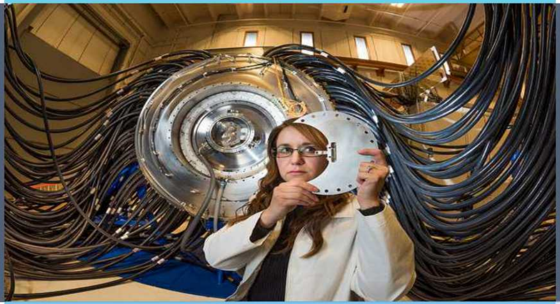
SAND2019-11301C

Scaling of Stagnation Parameters in Magnetized Liner Inertial Fusion Experiments



PRESENTED BY

Matthew R. Gomez

For the MagLIF team

At the 11th International Conference of Inertial Fusion Sciences and Applications

09/27/2019

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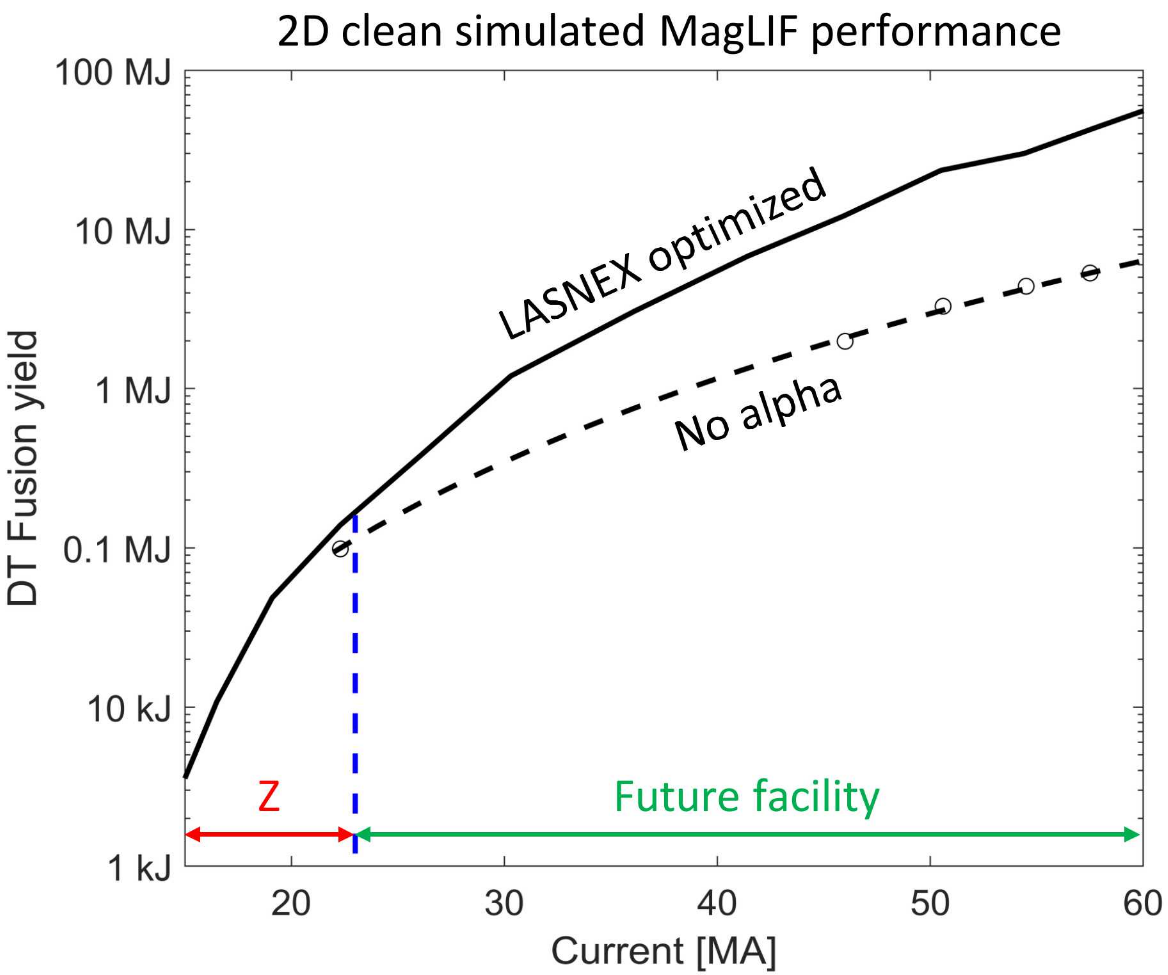
Thanks to my collaborators

D. A. Yager-Elorriaga, C. E. Myers, S. A. Slutz,
M. R. Weis, C. A. Jennings, D. C. Lamppa,
A. J. Harvey-Thompson, M. Geissel, P. F. Knapp,
E. C. Harding, S. B. Hansen, M. Mangan, C. L. Ruiz,
G. A. Chandler, T. J. Webb, T. Moore,
G. R. Laity, D. J. Ampleford, K. J. Peterson,
G. A. Rochau, D. B. Sinars

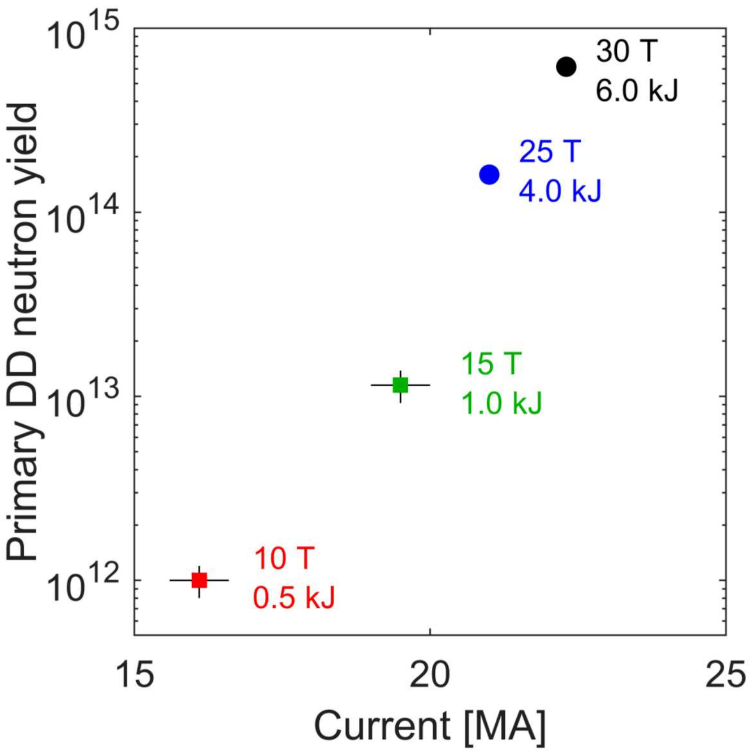
The US national ICF program is identifying credible paths to multi-MJ fusion yield



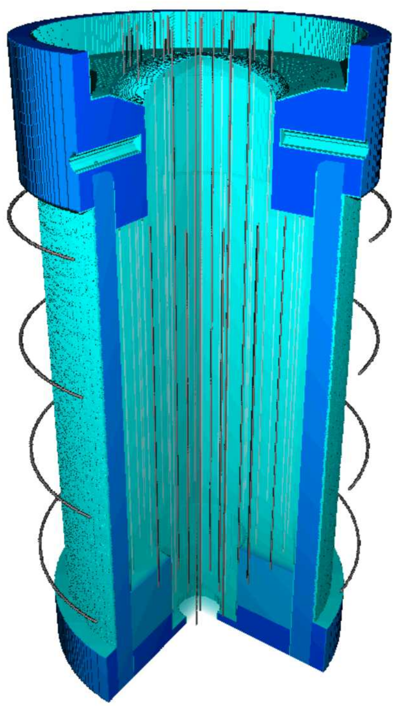
- MagLIF can access multi-MJ yields at achievable driver energies for a future facility
- This scaling is contingent on understanding degradation mechanisms (e.g., 3D effects, mix) and the interplay between the physics of magnetization, preheat, and implosion

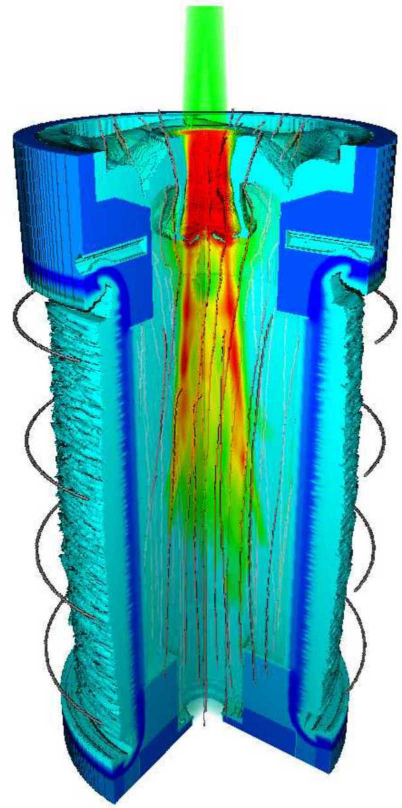
MagLIF has demonstrated the exciting potential of magneto-inertial fusion

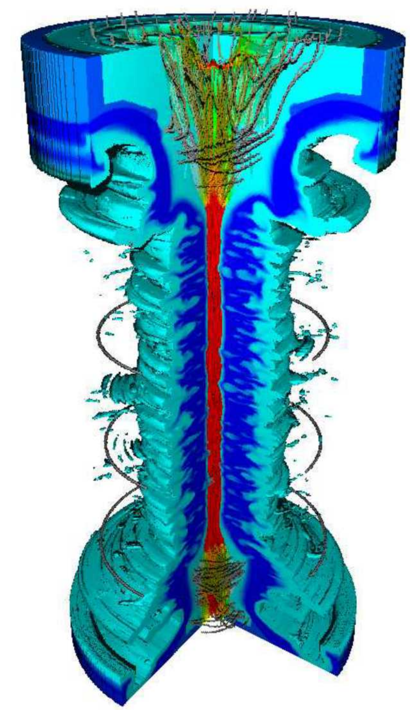
- MagLIF produces fusion-relevant temperatures, significant neutron yields, and magnetic trapping of charged fusion products
- Improvements to the platform have enabled an order of magnitude increase in neutron yield, consistent with simulation predictions
- Parametric scans in laser energy and initial magnetization show the expected trends in target performance
- Additional improvements to the platform are underway, which are expected to increase neutron production by another order of magnitude



MagLIF is a magneto-inertial fusion concept that relies on three components to produce fusion conditions at stagnation







Magnetization

- Suppress radial thermal conduction losses
- Enable slow implosion with thick target walls

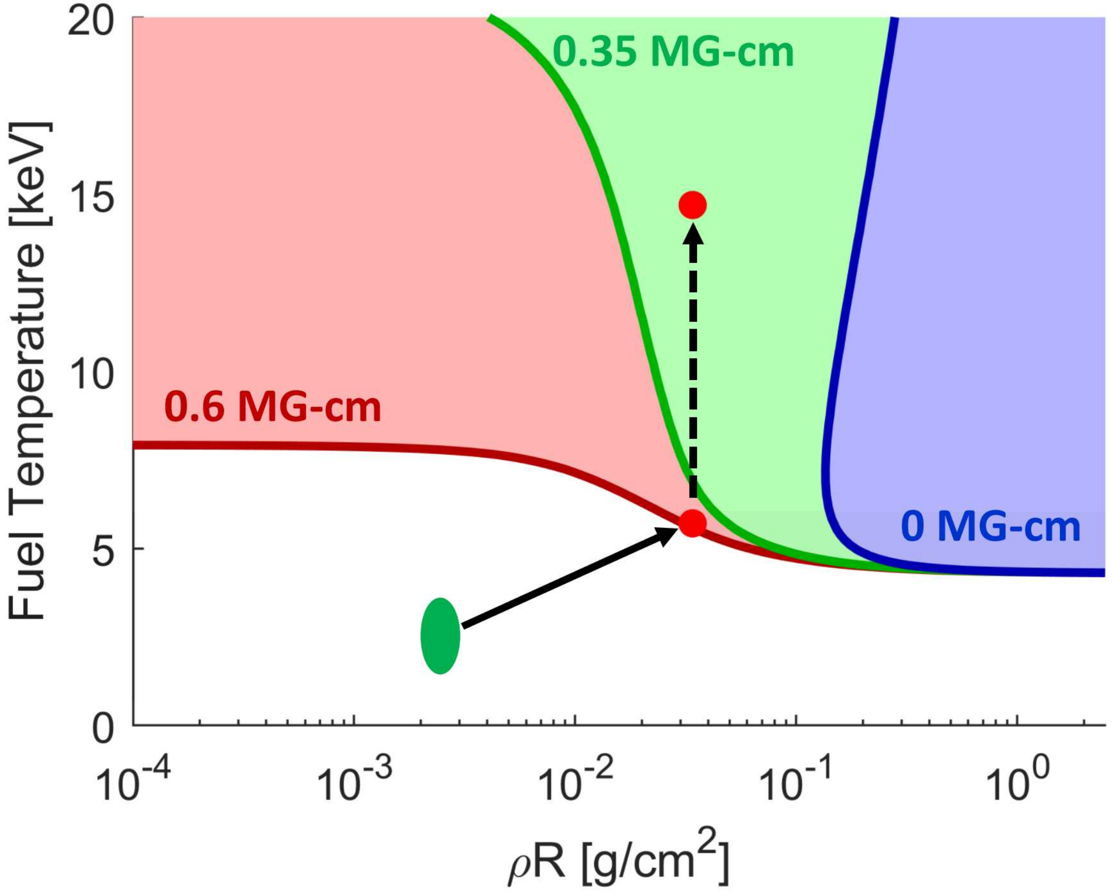
Preheat

- Increase fuel adiabat to limit required convergence

Implosion

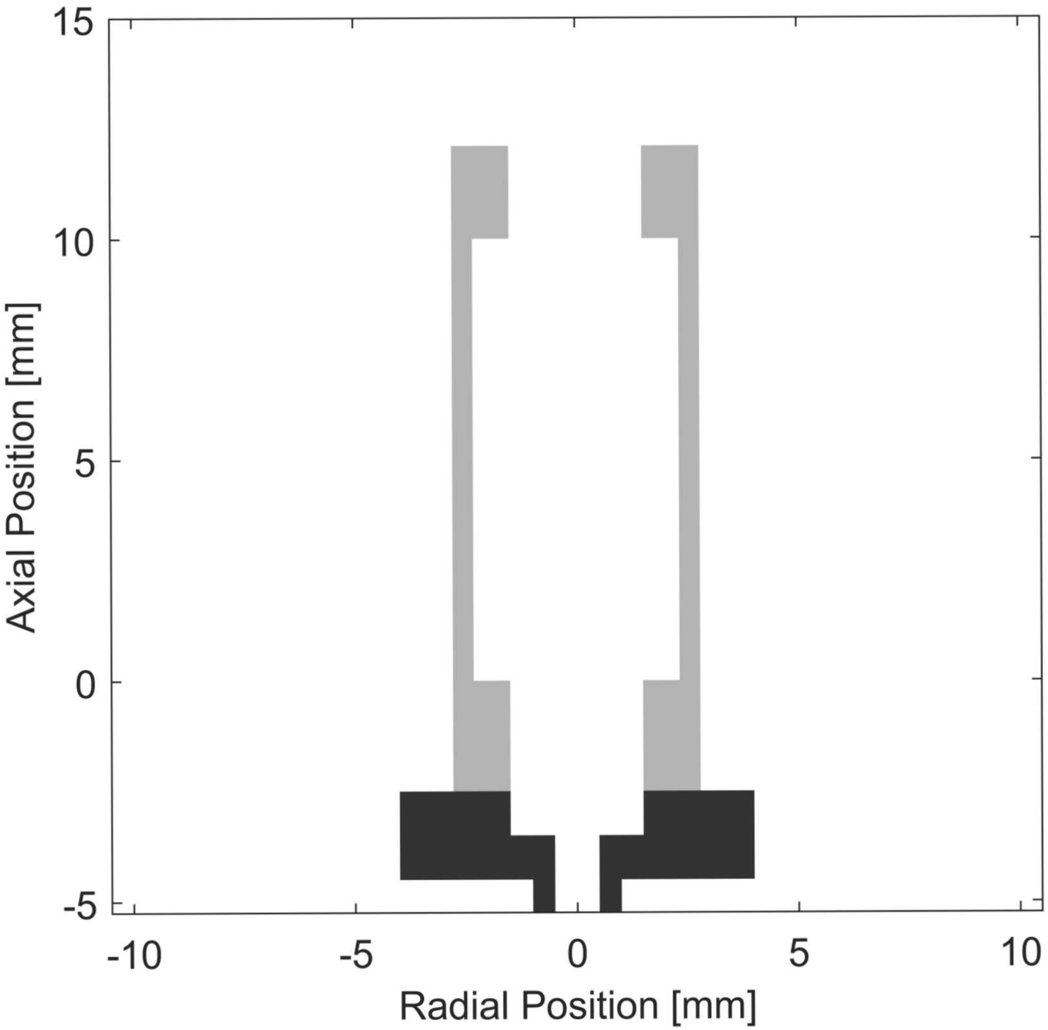
- PdV work to heat fuel
- Amplify B-field through flux compression

Magneto-inertial fusion requires magnetic fields to trap charged fusion products



- Ignition-scale MIF designs achieve self-heating through magnetically-trapped charged fusion products
  - Low initial fuel density
  - Cylindrical convergence: density ~ $1/R^2$
  - Relatively small radius
- Large magnetic fields trap charged fusion products opening up a larger ignition space

A quick introduction to the MagLIF experimental geometry



- Target body is beryllium
- 10 mm tall
- 5.58 mm outer diameter
- 0.465 mm wall thickness

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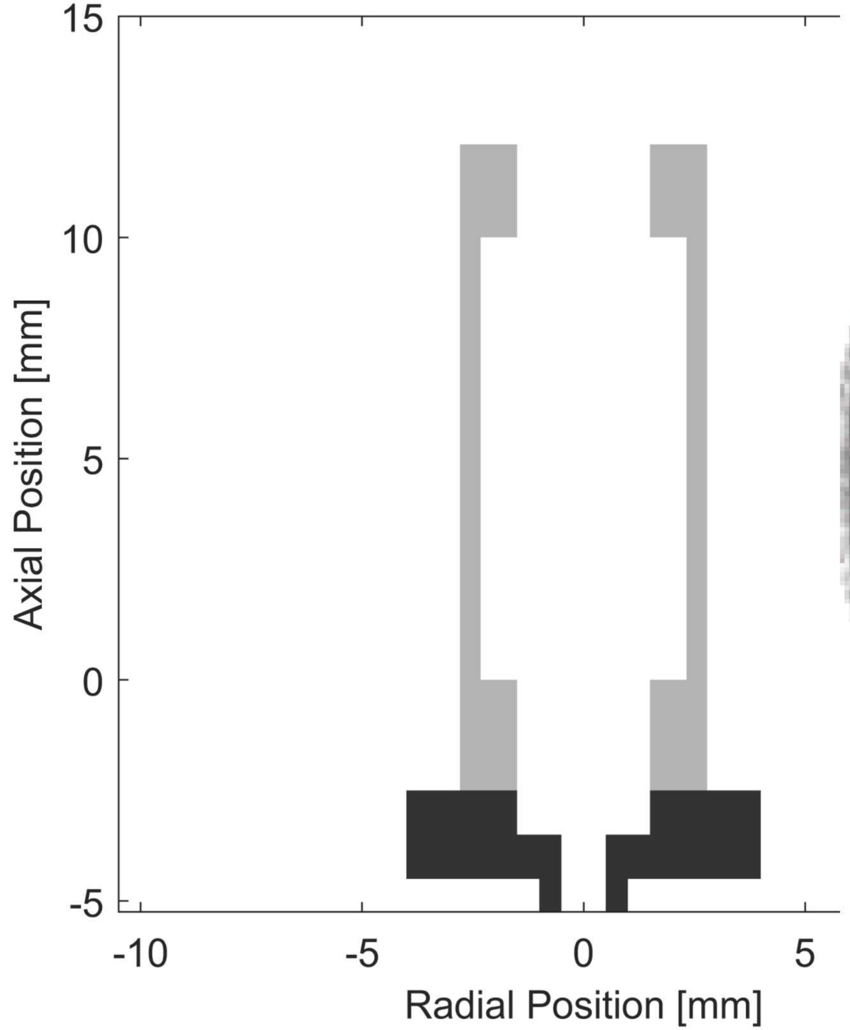

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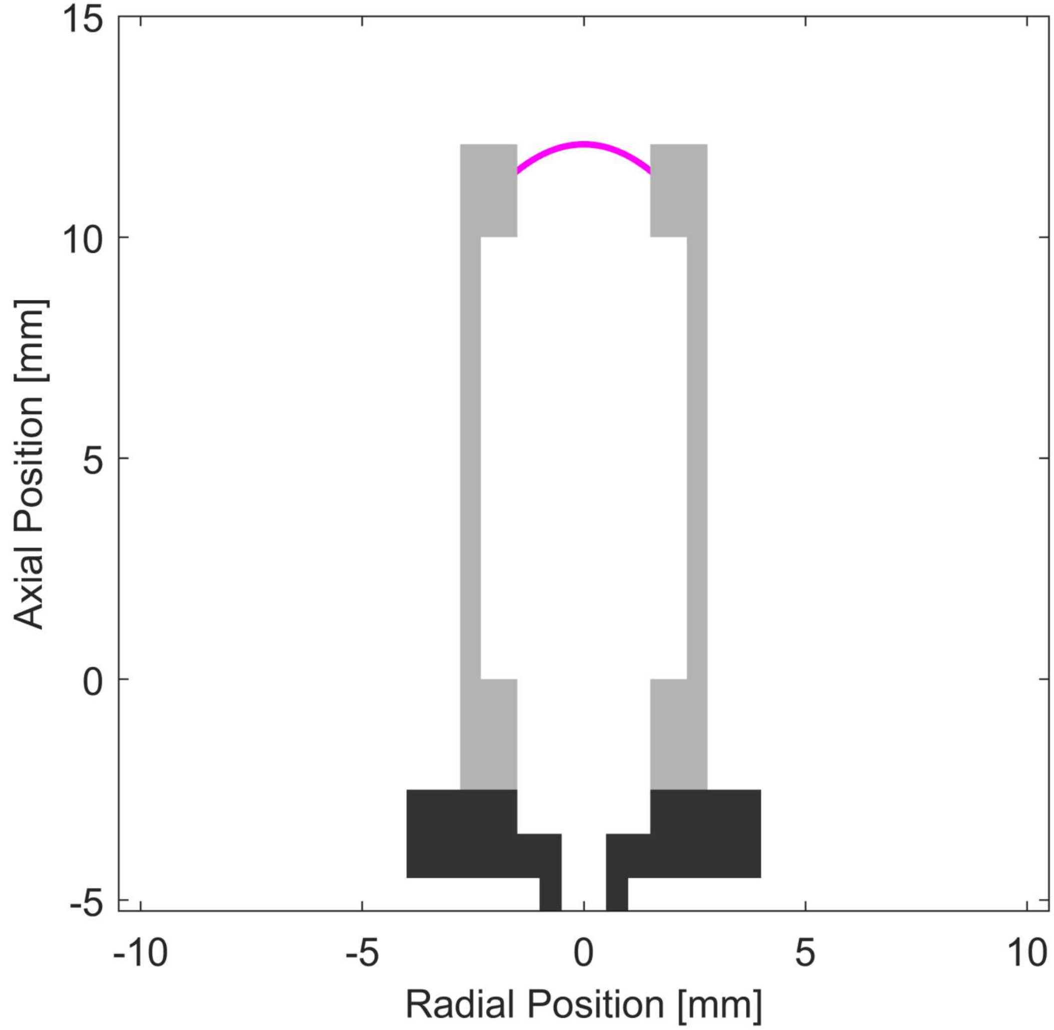
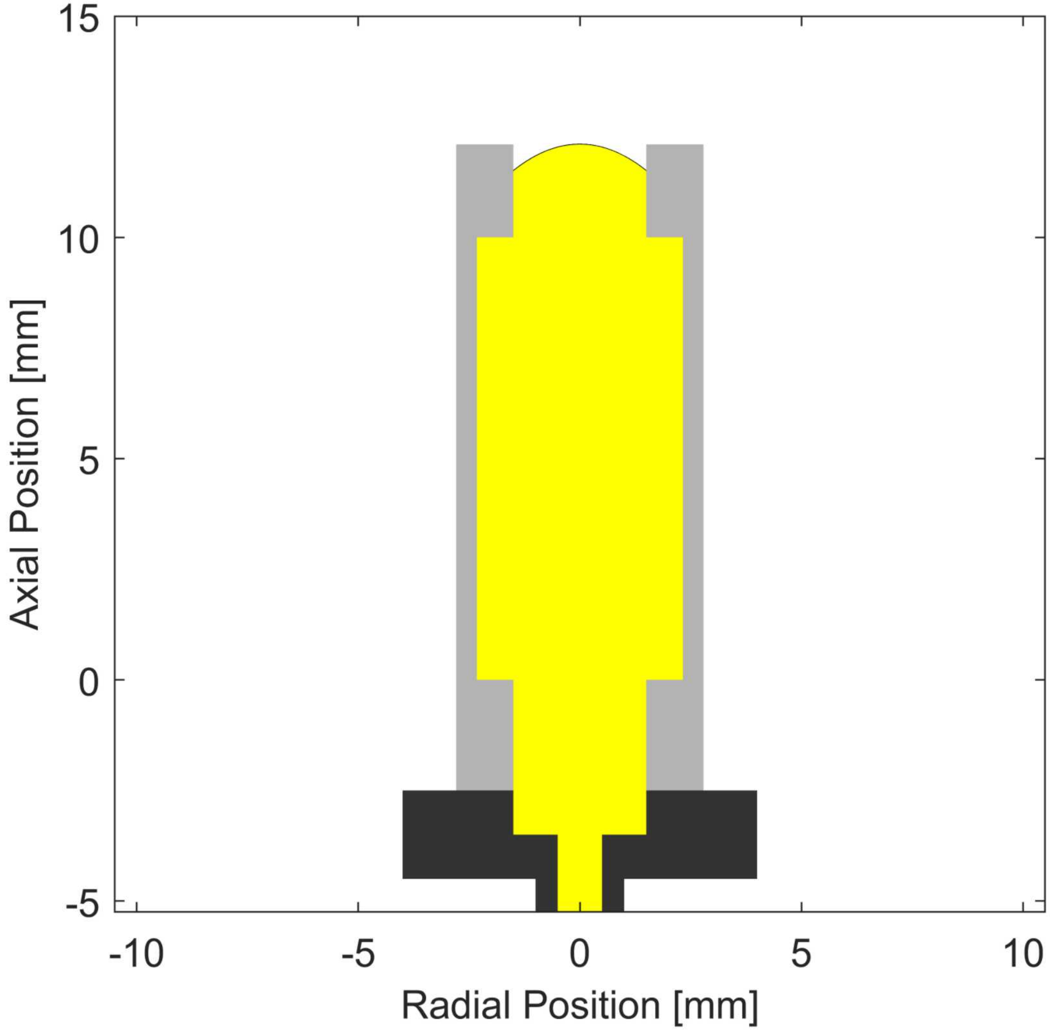


- Laser entrance hole window is polyimide
- 1-3 µm thick
- 2-3 mm diameter

A quick introduction to the MagLIF experimental geometry



- Fuel is deuterium
- Densities between 0.7 mg/cm^3 and 1.4 mg/cm^3

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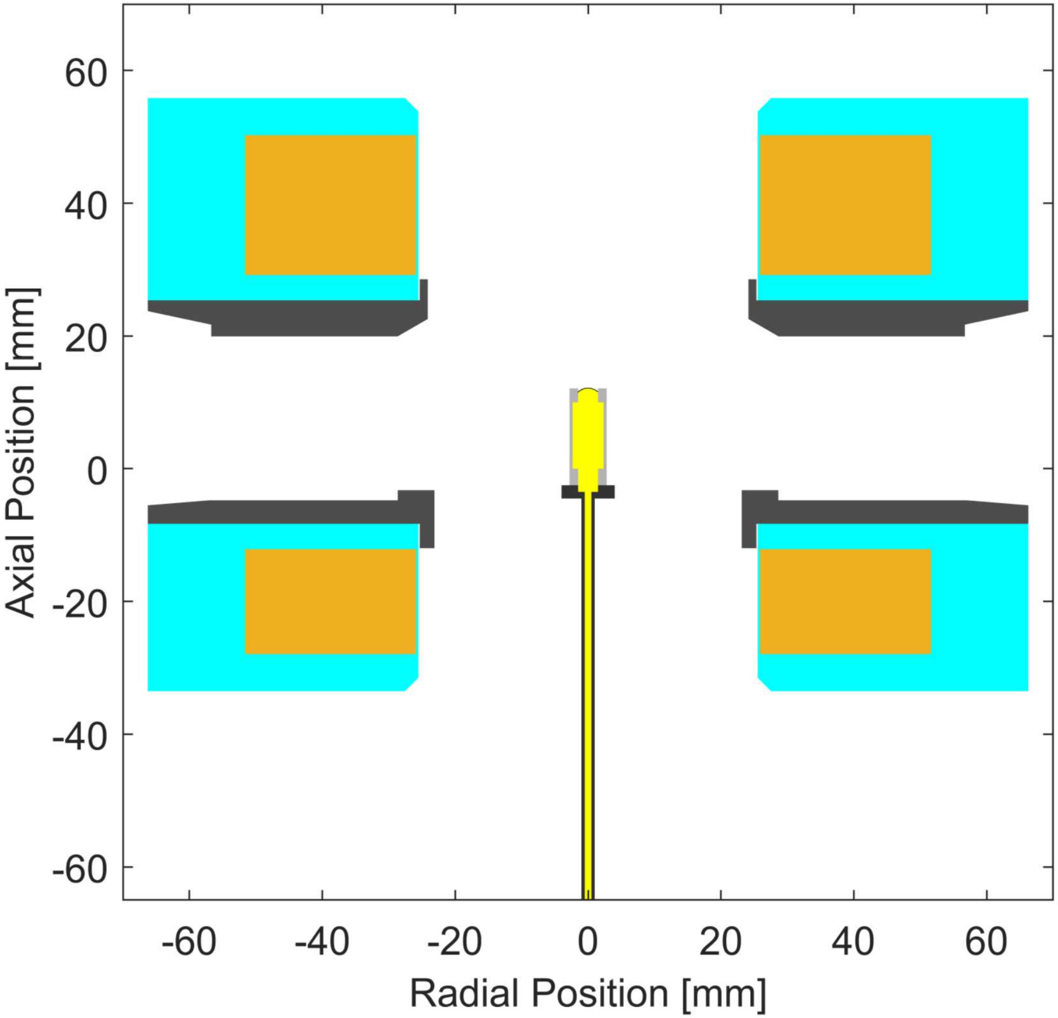

- Axial magnetic field applied with Helmholtz-like coils
- Typically 10 T
- Risetime is several ms to allow field to diffuse through conductors
- Maintain radial diagnostic access with split coil design

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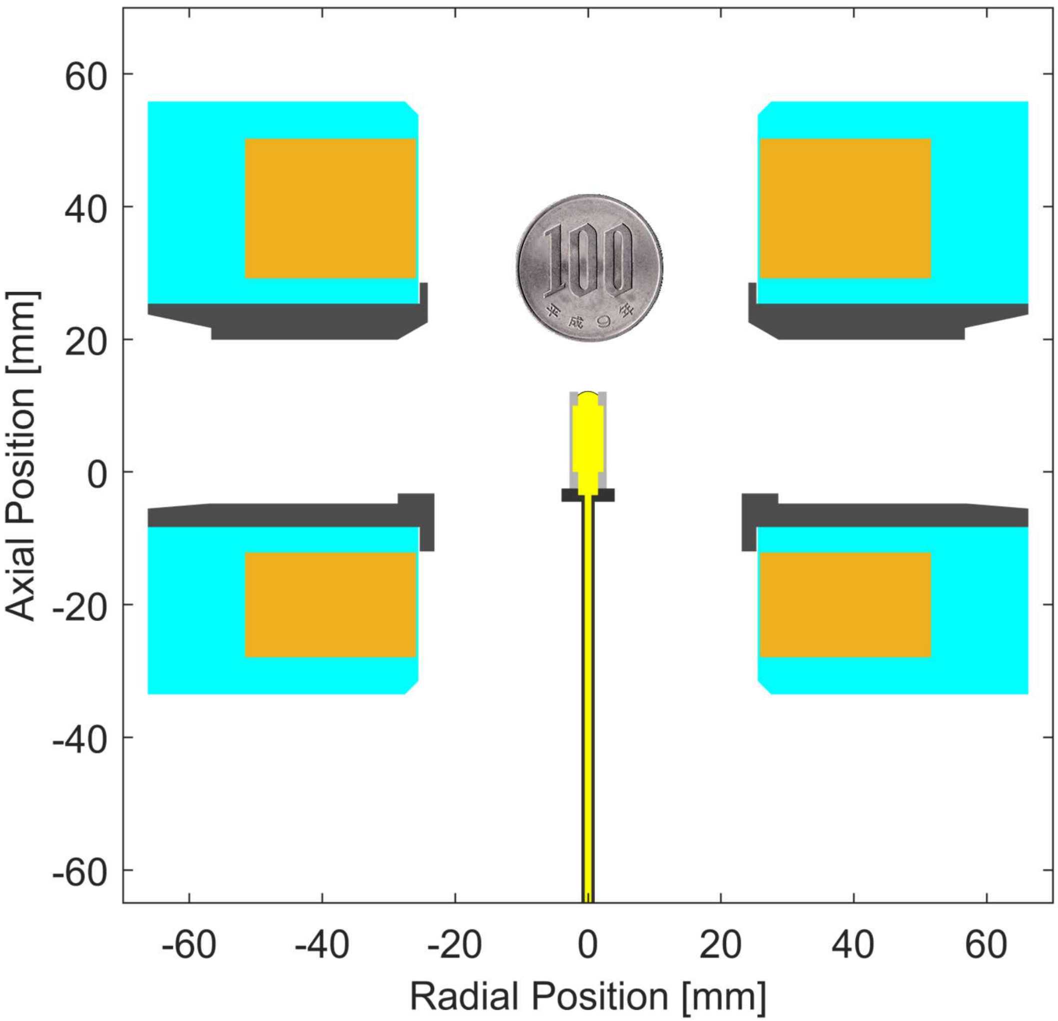

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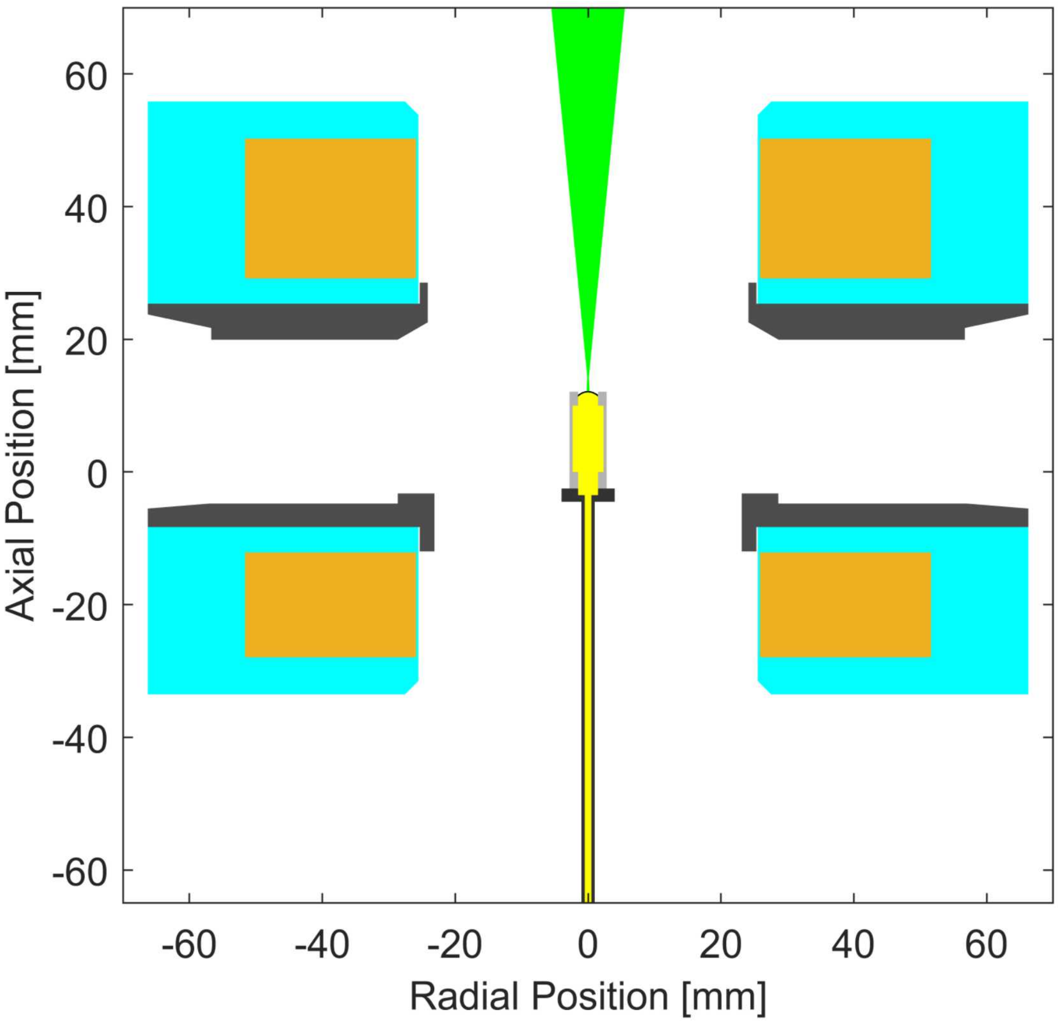
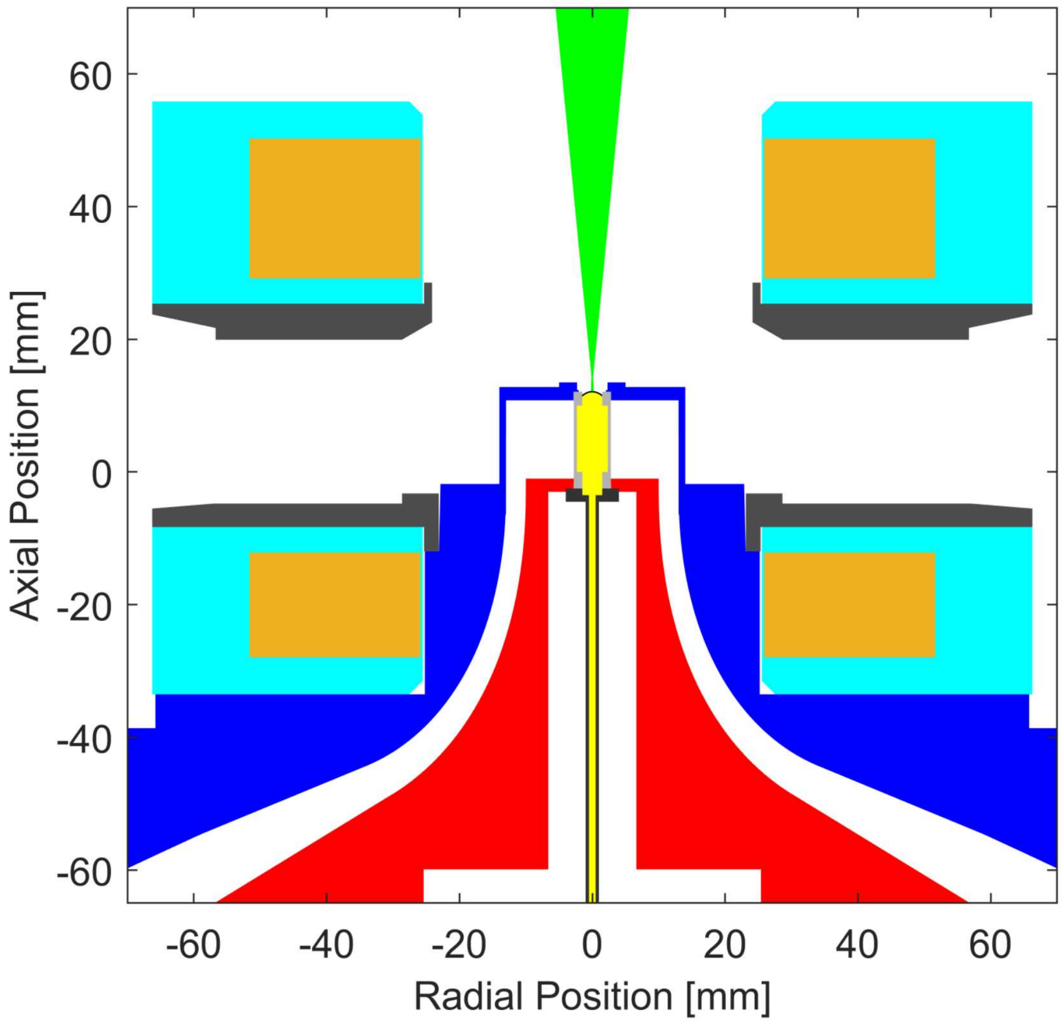


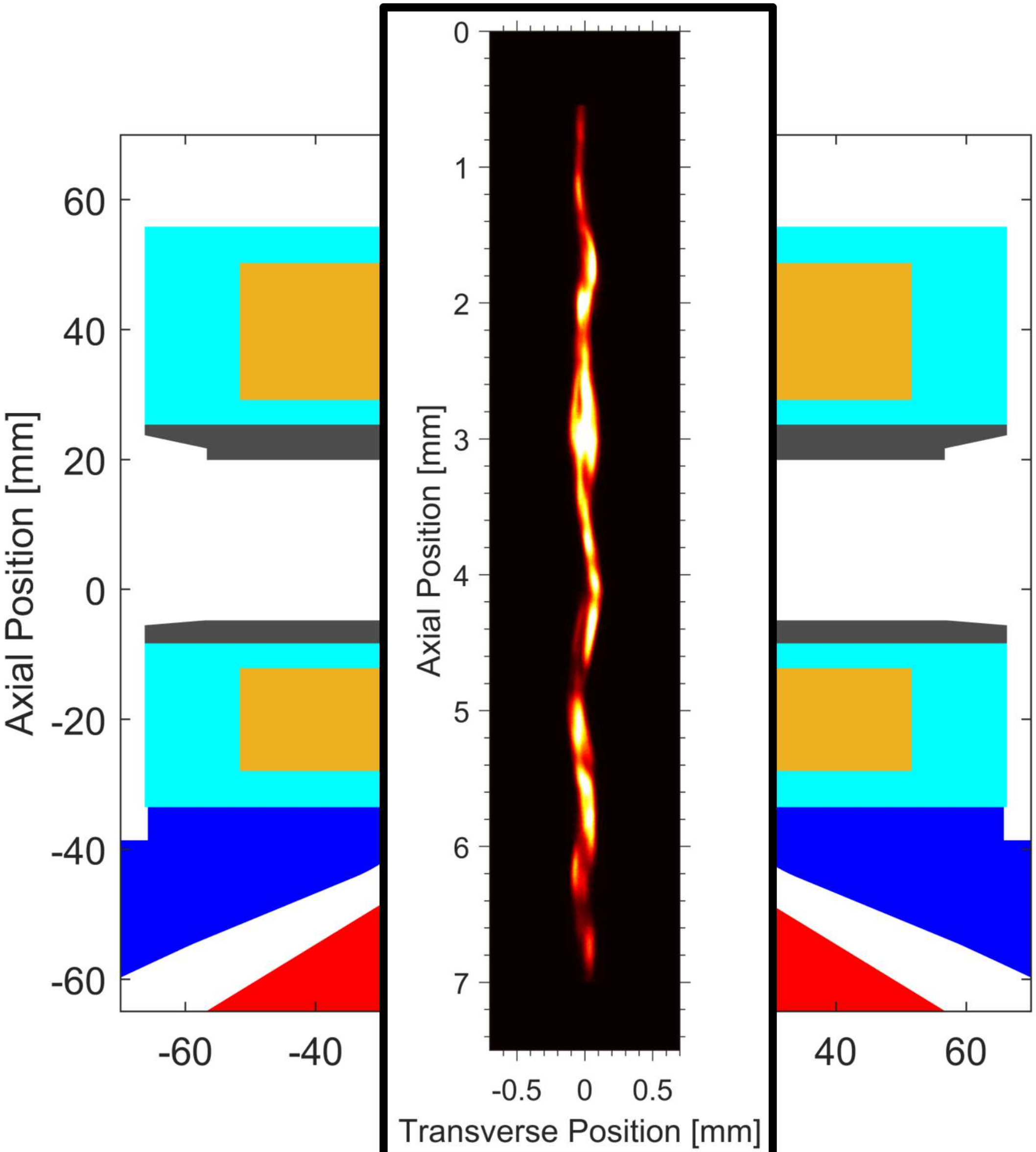
- Laser enters target axially through LEH
- 527 nm, multi-kJ, up to 1 TW laser
- 5-10% n_e/n_{crit}
- Beam smoothing with DPP available
- Fuel reaches up to 1 keV on axis with an average temp ~100 eV

A quick introduction to the MagLIF experimental geometry



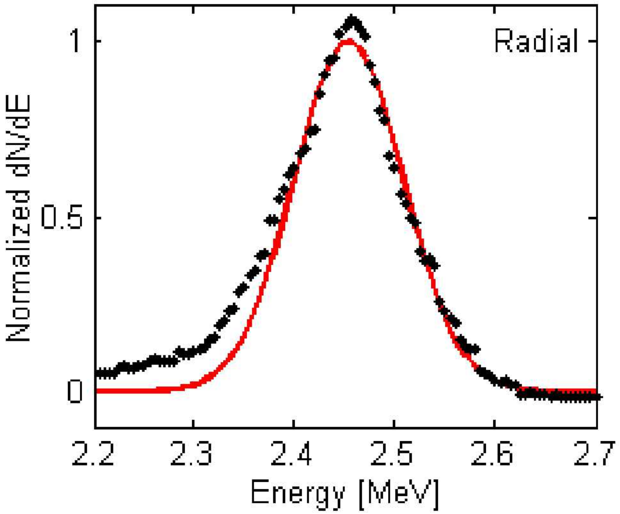
- Current is delivered to the target via the final transmission line
- 15-20 MA flows axially in the target
- Target radially implodes over 100 ns with CR ≈ 30-40

A quick introduction to the MagLIF experimental geometry



- Current is delivered to the target via the final transmission line
- 15-20 MA flows axially in the target
- Target radially implodes over 100 ns with CR ≈ 30-40
- High aspect ratio stagnation column with keV temperature and kT B-field

Initial MagLIF experiments demonstrated key aspects of magneto-inertial fusion



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

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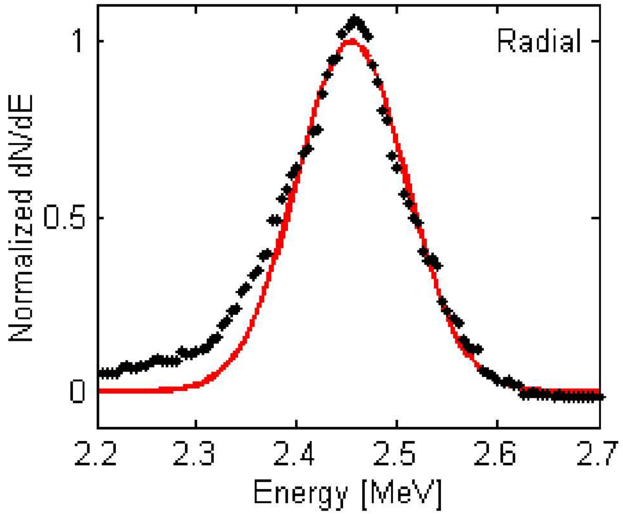
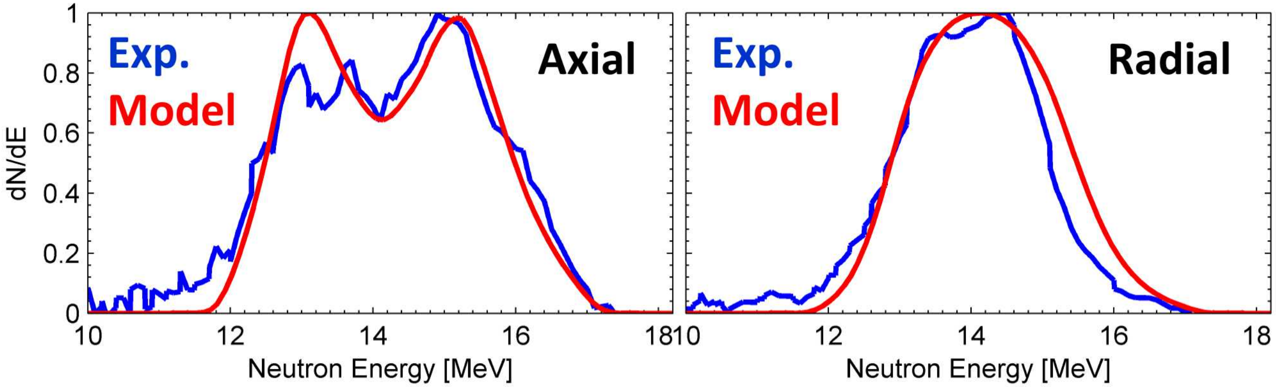


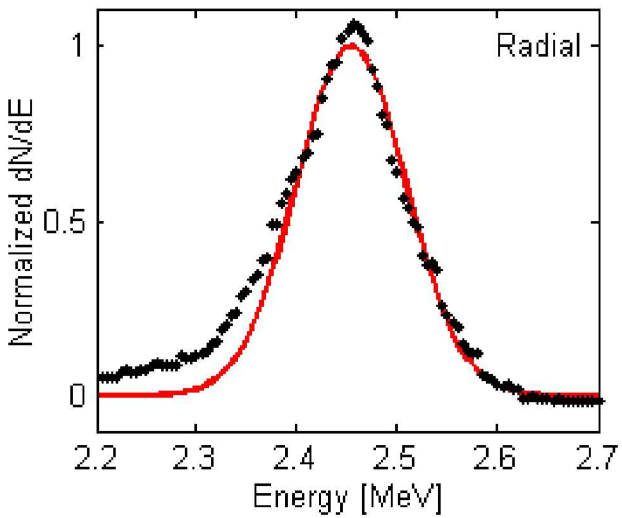
Thermonuclear neutron generation with fusion-relevant ion temperatures (2-3 keV)

Secondary DT Neutron Spectra



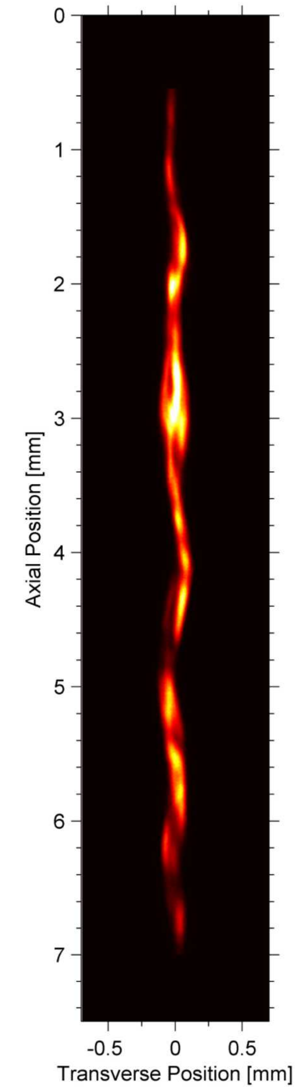
Highly magnetized fuel at stagnation (>0.3 MG-cm)

Initial MagLIF experiments demonstrated key aspects of magneto-inertial fusion

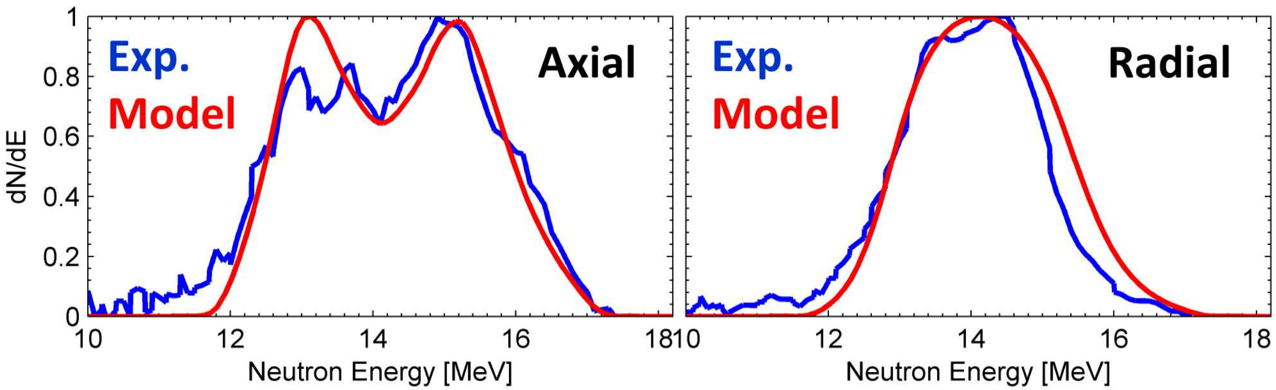


Thermonuclear neutron generation with fusion-relevant ion temperatures (2-3 keV)

High aspect ratio fuel column at CR > 30



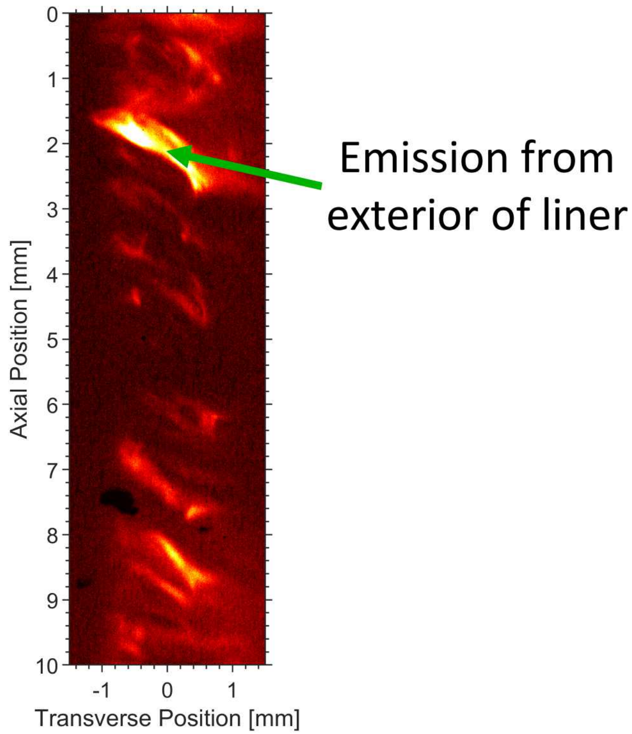
Secondary DT Neutron Spectra



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

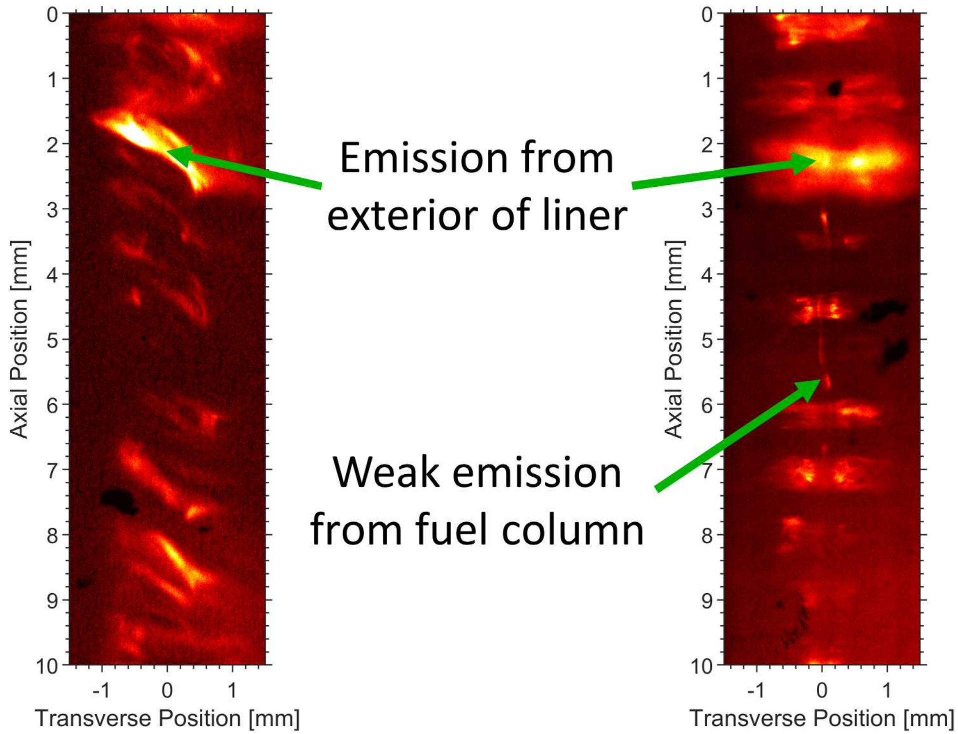
Perhaps most importantly, these experiments produced significant yield only when using both an applied B-field and laser preheat

10 T B-field
No laser preheat
1×10^{10} DD neutrons

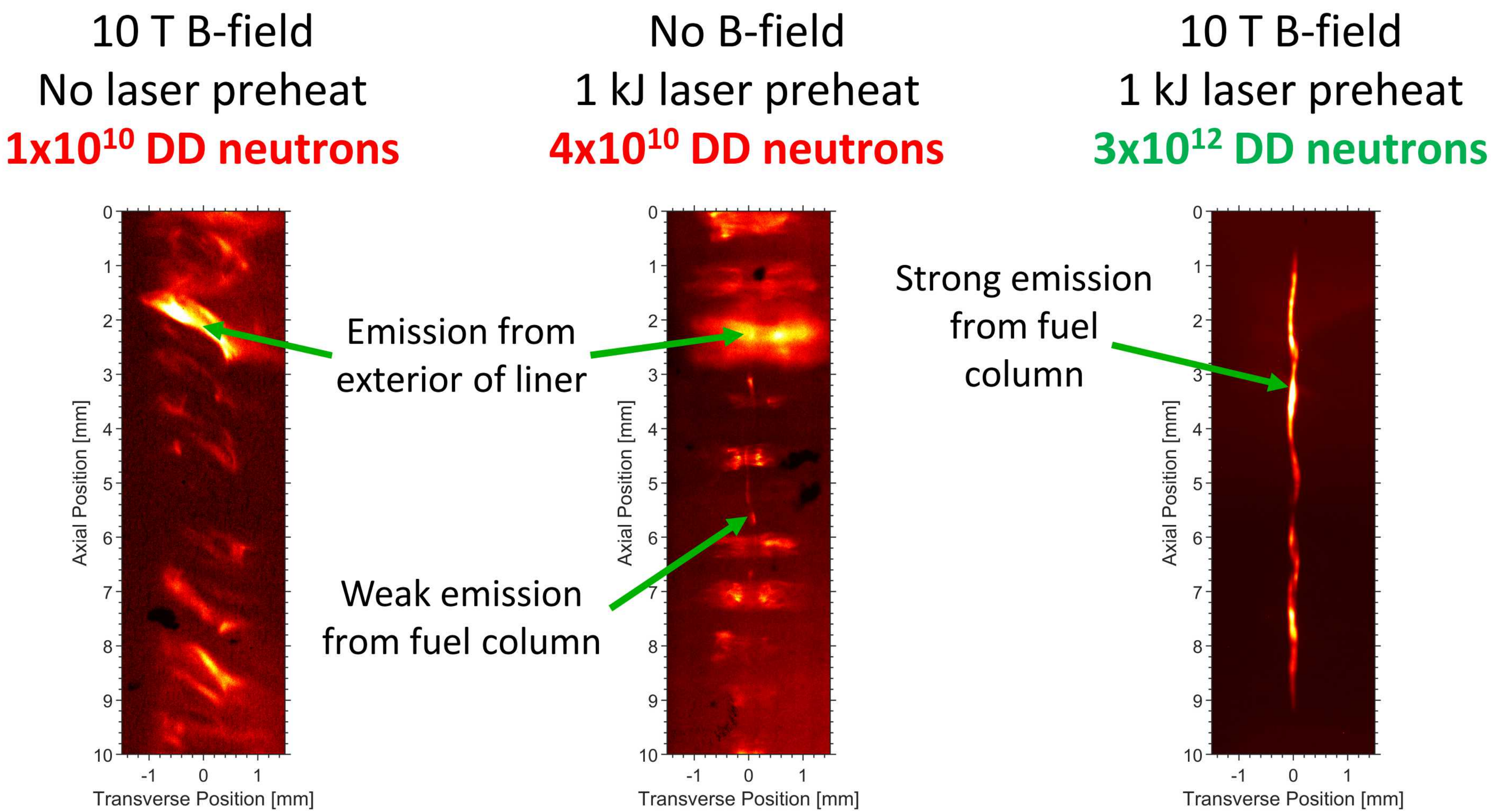


Perhaps most importantly, these experiments produced significant yield only when using both an applied B-field and laser preheat

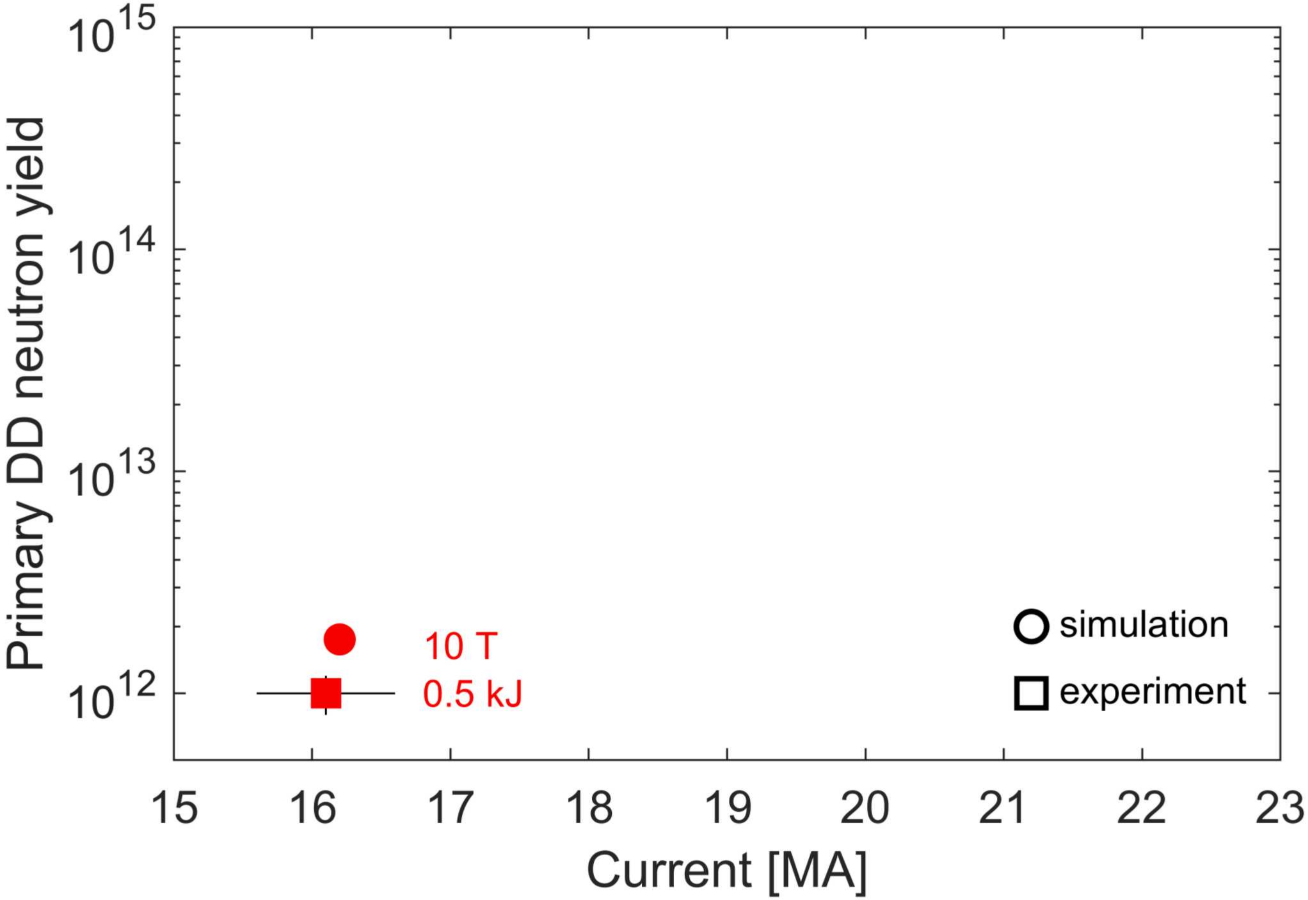
10 T B-field	No B-field
No laser preheat	1 kJ laser preheat
$1x10^{10}$ DD neutrons	**$4x10^{10}$ DD neutrons**



Perhaps most importantly, these experiments produced significant yield only when using both an applied B-field and laser preheat

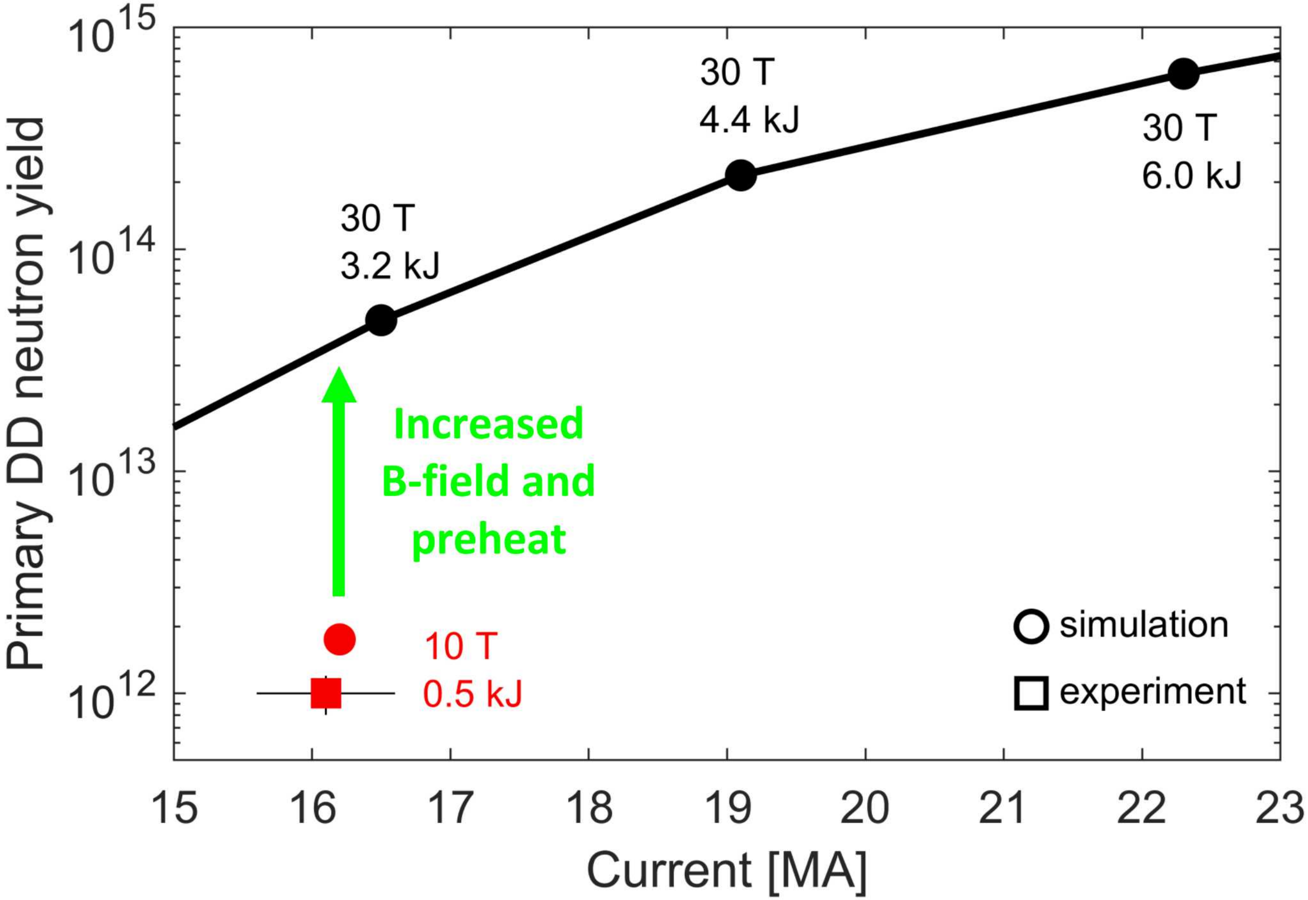


The initial MagLIF experiments established target performance in a new region of phase space



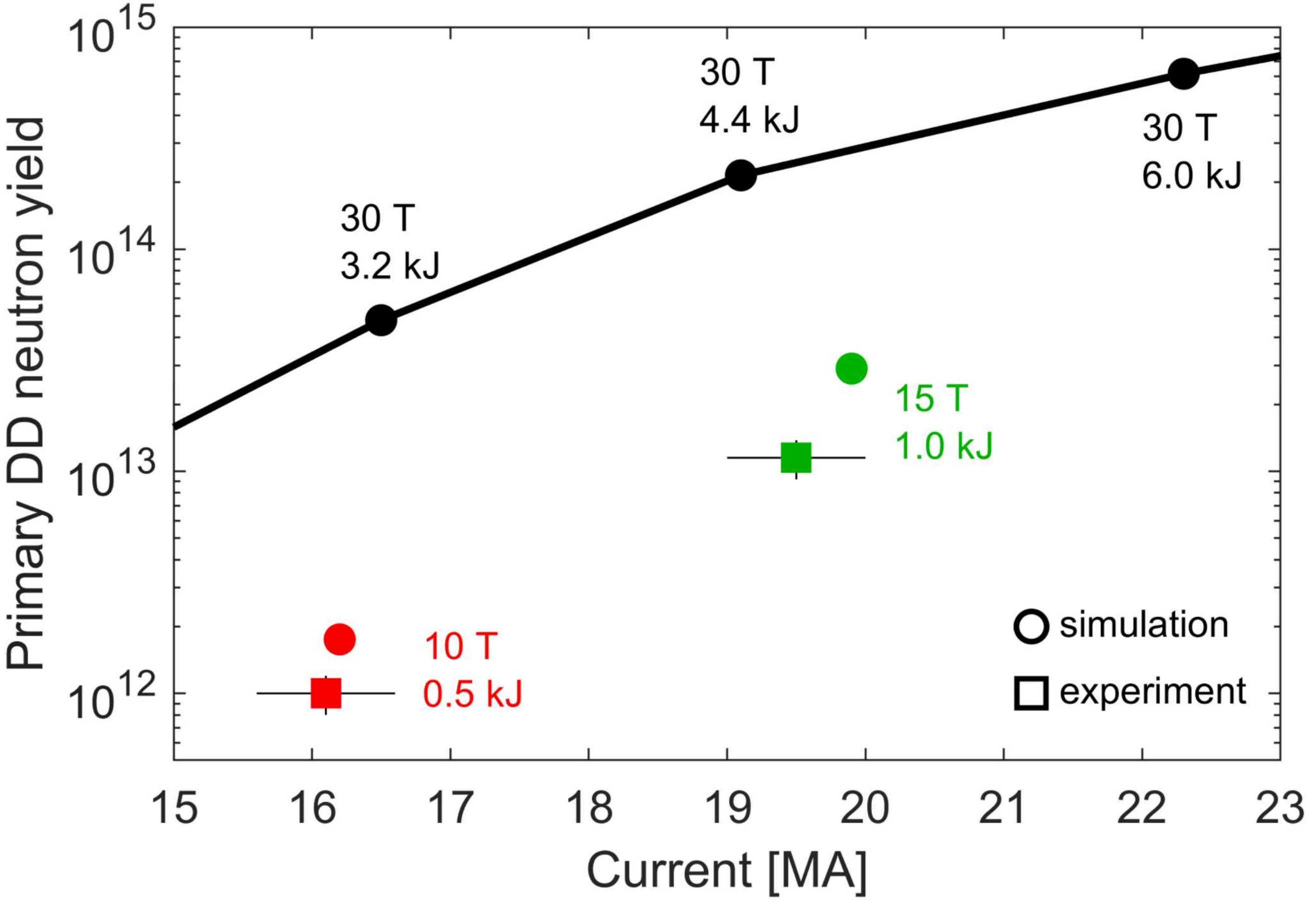
- Simulation of experiment matches to within 2x
- Simulation expected to be optimistic
  - 2D
  - No mix model

Same LASNEX model indicates significant increases fusion yields are possible on Z



- More than 10x improvement possible at fixed current with increased B-field and laser energy

Increases in applied B-field, laser preheat, and drive current increased neutron yield by >10x



- Simulation of experiment matches to within 3x
- Further improvement possible with additional increases in B-field, laser, and current

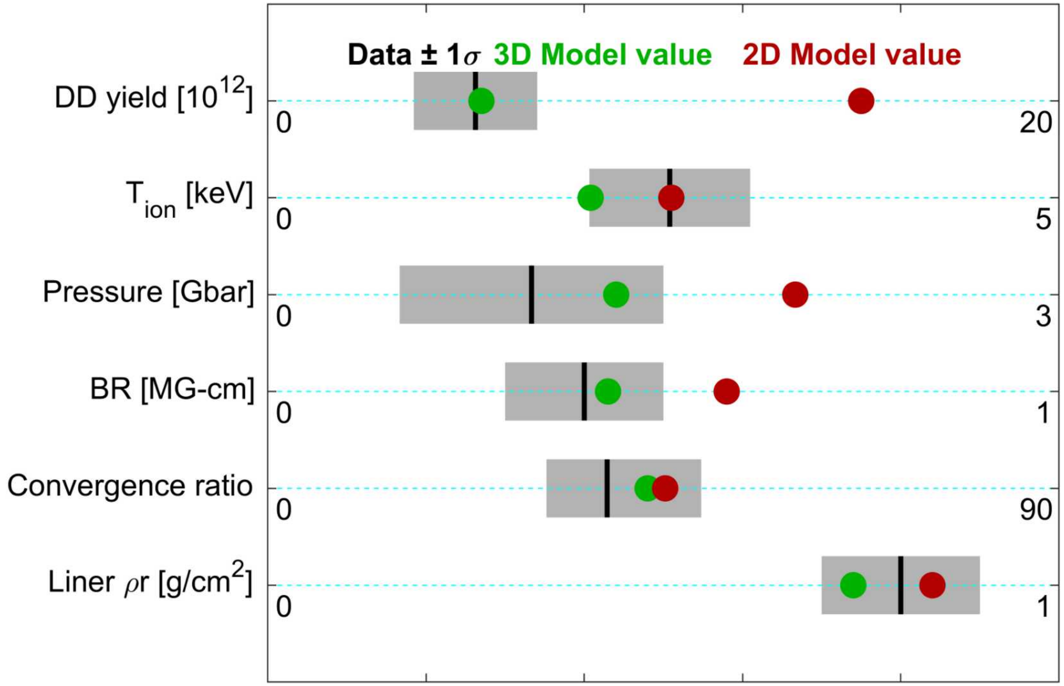
Fuel temperature and stagnation pressure also increased as expected with the improved platform

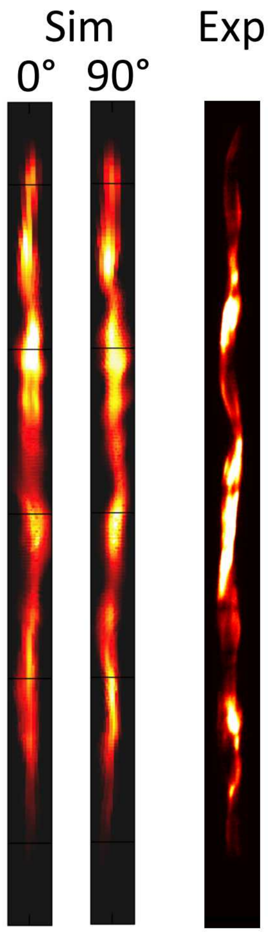
Shot	z2851	LASNEX	z3289	LASNEX
B-field [T]	10	10	15	15
Preheat energy [kJ]	0.5	0.5	1.0	1.0
Current [MA]	16.1	16.2	19.5	19.9
T_{ion} [keV]	1.8	1.6	3.1	2.6
P_{stag} [Gbar]	0.5	0.9	0.9	1.9

- 2D LASNEX calculations accurately predict the trend in ion temperature and stagnation pressure, though absolute values are off

3D effects may contribute to the discrepancy between clean 2D simulations and experiments

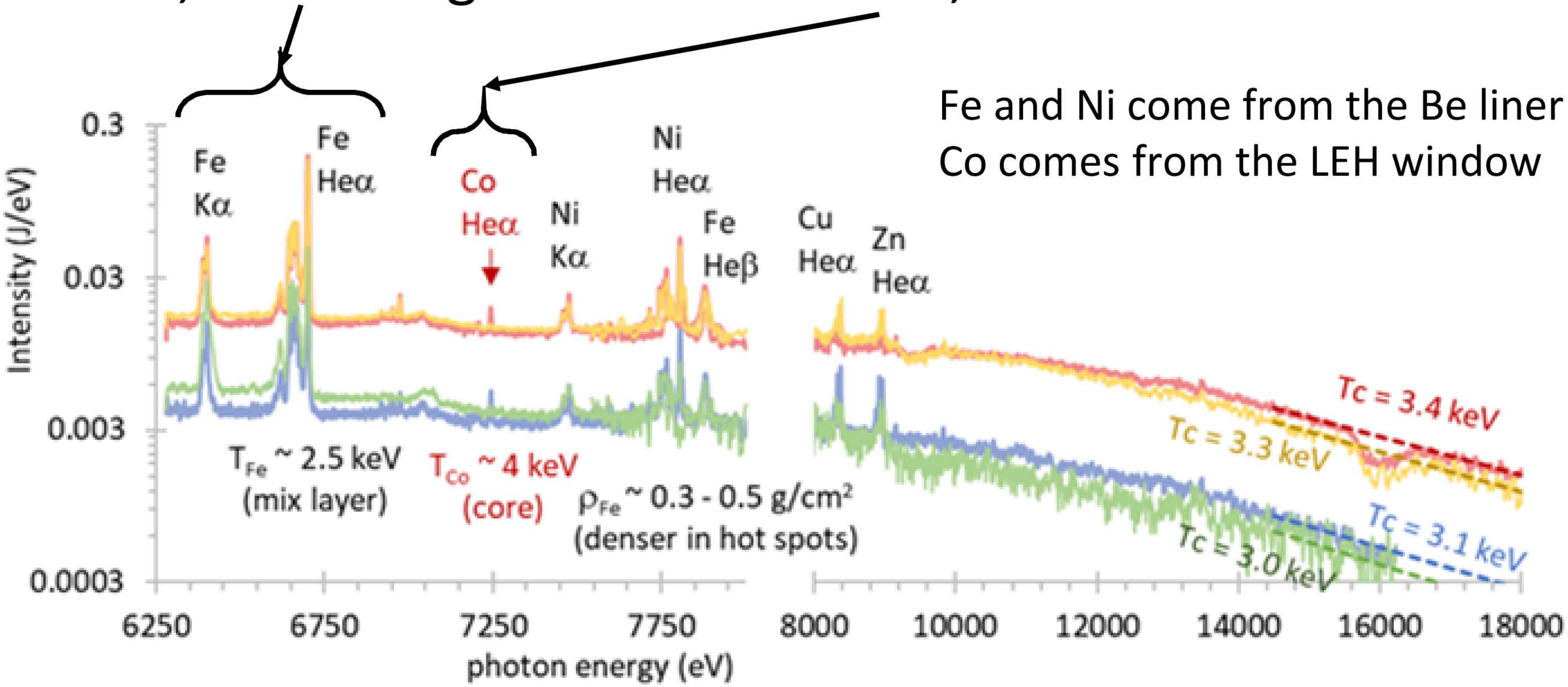
- Experimental stagnation parameters are more accurately reproduced in 3D HYDRA simulations
- 3D stagnation structures qualitatively match experiments





Mix likely also plays a role in the discrepancy between clean 2D simulations and experiments

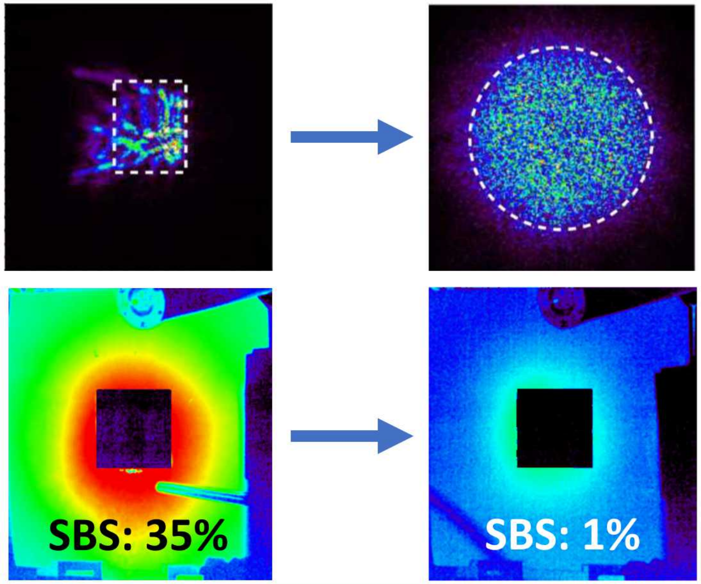
- Spectroscopic dopants are used to determine both the sources and quantities of mix
- Axially-resolved x-ray spectra indicate both a higher mix, cooler region and a low-mix, hotter core



Fe and Ni come from the Be liner
Co comes from the LEH window

Laser preheat energy coupling was increased by up to a factor of three with several key changes

- LEH window thickness was reduced from 3 µm to 1.5 µm (transmission ~30% → ~70%)
- 1.1 mm DPP was introduced to smooth the beam
  (SBS backscatter >30 % → ~1%)



M. Geissel, et al., Phys. Plasmas (2018).

See Adam Harvey-Thompson's presentation 6A06 Friday at 11:20

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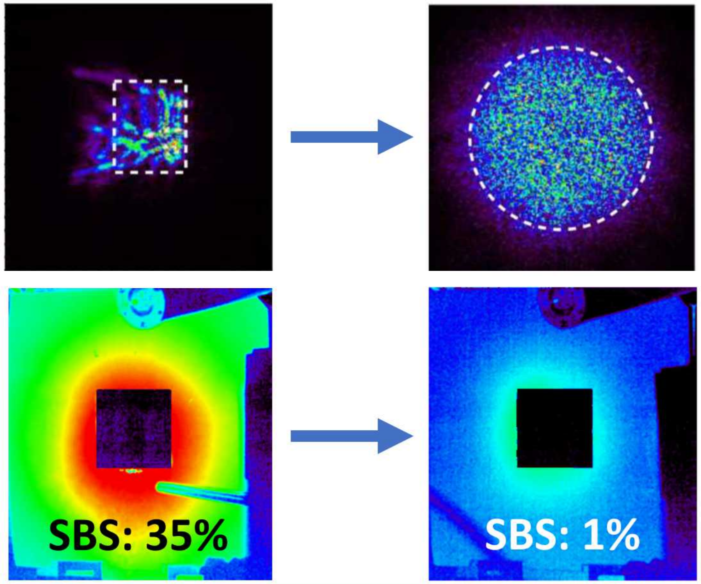
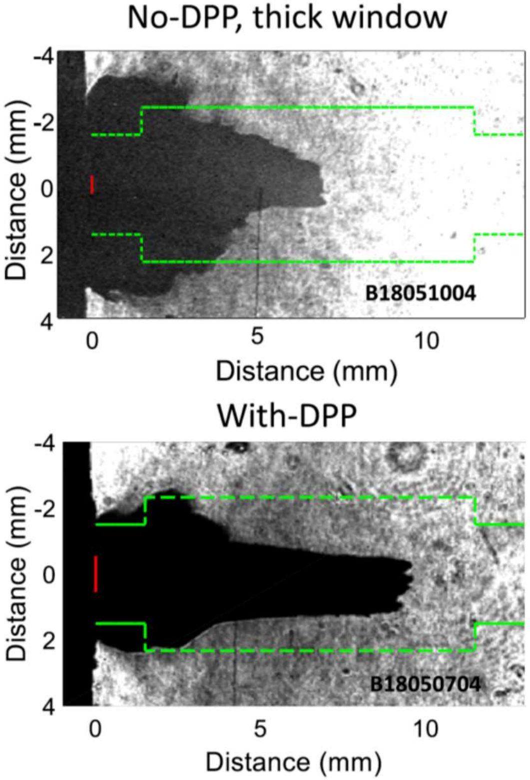


M. Geissel, et al., Phys. Plasmas (2018).

A.J. Harvey-Thompson, et al., Phys. Plasmas (2018).

Unable to accurately simulate due to substantial LPI

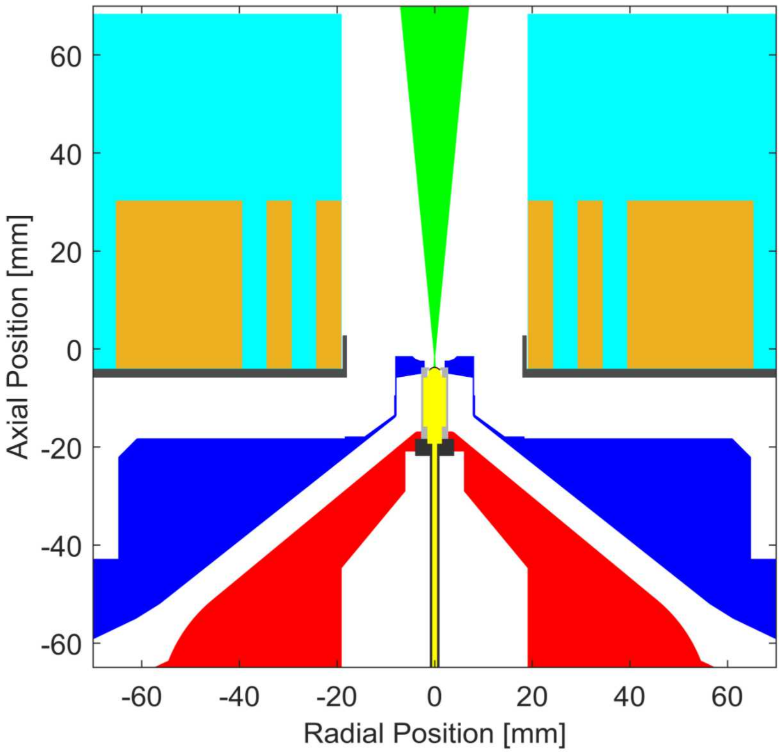


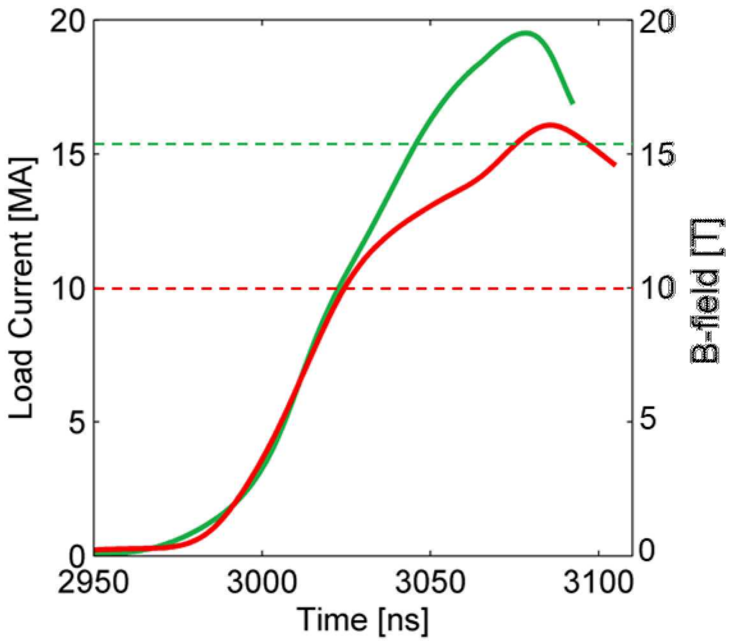
Simulations match this configuration

See Adam Harvey-Thompson's presentation 6A06 Friday at 11:20

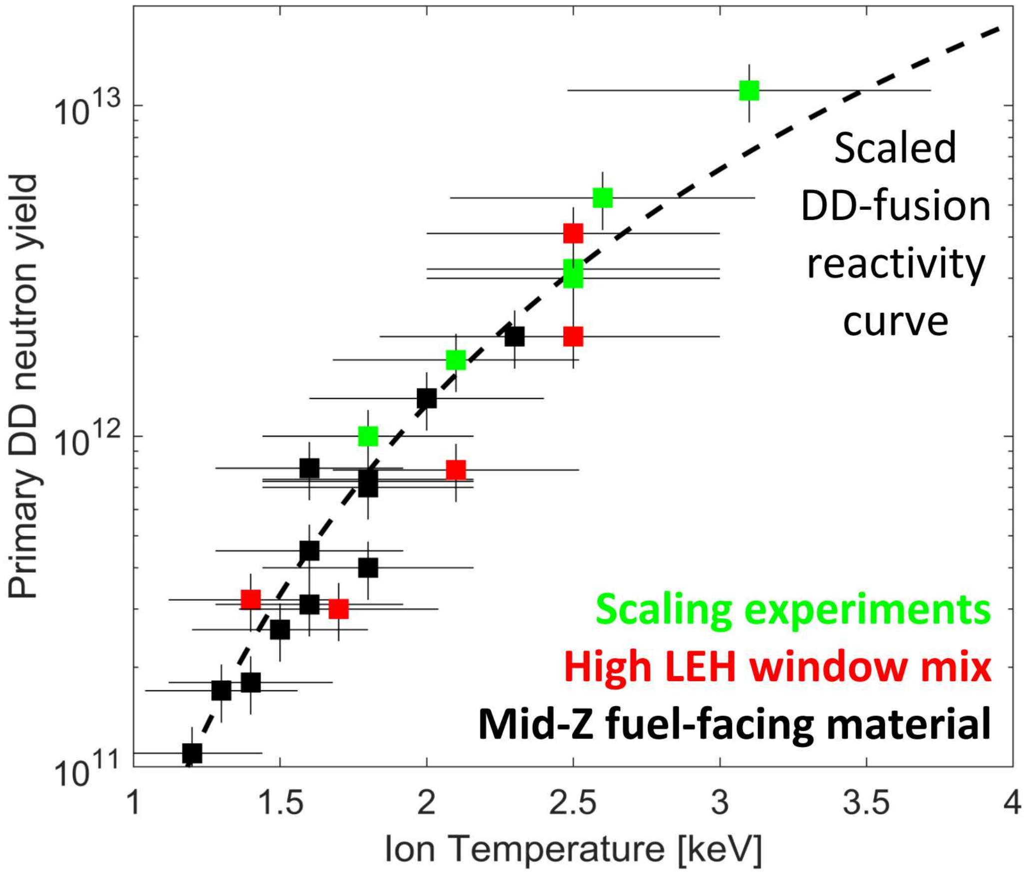
Magnetization and current coupling designs are linked so they were optimized simultaneously

- Conical transmission line with lower inductance and larger anode-cathode gaps reduced current losses allowing 19.5 MA to be delivered to the target
- Single, high performance coil delivered 15 T average field to the target while maintaining radial diagnostic access





Larger effort to understand MagLIF through focused physics studies aids our scaling work



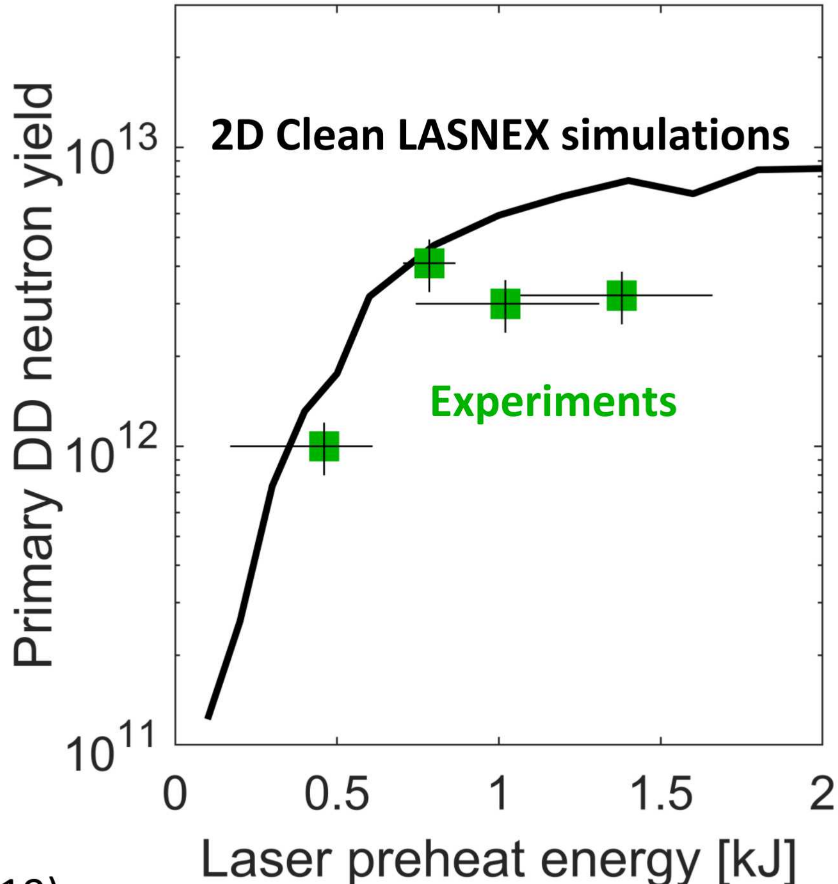
A.J. Harvey-Thompson, et al., Phys. Plasmas (2018).
S. A. Slutz, et al., Phys. Plasmas (2018).
P. F. Knapp, et al., Phys. Plasmas (2019).
M. R. Gomez, et al., IEEE TPS (2019).

- Significant effort to understand the source and quantity of mix during preheat and deceleration stages
- Modification of laser configuration and removal of mid-Z fuel-facing components enabled significant increases in ion temperature and neutron yield
- Parametric scans help identify key gradients in performance

Neutron yield rapidly increases with laser preheat energy and then plateaus as predicted

- Target performance is sensitive to preheat energy in low energy limit
- Plateau observed in experiments was predicted in simulations with Nernst term included

Target configuration, B-field (10 T), and load current (16 MA) held constant across experiments



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M. R. Gomez, et al., IEEE TPS (2019).
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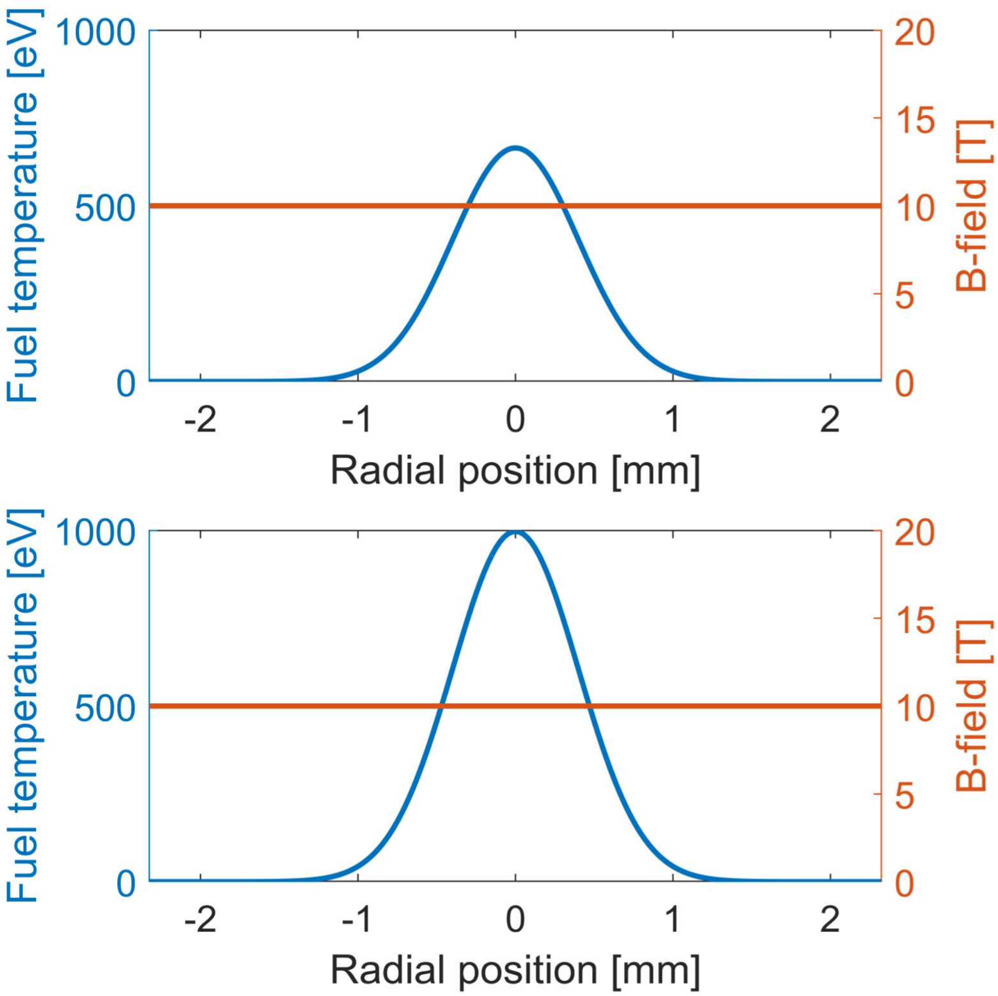
  - Increased preheat creates higher initial temperatures



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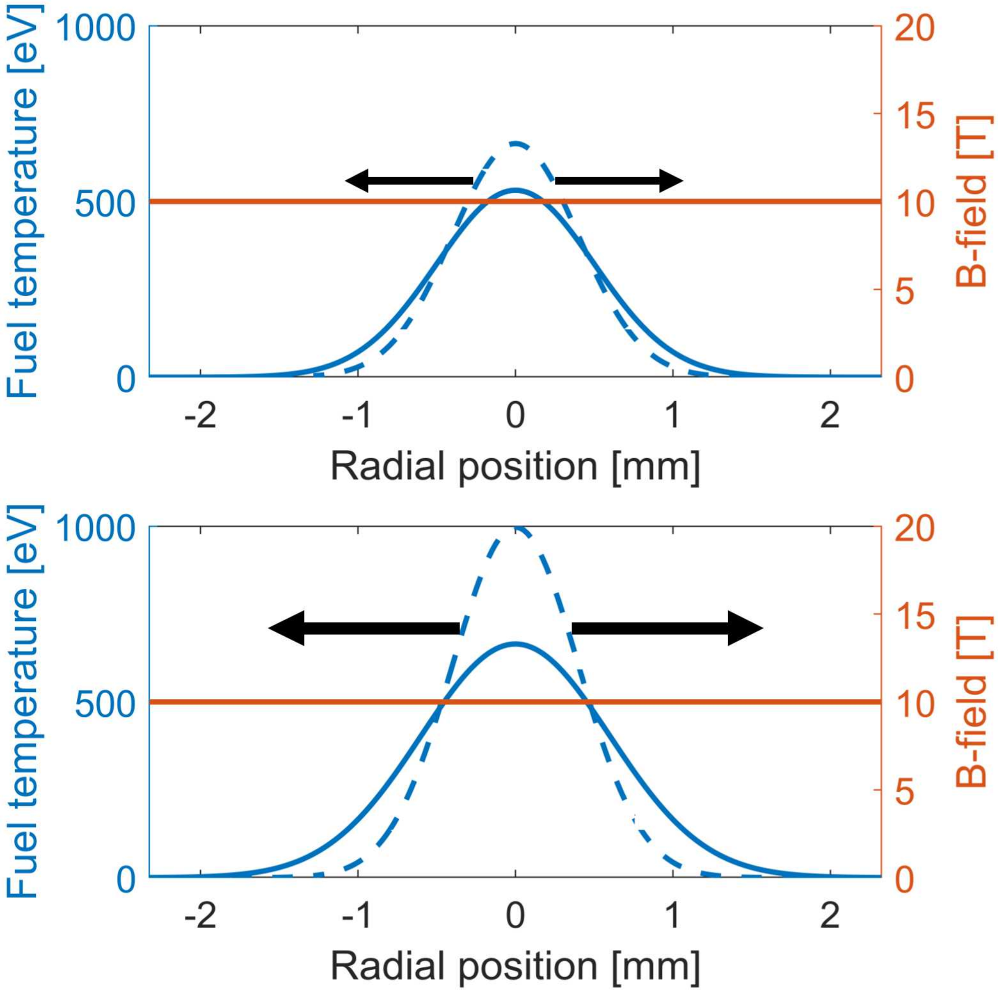
- Target performance is sensitive to preheat energy in low energy limit
- Plateau observed in experiments was predicted in simulations with Nernst term included
    - Increased preheat creates higher initial temperatures
    - The increased temperature gradient increases heat flux

$$\boldsymbol{Heat\ flux = -\kappa \frac{dT_e}{dr}}$$



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- Target performance is sensitive to preheat energy in low energy limit
- Plateau observed in experiments was predicted in simulations with Nernst term included
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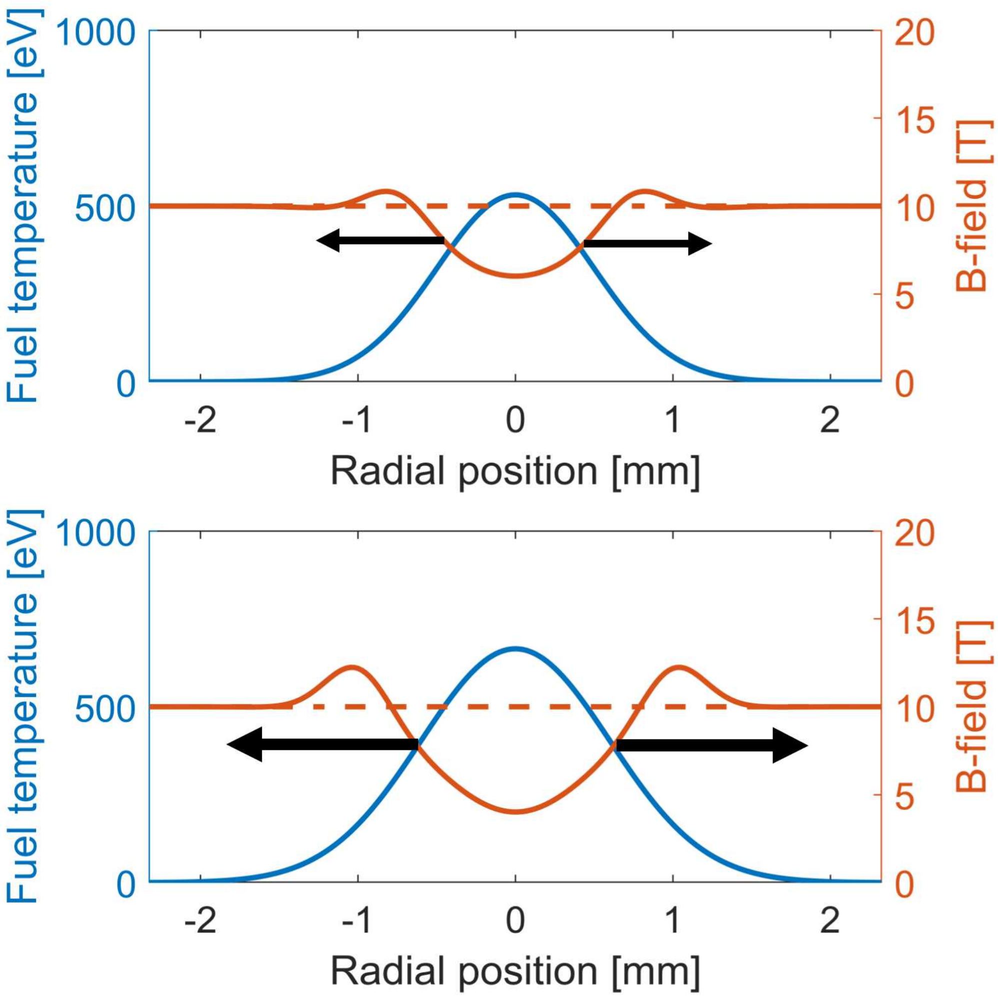
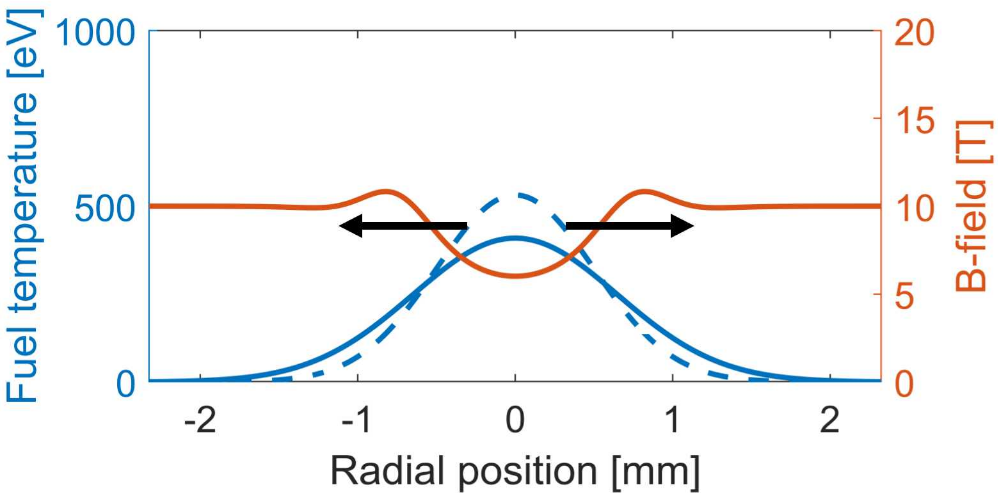
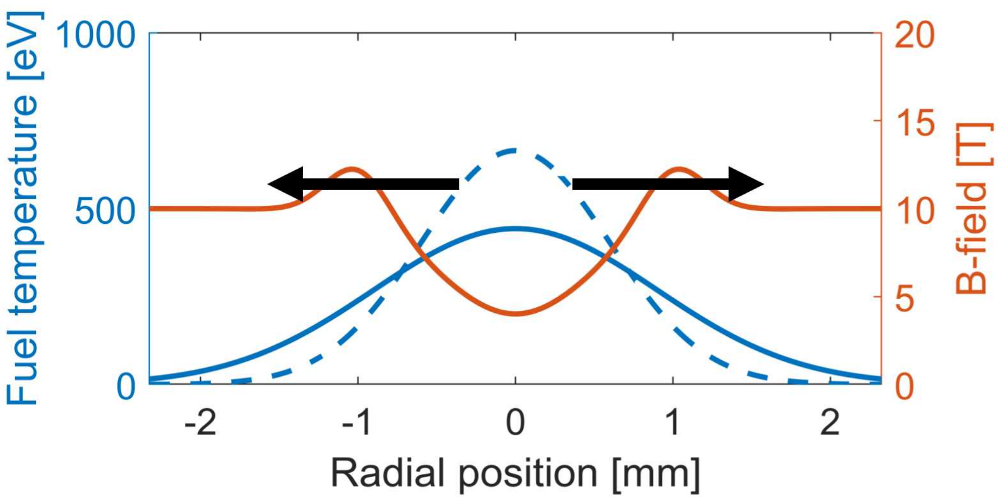
  - Magnetic field is advected with the heat flow – higher preheat loses more magnetic field



Neutron yield rapidly increases with laser preheat energy and then plateaus as predicted

- Target performance is sensitive to preheat energy in low energy limit
- Plateau observed in experiments was predicted in simulations with Nernst term included
  - Increased preheat creates higher initial temperatures
  - The increased temperature gradient increases heat flux
  - Magnetic field is advected with the heat flow – higher preheat loses more magnetic field
  - Reduced magnetic field increases heat flux



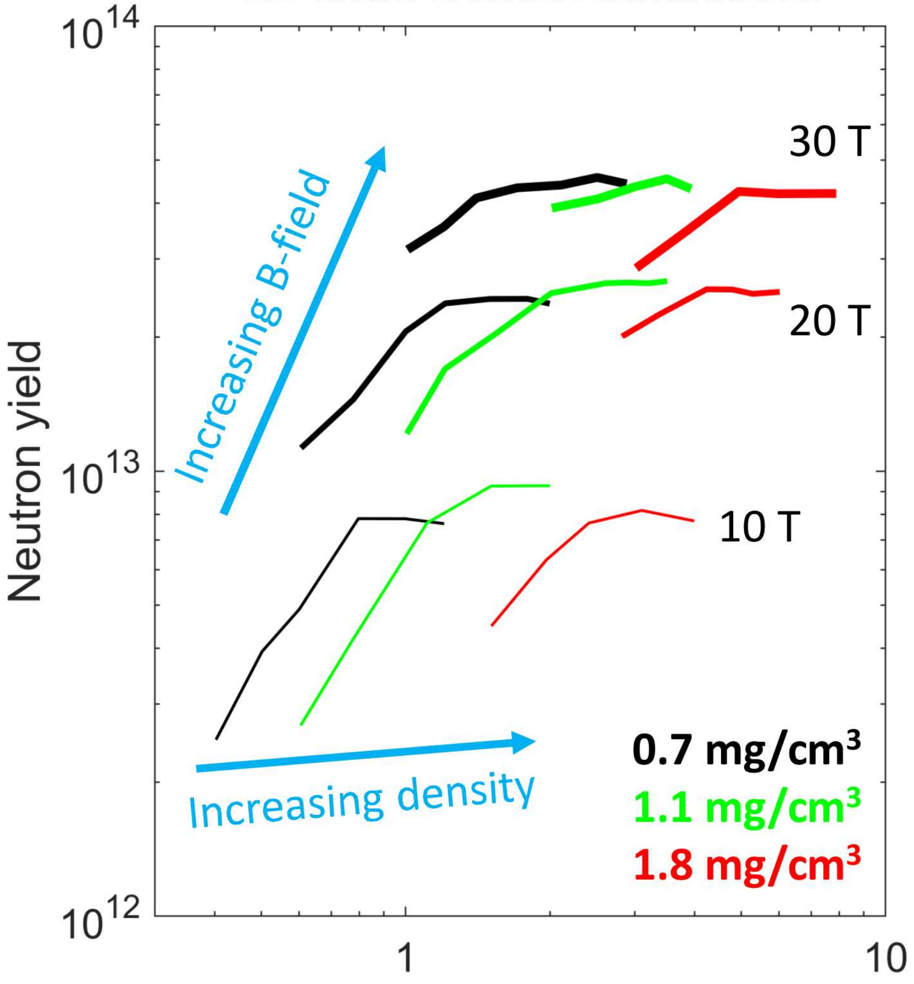


$$\boldsymbol{Heat\ flux = -\kappa \frac{dT_e}{dr}}$$

Neutron yield rapidly increases with laser preheat energy and then plateaus as predicted

- Target performance is sensitive to preheat energy in low energy limit
- Plateau observed in experiments was predicted in simulations with Nernst term included
- We observe similar stagnation temperatures in the high preheat limit, as expected
- Higher initial fuel density and/or higher magnetization are necessary to take advantage of further increases in preheat

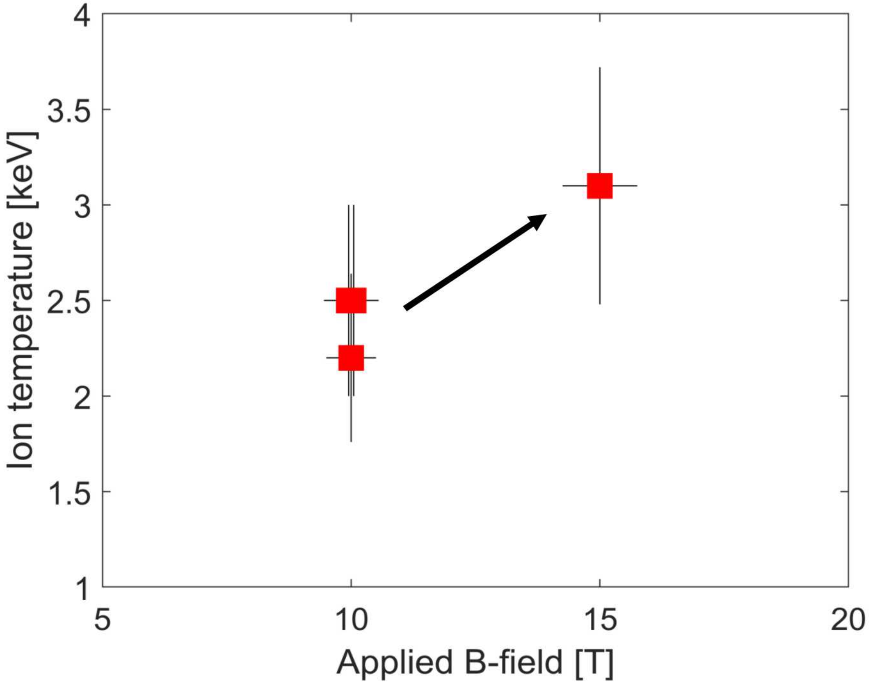
2D Clean LASNEX simulations

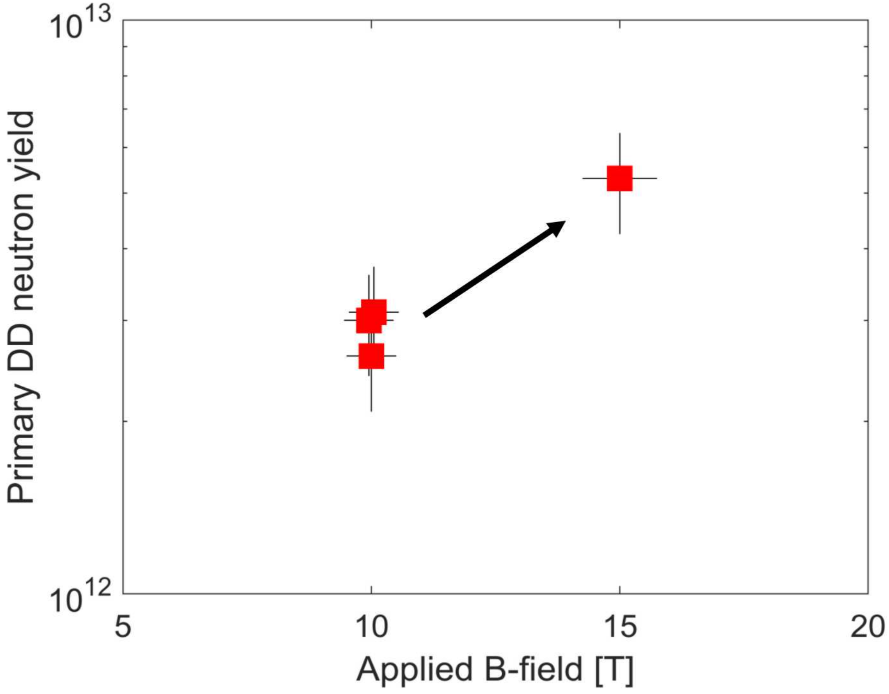


S. A. Slutz, et al., Phys. Plasmas (2018).

Ion temperature and neutron yield scale as expected with increased B-field

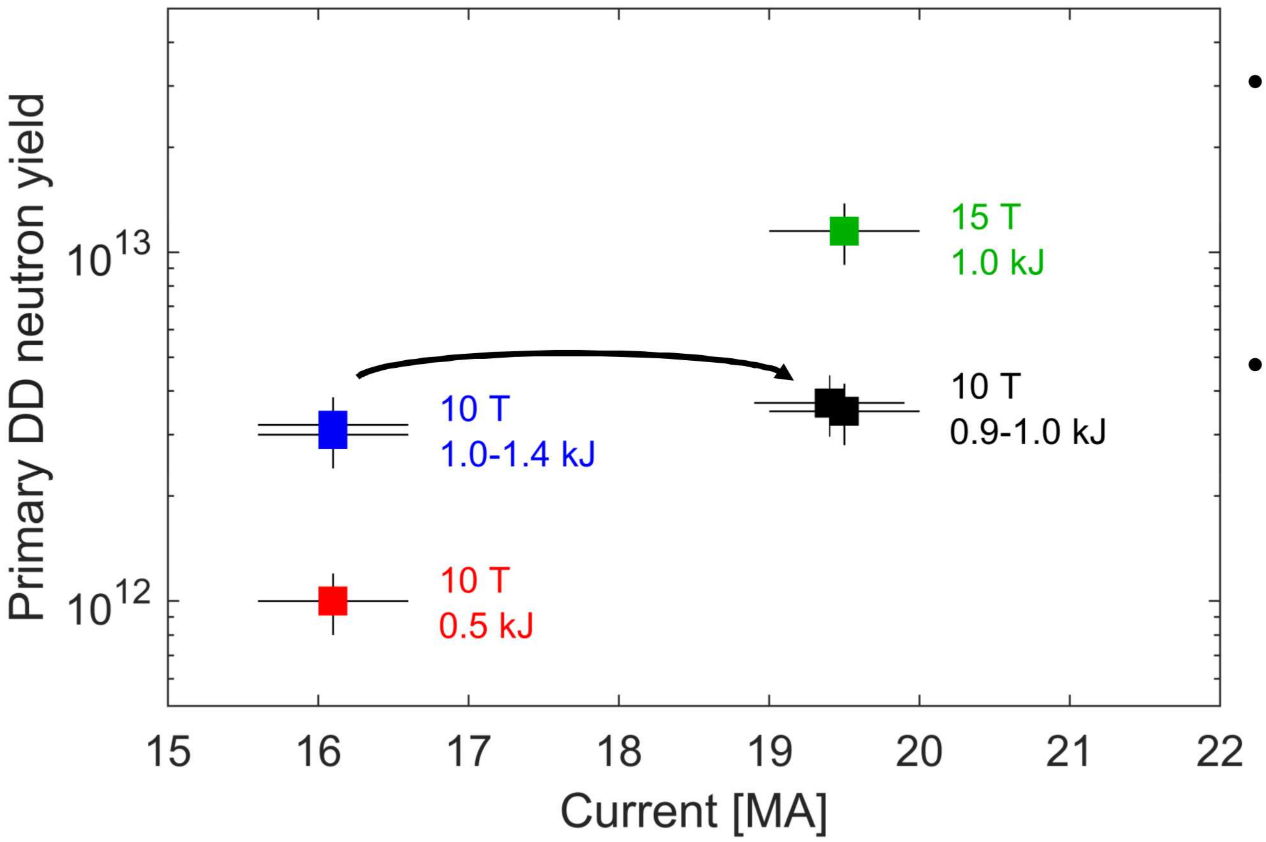
Target configuration, preheat energy (1 kJ), and load current (15.5 MA) held constant across experiments





- Increased magnetization reduces thermal conduction losses and decreases the impact of the Nernst effect
- We expect increasing in ion temperature with initial B-field, as observed
- With higher ion temperatures, the fusion reaction rate increases, so we also expected the higher neutron yields

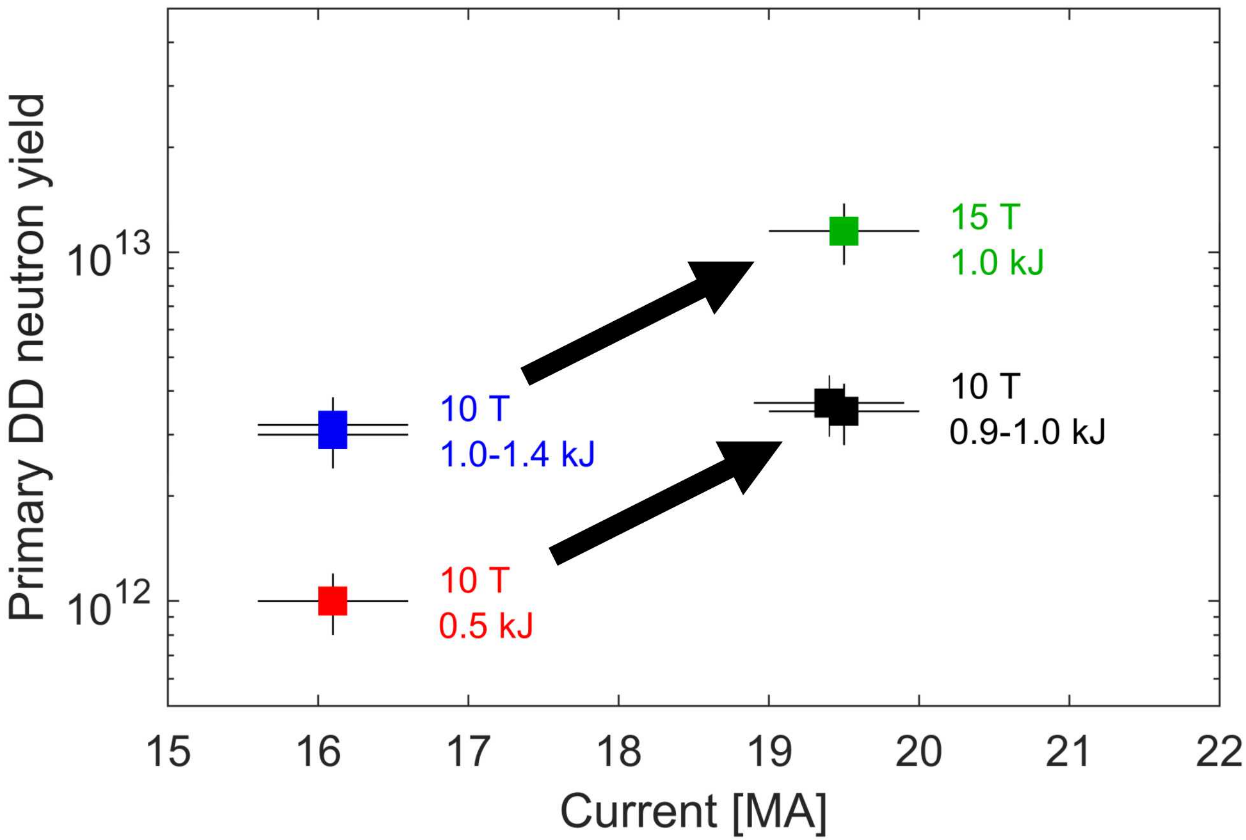
Target performance remained flat with increasing current unless B-field and preheat were also increased



- Simulations predict increased yield but also increased CR with fixed preheat and B-field and increasing current
- Experimental CR ≈ 40 and we do not observe a significant increase in CR with current

See Dave Ampleford's presentation 6A07 Friday at 11:40

Target performance remained flat with increasing current unless B-field and preheat were also increased

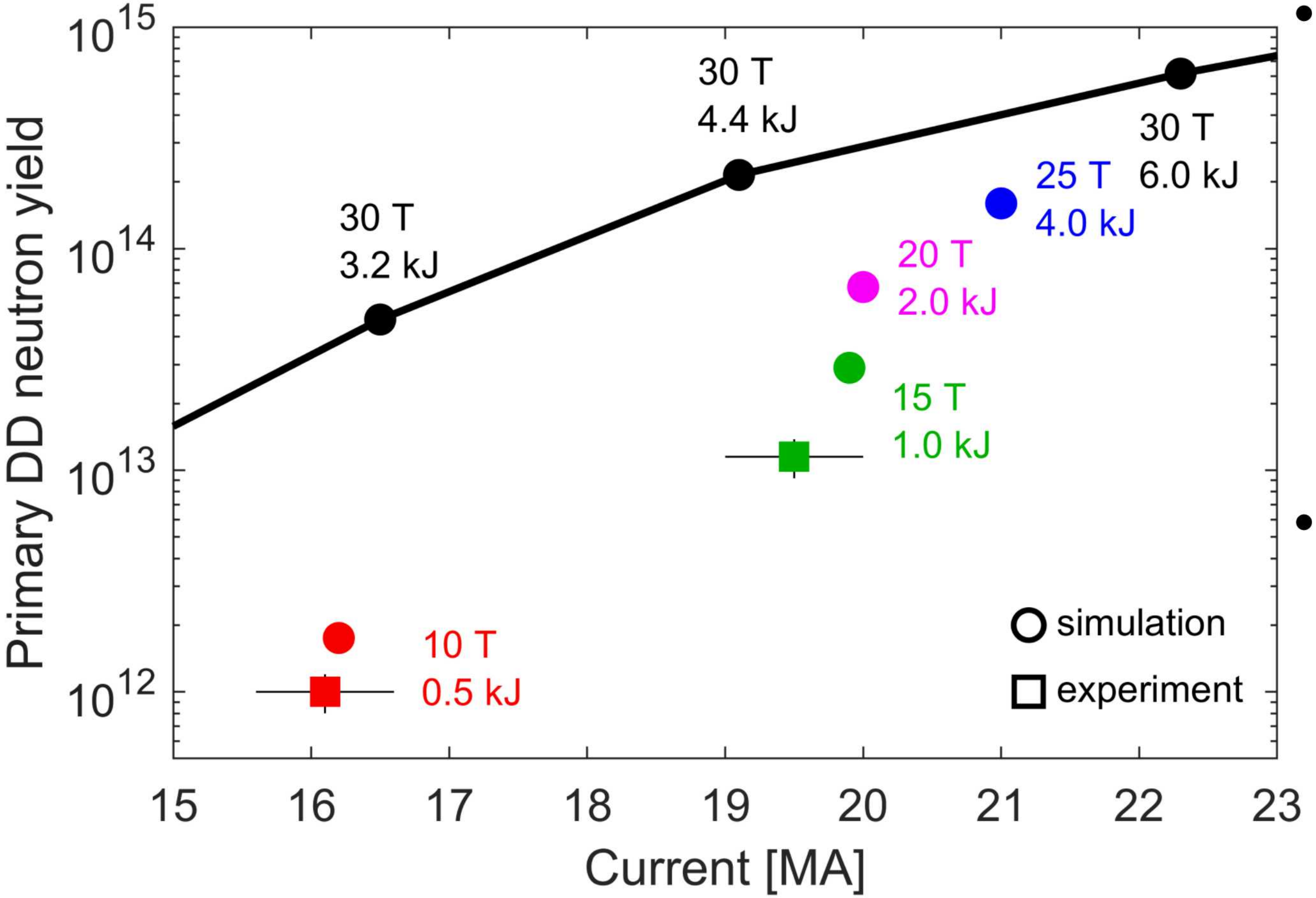


Simulations predict decreased convergence (≤30) in the limit of high preheat and magnetization

- Simulations predict increased yield but also increased CR with fixed preheat and B-field and increasing current
- Experimental CR ≈ 40 and we do not observe a significant increase in CR with current
- When B-field, preheat, and current are increased simultaneously, we observe significantly higher neutron yield, as expected

See Dave Ampleford's presentation 6A07 Friday at 11:40

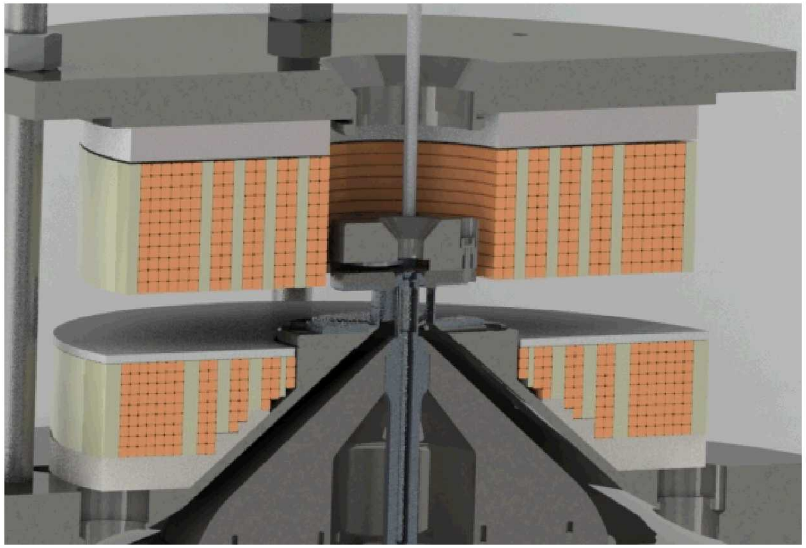
We will continue to test MagLIF scaling through further increases in magnetization, preheat, and drive current



- Our goal is to understand how target dynamics change with magnetization, preheat, and current drive
- With increased capabilities we can test scaling over a wider range, providing a more complete understanding

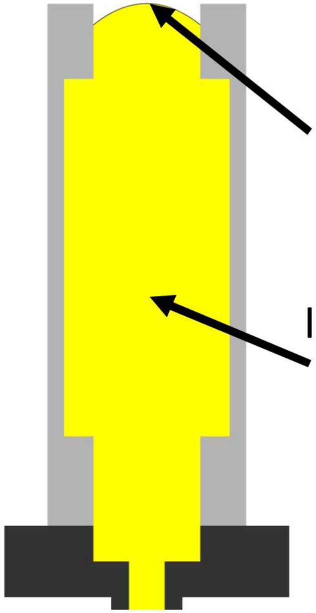
Developing 20-25 T, 2-4 kJ, 20-21 MA in the next 2 years

We are developing new coils and preheat protocols, which will be tested on Z in 2020



- New laser pulse shape recently tested on Z coupled 1.7 of 2.5 kJ on target
  - >2 kJ possible with present laser capability
- Cryogenic cooling to reduce window thickness will allow greater fraction of energy deposition in the fuel
  - Enables use of new phase plate (1.5 mm) with minimal energy loss to window

- New orbital winding capability allows improved internal reinforcement and complex coil cross sections
- Targets magnetized to 20-30 T
- Maintains radial diagnostic access



T. J. Awe, et al., Rev. Sci. Instrum. (2017).

MagLIF has demonstrated the exciting potential of magneto-inertial fusion

- MagLIF produces fusion-relevant temperatures, significant neutron yields, and magnetic trapping of charged fusion products
- Improvements to the platform have enabled an order of magnitude increase in neutron yield, consistent with simulation predictions
- Parametric scans in laser energy and initial magnetization show the expected trends in target performance
- Additional improvements to the platform are underway, which are expected to increase neutron production by another order of magnitude