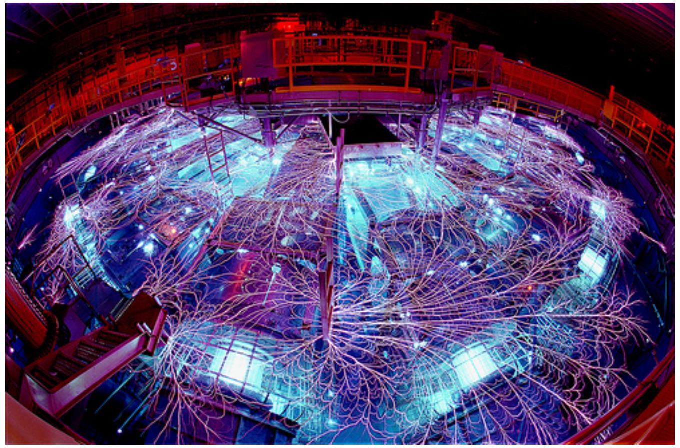
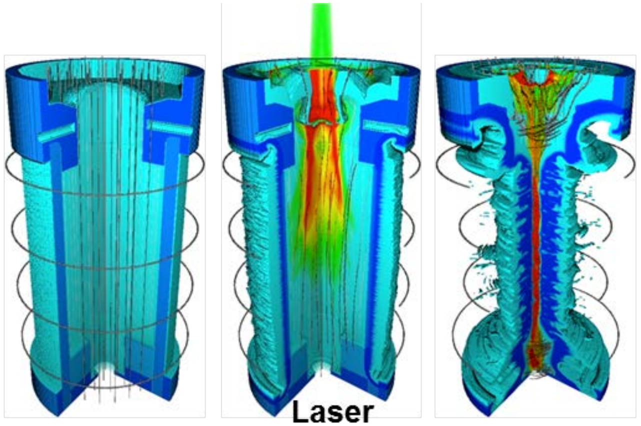
Exceptional service in the national interest





Magnetic Direct Drive Fusion Experiments on the Z Facility

Matthew R. Gomez

Radiation and Fusion Experiments Department

Sandia National Laboratories

Michigan Institute for Plasma Science and Engineering Seminar

March 8, 2017

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Nuclear fusion reactions can release a significant amount of energy

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

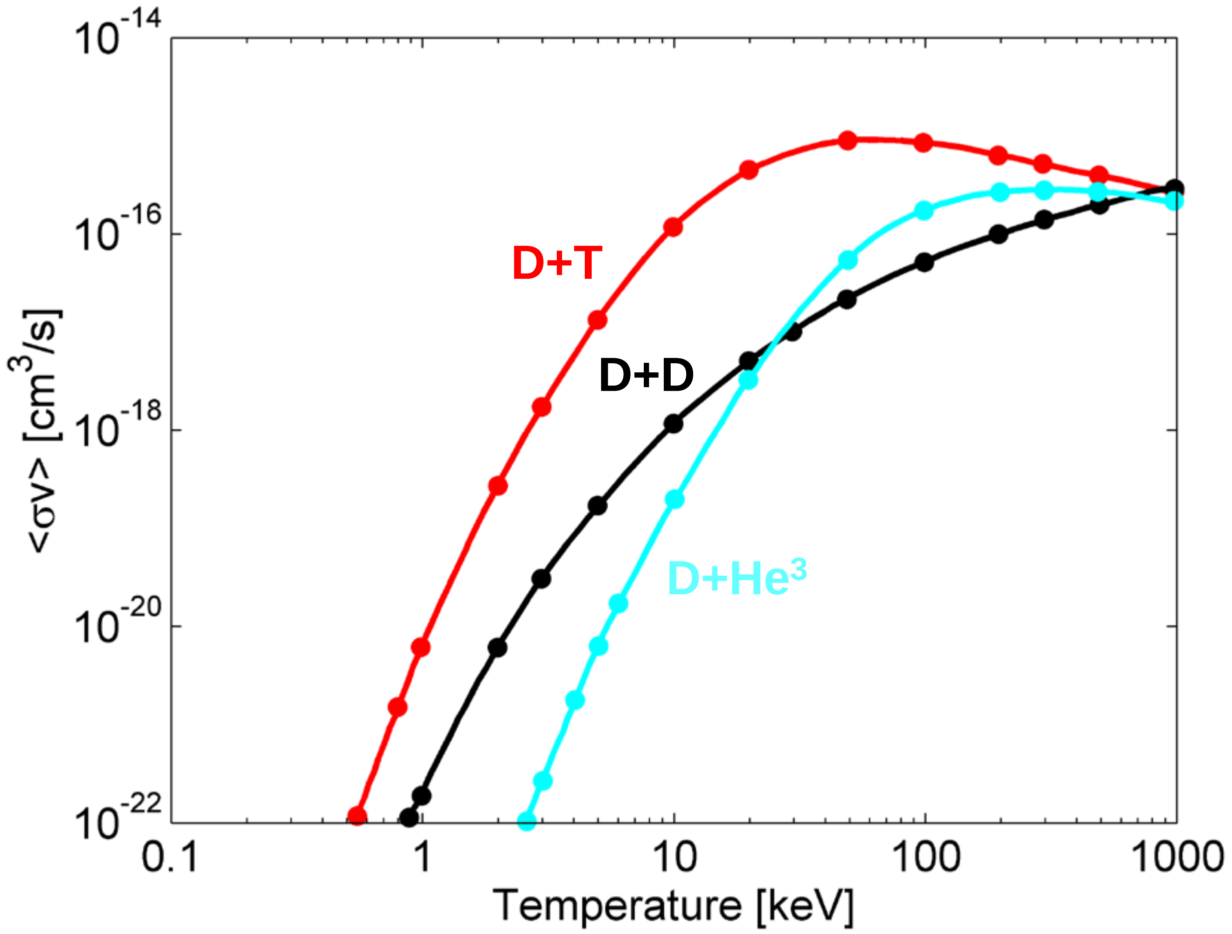
$$D + D \xrightarrow[50\%]{} T(1.01\ MeV) + p(3.02\ MeV) \qquad [Q = 4.03\ MeV]$$

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

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

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



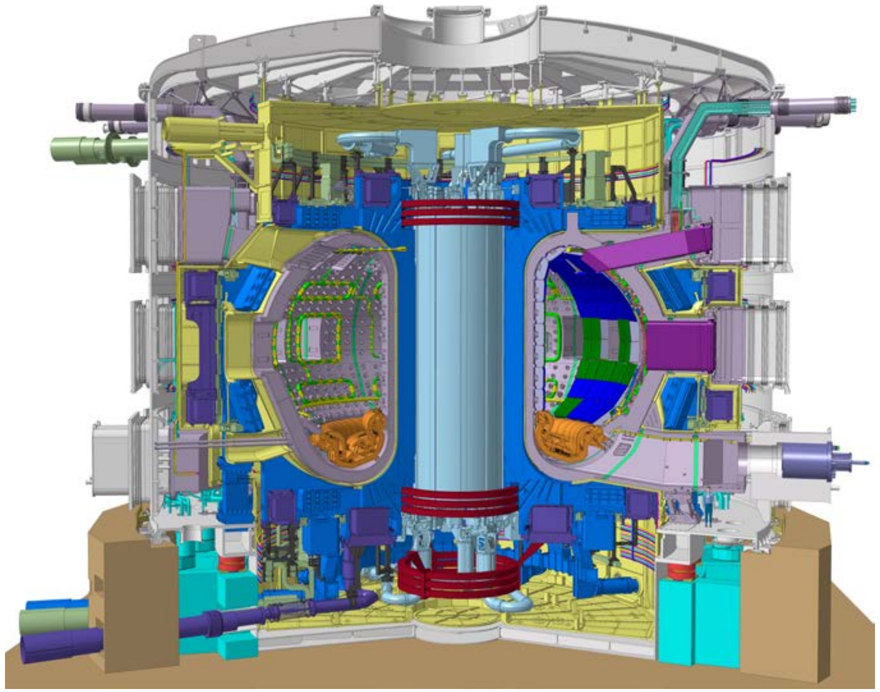
- All reaction rates drop precipitously at low temperatures
- D+T fusion has the highest rate across reasonable temperatures
- D+D fusion does not require tritium
- D+He^3 fusion does not produce neutrons

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

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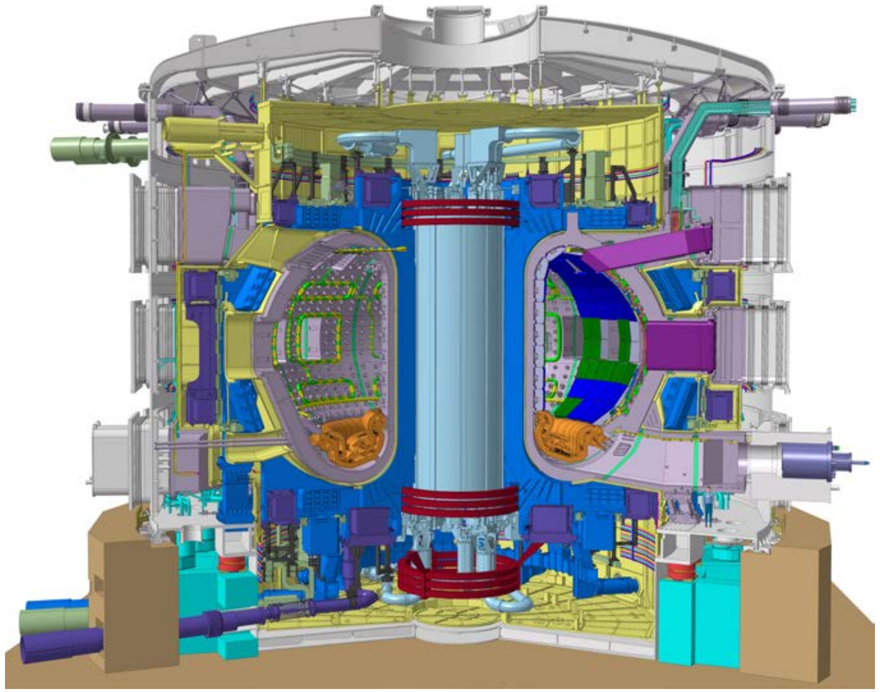
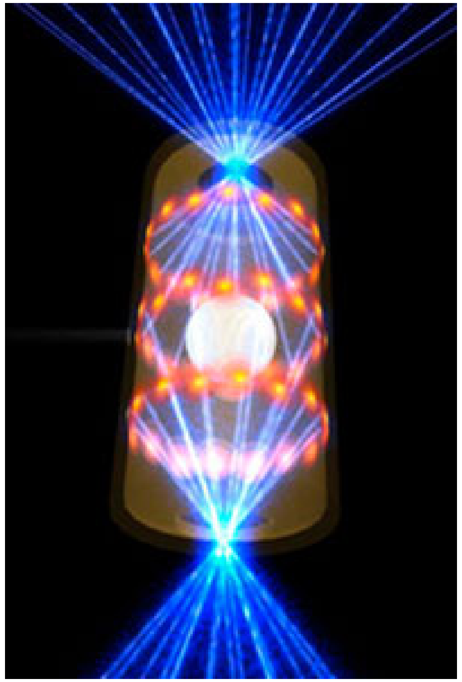
ITER



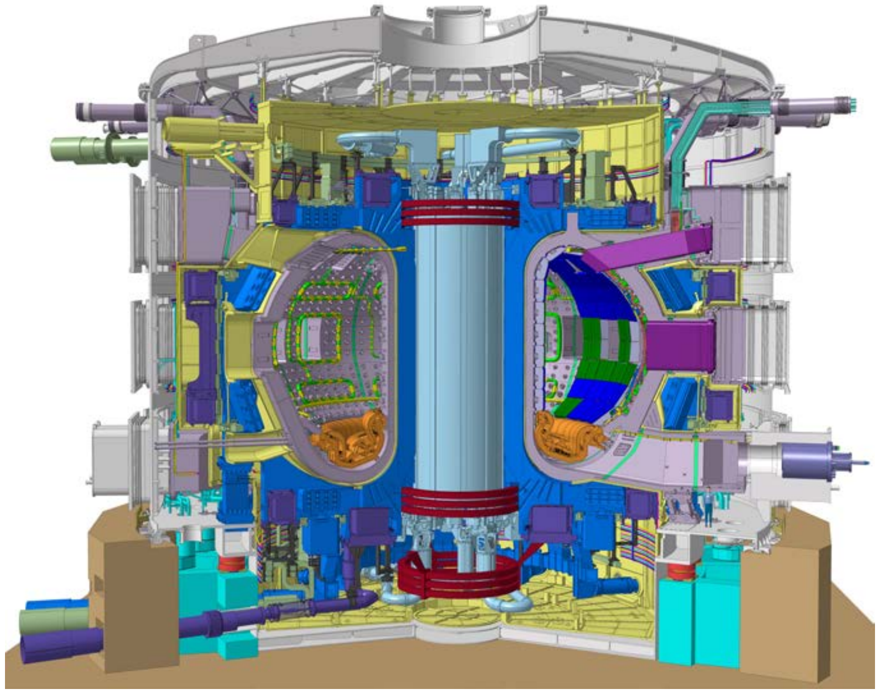
NIF hohlraum



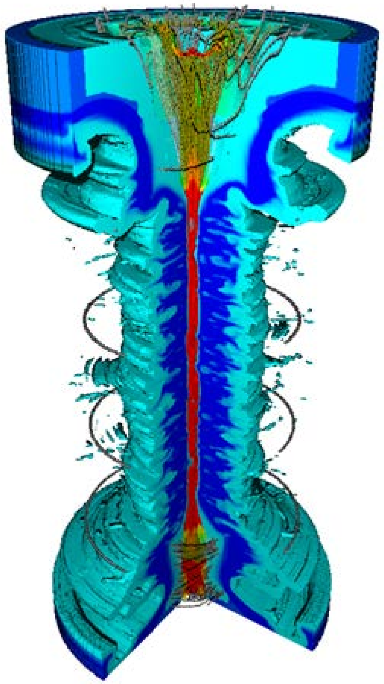
Density	1×10^{14} cm^{-3}		$2\text{-}20 \times 10^{25}$ cm^{-3}
Volume	8×10^{8} cm^{3}		6×10^{-8} cm^{3}
Duration	300-500 s		$5\text{-}10 \times 10^{-11}$ s
Magnetic field	100 kG		0 kG

Magneto-inertial fusion sits in the space between the two

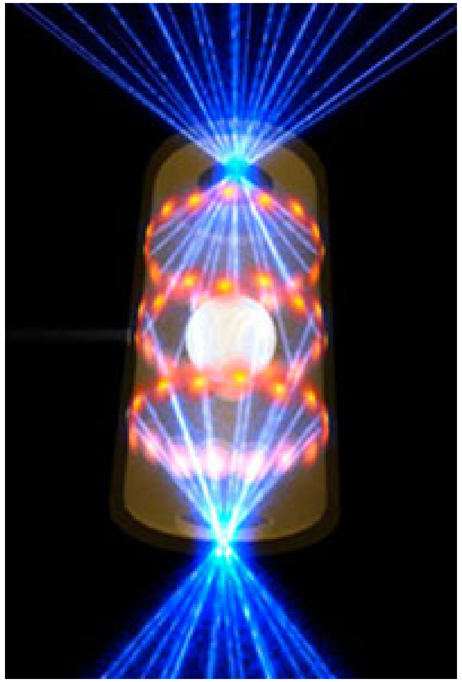
ITER



MagLIF stagnation



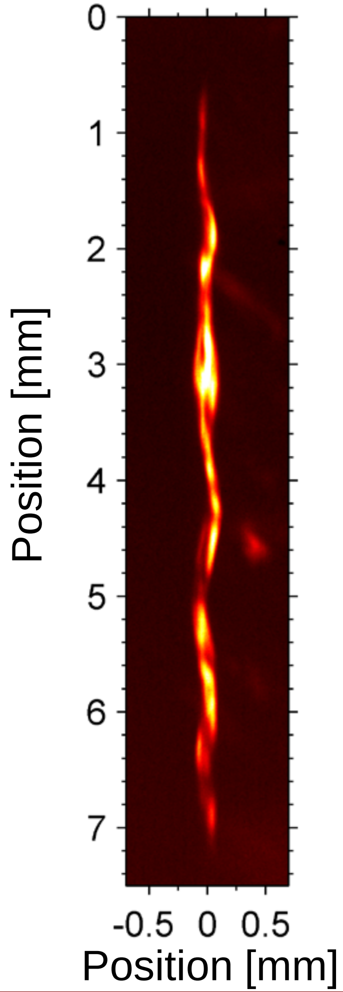
NIF hohlraum



Density	1×10^{14} cm^{-3}	1×10^{23} cm^{-3}	$2\text{-}20 \times 10^{25}$ cm^{-3}
Volume	8×10^{8} cm^{3}	8×10^{-5} cm^{3}	6×10^{-8} cm^{3}
Duration	300-500 s	$1\text{-}2 \times 10^{-9}$ s	$5\text{-}10 \times 10^{-11}$ s
Magnetic field	100 kG	50-100 MG	0 kG

We have demonstrated key aspects of magneto-inertial fusion on Sandia's Z facility

Well-behaved stagnation volume



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

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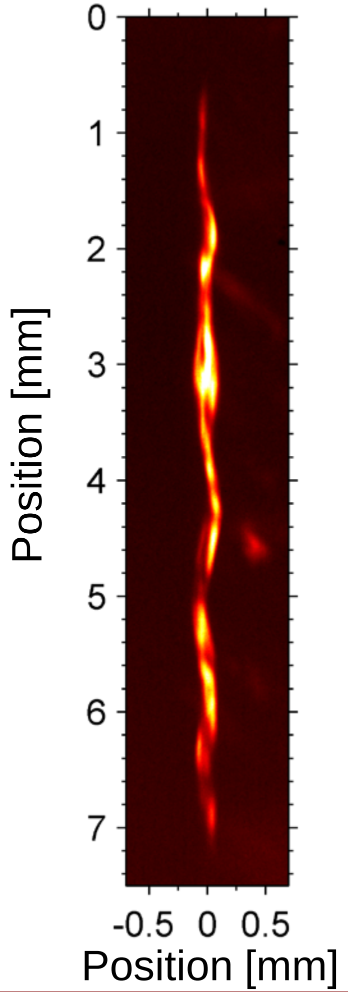
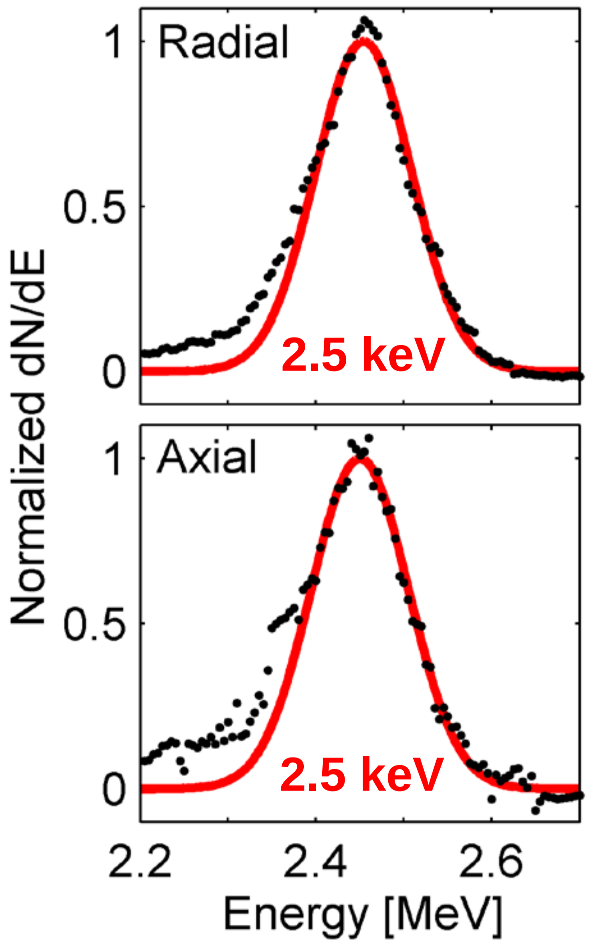


Relevant temperatures



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

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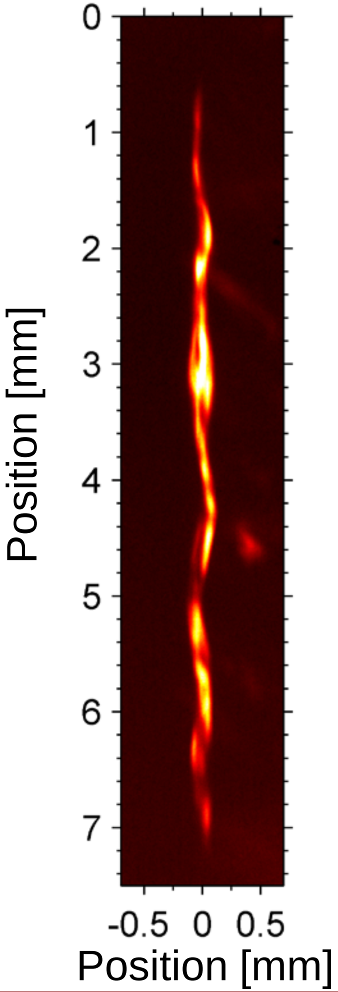
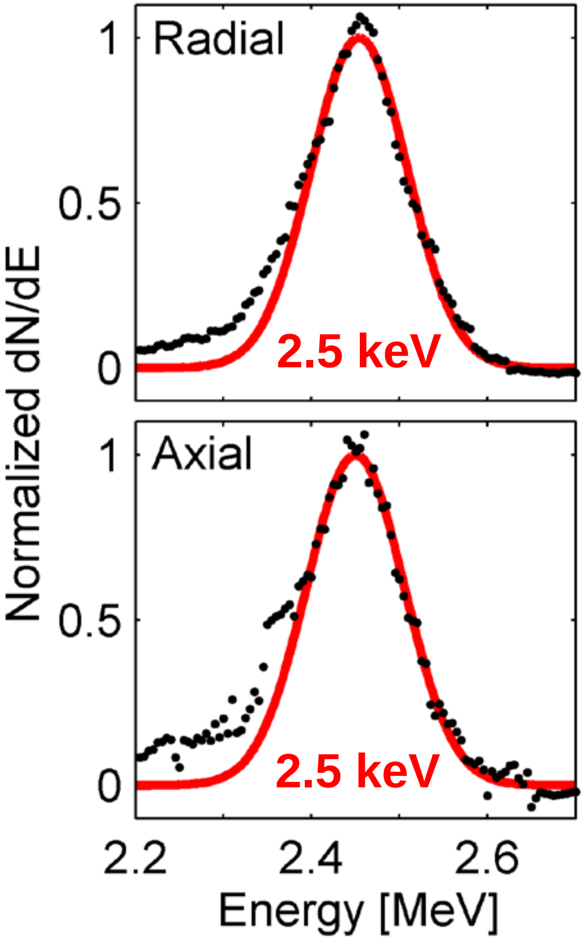
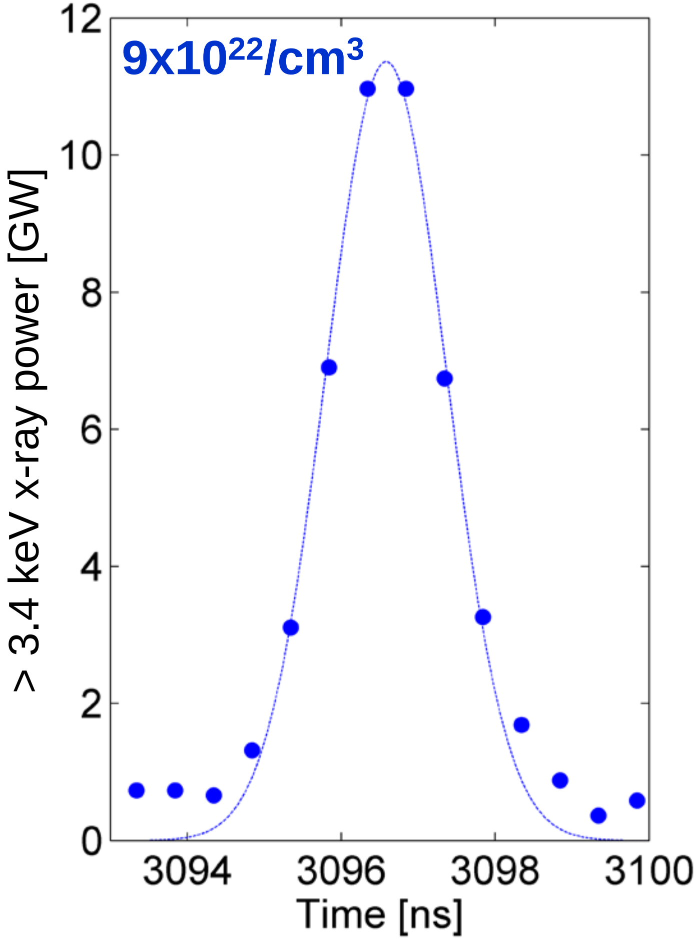


Relevant temperatures



Relevant densities



S. B. Hansen, et al., Phys. Plasmas 22, 056313 (2015).

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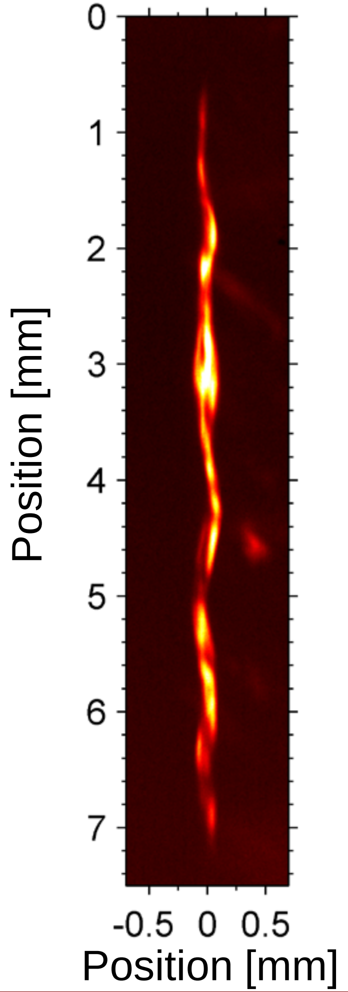
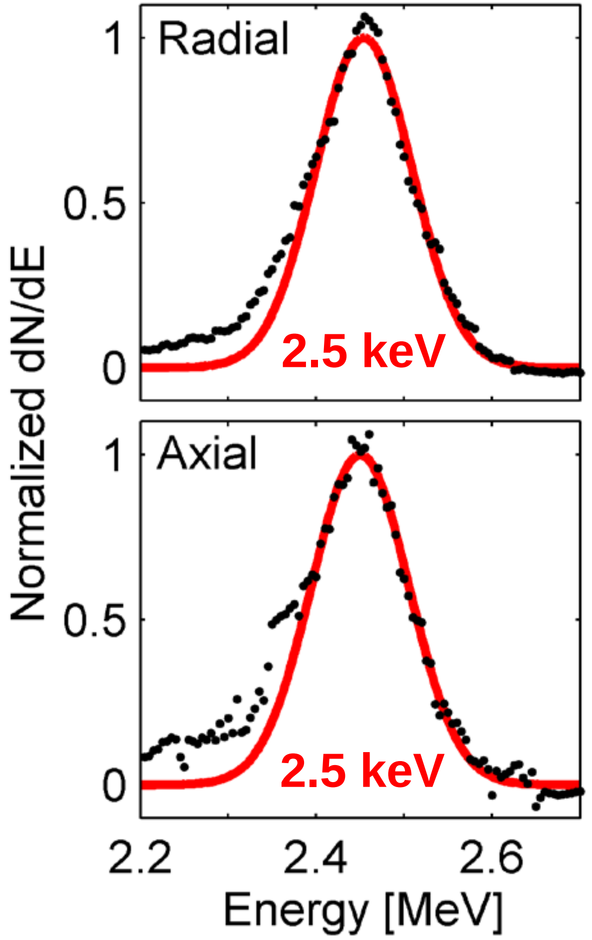
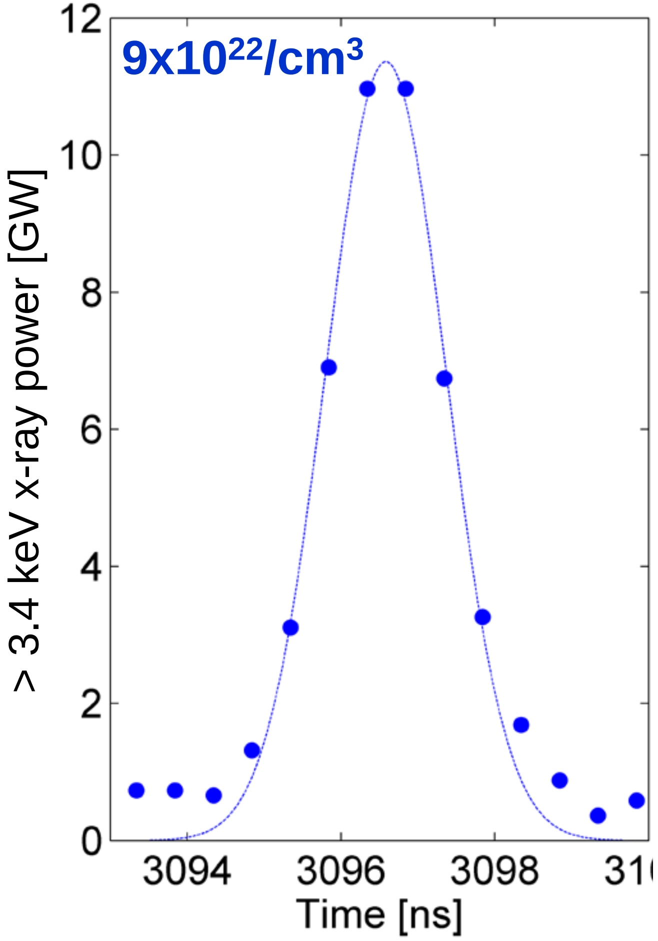
Well-behaved stagnation volume



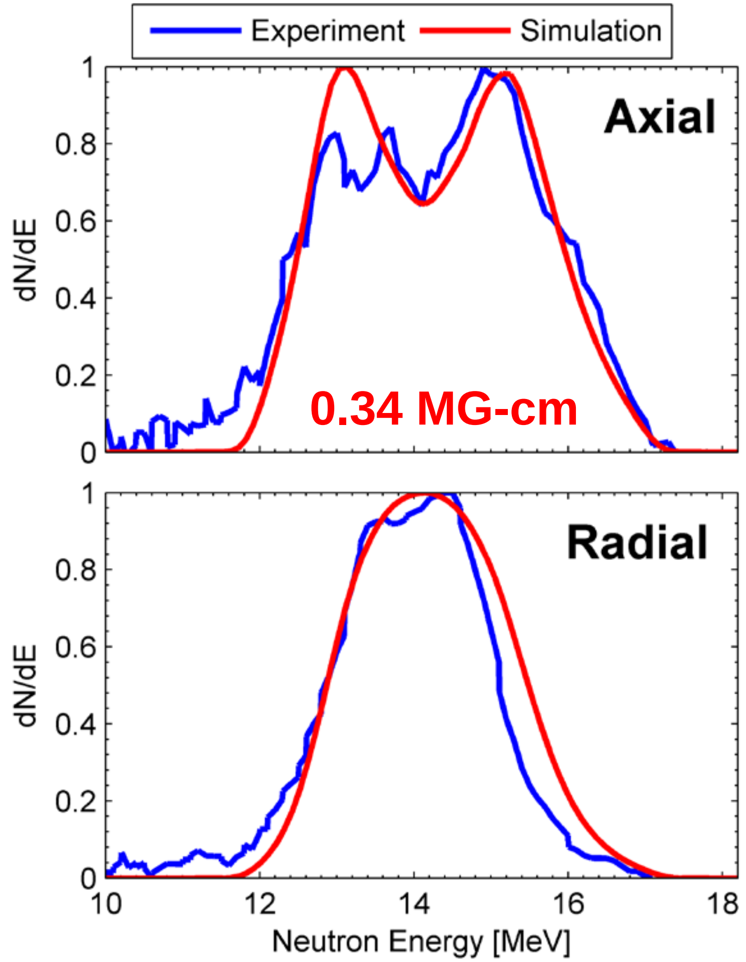
Relevant temperatures



Relevant densities

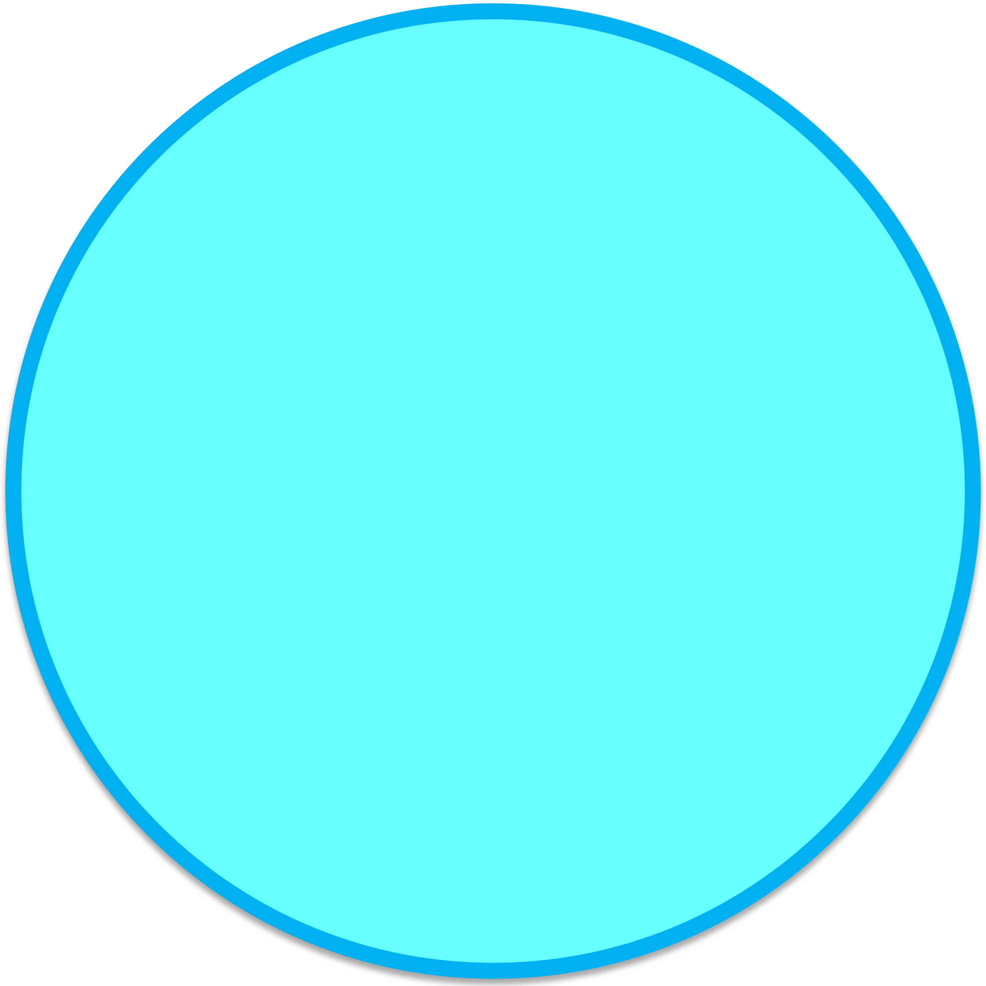


Relevant B-fields



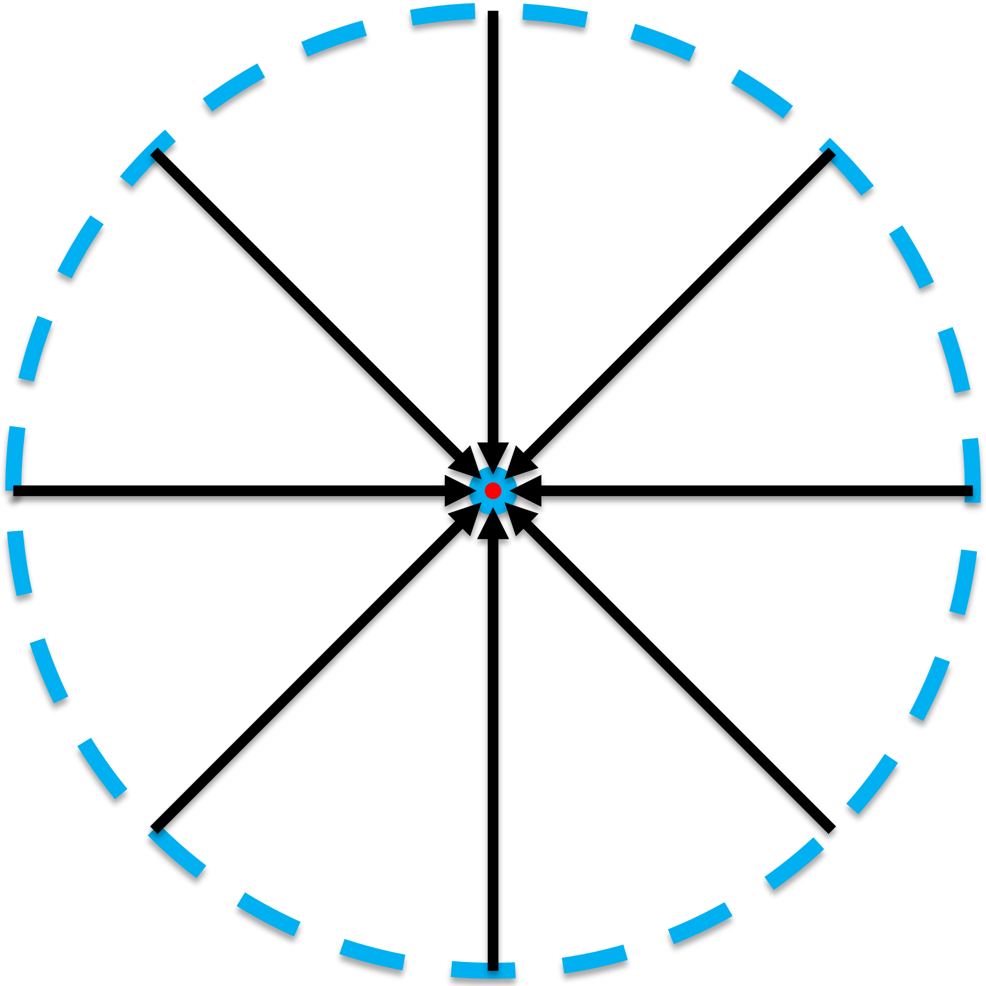
P. F. Schmit, et al., Phys. Rev. Lett. 113, 155004 (2014).

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

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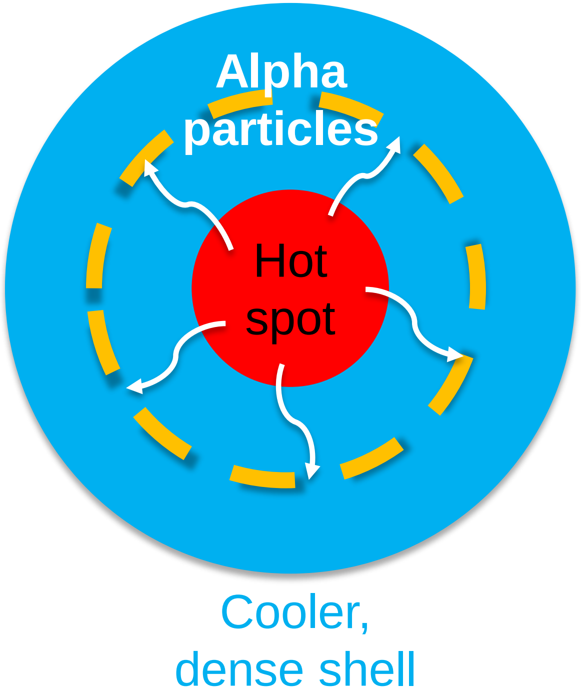
Zooming in



- 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

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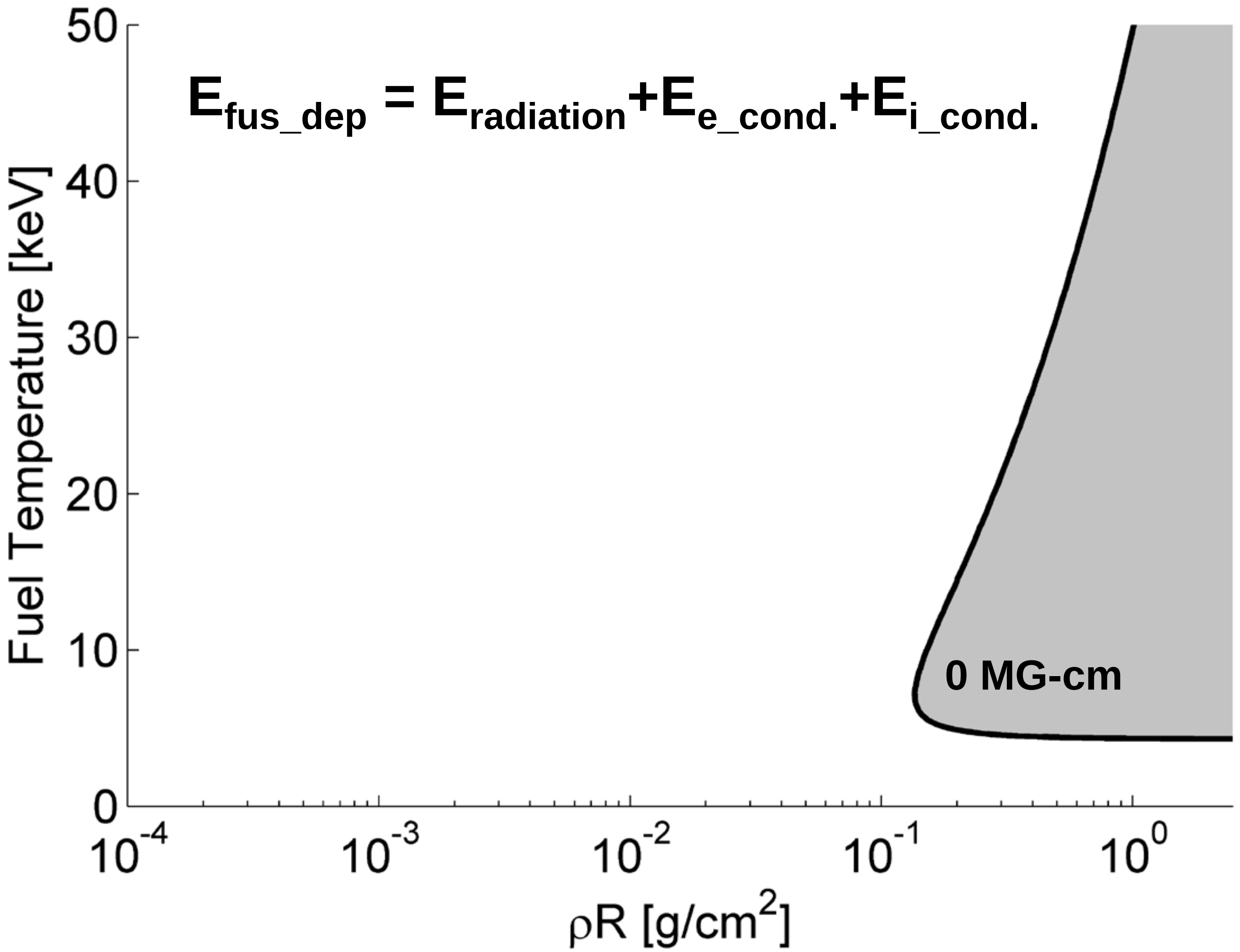
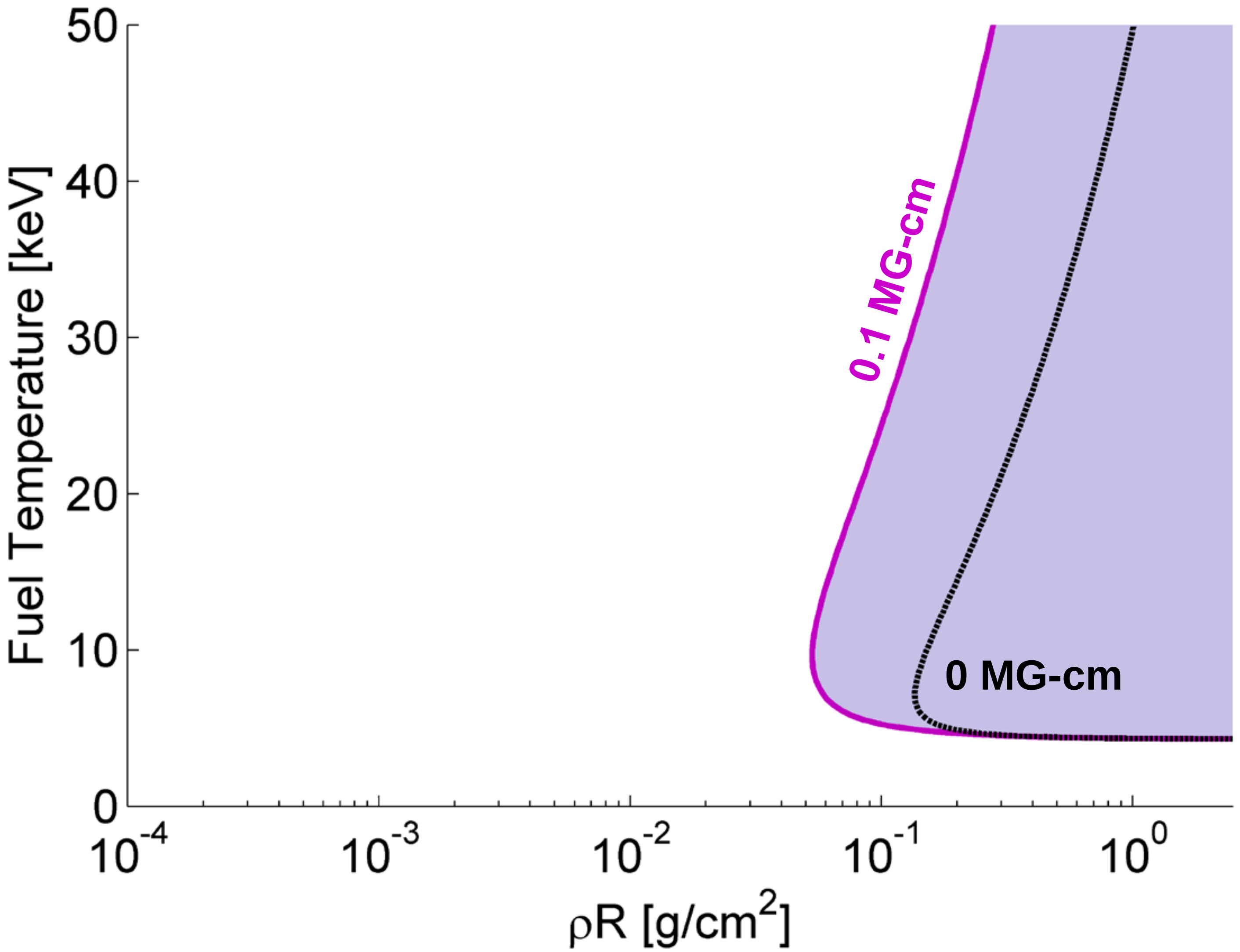


- There is a minimum fuel temperature of about 4.5 keV
  - This is where fusion heating outpaces radiation losses
- The minimum fuel areal density is around 0.2 g/cm^2
- Traditional ICF concepts attempt to operate in this minimum

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

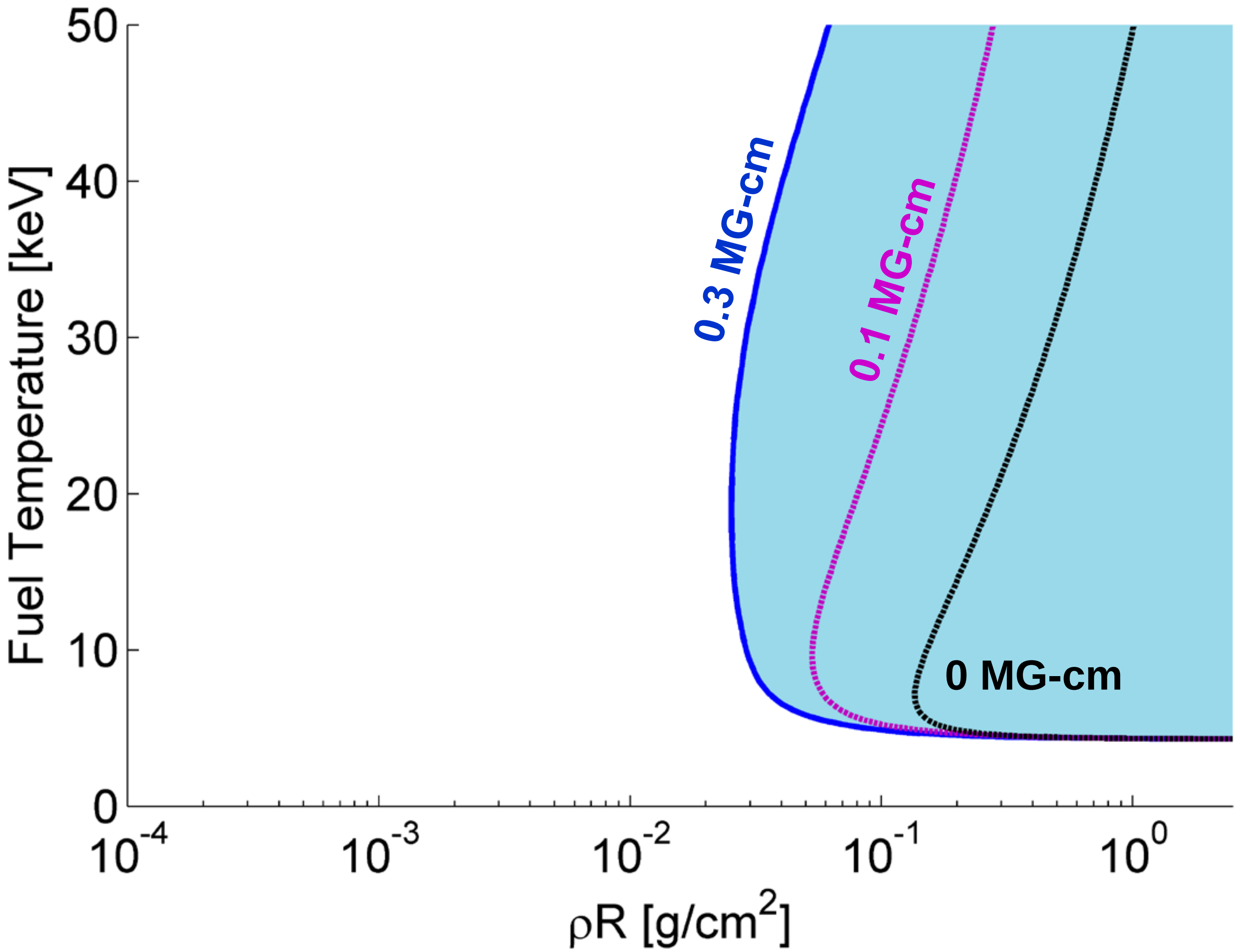
Magneto-inertial fusion utilizes magnetic fields to relax the stagnation requirements of ICF



- Applying a magnetic field opens up a larger region of parameter space
- This is sufficient field to neglect electron thermal conduction loss
- Note the minimum temperature does not change because it is driven by radiation losses

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

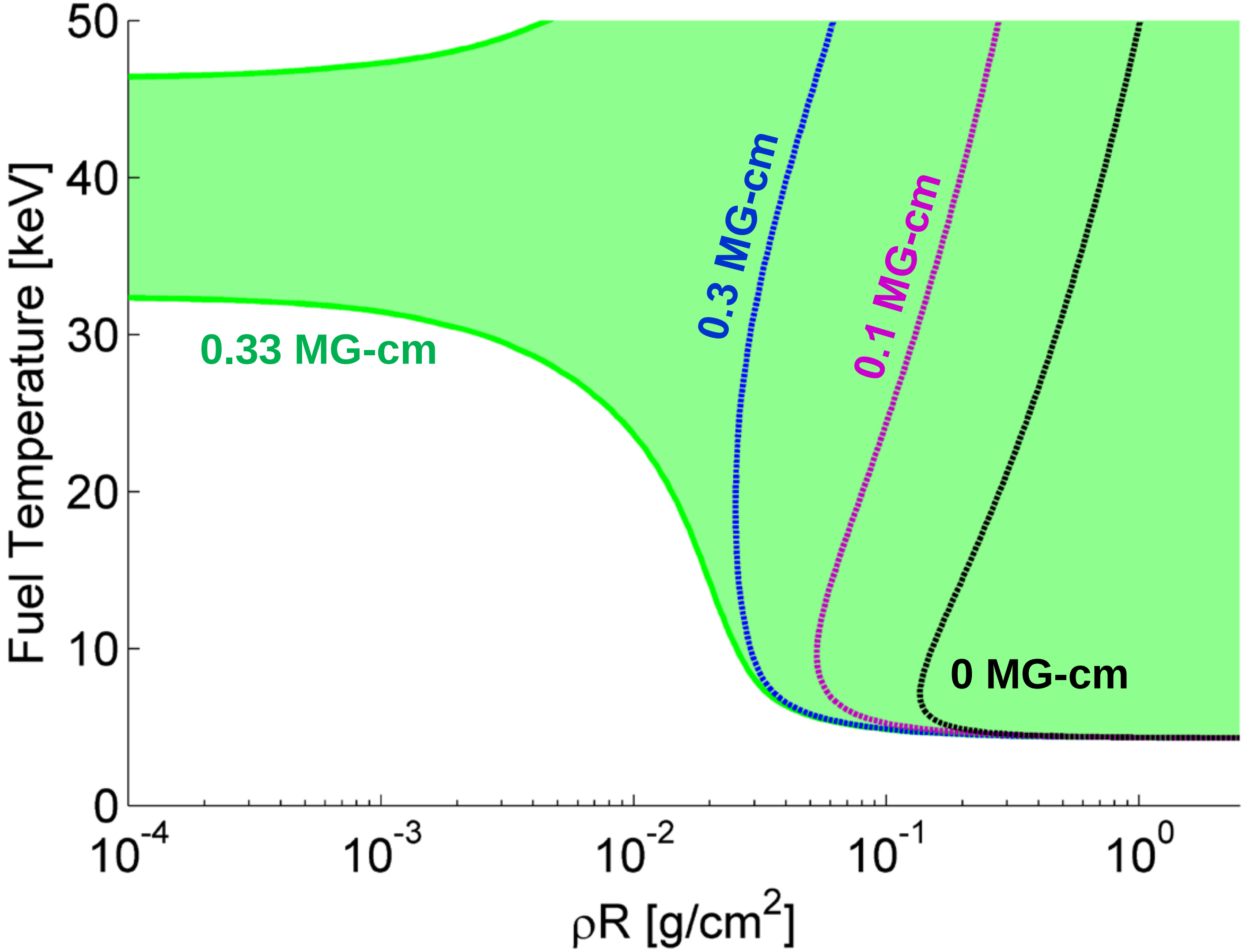
Magneto-inertial fusion utilizes magnetic fields to relax the stagnation requirements of ICF



- This is sufficient field to neglect ion thermal conduction losses
- The Larmor radius of fusion alphas is approximately the radius of the fuel

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

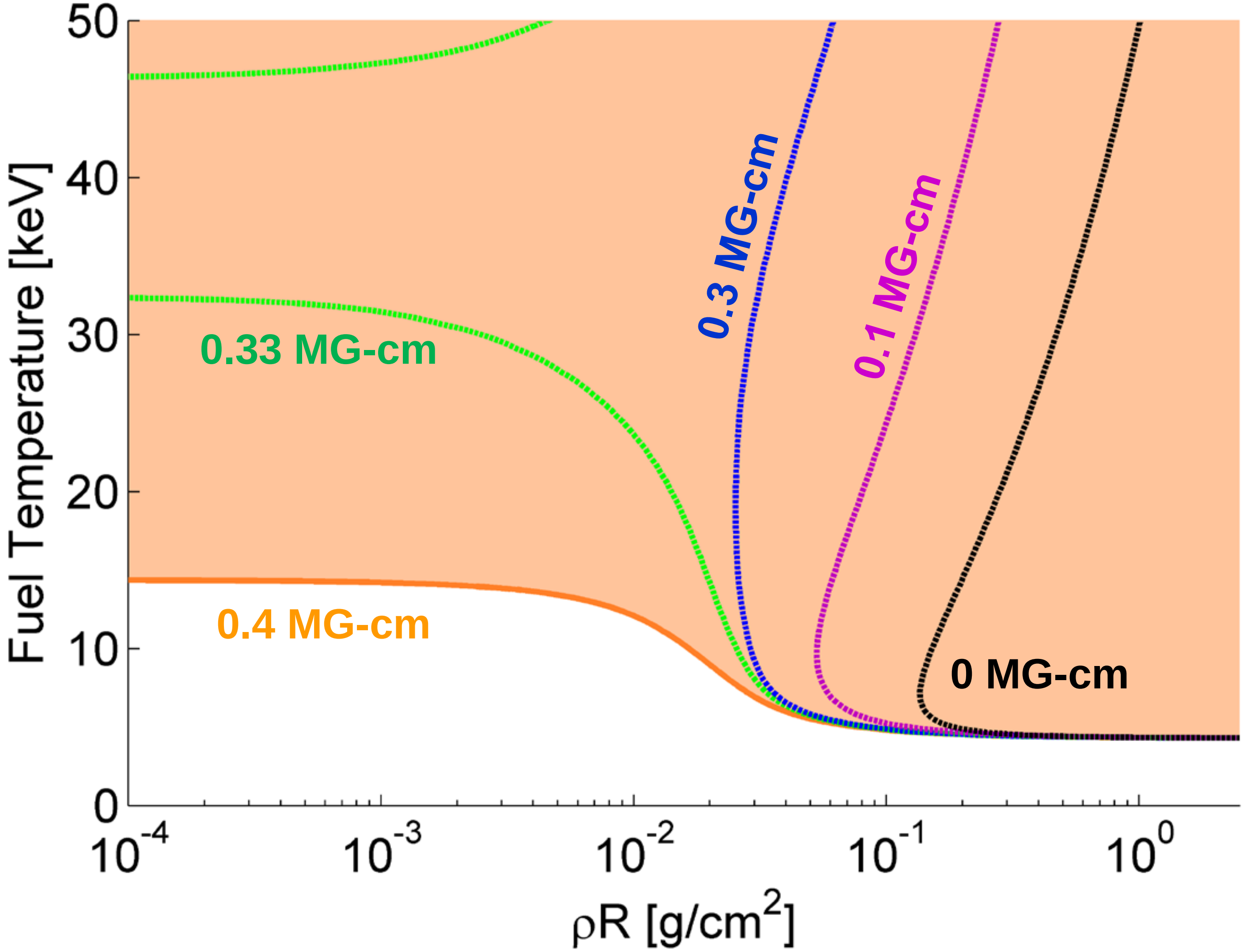
Magneto-inertial fusion utilizes magnetic fields to relax the stagnation requirements of ICF



- There are dramatic gains for small changes in the field when the Larmor radius is slightly less than the fuel radius
- Substantial increase in the fusion energy trapped in the fuel

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

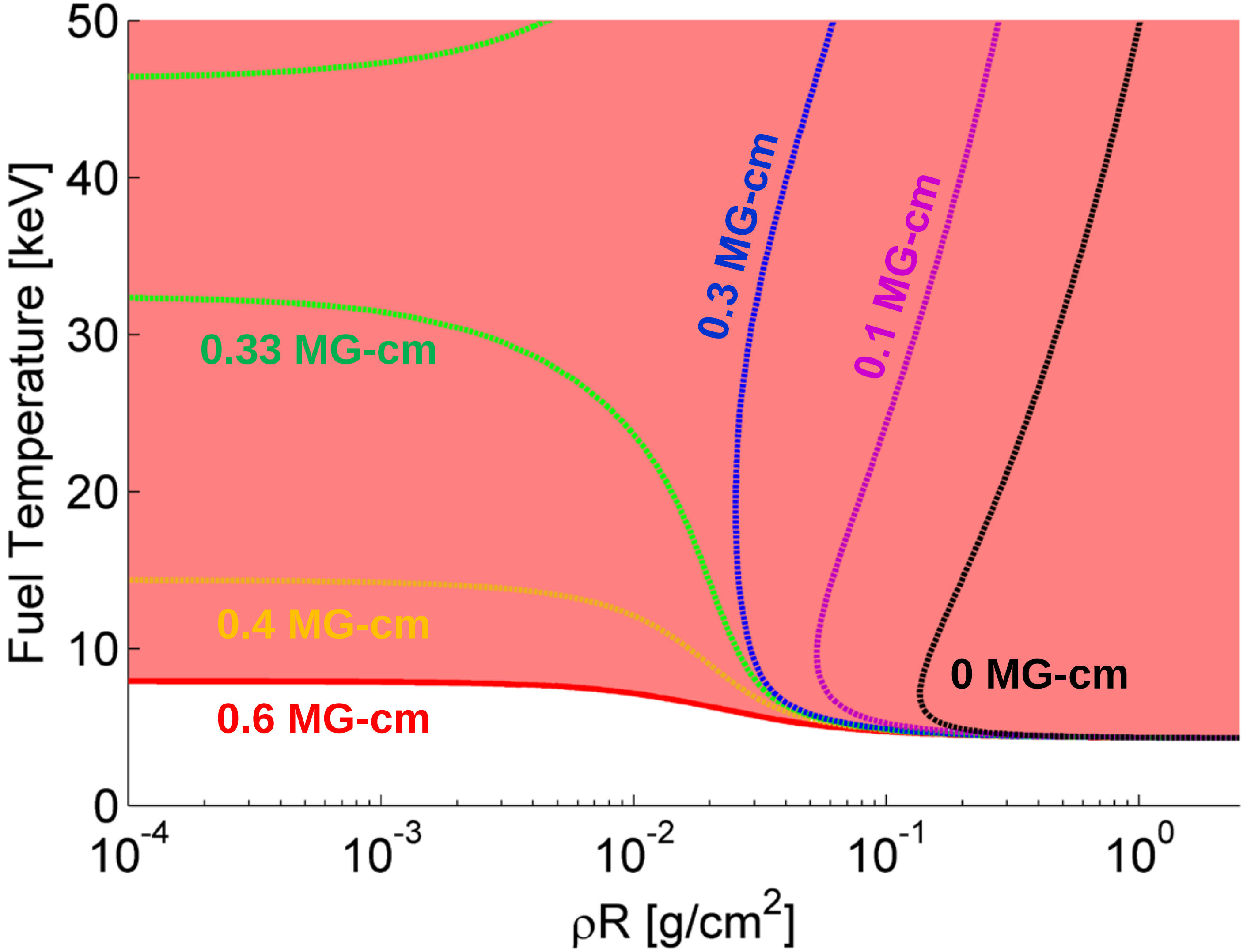
Magneto-inertial fusion utilizes magnetic fields to relax the stagnation requirements of ICF



- As field increases, confinement of the charged fusion-products is achieved through the magnetic field rather than the areal density

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

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



- When the Larmor radius is about half of the fuel radius, the effect begins to saturate

- This means there is an optimal field for a given fuel configuration

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

There are three major approaches to ICF being pursued in the United States

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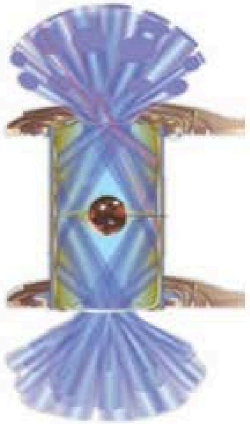
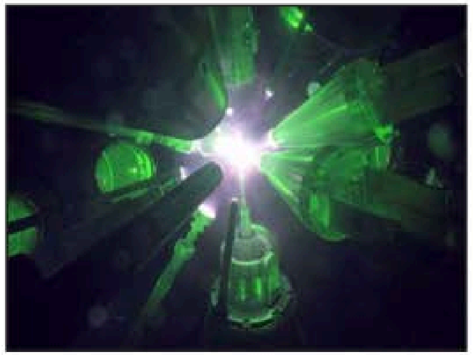
Laser x-ray drive

192 beams, 1.8 MJ, 400 TW

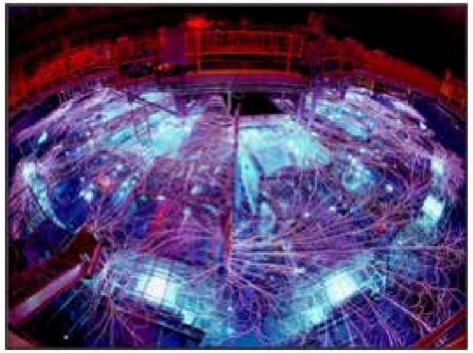


Laser direct drive

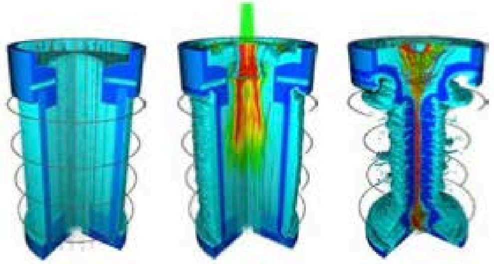
60 beams, 30 kJ, 20 TW



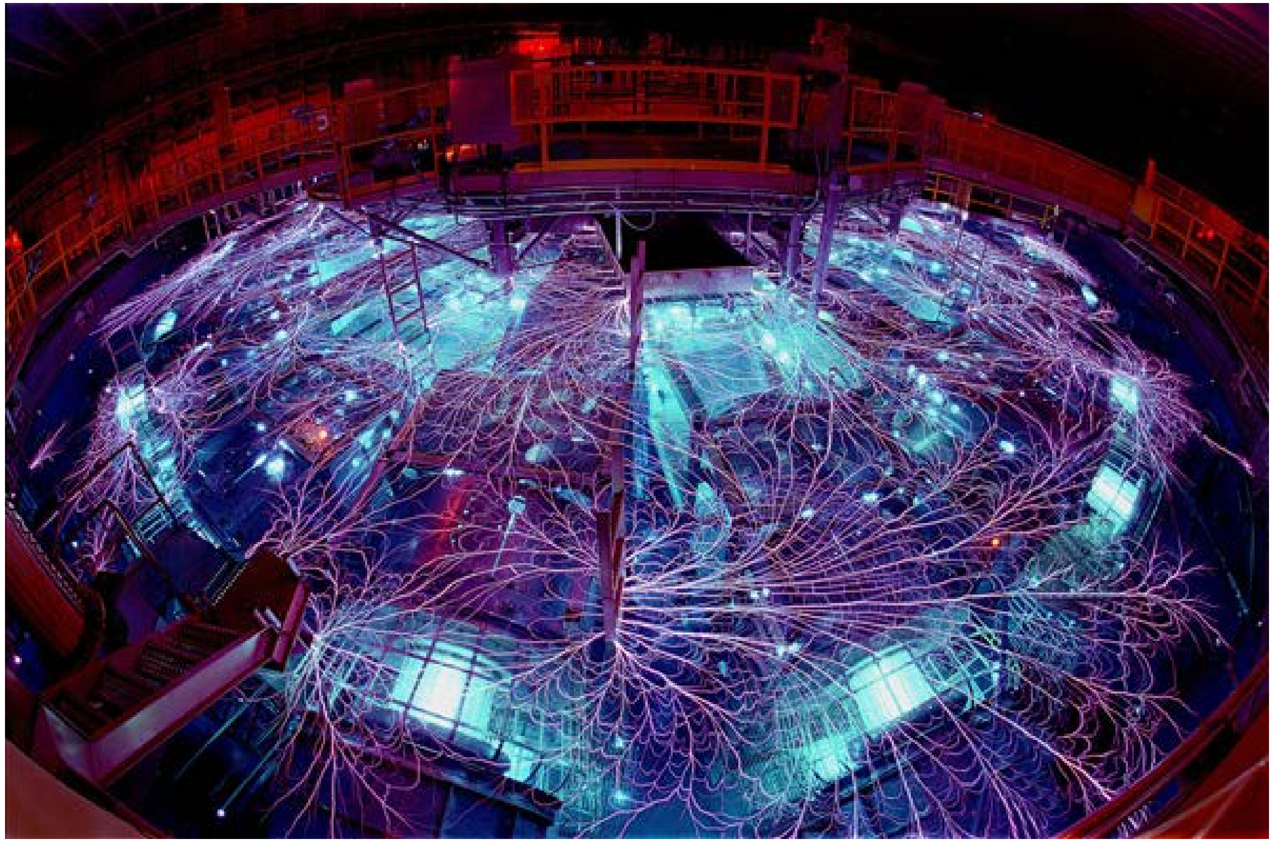
Magnetic direct drive



26 MA, 80 TW



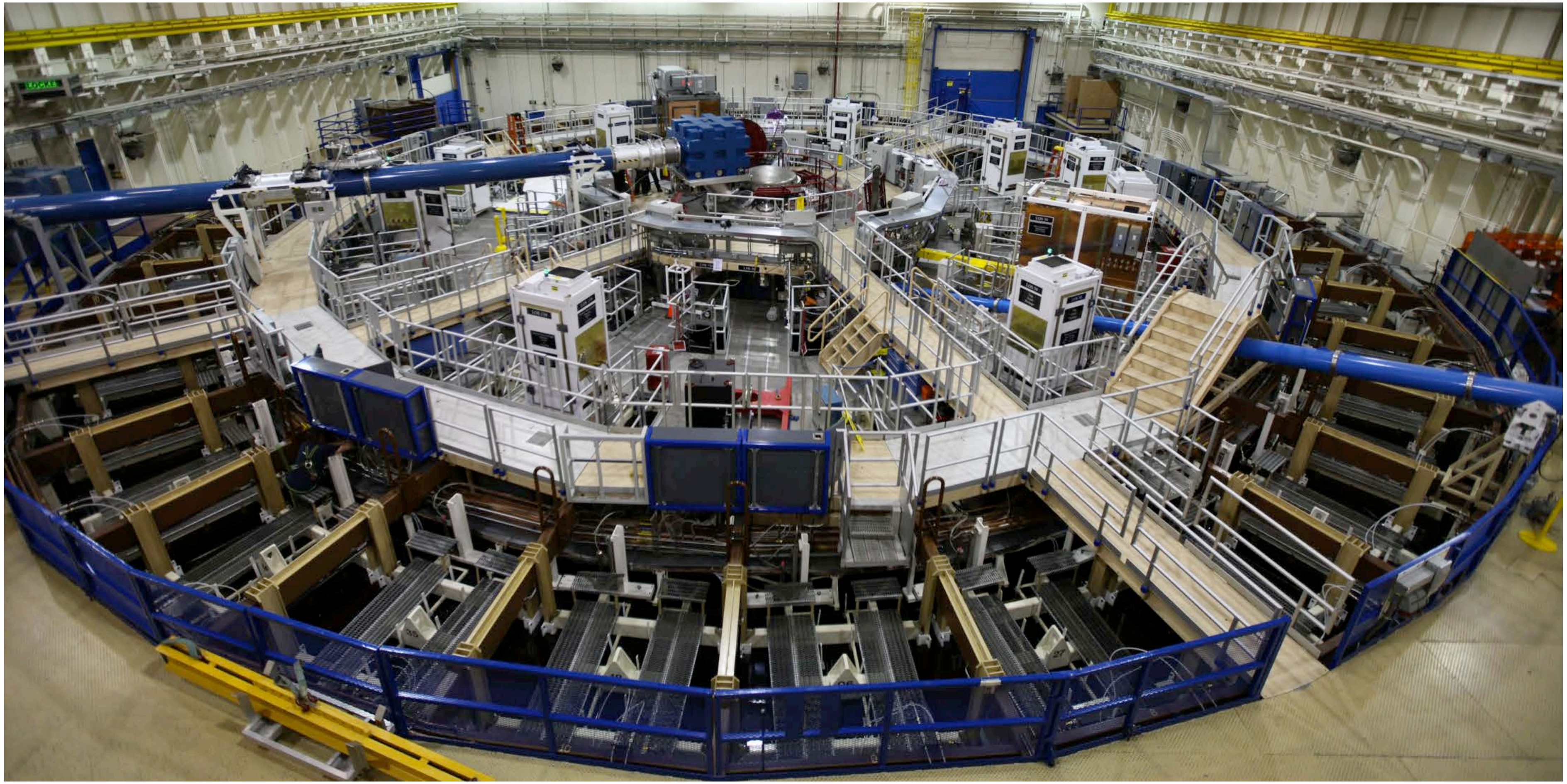
In magnetic direct drive, we use pulsed power to create high energy density matter



- What is pulsed power?
  - Store energy over relatively long period of time (seconds to minutes)
  - Discharging over a relatively short period of time (ns to μs)
  - Compression in time of ~10^9
- Z stores about 20 MJ of energy over about 3 minutes
  - Average power ~ 100 kW
- Z delivers around 3 MJ of energy in a 100 ns risetime pulse to the experiment
  - Peak power ~80 TW

M. K. Matzen, et al., Phys. Plasmas 12, 055503 (2005).

The energy of the Z machine is compressed in space as well as time



33 m

Energy storage volume is ~100 m^3

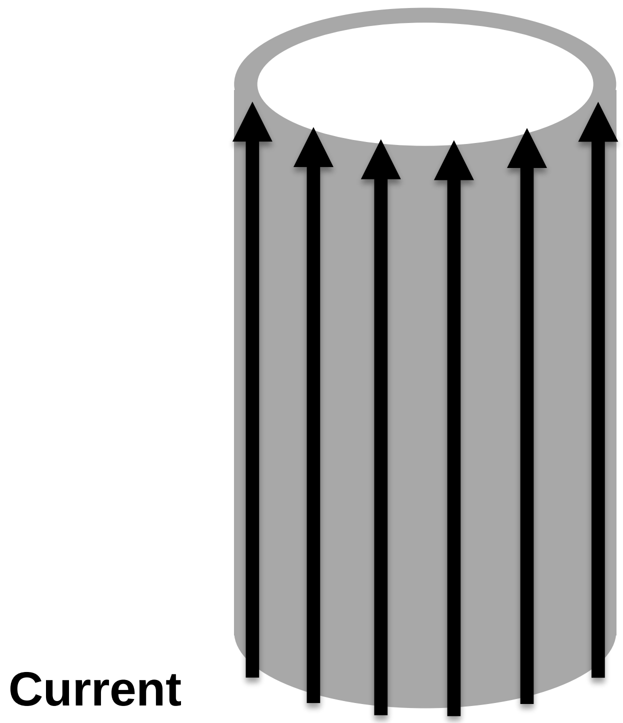
Target volume is ~0.1 cm^3

Compression in space is ~10^9

D. V. Rose, et al., Phys. Rev. ST Accel. Beams 13, 010402 (2010).

The enormous current of the Z Machine is used to accelerate matter to extreme velocities

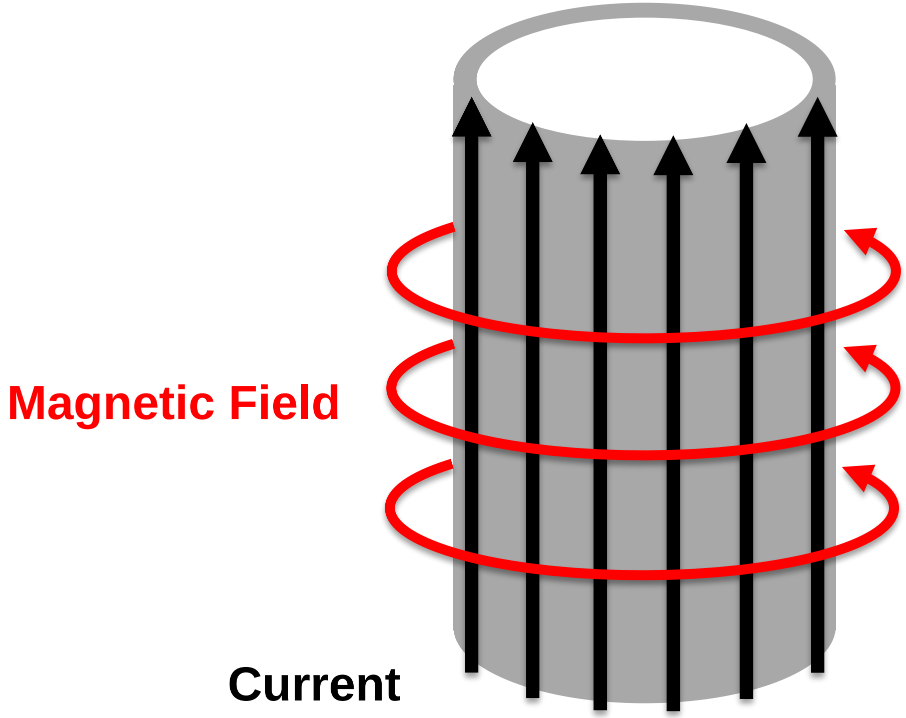
Cylindrical geometry



- Current flows through a conducting cylinder

The enormous current is used to accelerate matter to extreme velocities

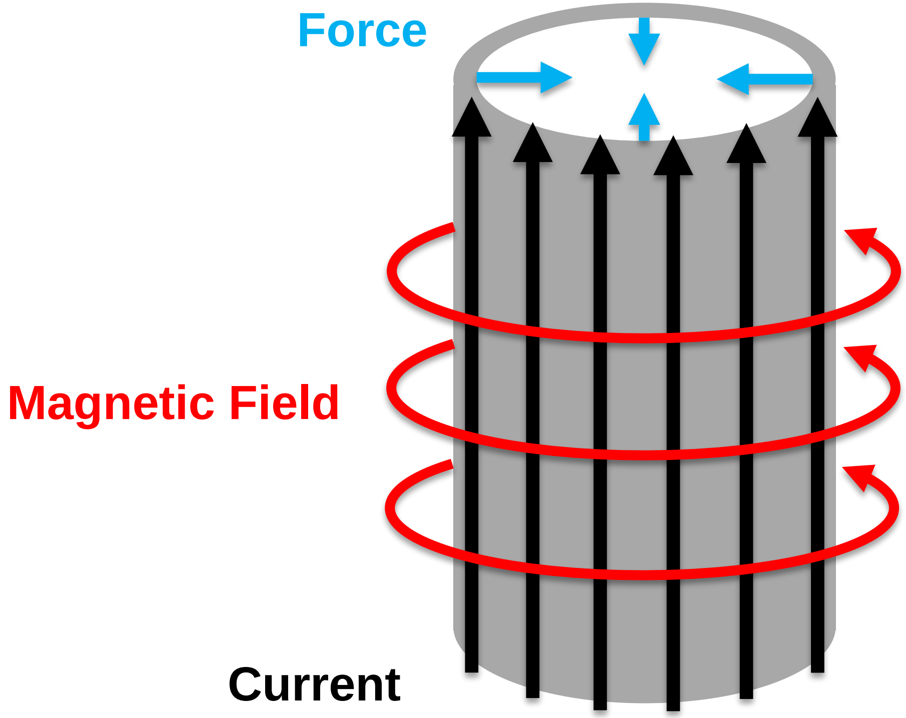
Cylindrical geometry



- Current flows through a conducting cylinder
- Produces a self-magnetic field

The enormous current is used to accelerate matter to extreme velocities

Cylindrical geometry



100 km/s range

- Current flows through a conducting cylinder
- Produces a self-magnetic field
- Generates a radially-inward force

The massive energy coupled to the target destroys the nearby components

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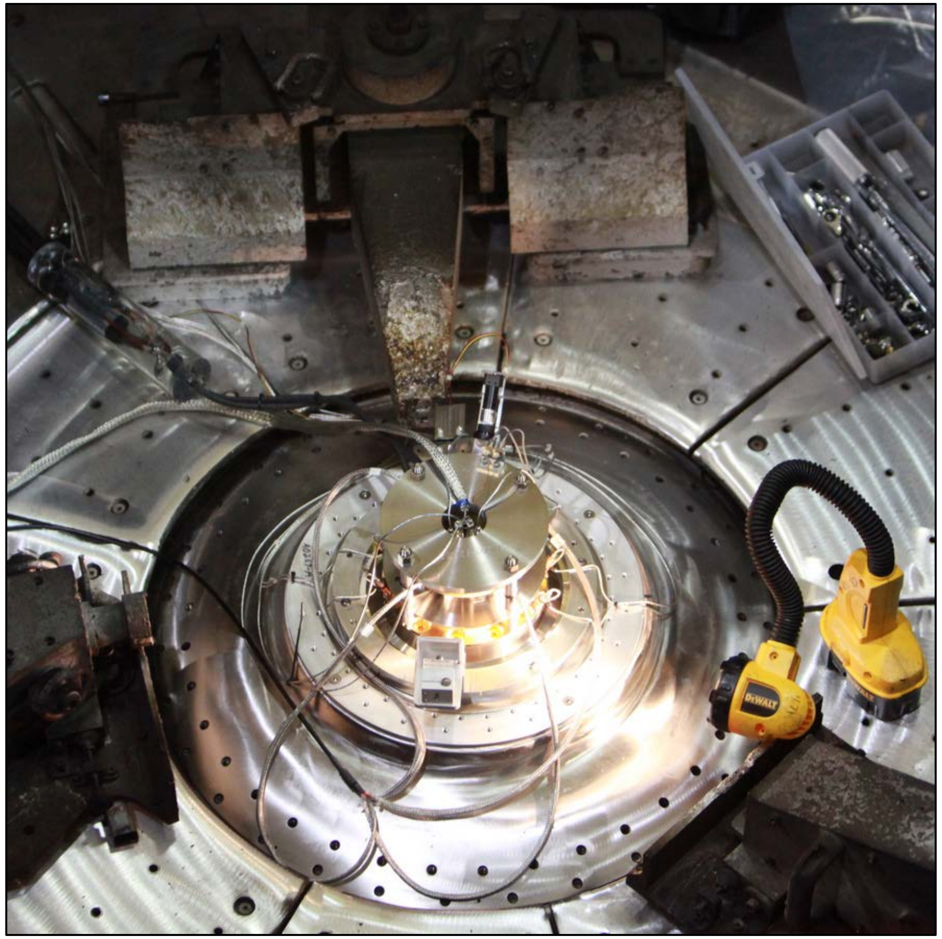
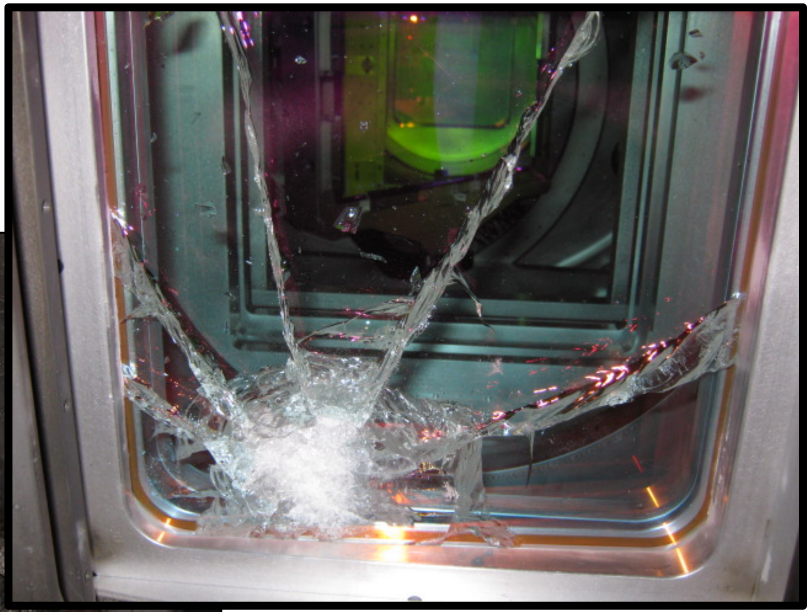
Before



After



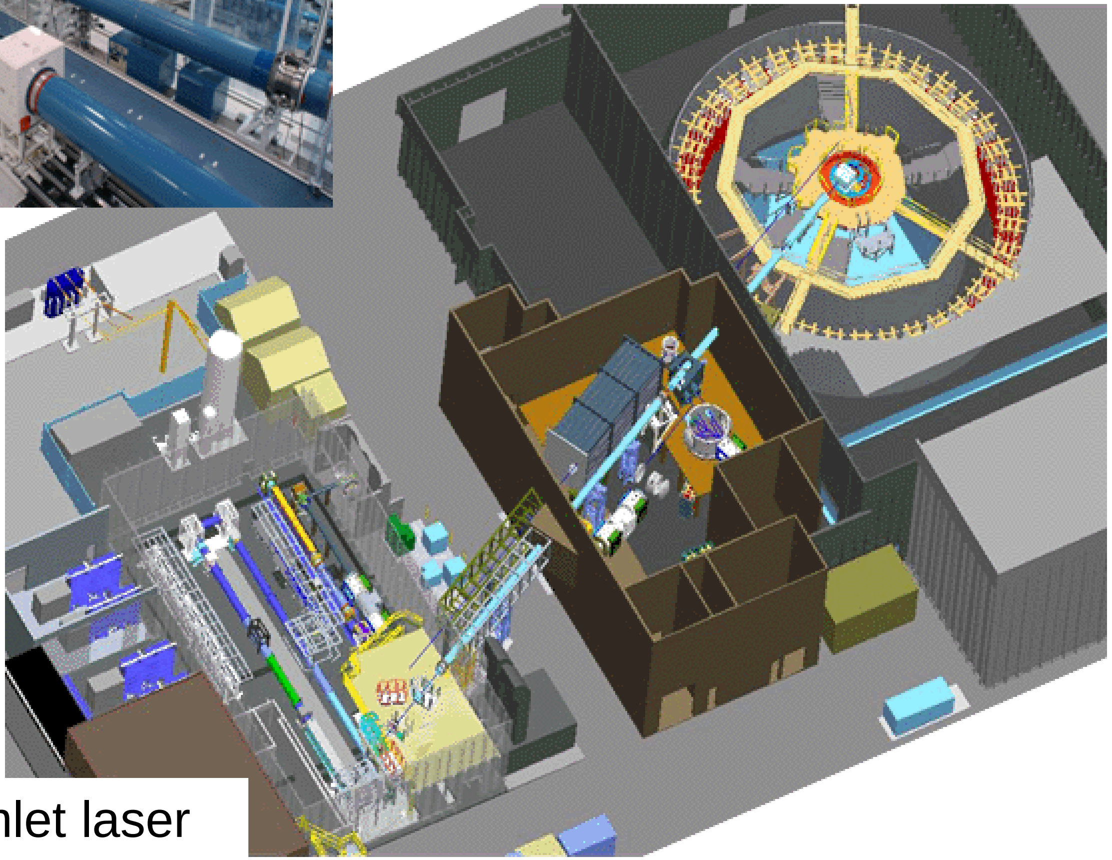
~3 MJ energy deposited

Clean up and reload limits us to 1 shot/day

In addition to our pulsed power machine, we have a multi-kJ, TW-class laser

Z-Beamlet High Bay

Z Machine



Z-Beamlet laser

- Originally a prototype beamline for the NIF
- Up to 4.5 kJ at 1 TW of 527 nm
- Up to 3 shots per day (4 hour cool down)
- With the Z machine or in separate experiments

P. Rambo, et al., Proc. SPIE 10014, 100140Z (2016).

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

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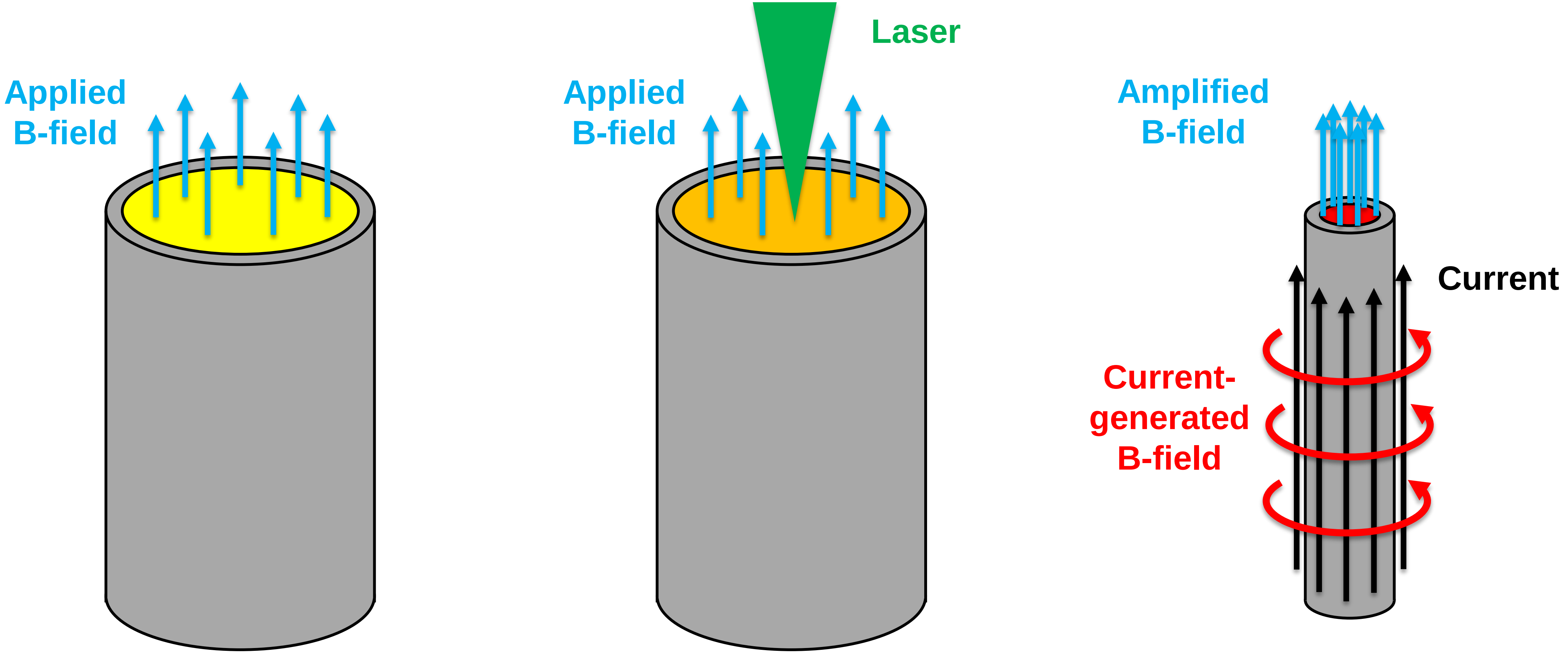


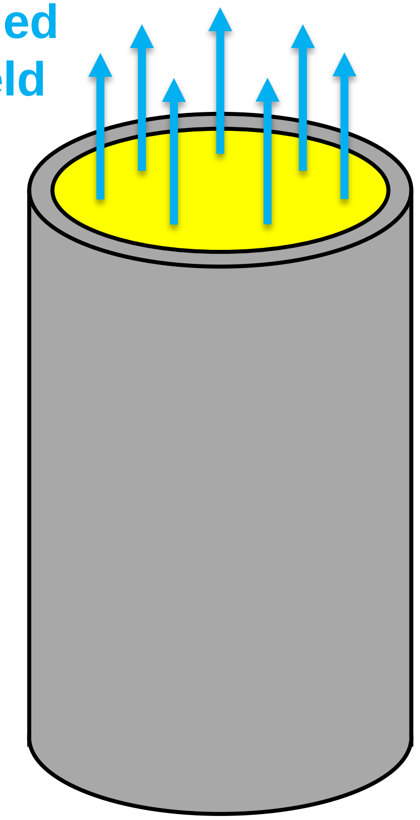
Apply axial magnetic field

Laser-heat the magnetized fuel

Compress the heated and magnetized fuel

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

An axial magnetic field is applied to limit radial charged particle transport



Apply axial magnetic field

- Metal cylinder contains ~$10^{20}/cm^3$ of deuterium gas
  - 1 cm tall, 0.5 cm diameter, 0.05 cm thick
- Helmholtz-like coils apply 100-300 kG
  - 3 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

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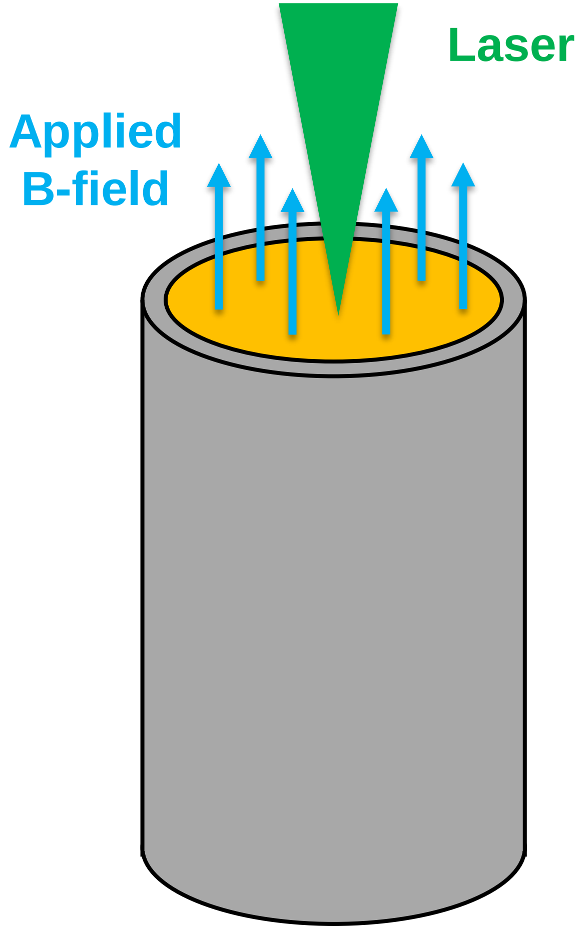
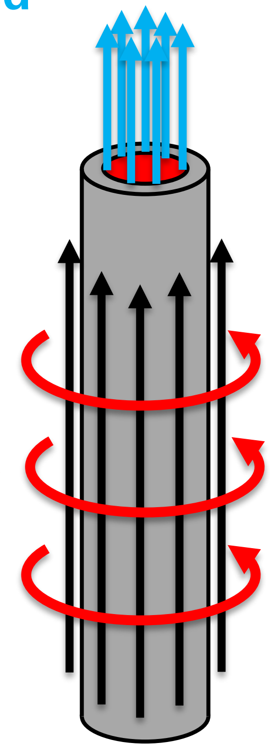


Laser-heat the magnetized fuel

- 527 nm, 2 ns, 2 kJ laser used to heat the fuel
  - Fuel has n_e ~ 5% of n_{crit}
  - Intensity is ~5e14 W/cm^2 (above many LPI thresholds)
- Laser must pass through ~1 µm thick plastic window
- Fuel is heated to ~100 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 ~17 MA, risetime is 100 ns
  - Generates ~30 MG 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 > 10 MG through flux compression

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

There are several key differences between this concept and traditional ICF

- Cylindrical vs spherical
  - Natural geometry for magnetic direct drive
  - Volume change for convergence ratio of 30 is 900 vs 27,000

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- Cylindrical vs spherical
  - Natural geometry for magnetic direct drive
  - Volume change for convergence ratio of 30 is 900 vs 27,000
- Relatively low implosion velocity (70 km/s vs 350 km/s)
  - Instability growth requires a thick, massive liner
  - Attempting to match implosion time to our driver
  - Relying on volumetric heating of fuel through PdV work, which requires pre-heated fuel

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- Cylindrical vs spherical
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  - Volume change for convergence ratio of 30 is 900 vs 27,000
- Relatively low implosion velocity (70 km/s vs 350 km/s)
  - Instability growth requires a thick, massive liner
  - Attempting to match implosion time to our driver
  - Relying on volumetric heating of fuel through PdV work, which requires pre-heated fuel
- Applied magnetic field
  - Lower required fuel areal density in the radial direction
  - Liner must provide tamping for fuel at stagnation

MagLIF is a relatively new concept (2008) with a lot of unknowns

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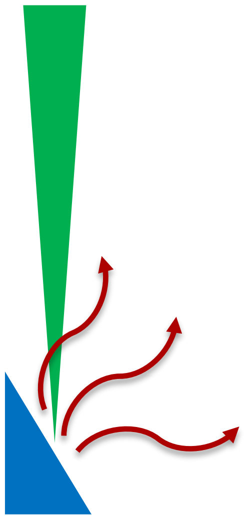
- Areas on which we have focused:
  - How do instabilities impact the implosion?
    - 2009-2012: heavy focus on liner stability experiments
  - Magnetizing several cm^3 with surrounding conductors to ~100 kG
    - 2011-2013: B-field coil development and testing
  - Can we effectively heat the fuel with a laser?
    - 2013-present: Laser heating studies

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

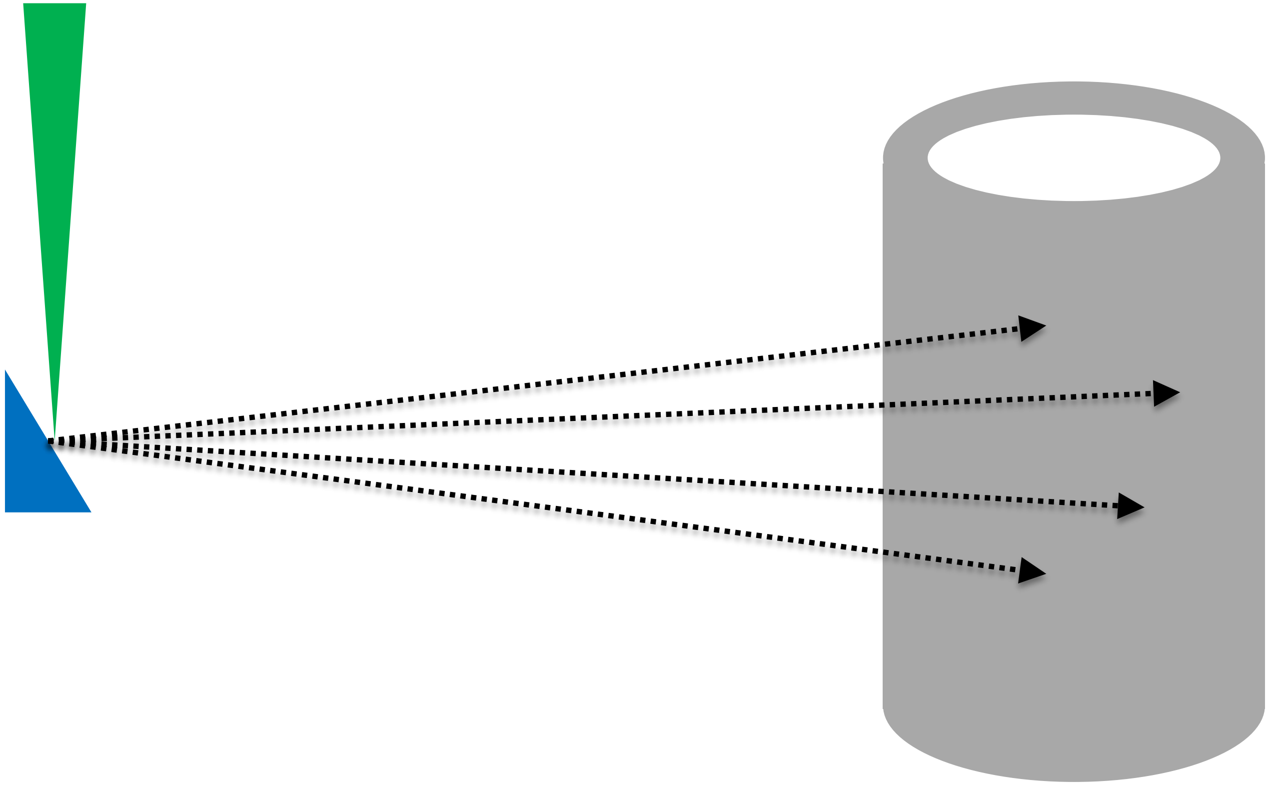
We use a monochromatic x-ray backlighter to check the stability of the implosions



1 kJ, 1 ns, 527 nm laser is focused on a manganese foil
The resultant plasma radiates x-rays

D. B. Sinars, et al., Rev. Sci. Instrum. 75, 3672 (2004).

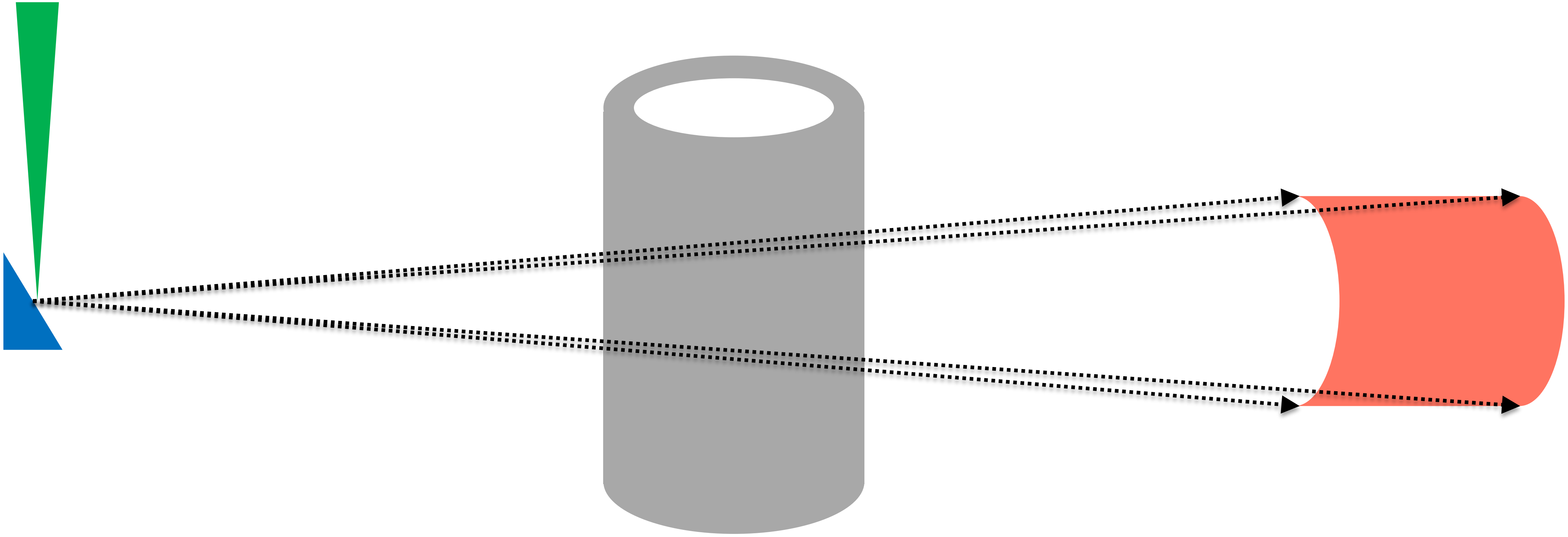
We use a monochromatic x-ray backlighter to check the stability of the implosions



Some of the x-rays pass through our imploding target, which attenuates the signal

D. B. Sinars, et al., Rev. Sci. Instrum. 75, 3672 (2004).

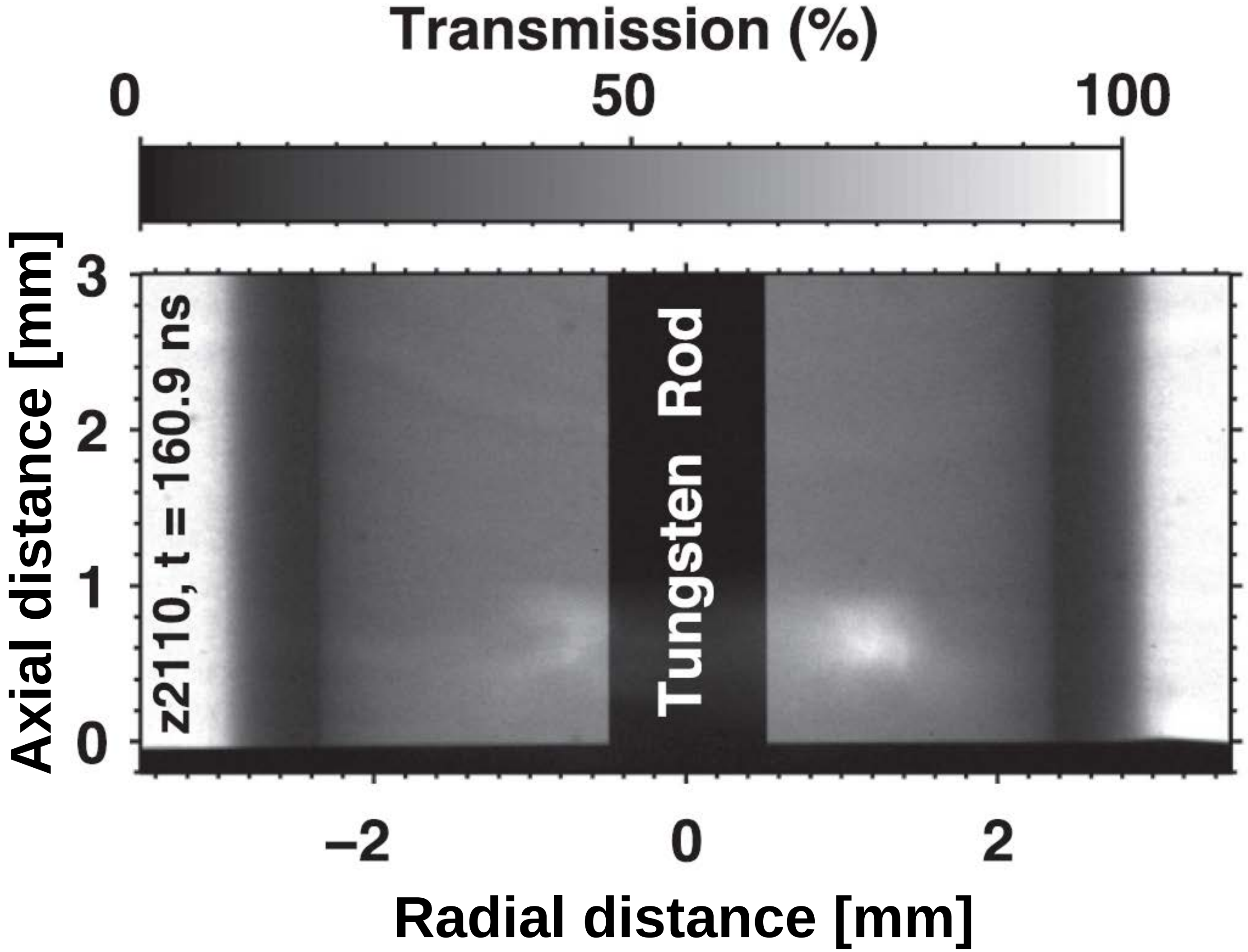
We use a monochromatic x-ray backlighter to check the stability of the implosions



A spherically bent crystal reflects manganese He-α x-rays (6.1 keV)
The signal is recorded on a time integrated detector

D. B. Sinars, et al., Rev. Sci. Instrum. 75, 3672 (2004).

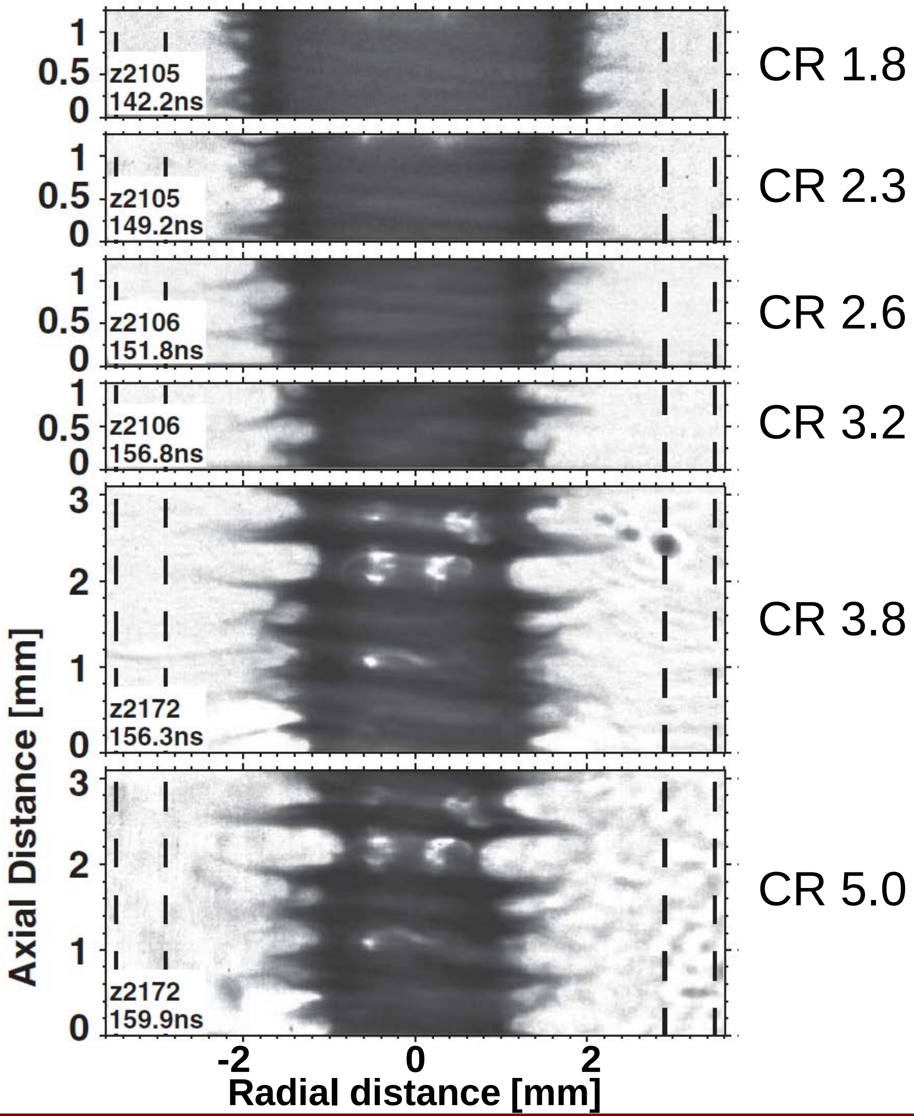
We use a monochromatic x-ray backlighter to check the stability of the implosions



- Image up to 4 mm of the height of the target
- Approximately 15 micron spatial resolution
- Transmission in the tens of percent range at this photon energy with beryllium

R. D. McBride, et al., Phys. Plasmas 20, 056309 (2013).

Radiographs throughout the implosion were collected on a series of experiments

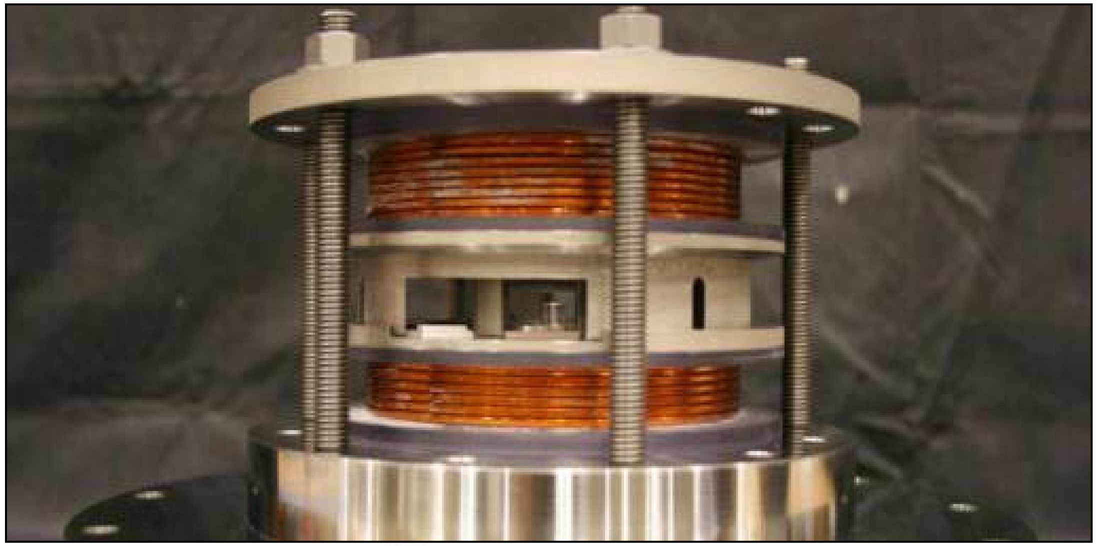


- Magneto-Rayleigh-Taylor instabilities develop and grow
  - Azimuthal correlation of instabilities
  - Use thick liners to limit feedthrough to inner surface
  - Massive liners implode at a relatively slow velocity compared to traditional ICF
- Relatively happy with liner stability
  - Inner surface is relatively straight at a convergence ratio of 5

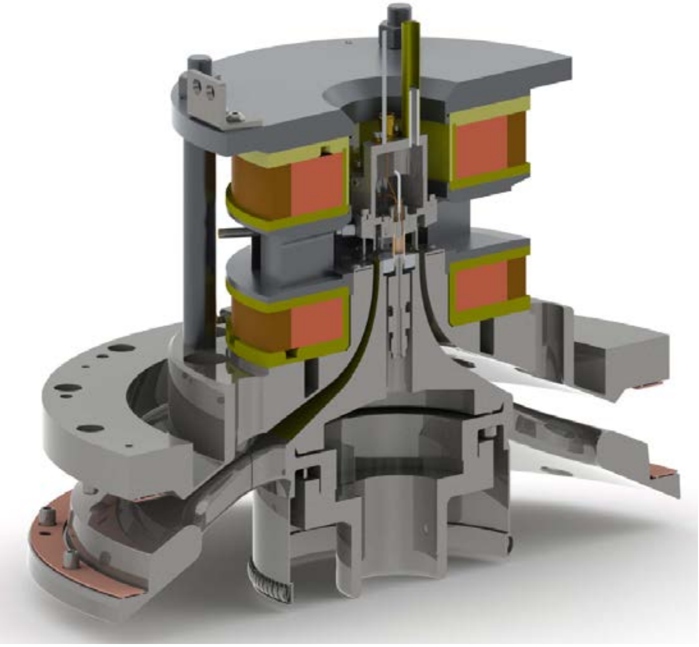
R. D. McBride, et al., Phys. Rev. Lett. 109, 135004 (2012).

We developed a set of single use coils to magnetize the fuel

Helmholtz like coils magnetize a 5 cm diameter, 10 cm tall region



~1 MJ capacitor bank to drive the coils

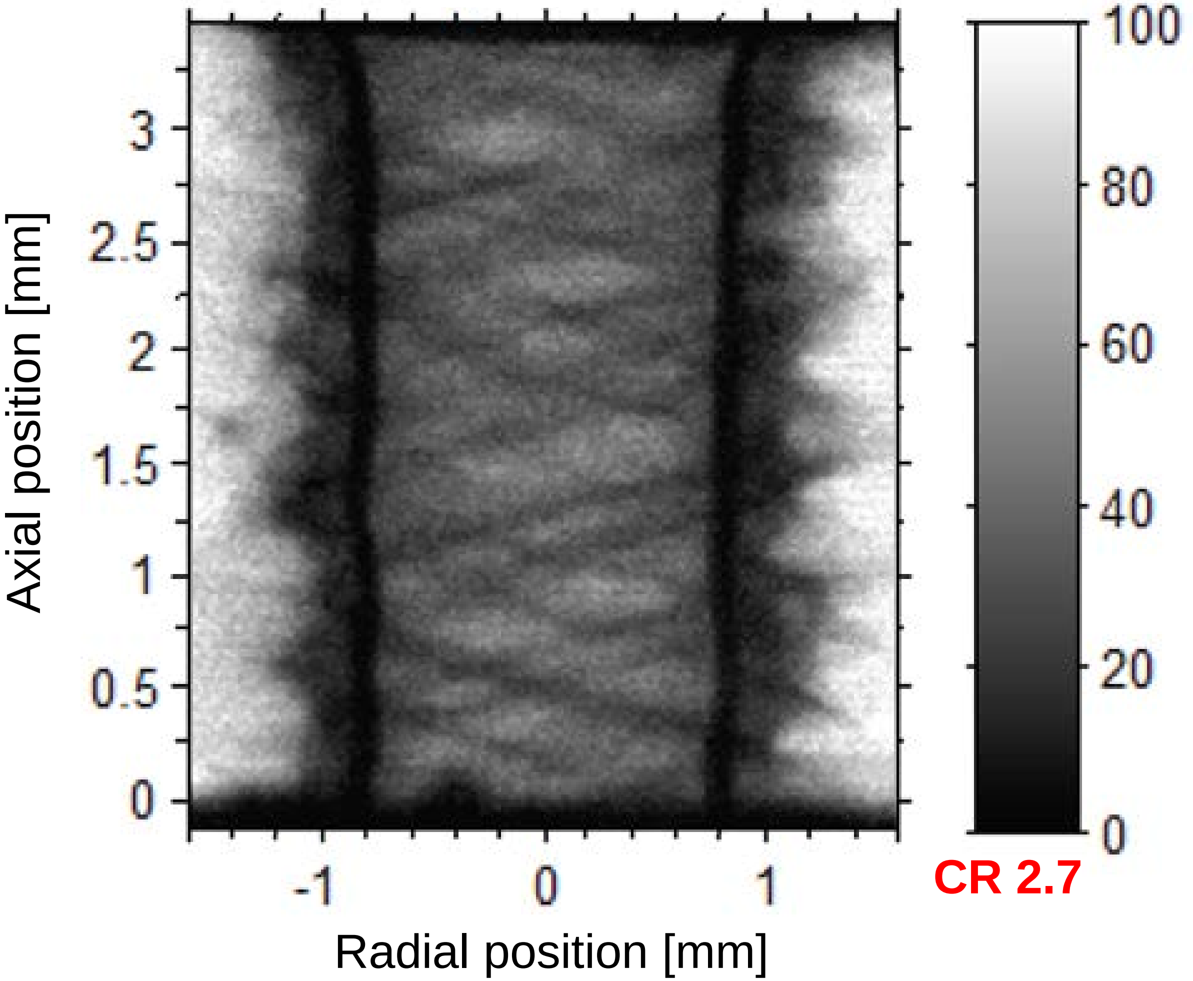


Magnetic field risetime is slow to allow diffusion through conductors

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

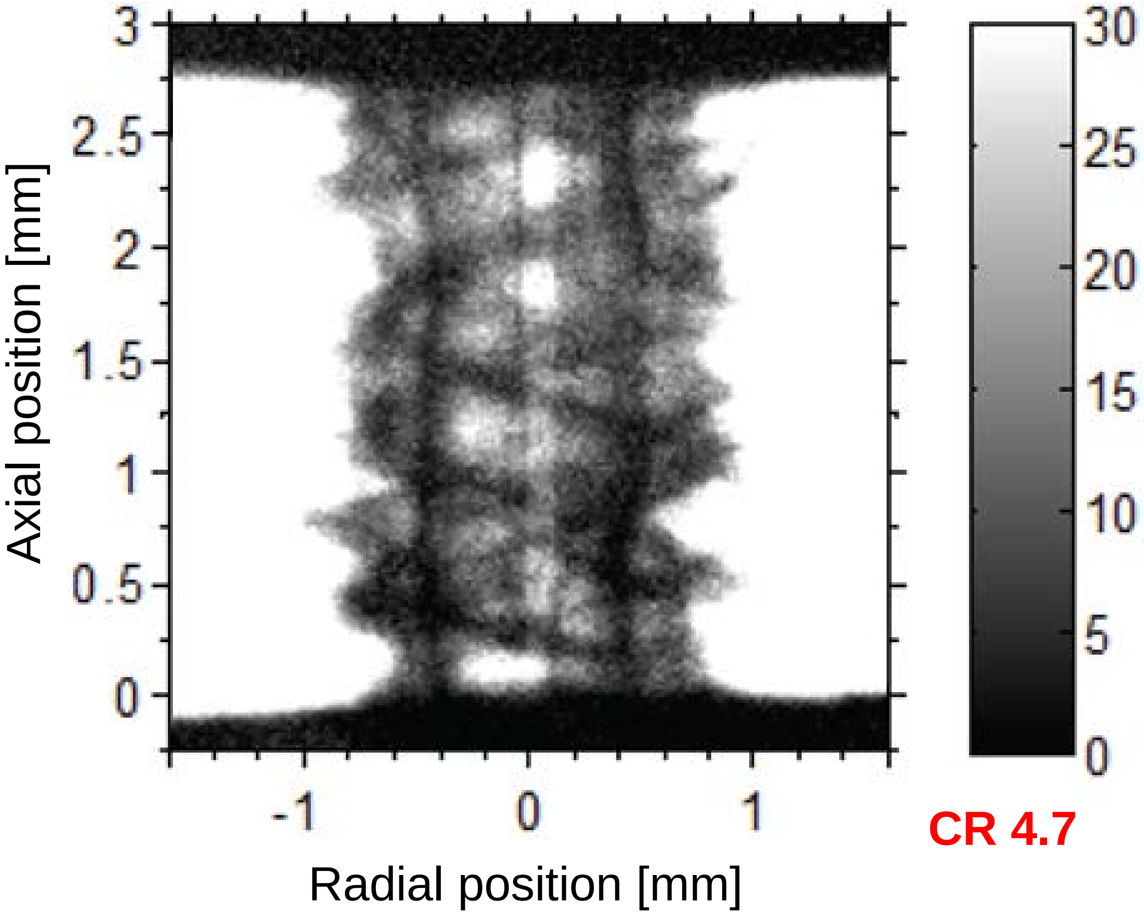
The axial B-field converted the azimuthal MRT structure into helical; stabilized the implosion

70 kG



CR 2.7

100 kG



CR 4.7

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

We also conducted a series of experiments to diagnose the laser heating stage of MagLIF

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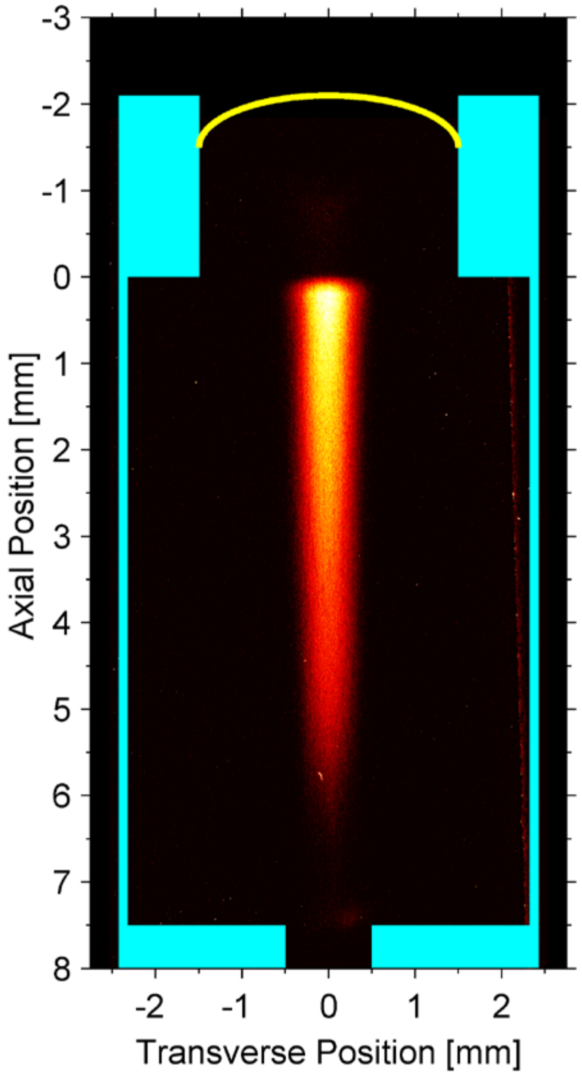
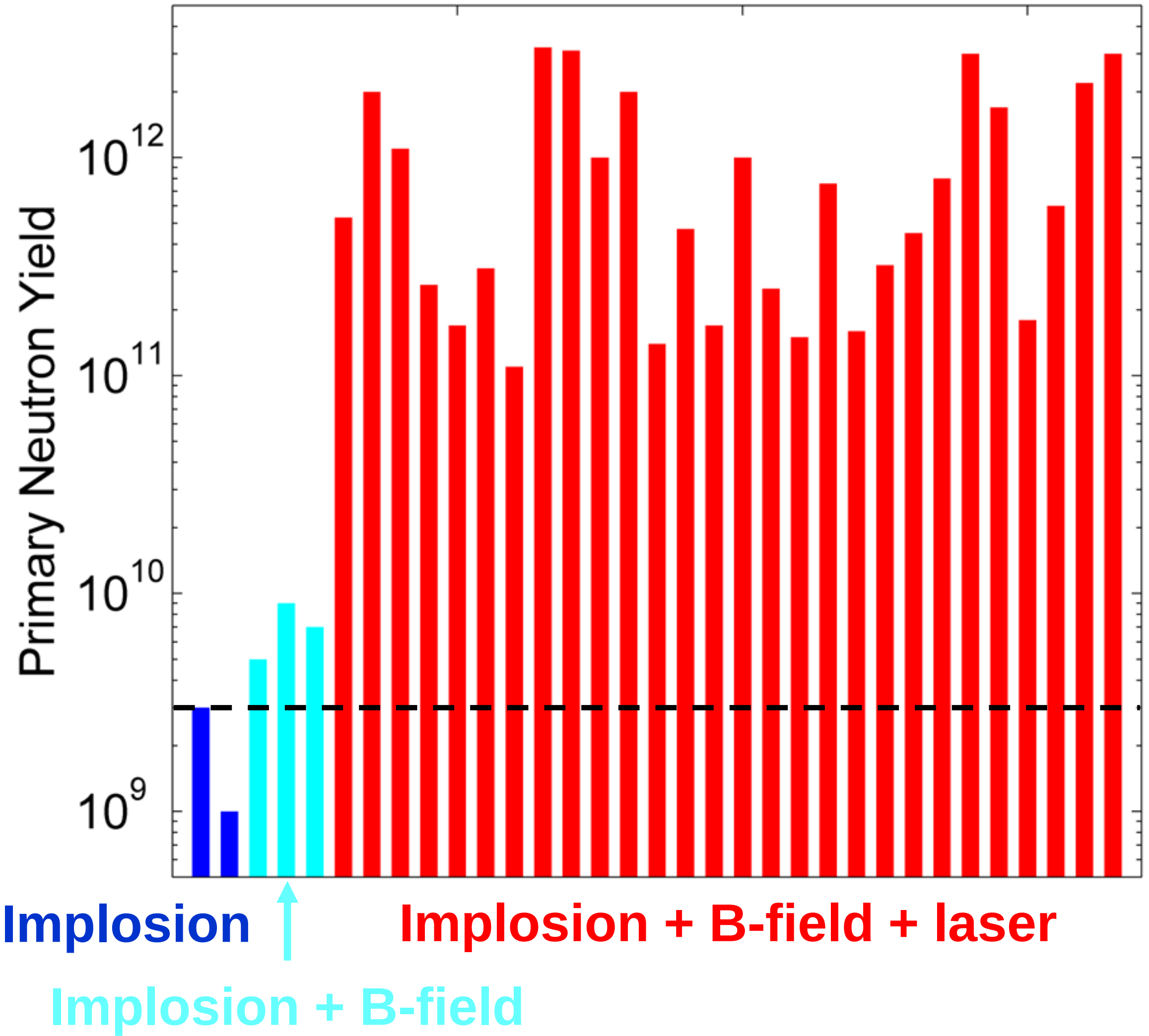


- X-ray self-emission images demonstrate that laser energy is coupled to the gas
  - D_2 gas with 0.1% atomic Ar
  - Imaging the Ar intercombination line at 3123 eV
- These images can be used to unfold a temperature map, but we are only sensitive to temperatures above 250 eV
  - Peak temperatures approach 1 keV
  - Much of the energy deposited in the gas could be hidden in the dark regions

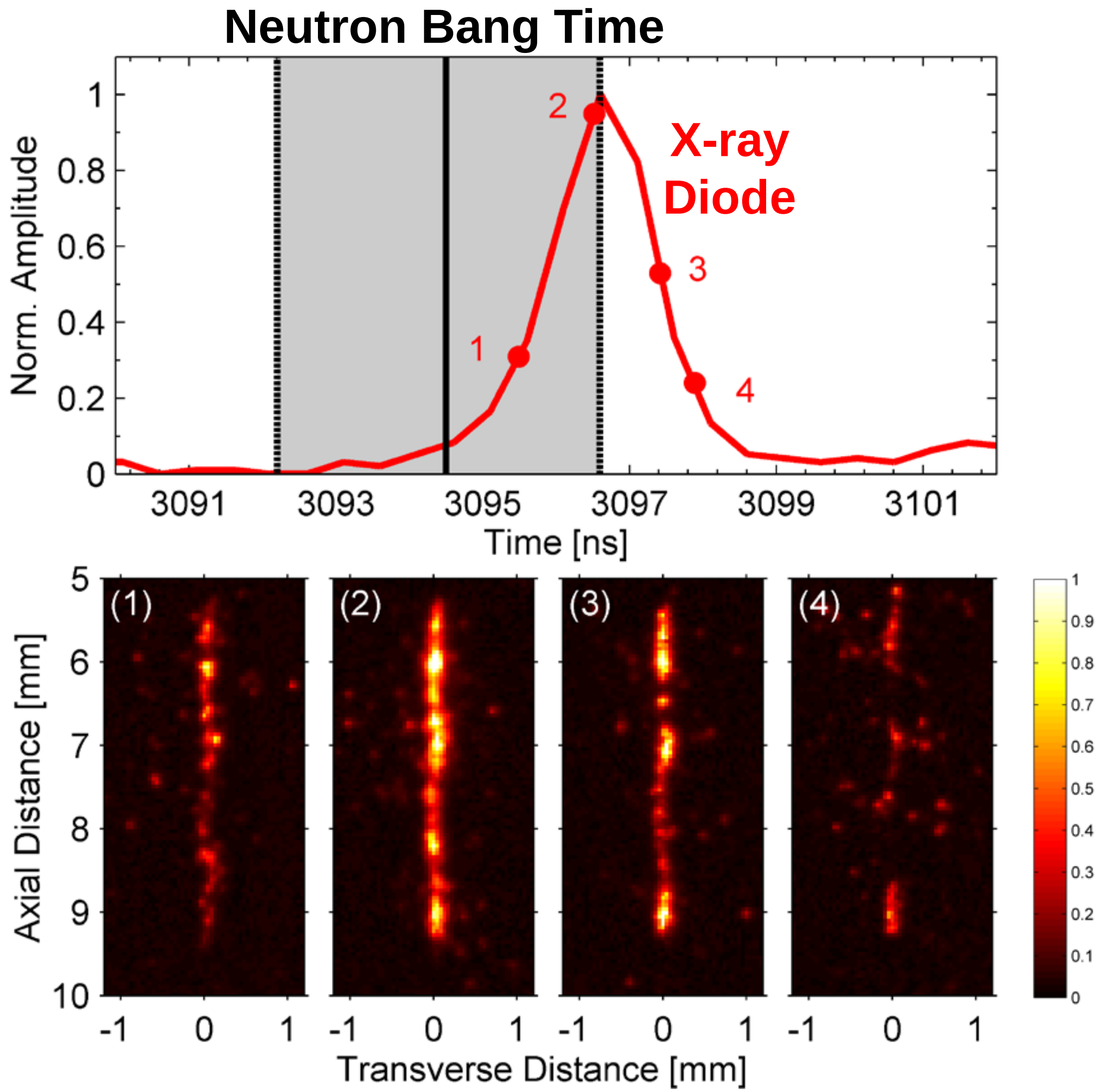
The primary neutron yield is highly dependent on effective magnetization and laser heating



- Experiments without the magnetic field and laser produce yields at the typical background level
- Adding just the magnetic field had a marginal change in yield
- In experiments where the magnetic field was applied and the laser heated the fuel, the yield increased by about 2 orders of magnitude

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

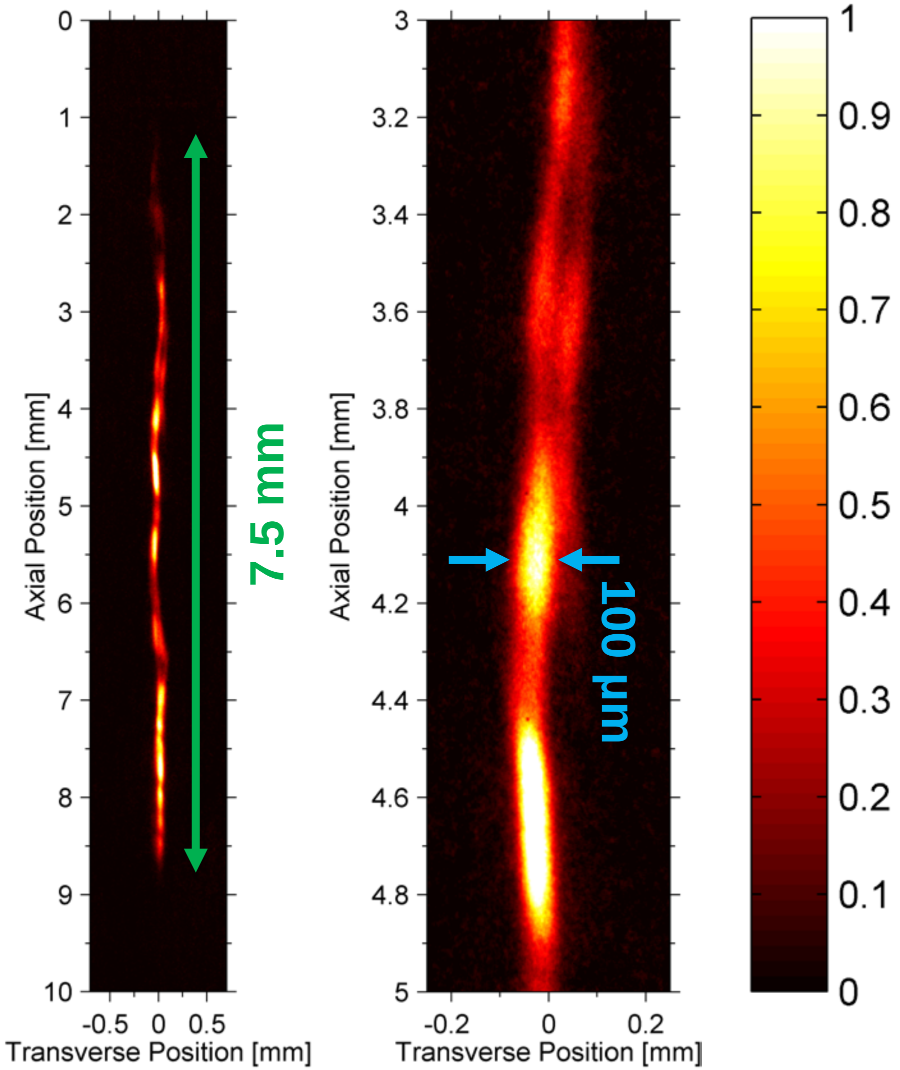
X-ray diodes and time-resolved x-ray pinhole images show the fuel radiating at stagnation



- Heavily-filtered diodes detect a 2 ns FWHM burst of x-rays
- Coincides with the neutron bang time measurement to within timing uncertainties
- Filtered pinhole images during the x-ray burst show a narrow emission column

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

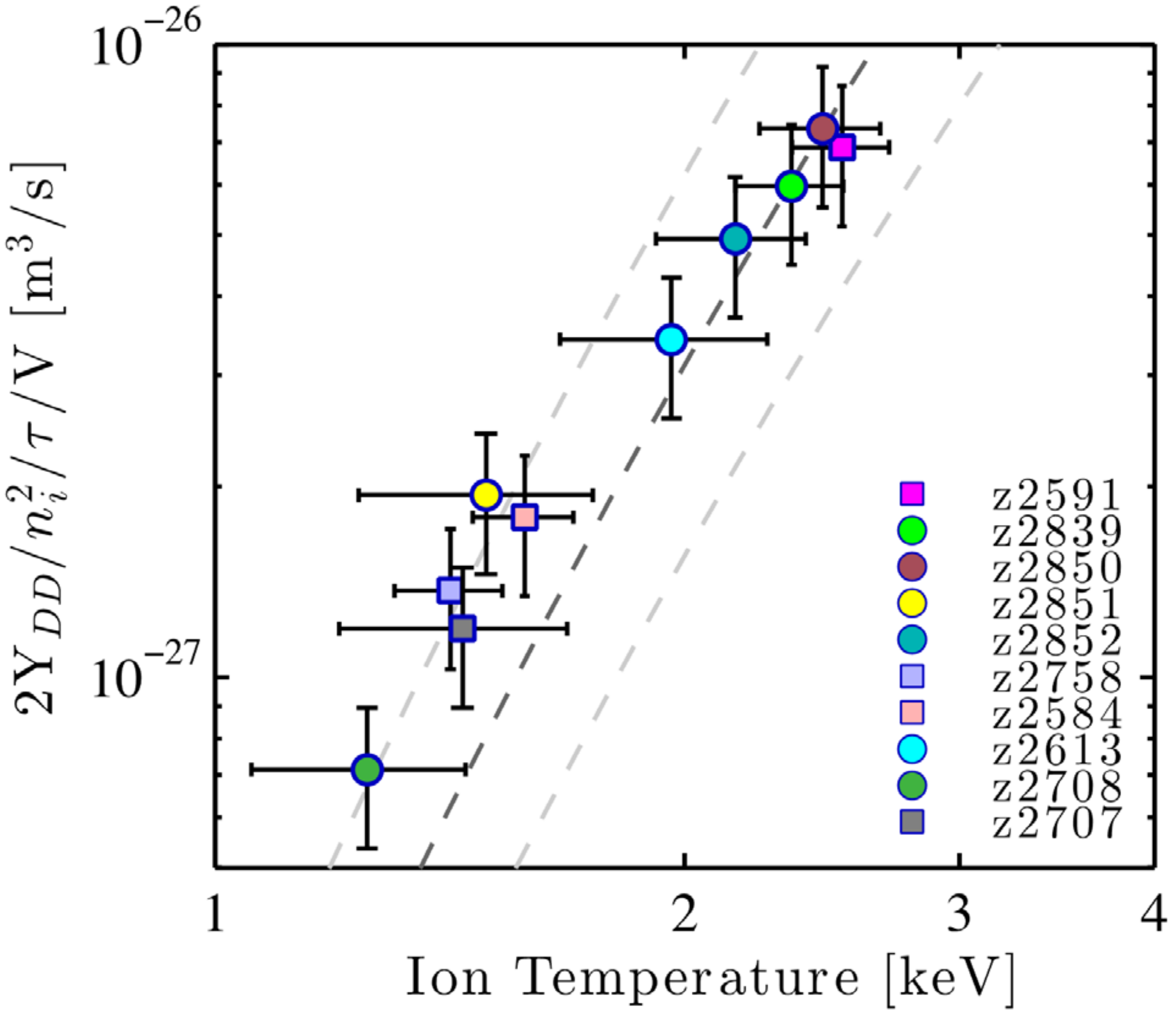
Our spherical crystal imaging system was repurposed to record x-ray emission from the fuel



- Hot fuel emission at stagnation gives information about the CR and uniformity of the plasma
- Hot fuel radius is CR ~45
- Helical structure to the emission column
- Intensity fluctuations a combination of emission and opacity variations

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

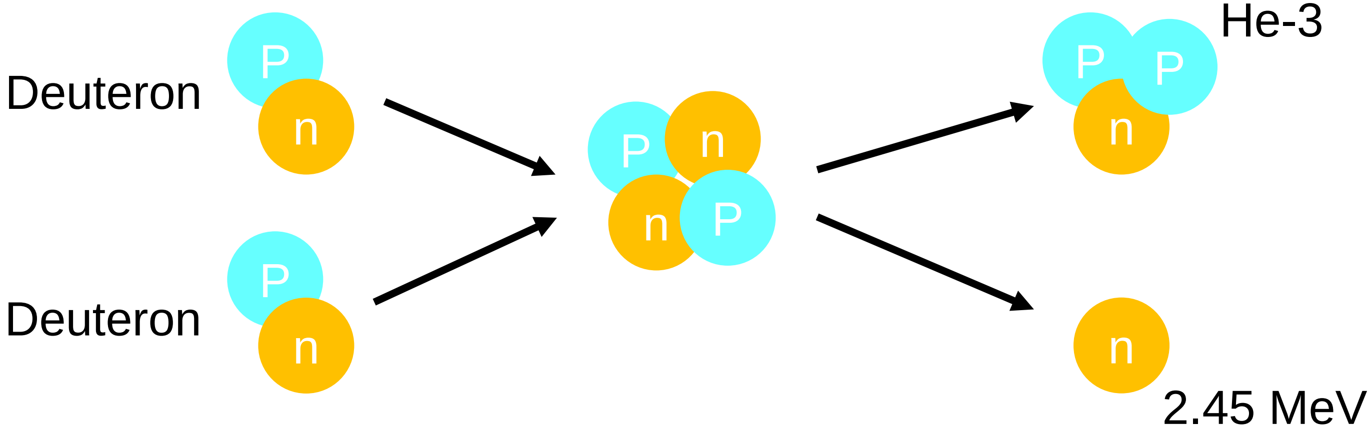
The primary neutron yield increases as the ion temperature increases



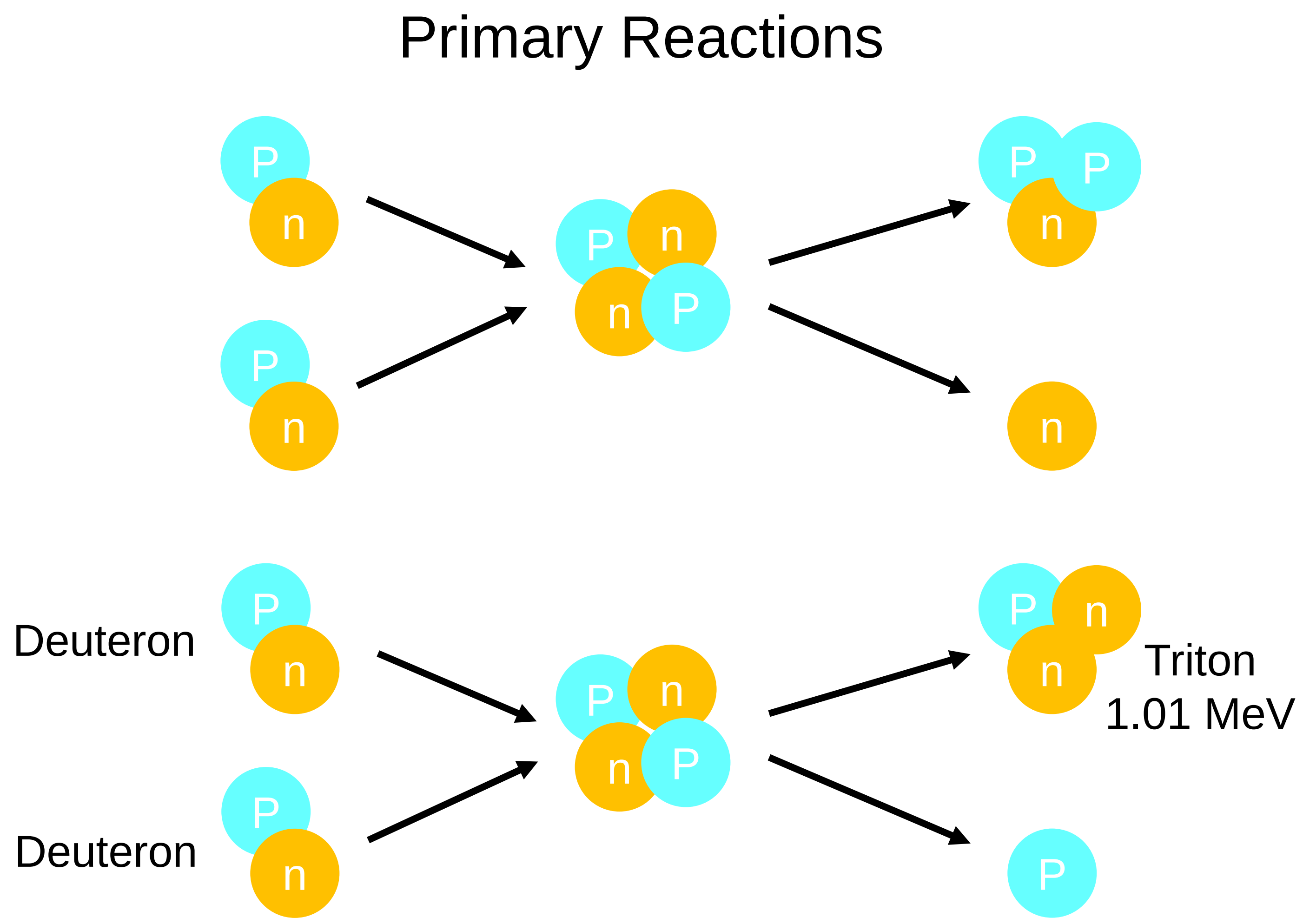
- Yield and ion temperature are related by the fusion reaction rate
- Experimental values roughly follow the trajectory of the fusion reaction rate
- This is expected for a thermonuclear plasma

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

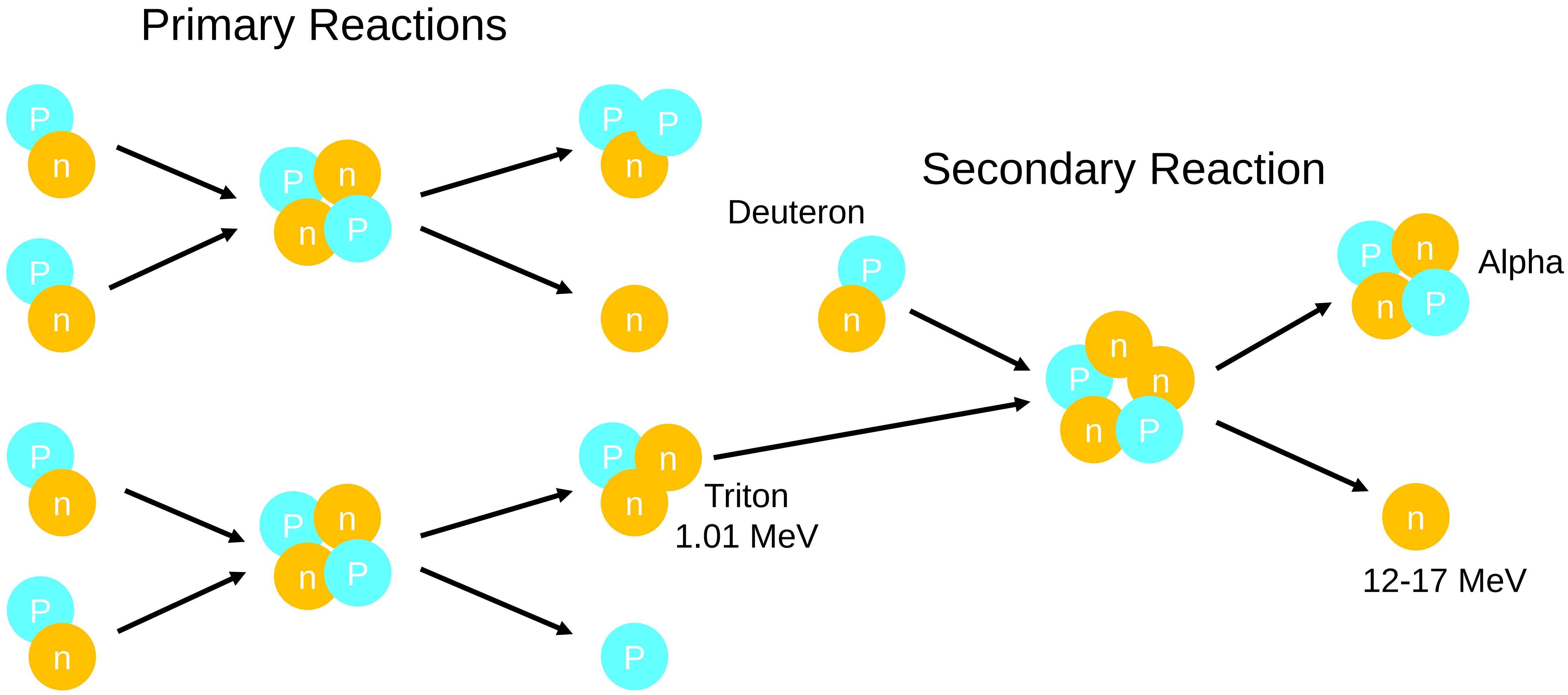
Primary Reactions



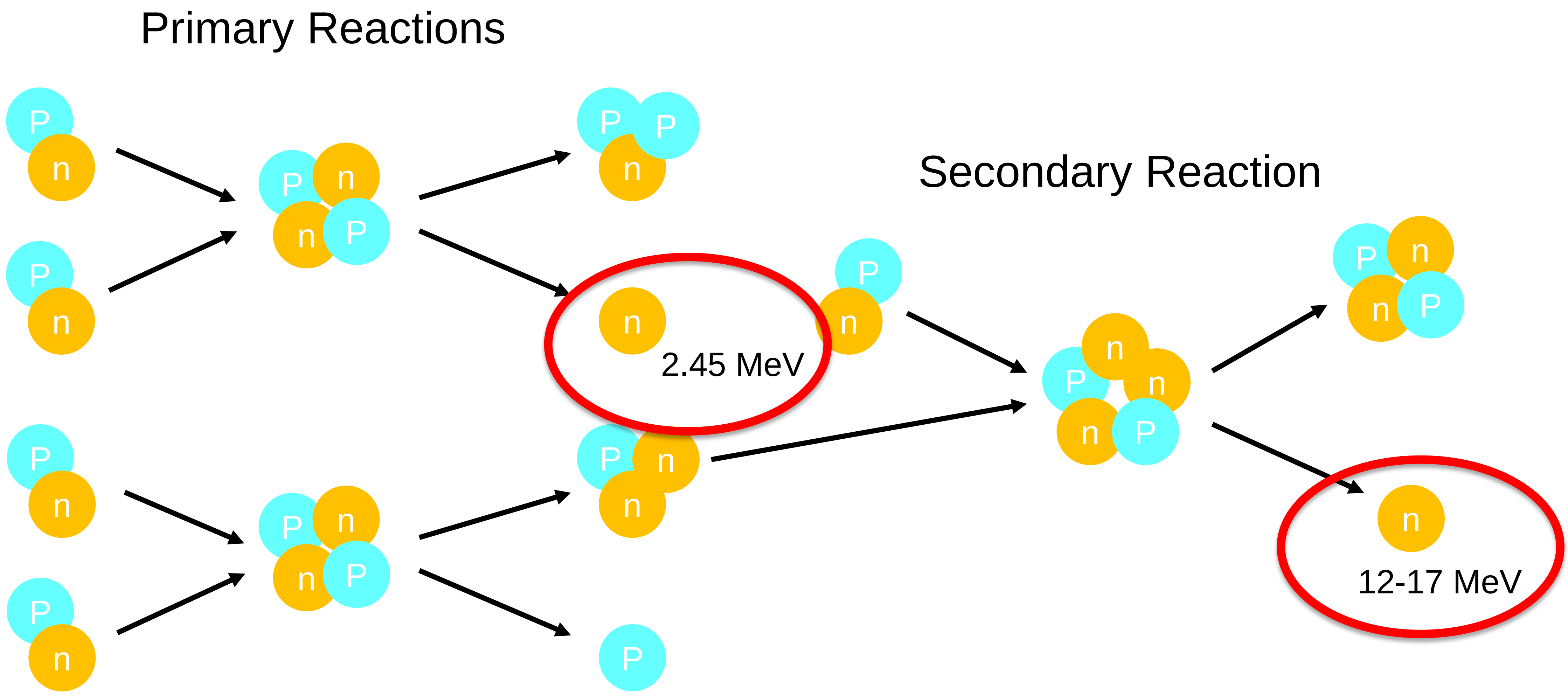
…and the other branch produces a triton…



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



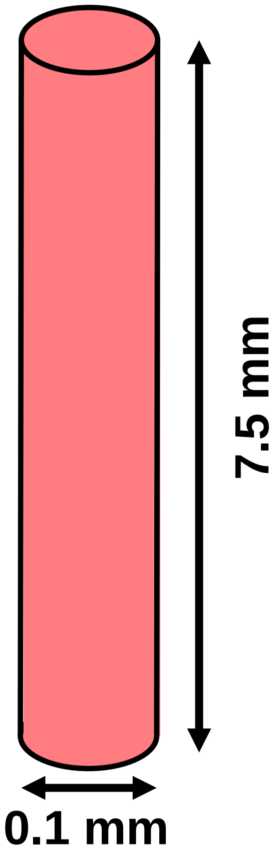
We measure both the primary and secondary neutrons



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

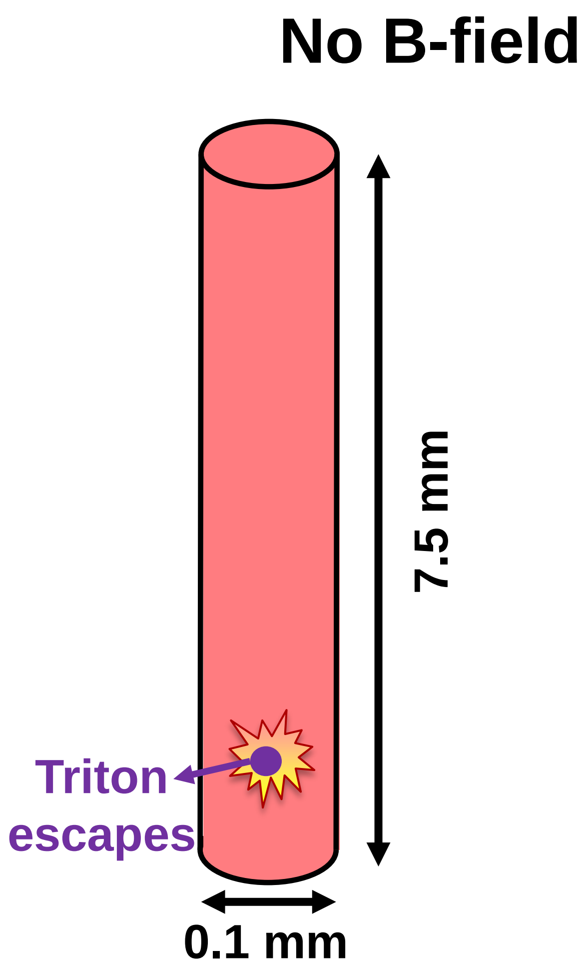
Secondary neutrons are produced when primary tritons react before exiting the fuel

No B-field



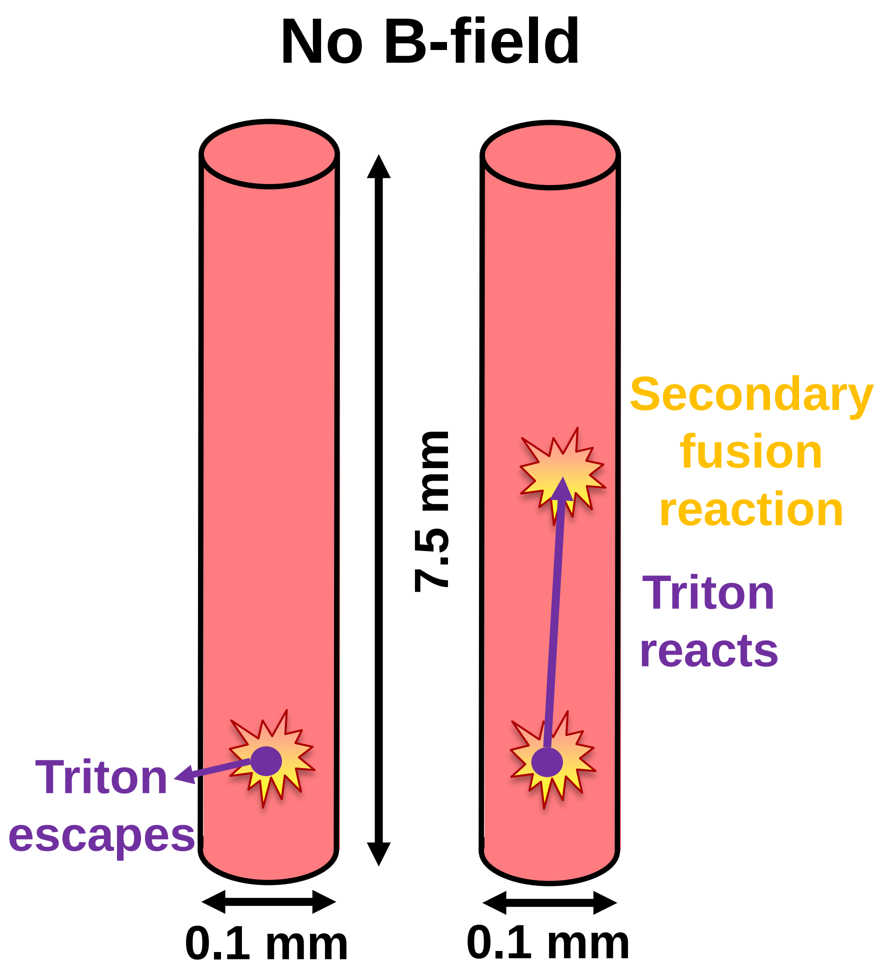
- High aspect ratio stagnation geometry
  - Height >> radius

Secondary neutrons are produced when primary tritons react before exiting the fuel



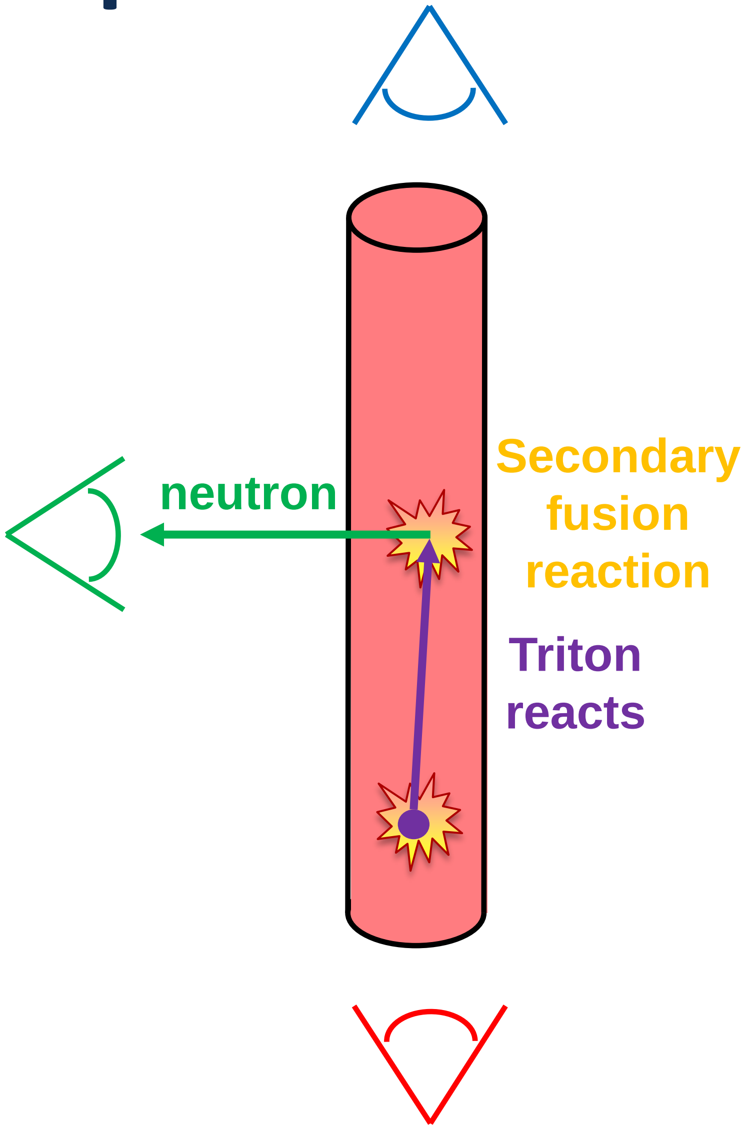
- High aspect ratio stagnation geometry
  - Height >> radius
- Consider 2 cases:
  - 1) Triton is created traveling radially
    - Very little probability of interacting prior to escaping

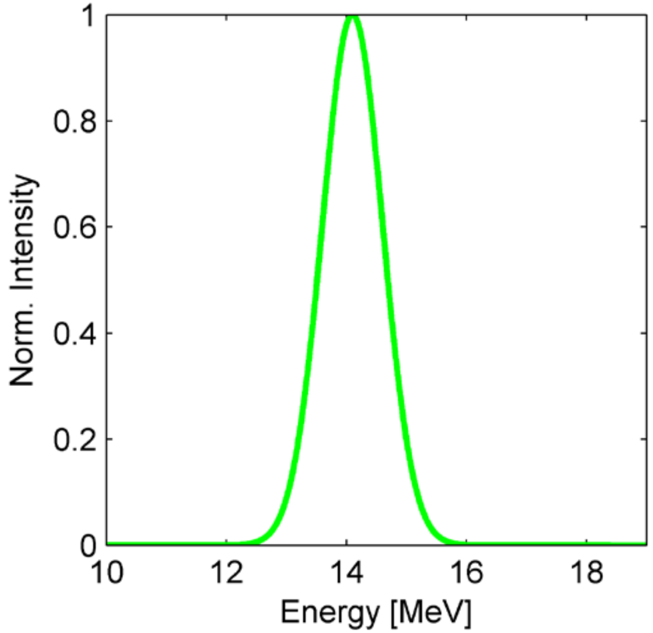
Secondary neutrons are produced when primary tritons react before exiting the fuel



- High aspect ratio stagnation geometry
  - Height >> radius
- Consider 2 cases:
  - 1) Triton is created traveling radially
    - Very little probability of interacting prior to escaping
  - 2) Triton is created traveling axially
    - High probability of fusion prior to escaping

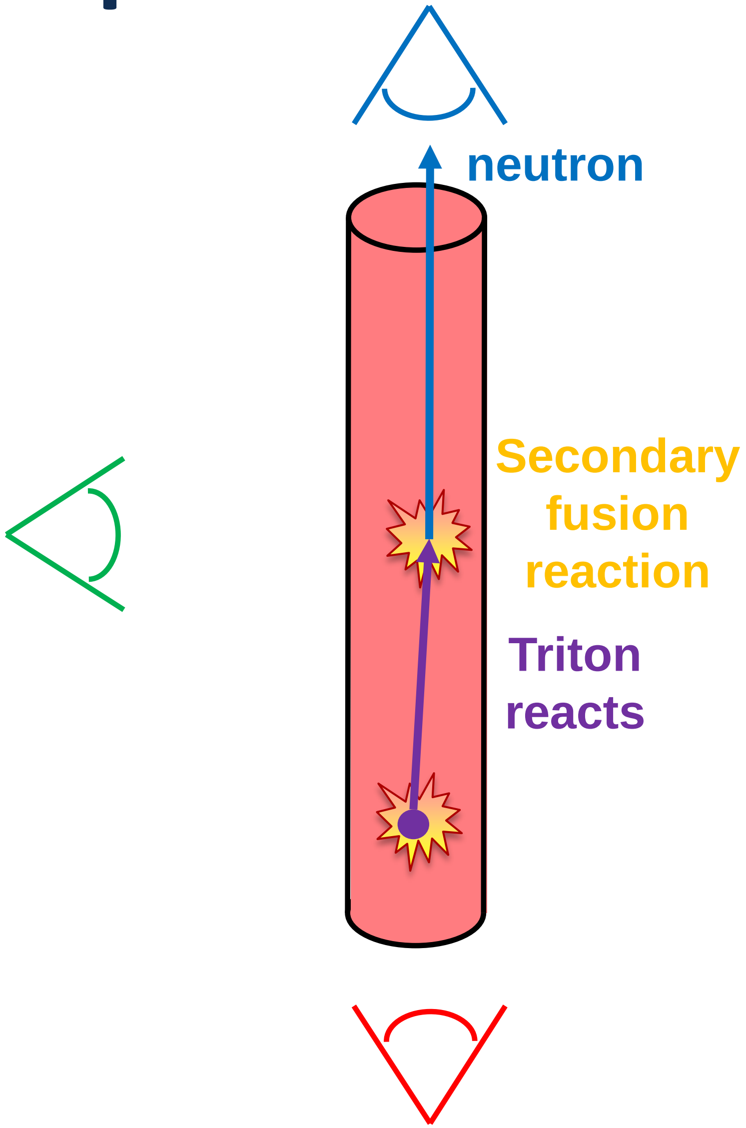
The secondary neutron energy spectra are not expected to be isotropic

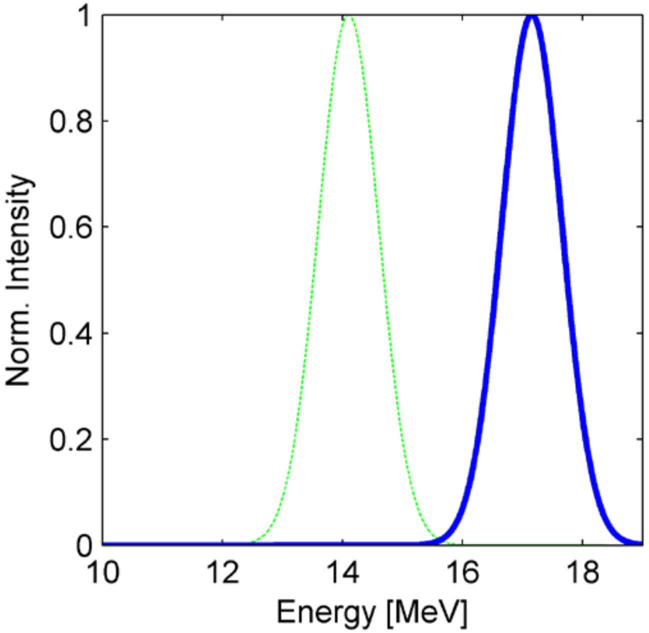




- Consider 3 detector locations:
  - Radial
    - Neutrons at nominal energy

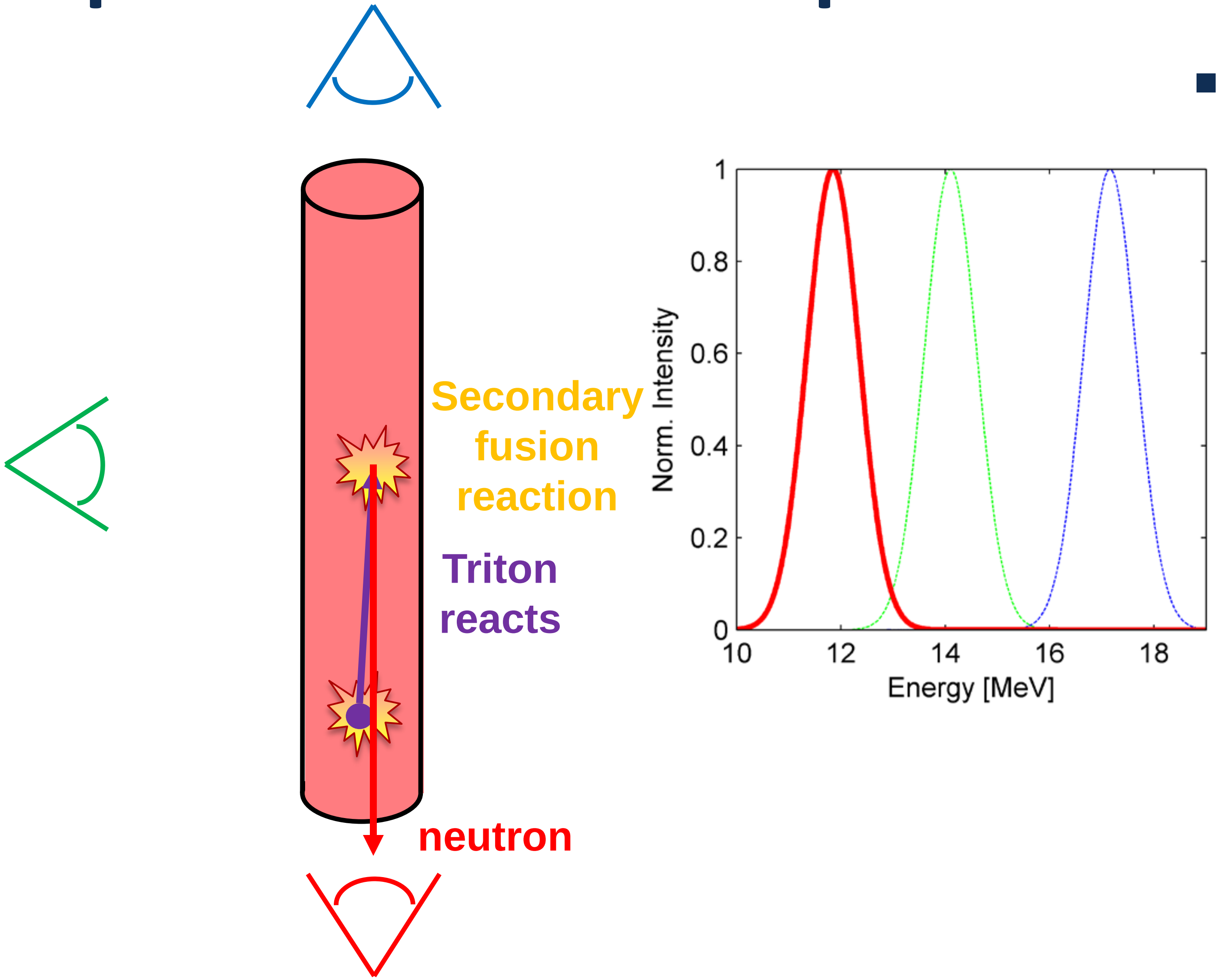
The secondary neutron energy spectra are not expected to be isotropic





- Consider 3 detector locations:
  - Radial
    - Neutrons at nominal energy
  - Axial (triton moving towards)
    - Neutrons shifted to higher energy

The secondary neutron energy spectra are not expected to be isotropic



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  - Radial
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    - Neutrons shifted to higher energy
  - Axial (triton moving away)
    - Neutrons shifted to lower energy

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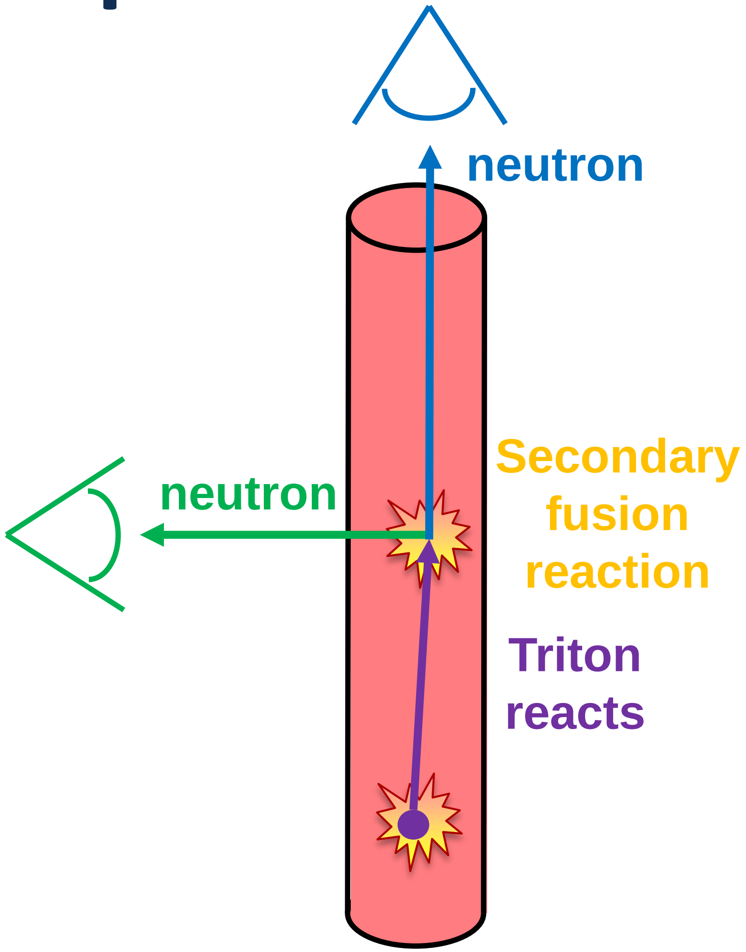
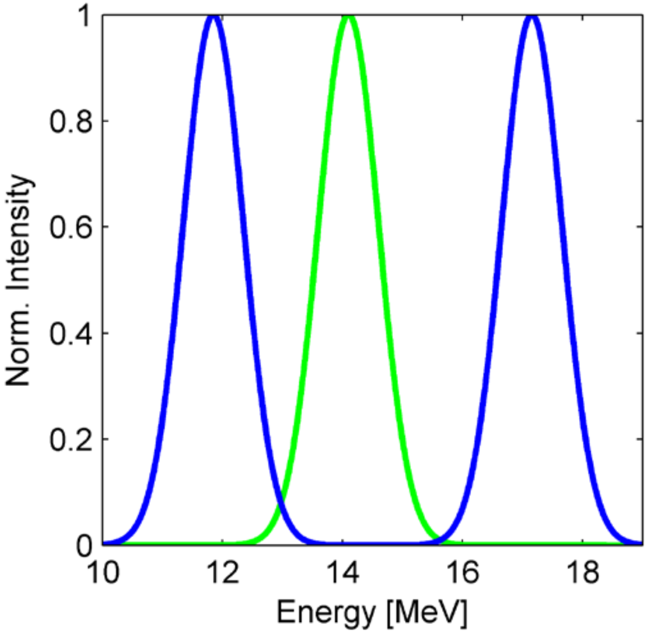
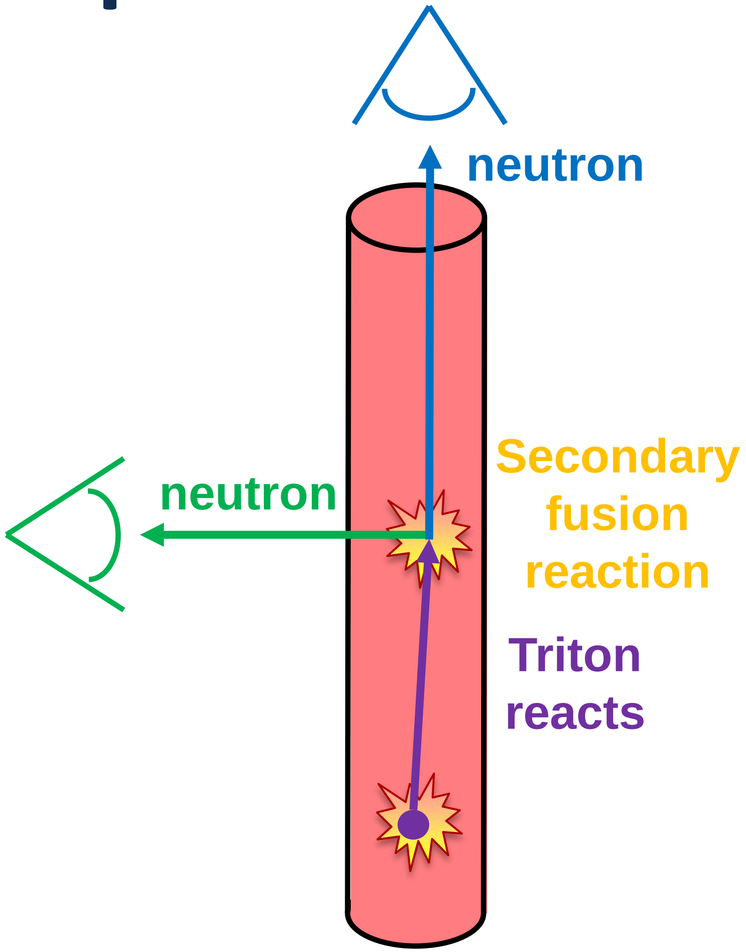
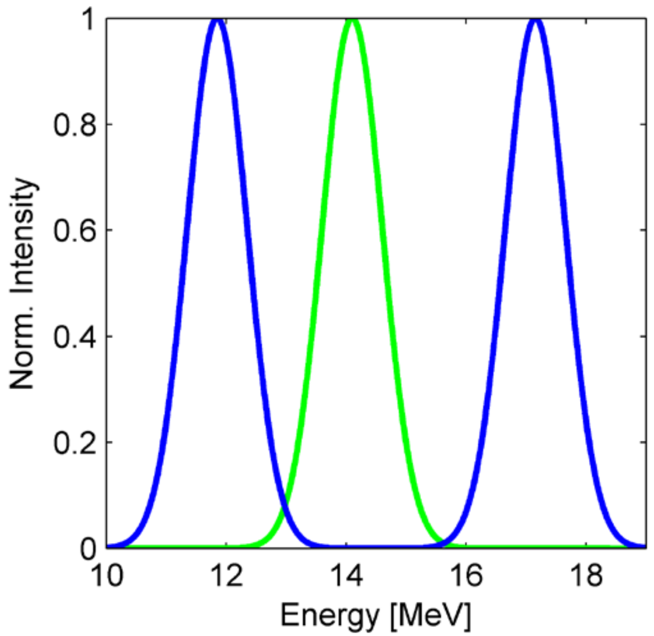




- Consider 3 detector locations:
  - Radial
    - Neutrons at nominal energy
  - Axial (triton moving towards)
    - Neutrons shifted to higher energy
  - Axial (triton moving away)
    - Neutrons shifted to lower energy
- Axial detectors will have double peaked structure

The secondary neutron energy spectra are not expected to be isotropic





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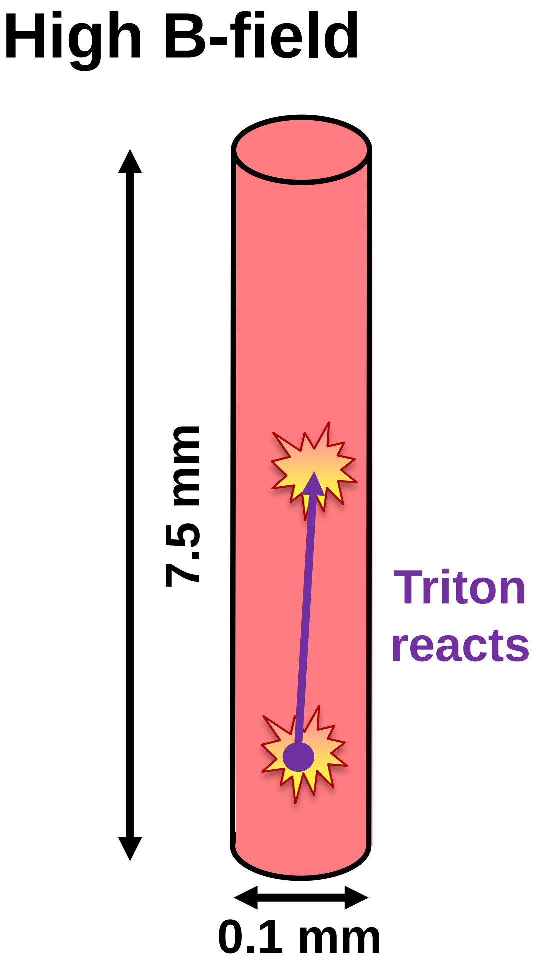
    - Neutrons at nominal energy
  - Axial (triton moving towards)
    - Neutrons shifted to higher energy
  - Axial (triton moving away)
    - Neutrons shifted to lower energy
- Axial detectors will have double peaked structure

It is important to note that the vast majority of tritons escape without interacting

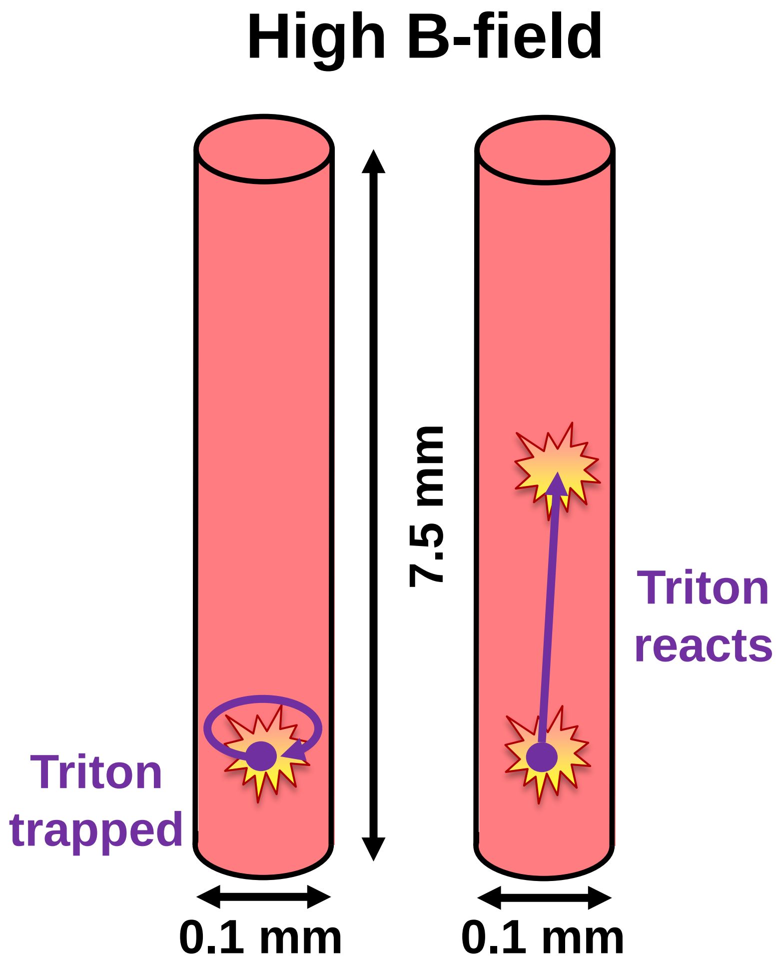
Adding a strong enough axial magnetic field allows tritons to interact for any initial direction



- Consider 2 cases:
  - 1) Triton is created traveling axially
    - Axial field has little impact on trajectory
    - Triton has a high probability of fusion

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

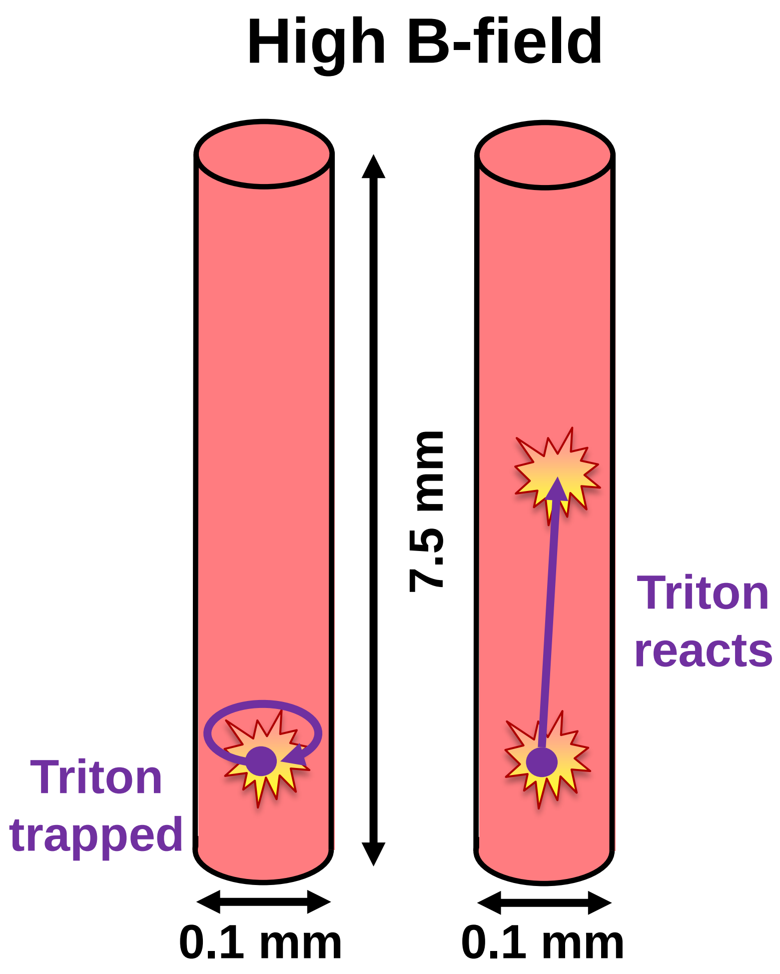
Adding a strong enough axial magnetic field allows tritons to interact for any initial direction



- Consider 2 cases:
  - 1) Triton is created traveling axially
    - Axial field has little impact on trajectory
    - Triton has a high probability of fusion
  - 2) Triton is created traveling radially
    - Axial magnetic field traps triton within fuel volume
    - Triton has a high probability of fusion

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

Adding a strong enough axial magnetic field allows tritons to interact for any initial direction



- Consider 2 cases:
  - 1) Triton is created traveling axially
    - Axial field has little impact on trajectory
    - Triton has a high probability of fusion
  - 2) Triton is created traveling radially
    - Axial magnetic field traps triton within fuel volume
    - Triton has a high probability of fusion
- With a high enough magnetic field, all tritons have equal probability of secondary fusion

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

Simulations indicate the secondary neutron spectra become isotropic with large B-field

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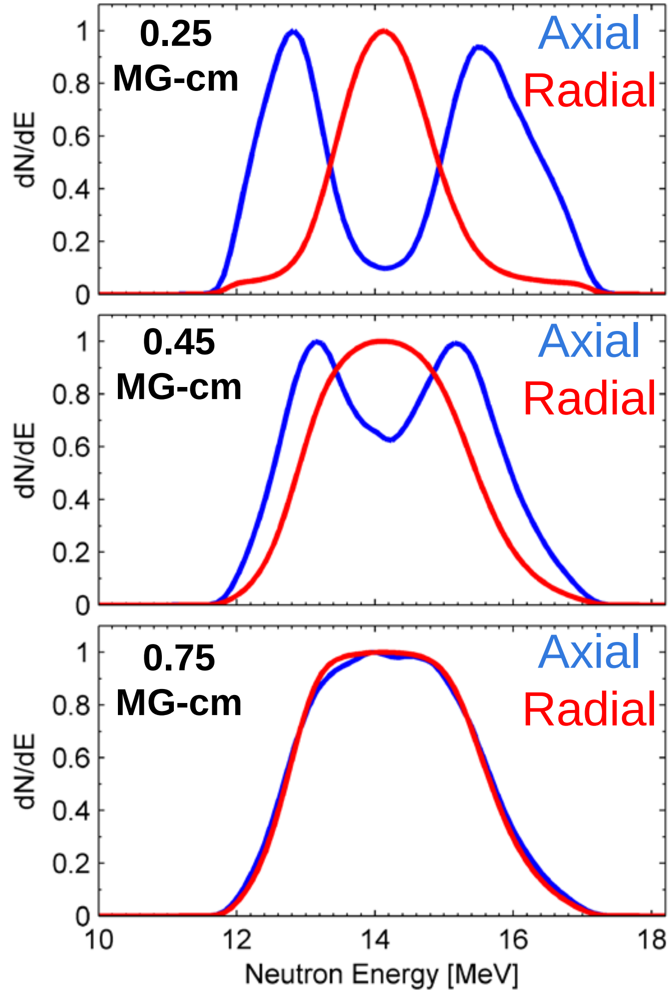
Simulated Spectra



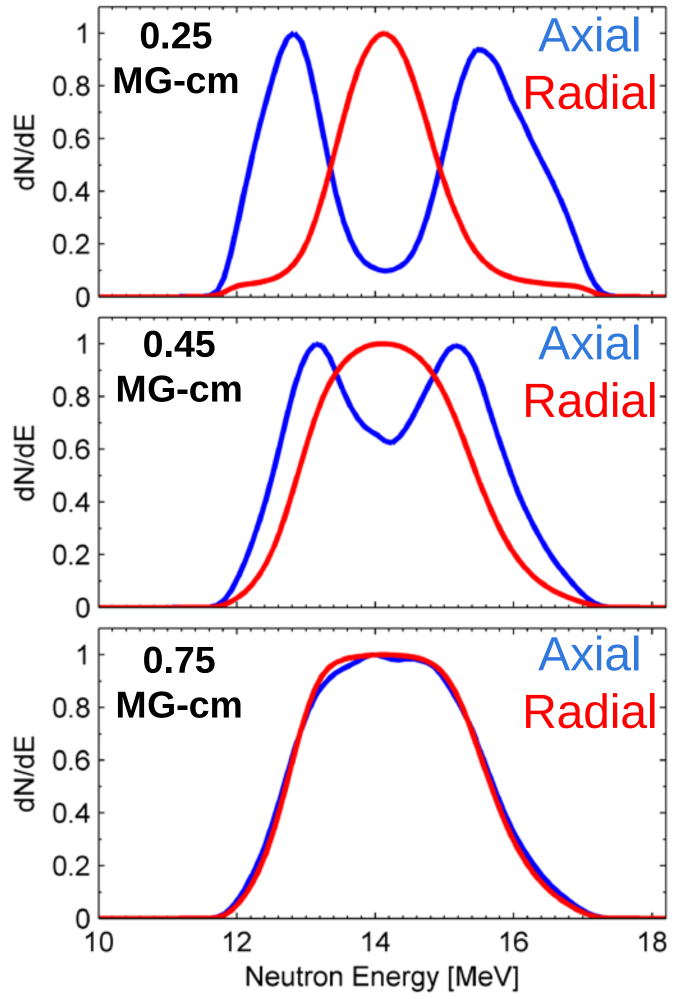
- As the magnetic field increases, a greater fraction of the radially directed tritons are trapped

- As the distribution of trapped tritons becomes more isotropic, the secondary neutron spectra also become more isotropic

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

Simulations indicate the secondary neutron spectra become isotropic with large B-field

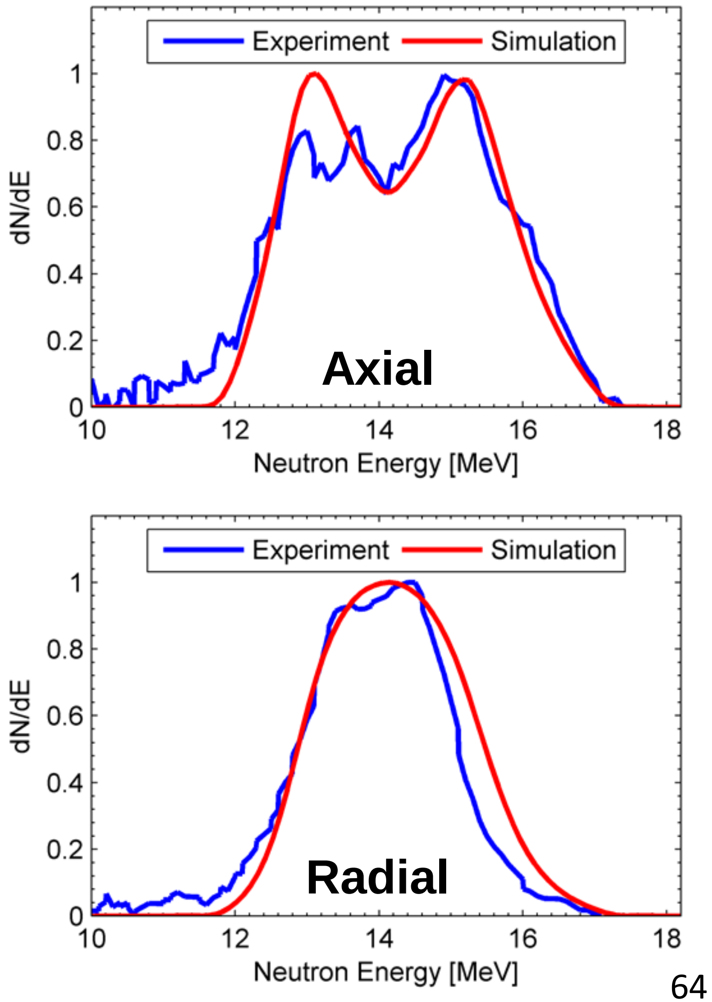
Simulated Spectra



- As the magnetic field increases, a greater fraction of the radially directed tritons are trapped

- As the distribution of trapped tritons becomes more isotropic, the secondary neutron spectra also become more isotropic

0.34 MG-cm



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

We've demonstrated interesting conditions and the fundamental requirements for MIF

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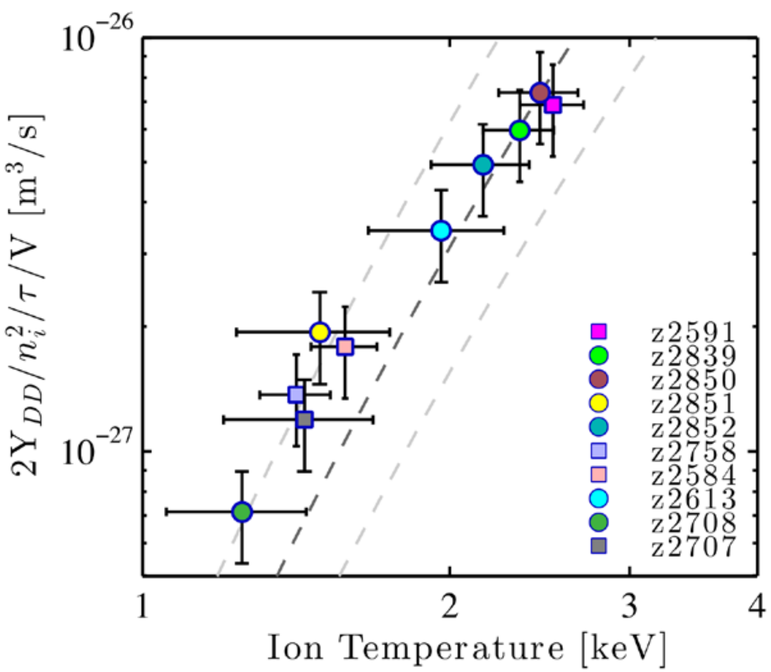
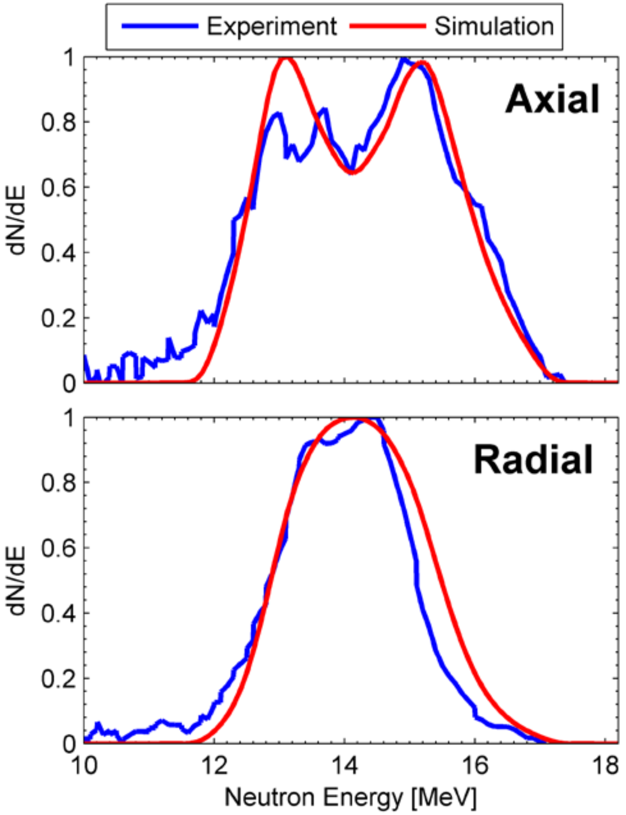
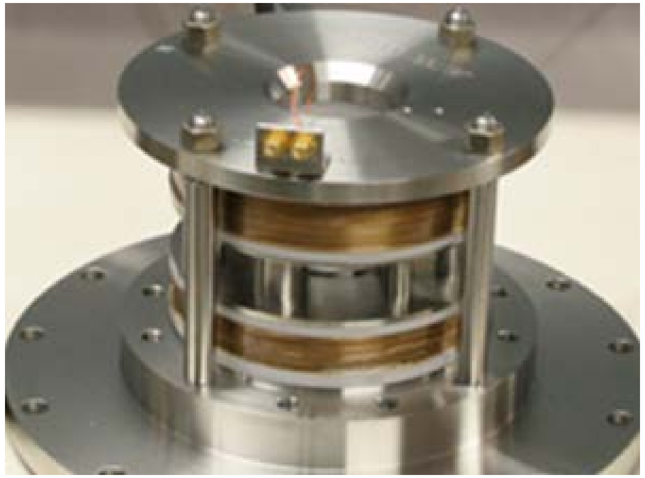
We have a thermonuclear plasma with high magnetic field



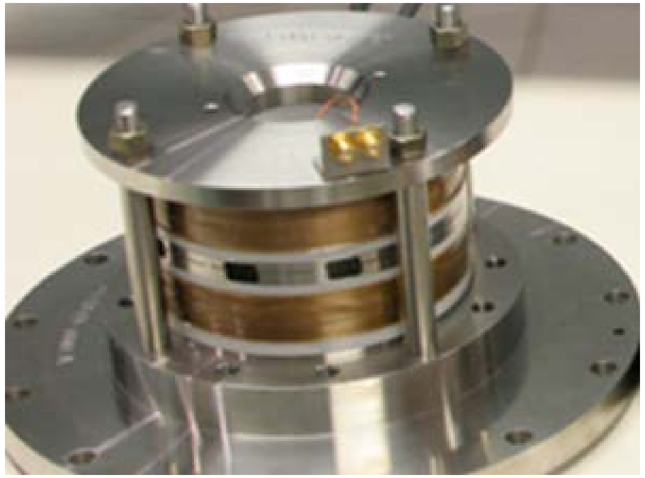


- Best performing experiment produced 0.6-1.2 kJ (DT equivalent)
- We are within a factor of a few of our goal for each of the stagnation conditions
- Based on reasonable improvements to the magnetic field, drive current, and laser we think we can get to at least 10 kJ
  - Simulations indicate we could exceed 100 kJ

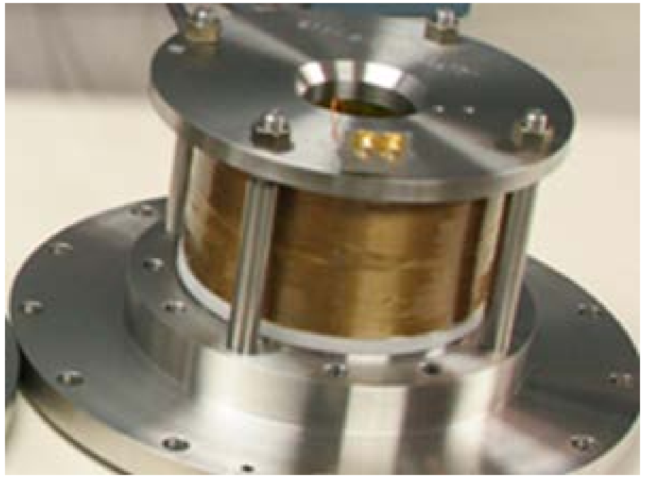
Increasing the axial magnetic field is straight forward, but limits diagnostic access



100 kG



200 kG



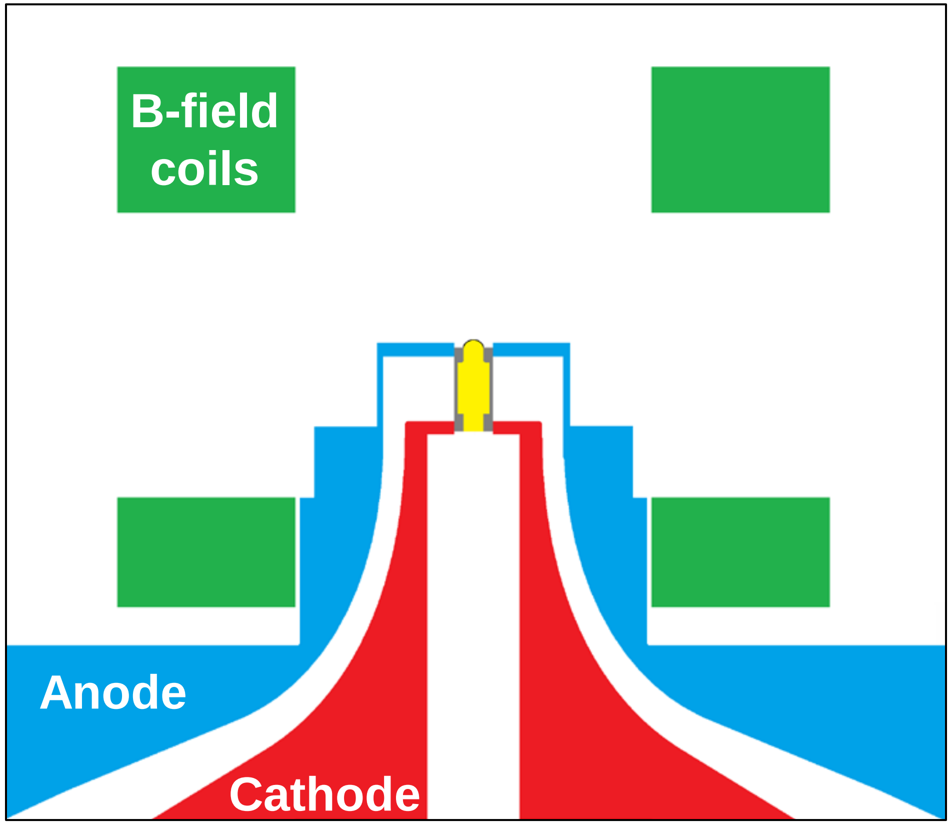
300 kG

- We currently operate at 100 kG
- We have designs that allow 200 kG with limited diagnostics and 300 kG with no x-ray access
- We are pursuing designs that increase the field without reducing access
  - Pushes the limit of coil technology

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

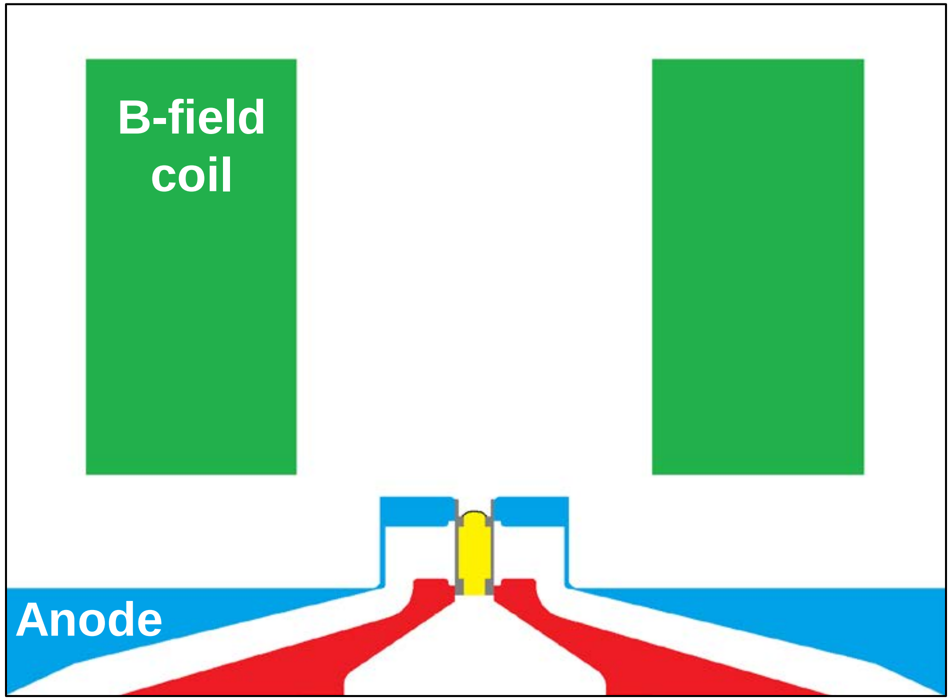
We have demonstrated increased current delivery with lower inductance designs

Standard Transmission Line (7 nH)



Peak load current 17 MA

New Transmission Line (4.5 nH)



Cathode

Peak load current ~20 MA

We are developing strategies to improve laser coupling to the fuel

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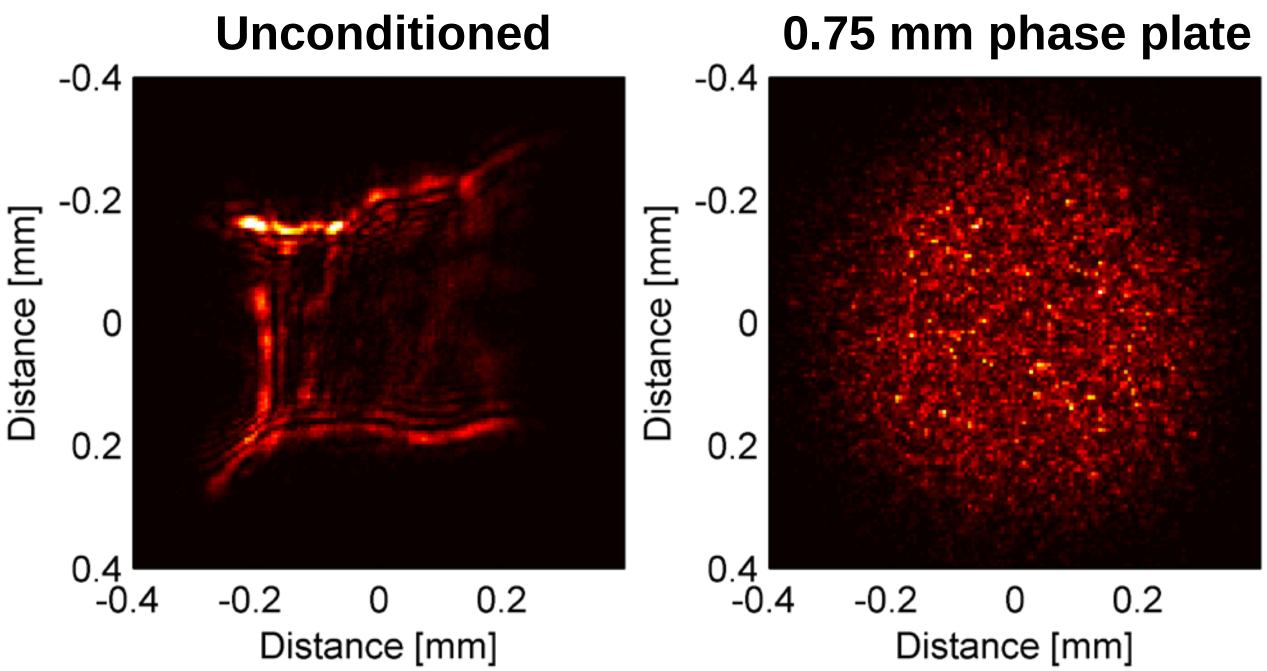
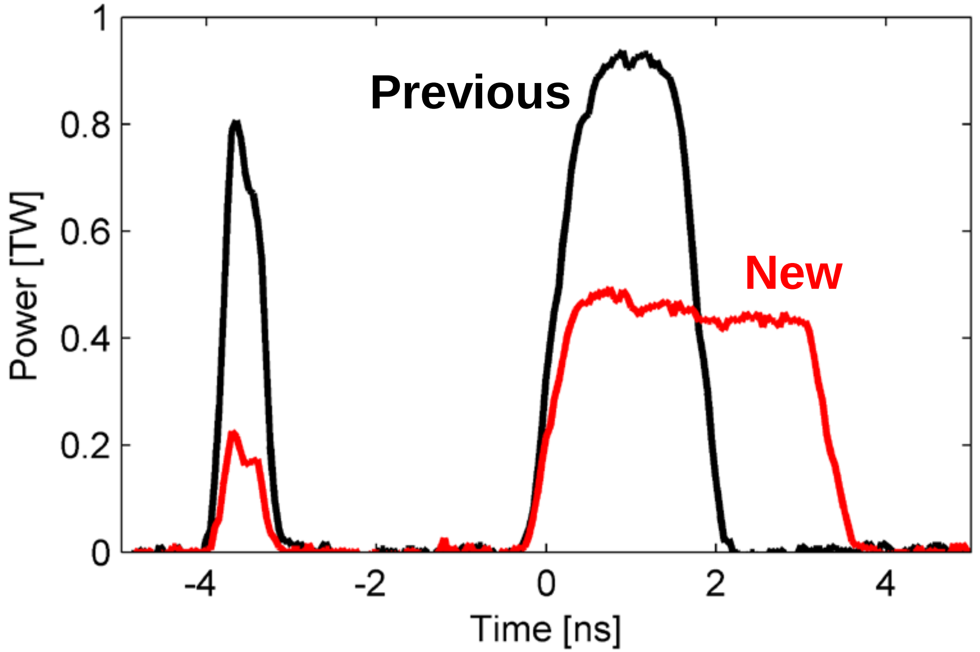
We are now testing beam smoothing with phase plates



We reduced laser power while maintaining energy



With these changes we reduced the intensity by an order of magnitude, which we expect to reduce the impact of laser plasma instabilities

We’ve spent some time developing a preliminary architecture for a new machine

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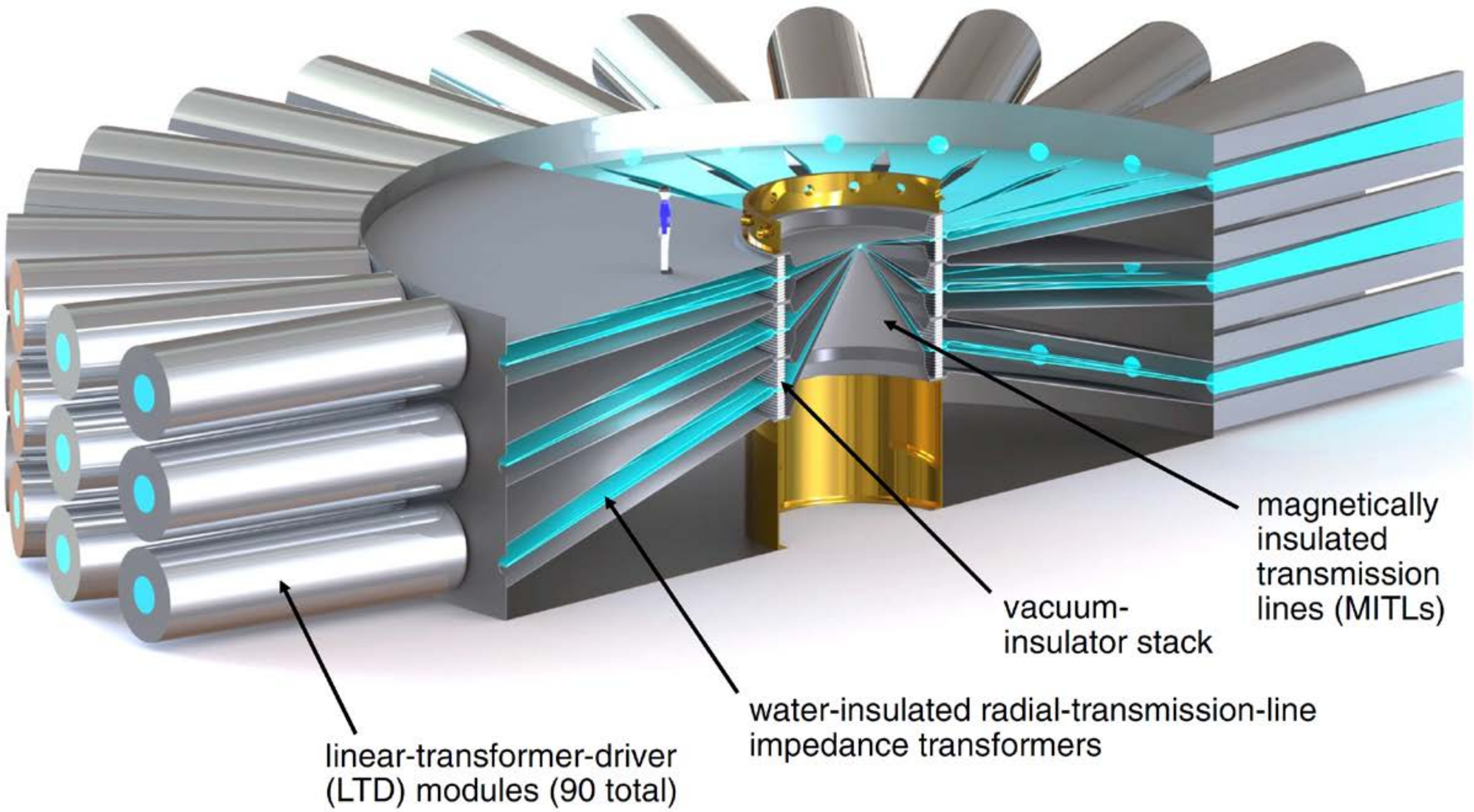
Based on relatively new technology called linear transformer drivers



- Design for a roughly 50 MA driver that would fit in the footprint of the existing facility
  - 2017-2020: Demonstrate understanding and further improvement of ICF concept
  - Early 2020s: Develop a reasonable path forward to 1-10 MJ on next facility
  - Late 2020s: Detailed design of a new machine
  - Circa 2030: Construction of new machine

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

This work is the collective effort of many exceptional scientists and engineers

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D.J. Ampleford, T.J. Awe, C.J. Bourdon, G.A. Chandler, P.J. Christenson, M.E. Cuneo, M. Geissel, K.D. Hahn, S.B. Hansen, E.C. Harding, A.J. Harvey-Thompson, M.H. Hess, B.T. Hutsel, C.A. Jennings, B. Jones, M.C. Jones, R.J. Kaye, P.F. Knapp, G. Laity, D.C. Lamppa, M.R. Lopez, M.R. Martin, M. K. Matzen, L.A. McPherson, T. Nagayama, J.S. Lash, K.J. Peterson, J.L. Porter, G.A. Rochau, D.C. Rovang, C.L. Ruiz, M.E. Savage, P.F. Schmit, J. Schwarz, D.B. Sinars, S.A. Slutz, I.C. Smith, W.A. Stygar, R.A. Vesey, M.R. Weis, E.P. Yu, *Sandia National Laboratories*

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R.D. McBride, *University of Michigan*

A. B. Sefkow, *Laboratory for Laser Energetics*

Thank you for your attention, any questions?