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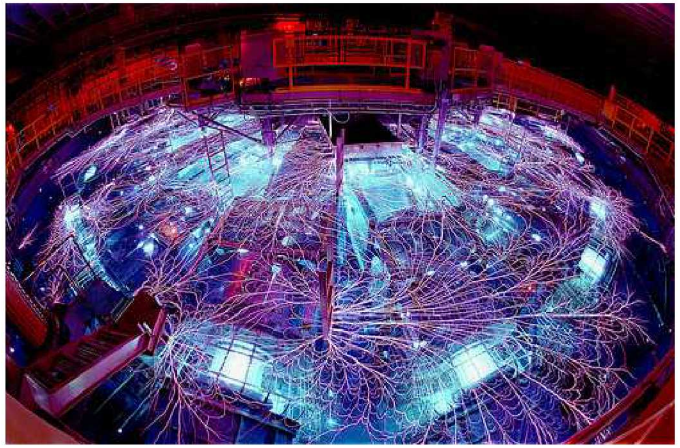

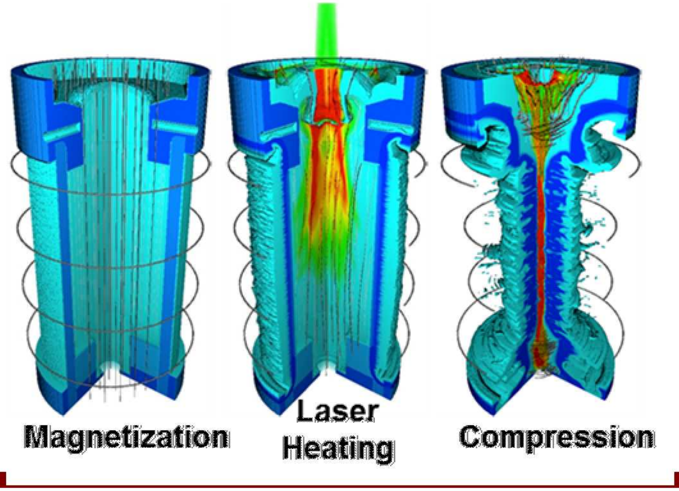

Magneto-inertial fusion: Relaxing the requirements for efficient fusion on the Z machine

Matthew R. Gomez
for the MagLIF team
Sandia National Laboratories

HEDP Seminar at General Atomics

October 3, 2018

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Outline

- **Introduction to magneto-inertial fusion**
  - Intro to Magnetized Liner Inertial Fusion (MagLIF)
- MagLIF experiments
  - Demonstration of the efficacy of magneto-inertial fusion
  - Improving target behavior
  - Identifying scaling trends
- Next generation experiments
  - Architecture of a next-generation pulsed power driver
  - Scaling to future drivers

Nuclear fusion reactions can release a significant amount of energy

$$D + T \xrightarrow[100\%]{} He^4(3.5\ MeV) + n(14.1\ MeV) \qquad [Q = 17.6\ MeV]$$

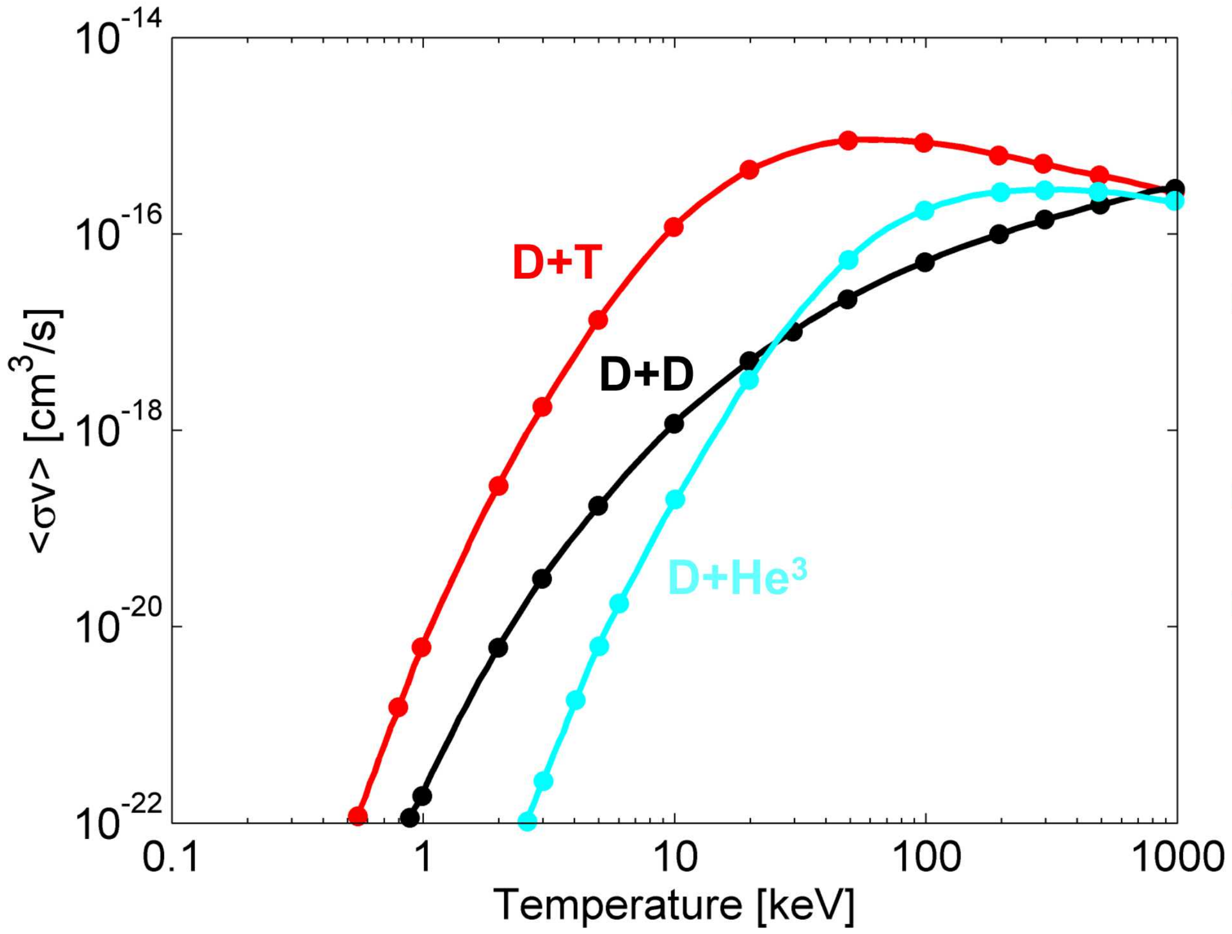
$$D + D \xrightarrow[50\%]{} T(1.01\ MeV) + p(3.02\ MeV) \qquad [Q = 4.03\ MeV]$$

$$\mathrm{D} + \mathrm{D} \xrightarrow[50\%]{} He^3(0.82\ MeV) + n(2.45\ MeV) \qquad [Q = 3.27\ MeV]$$

$$D + \ He^3 \xrightarrow[100\%]{} He^4(3.6\ MeV) + p(14.7\ MeV) \quad [Q = 18.3\ MeV]$$

All of these reactions are between two positively charged nuclei, so we need to the coulomb repulsion between the reactants to get them close enough to fuse

Fusion reactions require extreme temperatures



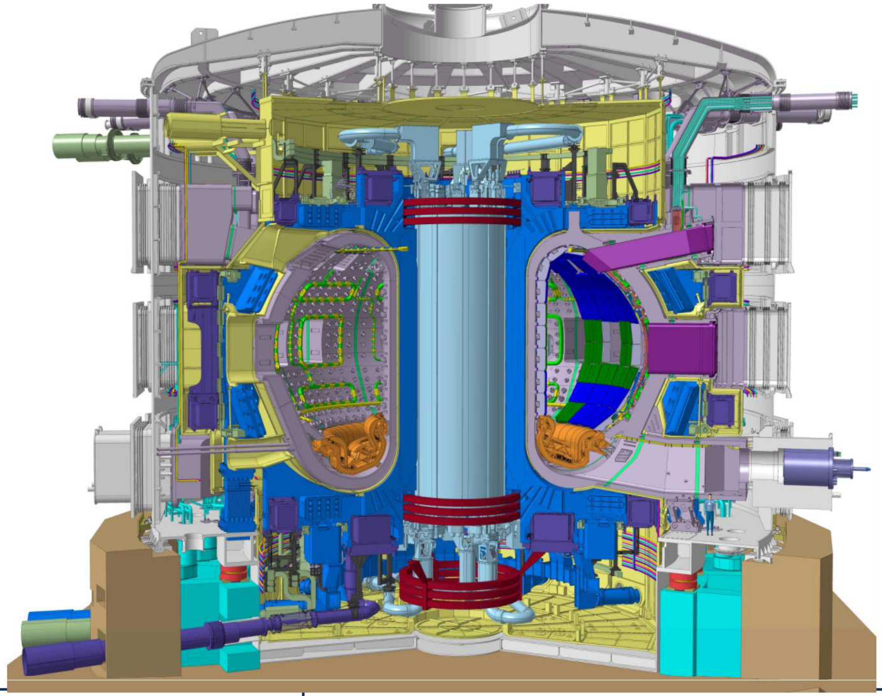
- All reaction rates drop precipitously at low temperatures
- D+T fusion has the highest rate across reasonable temperatures
- D+D fusion does not require tritium
- D+He^3 fusion does not produce neutrons

At these temperatures, confinement is an issue
The two main schemes being pursued are magnetic and inertial confinement

D. Keefe, Ann. Rev. Nucl. Particle Sci. 32, 391 (1982).

Magnetic confinement fusion holds a large volume at low density for a long duration

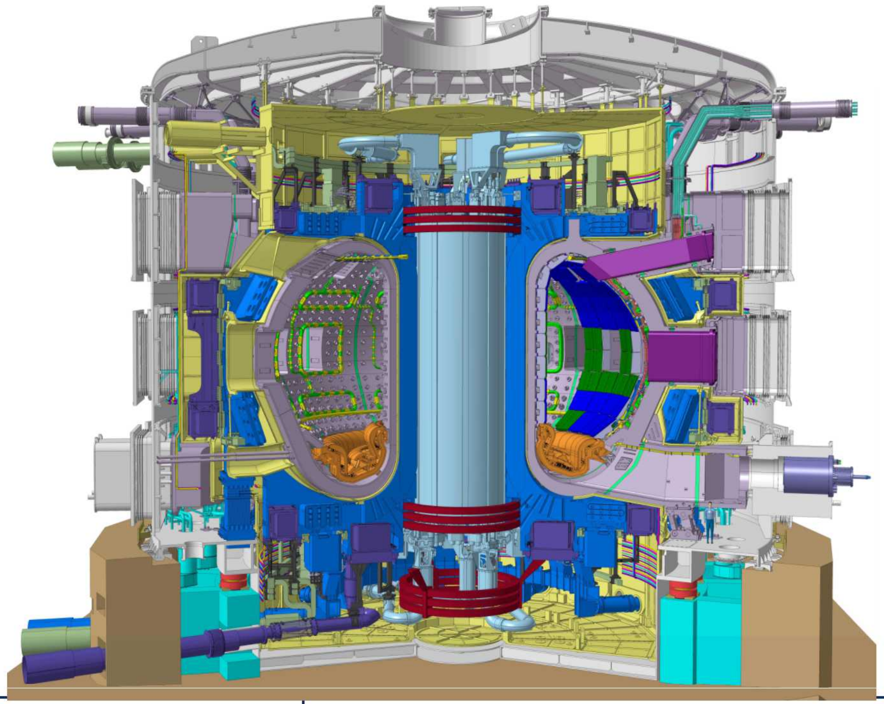
ITER



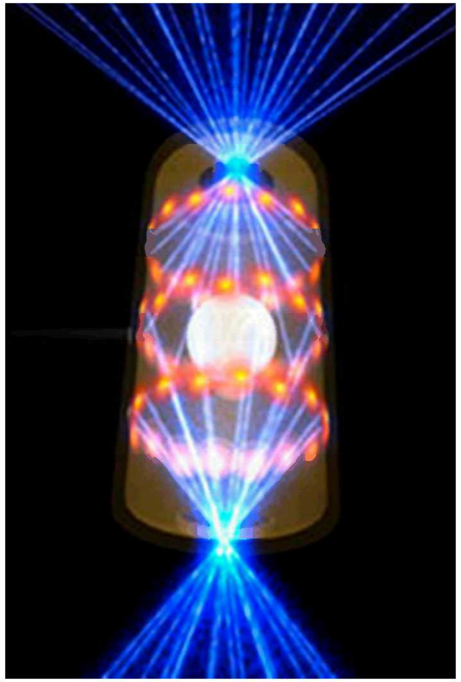
Density	1 x 10^{14} cm^{-3}		
Volume	8 x 10^{8} cm^{3}		
Duration	300-500 s		
Magnetic field	100 kG		

Inertial confinement fusion creates a high density over small volume and short duration

ITER



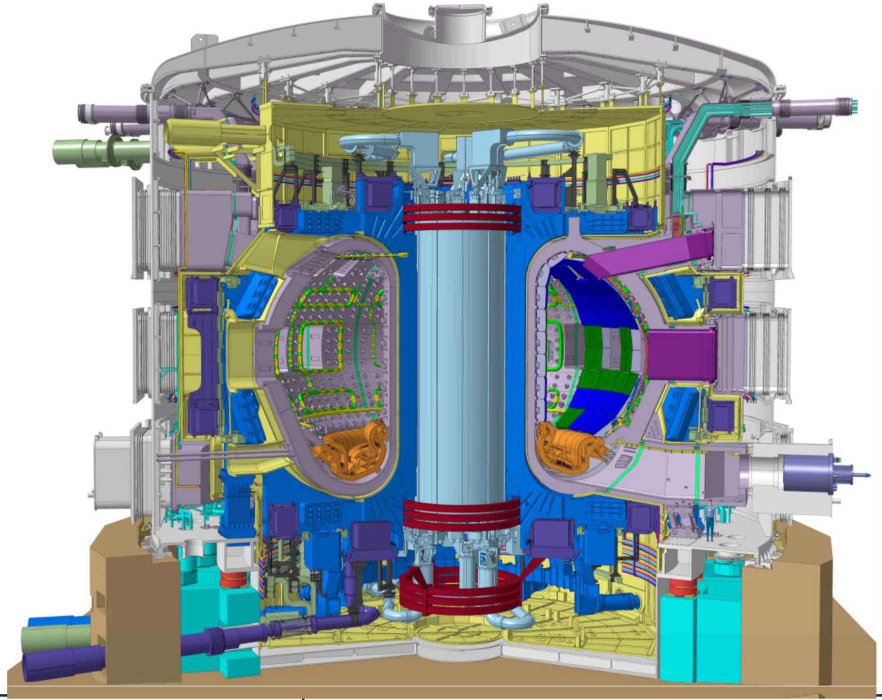
NIF hohlraum



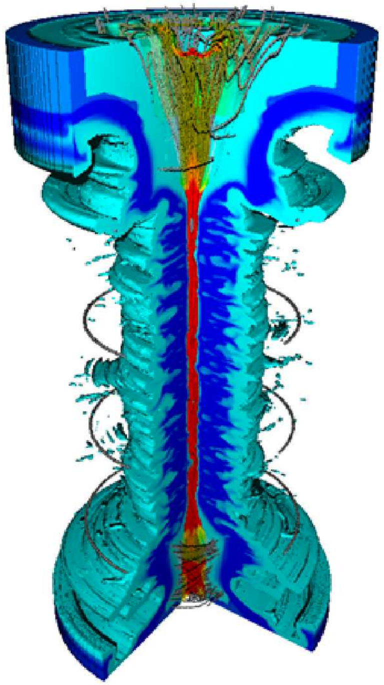
Density	1 x 10^{14} cm^{-3}		2-20 x 10^{25} cm^{-3}
Volume	8 x 10^{8} cm^{3}		6 x 10^{-8} cm^{3}
Duration	300-500 s		5-10 x 10^{-11} s
Magnetic field	100 kG		0 kG

Magneto-inertial fusion sits in the space between the two

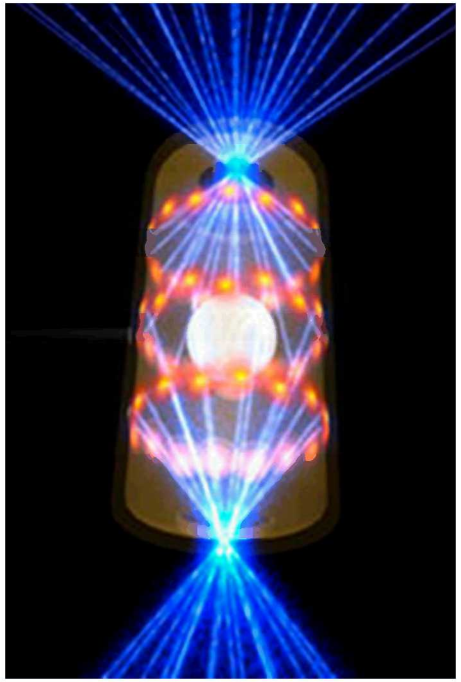
ITER



MagLIF stagnation

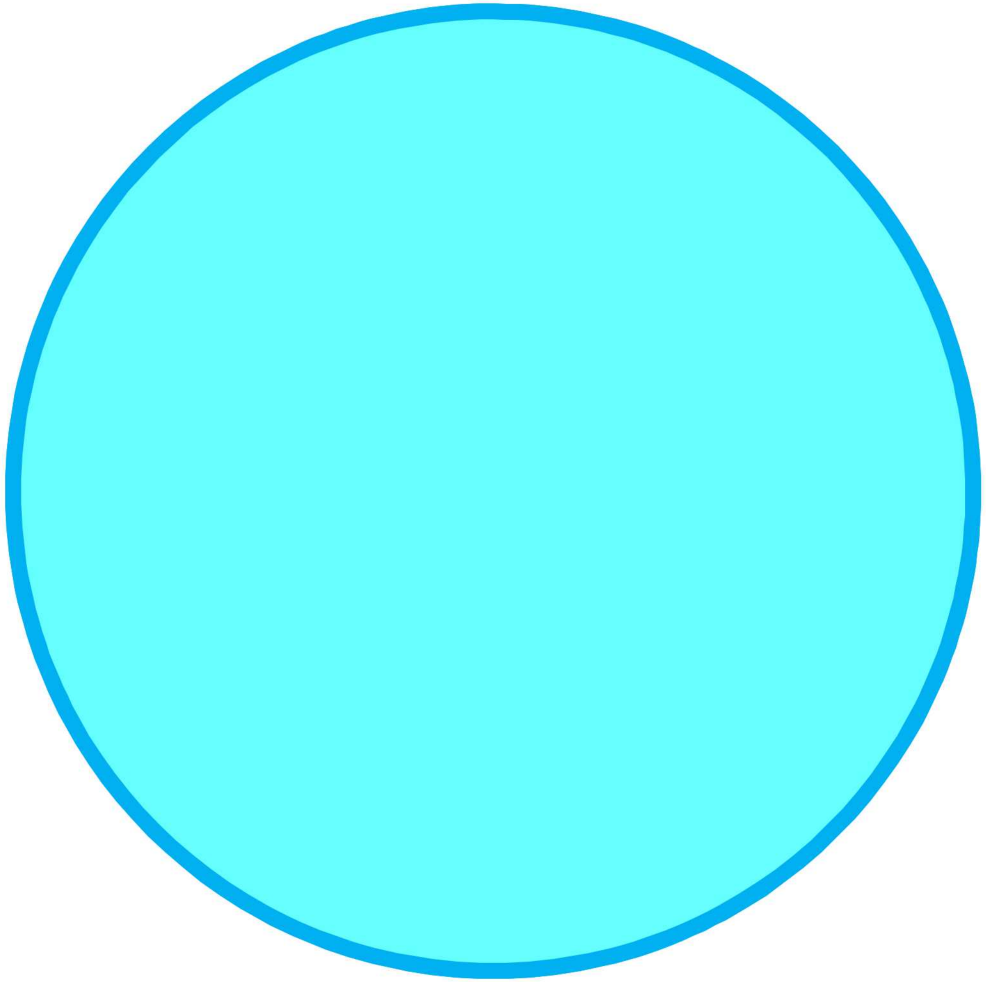


NIF hohlraum



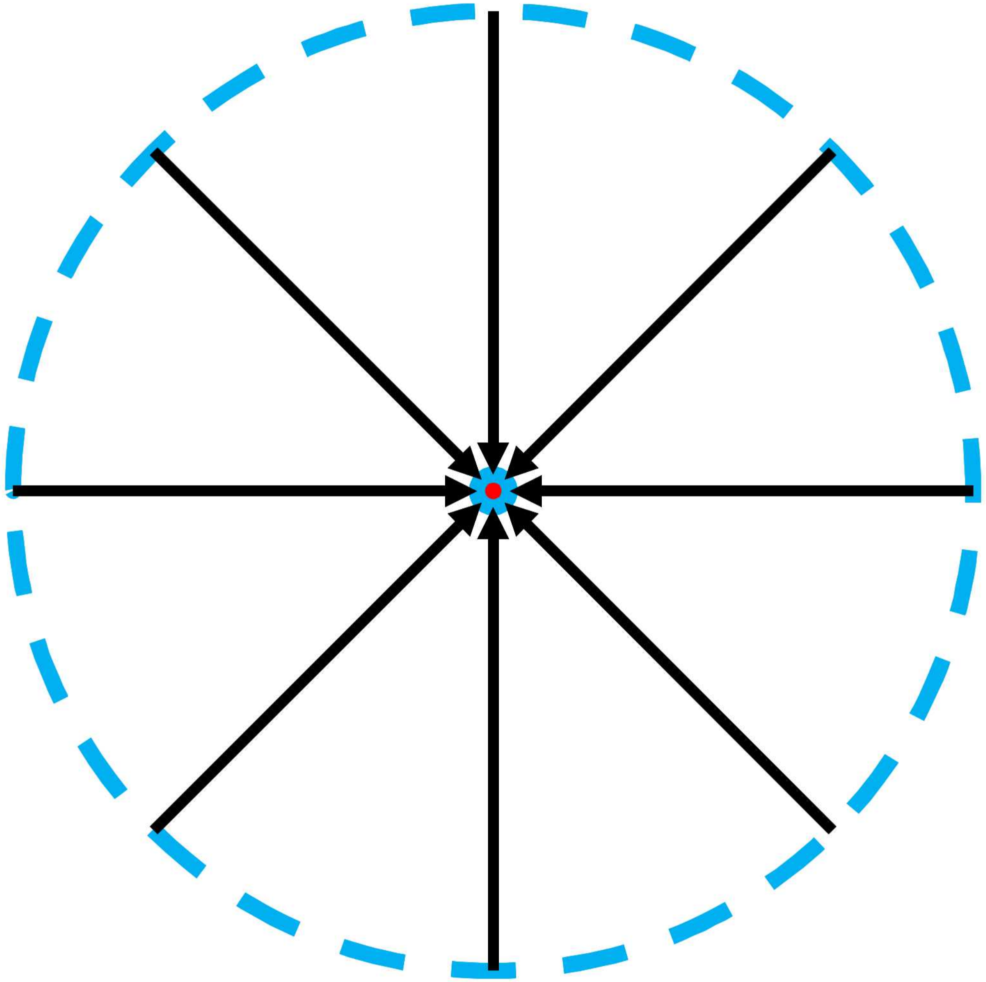
	ITER	MagLIF stagnation	NIF hohlraum
Density	1 x 10^{14} cm^{-3}	1 x 10^{23} cm^{-3}	2-20 x 10^{25} cm^{-3}
Volume	8 x 10^{8} cm^{3}	8 x 10^{-5} cm^{3}	6 x 10^{-8} cm^{3}
Duration	300-500 s	1-2 x 10^{-9} s	5-10 x 10^{-11} s
Magnetic field	100 kG	50-100 MG	0 kG

Since we are building from ICF, let's quickly review traditional ICF



- Start with a sphere containing DT

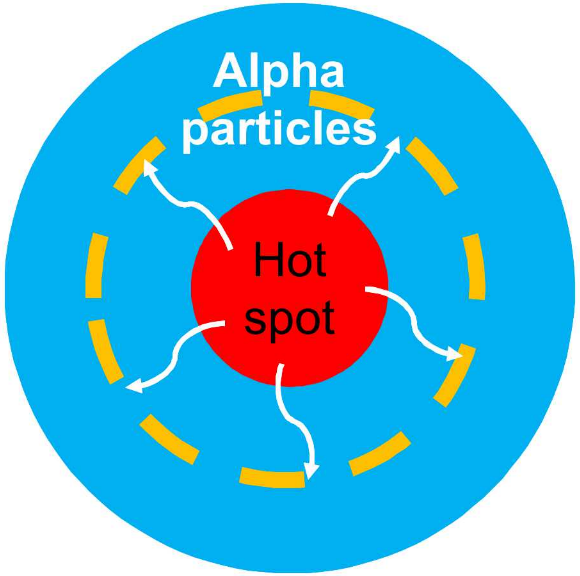
Since we are building from ICF, let's quickly review traditional ICF



- Start with a sphere containing DT
- Implode the sphere
  - Compress radius by ~30
    (volume decreases by ~27,000)
  - Series of shocks heat the center
    (hot spot)

Since we are building from ICF, let's quickly review traditional ICF

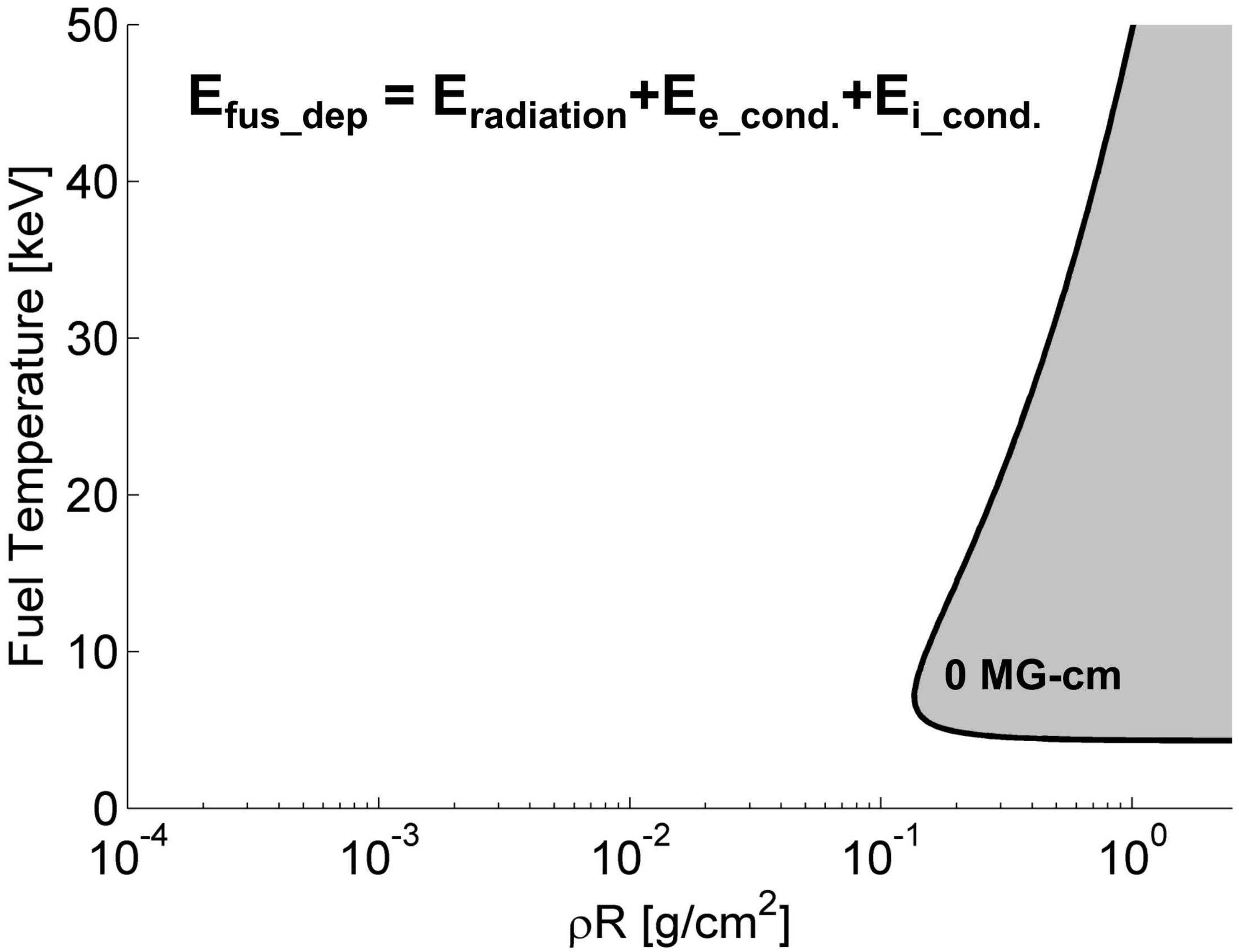
Zooming in



Cooler, dense shell

- Start with a sphere containing DT
- Implode the sphere
  - Compress radius by 30 (volume by 27,000)
  - Series of shocks heat the center (hot spot)
- Fuel in hot spot undergoes fusion
  - Fusion products heat surrounding dense fuel
- With a favorable power balance, a chain reaction occurs

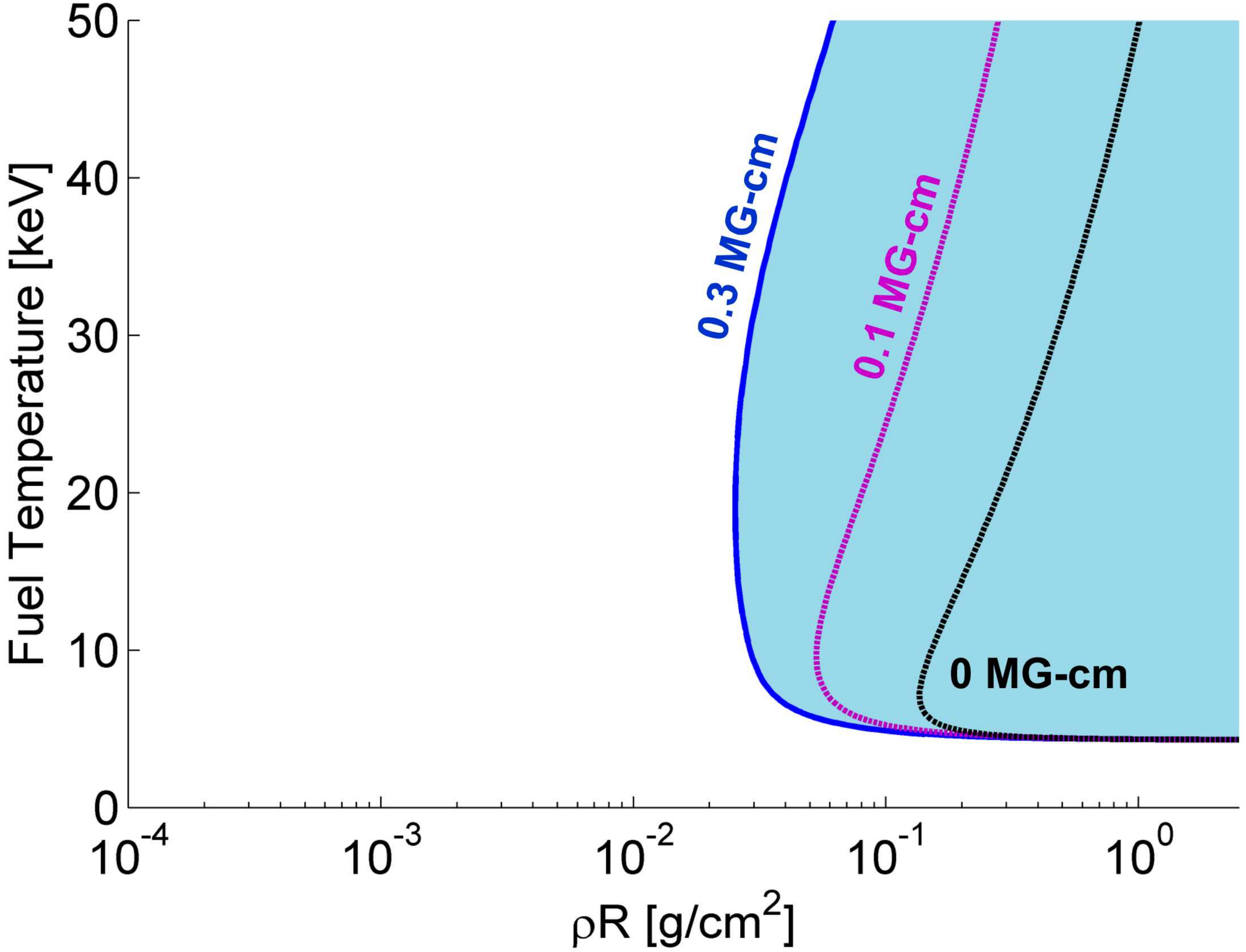
ICF has requirements on stagnation conditions to propagate a burn wave



- There is a minimum fuel temperature of about 4.5 keV
  - This is where fusion heating outpaces radiation losses
- The minimum fuel areal density is around 0.2 g/cm^2
- Traditional ICF concepts attempt to operate in this minimum

P. F. Knapp, et al., Phys. Plasmas 22, 056312 (2015).

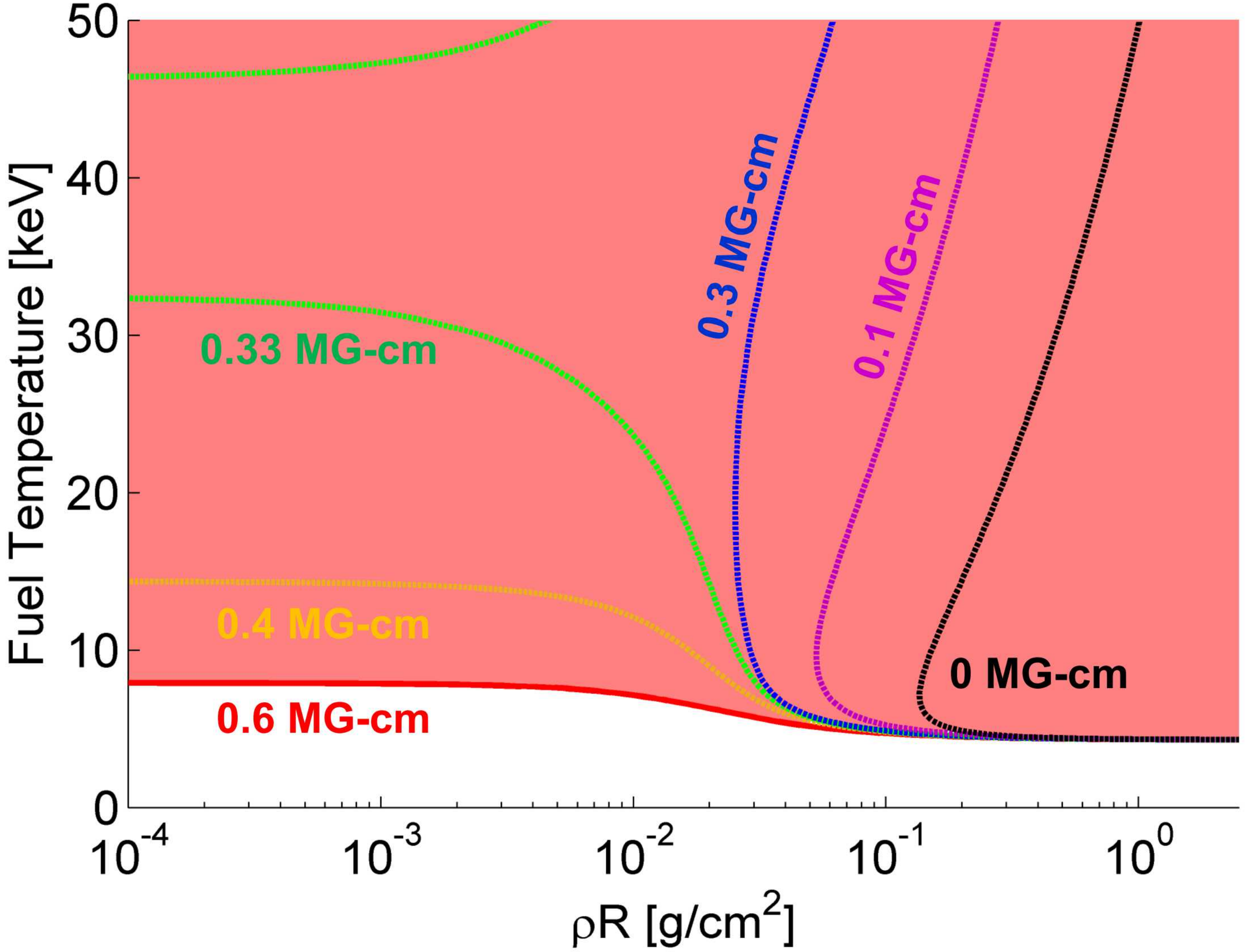
Magneto-inertial fusion utilizes magnetic fields to relax the stagnation requirements of ICF



- Applying a magnetic field opens up a larger region of parameter space
- The minimum temperature does not change because it is driven by radiation losses
- At 0.3 MG-cm, the Larmor radius of fusion alphas is approximately the radius of the fuel

P. F. Knapp, et al., Phys. Plasmas 22, 056312 (2015).

Magneto-inertial fusion utilizes magnetic fields to relax the stagnation requirements of ICF



- With a high enough magnetic-field-radius product, most charged fusion products become trapped
- This relaxes the areal density requirement of the fuel
- Good performance is possible over a much larger region of parameter space

P. F. Knapp, et al., Phys. Plasmas 22, 056312 (2015).

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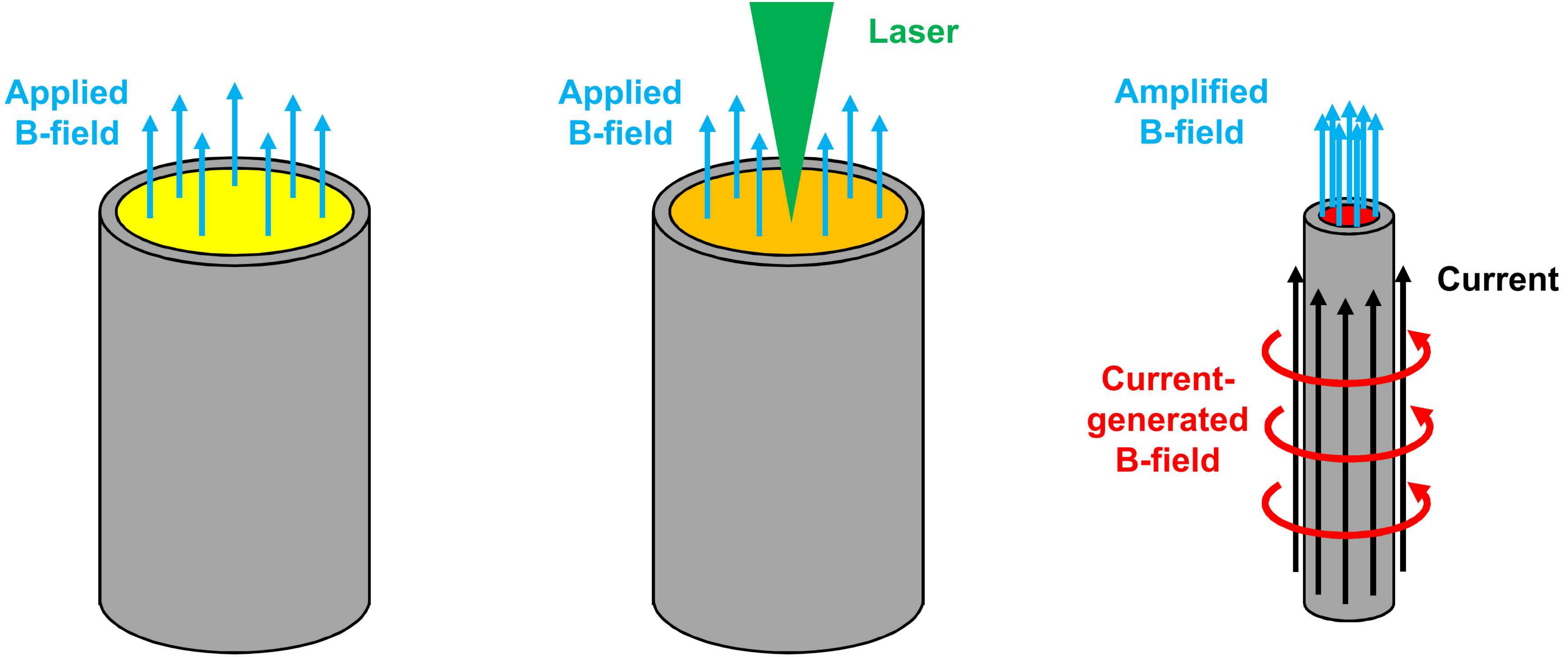
Magnetized Liner Inertial Fusion relies on three stages to produce fusion relevant conditions



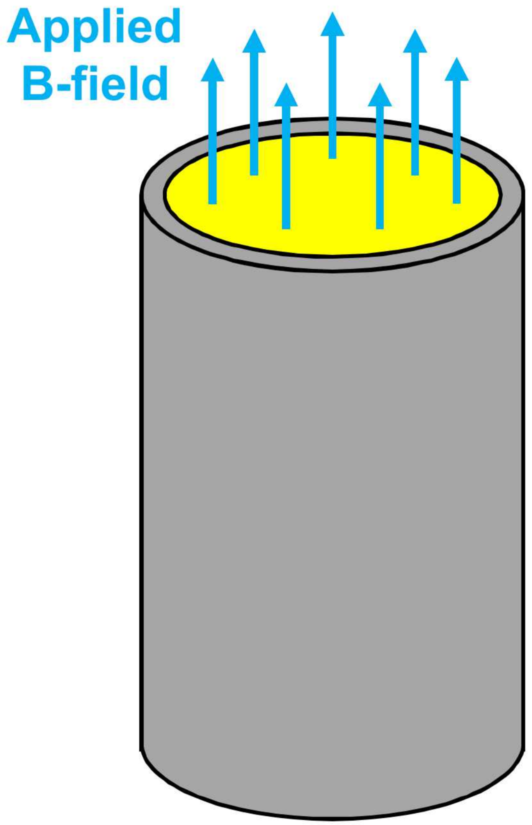
Apply axial magnetic field

Laser-heat the magnetized fuel

Compress the heated and magnetized fuel

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

We start with a metal cylinder containing fusion fuel

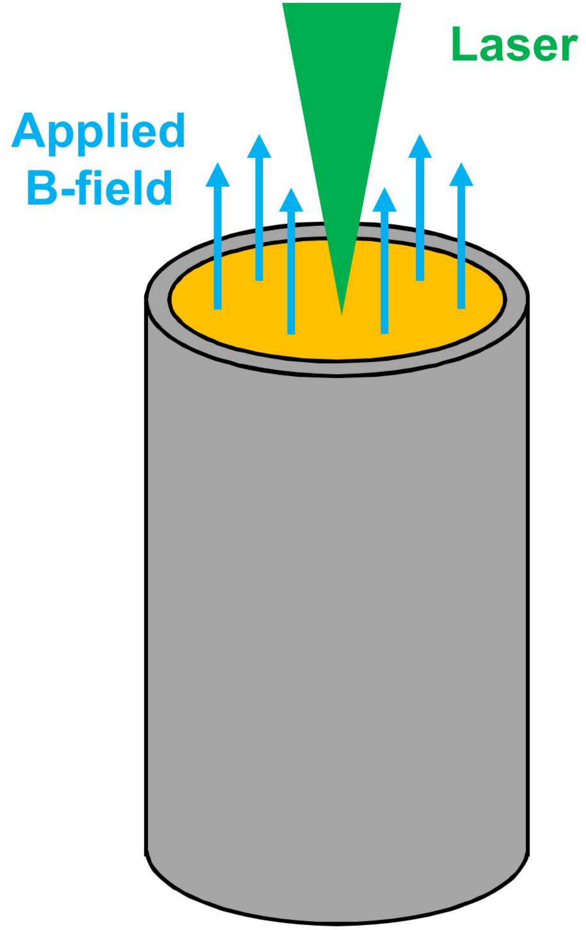


Apply axial magnetic field

- The metal cylinder (also called a liner or target) is 10 mm tall, about 5 mm in diameter, and has a wall thickness of about 0.5 mm
  - The fuel is about 1 mg/cc of deuterium gas
- Helmholtz-like coils apply 10s of T
  - few ms risetime to allow field to diffuse through conductors
  - The field will limit thermal transport in the radial direction when the fuel has been converted to a plasma

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

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

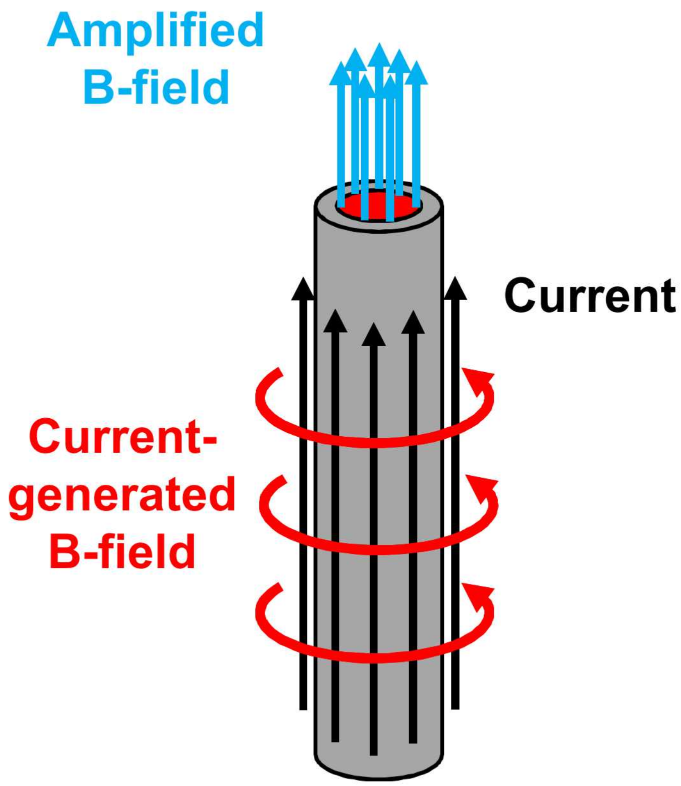


Laser-heat the magnetized fuel

- A green (527 nm) laser is used to heat the fuel in a few ns with a few kJ of energy
- 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).

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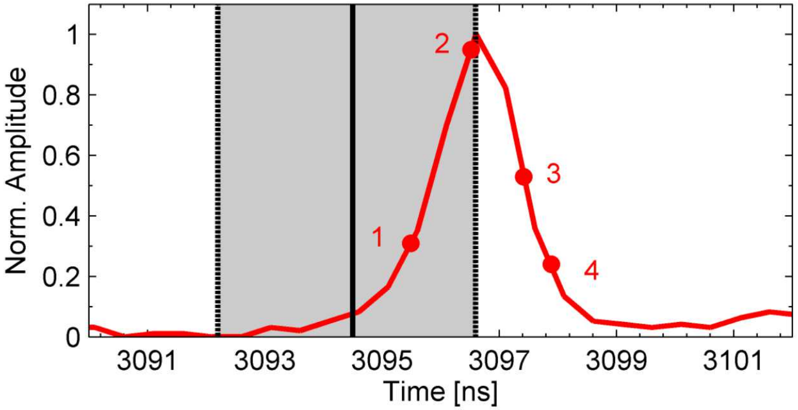
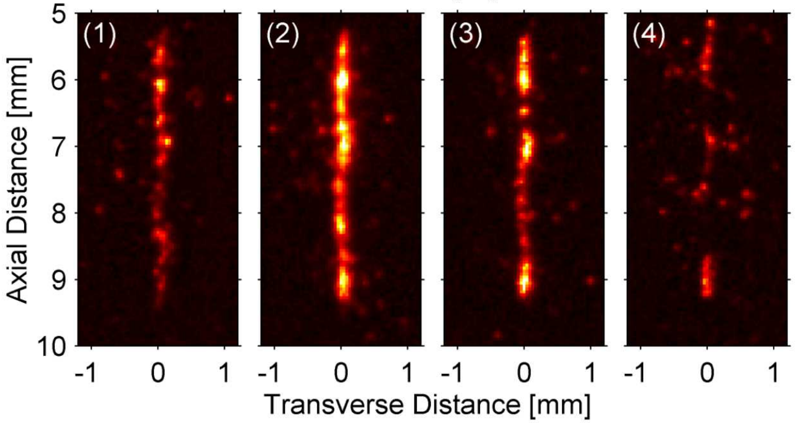
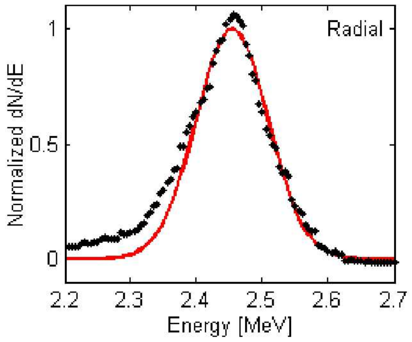
We collect a wide range of data to assess stagnation

Filtered x-ray powers

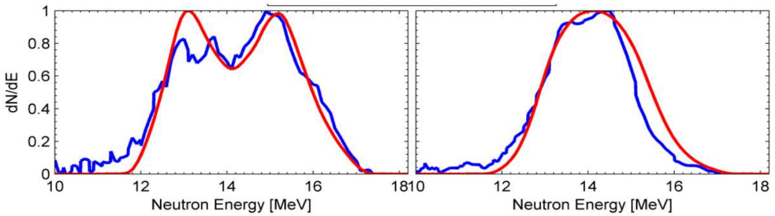


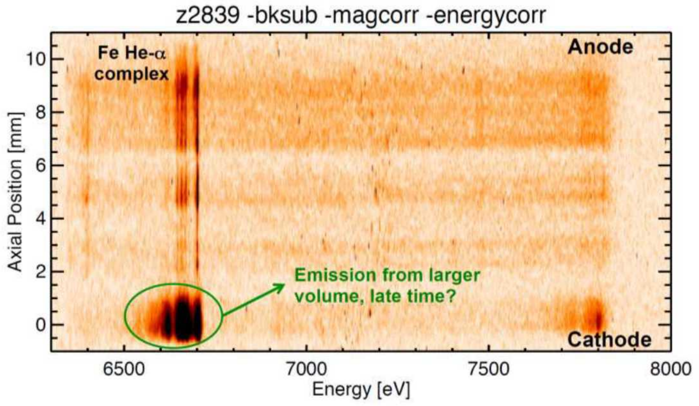


Time-resolved x-ray pinhole images

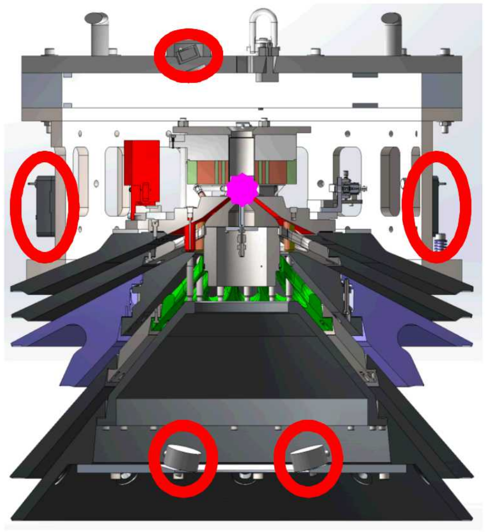


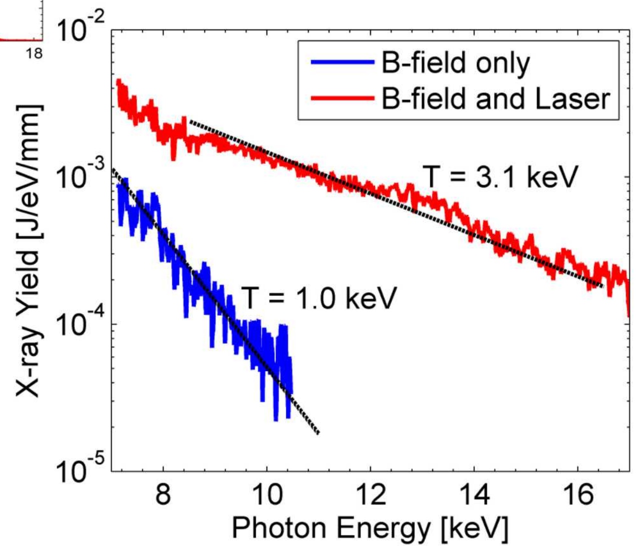
Primary and Secondary neutron yield and spectra





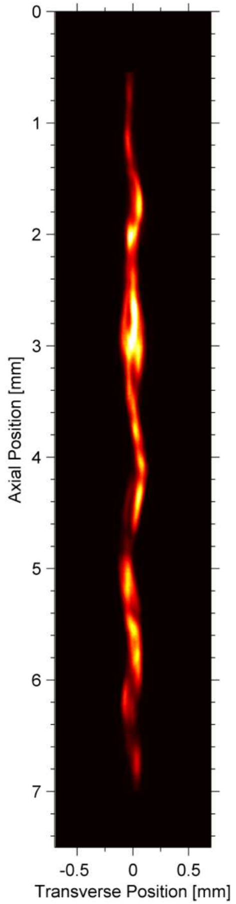
High resolution x-ray spectra





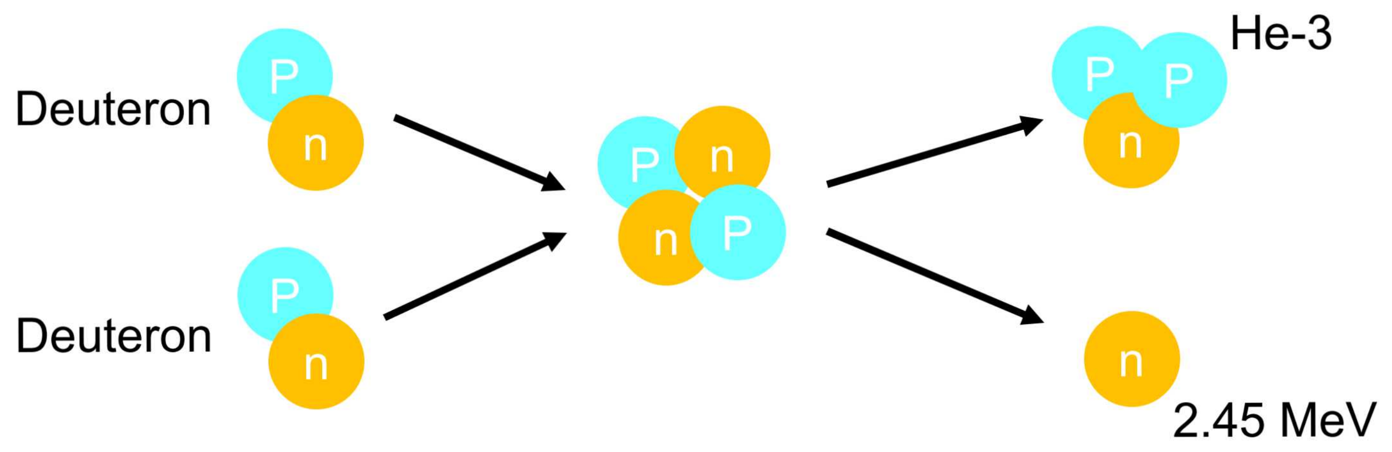
High energy x-ray spectra

Time-integrated high resolution images



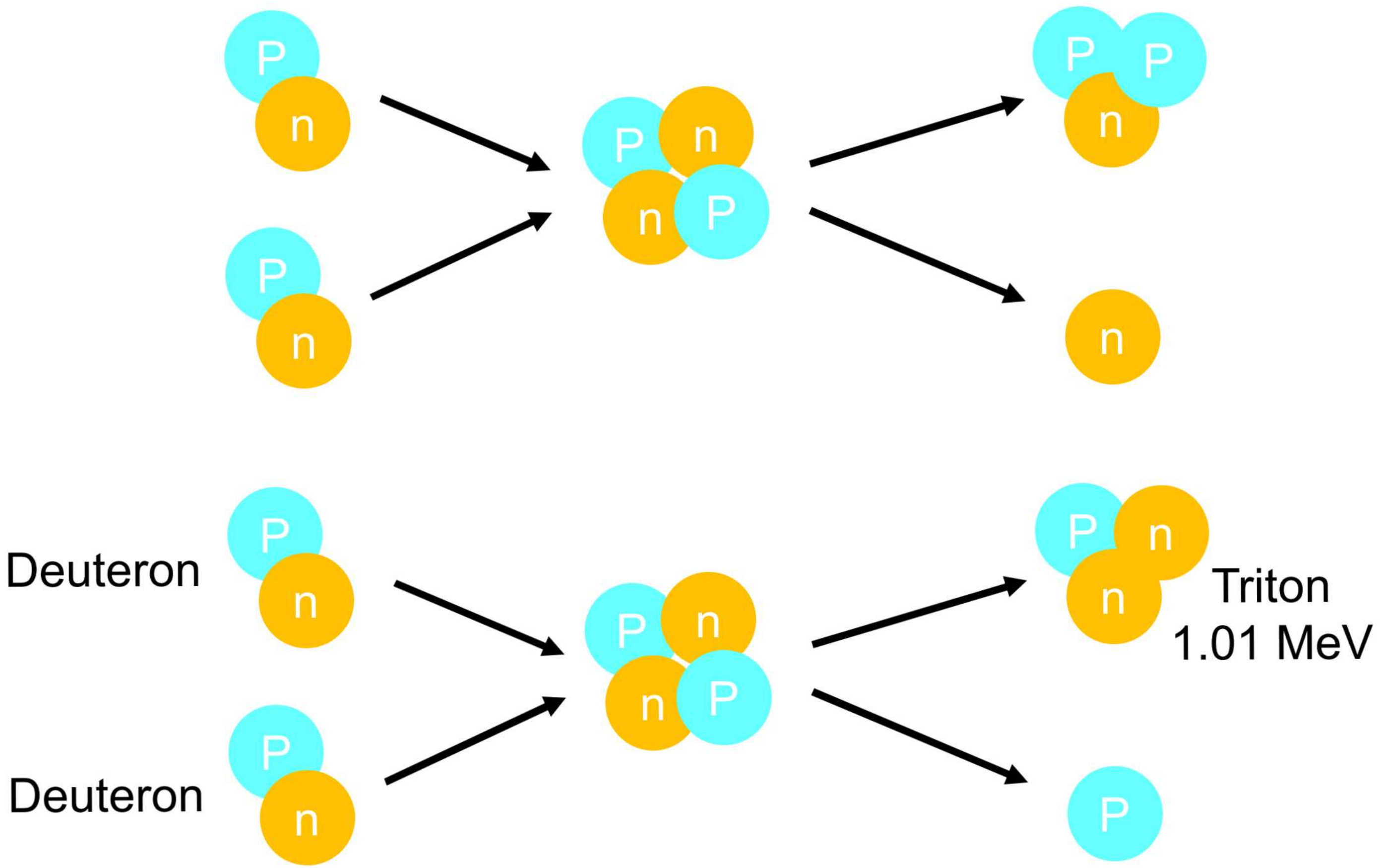
The fuel in these experiments is deuterium gas: one branch produces a neutron…

Primary Reactions

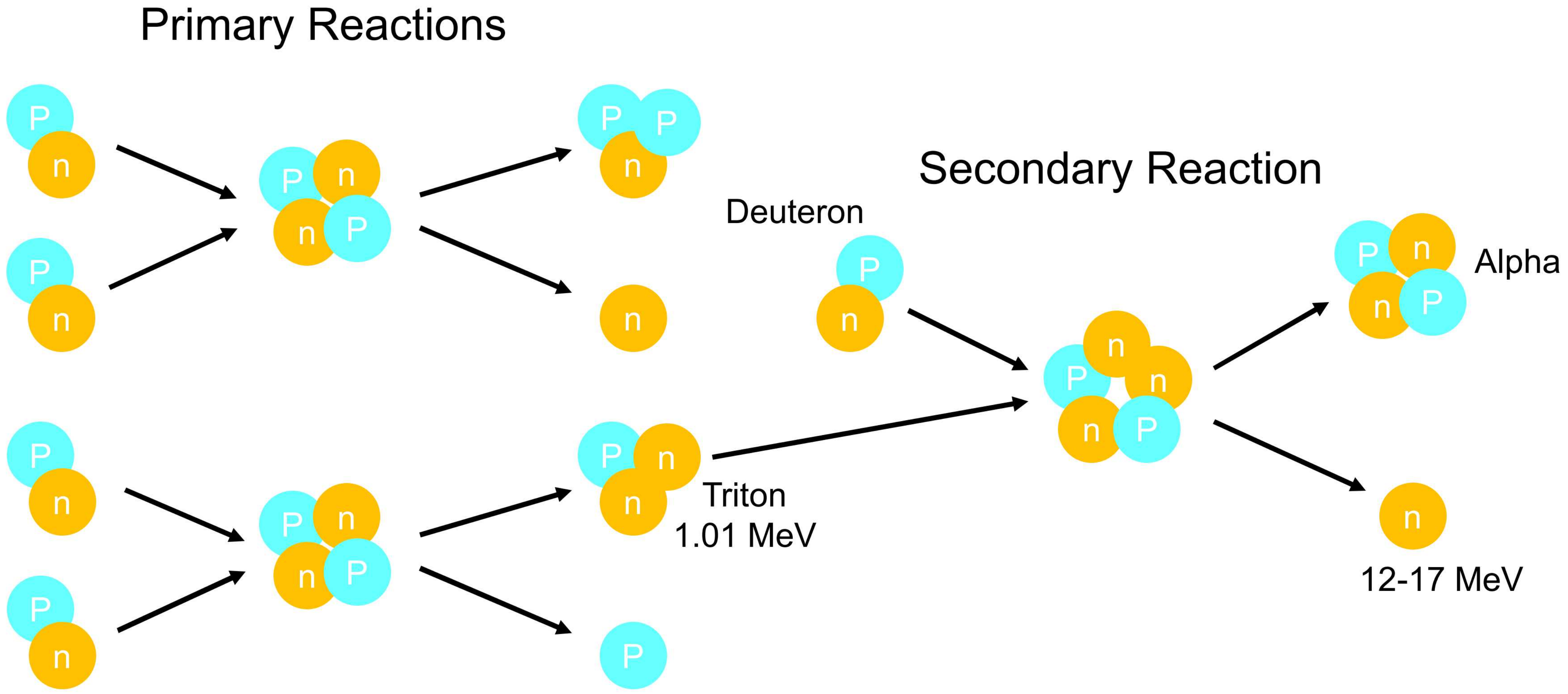


…and the other branch produces a triton…

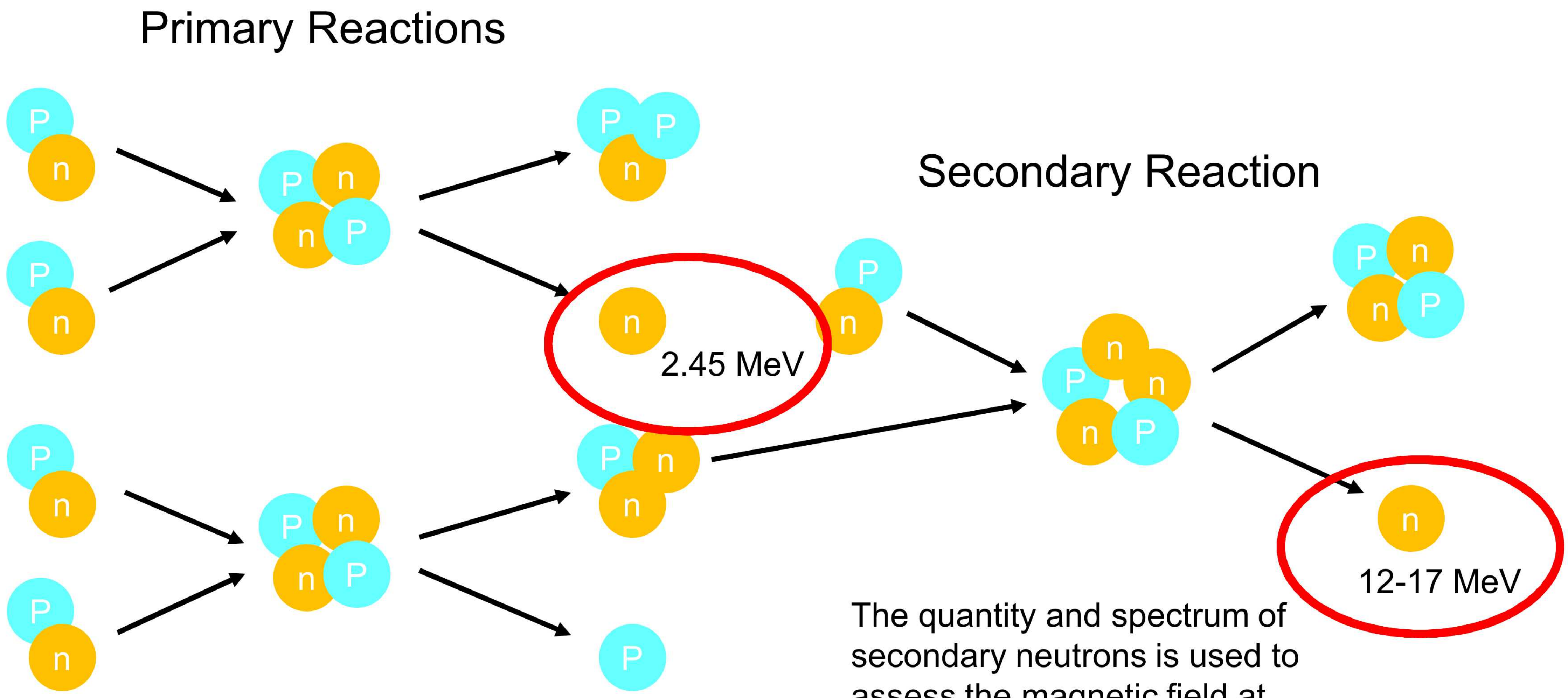
Primary Reactions



…which can fuse with a deuteron to produce a higher energy neutron



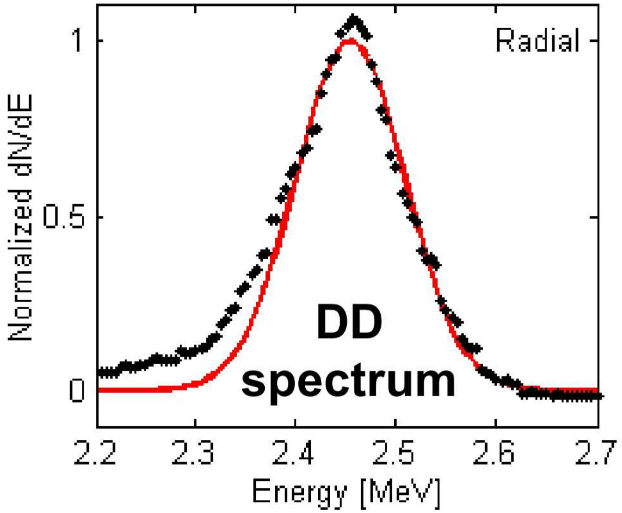
We measure both the primary and secondary neutrons



The quantity and spectrum of secondary neutrons is used to assess the magnetic field at stagnation

K. D. Hahn, et al., Rev. Sci. Instrum. 85, 043507 (2014).

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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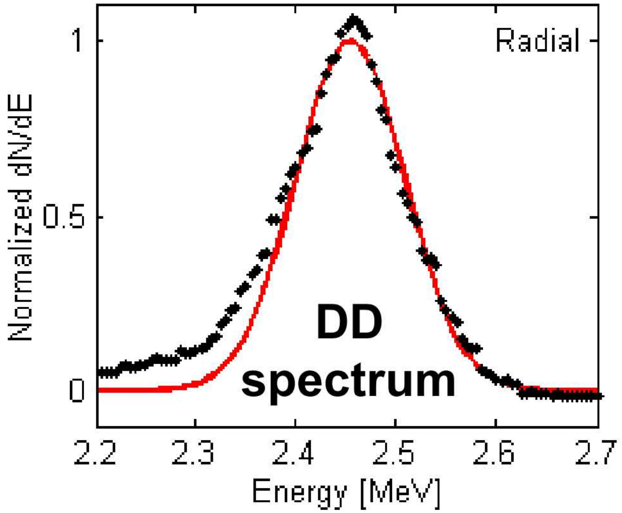
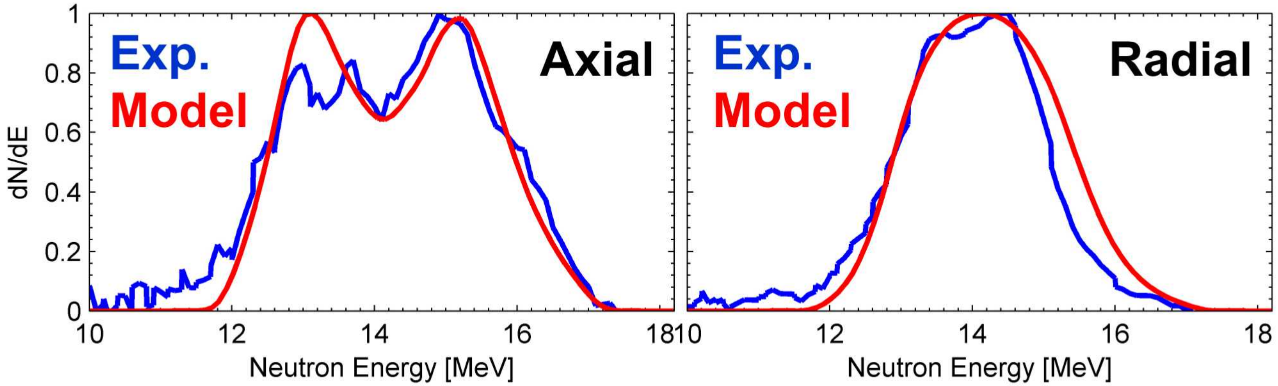


Thermonuclear neutron generation with fusion-relevant ion temperatures (2-3 keV)

Secondary DT Neutron Spectra



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

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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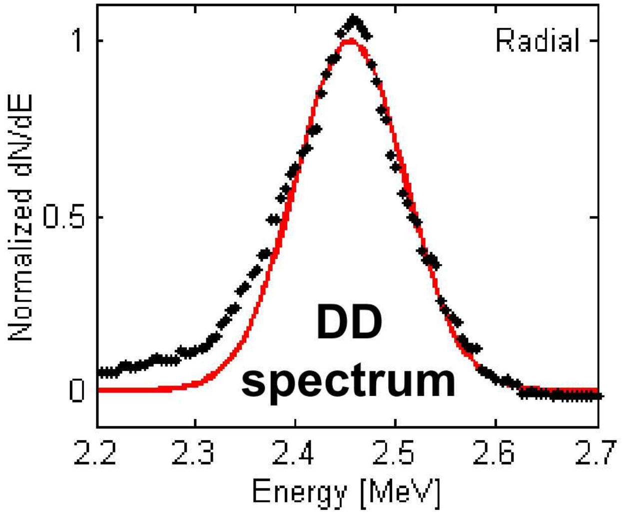
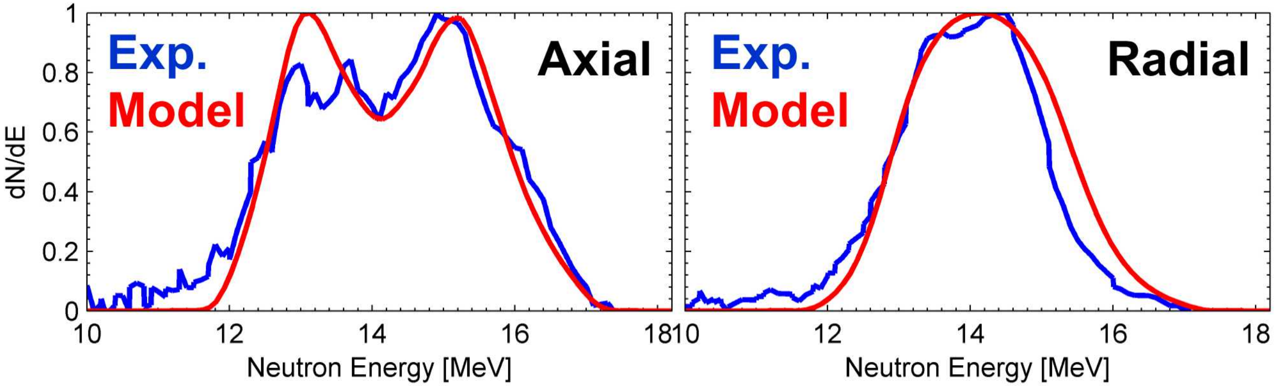


Thermonuclear neutron generation with fusion-relevant ion temperatures (2-3 keV)

Relatively stable fuel column at CR > 30

Secondary DT Neutron Spectra



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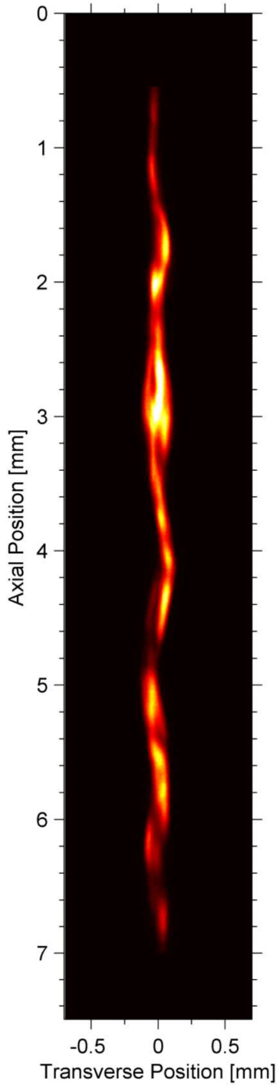

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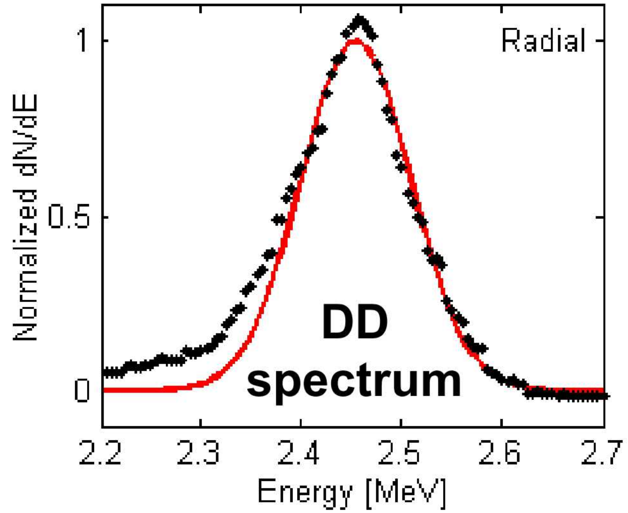

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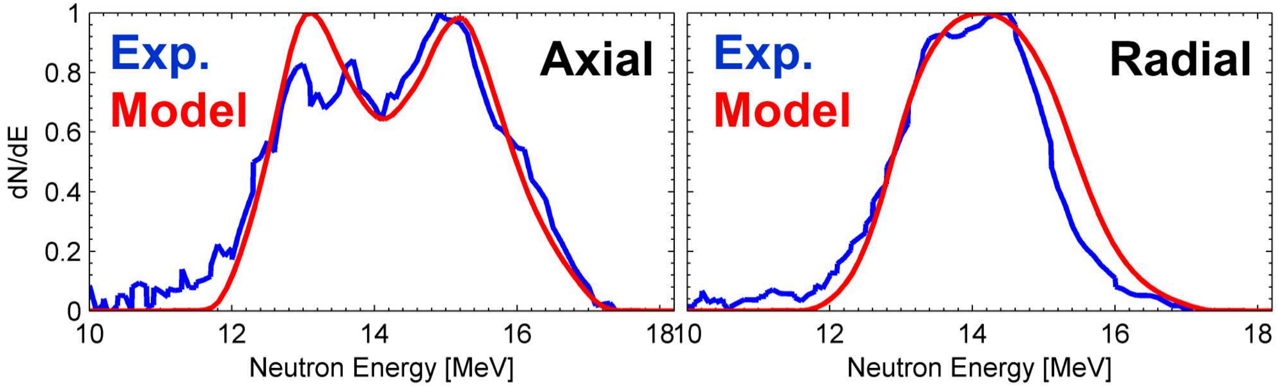

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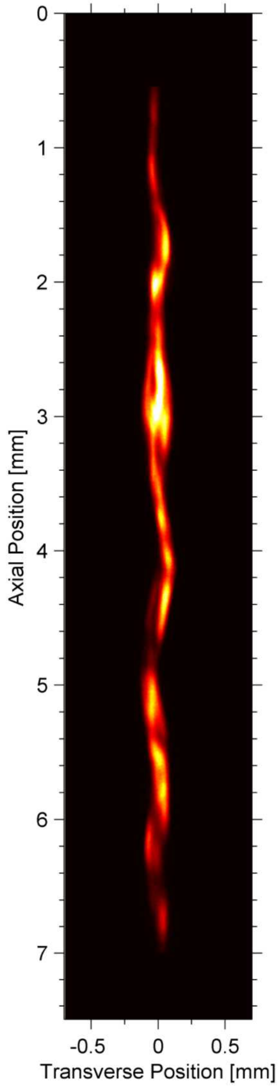

	No B-field	B-field
No Laser	3e9	1e10
Laser	4e10	2e12

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

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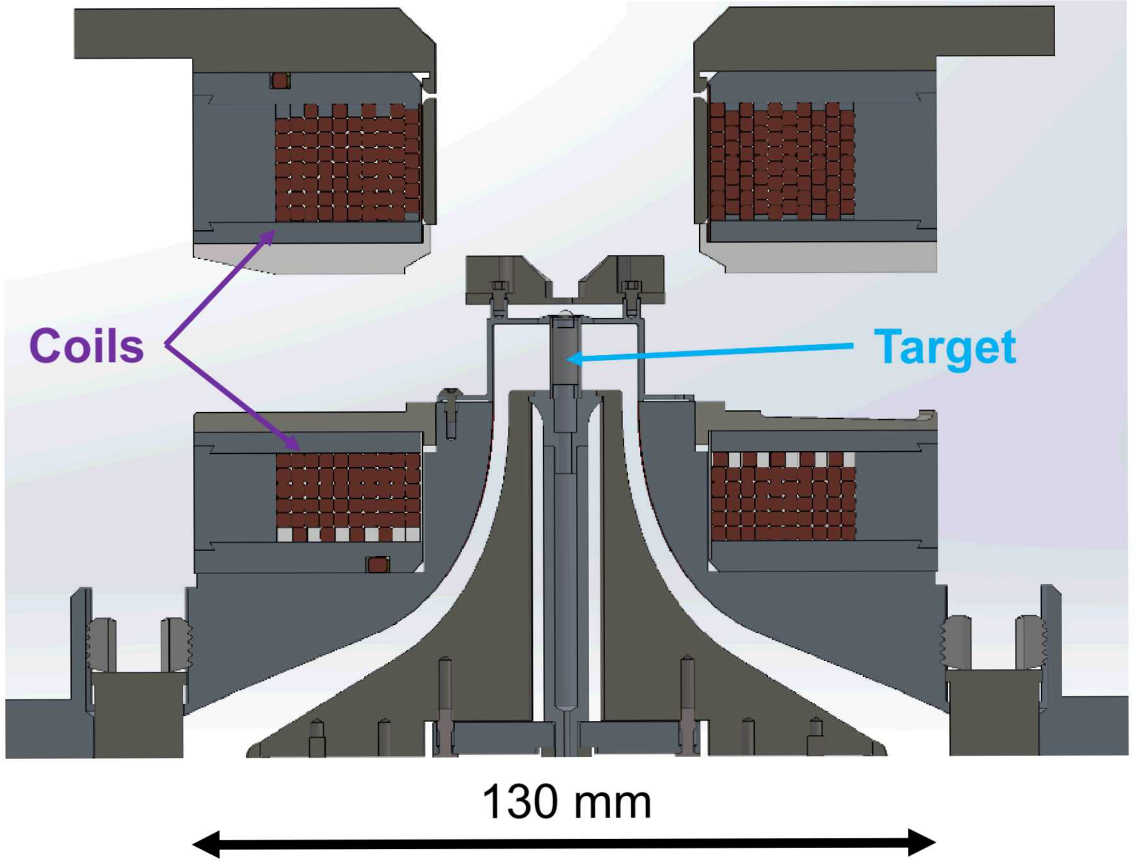
With our initial experiments, we targeted 2 kJ, 10 T, and 18 MA



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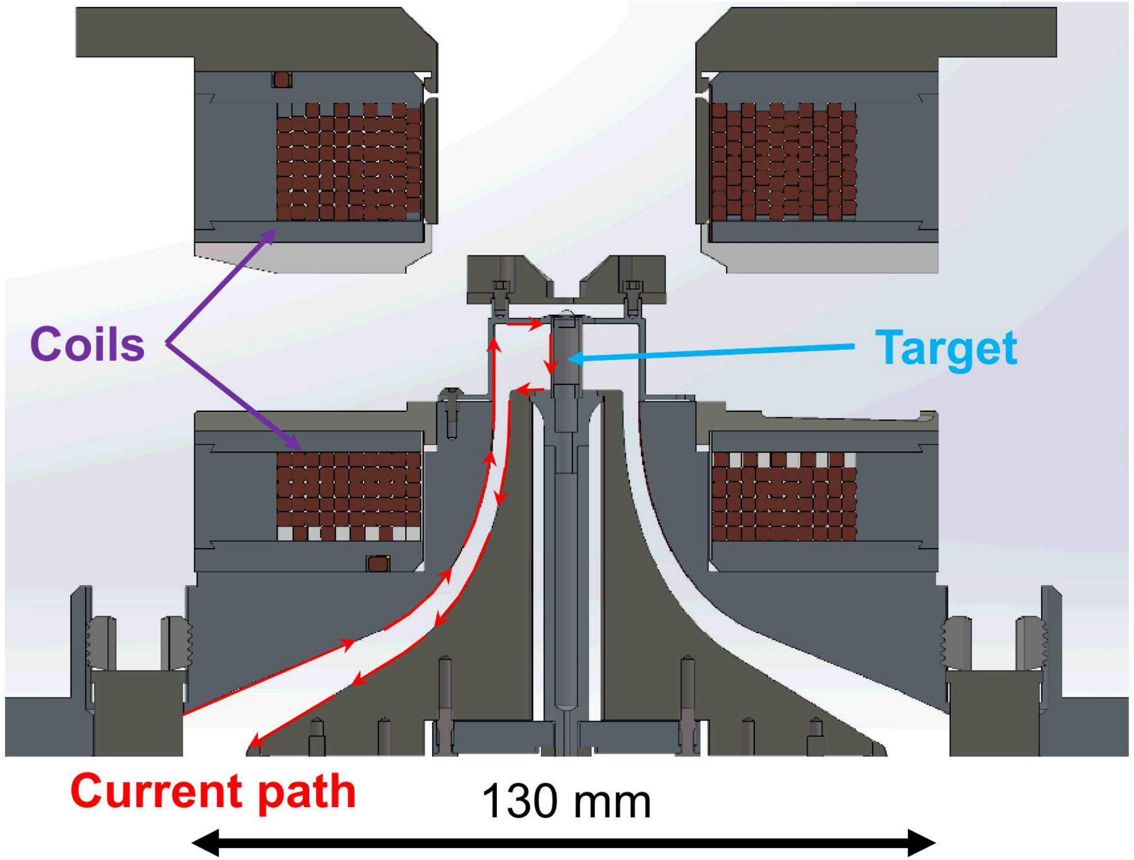

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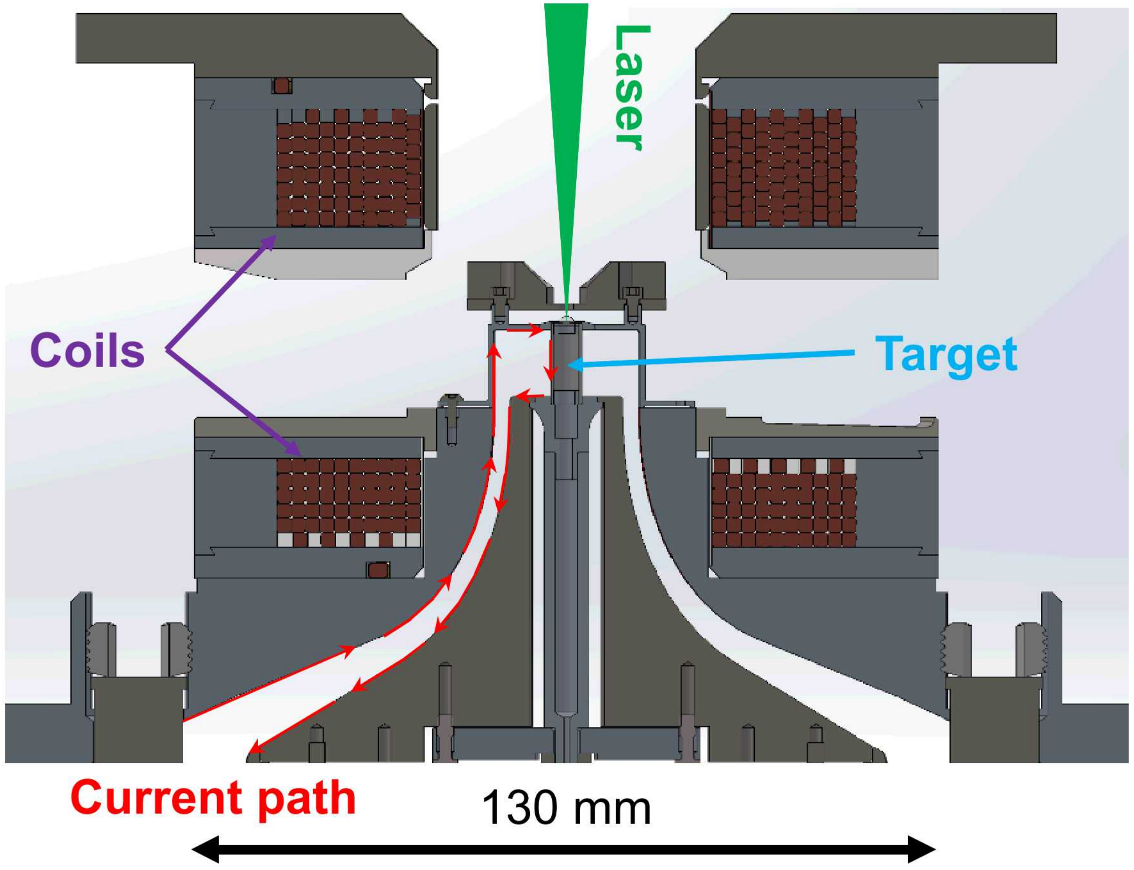
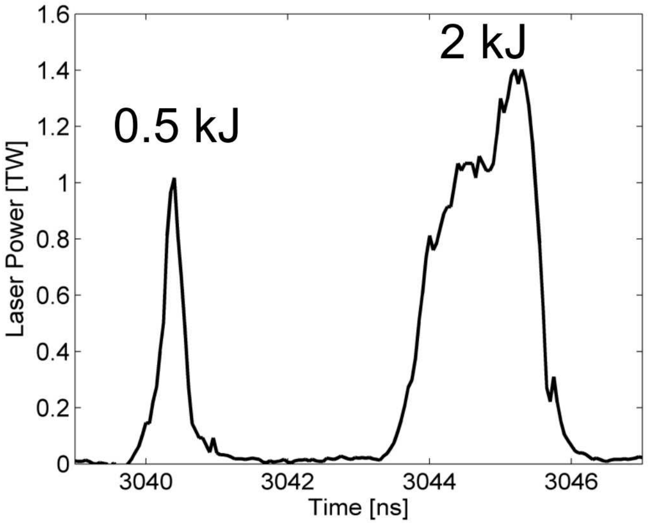


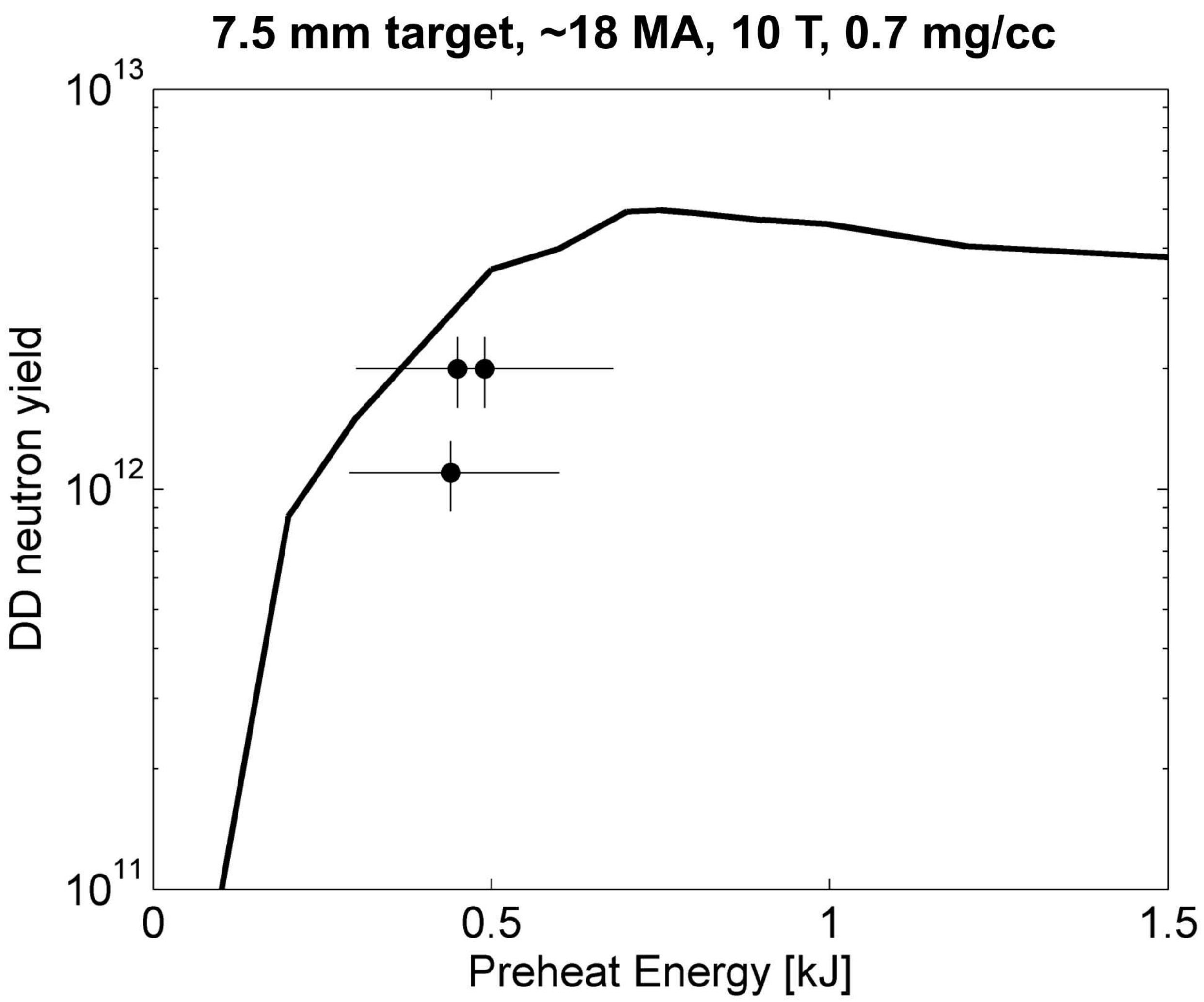
- 10 T had been previously demonstrated on Z and allowed full diagnostic access
- Only expected about 18 MA due to the high inductance inner-MITL extension required by the coils
- We believed our laser pre-pulse would disassemble the window, enabling the majority of the main pulse to be absorbed in the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



This configuration was predicted to produce more than $5x10^{12}$ DD neutrons (~1kJ DT)

The neutron yields in the initial experiments were lower than expected

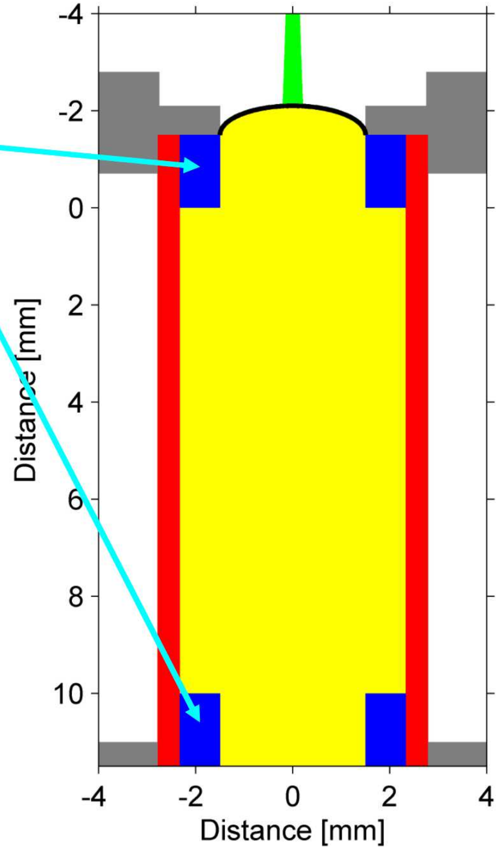
- Pre-shot neutron yield predictions were ~5e12
  - Performance is highly dependent on preheat energy
- Experimental neutron yields were about 2-4x lower than predicted
  - Consistent with low preheat energy according to simulations
  - Subsequent analysis indicates the laser energy coupled was significantly below 2 kJ, likely around 0.5 kJ
- Some of the degradation was due to low laser energy, the rest was likely due to mix and 3D effects

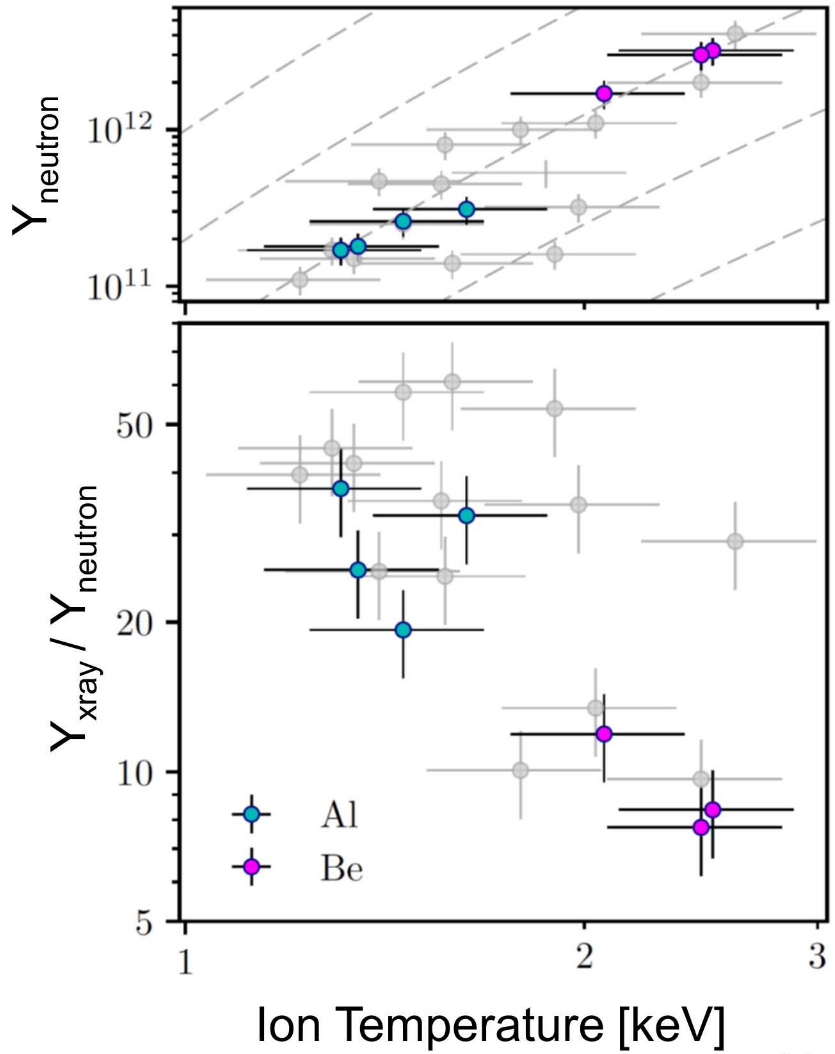


A. B. Sefkow, et al., Phys. Plasmas **21**, 072711 (2014). S. A. Slutz, et al., submitted to Phys. Plasmas (2018).

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

- There is a significant difference between Al and Be endcaps with ~1 kJ 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



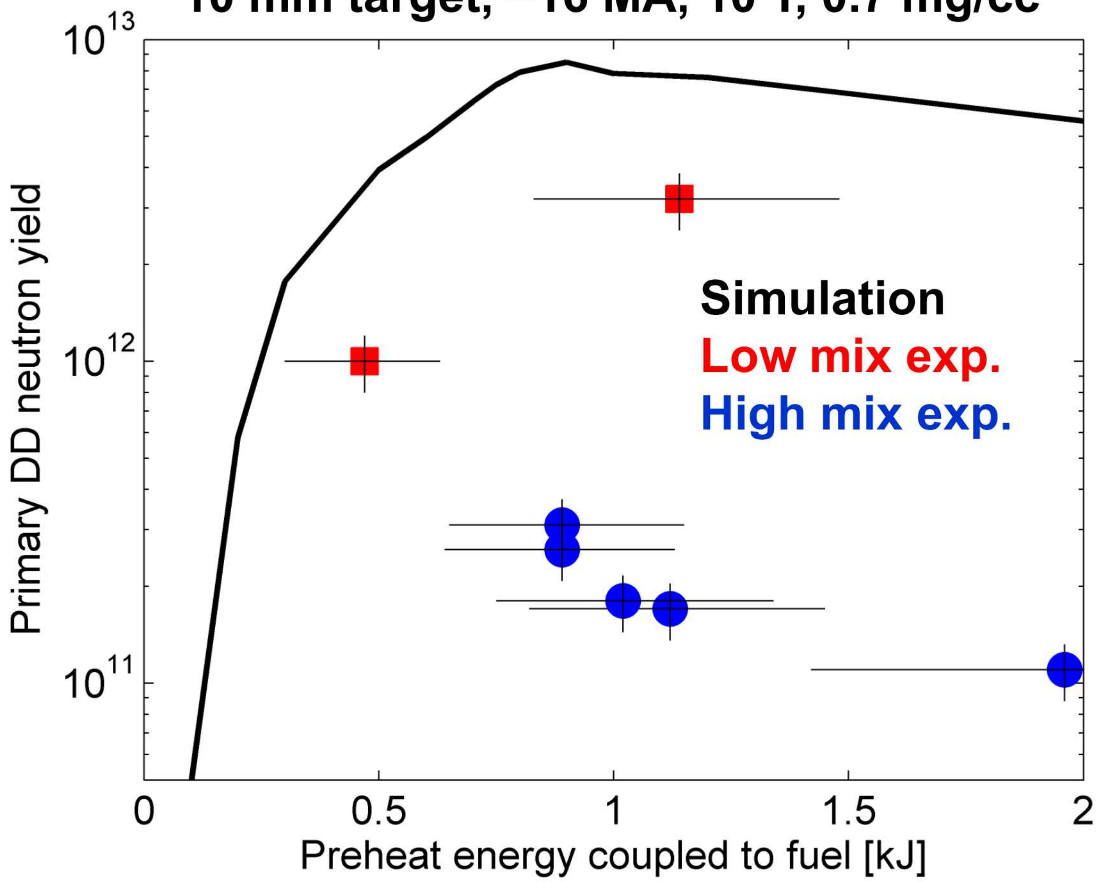


P. F. Knapp, et al., to be submitted.

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

- There is a significant difference between Al and Be endcaps with ~1 kJ 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
- We also looked at ~0.5 kJ vs ~1 kJ deposited with beryllium endcaps
  - Neutron yield increased by a factor of 2-3, similar to in clean 2D simulations

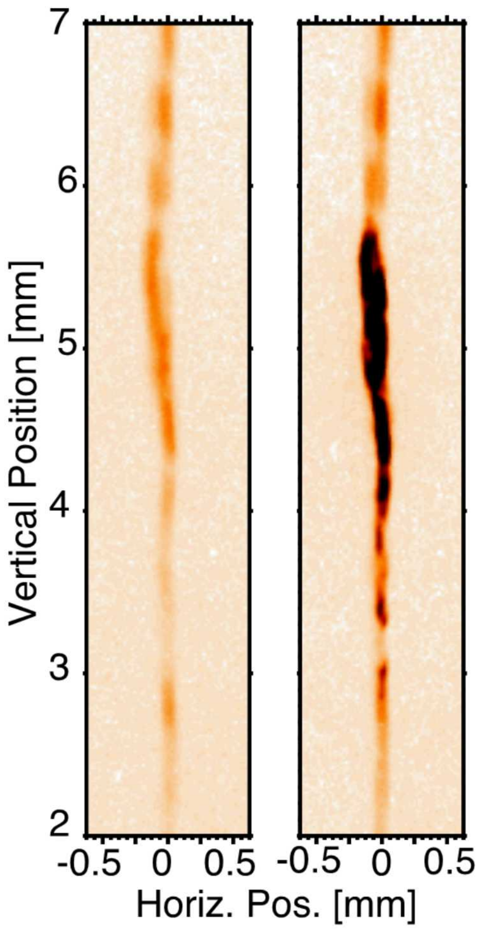
10 mm target, ~16 MA, 10 T, 0.7 mg/cc



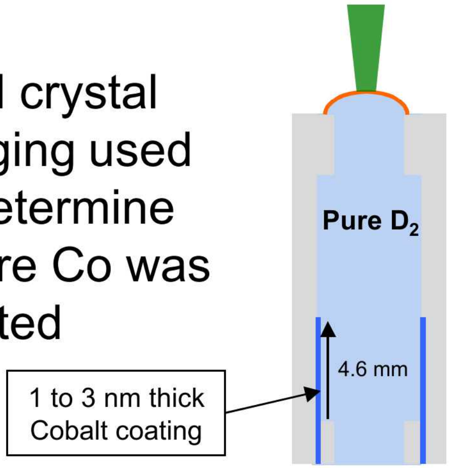
- Low mix experimental points are consistently about 50% of simulations
  - Mix and 3D effects could account for this difference

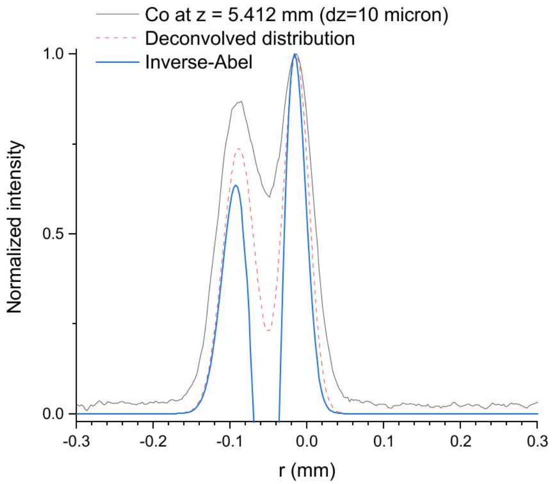
M. R. Gomez, et al., to be submitted.

Cobalt coatings on target components were used to assess the importance of mix



Dual crystal imaging used to determine where Co was located



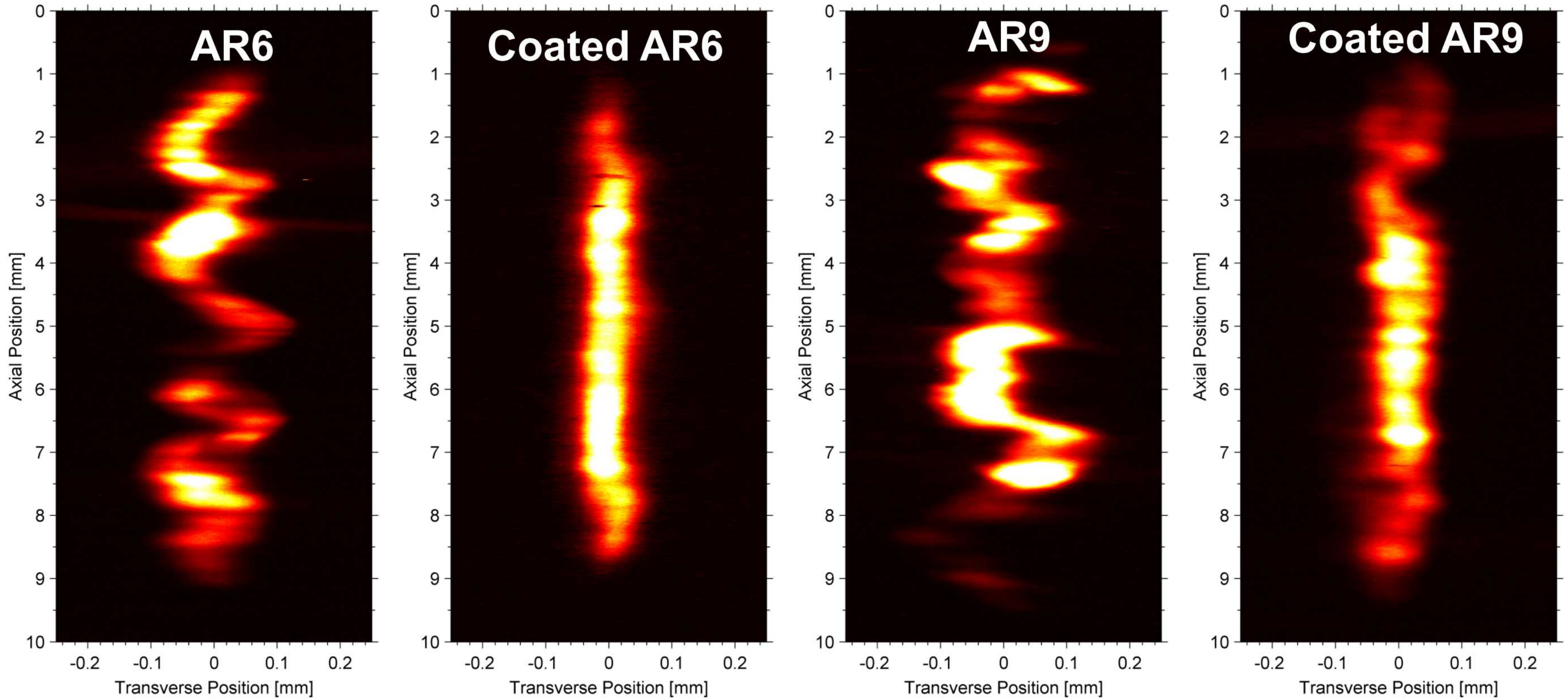


- A Co coating on the top endcap resulted in Co spectral lines observed at stagnation, indicating top endcap material was mixed into the fuel
- A Co coating on the bottom endcap resulted in significantly reduced neutron yield, indicating mix from the bottom endcap is also important
- A Co coating on a portion of the inner surface of the liner resulted in axially localized mix, indicating liner mix occurs late in time, likely during the deceleration phase just before stagnation

Experiments by E. C. Harding

A thick dielectric coating on the liner exterior significantly improved stagnation morphology

- Density perturbations from the electro-thermal instability seed the magneto-Rayleigh-Taylor instability
- The dielectric coating tamps the density modulations, reducing the impact of ETI



- With a dielectric coating, the helical structure at stagnation as well as the axial modulations were significantly reduced

Experiments by M. R. Gomez, D. J. Ampleford and C. A. Jennings

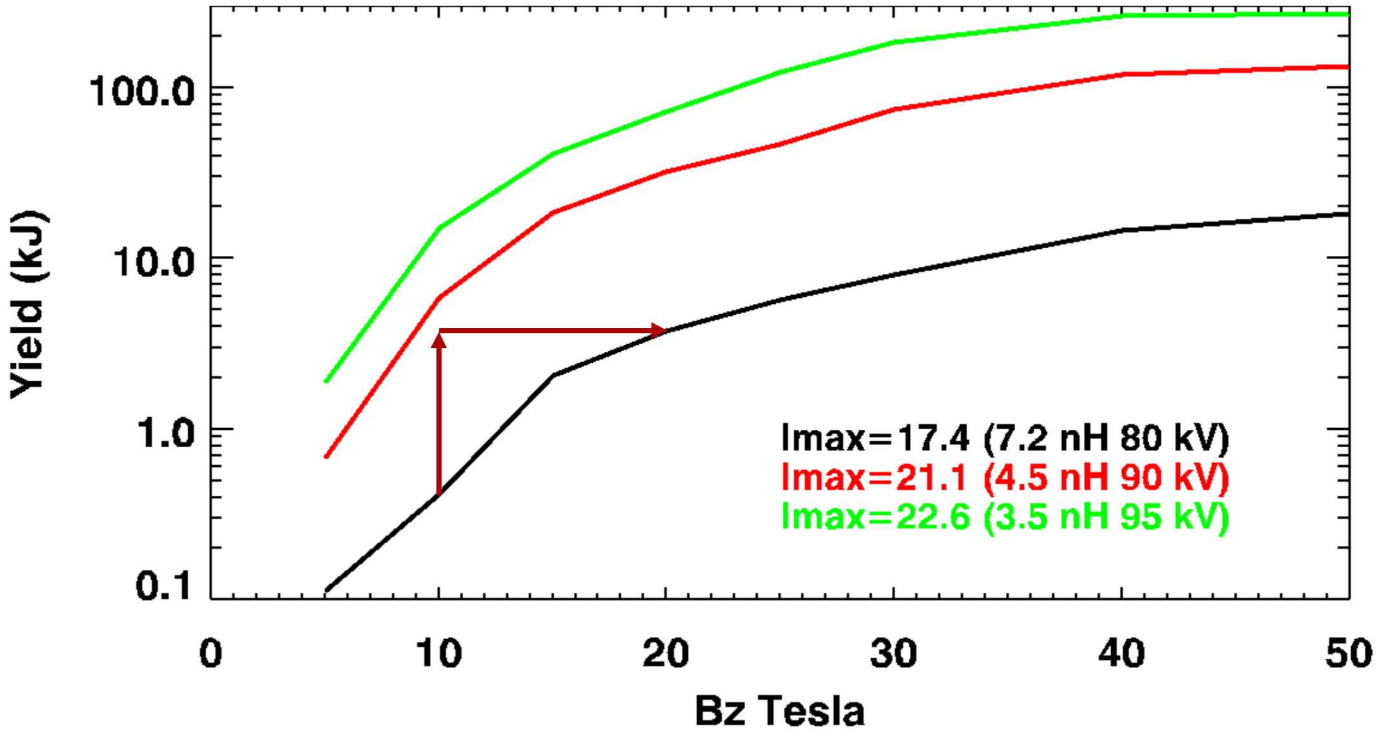
Outline

- Introduction to magneto-inertial fusion
  - Intro to Magnetized Liner Inertial Fusion (MagLIF)
- MagLIF experiments
  - Demonstration of the efficacy of magneto-inertial fusion
  - Improving target behavior
  - **Identifying scaling trends**
- Next generation experiments
  - Architecture of a next-generation pulsed power driver
  - Scaling to future drivers

Simulations predict the amplitude of the initial B-field has a strong impact on target performance

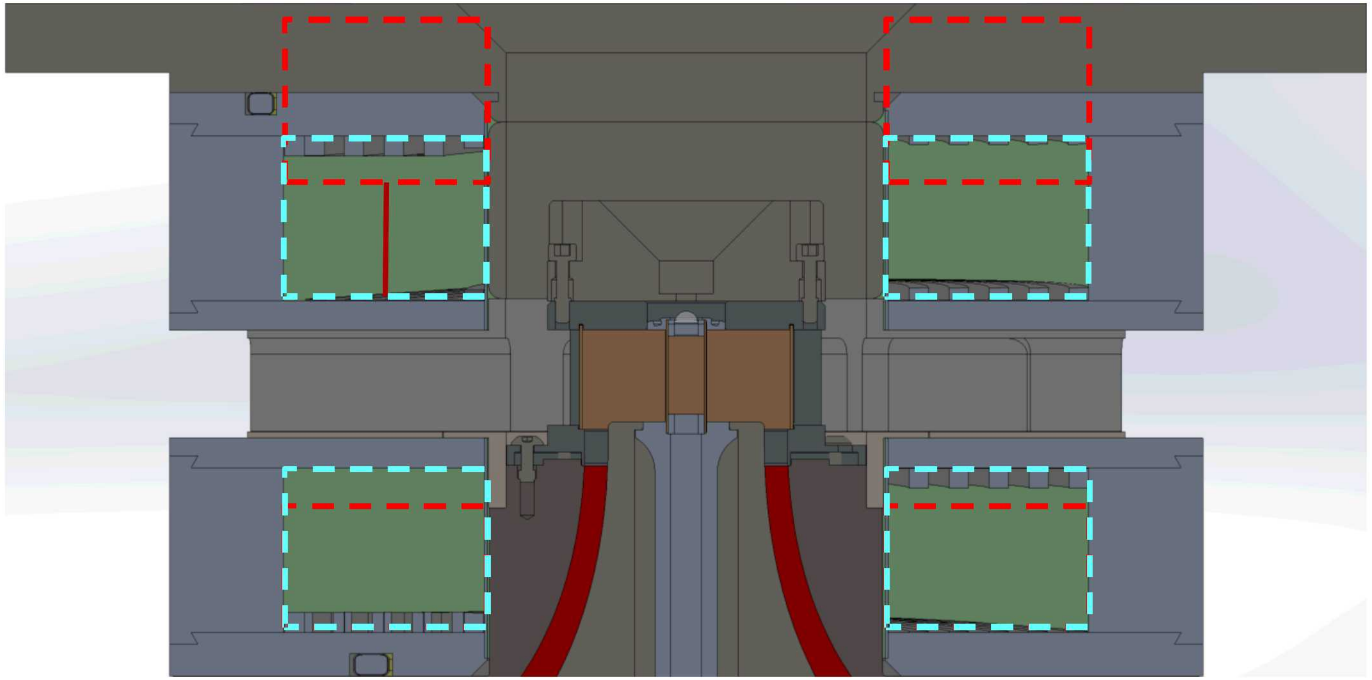
- Without any other changes, doubling the B-field to 20 T was expected to increase yield by about a factor of 2
- Simulations with greater laser energy deposition show an even stronger dependence
  - Nearly an order of magnitude increase in yield with 6 kJ of laser energy and 1.87 mg/cm^3 DT

Fuel = DT
Initial fuel density = 1.87 mg/cm^3
Preheat energy = 6 kJ



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

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



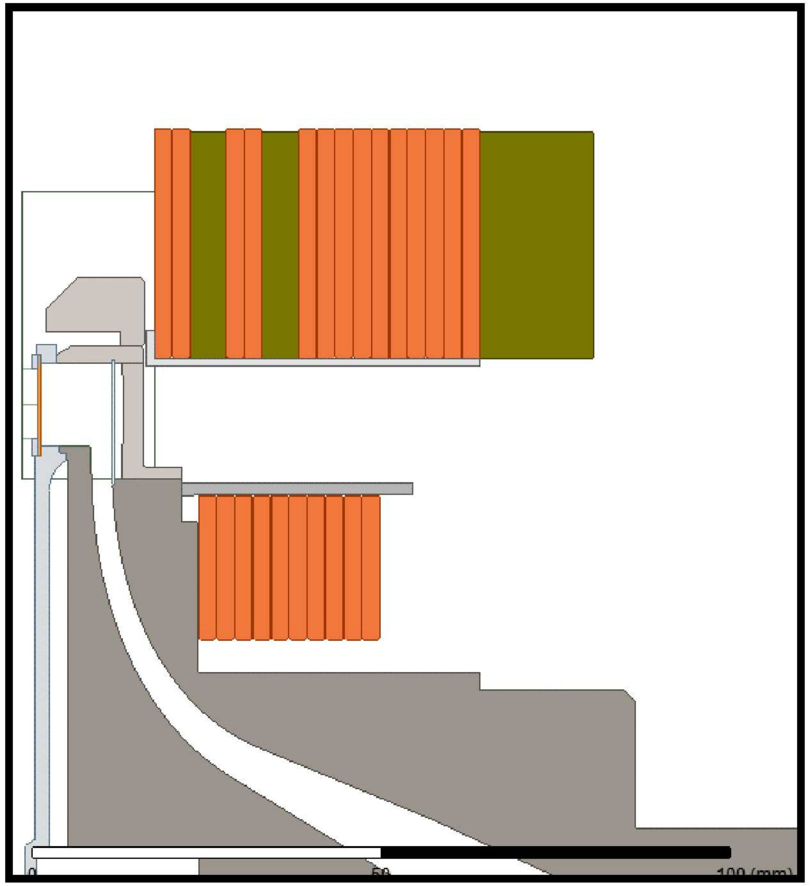
- Bottom coils increased from 60 turns to 80 turns
- Top coils lowered by 15 mm, eliminating 12 degree x-ray diagnostic access

- Applied B-field was increased from 10 to 15 T
- Simulations predicted an increase in primary neutron yield of about 1.5x
- **Experimental yield increased by 1.7x 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 and target 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
- Auto-Mag is an alternative path to high magnetic fields
  - Helical conducting paths in the liner generate an axial B-field in the target using Z's current
  - >50 T was demonstrated on Z in early 2018
  - Implosion stability is still under investigation



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.

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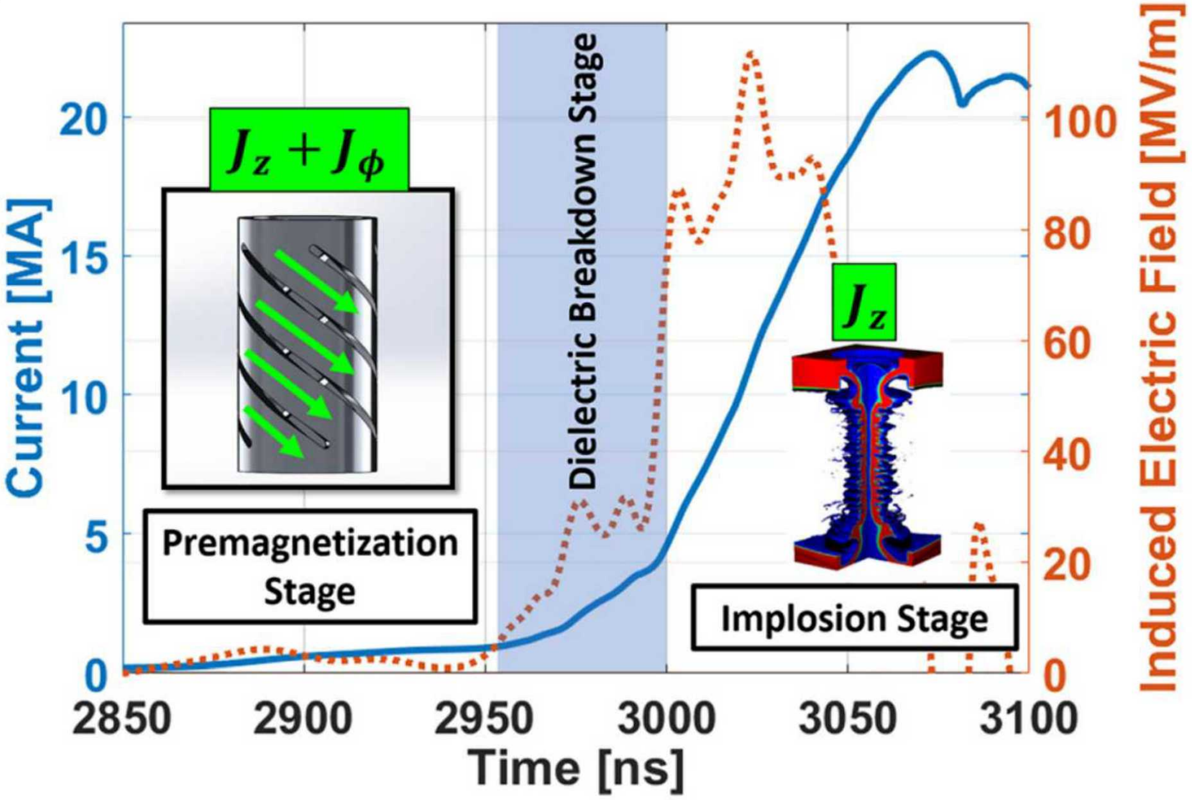
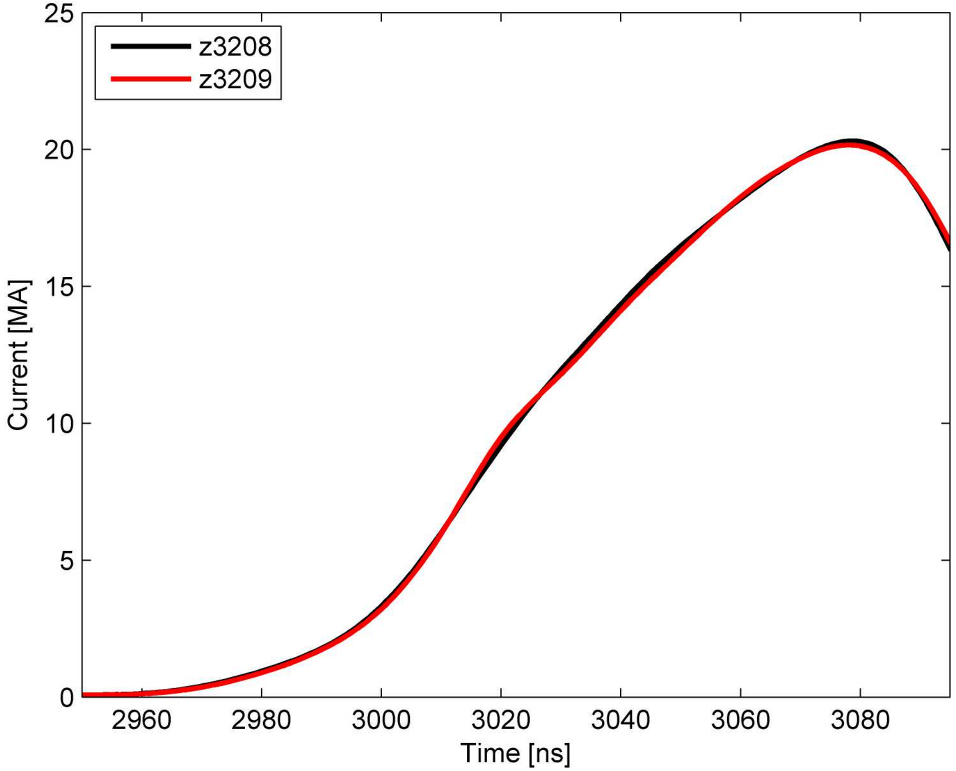


S. A. Slutz, et al., Phys. Plasmas **24**, 012704 (2017). G. A. Shipley, et al., Phys. Plasmas **25**, 052703 (2018).

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

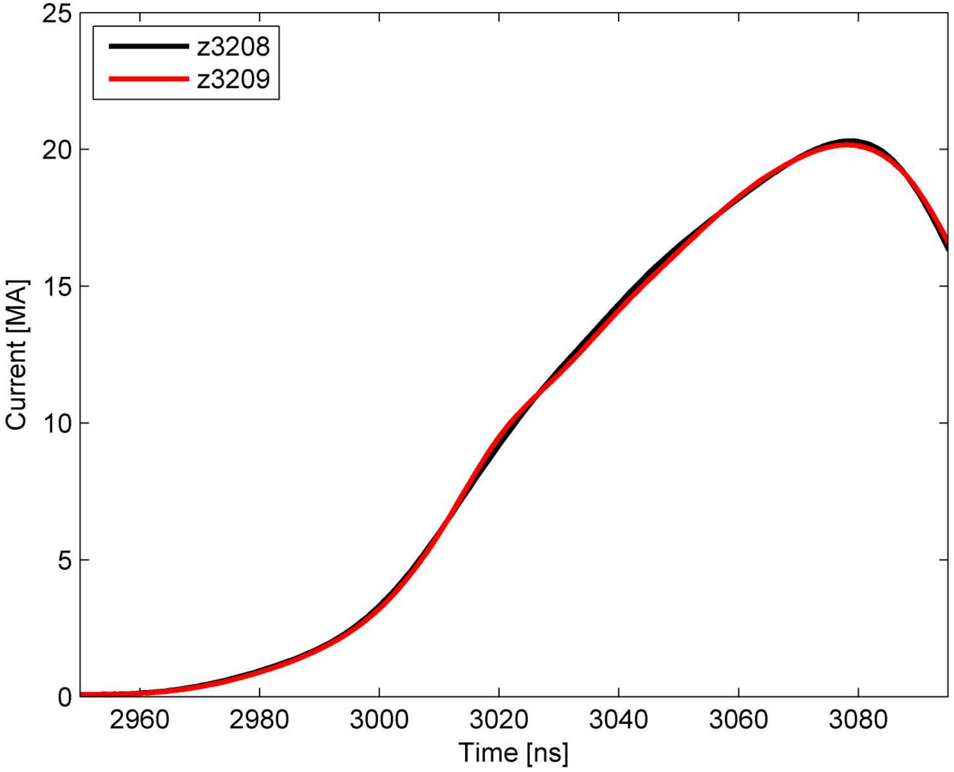
- 20 MA has been demonstrated
- 22 MA seems plausible with small modifications

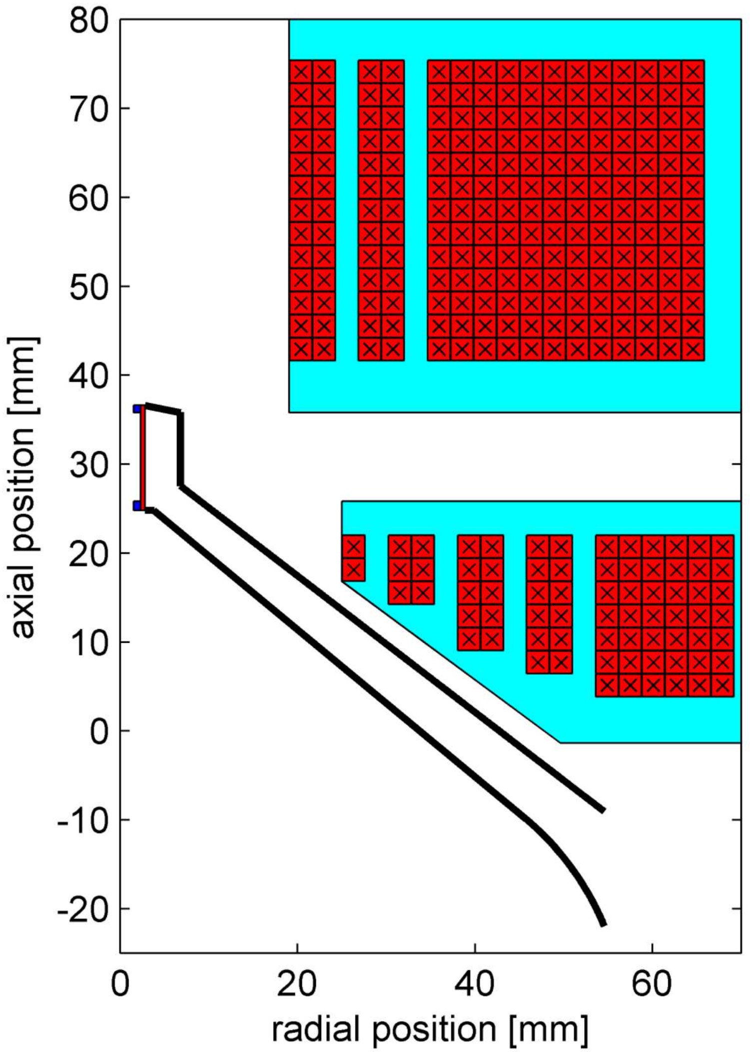


C. A. Jennings, et al., to be submitted.

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

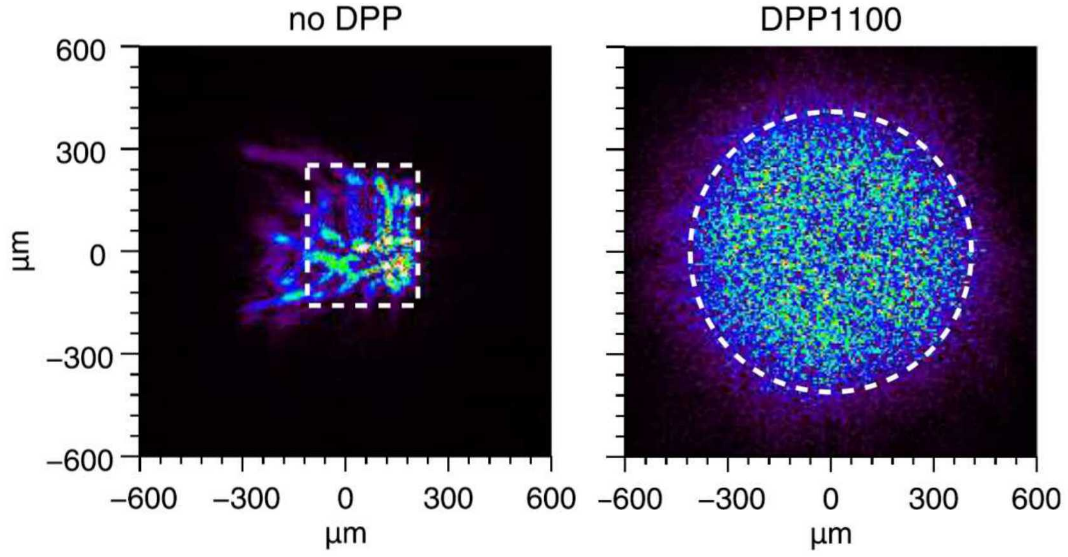


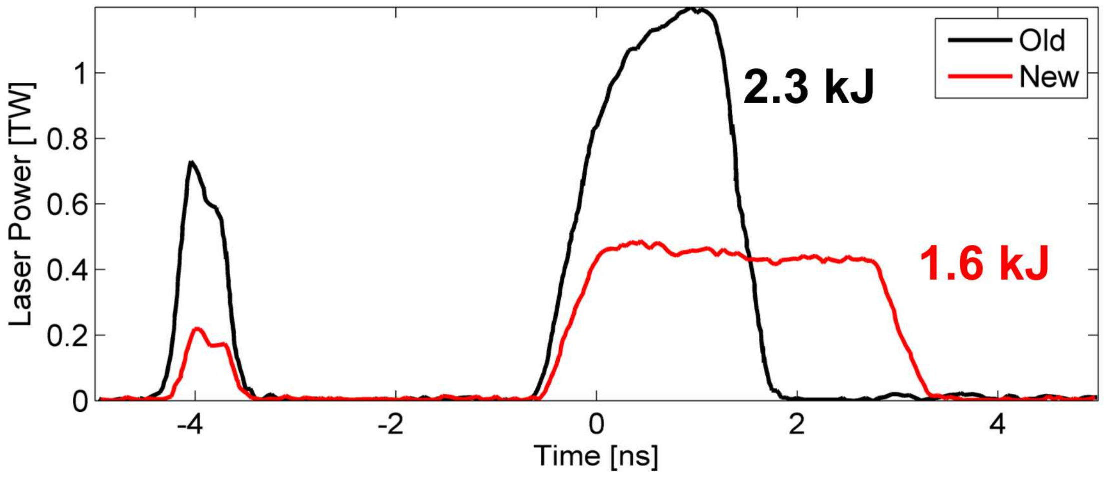


D. C. Lamppa, et al., to be submitted.

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

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

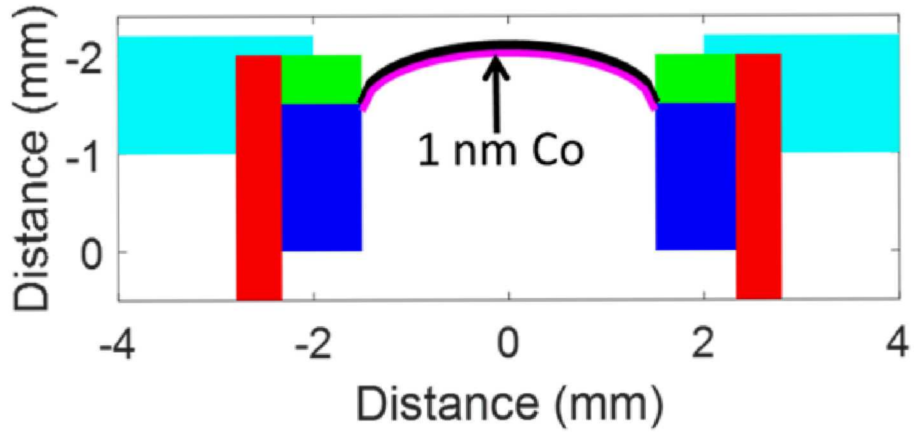




- Decreased laser power and larger spot size significantly decreased the laser intensity and laser plasma instability losses
- Goal was to couple a similar amount of energy in a more efficient, reliable way
  - Minimal change in energy coupled to fuel but efficiency improved significantly
- Observed 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., submitted to Phys. Plasmas (2018).

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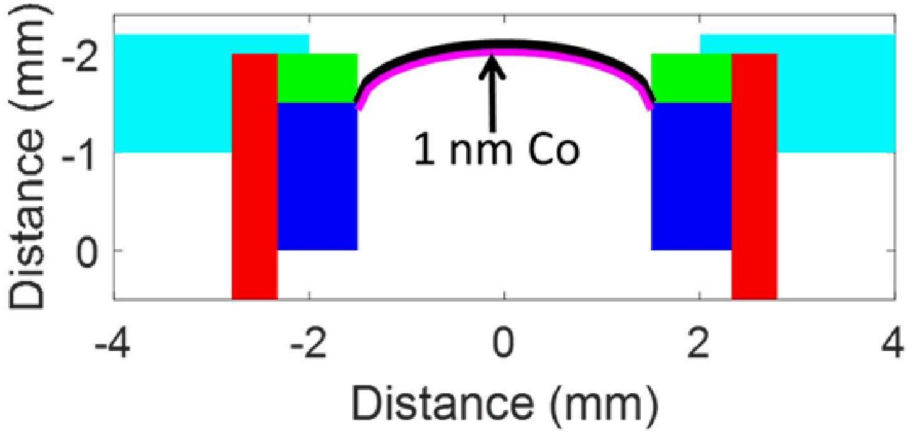

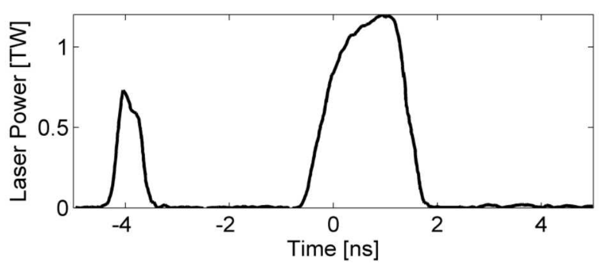

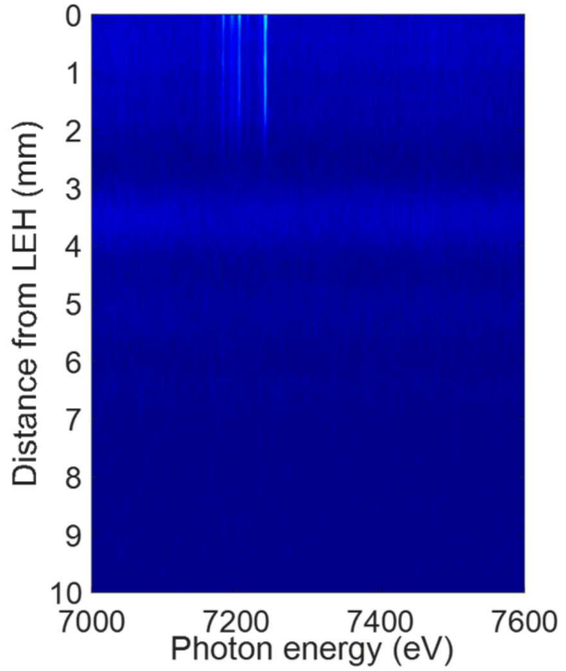

- Looking for Co K-shell emission at stagnation
- Window mix was observed in the top 3 mm of the target with the old laser configuration

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

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

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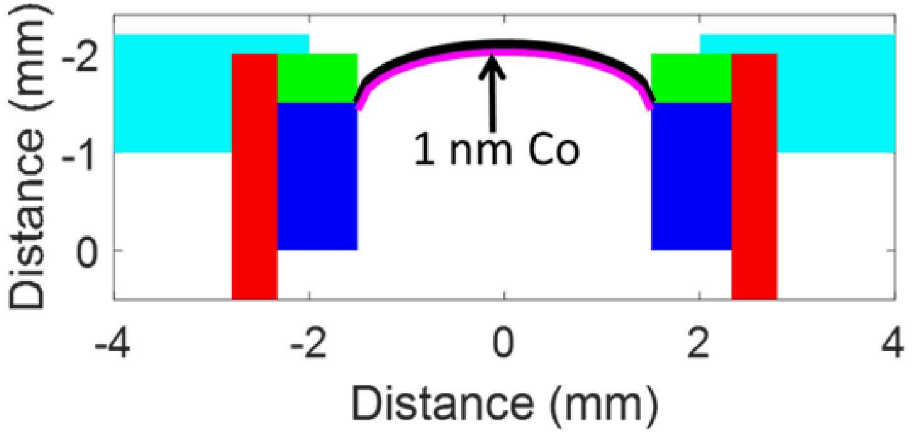
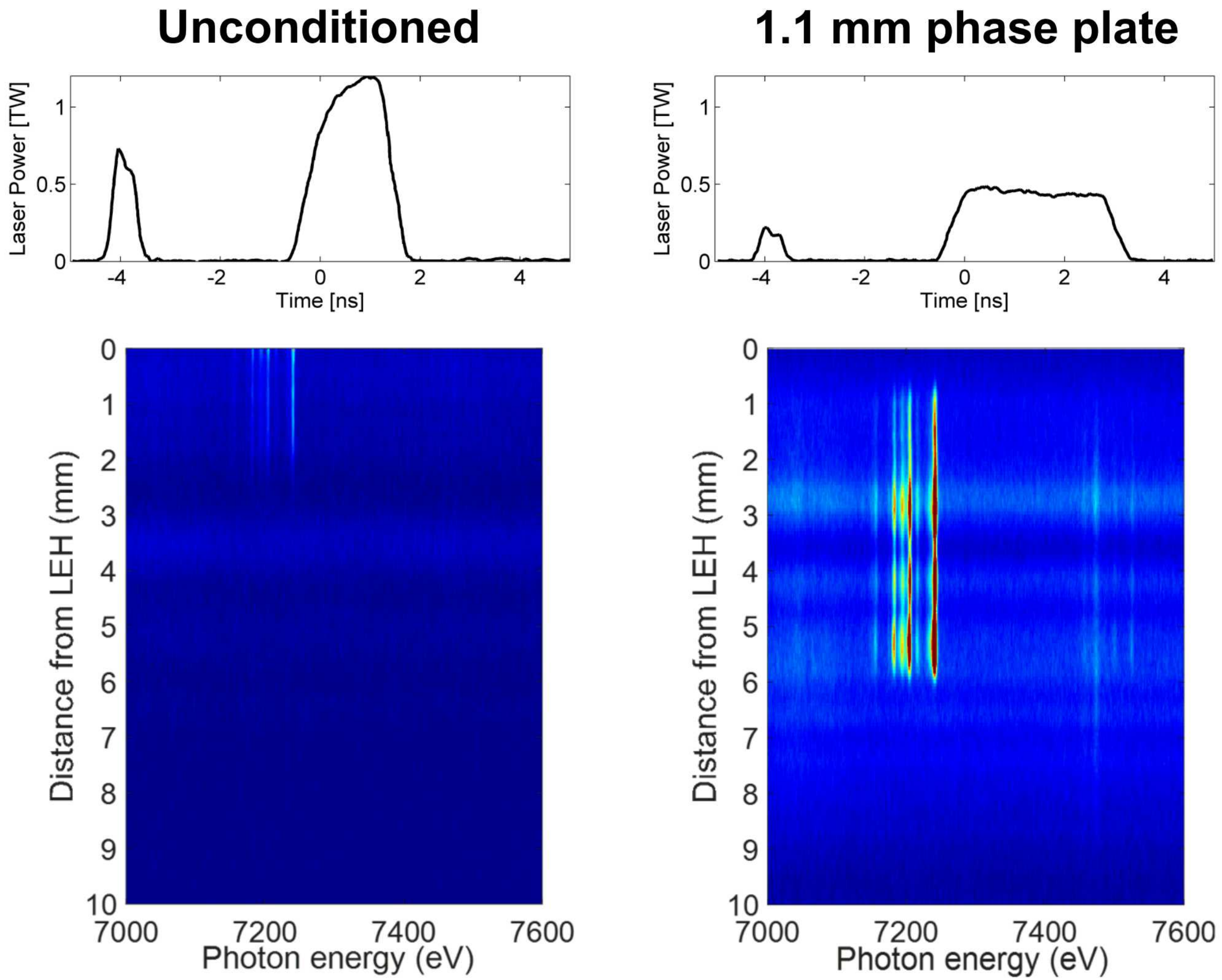
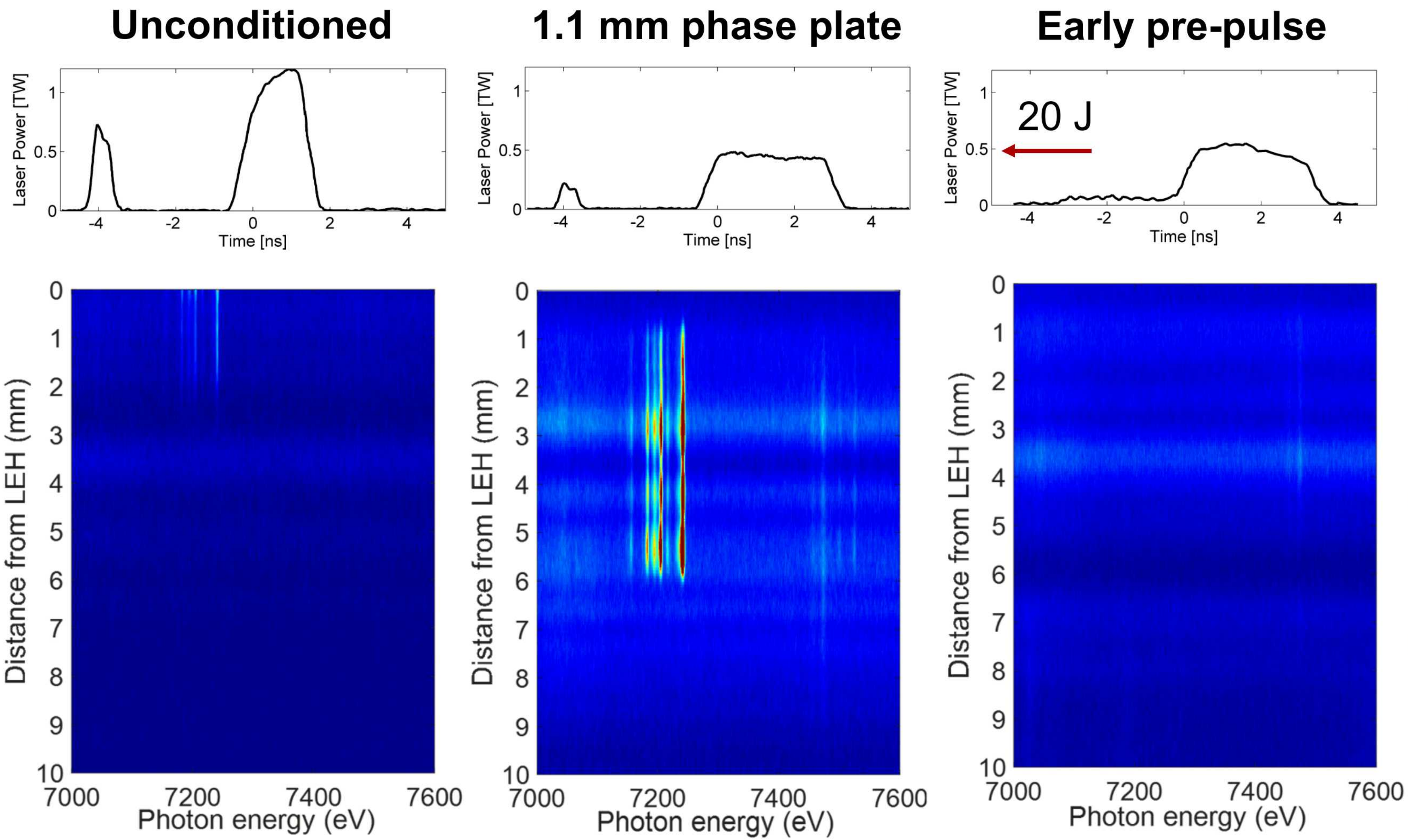


- Looking for Co K-shell emission at stagnation
- Window mix was observed in the top 3 mm of the target with the old laser configuration
- The new laser configuration with the 1.1 mm DPP injected window mix into the top 6 mm of the target!



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

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

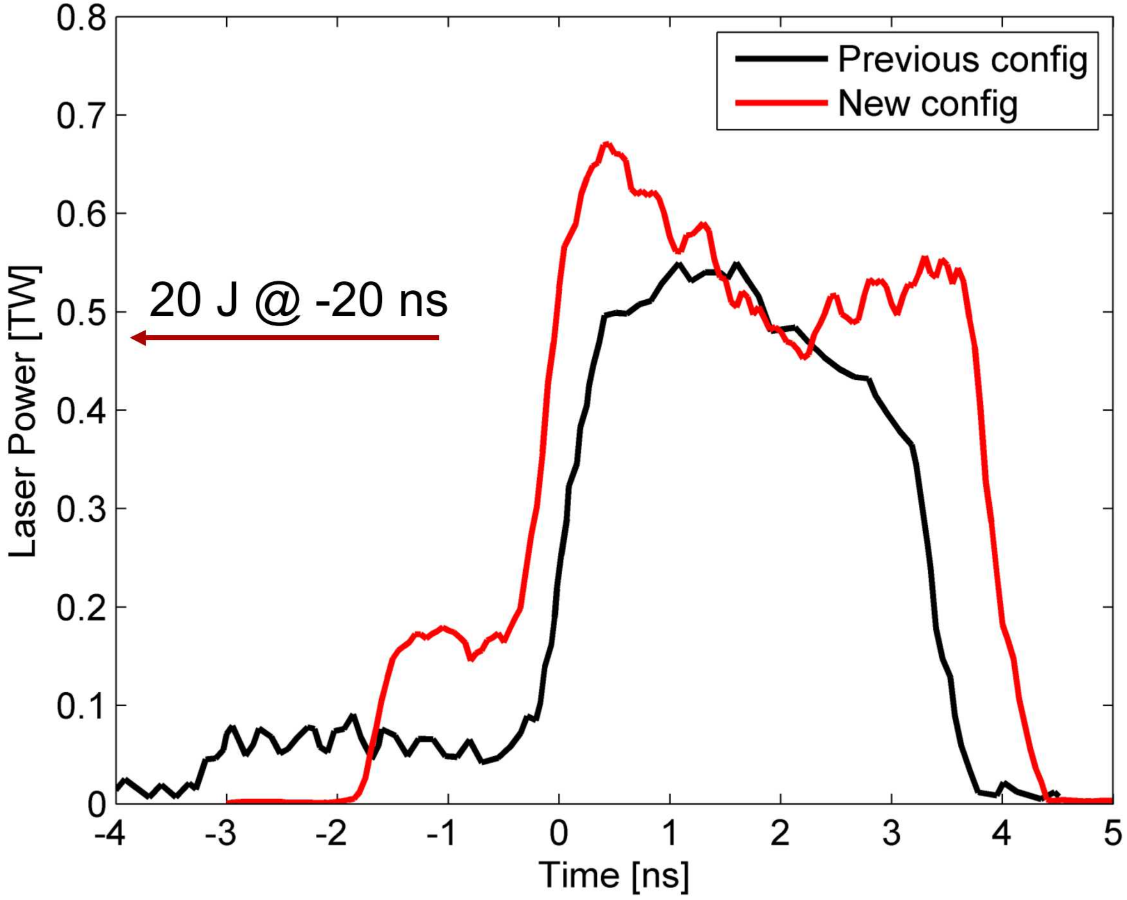


- Early pre-pulse configuration utilizes a 20 J pre-pulse approximately 20 ns early and a low intensity foot
  - 1.1 mm phase plate used
- Couples ~1 kJ to the fuel out of 1.8 kJ
- Slight increase in laser energy coupled to fuel with substantially less mix

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

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

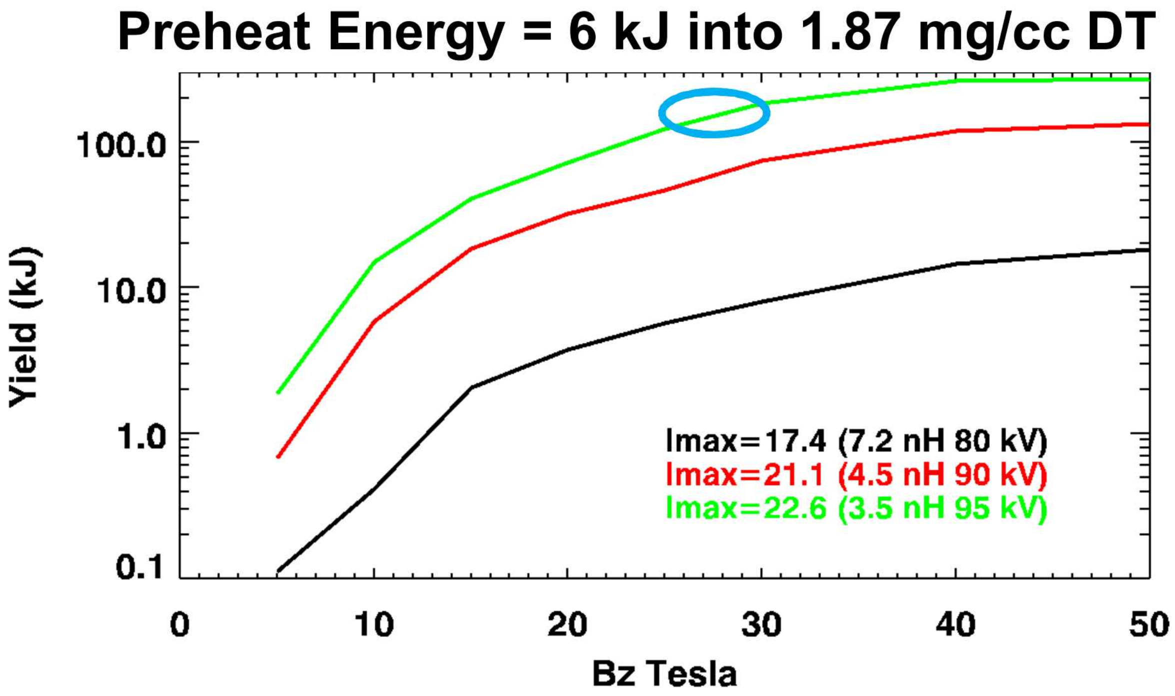
- Used the same low energy, very early pre-pulse to convert the window to plasma
- Shorter, higher intensity foot allowed more energy in the main pulse
  - 2500 J total energy
  - 1200-1400 J coupled
- **New record DD neutron yield of 1.1e13**
  - About 3x increase from 3.3e12
  - Minimal increase in mix from window
  - Used coated-AR9 target configuration



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

Our goal on Z is to produce a fusion yield of ~100 kJ DT-equivalent

- 2D simulations indicate an experiment with 22 MA, 25-30 T, and 6 kJ of laser heating could produce >100 kJ
- Presently we cannot produce these inputs simultaneously
- We are making progress in demonstrating scaling



Date	Liner	Fill (D2)	Current	B-field	Preheat	Yield (DT-eq.)
2014	AR=6	0.7 mg/cm^3	17-18 MA	10 T	0.2-0.6 kJ	0.2-0.4 kJ
Aug. 2018	AR=6	1.1 mg/cm^3	19-20 MA	15 T	1-1.4 kJ	~2.4 kJ
2020 Goal	TBD	~1.5 mg/cm^3	20-22 MA	20-30 T	2-4 kJ	~10 kJ
Z Goal	TBD	1.5 mg/cm^3	22 MA	25-30 T	6 kJ	100 kJ

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- **Next generation experiments**
  - **Architecture of a next-generation pulsed power driver**
  - **Scaling to future drivers**

We are exploring a modular architecture that is twice as electrically efficient as the Z machine

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Brick – "quantum" of next generation driver designs

5.2 GW/800 J per brick

Brick design is similar to what was used in early LTD designs

The overall inductance was lowered with a new switch design, and the capacitance was increased

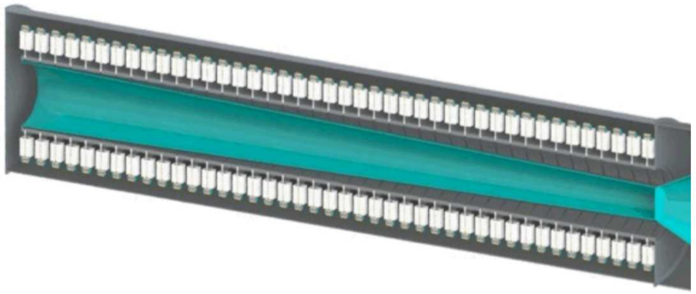
Cavity – multiple bricks connected in parallel

>100 GW/1.6 kJ per cavity

Each brick delivers 50 kA to a matched load

The full cavity delivers 1 MA at 100 kV to a matched load (assuming 20 bricks)

Module – multiple cavities connected in series



>4 TW/>0.67 MJ per module

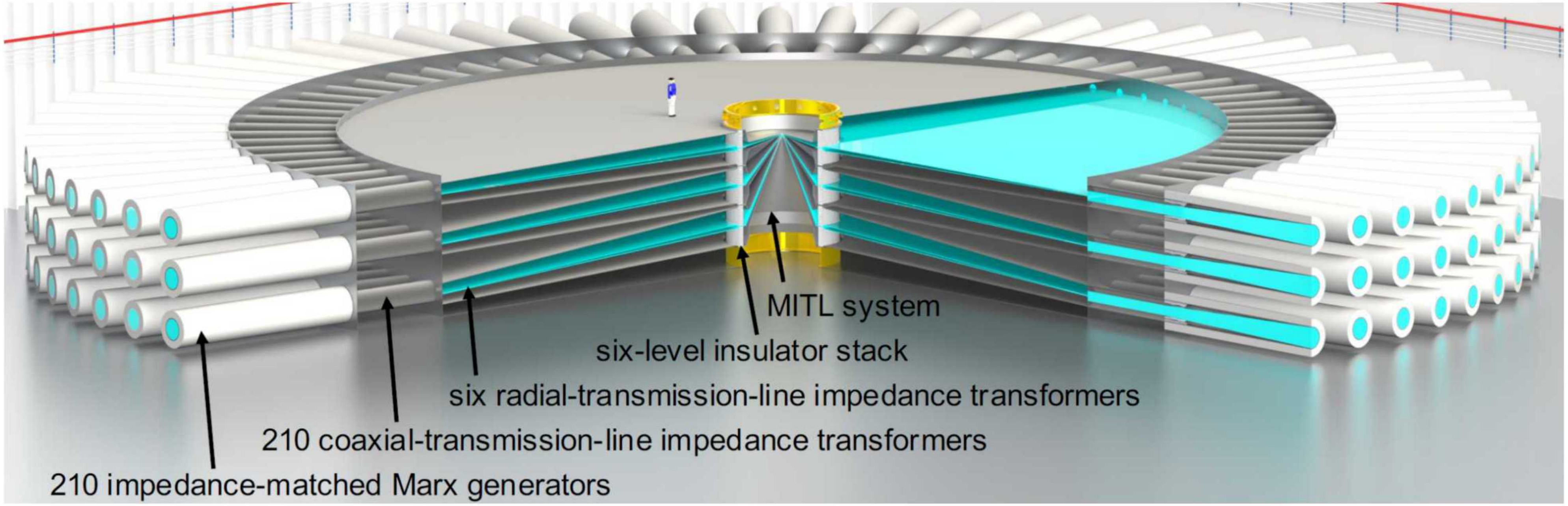
Voltage is increased by stacking cavities in series

A full module delivers 1 MA at 4.2 MV to a matched load (assuming 42 cavities)

W. A. Stygar, et al., Phys. Rev. Accel. Beams **18**, 110401 (2015).

Conceptual designs for a 960 TW next-gen. pulsed power driver are being developed

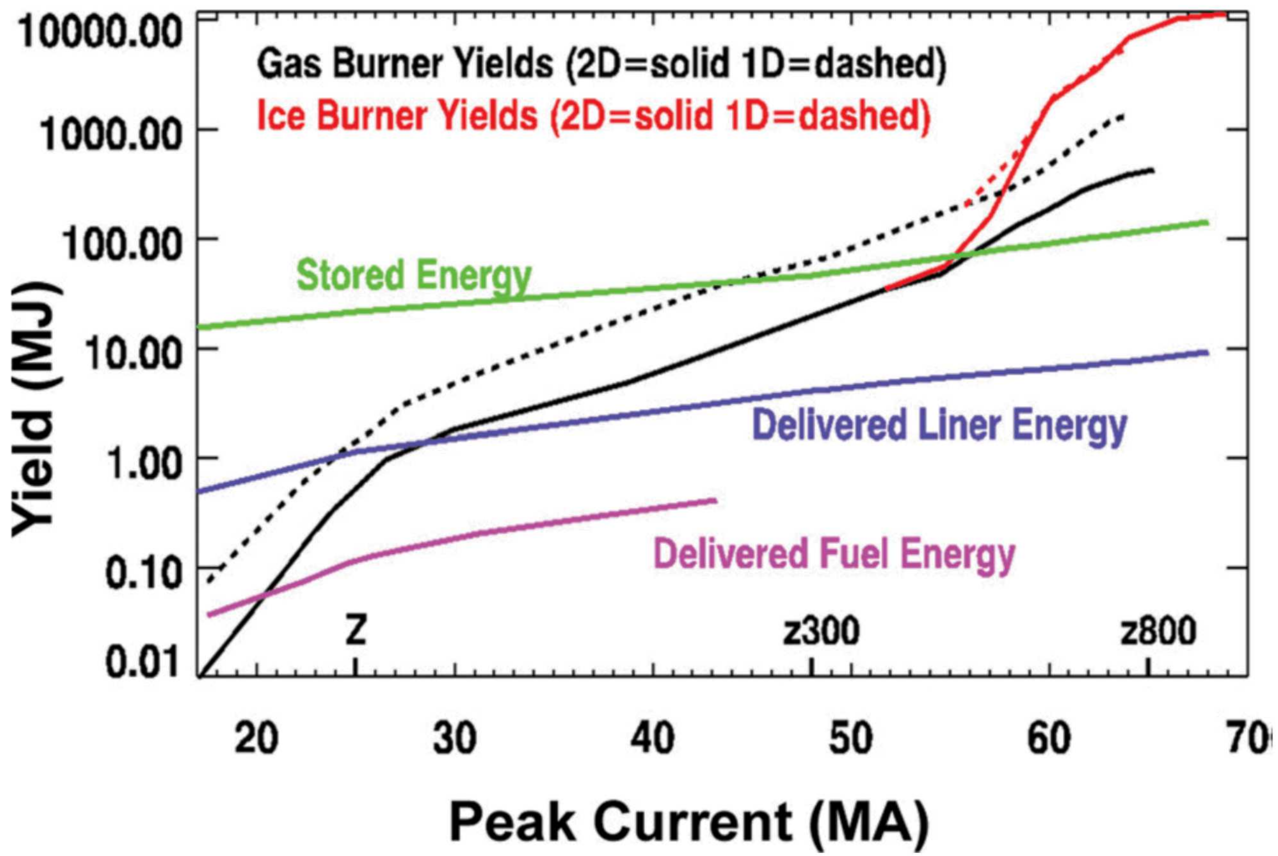
- 210 modules, each consisting of 42 cavities, which contain 20 bricks
- Total of over 350,000 capacitors and 175,000 switches
- This design utilizes impedance-matched Marx generators as opposed to LTDs
- The generator diameter would be 72 m (over twice that of Z)
- Energy stored: 141 MJ
- Nominal rise-time: 100 ns
- Pulse-shaping possible



W. A. Stygar, et al., Proc. IEEE PPC (2017).

MagLIF scaling calculations were conducted to assess performance on a next-generation driver

- Between 50 and 60 MA the predicted yield in 2D exceeds 100 MJ
  - The fusion energy also exceeds the stored energy of the driver in this range
- These calculations were conducted assuming negligible current loss, so the points for next generation 300 TW and 800 TW drivers should be shifted to lower currents
- At 60 MA, the ideal B-field reduces to about 15 T but the ideal laser heating energy is ~60 kJ with an initial fuel density around 10 mg/cm^3



S. A. Slutz, et al., Phys. Plasmas **23**, 022702 (2016).

We are pursuing a path to enable the generation of multi-MJ fusion yields in the laboratory

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- Our goals for the next 5 years:
  - Demonstrate understanding of the MagLIF concept
    - Expand our capabilities and continue to investigate scaling with applied B-field, laser energy coupling, and load current
  - Begin development of a full module for a next-generation pulsed power driver
    - ~40 cavities – ~1 MA at >4 MV
  - Develop next-generation simulation tools to better predict power flow delivery to the target as well as improve target simulations
    - High resolution, 3D, beyond MHD physics

Thank you for your attention

Questions?