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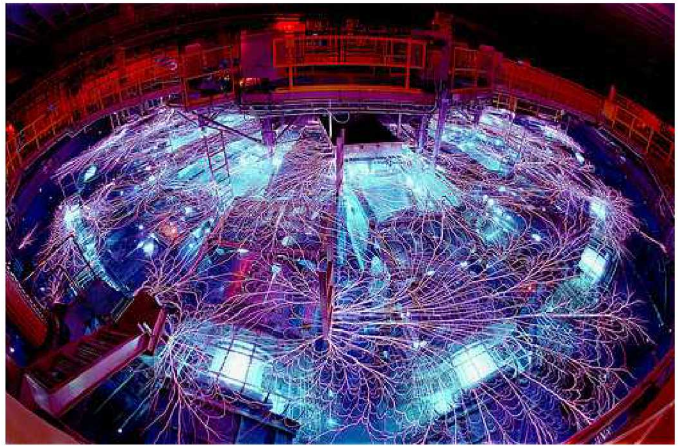


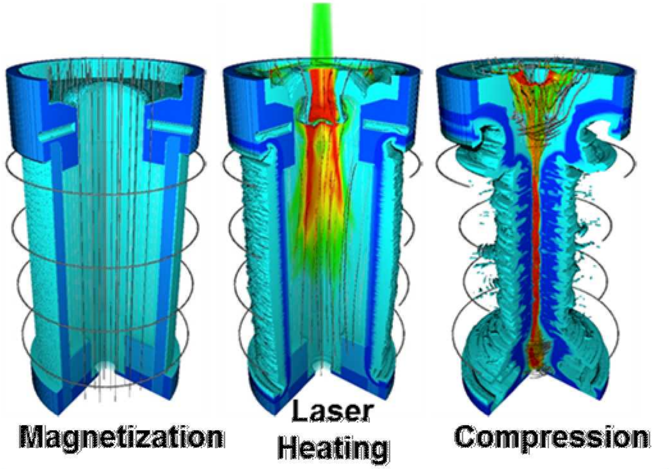
Assessing magnetized liner inertial fusion stagnation conditions and identifying trends

M. R. Gomez, S. A. Slutz, P. F. Knapp, K. D. Hahn, E. C. Harding, D. J. Ampleford, T. J. Awe, M. Geissel, S. B. Hansen, A. J. Harvey-Thompson, C. A. Jennings, C. E. Myers, K. J. Peterson, G. A. Rochau, D. B. Sinars, M. R. Weis, and D. A. Yager-Elorriaga

Sandia National Laboratories

45th IEEE International Conference on Plasma Science

June 25, 2018



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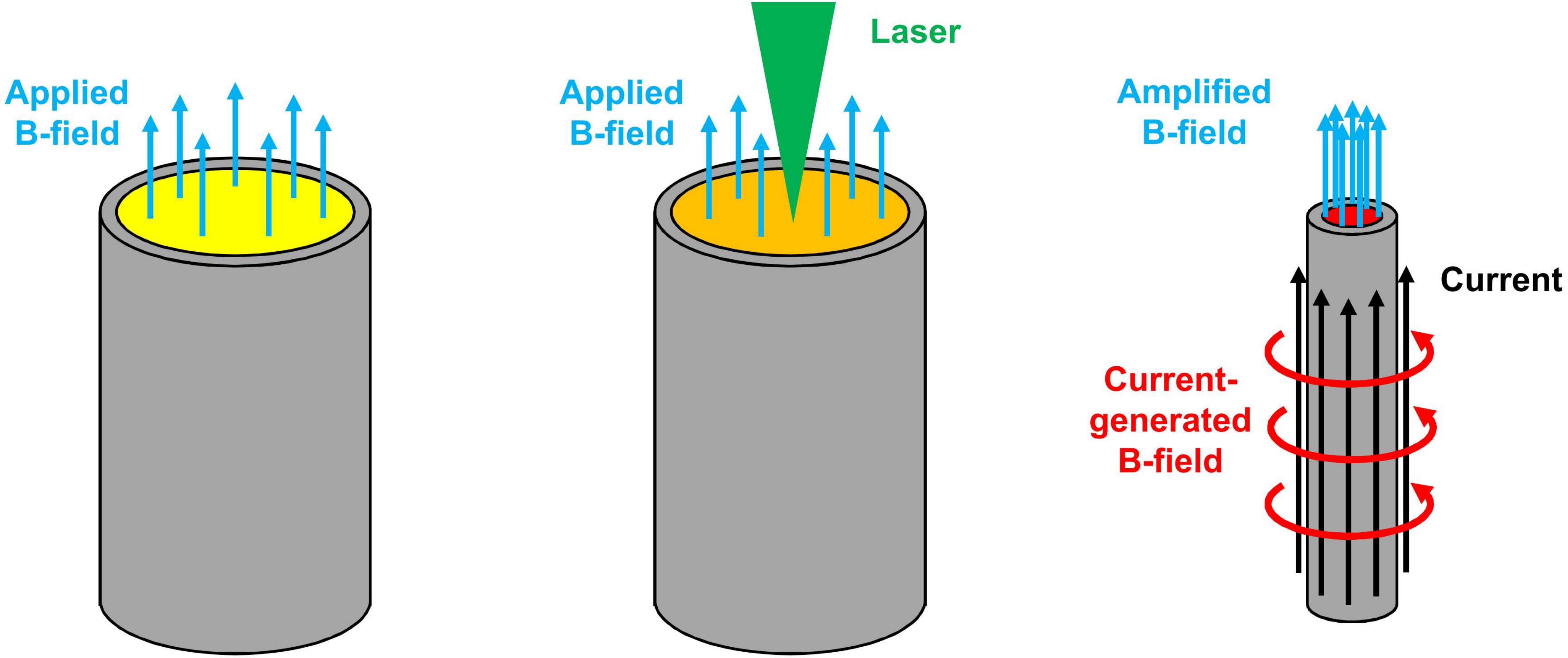
Outline

- Introduction
- Early experiments
  - Understanding laser energy deposition
  - Diagnosing and mitigating mix
- Improving capabilities
  - B-field
  - Load current
  - Laser energy deposition
- The Future

Magnetized Liner Inertial Fusion relies on three stages to produce fusion relevant conditions



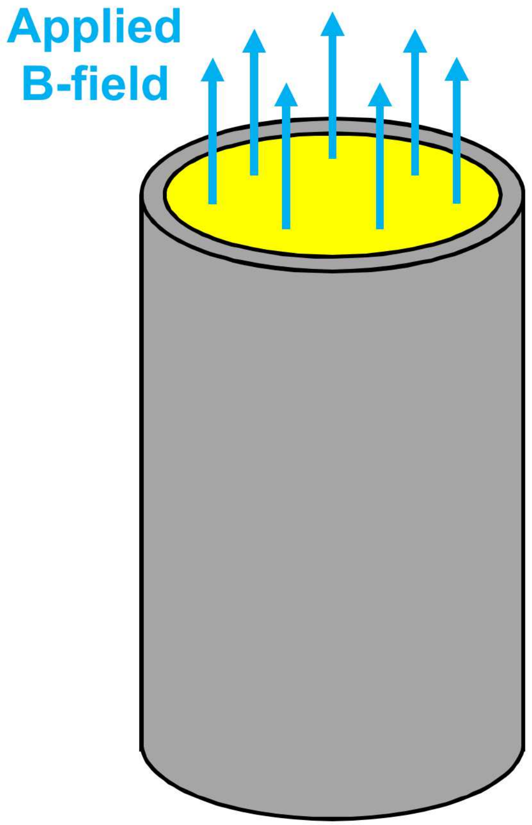
Apply axial magnetic field

Laser-heat the magnetized fuel

Compress the heated and magnetized fuel

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

The axial magnetic field is applied to limit radial charged particle transport during the implosion

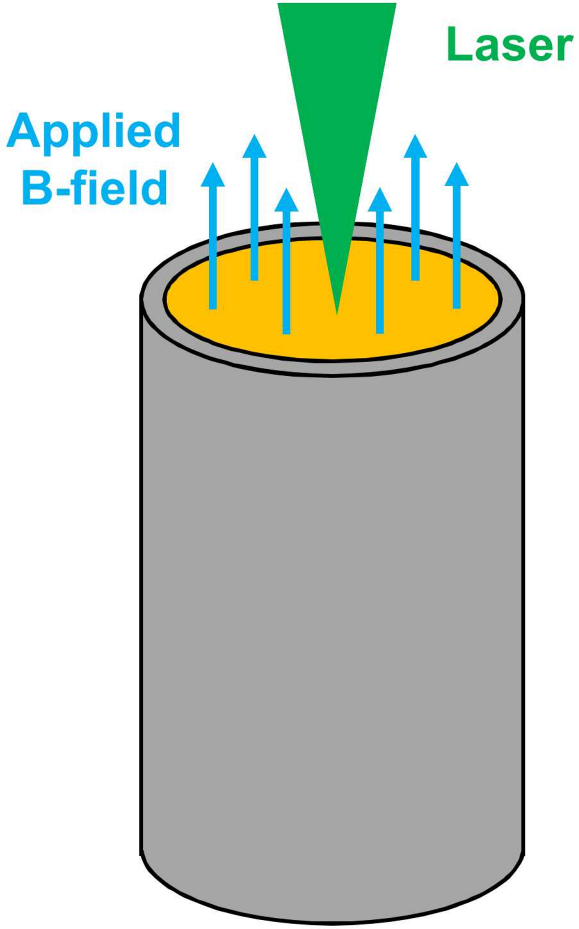


Apply axial magnetic field

- Metal cylinder contains of order 1 mg/cm^3 of deuterium gas
  - 10 mm tall, 5 mm diameter, 0.5 mm thick
- Helmholtz-like coils apply 10s of T
  - few ms risetime to allow field to diffuse through conductors

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

A laser is used to heat the fuel at the start of the implosion

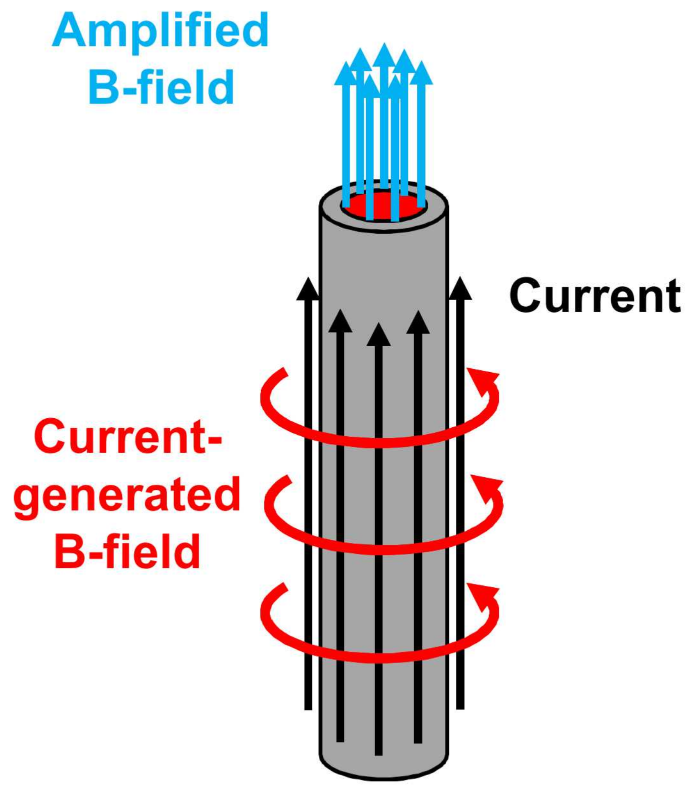


Laser-heat the magnetized fuel

- 527 nm, few ns, few kJ laser used to heat the fuel
- Laser must pass through 1-3 μm thick plastic window
  - Can lose many hundreds of joules to absorption in and scattering off of the plastic
- Fuel is heated to hundreds of eV
  - Recall the axial magnetic field limits thermal conduction in the radial direction

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

The current from the Z machine is used to implode the target



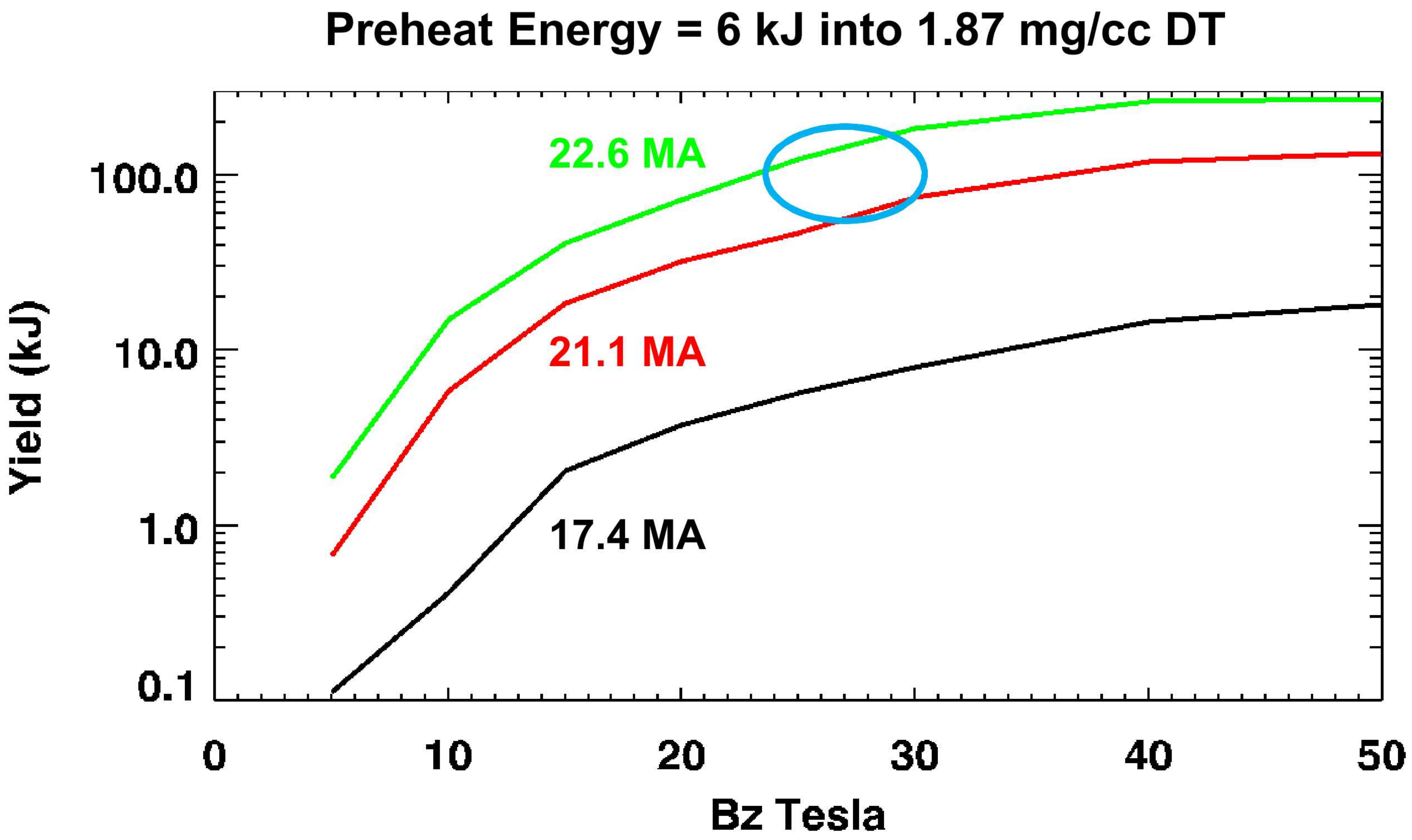
Compress the heated and magnetized fuel

- Axial current is 15-20 MA, risetime is 100 ns
  - Generates ~3 kT azimuthal B-field
  - Metal cylinder implodes at ~70 km/s
- Fuel is nearly adiabatically compressed, which further heats the fuel to keV temperatures
- Axial magnetic field is increased to 1-10 kT through flux compression

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

Our goal on Z is to create fusion conditions that would produce a yield of 100 kJ with DT

- Simulations indicate a viable region of parameter space exists
- 22+ MA and 25+ T with 6 kJ of preheat
- We are improving our capabilities to allow us to access this region of parameter space



S. A. Slutz, et al., to be submitted.

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- **Early experiments**
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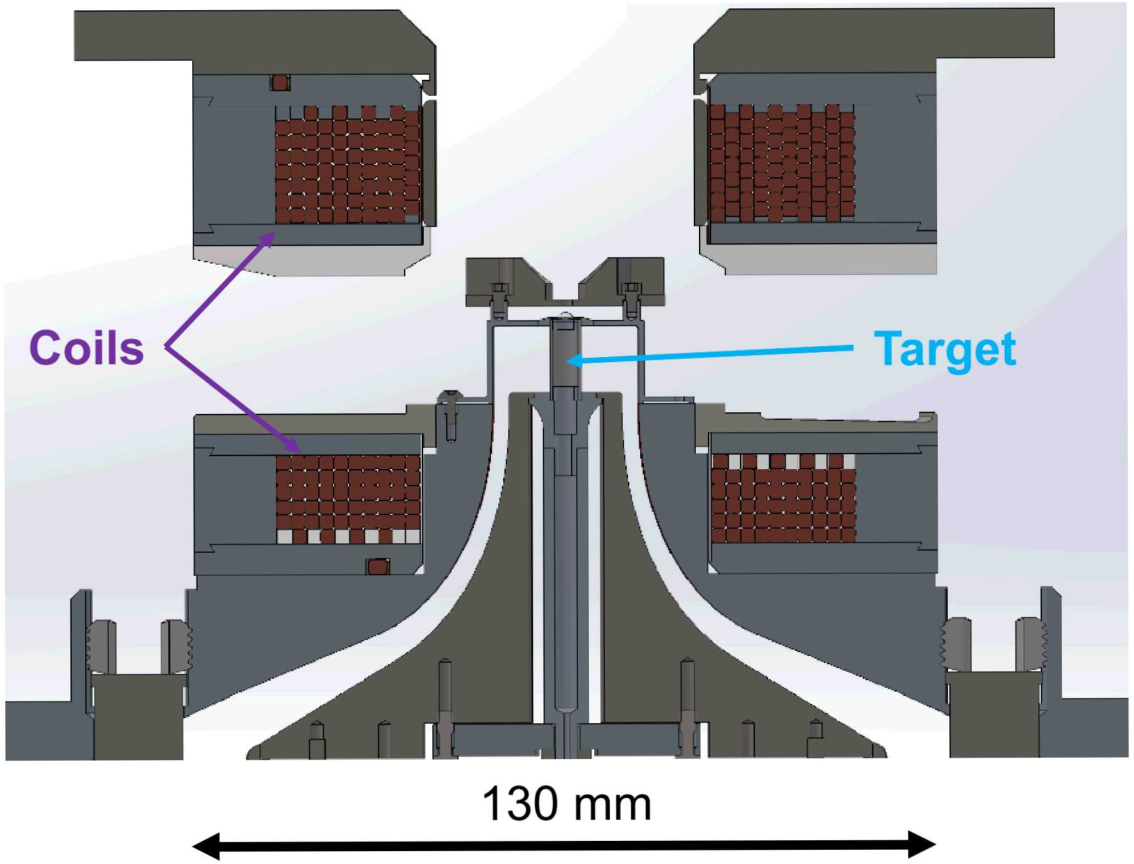
- The Future

With our initial experiments, we targeted 2 kJ, 10 T, and 18 MA



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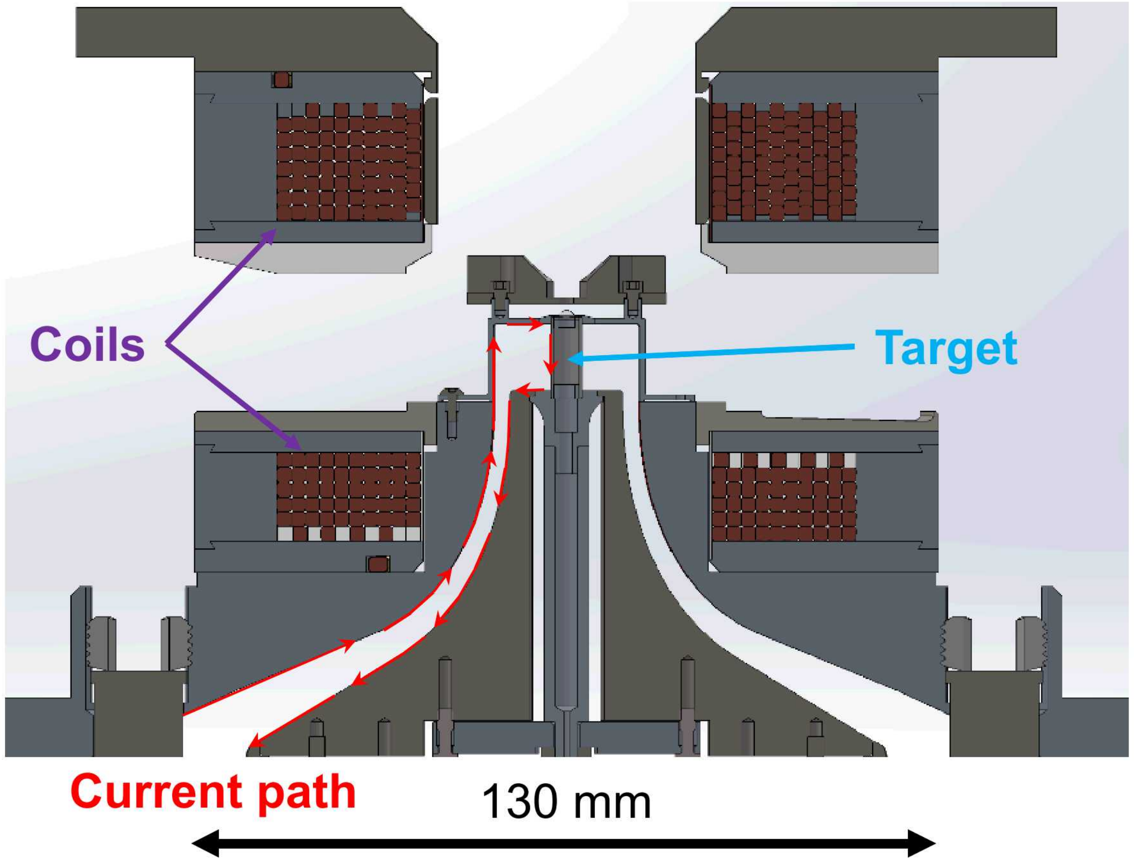

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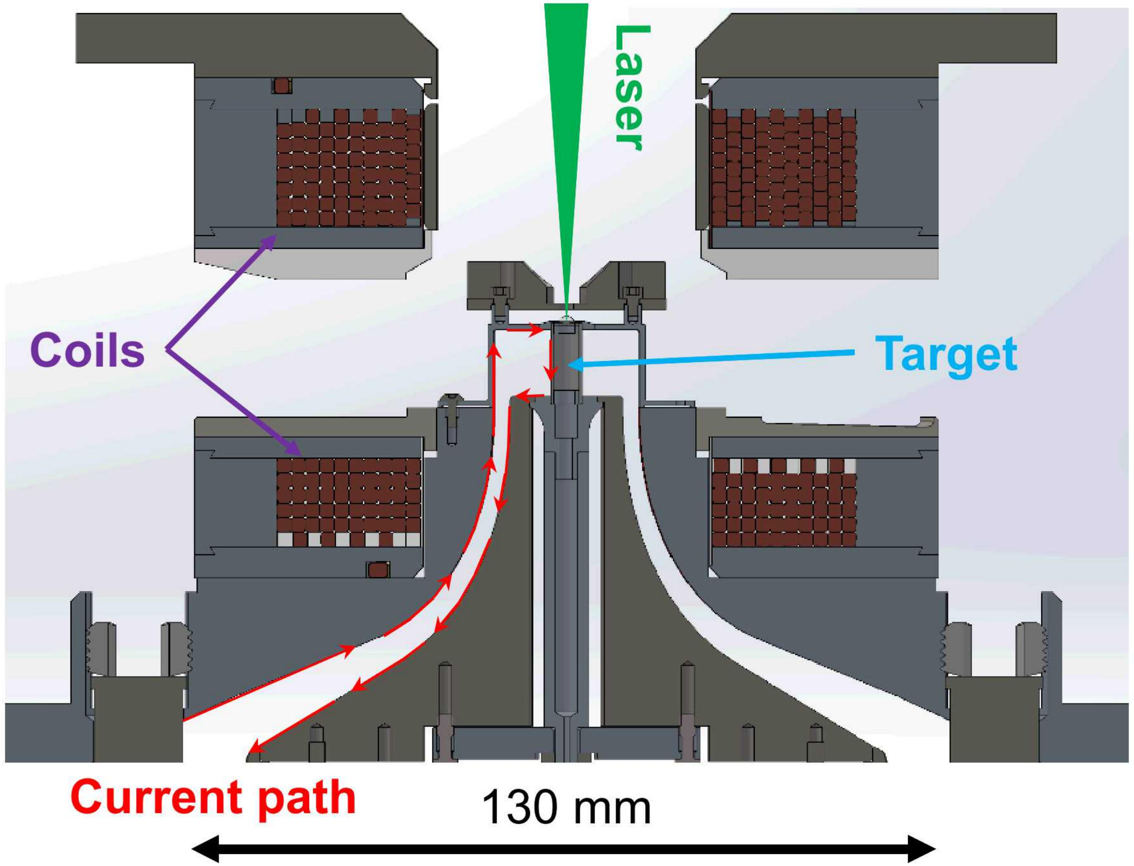
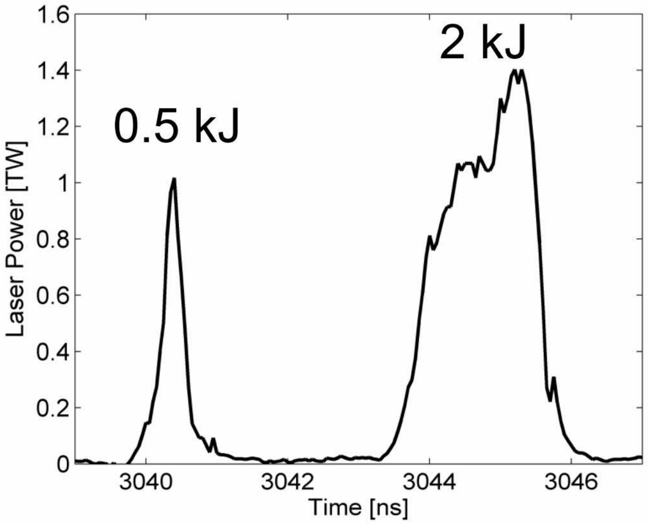
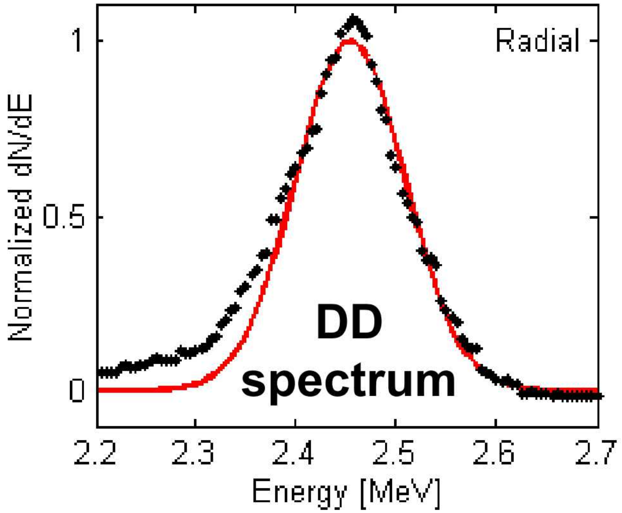


- 10 T had been previously demonstrated on Z and allowed full diagnostic access
- Only expected about 18 MA due to the high inductance inner-MITL extension required by the coils
- We believed our laser pre-pulse would disassemble the window, enabling the majority of the main pulse to be absorbed in the fuel



This configuration was predicted to produce nearly 10^{13} DD neutrons (~2kJ DT)

The first round of experiments demonstrated the fundamental requirements for MIF



Thermonuclear neutron generation with fusion-relevant ion temperatures (2-3 keV)

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

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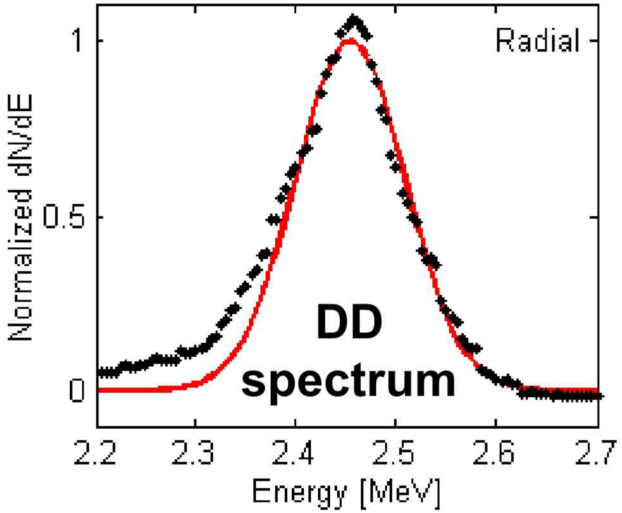
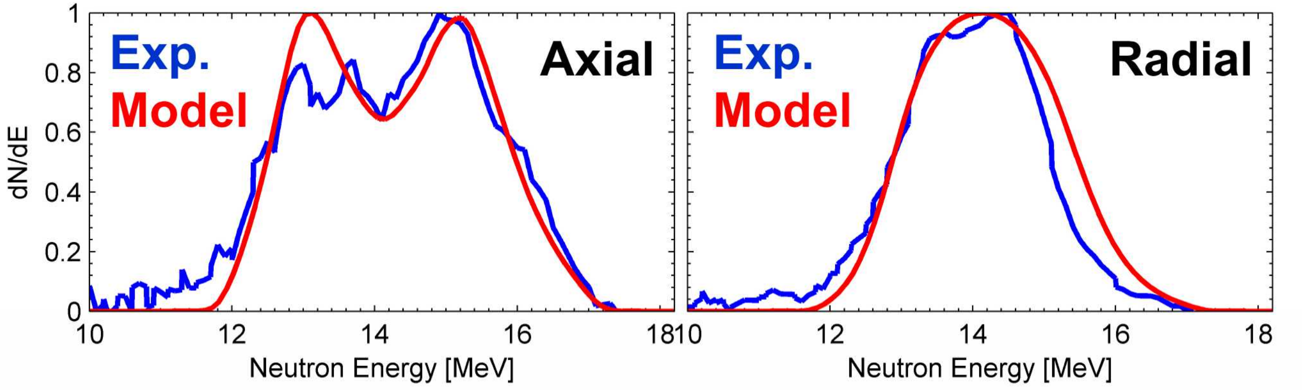


Thermonuclear neutron generation with fusion-relevant ion temperatures (2-3 keV)

Secondary DT Neutron Spectra



Highly magnetized fuel at stagnation (>0.3 MG-cm)

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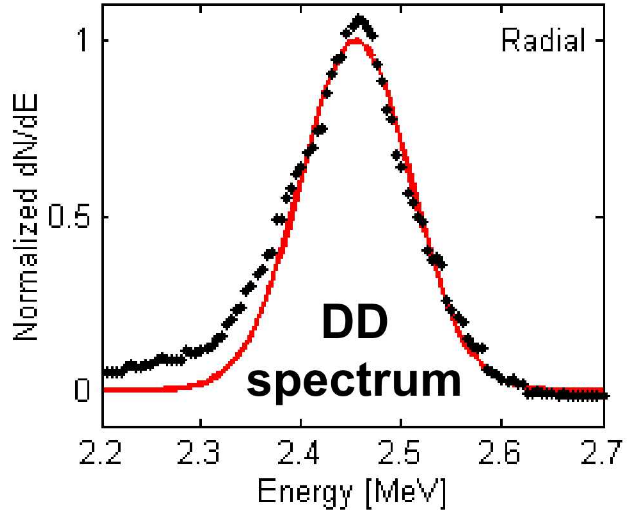
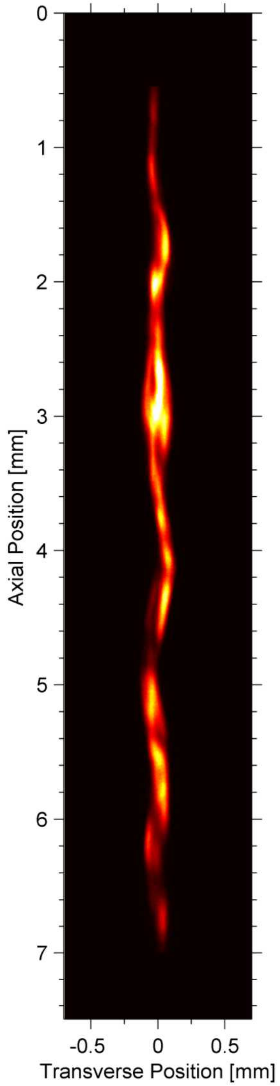
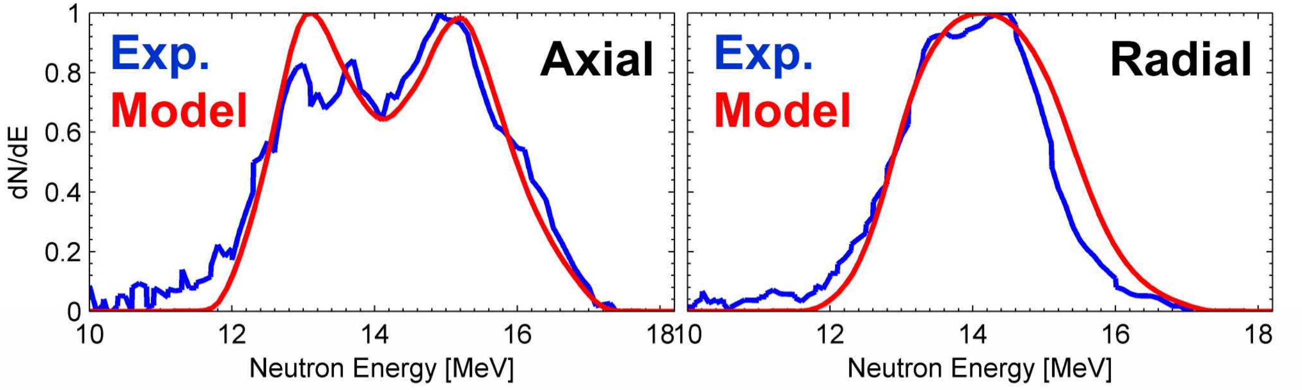


Thermonuclear neutron generation with fusion-relevant ion temperatures (2-3 keV)

Relatively stable fuel column at CR > 30



Secondary DT Neutron Spectra



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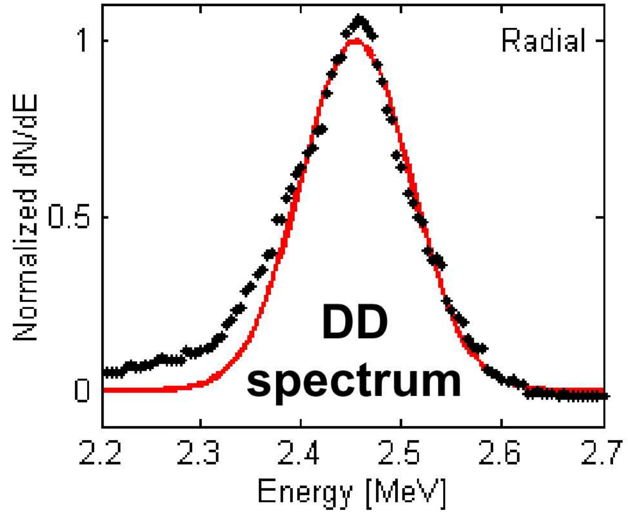

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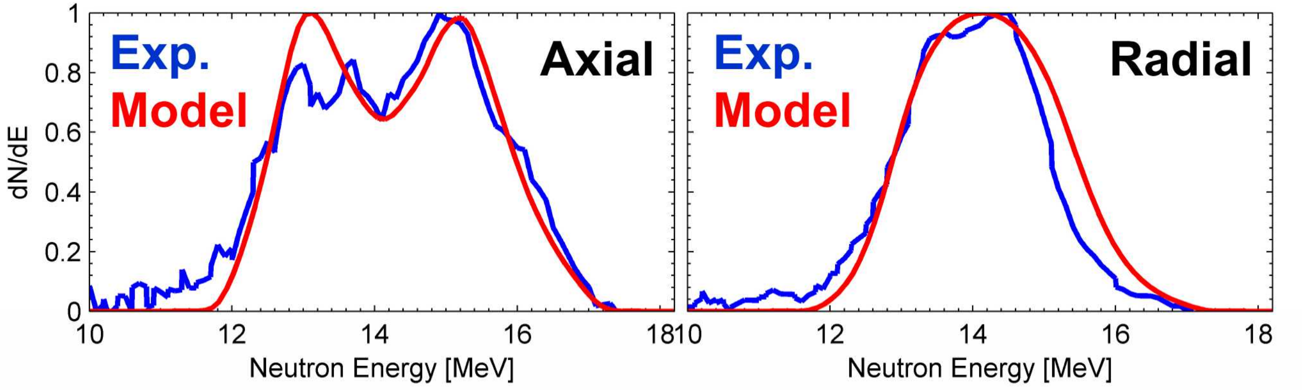

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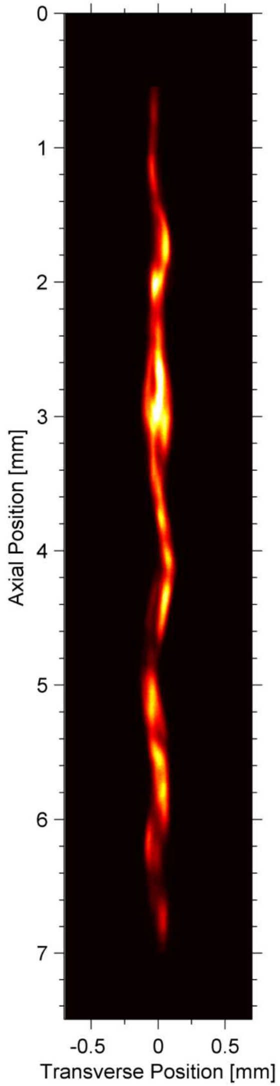


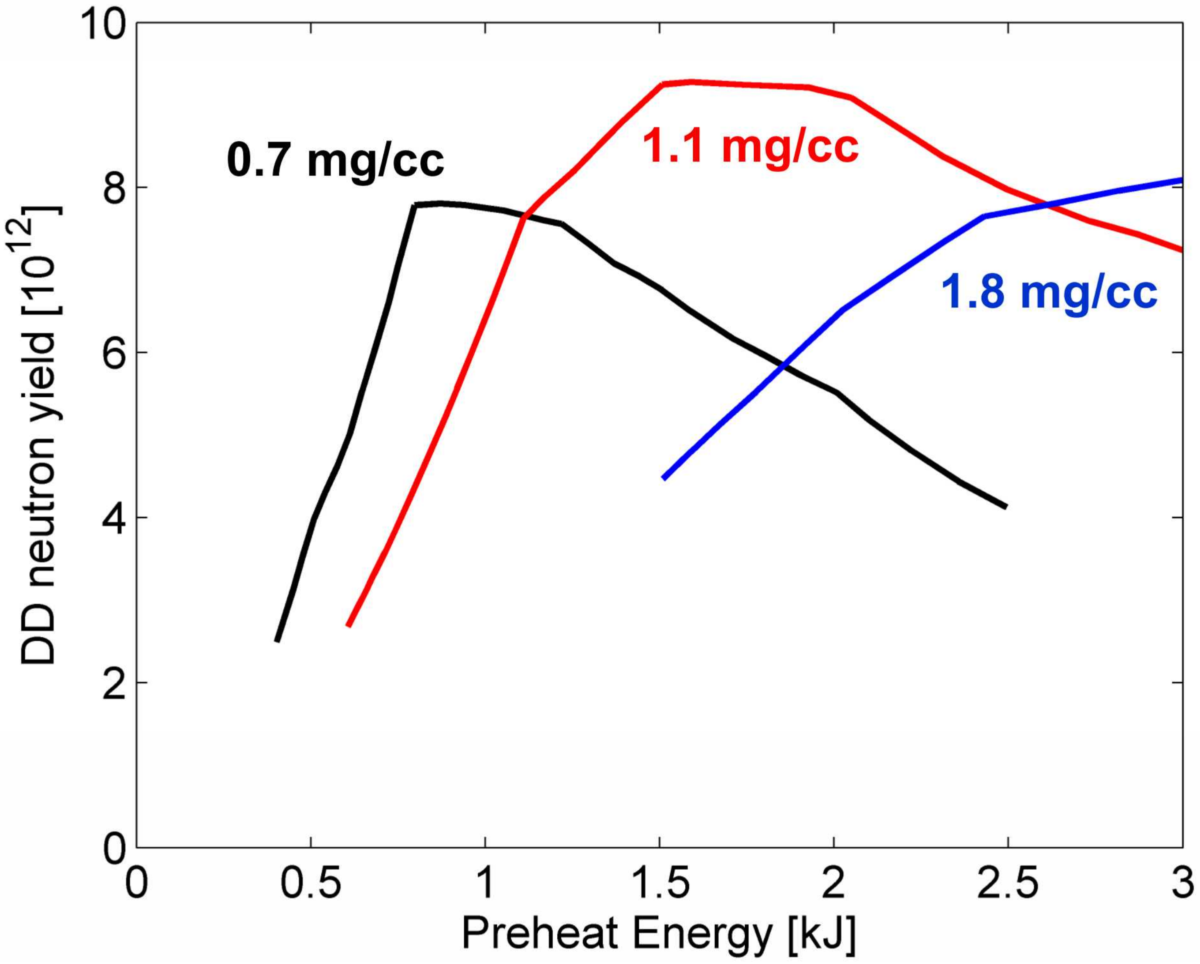
	No B-field	B-field
No Laser	3e9	1e10
Laser	4e10	2e12

Highly diagnosable primary DD neutron yield **only when using B-field and preheat** ($\sim 10^{12}$)

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

The neutron yields in the initial experiments were lower than expected

- Pre-shot yield predictions were ~1e13
  - Performance is highly dependent on preheat energy
  - Higher fuel densities require more laser energy



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

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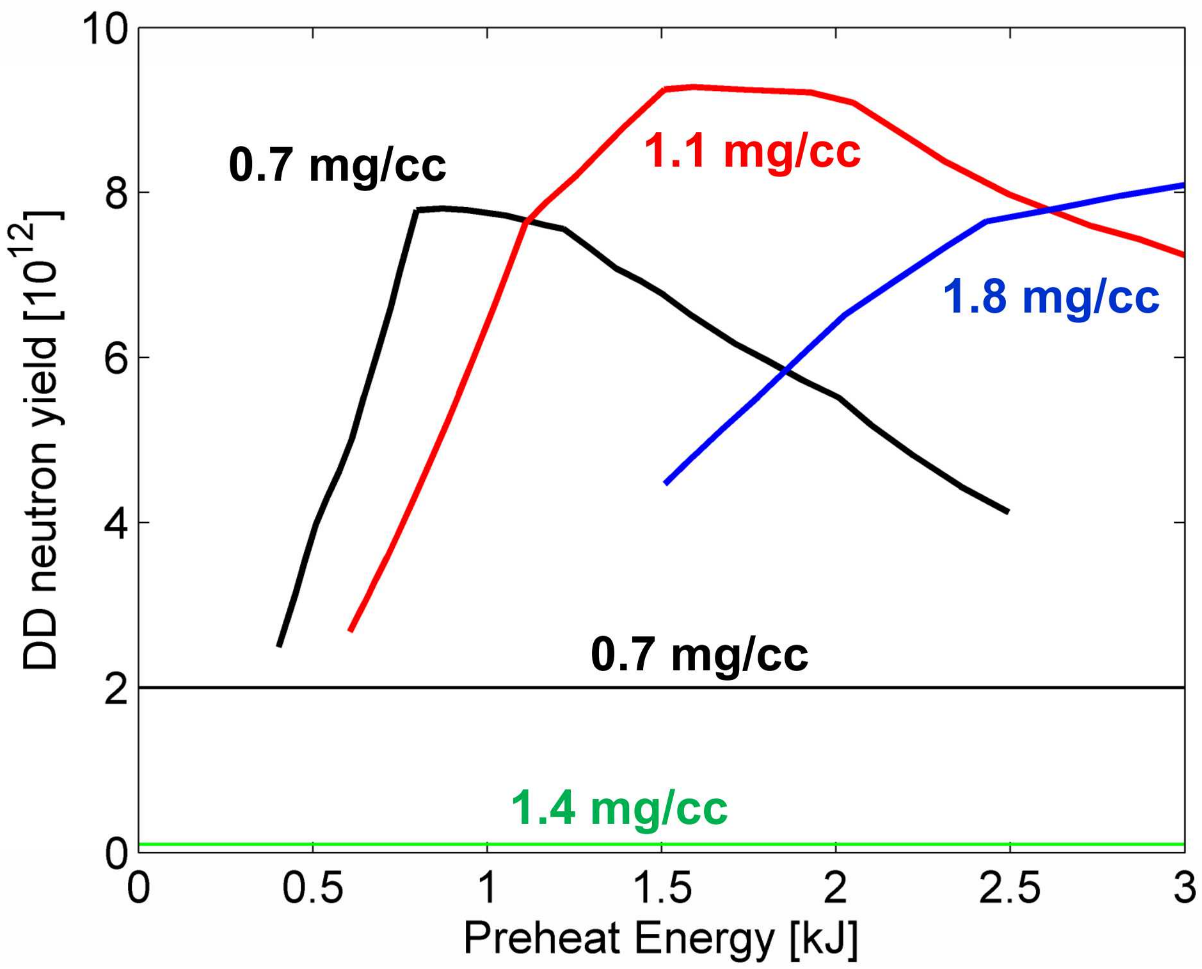

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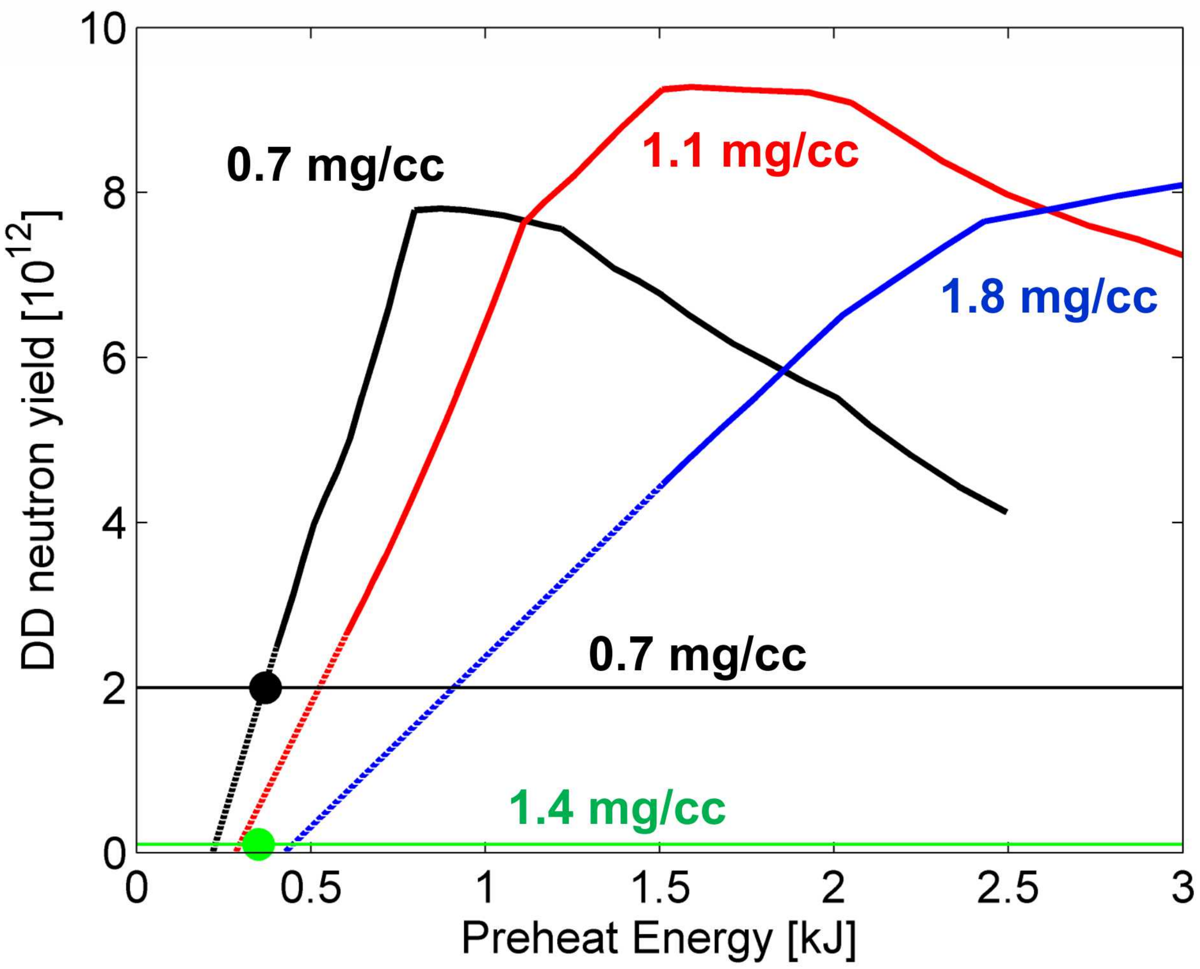
The neutron yields in the initial experiments were lower than expected

- Pre-shot yield predictions were ~1e13
  - Performance is highly dependent on preheat energy
  - Higher fuel densities require more laser energy
- Experimental yields were much lower
- Consistent with low preheat energy, but we don't diagnose preheat in situ
  - We developed a methodology to estimate the laser energy coupled to the fuel via offline experiments



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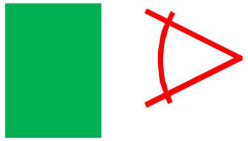
We estimate the laser energy coupled to the fuel by accounting for the known loss mechanisms



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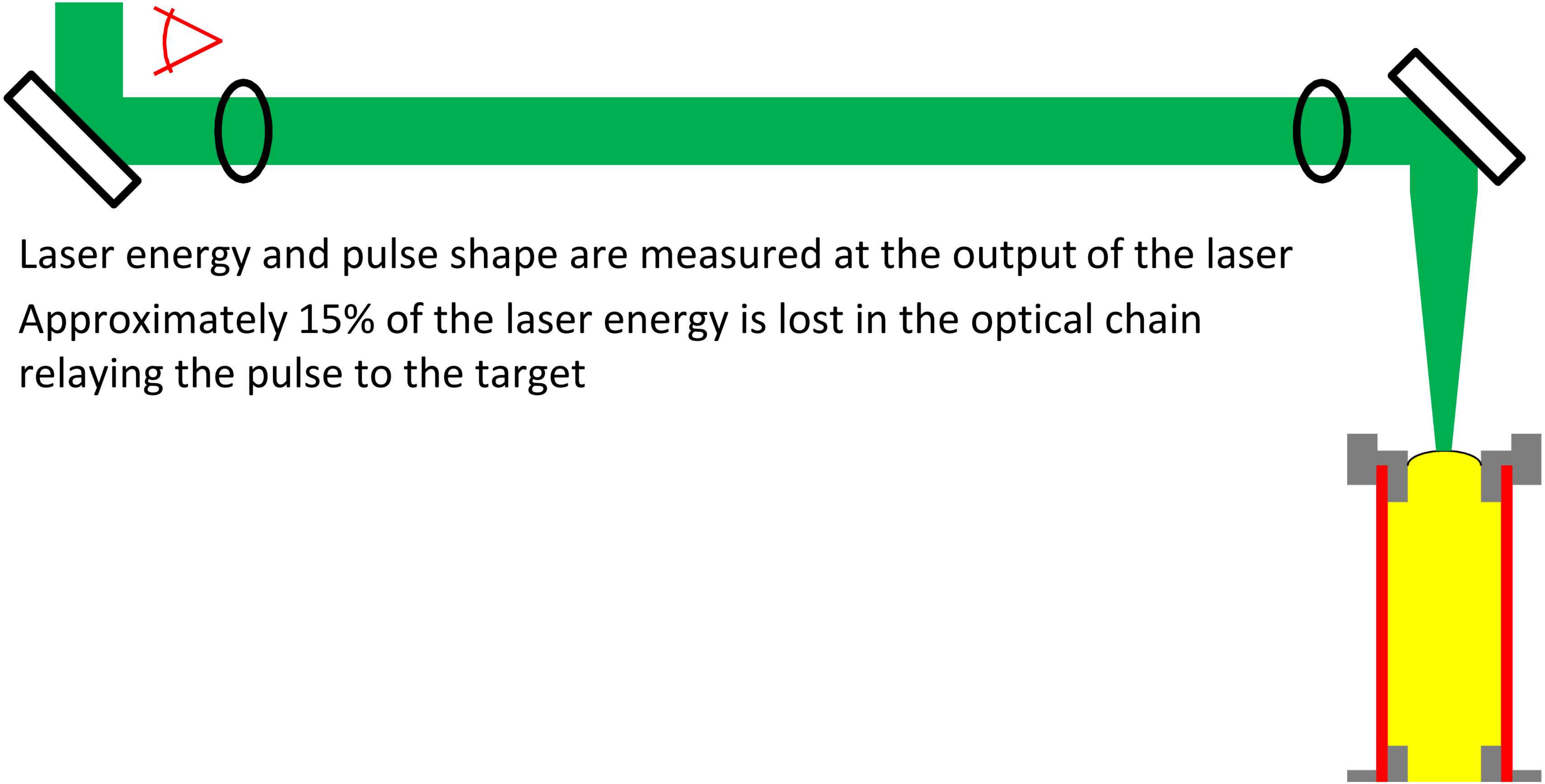

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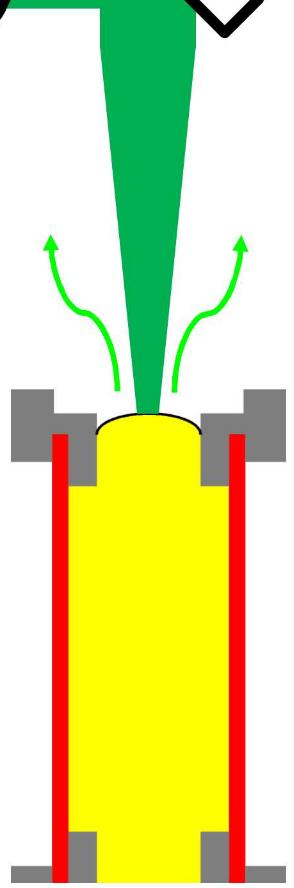
- Laser plasma instabilities cause intensity-dependent losses when the laser interacts with the window and fuel
  - Stimulated Brillouin Scattering, Stimulated Raman Scattering, etc.



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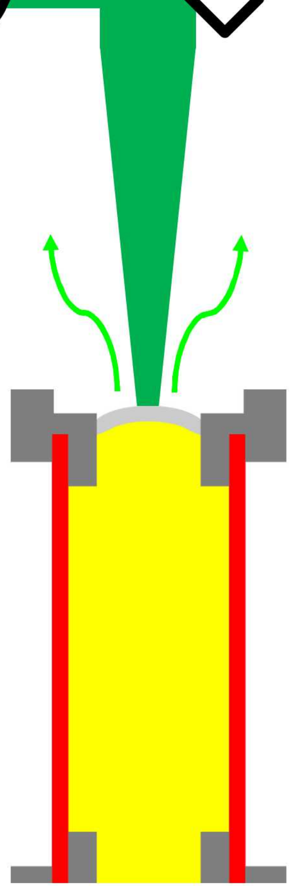

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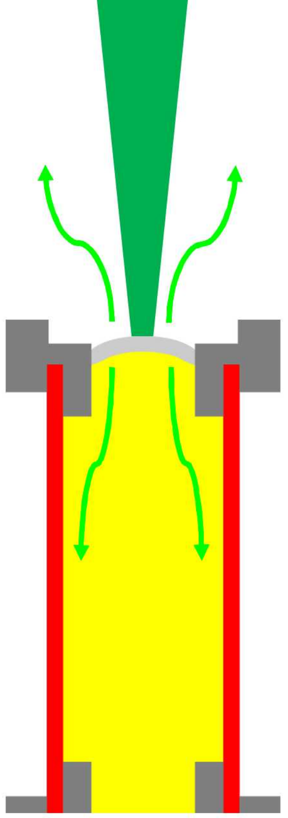
- Laser energy is forward scattered out of the laser cone



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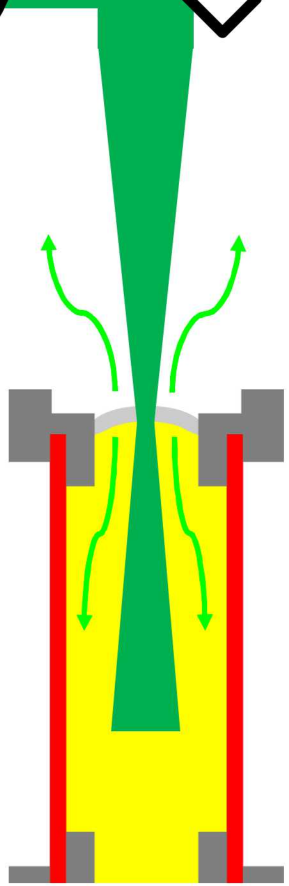
- Laser energy is forward scattered out of the laser cone
- Laser energy is absorbed in the fuel, which heats and becomes transmissive



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- Laser energy and pulse shape are measured at the output of the laser
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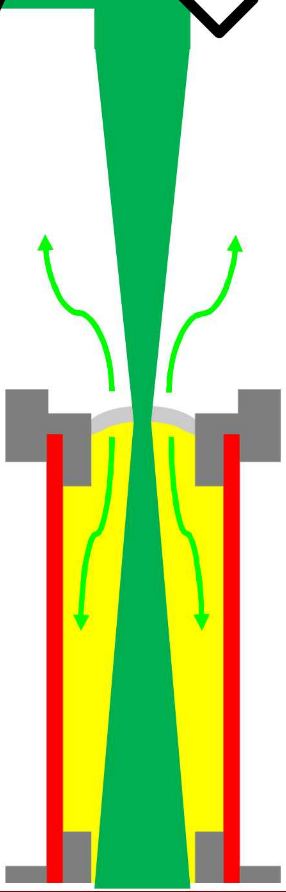
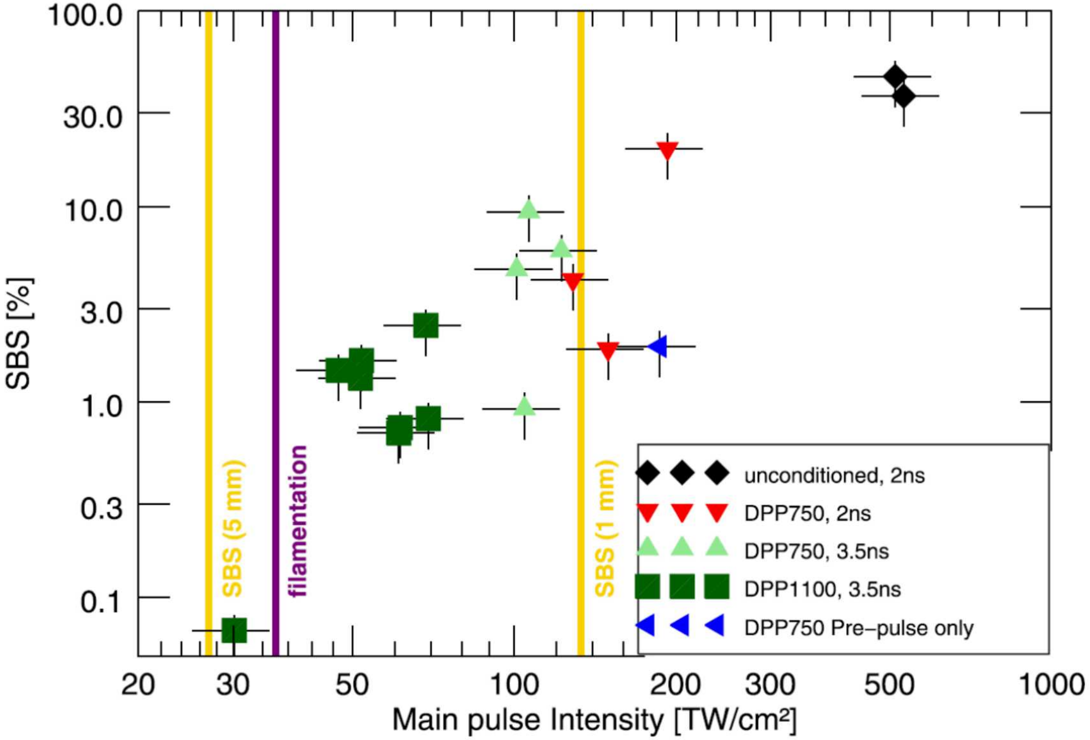
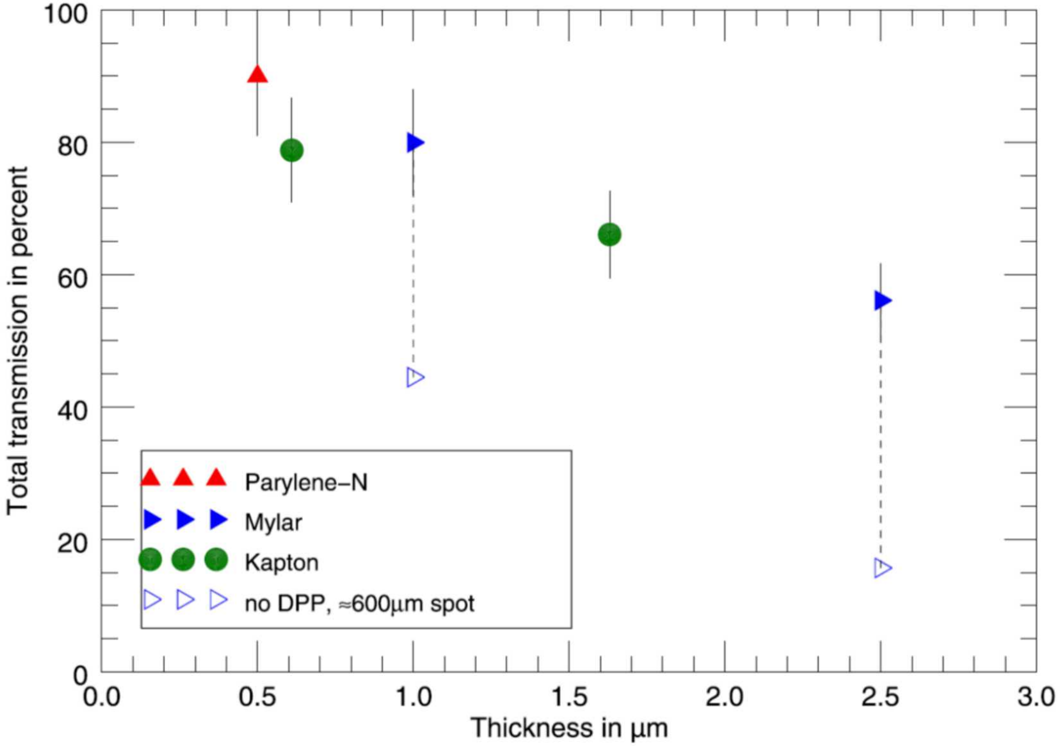
- Laser plasma instabilities cause intensity-dependent losses when the laser interacts with the window and fuel
- The window absorbs energy, heats, and becomes transmissive
- Laser energy is forward scattered out of the laser cone
- Laser energy is absorbed in the fuel
- Some energy may exit the bottom of the target



Loss mechanisms were assessed with offline experiments to determine the coupled energy





- Based on this analysis, the energy coupled in the initial experiments was 300-400 J
- Simulations indicate that the lower fuel density (0.7 mg/cc) should work well in this regime, but the higher fuel density (1.4 mg/cc) should not

M. Geissel, et al., Phys. Plasmas **25**, 022706 (2018).

We improved energy coupling in subsequent experiments in order to improve performance

- Window thickness is proportional to both the window radius and the initial fuel pressure
  - Fuel pressure was reduced from 120 PSI to 60 PSI
  - Window thickness was reduced from 3.5 μm to 1.75 μm

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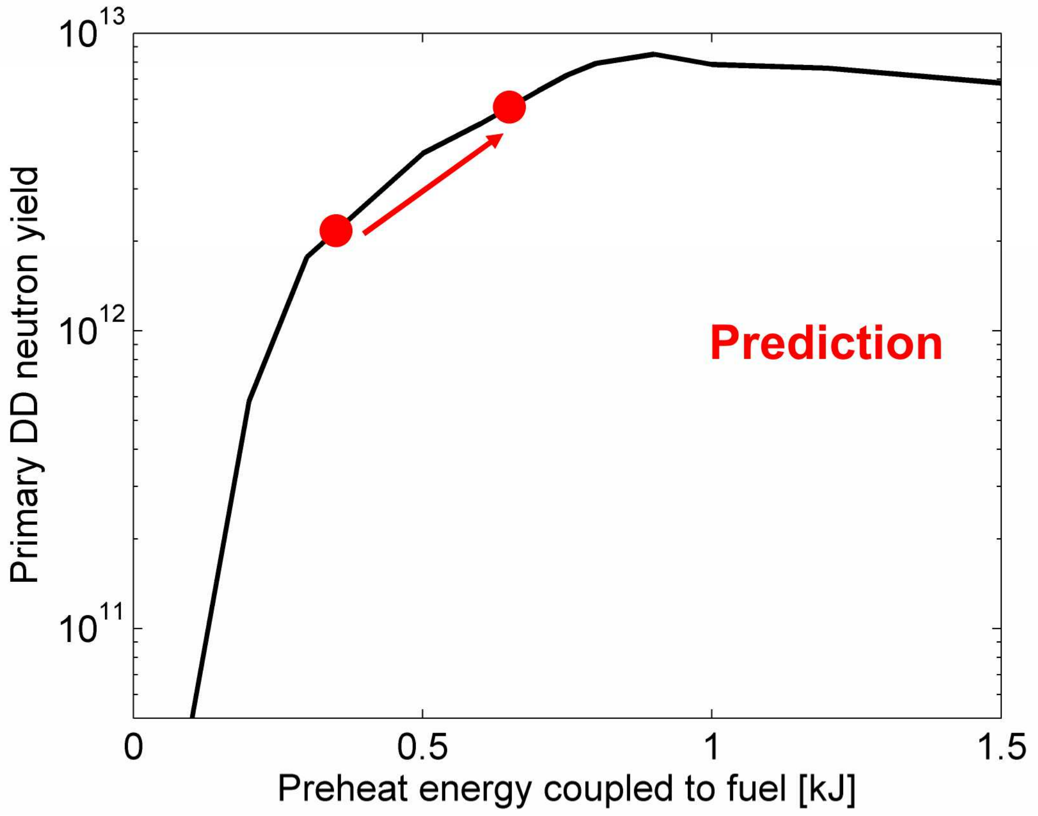
  - Still only about 600-700 J
  - Predicted to increase yield 2.5x



M. R. Gomez, et al., Phys. Plasmas **22**, 056306 (2015). P. F. Knapp, et al., to be submitted.

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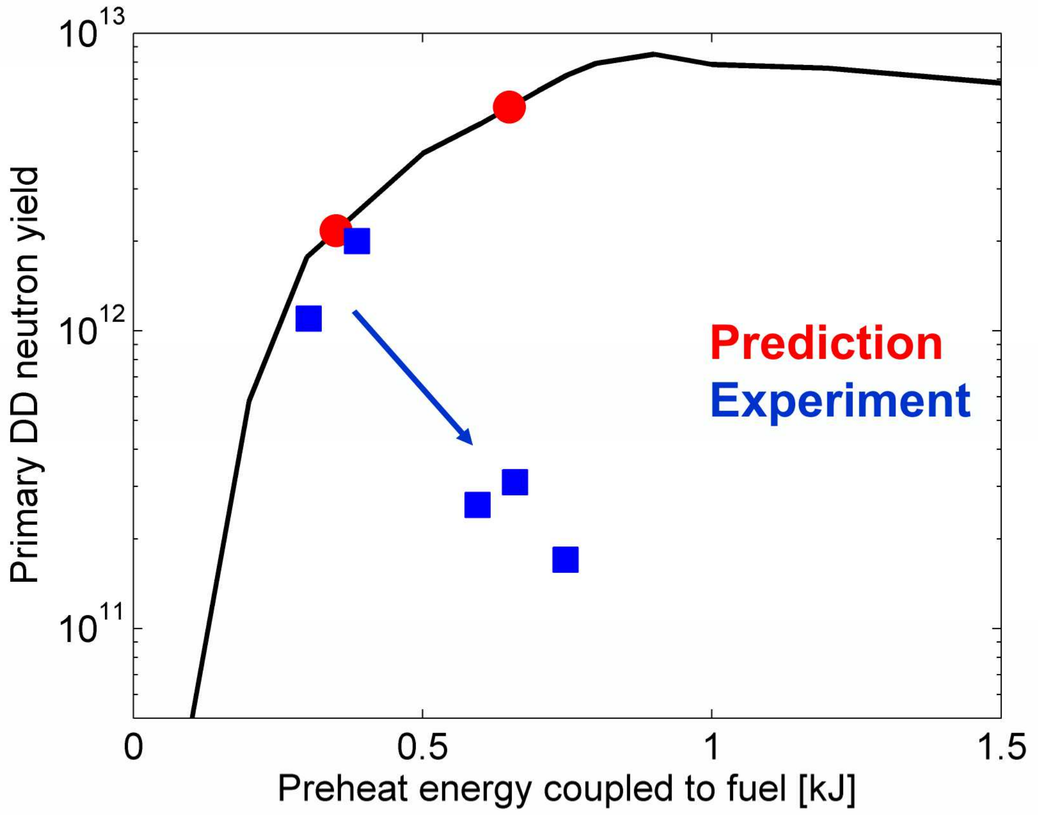
- Greater energy coupled to the fuel
  - Still only about 600-700 J
  - Predicted to increase yield 2.5x
- Observed significantly lower neutron yield
  - X-ray signals still bright
  - Hypothesized that mix from aluminum components increased with laser energy
  - Developed a methodology to assess stagnation pressure and mix given experimental observables



M. R. Gomez, et al., Phys. Plasmas **22**, 056306 (2015).

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We collect a wide range of data to assess stagnation

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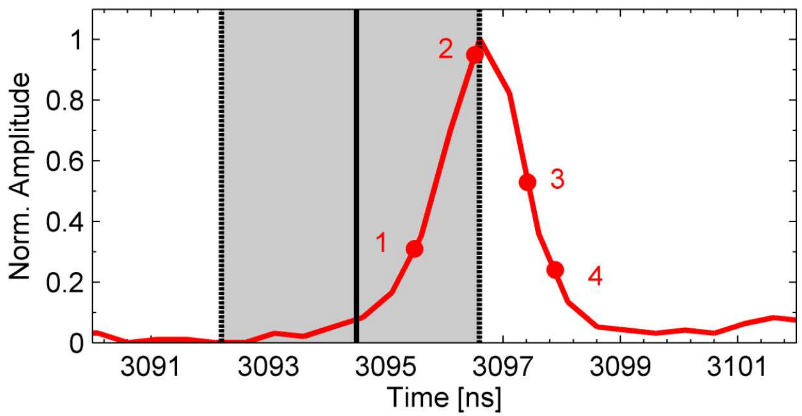
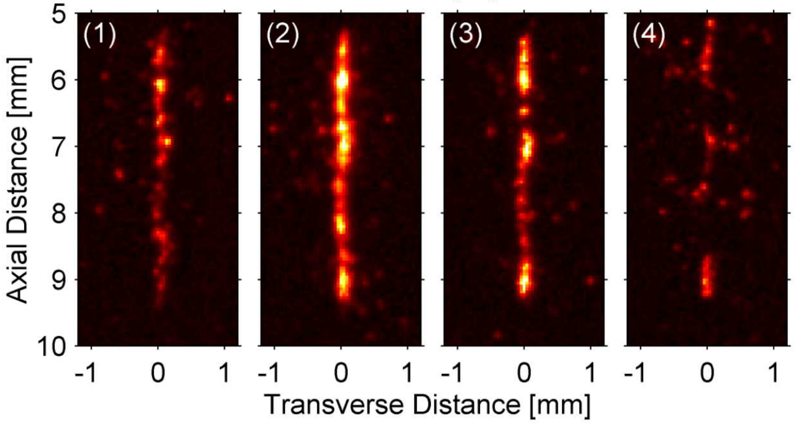
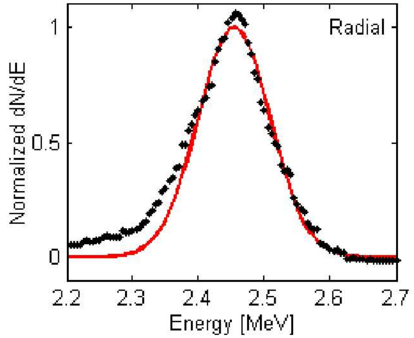
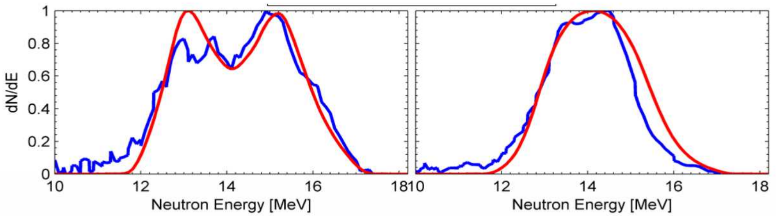
Filtered x-ray powers



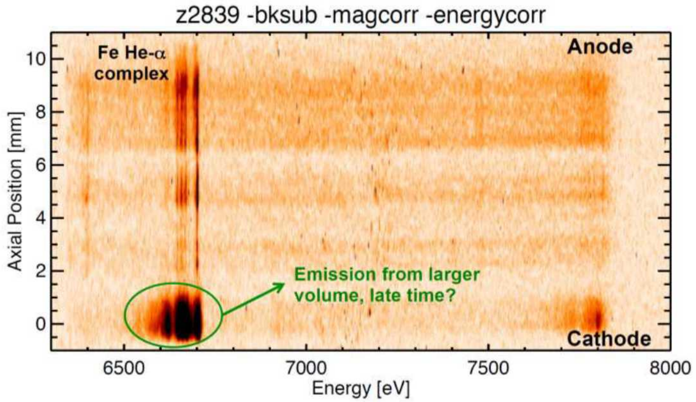


Time-resolved x-ray pinhole images

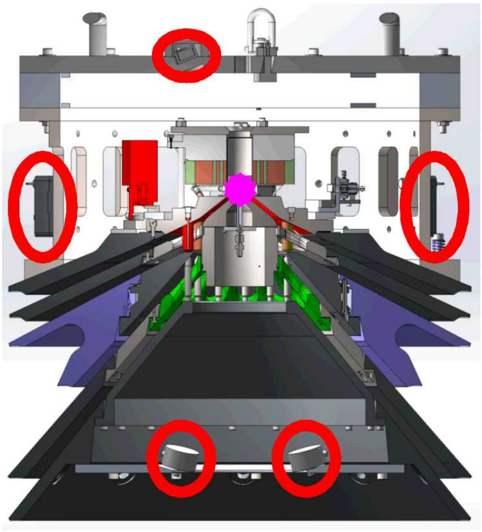


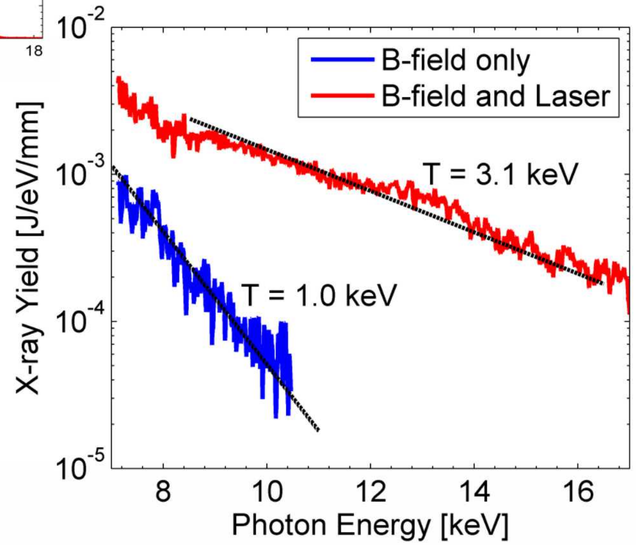


Primary and Secondary neutron yield and spectra



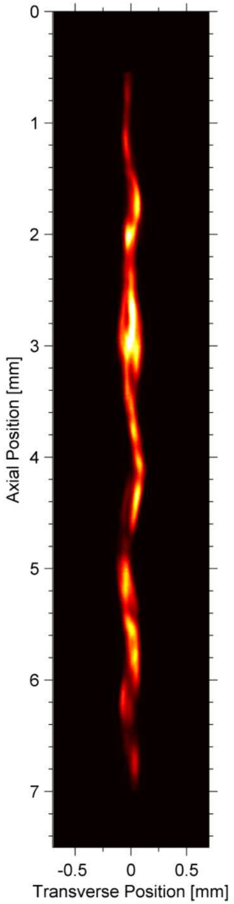
High resolution x-ray spectra





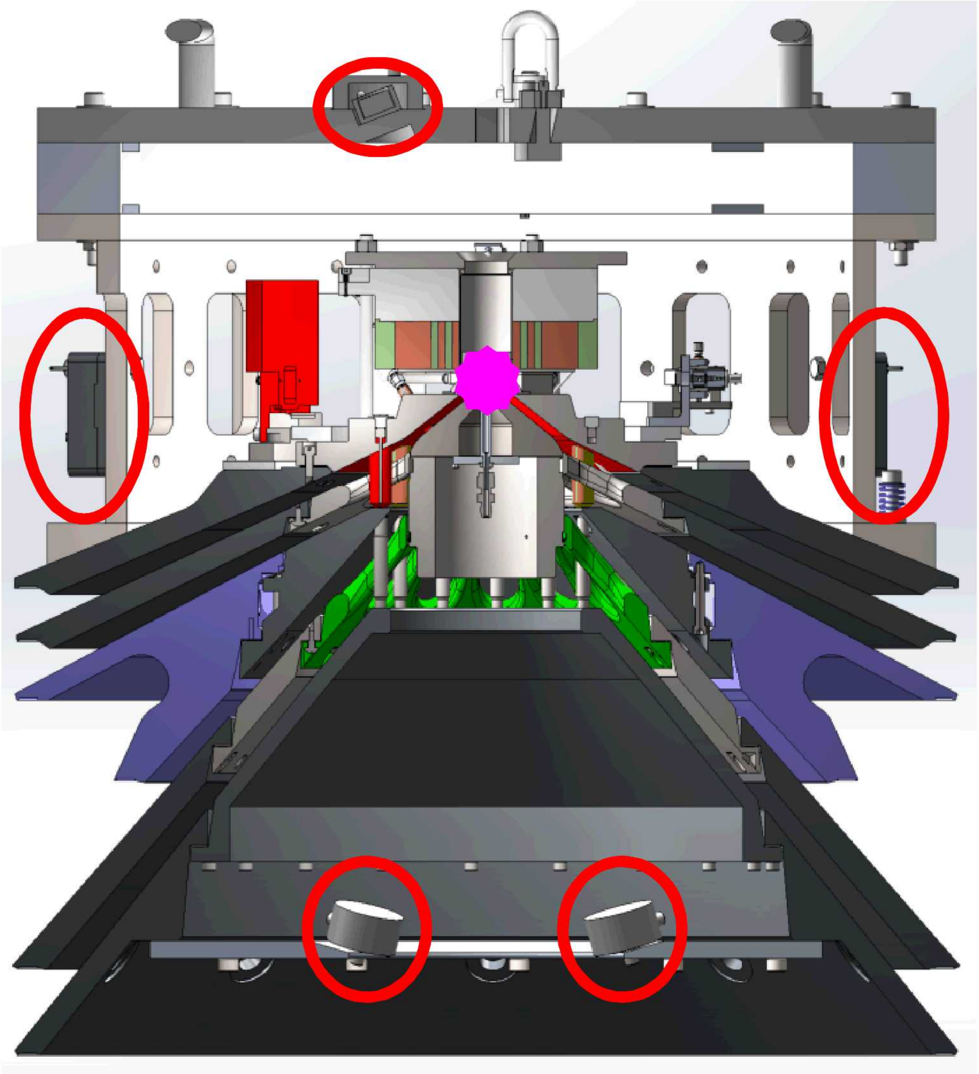
High energy x-ray spectra

Time-integrated high resolution images



We estimate the stagnation pressure and mix fraction based on measured stagnation conditions

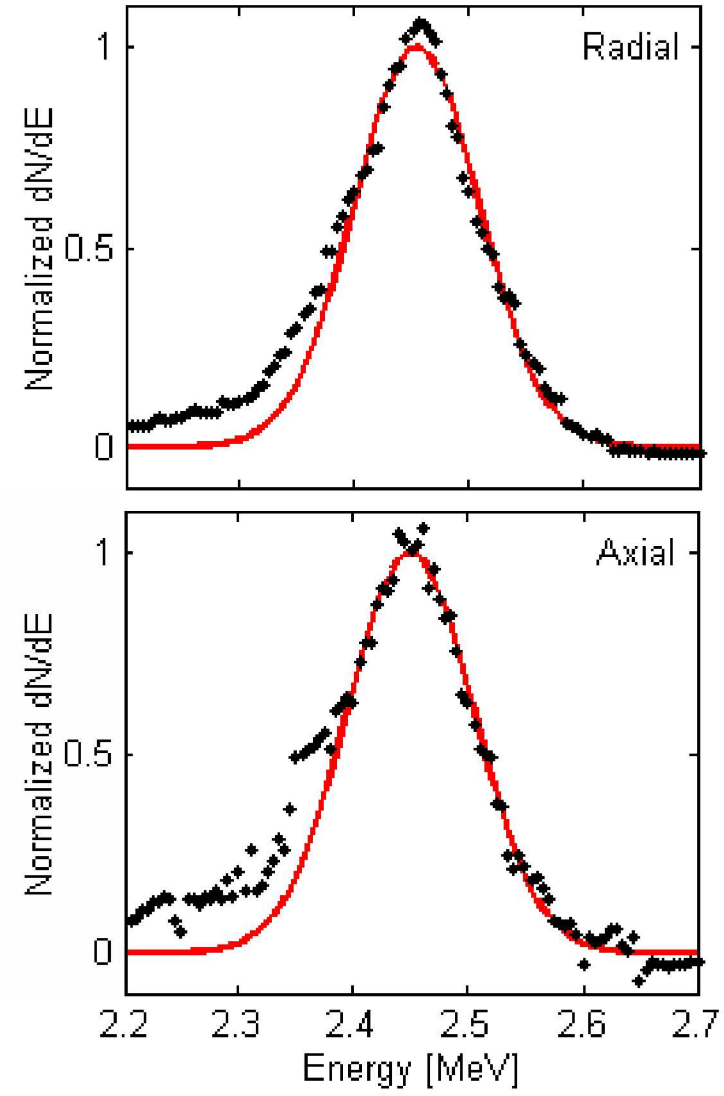
- The neutron yield comes from indium activation samples
  - Nine activation samples are located at various polar and azimuthal angles



Typical neutron yields are ~10^{12}

We estimate the stagnation pressure and mix fraction based on measured stagnation conditions

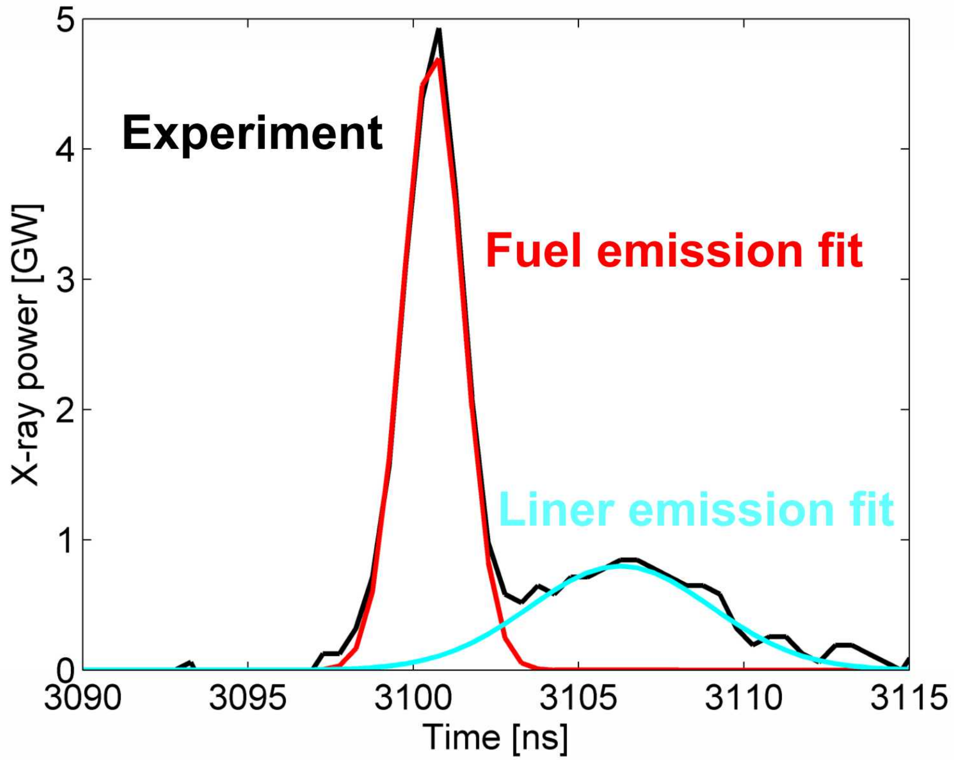
- The neutron yield comes from indium activation samples
- The burn-averaged ion temperature comes from a fit to the primary neutron peak in the time of flight spectrum
  - Five NTOF detectors are located at various azimuthal and polar angles



Typical ion temperatures are 1.5-3 keV

We estimate the stagnation pressure and mix fraction based on measured stagnation conditions

- The neutron yield comes from indium activation samples
- The burn-averaged ion temperature comes from a fit to the primary neutron peak in the time of flight spectrum
- The burn duration and x-ray yield come from PCD and SiD detectors
  - Six filtered diodes provide different spectral sensitivities

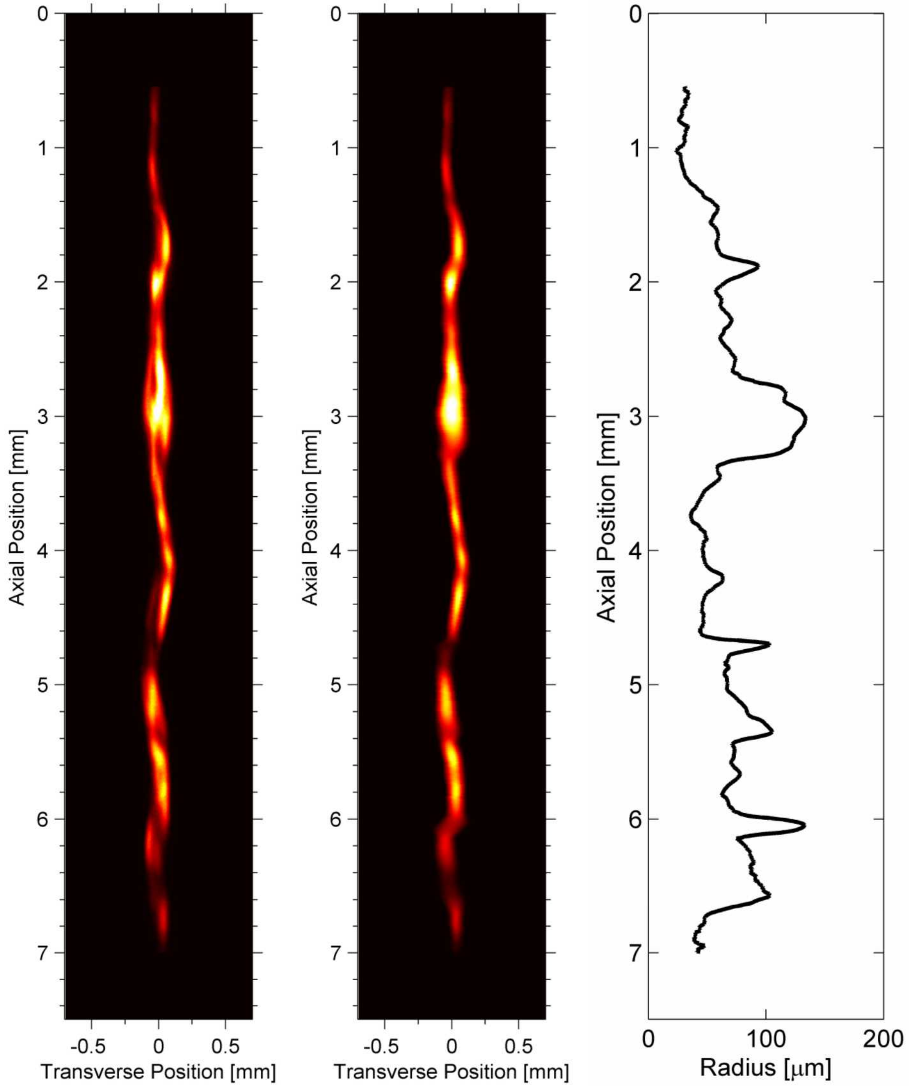


Typical burn widths are 1-2 ns

Typical x-ray yields are 1-10 J

We estimate the stagnation pressure and mix fraction based on measured stagnation conditions

- The neutron yield comes from indium activation samples
- The burn-averaged ion temperature comes from a fit to the primary neutron peak in the time of flight spectrum
- The burn duration and x-ray yield come from PCD and SiD detectors
- The plasma volume comes from a spherical crystal image of the x-ray continuum at stagnation



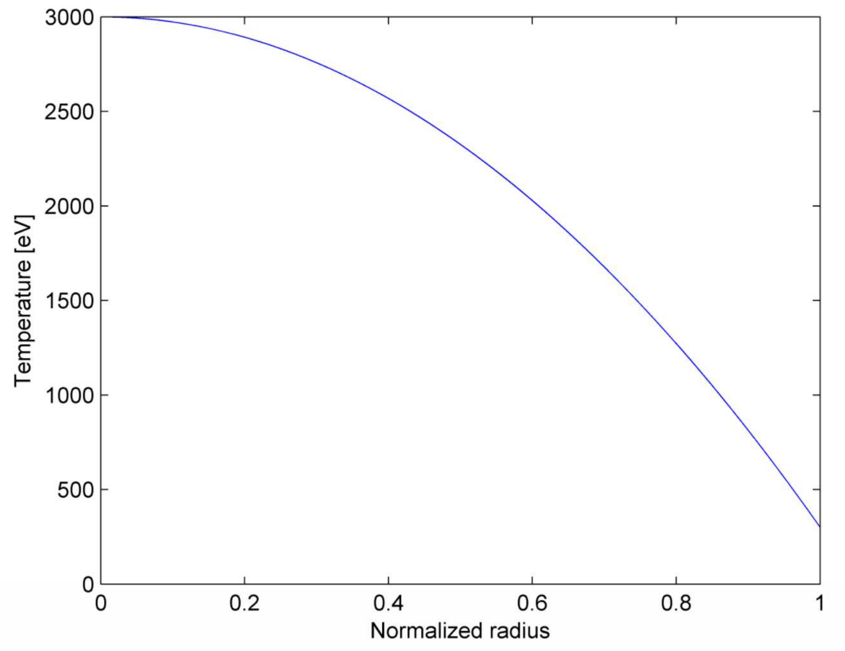
Typical average radius is 50-80 μm

Typical volume is ~0.1 mm³

We estimate the stagnation pressure and mix fraction based on measured stagnation conditions

- The neutron yield comes from indium activation samples
- The burn-averaged ion temperature comes from a fit to the primary neutron peak in the time of flight spectrum
- The burn duration and x-ray yield come from PCD and SiD detectors
- The plasma volume comes from a spherical crystal image of the x-ray continuum at stagnation
- This is all tied together with a relatively simple isobaric stagnation model

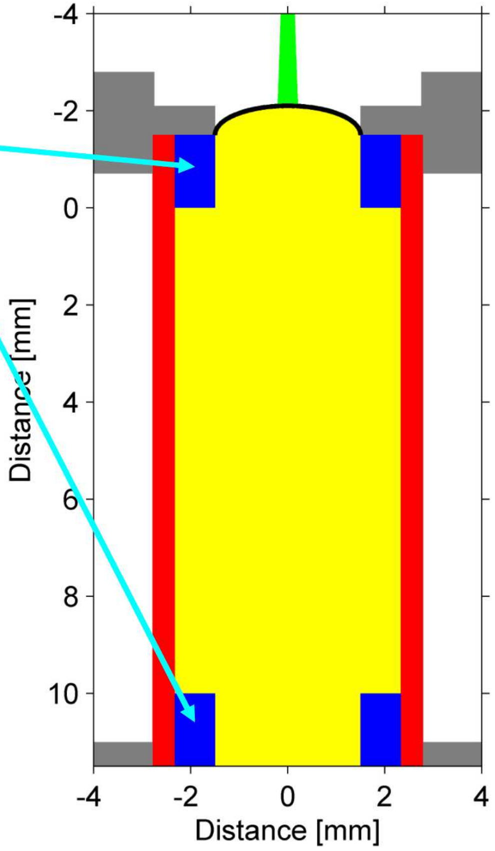
$$T(r) = T_{peak} * (1 - (0.9) * r^4)$$

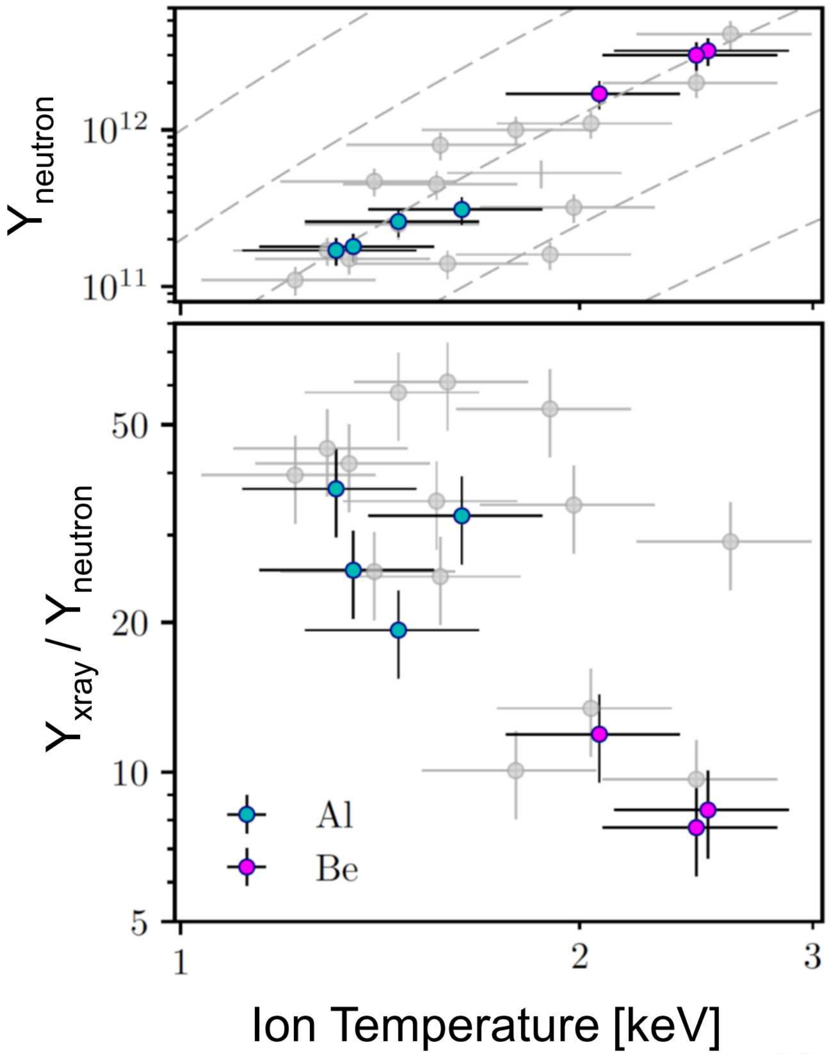


Assumes the temperature at the edge of the plasma is ~10% of the peak temperature

We replaced plasma-facing Al components with Be and observed record performance

- There is a significant difference between Al and Be endcaps with ~700 J of preheat energy
  - Neutron yield increased by an order of magnitude
  - Ratio of x-ray to neutron yield decreased by a factor of several
    - Similar mix levels, but lower Z with Be





P. F. Knapp, et al., to be submitted.

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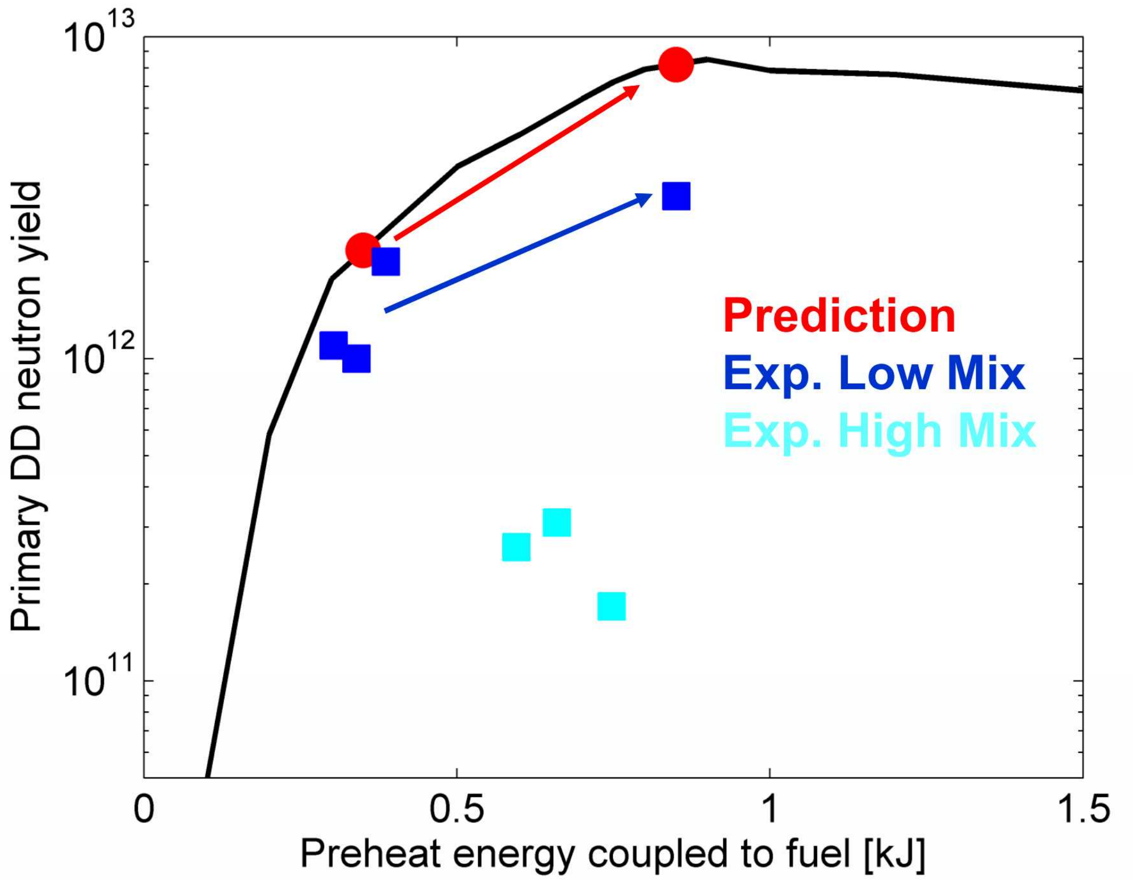
  - Neutron yield increased by an order of magnitude
  - Ratio of x-ray to neutron yield decreased by a factor of several
    - Similar mix levels, but lower Z with Be
- We also looked at ~300 J vs ~700 J deposited with beryllium endcaps
  - Neutron yield increased by a factor of 2-3, similar to in clean 2D simulations



- Experimental points are consistently about 50% of simulations
  - Mix and 3D effects could account for this difference

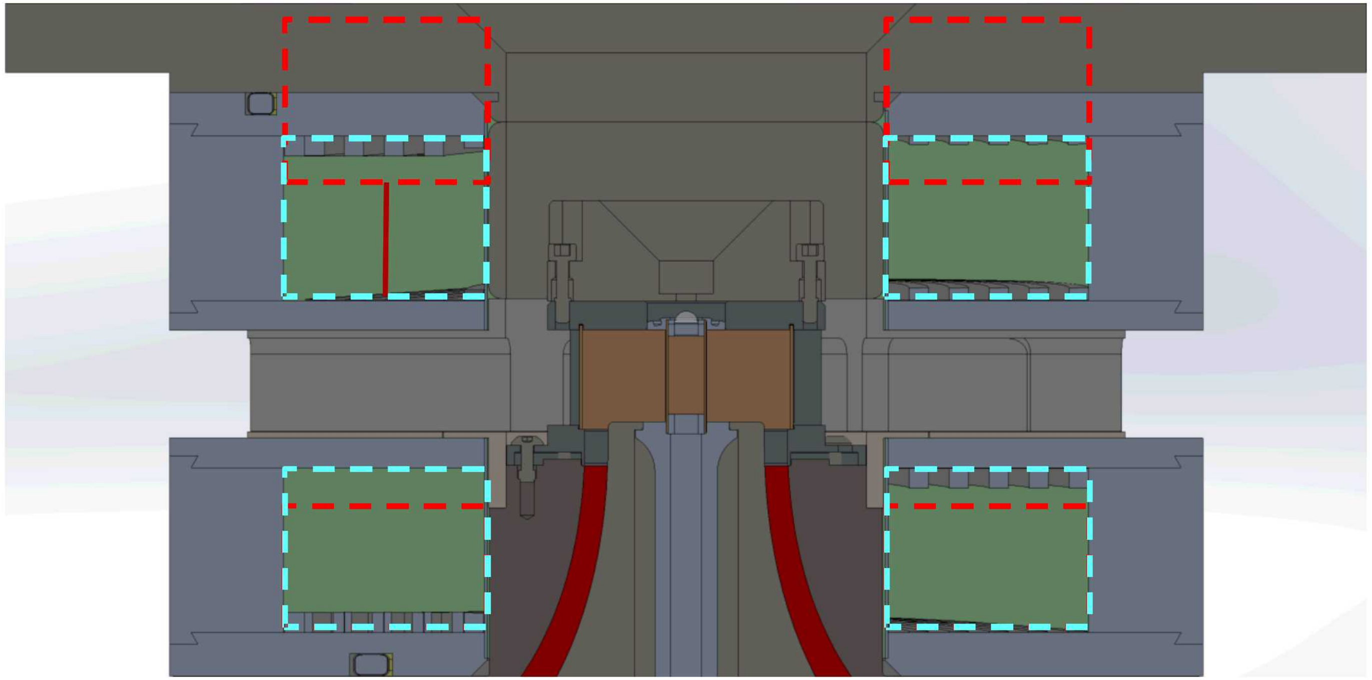
P. F. Knapp, et al., to be submitted.

Outline

- Introduction
- Early experiments
  - Understanding laser energy deposition
  - Diagnosing and mitigating mix
- **Improving capabilities**
  - B-field
  - Load current
  - Laser energy deposition
- The Future

Axial B-field was increased with modest change in coil configuration resulting in record performance

Sandia National Laboratories



- Bottom coils increased from 60 turns to 80 turns
- Top coils lowered by 15 mm, eliminating 12 degree x-ray diagnostic access

- Applied B-field was increased from 10 to 15 T
- Simulations predicted an increase in primary neutron yield between 1.5-2x
- Experimental yield nearly doubled from 3.1e12 to 5.5e12
- DD/DT yield ratio decreased to ~50, which is an indication of increased magnetization at stagnation

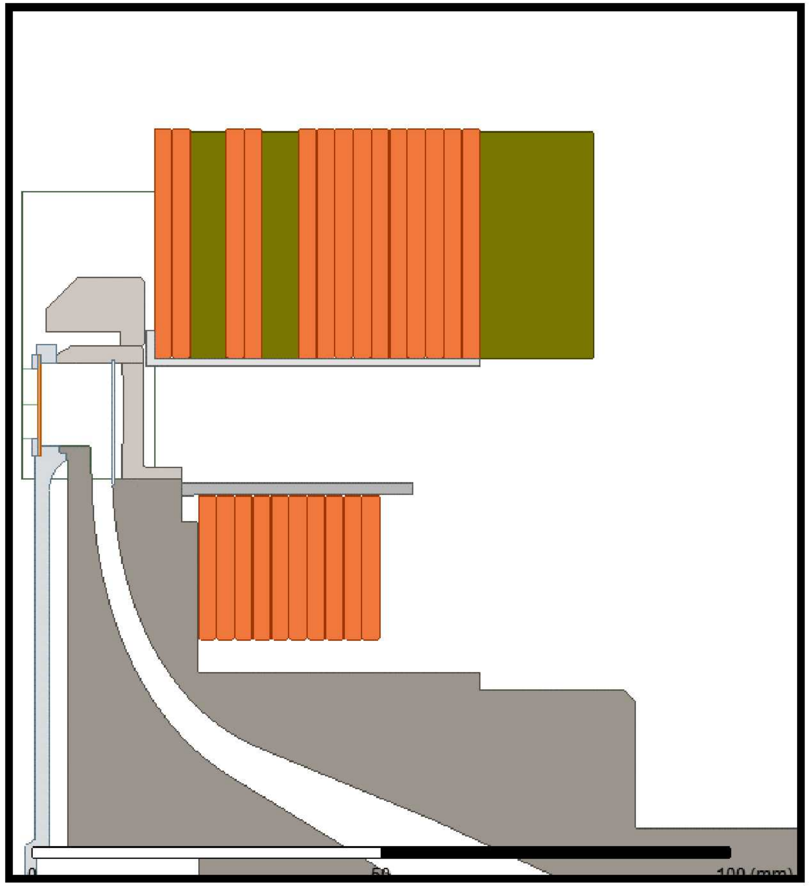
D. C. Rovang, et al., Rev. Sci. Instrum. **85**, 124701 (2014).

Experiments by D. J. Ampleford and C. A. Jennings

New coil designs could allow 25 T operation without giving up diagnostic access

- Exceeding 15 T requires developing new coil configurations or giving up diagnostic access
  - A larger top coil, which enables 20 T with diagnostic access, was developed during 2017 and tested earlier this year
  - A new bottom coil could further increase B-field, but this MITL configuration is not compatible with >20 MA, so we have not pursued this

- For an alternative path to achieving even higher fields, see Gabe Shipley's talk on Auto-Mag later in this session

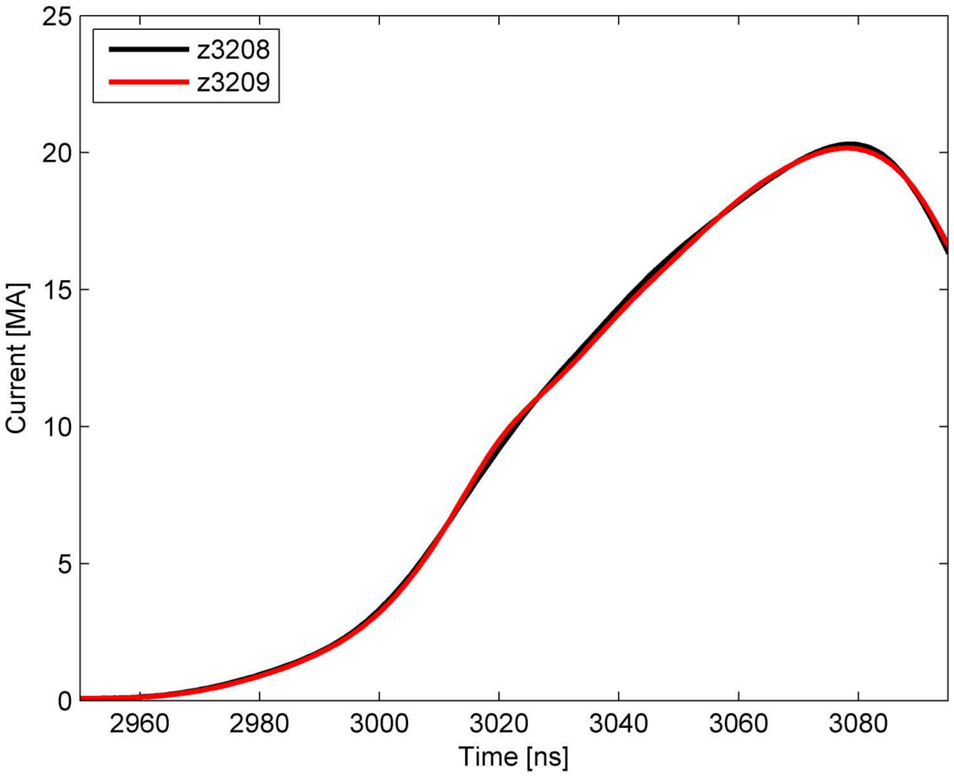


80-turn Coil + Low-L Coil
20 – 22T avg. field in Standard Feed
(~17 MA drive current)

D. C. Lamppa, et al., to be submitted.

A reduction of the load inductance led to a new record load current

- 20 MA has been demonstrated
- 22 MA seems plausible with small modifications

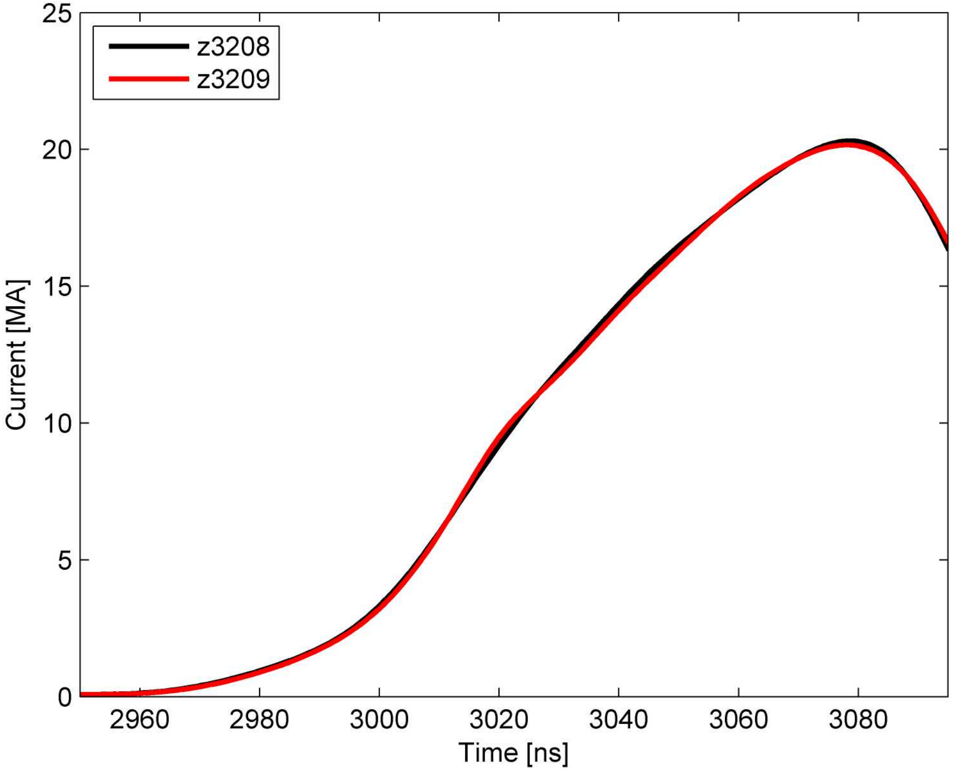


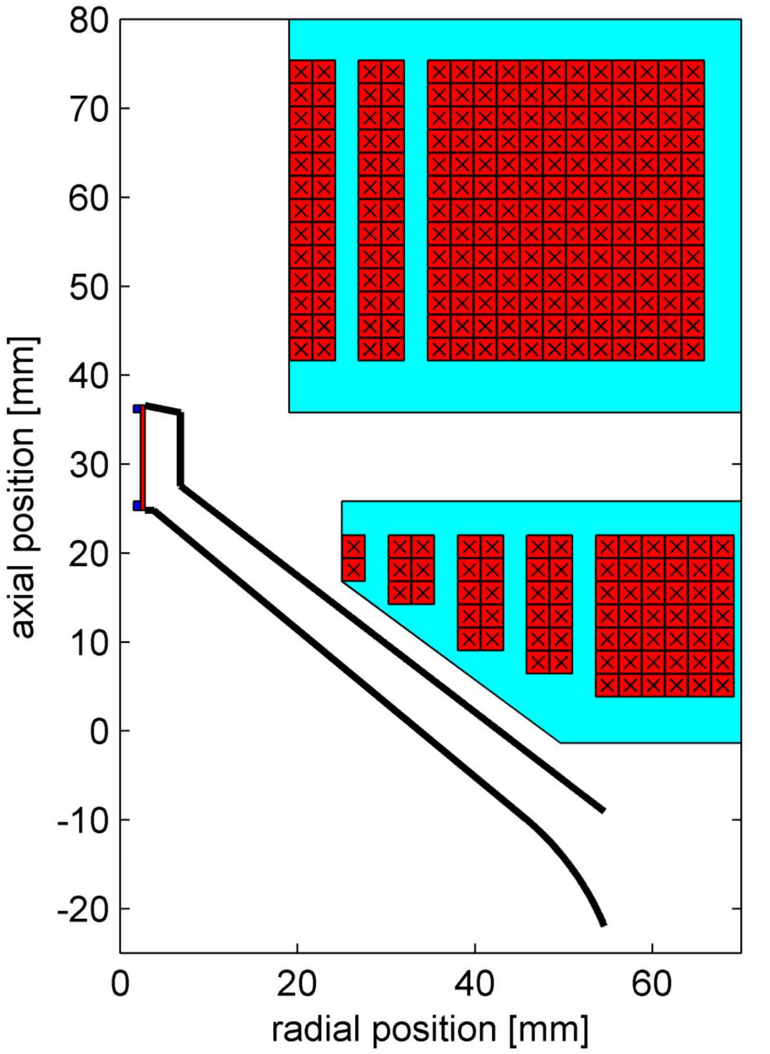
D. C. Lamppa, et al., to be submitted.

S. A. Slutz, et al., to be submitted.

A reduction of the load inductance led to a new record load current

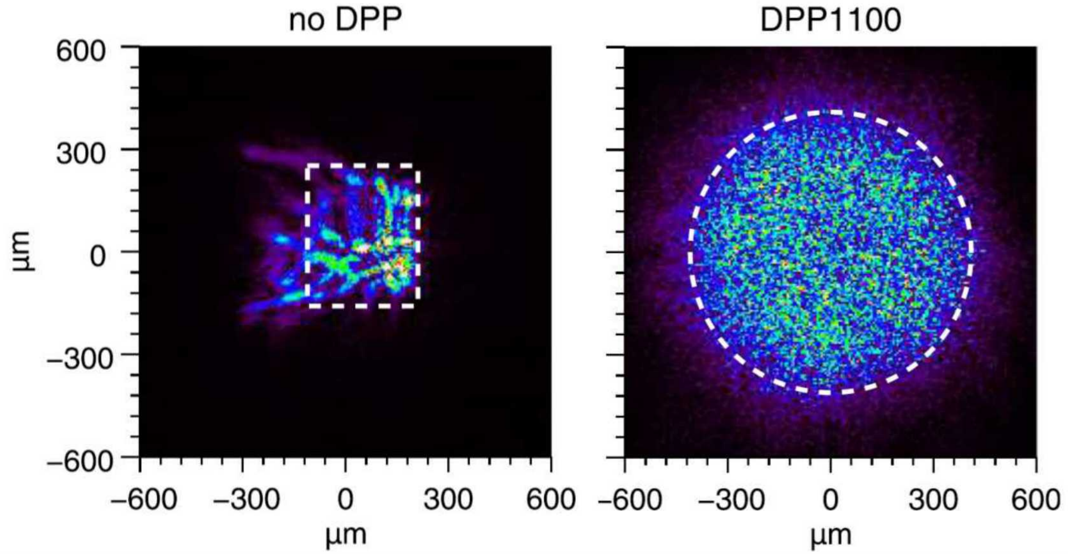
- 20 MA has been demonstrated
- 22 MA seems plausible with small modifications
- This configuration is also compatible with >20 T operation
  - Requires new bottom coil development

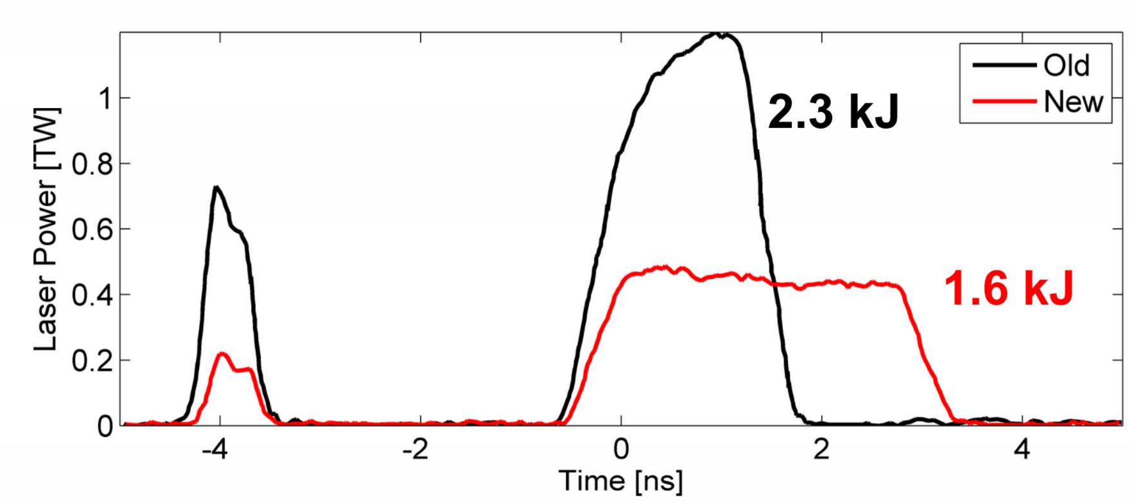




D. C. Lamppa, et al., to be submitted. S. A. Slutz, et al., to be submitted.

Laser coupling was improved using a new pulse shape and a phase plate to smooth the beam

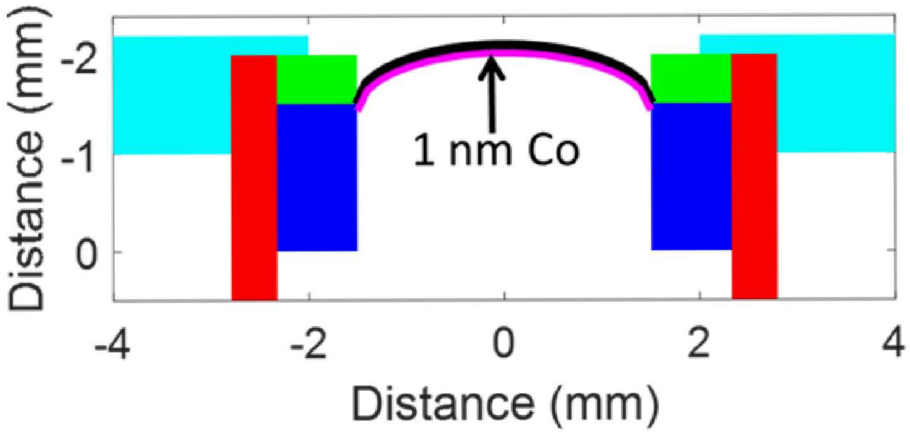




- Decreased laser power and larger spot size significantly decreased the laser intensity and laser plasma instability losses
- Goal was to couple a similar amount of energy in a more efficient, reliable way
  - Marginal increase in total energy coupled from 600-700 J to 700-800 J
  - Efficiency improved from 30% to 50%
- Observed an increase in yield from 3e12 to 4e12 but also observed an increase in mix
- Suspected that window mix was important so we developed a technique to measure window mix spectroscopically

M. Geissel, et al., Phys. Plasmas **25**, 022706 (2018). Experiments by A. J. Harvey-Thompson and M. R. Weis

A cobalt tracer on the LEH window was used to track the depth of window mix



- Looking for Co K-shell emission at stagnation

A. J. Harvey-Thompson, et al., to be submitted.

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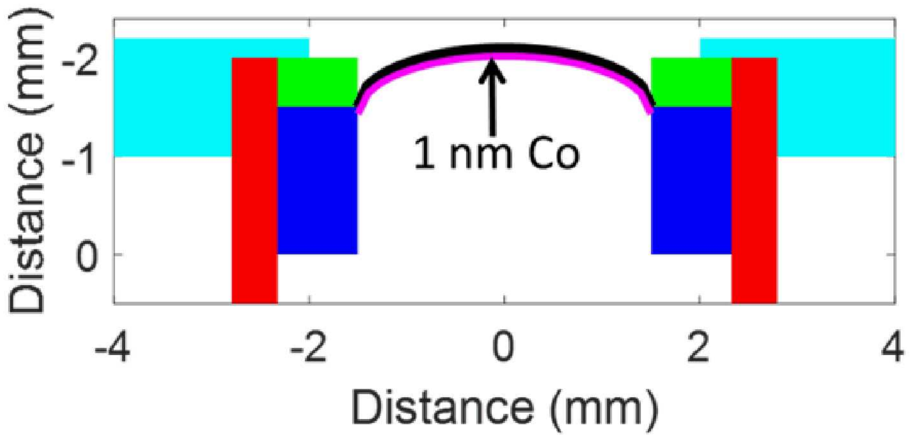
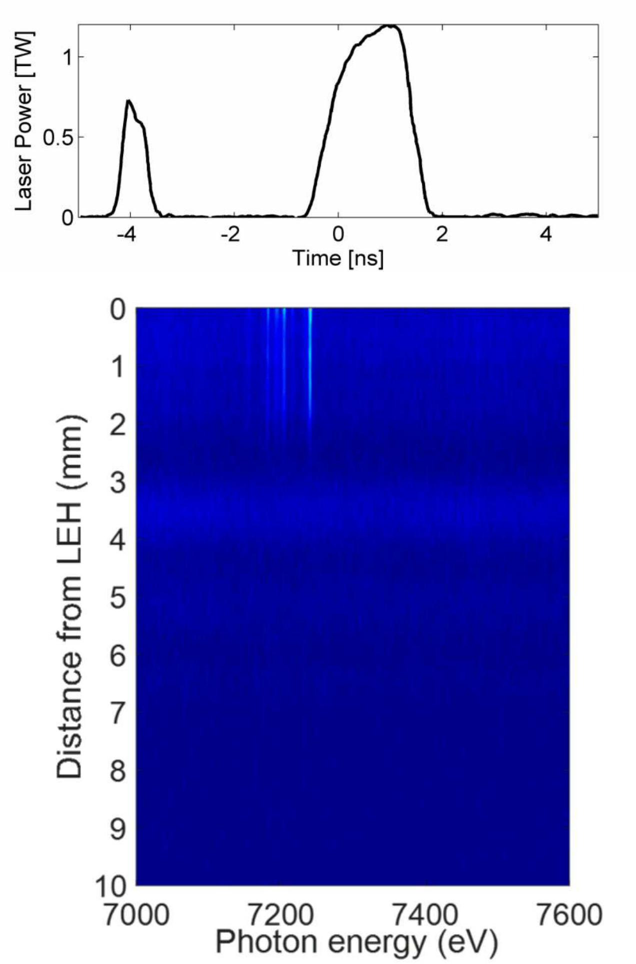


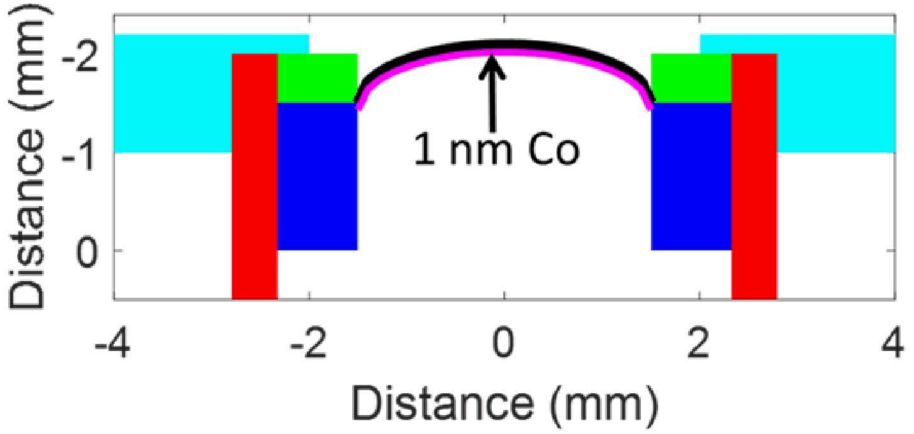
- Looking for Co K-shell emission at stagnation
- Window mix was observed in the top 3 mm of the target with the old laser configuration

Unconditioned

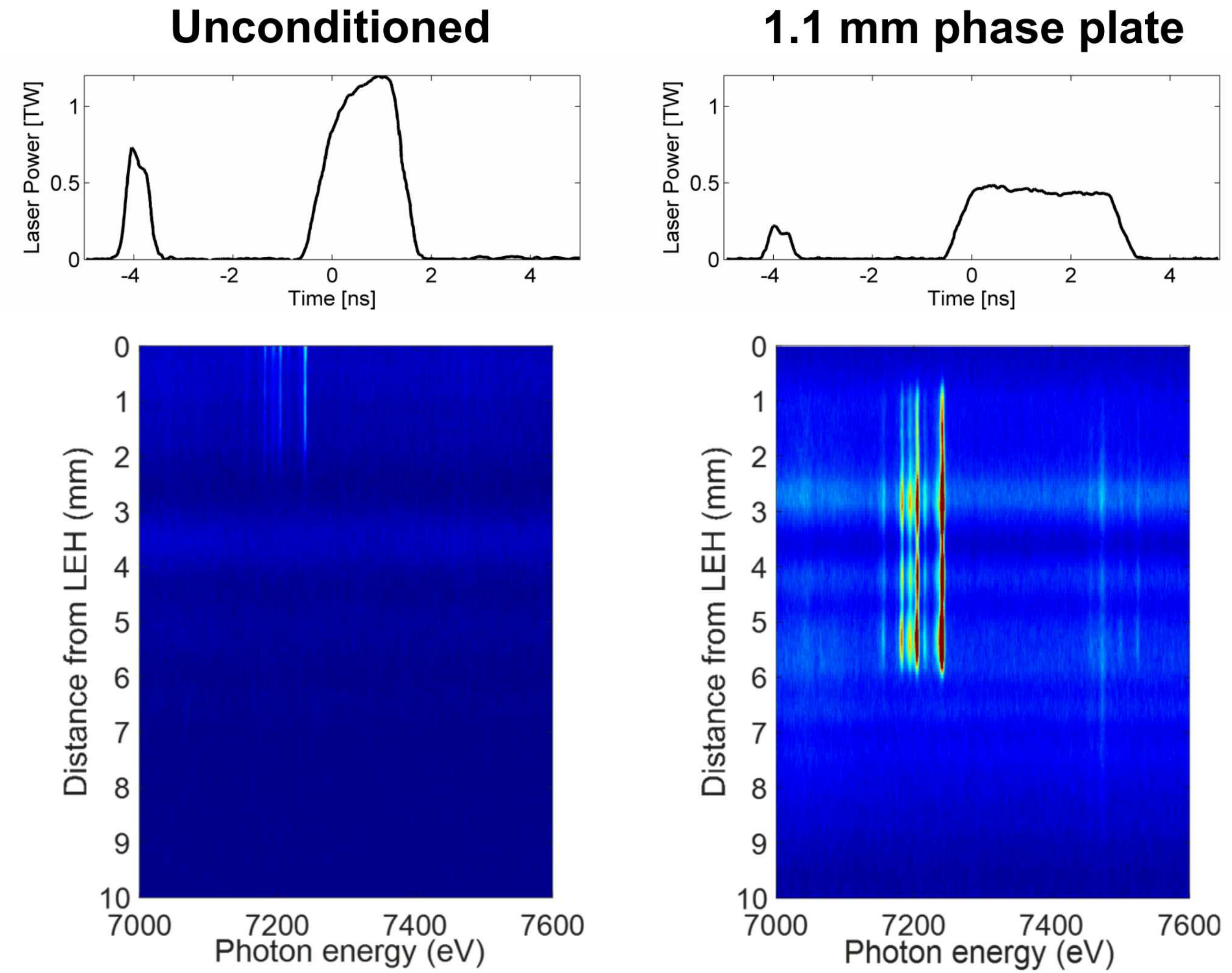


A. J. Harvey-Thompson, et al., to be submitted.

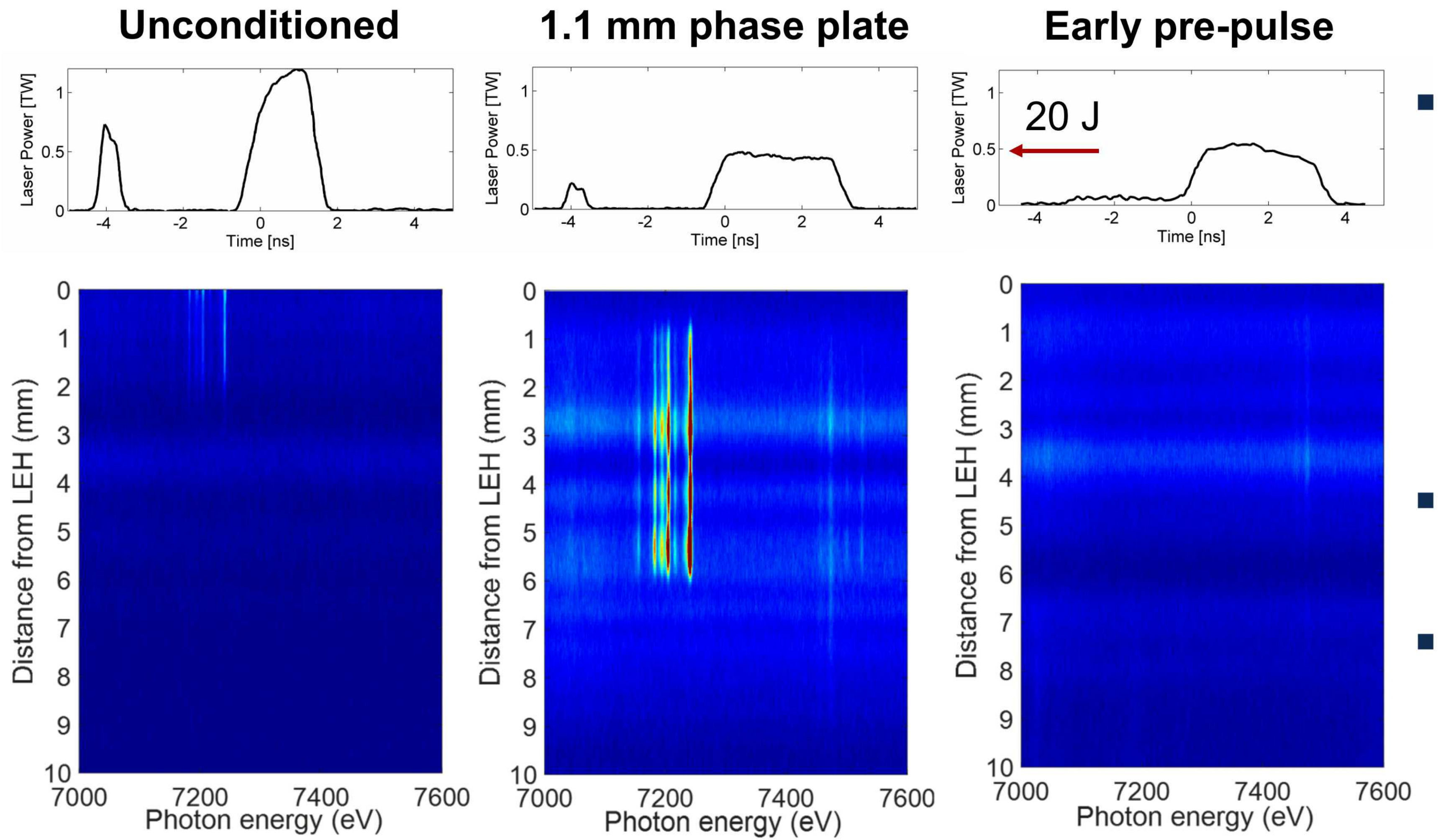
A cobalt tracer on the LEH window was used to track the depth of window mix



- Looking for Co K-shell emission at stagnation
- Window mix was observed in the top 3 mm of the target with the old laser configuration
- The new laser configuration with the 1.1 mm DPP injected window mix into the top 6 mm of the target!



Simulations predicted a small change in laser pulse shape would greatly reduce window mix

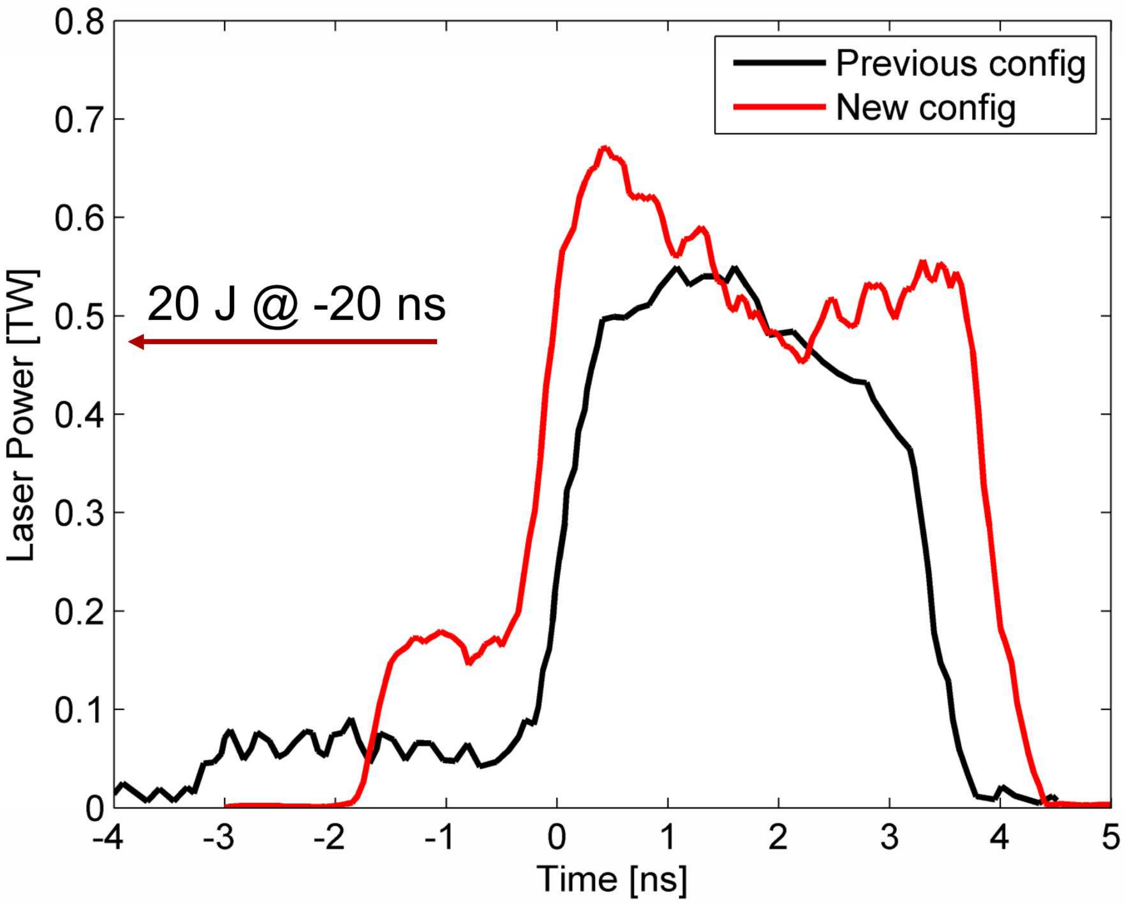


- Early pre-pulse configuration utilizes a 20 J pre-pulse approximately 20 ns early and a low intensity foot
  - 1.1 mm phase plate used
- Couples ~1 kJ to the fuel out of 1.8 kJ
- Slight increase in laser energy coupled to fuel with substantially less mix

A. J. Harvey-Thompson, et al., to be submitted.

A higher energy version of this new laser configuration produced record performance

- Used the same low energy, very early pre-pulse to convert the window to plasma
- Shorter, higher intensity foot allowed more energy in the main pulse
  - 2500 J total energy
  - 1200-1400 J coupled



Experiments by A. J. Harvey-Thompson, M. R. Weis, and M. Geissel

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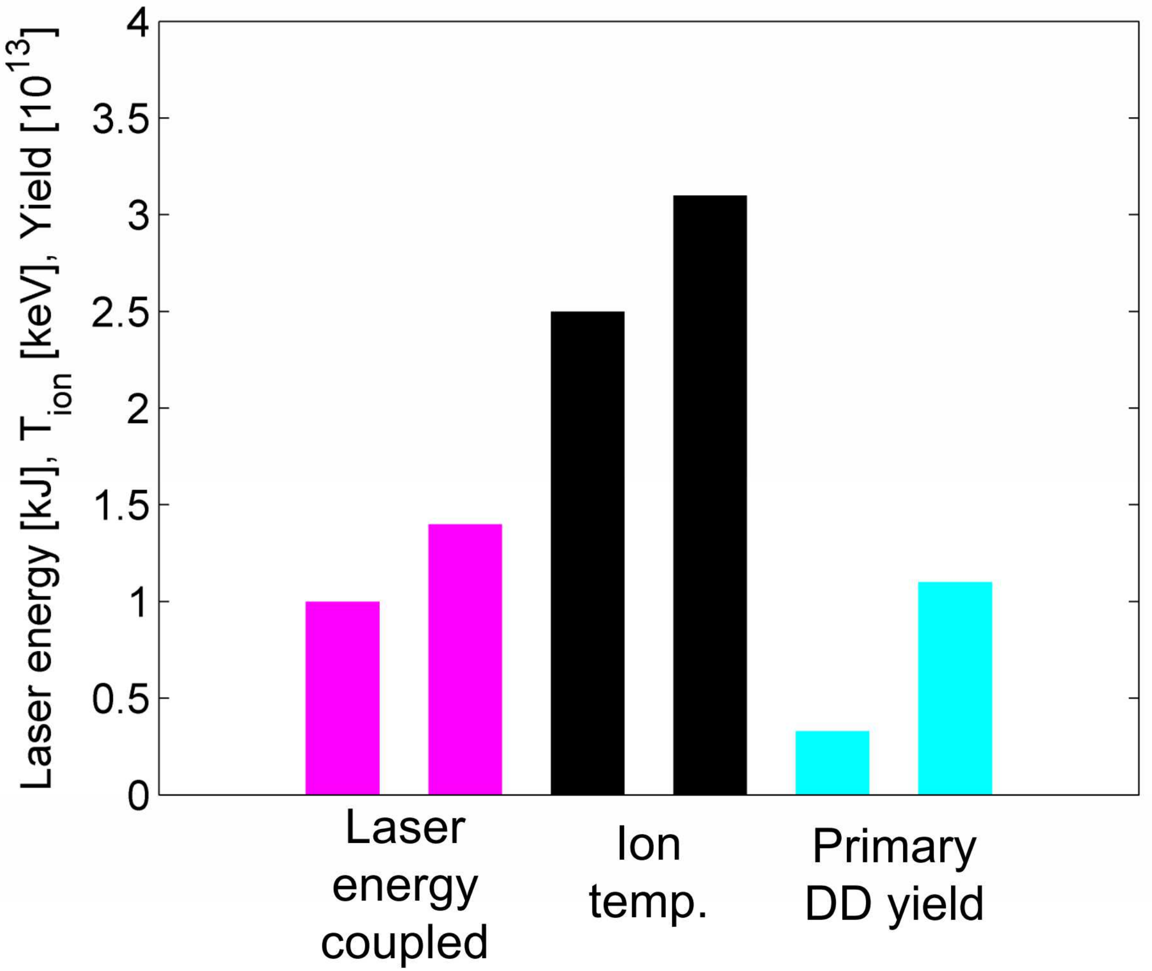
  - 2500 J total energy
  - 1200-1400 J coupled
- New record DD neutron yield of 1.1e13
  - About 3x increase from 3.3e12
  - Minimal increase in mix



Experiments by A. J. Harvey-Thompson, M. R. Weis, and M. Geissel

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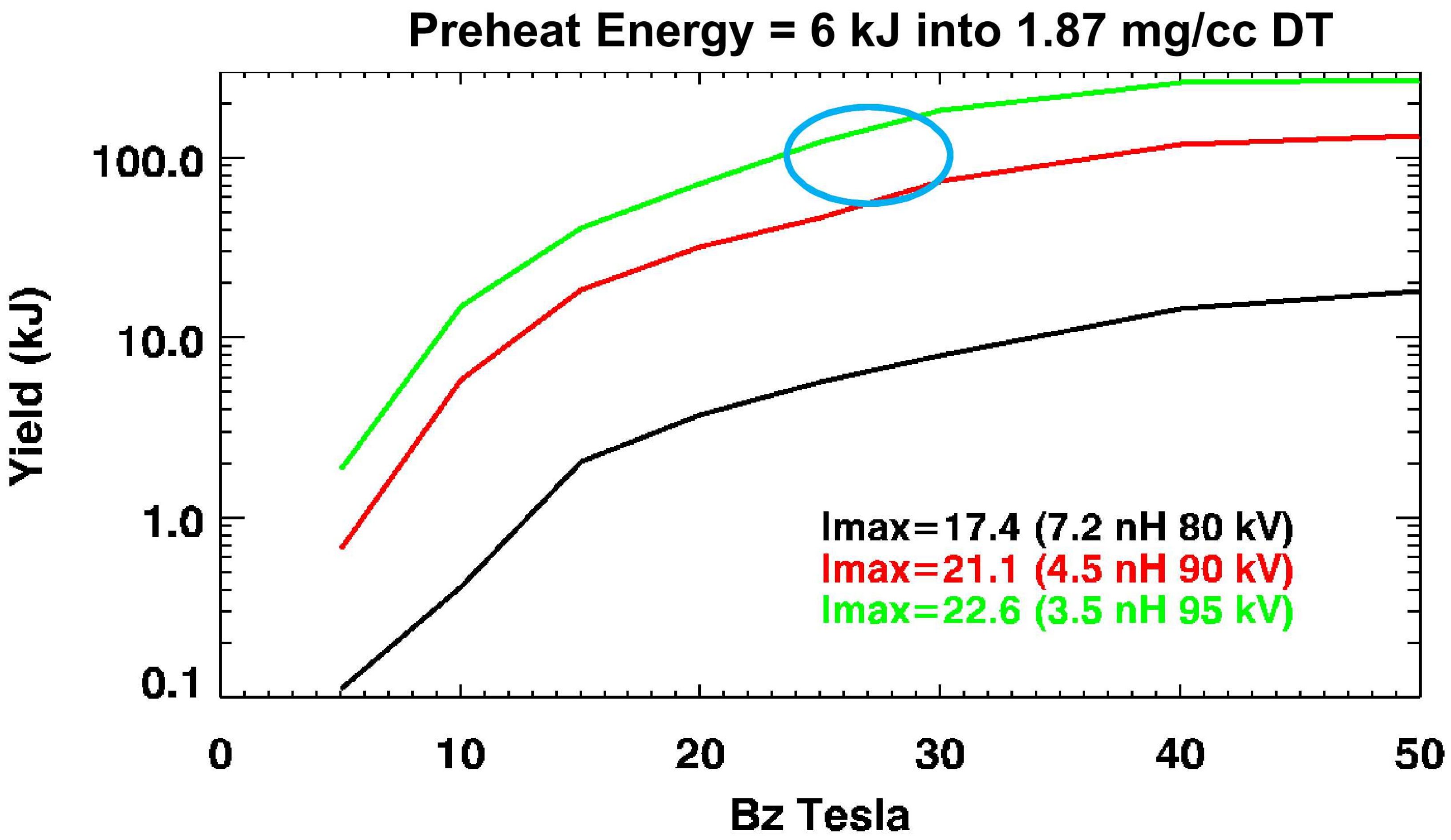
We have made significant progress towards our goal of 100 kJ DT yield with MagLIF

- We believe that we must deliver 25-30 T, 4-6 kJ, and 22-24 MA to reach 100 kJ DT



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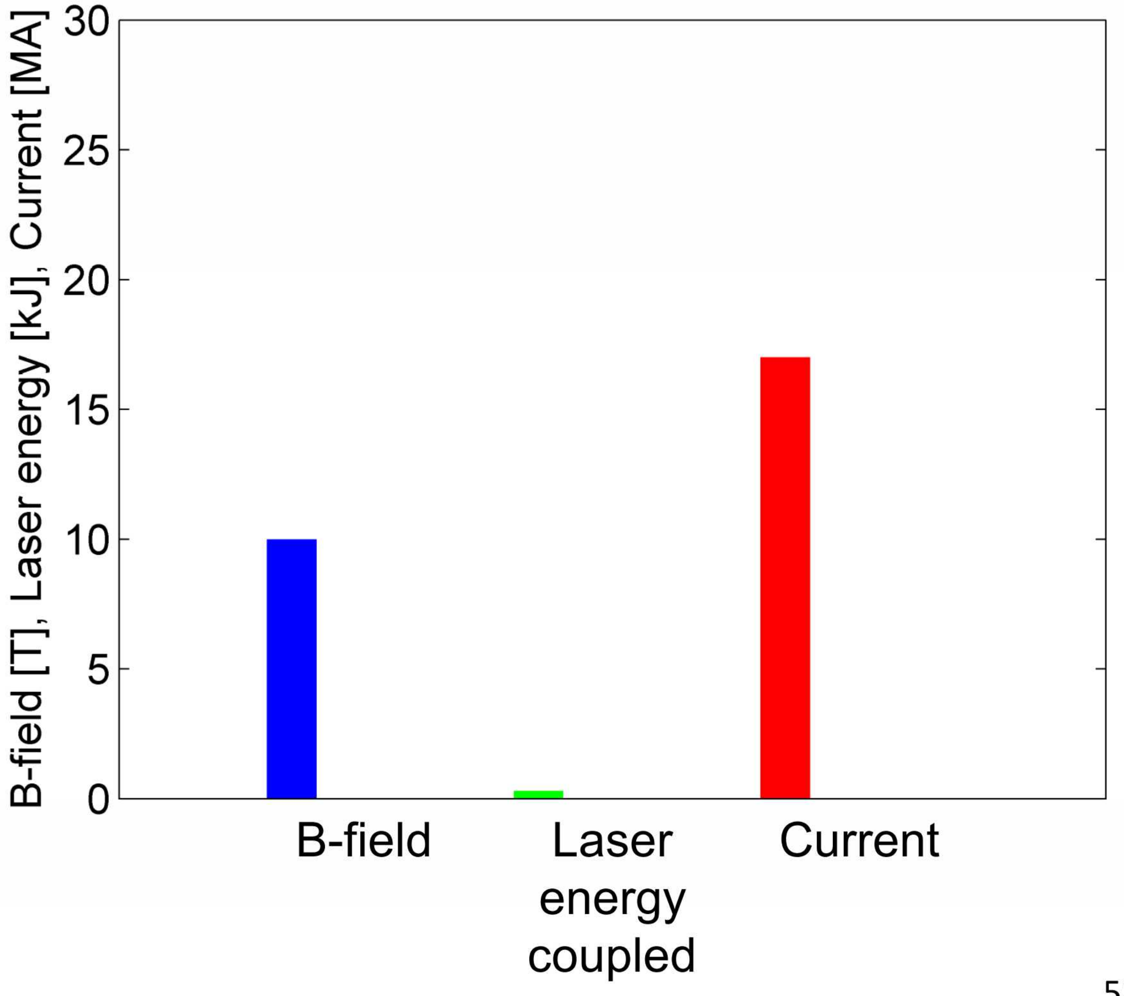

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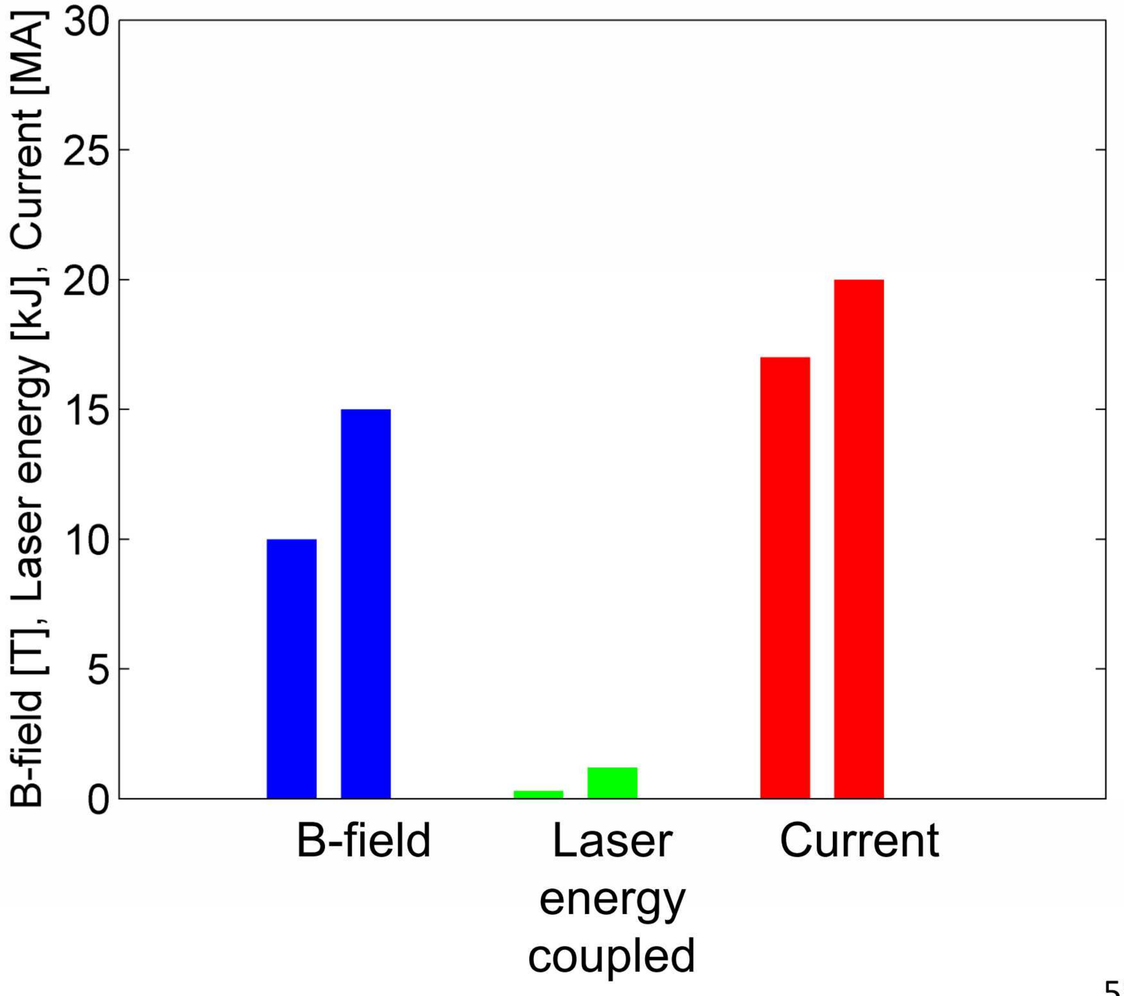

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  - Our best experiment to date produced ~2.4 kJ DT
- We think we can get to 15 T, 2 kJ, and 20 MA this year
  - Expected to further increase the yield by 2-3x
- We have path to reach 25+ T, 4+ kJ, and 22+ MA in the next few years
  - 10s to 100 kJ DT!