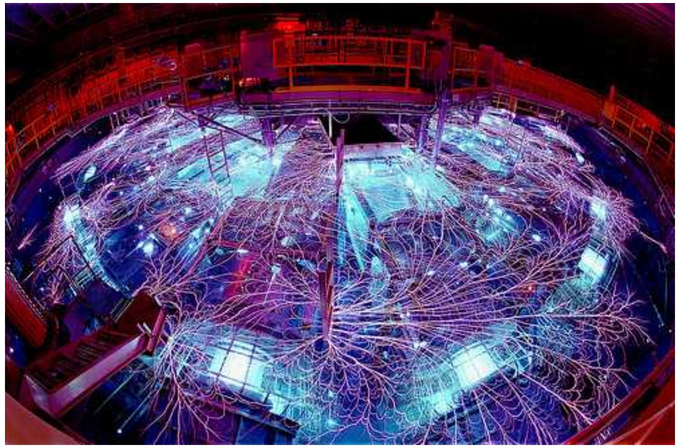
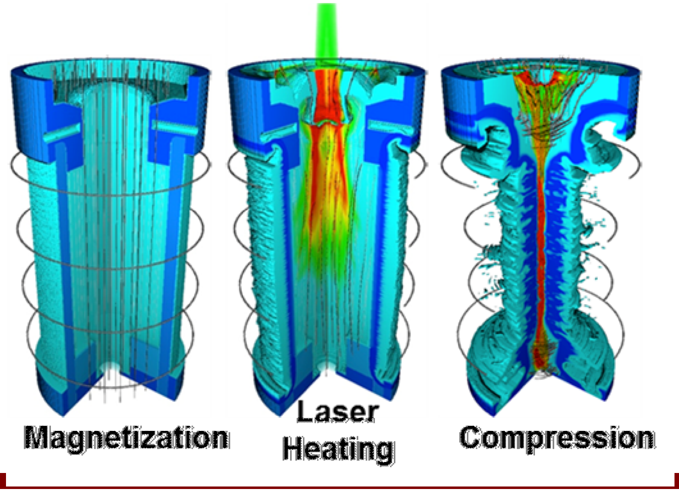
SAND2017-1838PE





Pulsed-Power-Driven Magneto-Inertial Fusion Research on the Z Facility

Matthew R. Gomez

Radiation and Fusion Experiments Department

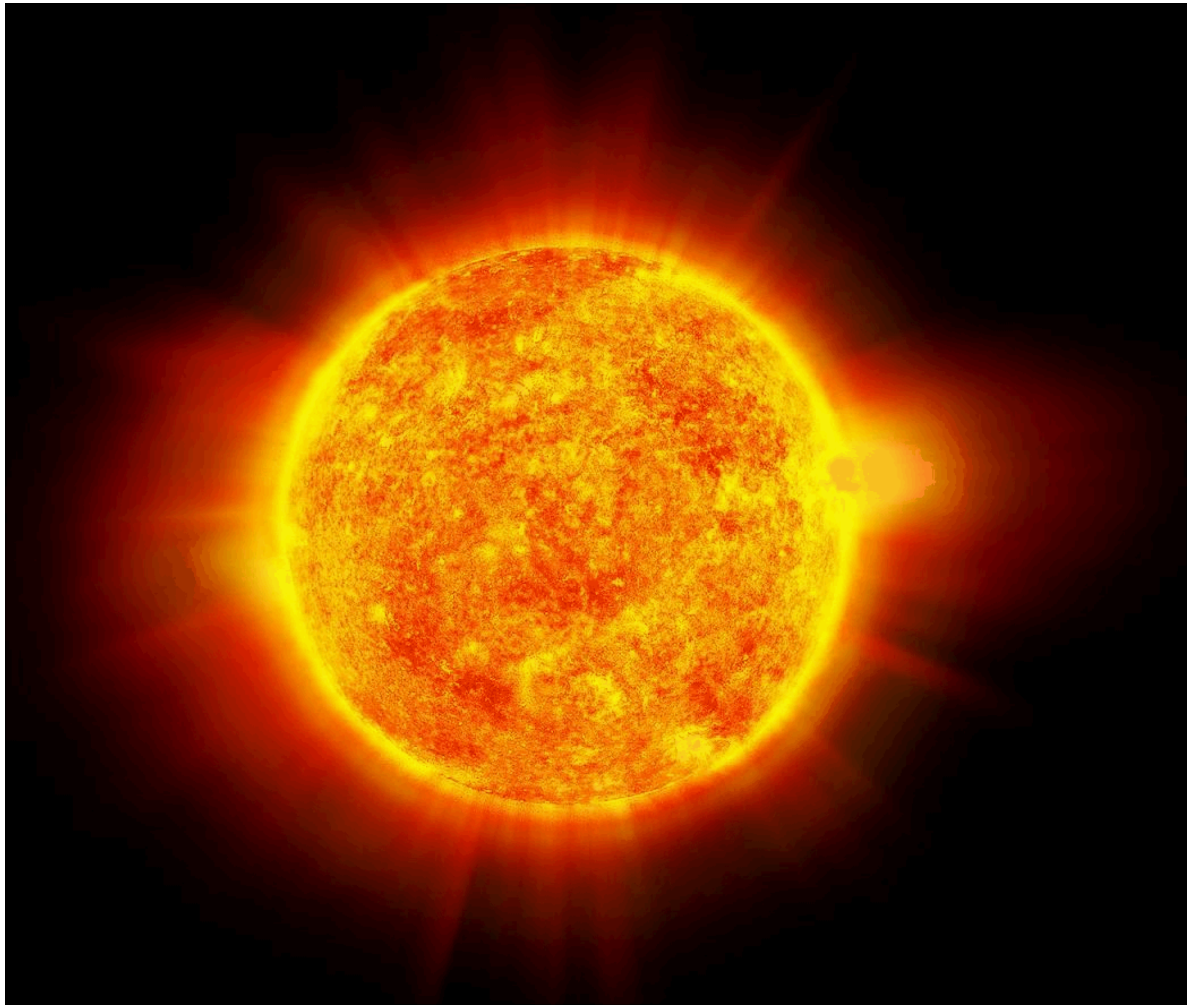
Sandia National Laboratories

Seminar at the University of California – Los Angeles,

January 12, 2017

Sandia National Laboratories is a multi-program laboratory managed and operated by Sandia Corporation, a wholly owned subsidiary of Lockheed Martin Corporation, for the U.S. Department of Energy's National Nuclear Security Administration under contract DE-AC04-94AL85000.

Thermonuclear fusion powers the stars…



- Gravitational confinement is clearly very effective but what can we do on Earth?
- Magnetic confinement has been studied since around 1950
  - Currently the flagship project is ITER
- Inertial confinement has been associated with lasers for over 50 years
  - The flagship facility is the NIF
- We have made steady progress in both MCF and ICF over the last half-century

Magnetic confinement fusion utilizes magnetic fields hold a plasma while fusion reactions occur

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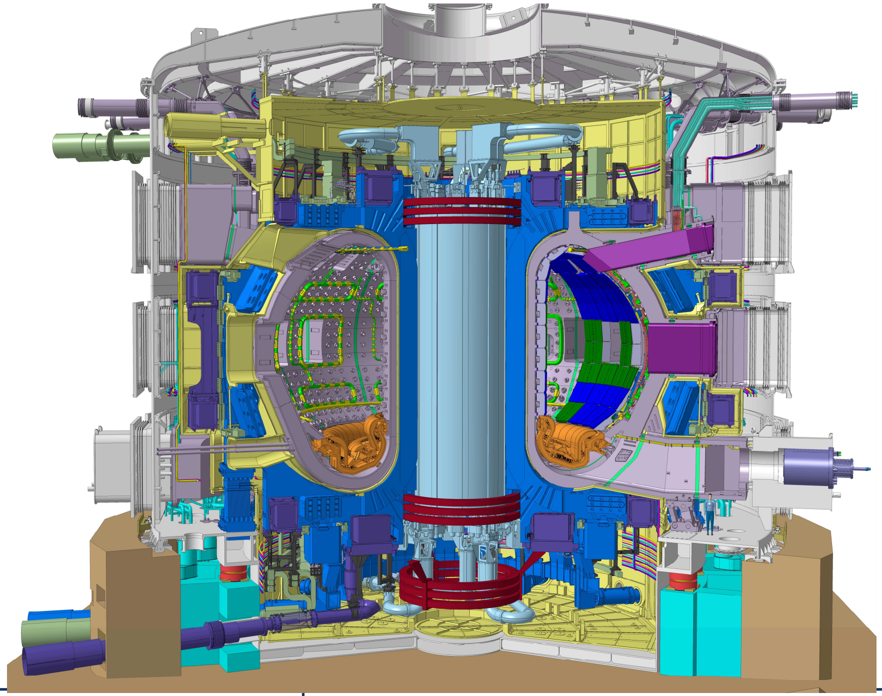
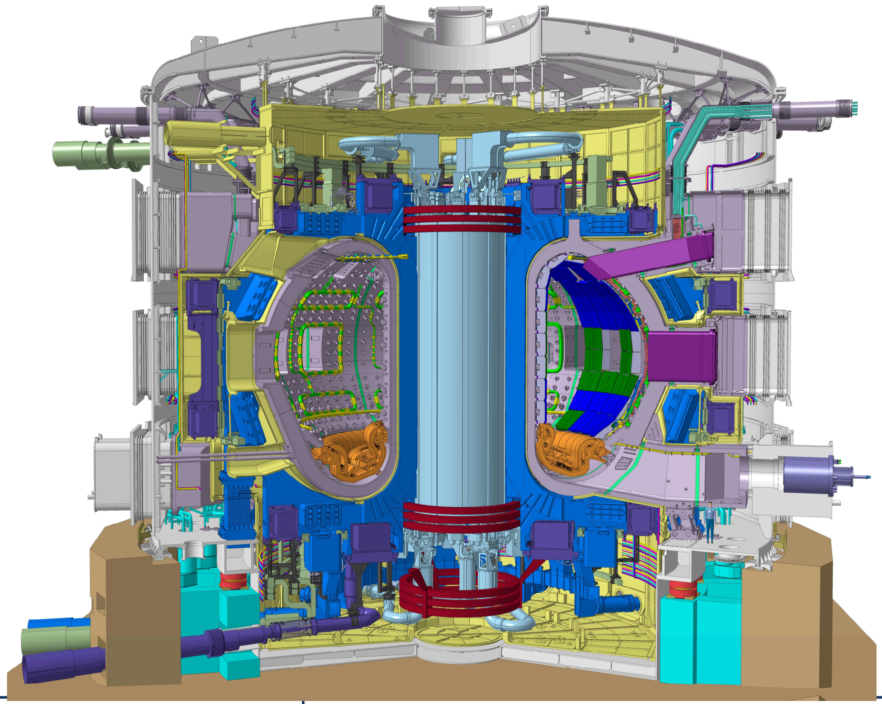
ITER



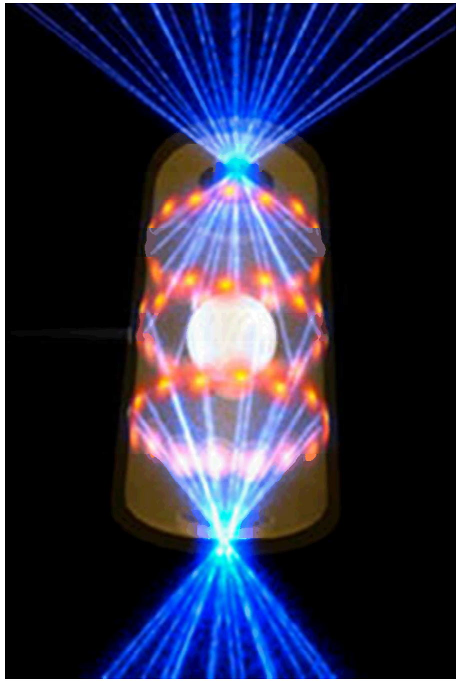
Density	1×10^{14} cm^{-3}		
Volume	8×10^{8} cm^{3}		
Duration	300-500 s		
Magnetic field	100 kG		

Inertial confinement fusion relies on sufficient fusion reactions occurring prior to falling apart

ITER



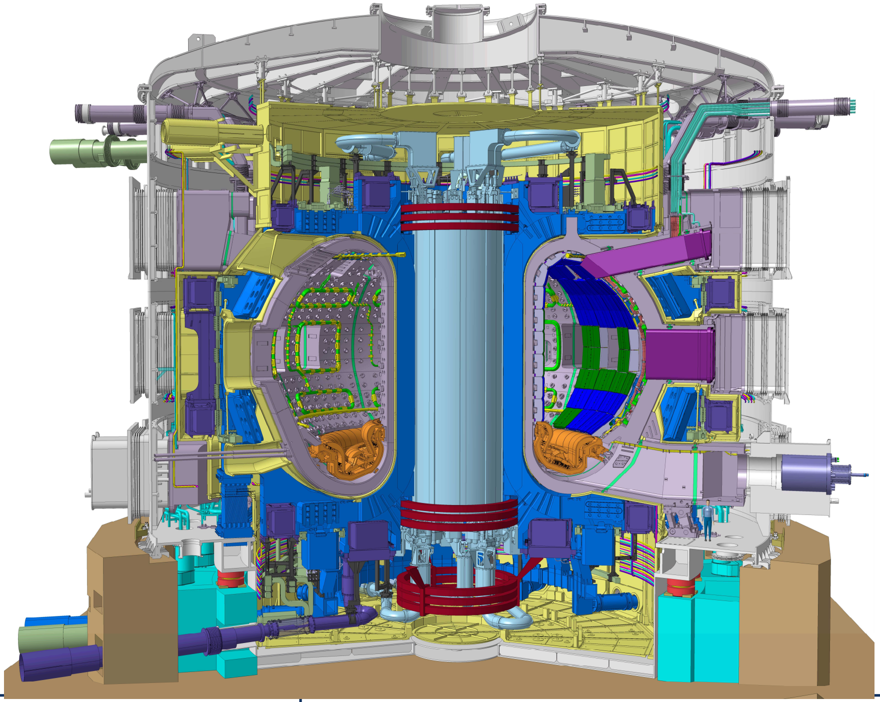
NIF hohlraum



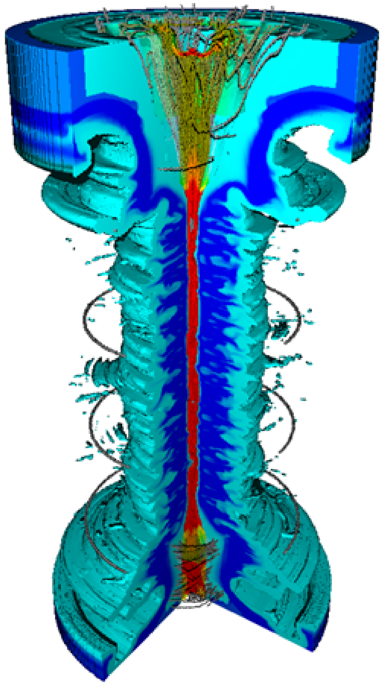
Density	1 x 10^{14} cm^{-3}		2-20 x 10^{25} cm^{-3}
Volume	8 x 10^{8} cm^{3}		6 x 10^{-8} cm^{3}
Duration	300-500 s		5-10 x 10^{-11} s
Magnetic field	100 kG		0 kG

Magneto-inertial fusion sits in the space between magnetic and inertial confinement fusion

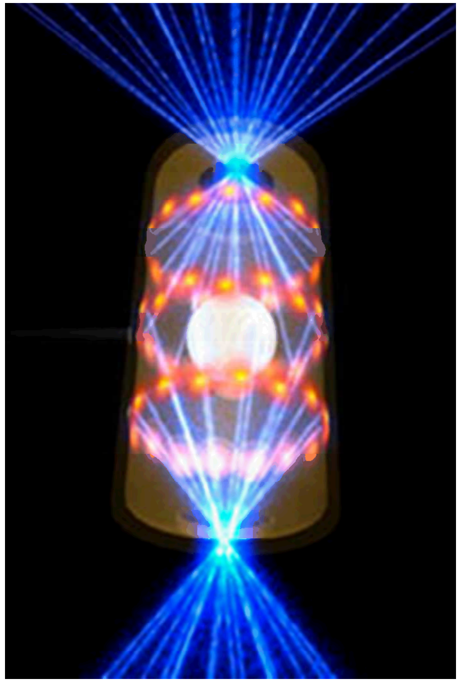
ITER



MIF concept



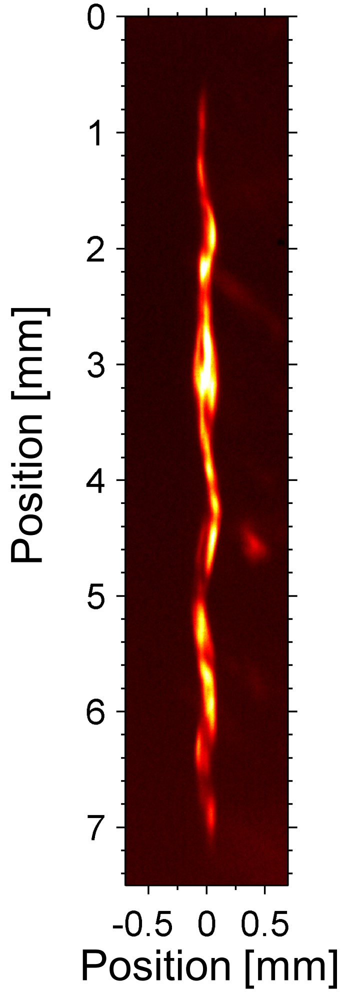
NIF hohlraum



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

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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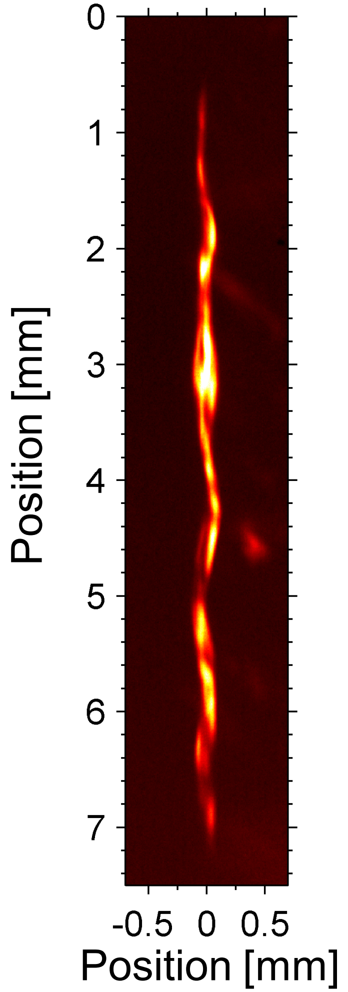
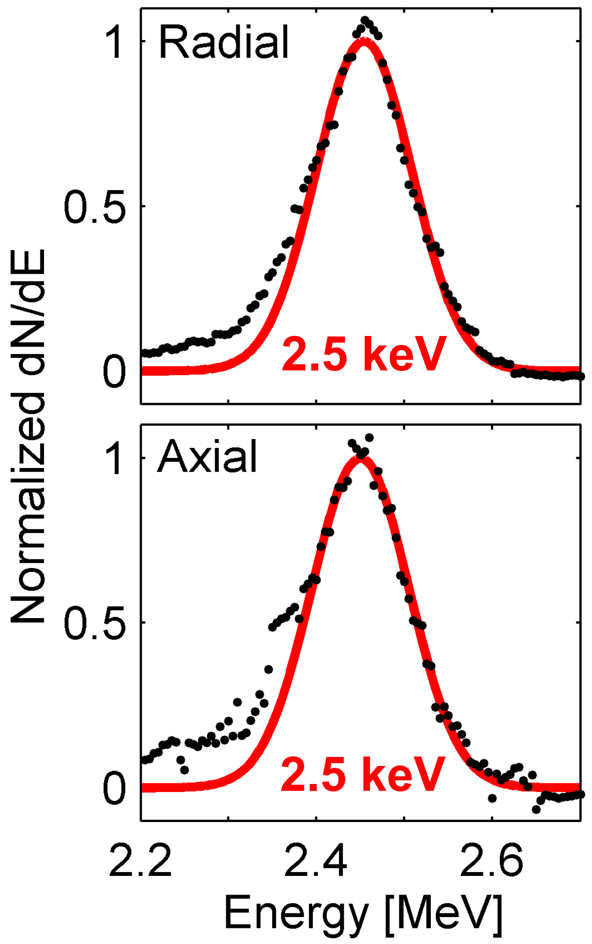


Relevant temperatures



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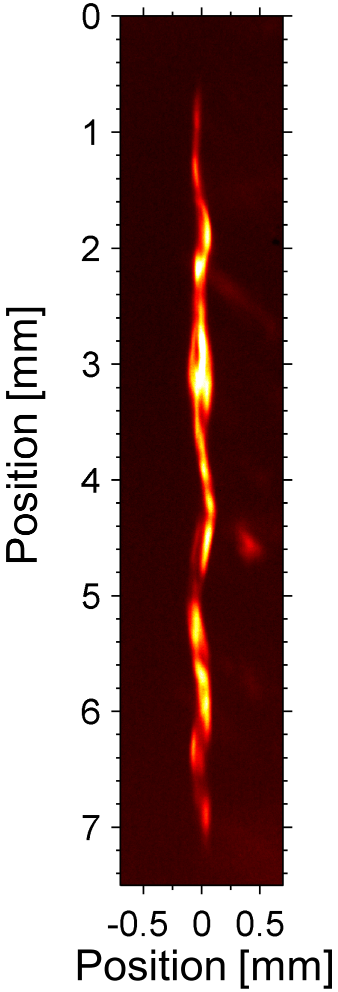
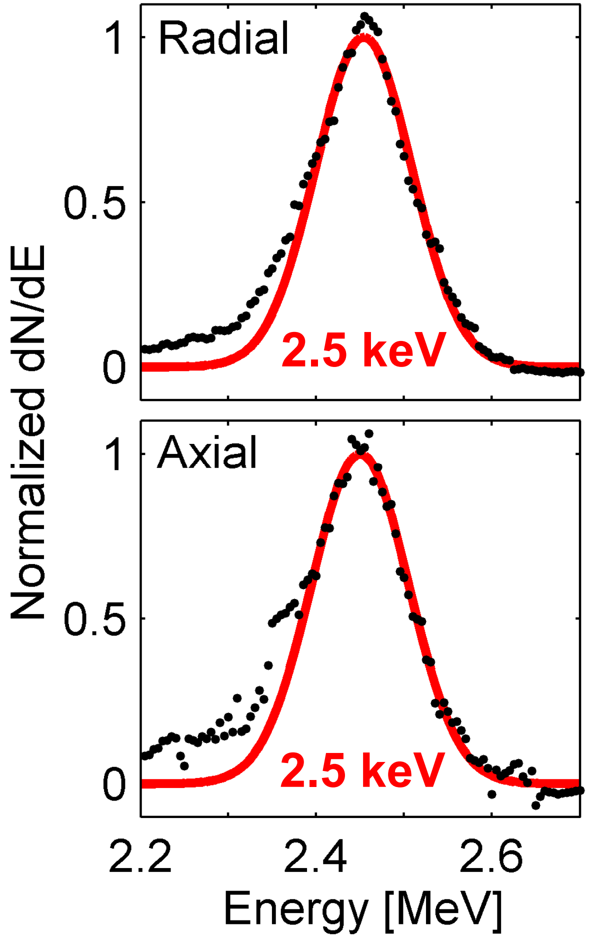
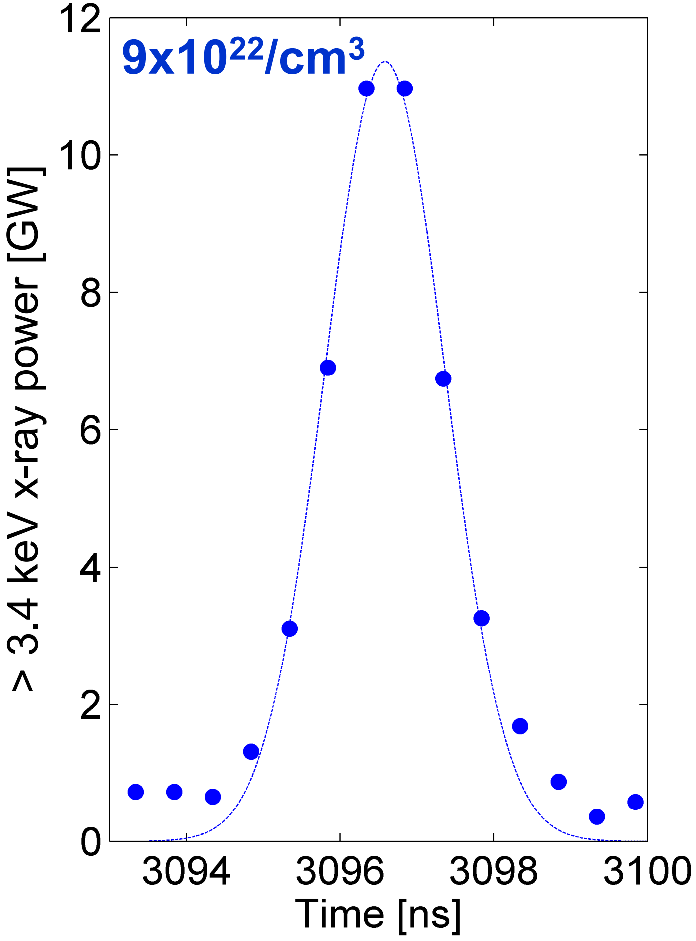
Well-behaved stagnation volume



Relevant temperatures



Relevant densities



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

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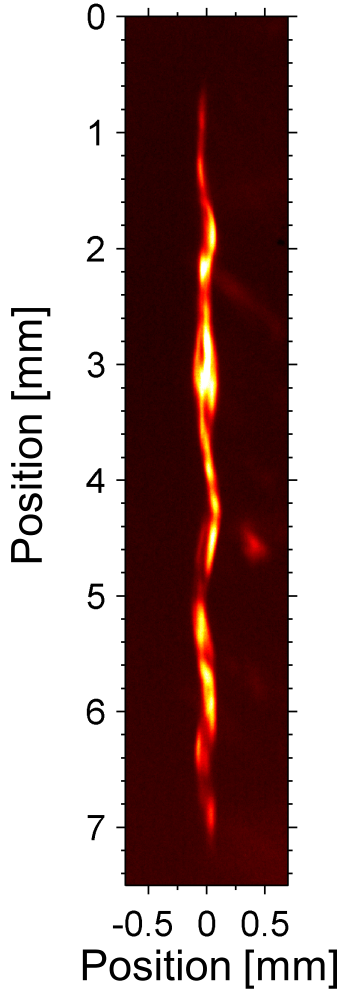
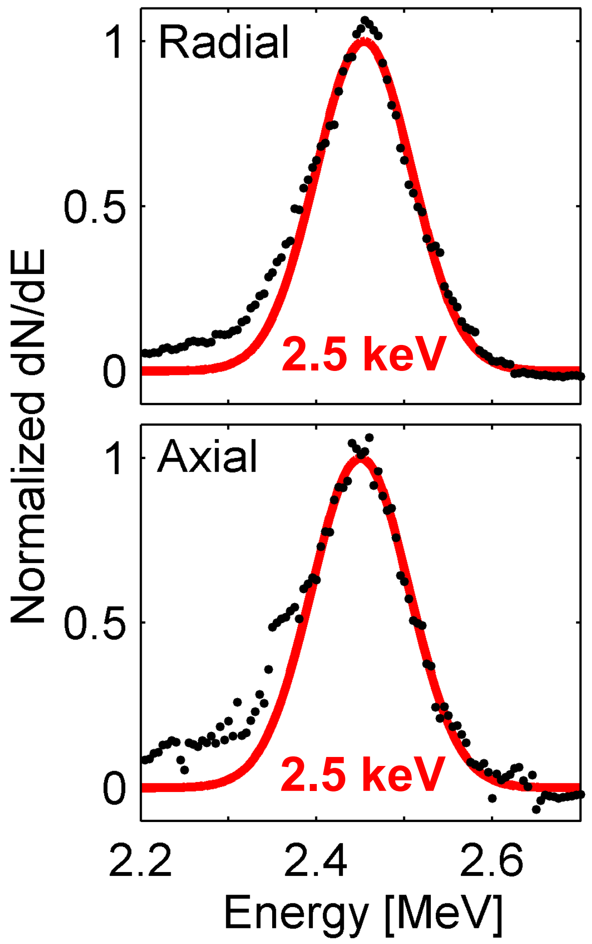
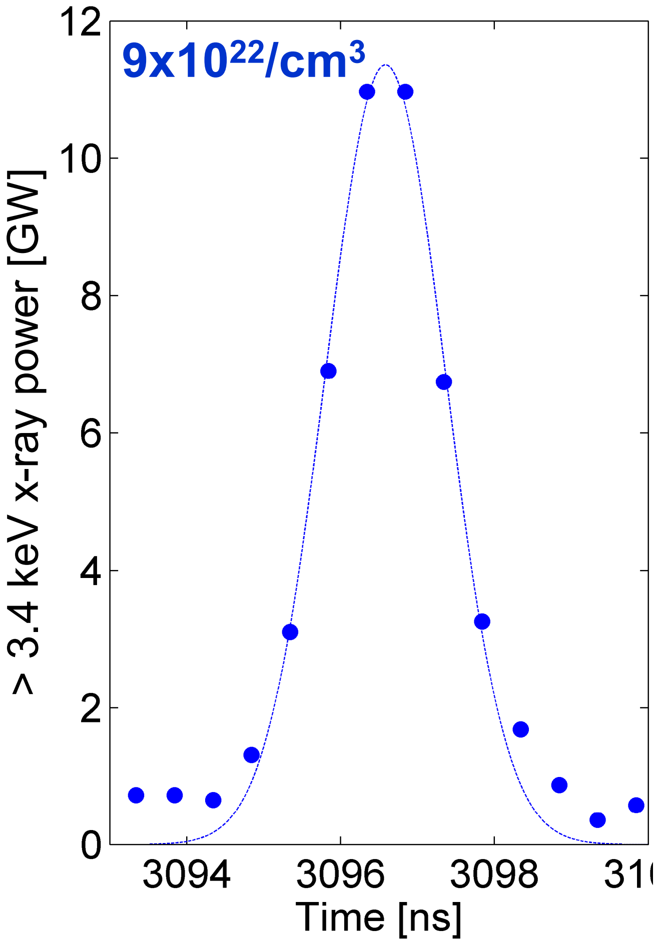


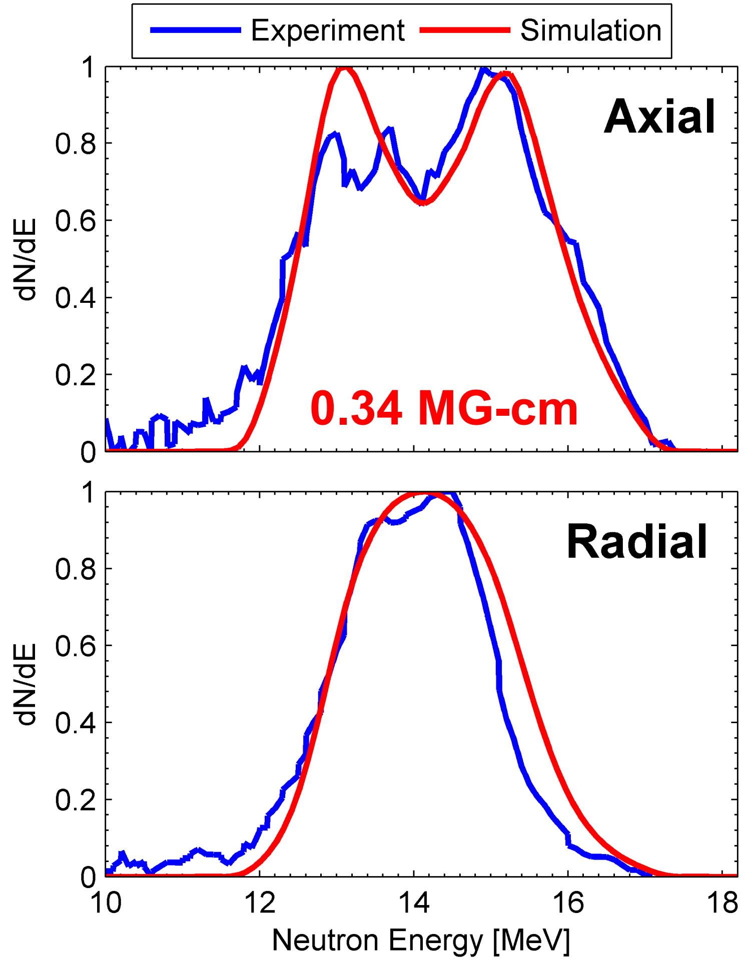
Relevant temperatures



Relevant densities



Relevant B-fields

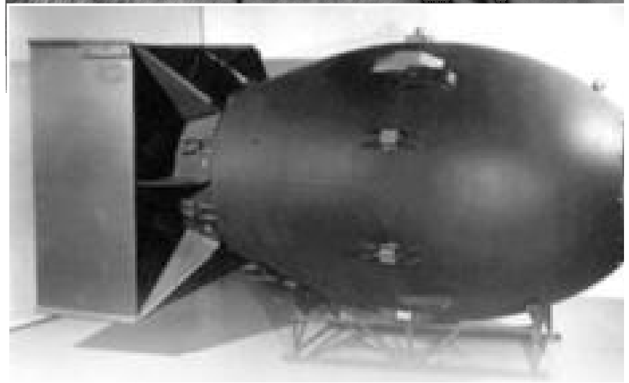


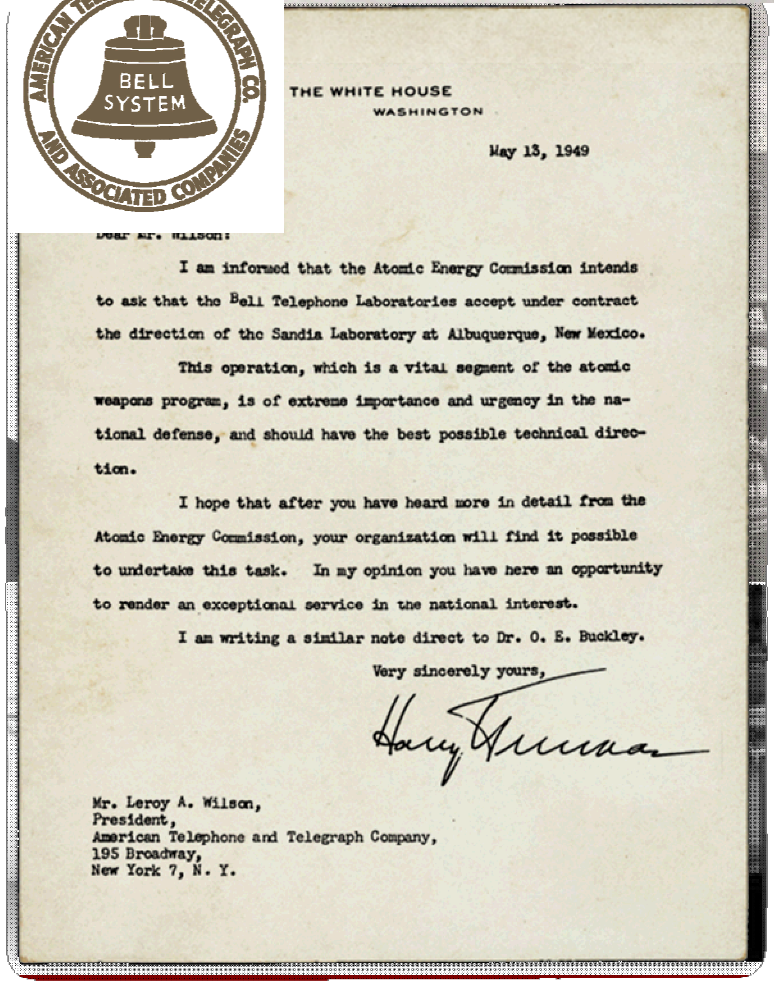
P. F. Schmit, et al., Phys. Rev. Lett. 113, 155004 (2014).

Sandia National Laboratories' history dates back to World War 2

Sandia National Laboratories

Exceptional service in the national interest





THE WHITE HOUSE
WASHINGTON

May 13, 1949

Dear Mr. Wilson:

I am informed that the Atomic Energy Commission intends to ask that the Bell Telephone Laboratories accept under contract the direction of the Sandia Laboratory at Albuquerque, New Mexico.

This operation, which is a vital segment of the atomic weapons program, is of extreme importance and urgency in the national defense, and should have the best possible technical direction.

I hope that after you have heard more in detail from the Atomic Energy Commission, your organization will find it possible to undertake this task. In my opinion you have here an opportunity to render an exceptional service in the national interest.

I am writing a similar note direct to Dr. O. E. Buckley.

Very sincerely yours,

Harry Truman

Mr. Leroy A. Wilson,
President,
American Telephone and Telegraph Company,
195 Broadway,
New York 7, N. Y.

- **July 1945:** Los Alamos creates Z Division
  - Nonnuclear component engineering
- **November 1, 1949:** Sandia Laboratory established
- **1949–1993:** AT&T
- **1995–2017:** Lockheed Martin Corporation
- **2017-Beyond:** Honeywell Corporation

Sandia has sites across the United States, but the majority of its employees are located in NM

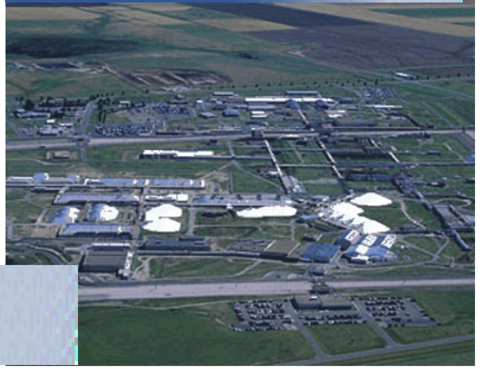
Albuquerque, New Mexico

Livermore, California

Kauai, Hawaii

Waste Isolation Pilot Plant, Carlsbad, New Mexico

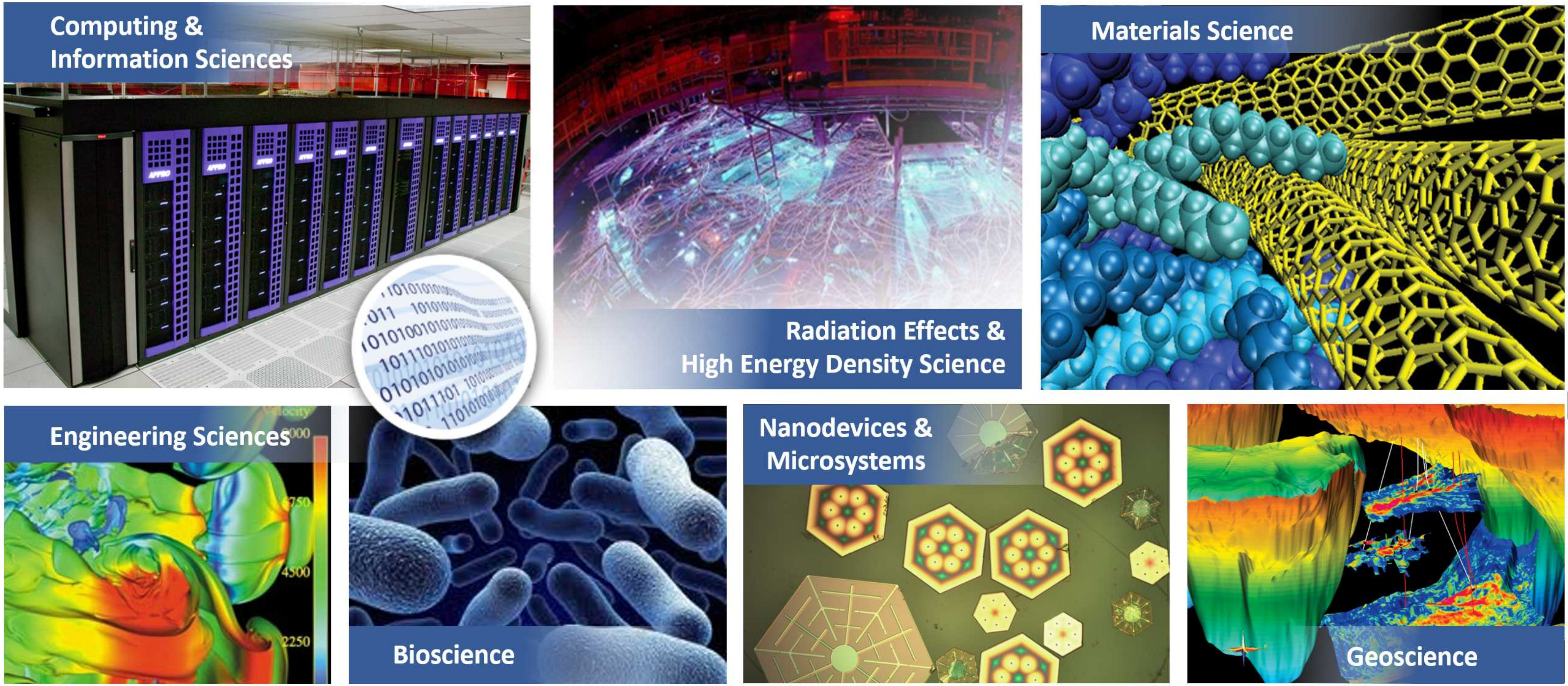
Pantex Plant, Amarillo, Texas



Tonopah, Nevada

Sandia has "Research Foundations" that span a wide range of science and engineering

Sandia National Laboratories



Matter in the High Energy Density state has an energy density equivalent to at least 1 Mbar

- High energy density matter is in a state well outside of what we normally experience

- 1 Mbar > 10^6 atmospheres

- 1 Mbar = 100 kJ/cm^3

Matter in the High Energy Density state has an energy density equivalent to at least 1 Mbar

1 Mbar = 100 kJ/cm^3

- A Toyota 4runner weighs about 4600 lbs
- Traveling at 70 MPH it has a kinetic energy of ~ 1 MJ
- Its volume is ~ 10 million cm^3
- Energy density ~ 0.1 J/cm^3

Matter in the High Energy Density state has an energy density equivalent to at least 1 Mbar

1 Mbar = 100 kJ/cm^3

- A baseball weighs 0.145 kg
- Traveling at 100 mph it has a kinetic energy of ~ 150 J
- Its volume is ~ 200 cm^3
- Energy density ~ 1 J/cm^3

Matter in the High Energy Density state has an energy density equivalent to at least 1 Mbar

Sandia National Laboratories

1 Mbar = 100 kJ/cm^3

- Burning a match releases about 1 kJ of energy
- The volume of a match is ~ 0.33 cm^3
- Energy density ~ 3 kJ/cm^3

Matter in the High Energy Density state has an energy density equivalent to at least 1 Mbar

1 Mbar = 100 kJ/cm^3

- A stick of dynamite has a stored energy of about 1-2 MJ
- A stick of dynamite is 20 cm long and 3.2 cm in diameter
  - Volume = 161 cm^3
- Energy density ~10 kJ/cm^3

The HED regime is beyond what we normally experience, but common in the universe

HED regime

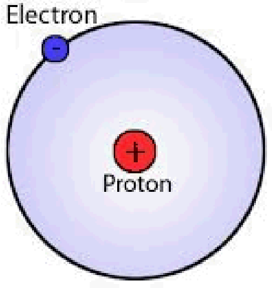
Baseball

10^{-5} Mbar

Dynamite

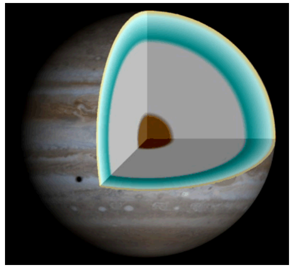
0.1 Mbar

Internal Energy of H atom



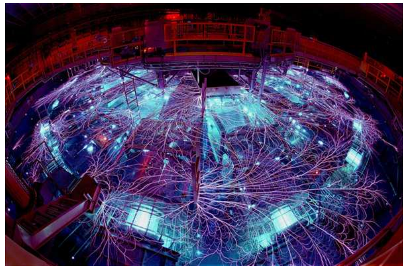
1 Mbar

Metallic H in Jupiter's core



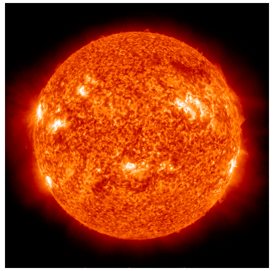
30 Mbar

Z Machine magnetic pressure



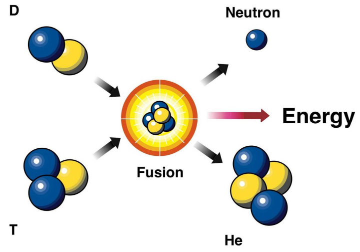
100 Mbar

Center of Sun



250,000 Mbar

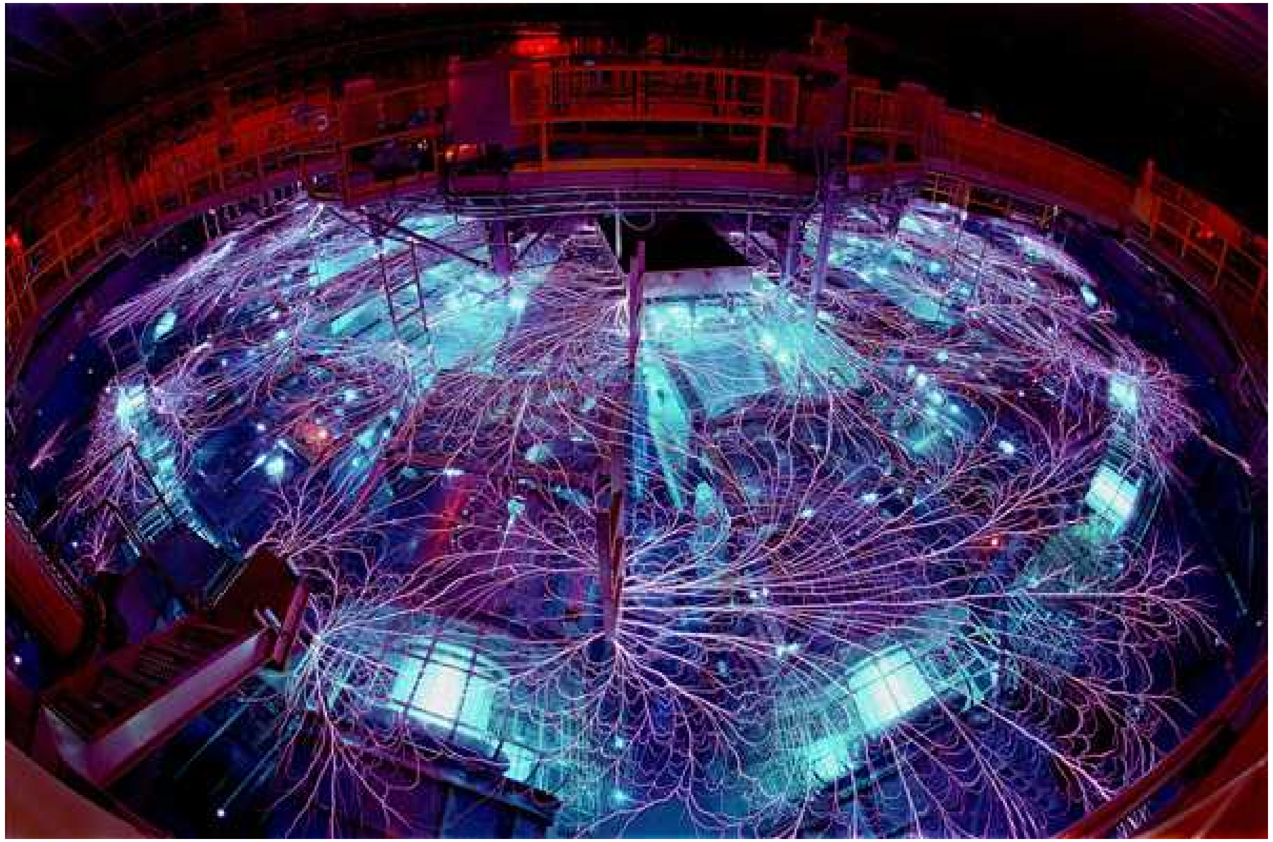
Burning ICF plasma



800,000 Mbar

Z can access the HED regime

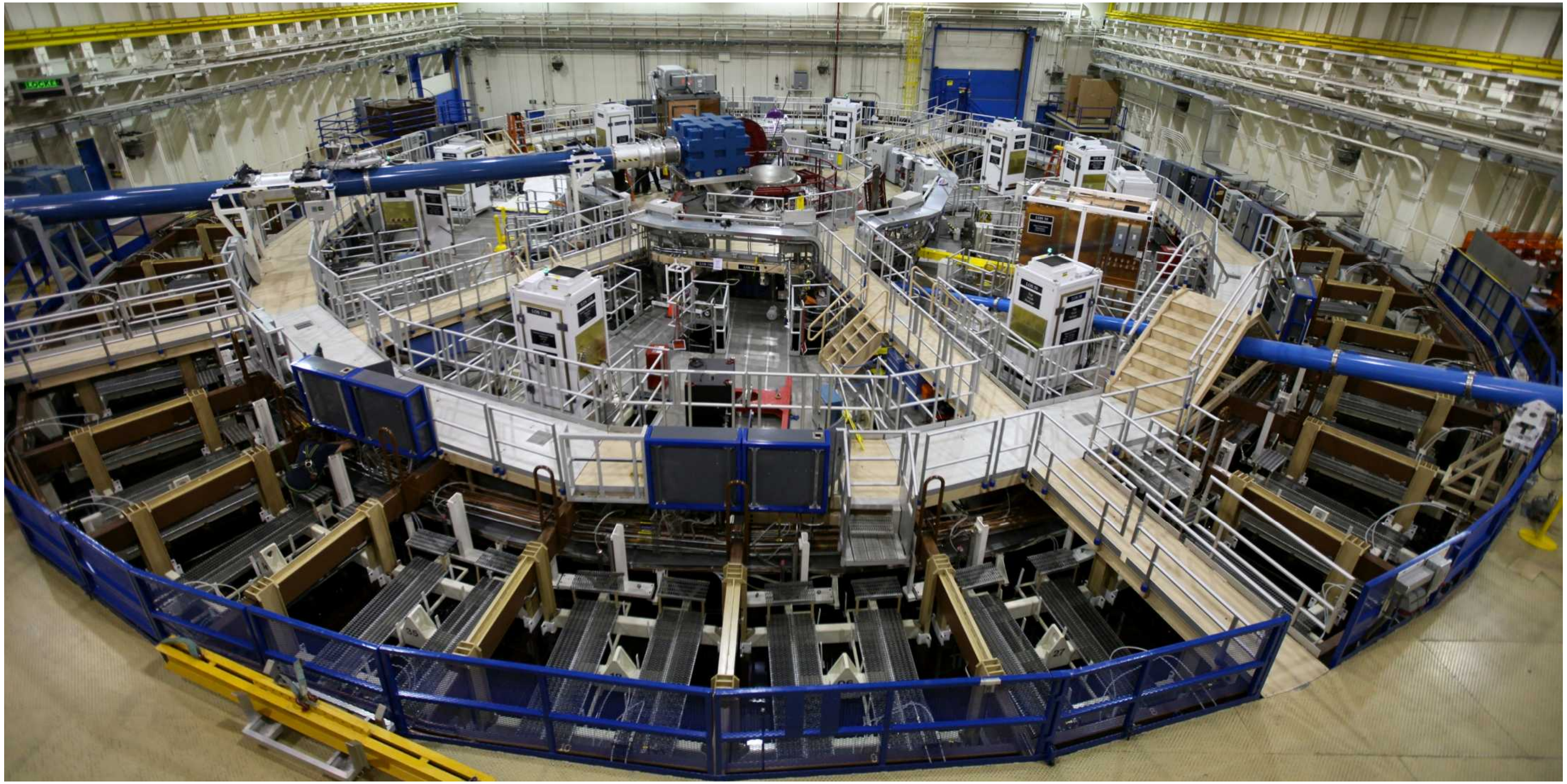
We use pulsed power to create high energy density matter



- 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

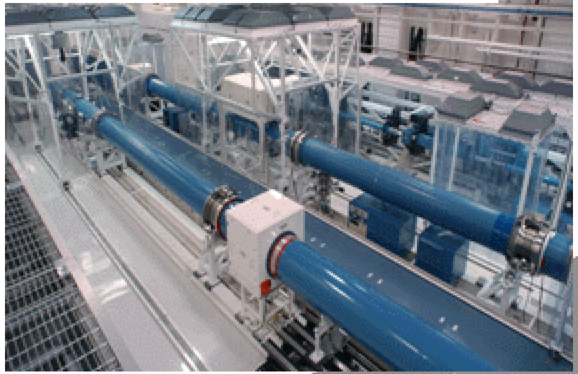
Target volume is ~0.1 cm^3

Compression in space is ~10^9

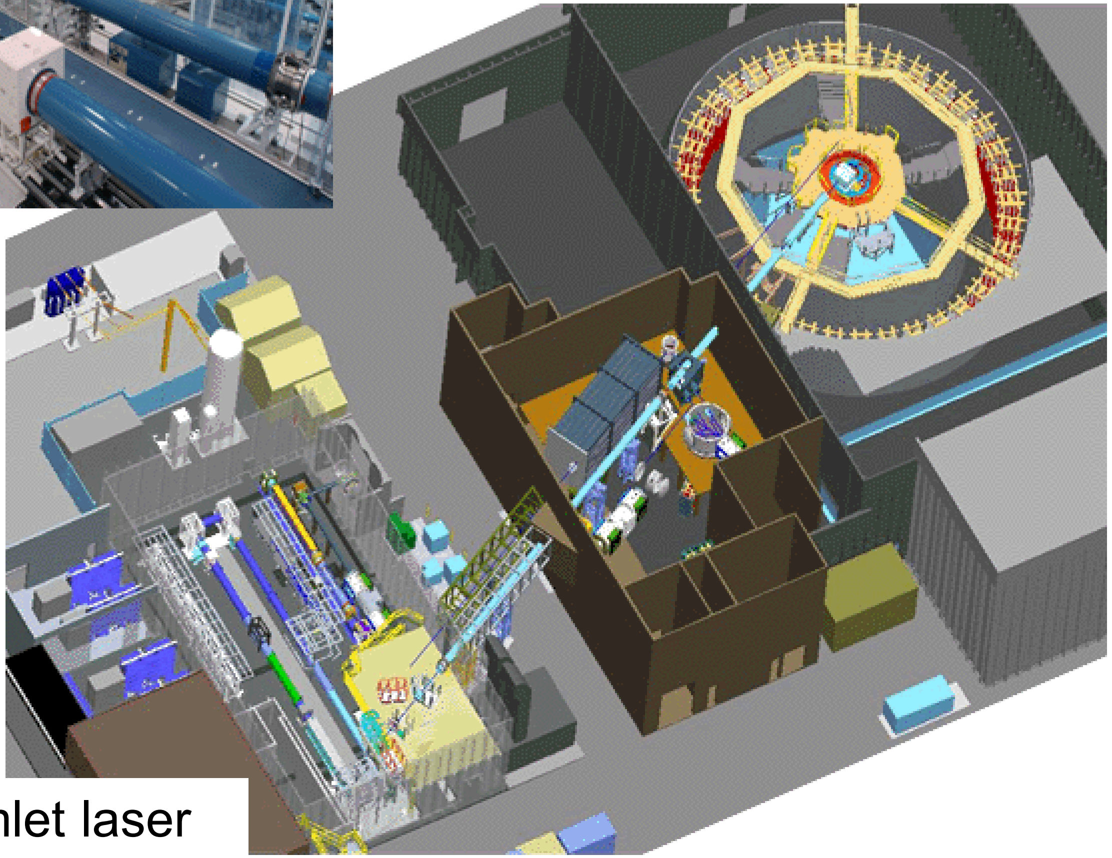
D. V. Rose, et al., Phys. Rev. ST Accel. Beams 13, 010402 (2010).

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

Z-Beamlet High Bay



Z Machine



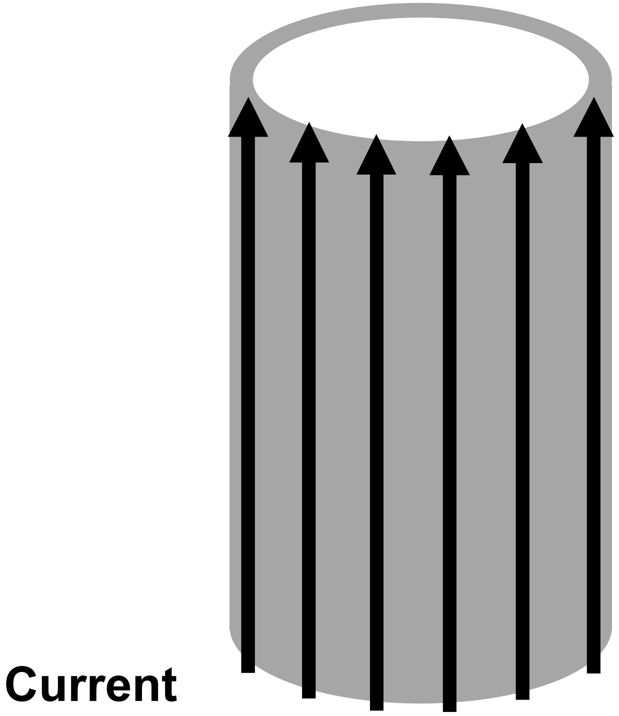
Z-Beamlet laser

- 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).

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

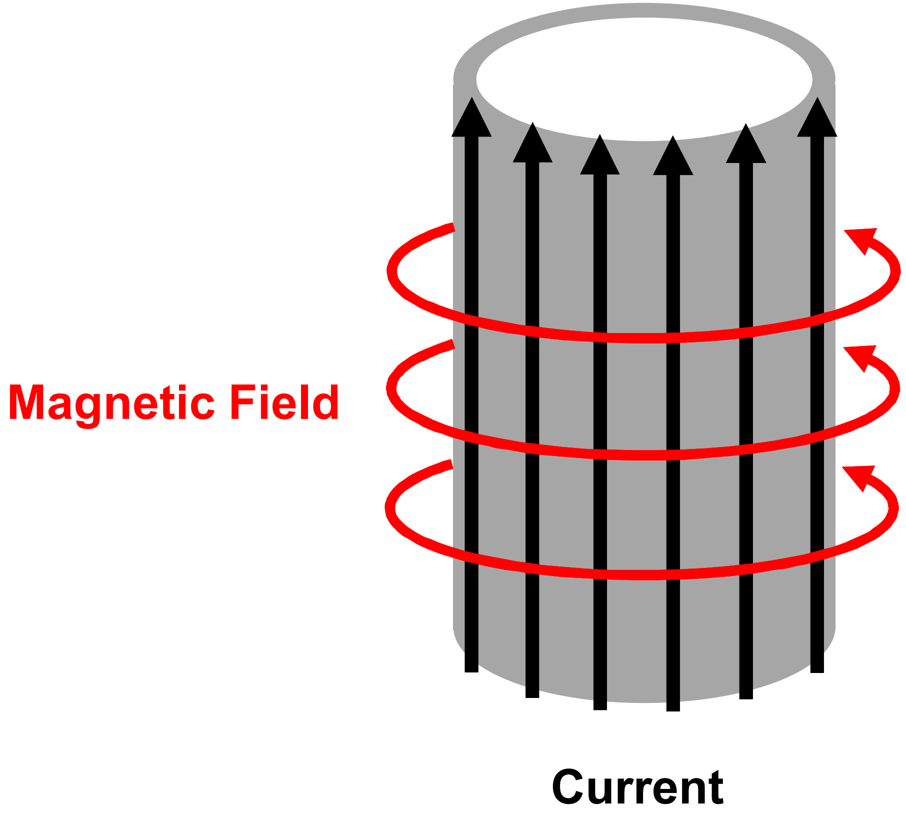
Cylindrical geometry
Radiation sources and ICF



- Current flows through a conducting cylinder

The enormous current is used to accelerate matter to extreme velocities

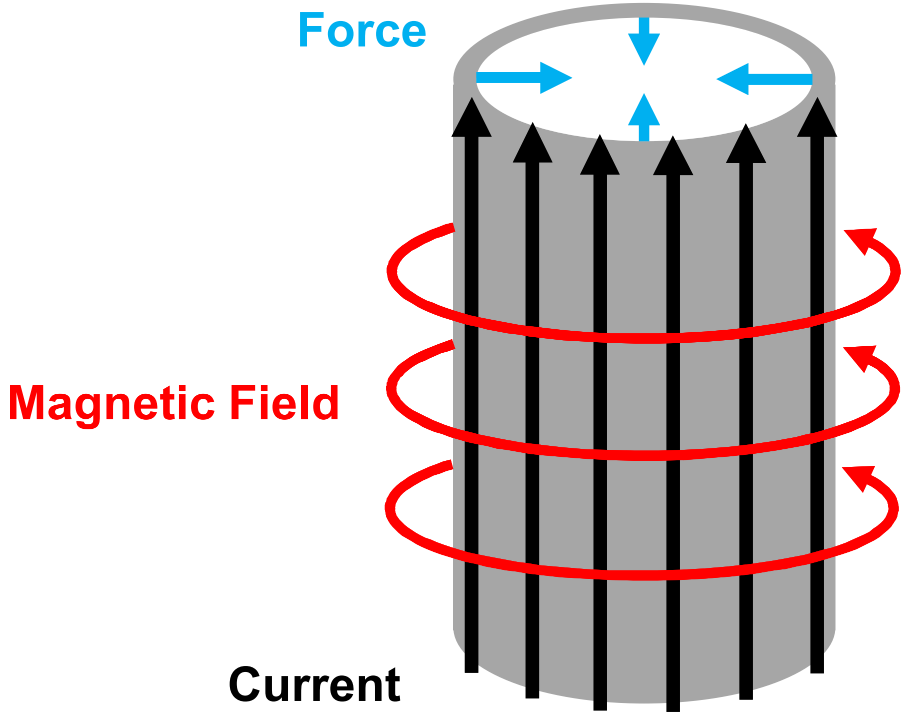
Cylindrical geometry
Radiation sources and ICF



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

The enormous current is used to accelerate matter to extreme velocities

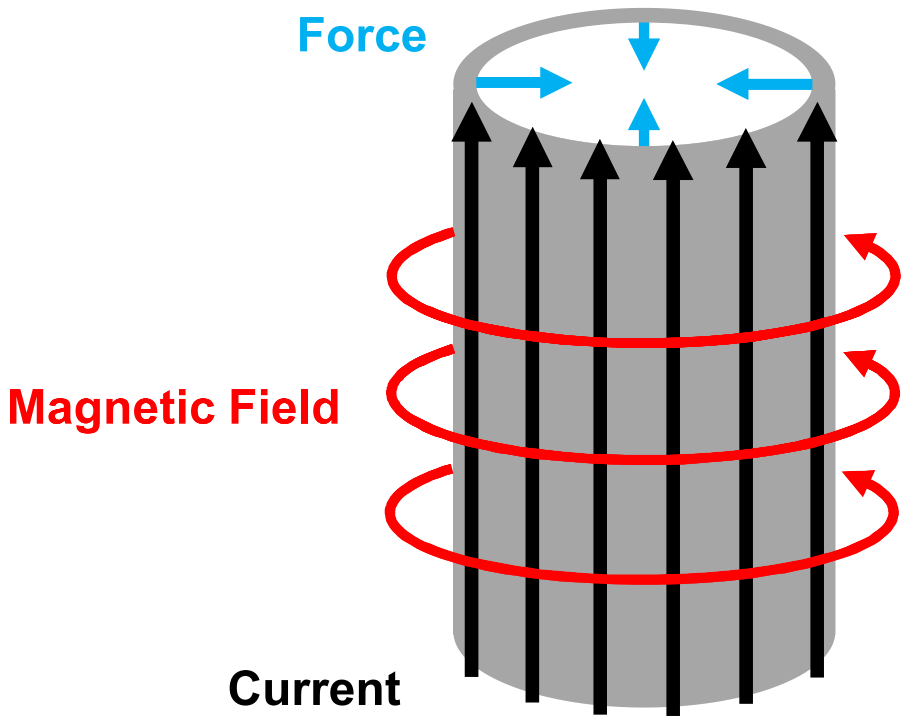
Cylindrical geometry
Radiation sources and ICF



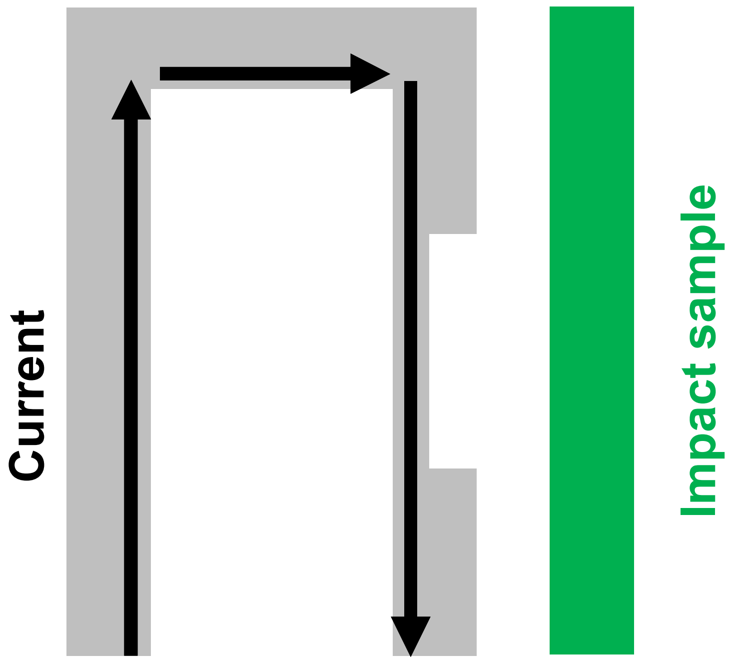
- Current flows through a conducting cylinder
- Produces a self-magnetic field
- Generates a radially-inward force

The enormous current is used to accelerate matter to extreme velocities

Cylindrical geometry
Radiation sources and ICF



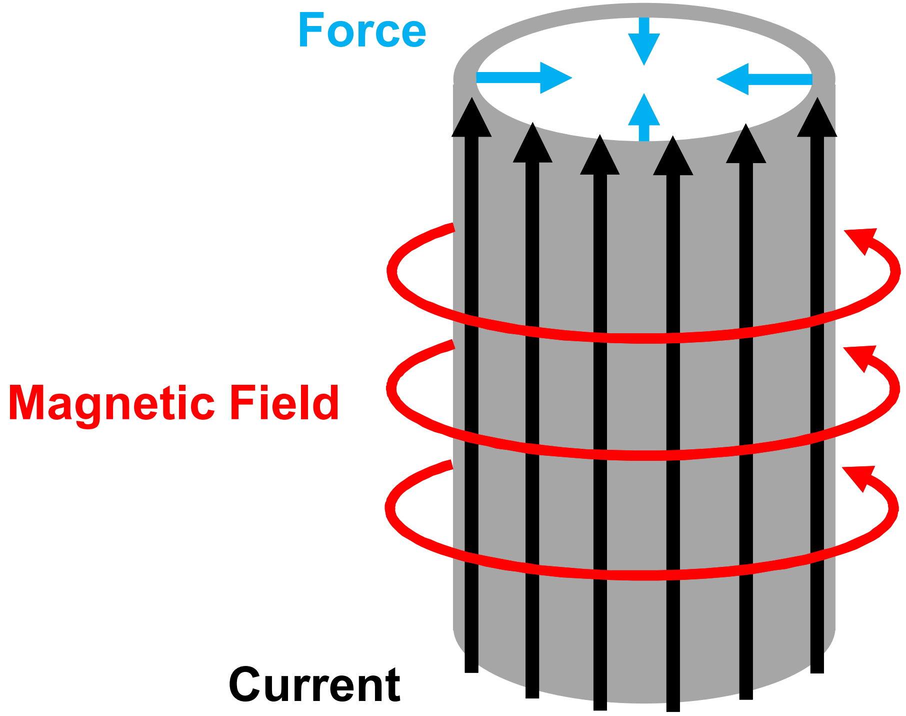
Planar geometry
Dynamic materials properties



The enormous current is used to accelerate matter to extreme velocities

Cylindrical geometry

Radiation sources and ICF



Planar geometry

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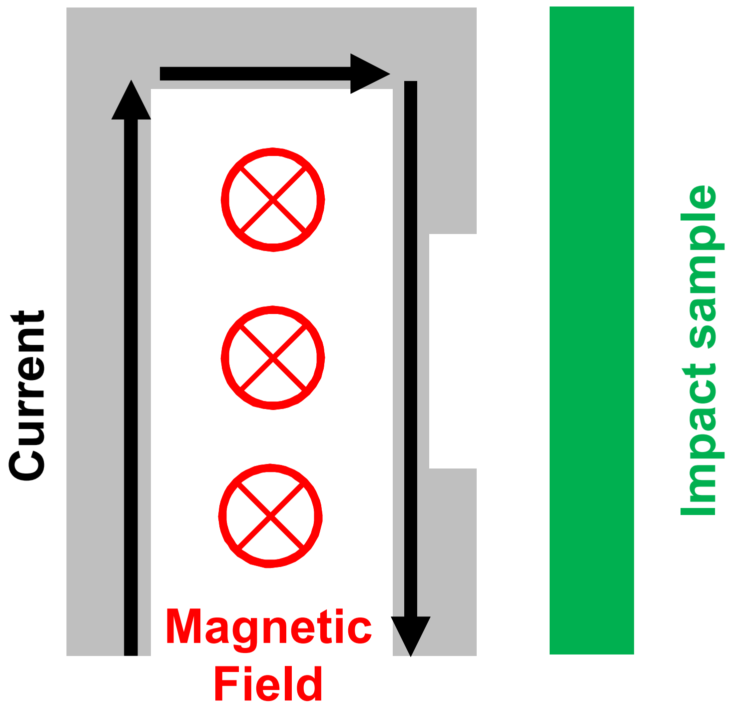

The enormous current is used to accelerate matter to extreme velocities

Cylindrical geometry
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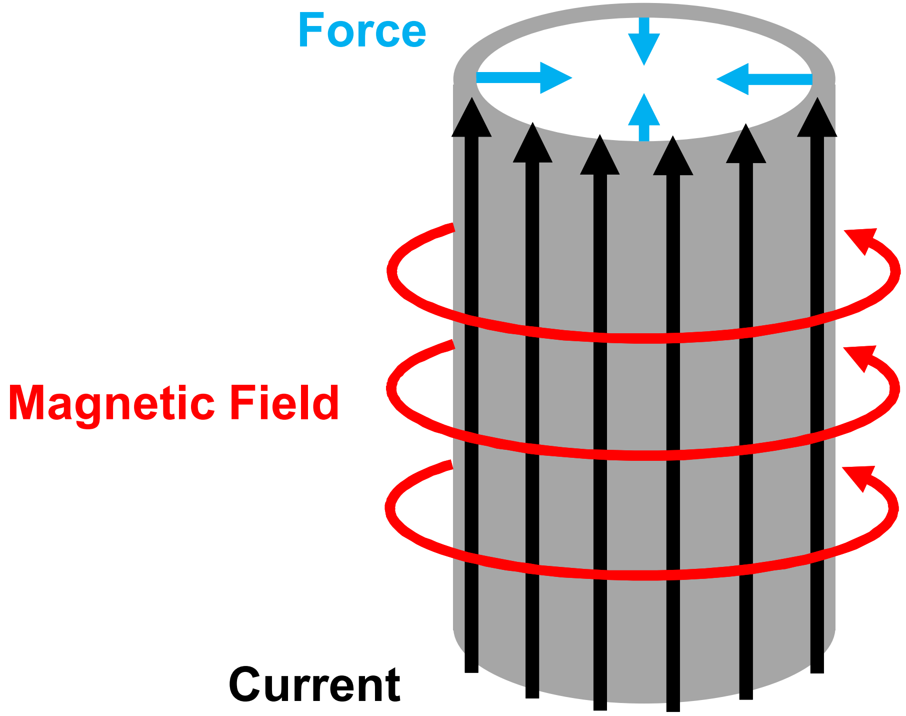

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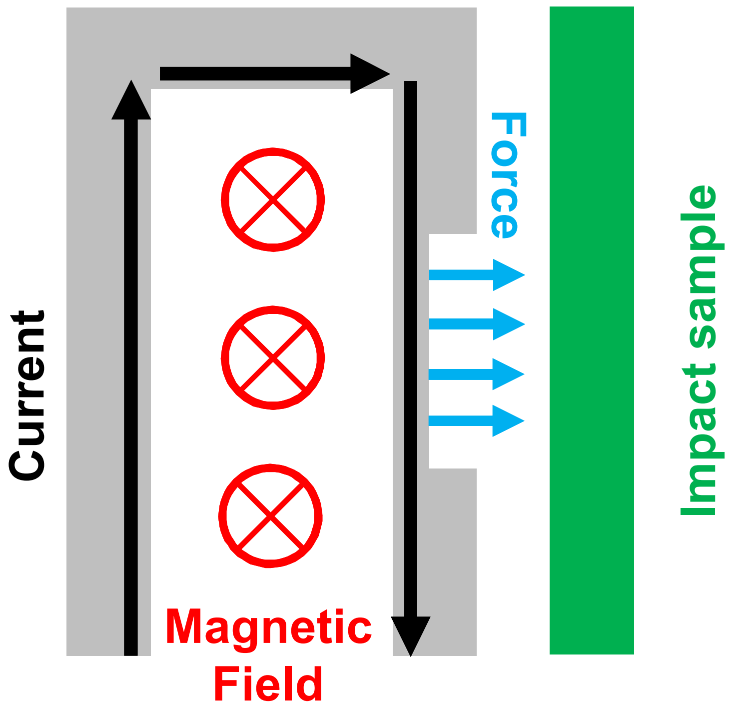
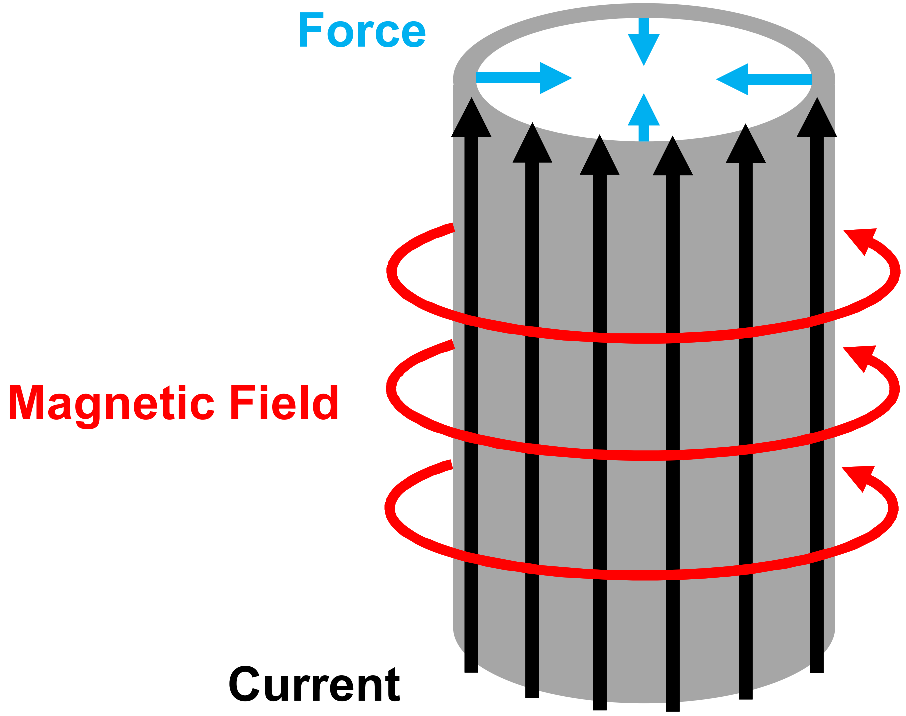


The enormous current is used to accelerate matter to extreme velocities

Cylindrical geometry

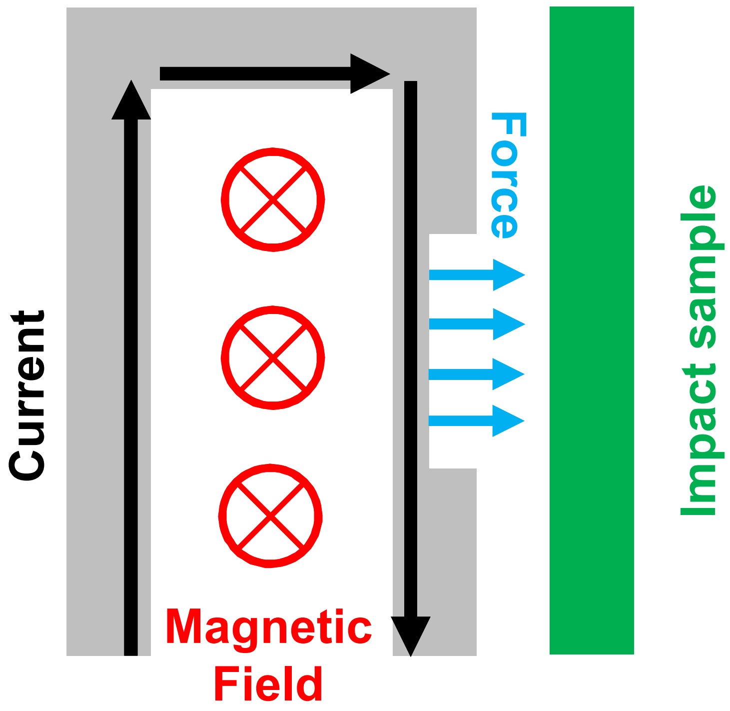
Radiation sources and ICF



100-1000 km/s range

Planar geometry

Dynamic materials properties



10-100 km/s range

All of this energy completely destroys the nearby components

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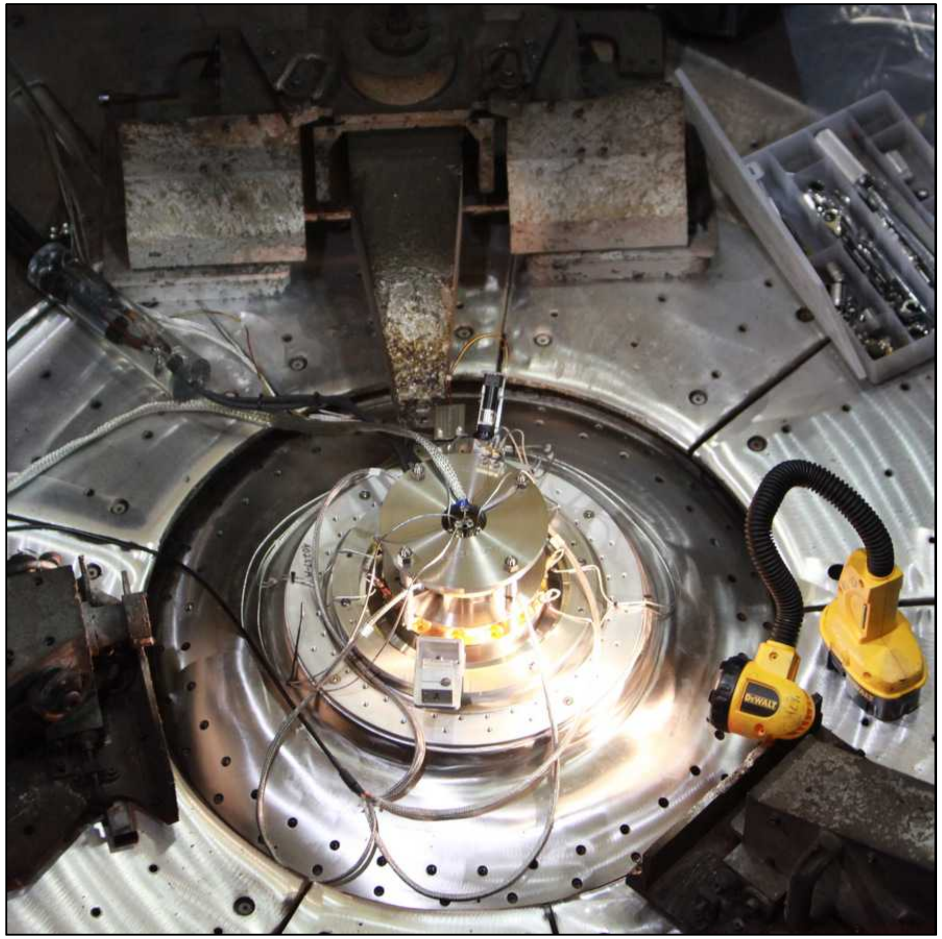
Before

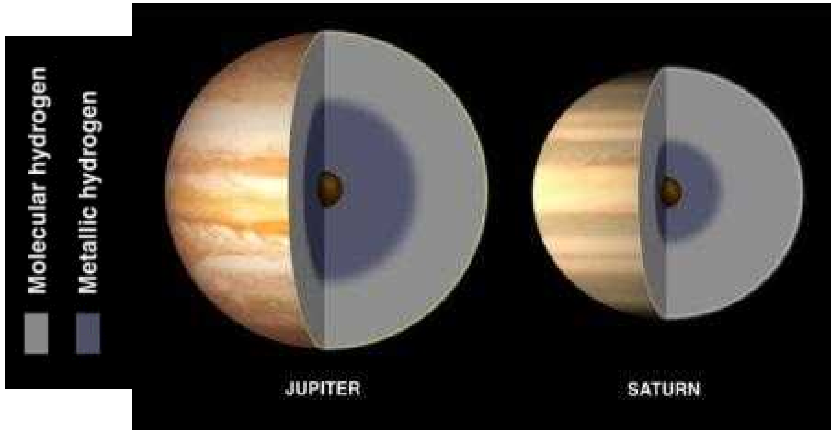


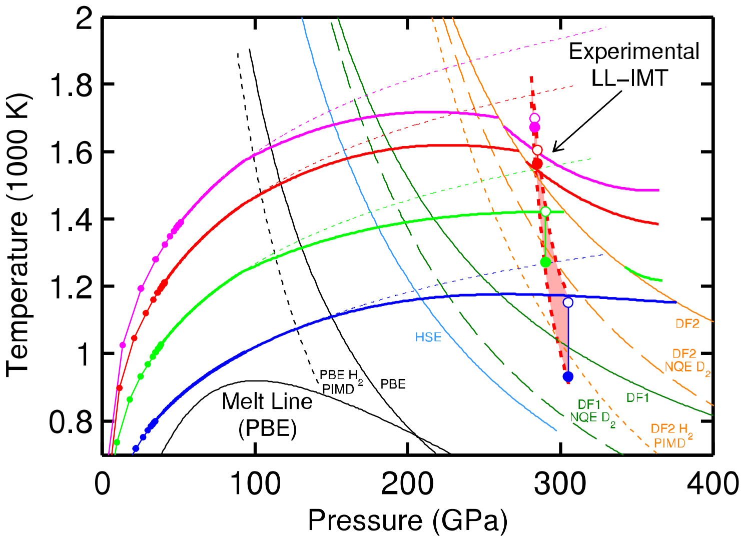
After

- Debris impacts laser optics and diagnostics
- Clean up and reload limits us to 1 shot/day
- Diagnostic housings are 2.5 cm thick tungsten

We use the Z machine to investigate a variety of high energy density areas

Dynamic Material Properties





M. D. Knudson, et al., Science 348, 6242 p. 1455 (2015).

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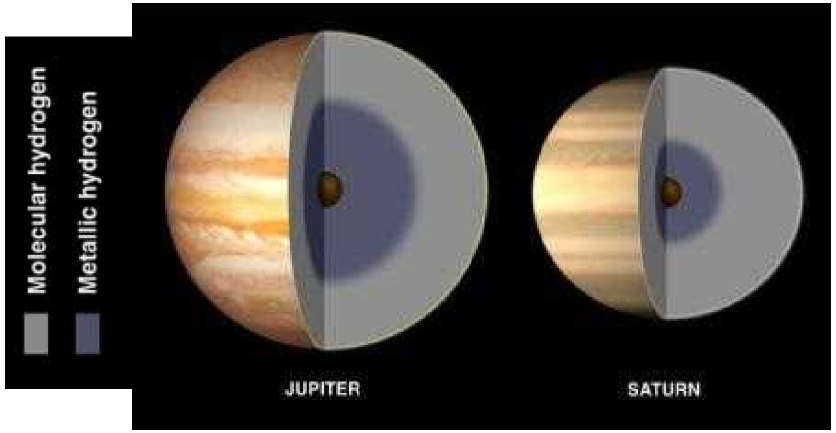
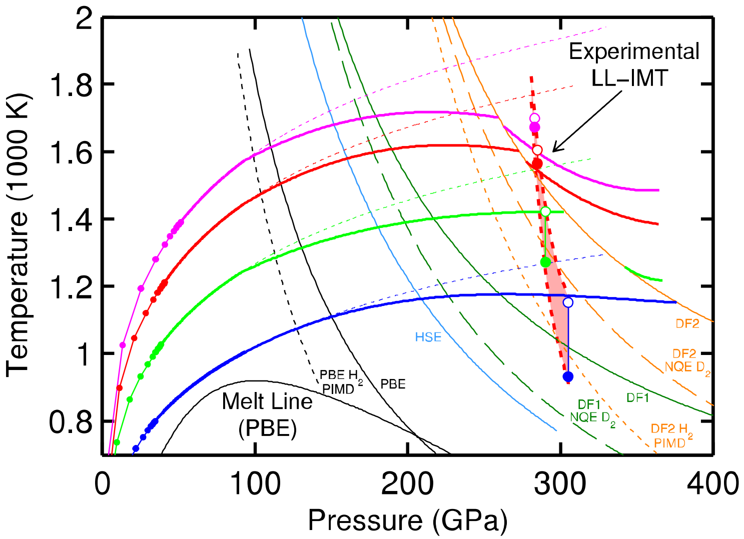
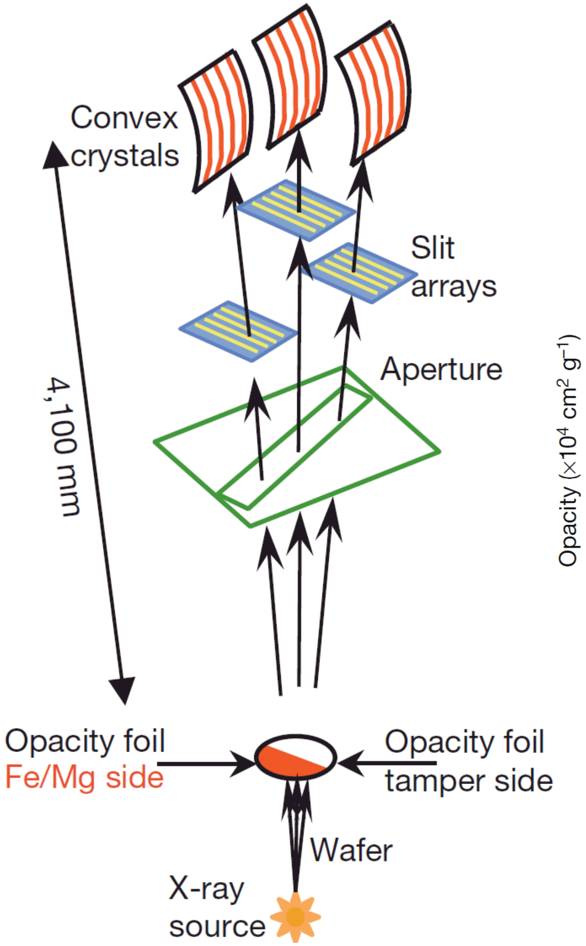
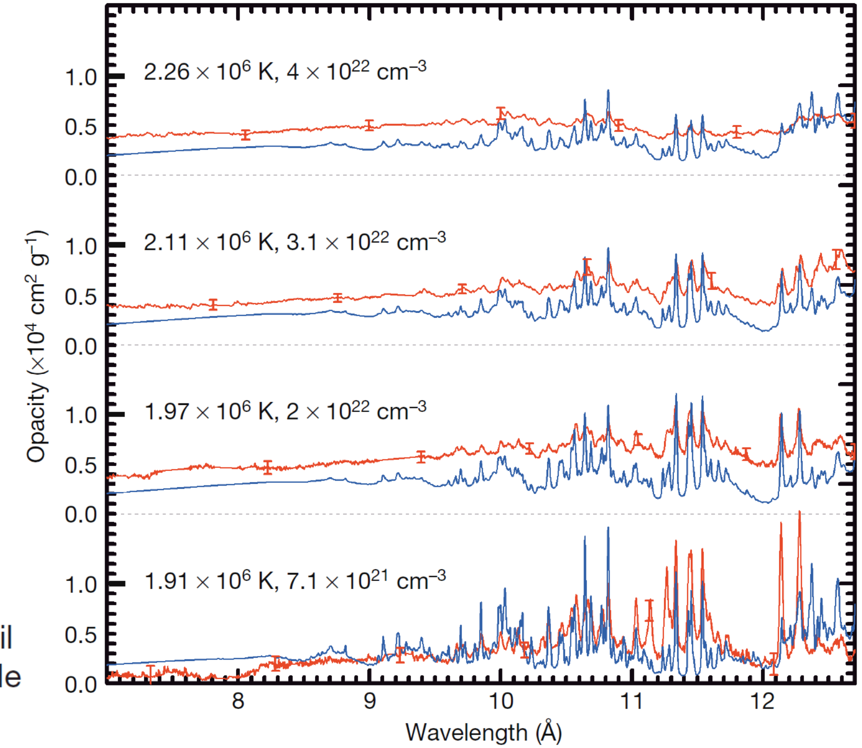




Radiation Physics





M. D. Knudson, et al., Science 348, 6242 p. 1455 (2015).

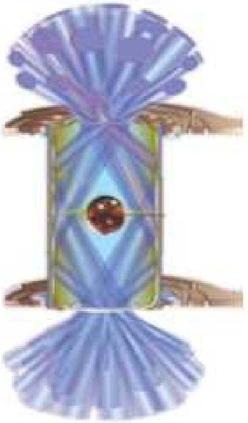
J. E. Bailey, et al., Nature 517, 7532 p. 56 (2015).

This talk is focused on Sandia's inertial confinement fusion efforts

Laser x-ray drive	Laser direct drive	Magnetic direct drive

Laser x-ray drive

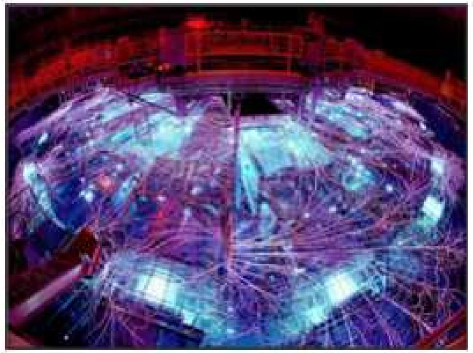
192 beams, 1.8 MJ, 400 TW



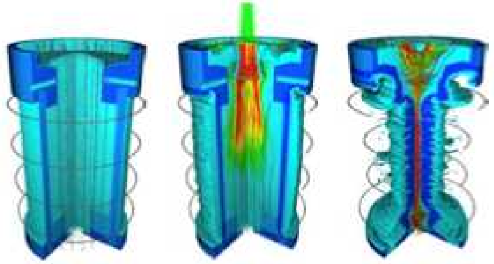
Laser direct drive

60 beams, 30 kJ, 20 TW

Magnetic direct drive

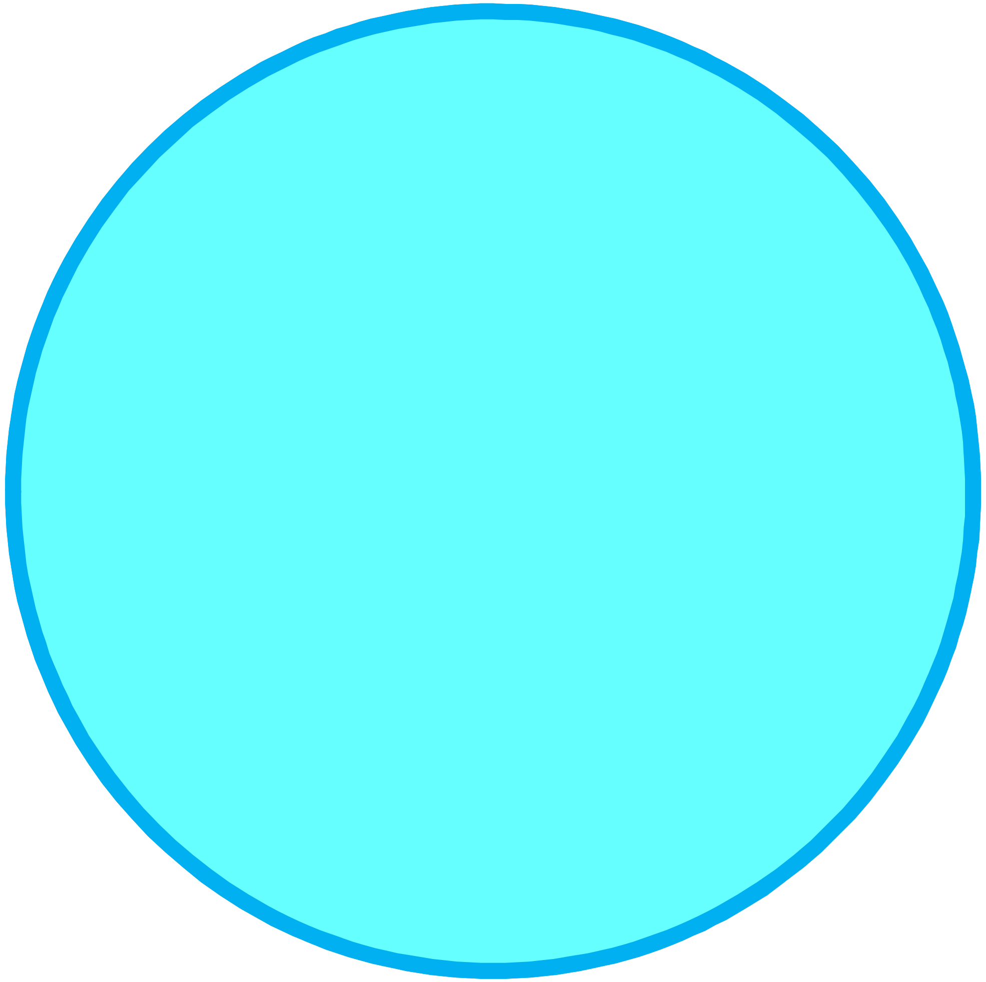


26 MA, 80 TW



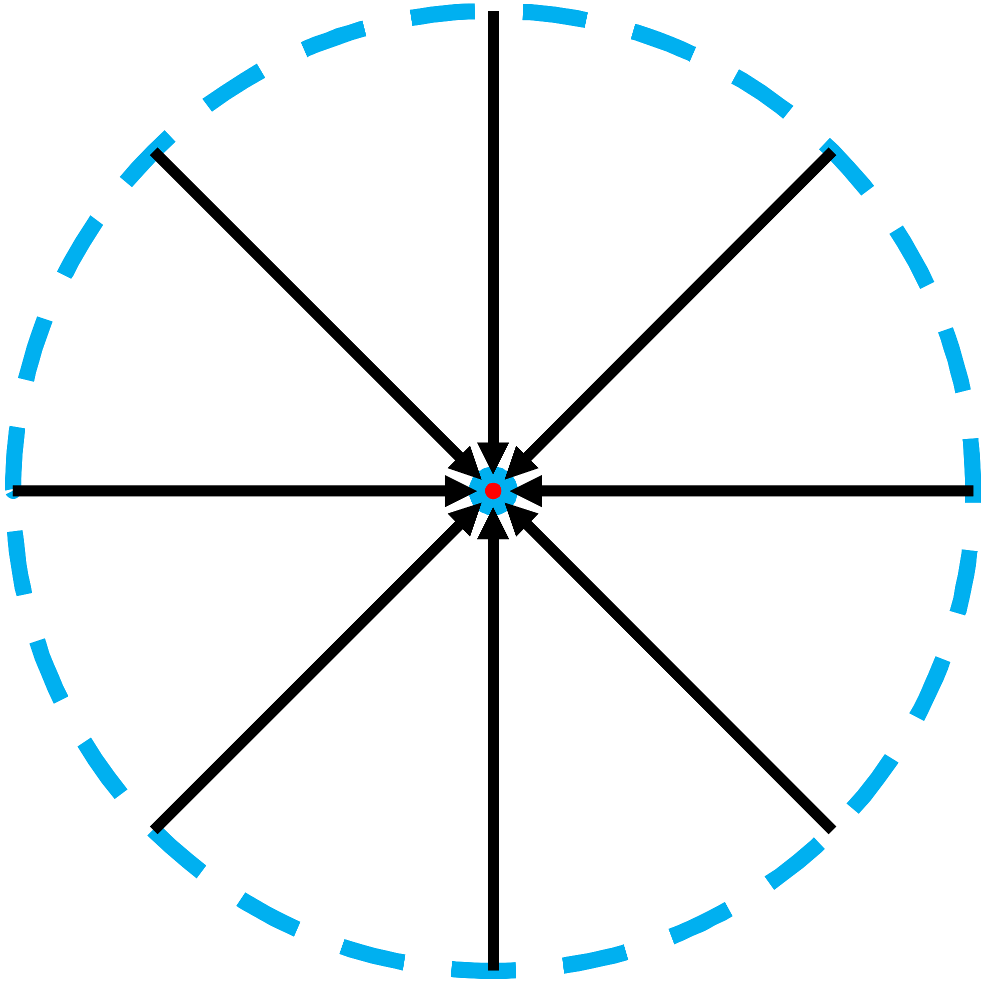
Magnetization | Laser heating | Compression

But first, a quick review of traditional ICF



- Start with a sphere containing DT

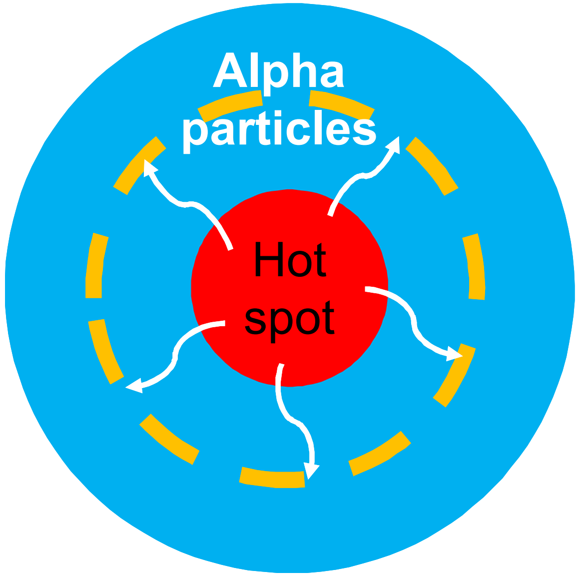
But first, a quick review of traditional ICF



- 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)

But first, a quick review of traditional ICF

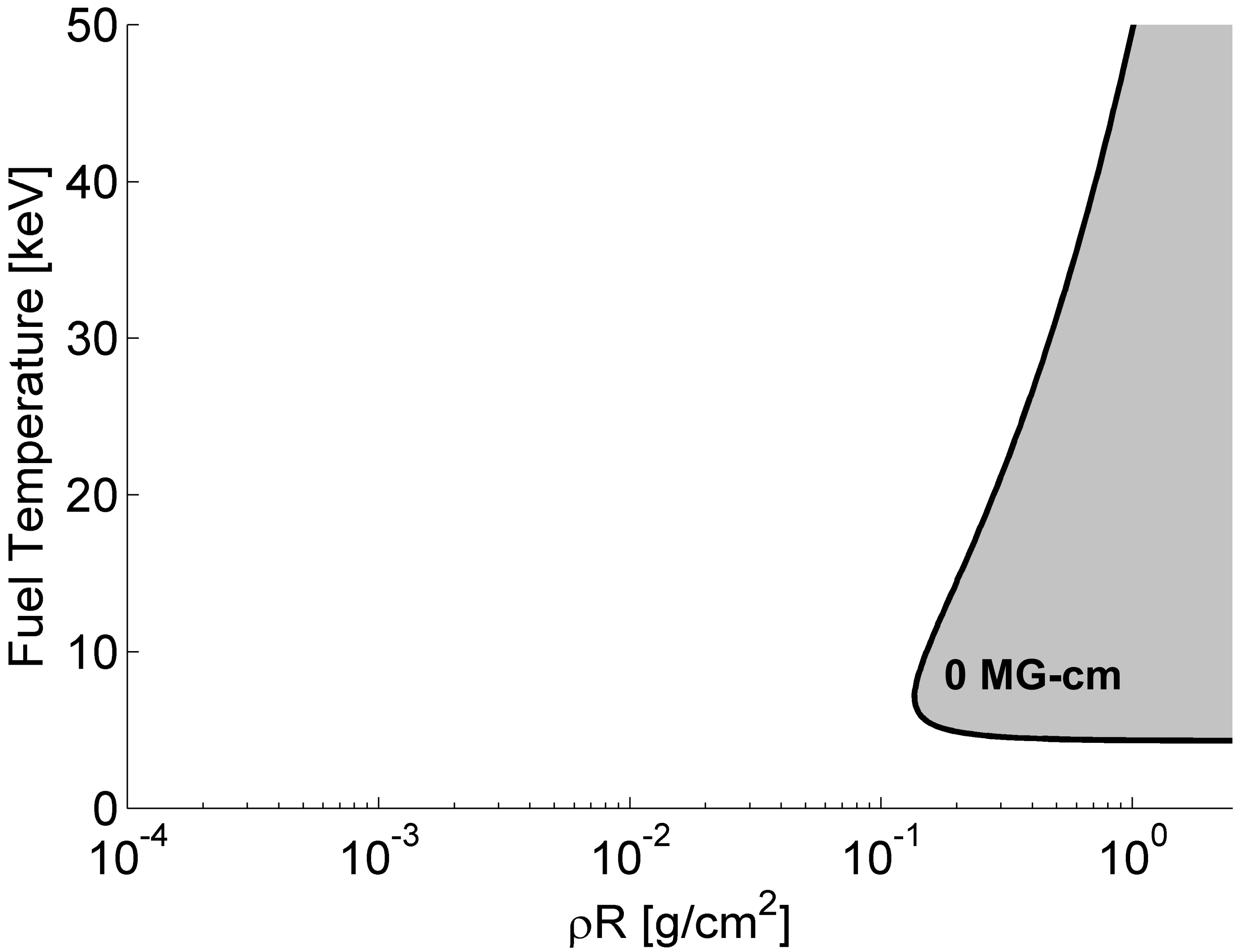
Zooming in



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

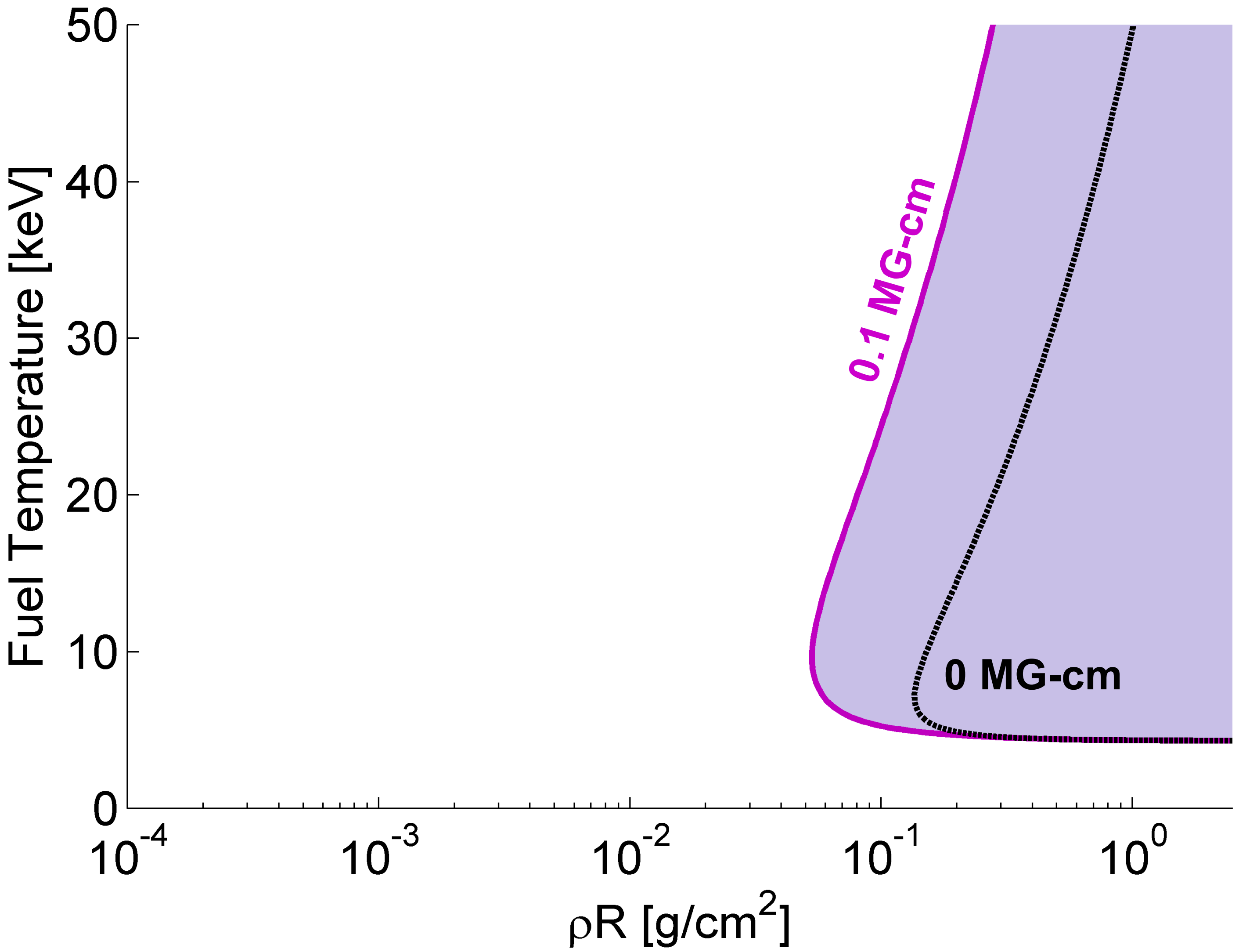
ICF has requirements on fuel temperature and areal density for gains to exceed losses



- 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).

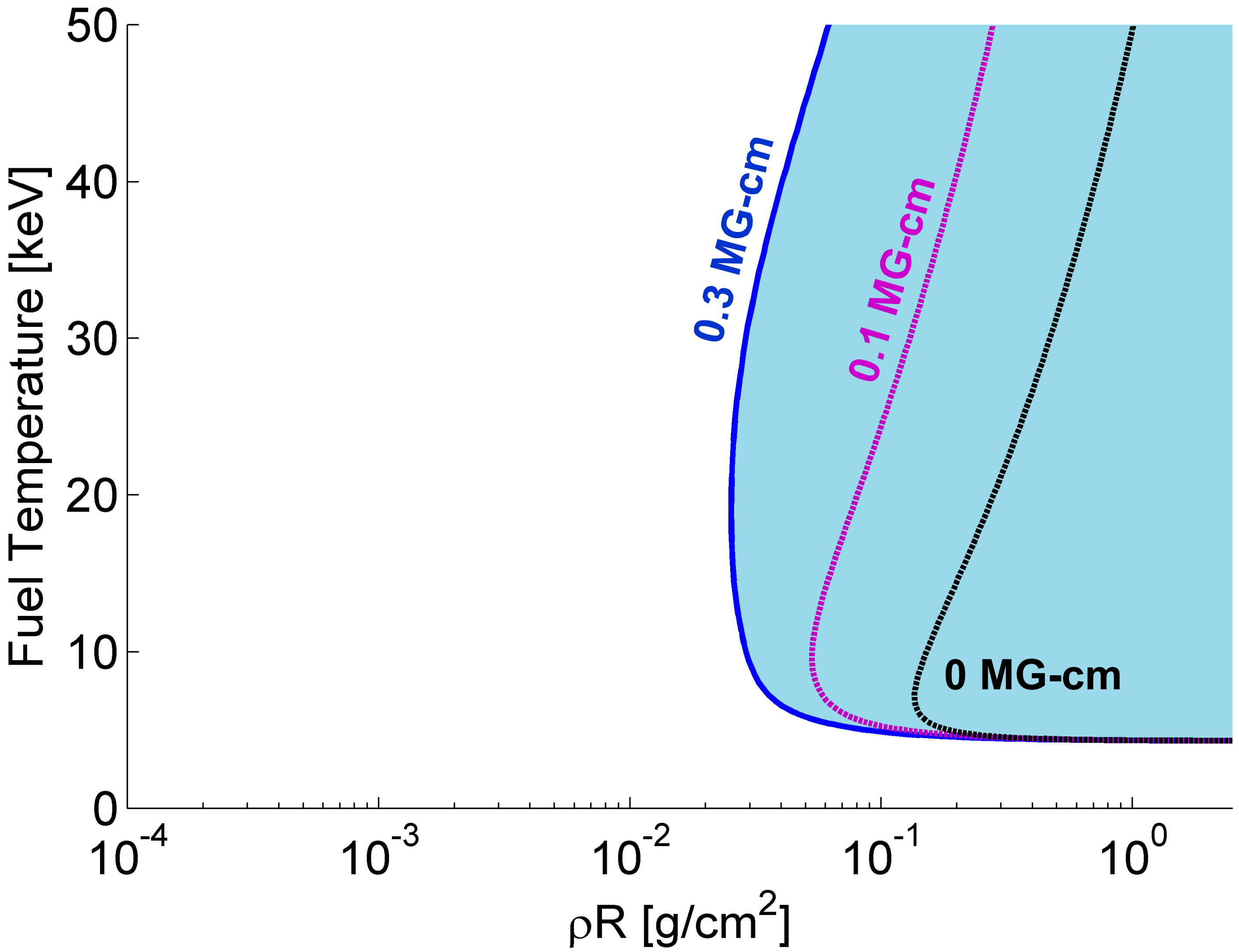
Magneto-inertial fusion utilizes magnetic fields to relax the stagnation requirements of ICF



- 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).

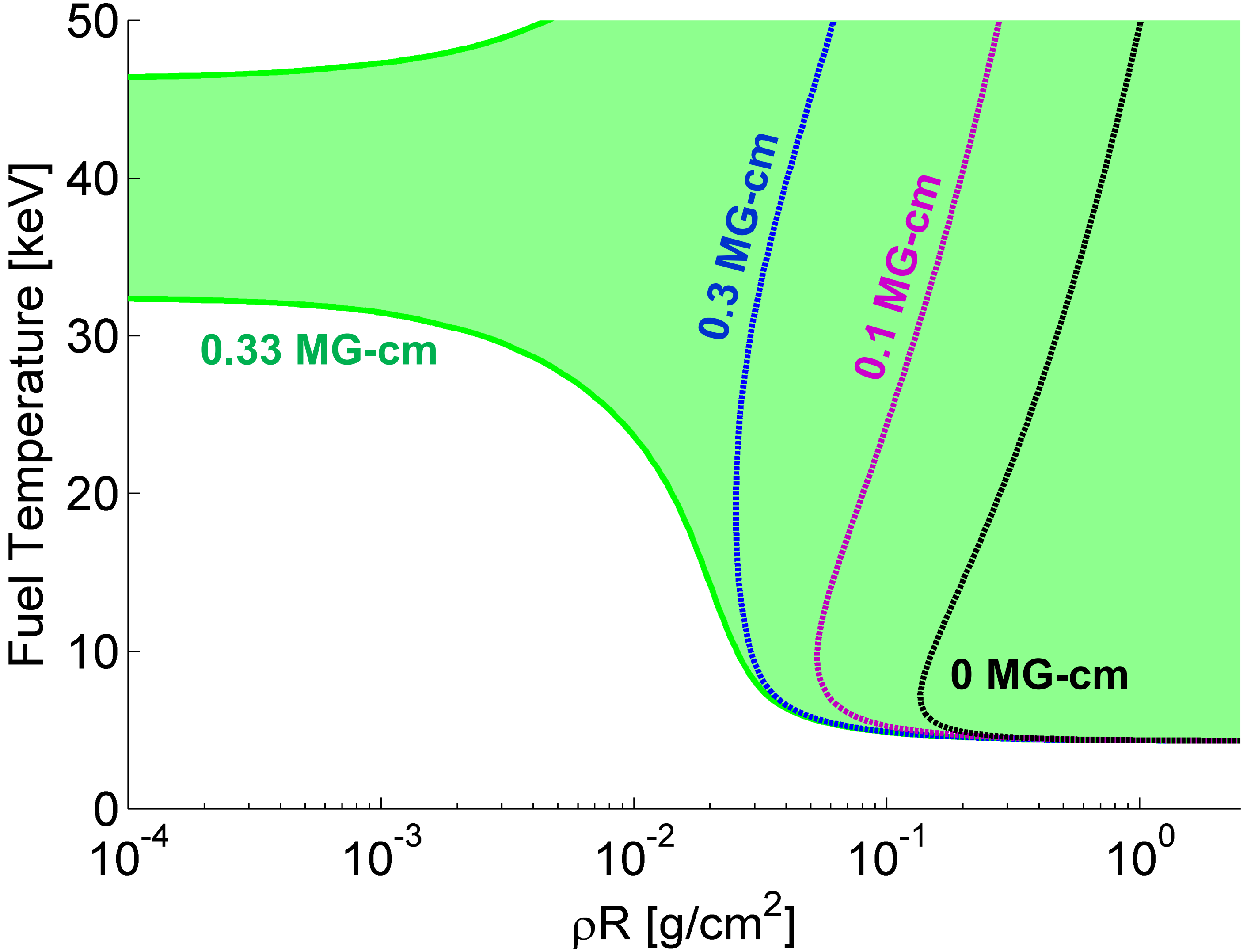
Magneto-inertial fusion utilizes magnetic fields to relax the stagnation requirements of ICF



- 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).

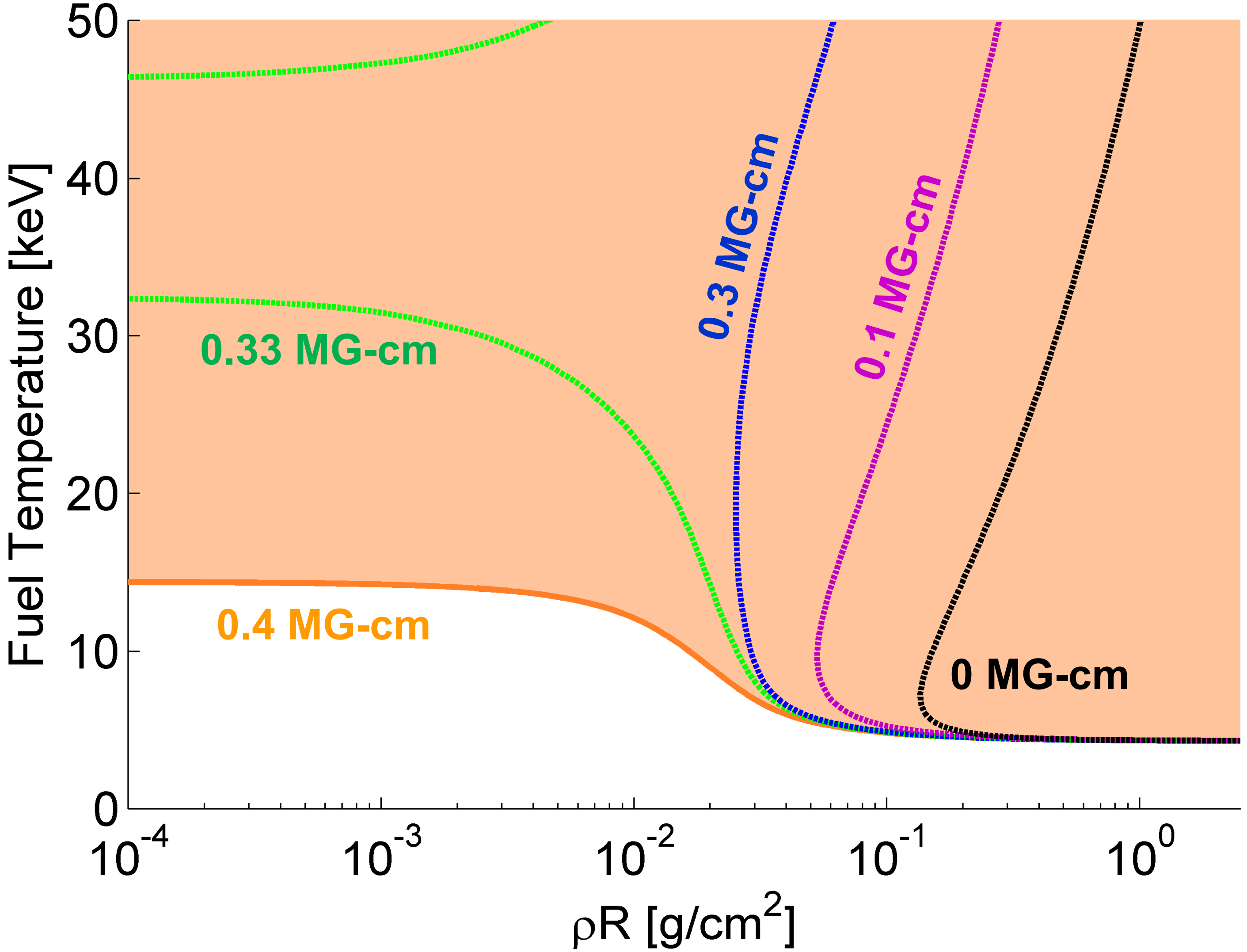
Magneto-inertial fusion utilizes magnetic fields to relax the stagnation requirements of ICF



- 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

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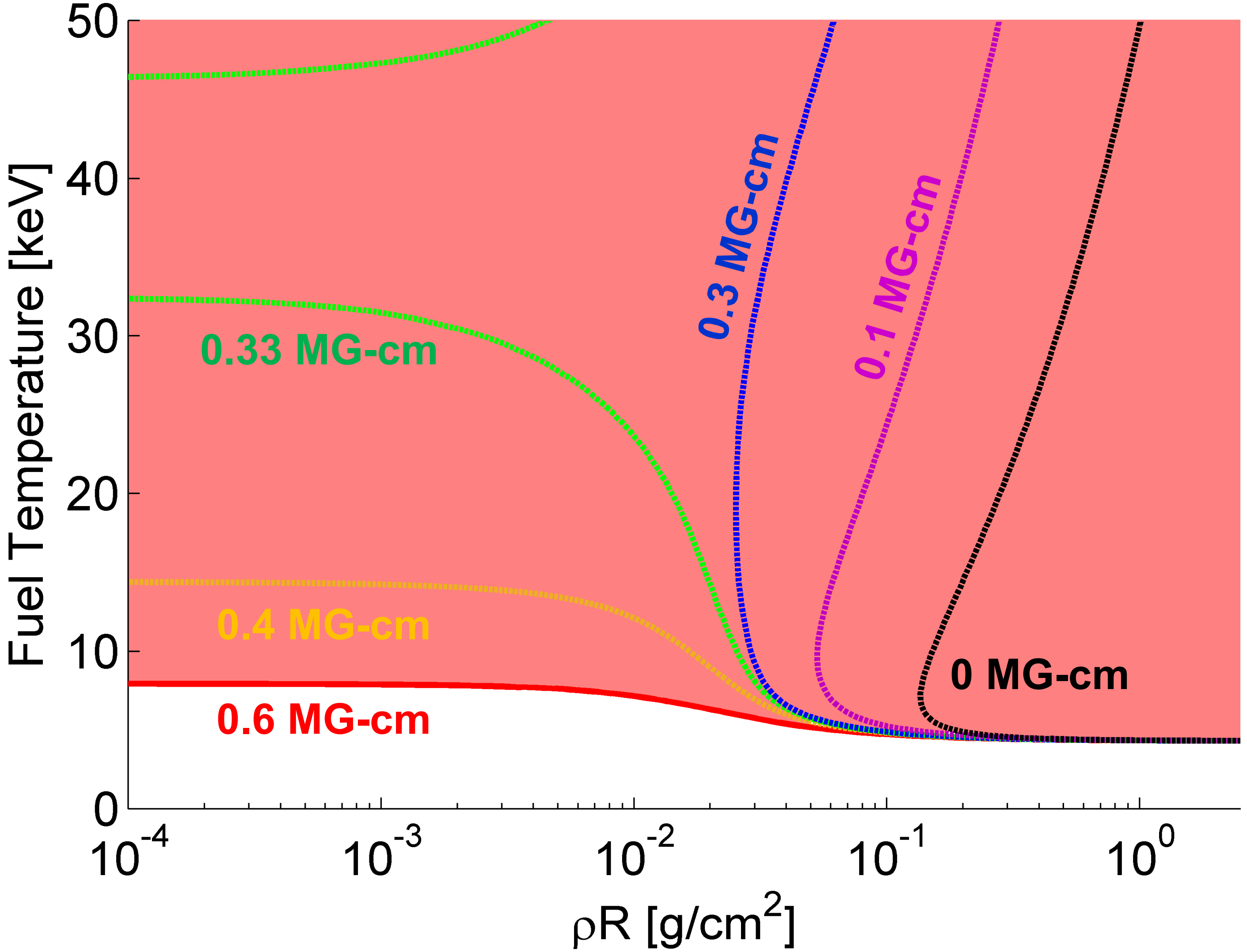
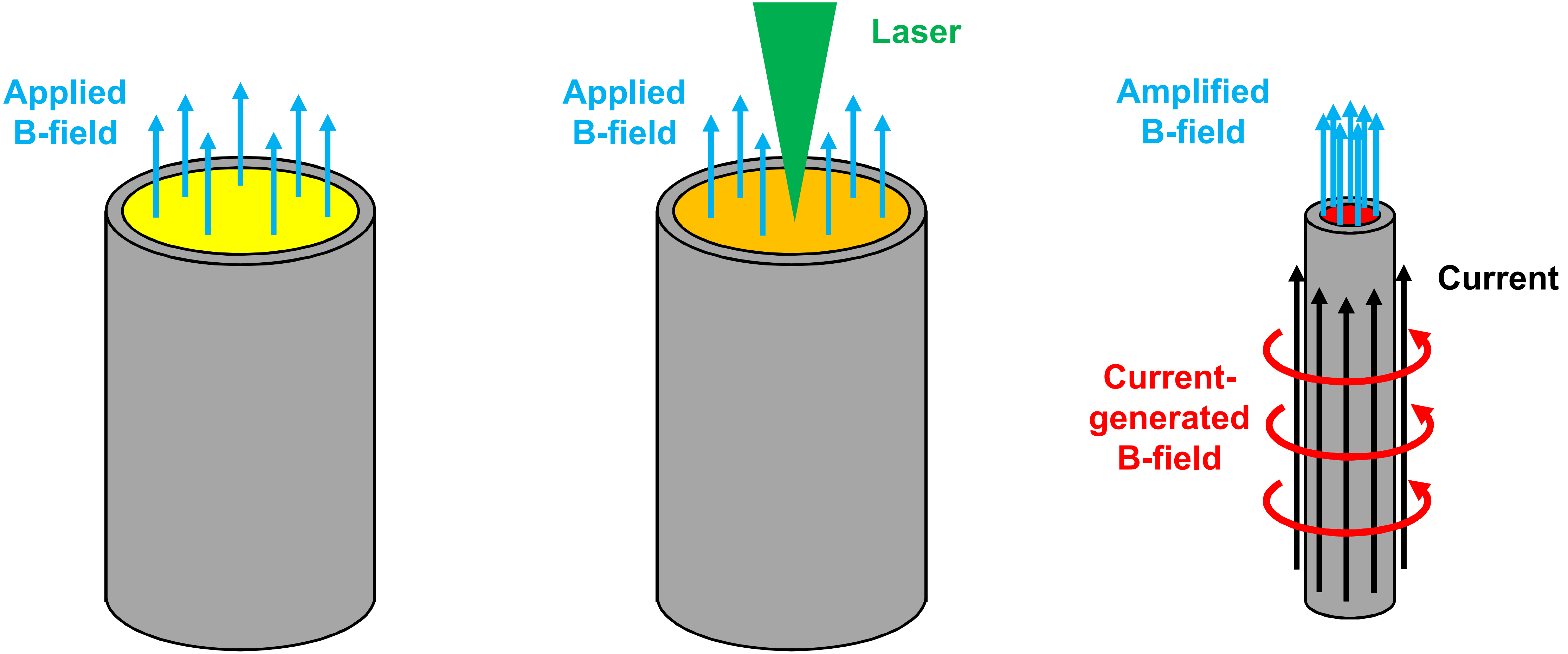


- When the Larmor radius is about half of the fuel radius, the effect begins to saturate
- This means there is an optimal field for a given fuel configuration

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

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



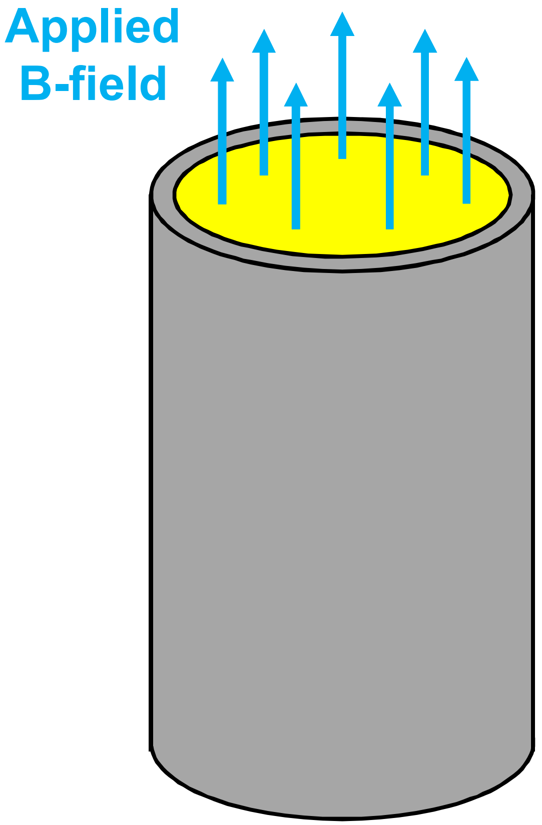
Apply axial magnetic field

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

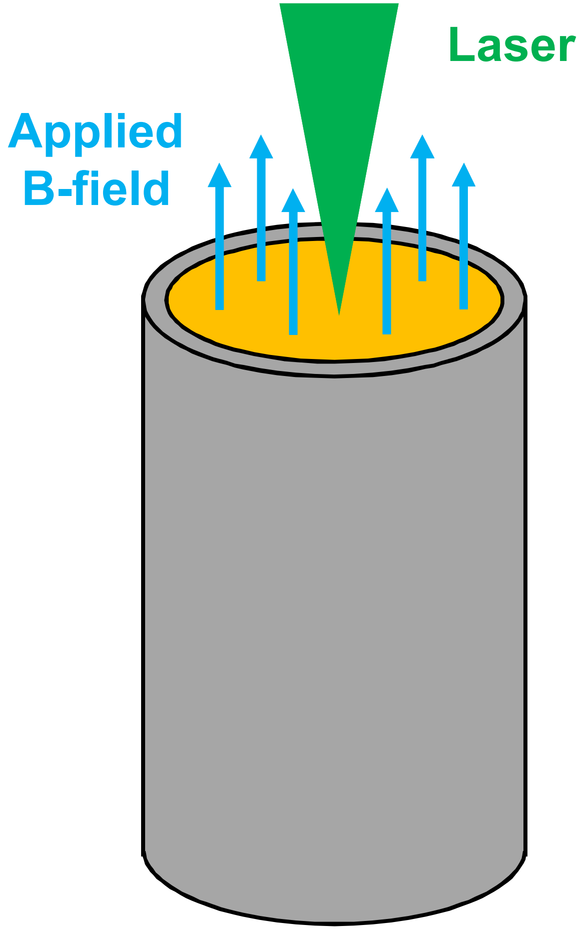


Apply axial magnetic field

- Metal cylinder contains ~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

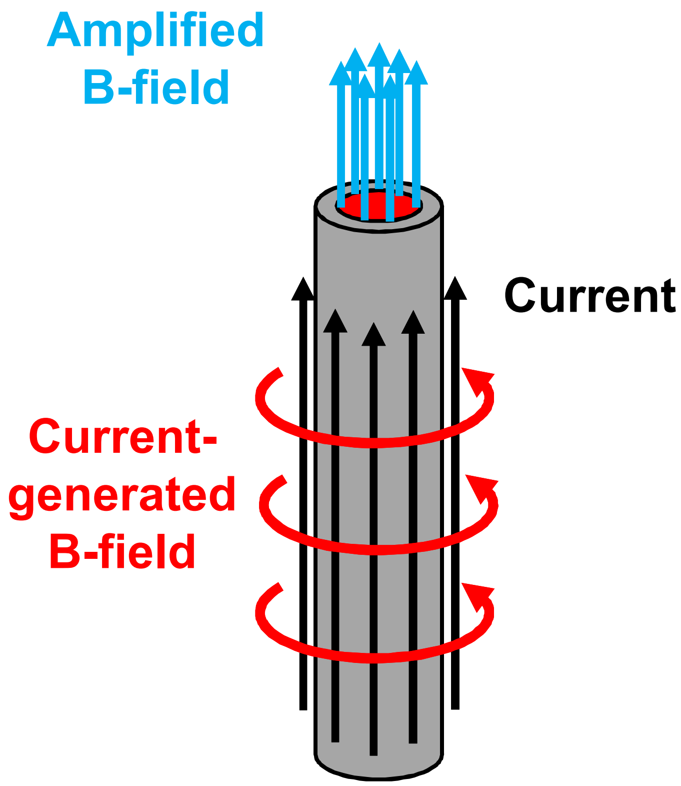


Laser-heat the magnetized fuel

- 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 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).

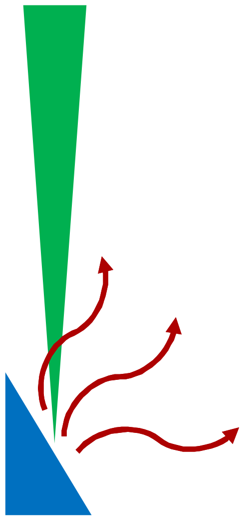
This is a relatively new concept (2008) with a lot of unknowns

- Things we worried/worry about
  - Will instabilities shred the liner before it can compress the fuel?
  - How to magnetize a several cm^3 volume with surrounding conductors to ~100 kG?
  - Can we effectively heat the fuel with a laser?

- We devoted some time to each of these issues
  - 2009-2012: heavy focus on liner stability experiments
  - 2011-2013: B-field coil development and testing
  - 2013-present: Laser heating studies

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

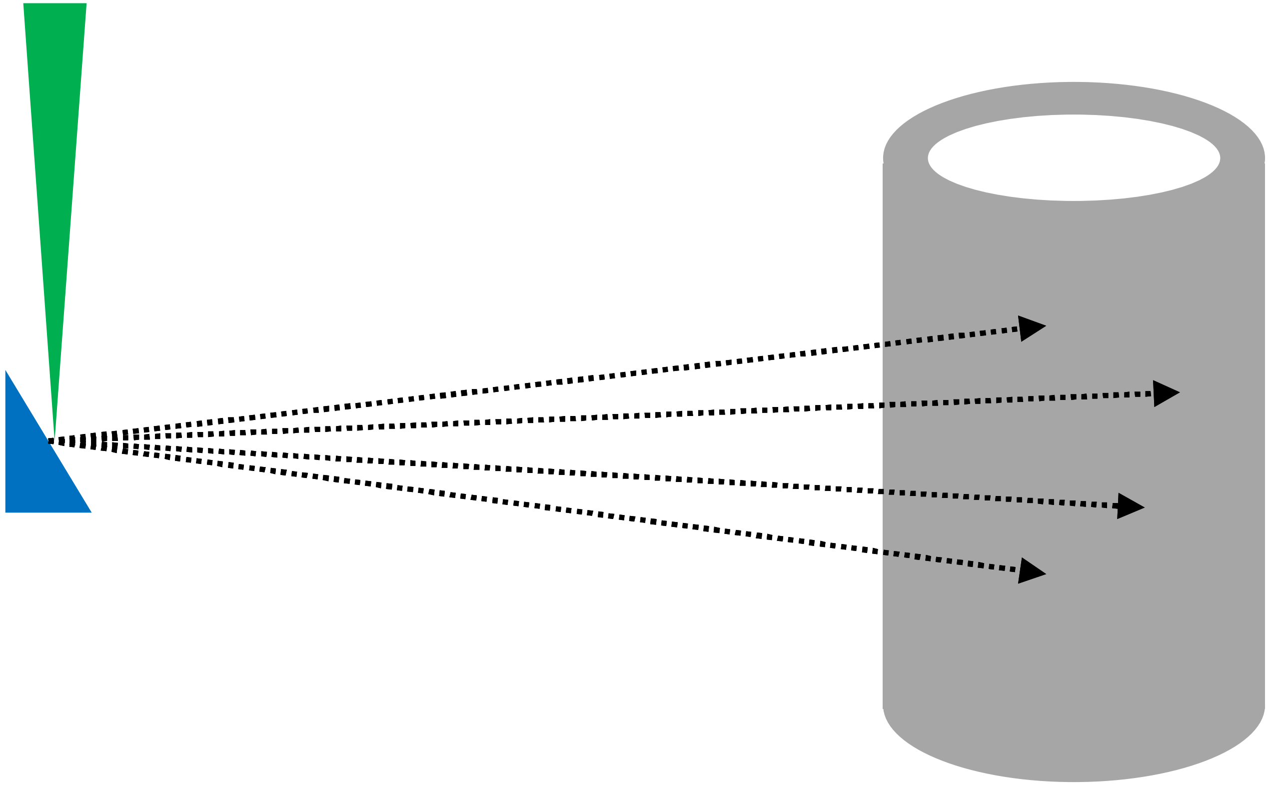
We use a monochromatic x-ray backlighter to check the stability of the implosions



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

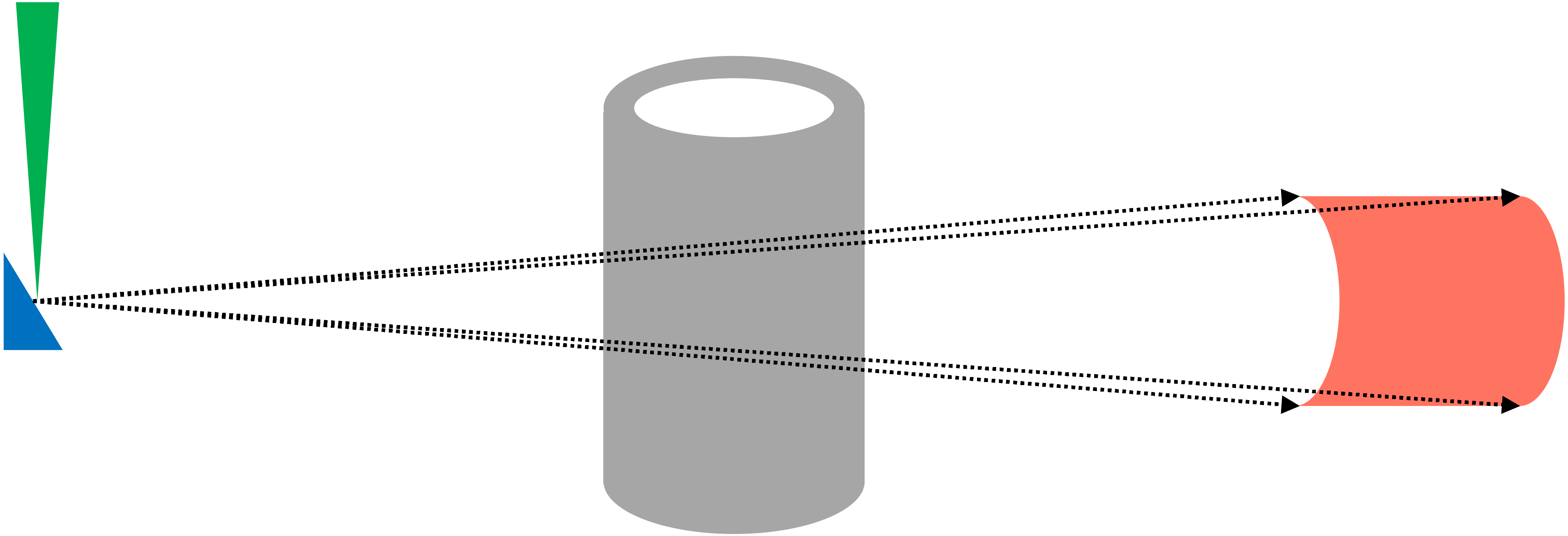
D. B. Sinars, et al., Rev. Sci. Instrum. 75, 3672 (2004).

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

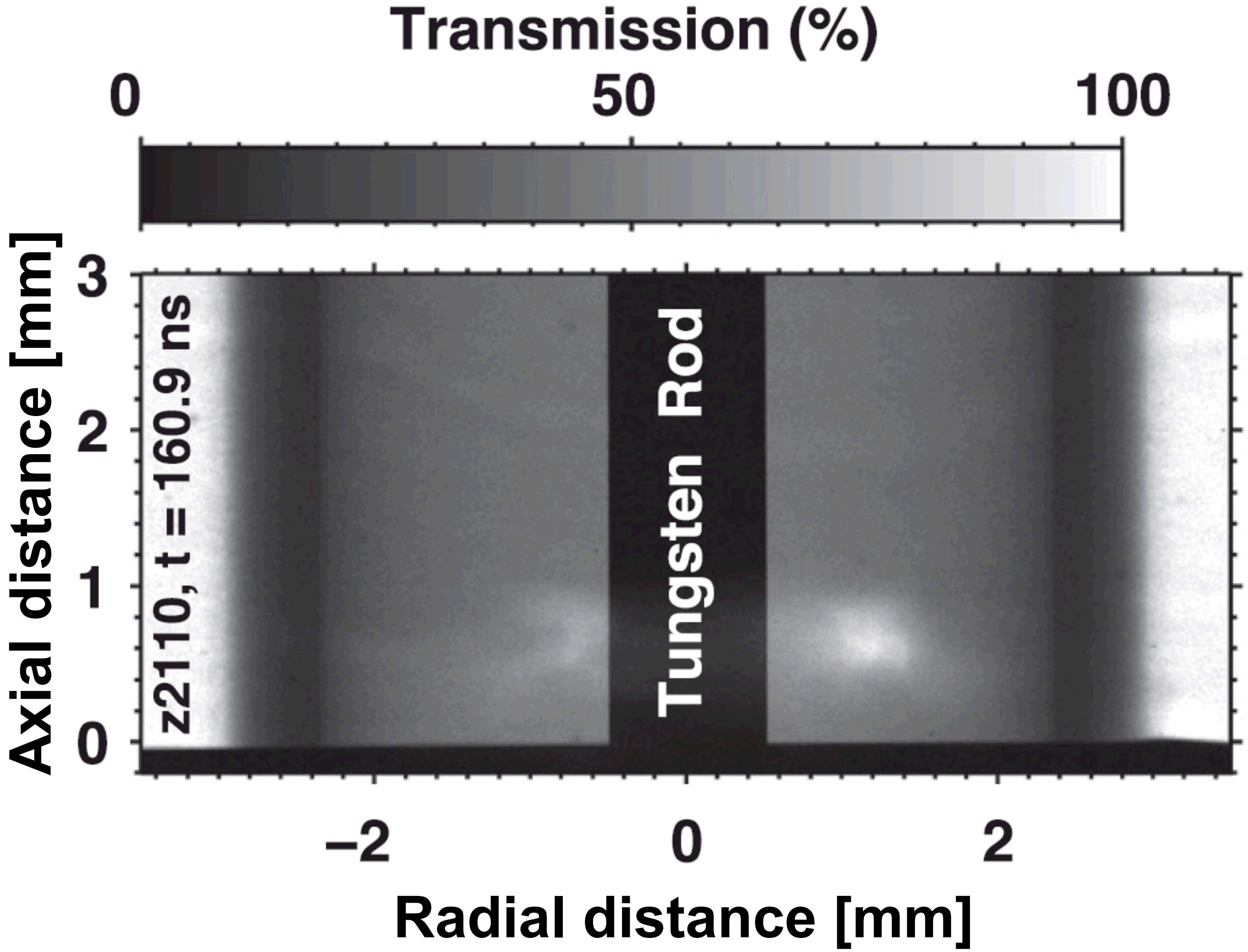
We use a monochromatic x-ray backlighter to check the stability of the implosions



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).

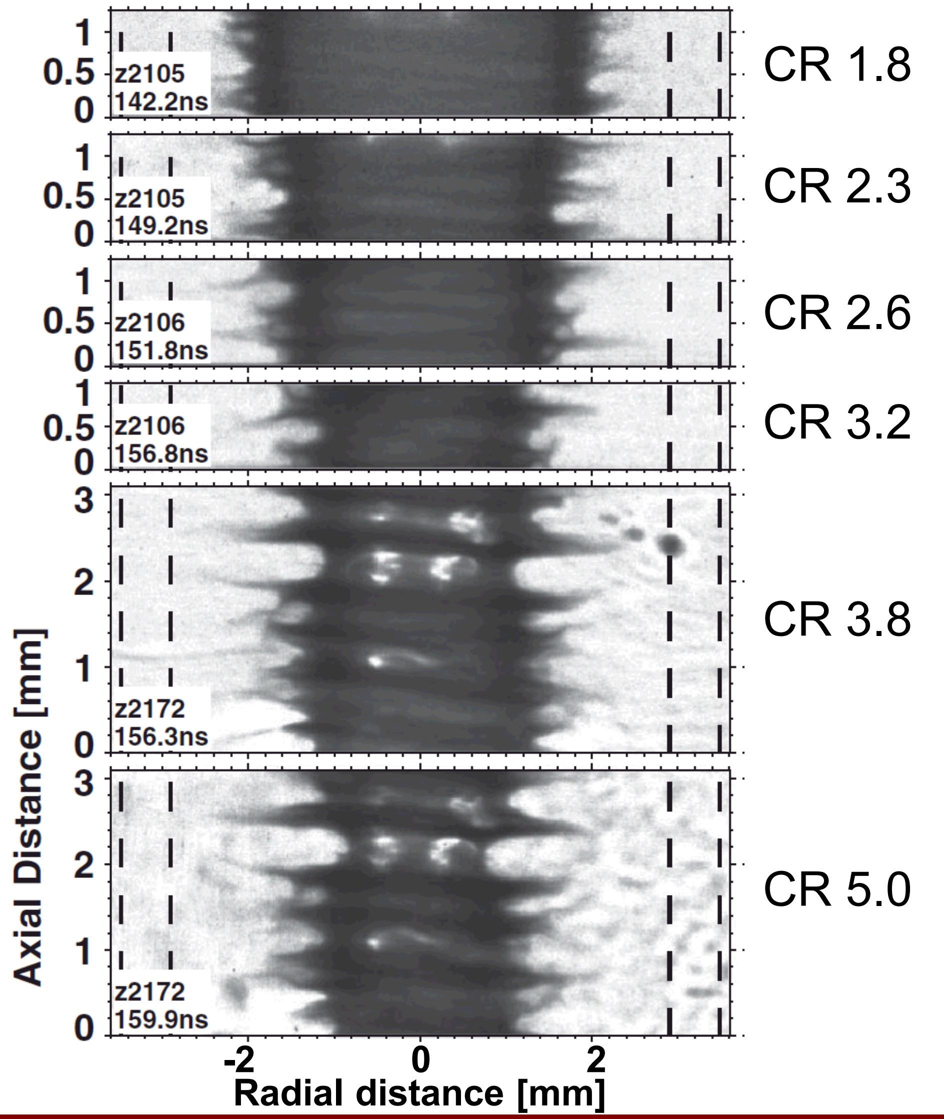
We use a monochromatic x-ray backlighter to check the stability of the implosions



- 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).

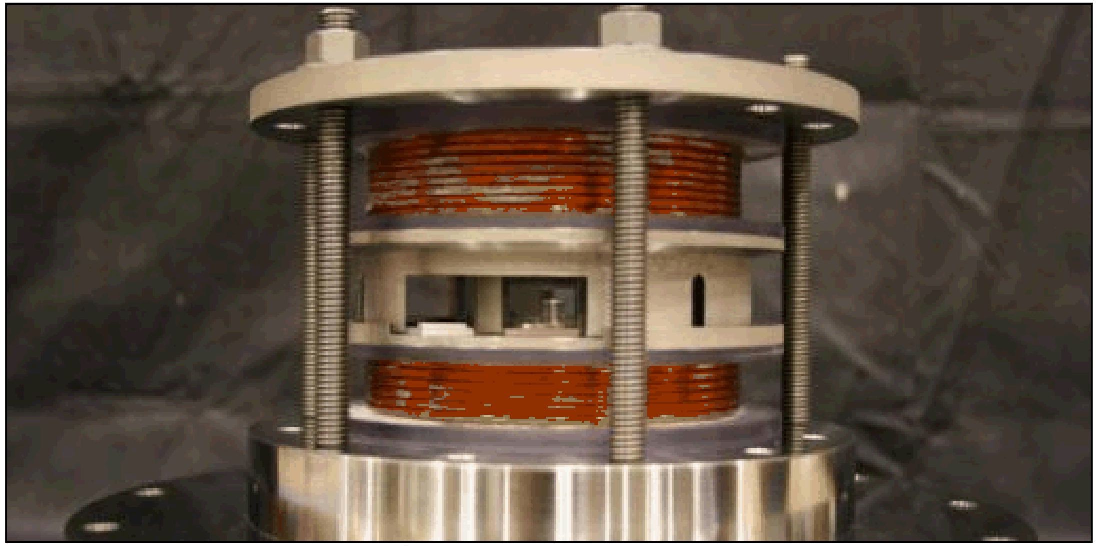
Radiographs throughout the implosion were collected on a series of experiments



- Magneto-Rayleigh-Taylor instabilities develop and grow
  - Azimuthal correlation of instabilities
  - Use thick liners to limit feedthrough to inner surface
  - Massive liners implode on a relatively slow time scale compared to traditional ICF
- Relatively happy with liner stability
  - Inner surface is relatively straight at a convergence ratio of 5
    - 82% of implosion distance to CR 40

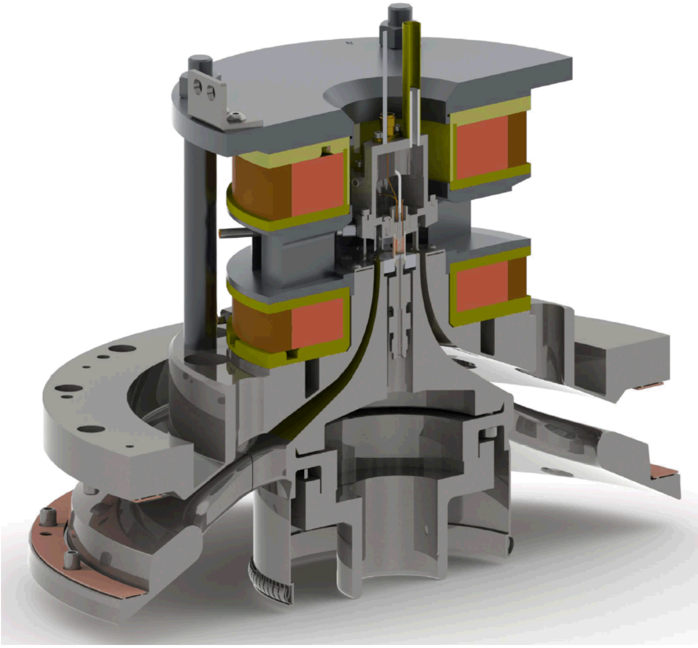
R. D. McBride, et al., Phys. Rev. Lett. 109, 135004 (2012).

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

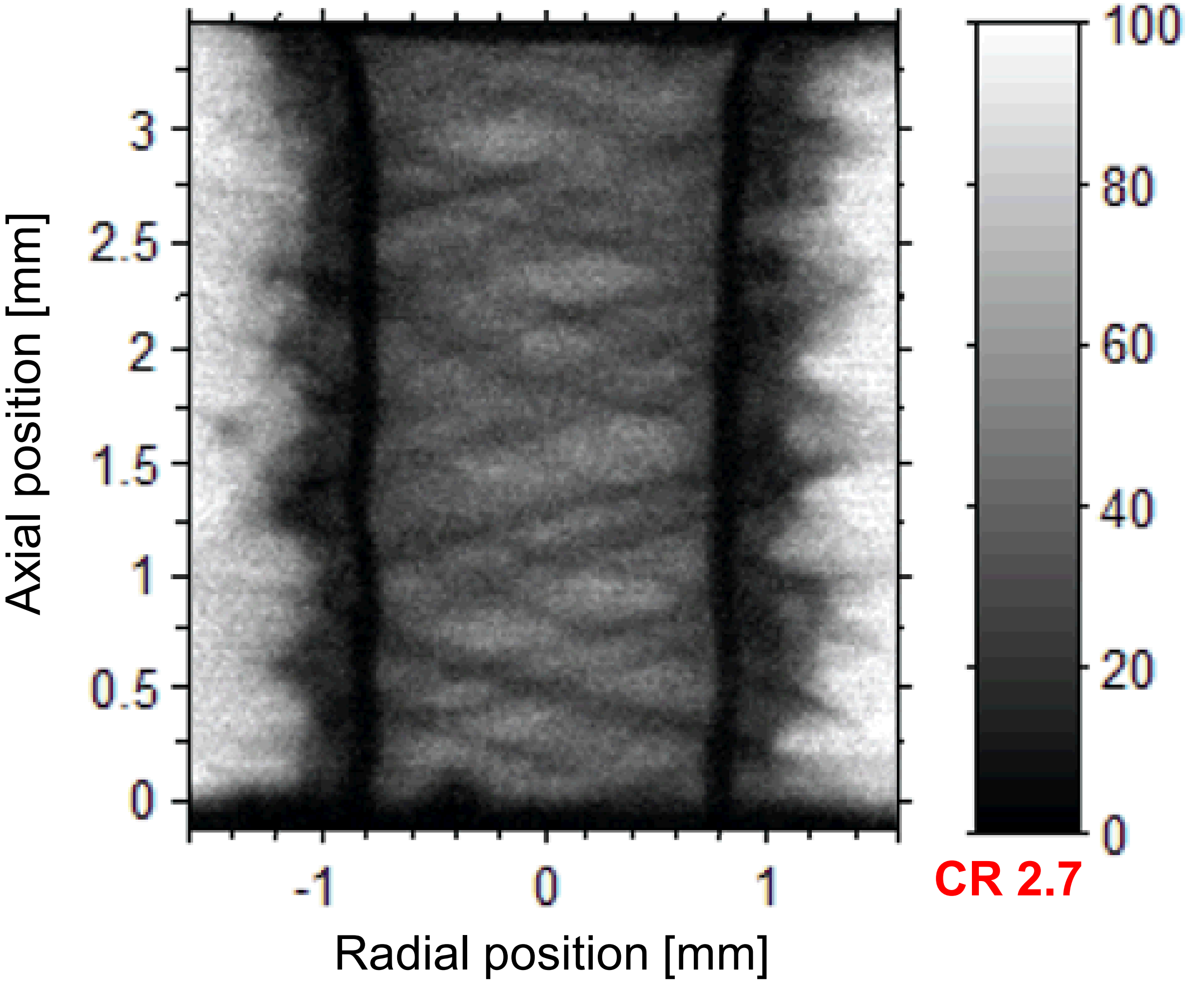


Magnetic field risetime is slow to allow diffusion through conductors

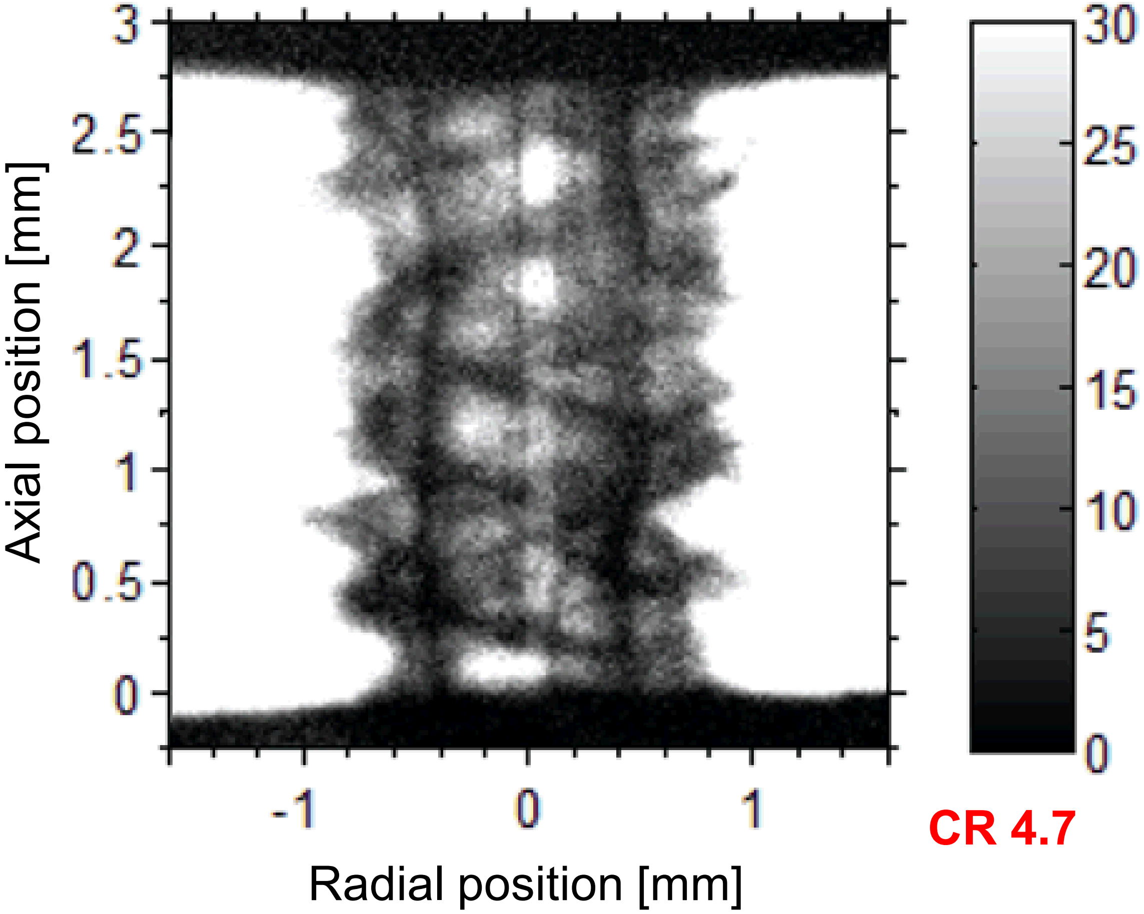
D. C. Rovang, et al., Rev. Sci. Instrum. 85, 124701 (2014).

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

70 kG

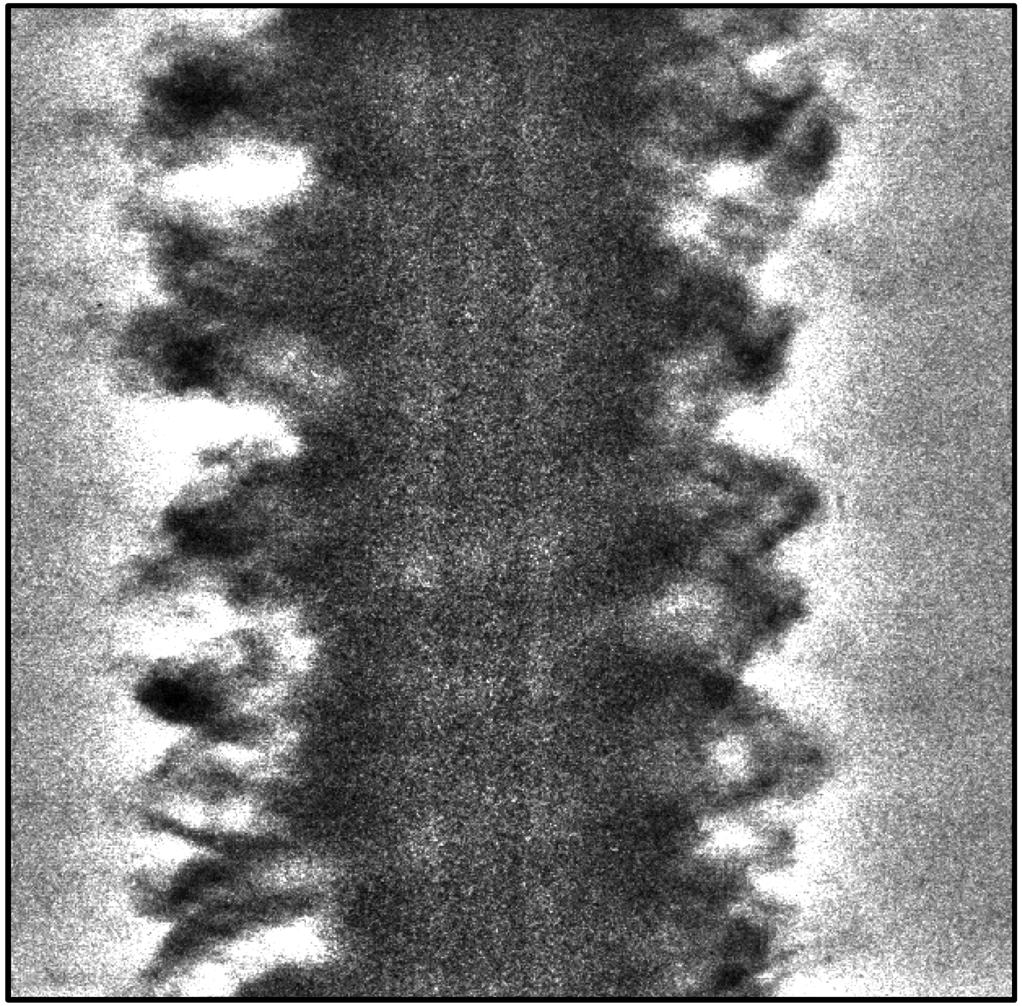


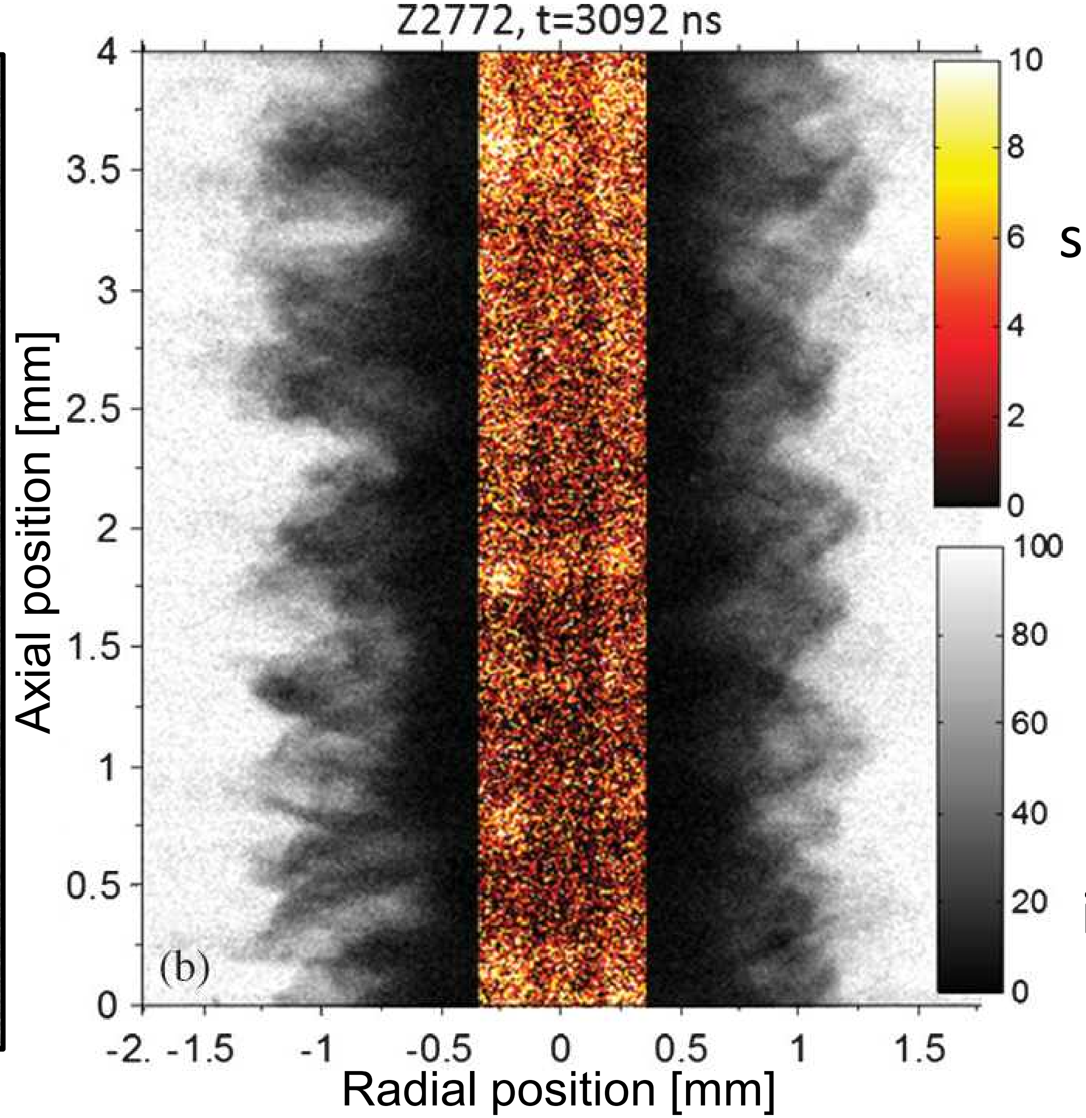
100 kG



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

We obtained a very stable high convergence image with axial magnetic field





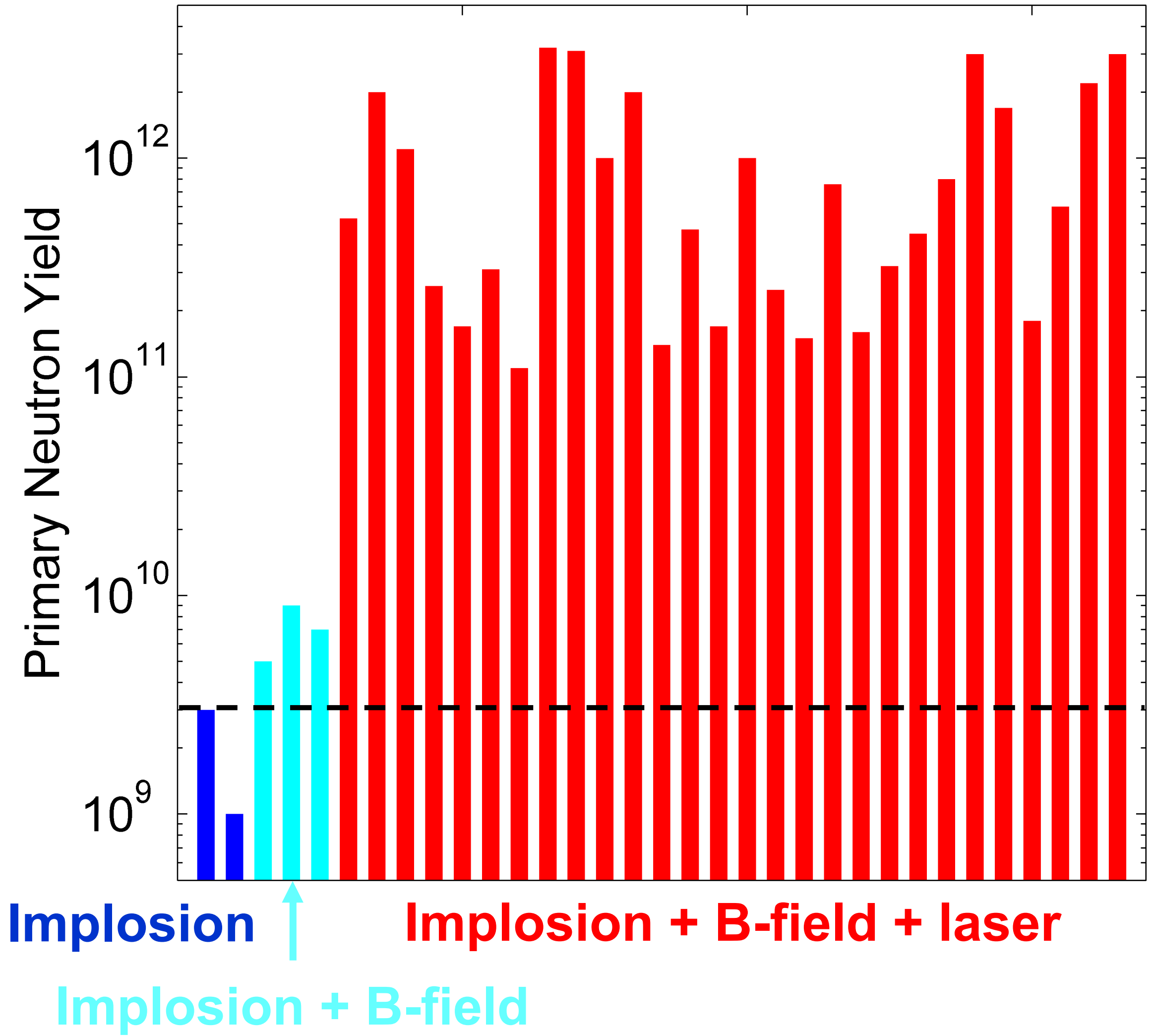
Relatively straight inner surface at CR 20

97% of implosion distance

Move on to experiments including laser heating

T. J. Awe, et al., Phys. Rev. Lett. 116, 065001 (2016).

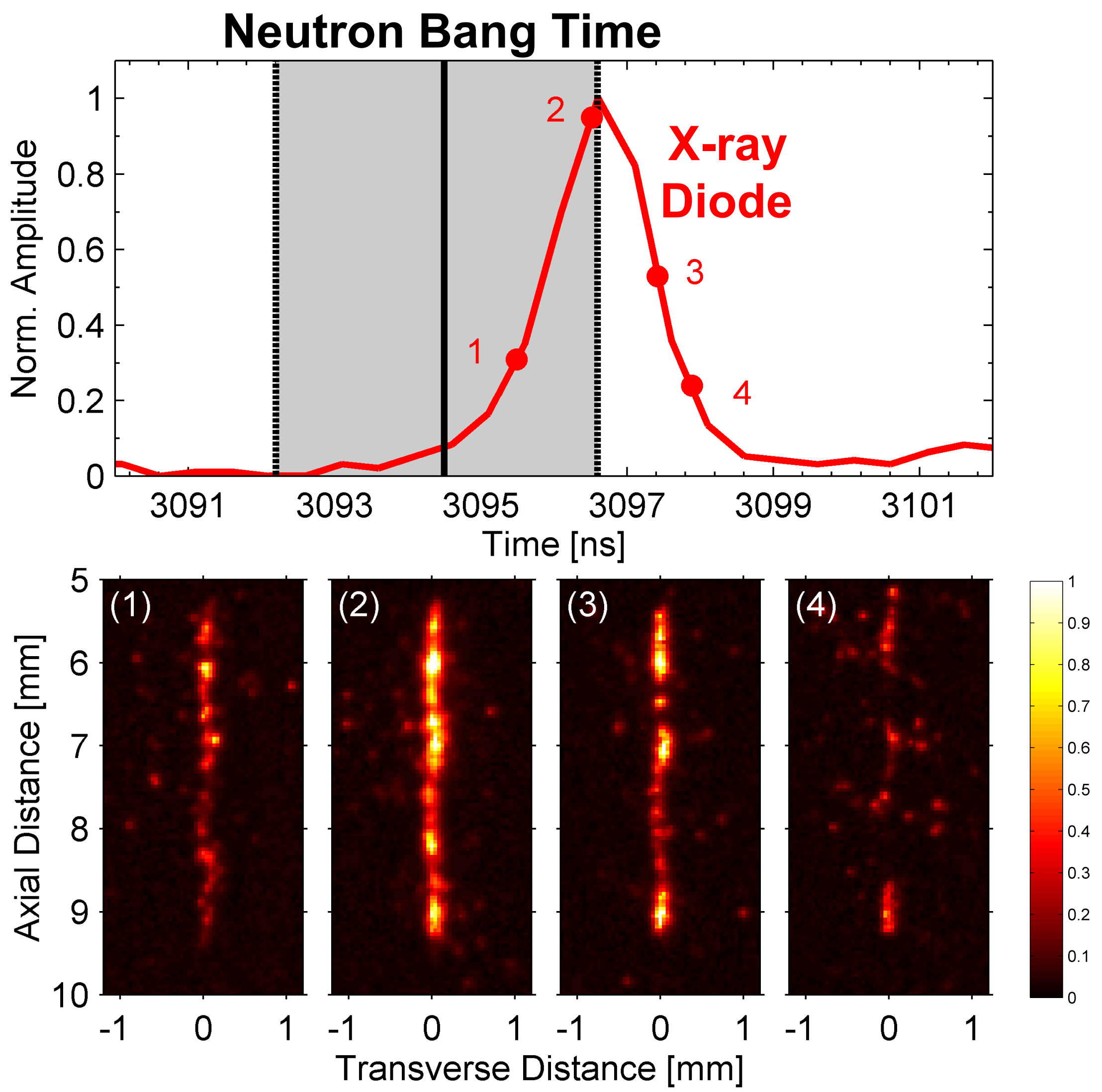
The primary neutron yield is highly dependent on effective magnetization and laser heating



- 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).

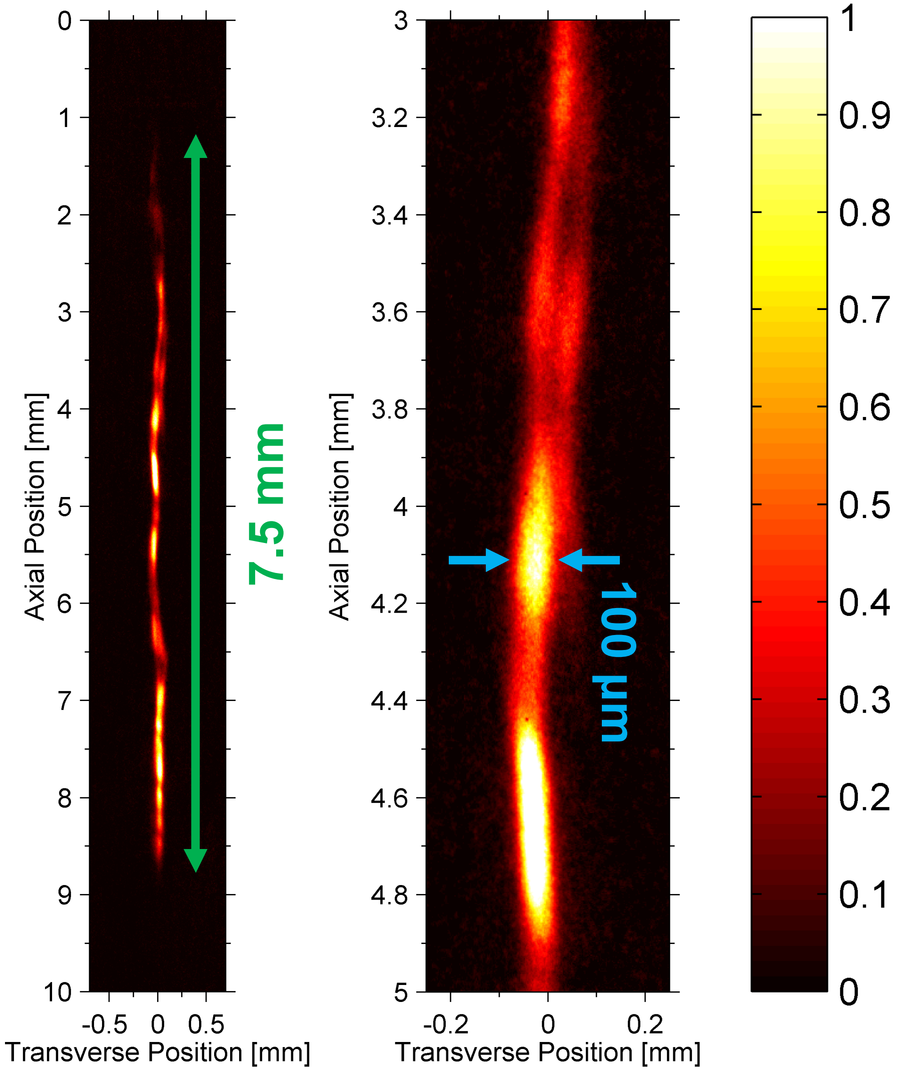
X-ray diodes and time-resolved x-ray pinhole images show the fuel radiating at stagnation



- 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).

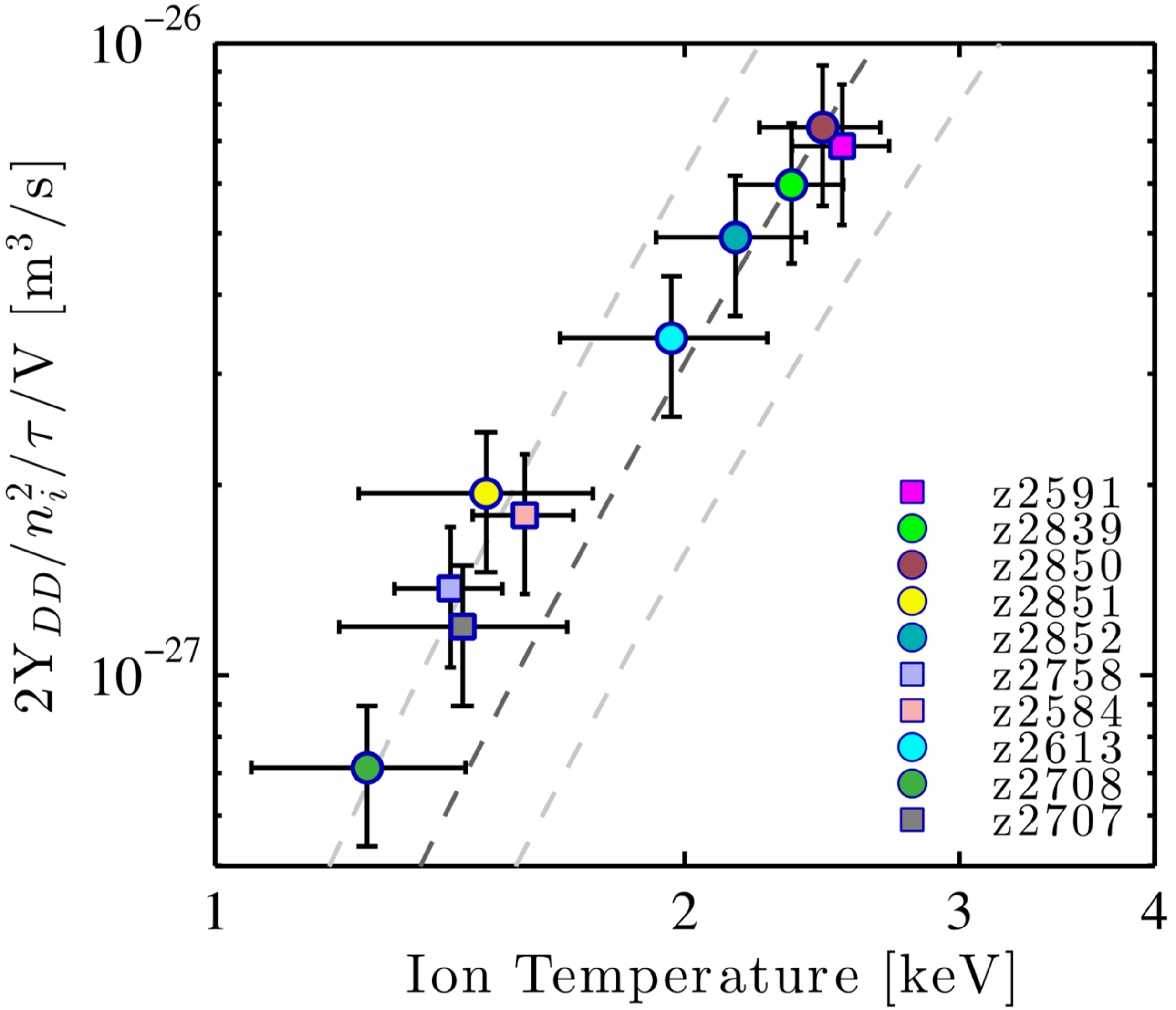
Our spherical crystal imaging system was repurposed to record x-ray emission from the fuel



- 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).

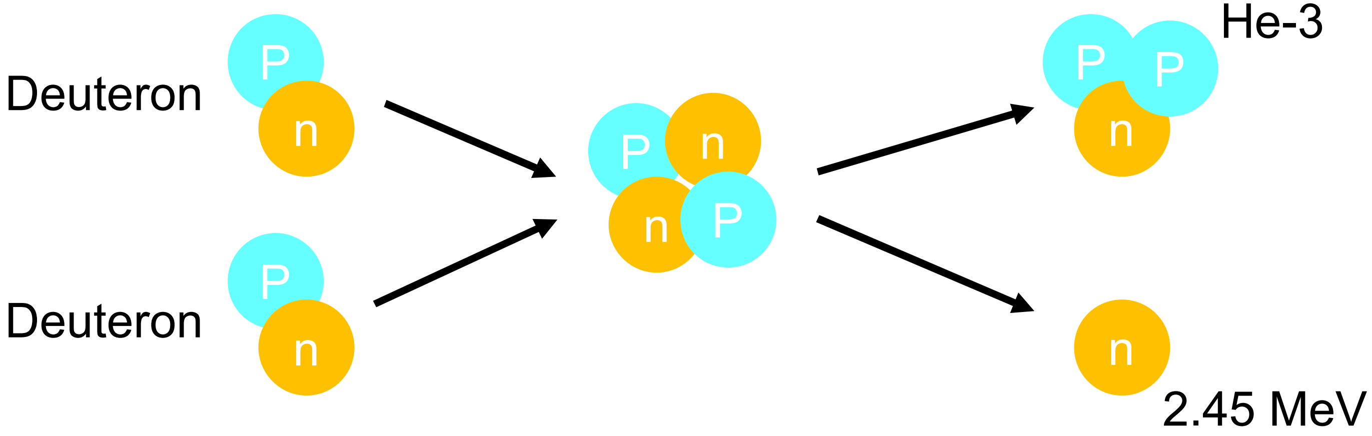
The primary neutron increases as the ion temperature increases



- 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

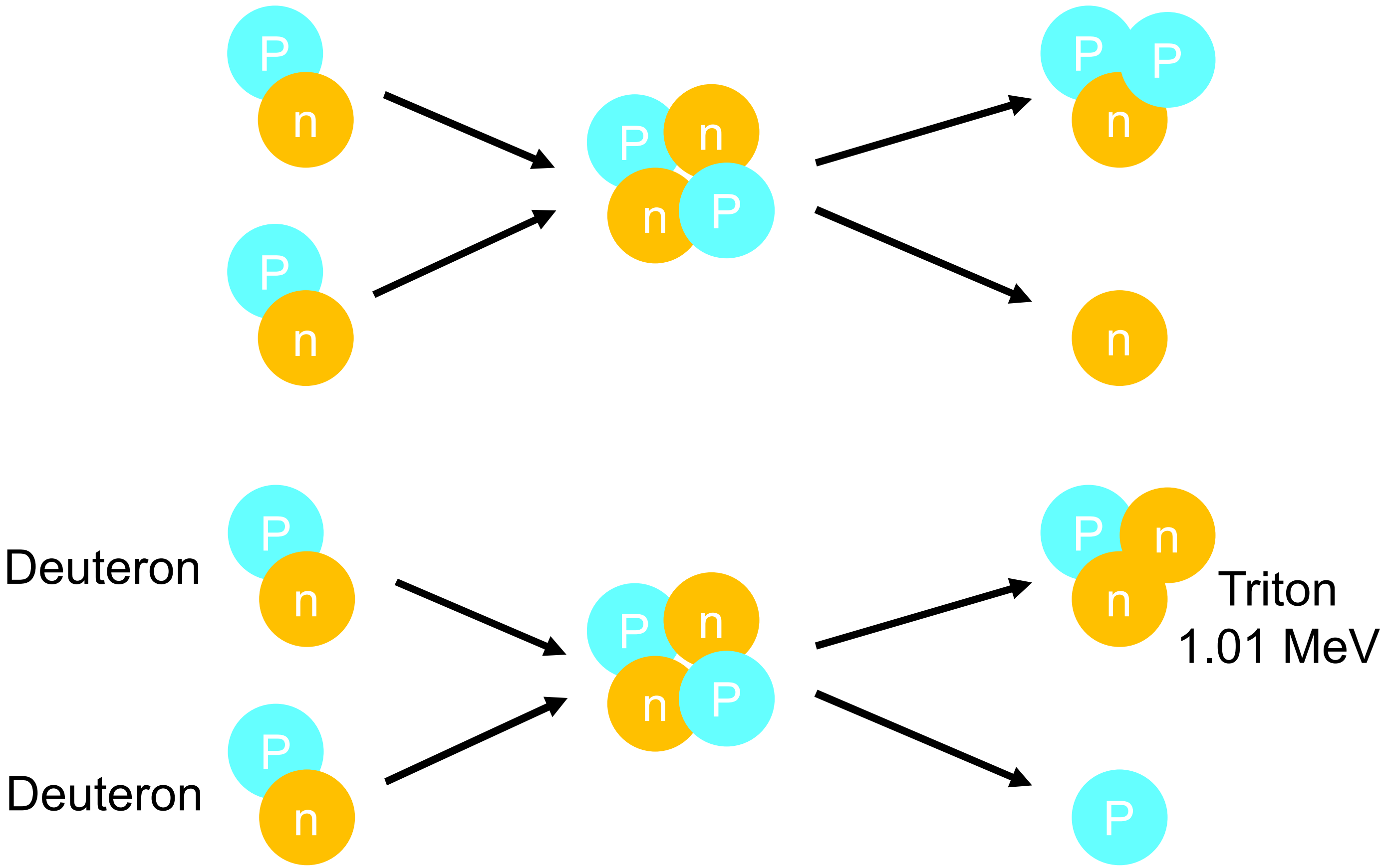
The fuel in these experiments is deuterium gas: one branch produces a neutron…

Primary Reactions

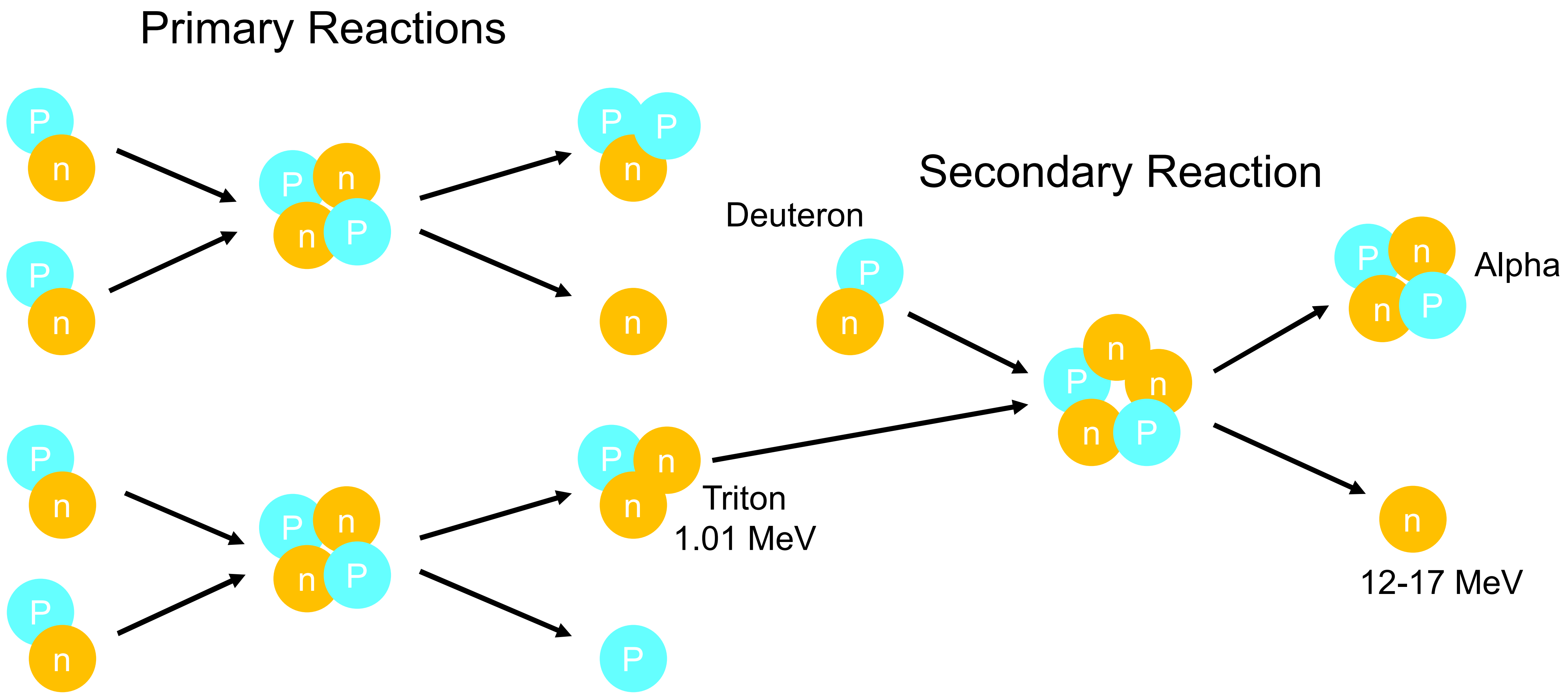


…and the other branch produces a triton…

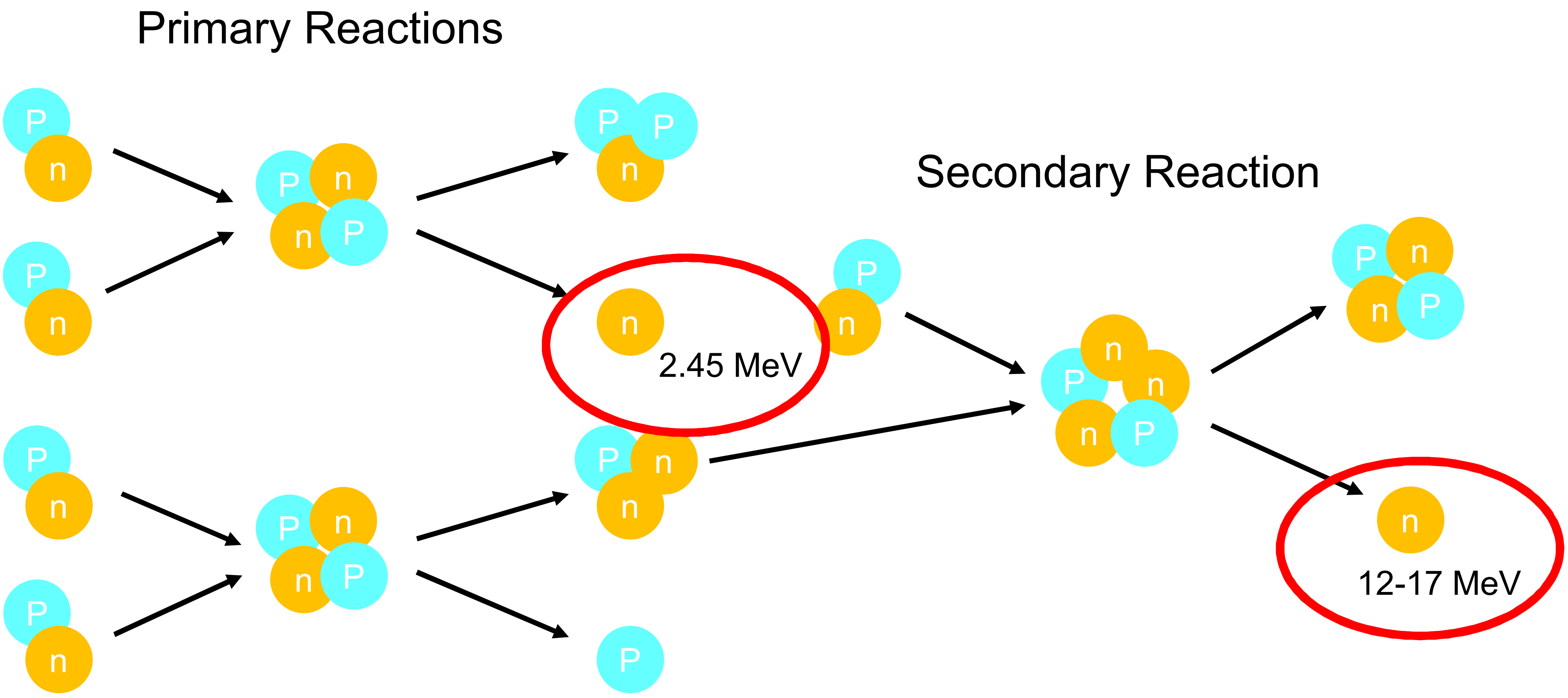
Primary Reactions



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



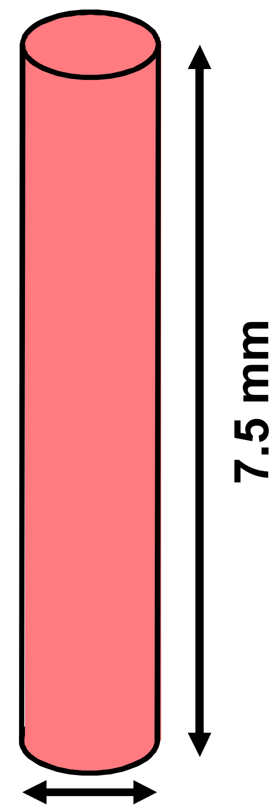
We measure both the primary and secondary neutrons



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

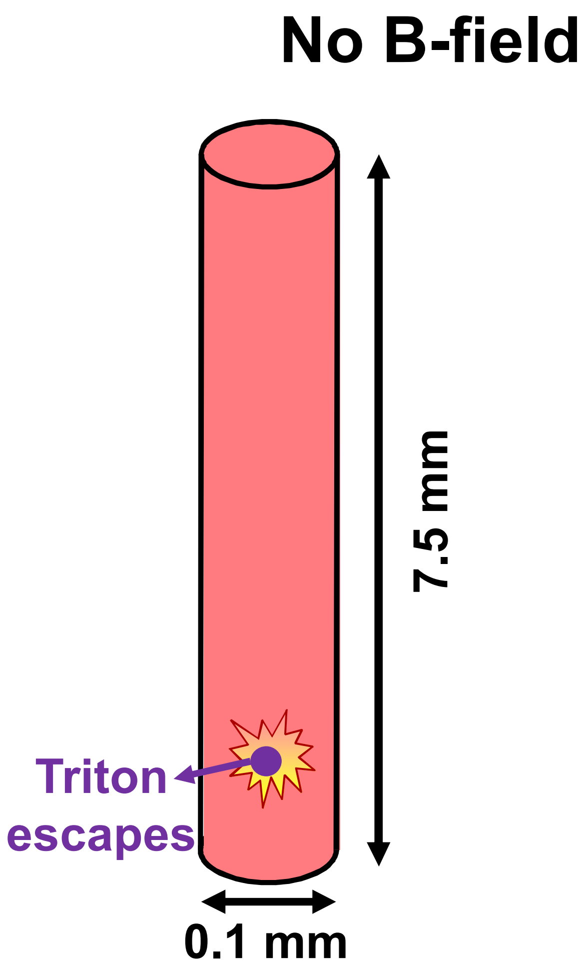
Secondary neutrons are produced when primary tritons react before exiting the fuel

No B-field



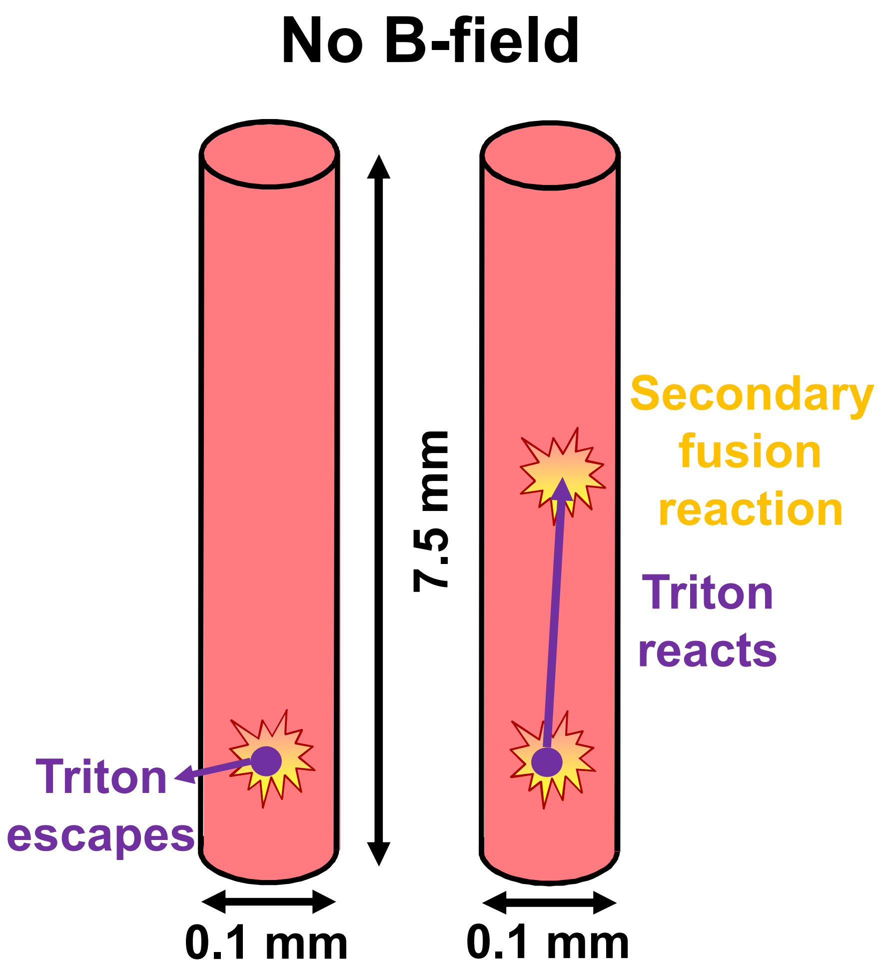
- High aspect ratio stagnation geometry
  - Height >> radius

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



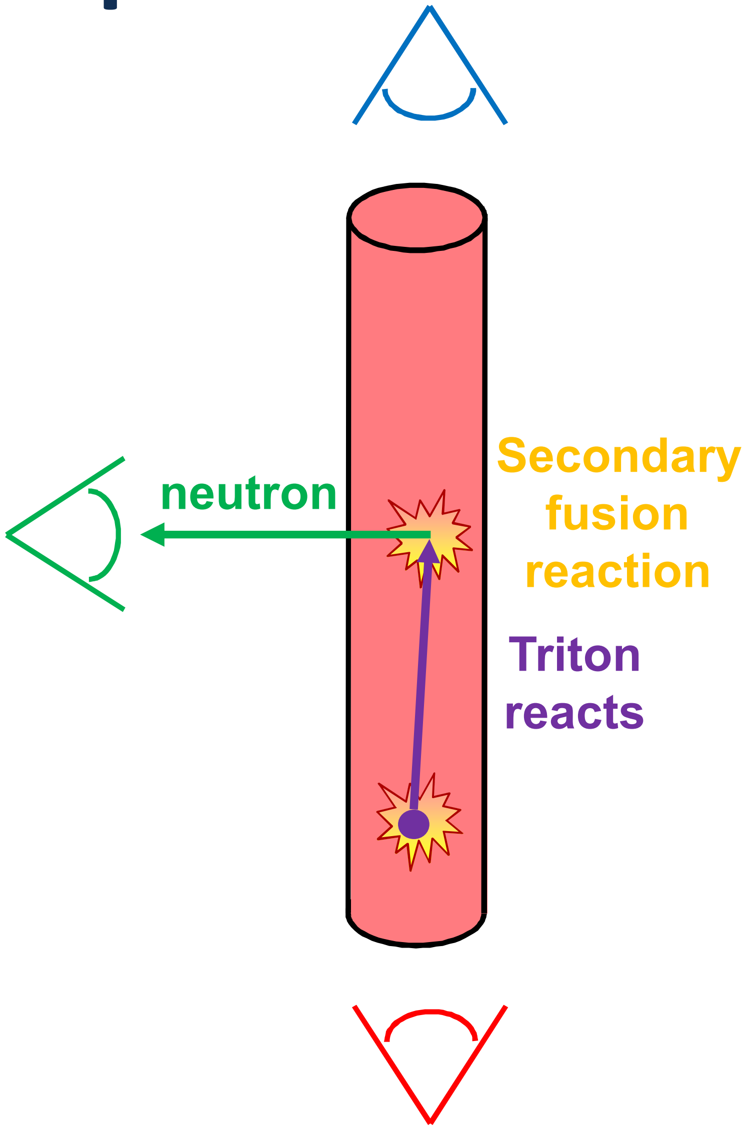
- High aspect ratio stagnation geometry
  - Height >> radius
- Consider 2 cases:
  - 1) Triton is created traveling radially
    - Very little probability of interacting prior to escaping

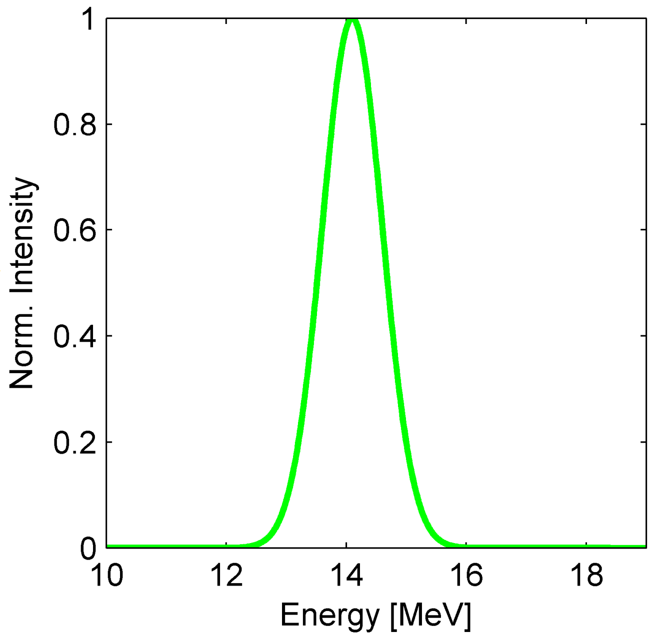
Secondary neutrons are produced when primary tritons react before exiting the fuel



- 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

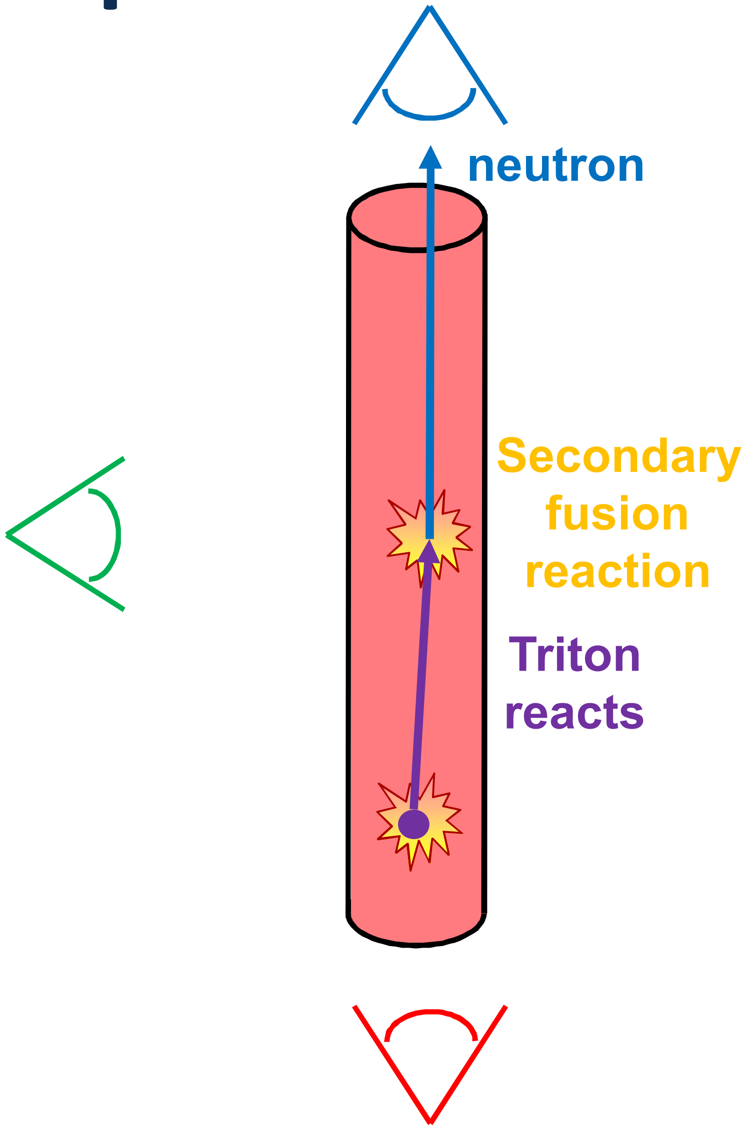
The secondary neutron energy spectra are not expected to be isotropic

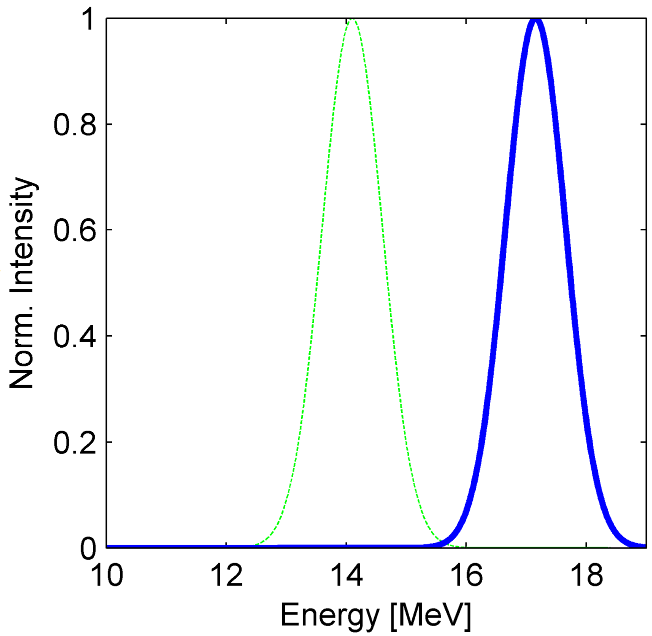




- Consider 3 detector locations:
  - Radial
    - Neutrons at nominal energy

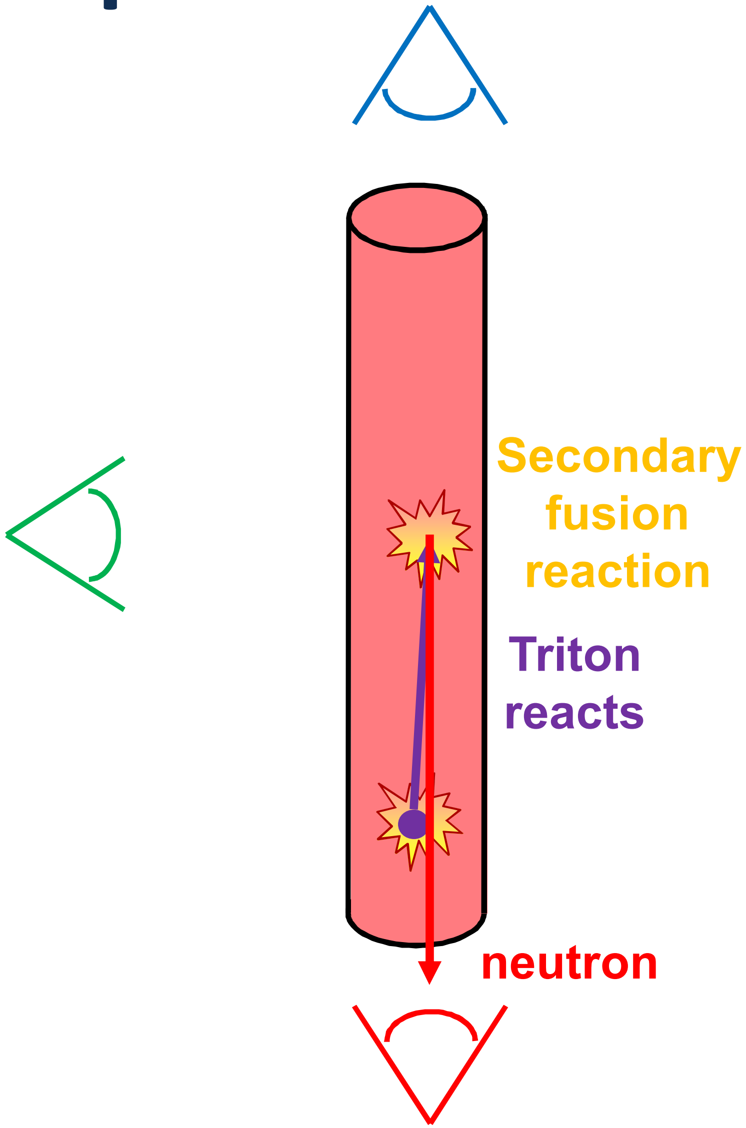
The secondary neutron energy spectra are not expected to be isotropic

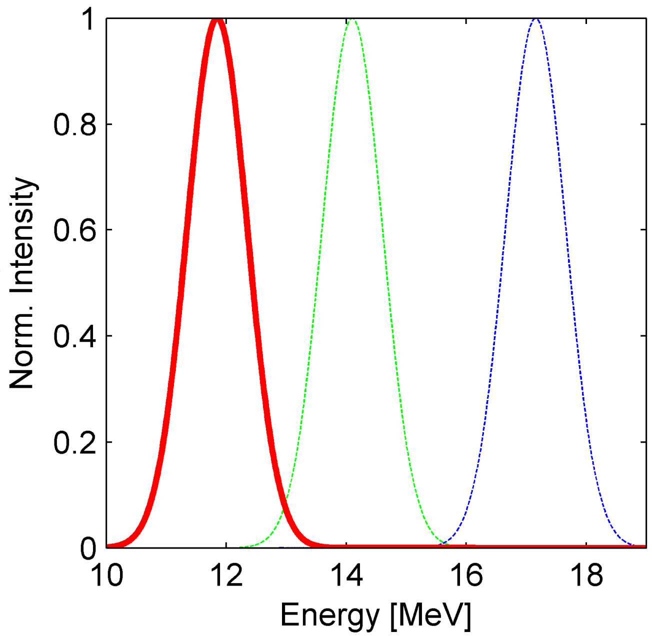




- Consider 3 detector locations:
  - Radial
    - Neutrons at nominal energy
  - Axial (triton moving towards)
    - Neutrons shifted to higher energy

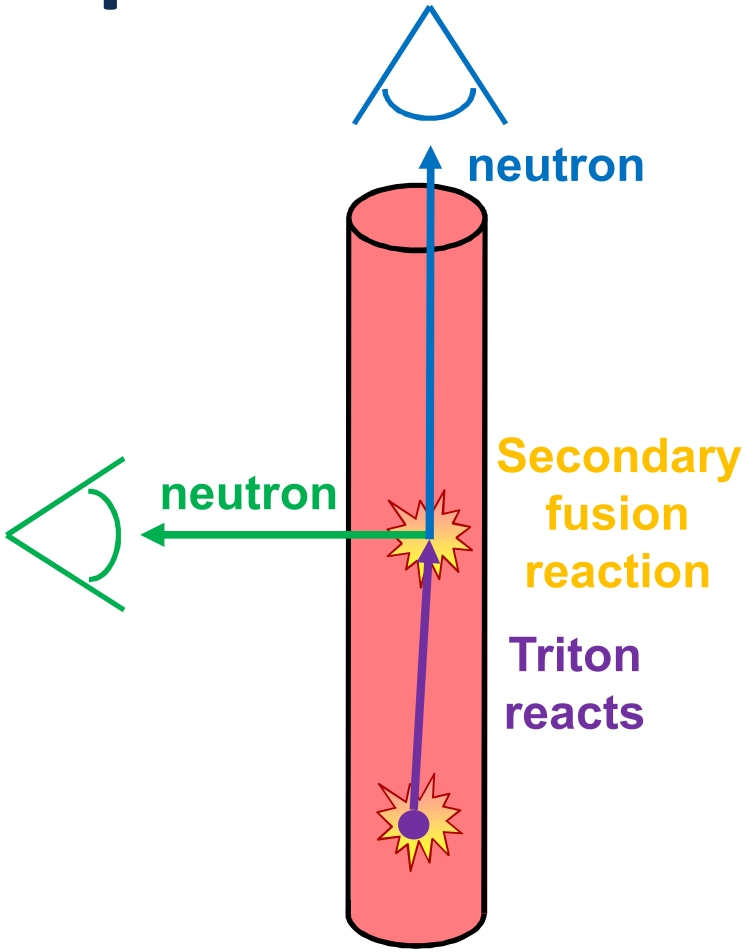
The secondary neutron energy spectra are not expected to be isotropic

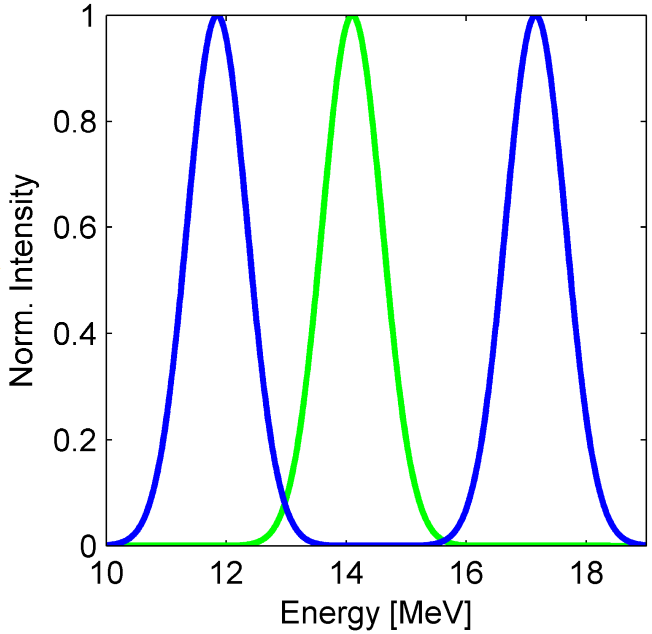




- Consider 3 detector locations:
  - Radial
    - Neutrons at nominal energy
  - Axial (triton moving towards)
    - Neutrons shifted to higher energy
  - Axial (triton moving away)
    - Neutrons shifted to lower energy

The secondary neutron energy spectra are not expected to be isotropic

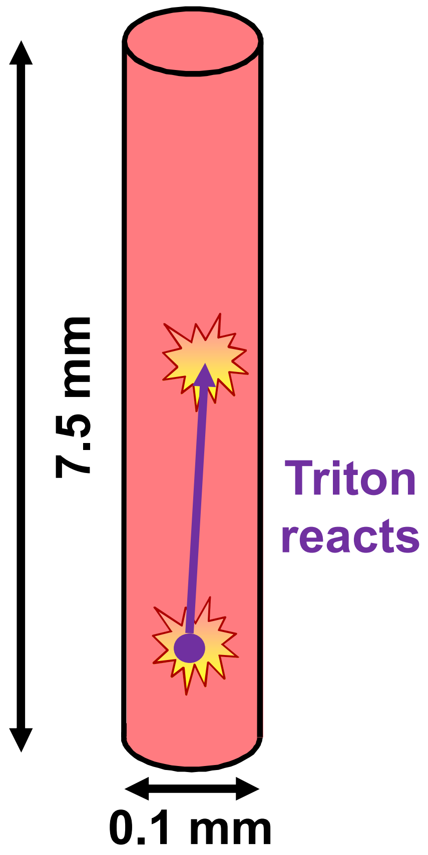




- Consider 3 detector locations:
  - Radial
    - Neutrons at nominal energy
  - Axial (triton moving towards)
    - Neutrons shifted to higher energy
  - Axial (triton moving away)
    - Neutrons shifted to lower energy
- Axial detectors will have double peaked structure

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

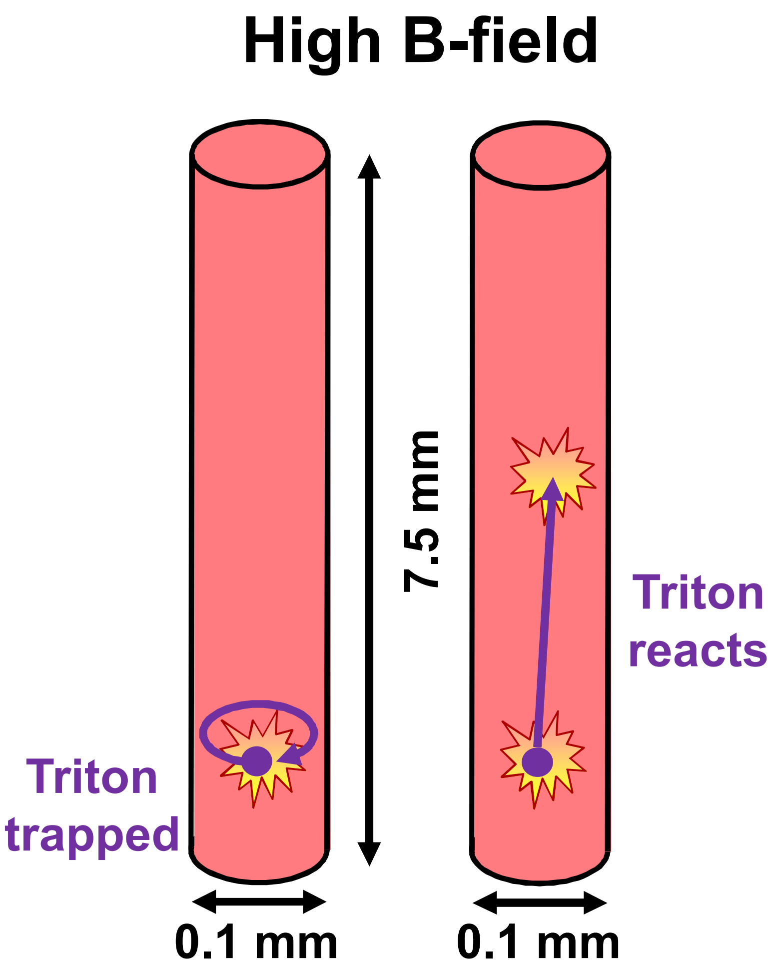
High B-field



- 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

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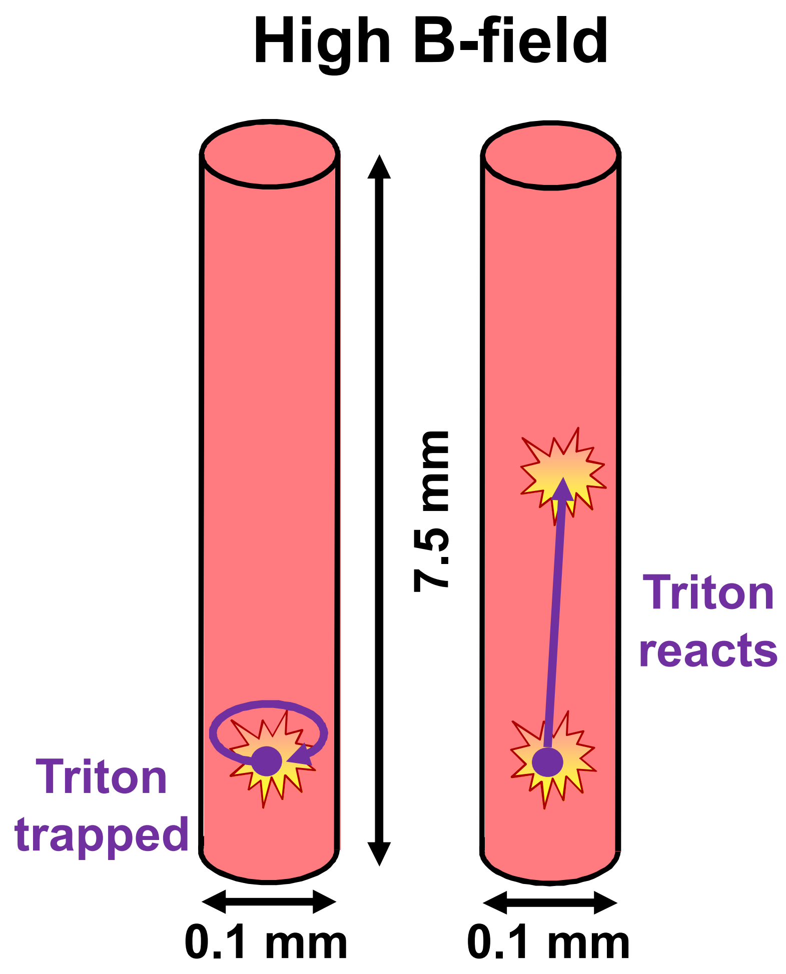

- Consider 2 cases:
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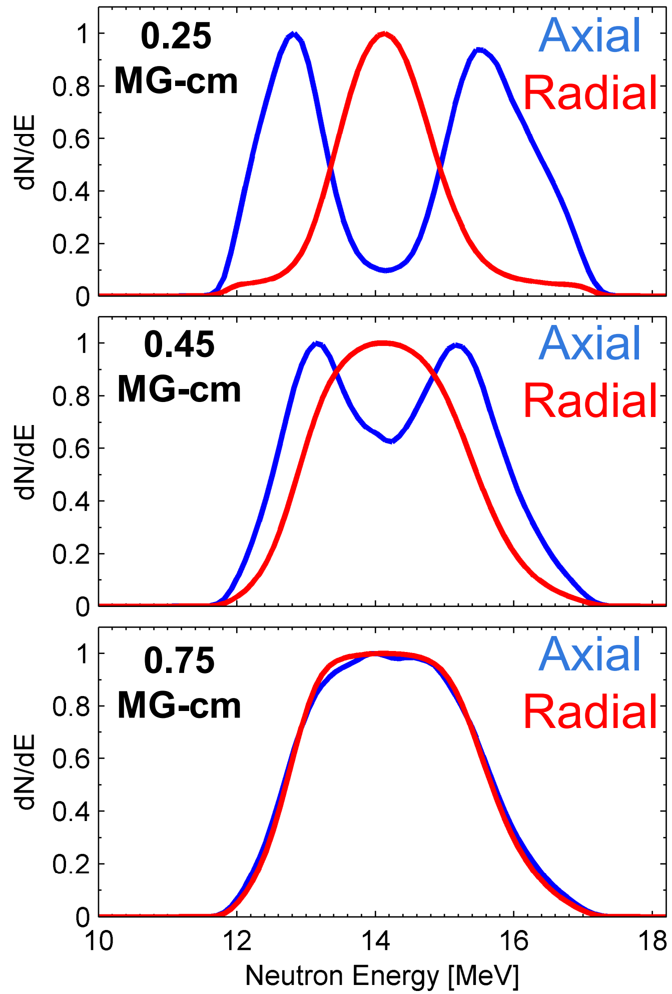
    - Triton has a high probability of fusion
  - 2) Triton is created traveling radially
    - Axial magnetic field traps triton within fuel volume
    - Triton has a high probability of fusion
- With a high enough magnetic field, all tritons have equal probability of secondary fusion

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

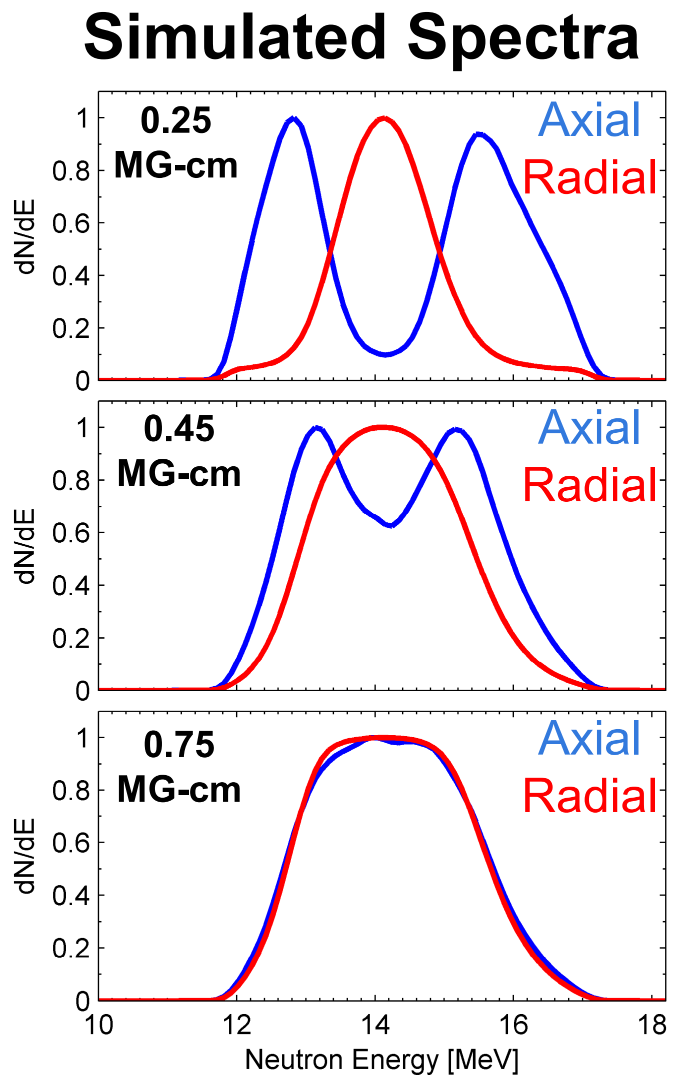


- As the magnetic field increases, a greater fraction of the radially directed tritons are trapped

- 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).

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



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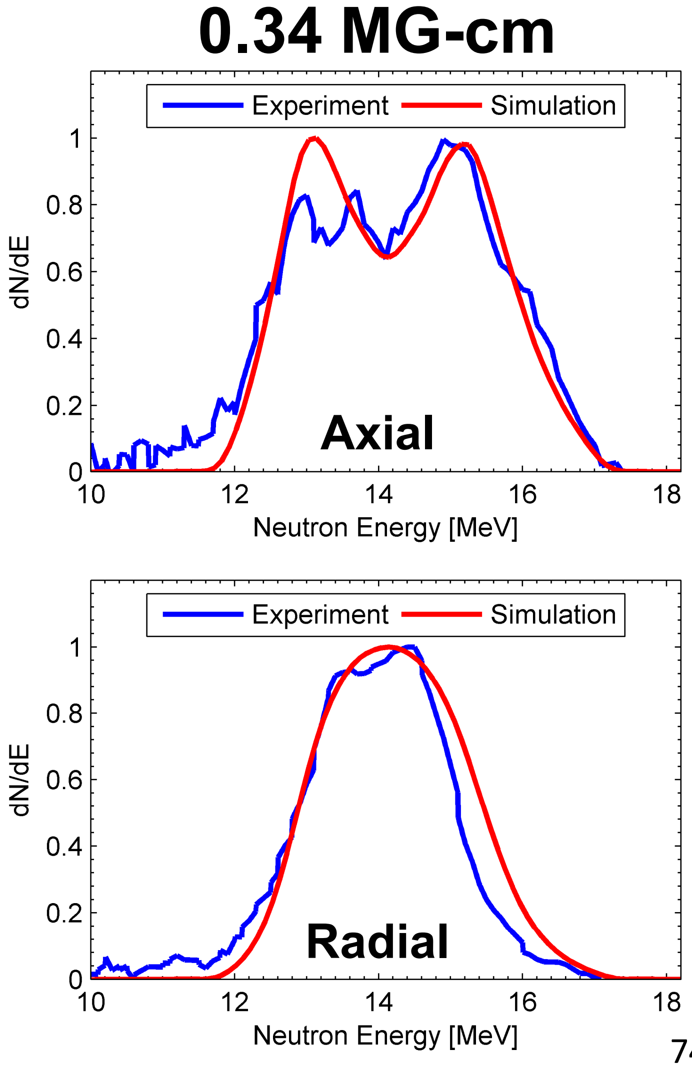
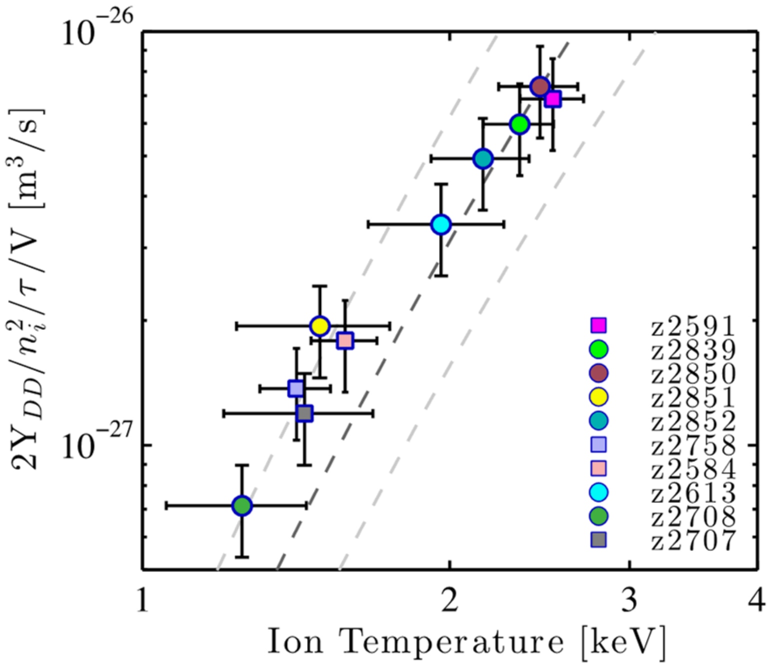
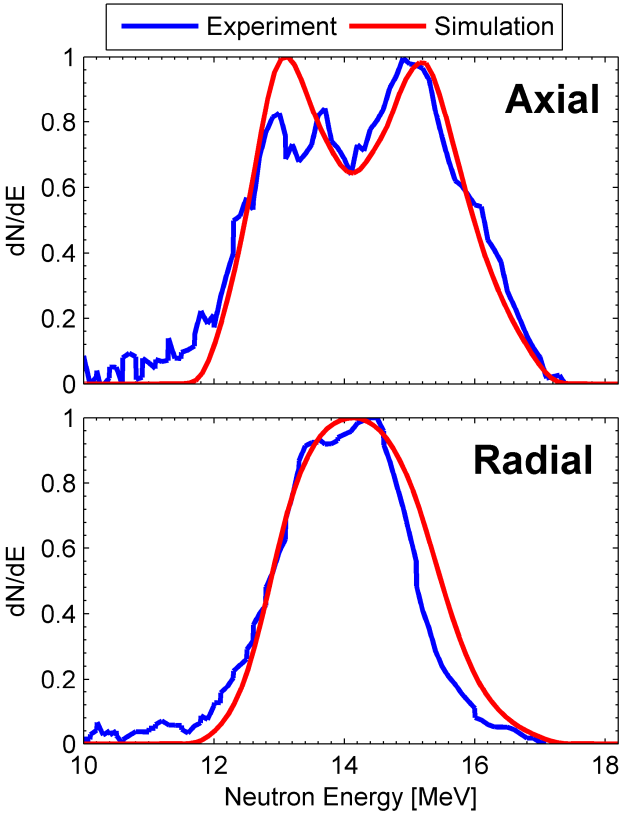


P. F. Schmit, et al., Phys. Rev. Lett. 113, 155004 (2014).

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

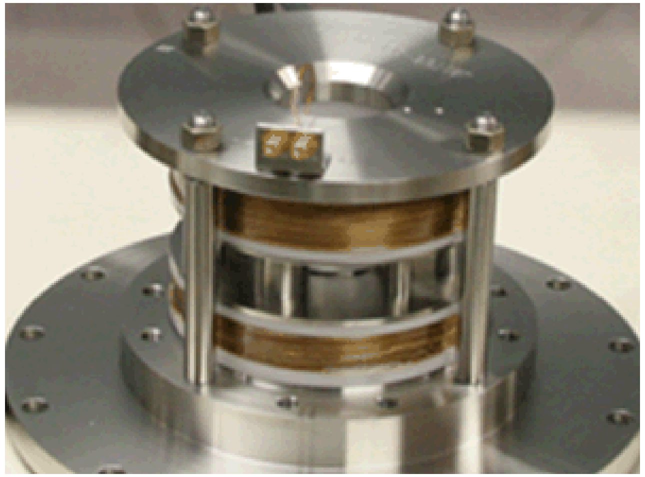
We have a thermonuclear plasma with high magnetic field



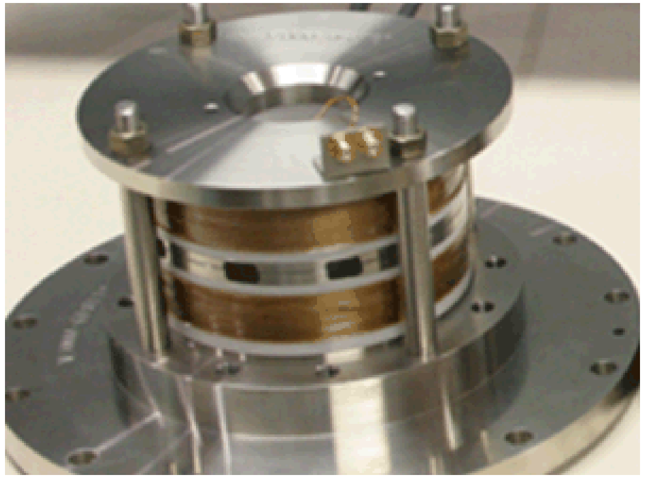


- Best performing experiment produced 0.4-0.9 kJ (DT equivalent)
- We are within a factor of a few of our goal for each of the stagnation conditions
- Based on reasonable improvements to the magnetic field, drive current, and laser we think we can get to at least 10 kJ
  - Simulations indicate we could exceed 100 kJ

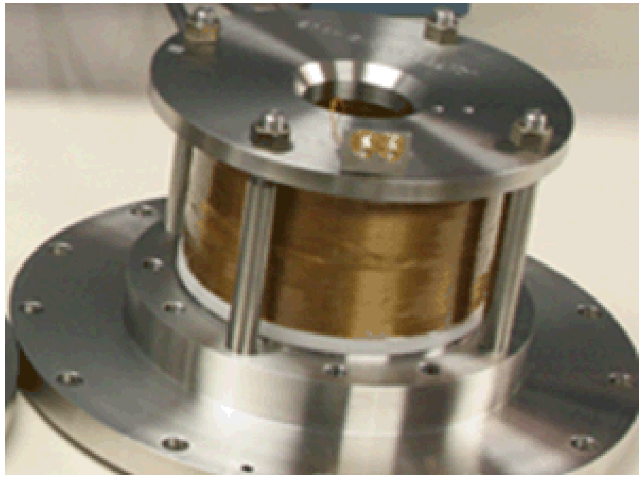
Increasing the axial magnetic field is straight forward, but limits diagnostic access



100 kG



200 kG



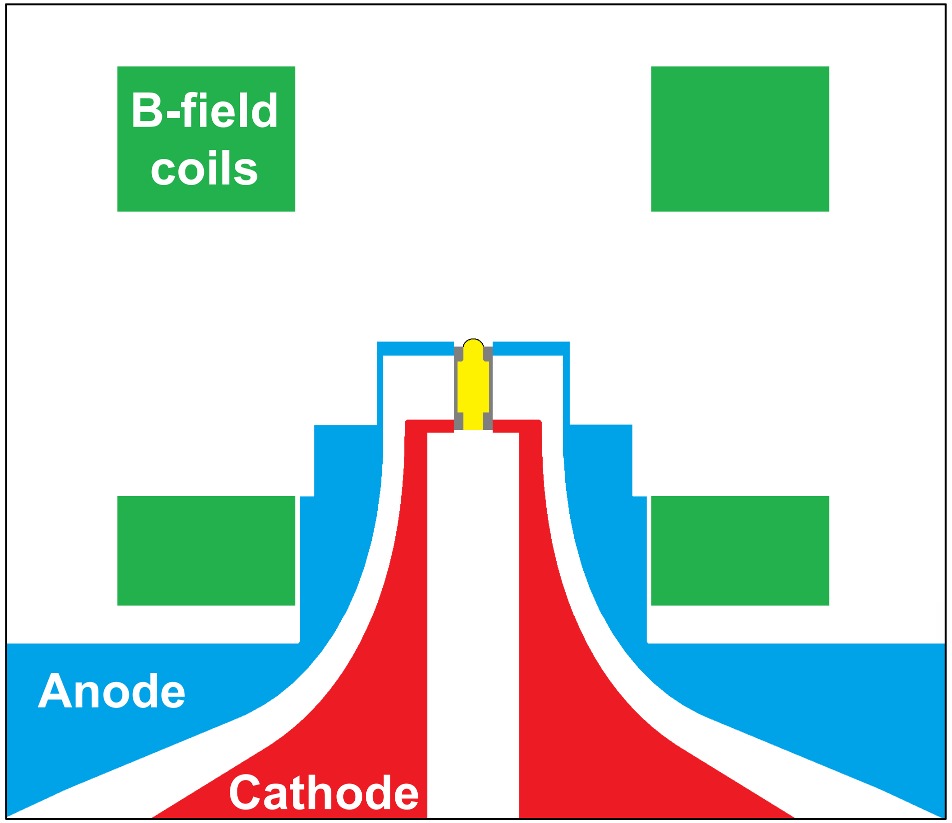
300 kG

- 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

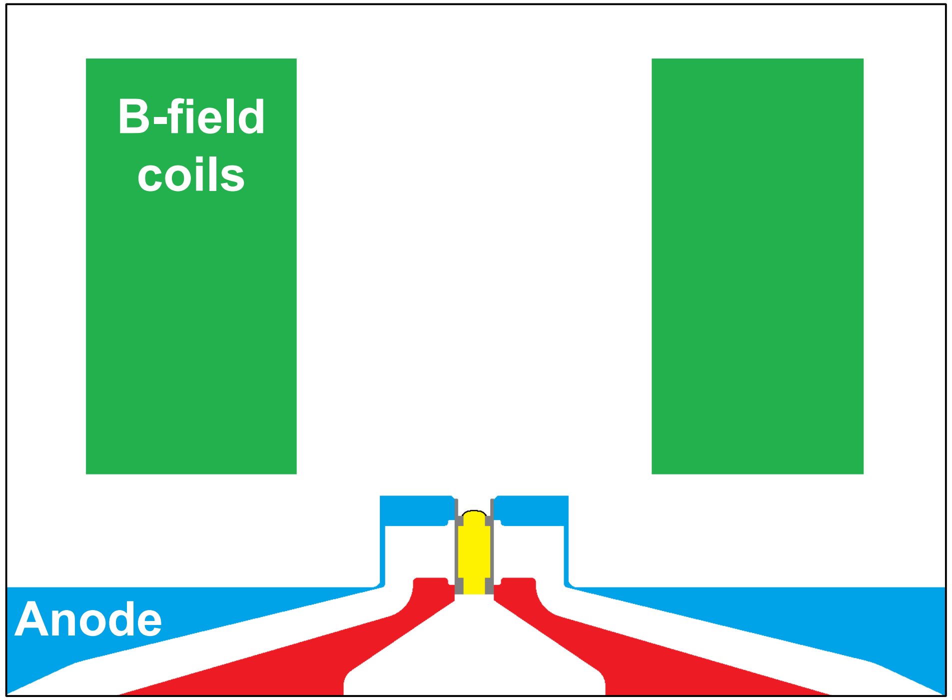
D. C. Rovang, et al., Rev. Sci. Instrum. 85, 124701 (2014).

We have demonstrated increased current delivery with lower inductance designs

Standard Transmission Line (7 nH)



New Transmission Line (4.5 nH)



Cathode

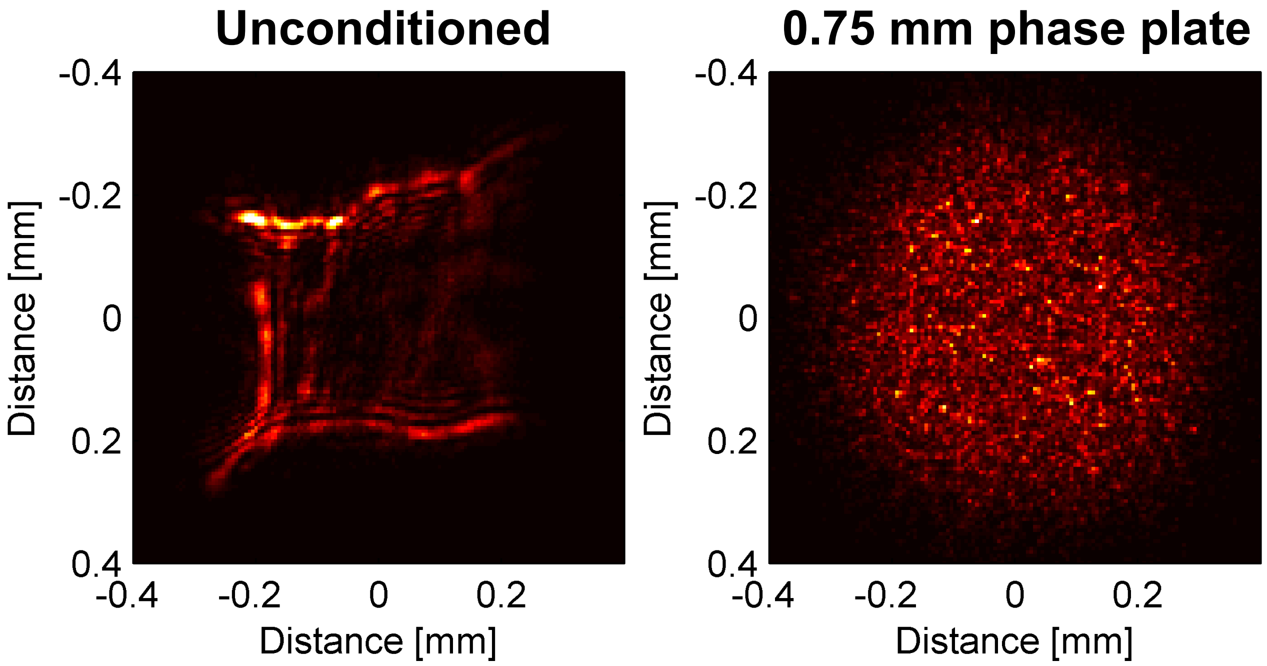
Peak load current 17 MA

Peak load current 20 MA

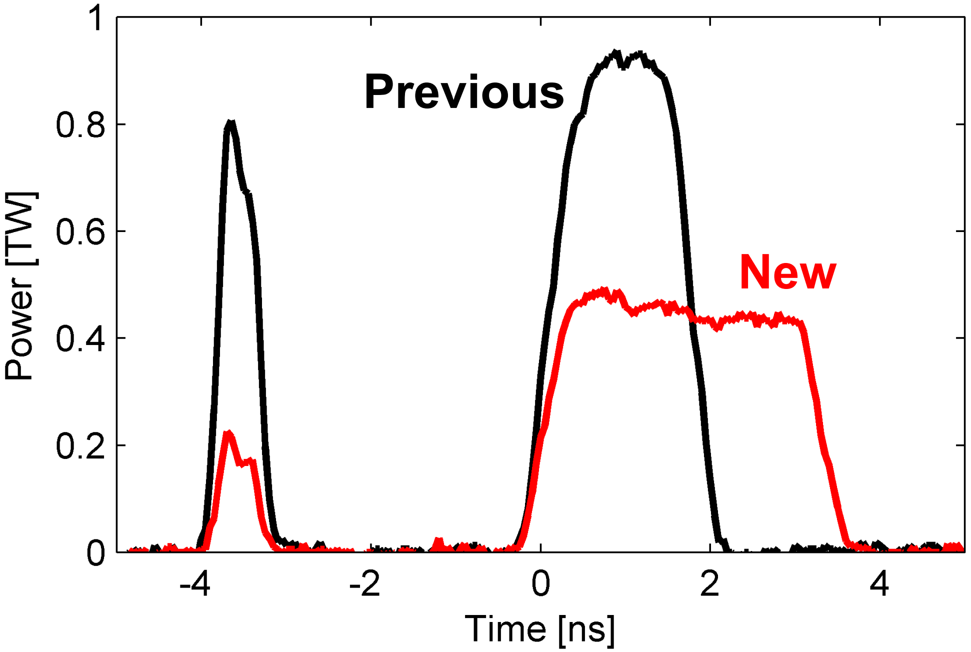
We are developing strategies to improve laser coupling to the fuel

Sandia National Laboratories

We are now testing beam smoothing with phase plates



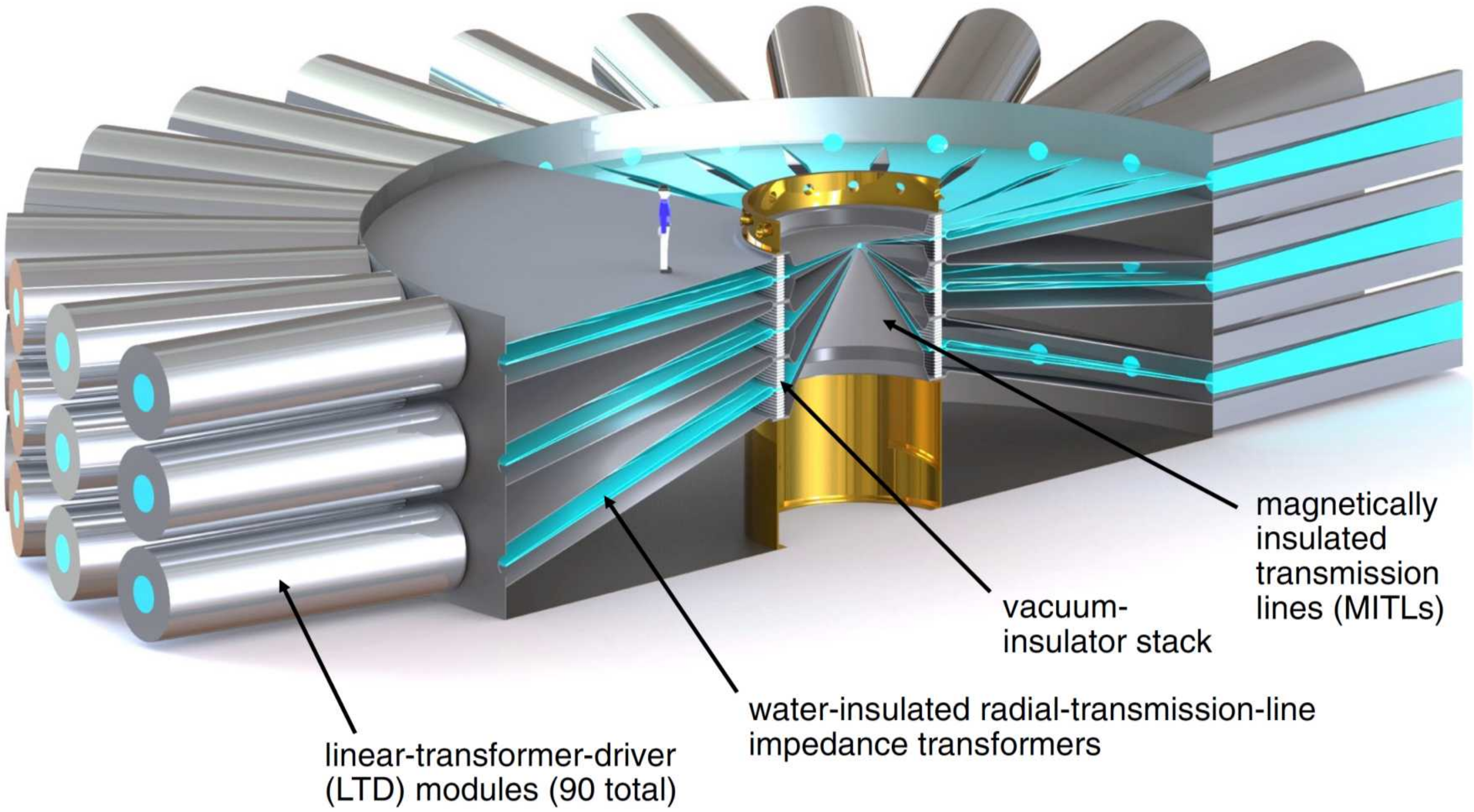
We reduced laser power while maintaining energy



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

We'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 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

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*

R.R. Paguio, D.G. Schroen, K. Tomlinson, *General Atomics*

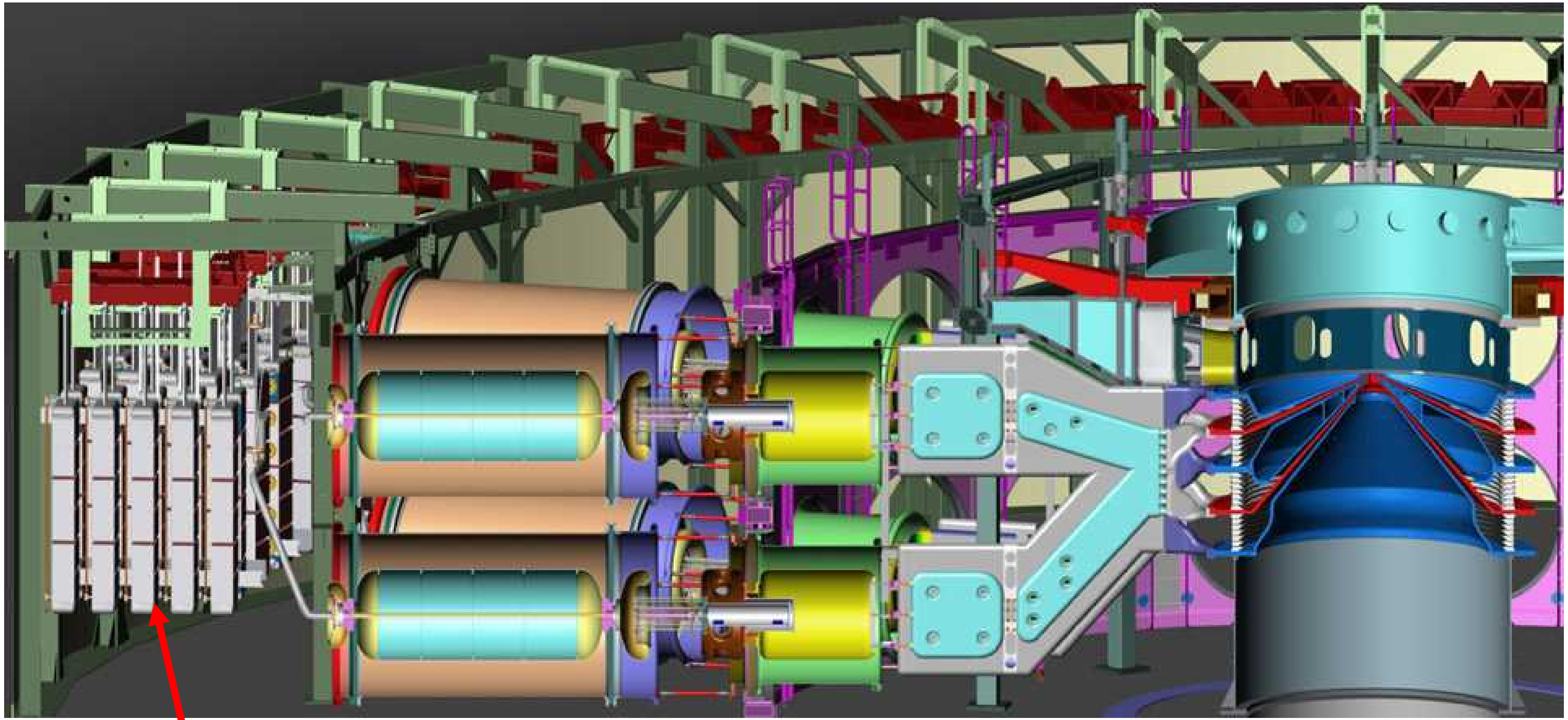
B.E. Blue, M.C. Herrmann, *Lawrence Livermore National Laboratories*

R.D. McBride, *University of Michigan*

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

Thank you for your attention, any questions?

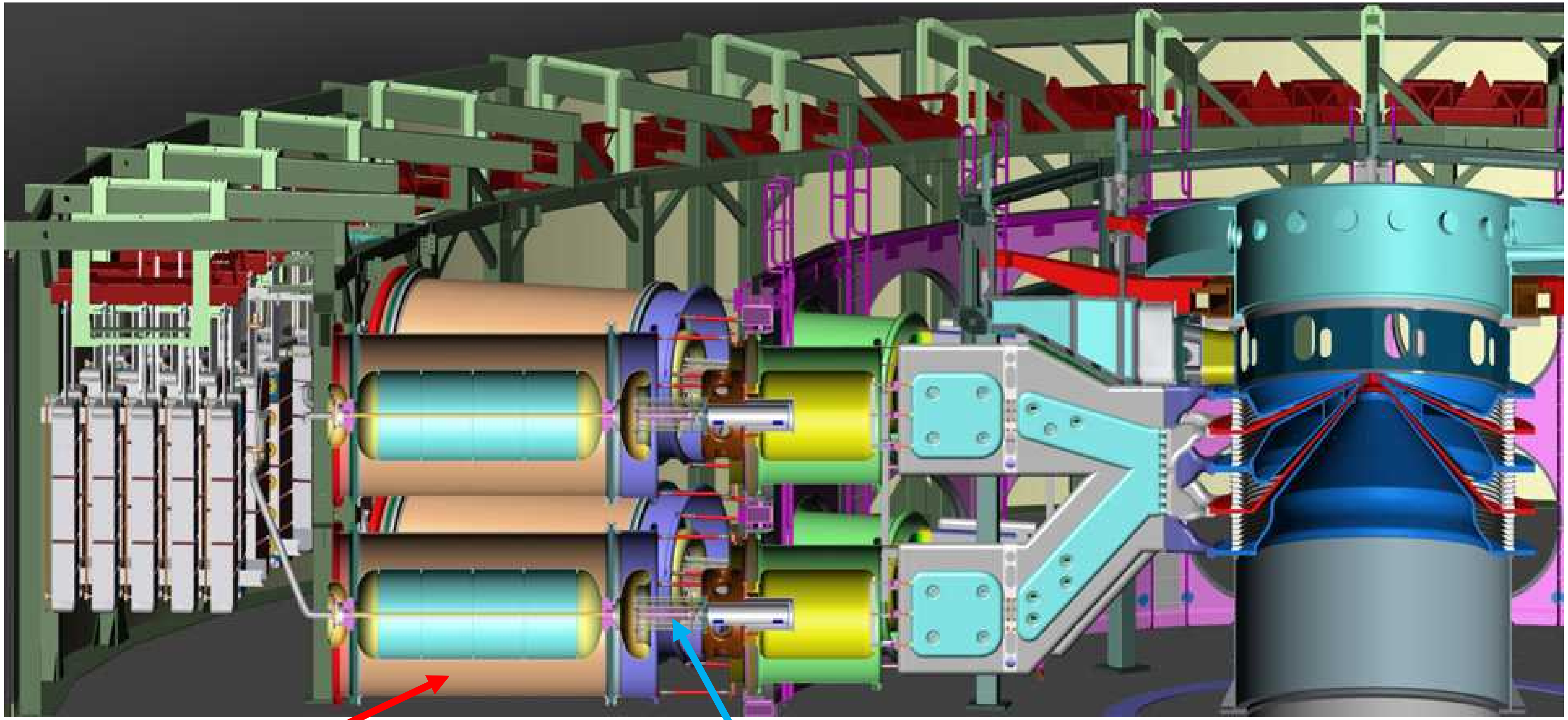
The Z machine uses Marx banks to generate high voltage electrical pulses



Marx bank

- Each Marx bank has 60 capacitors
- Each capacitor is charged to 85 kV
- **Output voltage is > 5 MV**
- 36 Mark bank outputs are parallelized to increase current

We use pulse compression stages to reduce the risetime of the current

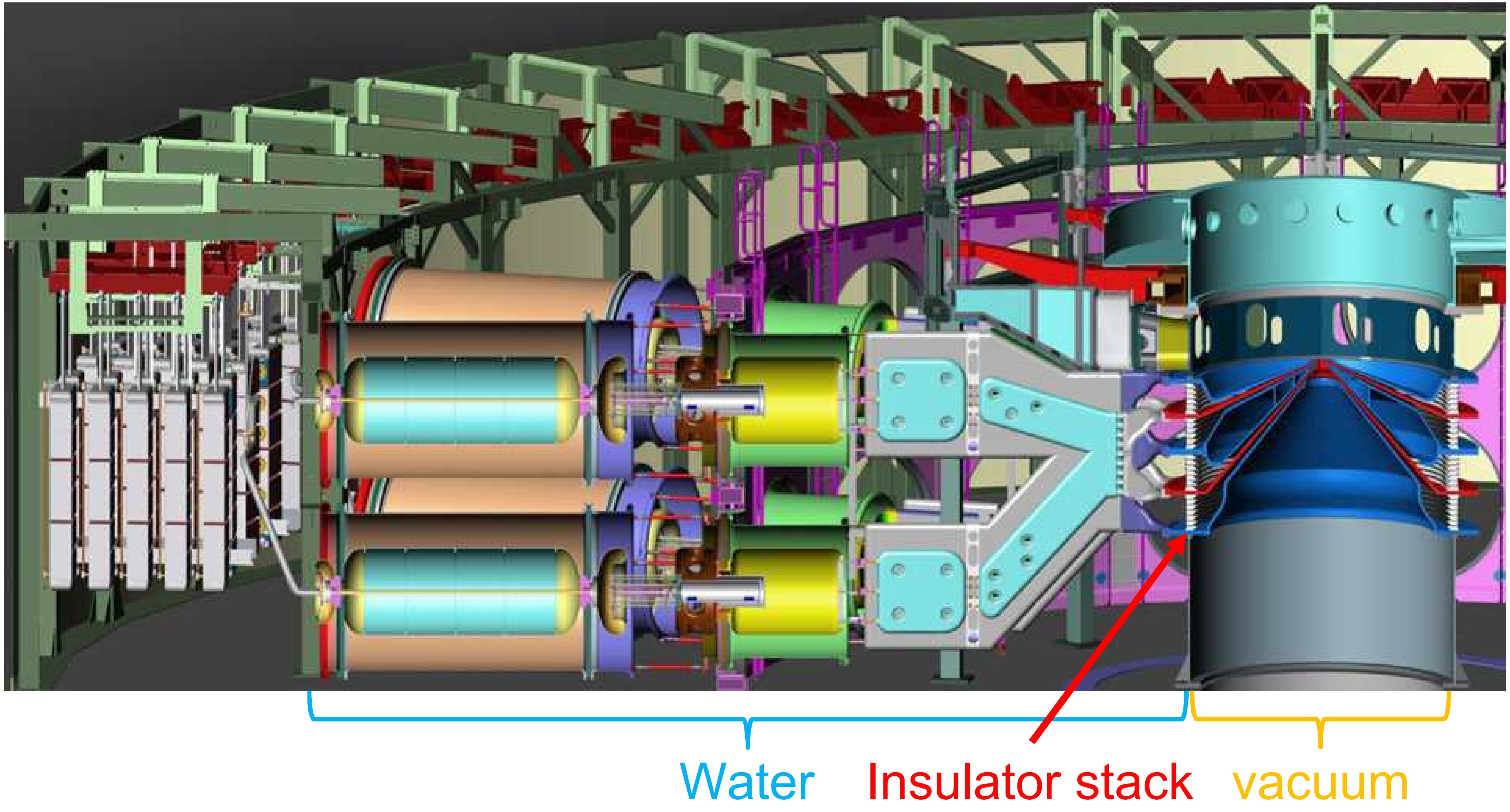


- Water capacitors are used to temporarily store and the output of the Marx bank
- Electrical pulse is discharged through laser-triggered high voltage switch

Water capacitor   Laser-triggered switch

Electrical power reaches 80 TW

The compressed electrical pulse is transmitted into vacuum through an insulator stack



- Several transmission lines in parallel to reduce inductance
- Allows up to 26 MA to drive the experiment
- Electrical power at load is ~4x average global power usage