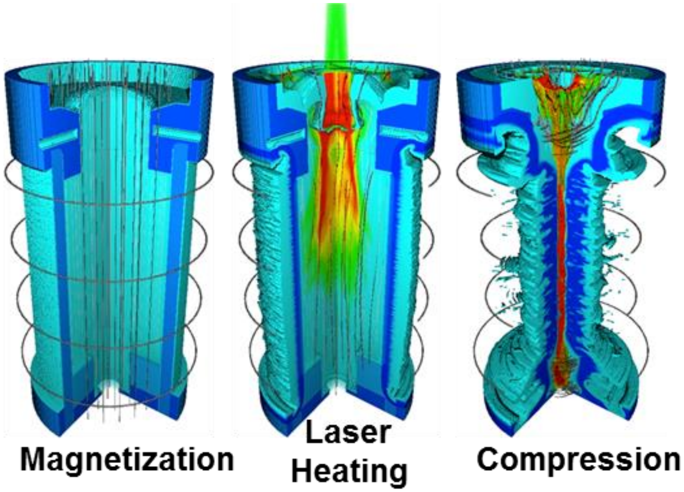

Experimental Verification of the Magnetized Liner Inertial Fusion (MagLIF) Concept

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U.S. DEPARTMENT OF ENERGY

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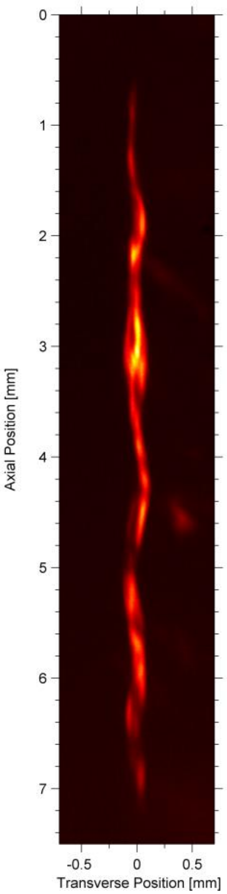
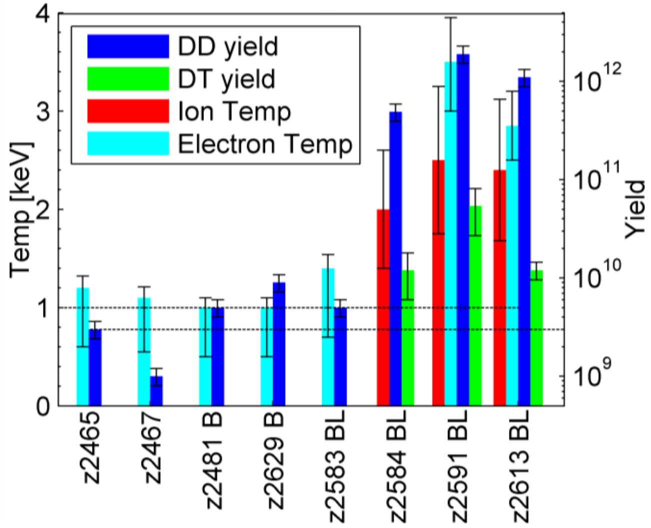
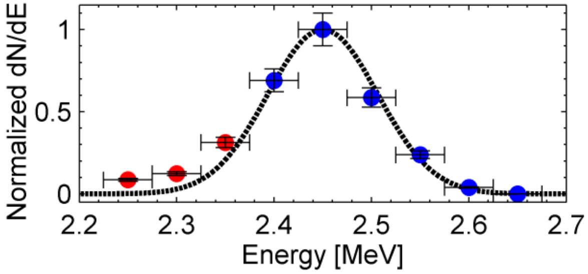
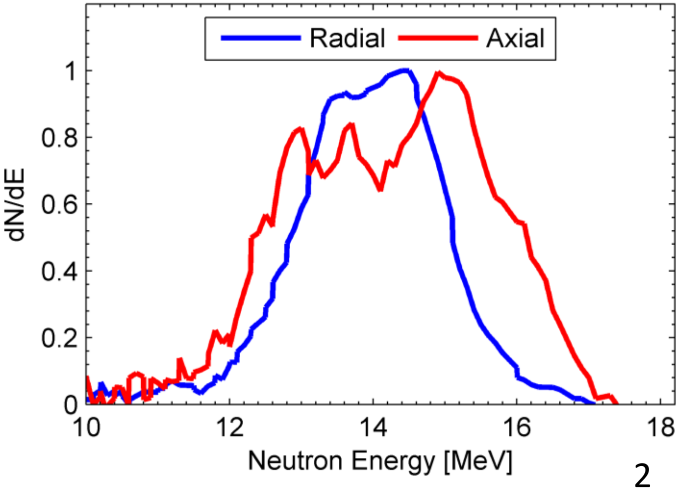
First integrated MagLIF experiments successfully demonstrated the concept



- **Thermonuclear neutron generation up to 2e12 DD**
- **Fusion-relevant stagnation temperatures**
- **Stable pinch with narrow emission column at stagnation**
- **Successful flux compression**







Outline

- Summary of experimental results
- Define Magnetized Liner Inertial Fusion (MagLIF)
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- Details of integrated MagLIF experimental results
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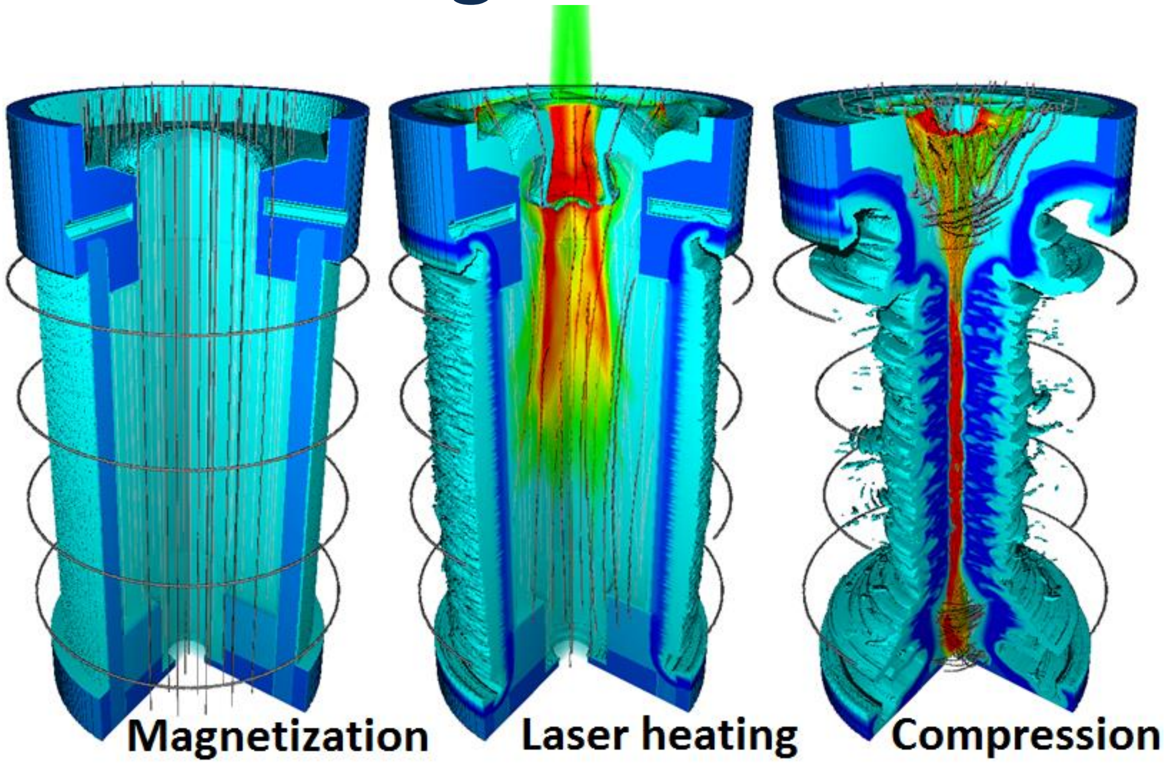
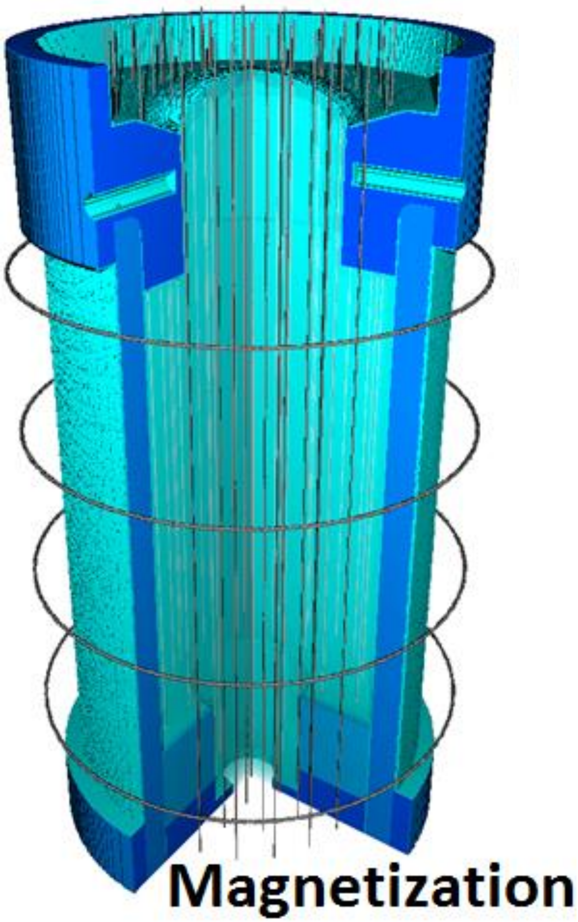
- The future

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



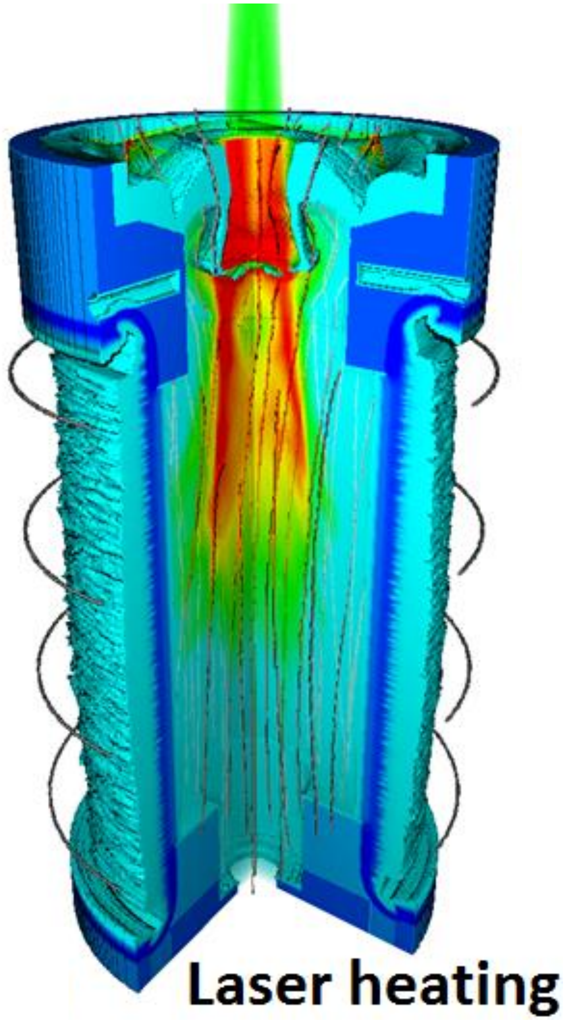
Magnetization and laser heating relax the implosion velocity, areal density, and convergence requirements of inertial confinement fusion

Stage 1: Magnetization



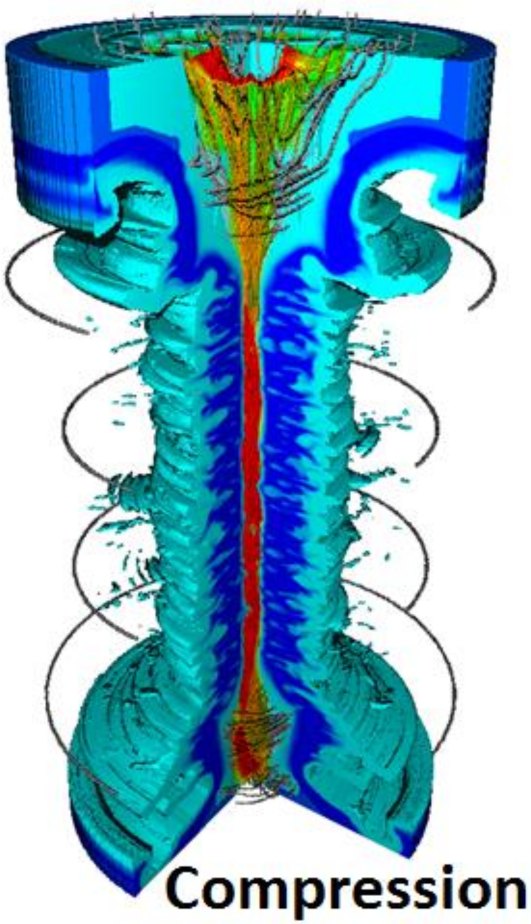
- Be liner containing fusion fuel
  - D2 gas ~ mg/cc ($n_e/n_{crit} < 0.1$)
- Axial magnetic field is applied to target
  - 10-30 T
  - ~ ms risetime
- Z current starts creating an azimuthal drive field

Stage 2: Laser Heating



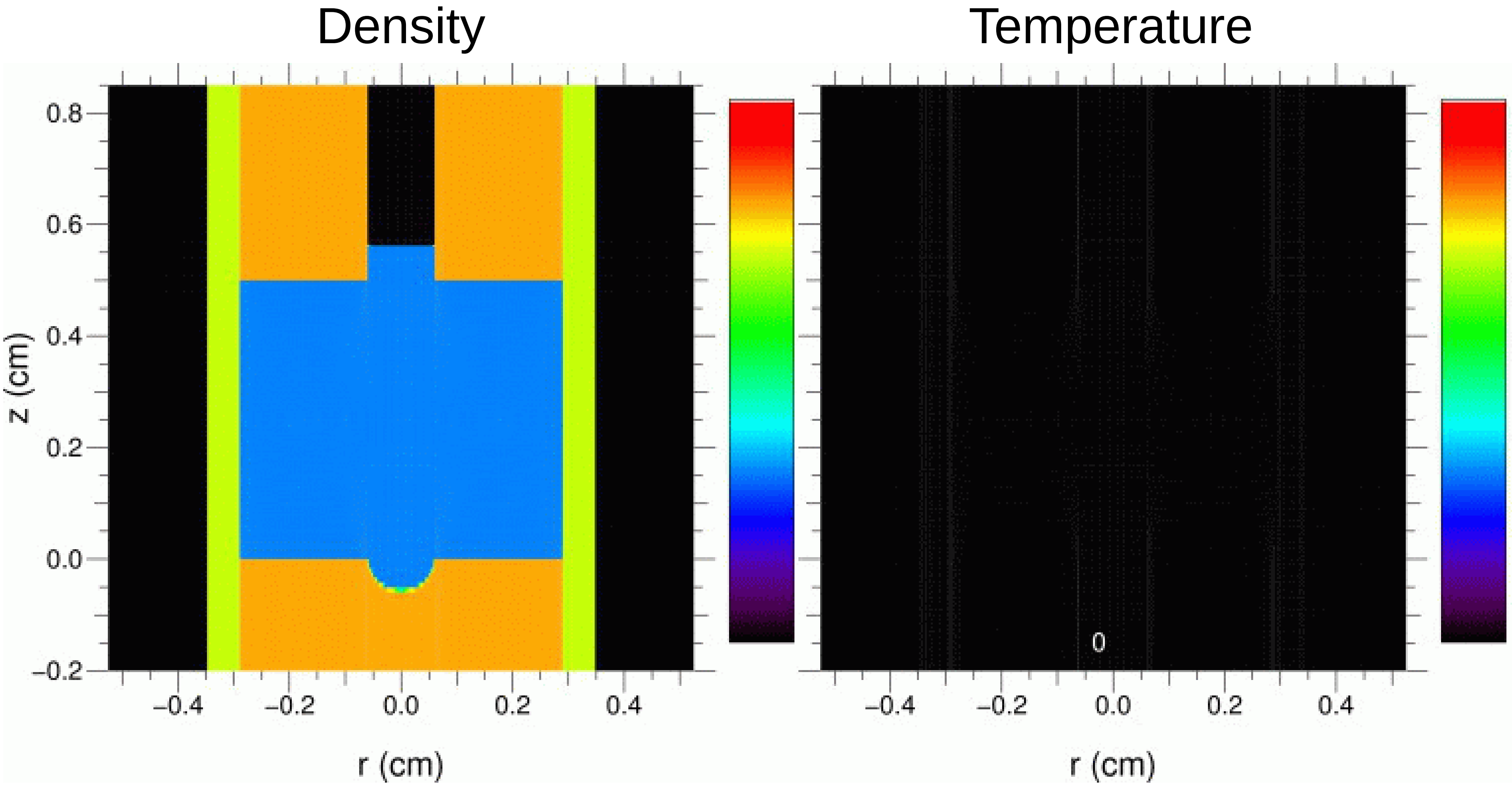
- Liner begins to compress
  - OD is moving but ID is stationary
- Laser heats the fuel
  - T_e ~ 100s of eV
- Liner ID begins to implode
- Fuel conditions isotropize over the 10s of ns of the implosion

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 though PdV work to keV temperatures
- Liner stagnates
  - Plasma pressure exceeds drive pressure

Putting it all together…



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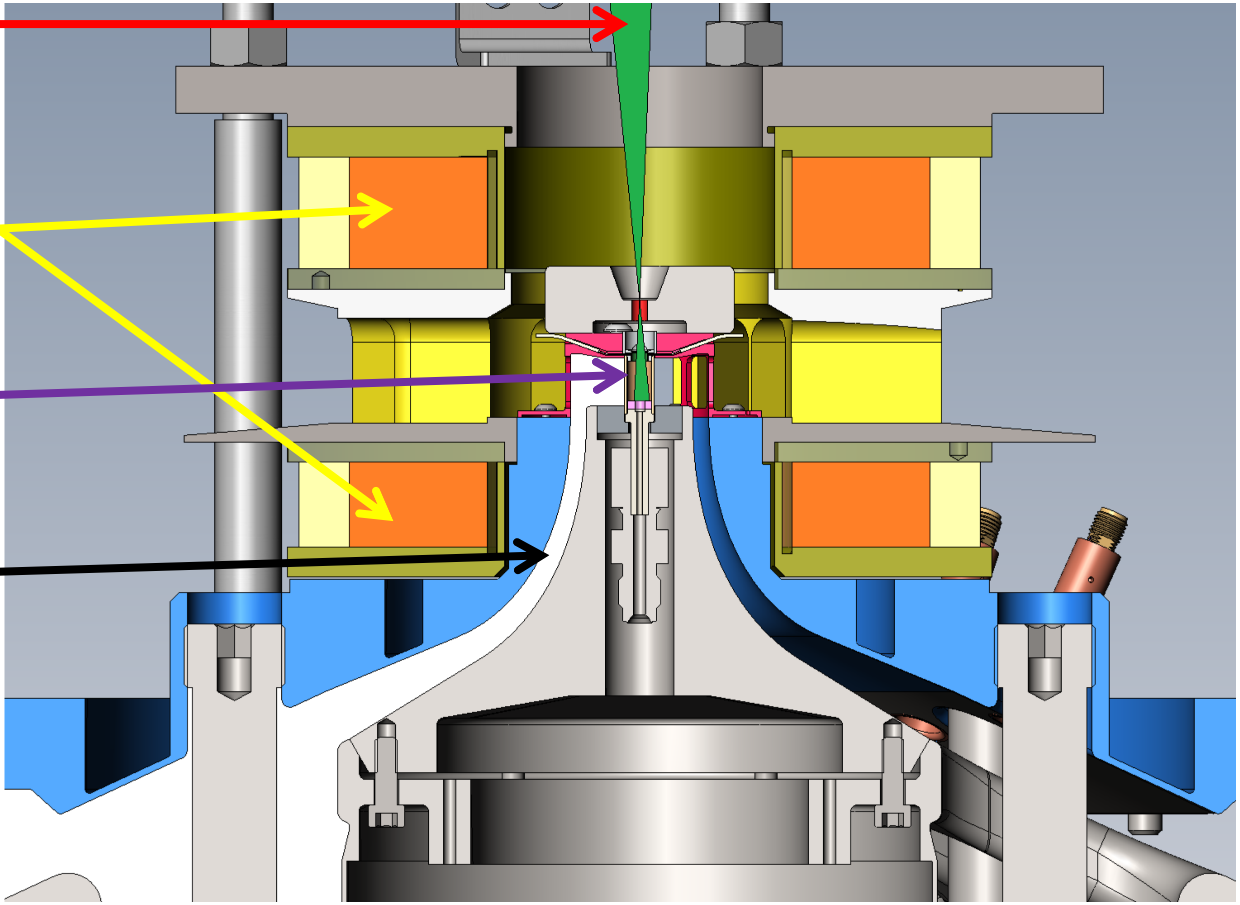
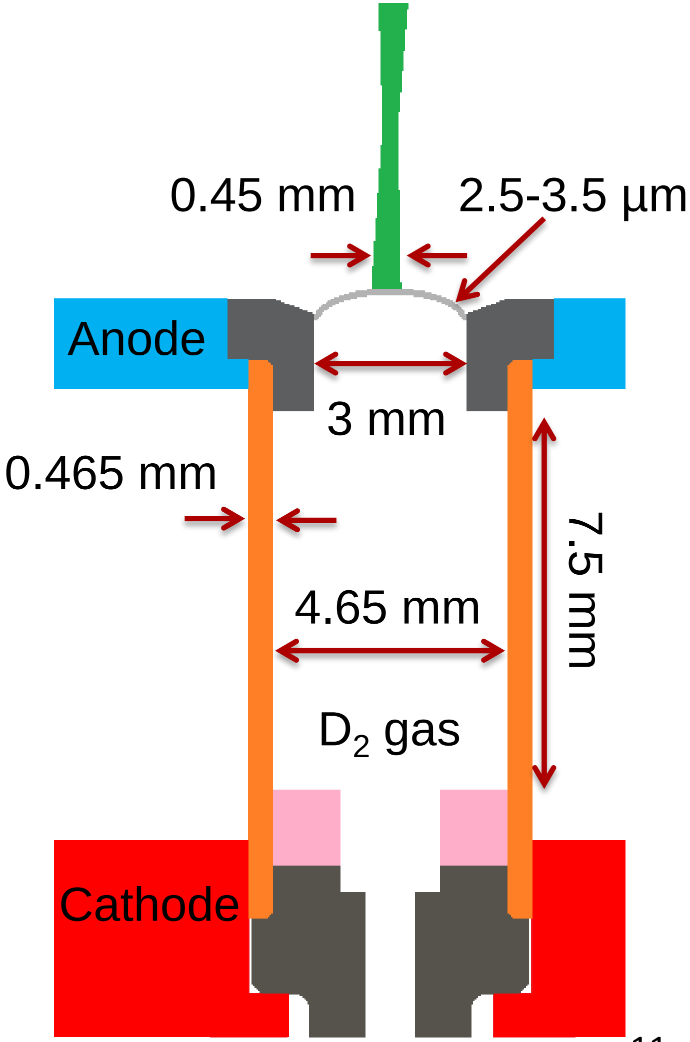
Prior to the integrated experiments, a series of focused experiments were conducted to test all of the critical components of MagLIF



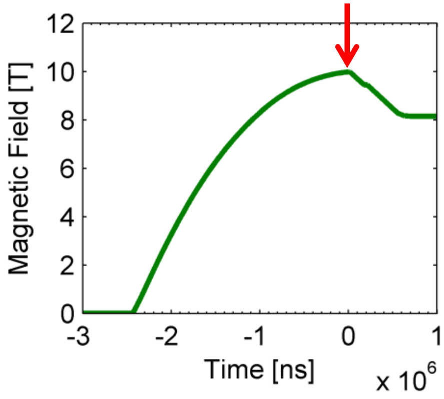
- **Laser preheat**
  - **>20 laser-only experiments**
- **Applied magnetic field**
  - **>10 experiments**
- **Liner Stability**
  - **>30 experiments**
- **Modified power flow**
  - **Geometry scan to minimize losses**
  - **>20 experiments**
- **Fully integrated shots**
  - **5 Z + ZBL shots**

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**



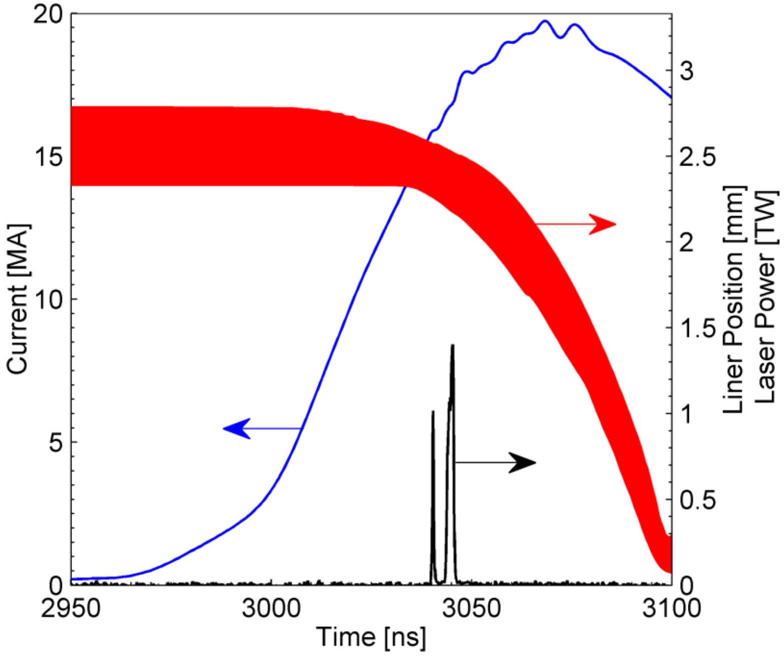
Initial experiments were conducted at I = 19 MA, B = 10 T, and Laser = 2.5 kJ



Time of experiment

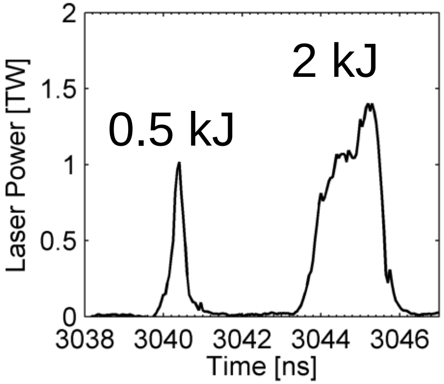
Magnetic field risetime is approximately 2 ms

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:
1st pulse intended to destroy LEH
2nd pulse intended to heat fuel



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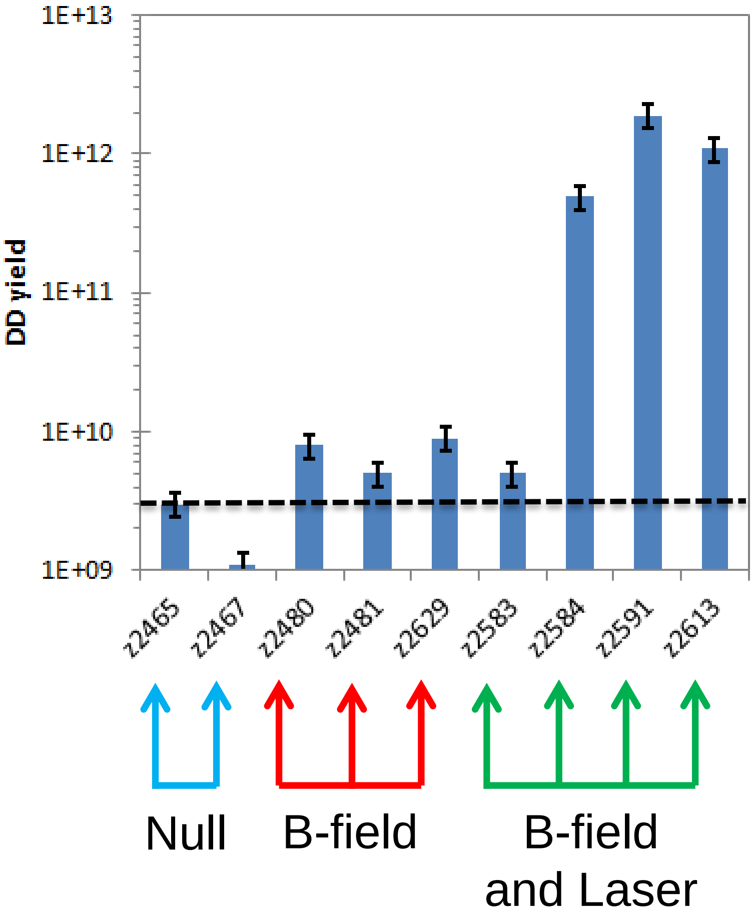
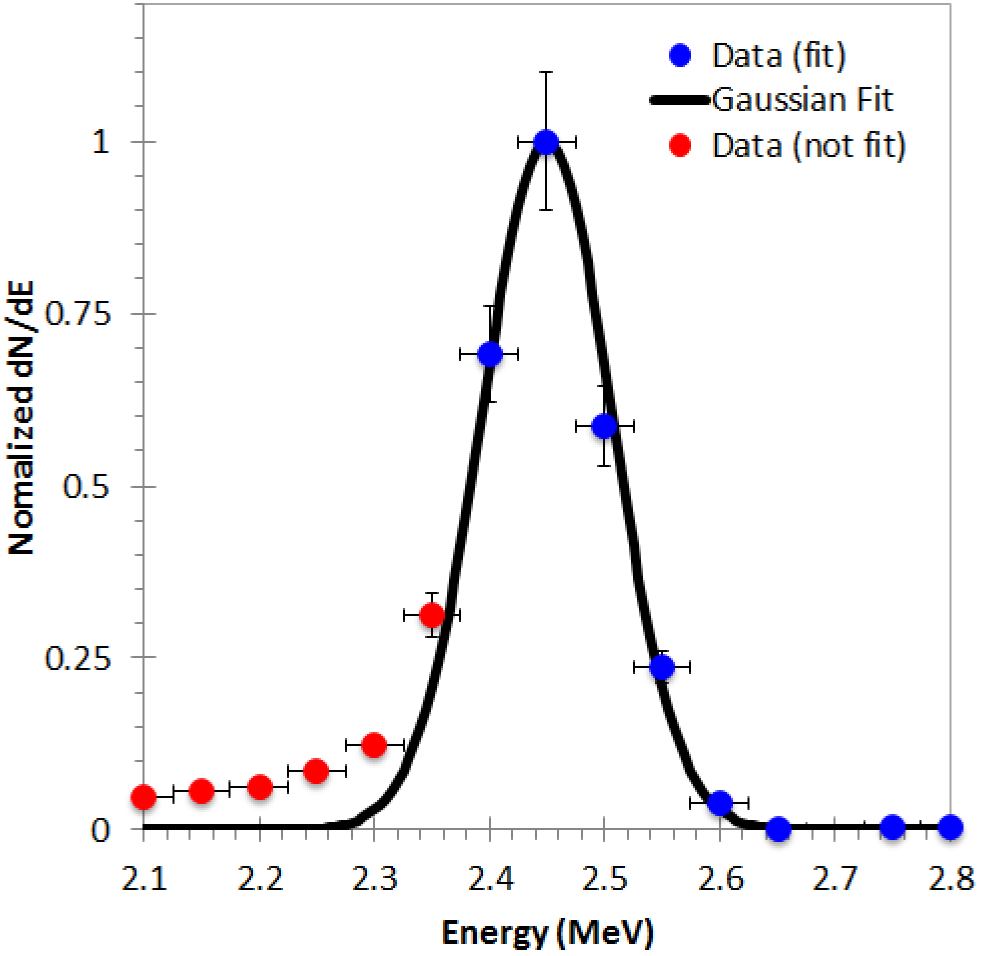
Thermonuclear DD yields in excess of 10^{12} were observed in experiments with laser and B-field



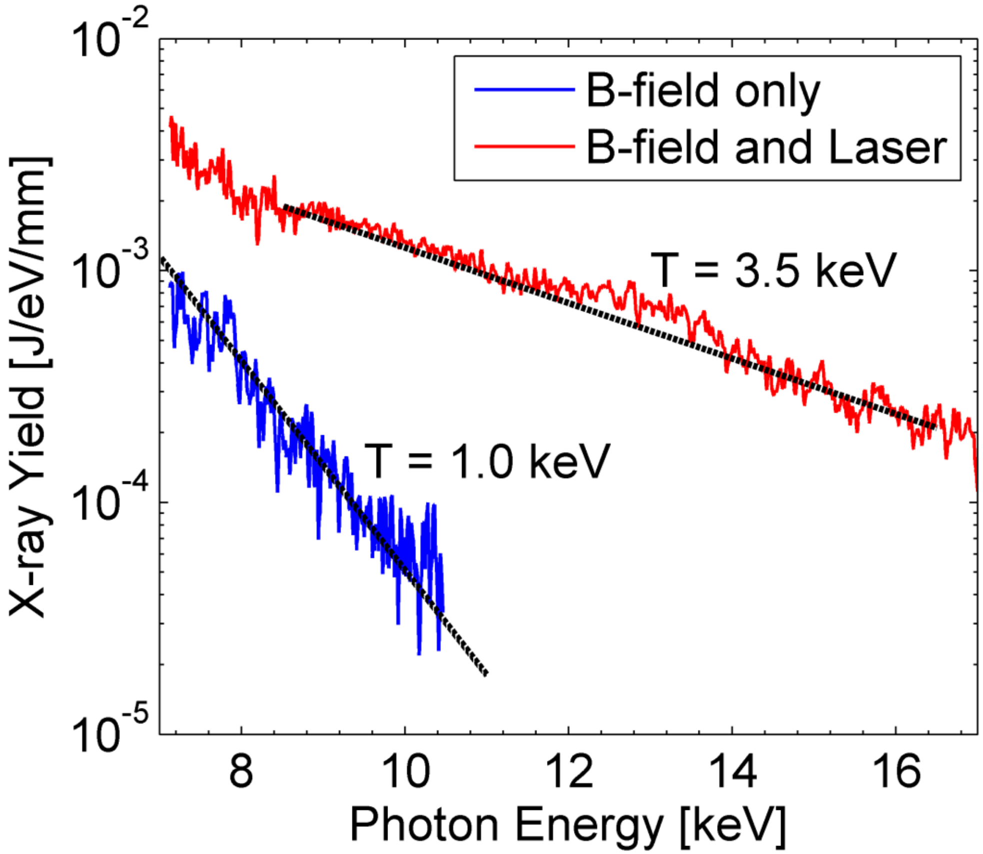
- **High yields were only observed on experiments incorporating both applied magnetic field and laser heating**
- **A series of experiments without laser and/or B-field produced yields at the background level of the measurement**
- **Result of z2583 is not well understood nor reproduced at this time**

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



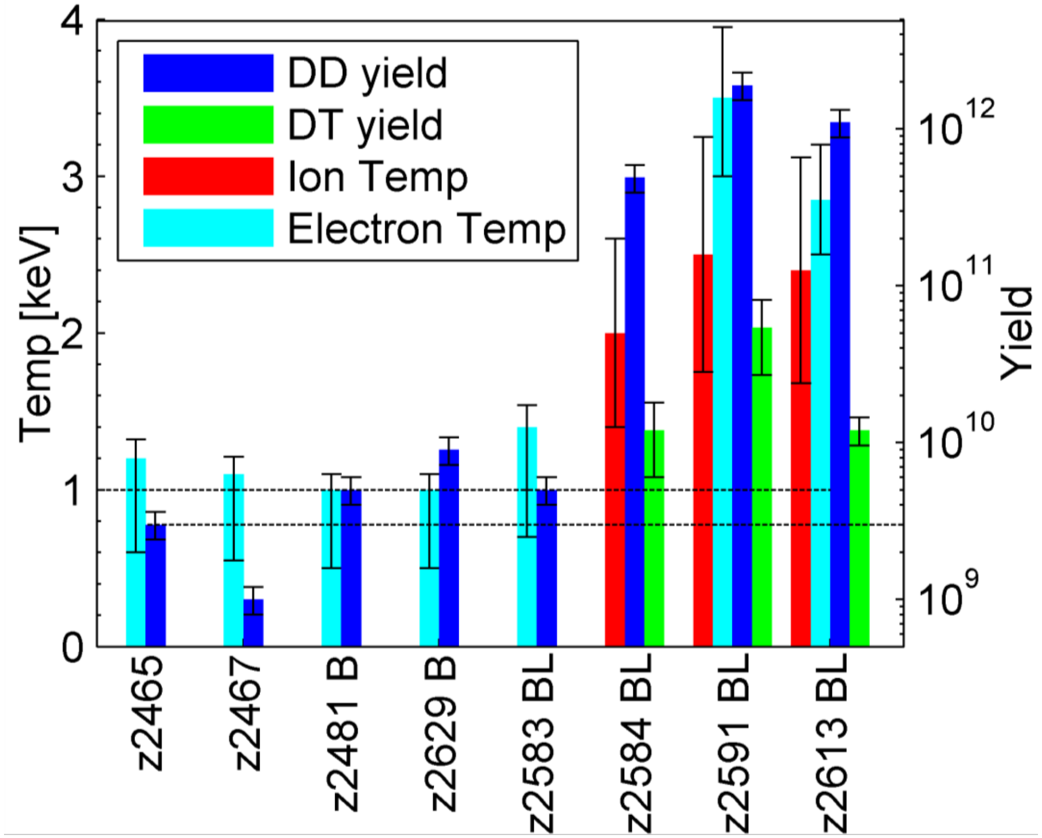
- DD neutron peak observed in experiments with significant yield (>1e10)
- Gaussian profile fit to high energy side of peak to determine ion temp
- Ion temperatures were between 2 and 2.5 keV for high yield experiments

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



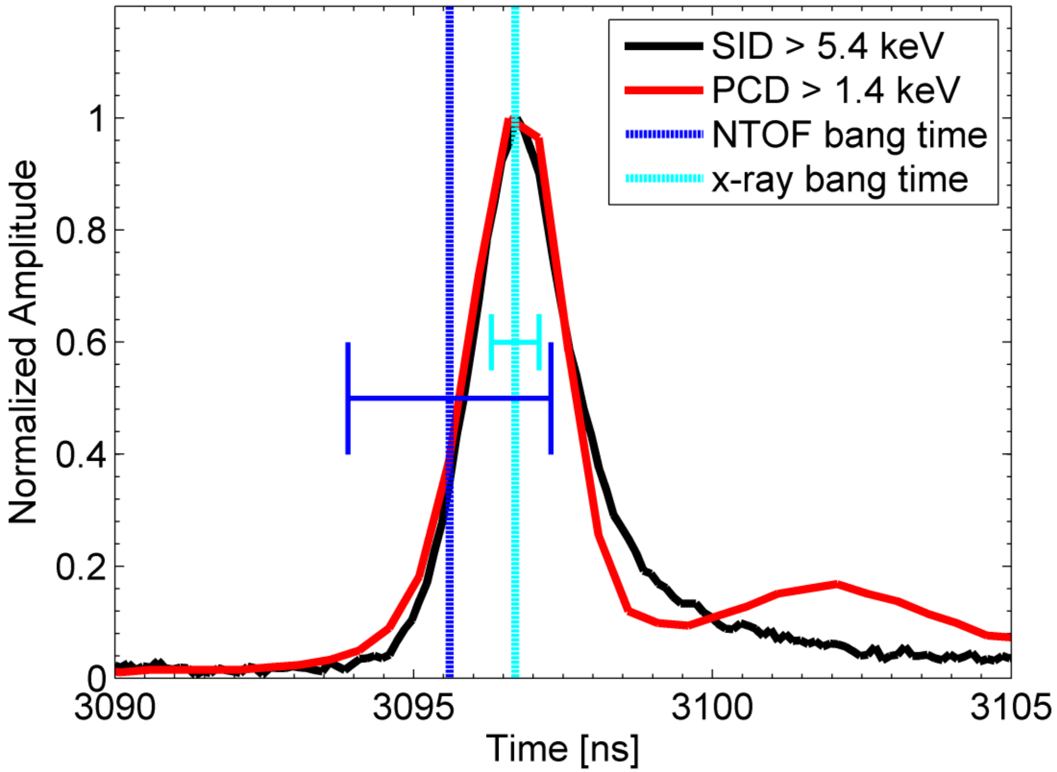
- Electron temperatures inferred from continuum emission
- > 2 keV observed on shots with yield
- Approximately 1 keV observed on shots without yield
- Lower bound on measurement capability is around 1 keV

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



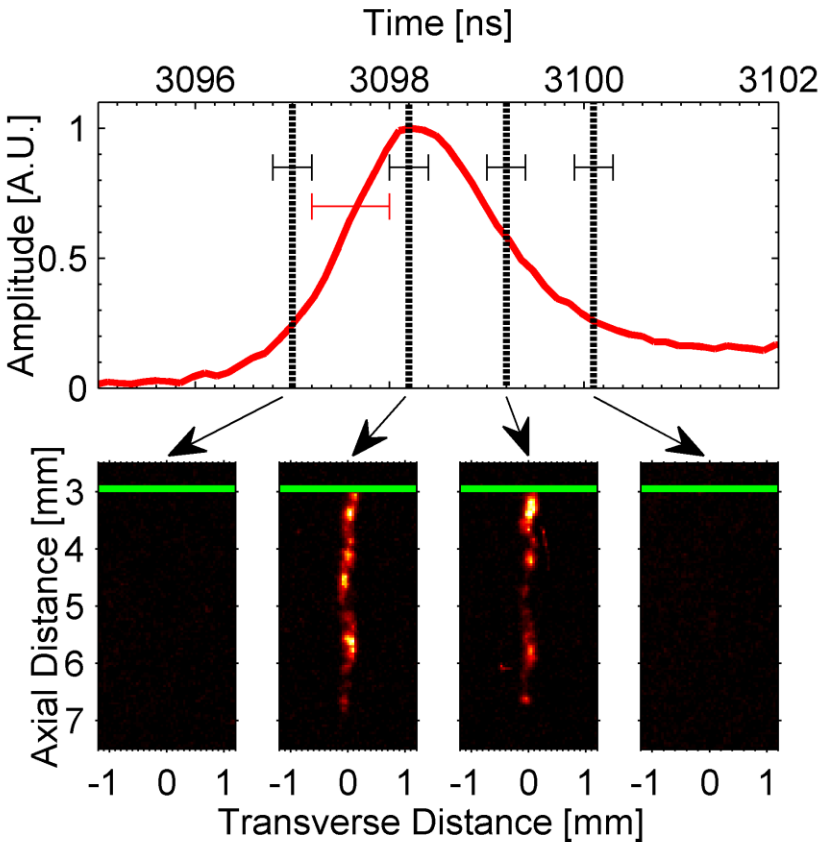
- Experiments with $T_{electron} \approx 1$ keV have negligible DD yield
- For $T_i \approx T_e > 2$ keV, significant yield is observed
- Measurable DT yield is observed on experiments with high DD yield (more on this later)

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**

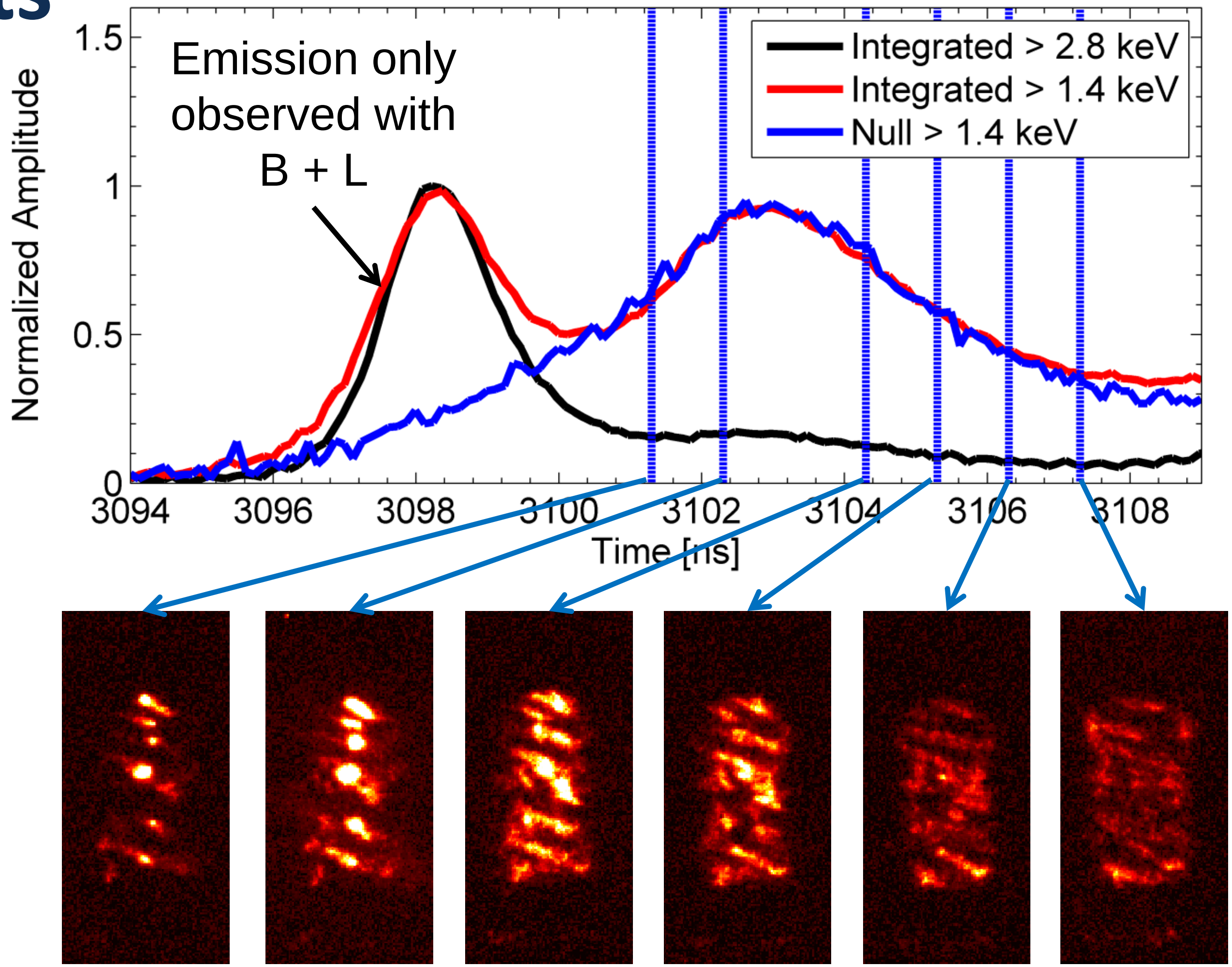
Time-resolved x-ray pinhole imaging (hν > 2.8 keV) shows a narrow emission column during peak in X-ray signal



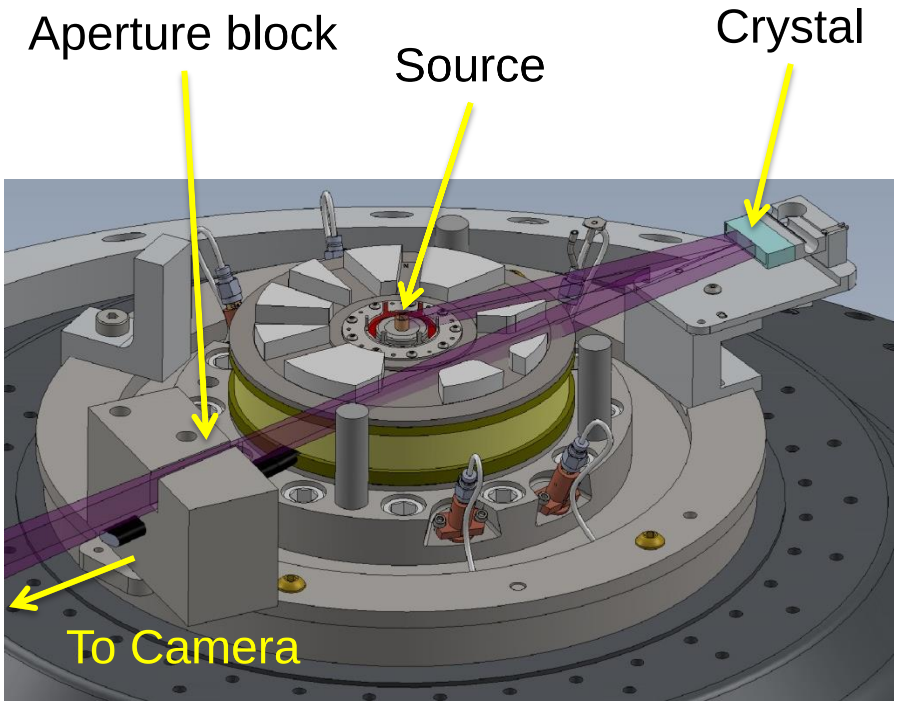
- **Emission column is observed only during the peak in the x-ray signal**
- **Emission column is only observed on experiments with high neutron yield**
- **Stagnation column width is at the resolution limit of the instrument (~150 microns)**

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**



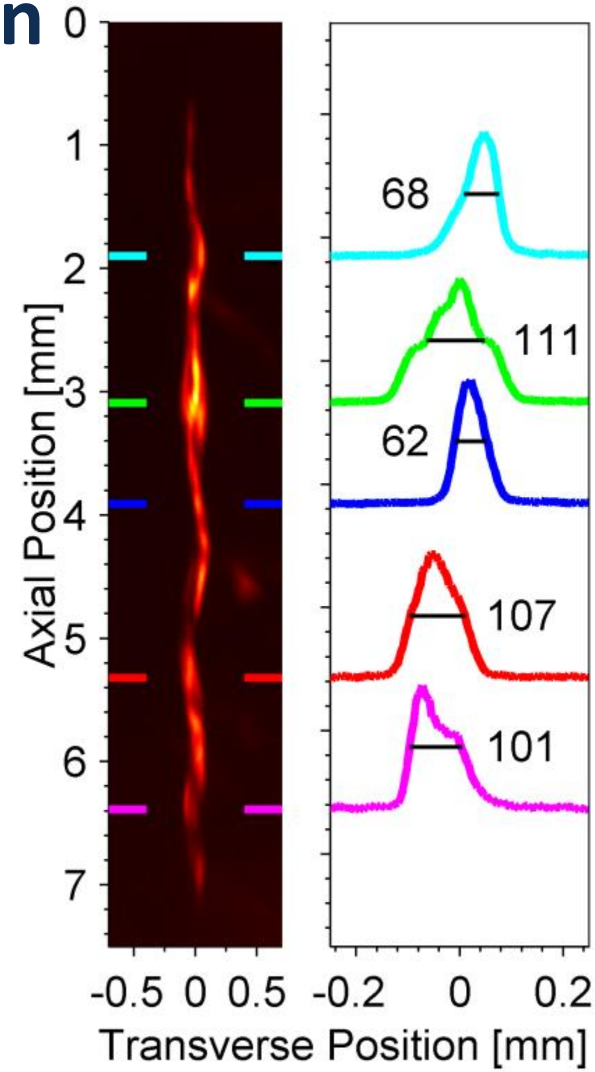
A new self-emission diagnostic was developed, which helps diagnose the stagnation column with high resolution



- **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 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



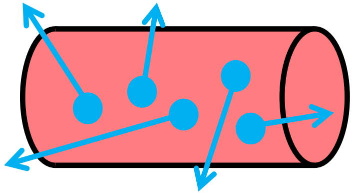
Measured and inferred stagnation parameters are consistent with the measured DD yield

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

Yield$_{DT}$/Yield$_{DD}$ and NTOF spectra indicate significant magnetic flux compression

B*r = 0

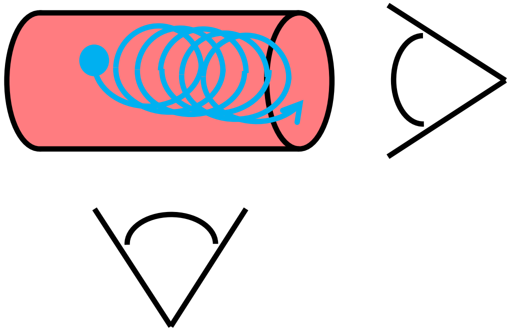
$Y_{DT}/Y_{DD} \sim 10^{-4}$

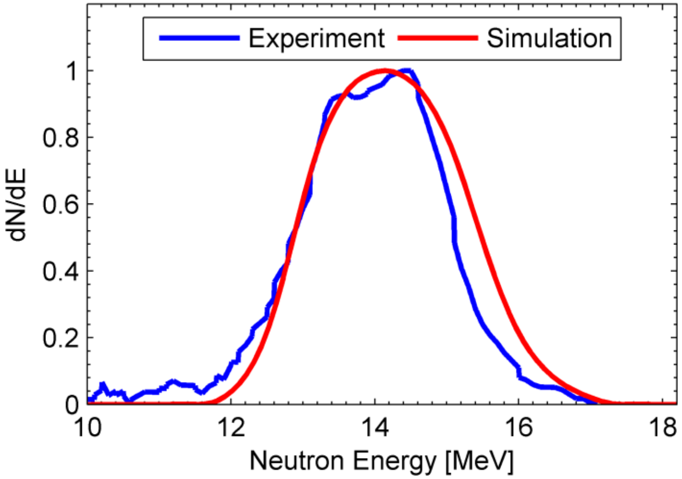


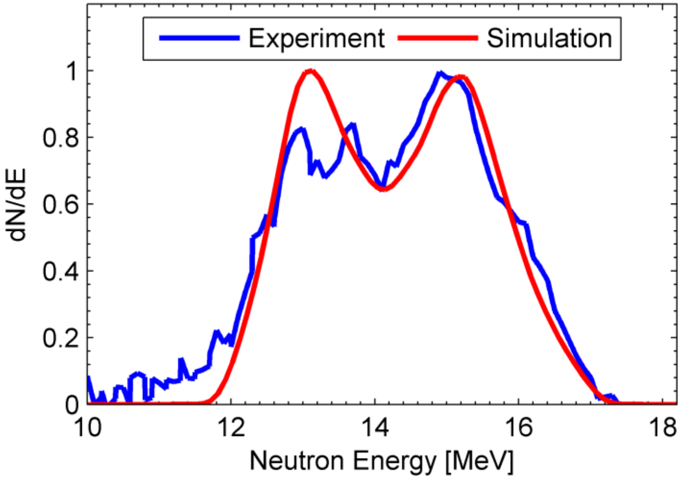
Relatively low estimated ρr for these experiments (2.0 mg/cm^2)

B*r > 40 T-cm

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





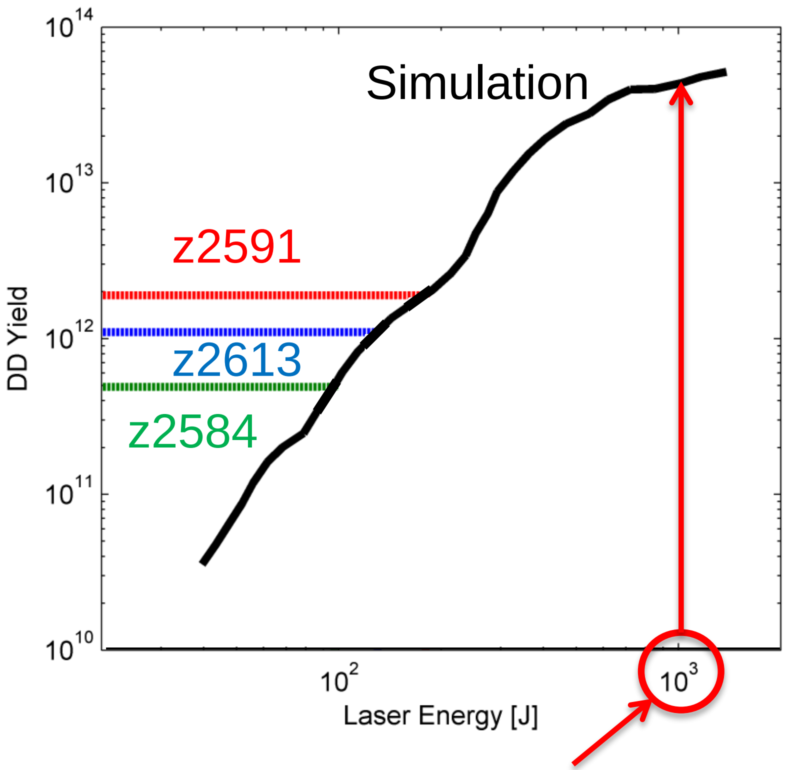


Y_{DT}/Y_{DD} = 1.3-4.3 x 10^{-2} is consistent with B*r = 40-110 T-cm

NTOF spectra are consistent with B*r ≈ 45 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 ± 1.5 MA	19 MA
Implosion time	90 ± 1 ns	90 ns
Energy absorbed in gas	Less than 600 J	150 ± 50 J
R_{stag} hot plasma	44 ± 13 µm	40 µm
T_{ion}, T_{elec}	2.0-2.5 keV, 2.8-3.5 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)

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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
  - 4 kJ now available
  - 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

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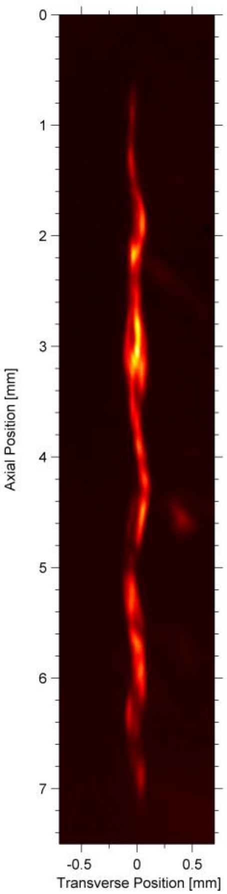

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