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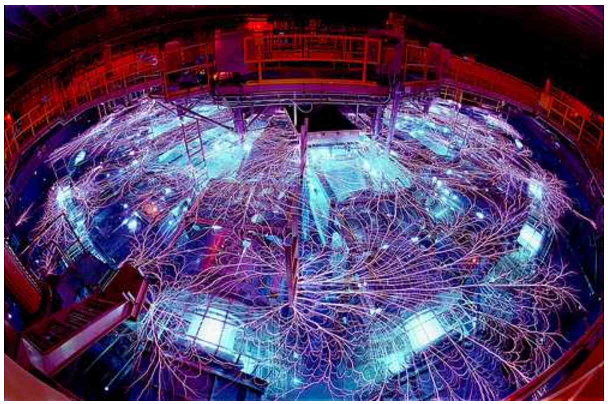

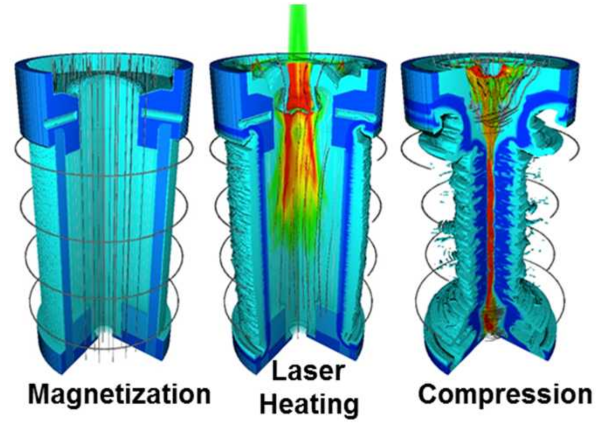

Demonstration of thermonuclear conditions in Magnetized Liner Inertial Fusion experiments

Matthew Gomez
for the MagLIF team
Sandia National Laboratories

56^{th} Annual Meeting of APS-DPP, New Orleans, LA, Oct 27, 2014

U.S. DEPARTMENT OF ENERGY

NNSA National Nuclear Security Administration

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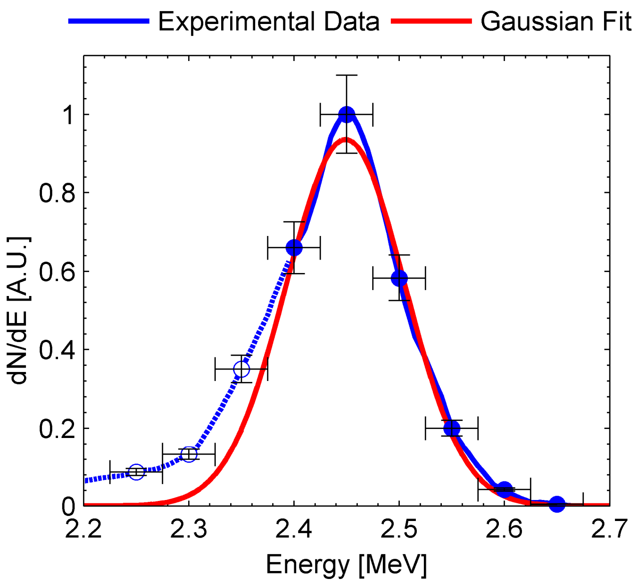
A magneto-inertial fusion concept called Magnetized liner Inertial Fusion has been successfully demonstrated

Thermonuclear neutron generation



Isotropic, Gaussian DD neutron spectra

A magneto-inertial fusion concept called Magnetized liner Inertial Fusion has been successfully demonstrated

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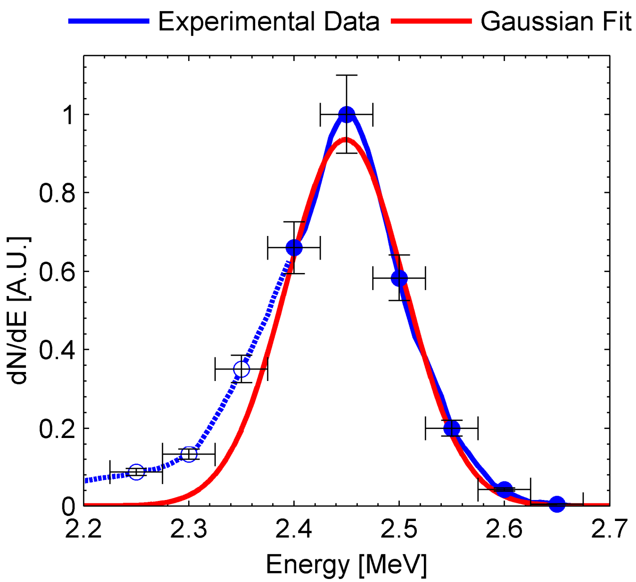
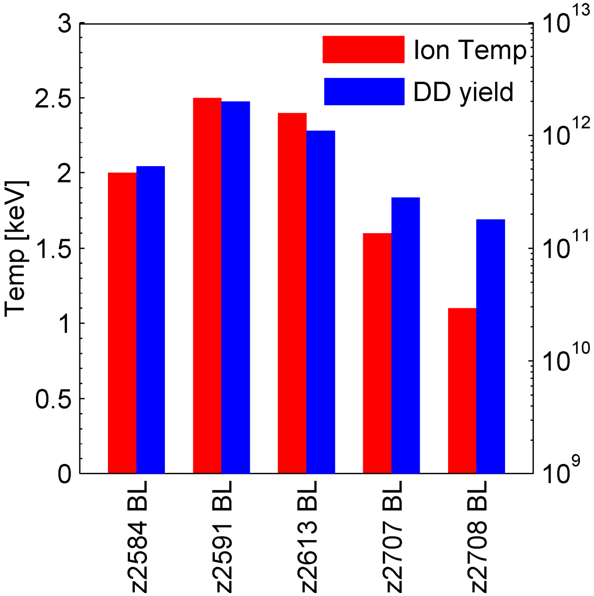
Thermonuclear neutron generation



Isotropic, Gaussian DD neutron spectra

High yields and temperatures



Max yield = 2e12
Max ion temp = 2.5 keV

A magneto-inertial fusion concept called Magnetized liner Inertial Fusion has been successfully demonstrated

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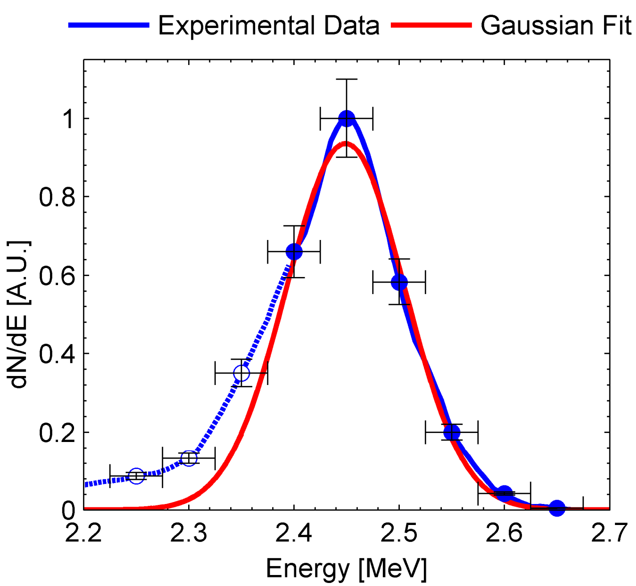
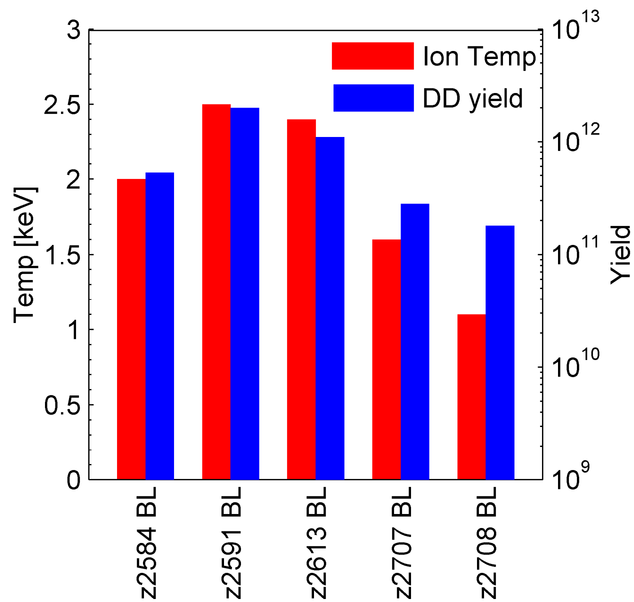
Thermonuclear neutron generation



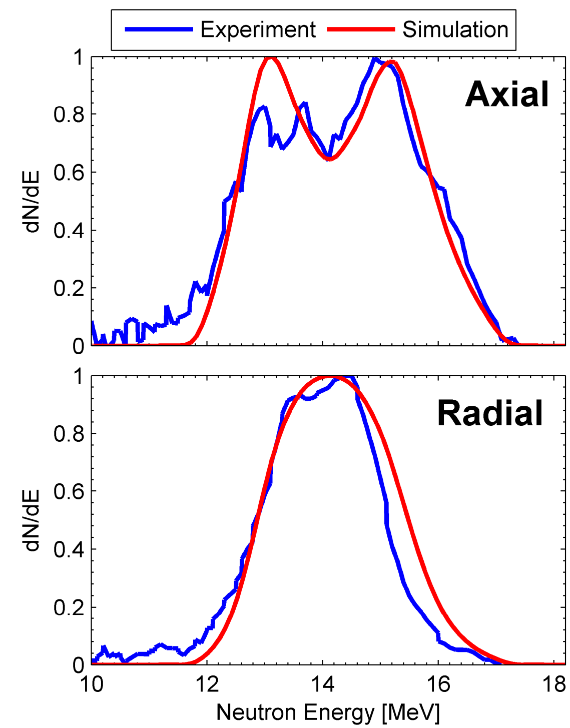
Isotropic, Gaussian DD neutron spectra

High yields and temperatures



Max yield = 2e12
Max ion temp = 2.5 keV

Magnetic flux compression



BR = 40 T-cm

Outline

- Background information
  - Define Magnetized Liner Inertial Fusion (MagLIF)
  - Describe the Z facility
  - Experiments leading to fully integrated experiments
- MagLIF experiments
  - Target design and experimental parameters
  - Temperatures and neutron yields
  - X-ray emission
  - Magnetic flux compression

Magnetized liner inertial fusion is a magneto-inertial fusion concept that we are evaluating on the Z facility

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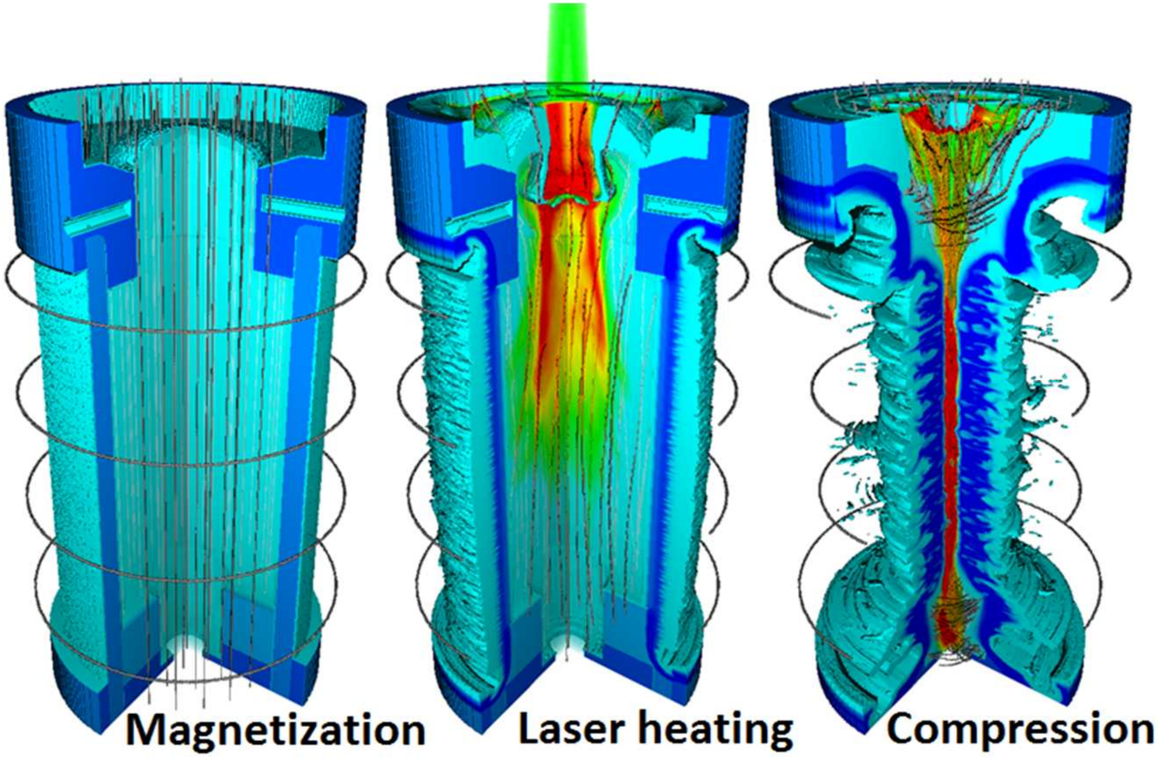
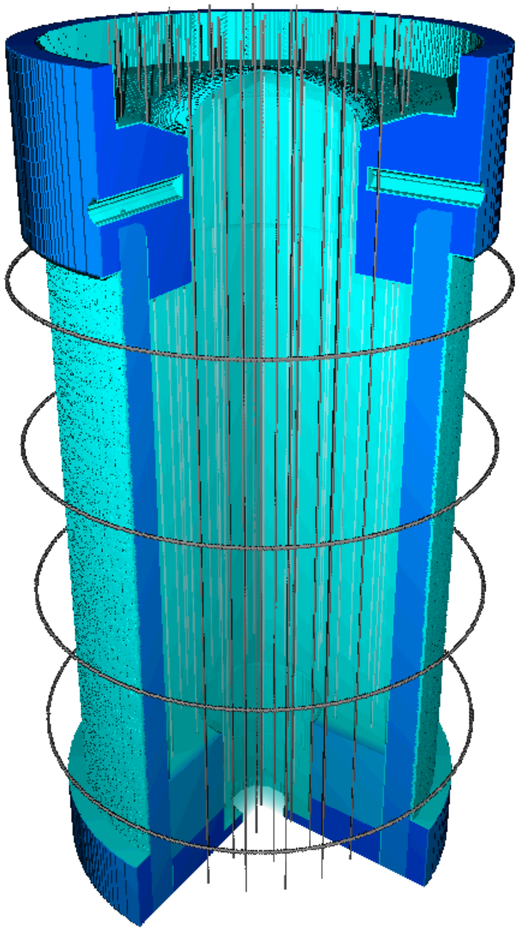


The insulating magnetic field and laser heating of the fuel allow relatively slow implosions to achieve the temperatures and pressures required to produce significant fusion reactions.

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

MagLIF has three stages: Stage 1 is Magnetization



- **Start with a thick metal liner containing gaseous fusion fuel**
- **An axial magnetic field is applied slowly so the field can diffuse through conductors**

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

MagLIF has three stages: Stage 2 is Laser heating

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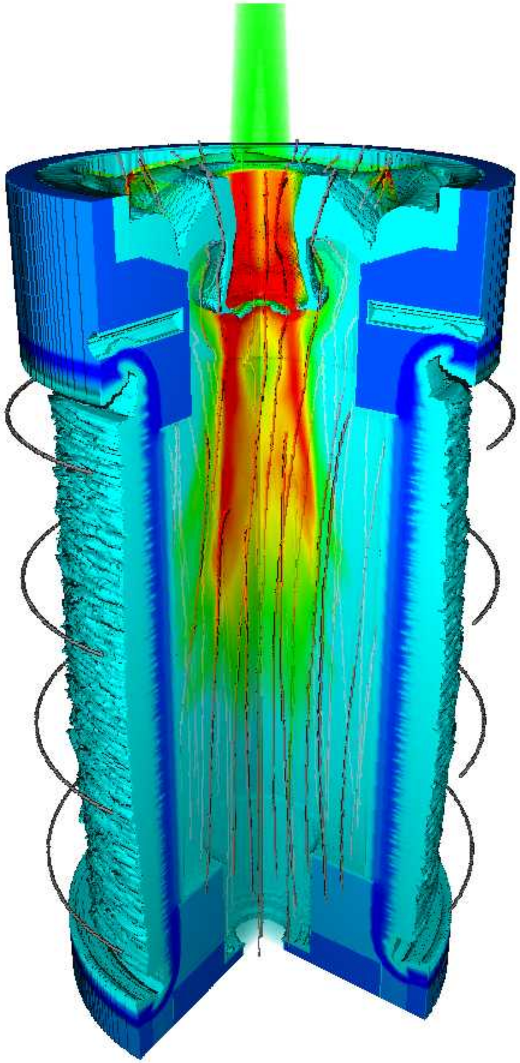
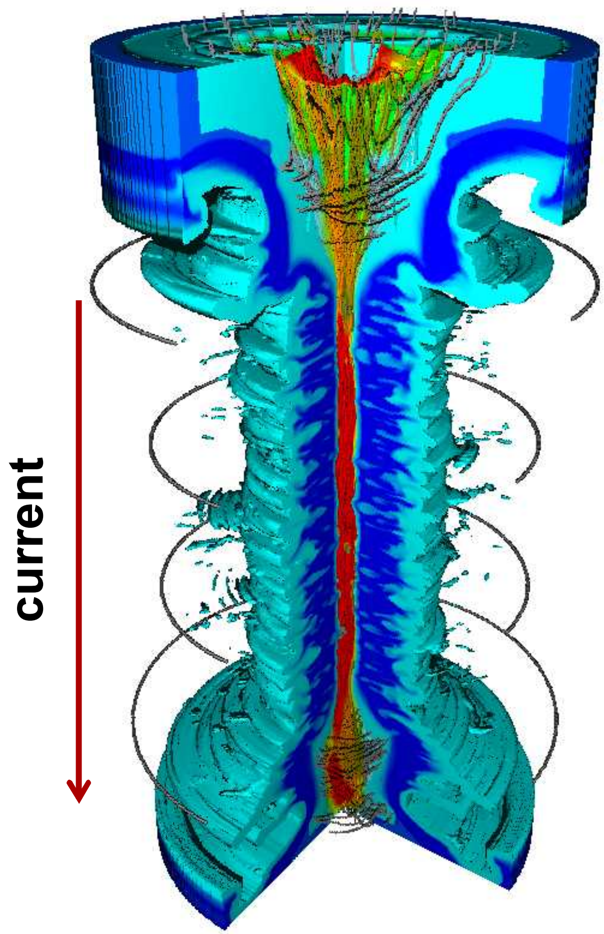


- **A laser enters the target axially**
- **The laser heats the fuel through inverse bremsstrahlung absorption**
- **The magnetic field insulates the warm gas from the cool liner**

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

MagLIF has three stages: Stage 3 is Compression



- **Current flowing on the outside of the target squeezes the liner which compresses the fuel and magnetic field**
- **The fuel heats through near adiabatic compression to fusion relevant temperatures**

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

We conduct these experiments on the Z machine, the world's largest pulsed power system

22 MJ stored energy, 3 MJ delivered to target

Up to 26 MA peak current with a 100 ns risetime

Up to 50 MG B-field, up to 100 Mbar pressure

The transition from wire arrays to MagLIF targets was a nontrivial task

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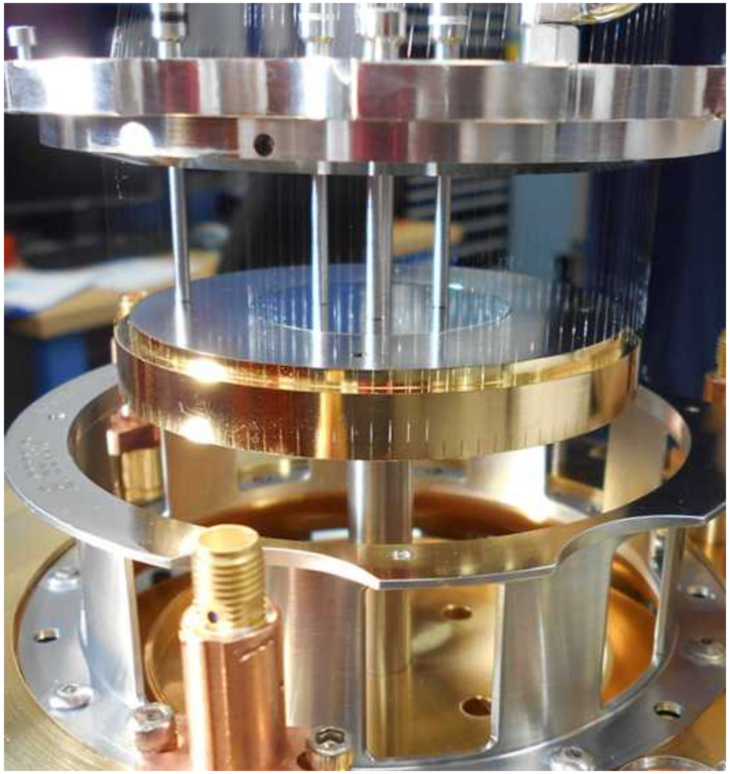
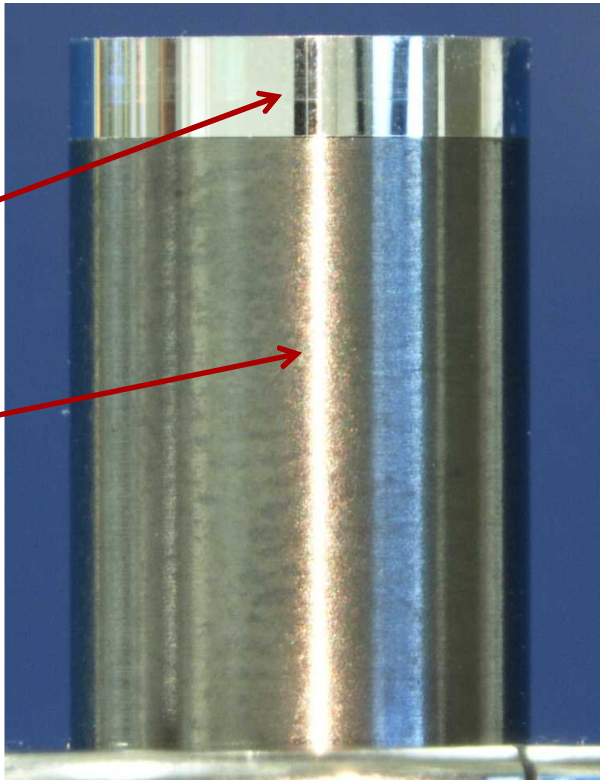
70 mm wire array



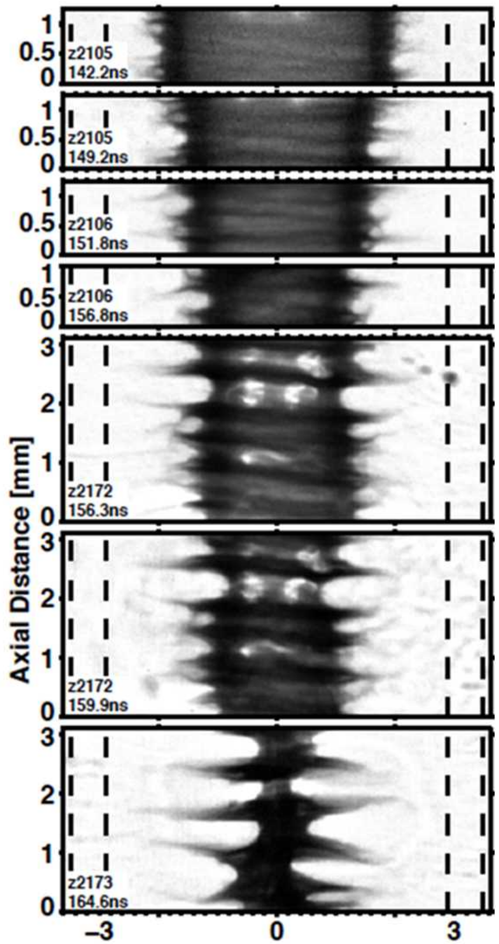
5.6 mm liner

10 x magnification



- Smaller targets with tighter tolerances
- Beryllium machining capability

Several experimental campaigns were conducted to investigate liner robustness



In MagLIF, liner stability is critical because the liner provides confinement at stagnation

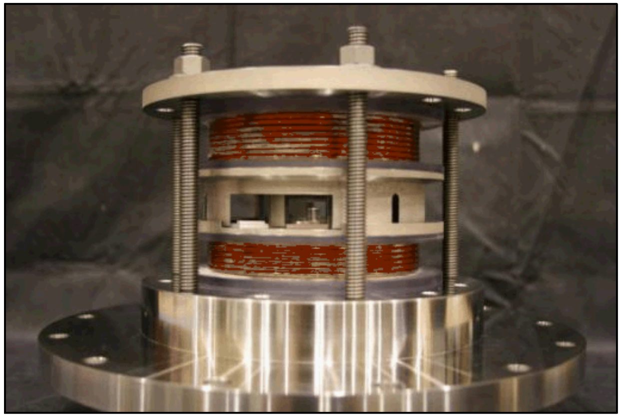
Smooth beryllium liners were imploded and radiography was used to assess liner stability

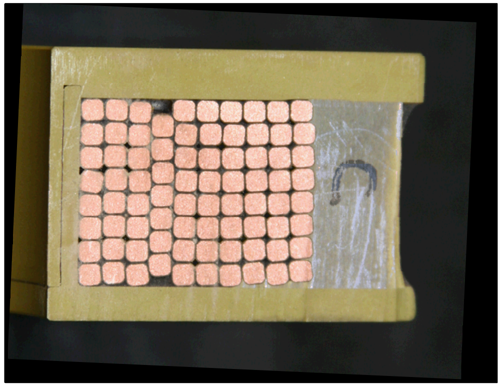
During the implosion, the magneto-Rayleigh-Taylor instability develops azimuthally correlated bubbles and spikes

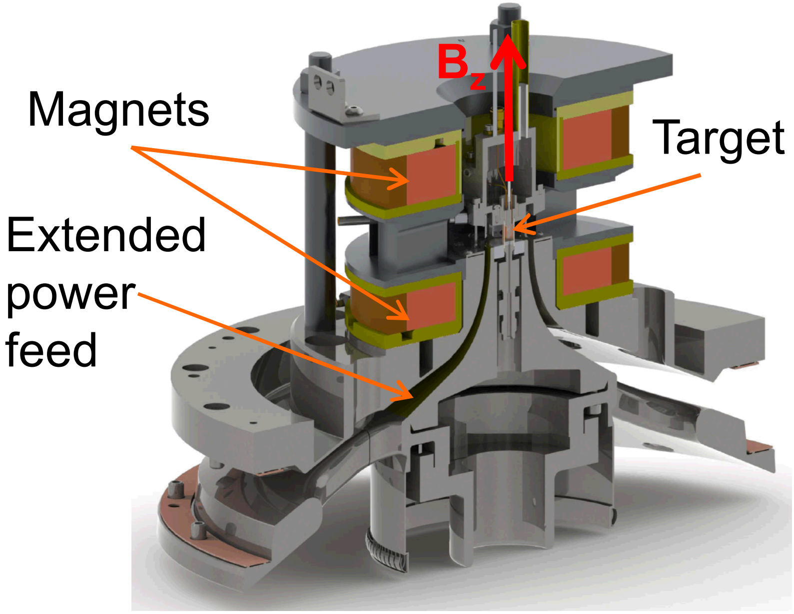
Based on experiments and simulations, aspect ratio 6 liners are at the limit of acceptable stability

R. D. McBride et al., PRL 109, 135004 (2012).

We developed the capability to apply uniform, pulsed magnetic fields to cm-scale targets







Applied B-field on Z

Capacitor bank: 900 kJ, 8 mF, 15 kV

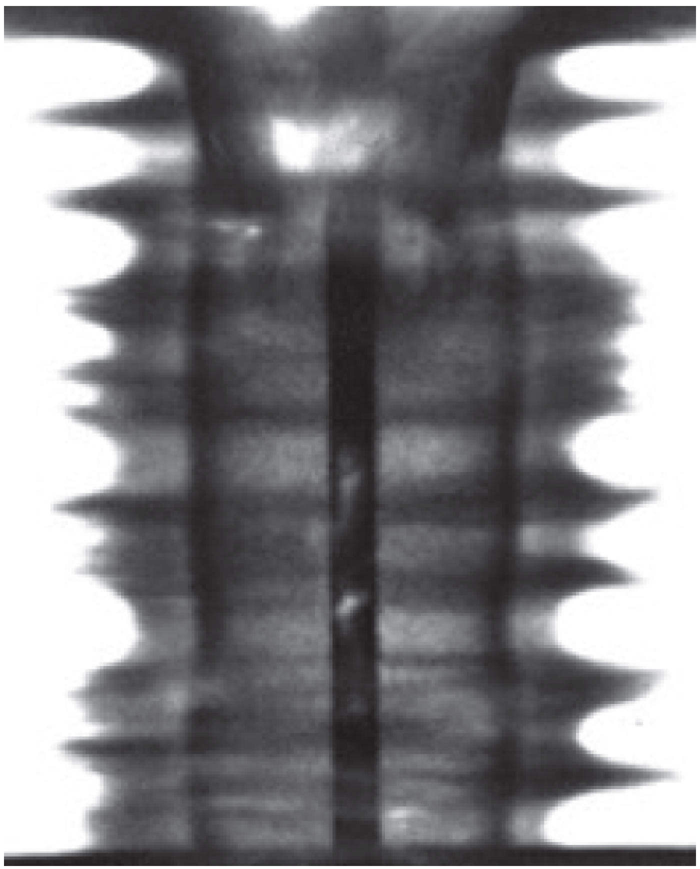
Full diagnostic access coils: up to 10 T

Limited diagnostic access coils: 15-20 T

No diagnostic access coils: 25-30 T

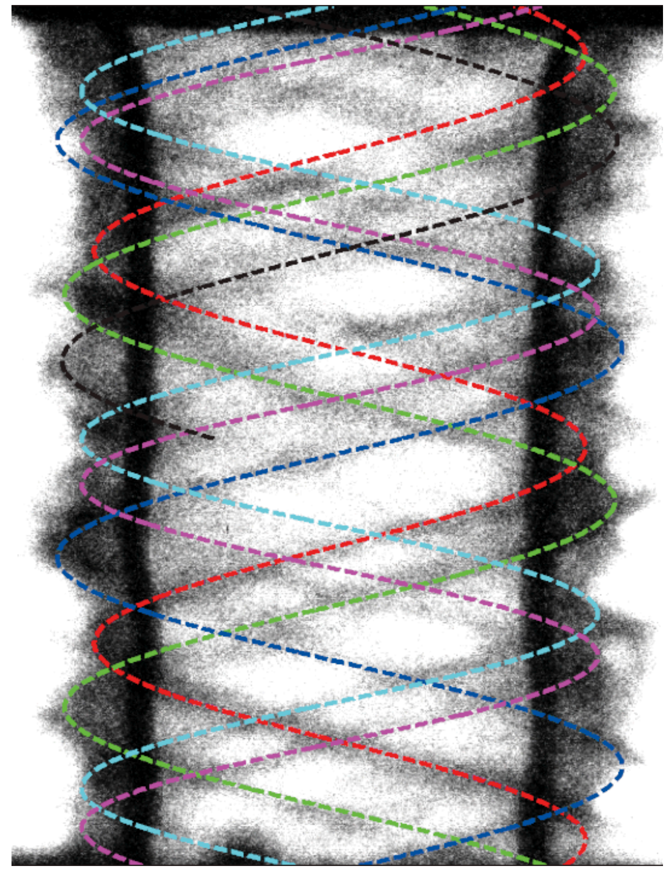
Addition of the axial B-field dramatically modified instability growth

Without axial B-field



Azimuthal MRT structure

With axial B-field

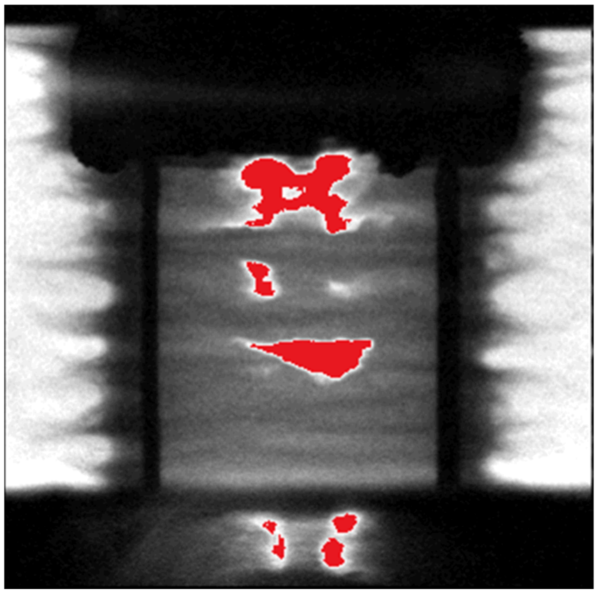


Helical MRT structure

T. J. Awe et al., Phys. Rev. Lett. 111, 235005 (2013).

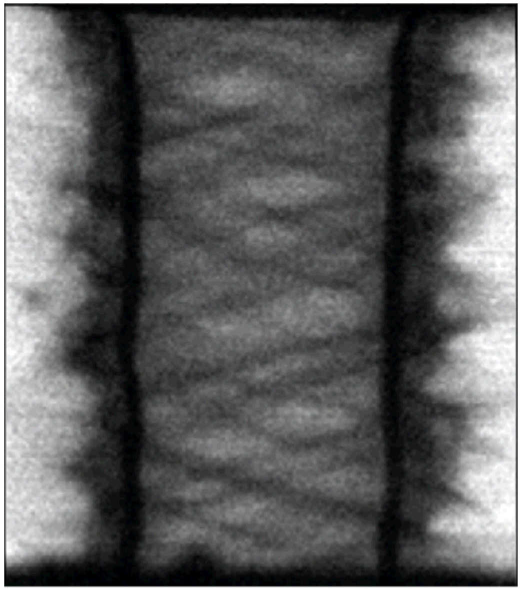
Addition of the axial B-field also appears to stabilize late-time instabilities in the liner

Without axial B-field

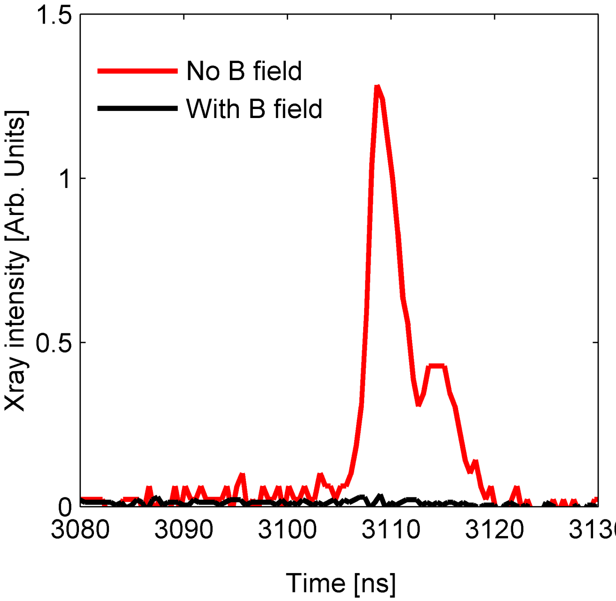


Time-integrated self-emission from target at 6.1 keV

With axial B-field



No time-integrated self-emission observed

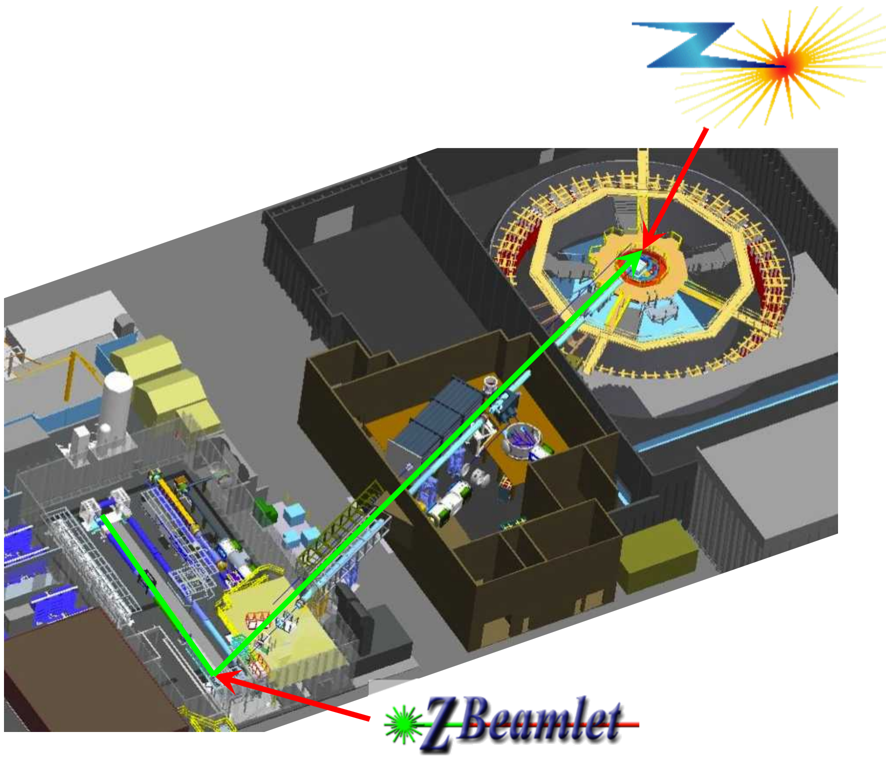


Emission signal for x rays > 4 keV

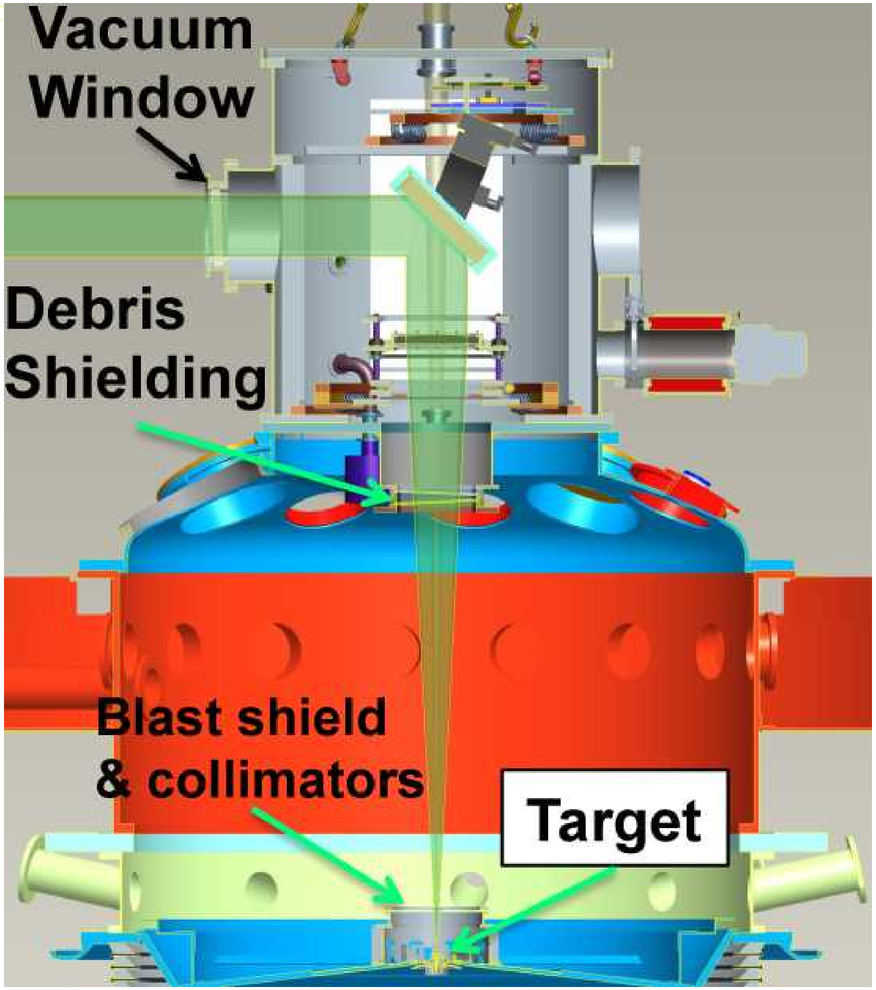
Time integrated self emission due to MRT instability is dramatically reduced with B field present

T. J. Awe et al., Phys. Plasmas 21, 056303 (2014).

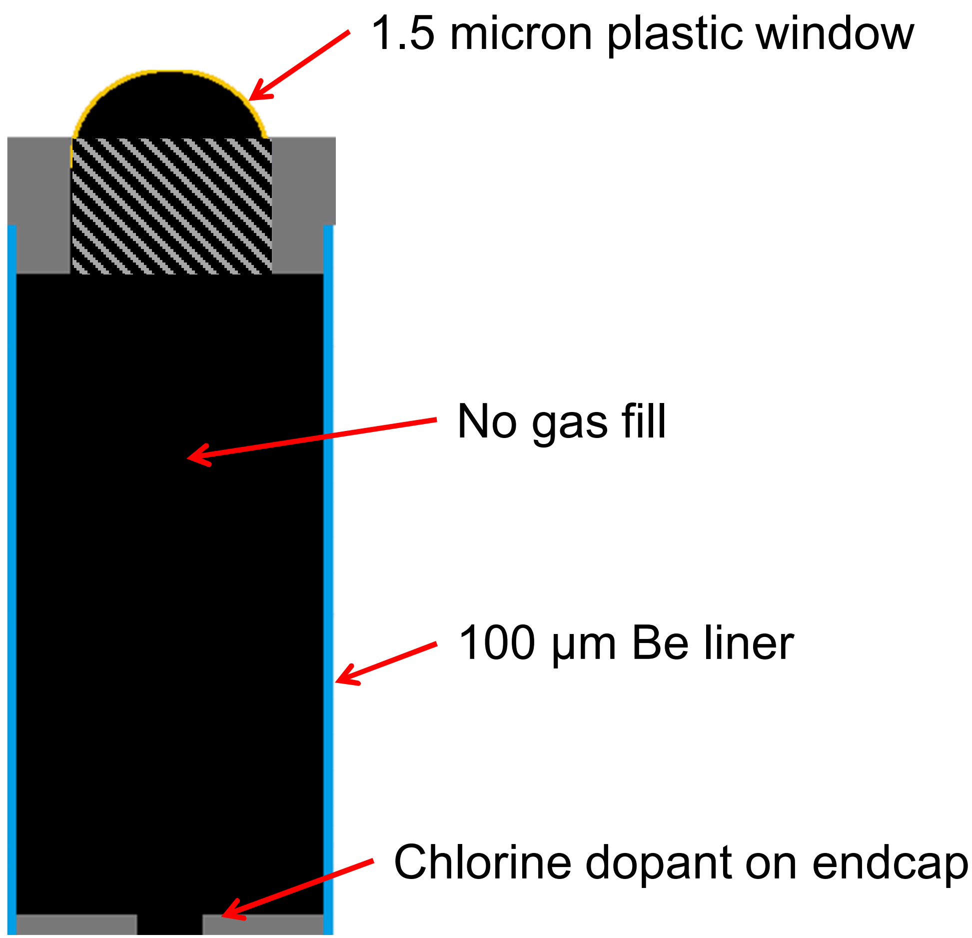
The Z Beamlet laser was diverted from the backlighter diagnostic to heat the fuel in MagLIF



2ω Nd:glass (527 nm)
1 TW, up to 4 kJ,
up to 6 ns pulse length



In laser heating experiments energy was transmitted through the LEH and coupled to the fuel



In laser heating experiments energy was transmitted through the LEH and coupled to the fuel

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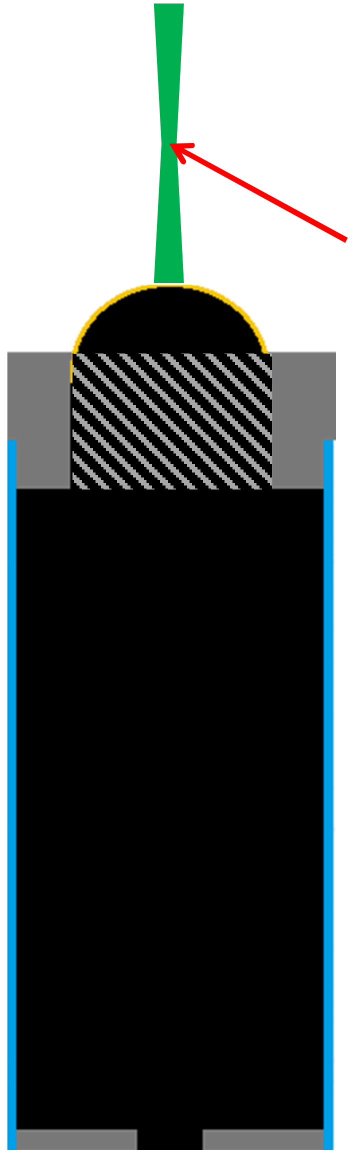
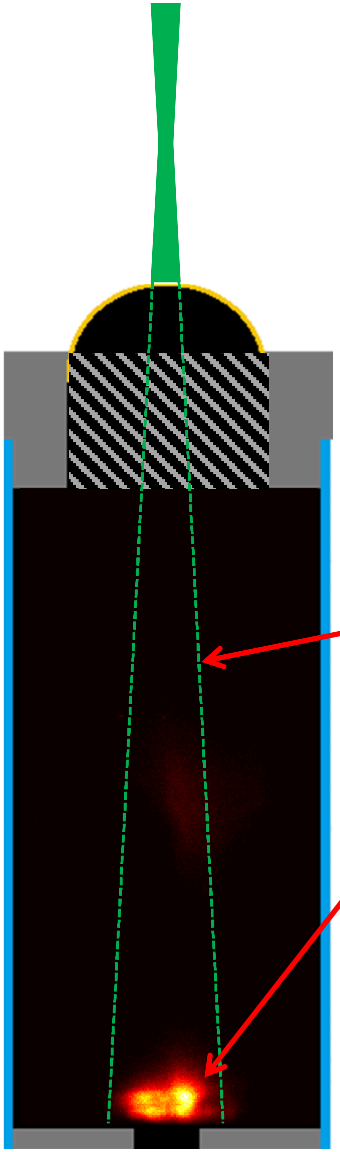


3.3 kJ, 4 ns pulse
500 µm square spot on window
No beam smoothing

Expected transmission based on calorimetry tests is 1.6 kJ

In laser heating experiments energy was transmitted through the LEH and coupled to the fuel

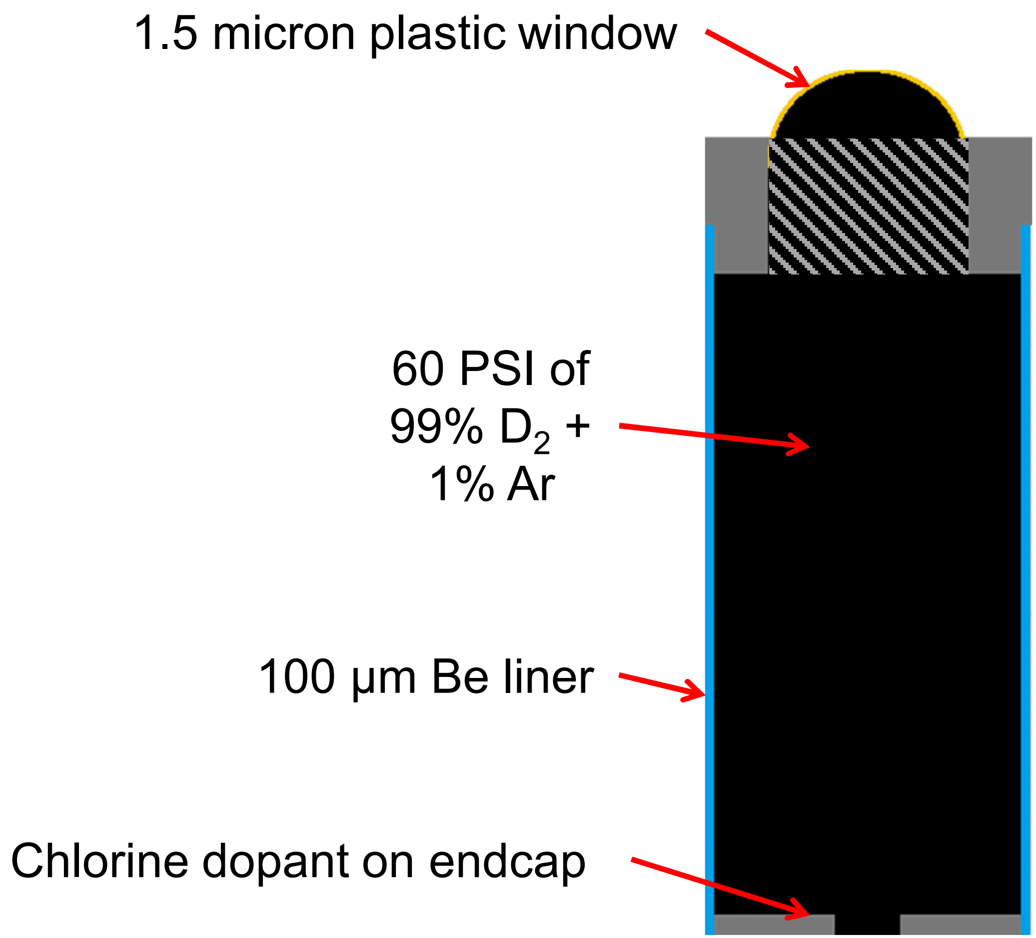


F/10 projection of laser

K shell emission from chlorine (and possibly calcium and vanadium)

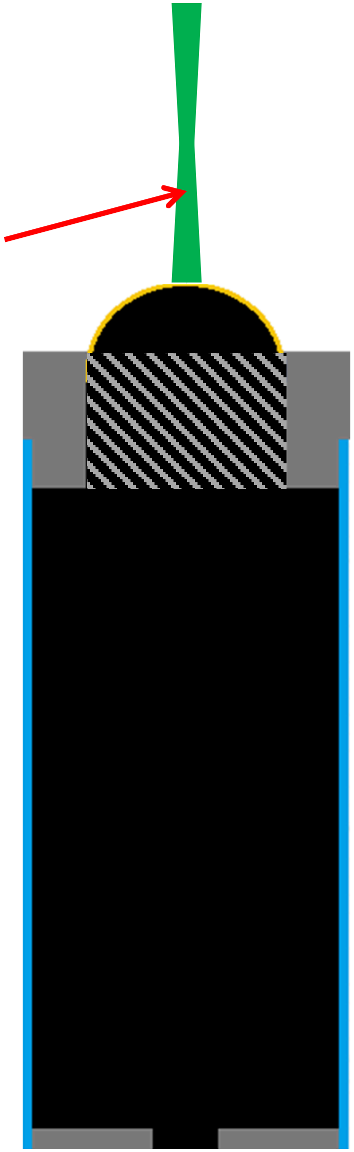
Emissivity weighted temperature is 600 eV

In laser heating experiments energy was transmitted through the LEH and coupled to the fuel



In laser heating experiments energy was transmitted through the LEH and coupled to the fuel

2.4 kJ, 2 ns pulse
500 μm square spot on window
No beam smoothing



Expected transmission based on calorimetry tests is 1.2 kJ

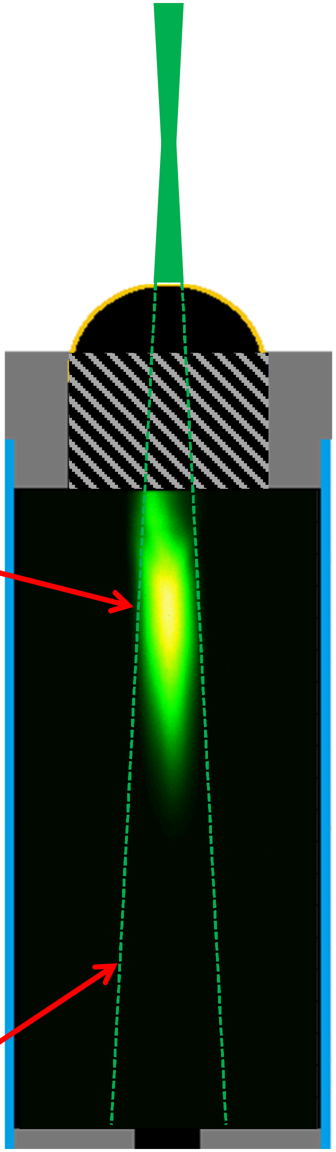
See Matthias Geissel's talk – GO4.00011

In laser heating experiments energy was transmitted through the LEH and coupled to the fuel

K shell emission from argon

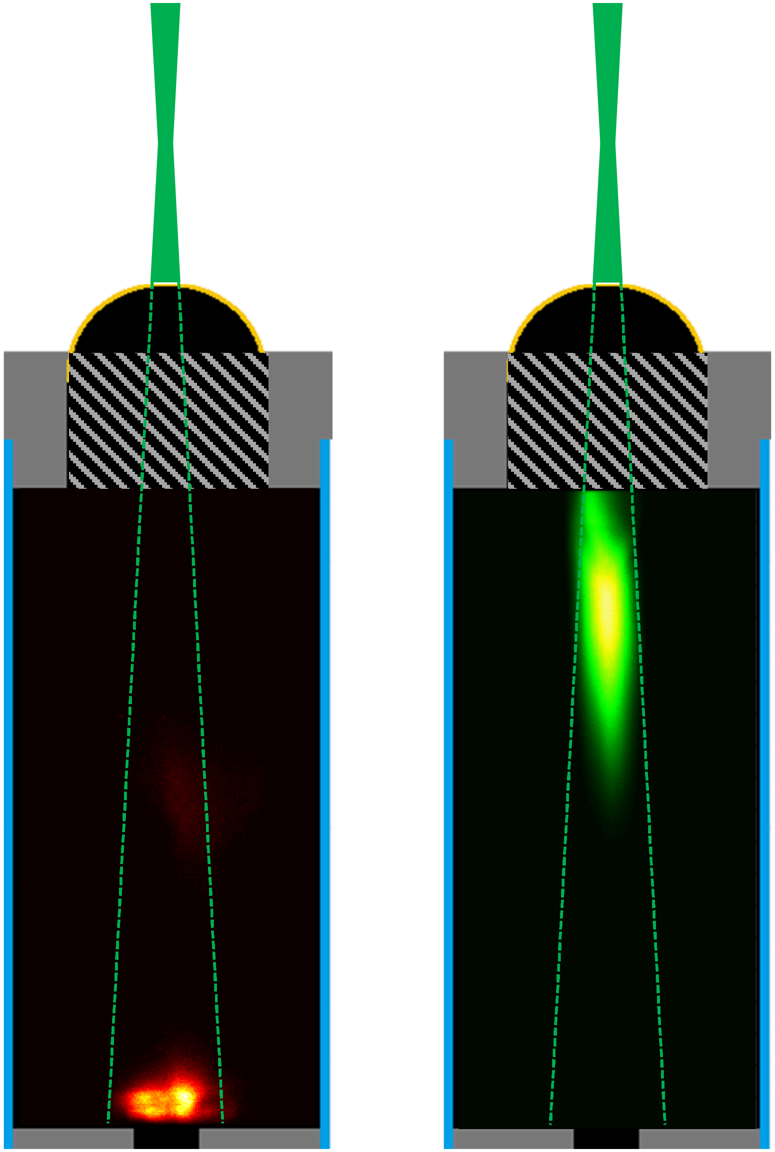
Emissivity weighted temperature is 500 eV

F/10 projection of laser



In laser heating experiments energy was transmitted through the LEH and coupled to the fuel

Transmission through LEH is not ideal, but enough energy is transmitted to heat bottom endcap



Heated volume of fuel is smaller than desired and peak temperature is a little low

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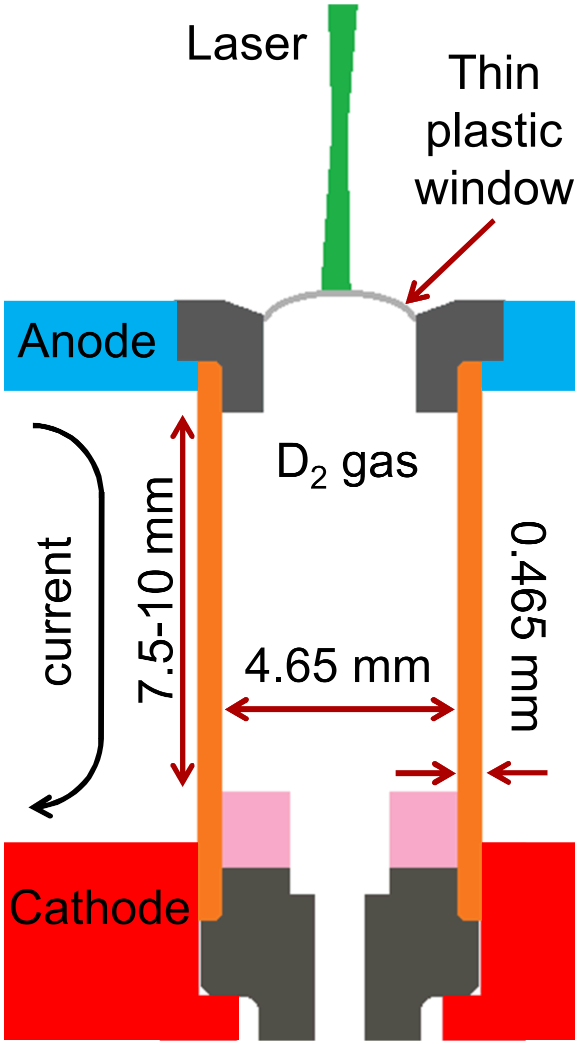
The target design is a product of focused experiments and extensive simulation efforts

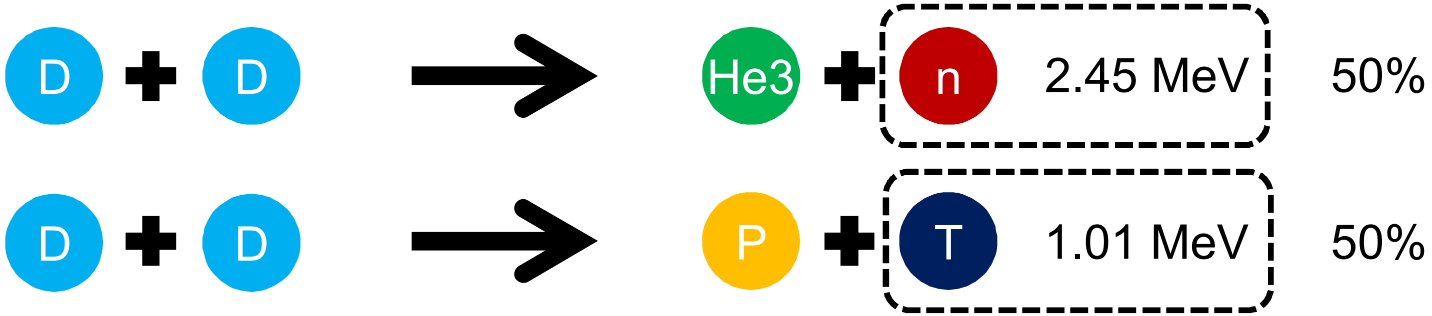
- **Beryllium liner with aspect ratio 6**
  - **Thick liner is more robust to instabilities**
  - **Slow implosion (70 km/s) is matched to current risetime**
  - **Still allows diagnostic access for x rays > 5 keV**
- **The laser enters through 1-3 micron plastic window above the target**
  - **Standoff between LEH and imploding region**
  - **Exit hole at bottom of target**



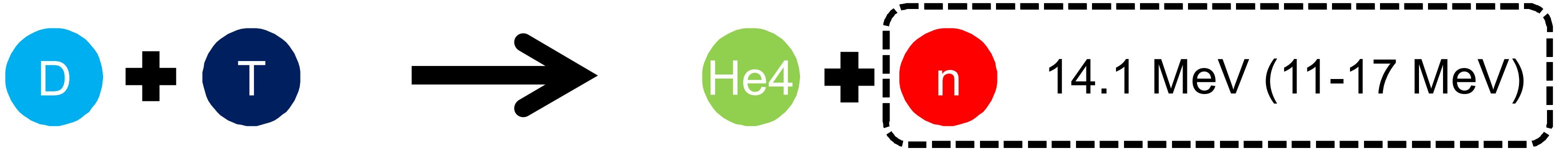
A. B. Sefkow et al., Phys. Plasmas 21, 072711 (2014). See Adam Sefkow's talk – GO4.0005

These experiments utilize deuterium gas as the fusion fuel

- Primary reactions

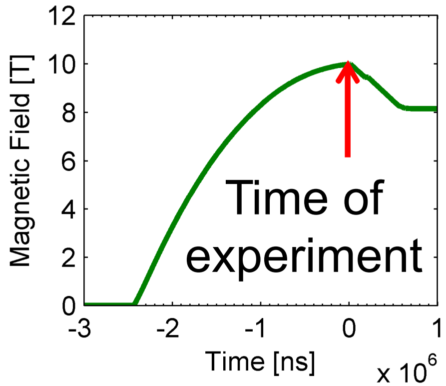


- Secondary reactions



- Triton may still retain fraction of birth energy when reacting

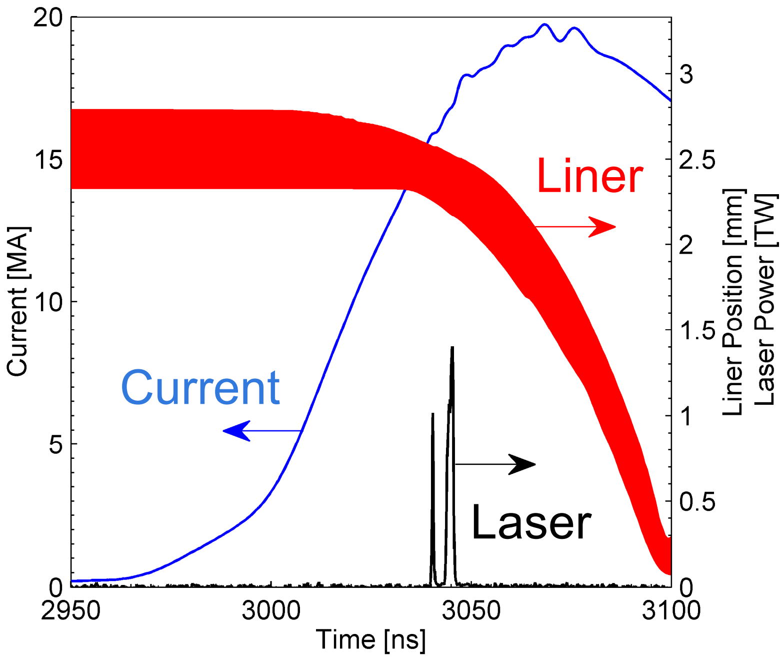
The initial experiments used the maximum magnetic field, current, and laser energy available



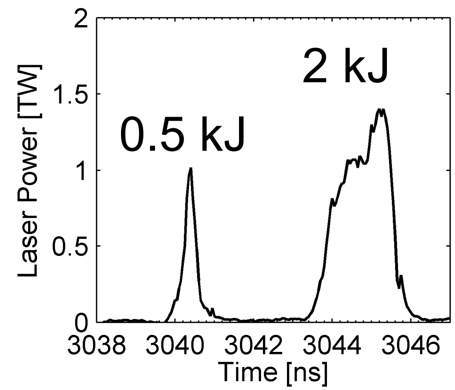
Magnetic field risetime is approximately 2 ms

B is constant over the timescale of the experiment

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

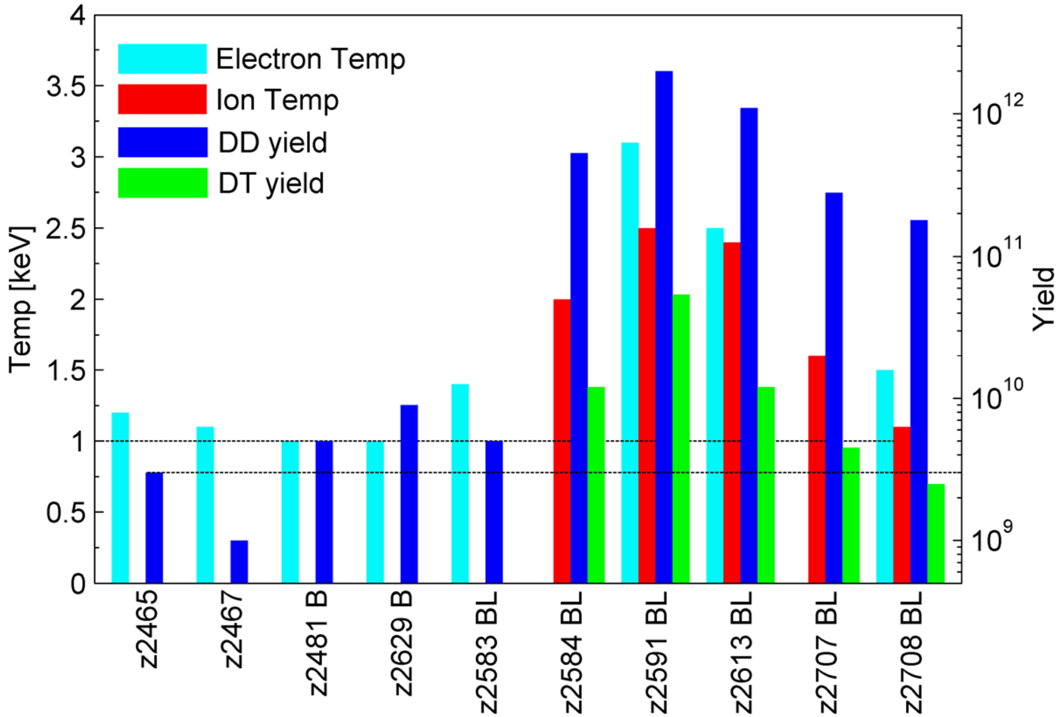


Laser energy is split into 2 pulses:
1st pulse intended to destroy LEH
2nd pulse intended to heat fuel



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

High temperatures and yields were only observed in fully integrated experiments



Some fully-integrated experiments did not produce high yields or temperatures

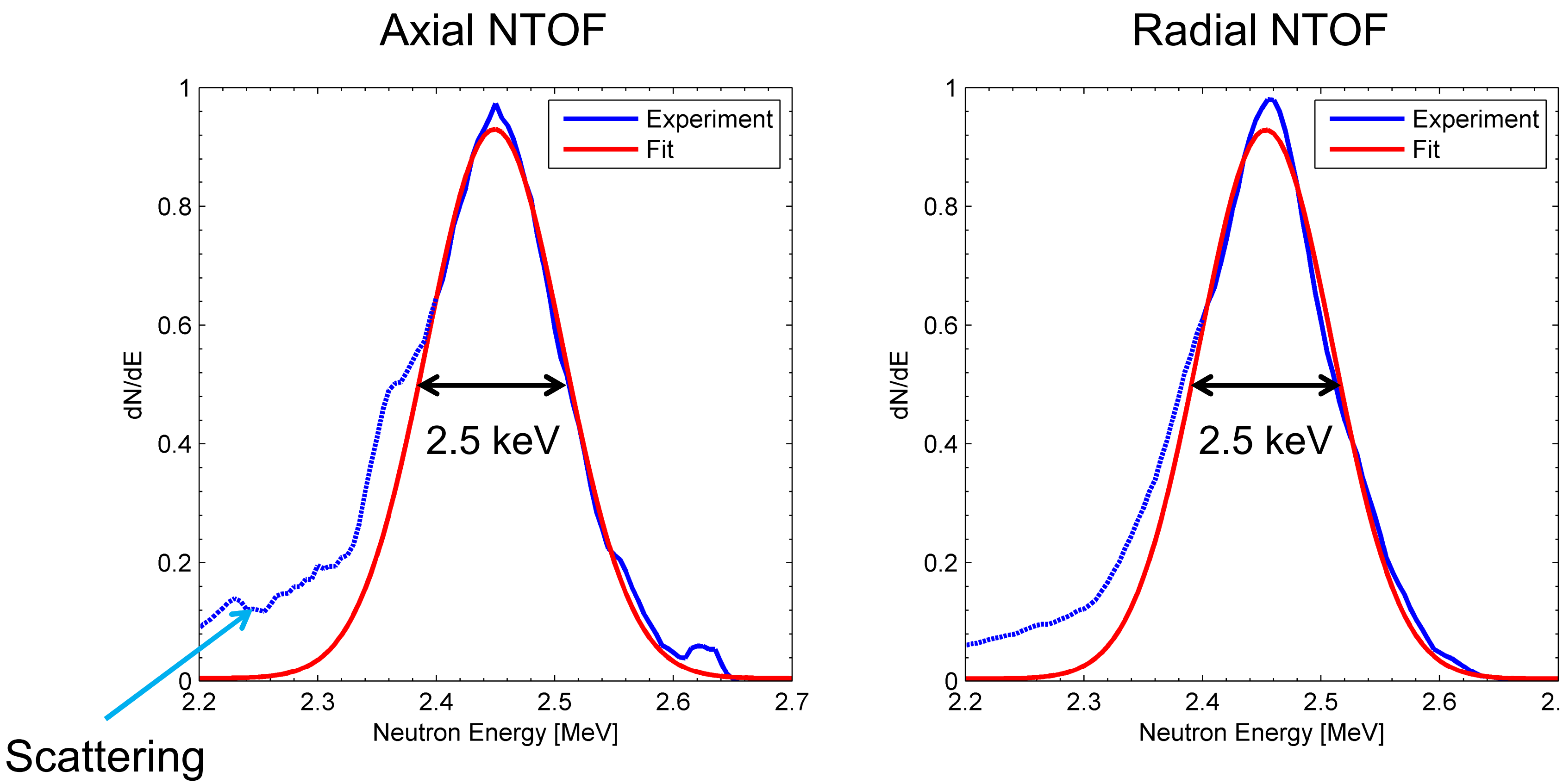
No experiments without laser or B-field have produced high yields or temperatures

These implosions are SLOW – 70 km/s peak
Without the preheating the fuel, the required convergence is >100
Without the magnetic field, the fuel cannot maintain the preheat

Experiments require laser heating and insulating magnetic field to be successful

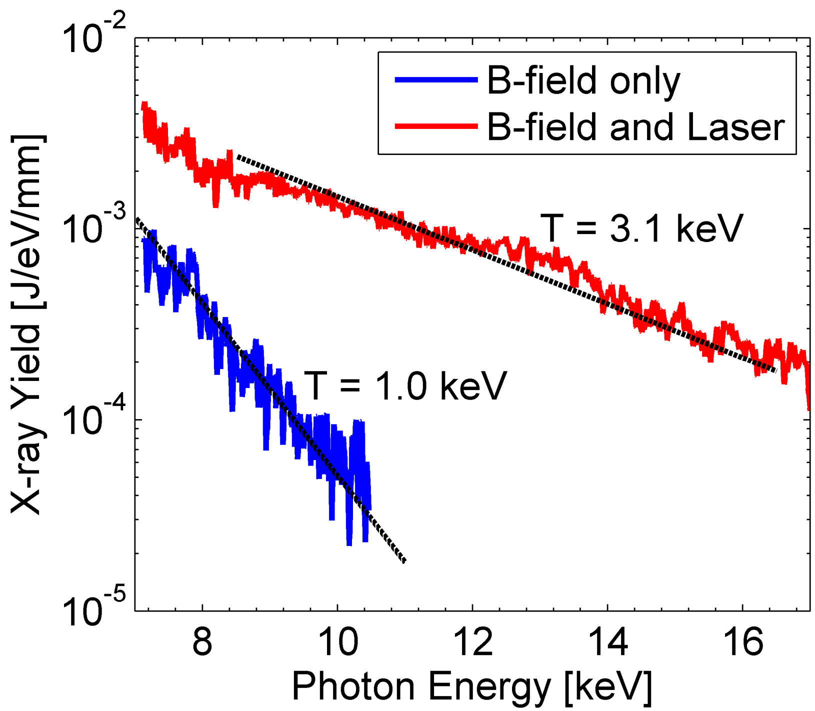
M. R. Gomez et al., Phys. Rev. Lett. 113, 155003 (2014).

Isotropic, Gaussian DD spectra are consistent with thermonuclear neutron generation



Ion temp is determined from the width of the DD peak in the neutron spectrum
Fit applied to the high energy side of the DD peak

Electron stagnation temperatures are consistent with ion temperatures



Electron temperature is determined from the slope of the continuum emission in the high energy x-ray spectrum

Signal is difficult to resolve in experiments with temperatures less than or equal to 1 keV

High temperatures were only observed in experiments that incorporated the magnetic field and laser heating

Primary neutron yield increases with stagnation temperature as expected

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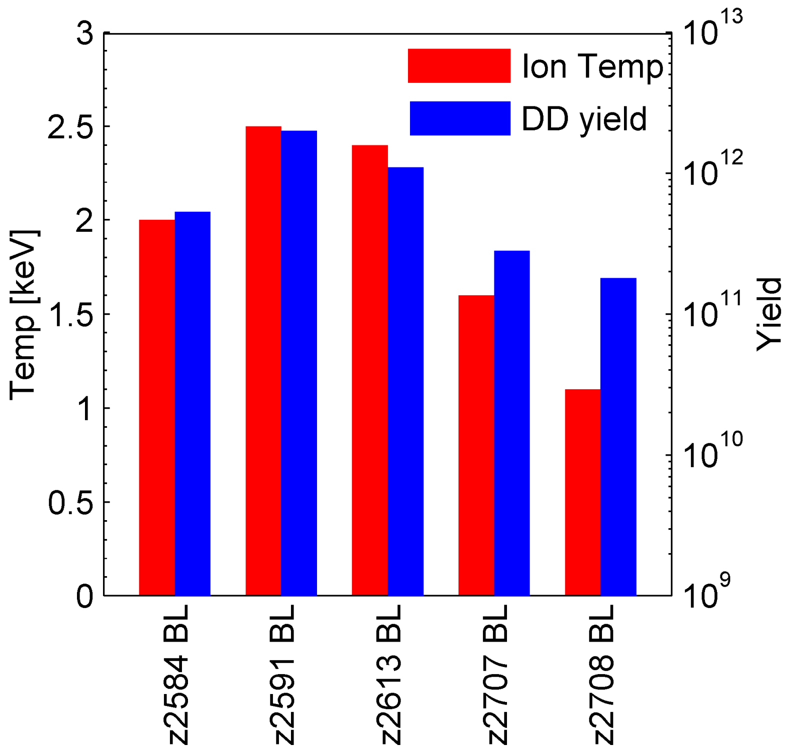
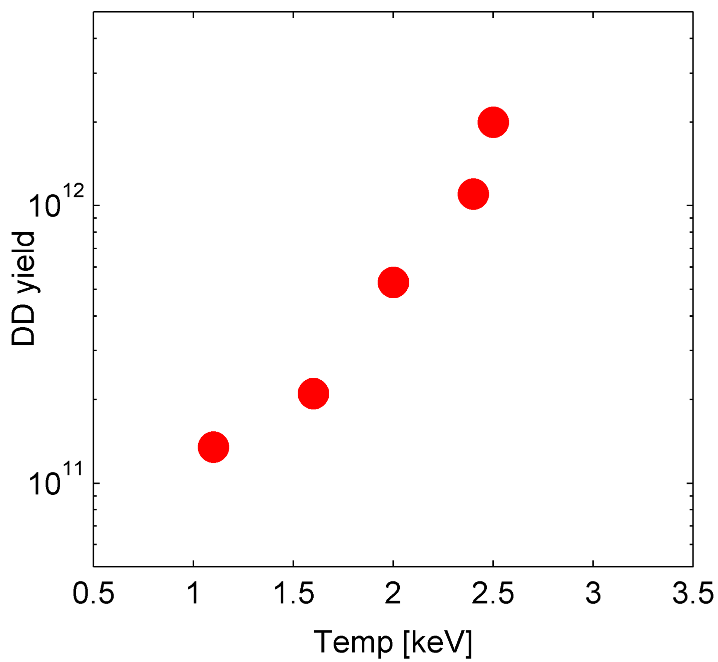
Comparing experiments with with measurable ion temperatures

DD yield ranges from 1.8e11 to 2.0e12
Temperature ranges from 1.1 to 2.5 keV

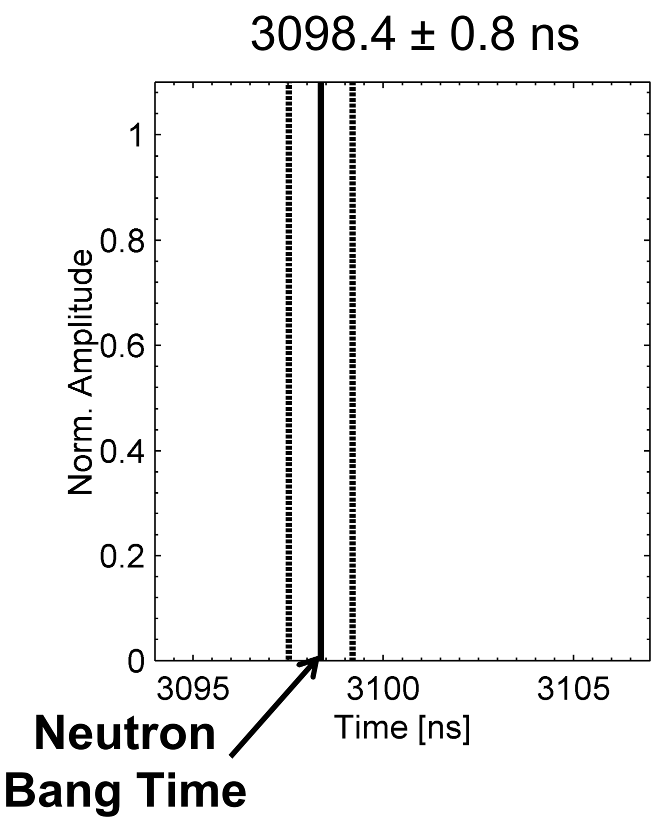




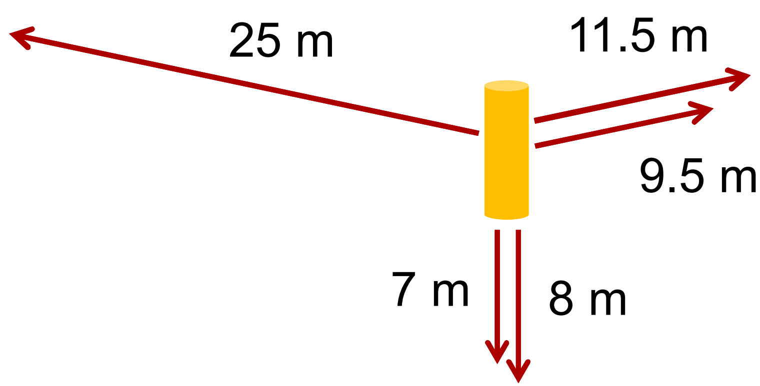
Note: 2707 and 2708 yields scaled down to account for difference in target length

Yield increases with increasing ion temperature

X ray emission timing is consistent with neutron bang time



Neutron bang time was calculated using 5 NTOF detectors at different distances from the source



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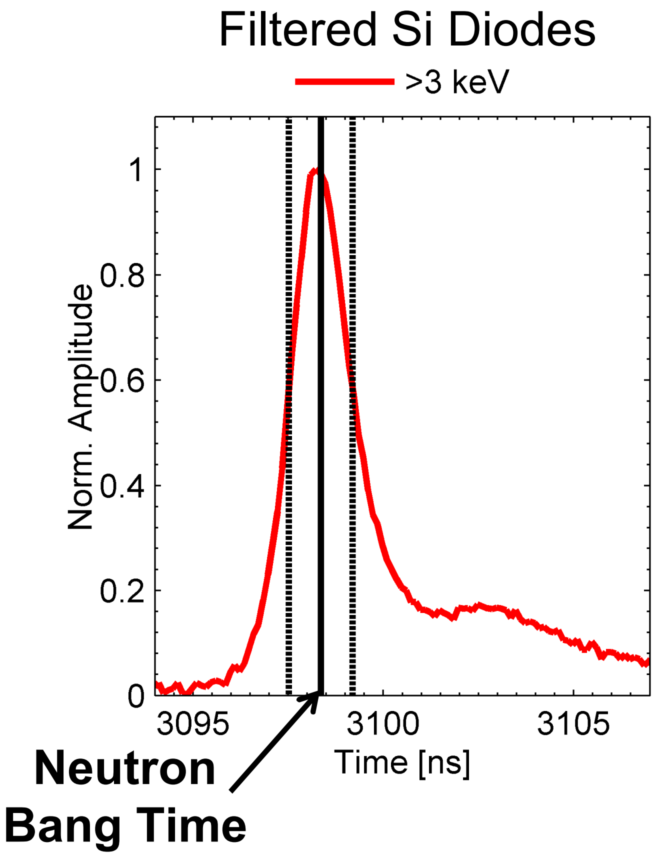

High energy emission is only observed in experiments with laser and B-field

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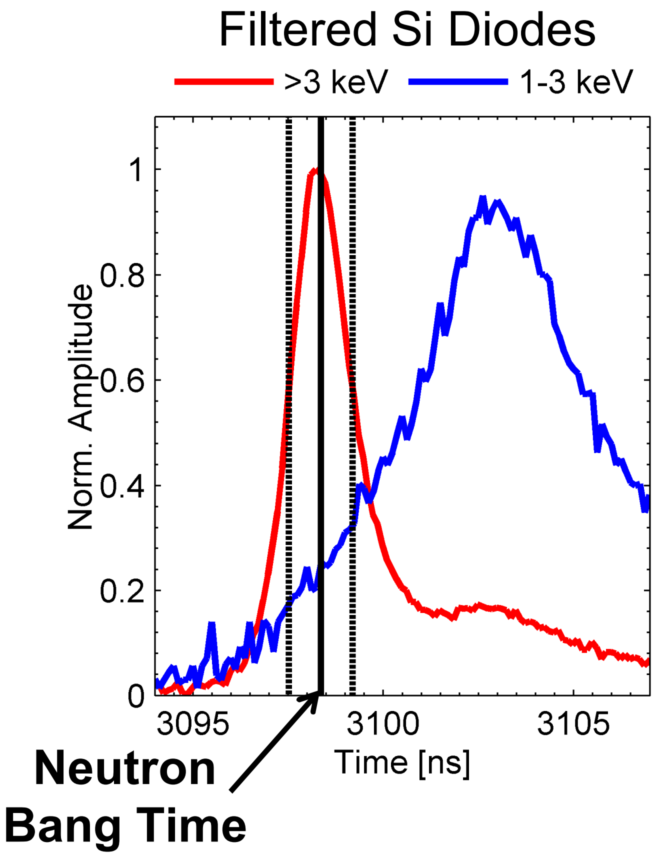

High energy emission is only observed in experiments with laser and B-field

Low energy emission is observed with and without laser and B-field

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

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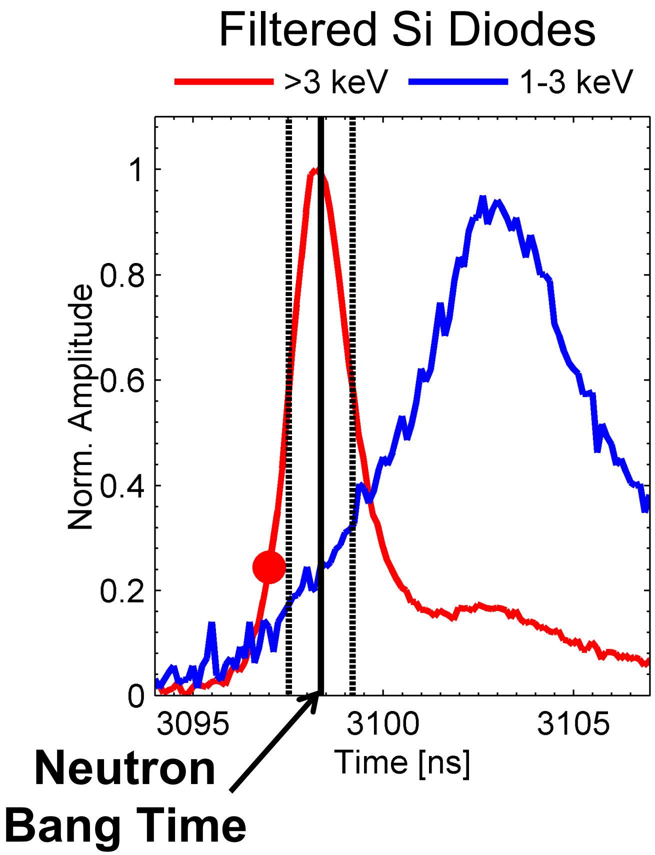

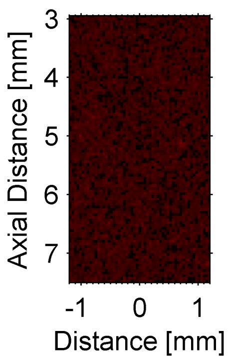

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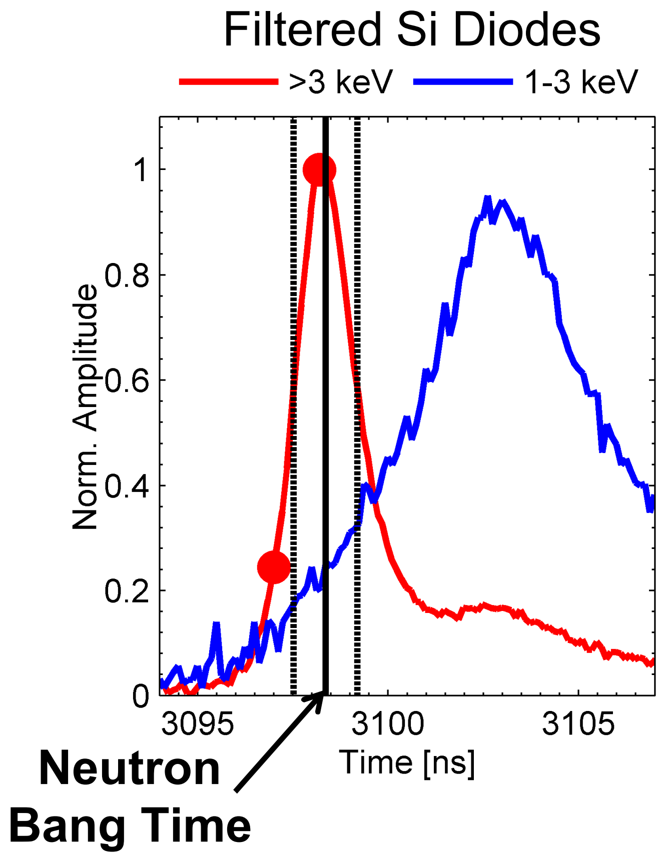

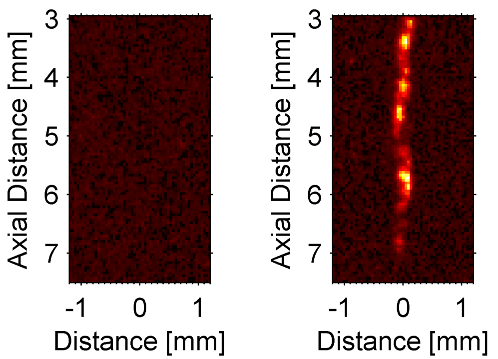

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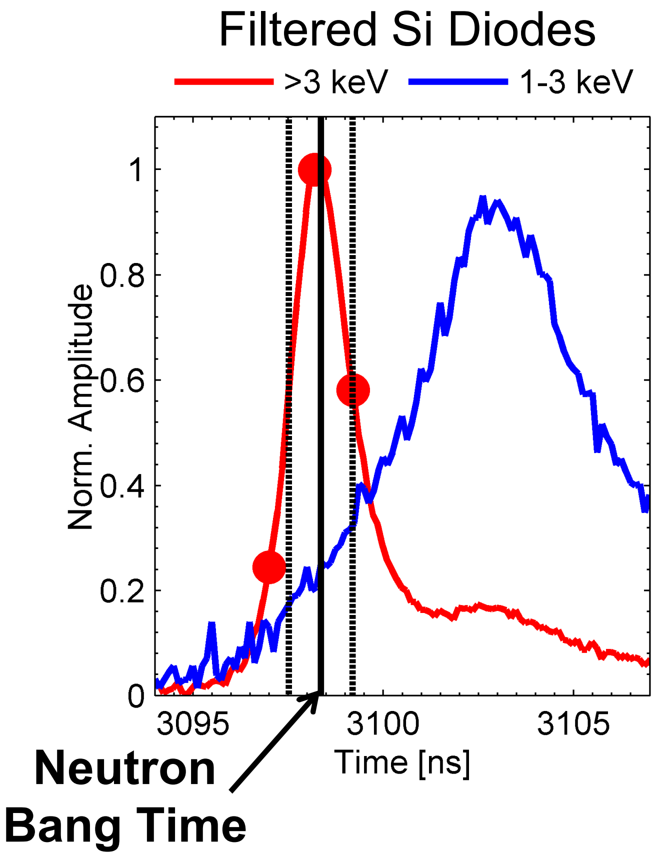
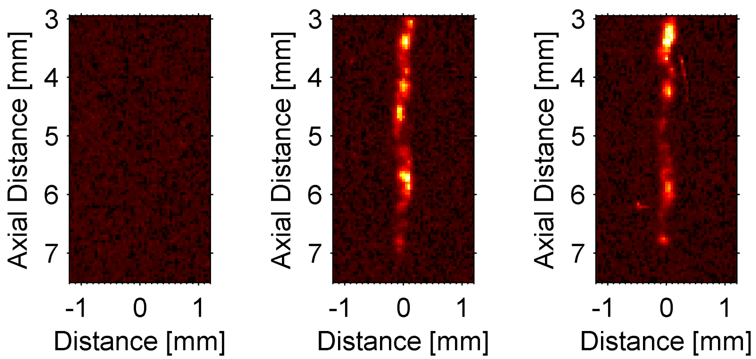
X ray emission timing is consistent with neutron bang time





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

Low energy emission is observed with and without laser and B-field

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

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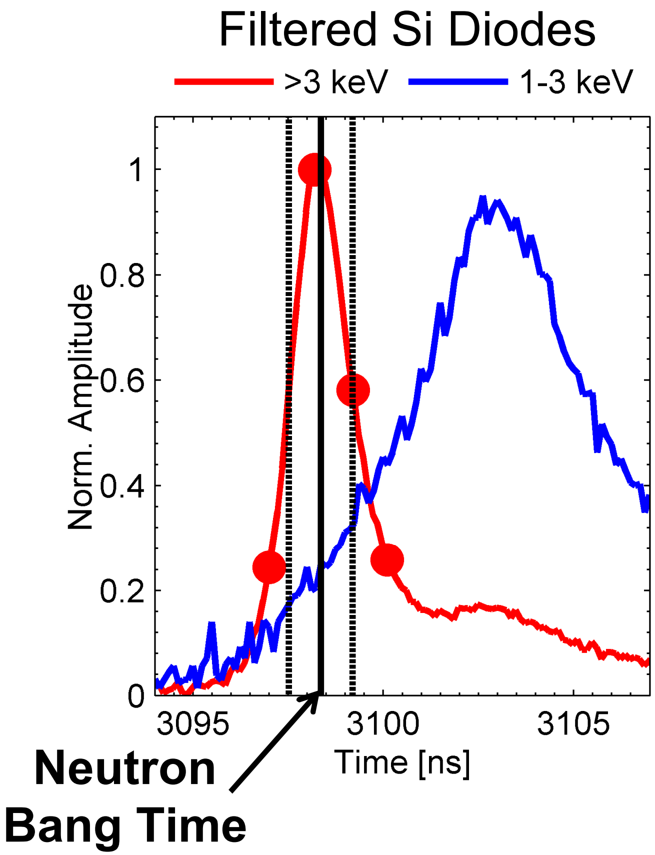

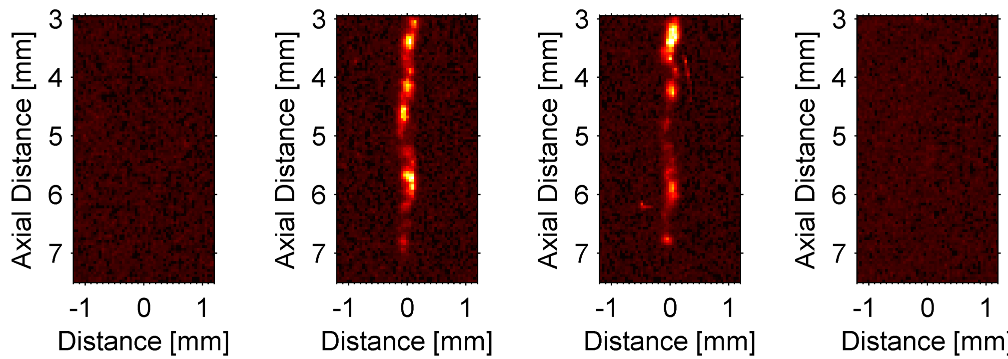

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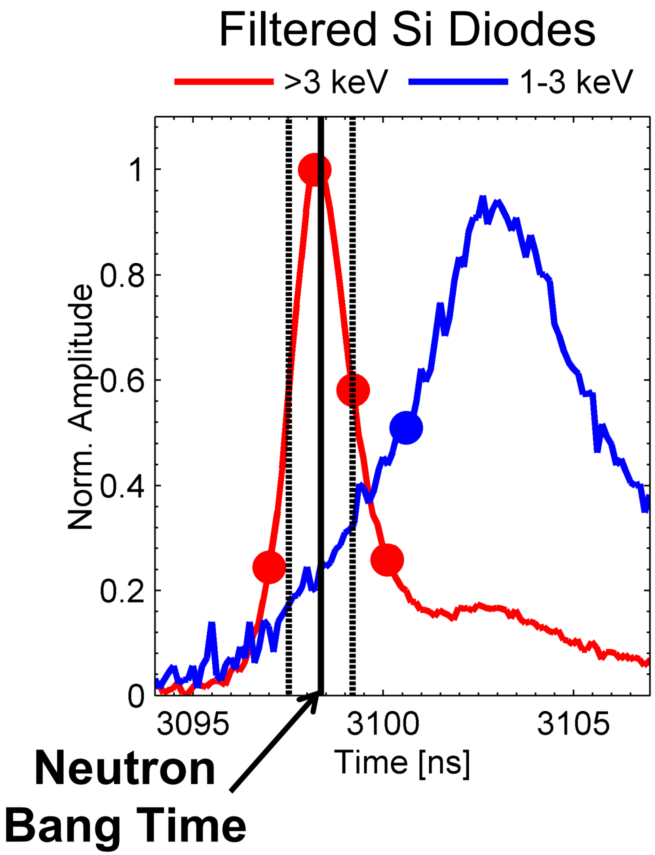

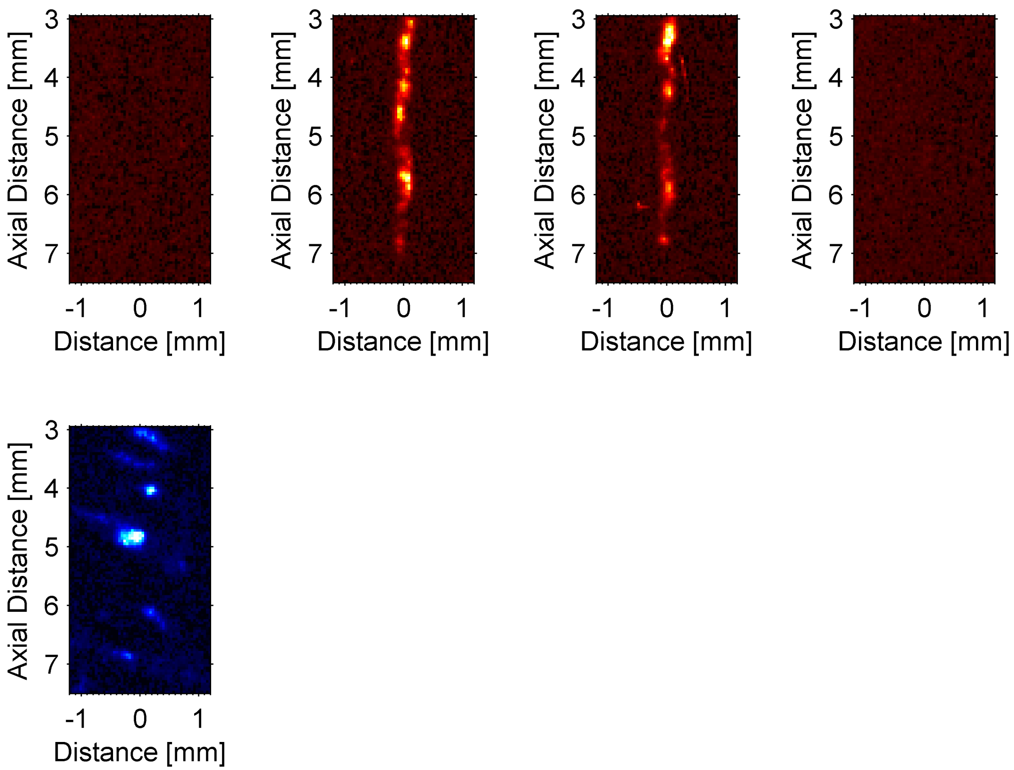

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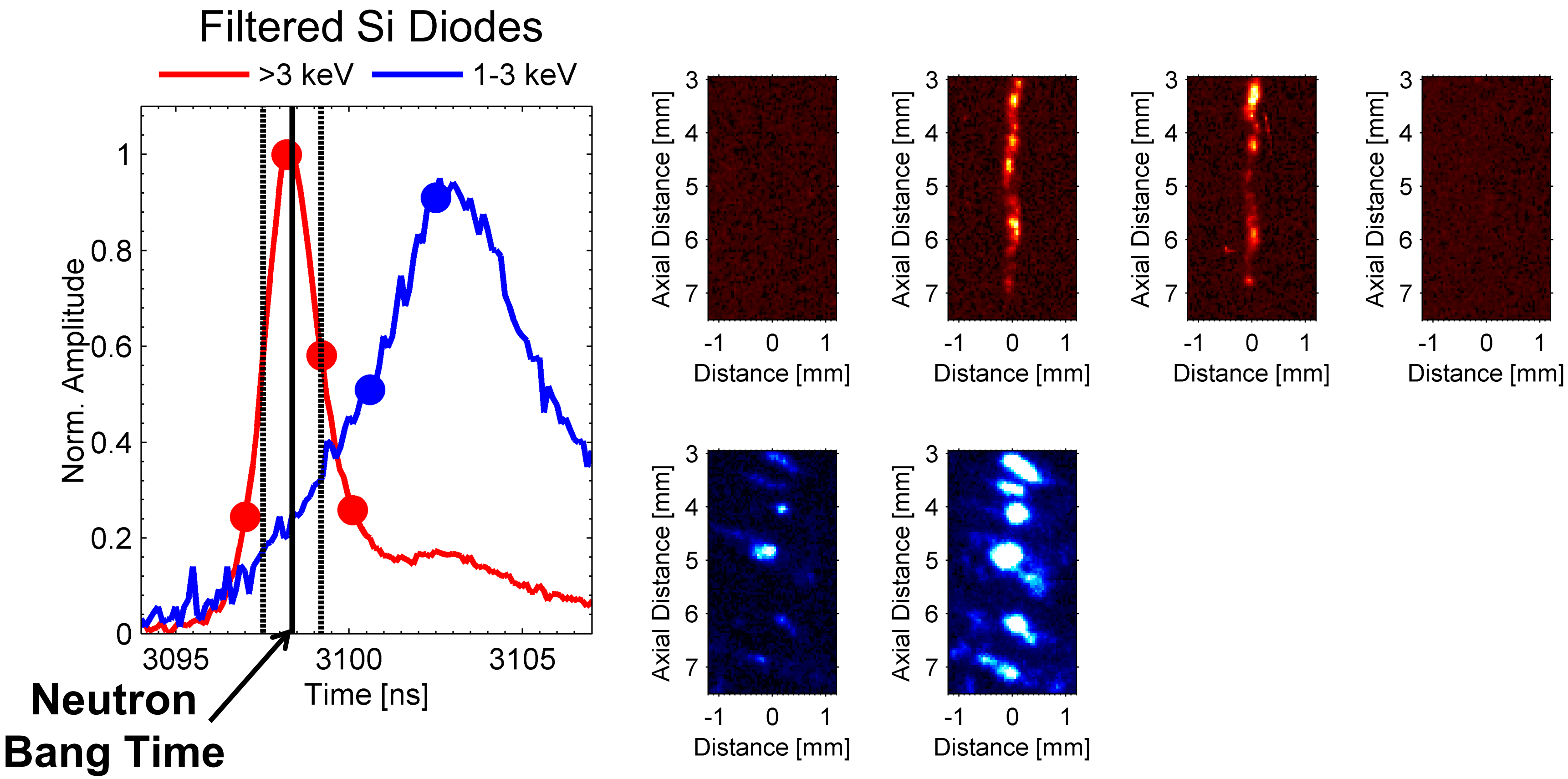

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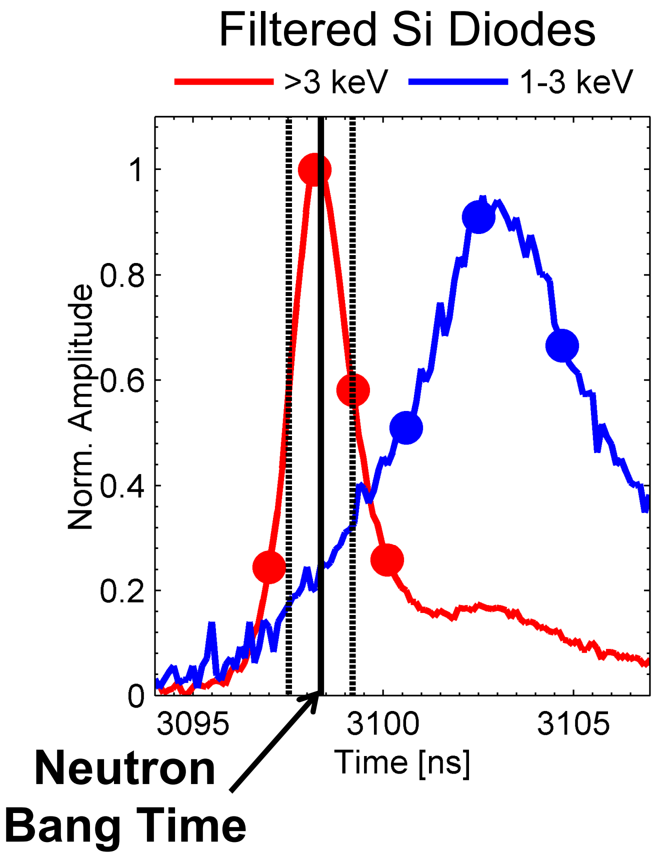

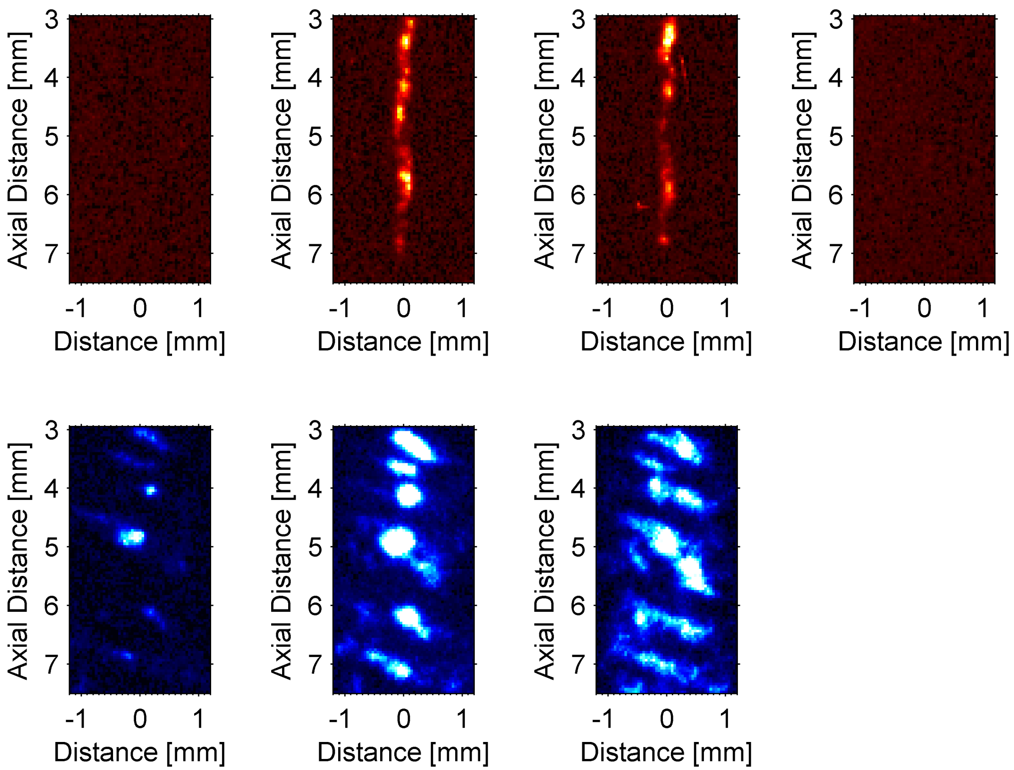

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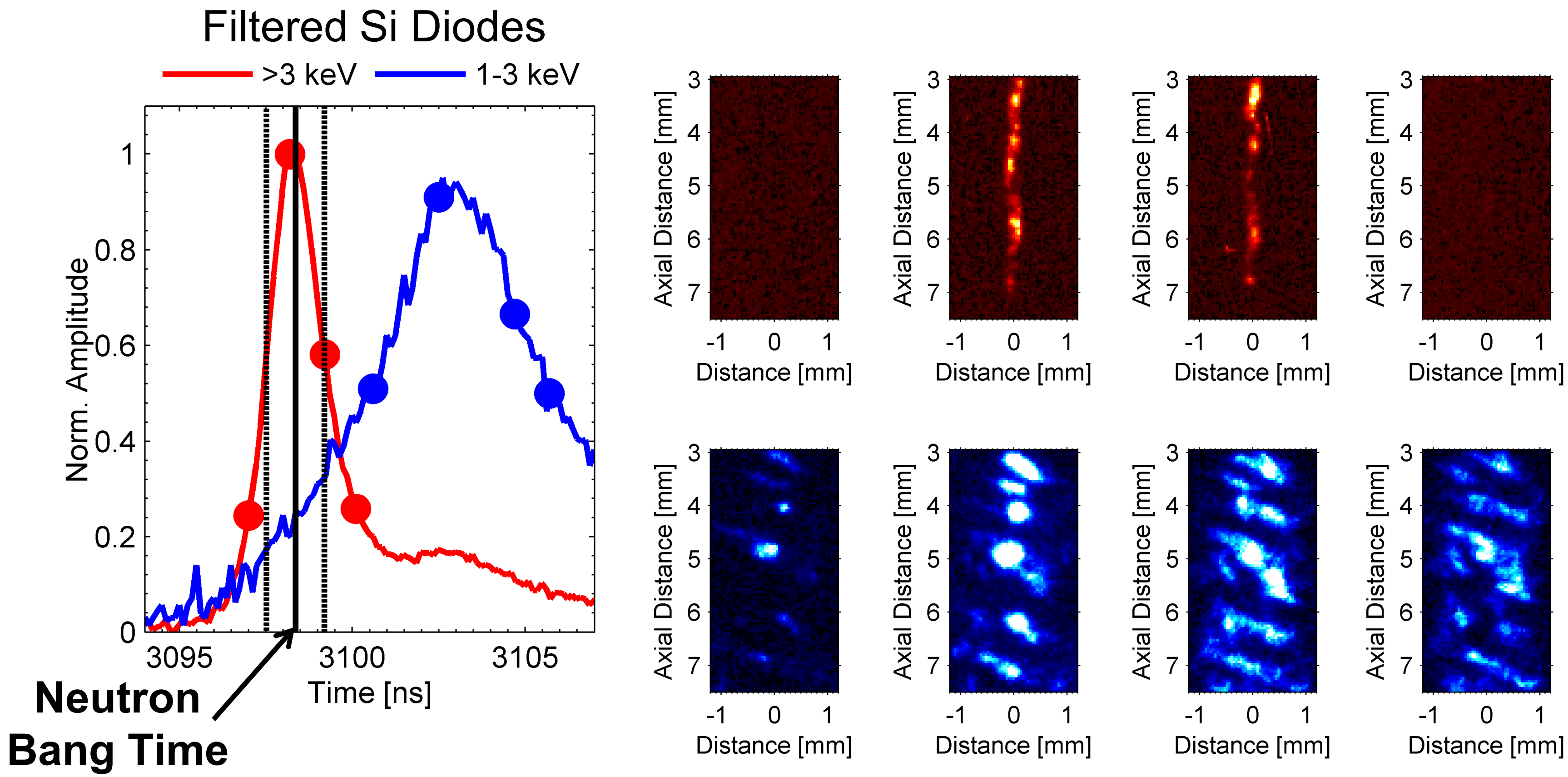

High energy emission is only observed in experiments with laser and B-field

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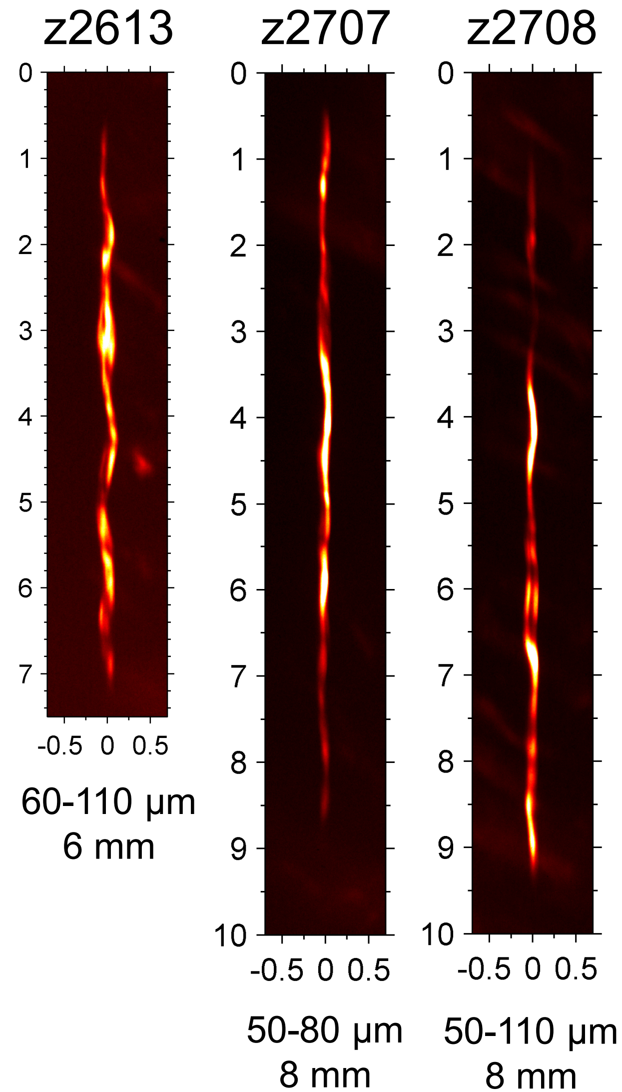
M. R. Gomez et al., Phys. Rev. Lett. 113, 155003 (2014).

X ray emission from the fuel shows a high aspect ratio stagnation column

- **Emission region does not define the fuel-liner boundary, but defines the hottest region of the fuel**
- **Emission FWHM is 50-110 µm**
- **Emission height is approximately 80% of target height**
- **Axial intensity variations indicate variations in both the fuel conditions (temperature and density) and the liner opacity**
- **Stagnation column is weakly helical**

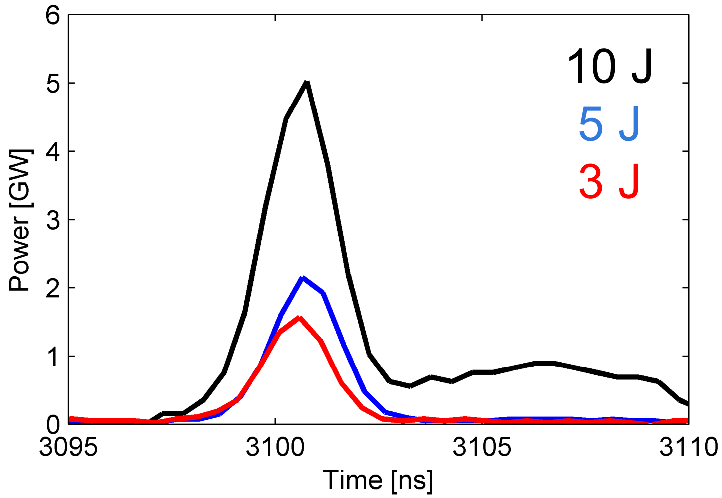


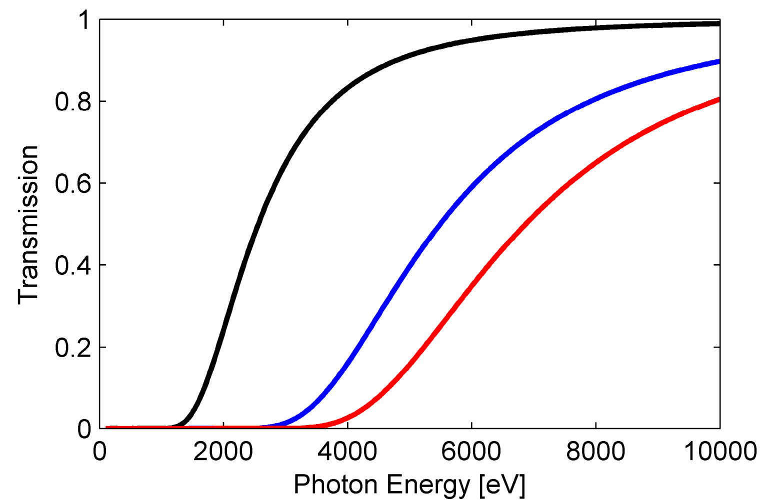
M. R. Gomez et al., Phys. Rev. Lett. 113, 155003 (2014).

Fuel density at stagnation is determined from x ray diagnostics

Using the temperature derived from x-ray spectroscopy, the source size derived from x-ray imaging, and the radiated energy determined from PCD signals, the density of the fuel was calculated

25 microns Kapton 250 microns Kapton 500 microns Kapton





Details of this calculation will be given in the following presentation

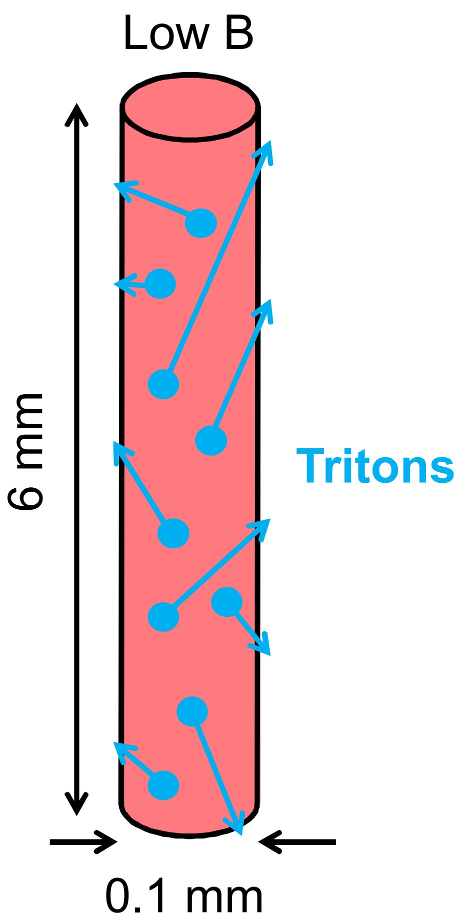
See Stephanie Hansen’s talk – CI1.00006

Stagnation conditions are consistent with the measured thermonuclear yields

- **Volume of hot fuel = 2-5 x 10^{-5} cm^3**
- **Peak X ray emission ≈ 1 ns**
- **Stagnation density = 0.7-2 x $10^{23}/cm^3$**
- **Stagnation temperature = 2.5-3.1 keV**
  - **$\langle \sigma v \rangle \approx$ 1.3-2.8 x 10^{-20} cm^3/s**
- **$f = 0.5n^2\langle \sigma v \rangle \approx$ 0.28-5.6 x $10^{26}/cm^3s$**
- **Calculated Yield = $\tau V f \approx$ 6e11-3e13 DD neutrons**

- **Measured yield = 2e12 DD neutrons**

Magnetic flux compression demonstrated through secondary neutron yield and spectra



ρR ~ 2 mg/cm^2
ρZ ~ 200 mg/cm^2

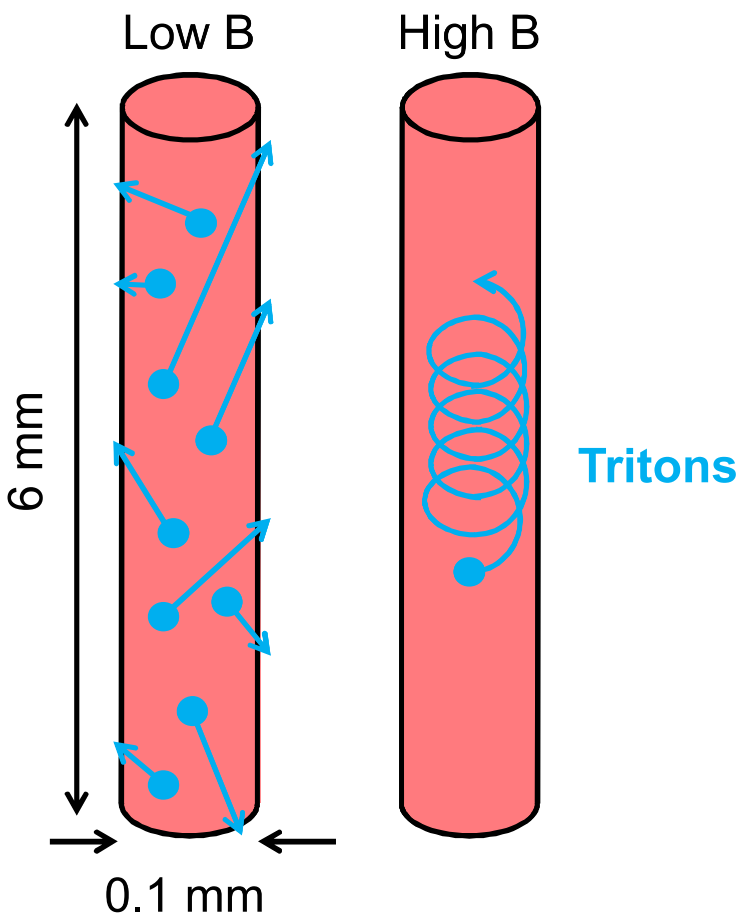
In a high aspect ratio cylinder the effective areal density of the fuel is approximately the radial areal density

For ρR ~ 2 mg/cm^2

DD/DT yield ratio > 1000

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

Magnetic flux compression demonstrated through secondary neutron yield and spectra



$\rho R \sim 2$ mg/cm^2
$\rho Z \sim 200$ mg/cm^2

In a highly magnetized cylinder the effective areal density of the fuel becomes much larger because the tritons cannot escape radially.

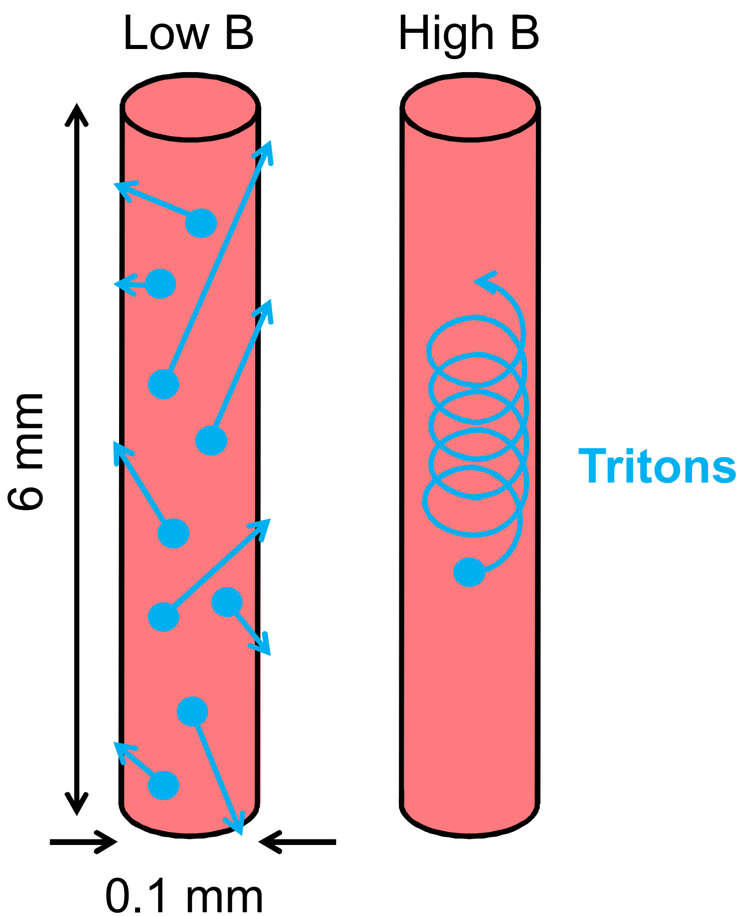
For $\rho R \sim 2$ mg/cm^2

DD/DT yield ratio > 1000
(unless significantly magnetized)

We observed DT yields as high as 5e10
DD/DT ~ 50-100

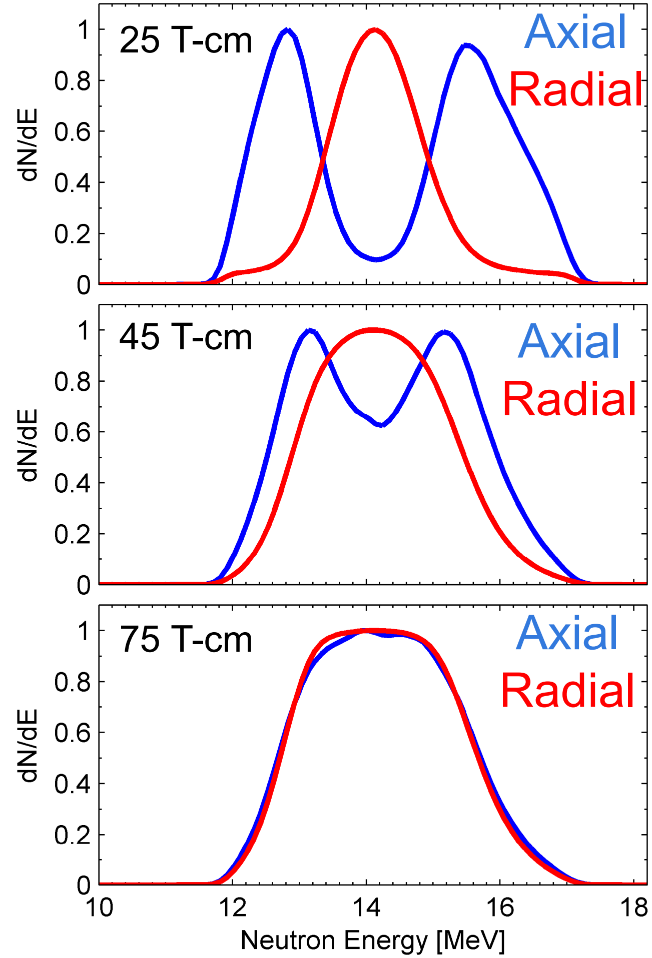
P. F. Schmit, P. F. Knapp et al., Phys. Rev. Lett. 113, 155004 (2014).

Magnetic flux compression demonstrated through secondary neutron yield and spectra



DT spectra are very sensitive to BR in this regime

As BR increases the distance between peaks in the axial spectra decreases



Our DT/DD yield ratio and DT spectra are consistent with BR ≈ 40 ± 7 T-cm

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

The Magnetized liner Inertial Fusion concept was successfully demonstrated

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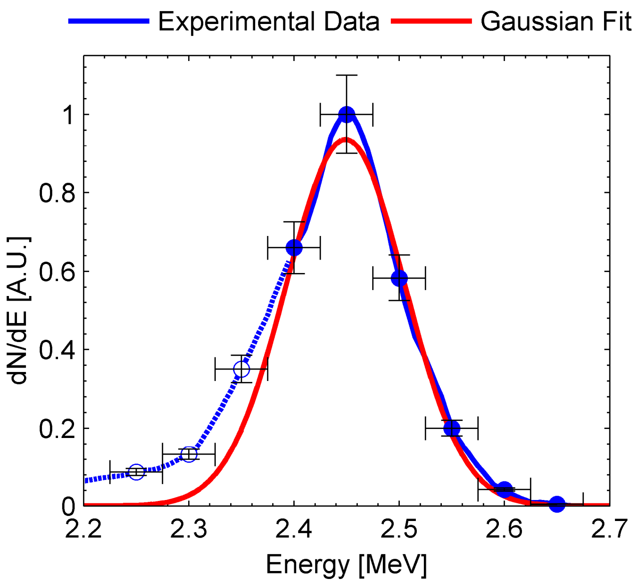
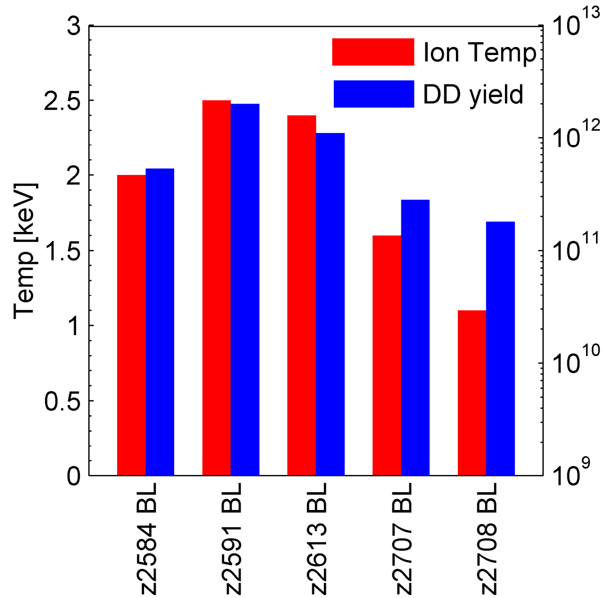
Thermonuclear neutron generation



Isotropic, Gaussian DD neutron spectra

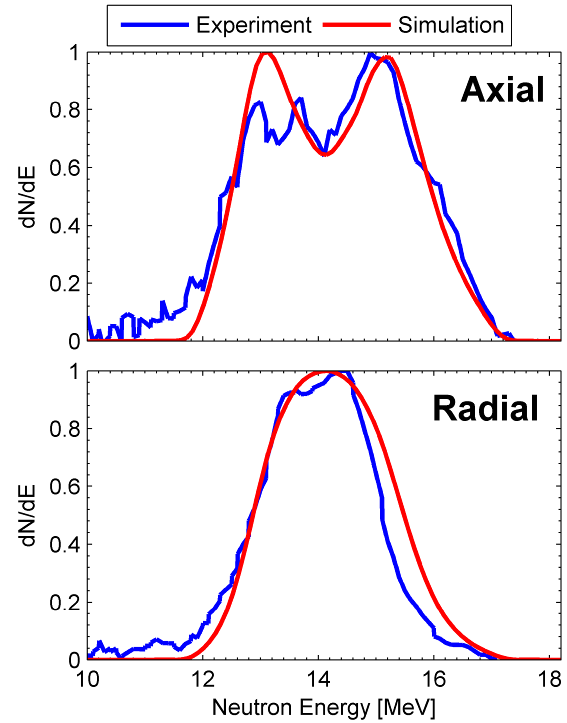
High yields and temperatures



Max yield = 2e12

Max ion temp = 2.5 keV

Magnetic flux compression



BR = 40 T-cm

Thanks to the members of the MagLIF team

- 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
- Oral session on MagLIF: GO4 – Tuesday AM
- MagLIF-related posters: JP8 – Tuesday PM
- Stick around for Stephanie's talk "Diagnosing stagnation conditions, mix and drive in MagLIF experiments"