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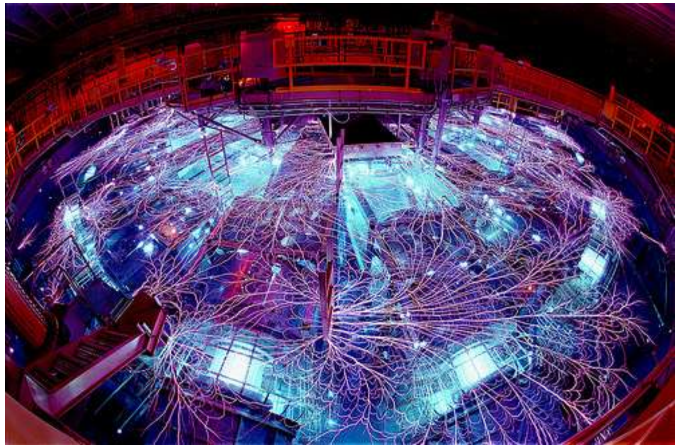


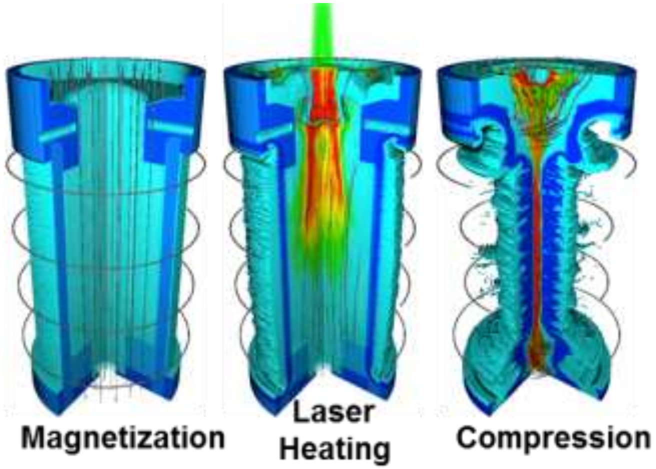
Magnetic Direct Drive Magneto-Inertial Fusion Efforts on the Z Machine

Matthew Gomez

Sandia National Laboratories

Presented at the 11th Annual
Stewardship Science Graduate Fellowship Program Review

June 22, 2017



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U.S. DEPARTMENT OF ENERGY

NNSA

Personal background

Doctoral Committee:

Professor Ronald M. Gilgenbach, Chair
Professor Yue Y. Lau
Professor Brian E. Gilchrist
Assistant Professor John E. Foster
Michael E. Cuneo, Sandia National Laboratories

2005 2006 2007 2008 2009 2010 2011

The Z machine employs pulsed power to create high energy density matter

33 m

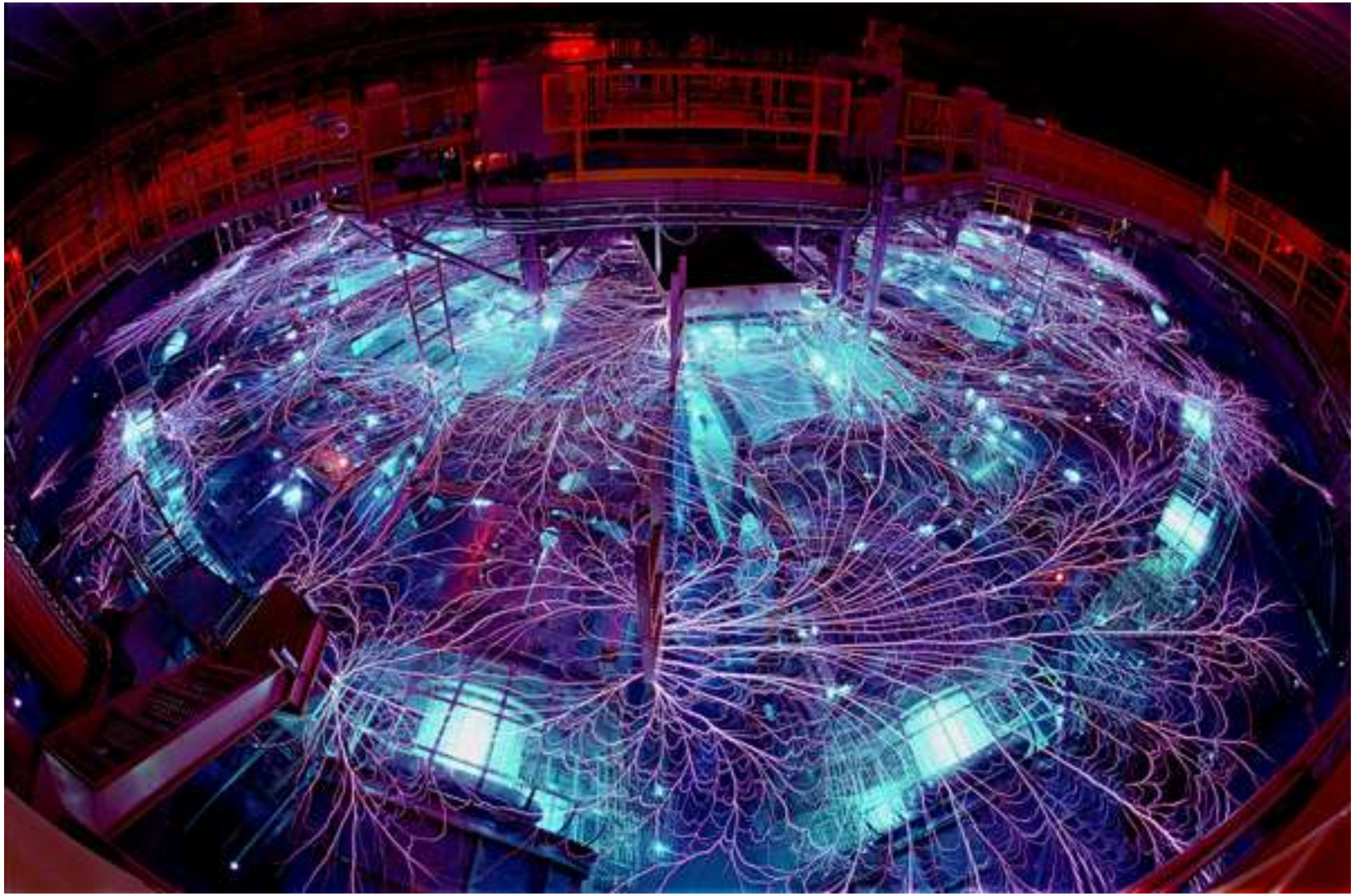
Energy storage volume is ~100 m^3

Target volume is ~0.1 cm^3

Compression in space is ~10^9

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

Pulsed power also compresses energy in time



Energy is stored in capacitors over minutes

Energy is delivered to the load in 100-1000 ns

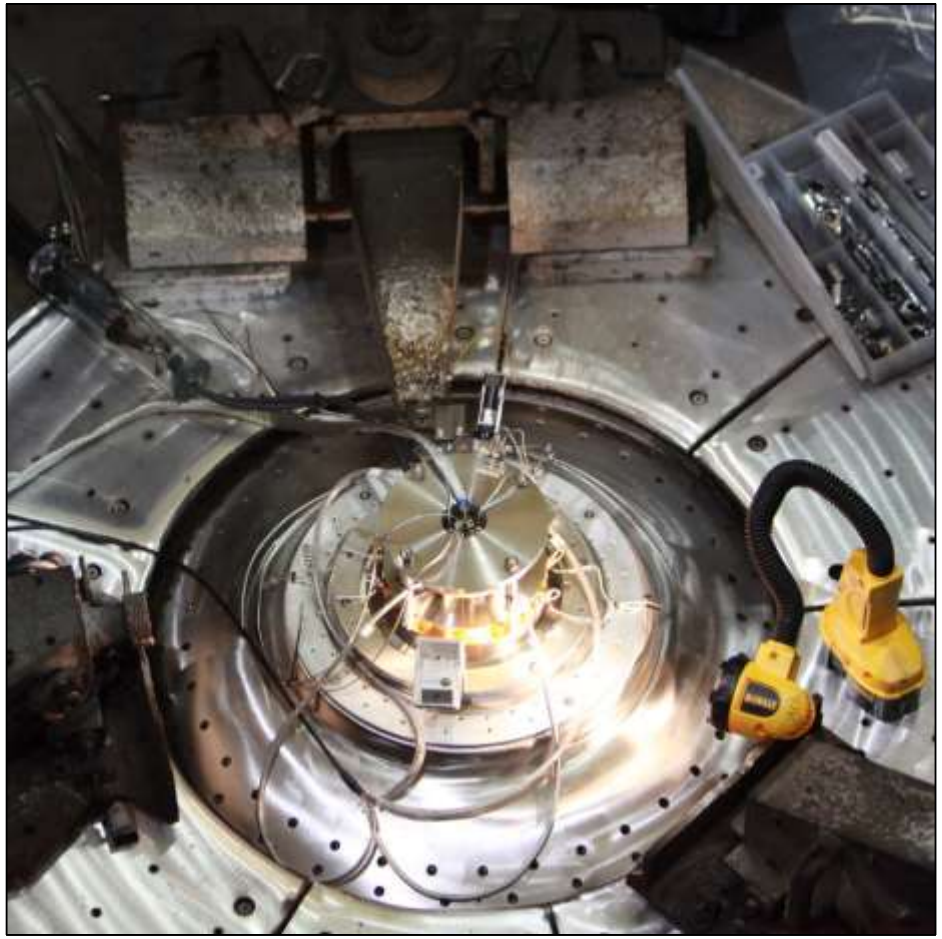
Compression in time is ~10^9

Peak electrical power is ~80 TW

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

The massive energy coupled to the target destroys the nearby components

Before

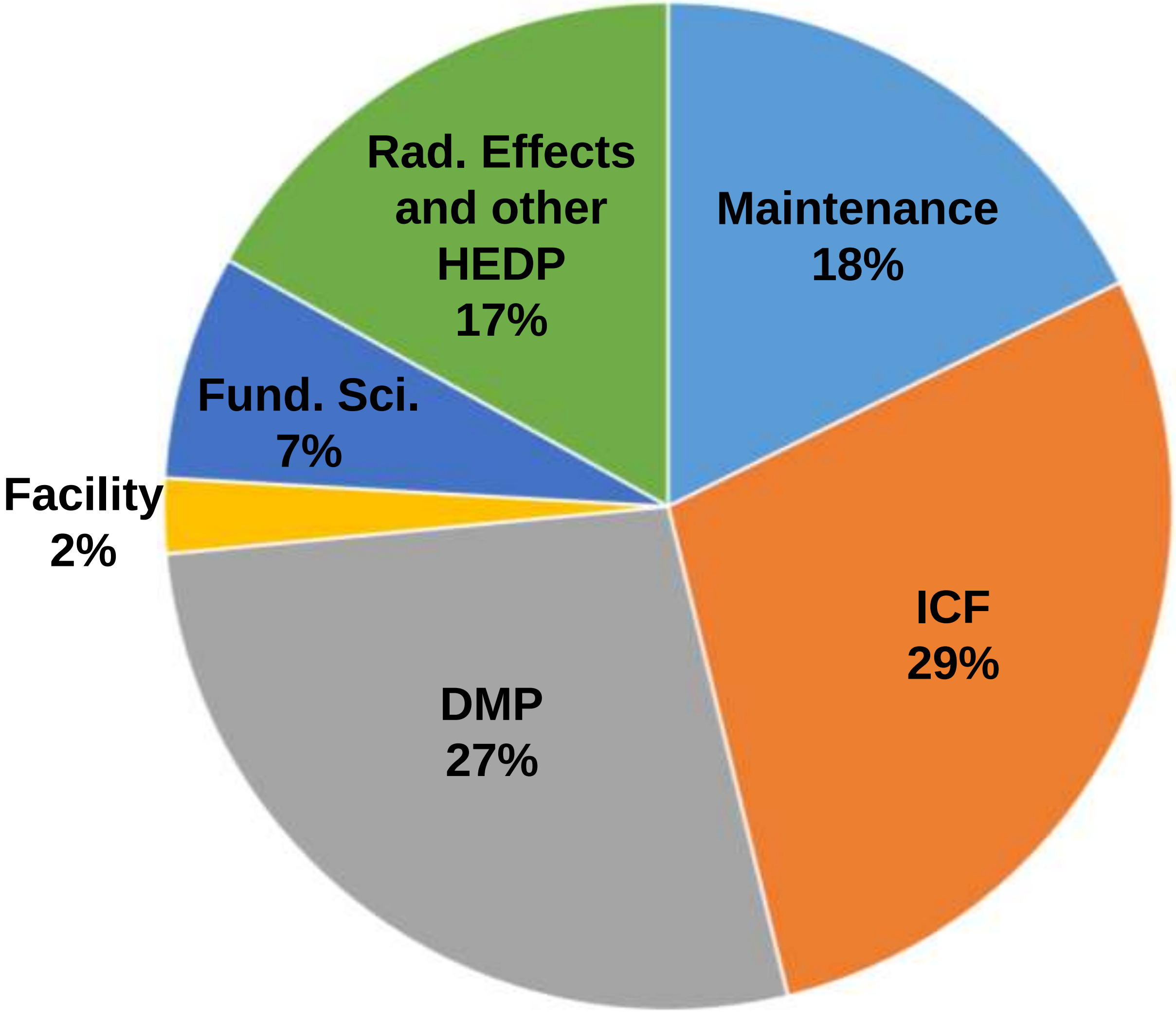


After

~3 MJ energy deposited

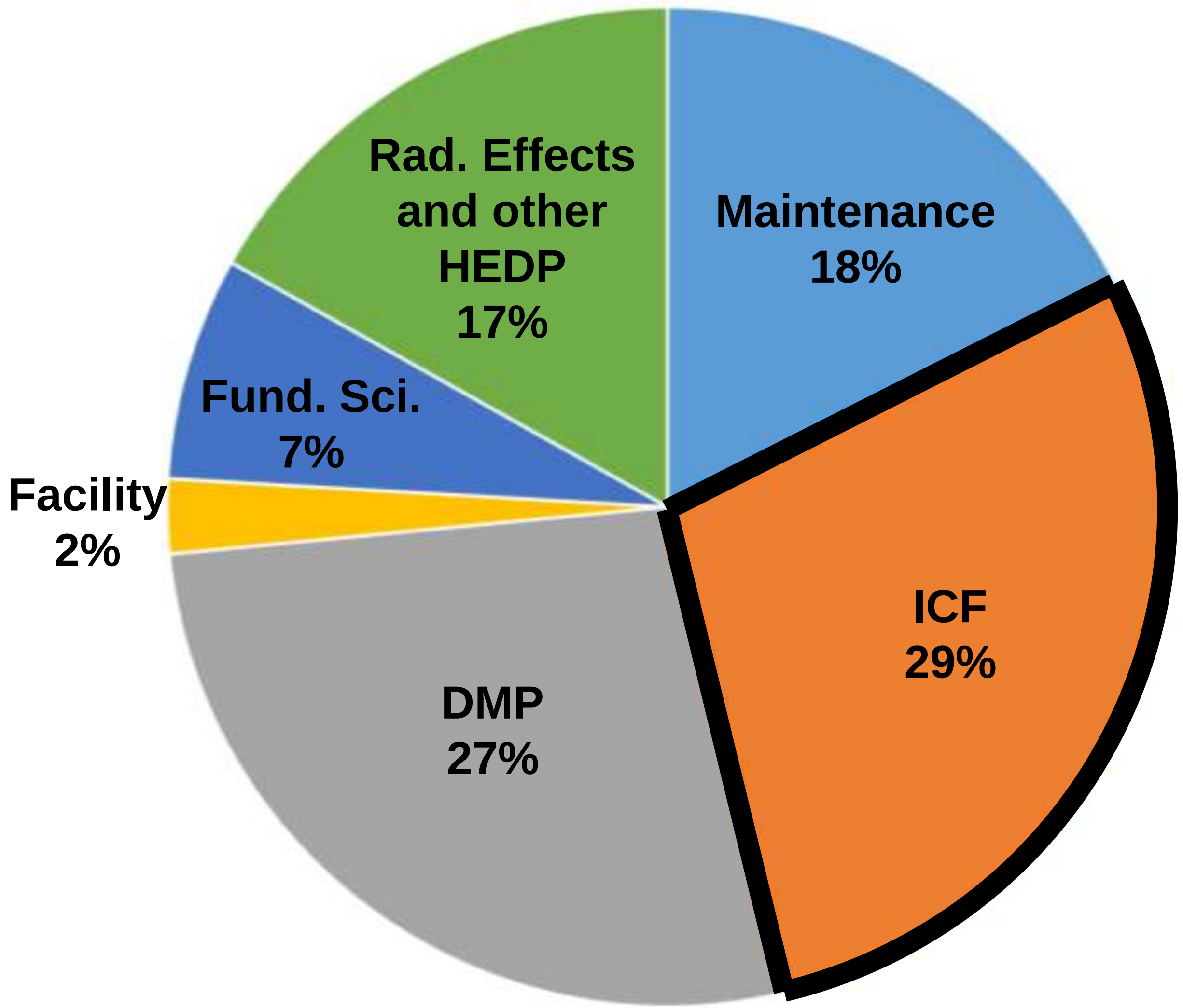
Clean up and reload limits us to 1 shot/day

Time on the Z facility is split between a few major stewardship science efforts



- This is based on our schedule for CY2017
- Approximately 250 working days
- We expect around 160 shots this year
  - Some experiments take more than 1 day to complete
  - We completed an insulator stack rebuild this year (about 20 days)
    - Every few years or so
  - We are rebuilding our transmission line refurbishment facility (about 14 days)
    - Every decade or so

Time on the Z facility is split between a few major stewardship science efforts



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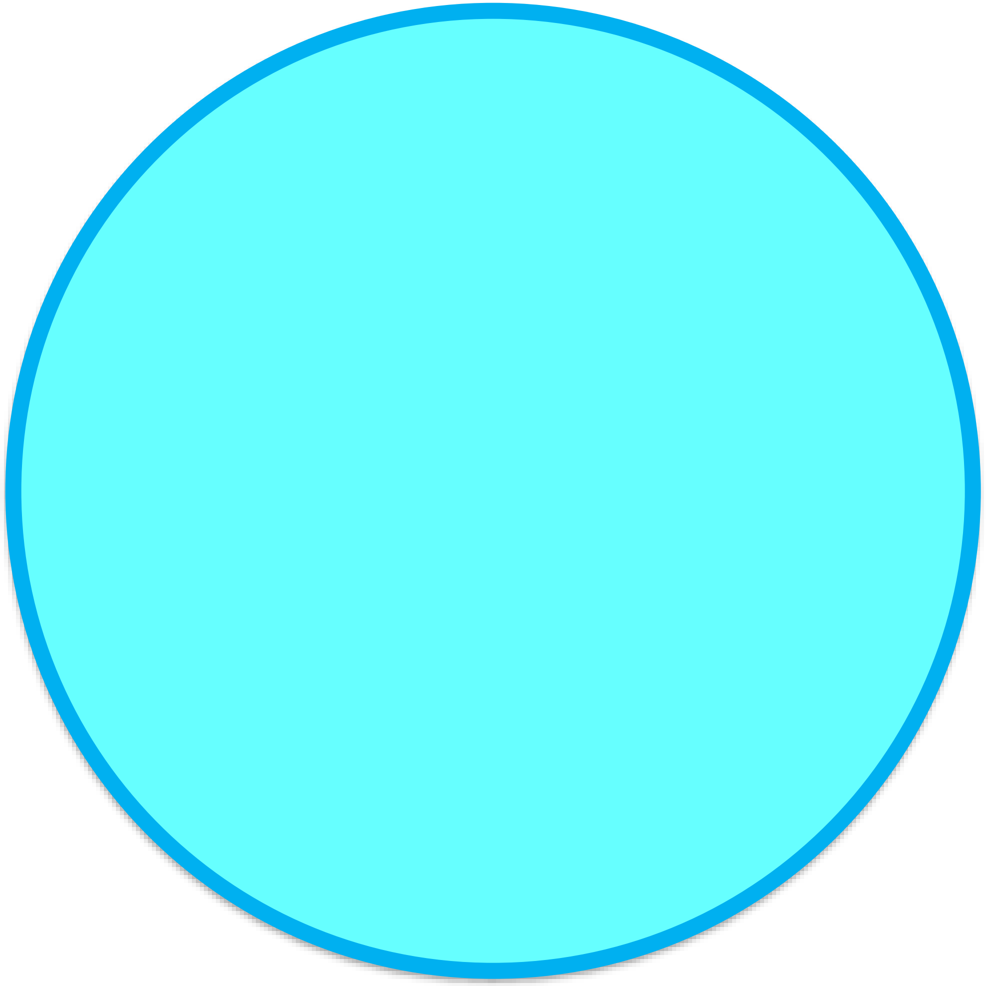
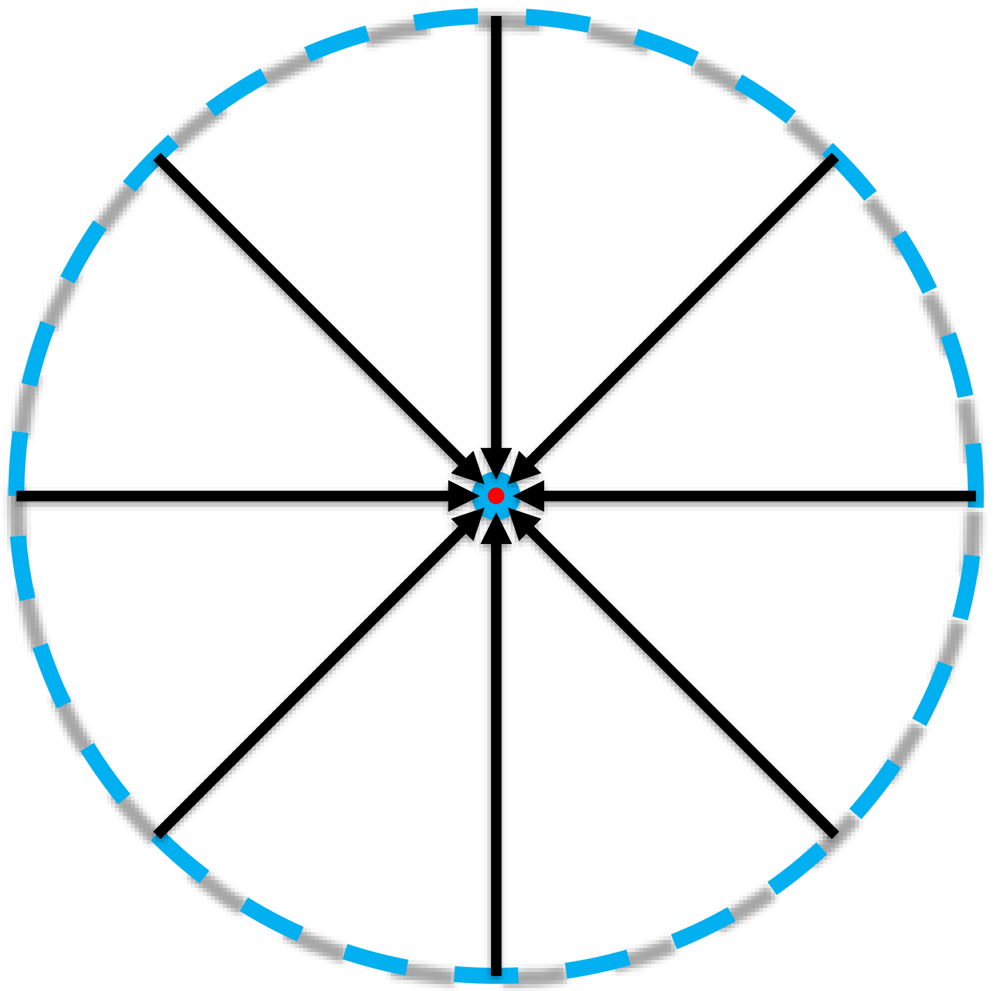
A quick review of traditional ICF



- Start with a sphere containing DT

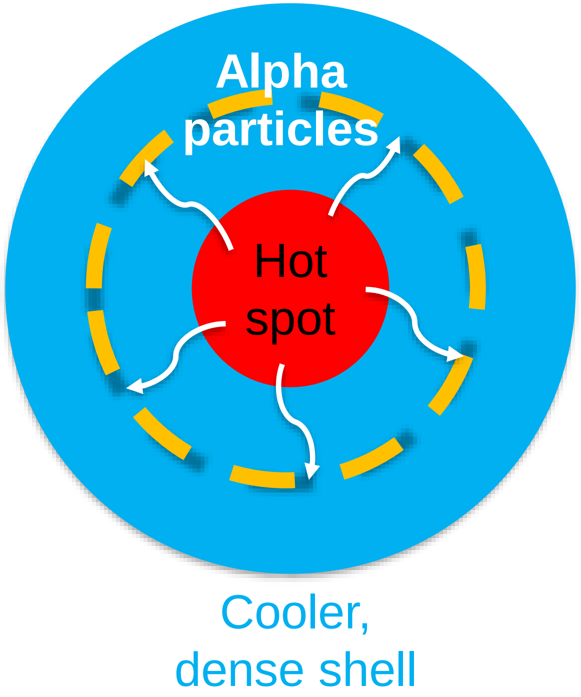
A quick review of traditional ICF



- 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)

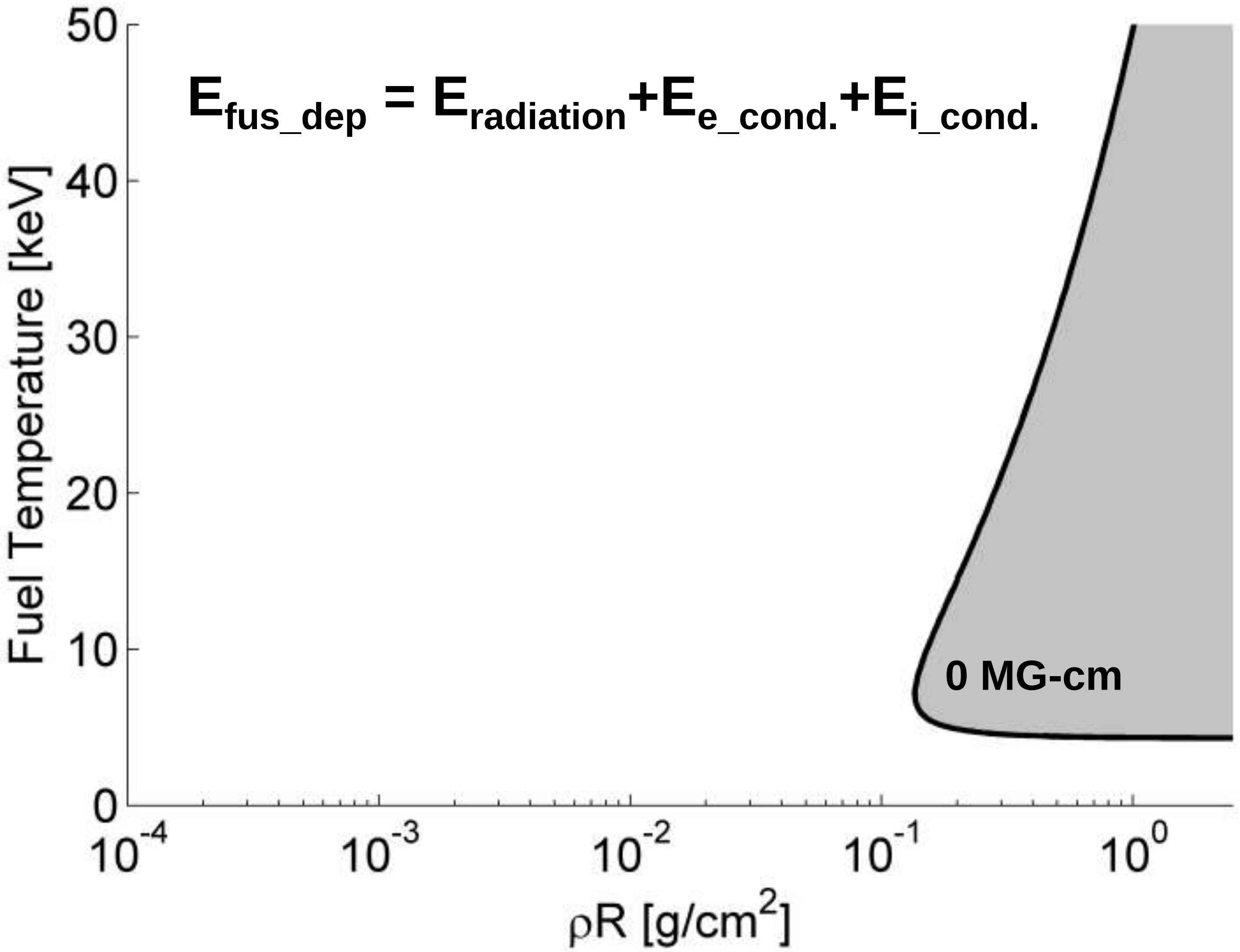
A quick review of traditional ICF

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

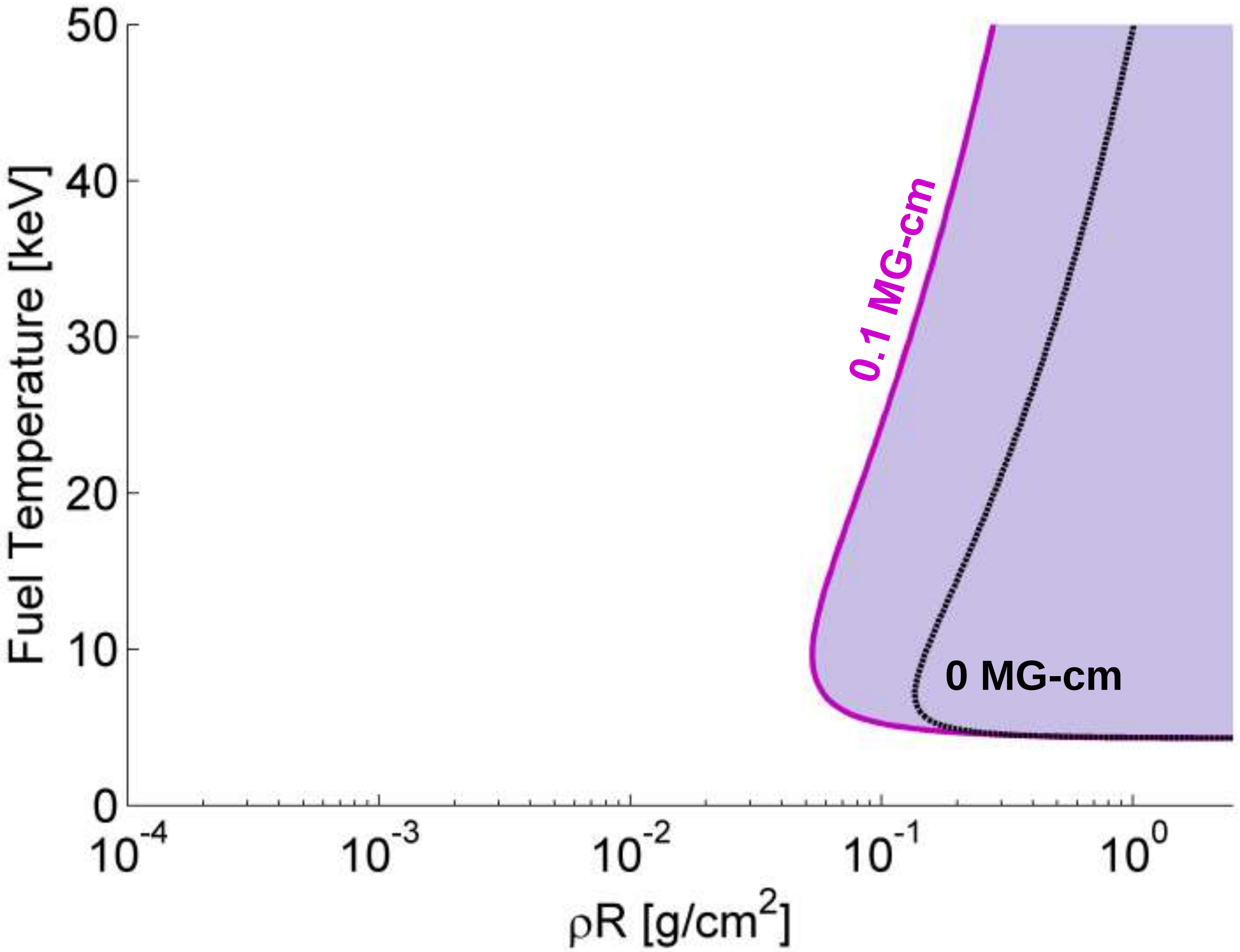
ICF has requirements on stagnation conditions to propagate a burn wave



- 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).

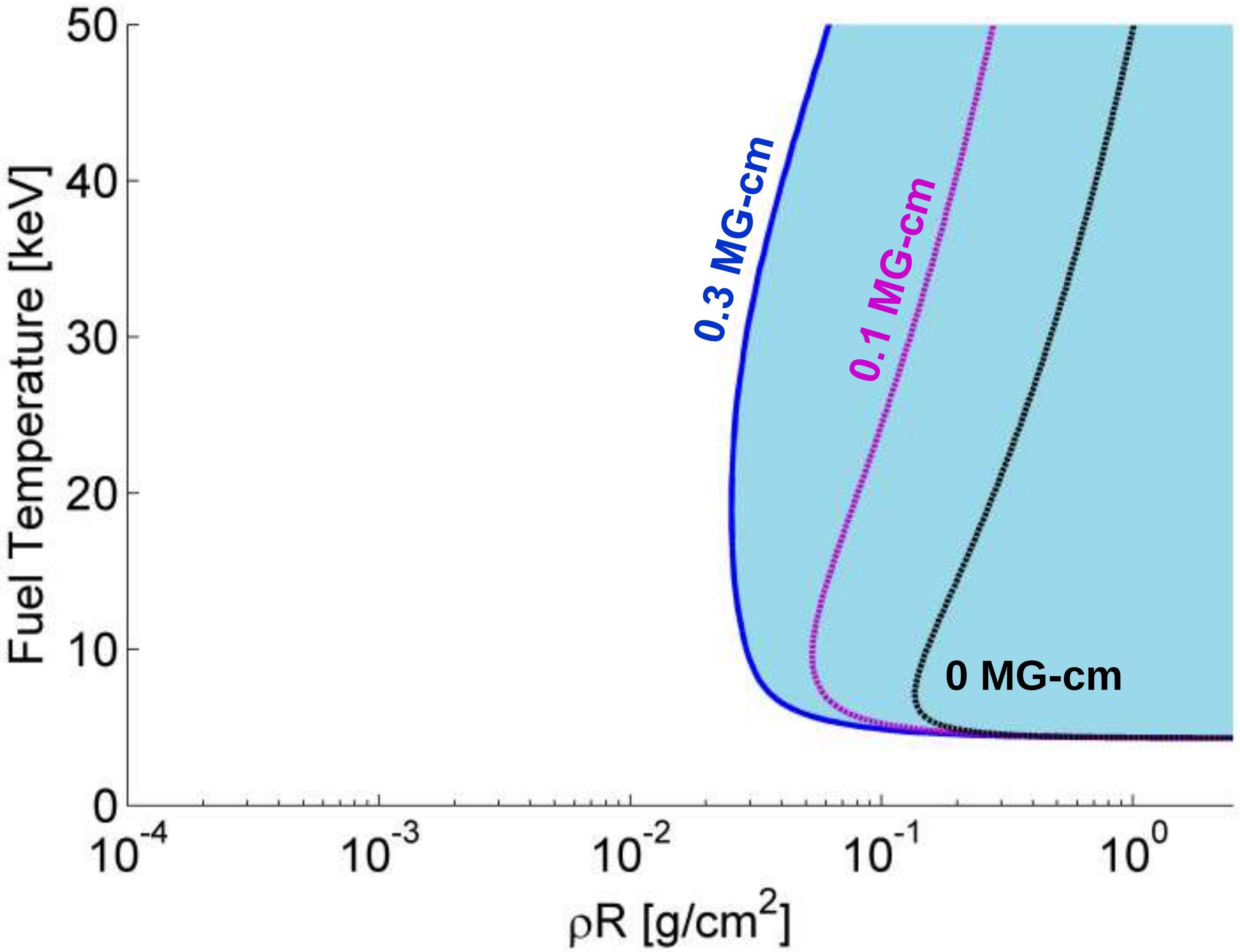
Magneto-inertial fusion utilizes magnetic fields to relax the stagnation requirements of ICF



- 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).

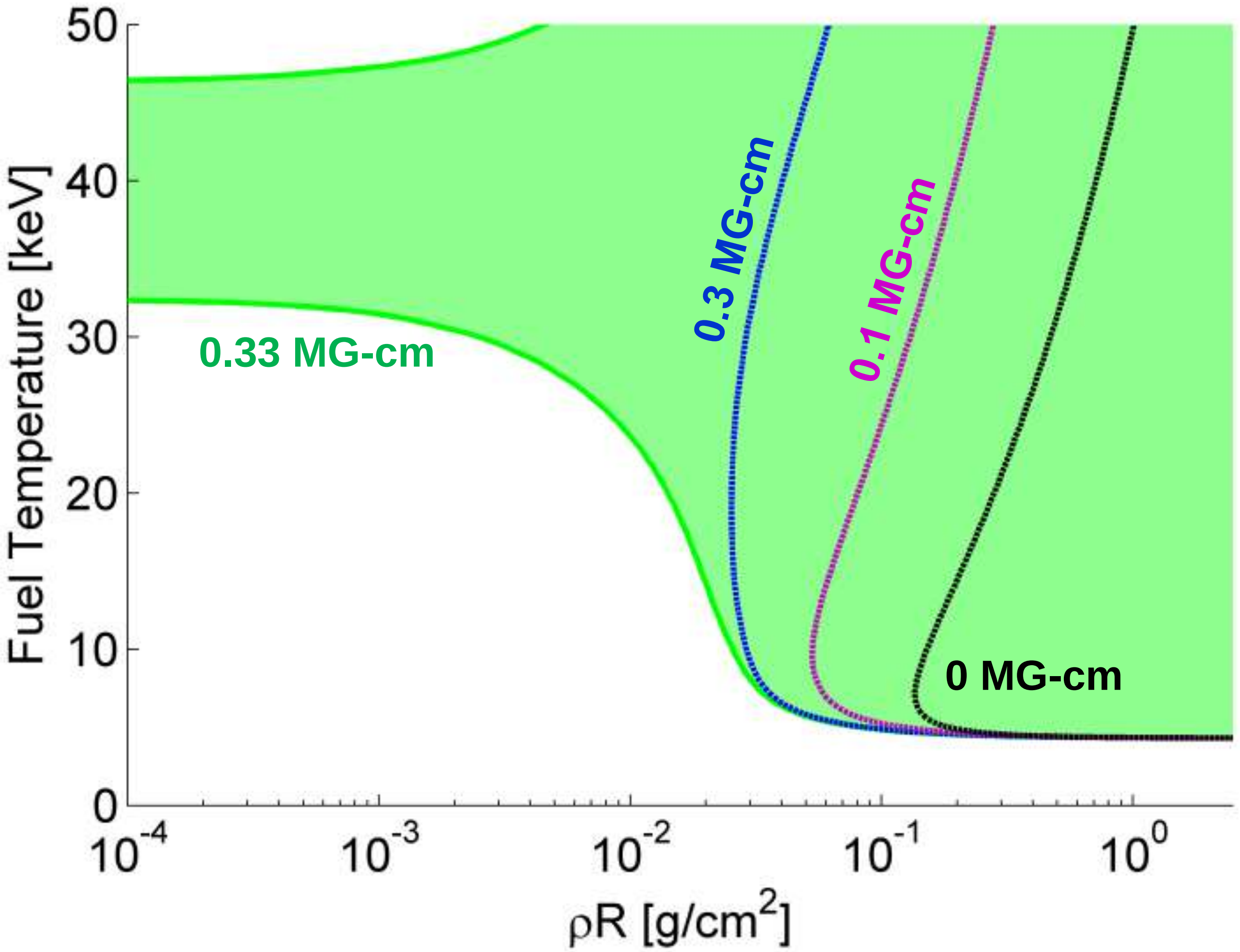
Magneto-inertial fusion utilizes magnetic fields to relax the stagnation requirements of ICF



- 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).

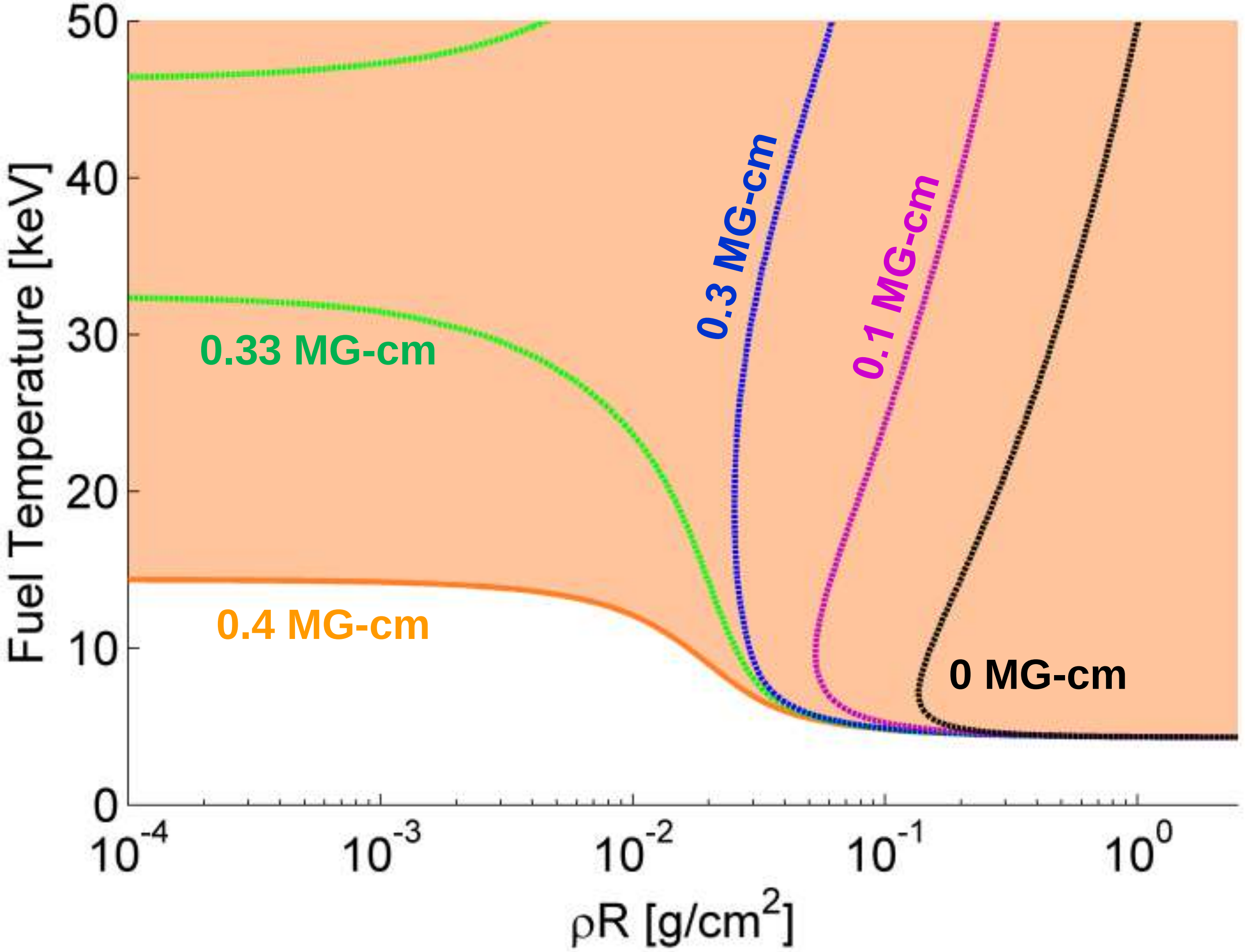
Magneto-inertial fusion utilizes magnetic fields to relax the stagnation requirements of ICF



- 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).

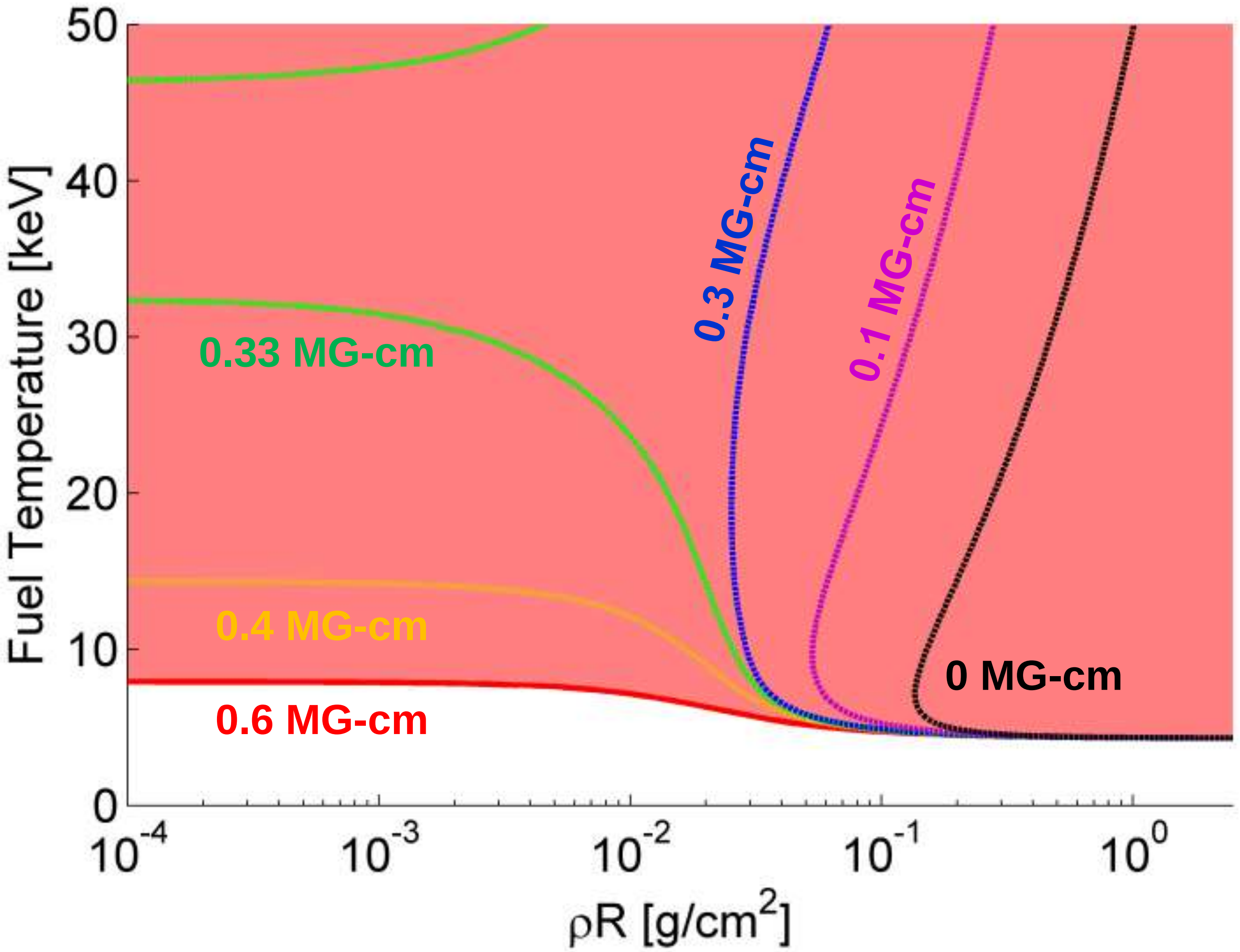
Magneto-inertial fusion utilizes magnetic fields to relax the stagnation requirements of ICF



- 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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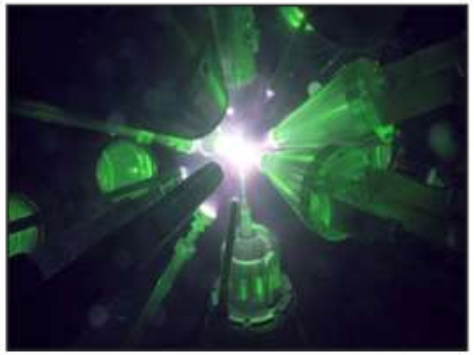
Laser Indirect Drive

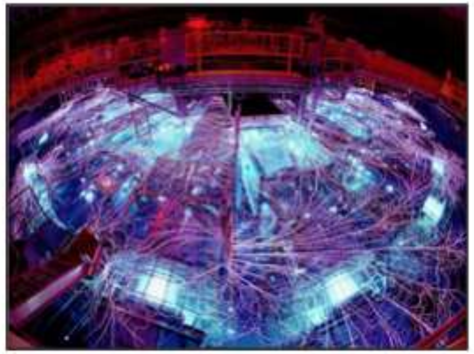
192 beams, 1.8 MJ, 400 TW

Laser Direct Drive

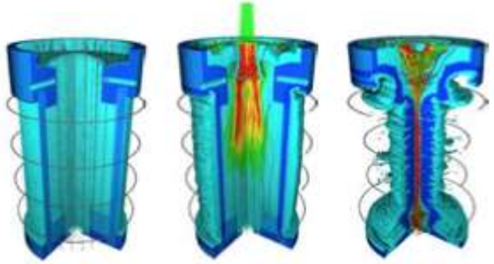
60 beams, 30 kJ, 20 TW



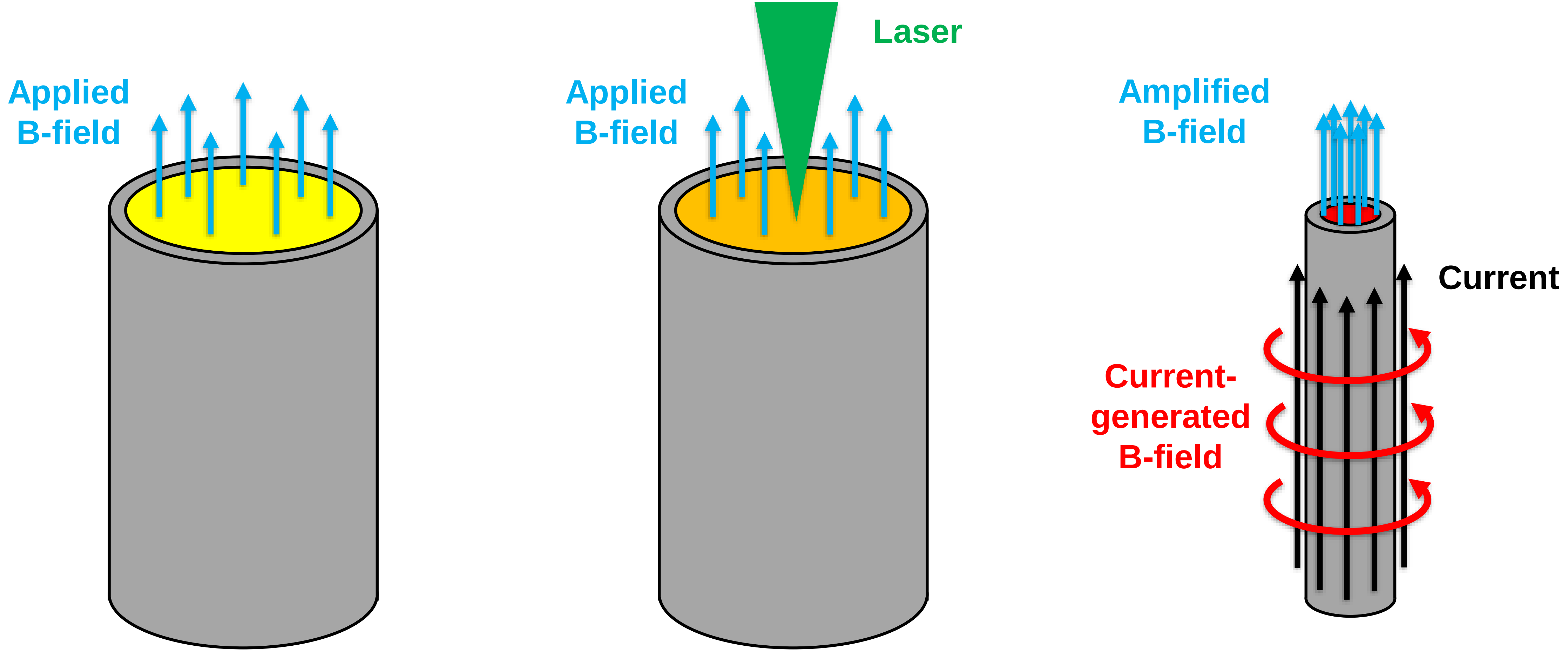
Magnetic Direct Drive



26 MA, 80 TW



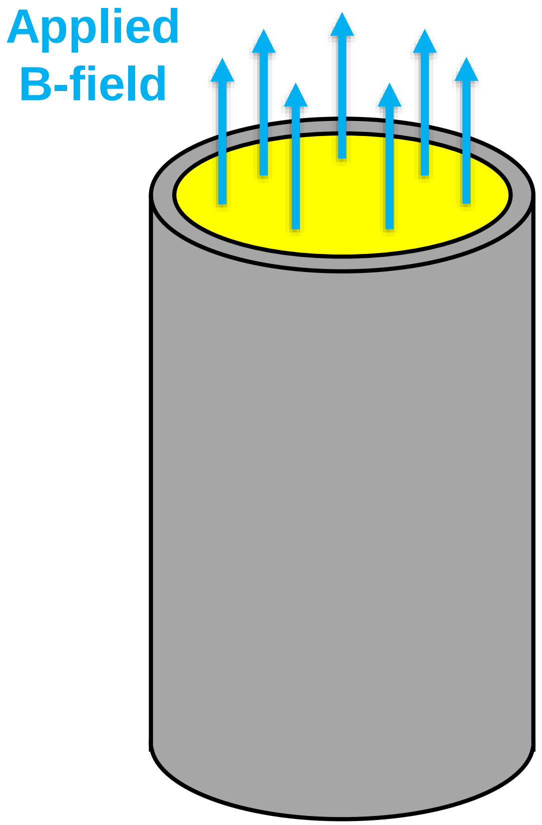
Magnetized Liner Inertial Fusion relies on three stages to produce fusion relevant conditions



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).

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

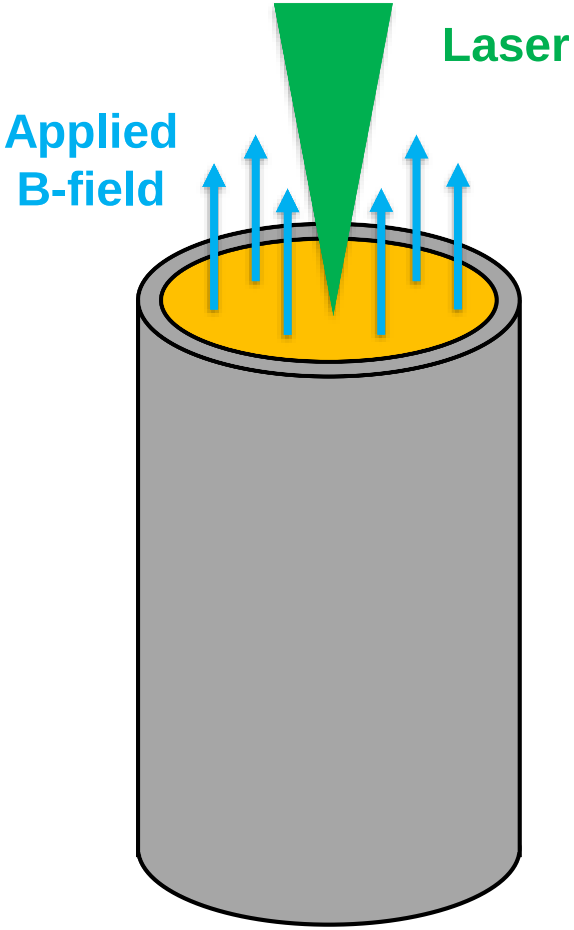


Apply axial magnetic field

- Metal cylinder contains ~1 mg/cm^3 of deuterium gas
  - 10 mm tall, 5 mm diameter, 0.5 mm thick
- Helmholtz-like coils apply 10-30 T
  - 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

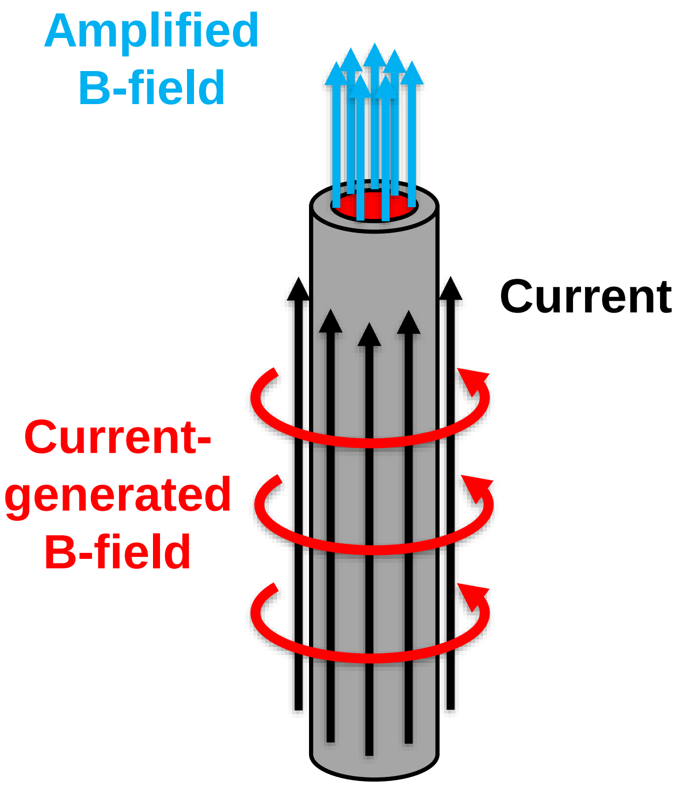


Laser-heat the magnetized fuel

- 527 nm, 2 ns, 2 kJ laser used to heat the fuel
- Laser must pass through ~1 µm thick plastic window
  - Lose about half of the laser energy to the plastic
- 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

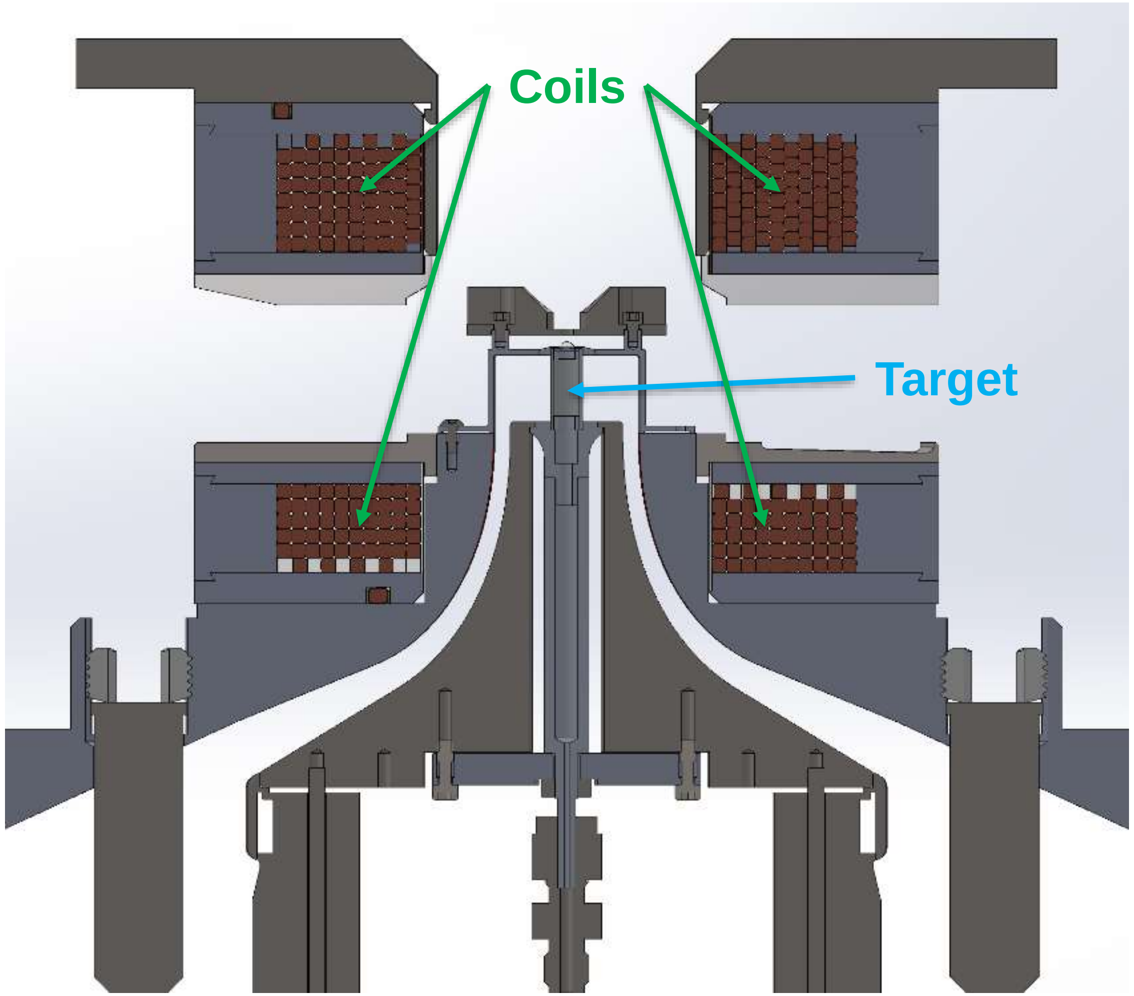


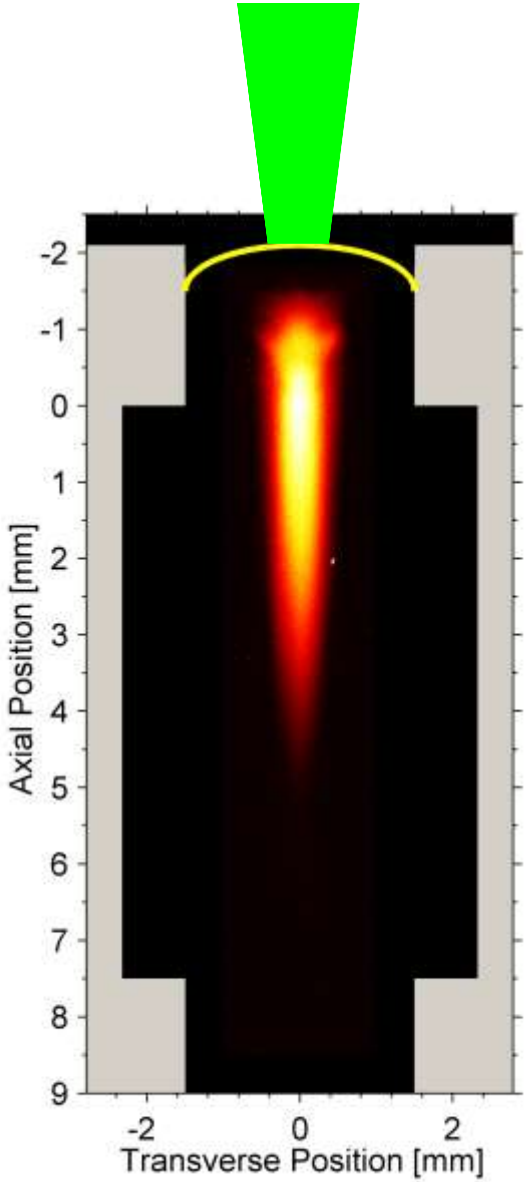
Compress the heated and magnetized fuel

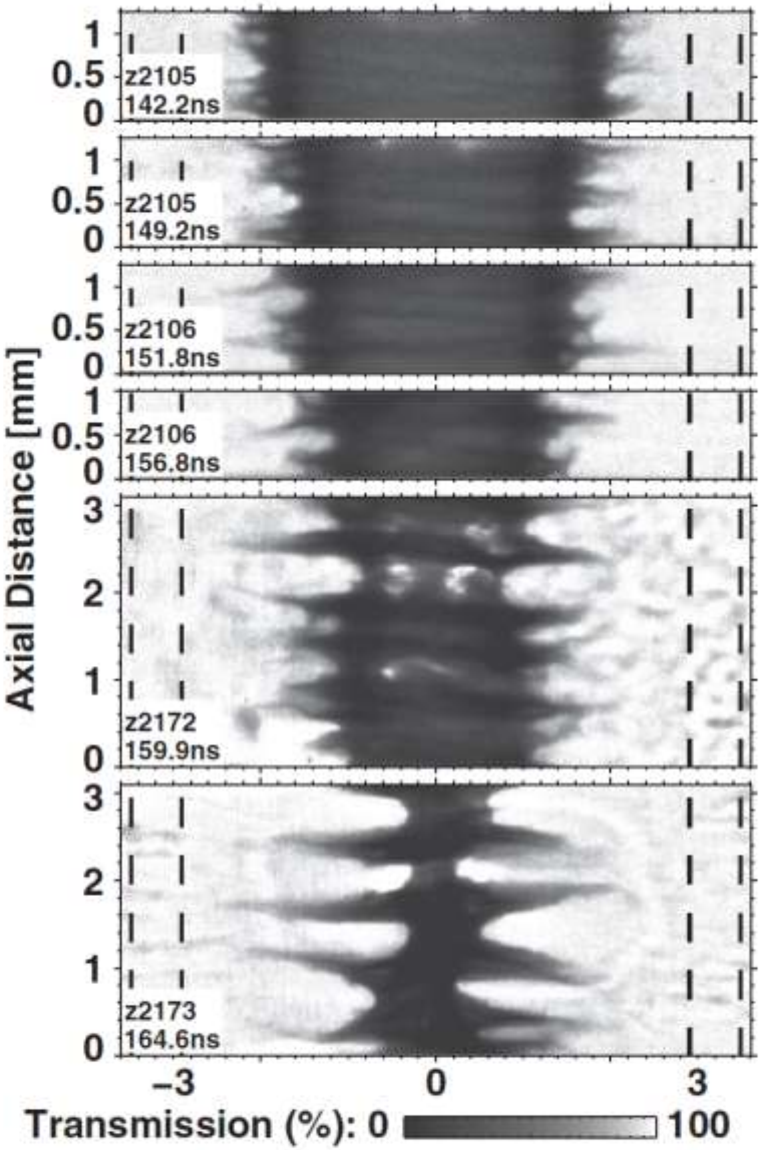
- Axial current is ~17 MA, risetime is 100 ns
  - Generates ~3 kT azimuthal B-field
  - Metal cylinder implodes at ~70 km/s
- Fuel is nearly adiabatically compressed, which further heats the fuel to keV temperatures
- Axial magnetic field is increased to 1-10 kT through flux compression

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

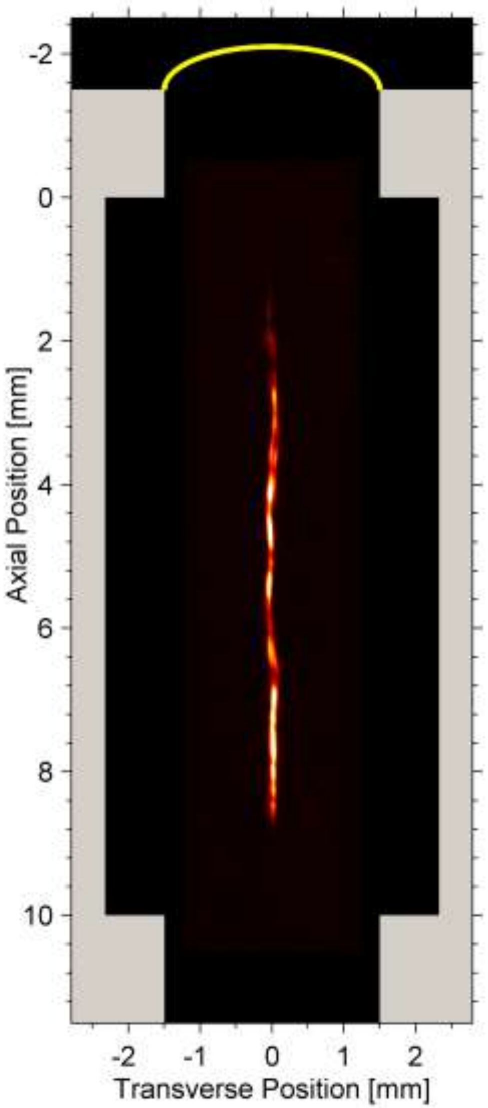
We do our best to understand each stage of the experiment





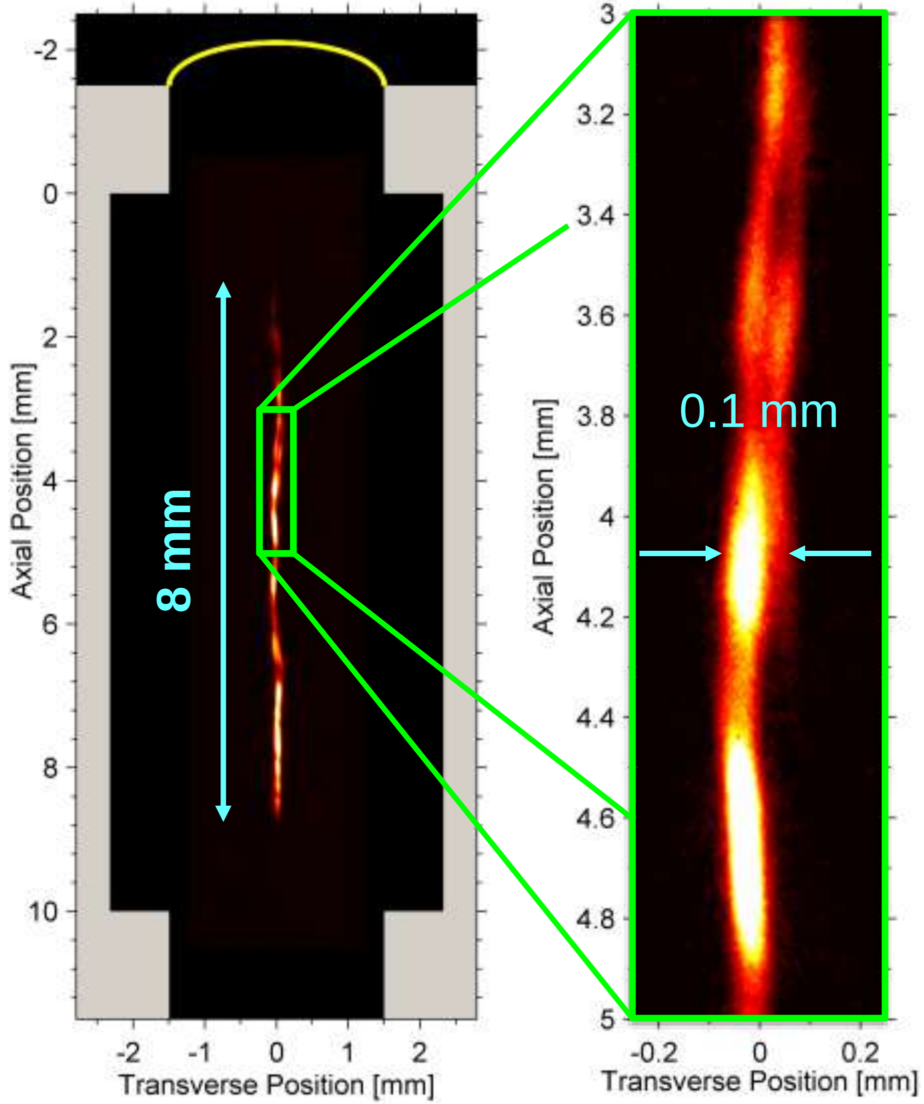


High aspect ratio stagnation column emits a burst of thermonuclear neutrons



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

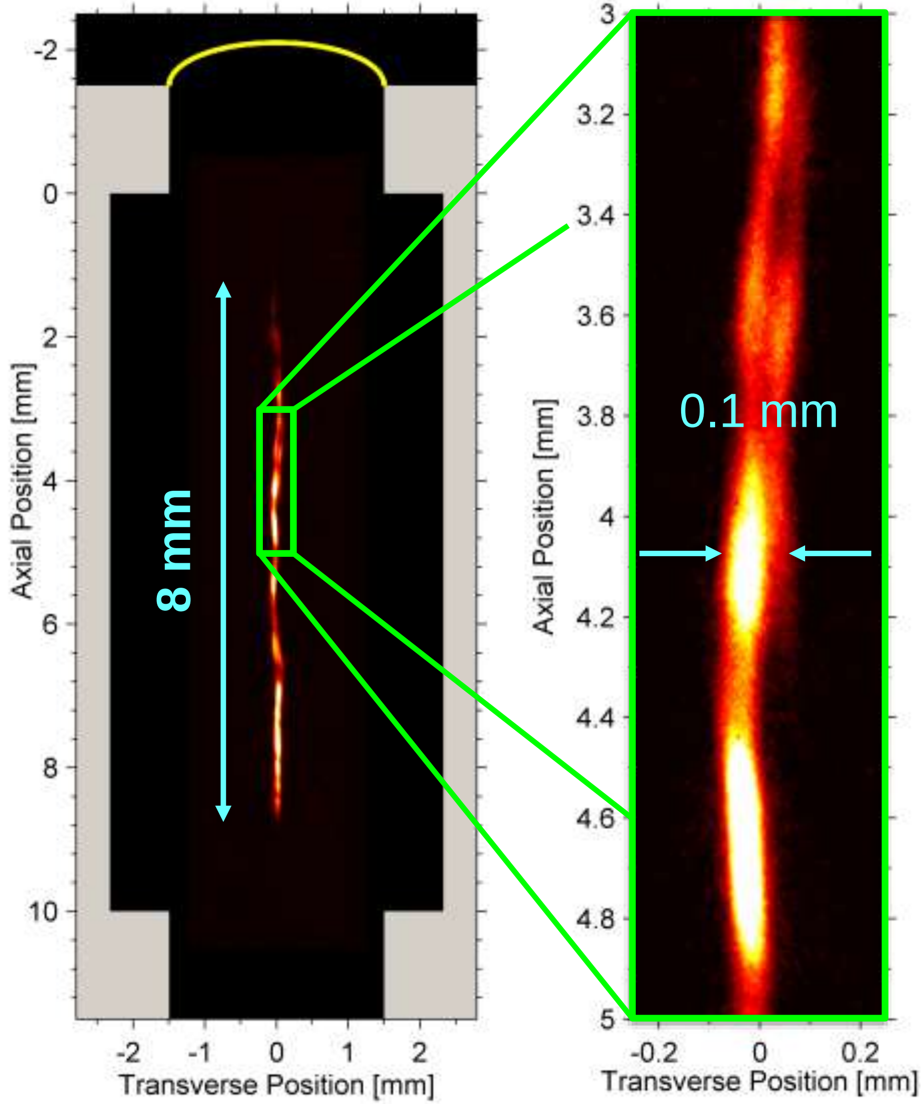
High aspect ratio stagnation column emits a burst of thermonuclear neutrons



- Stagnation column is about 8 mm tall and 0.1 mm wide
- Initial target diameter is about 4.6 mm, so this is a very high convergence

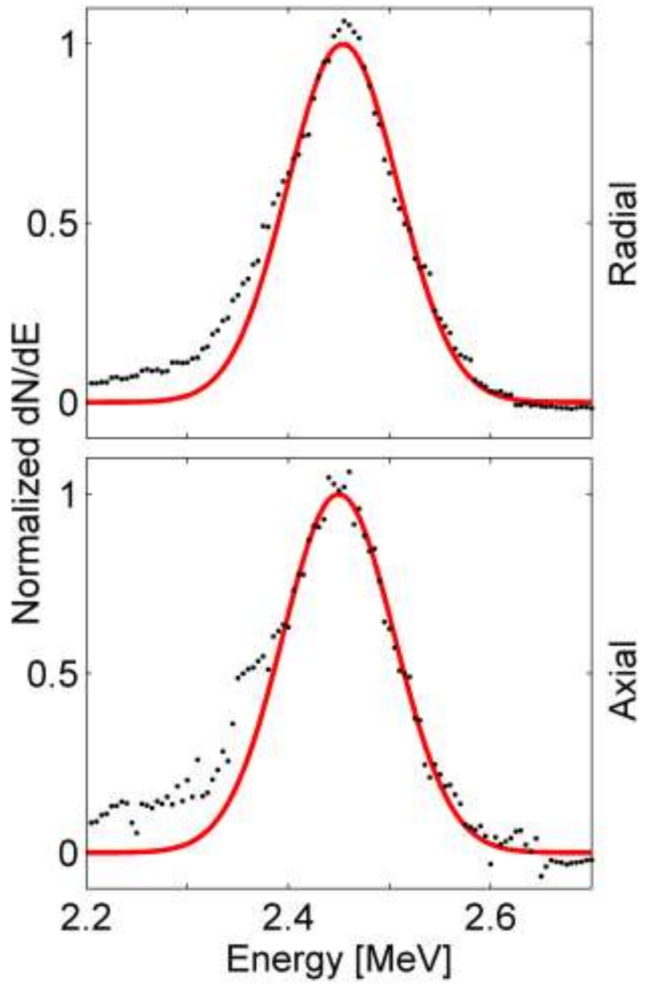
M. R. Gomez, et al., Phys. Rev. Lett. 113, 155003 (2014).

High aspect ratio stagnation column emits a burst of thermonuclear neutrons



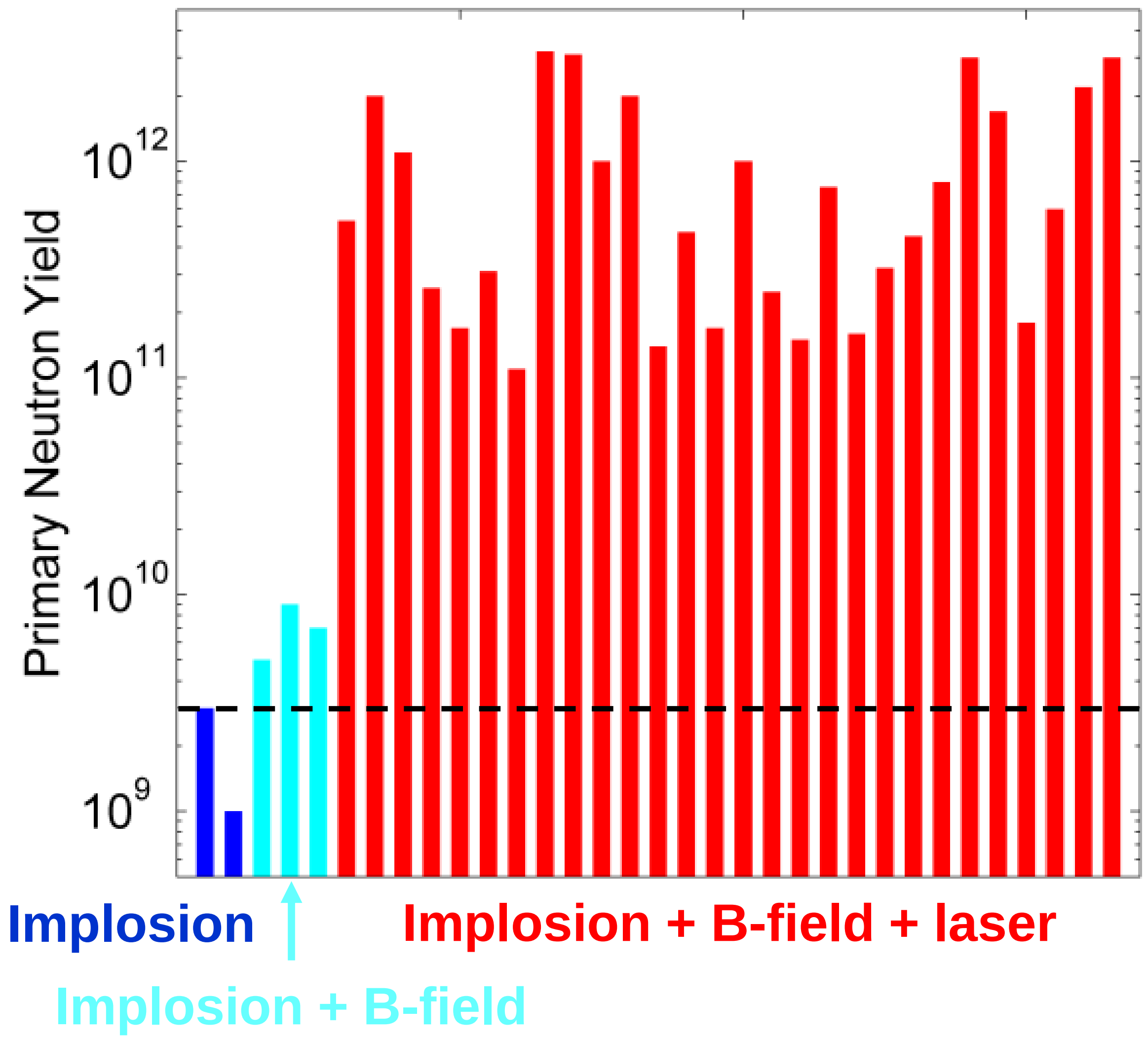
- Stagnation column is about 8 mm tall and 0.1 mm wide
- Initial target diameter is about 4.6 mm, so this is a very high convergence

- Primary neutron yield and spectra are isotropic
- Neutron production follows expected trend with ion temperature



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

Primary neutron yields up to 4e12 produced when the B-field and laser heating are included



- 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

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

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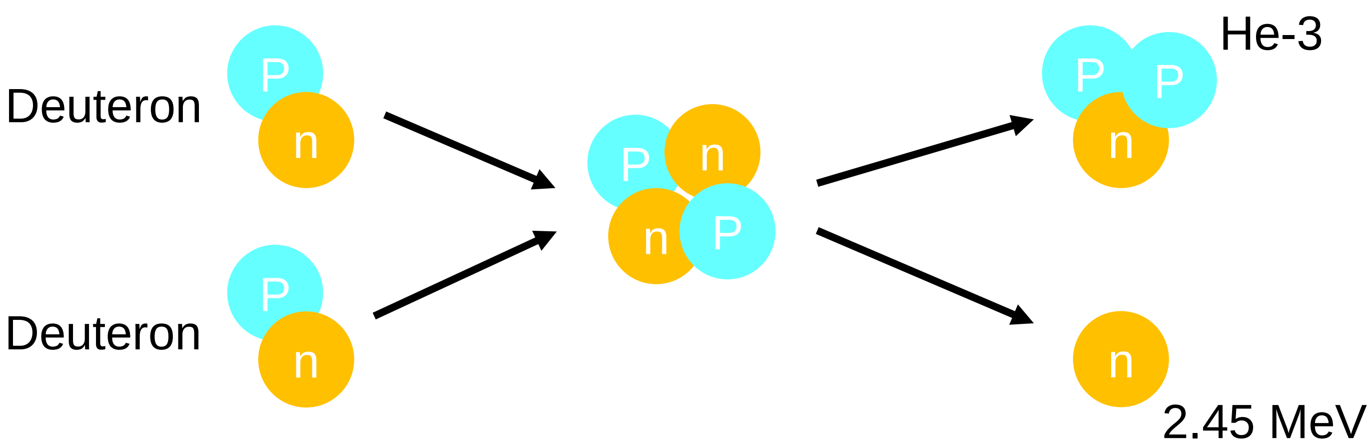
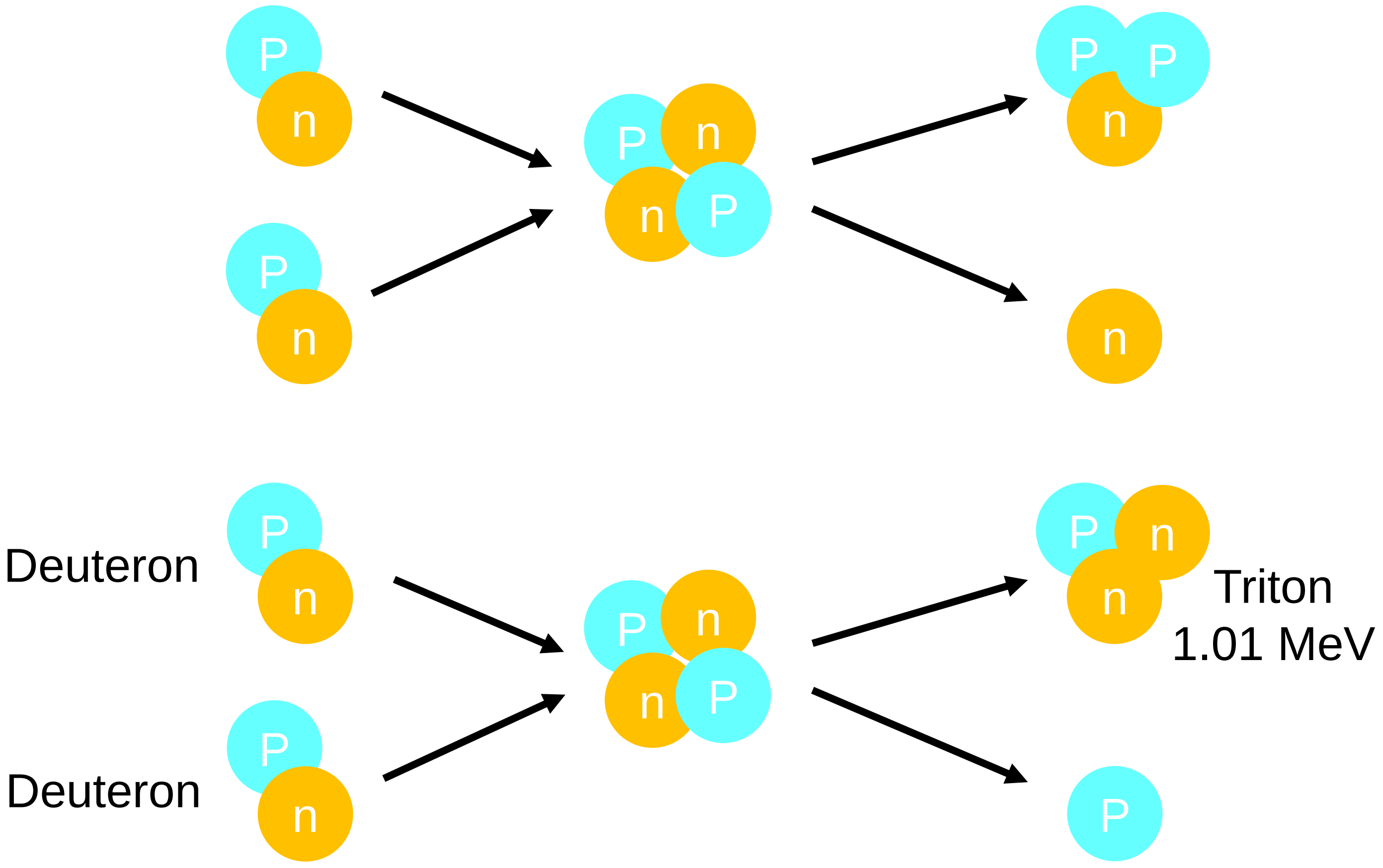
Primary Reactions

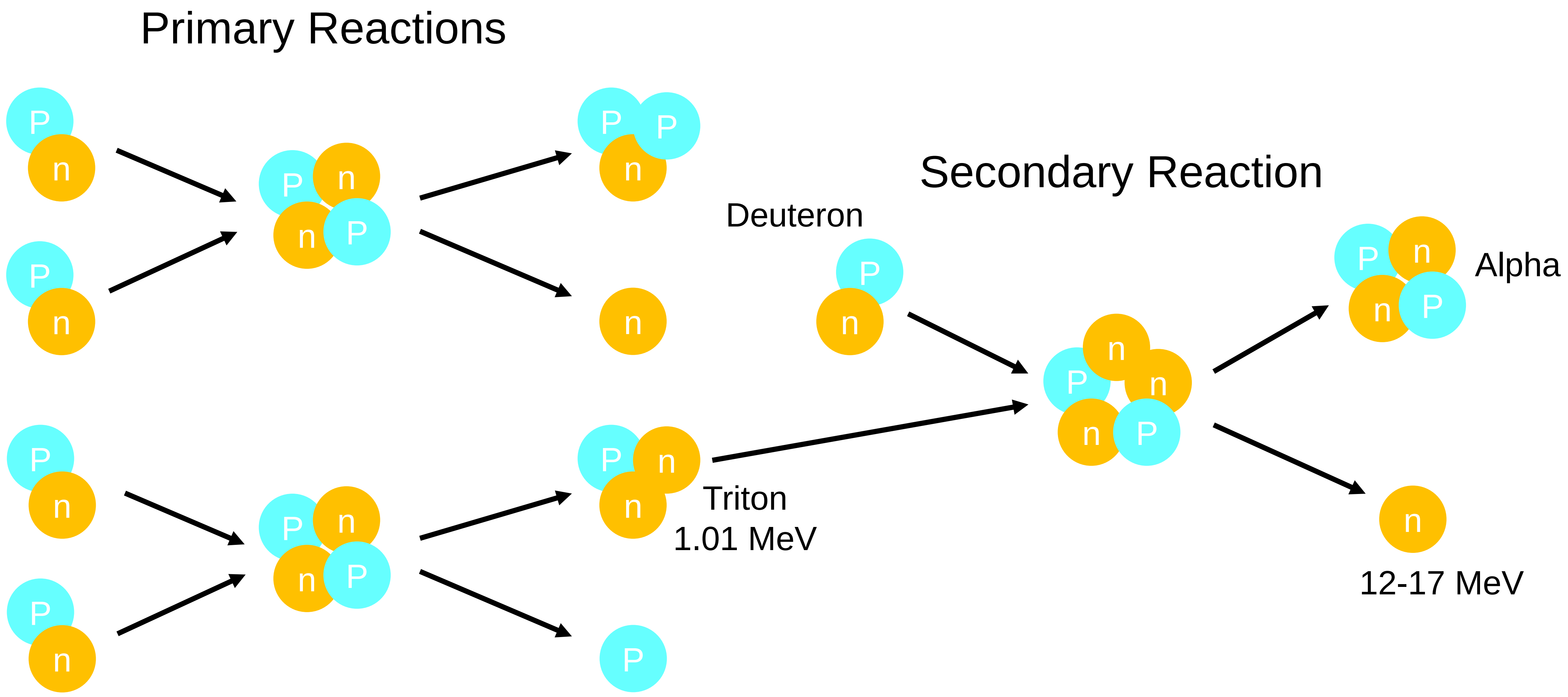


…and the other branch produces a triton…

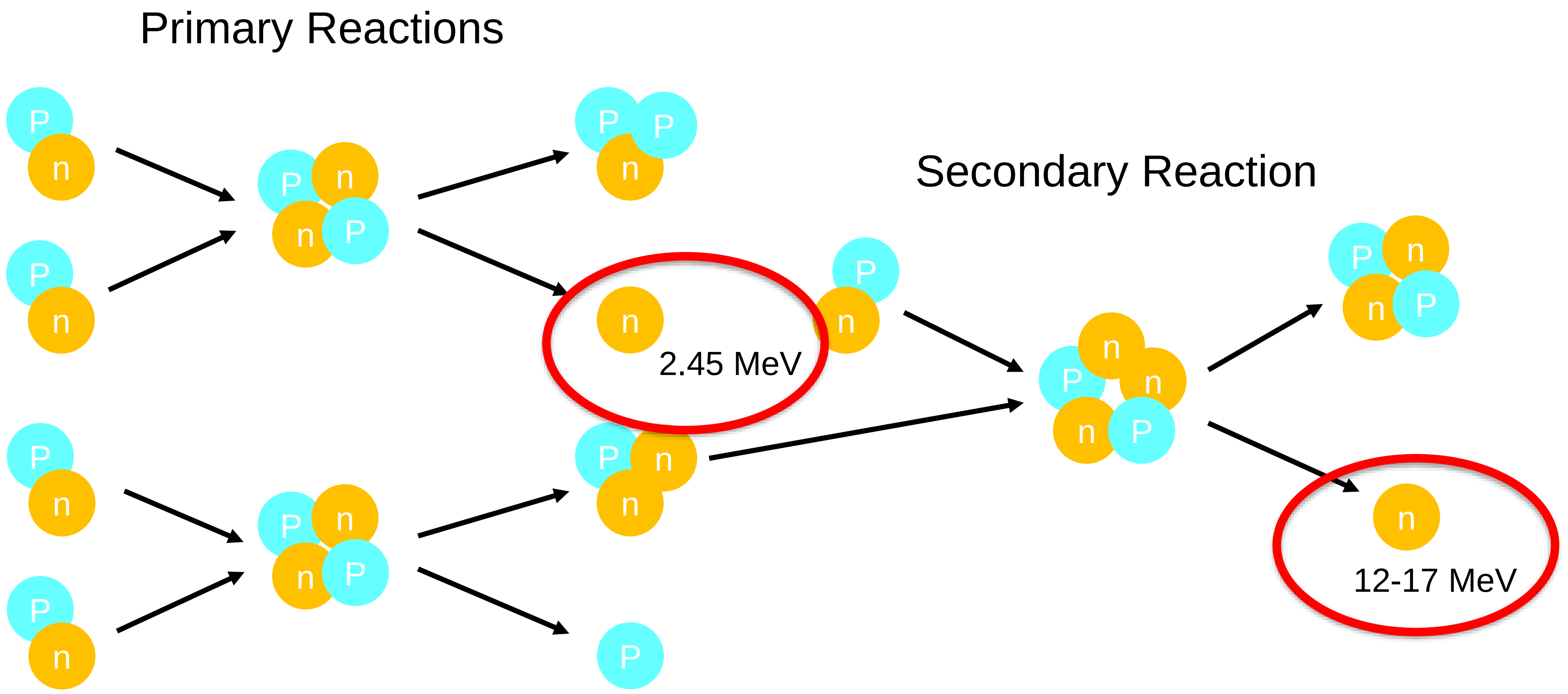
Primary Reactions



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

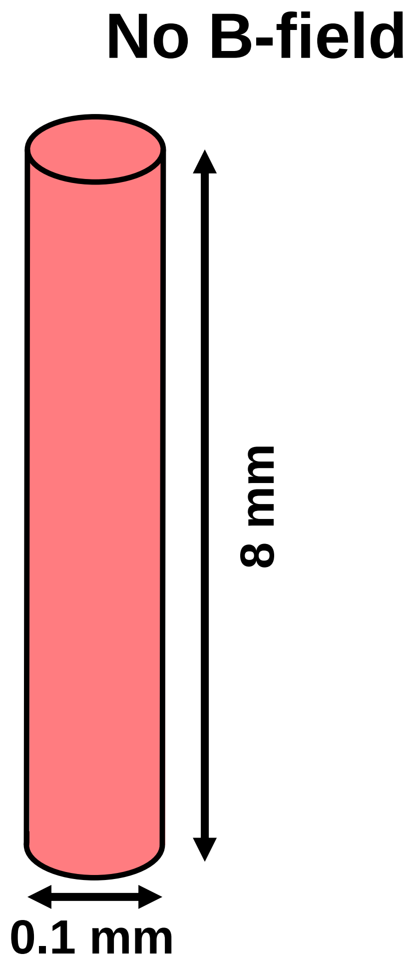


We measure both the primary and secondary neutrons



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

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



- High aspect ratio stagnation geometry
  - Height >> radius

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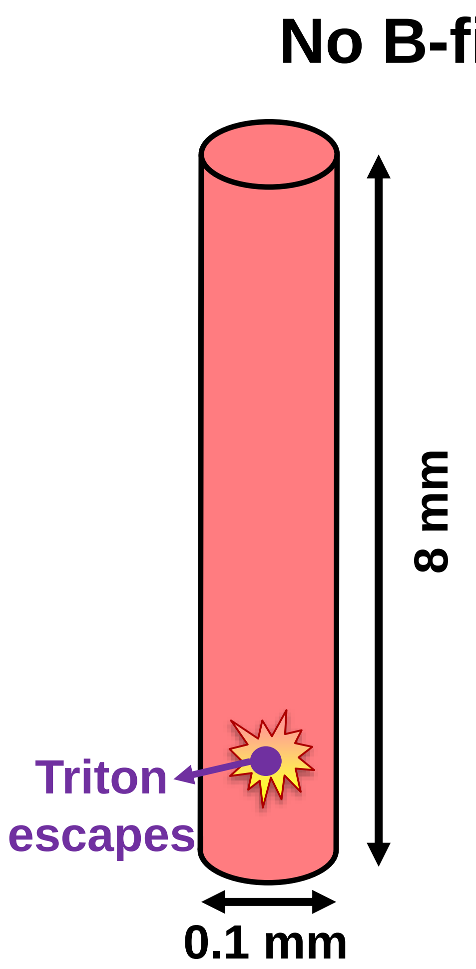
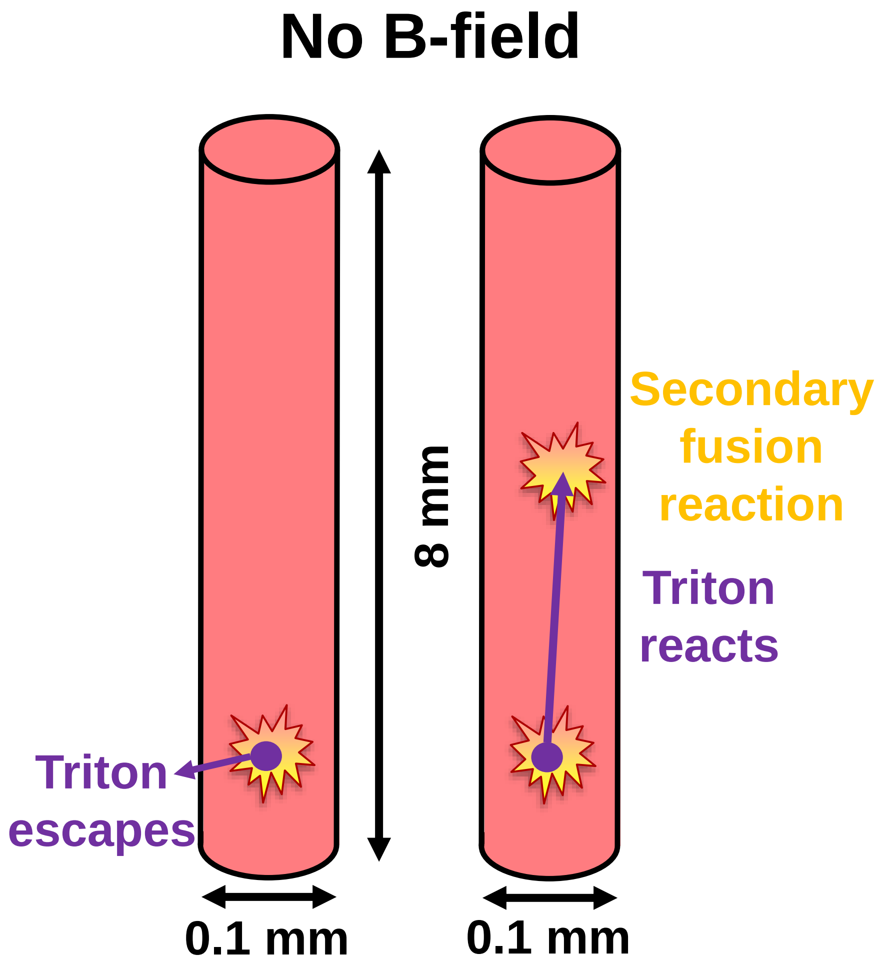


- High aspect ratio stagnation geometry
  - Height >> radius
- Consider 2 cases:
  - 1) Triton is created traveling radially
    - Very little probability of interacting prior to escaping

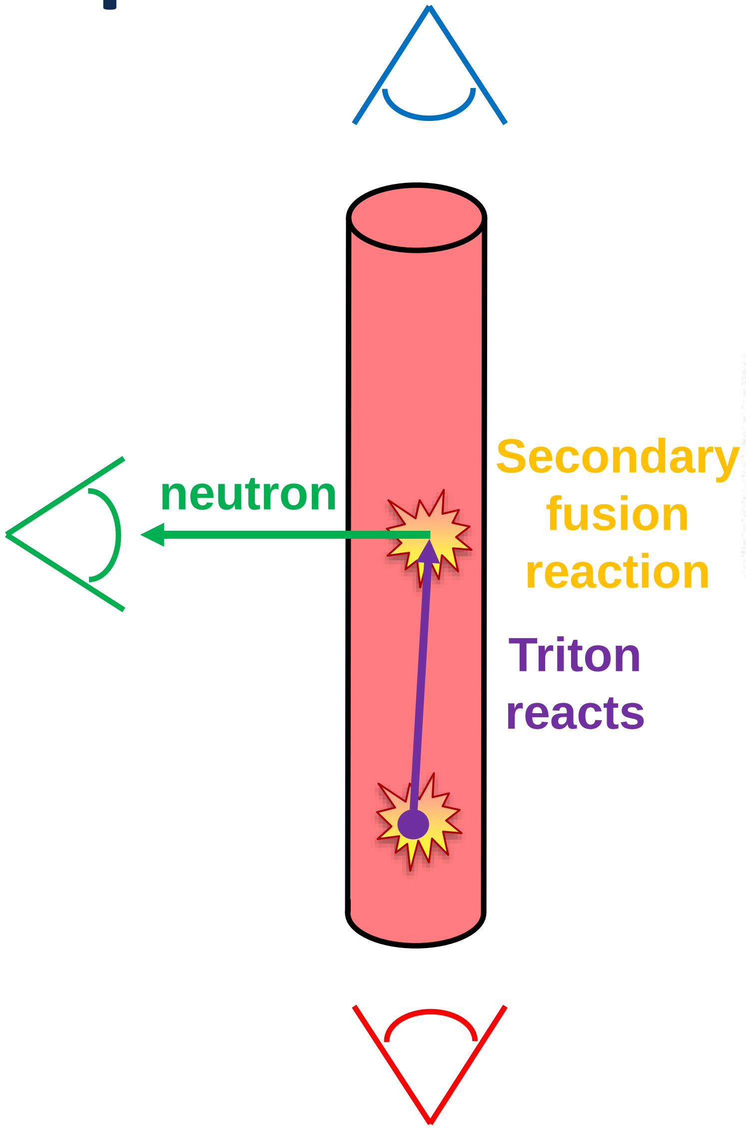
Secondary neutrons are produced when primary tritons react before exiting the fuel

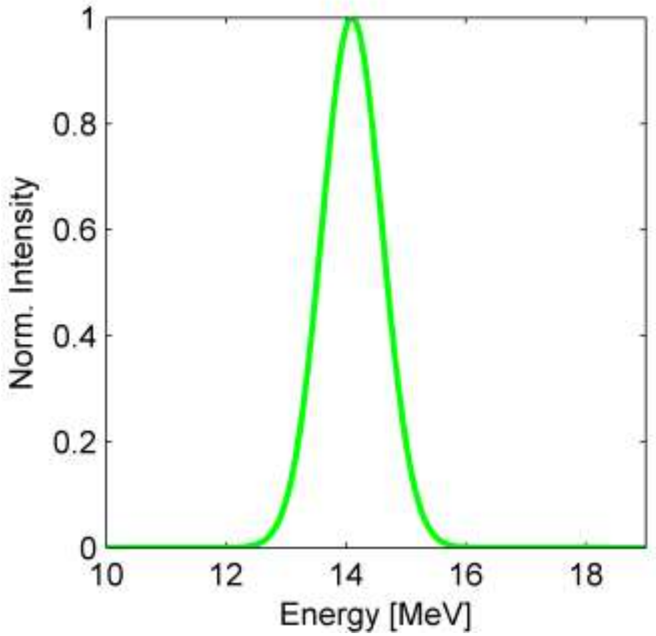


- High aspect ratio stagnation geometry
  - Height >> radius

- 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

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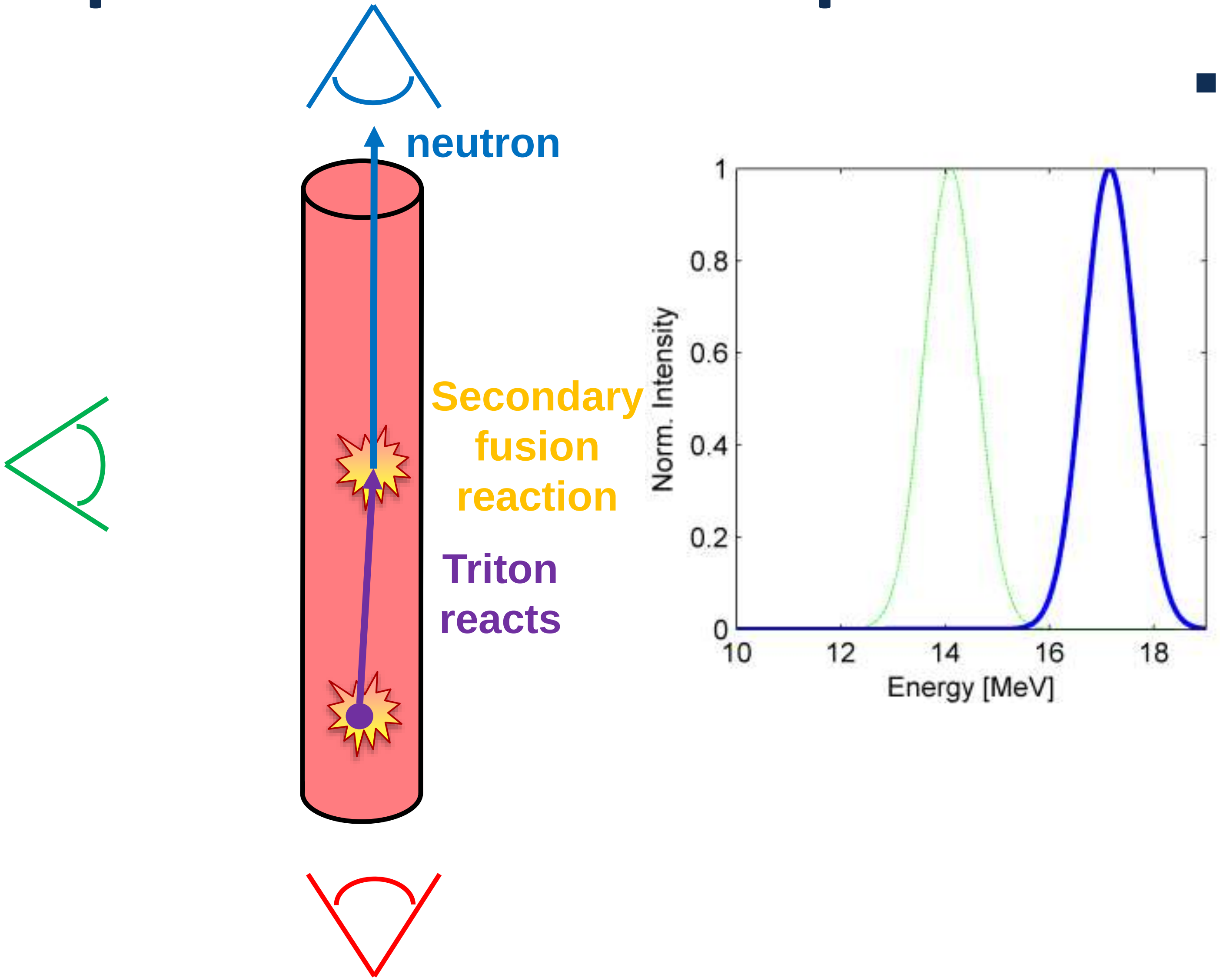

- Consider 3 detector locations:
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    - Neutrons at nominal energy
  - Axial (triton moving towards)
    - Neutrons shifted to higher energy

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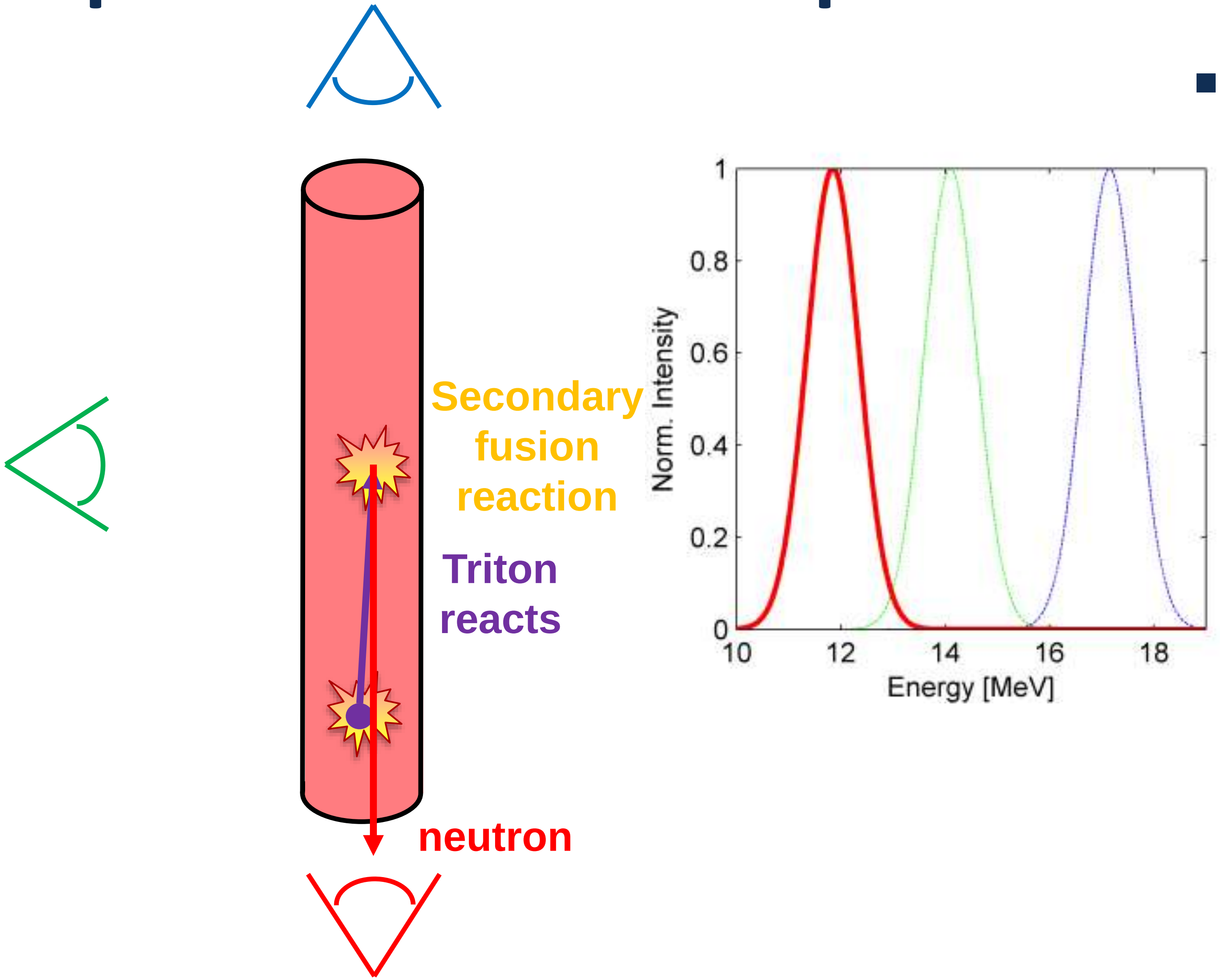

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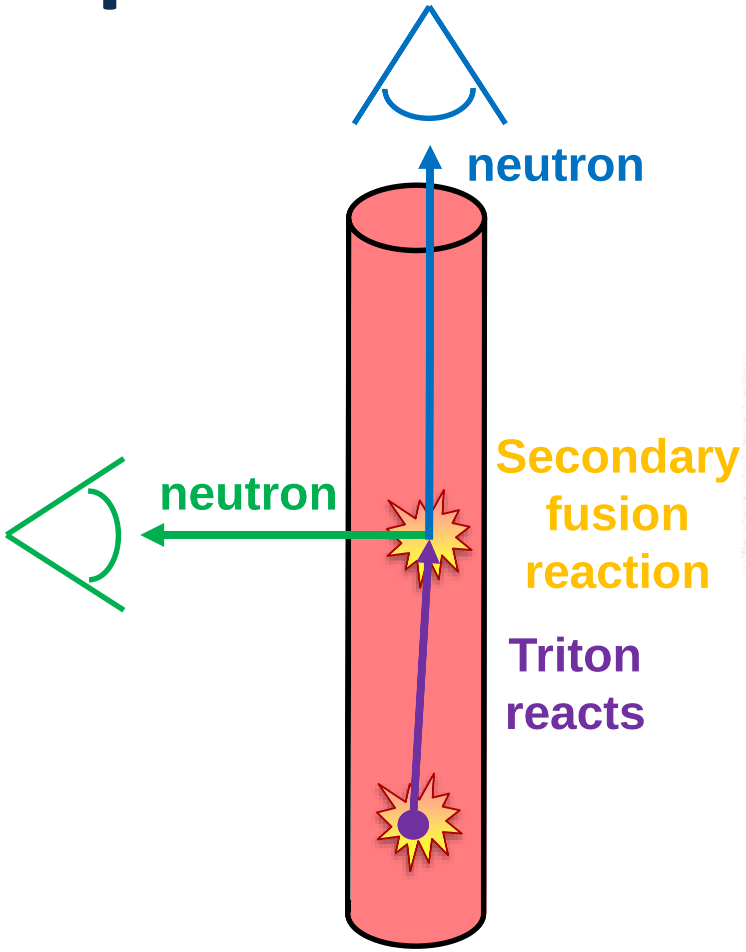

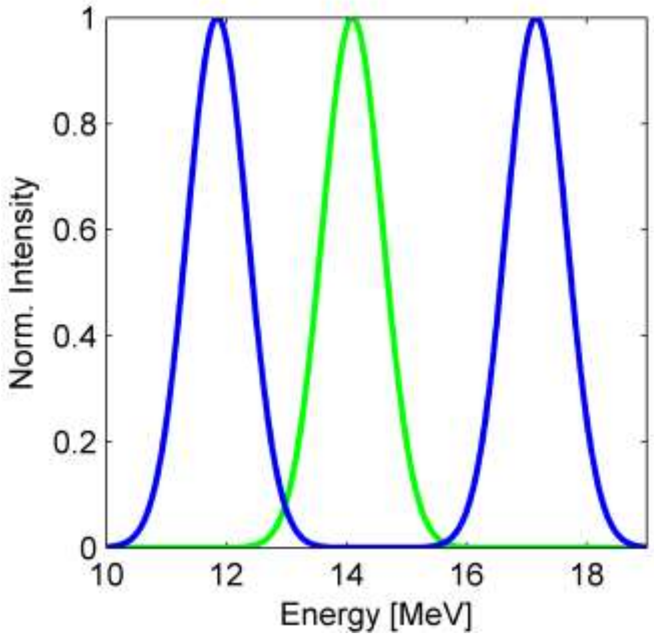

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  - Axial (triton moving towards)
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- Axial detectors will have double peaked structure

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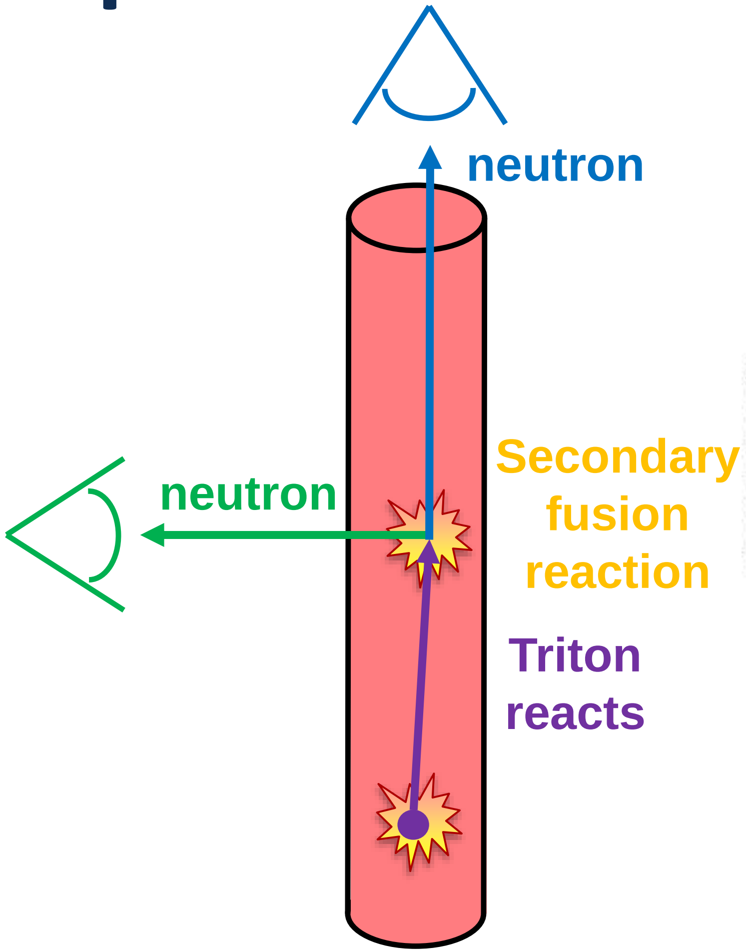

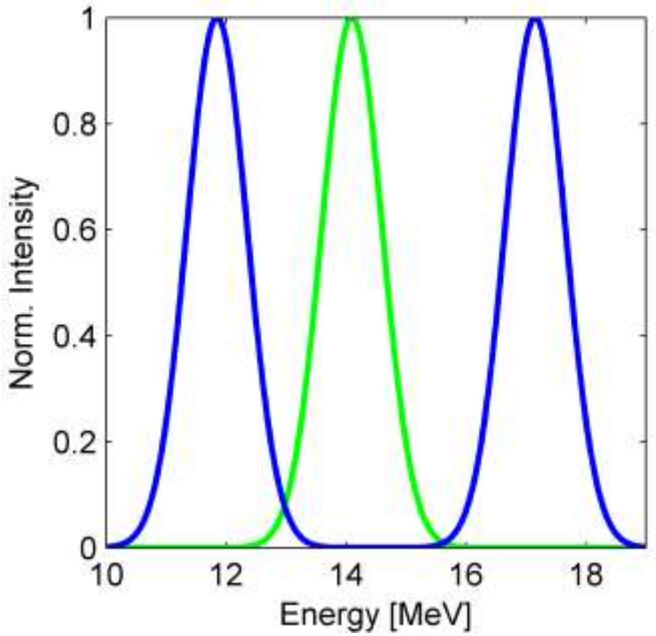

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    - Neutrons at nominal energy
  - Axial (triton moving towards)
    - Neutrons shifted to higher energy
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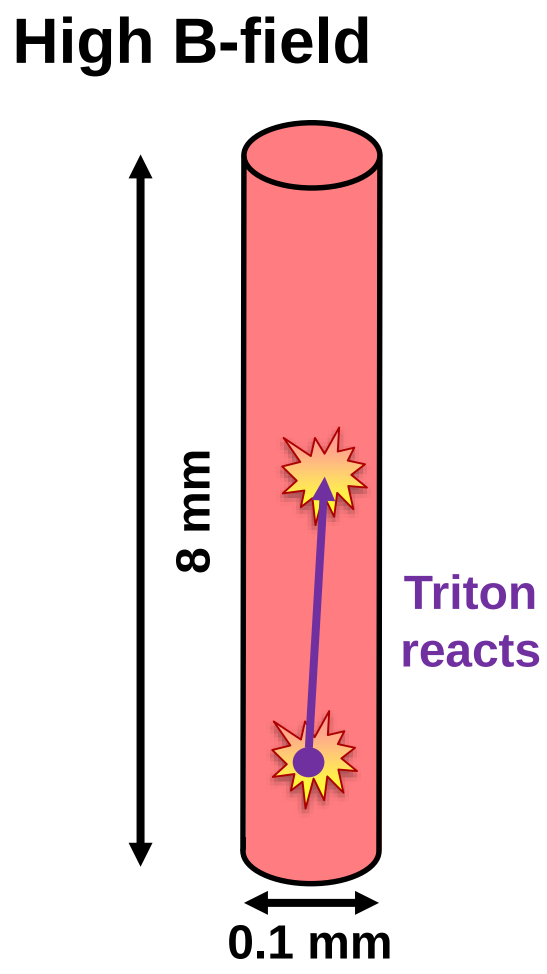
- Axial detectors will have double peaked structure

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).

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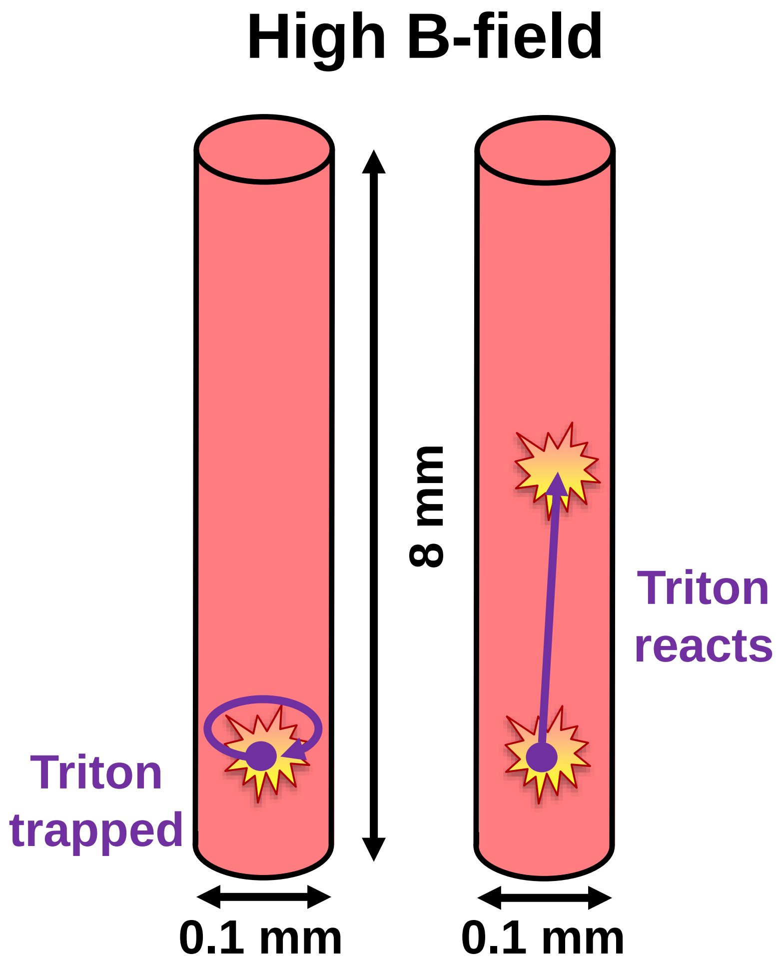
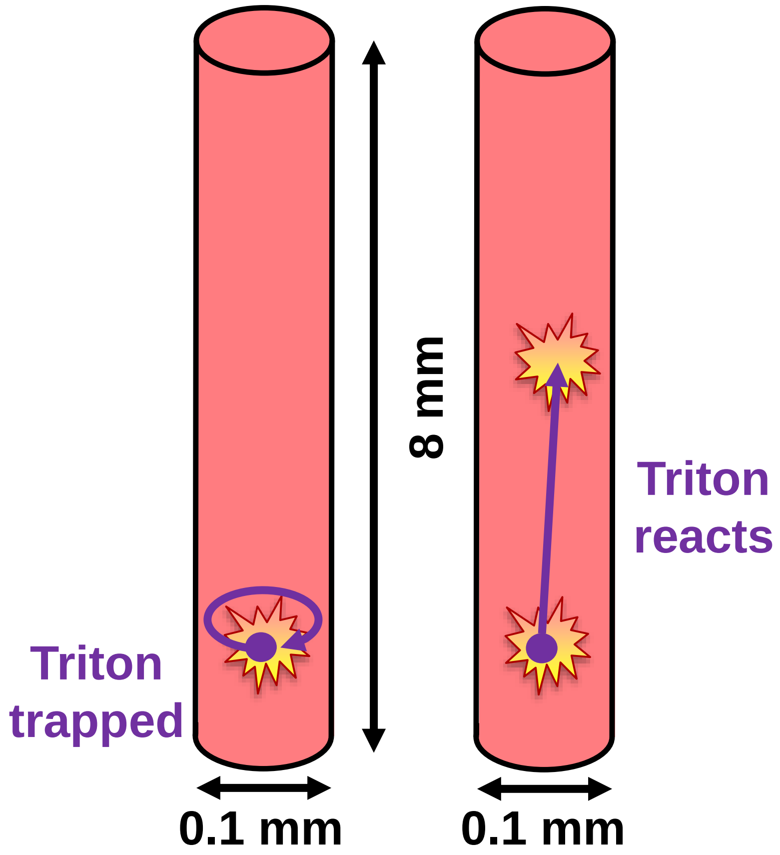


- Consider 2 cases:
  - 1) Triton is created traveling axially
    - Axial field has little impact on trajectory
    - Triton has a high probability of fusion
  - 2) Triton is created traveling radially
    - Axial magnetic field traps triton within fuel volume
    - Triton has a high probability of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

High B-field



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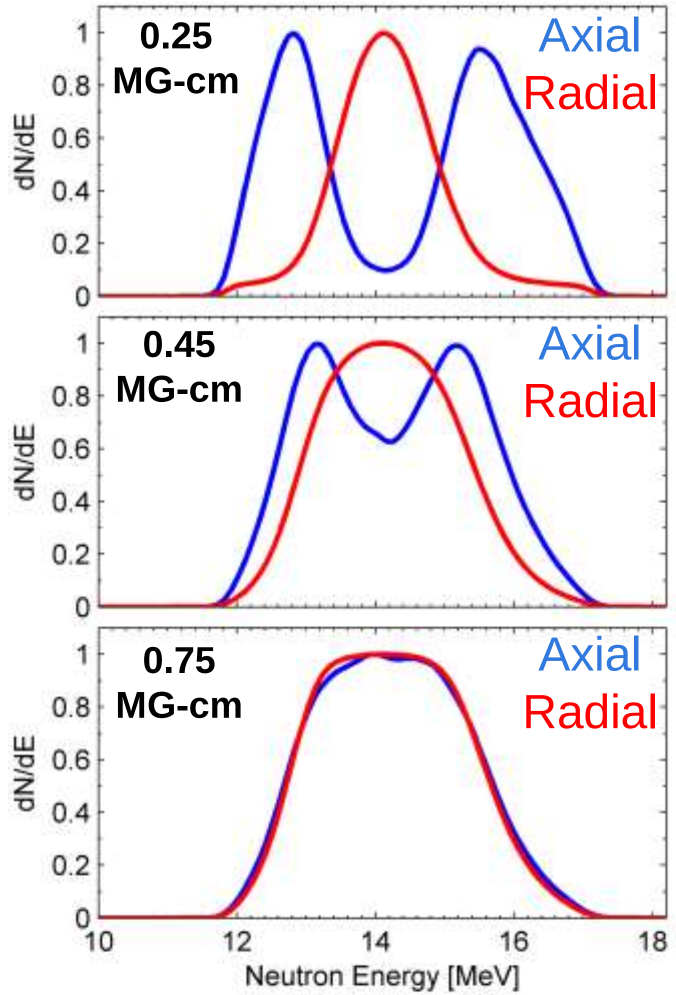
  - 1) Triton is created traveling axially
    - Axial field has little impact on trajectory
    - Triton has a high probability of fusion
  - 2) Triton is created traveling radially
    - Axial magnetic field traps triton within fuel volume
    - Triton has a high probability of fusion

- 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

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).

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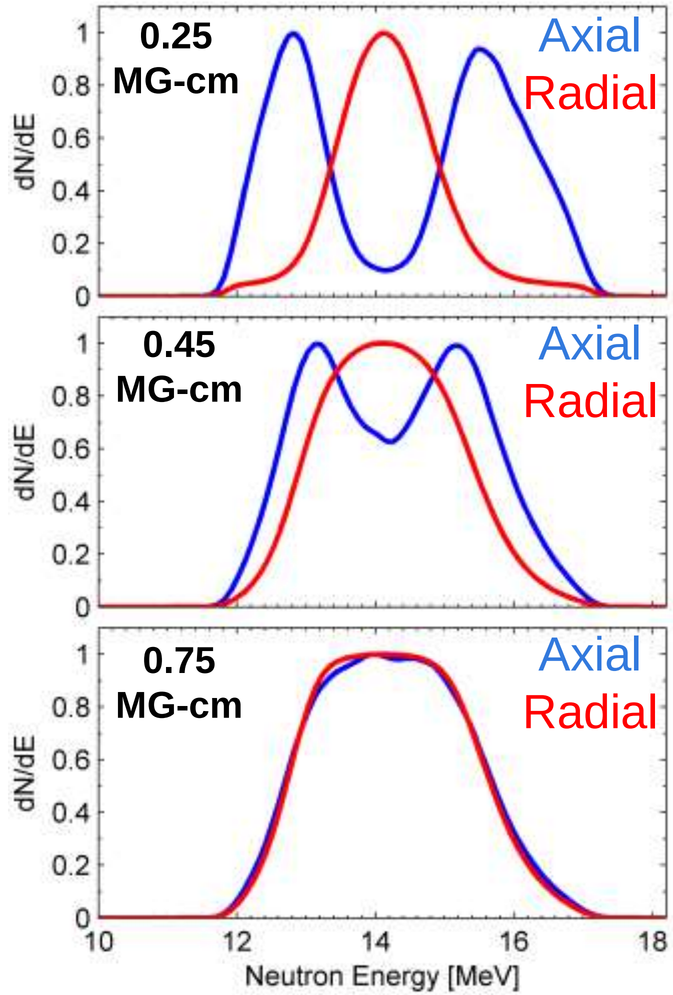

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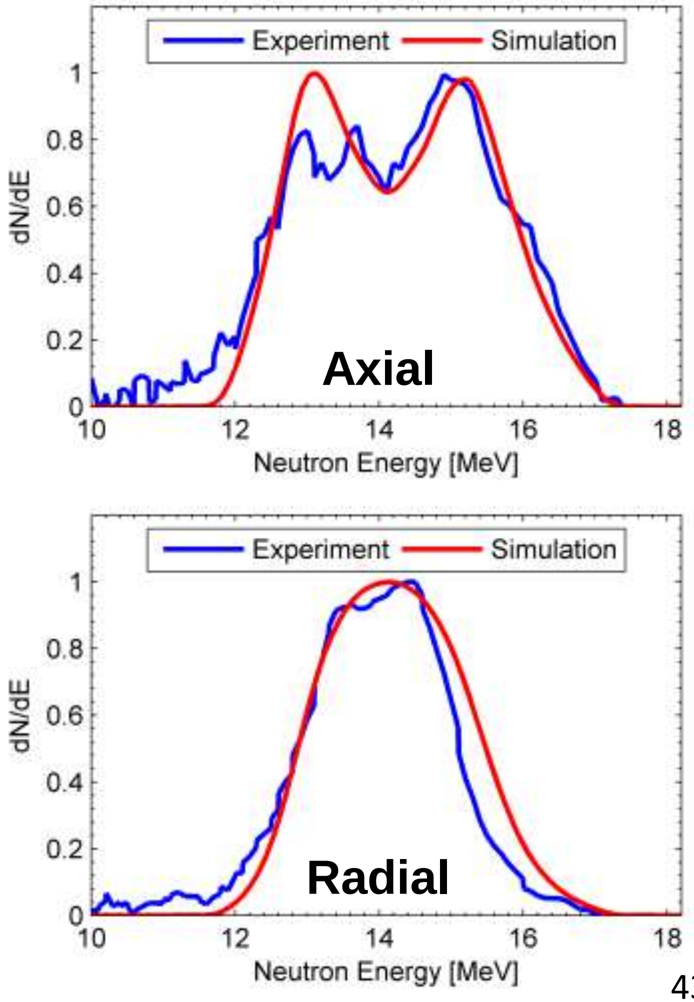
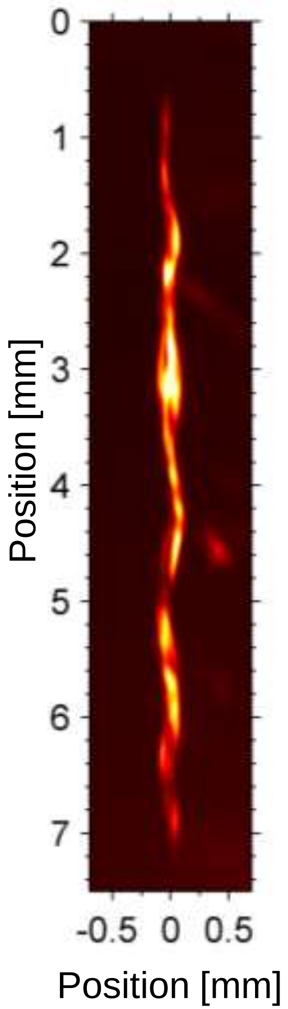
0.34 MG-cm

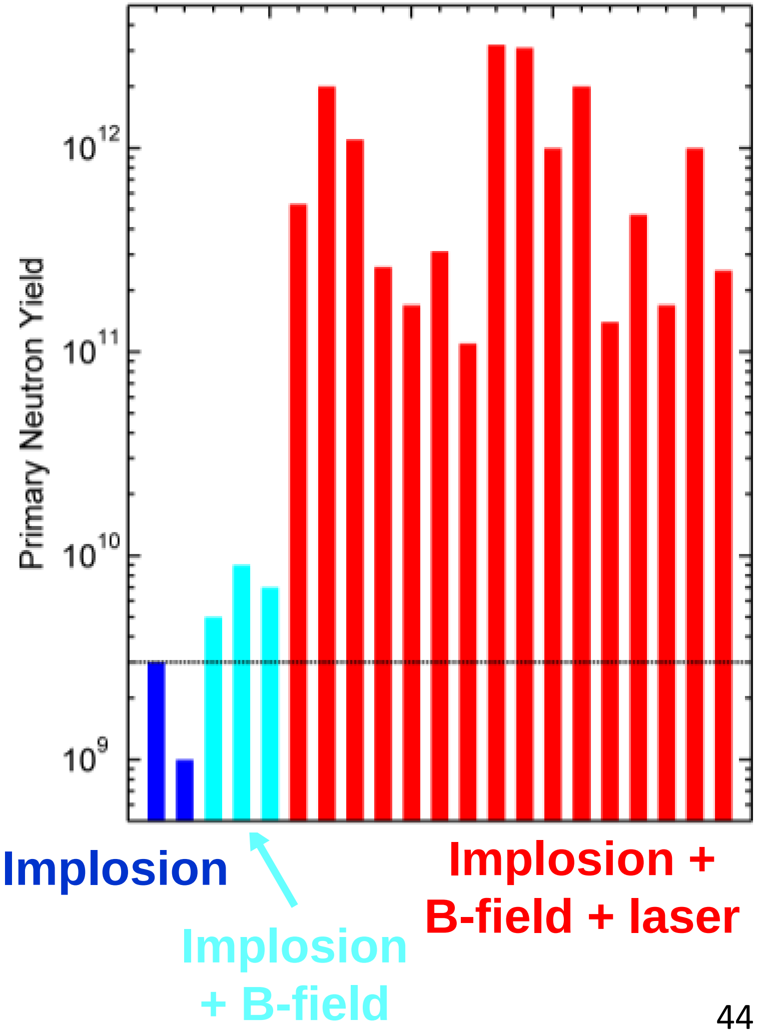


P. F. Schmit, et al., Phys. Rev. Lett. 113, 155004 (2014).

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



- Measured ion temperatures, magnetic fields, and plasma densities are within about a factor of two of our goals for Z
- We have demonstrated up to about 1 kJ of DT-equivalent yield so far
- In order to further improve performance we need to simultaneously increase initial fuel density, applied B-field, laser energy, and drive current

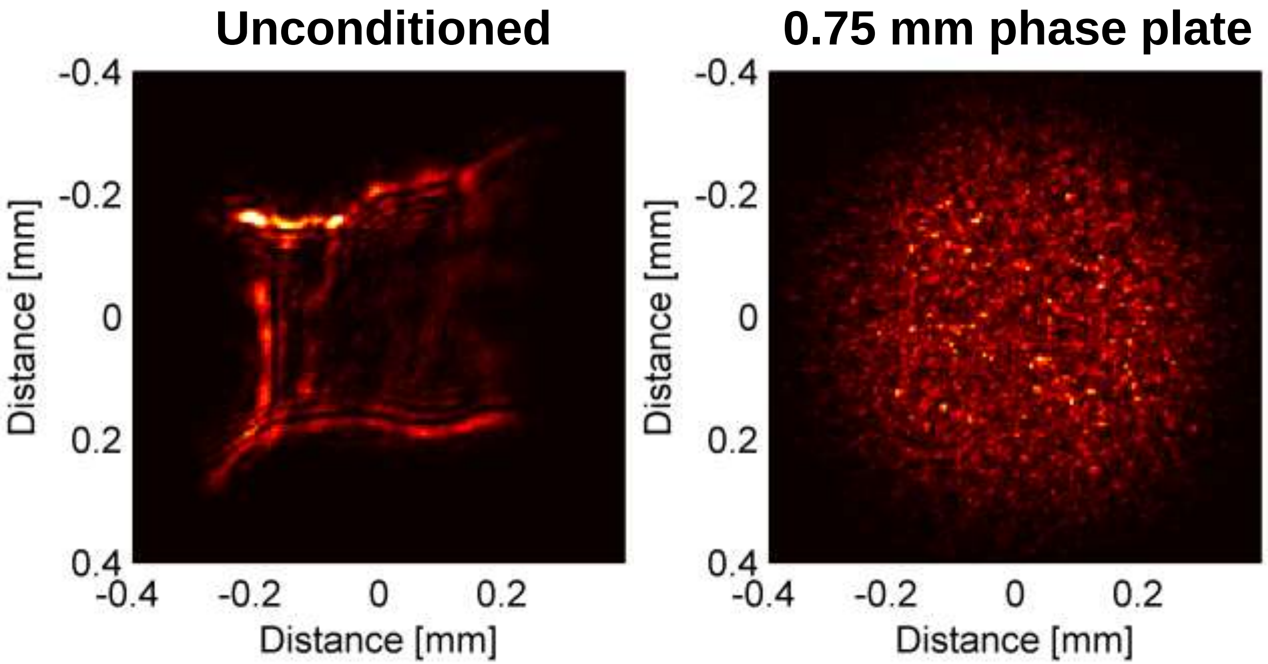


M. R. Gomez, et al., Phys. Rev. Lett. 113, 155003 (2014). P. F. Schmit, et al., Phys. Rev. Lett. 113, 155004 (2014).

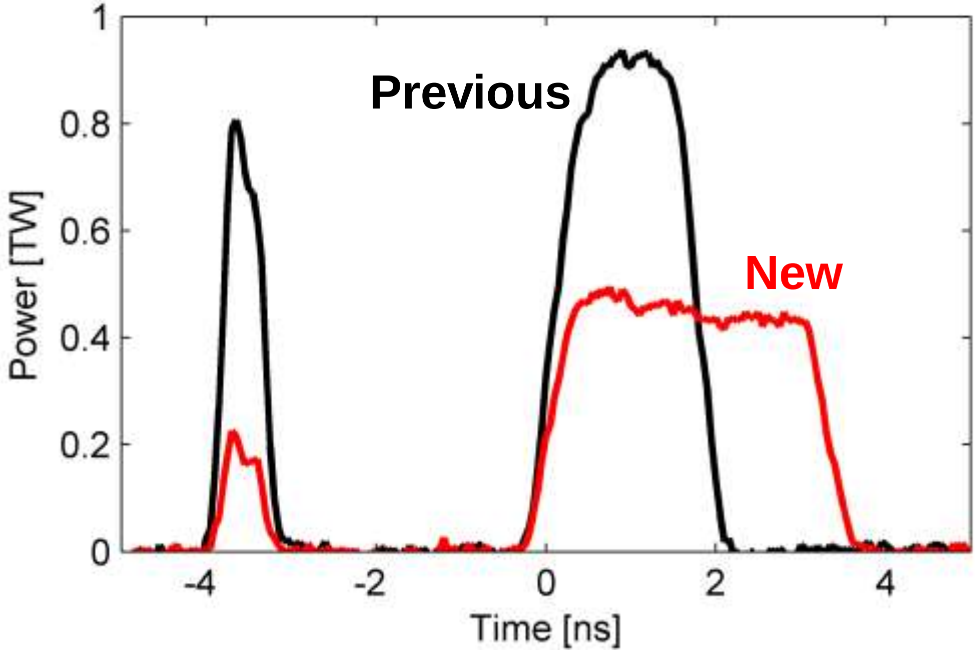
We are developing strategies to improve laser coupling to the fuel

Sandia National Laboratories

We are now testing beam smoothing with phase plates



We reduced laser power while maintaining energy

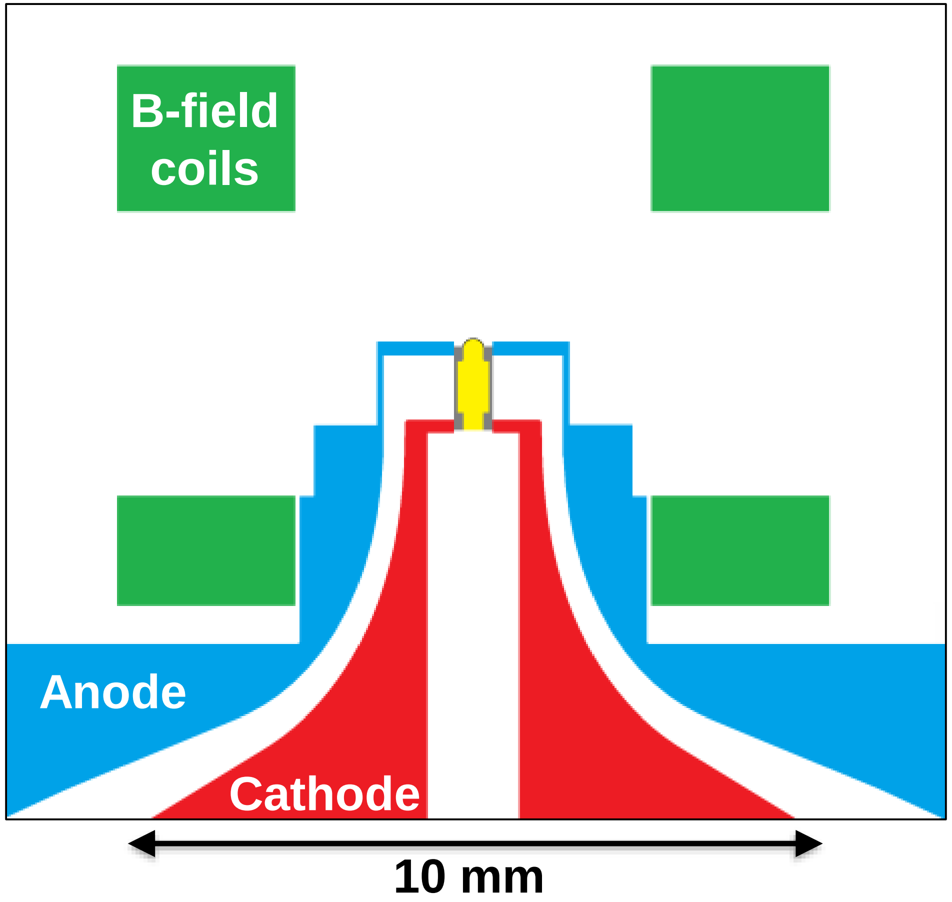


With these changes we reduced the intensity by an order of magnitude, which we expect to reduce the impact of laser plasma instabilities

We have demonstrated increased current delivery with lower inductance designs

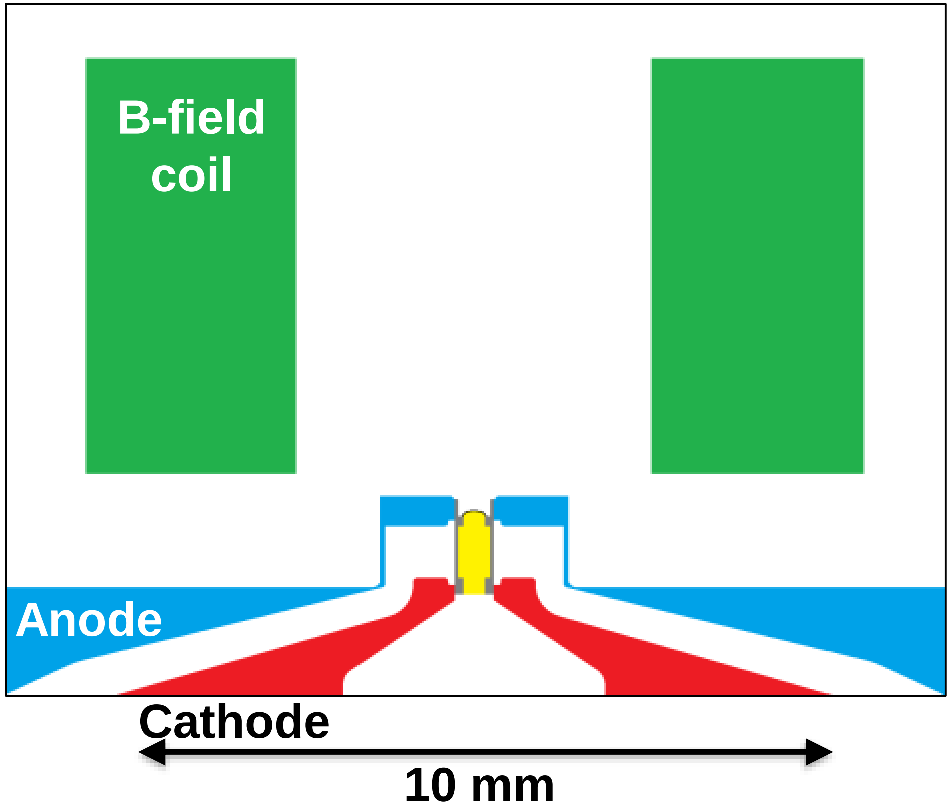
Standard Transmission Line (7 nH)

Peak load current 17 MA

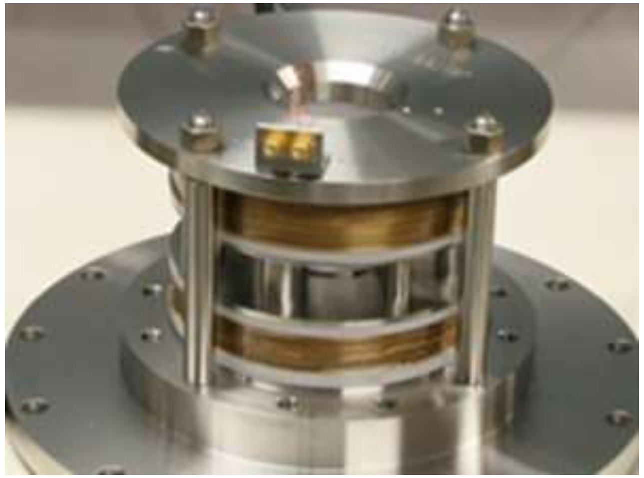


New Transmission Line (4.5 nH)

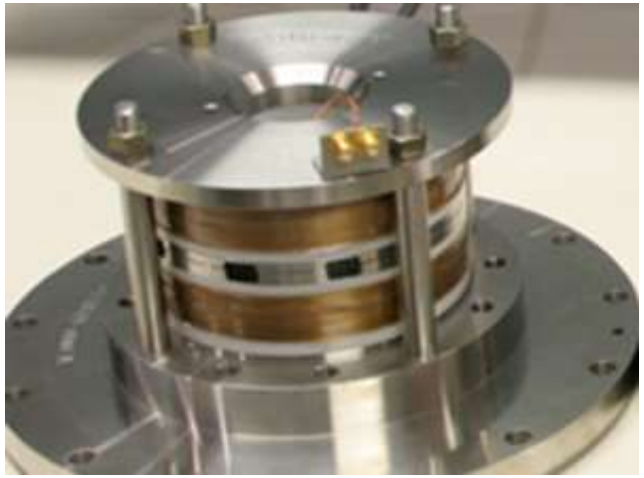
Peak load current ~20 MA



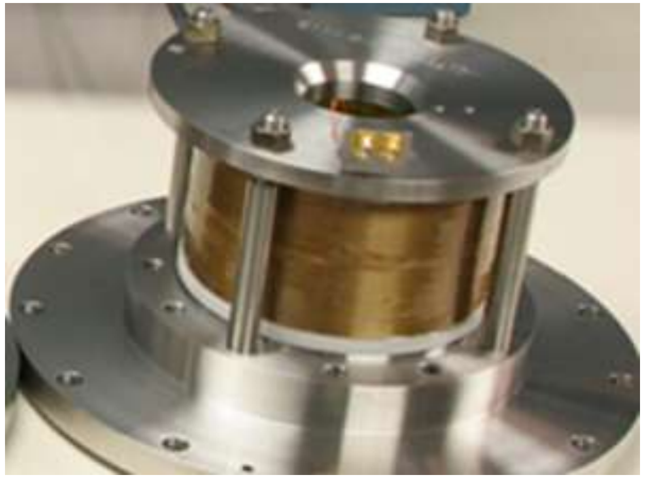
Increasing the axial magnetic field is straight forward, but limits diagnostic access



10 T



15-20 T



25-30 T

- We currently operate at 10 T
- We have designs that allow up to 20 T with limited diagnostics and up to 30 T with no x-ray access
- We are pursuing designs that increase the field without reducing access
  - Pushes the limit of coil technology

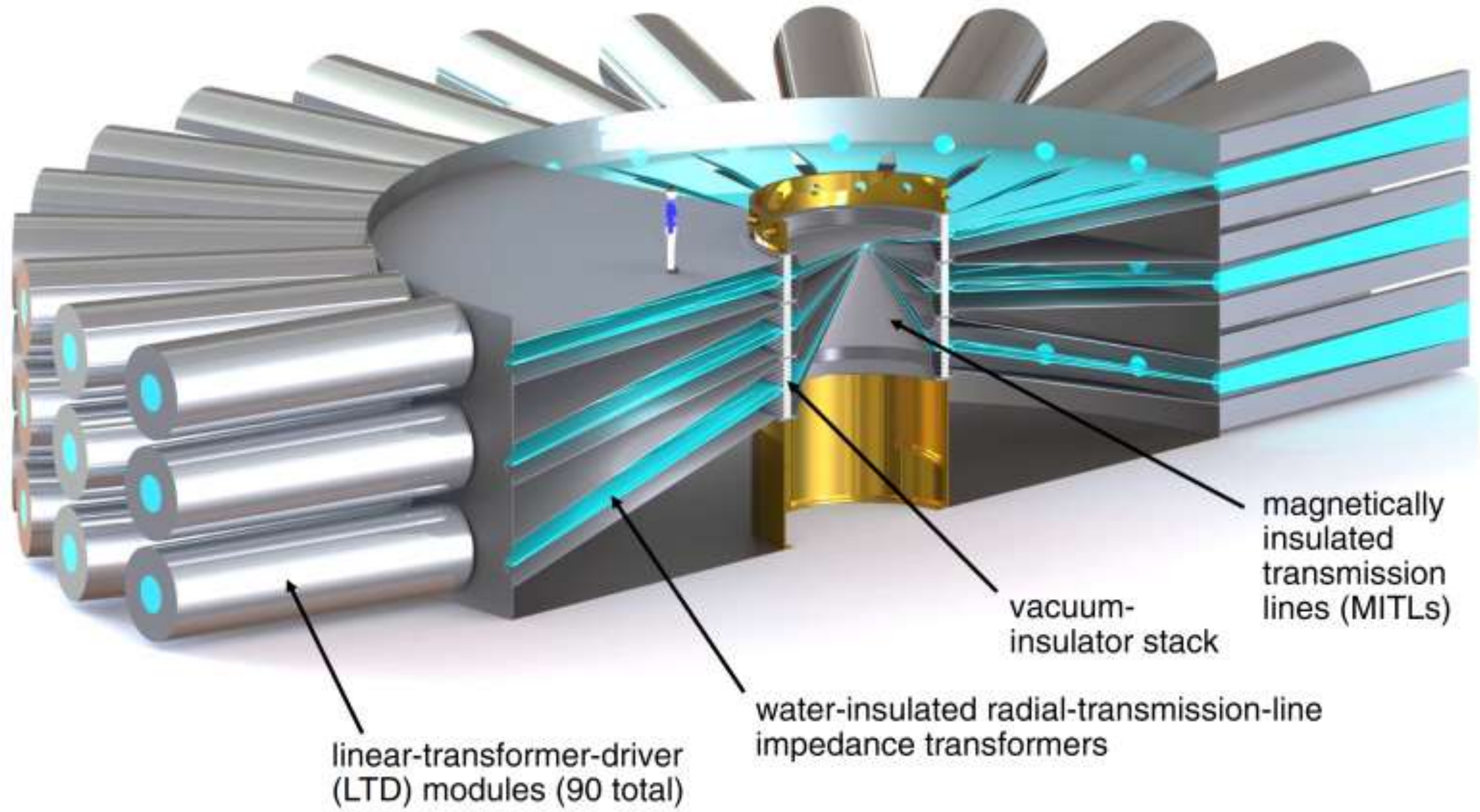
D. C. Rovang, et al., Rev. Sci. Instrum. 85, 124701 (2014).

We need increased fuel density, laser energy, and B-field to take advantage of higher current

- Our standard capability is 10 T, 0.5-1 kJ, and 16-18 MA
  - We are targeting 15-20 T, 1-2 kJ, and 19-20 MA in the near term
  - We would like to reach 20-30 T, 2-4 kJ, and 20-22 MA by 2020
- New coil designs should enable magnetic fields 18-26 T that are compatible with low inductance inner-MITL configurations
- New laser heating configurations with beam smoothing have demonstrated an increase in stagnation performance
- Experiments that combine increased magnetic field, laser energy, and current are planned for later this year

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

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).