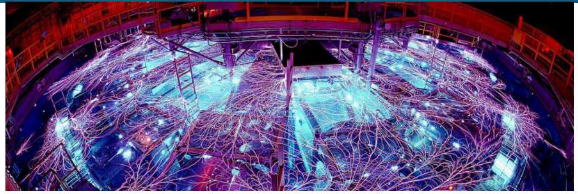
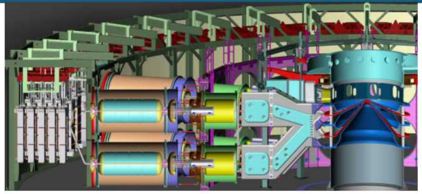
SAND2019-12867C

Performance scaling with drive parameters in Magnetized Liner Inertial Fusion experiments





PRESENTED BY

Matthew R. Gomez

For the MagLIF team

At the 61st Annual Meeting of the American Physical Society – Division of Plasma Physics

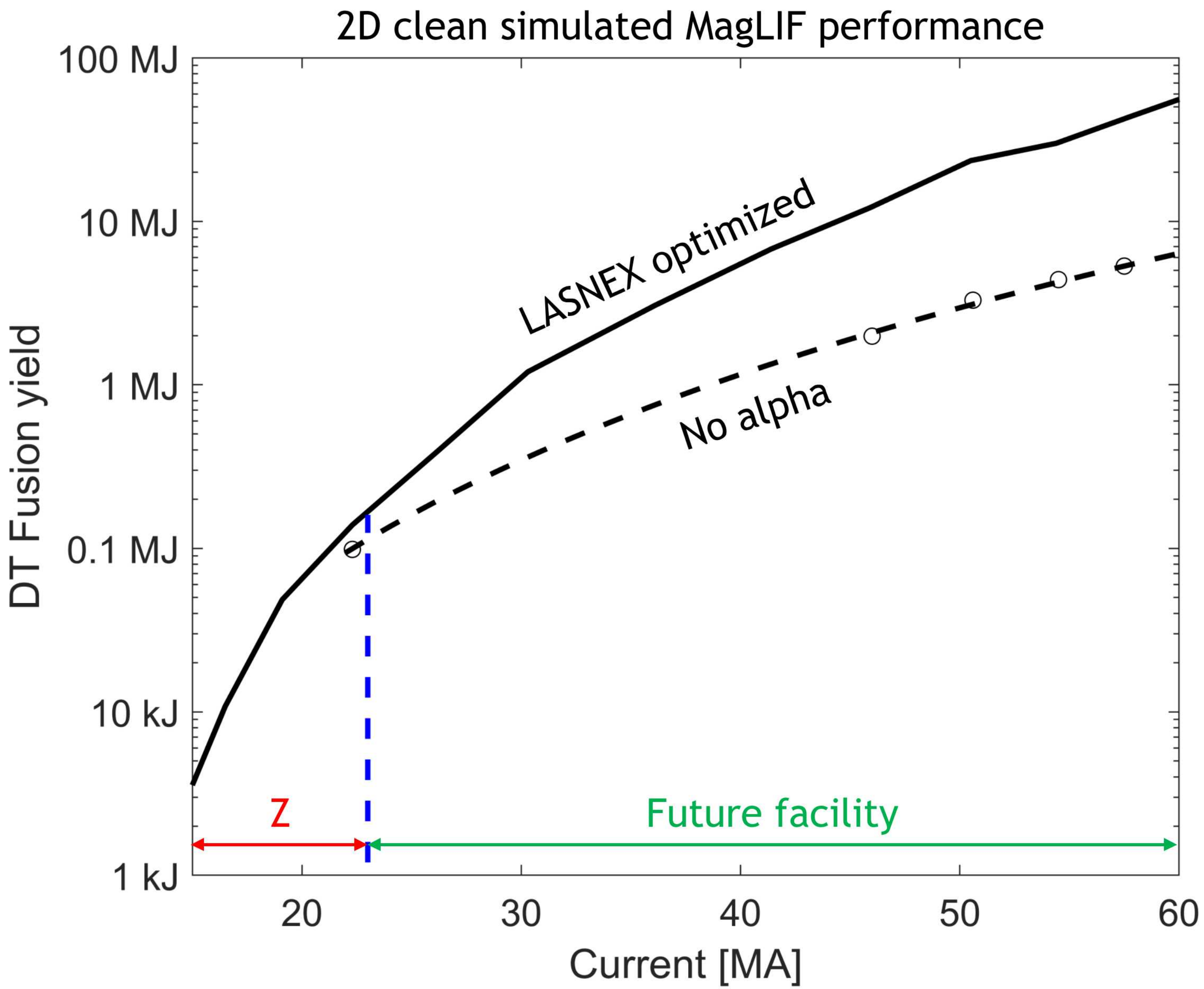
10/22/2019

Sandia National Laboratories is a multimission laboratory managed and operated by National Technology & Engineering Solutions of Sandia, LLC, a wholly owned subsidiary of Honeywell International Inc., for the U.S. Department of Energy's National Nuclear Security Administration under contract DE-NA0003525.

Thanks to my collaborators

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

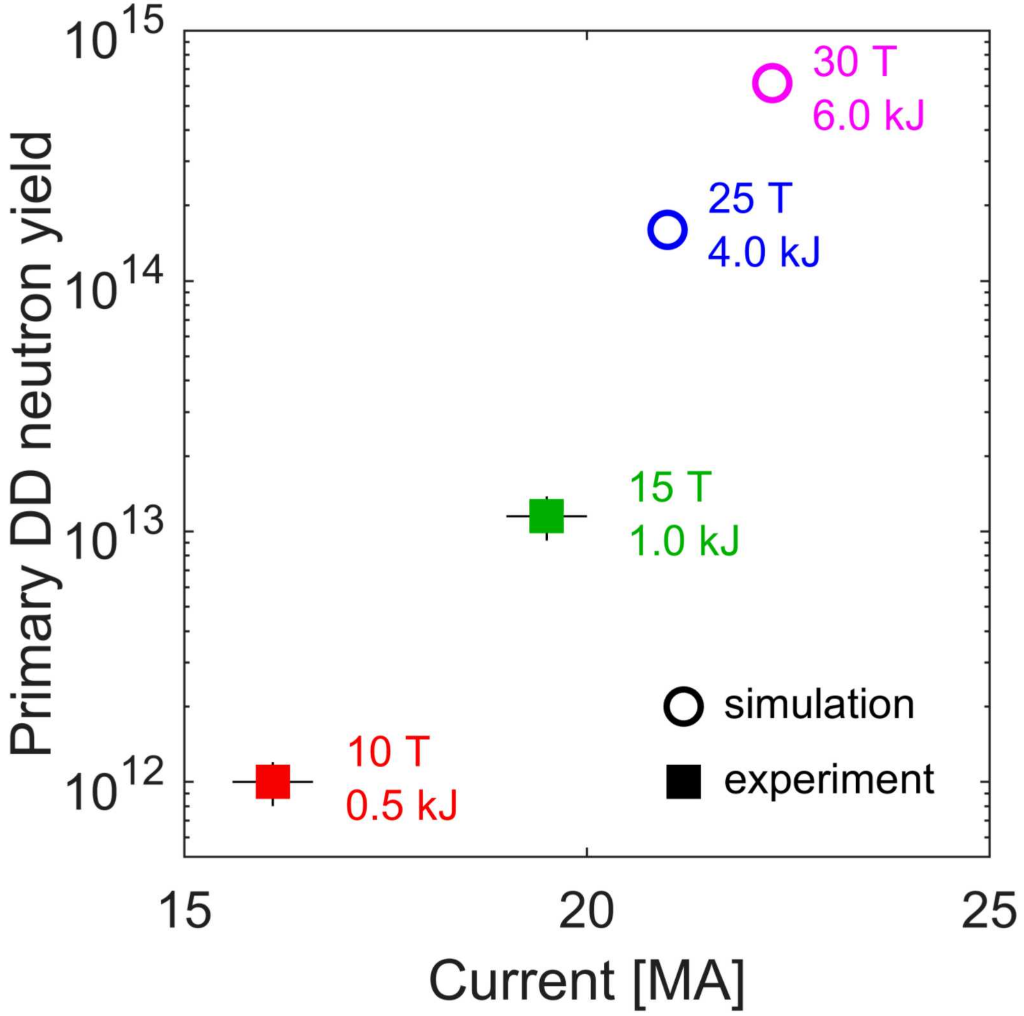
The US national ICF program is identifying credible paths to multi-MJ fusion yield



- MagLIF can access multi-MJ yields through volume ignition 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 on the Z machine

- 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



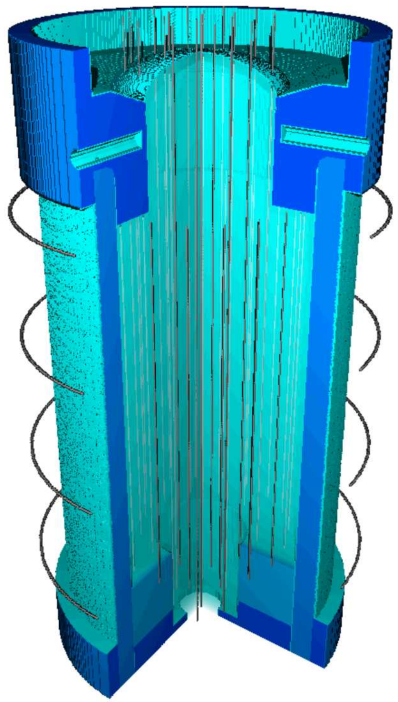
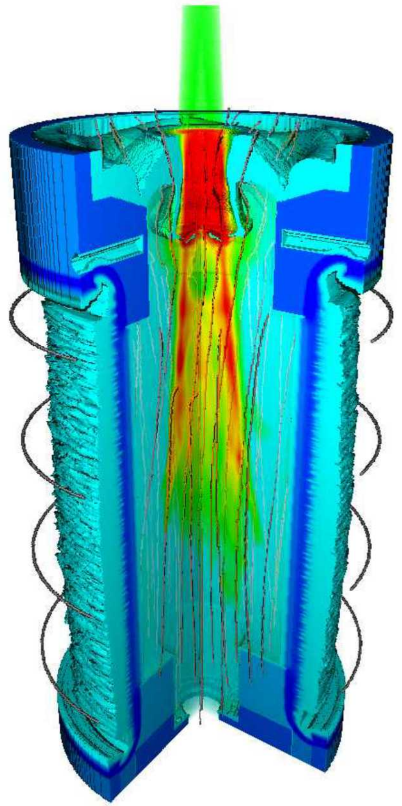
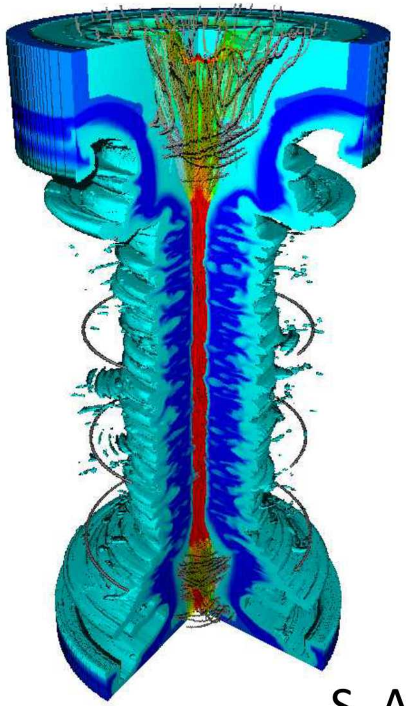
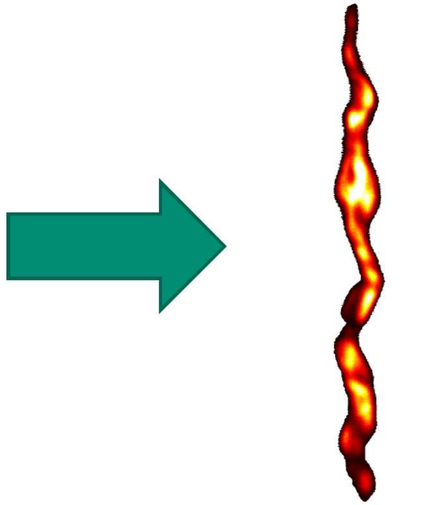
MagLIF is a magneto-inertial fusion concept that relies on three components to produce fusion conditions at stagnation

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

Preheat
- Increase fuel adiabat to limit required convergence

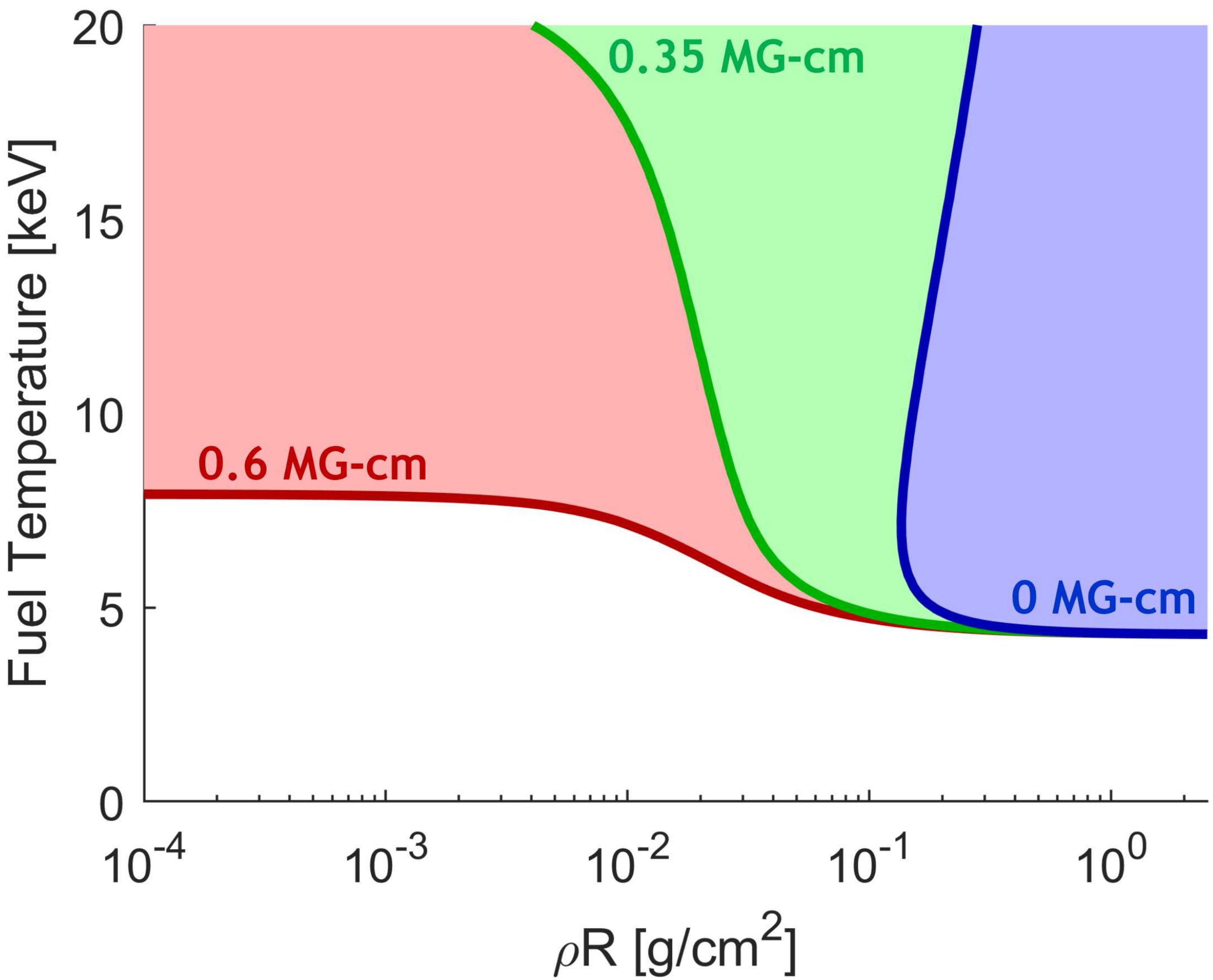
Implosion
- PdV work to heat fuel
- Amplify B-field through flux compression

Stagnation
- Several keV temperature
- Several kT B-field to trap charged fusion products

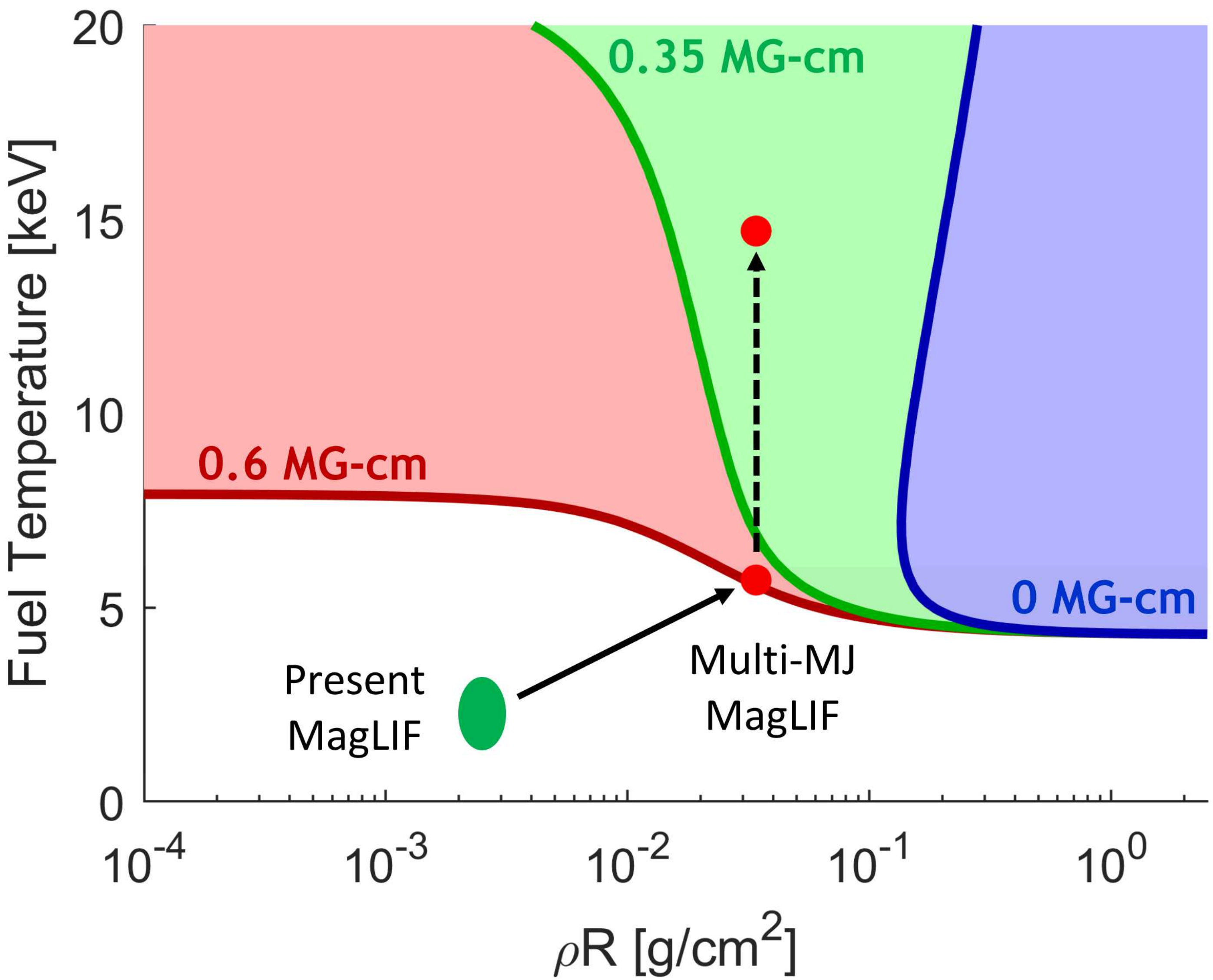
S. A. Slutz, et al., Phys. Plasmas (2010).

Magneto-inertial fusion requires large magnetic field 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 ~ $1/R^2$
- Large magnetic fields trap charged fusion products opening up a larger ignition space

Magneto-inertial fusion requires large magnetic field to trap charged fusion products



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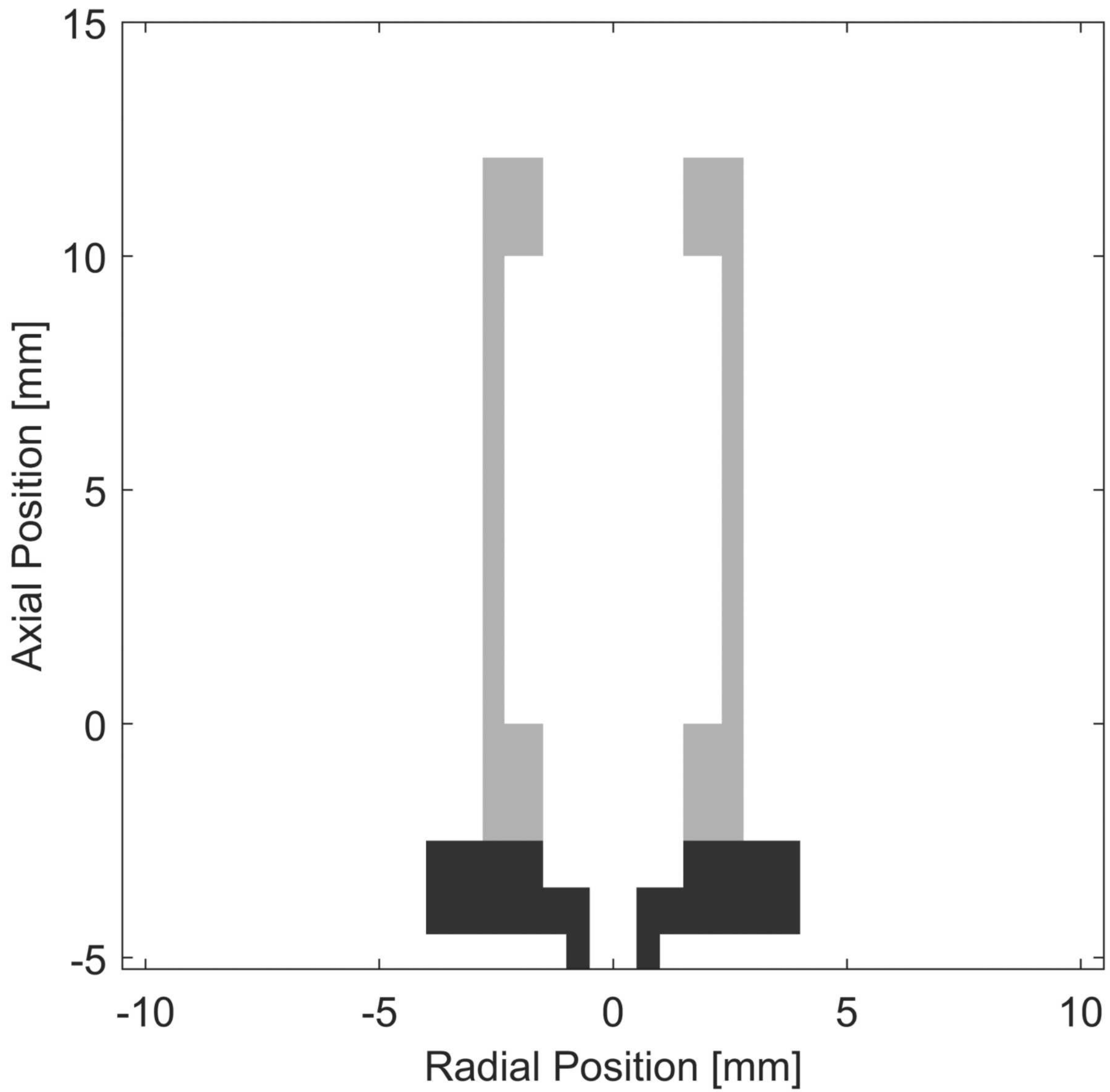
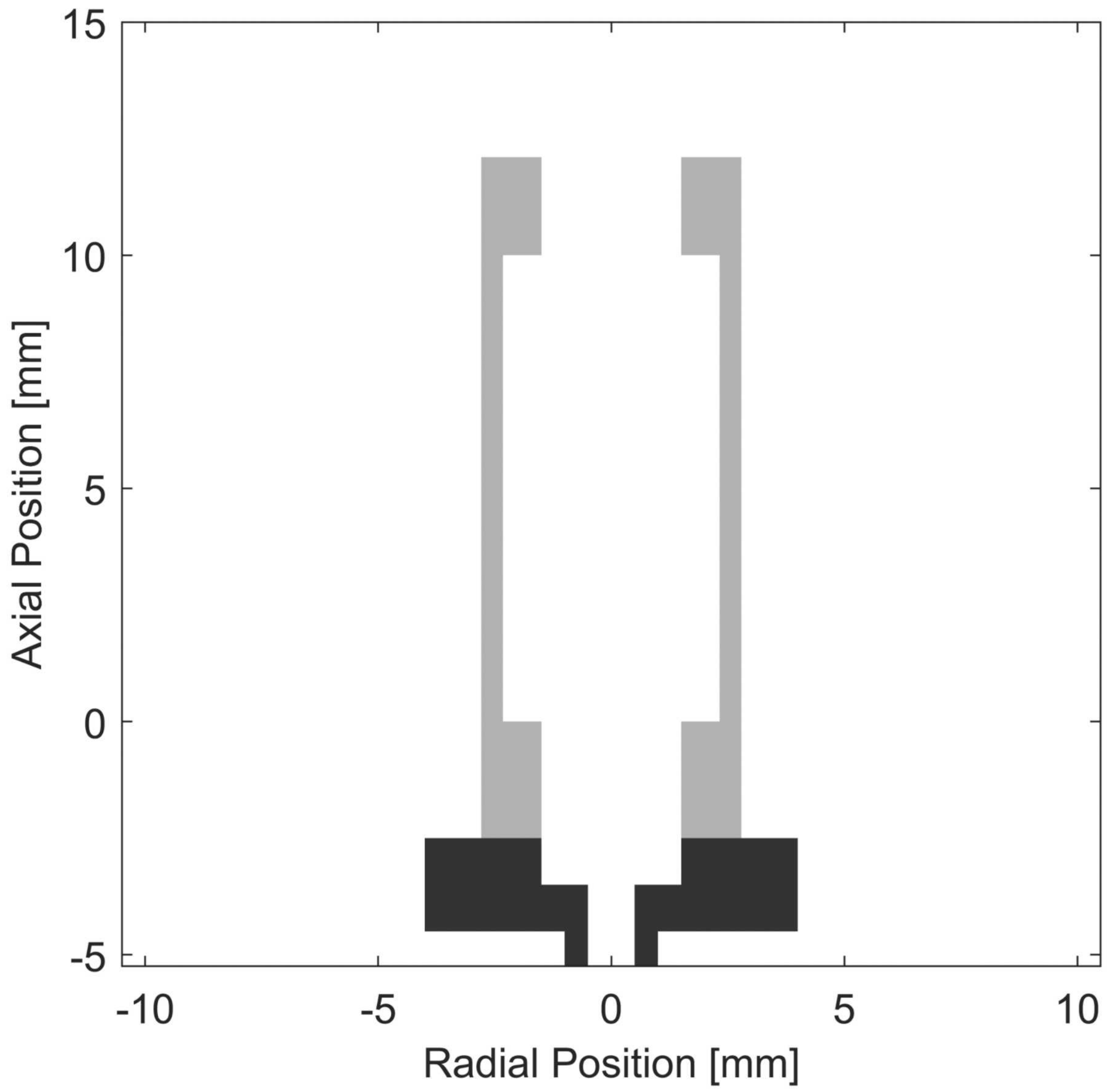
A quick review of the MagLIF experimental geometry



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

A quick review of the MagLIF experimental geometry



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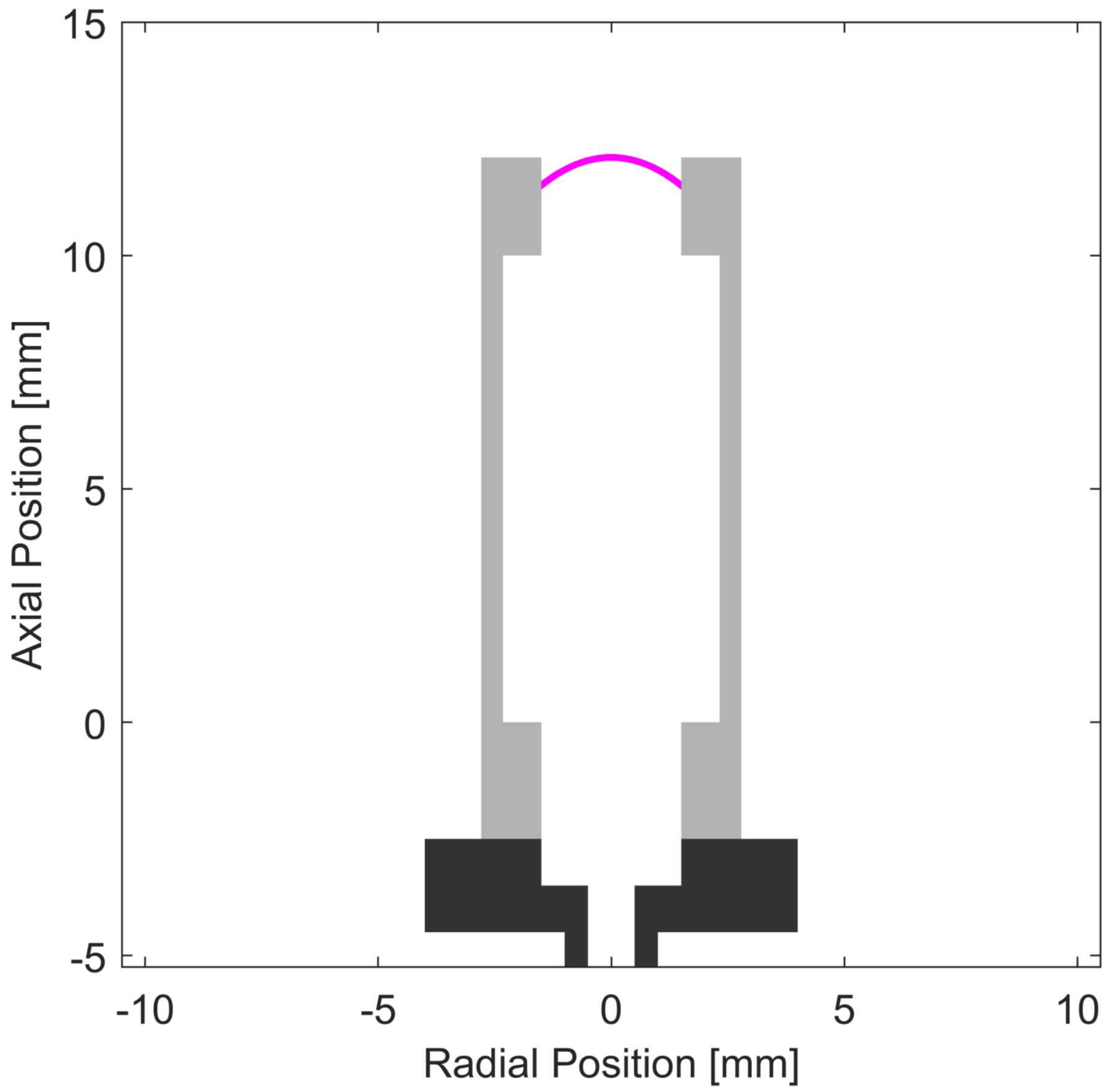
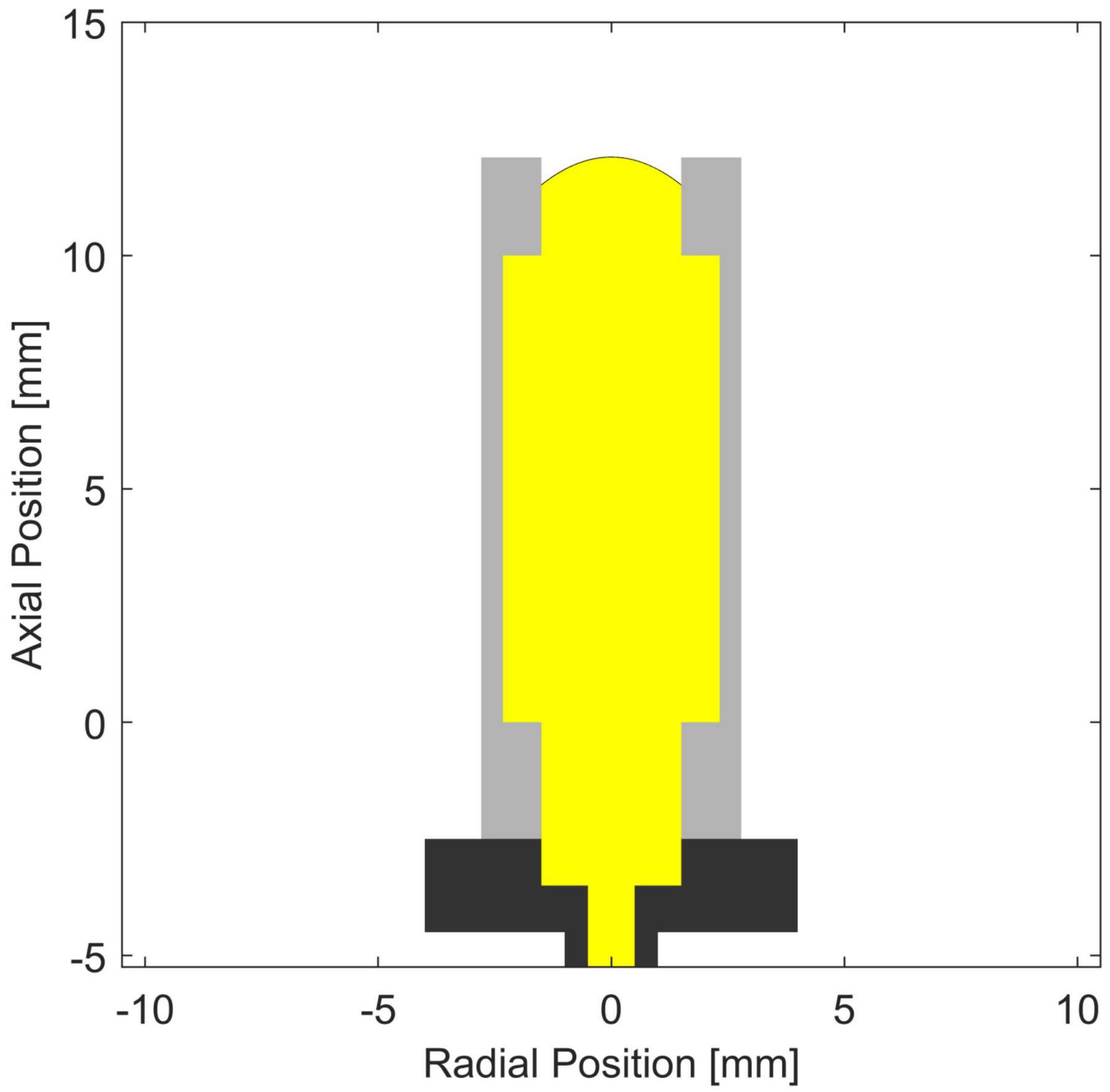


- Laser entrance window is polyimide
- 1-3 µm thick
- 2-3 mm diameter opening

A quick review of the MagLIF experimental geometry



- Fuel is deuterium gas
  - D + D → ^{3}He + n (2.45 MeV)
  - D + D → P + T (1.01 MeV)
  - Secondary neutrons (12-17 MeV) from trapped fusion tritons
- Densities between 0.7 mg/cm^3 and 1.4 mg/cm^3

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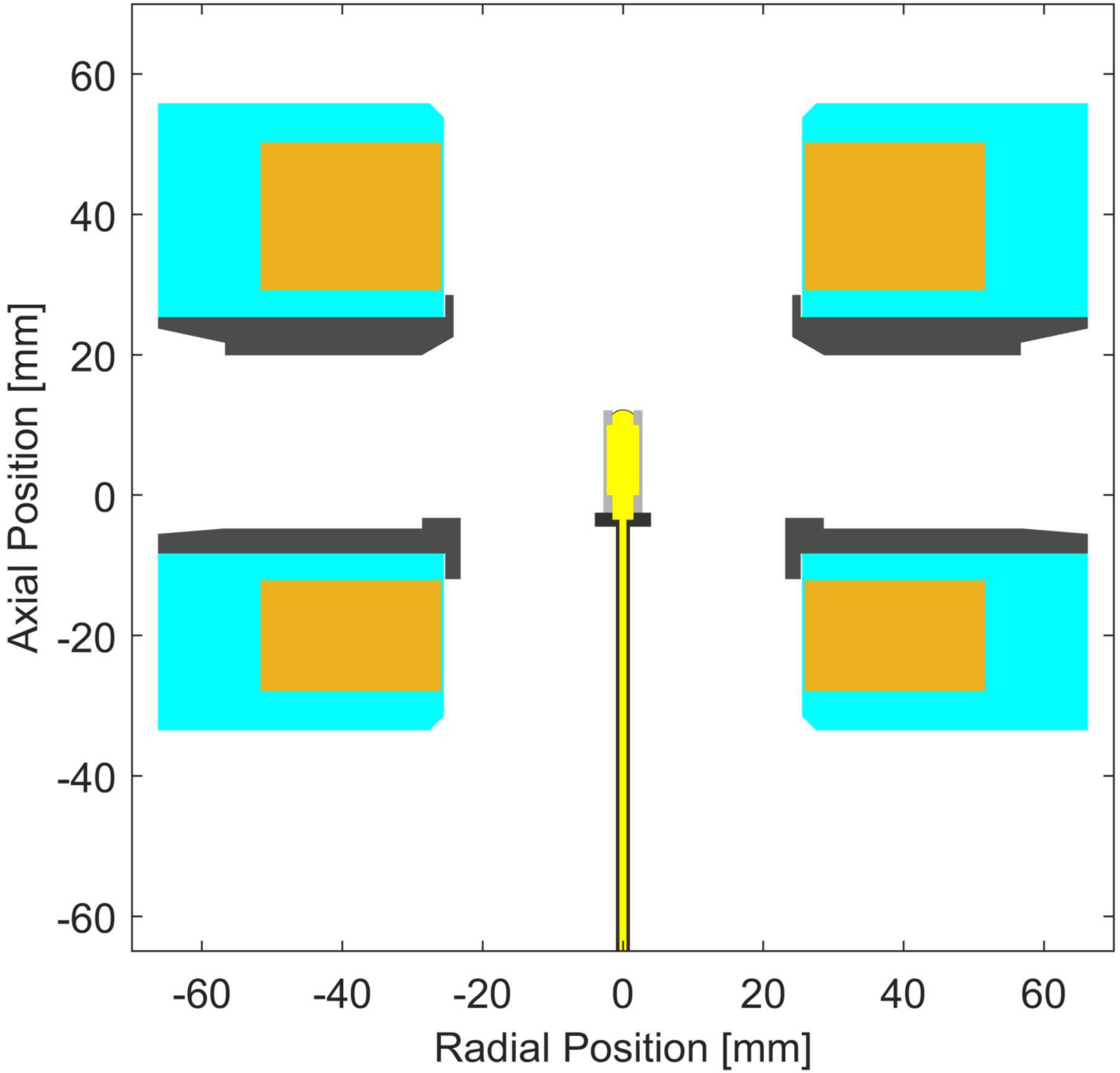
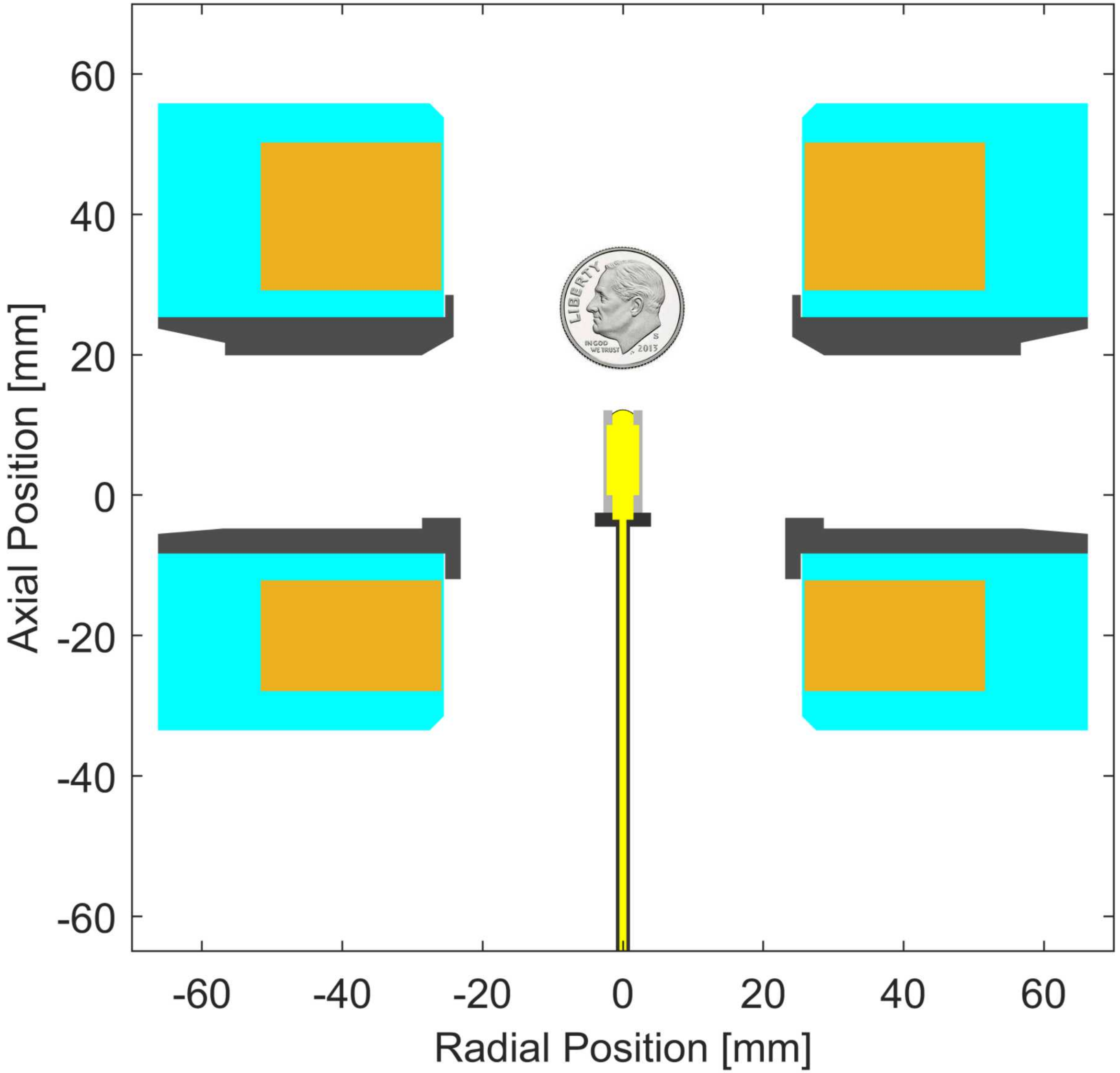


- Axial magnetic field applied with Helmholtz-like coils
- Typically 10 T
- Risetime is several ms to allow field to diffuse through conductors
- Split coil design allows radial diagnostic access

A quick review of the MagLIF experimental geometry



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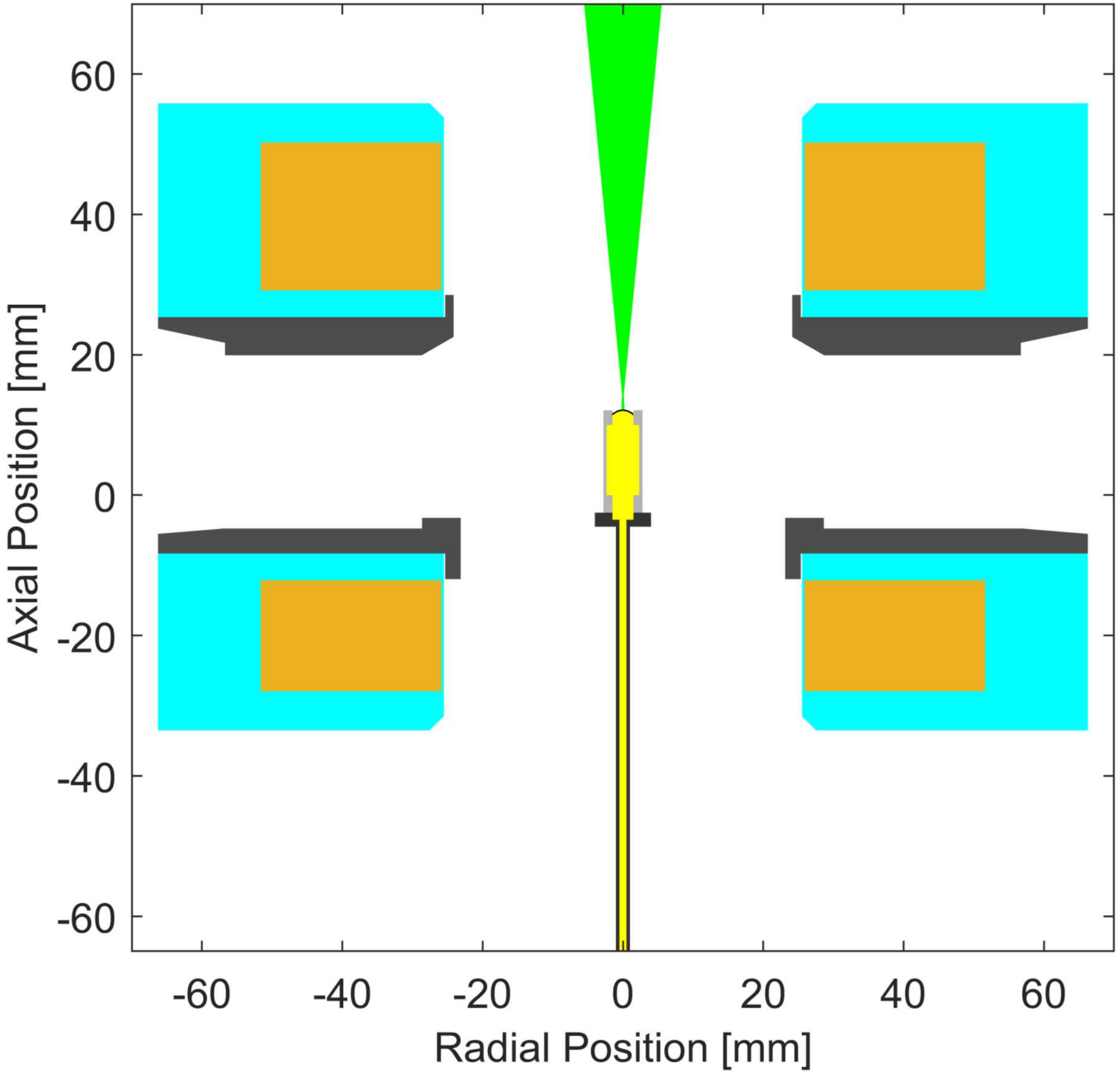
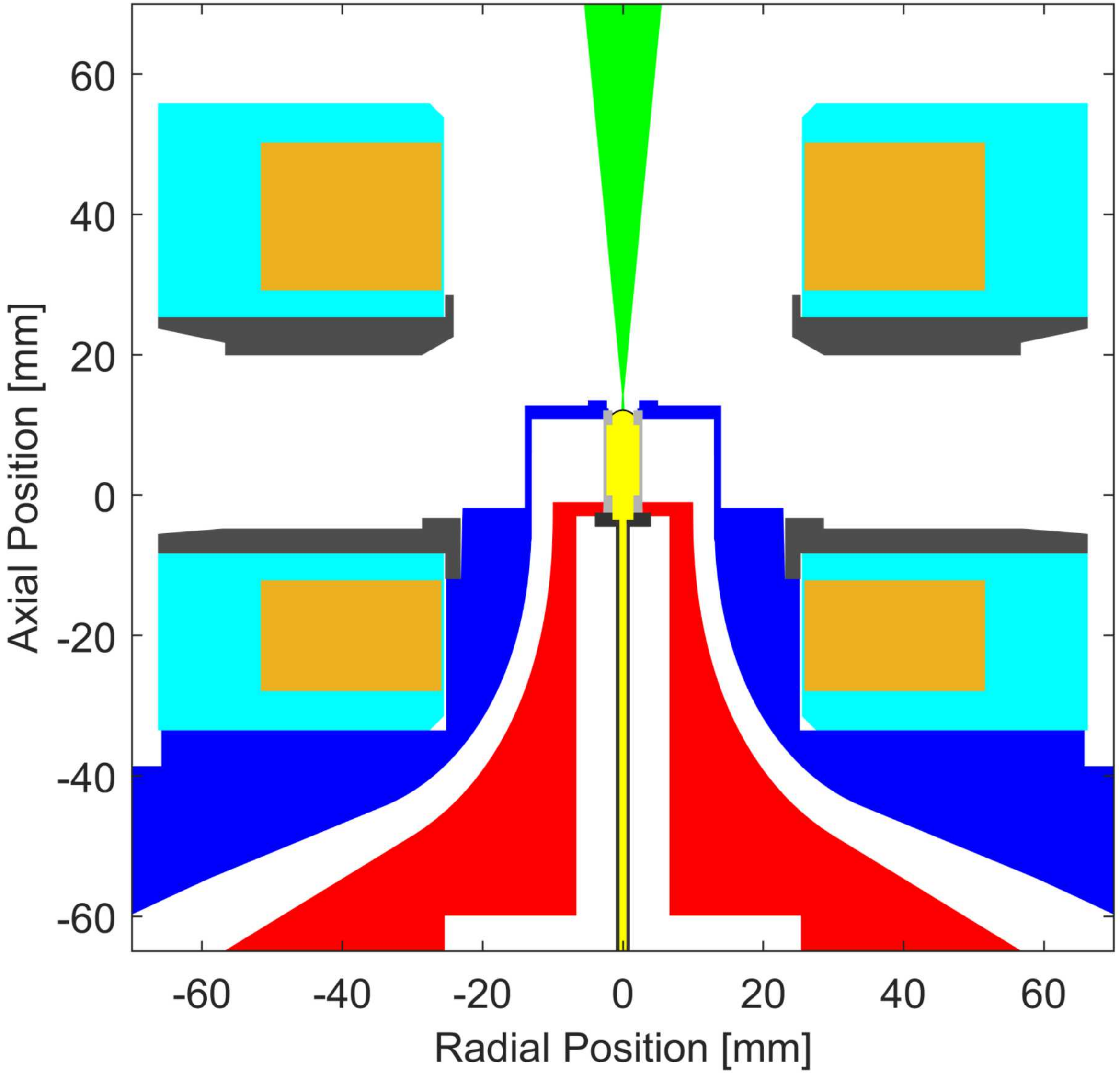


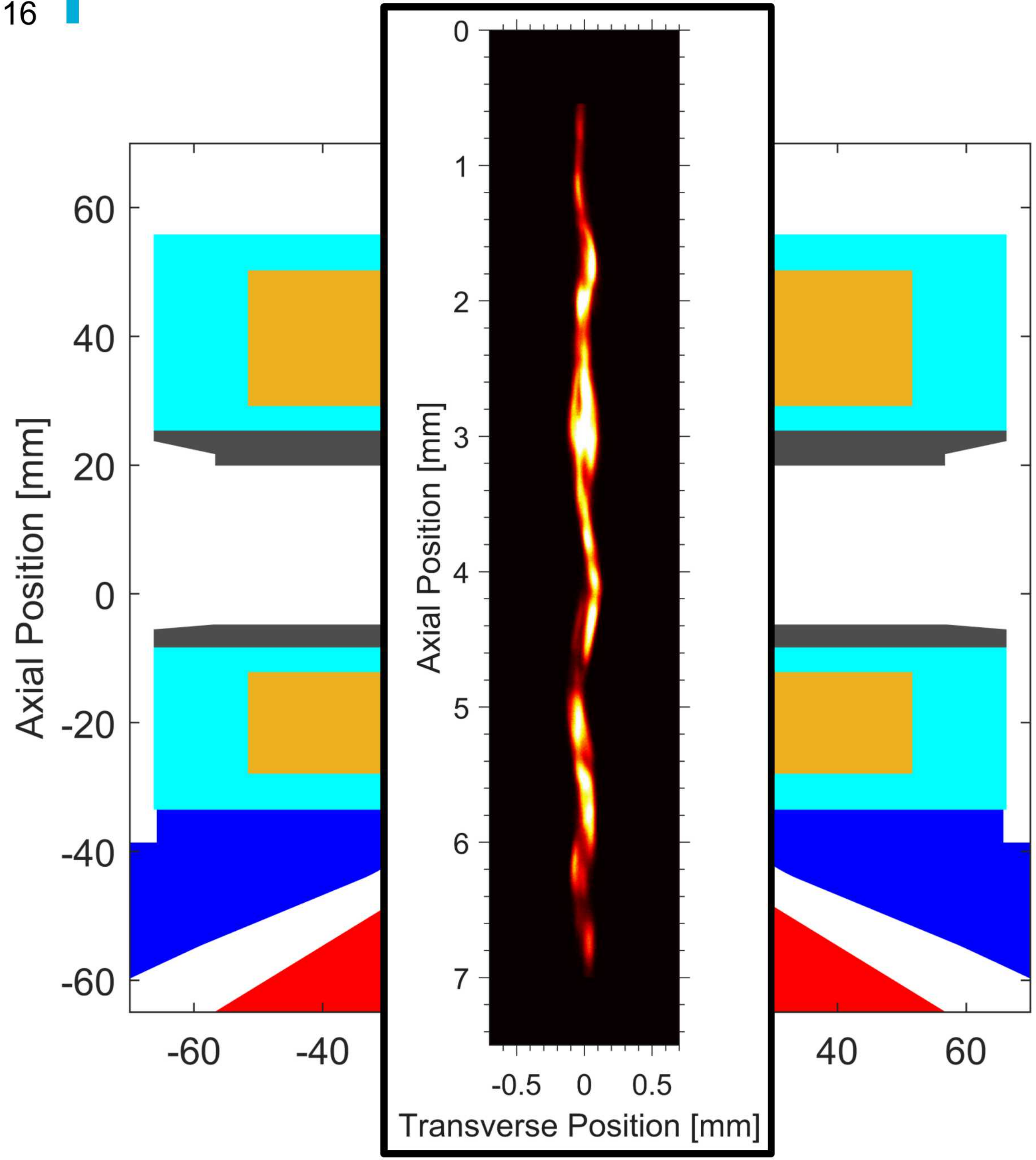
- Laser enters target axially through the laser entrance hole window
- 527 nm, multi-kJ, up to 1 TW laser
- Fuel density is 5-10% of n_{crit}
- Beam smoothing with distributed phase plate available
- Fuel reaches up to 1 keV on axis with average temperature ~100 eV

A quick review of the MagLIF experimental geometry



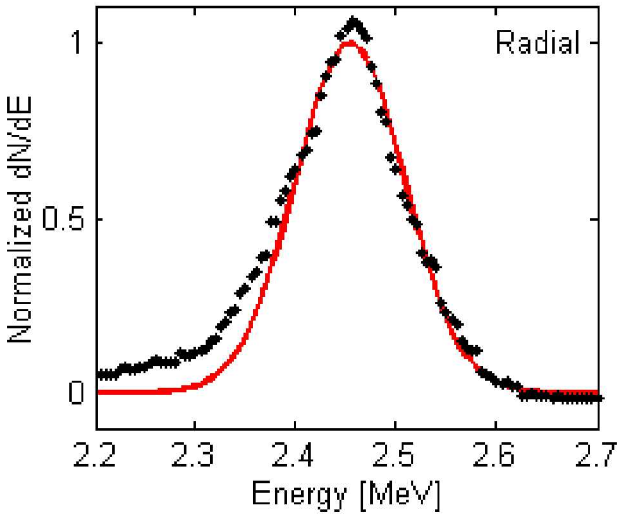
- Current is delivered to the target via the final transmission line
- 15-20 MA flows axially in the target
- Target radially implodes over 100 ns

A quick review of 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
- High aspect ratio stagnation column with keV temperature and kT B-field
- Fuel converges ≈ 30-40

The initial MagLIF experiments demonstrated key aspects of magneto-inertial fusion



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

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

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

S. B. Hansen, et al.,
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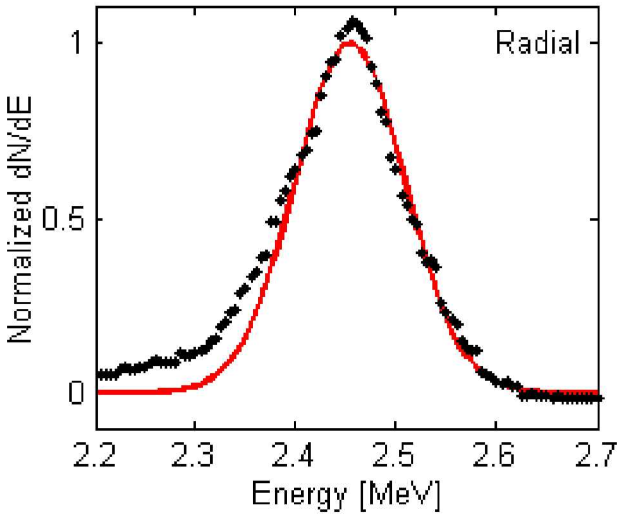
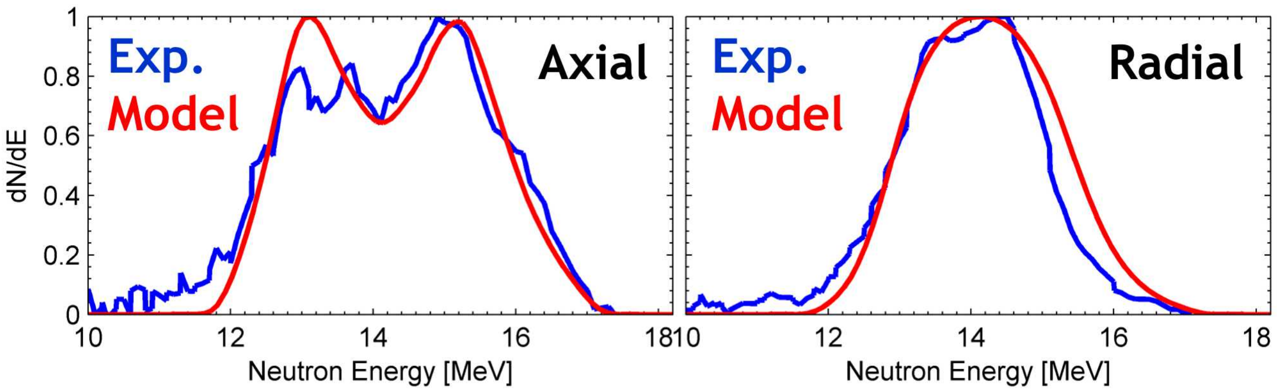


Thermonuclear neutron generation with fusion-relevant ion temperatures (2-3 keV)

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

Secondary DT Neutron Spectra



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

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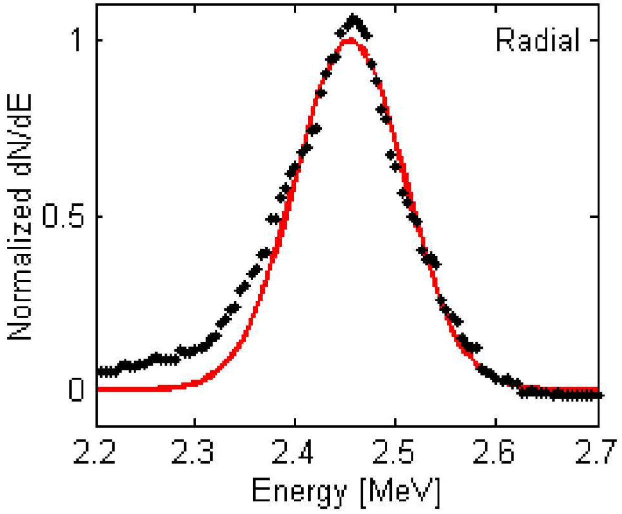
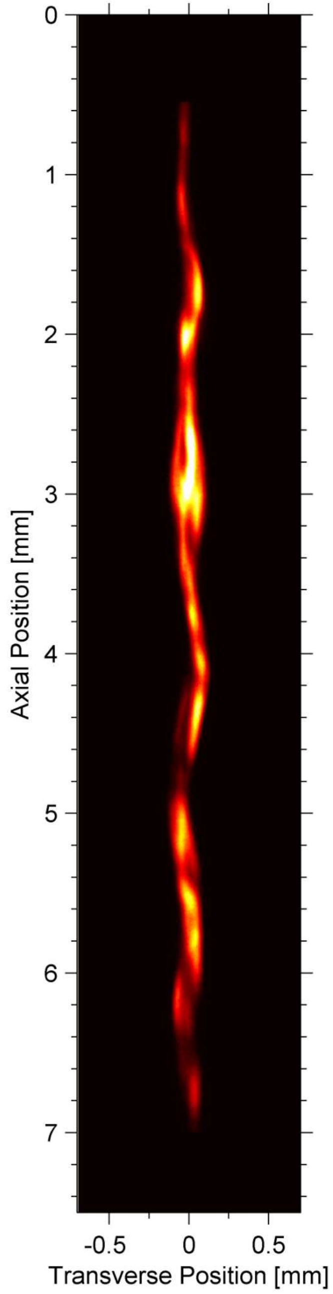
The initial MagLIF experiments demonstrated key aspects of magneto-inertial fusion



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

High aspect ratio fuel column at CR > 30



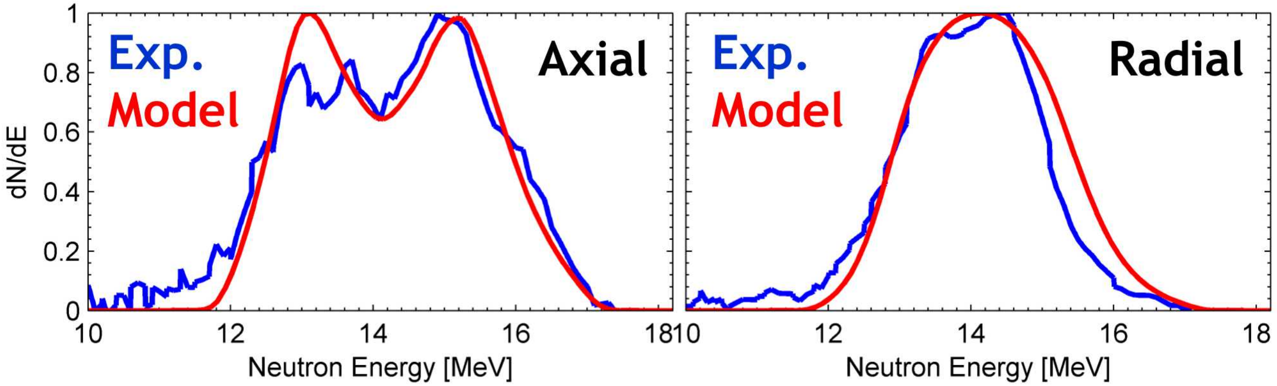
Highly magnetized fuel at stagnation (>0.3 MG-cm)

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

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

S. B. Hansen, et al., Phys. Plasmas (2015).

Secondary DT Neutron Spectra

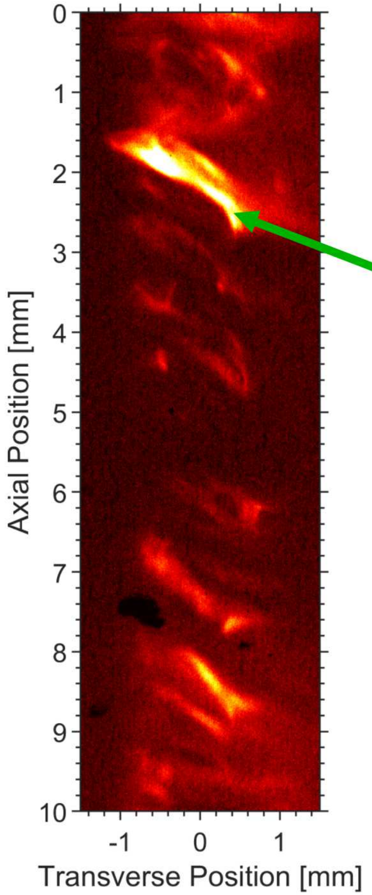


Perhaps most importantly, these experiments produced significant fusion yield only when using both an applied B-field and laser preheat

10 T B-field

No laser preheat

1×10^{10} DD neutrons

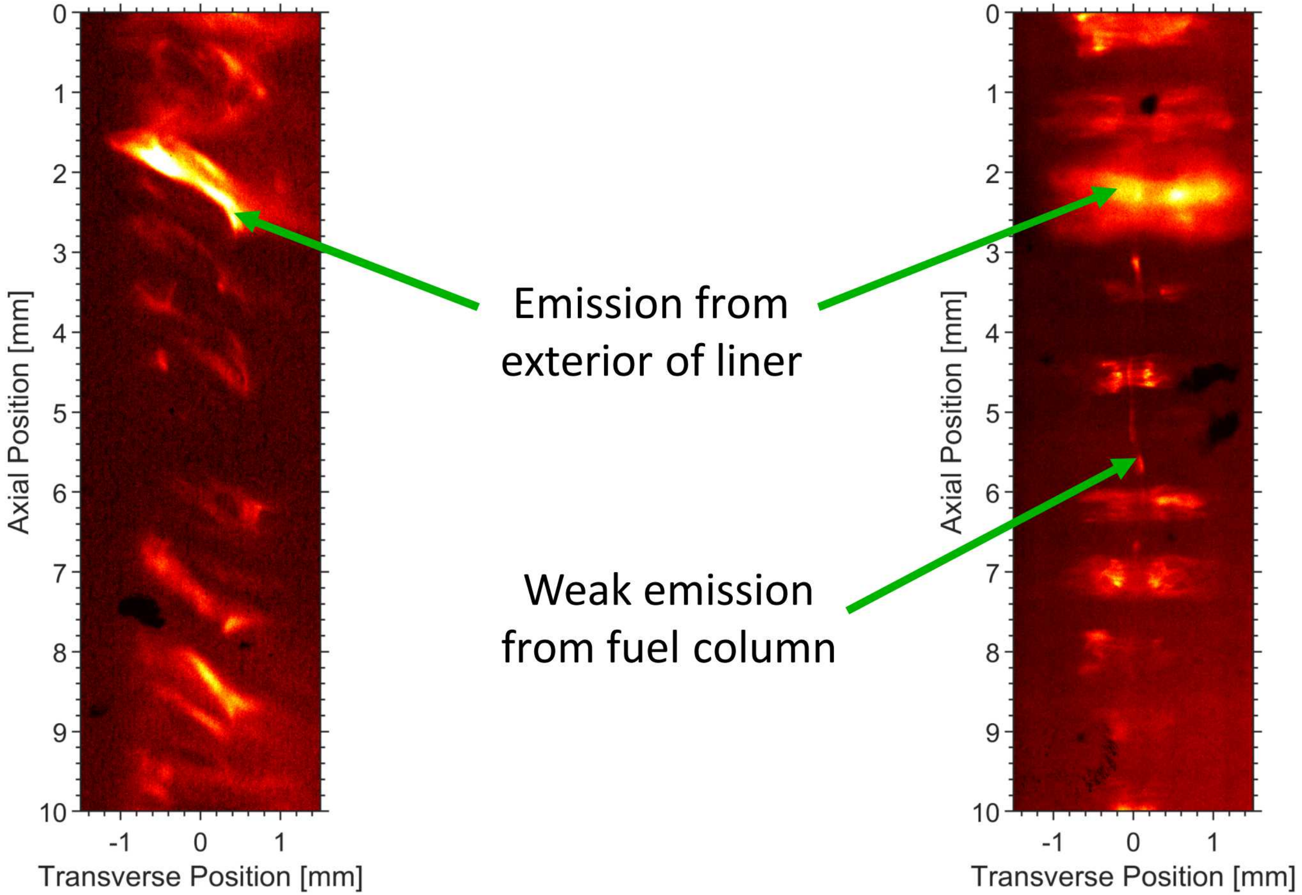


Emission from exterior of liner

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

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

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

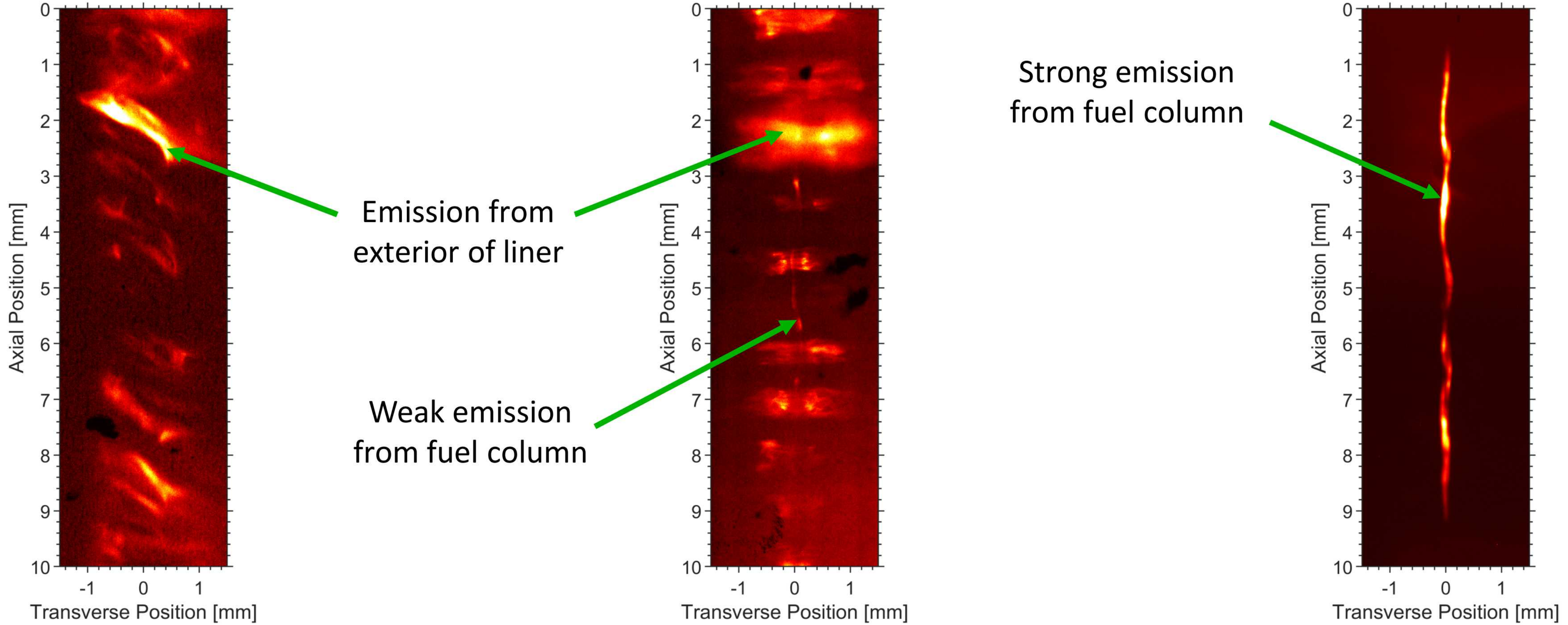


Perhaps most importantly, these experiments produced significant fusion yield only when using both an applied B-field and laser preheat

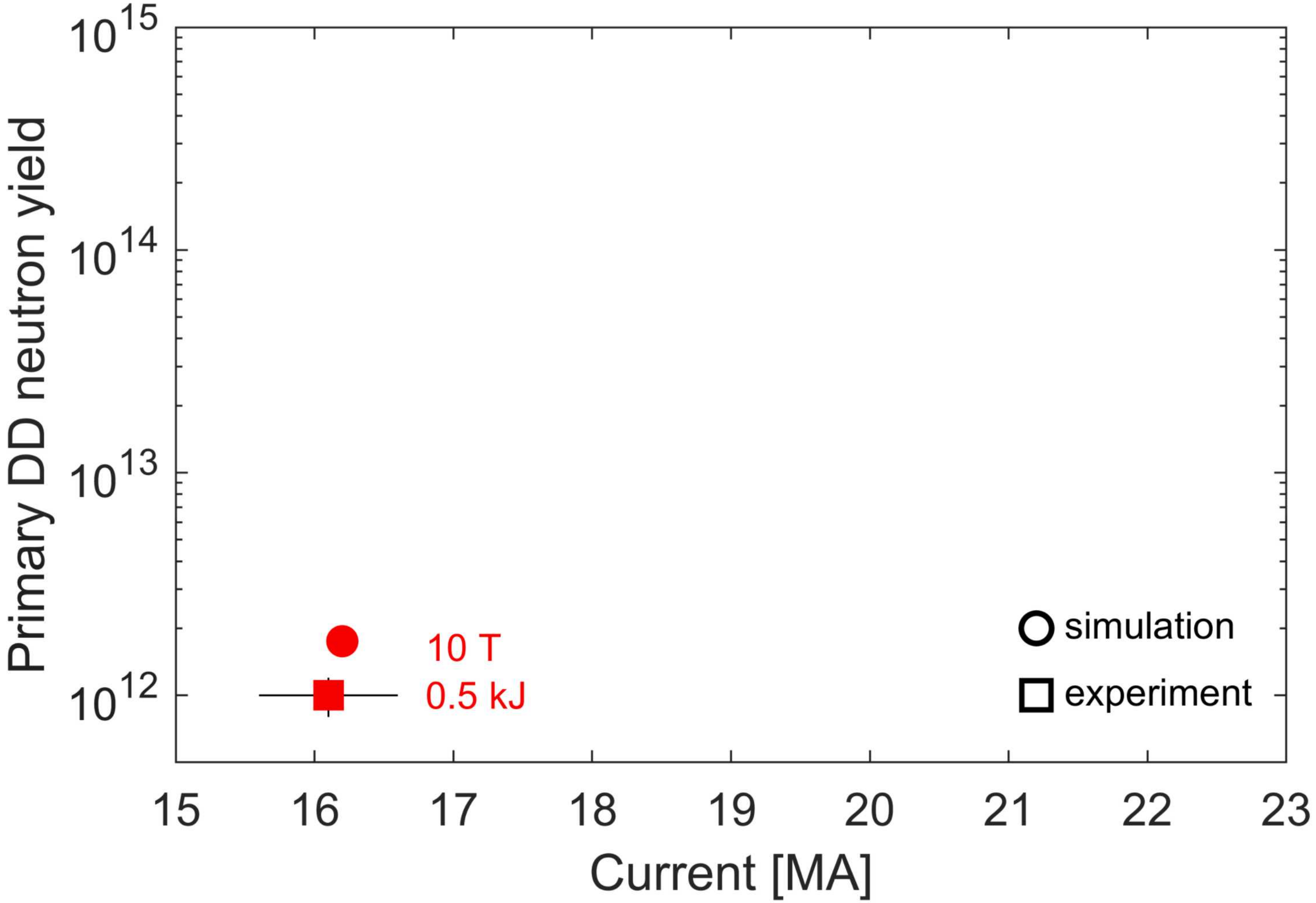
10 T B-field
No laser preheat
$1x10^{10}$ DD neutrons

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

10 T B-field
1 kJ laser preheat
$3x10^{12}$ DD neutrons



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

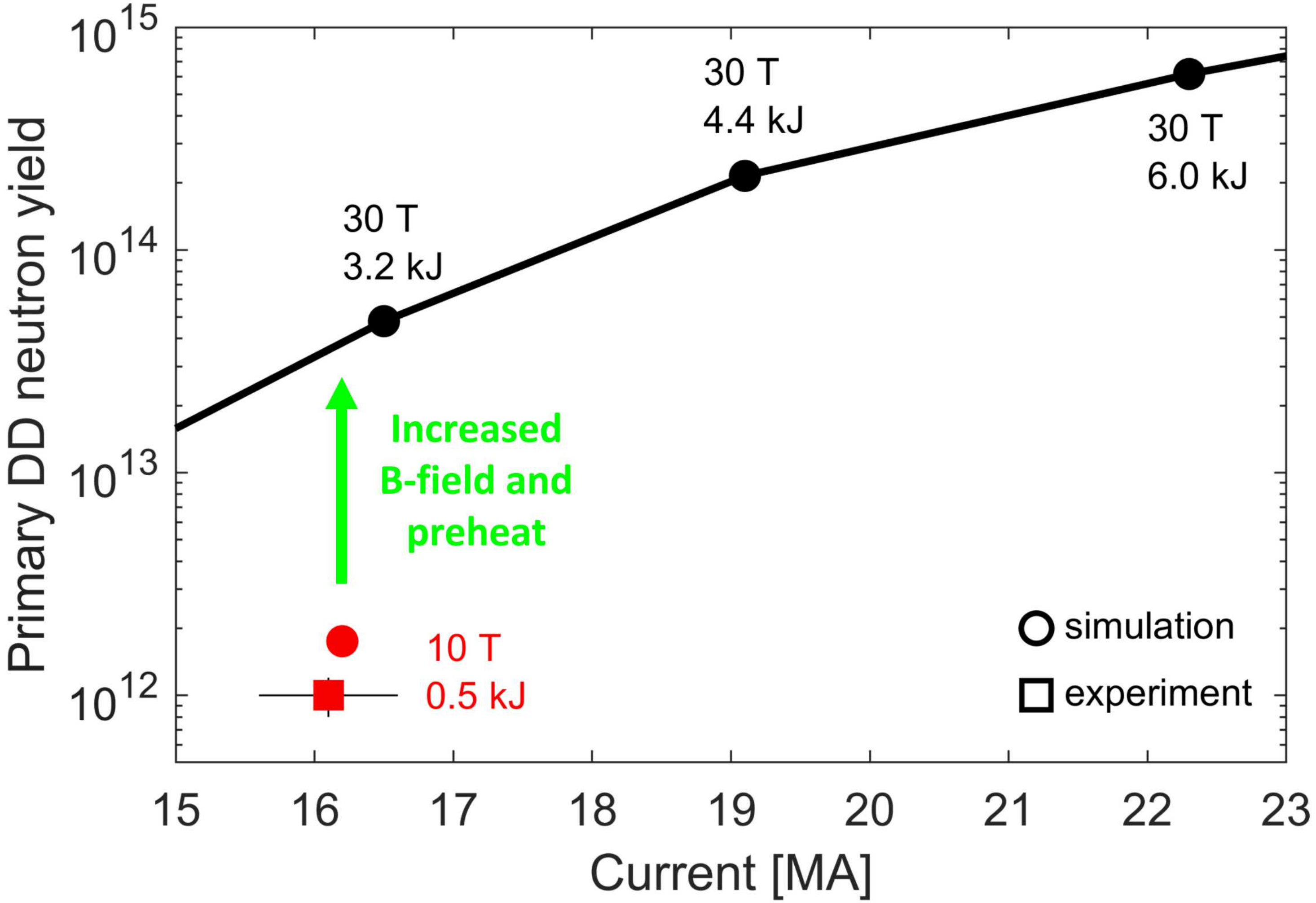


- Simulation matches experiment to within 2x
- Simulation expected to be optimistic
  - 2D – cannot capture helical instability structure
  - No mix model included

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

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

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



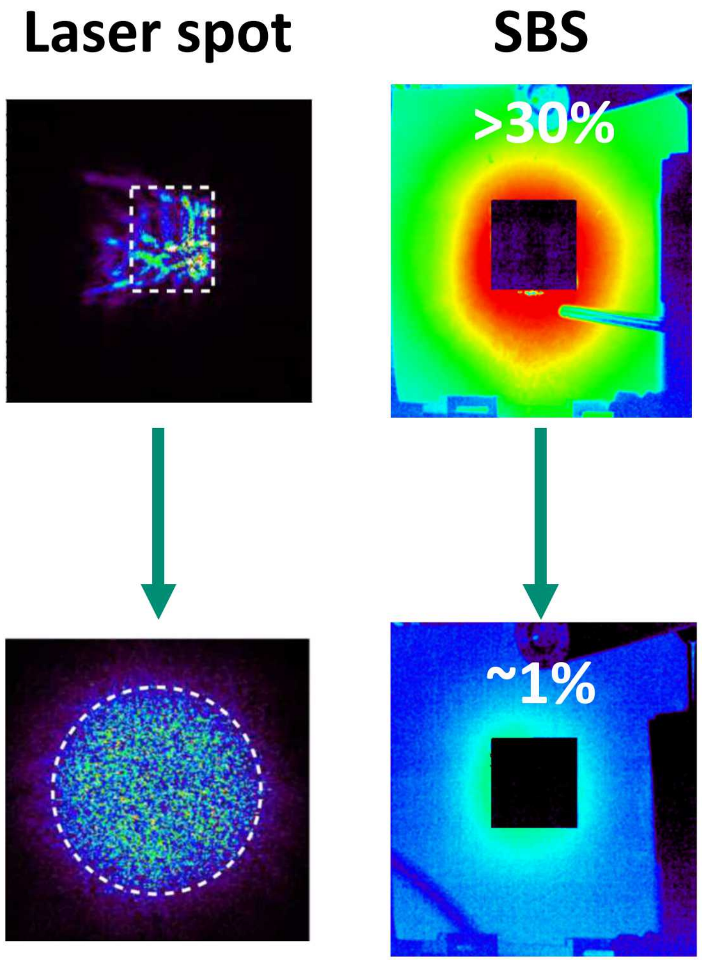
- >5x10^{14} DD neutrons possible at the upper limit of what is possible on Z
  - Roughly 100 kJ of DT-equivalent fusion yield
- More than 10x improvement possible at a fixed current by increasing B-field and laser preheat energy

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

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

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

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



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

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- LEH window thickness reduced from 3 to 1.5 µm (transmission ~30% → 70%)
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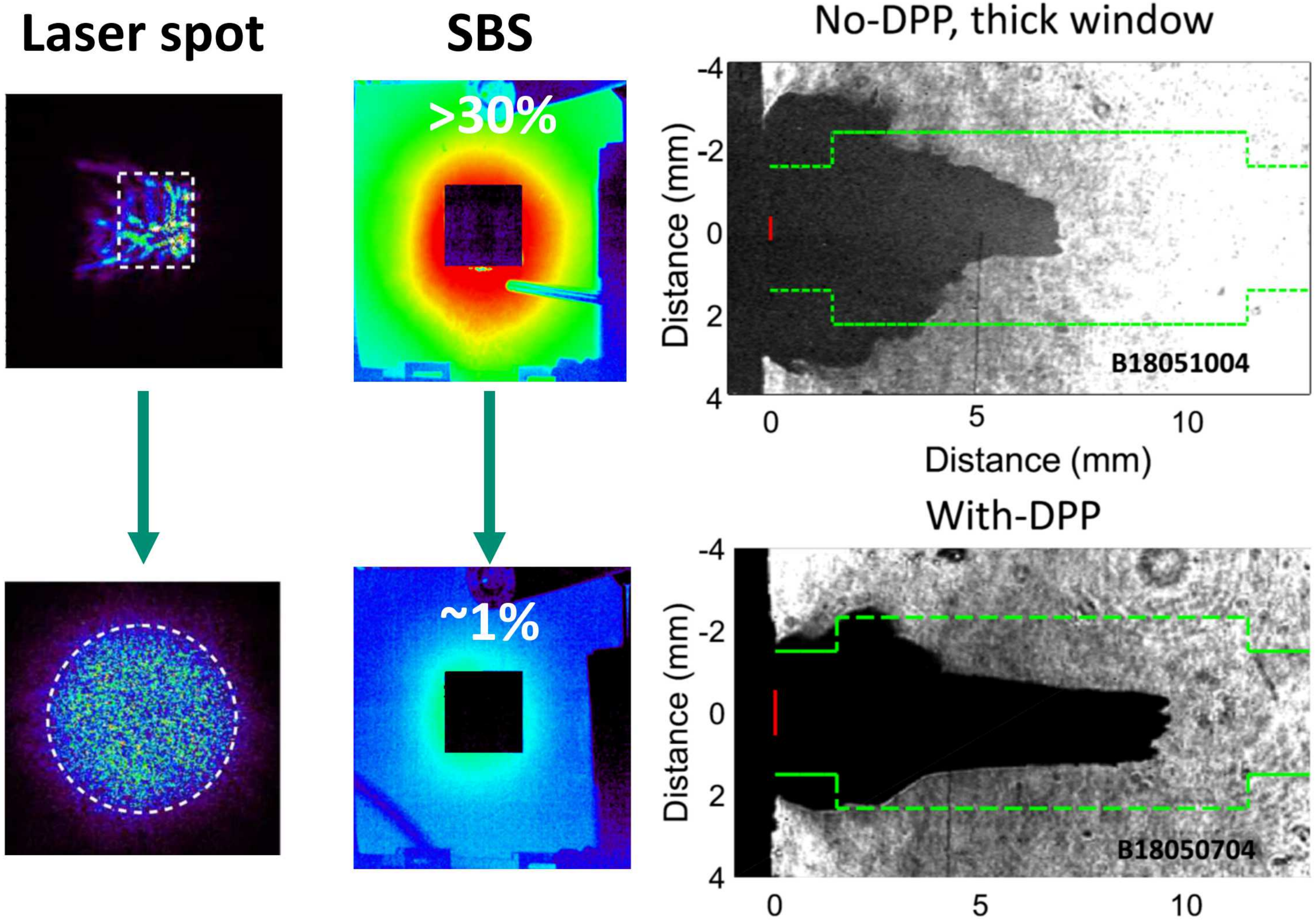
Unable to accurately simulate due to substantial LPI



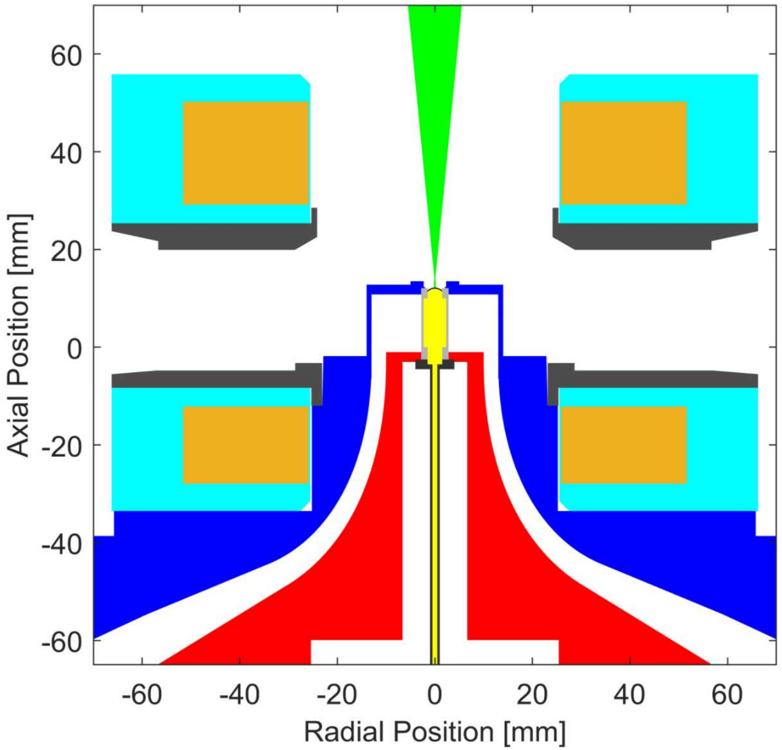
Simulations match this configuration

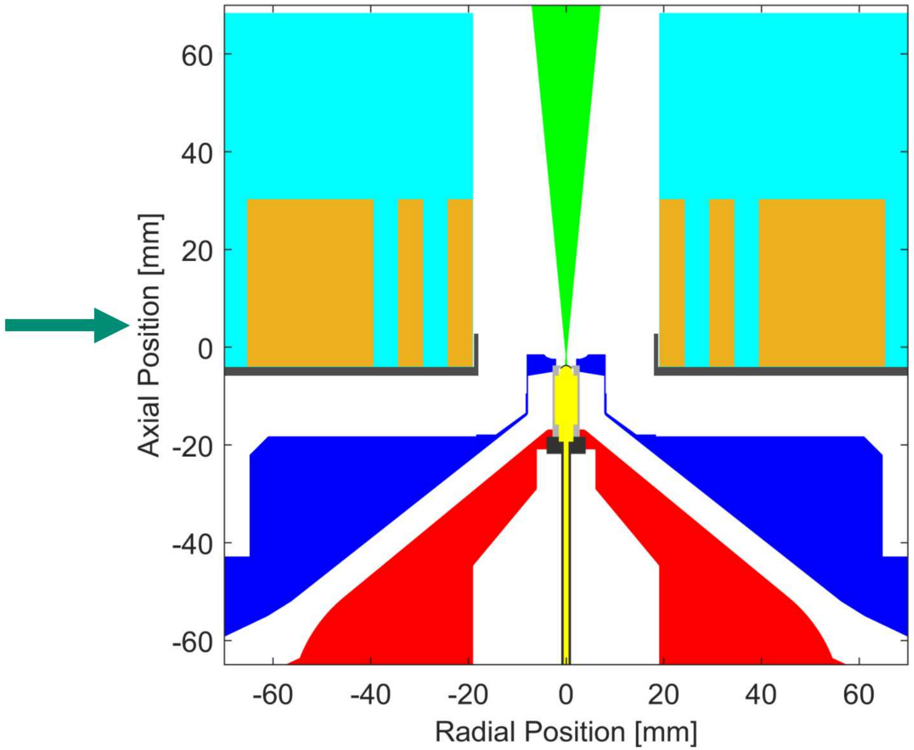
M. Geissel, et al., Phys. Plasmas (2018).

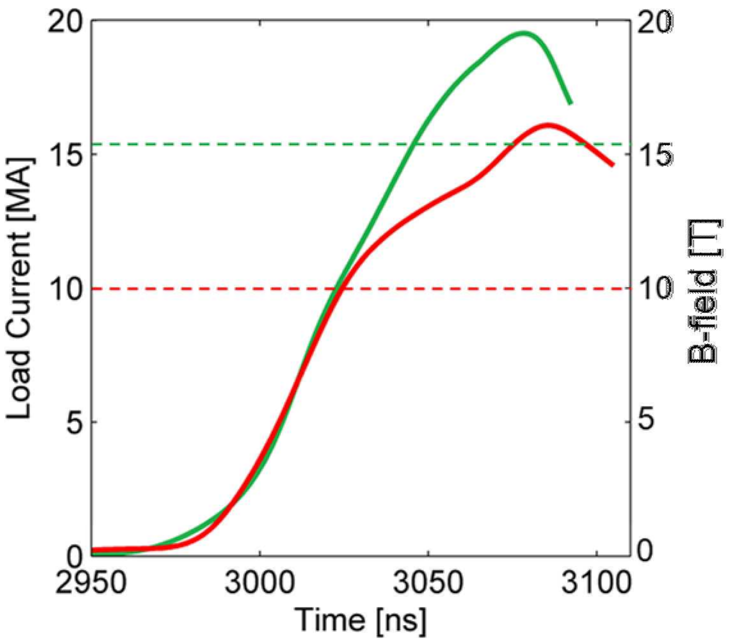
A. J. Harvey-Thompson, et al., Phys. Plasmas (2018).

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

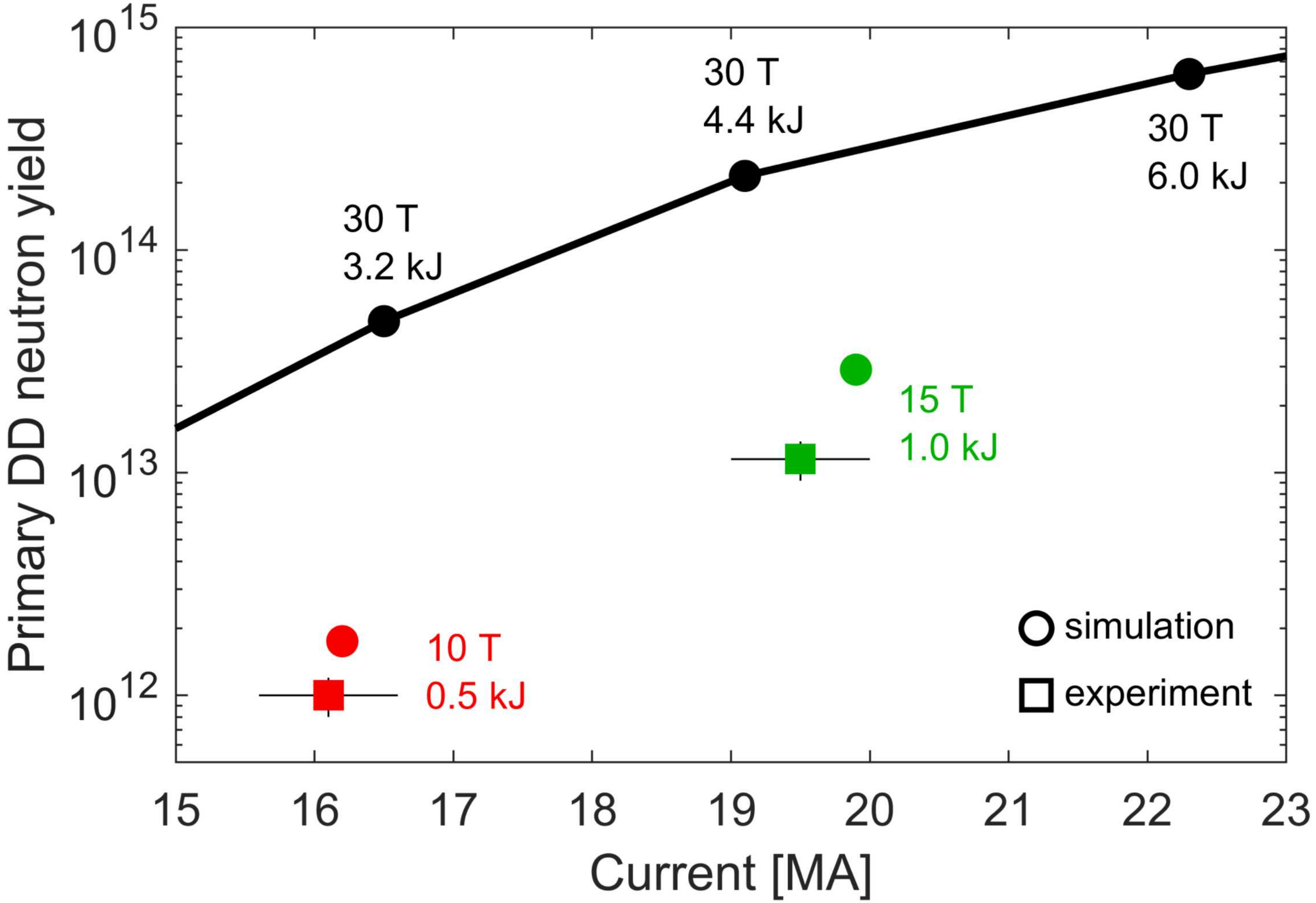
- Conical transmission line with lower inductance and larger anode-cathode gaps reduced current losses allowing 19.5 MA to be delivered to the target
- Single, high performance coil delivered 15 T average field to the target while maintaining radial diagnostic access







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 applied B-field, laser preheat energy, and drive current

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

Shot	z2851		z3289	
B-field [T]	10		15	
Preheat energy [kJ]	0.5		1.0	
Current [MA]	16.1		19.5	
T_{ion} [keV]	1.8		3.1	
P_{stag} [Gbar]	0.5		0.9	
DD neutron yield	1.0e12		1.1e13	

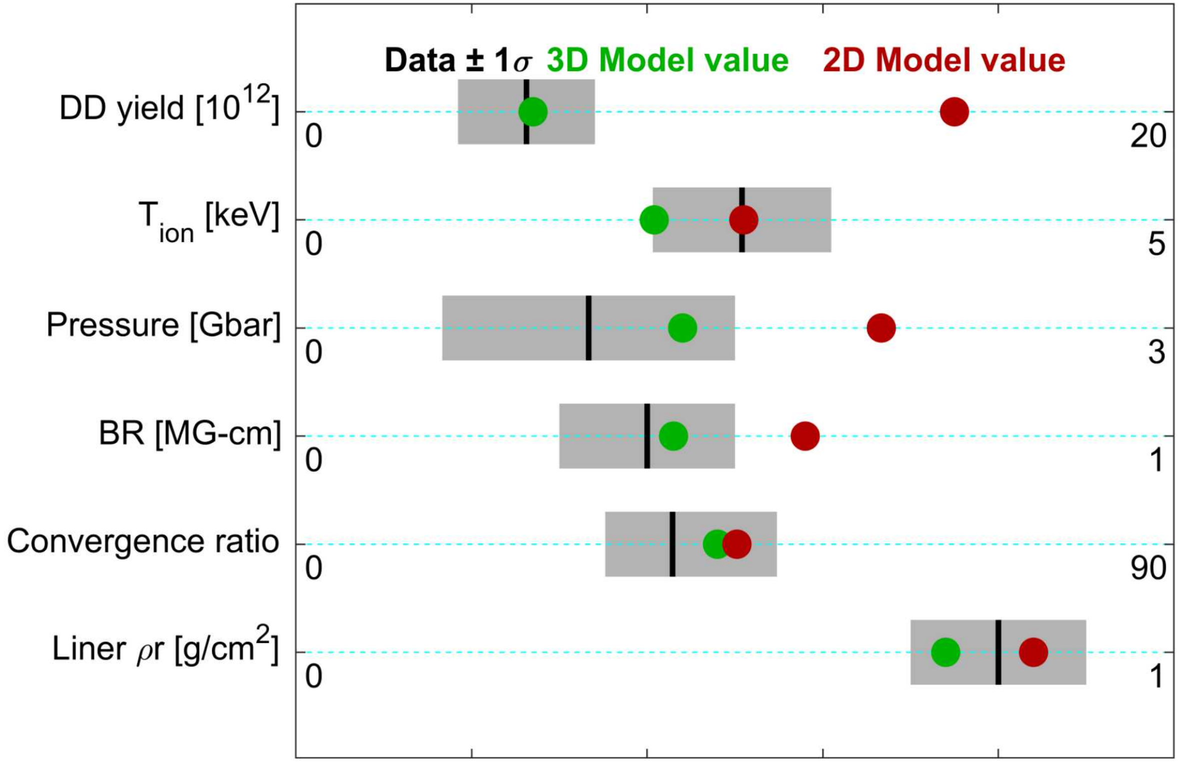
Fuel temperature and stagnation pressure also increased as expected with the improved platform

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**
DD neutron yield	1.0e12	1.8e12	1.1e13	2.9e13

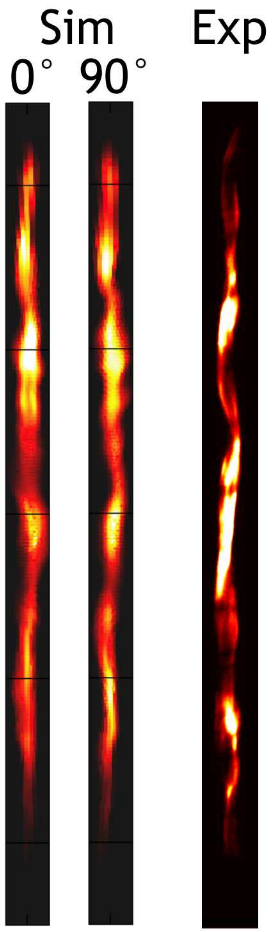
- 2D LASNEX calculations accurately predict the trend in ion temperature, stagnation pressure, and neutron yield production, though the absolute values are off

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

- We are just starting to explore the impact of 3D effects with HYDRA
- Experimental stagnation parameters are more accurately reproduced in 3D HYDRA simulations compared to 2D HYDRA simulations
- 3D stagnation structures qualitatively match experiments

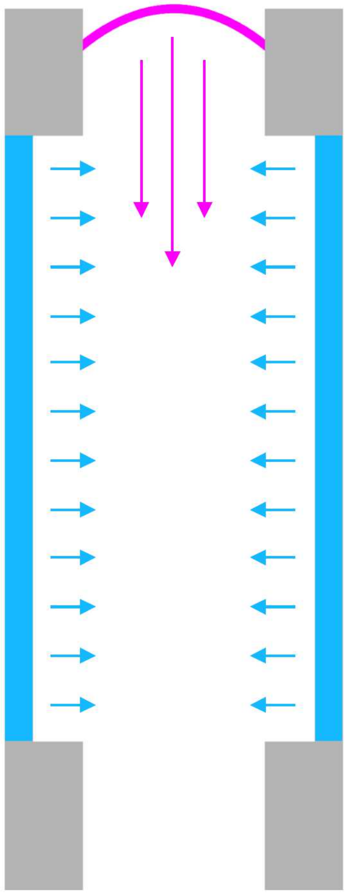


For more information see Matt Weis' talk (TO6.00002) in the magneto-inertial fusion section on Thursday morning



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
  - Mid-Z materials act as tracers for Be and polyimide mix



Co comes from the LEH window

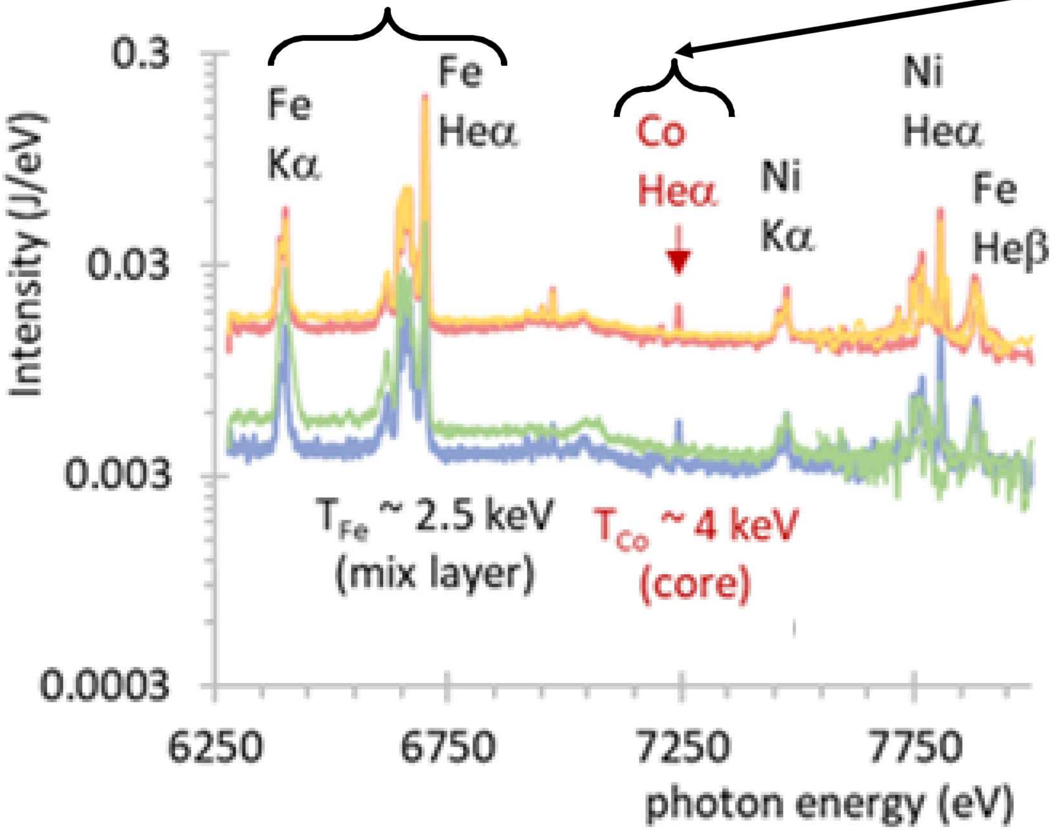
Primarily introduced to the center of the fuel during preheat

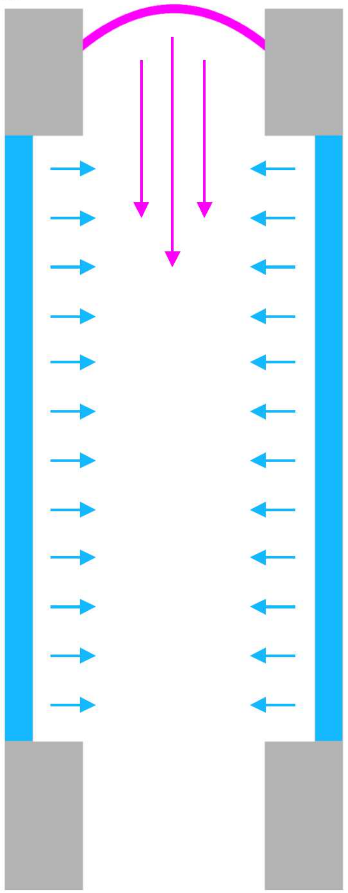
Fe and Ni come from the Be liner

Primarily introduced to the edges of the fuel during deceleration

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 low mix, hotter core and a higher mix, cooler region





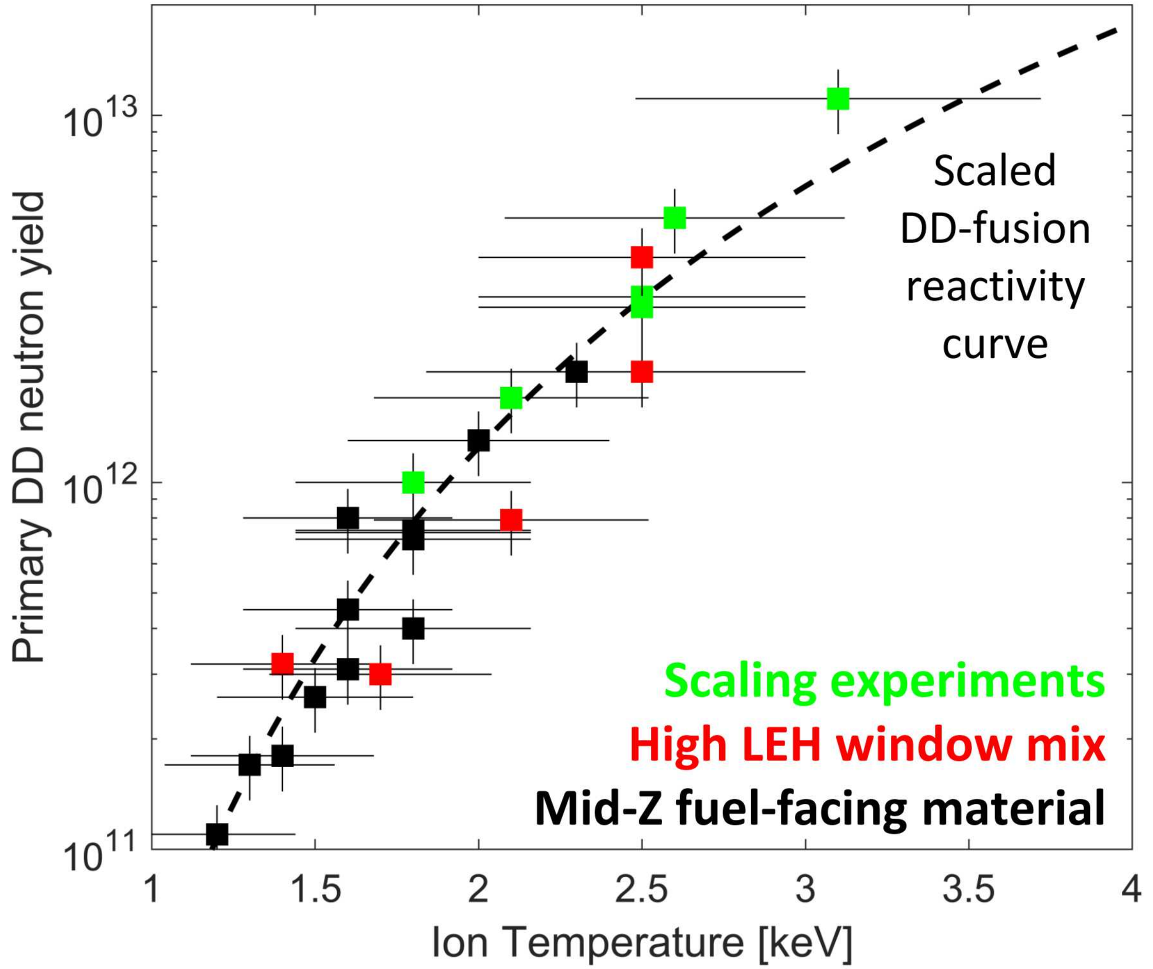
Co comes from the LEH window

Primarily introduced to the center of the fuel during preheat

Fe and Ni come from the Be liner

Primarily introduced to the edges of the fuel during deceleration

Our 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 put into understanding the source and quantity of mix during the 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
- We are presently developing new diagnostic capabilities to better diagnose the timing, location, and quantities of mix on Z

Parametric scans of input parameters allow us to isolate the impact of individual changes on target performance

- Accurately predicting the performance gradients gives us confidence that we understand scaling in MagLIF

- Preheat energy scan (0.5 to 1.4 kJ)
  - Hold target geometry, applied B-field, fuel density, and drive current fixed

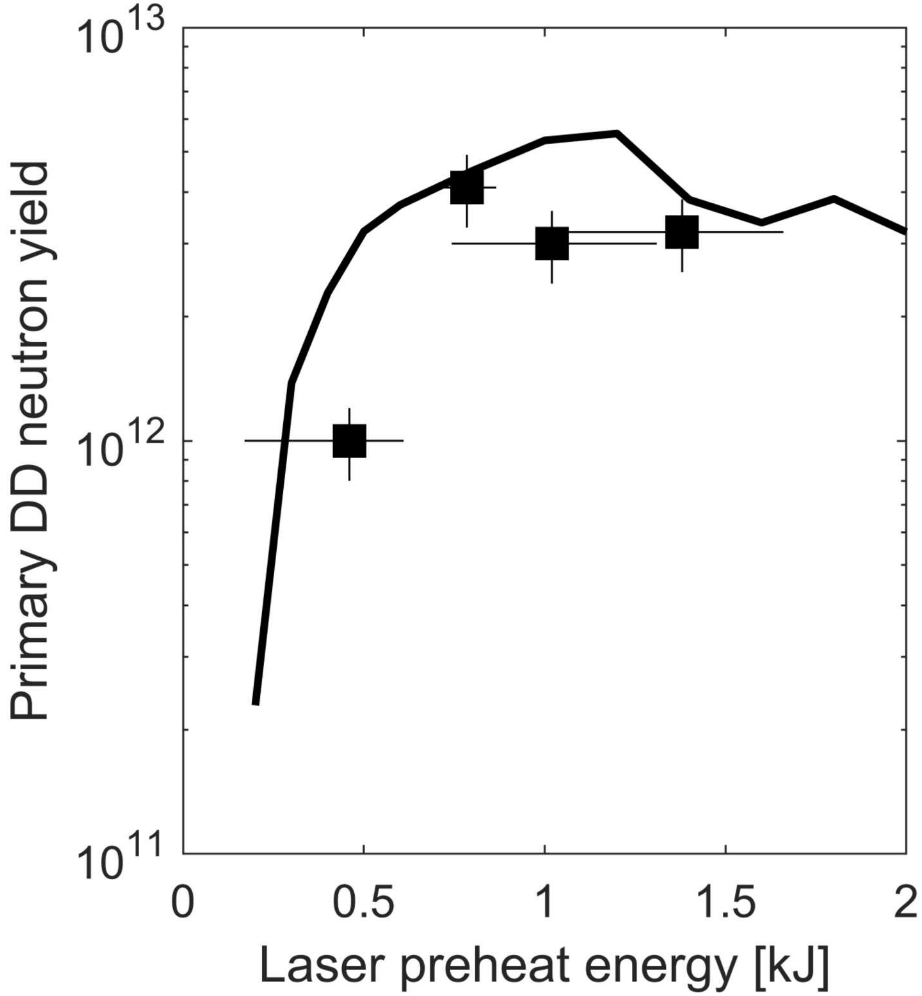
- Applied B-field scan (10 to 15 T)
  - Hold target geometry, fuel density, preheat energy, and drive current fixed

- Drive current scan (16 to 19.5 MA)
  - Hold target geometry, applied B-field, fuel density, and preheat energy fixed

Neutron yield rapidly increases with laser preheat energy and then plateaus due to the Nernst effect

- Target performance is sensitive to preheat energy in the low energy limit
- Plateau in neutron yield observed in experiments was predicted in LASNEX simulations that included the Nernst effect

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



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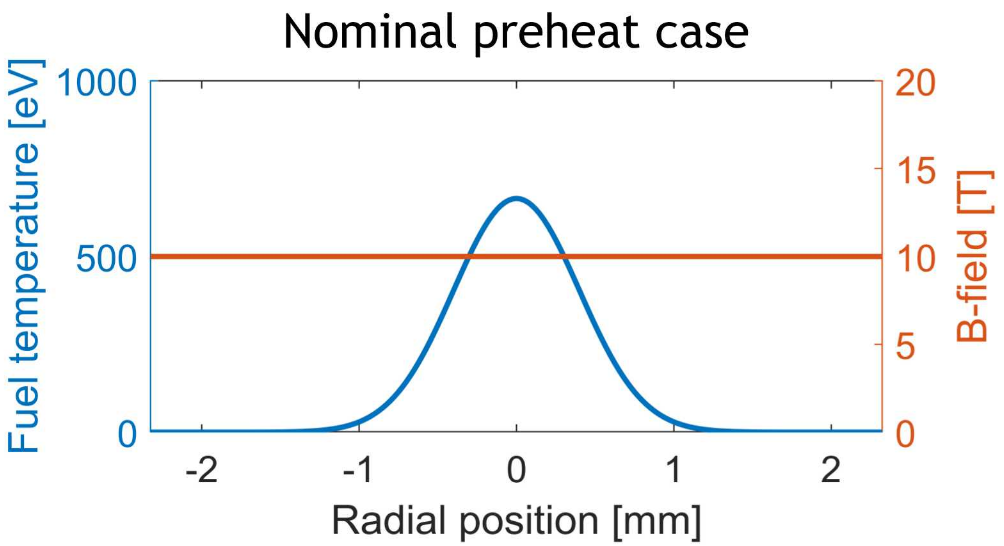
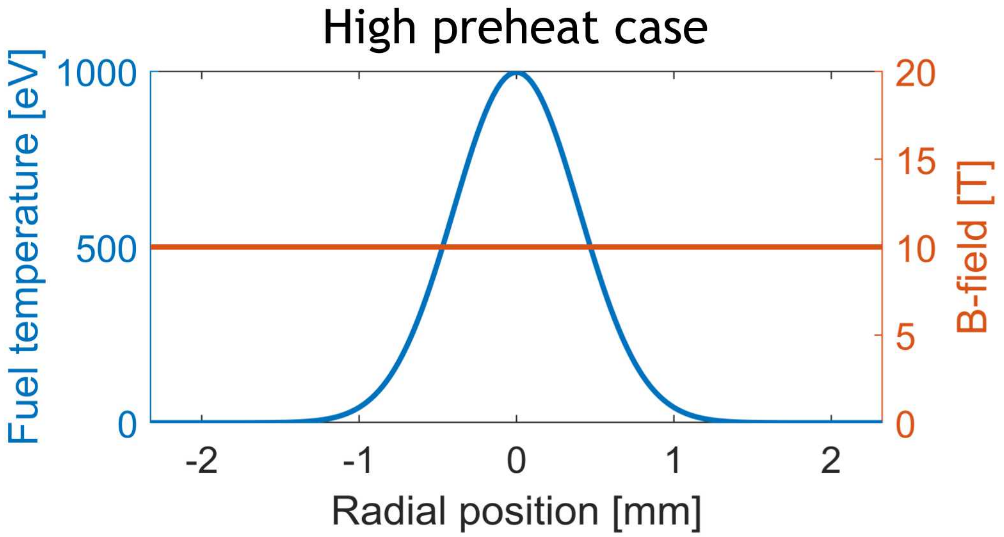
A.J. Harvey-Thompson, et al., Phys. Plasmas (2019).

Neutron yield rapidly increases with laser preheat energy and then plateaus due to the Nernst effect

- Target performance is sensitive to preheat energy in the low energy limit
- Plateau in neutron yield observed in experiments was predicted in LASNEX simulations that included the Nernst effect
  - Increased preheat creates higher initial temperature on axis

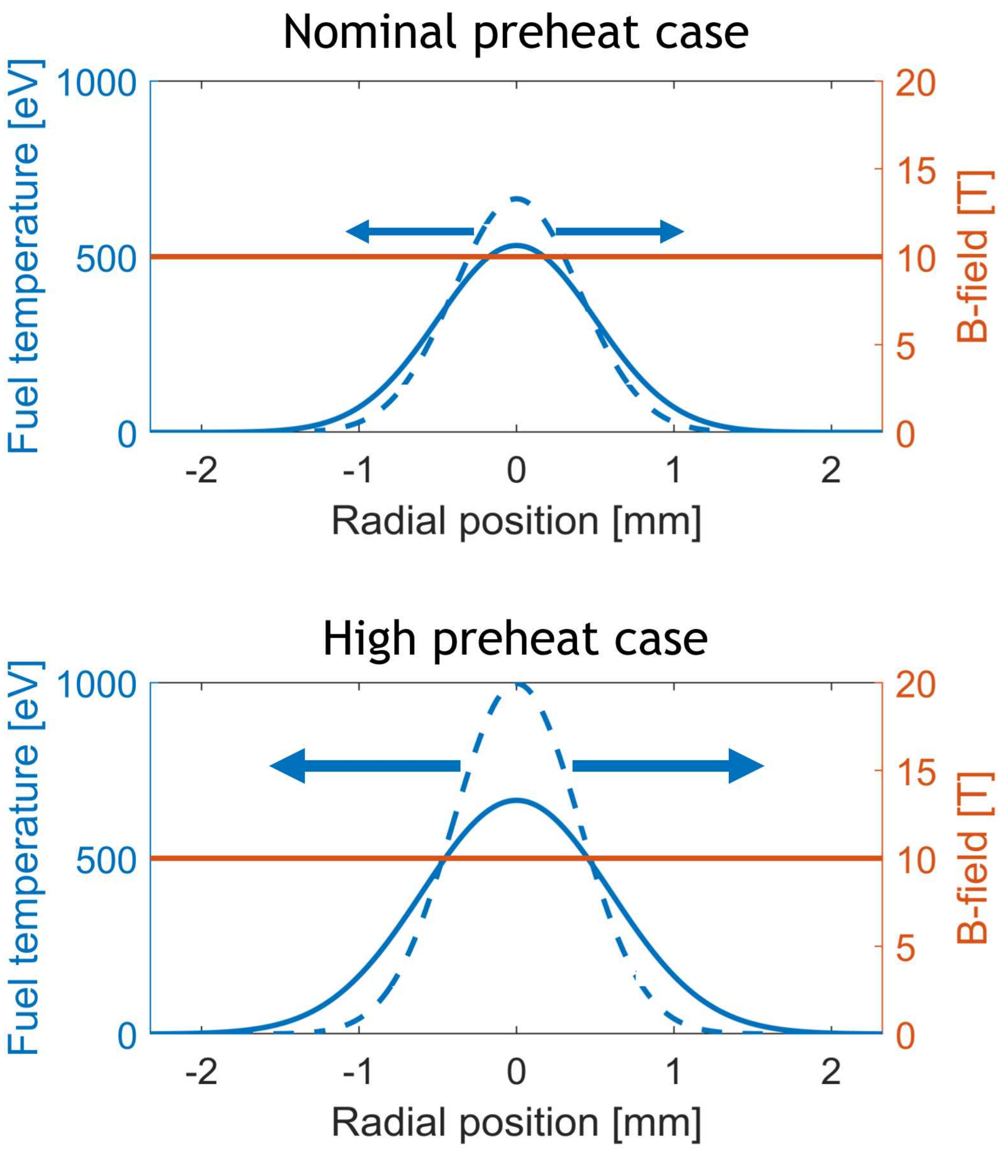




Neutron yield rapidly increases with laser preheat energy and then plateaus due to the Nernst effect

- Target performance is sensitive to preheat energy in the low energy limit
- Plateau in neutron yield observed in experiments was predicted in LASNEX simulations that included the Nernst effect
  - Increased preheat creates higher initial temperature on axis
  - The increased temperature gradient increases the heat flux to cooler fuel

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



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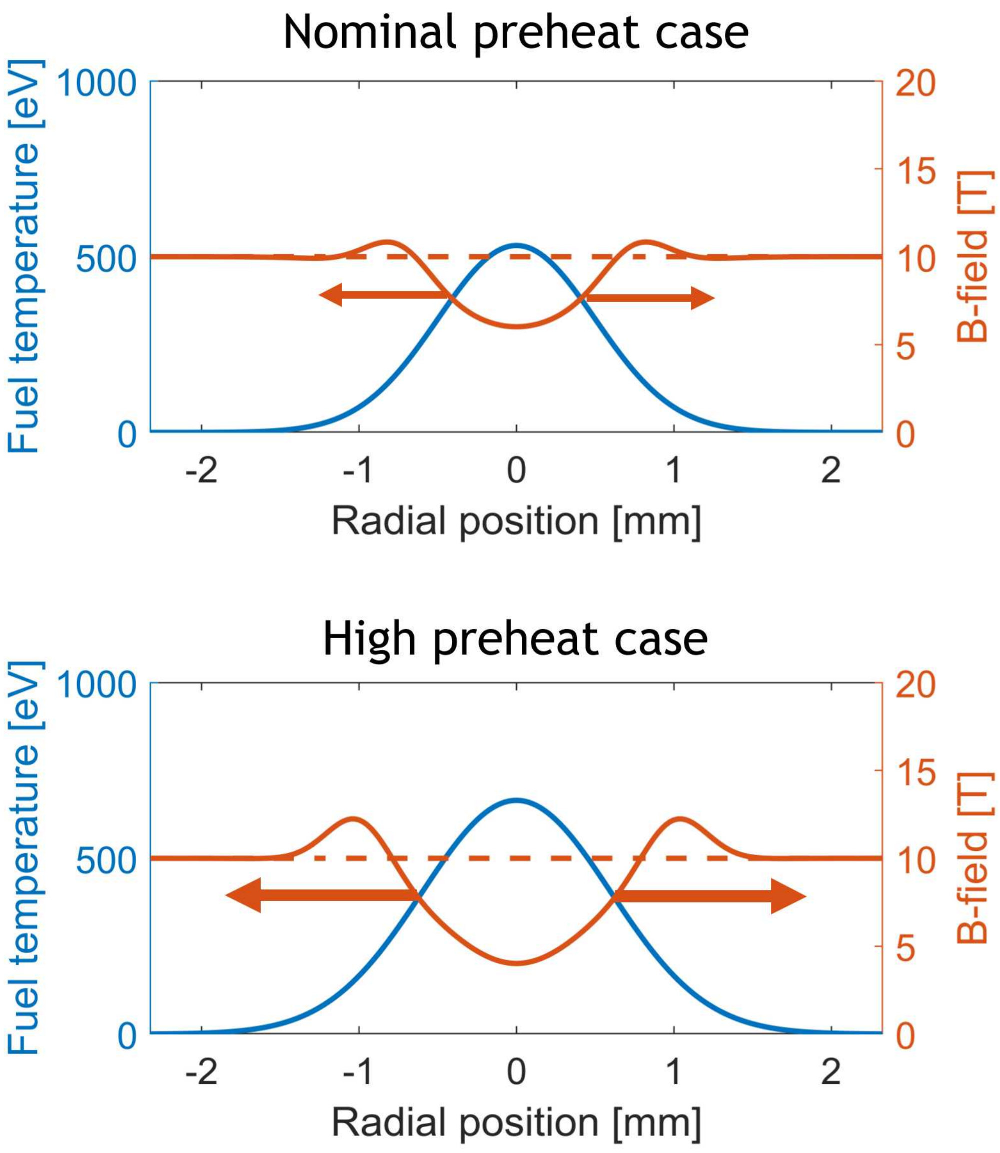

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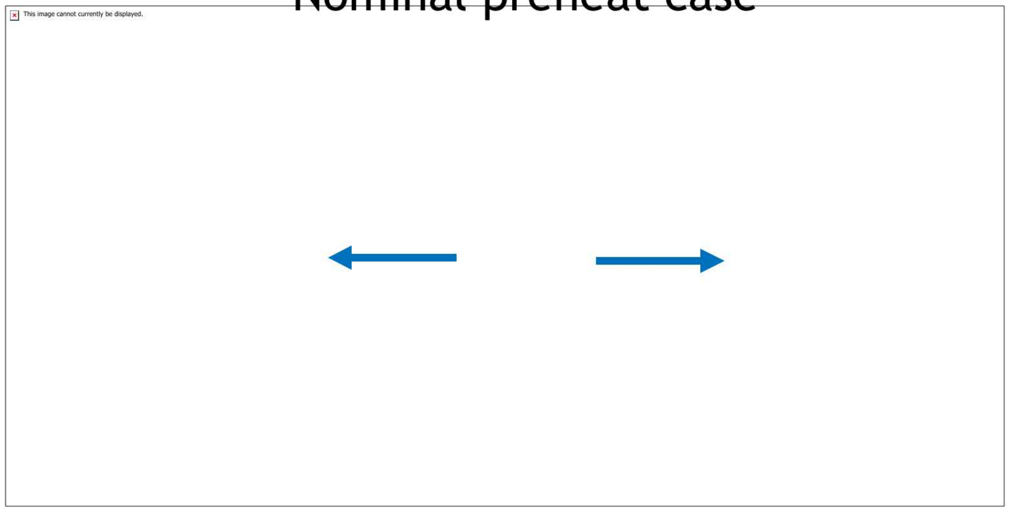
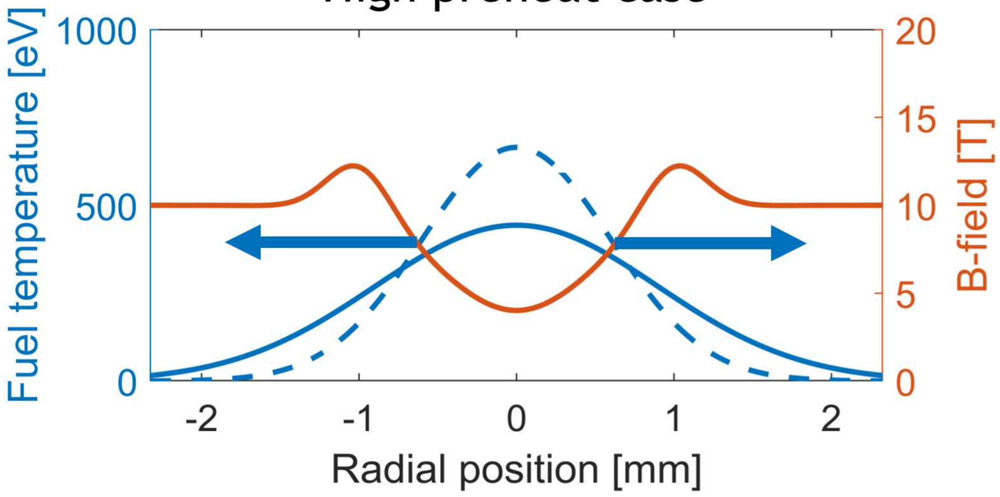
  - The increased temperature gradient increases the heat flux to cooler fuel
  - Magnetic field is advected with the heat flow – higher preheat loses more magnetic field
  - Reduced magnetic field increases heat flux

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

Nominal preheat case

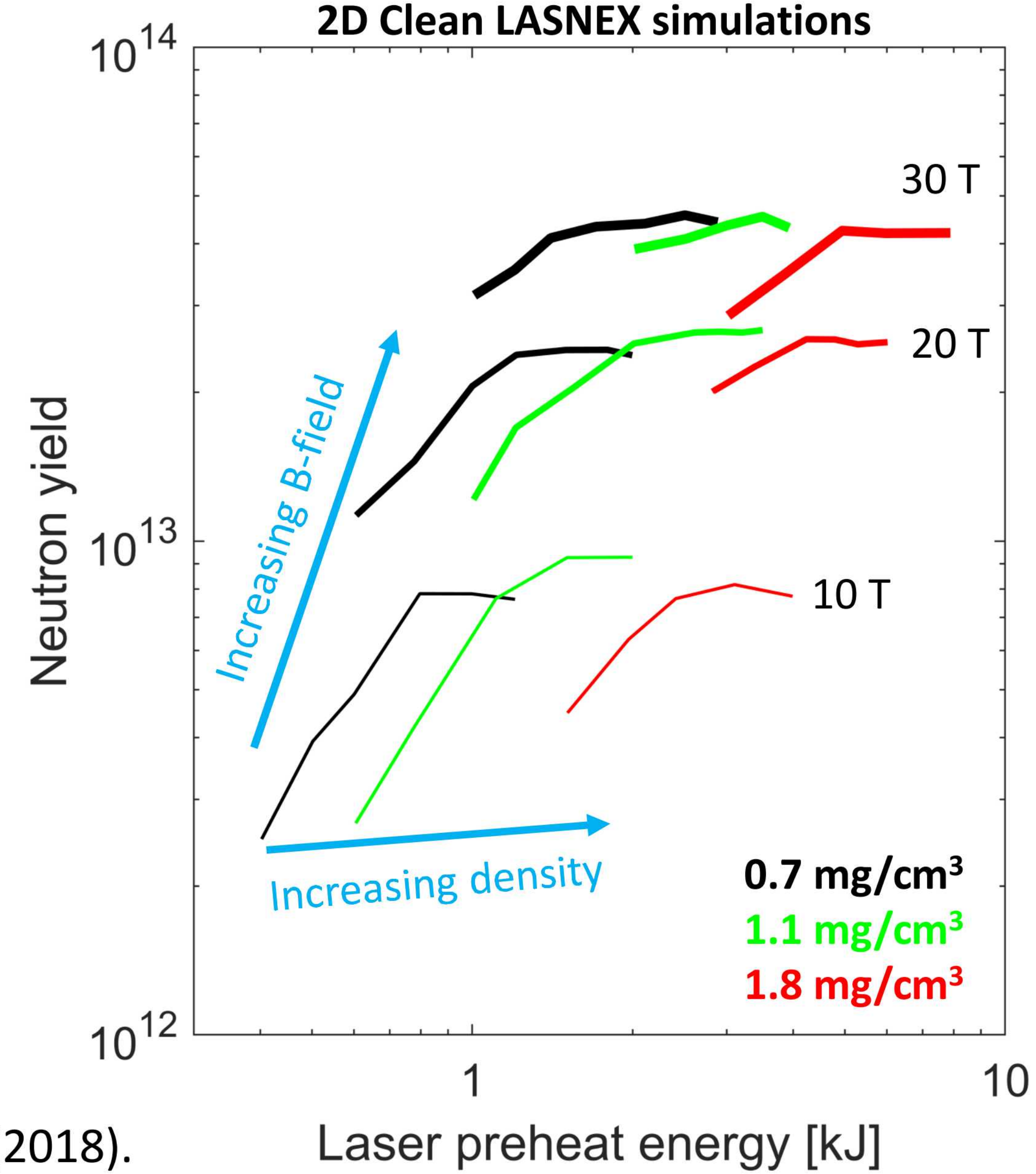


High preheat case



Neutron yield rapidly increases with laser preheat energy and then plateaus due to the Nernst effect

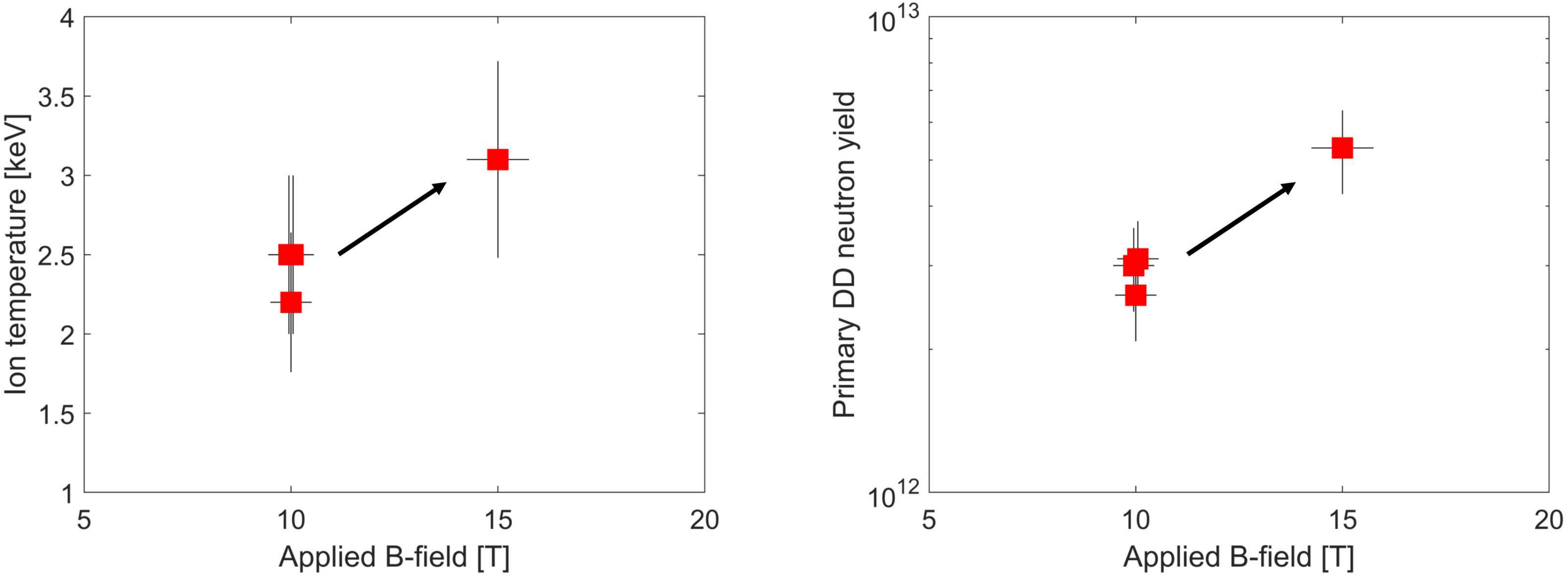
- Target performance is sensitive to preheat energy in the low energy limit
- Plateau in neutron yield observed in experiments was predicted in LASNEX simulations that included the Nernst effect
- We observe similar stagnation temperatures for nominal preheat and in the high preheat limit, as expected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



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

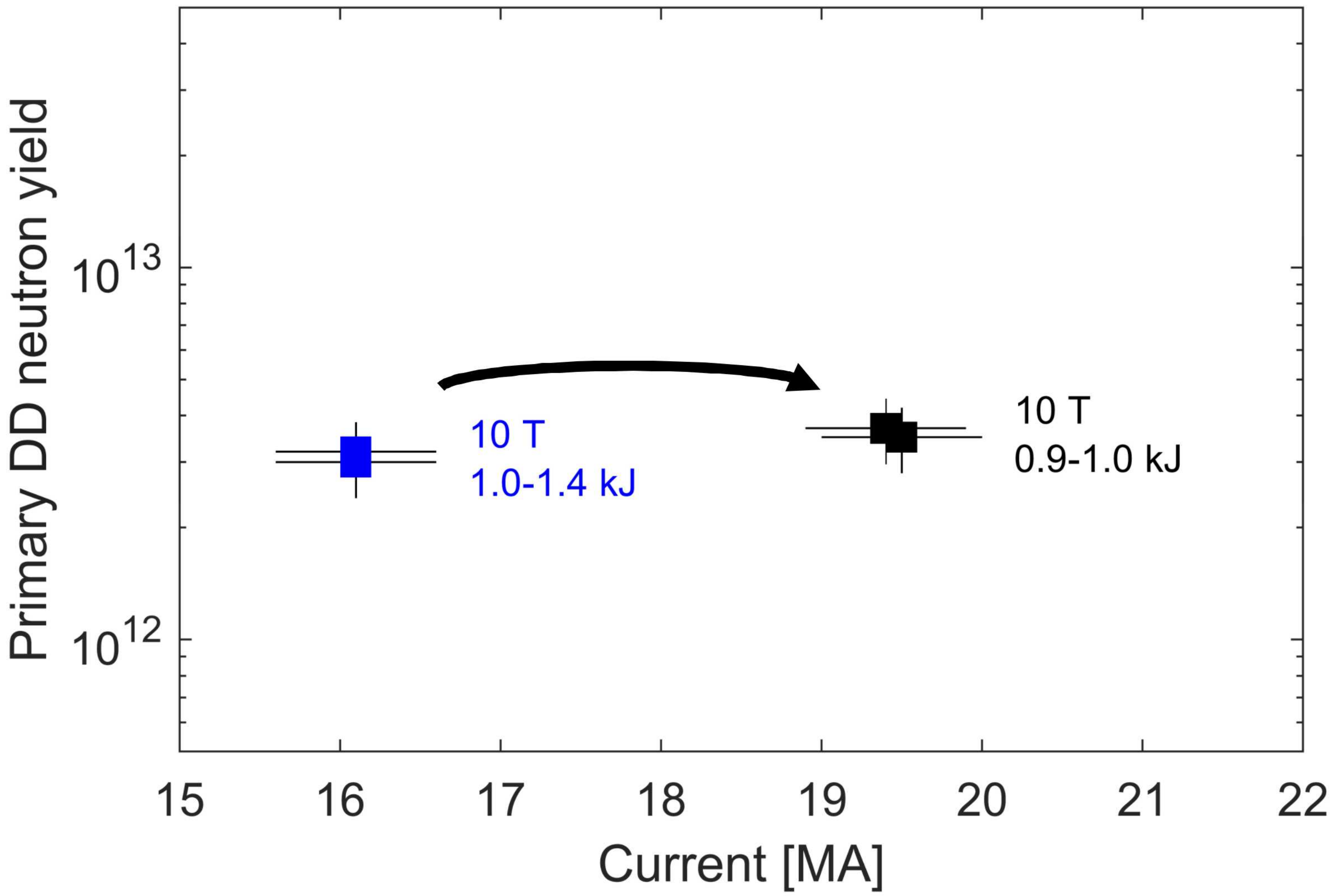
Ion temperature and neutron yield scale as expected with increased B-field

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



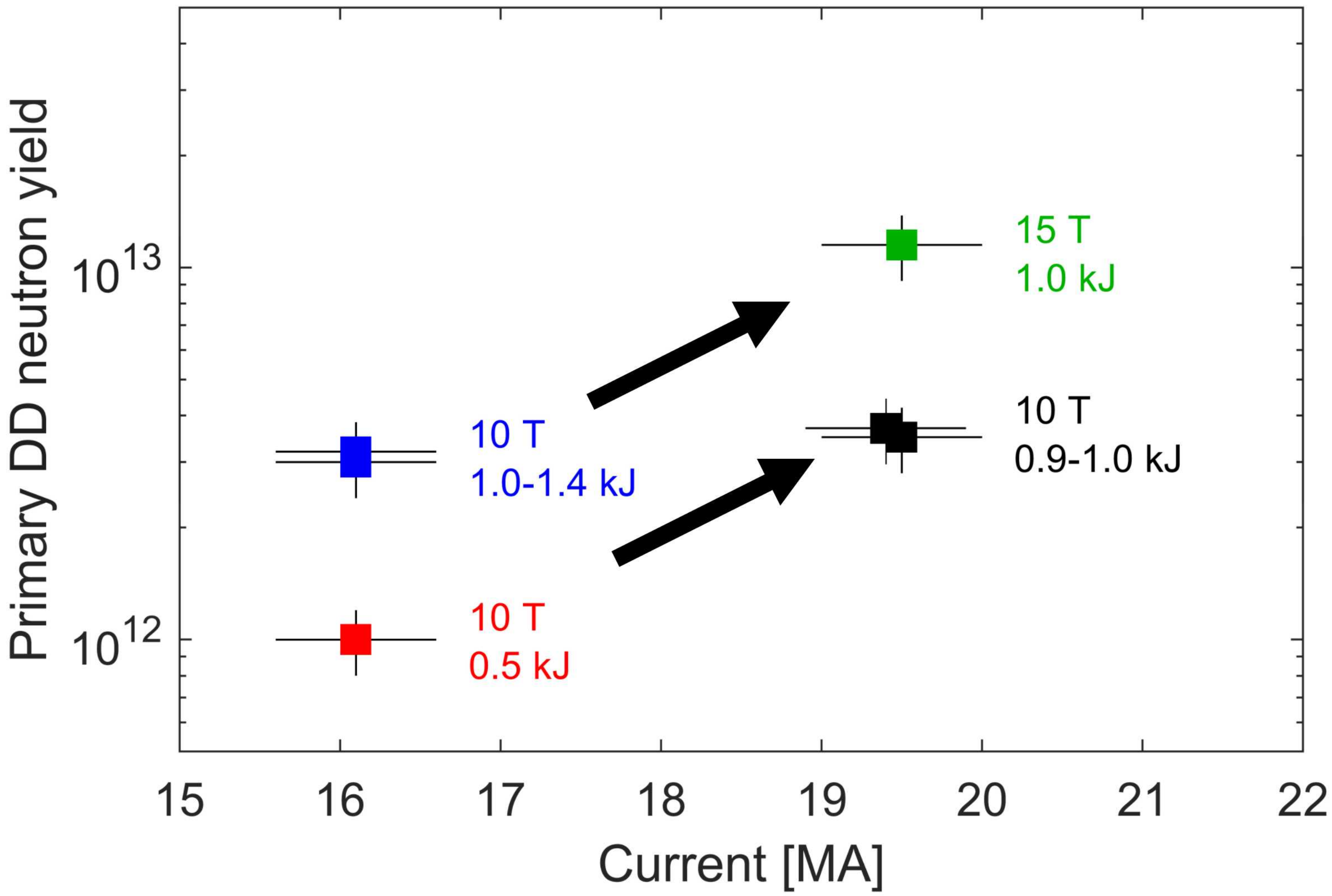
- Increased magnetization reduces thermal conduction losses and decreases the impact of the Nernst effect
- We expected increasing ion temperature with initial B-field, as observed – with higher ion temperatures, the fusion reaction rate increases, so we also expected higher neutron yields

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



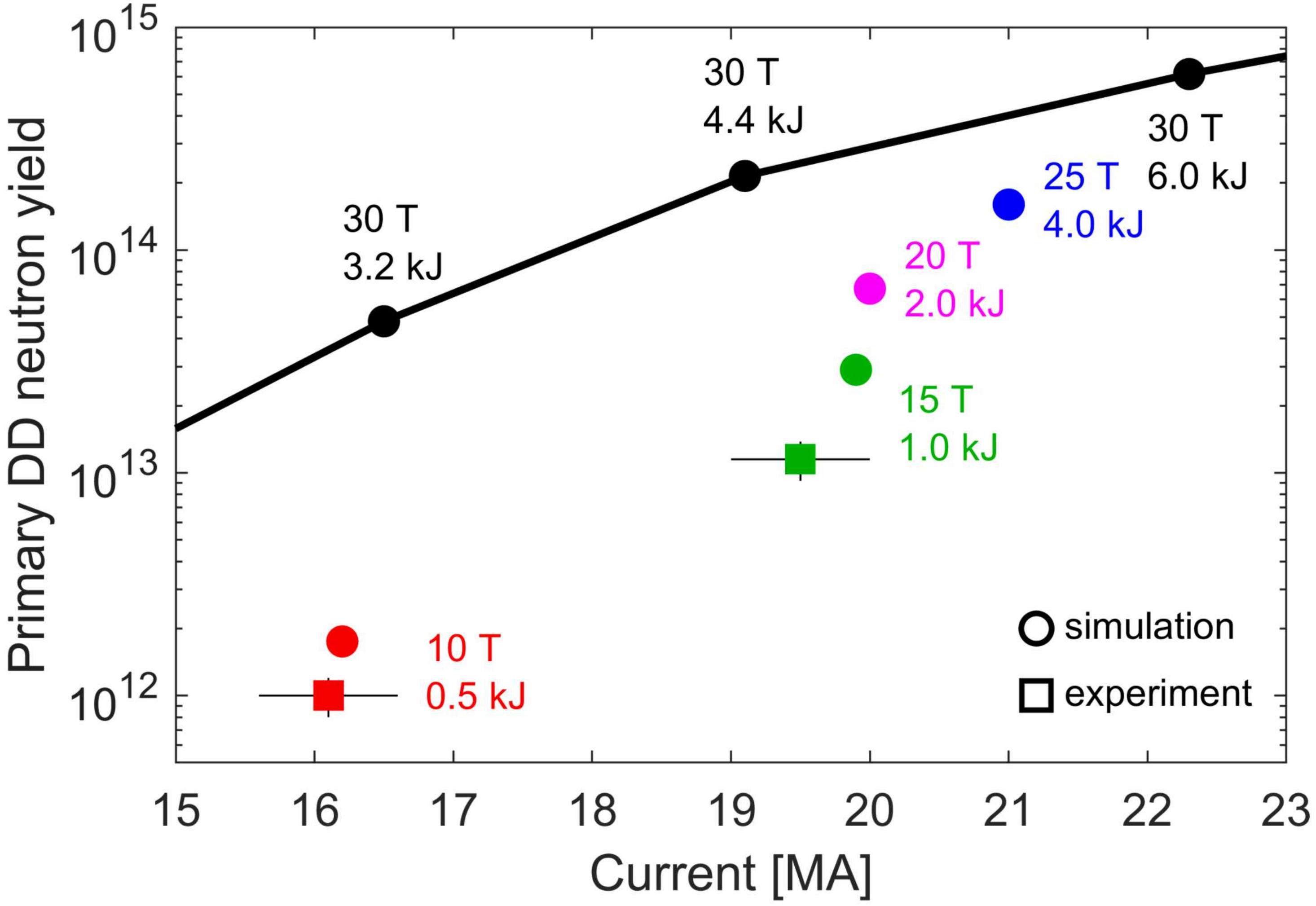
- Simulations predict increased yield but also increased CR with fixed B-field and preheat and increasing current
- Experimental CR ≈ 40
    - We do not observe a significant increase in CR for the higher current case

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



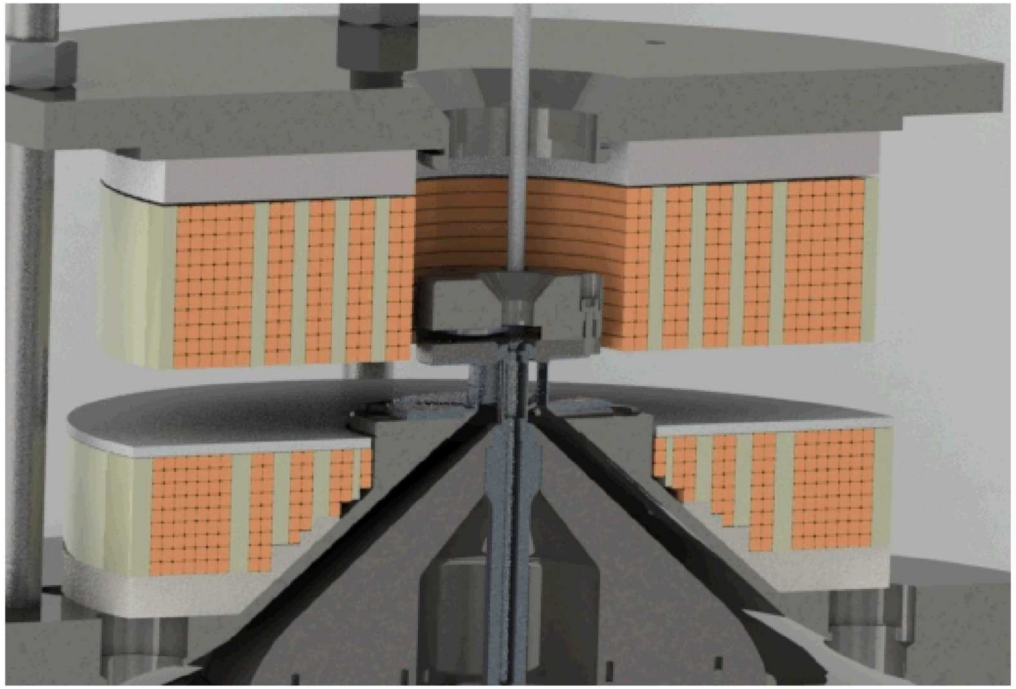
- Simulations predict increased yield but also increased CR with fixed B-field and preheat and increasing current
- Experimental CR ≈ 40
  - We do not observe a significant increase in CR for the higher current case
- When B-field, preheat, and current are increased simultaneously, we observe significantly higher neutron yield as expected
  - Simulations predict decreased convergence (≤30) in the limit of the highest preheat and B-field

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



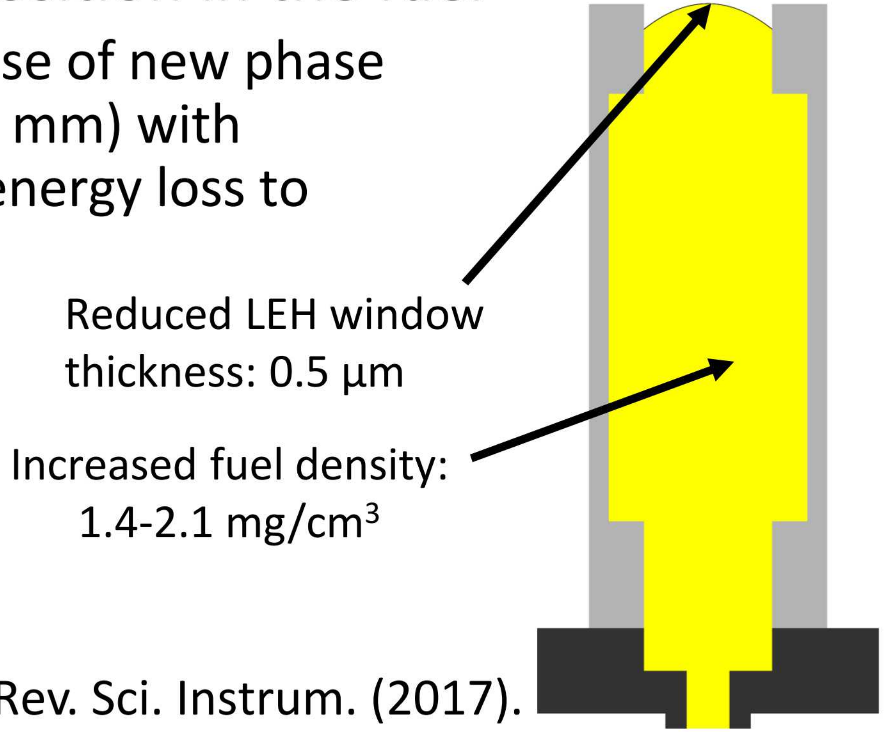
- Our goal is to understand how target dynamics change with magnetization, preheat, and drive current
- With increased capabilities, we can test scaling over a wider range, providing a more complete understanding
- We are targeting 20-25 T, 2-4 kJ of preheat, and 20-21 MA in the next 2 years

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



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

- New laser pulse shape recently tested on Z coupled 1.7 out 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



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

MagLIF has demonstrated the exciting potential of magneto-inertial fusion on the Z machine

- 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