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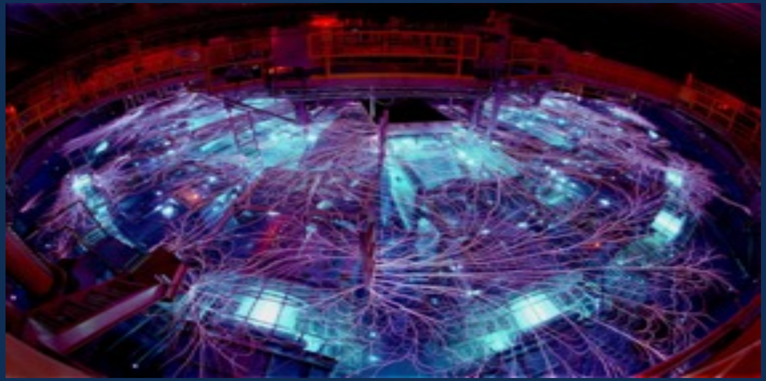

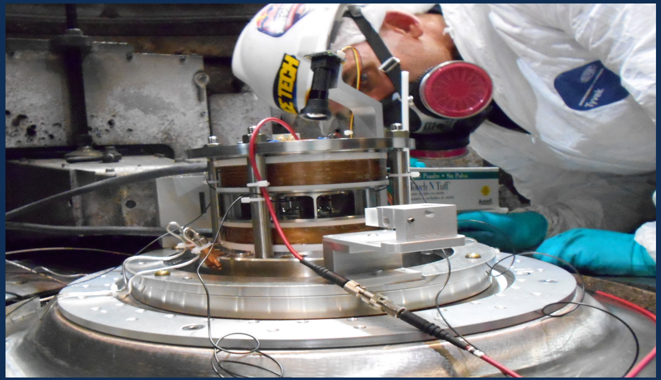

Introduction to Magneto-Inertial Fusion on Z

Kyle Peterson

Manager, Radiation & Inertial Confinement Fusion Target Design

2017 HEDS summer school

U.S. DEPARTMENT OF ENERGY NNSA

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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, M.R. Gomez, 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, G. Laity, D.C. Lamppa, M.R. Lopez, M.R. Martin, M. K. Matzen, L.A. McPherson, T. Nagayama, J.S. Lash, P.F. Knapp, 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*

Irvin R. Lindemuth

Thermonuclear fusion powers the galaxy. Can we use it to power earth?

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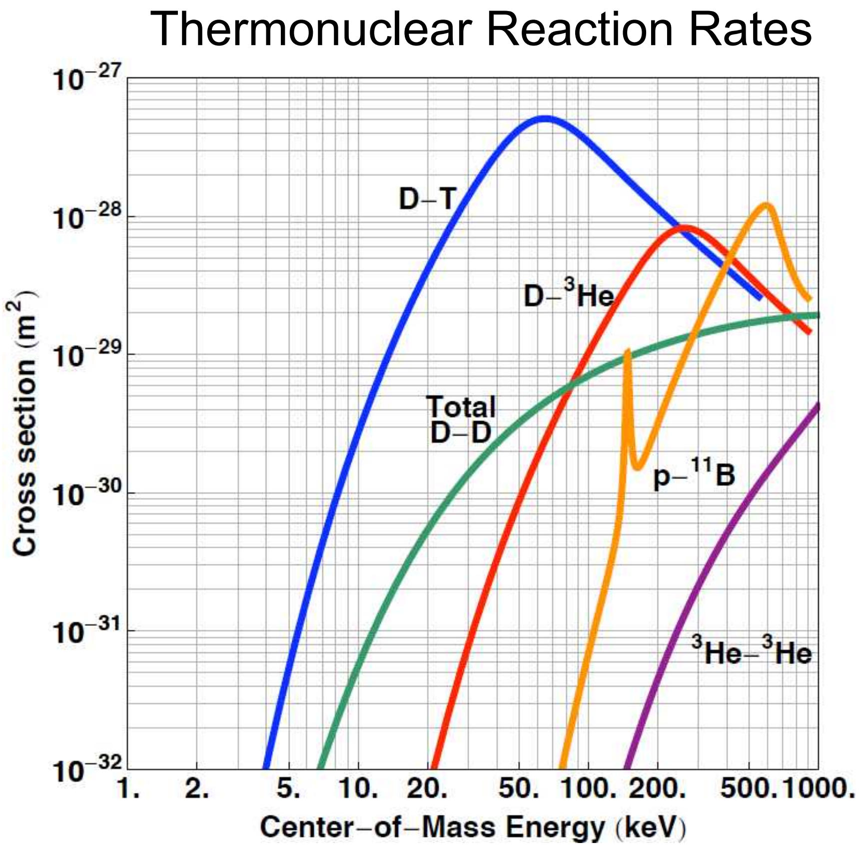
$$Y_{\text{fus}} = Q n_1 n_2 \langle \sigma v \rangle V \tau$$

A galaxy of controlled fusion reactors

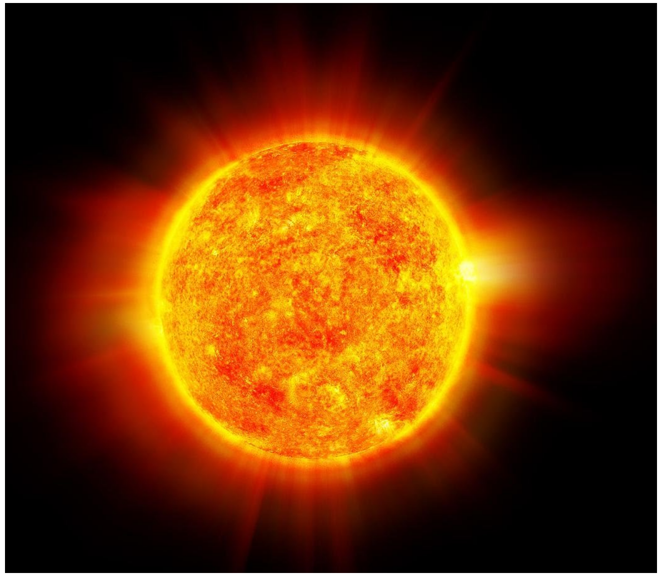
We need high temperatures, ~4 keV for D-T



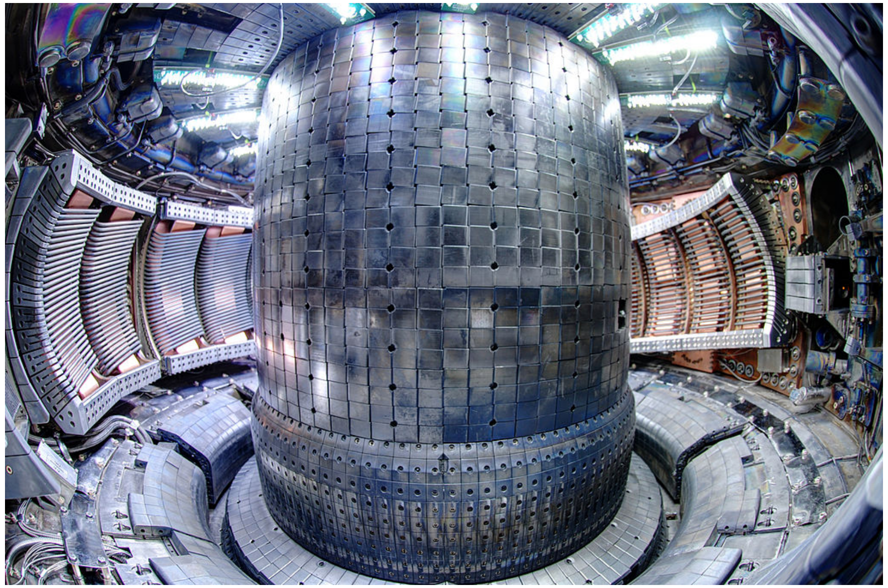
$$4 \text{ keV} \approx 40 \text{ Million K}$$

But there is (at least) one other significant challenge… confinement!

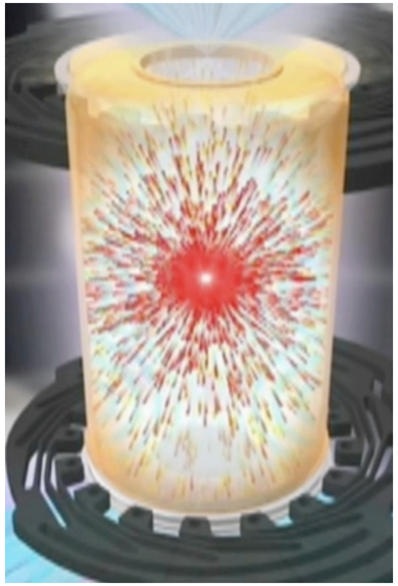
Gravitational



Magnetic



Inertial



steady-state
controlled fusion reactor

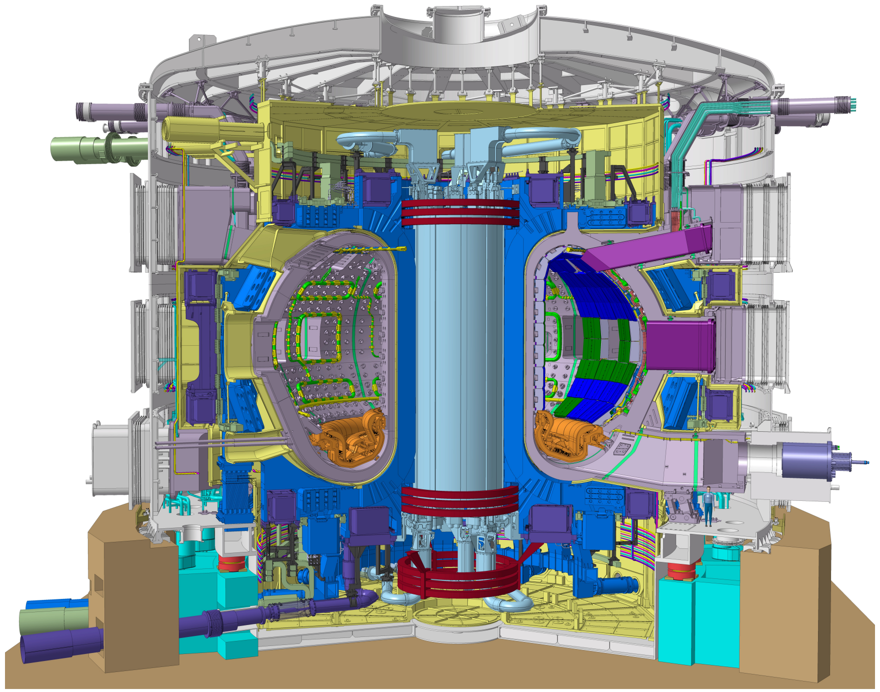
$\tau \sim \infty$

- magnetic confinement studied since 1950s
- Currently, the flagship project is ITER
- Ideally steady-state , τ ~ 300-500 s

- studied over 50 years with lasers
- Currently, the flagship is NIF
- Pulsed operation, τ ~ 10 ps

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

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 relies on sufficient fusion reactions occurring prior to falling apart

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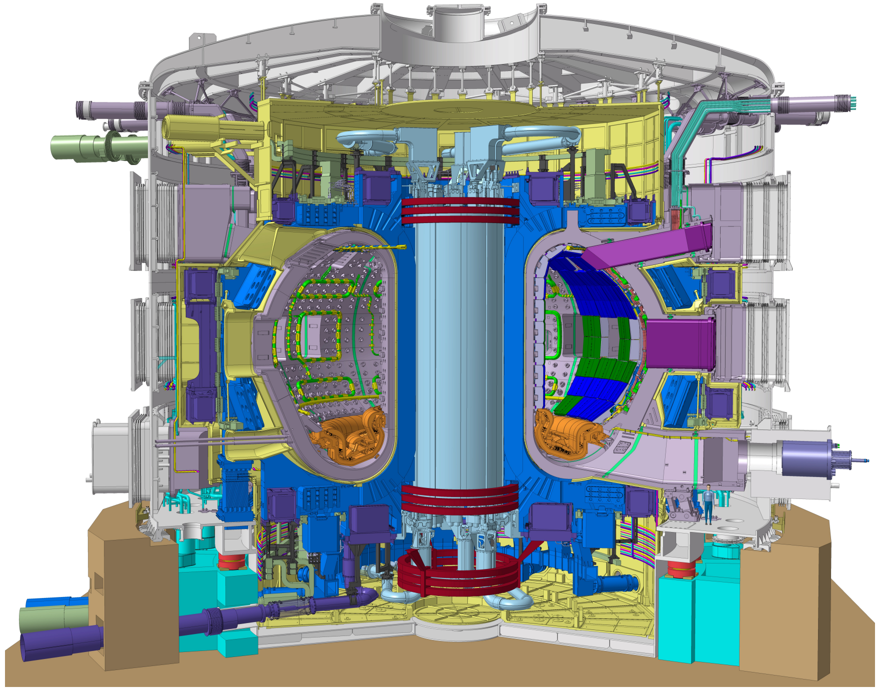
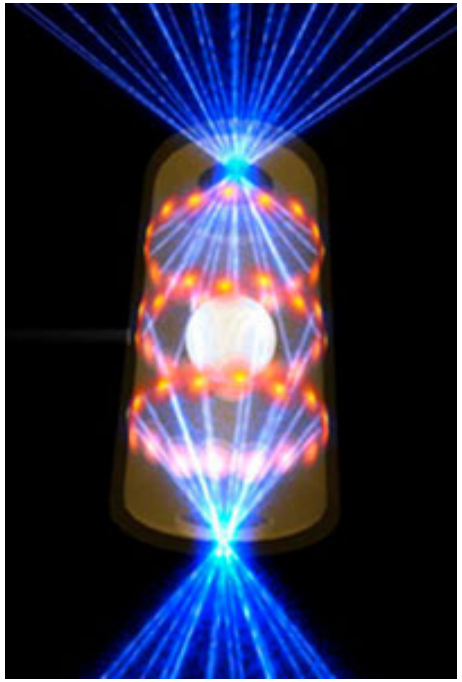
ITER



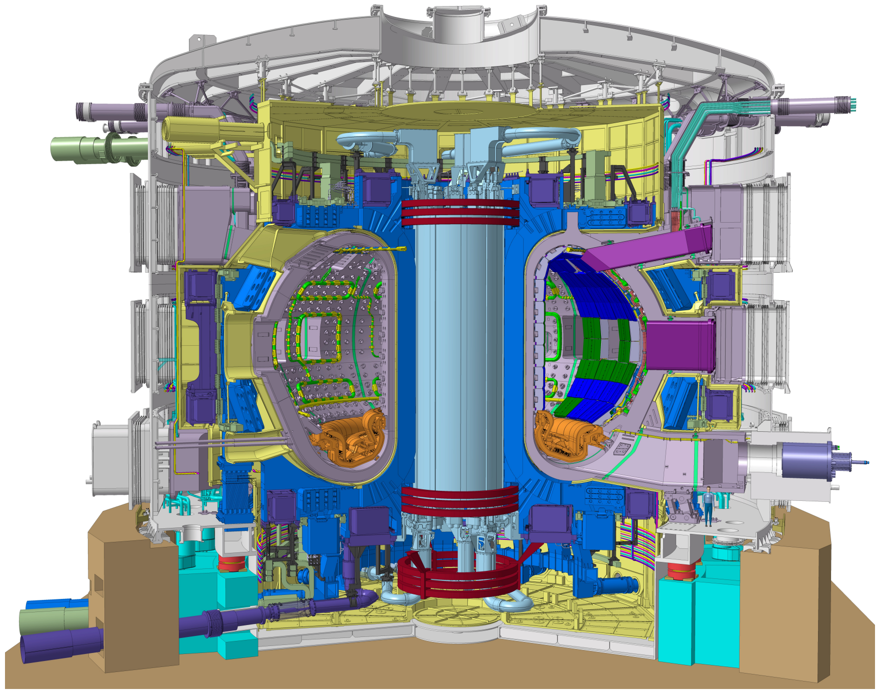
NIF hohlraum



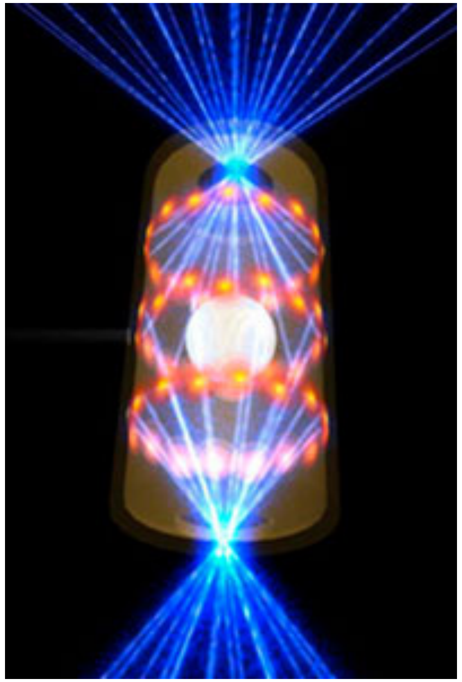
Density	1×10^{14} cm^{-3}		$2\text{-}20 \times 10^{25}$ cm^{-3}
Volume	8×10^{8} cm^{3}		6×10^{-8} cm^{3}
Duration	300-500 s		$5\text{-}10 \times 10^{-11}$ s
Magnetic field	100 kG		0 kG

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

ITER



NIF hohlraum



Both approaches are very expensive!

Is there a confinement approach at intermediate densities? **YES!**

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

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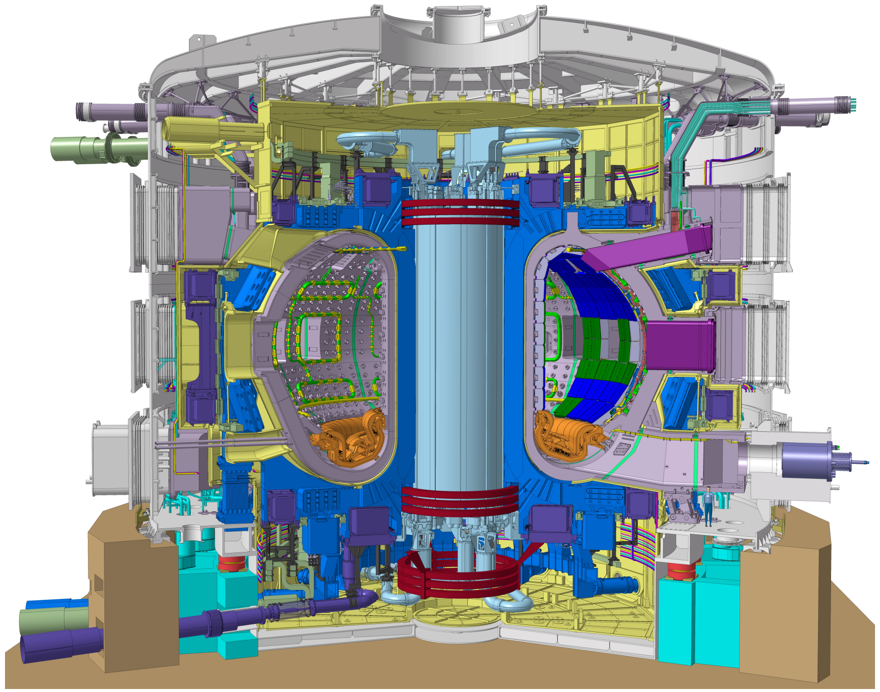
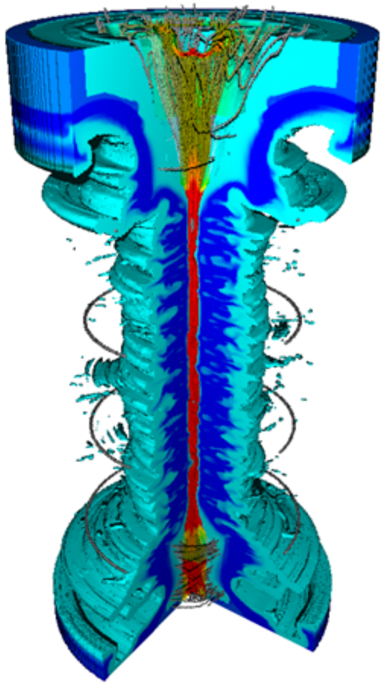
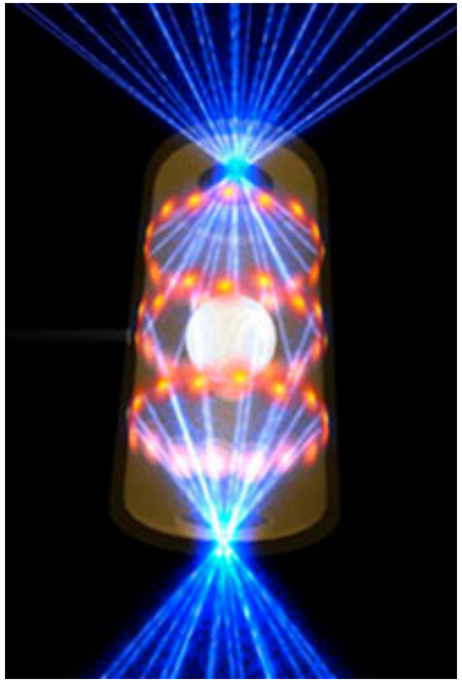
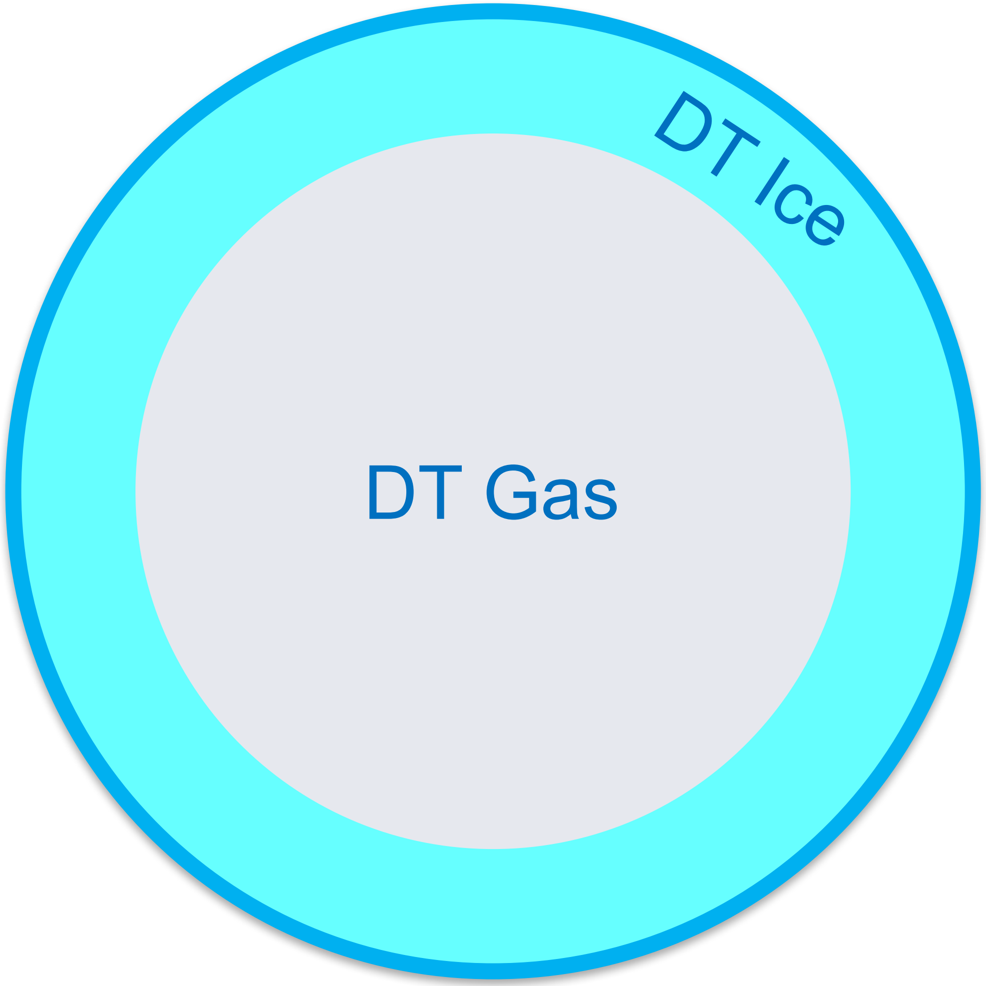
ITER	One example: MagLIF	NIF hohlraum
		

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

A quick review of traditional ICF…



- Start with a sphere containing DT

A quick review of traditional ICF…

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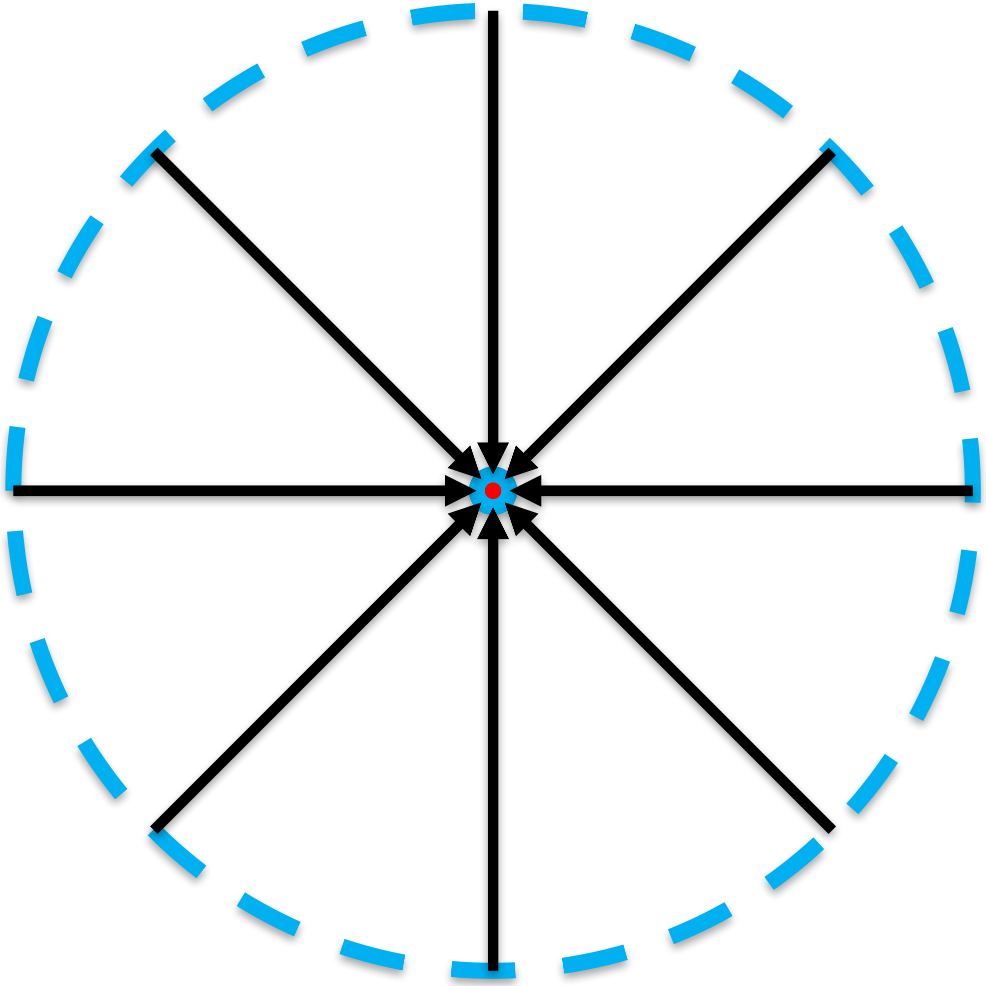
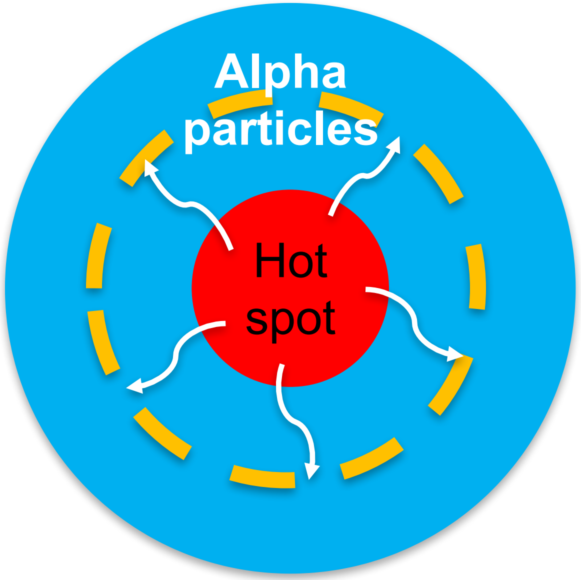


- Start with a sphere containing DT
- Implode the sphere
  - Compress radius by 30 (volume by 27,000)
  - Series of shocks heat the center (hot spot)

A quick review of traditional ICF…

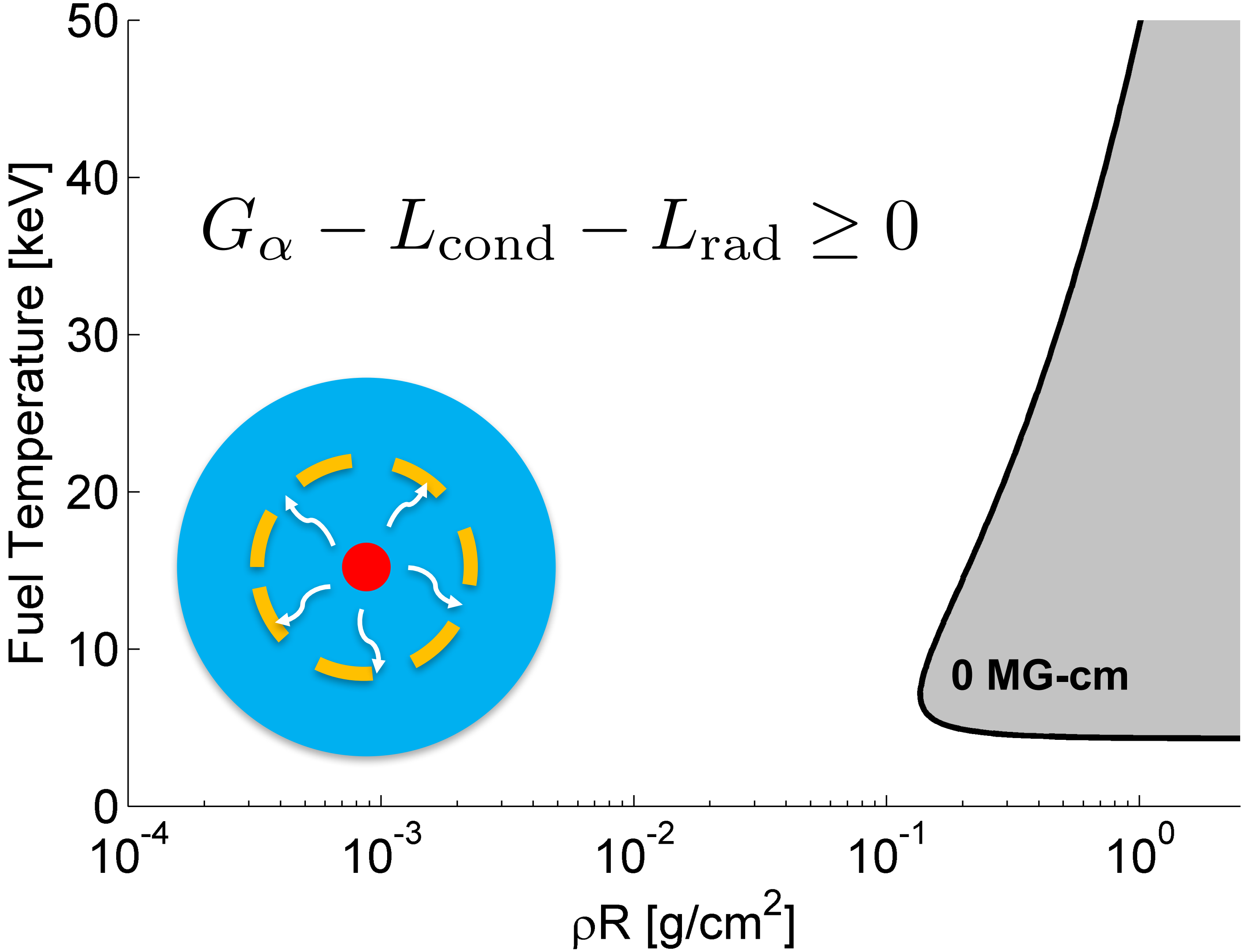
Zooming in



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 (3.5 MeV a-particles) heat surrounding dense fuel
- With a favorable power balance, a chain reaction occurs
  - For parameters of interest on the NIF, this requires P_{HS} > 300 Gbar and ρ_{cold} > 1000 g/cm^3

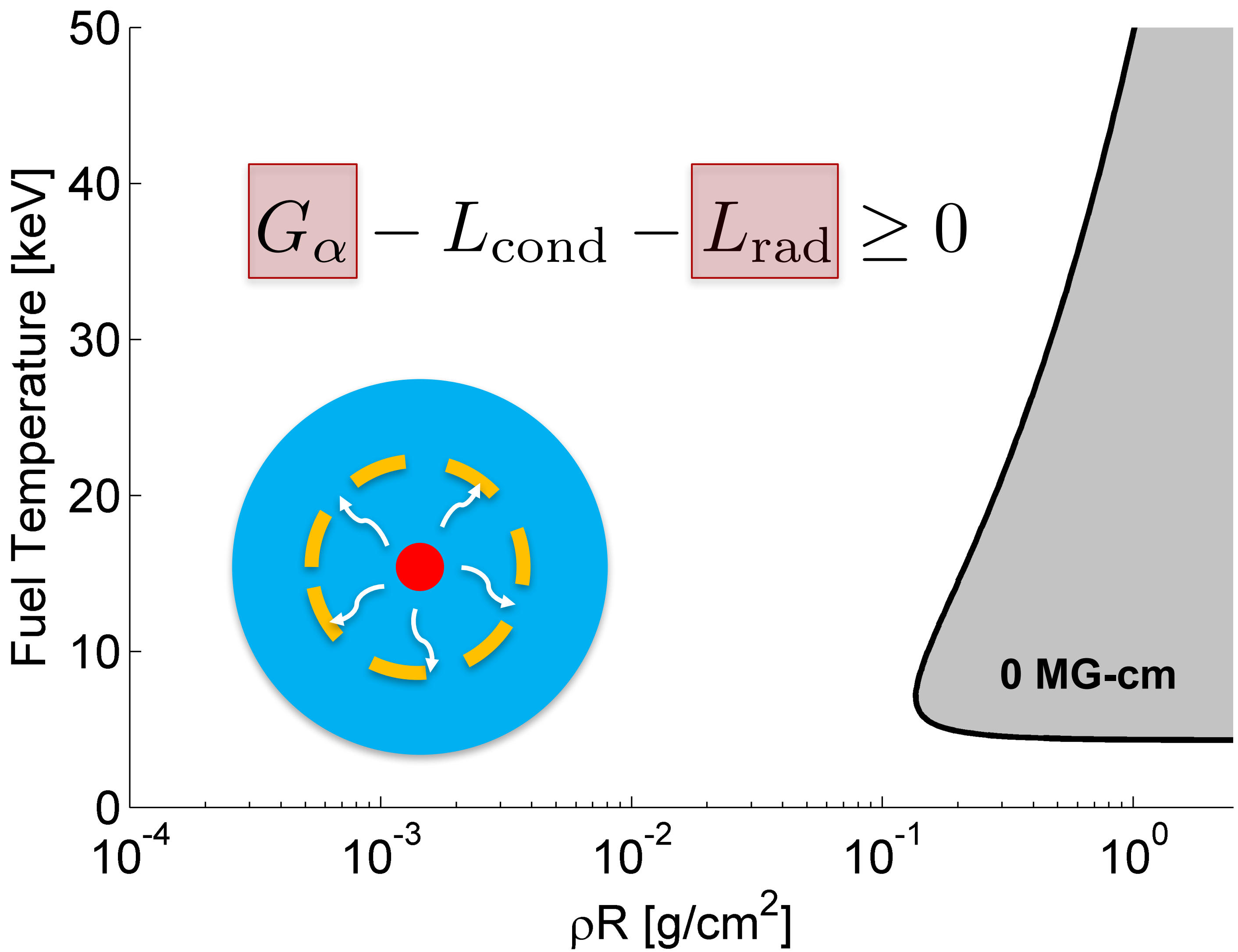
In order for an ICF to produce fusion gain, both high temperatures and sufficient confinement (areal density) is required



- There is a minimum fuel temperature of about 4.5 keV

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

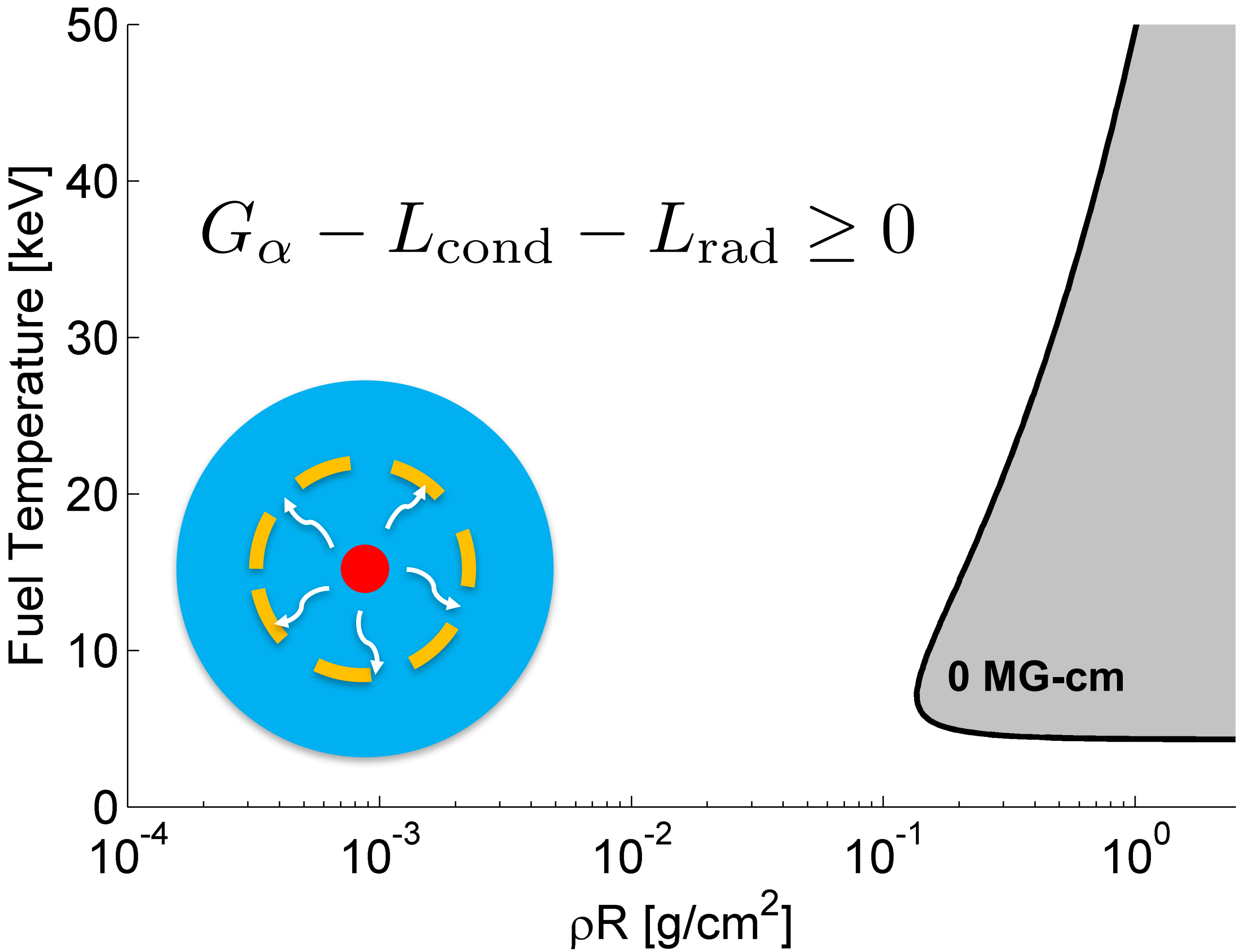
In order for an ICF to produce fusion gain, both high temperatures and sufficient confinement (areal density) is required



- There is a minimum fuel temperature of about 4.5 keV
  - This is where fusion heating outpaces radiation losses

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

In order for an ICF to produce fusion gain, both high temperatures and sufficient confinement (areal density) is required

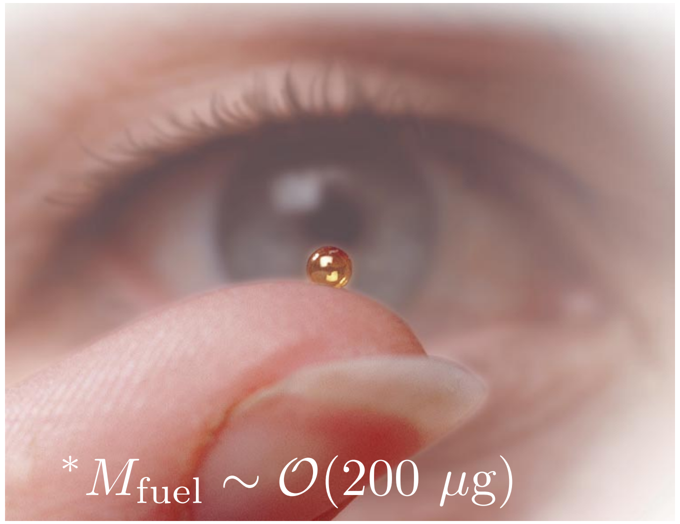


- There is a minimum fuel temperature of about 4.5 keV
  - This is where fusion heating outpaces radiation losses
- The minimum fuel areal density is around 0.2 g/cm^2
- Traditional ICF concepts attempt to operate in this minimum

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

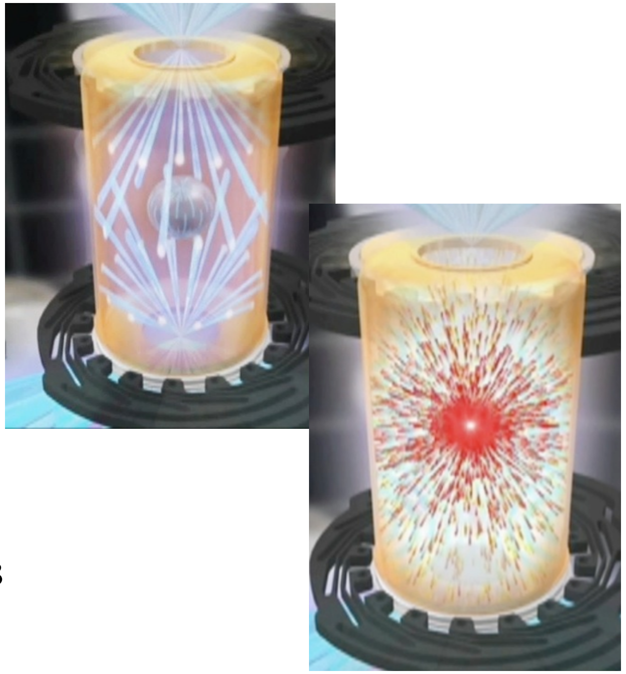
Ignition conditions necessitate high compression

Ignition requirements: $\begin{cases} \rho R > 0.2 - 0.5 \text{ g/cm}^2 \\ T = 5 - 12 \text{ keV} \end{cases}$



$$Y \propto M_{\text{fuel}} = \frac{4\pi}{3} \frac{(\rho R)^3}{\rho^2}$$

$$\rho = \rho_0 \left(\frac{R_0}{R}\right)^3 \equiv \rho_0 (CR)^3$$



$\mathcal{O}\left(10^2\ \text{MJ}\right)$

$$\rho R \propto \left(\rho_0^2 M_{\text{fuel}}\right)^{\frac{1}{3}} (CR)^2$$

$$(CR)_{\text{NIF}} \approx 30 - 40$$

Very small fuel mass requires immense compression to obtain adequate confinement for burn

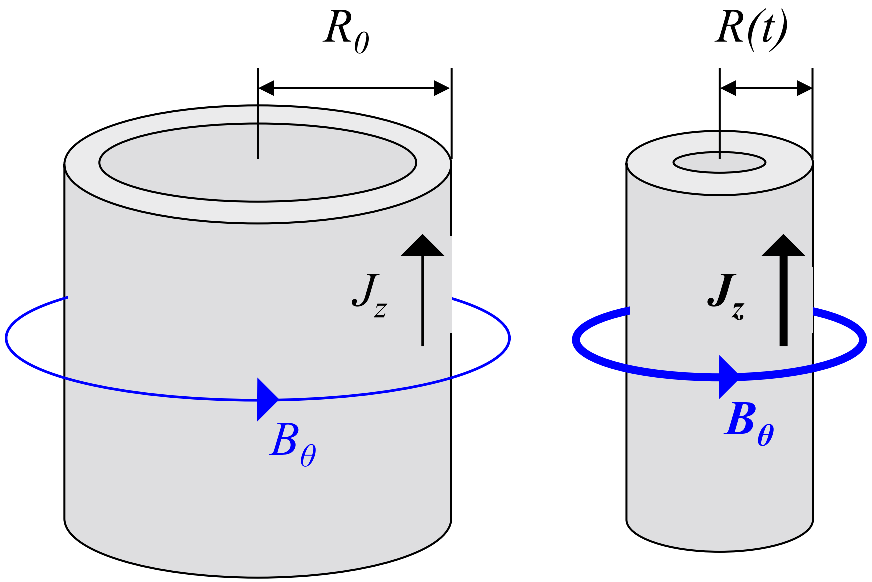
*S. W. Haan *et al.*, Physics of Plasmas **18**, 051001 (2011).

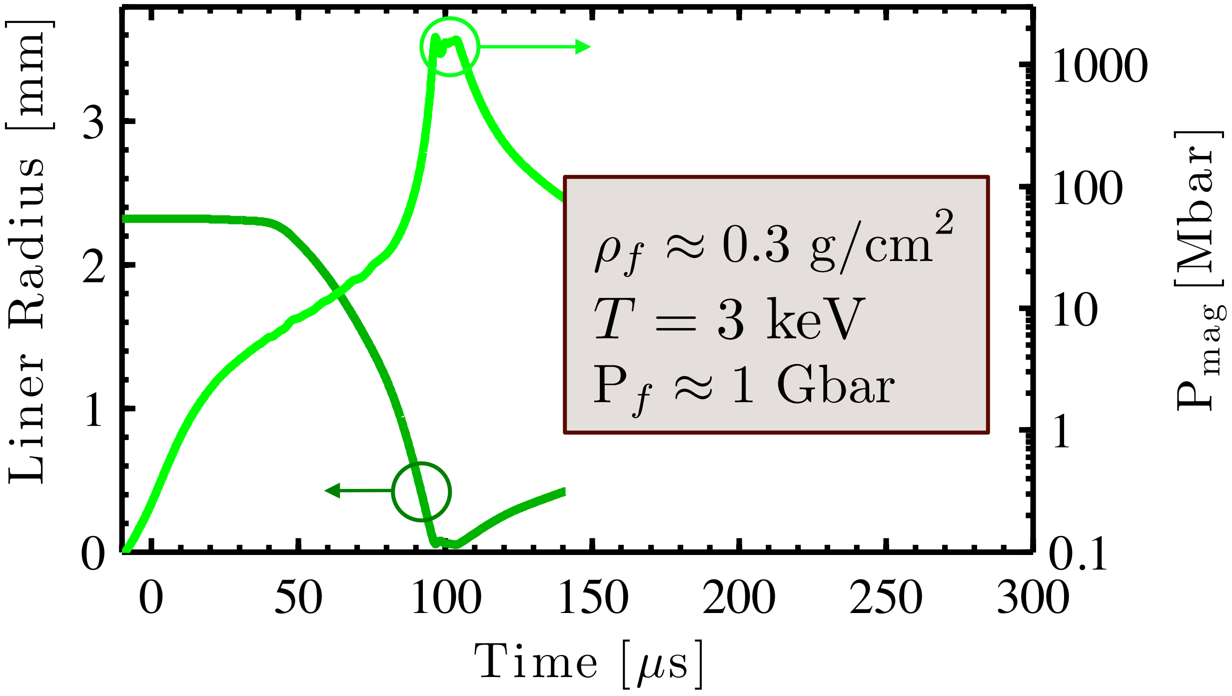
Image source: llnl.gov

Laser direct drive or indirect drive is typically used to drive ICF implosions, but magnetically-driven cylindrical implosions are another efficient alternative

$$P = \frac{B^2}{2\mu_o} = 140 \cdot \left(\frac{I_{[MA]}/30}{R(t)_{[mm]}} \right)^2 \quad [\text{Mbar}]$$

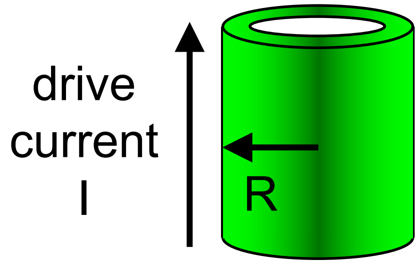
$$\rho\left(\frac{\partial \mathbf{u}}{\partial t} + (\mathbf{u}\cdot\nabla)\mathbf{u}\right) = \frac{\mathbf{J}\times\mathbf{B}}{c} - \nabla P$$

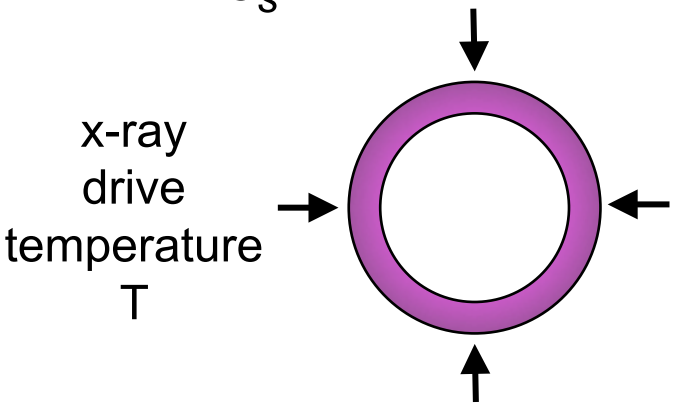




Magnetic drive pressures on Z can be comparable to the drive pressure in radiation driven capsules

Magnetically-Driven Cylinder	Radiation-Driven Sphere
$P = \frac{B^2}{2\mu_o} = 141\left(\frac{I_{MA}/30}{R_{mm}}\right)^2$ MBar	$P = \frac{(2/5)(1-\alpha)\sigma T^4}{C_s} = 3T^{3.5}$ MBar
140 MBar at 30 MA and 1 mm	140 MBar at 300 eV





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

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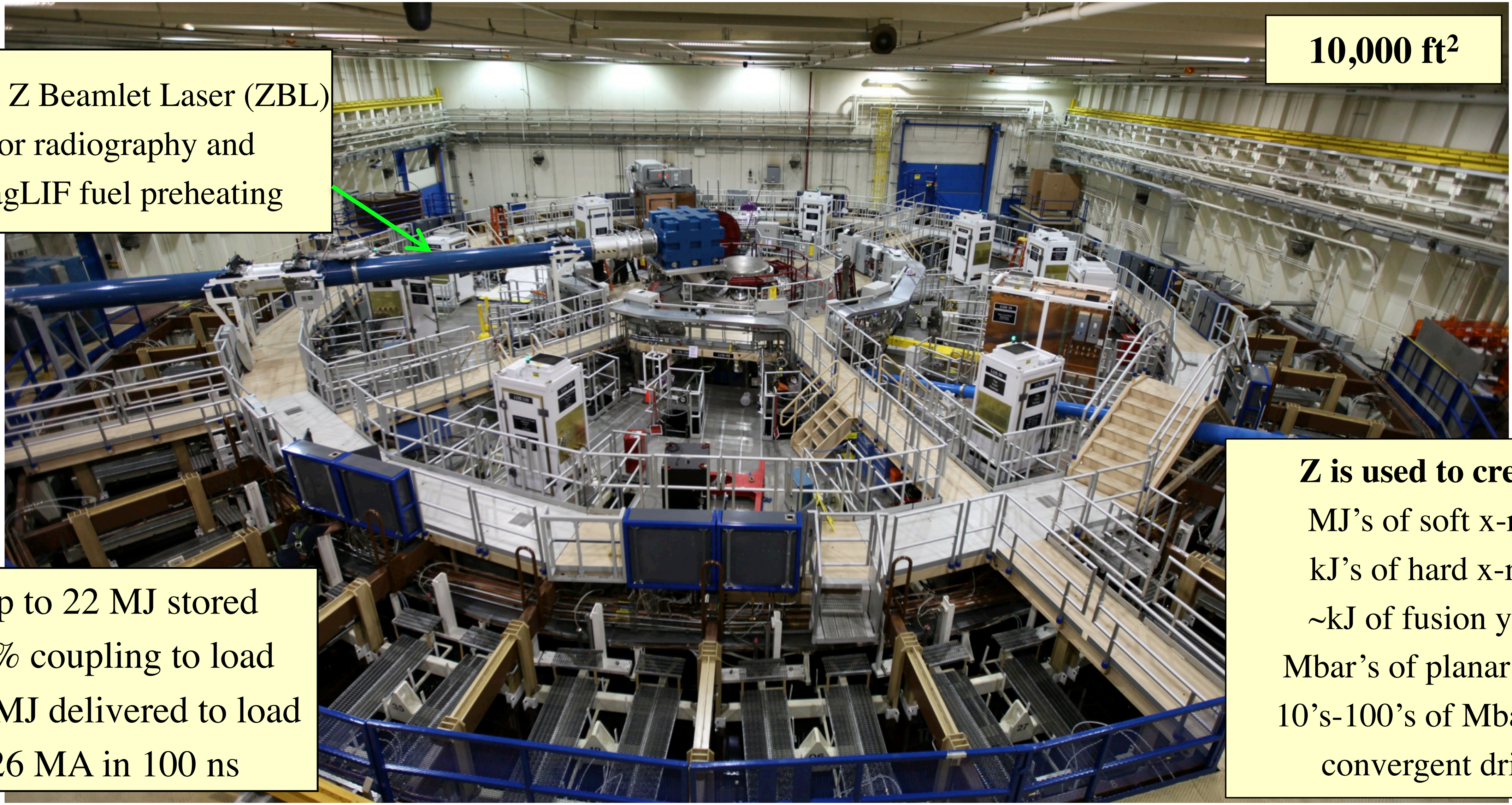


10,000 ft^2

1–4 kJ Z Beamlet Laser (ZBL) for radiography and MagLIF fuel preheating

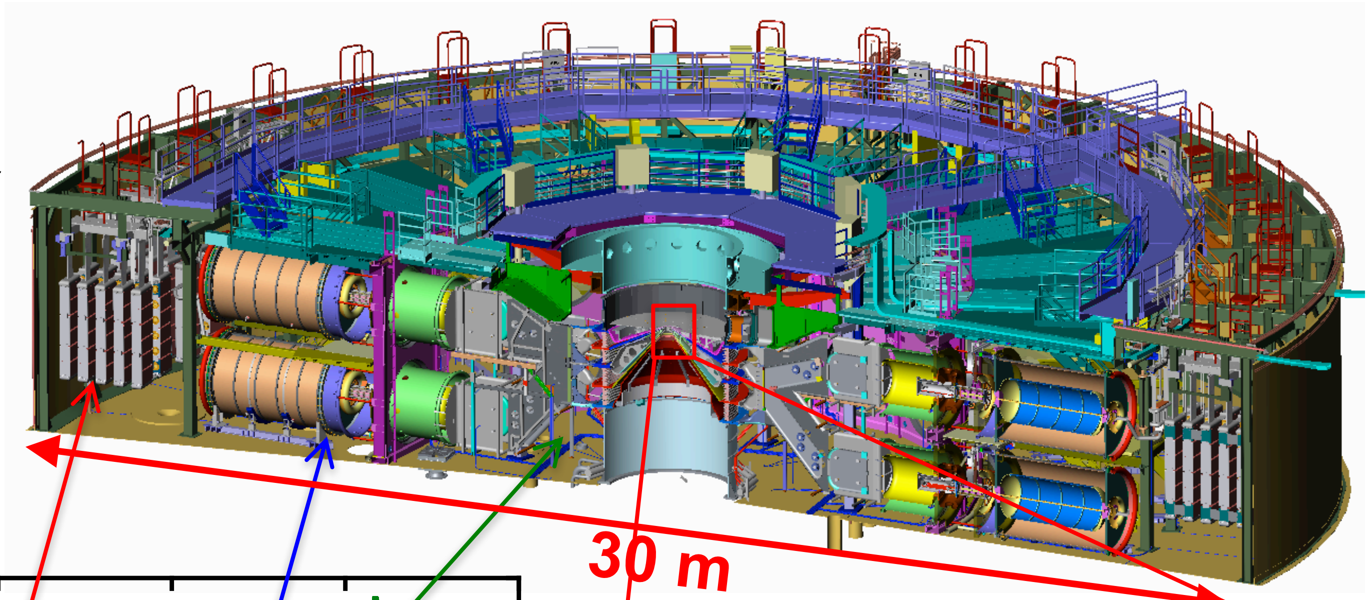
Z is used to create:
MJ’s of soft x-rays
kJ’s of hard x-rays
~kJ of fusion yield
Mbar’s of planar drive
10’s-100’s of Mbar’s of convergent drive

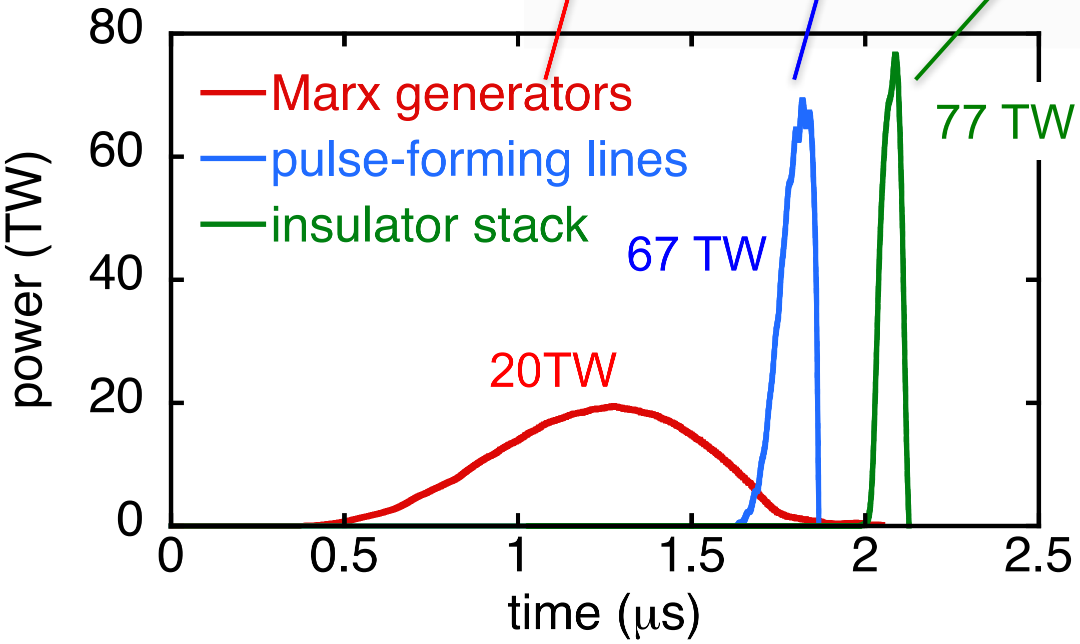
Up to 22 MJ stored
15% coupling to load
1–3 MJ delivered to load
26 MA in 100 ns

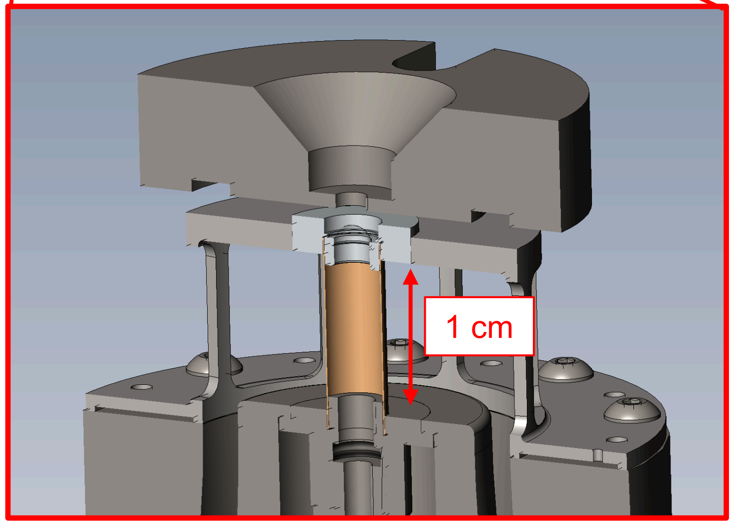
Pulsed-power is all about energy compression in both space and time

Energy compression achieved by a sequence of storage and switching techniques :

- Voltages are added in series
- Currents are added in parallel







Debris from MagLIF experiments must be carefully managed (several MJ energy release equivalent to few sticks of dynamite)

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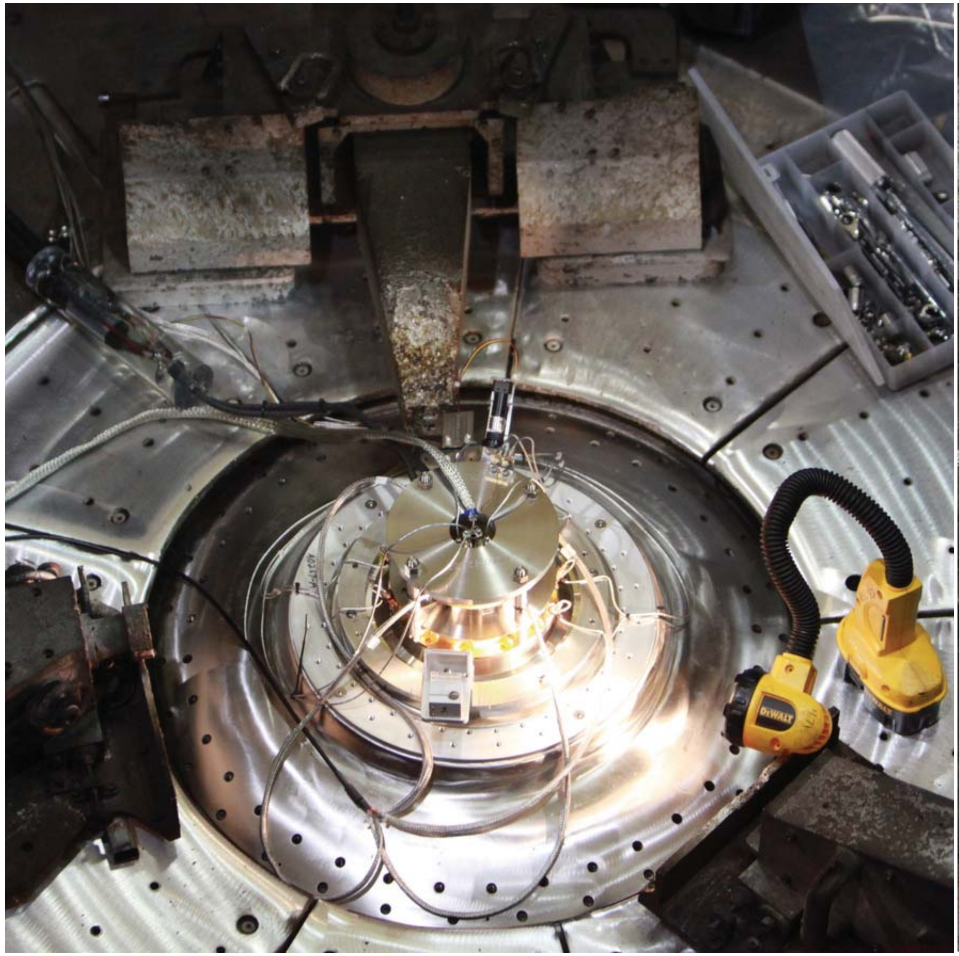
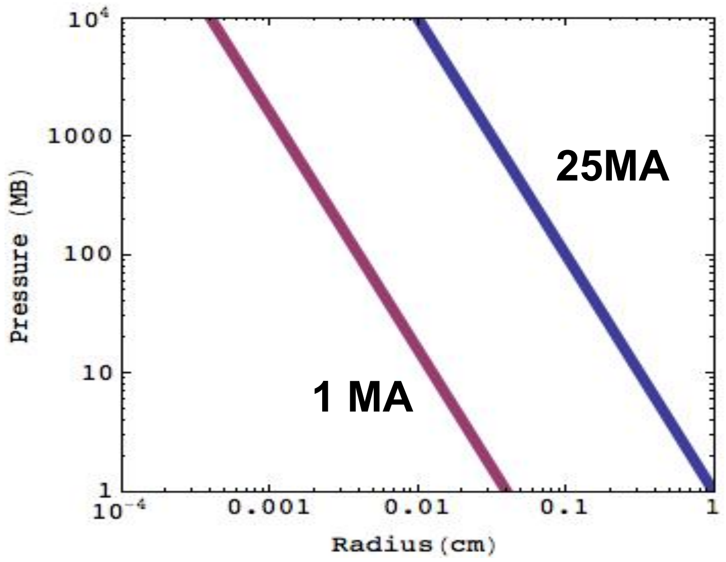


Pre-shot photo of coils & target hardware

Post-shot photo

Magnetic implosions can efficiently perform work on the fuel while reaching very high pressures, if the current can reach small radius



$$B_\theta(G) \sim \frac{I(\mathrm{A})}{5R(\mathrm{cm})} \qquad P \sim \frac{B^2}{8\pi} \sim \frac{I^2}{R^2}$$

A current carrying cylinder is driven more strongly the farther it converges

What limits current delivery to small radius?

- Ideal driver limits (dL/dt >0 eventually causes dI/dt<0)
- Power flow losses
- Asymmetric current delivery (displacement of magnetic center from geometric center)
- 3D current redistribution
- Current shunting in target

A magnetic implosion continues to extract energy as it implodes:

$$E_{kin} \sim I^2 \log\left(\frac{R_0}{R_f}\right)$$

Instabilities increase with amount of convergence and ultimately limit the achievable pressure

- Key challenge for all ICF concepts
- Rayleigh-Taylor (RT) instabilities occur along accelerating interfaces
- Cylindrical geometry requires higher convergence than spherical

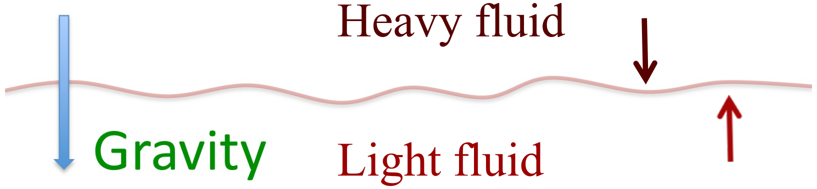


Image sources: physicscentral.com, large.stanford.edu

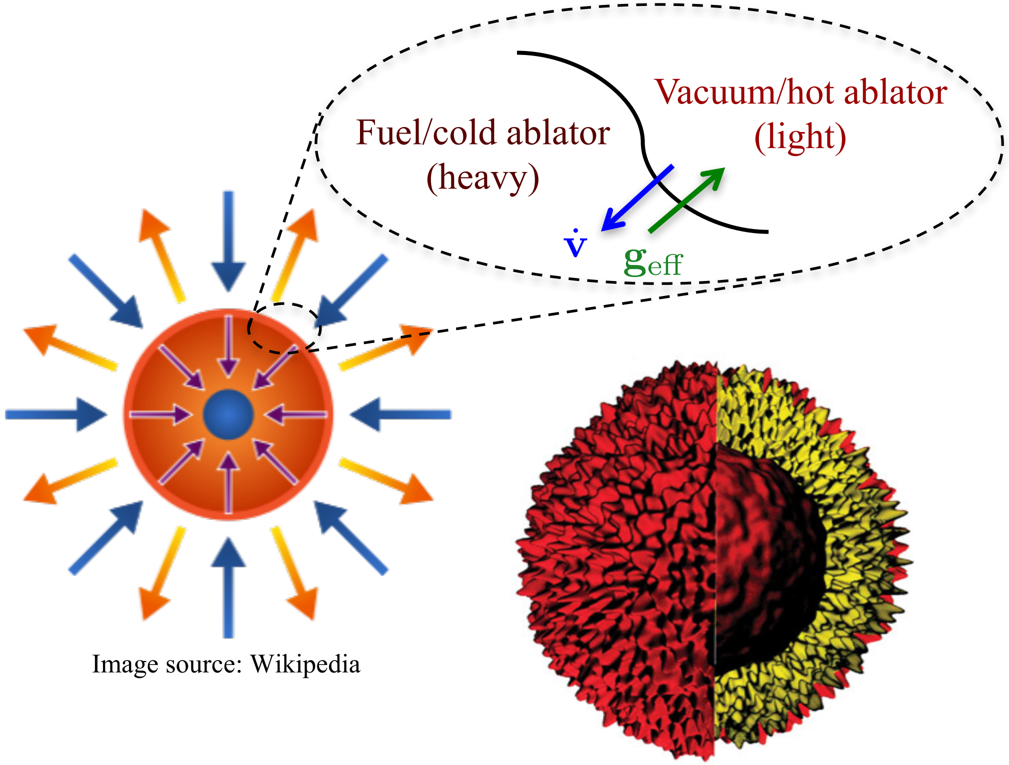


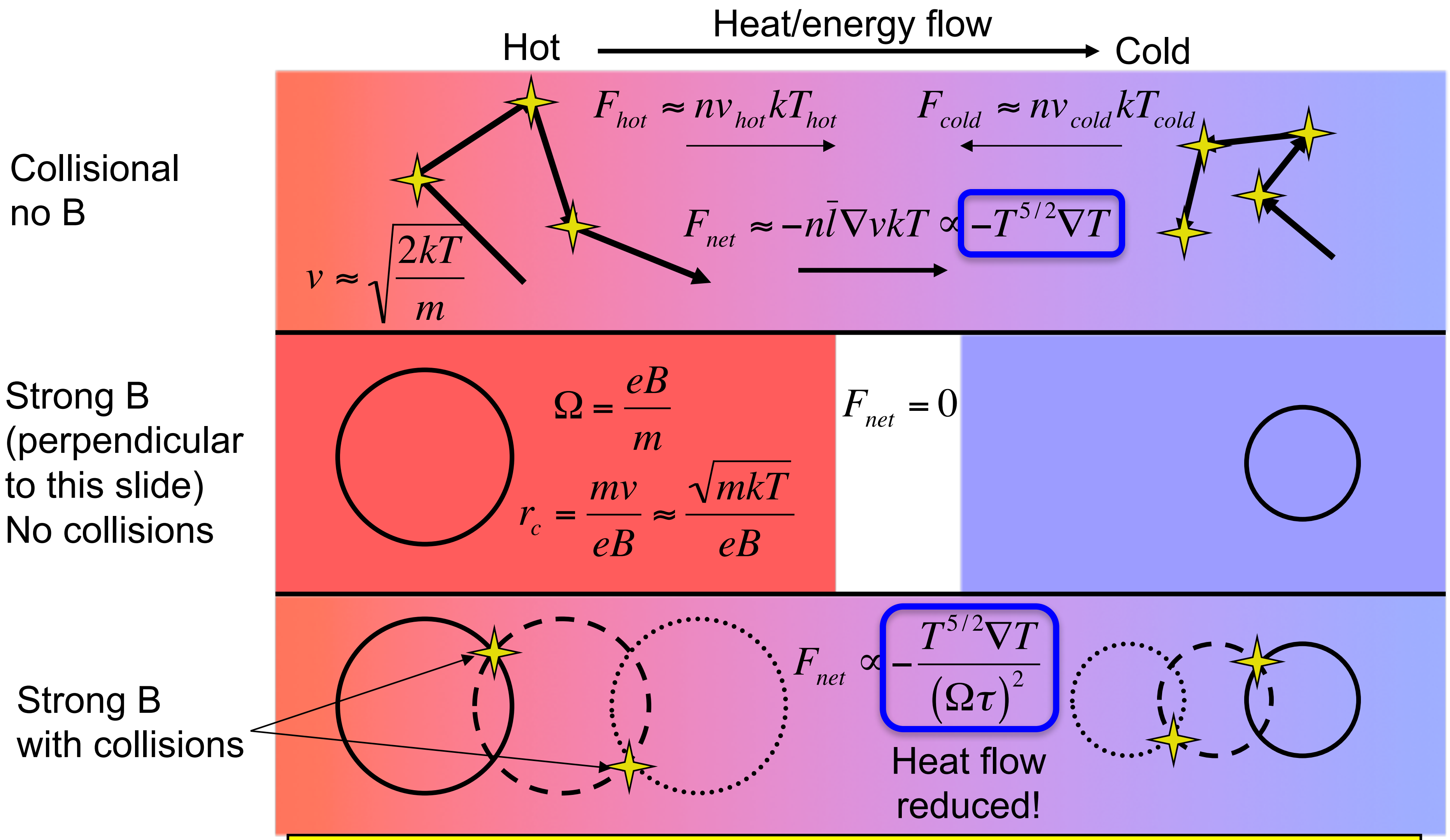
Image source: Wikipedia

Image source: llnl.gov

Magneto-inertial Fusion attempts to operate in an intermediate fuel density space between magnetic confinement fusion and inertial confinement fusion

- Strategy:
  - Reduce fuel density (compared to ICF) to suppress radiation losses
  - Use a magnetic field to suppress the thermal conduction losses during compression (Not confine the plasma!)
  - Reduce required target convergence
- Requirements:
  - Magnetized fuel
  - Pre-heated fuel
  - Compression system
    - Pre-heated and pre-magnetized plasma compressed until fusion is achieved
- The terms **MTF** (Magnetized Target Fusion) and **MIF** (Magneto Inertial Fusion) generally used interchangeably

Particle transport can be reduced by strong magnetic fields, even in collisional plasmas



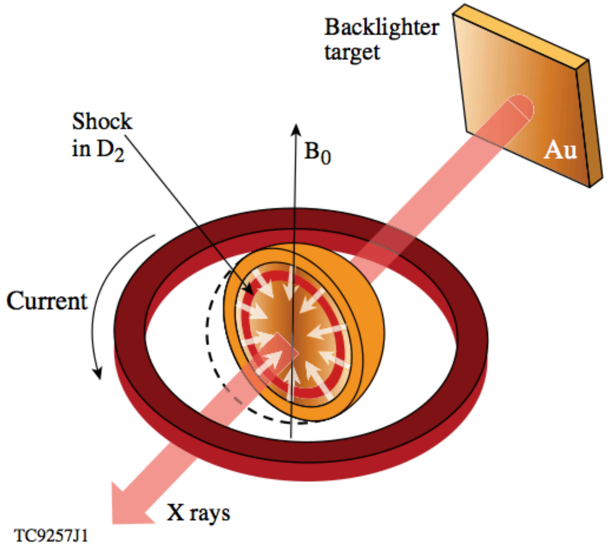
"Anomalous" heat transport can reduce the benefit of magnetic fields (e.g., in tokamaks) but there remains a significant benefit

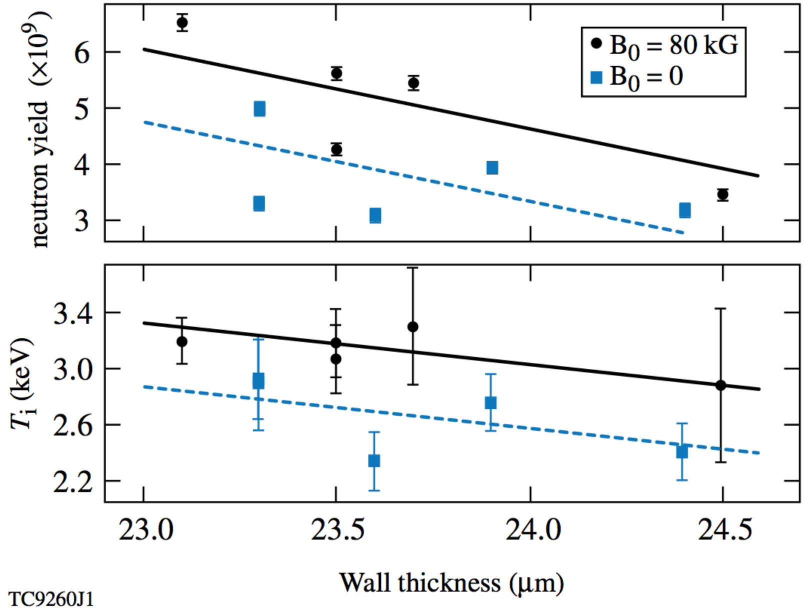
The potential benefits of strong magnetic fields in fusing plasmas has been known for quite some time

- 1945 - Benefits of magnetized plasmas for fusing plasmas recognized
  - “A possible method of cutting down the conduction to the walls would be the application of a strong magnetic field, H. This tends to make the electrons go in circles between collisions, so impedes their mobility. Actually, it makes them go in spirals, and does not reduce the conductivity parallel to H but only to the other two dimensions, so one would probably want to design the container elongated in the direction of H, or even toroidal...with the lines of force never leaving the deuterium...rather large fields will be required...thus a field in excess of 20,000 gausses would help reduce conduction loss.” - **Enrico Fermi, "Super Lecture No. 5--Thermal Conduction as Affected by a Magnetic Field," Los Alamos Report 344, Sept. 17, 1945.**

- 1949 - R. Landshoff, Phys. Rev. 76, 904

Laser-driven spherical capsule implosions at the University of Rochester* showed clear indicators of higher temperatures (and yields) due to fuel magnetization





- Simple axial field used in a spherical implosion geometry
- Field suppressed electron heat conduction losses along one direction
- The resulting 30% increase in temperature and 15% increase in yield is consistent with rough estimates for heat loss suppression

* P.Y. Chang *et al.*, Phys. Rev. Lett. 107, 035006 (2011).

Many groups have proposed using magnetic fields to help with pulsed fusion concepts, however all have been relatively small efforts.

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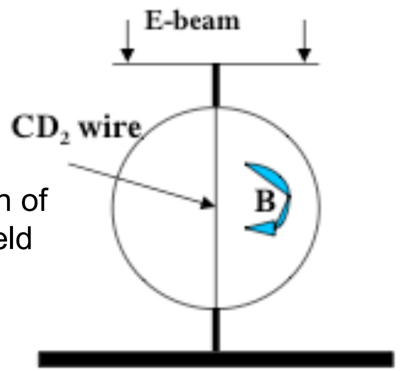
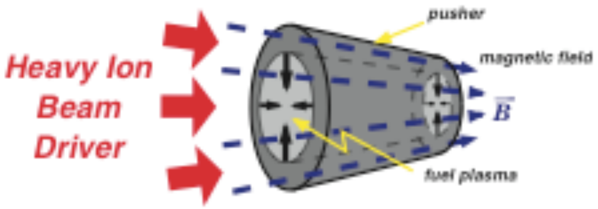
SNL Phi Target

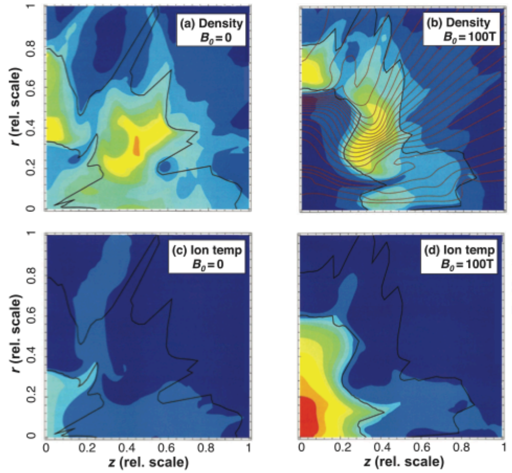


1982 Demonstration of enhanced fusion yield with magnetization (~1e6 DD yield)

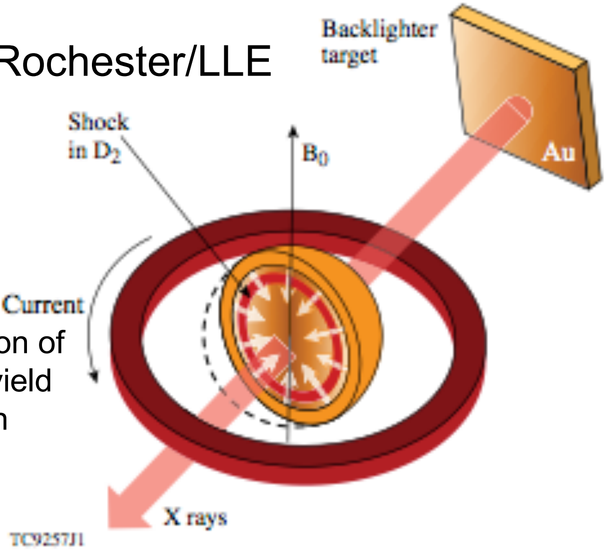
Max Planck/ITEP



LLNL (Perkins *et al.*, 2013)



University of Rochester/LLE



2011 Demonstration of enhanced fusion yield with magnetization (~5e9 DD yield)

P.Y. Chang *et al.*, Phys. Rev. Lett. (2011).

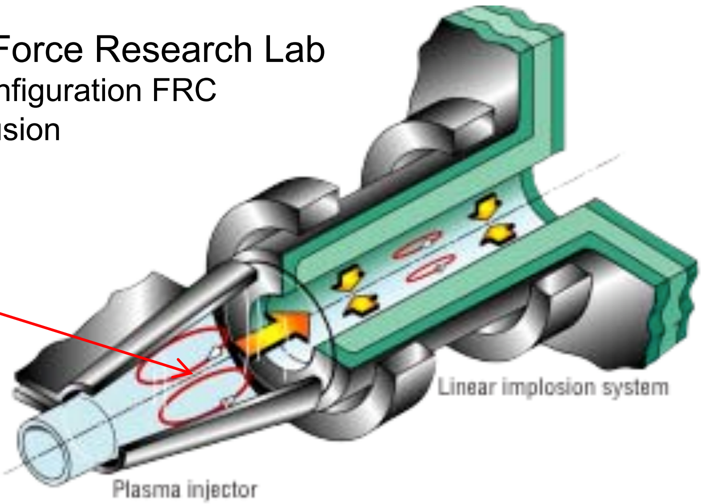
Los Alamos/Air Force Research Lab

Field Reversed Configuration FRC

Magnetic Target Fusion

Shiva Star

closed field lines FRC



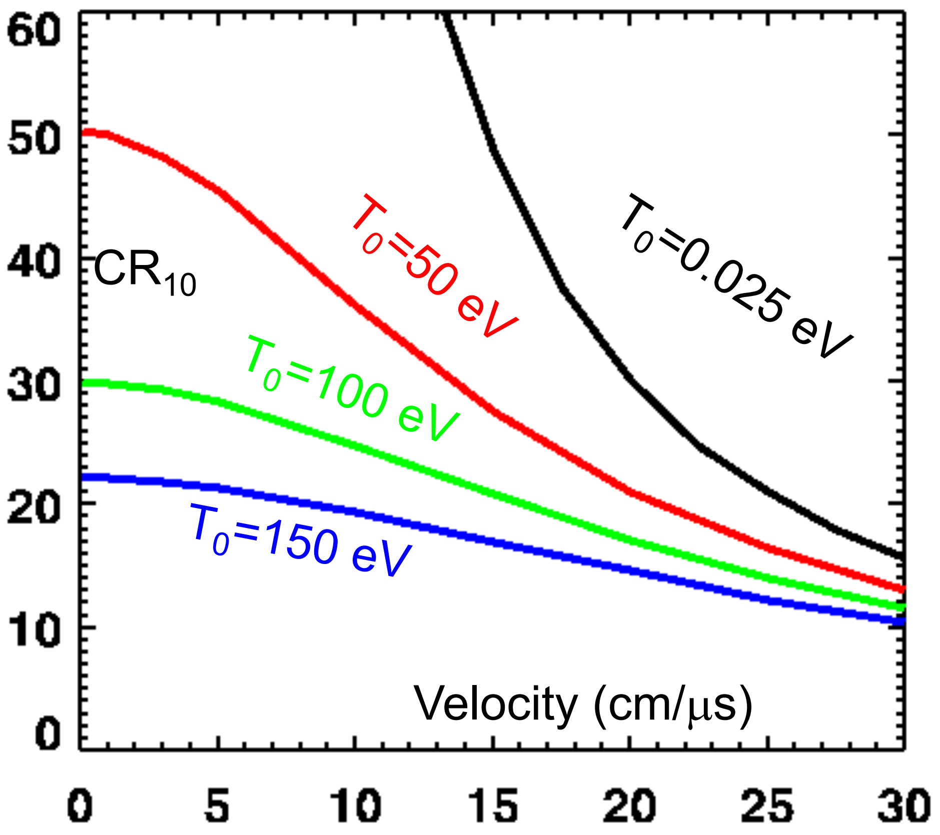
and many more groups besides these…

There is a resurgence of interest in magneto-inertial fusion research in the United States

- **Currently supported ARPA-E MIF projects in the USA ($30M)**
  - California Institute of Technology & Los Alamos National Laboratory
  - Helion Energy, Inc.
  - Lawrence Berkeley National Laboratory & Cornell University
  - Los Alamos National Laboratory & Hyper V Technologies (~100 ns)
  - Magneto-Inertial Fusion Technologies, Inc.
  - NumerEx, LLC & National High Magnetic Field Laboratory
  - Sandia National Laboratories & University of Rochester (~1-10 ns)
  - Swarthmore College & Bryn Mawr College
  - University of Washington & Lawrence Livermore National Laboratory
- **Other MIF projects are also pursued:**
  - General Fusion
  - Tri-alpha
  - Los Alamos National Laboratory & Air Force Research Laboratory (~10 μs)
- **Other countries also interested in MIF (e.g., Russian MAGO concept)**

Preheating the fuel enables fusion temperatures to be achieved with less compression

Simulation with constant velocity

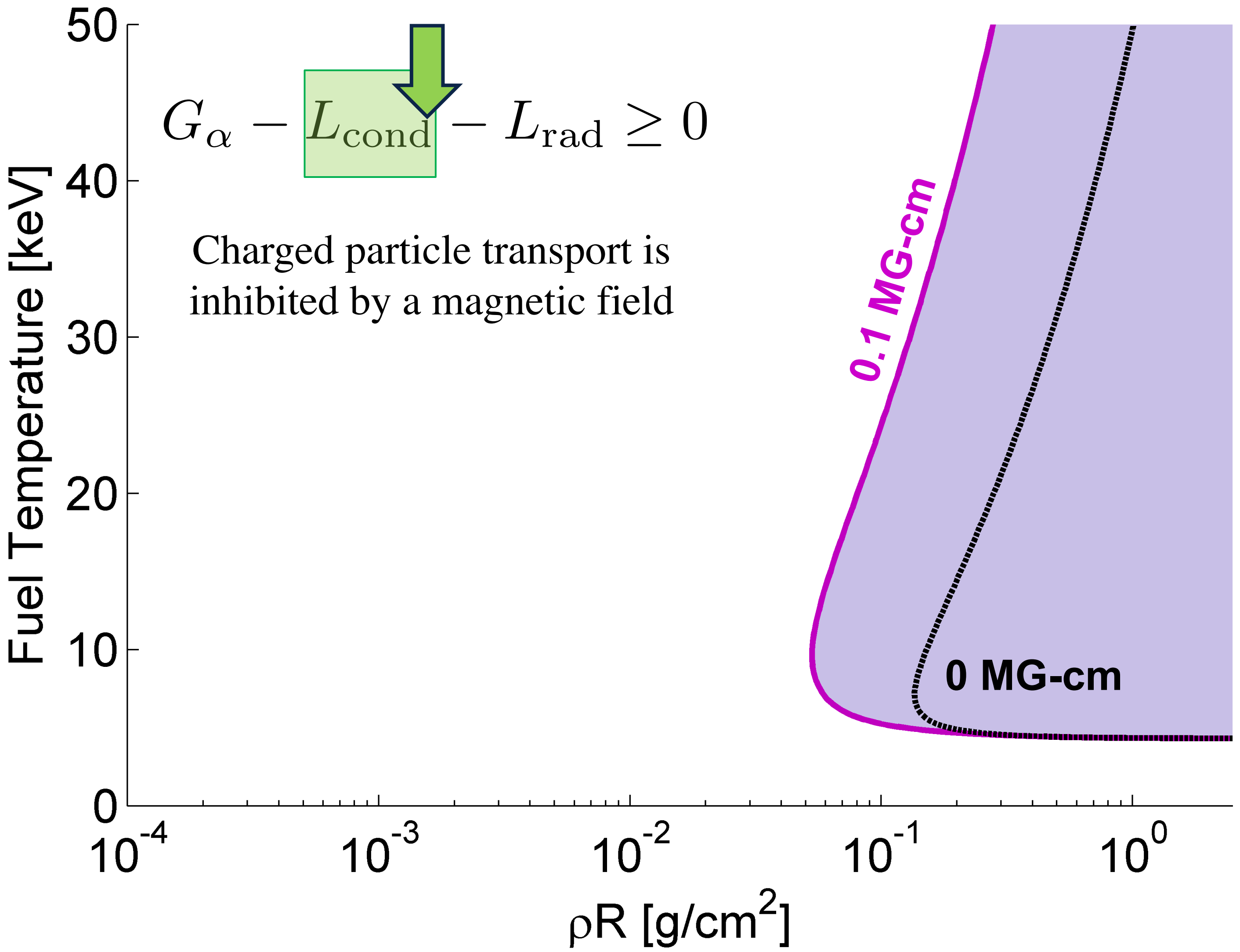


Temperature rise for an ideal adiabatic cylindrical compression

- CR_{10} = Convergence Ratio (R_0/R_f) needed to obtain 10 keV (ignition) with no radiation losses or conductivity
- Only possible if electrons are magnetized throughout the implosion!
- Magneto-inertial fusion concepts attempt to adiabatically compress the fuel to ignition

$$T = T_0 (r_0/r_f)^{4/3}$$

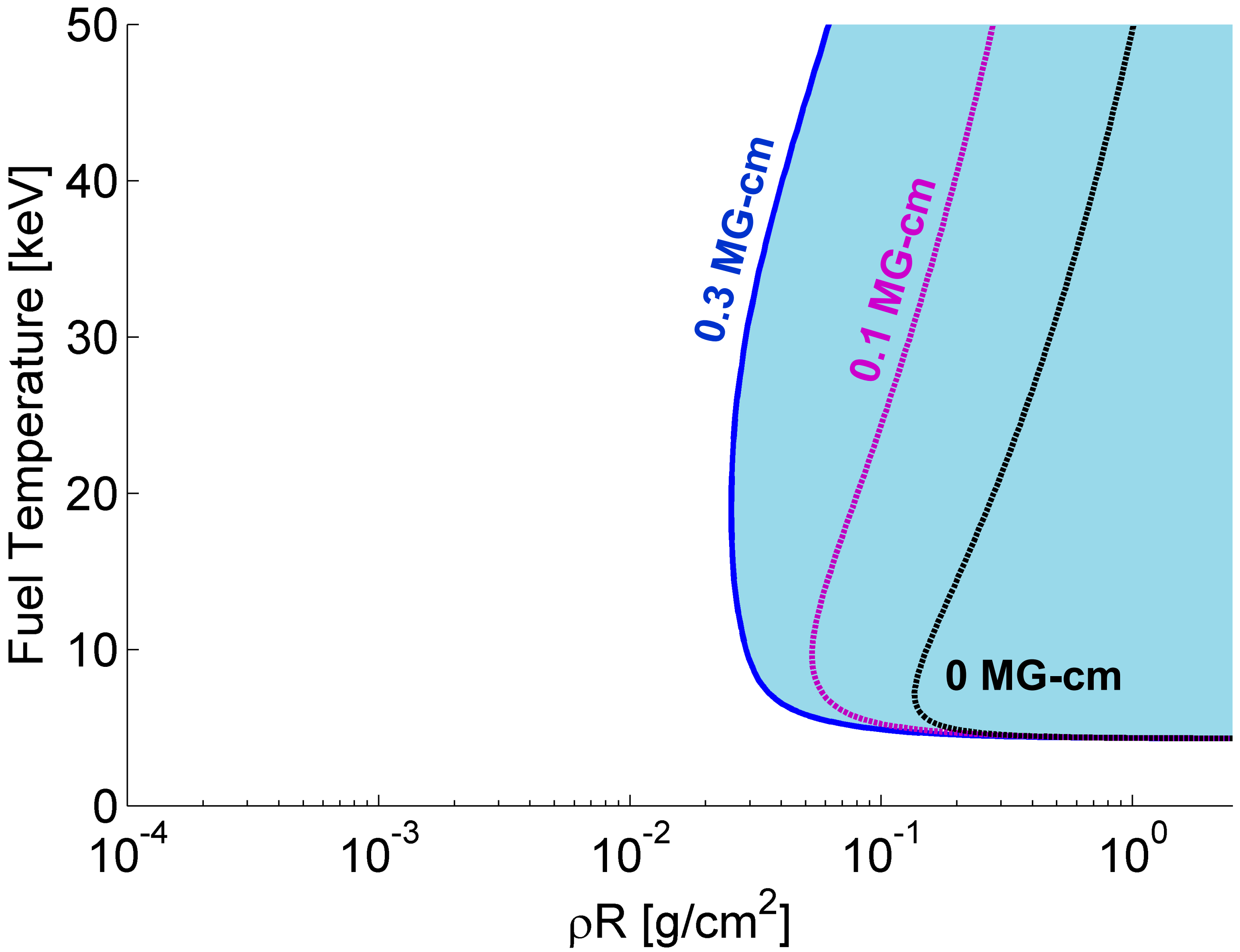
Magneto-inertial fusion (MIF) utilizes magnetic fields to relax the stagnation requirements of ICF



- Applying a magnetic field opens up a larger region of parameter space – confinement time increases
- 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).

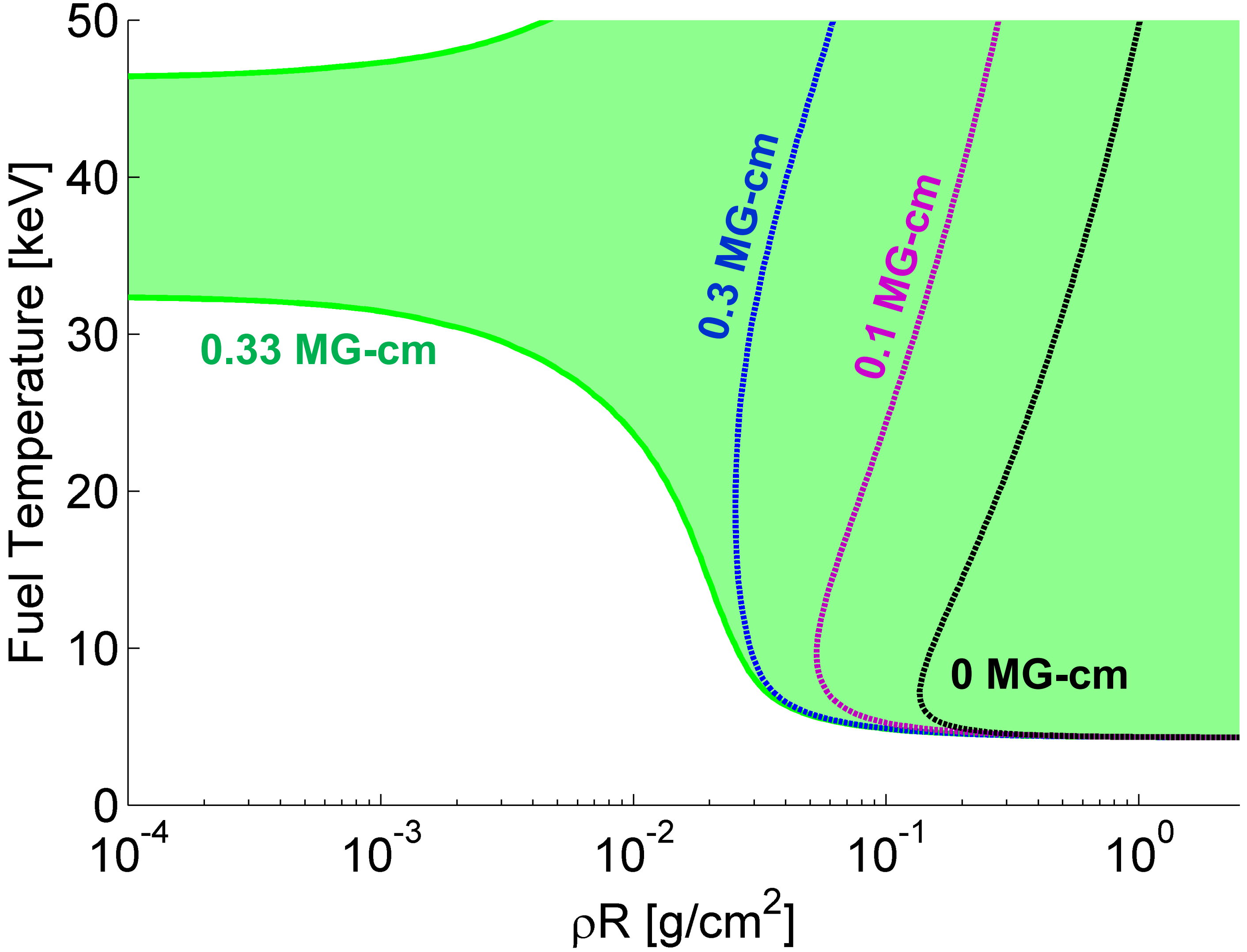
Magneto-inertial fusion (MIF) utilizes magnetic fields to relax the stagnation requirements of ICF



- 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).

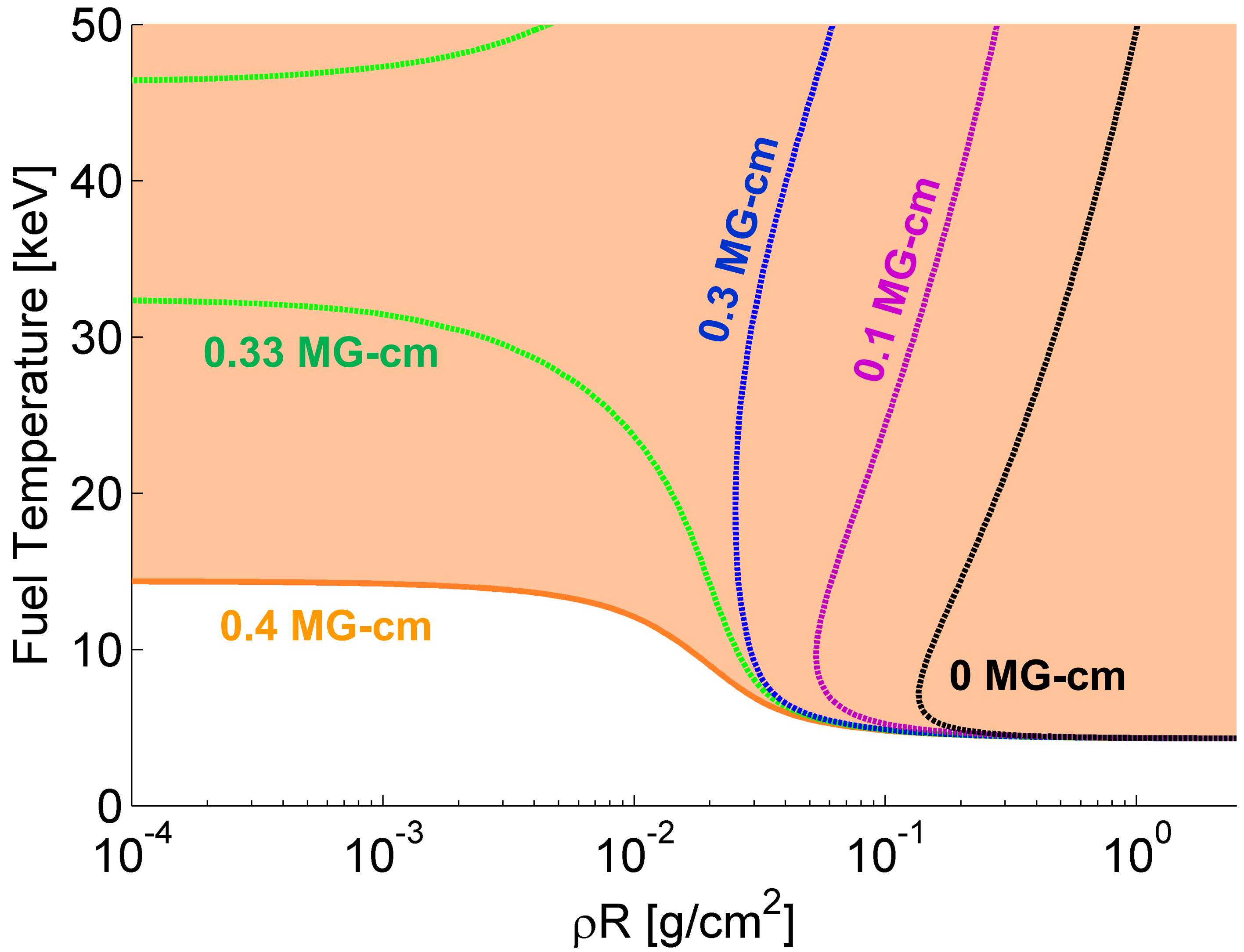
Magneto-inertial fusion (MIF) utilizes magnetic fields to relax the stagnation requirements of ICF



- 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 (MIF) 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 (MIF) utilizes magnetic fields to relax the stagnation requirements of ICF

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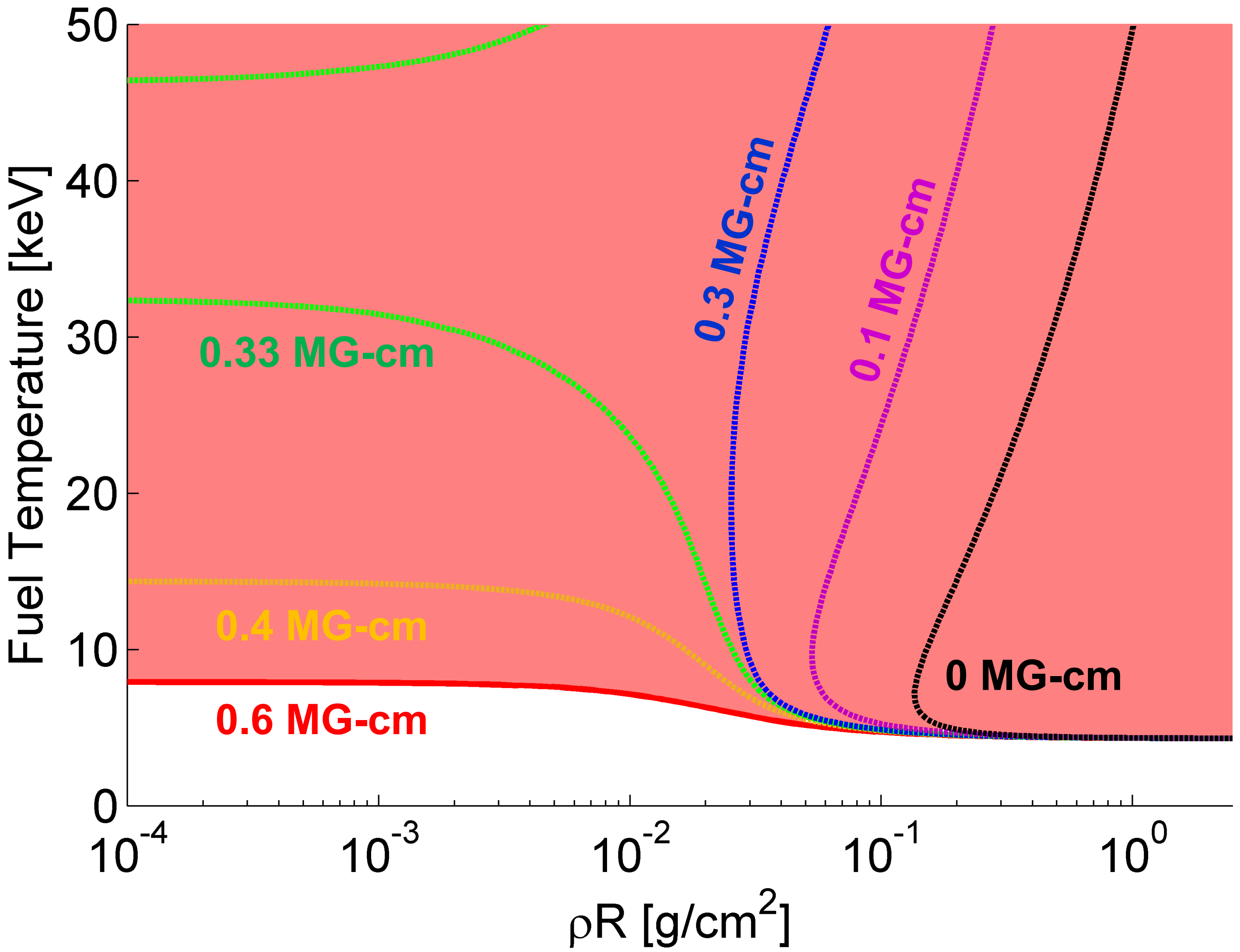
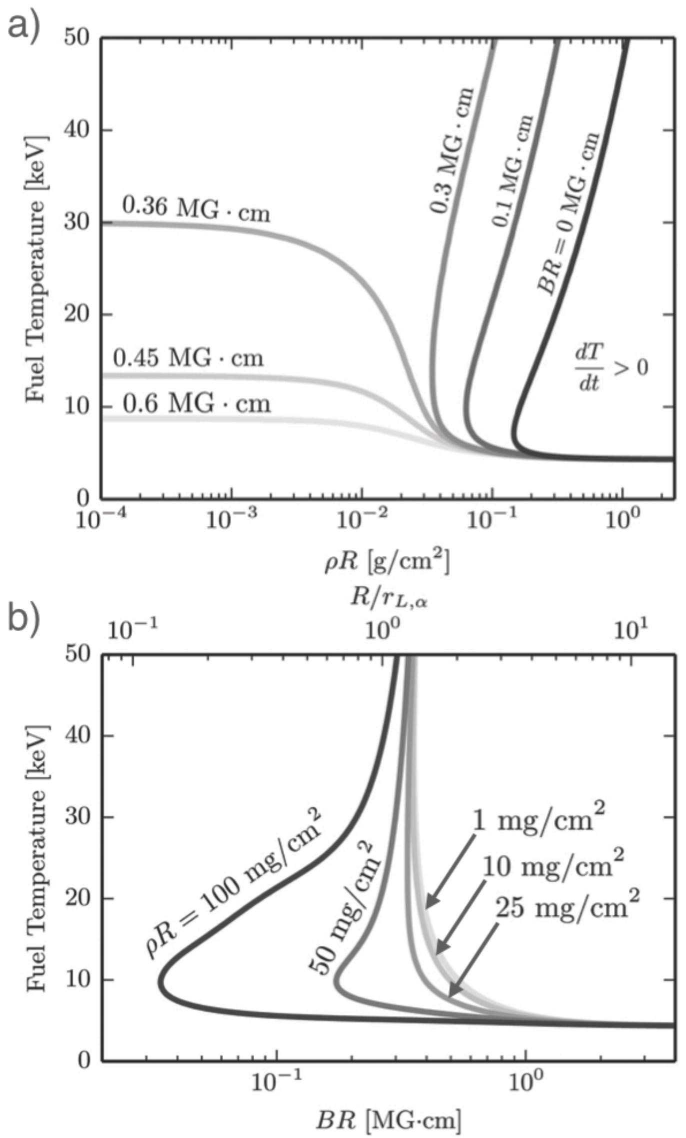


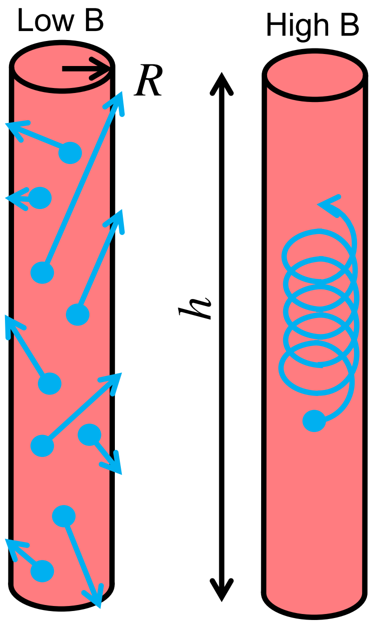
- When the Larmor radius is about half of the fuel radius, the effect begins to saturate
- This means there is an optimal field for a given fuel configuration

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

In MIF, charged particle confinement is determined by the magnetization ("BR") and not the fuel areal density ("ρR") as in ICF



$$\frac{R}{r_\alpha} = \frac{BR\ [T\cdot\mathrm{cm}]}{26.5} = \frac{BR\ [G\cdot\mathrm{cm}]}{2.65e5} \approx 4BR\ [MG\cdot\mathrm{cm}]$$



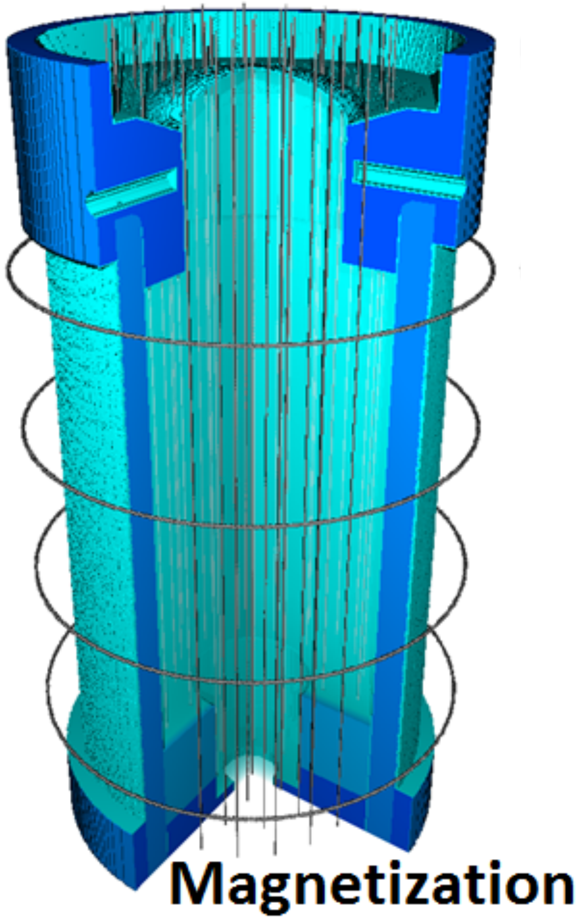
Fraction of trapped α's (tritons) is a function of ***BR*** only

At BR>0.5 MG-cm the effects saturate (particles are well confined).

However, areal density of the **liner** compressing the fuel is also important to the inertial confinement of the liner/fuel assembly

Basko *et al*. Nuclear Fusion 40, 59 (2000); P.F. Knapp *et al*., Phys. Plasmas (2015).

MagLIF[1,2] is an MIF concept that relies on three stages to heat, compress and confine fusion fuel



Stage 1: Magnetization

- **Be liner containing fusion fuel**
  - **D_2 gas ~ mg/cc (n_e/n_{crit} < 0.1)**
- **Axial magnetic field is applied to target**
  - **100-300 kG**
  - **~ ms risetime**
- **Z current starts creating an azimuthal drive field**

[1] S. A. Slutz, *et al.*, Phys. Plasmas **17** 056303 (2010)
[2] A.B. Sefkow, *et al.*, Phys. Plasmas, **21** 072711 (2014)

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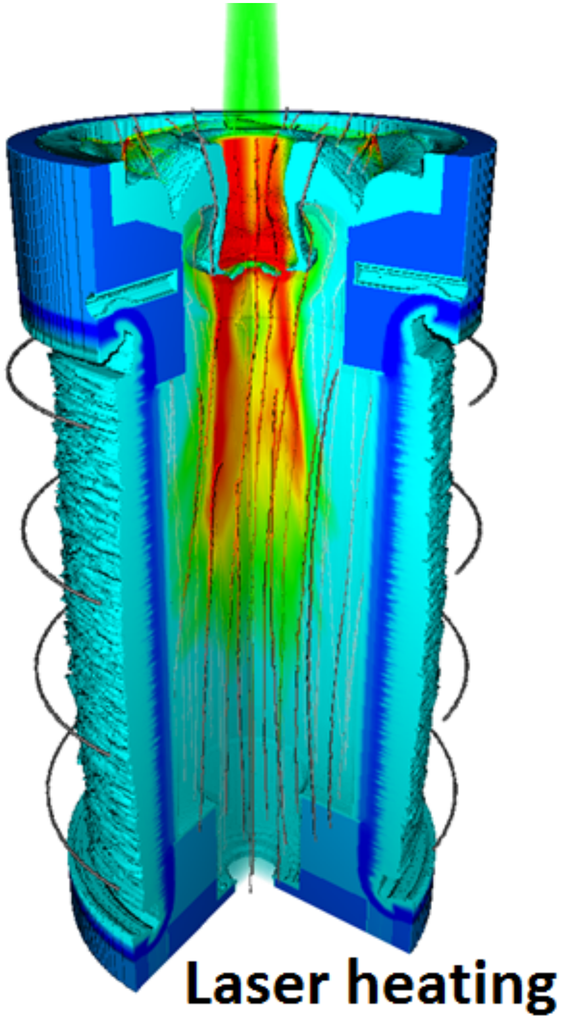

Stage 2: Laser Heating

- Liner begins to compress
  - OD is moving but ID is stationary
- Laser heats the fuel
  - T_e ~ 100s of eV
- Liner ID begins to implode
- Simulations indicate that fuel conditions isotropize over the 10s of ns of the implosion

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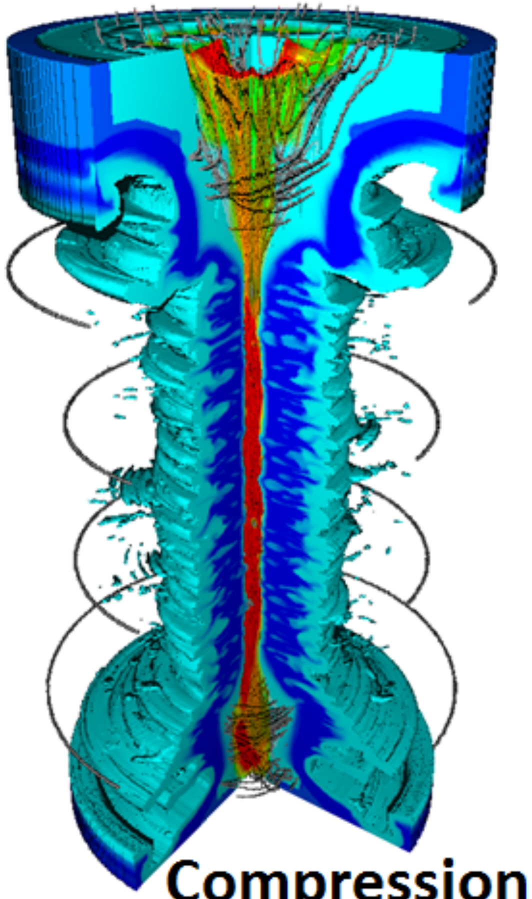
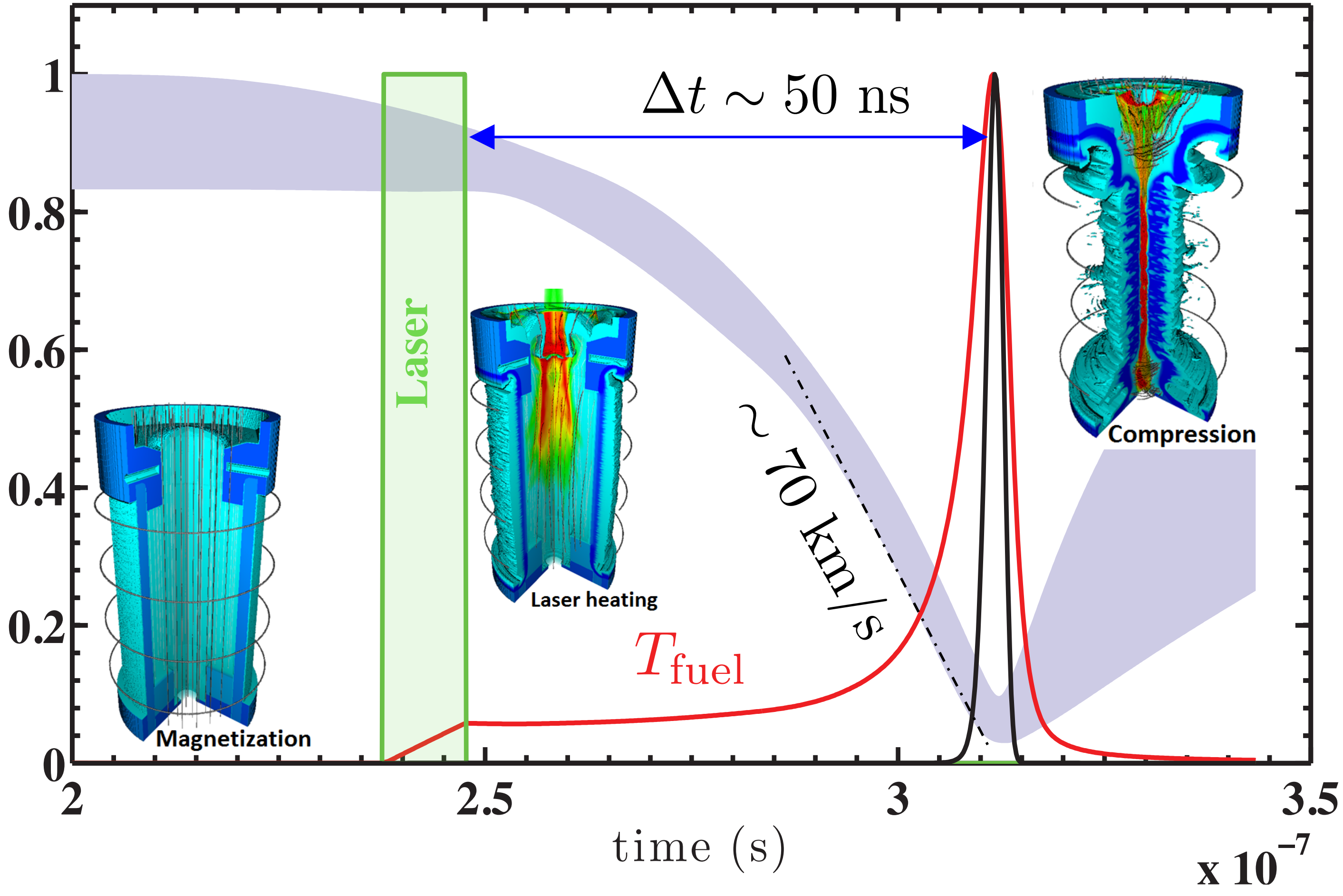


Stage 3: Compression

- **Axial magnetic field insulates fuel from liner throughout implosion**
  - **Field increases substantially through magnetic flux compression**
- **Fuel is heated through *PdV* work to keV temperatures**
- **Liner stagnates**
  - **Plasma pressure exceeds drive pressure**

[1] S. A. Slutz, *et al.*, Phys. Plasmas **17** 056303 (2010)
[2] A.B. Sefkow, *et al.*, Phys. Plasmas, **21** 072711 (2014)

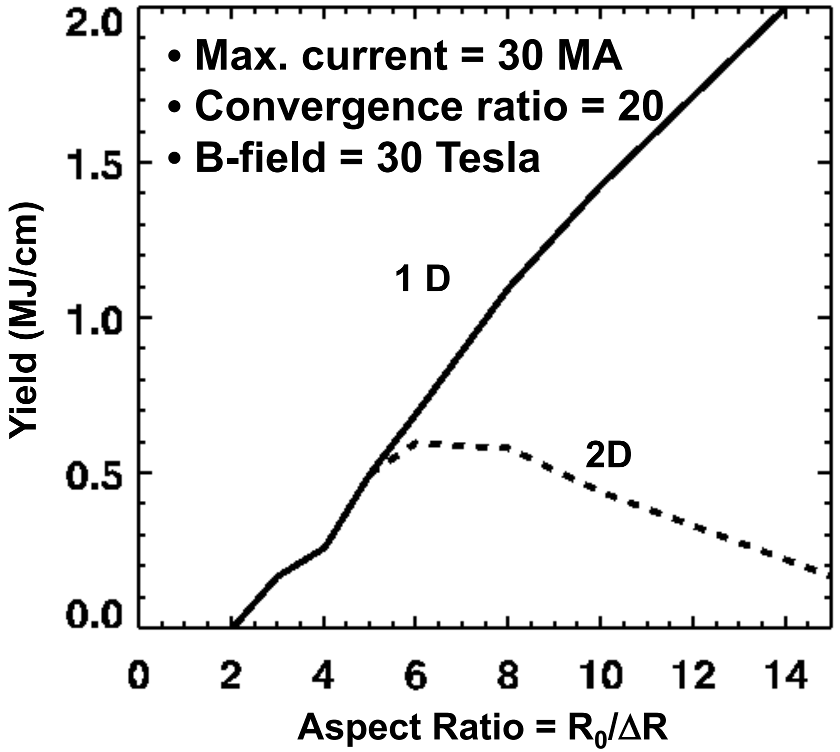
Magnetization and preheat reduce peak velocity required for ignition compared to traditional ICF

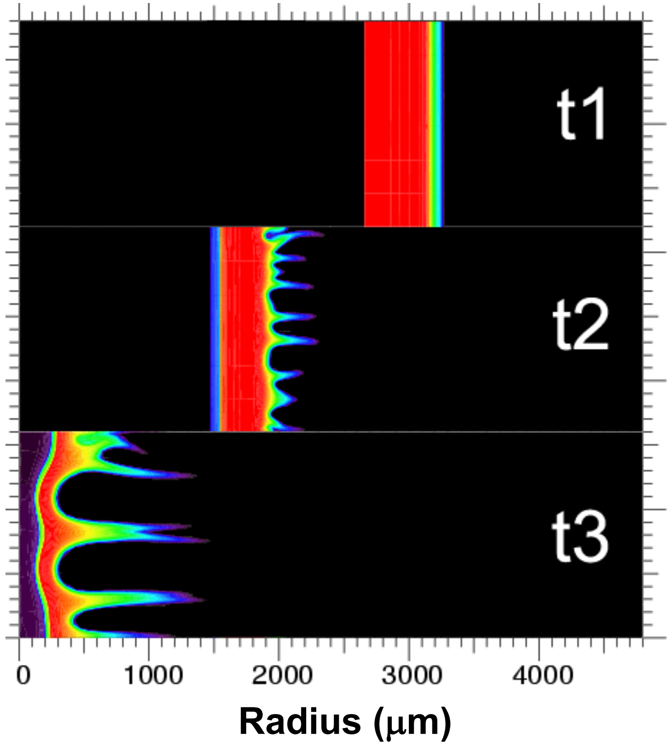


- Magnetization confines 3.5 MeV α-particles at lower ρR
- Preheating + magnetization allows ignition temperature to be reached at a lower implosion velocity[1]

[1] S. A. Slutz, *et al*., Phys. Plasmas **17** 056303 (2010)
[2] S. A. Slutz. and R.A. Vesey, PRL **108**, 025003 (2012)

Reducing the implosion velocity requirements through fuel heating and magnetization allows us to use thicker, more massive liners to compress the fuel that are more stable





• The Magneto-Rayleigh-Taylor instability degrades the yield as the aspect ratio is increased (due to decreased liner ρR)

• Simulations of AR=6 Be liner show reasonably uniform fuel compression and sufficient liner ρR at stagnation to inertially confine the fuel

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

MagLIF experiments are complicated to field and analyze

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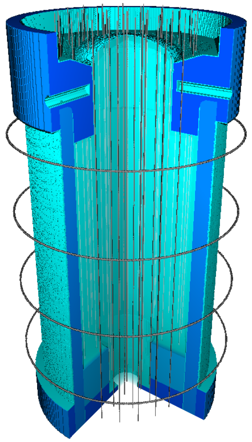
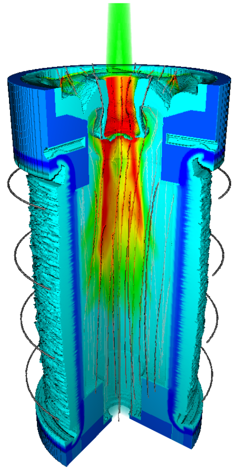


Magnetization

- 10-30 T axial B-field
- 3 ms risetime
- ~1 mg/cm^3 initial density

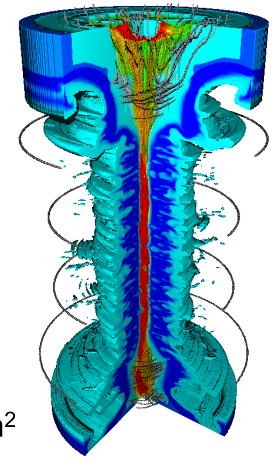


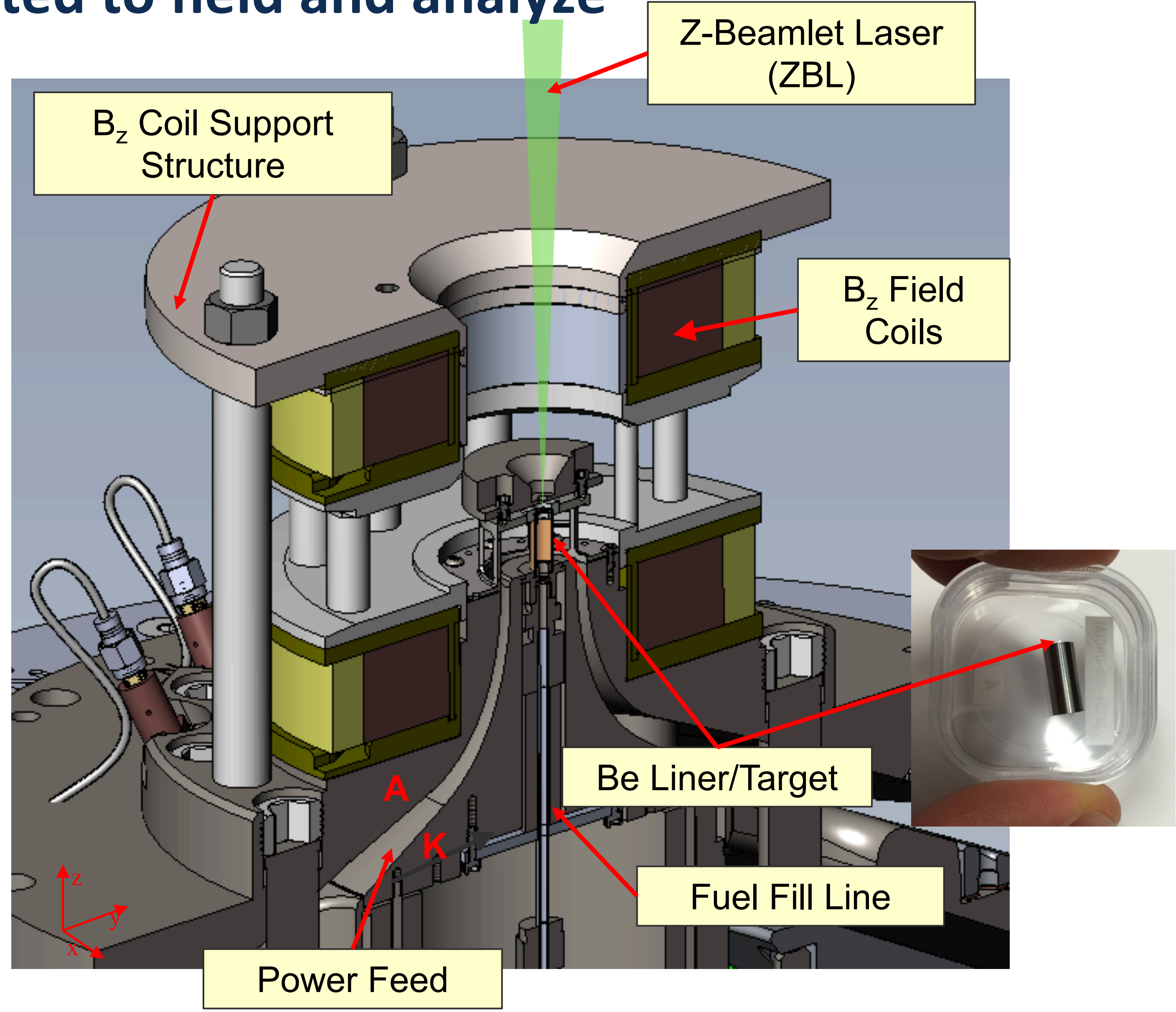
Laser Heating

- 1-4 kJ, 1-4 ns
- 2ω, f/10 beam
- ~50 ns from preheat to stagnation

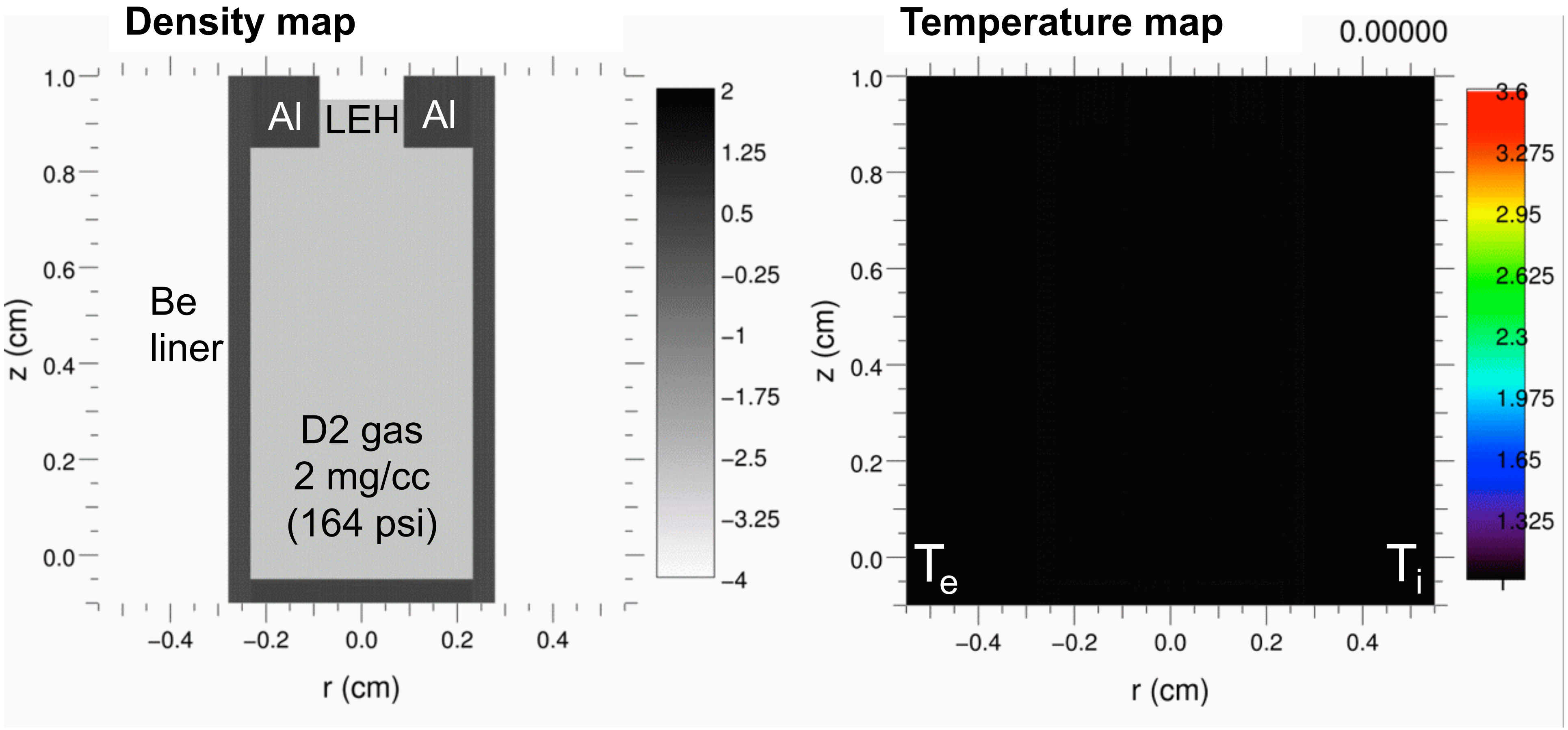
Implosion and Stagnation

- CR = 25-40
- Burn duration 1-2 ns
- Flux compression >>100x B_0
- ρR_f ~ 0.01 g/cm^2, ρL_f ~1 g/cm^2



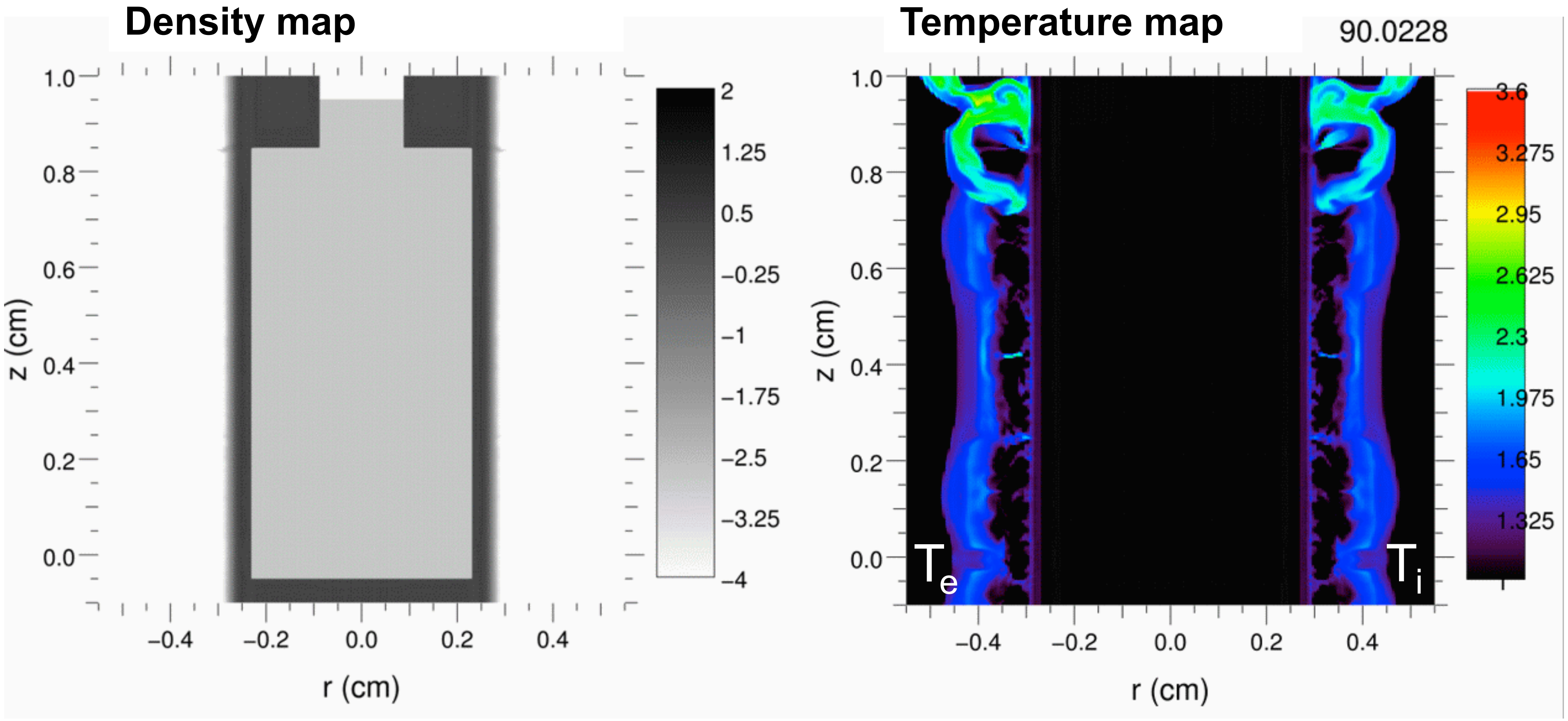


An example fully integrated 2D HYDRA calculation illustrates the stages of a MagLIF implosion



Example calculations by A.B. Sefkow: DD fuel, I=18 MA, B_Z=10 T, E_{LASER}=2.6 kJ

The fusion fuel is preheated using the Z-Beamlet laser after the liner begins to implode



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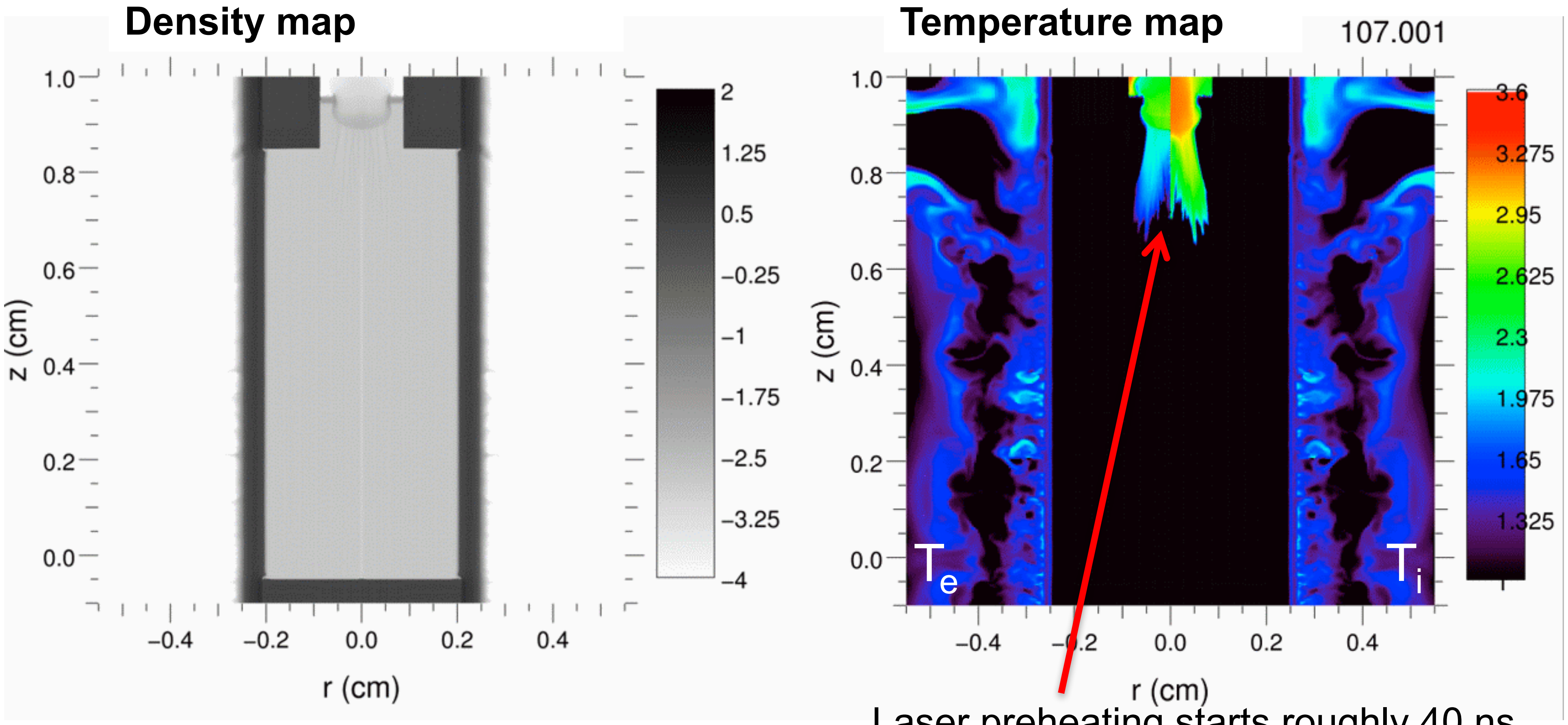

Laser preheating starts roughly 40 ns before the liner reaches the axis

Example calculations by A.B. Sefkow: DD fuel, I=18 MA, B_Z=10 T, E_{LASER}=2.6 kJ

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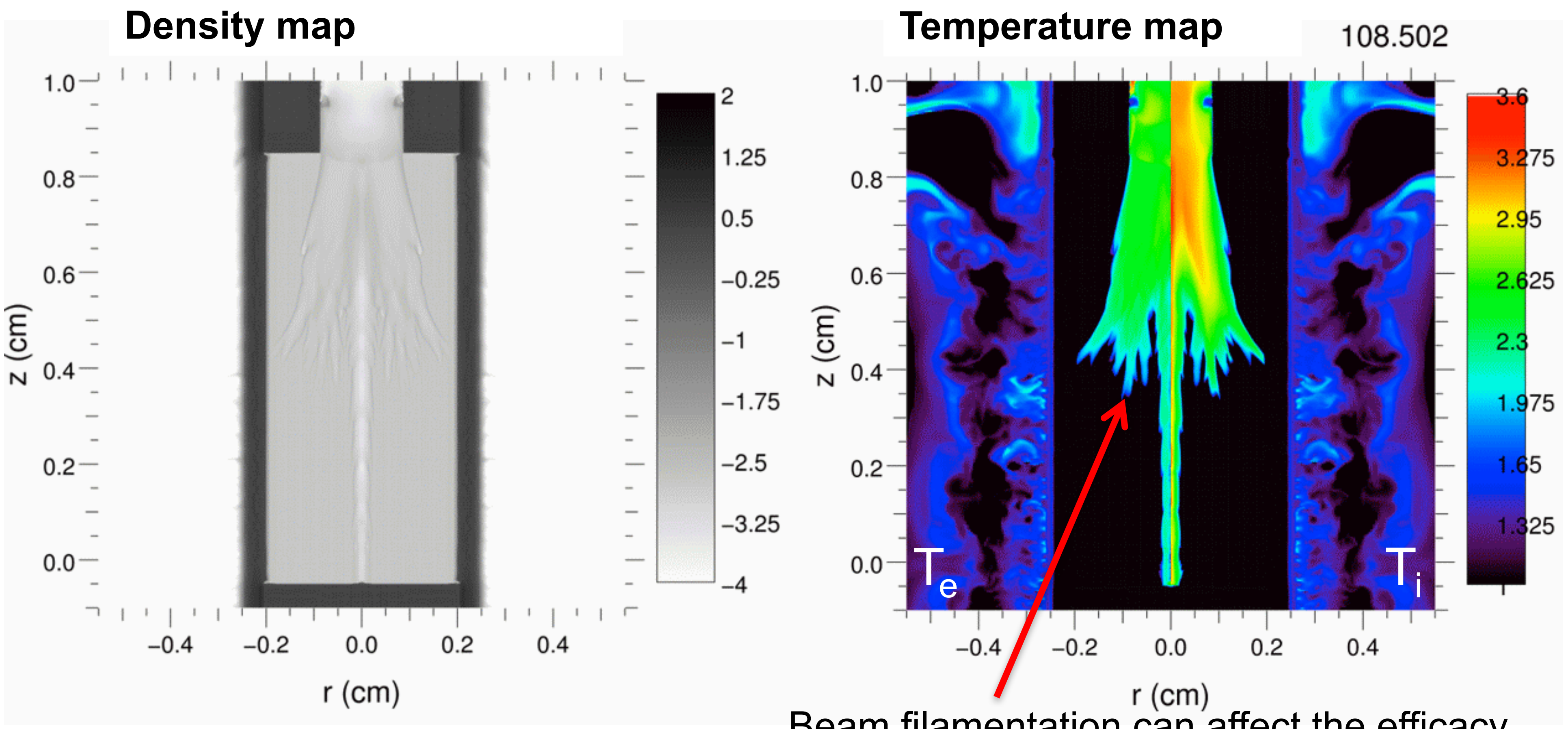
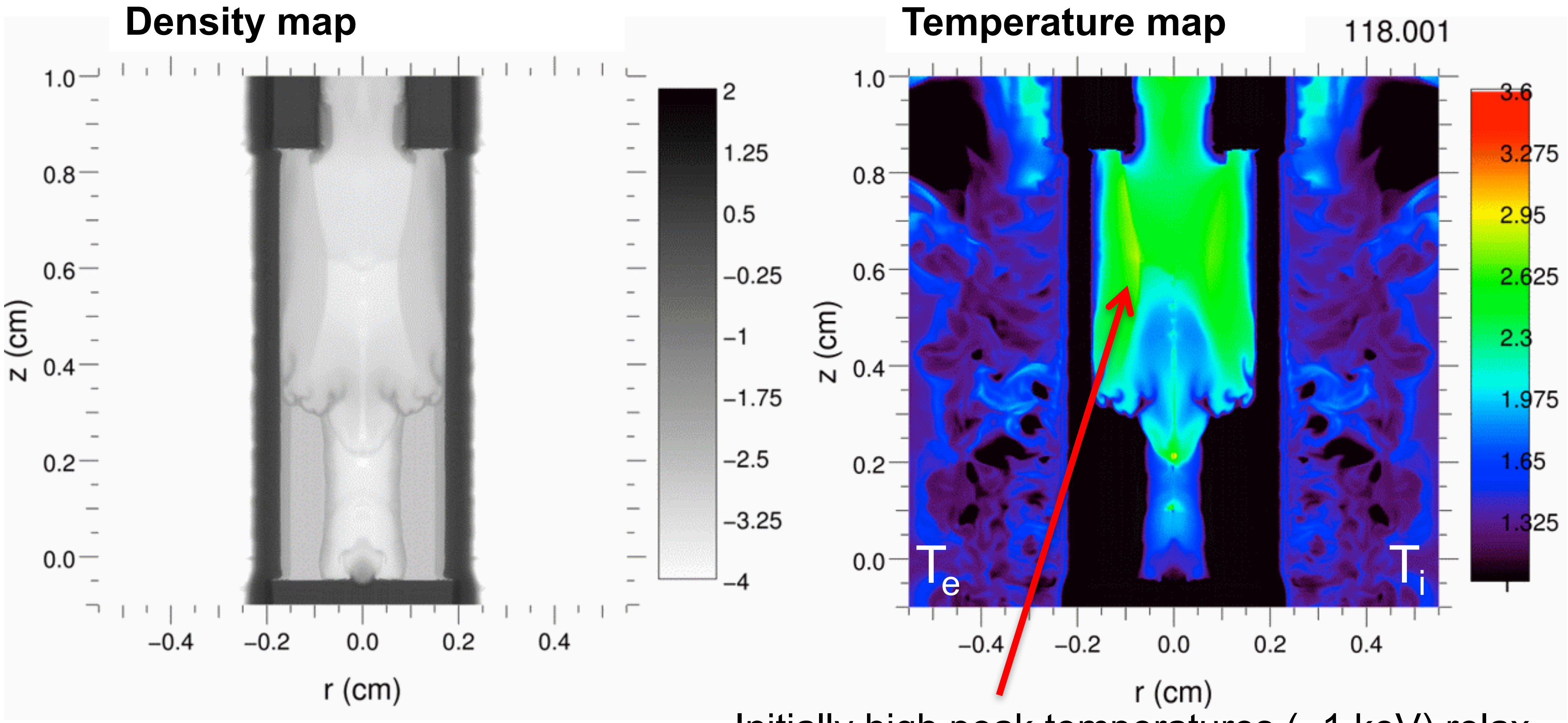


Beam filamentation can affect the efficacy and depth of laser coupling to the fuel

Example calculations by A.B. Sefkow: DD fuel, I=18 MA, B_Z=10 T, E_{LASER}=2.6 kJ

The preheated fuel is then compressed by the imploding liner, reducing the convergence required to reach fusion temperatures



Initially high peak temperatures (~1 keV) relax to ~300 eV as the energy diffuses into the fuel

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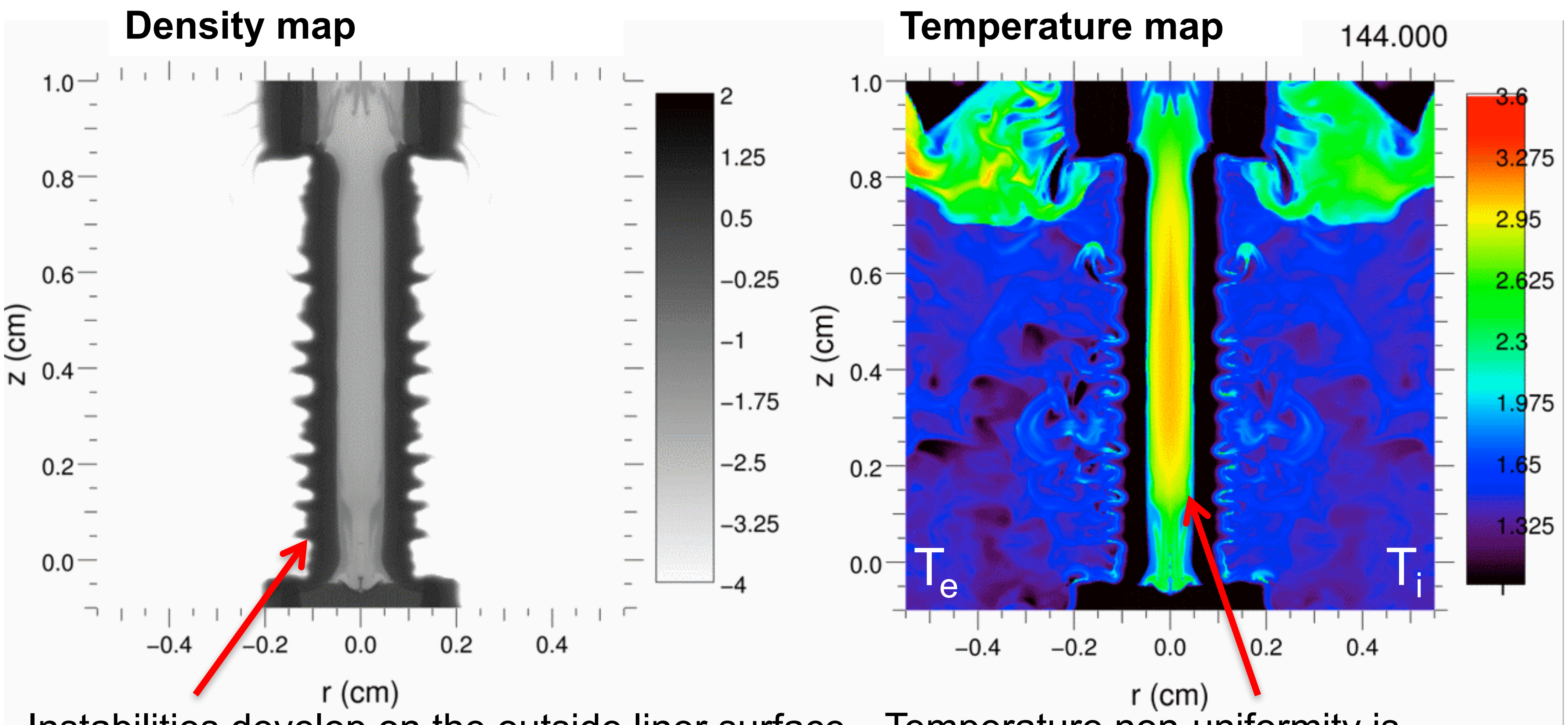

Instabilities develop on the outside liner surface, but impact on fuel mitigated by use of thick liner

Temperature non-uniformity is smoothed out during compression

Example calculations by A.B. Sefkow: DD fuel, I=18 MA, B_Z=10 T, E_{LASER}=2.6 kJ

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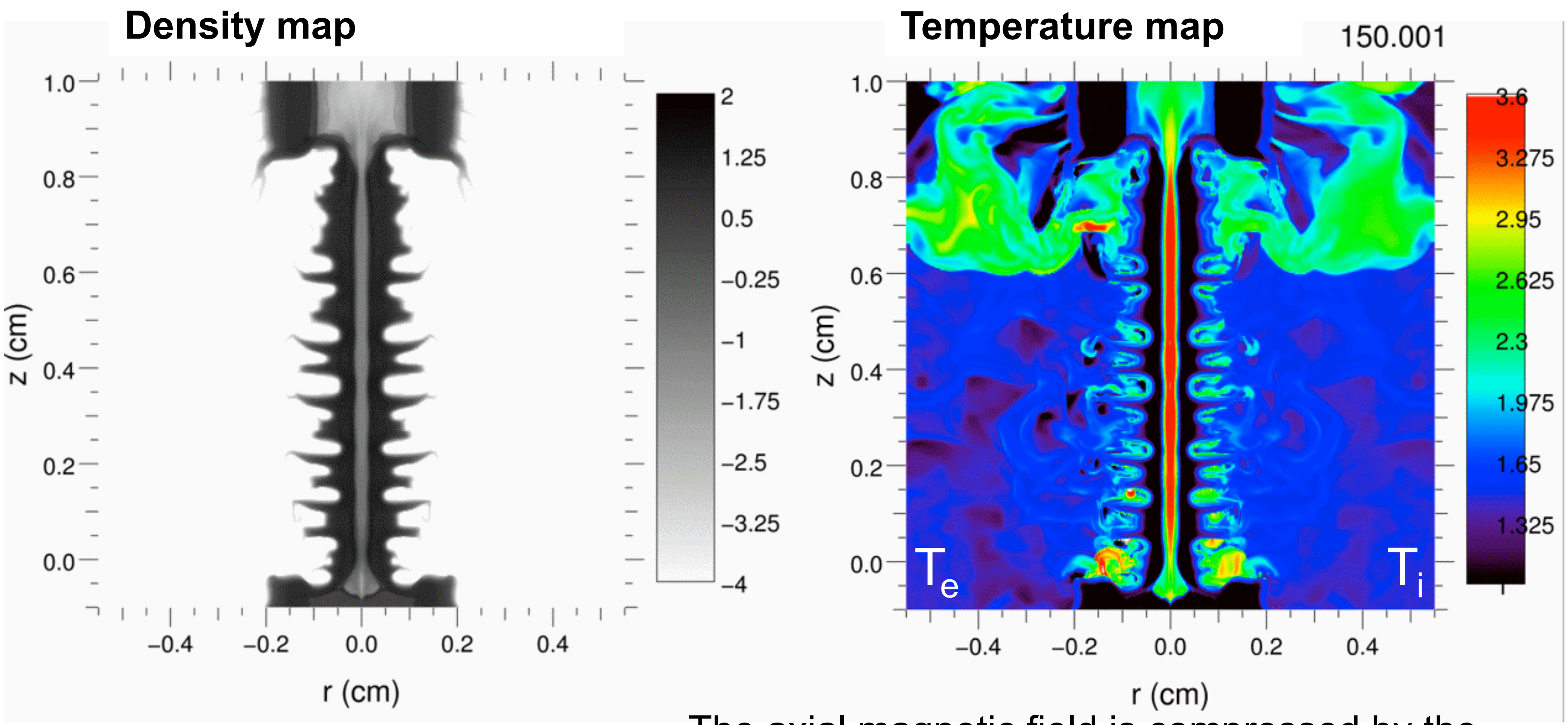
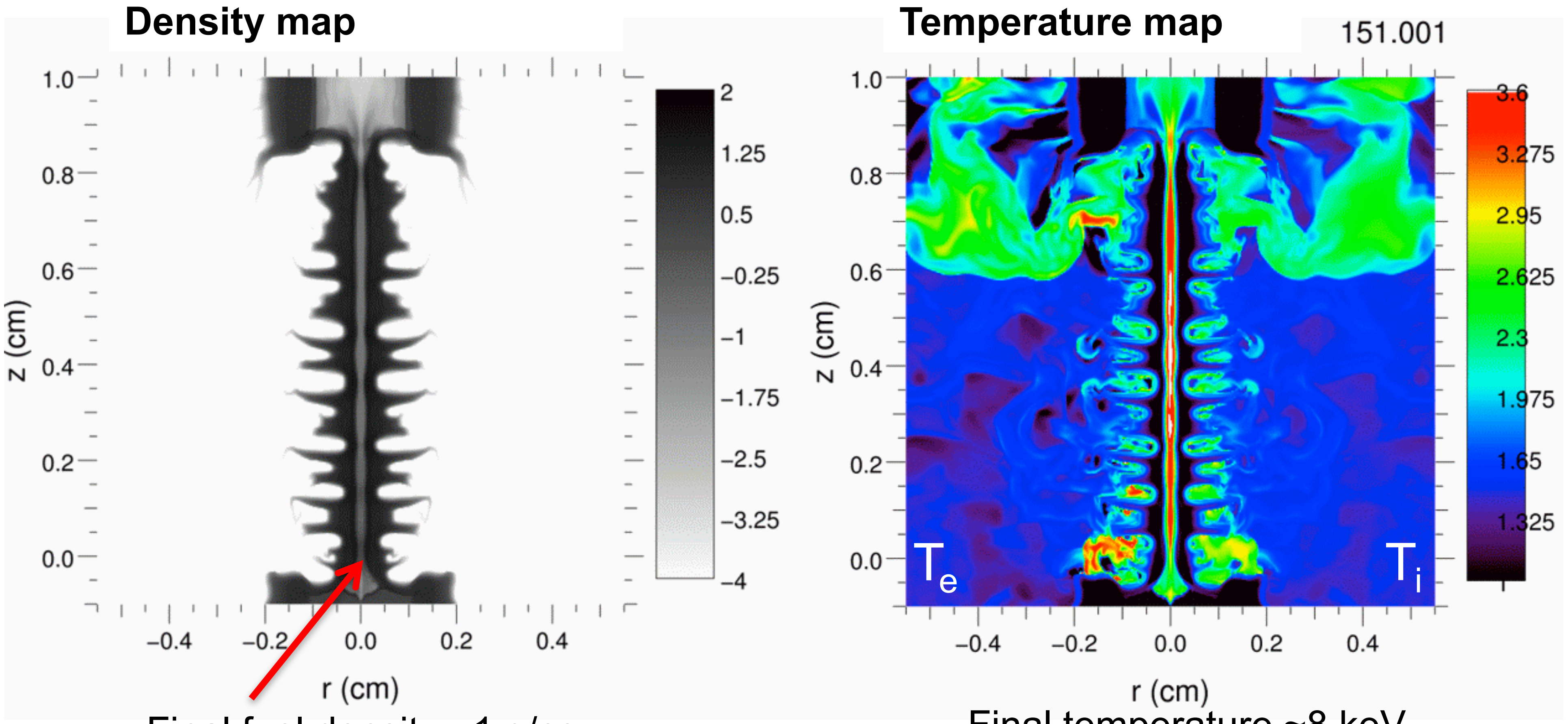


The axial magnetic field is compressed by the liner (some loss due to Nernst) and suppresses heat loss to the relatively cold liner

The preheated fuel is then compressed by the imploding liner, reducing the convergence required to reach fusion temperatures

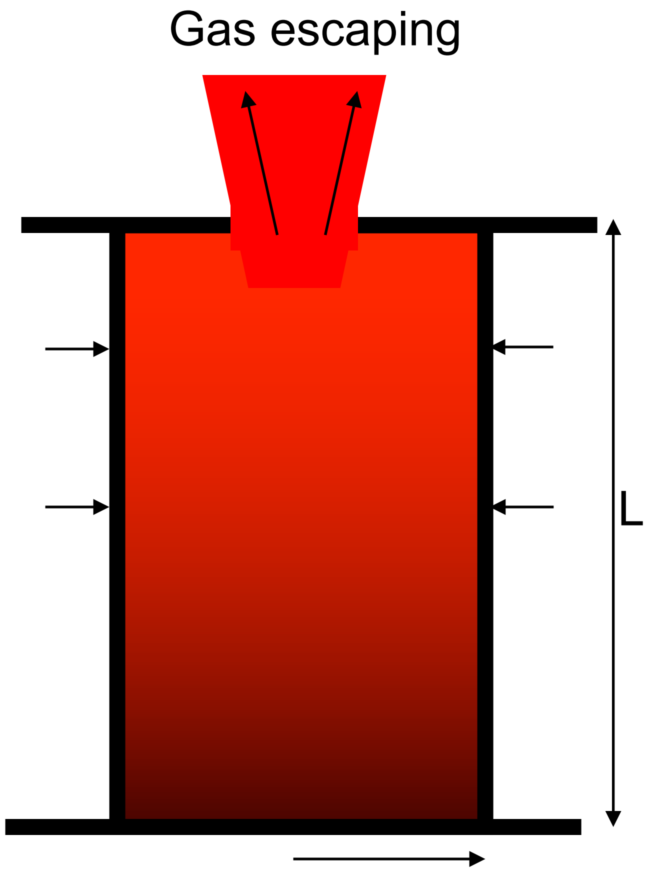


Final fuel density ~1 g/cc
Inertial confinement provided by liner

Final temperature ~8 keV
Peak Bfield >13000 T, Radial CR~23

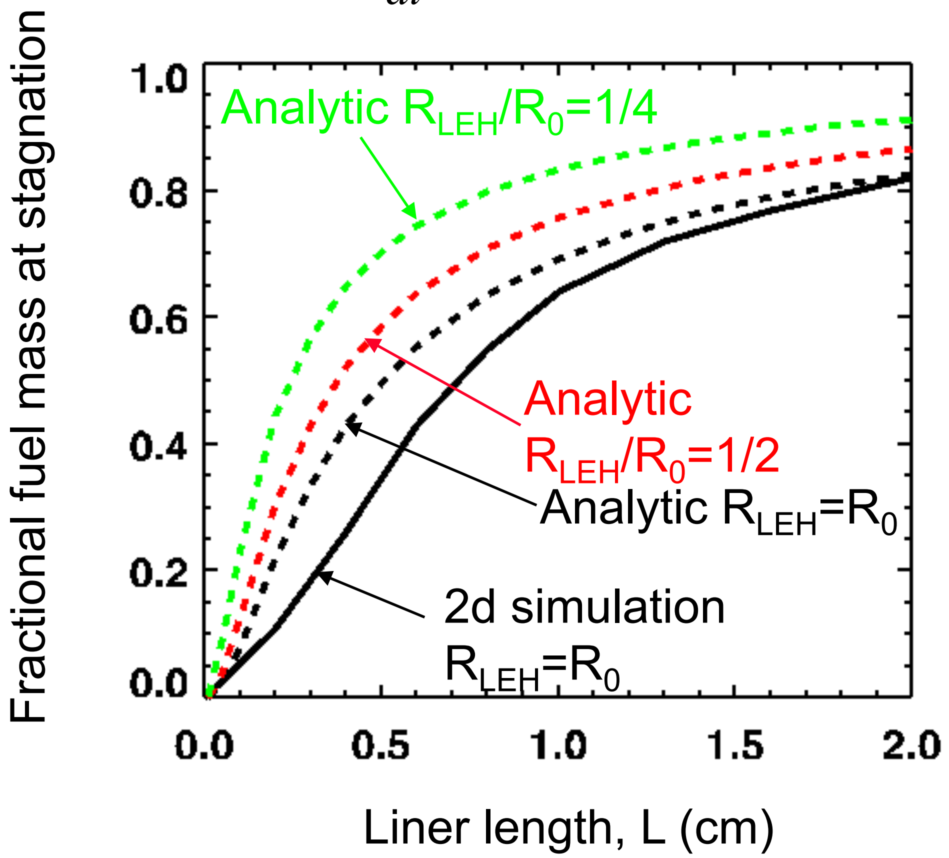
Example calculations by A.B. Sefkow: DD fuel, I=18 MA, B_Z=10 T, E_{LASER}=2.6 kJ

Analytic estimates and 2D simulations suggest the loss of fuel through the laser entrance hole should be manageable



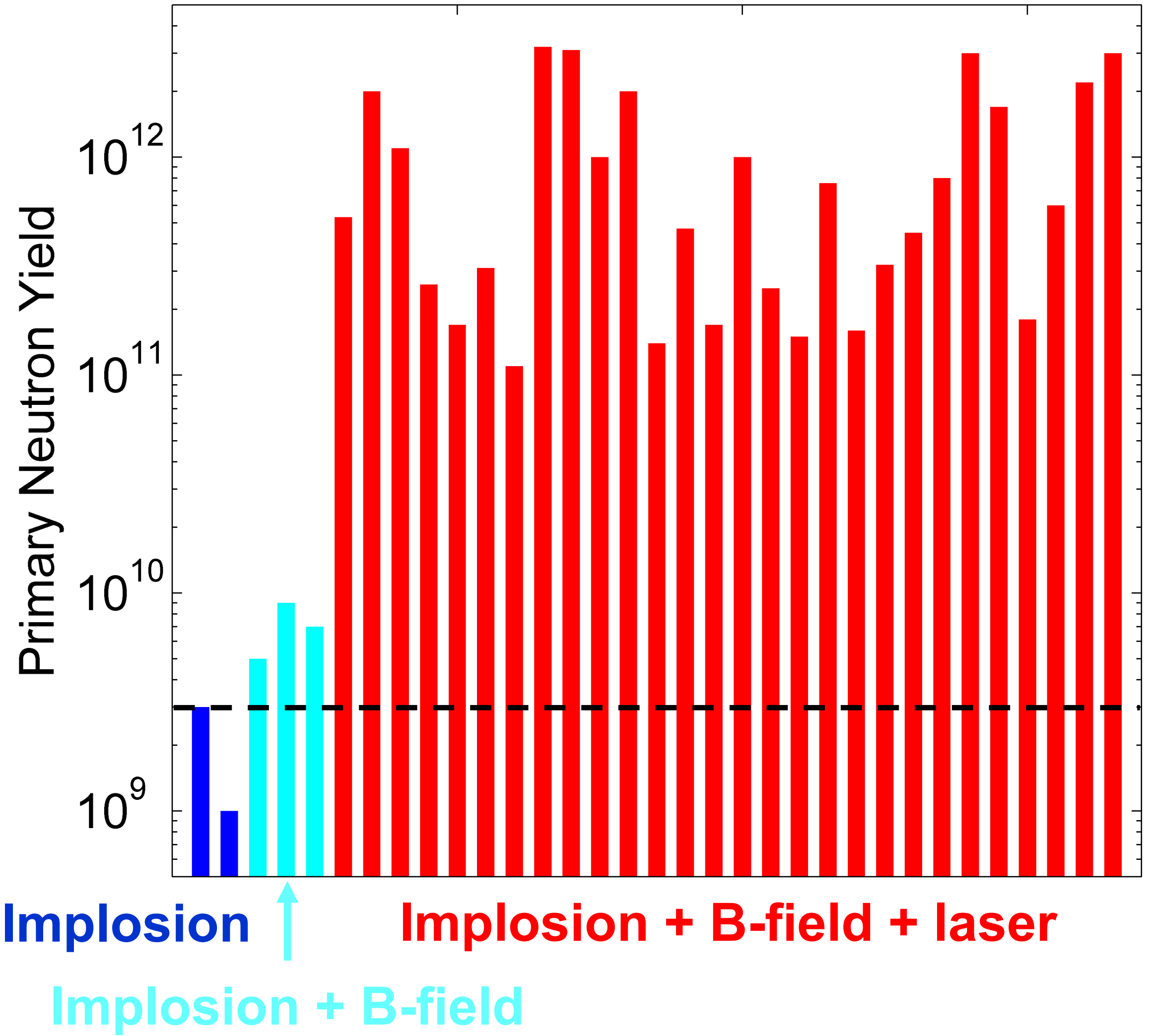
$$r(t) \sim r_0\left[1-\left(t/t_P\right)^{5/3}\right]$$

$$\frac{dM}{dt} \approx 0.31 c_{s0}\rho_0 \pi r_{LEH}^2$$



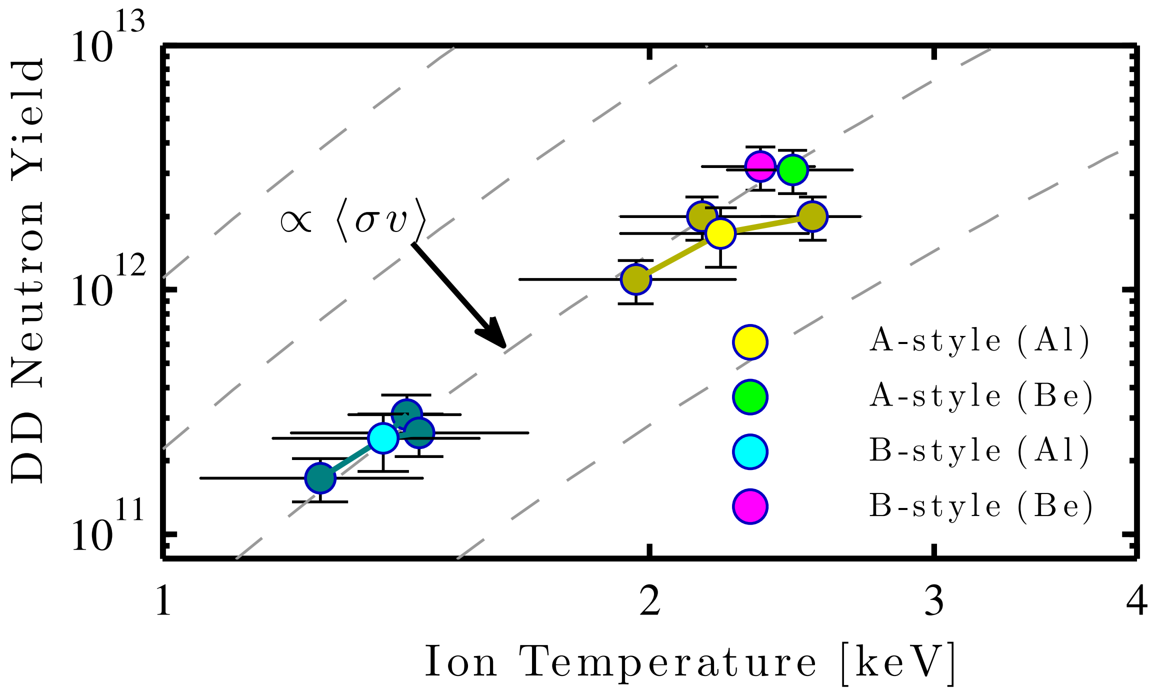
Note: Unlike most MIF approaches which use closed field line geometries, MagLIF has an open geometry

Primary neutron yields up to 4e12 produced only 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

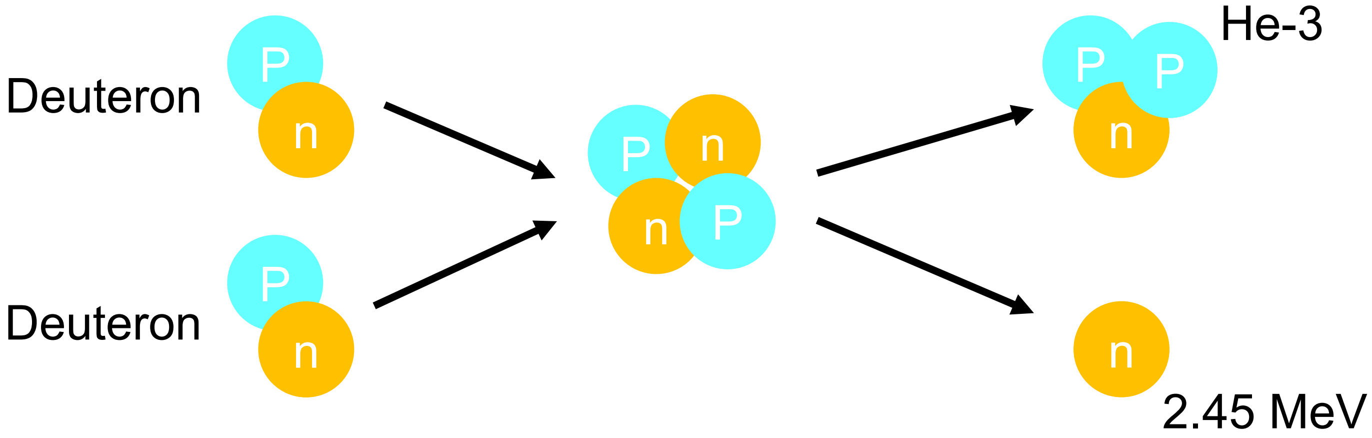
The primary neutron yield increases as the ion temperature increases



- 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 use of D-D fuel in our current MagLIF experiments allows us to measure magnetization

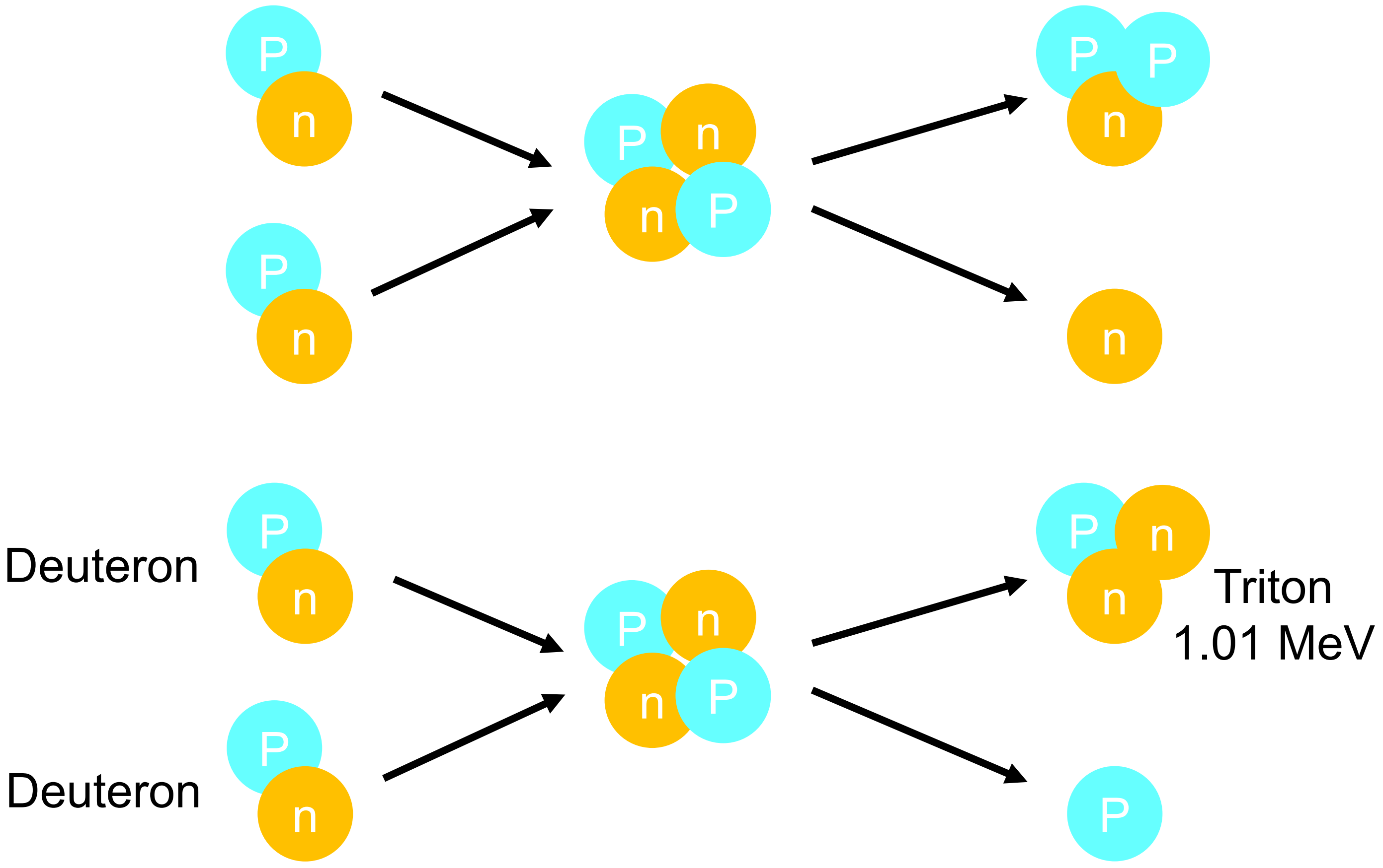
Primary Reactions



One branch of the D-D reaction produces 2.45 MeV neutrons and an energetic alpha particle...

The use of D-D fuel in our current MagLIF experiments allows us to measure magnetization

Primary Reactions

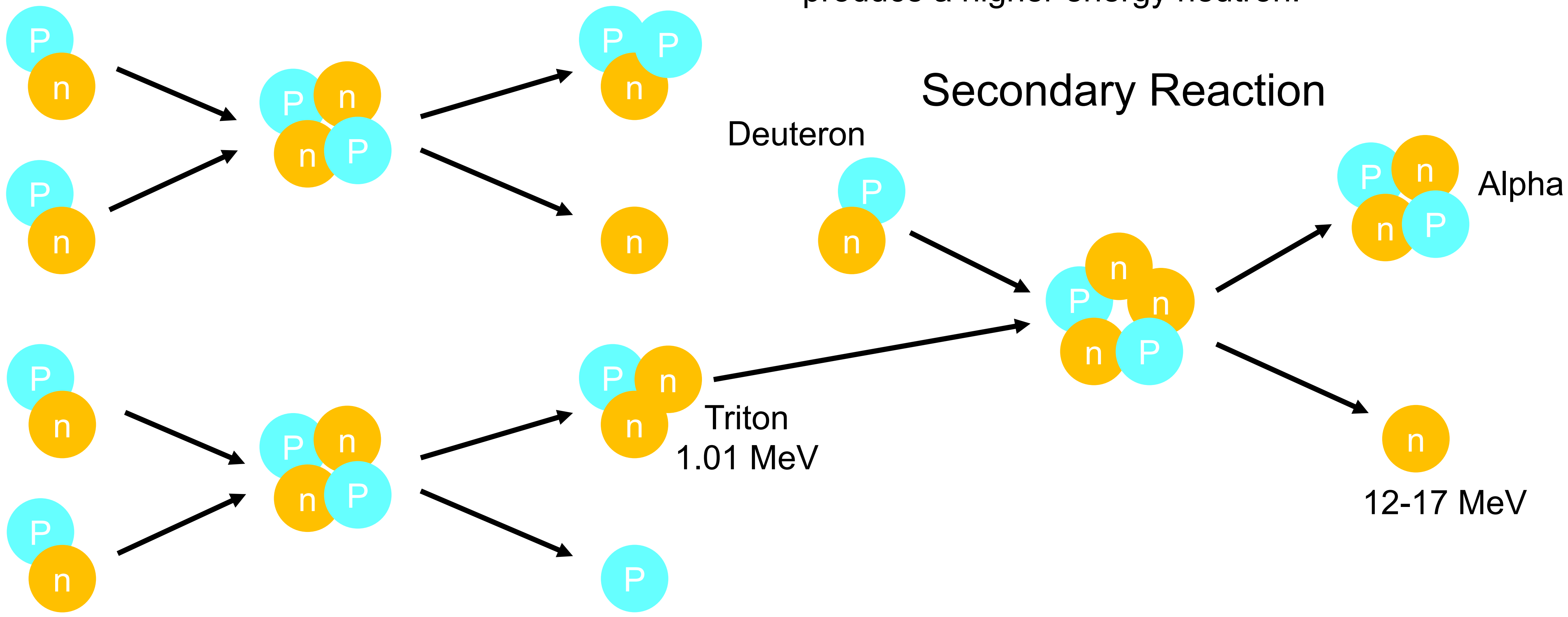


… the other branch produces a 1 MeV triton and energetic proton.

The use of D-D fuel in our current MagLIF experiments allows us to measure magnetization

Primary Reactions

The tritons can fuse with other deuterons to produce a higher energy neutron.



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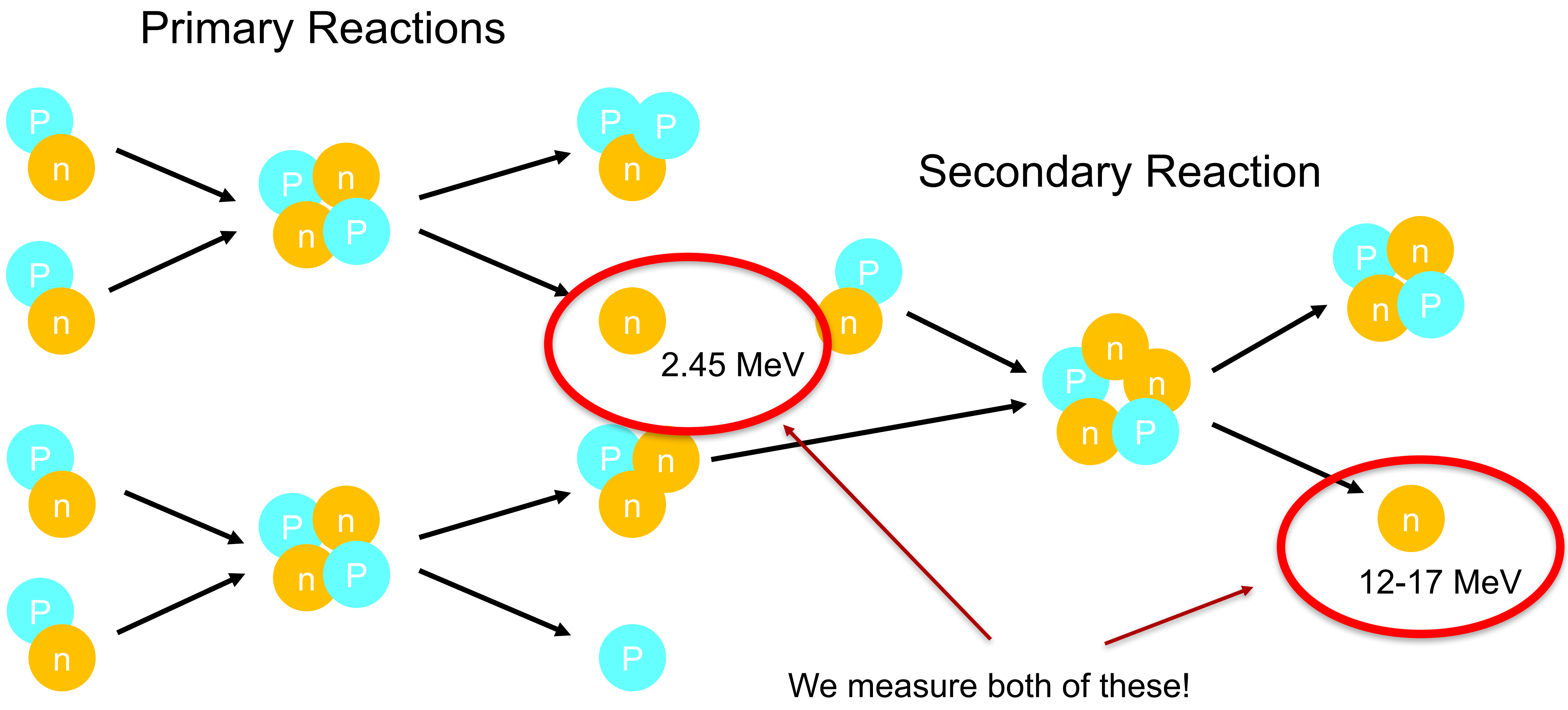

K. D. Hahn, et al., Rev. Sci. Instrum. 85, 043507 (2014).

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

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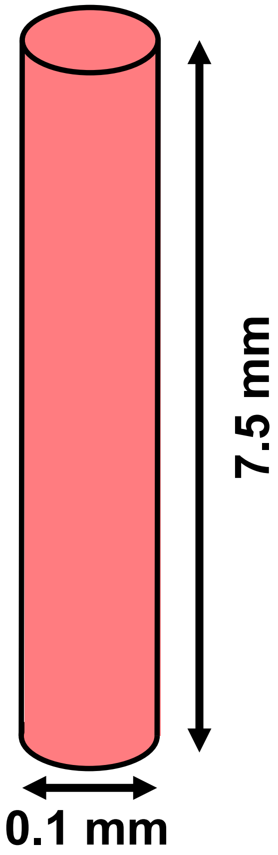
No B-field



- High aspect ratio stagnation geometry
  - Height >> radius

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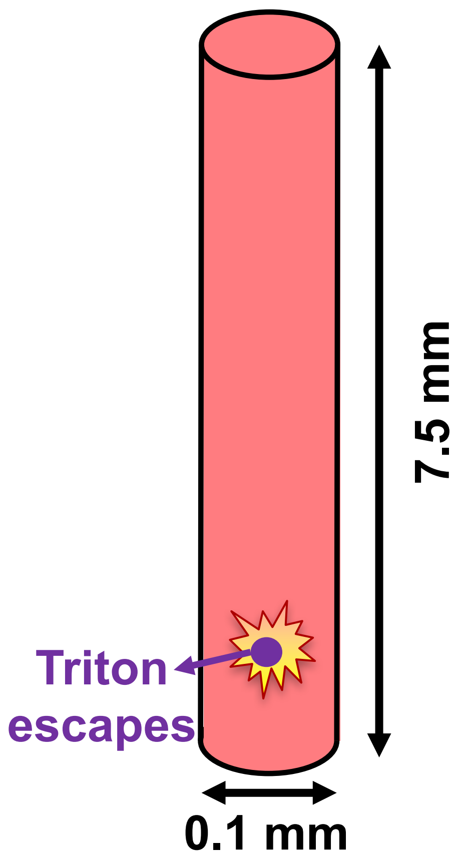

- High aspect ratio stagnation geometry
  - Height >> radius
- Consider 2 cases:
  - 1) Triton is created traveling radially
    - Very little probability of interacting prior to escaping

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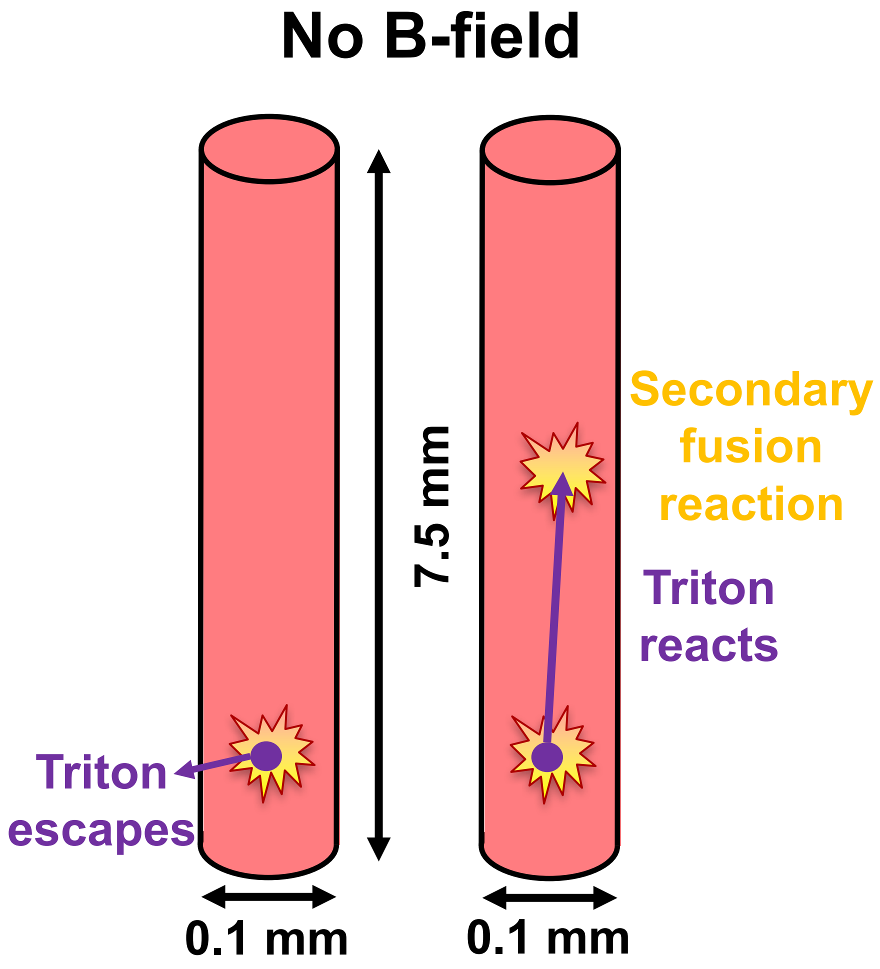
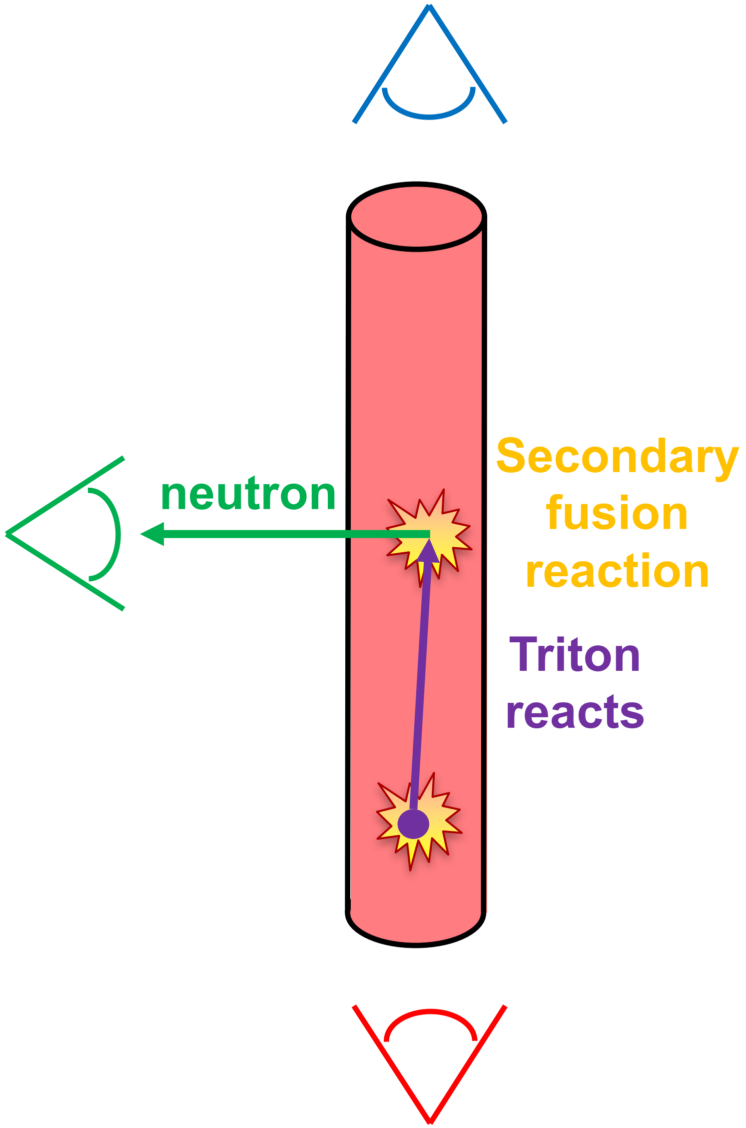
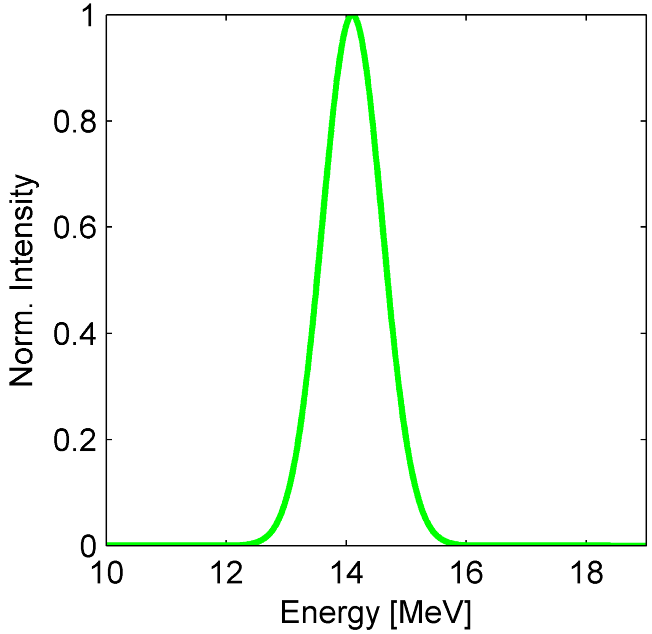


- High aspect ratio stagnation geometry
  - Height >> radius
- Consider 2 cases:
  - 1) Triton is created traveling radially
    - Very little probability of interacting prior to escaping
  - 2) Triton is created traveling axially
    - High probability of fusion prior to escaping

The secondary neutron energy spectra are not expected to be isotropic





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

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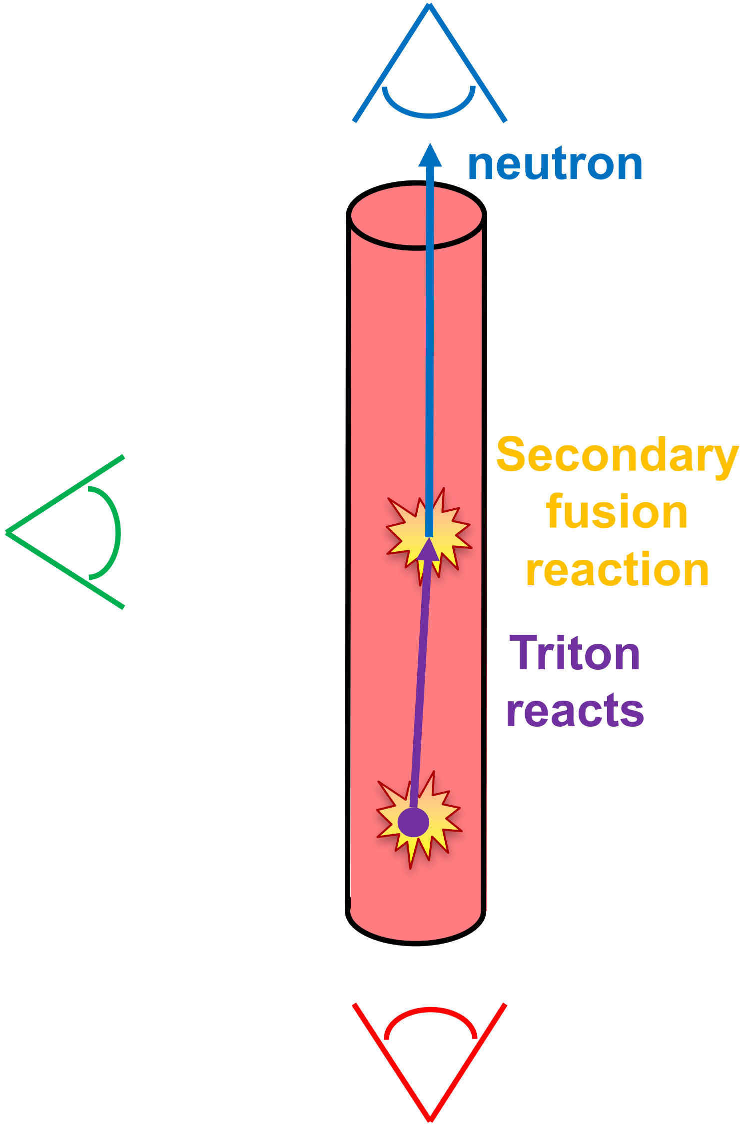

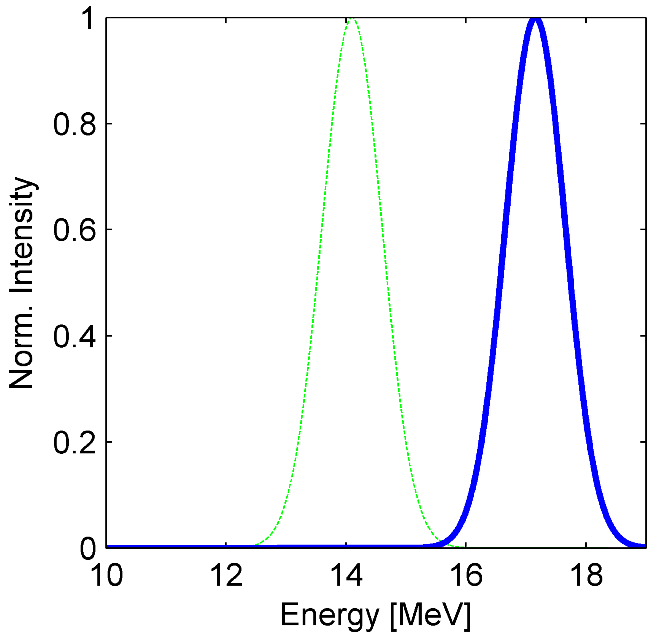

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  - Axial (triton moving towards)
    - Neutrons shifted to higher energy

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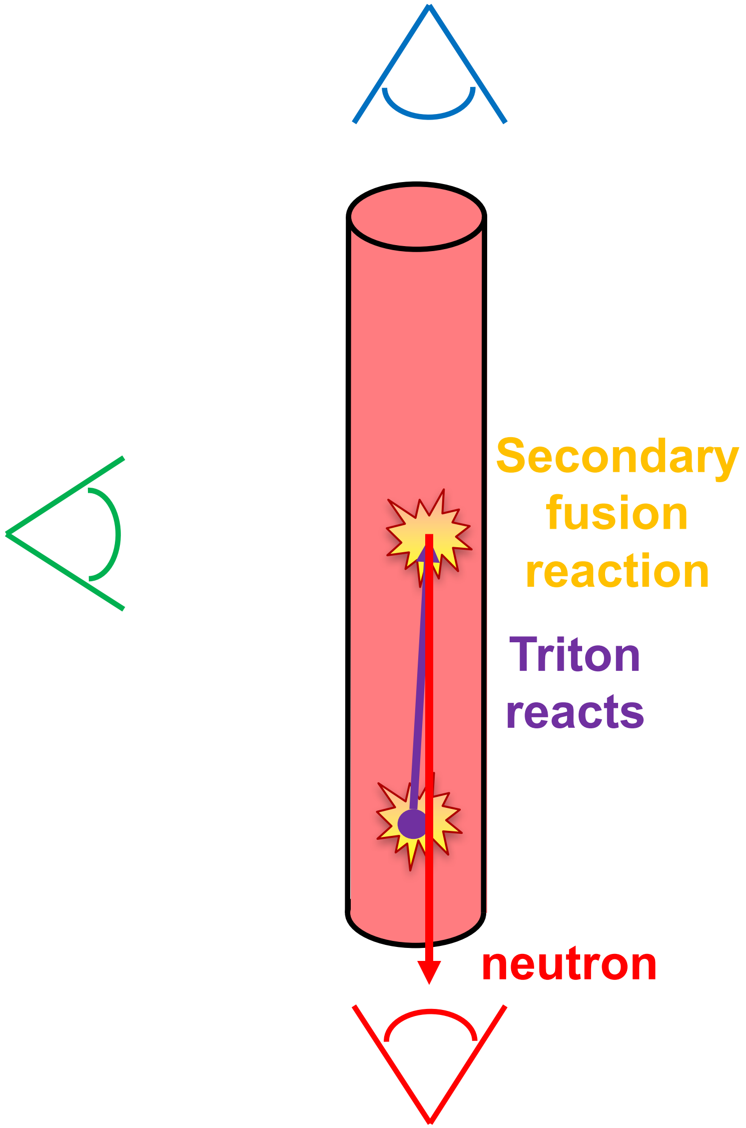

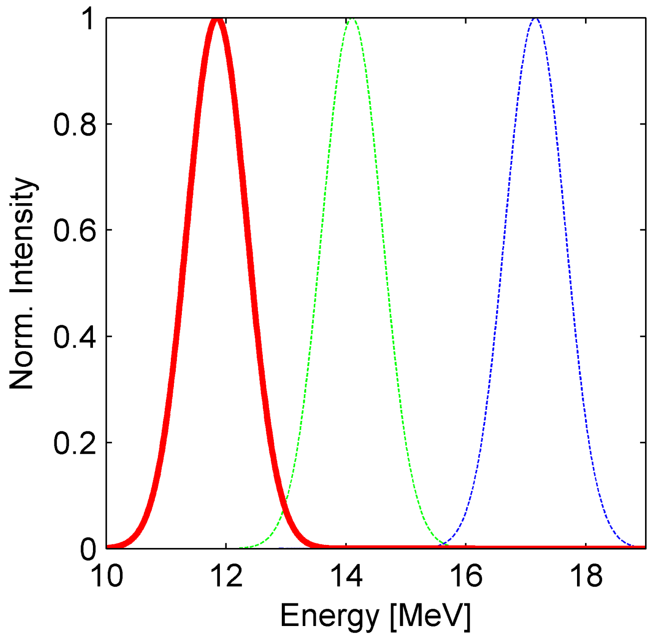

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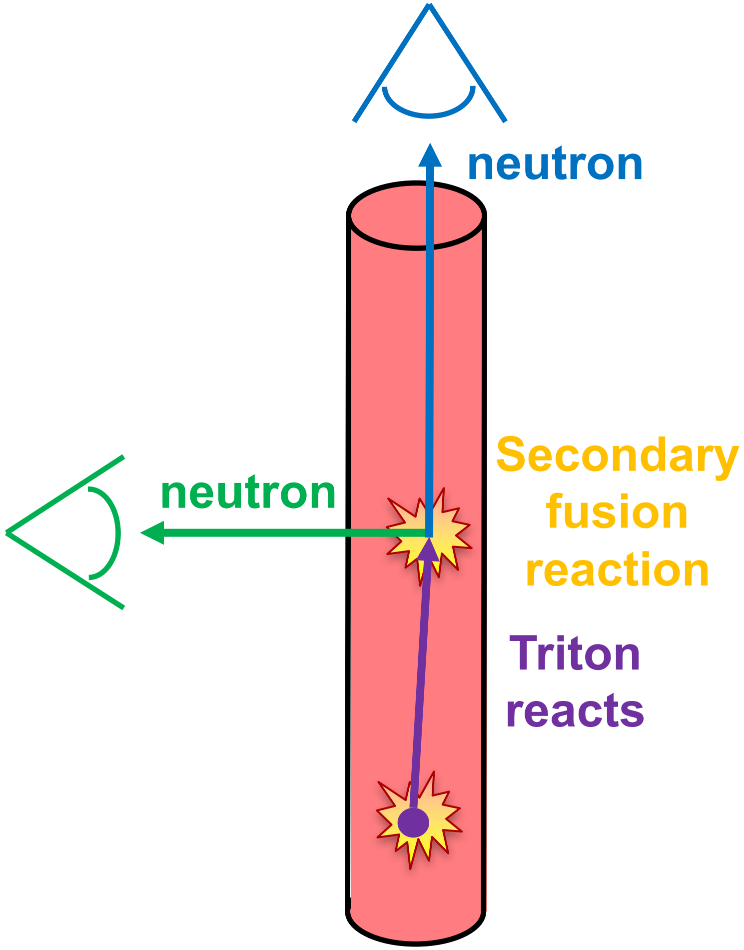

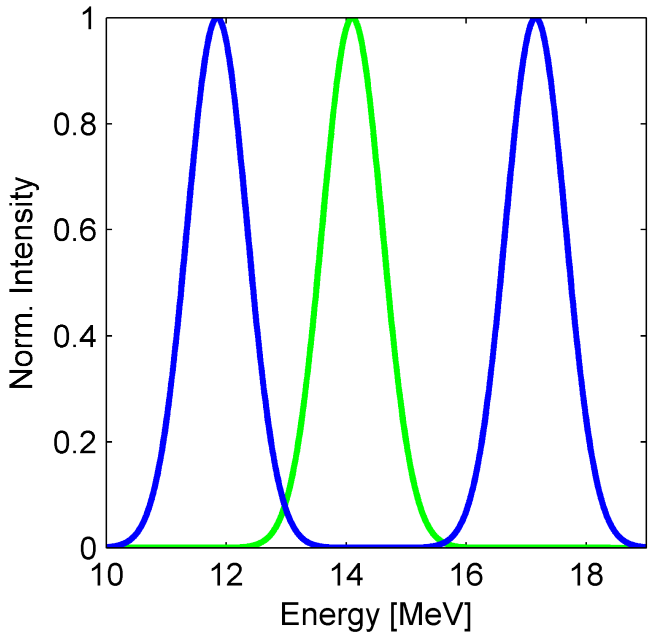

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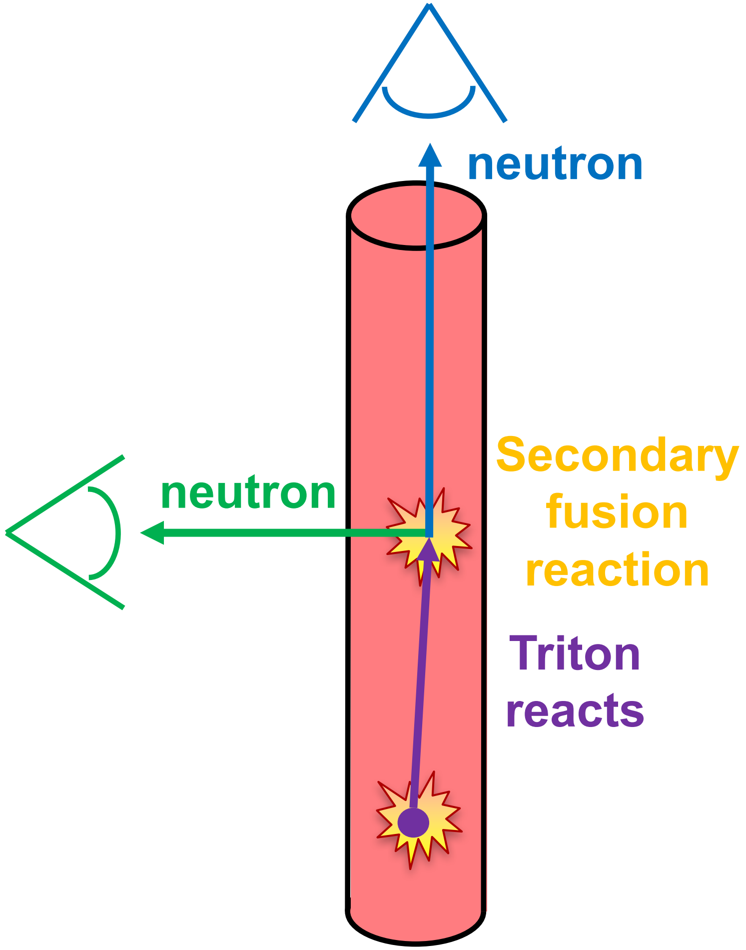
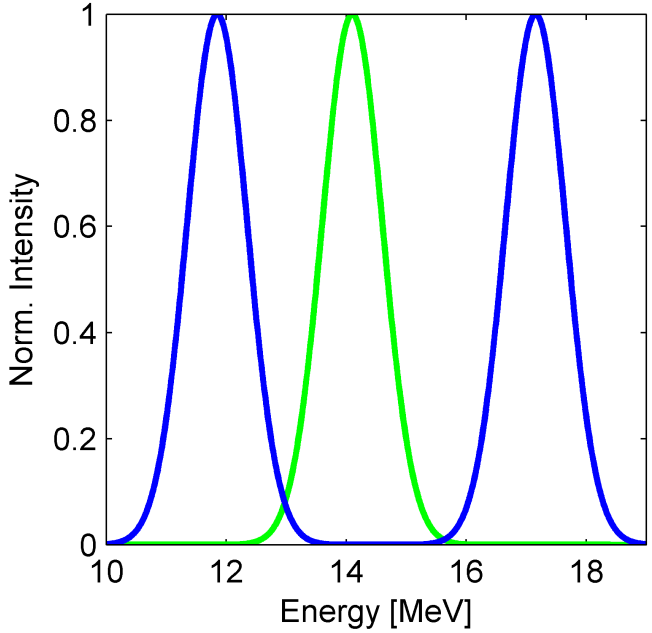
- Axial detectors will have double peaked structure

The secondary neutron energy spectra are not expected to be isotropic





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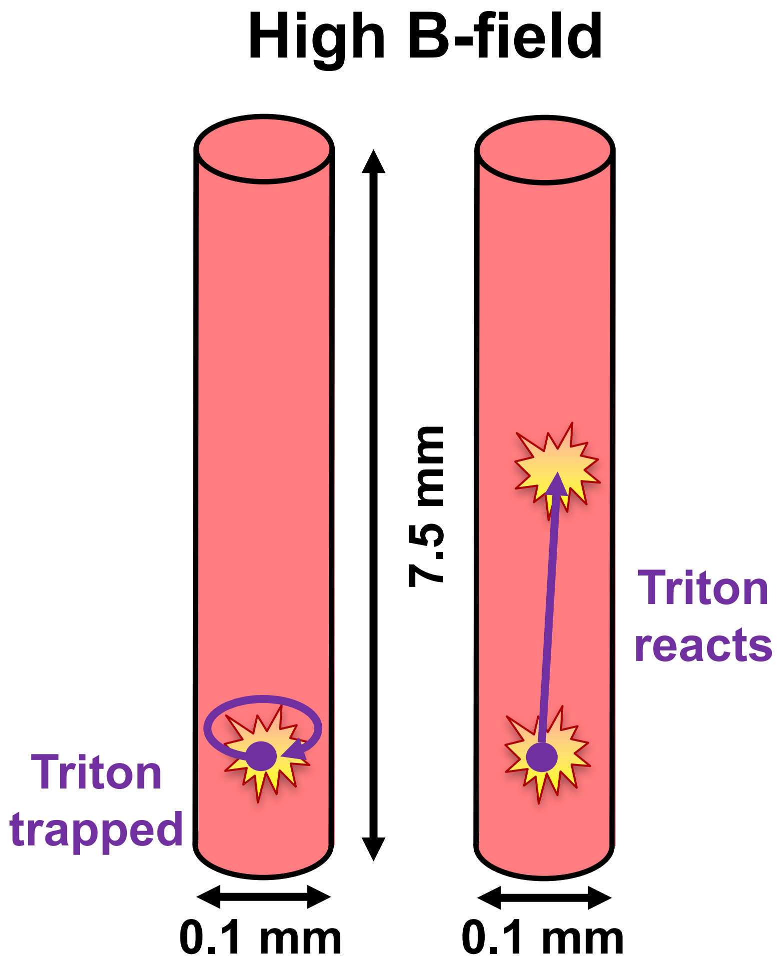
- Axial detectors will have double peaked structure

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
  - 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).

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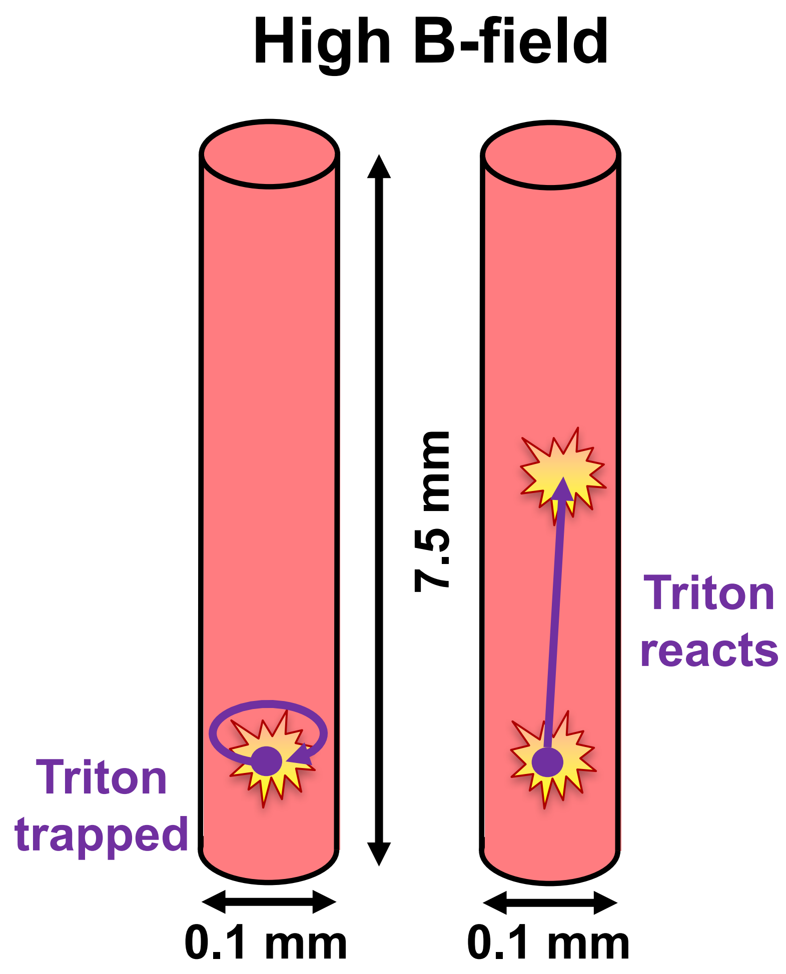
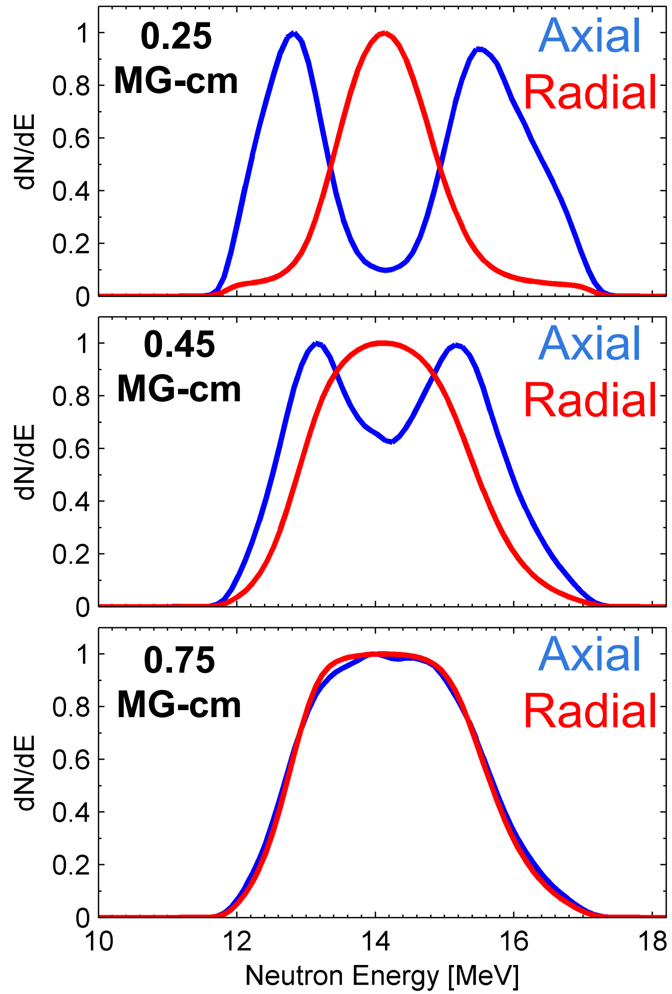


- Consider 2 cases:
  - 1) Triton is created traveling axially
    - Axial field has little impact on trajectory
    - Triton has a high probability of fusion
  - 2) Triton is created traveling radially
    - Axial magnetic field traps triton within fuel volume
    - Triton has a high probability of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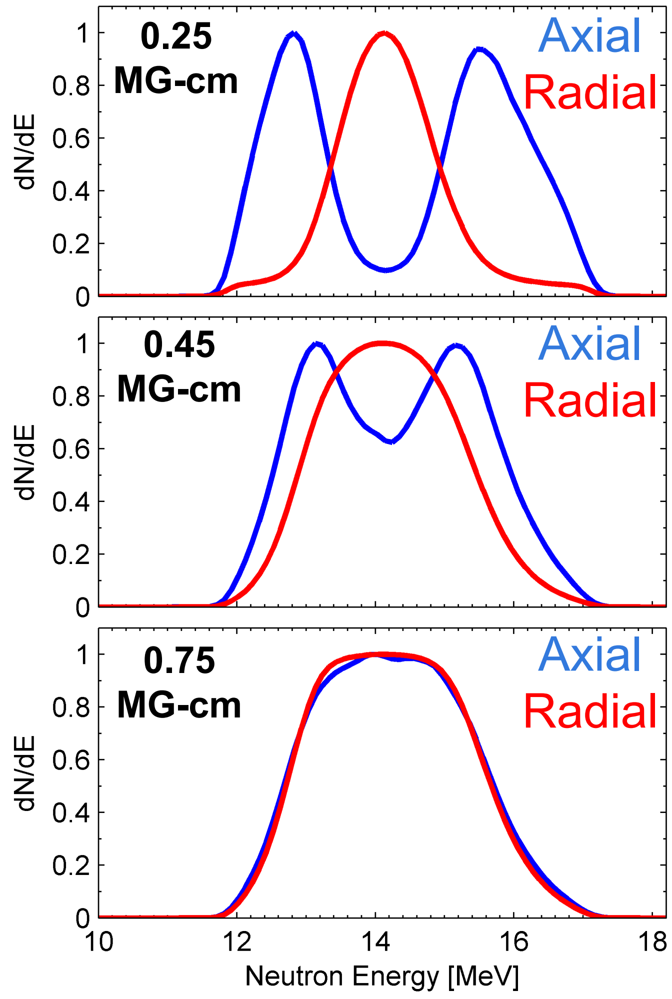

- As the magnetic field increases, a greater fraction of the radially directed tritons are trapped
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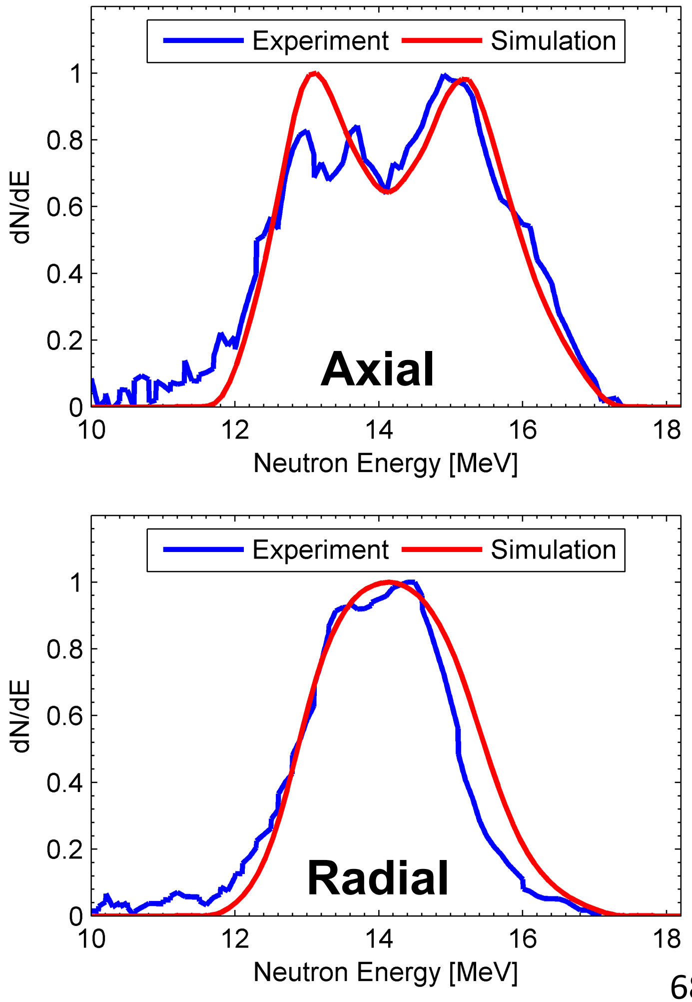
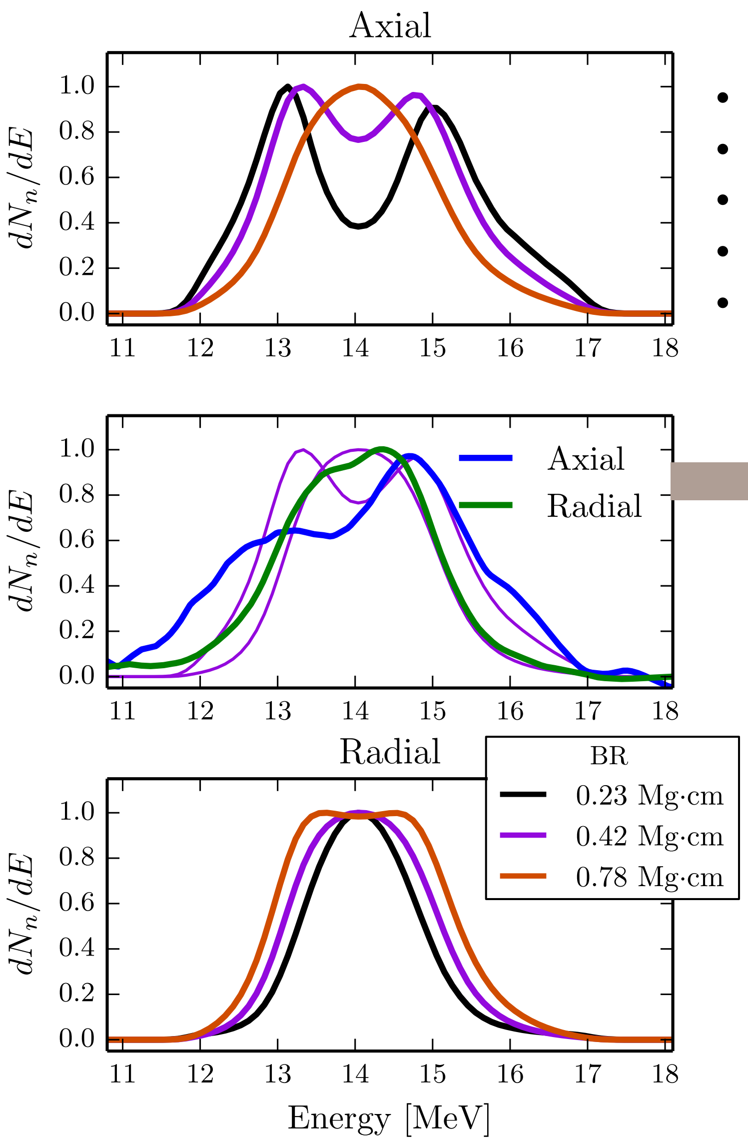
0.34 MG-cm



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

DT Spectra are used in conjunction with measured DT/DD ratio to constrain the stagnation *BR*

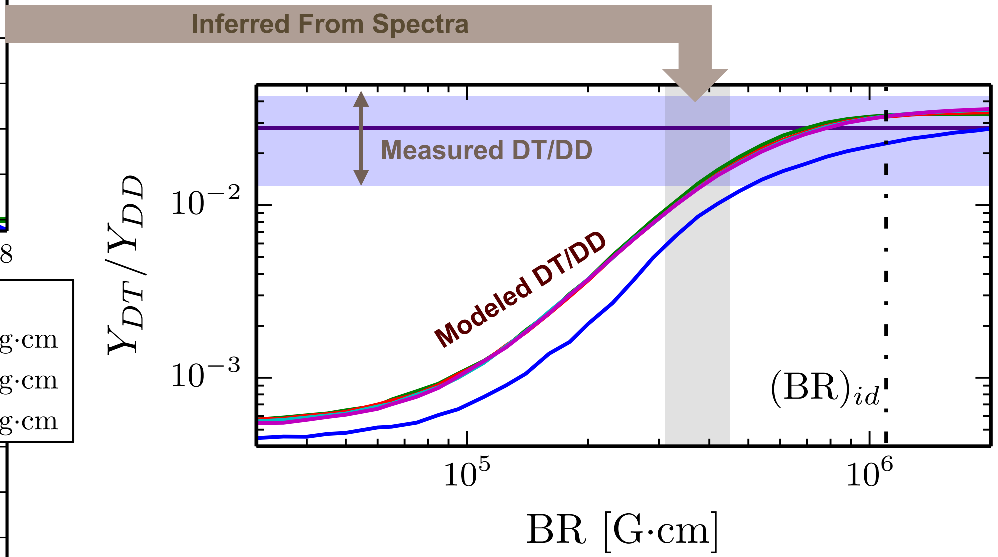


- $T_i \sim T_e$=3.1 keV
- ρ=0.5 g/cc
- R=50–100 μm
- ρR=2-5 mg/cm^2
- ρZ~0.3 g/cm^2

- Not a rigorous fit to the spectra
- Considering only the high energy half of the spectra (scattering)
- In reasonable agreement with integrated 2D simulations[2]

$$(B_z R)_{stag} = 5.3 \times 10^5 G \cdot \text{cm}$$

$$F_t \approx 55\%$$



Axial nonuniformities and azimuthal field are the biggest missing features that can contribute to the modeled spectra

$$BR \approx 4(\pm 0.7) \times 10^5 \ G \cdot \text{cm} \sim 17 \times (BR)_o$$

[2] A.B. Sefkow, *et al.*, Phys. Plasmas, **21** 072711 (2014)

Experimentally inferred stagnation *BR* indicates we are trapping 1 MeV tritons and magnetizing electrons

- Modeling suggests we are depositing >35% of the triton energy
- Scales to >40% α deposition

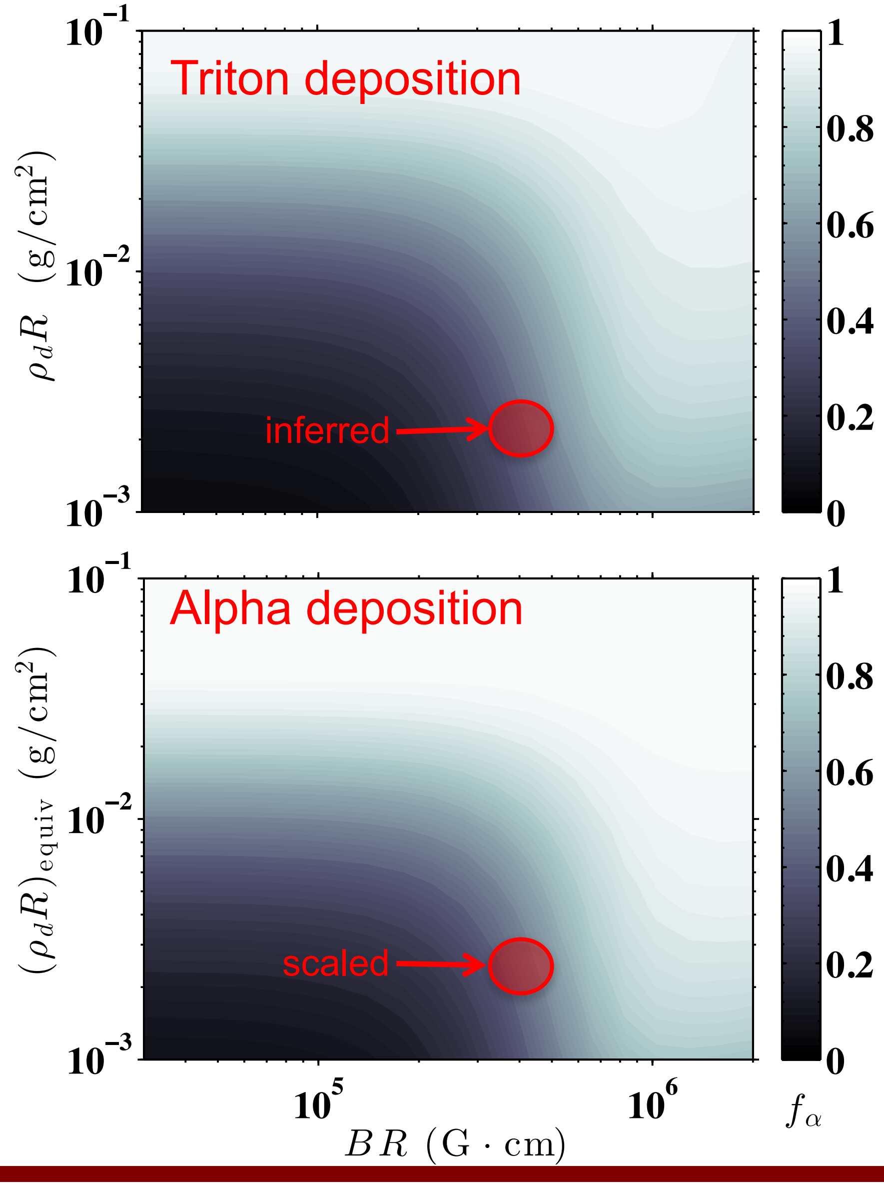
$$BR \sim 4 \times 10^5 G \cdot \text{cm} \rightarrow \frac{R}{r_\alpha} \sim 1.5 - 2$$

$$r_\alpha \approx 1.07 r_t$$

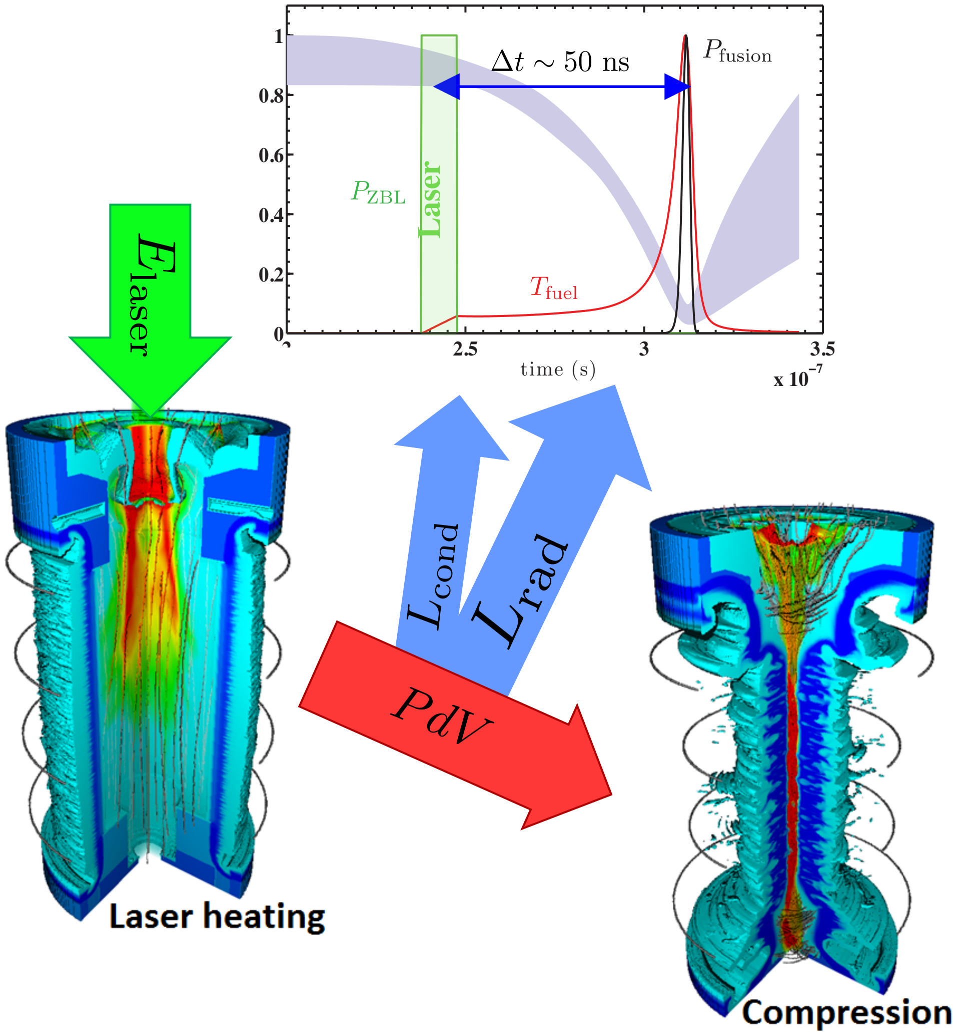
- Magnetizing fast tritons implies electrons are magnetized as well

$$\omega_{ct}\tau_{te} \approx \omega_{ce}\tau_{ee}$$

MagLIF works! We were able to compress flux, preheat the plasma and keep it hot and magnetize the burn products!

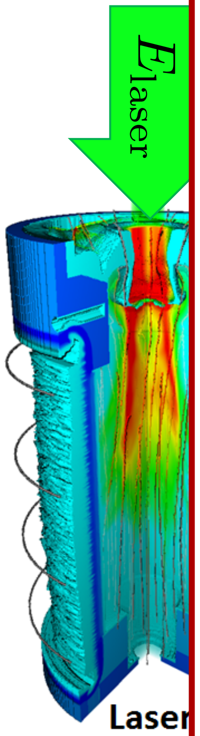


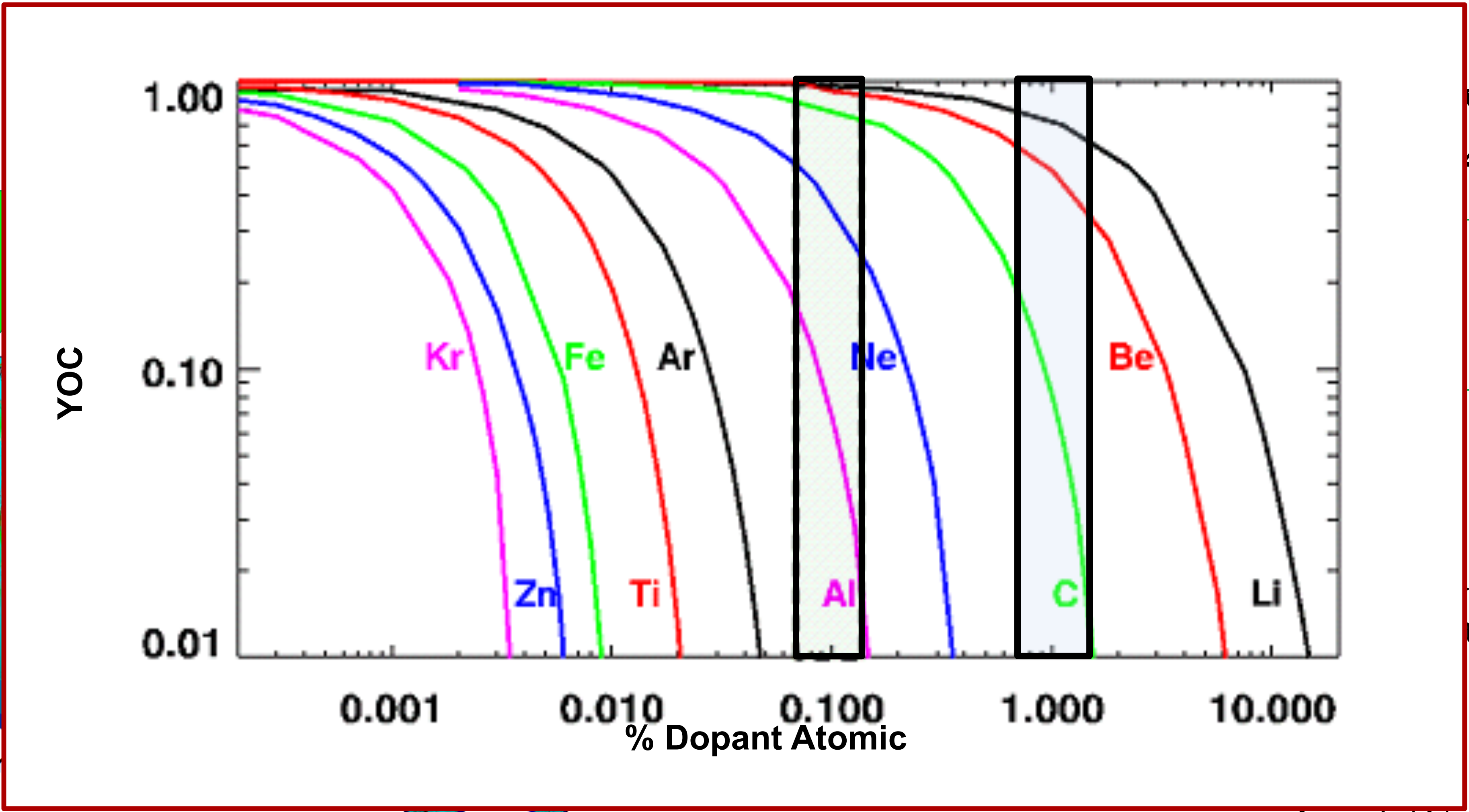
Mix degrades performance by enhancing losses due to radiation



- Approximate bremsstrahlung emission loss: $P_r \sim Z\,\rho^2 T^{1/2}$
- Z is the charge of the mix species
- Unlike traditional ICF, if contaminants get into the hot spot early (during laser heating), they have a long time to radiate heat away before stagnation

Mix degrades performance by enhancing losses due to radiation





$\sum_i \tilde{f_i j_i} \frac{e^{-h\nu/T}}{T^{5/2}}$

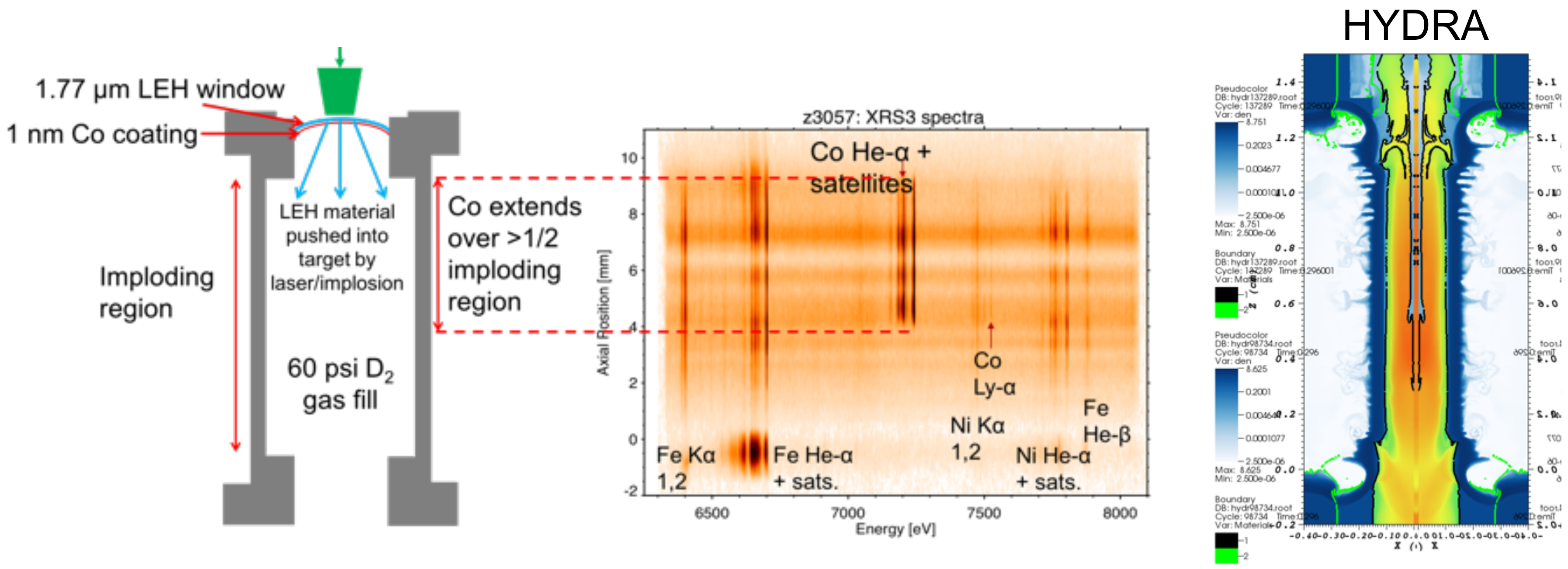
$e^{RyZ_i^2/T}$

rly, they have a long

tion

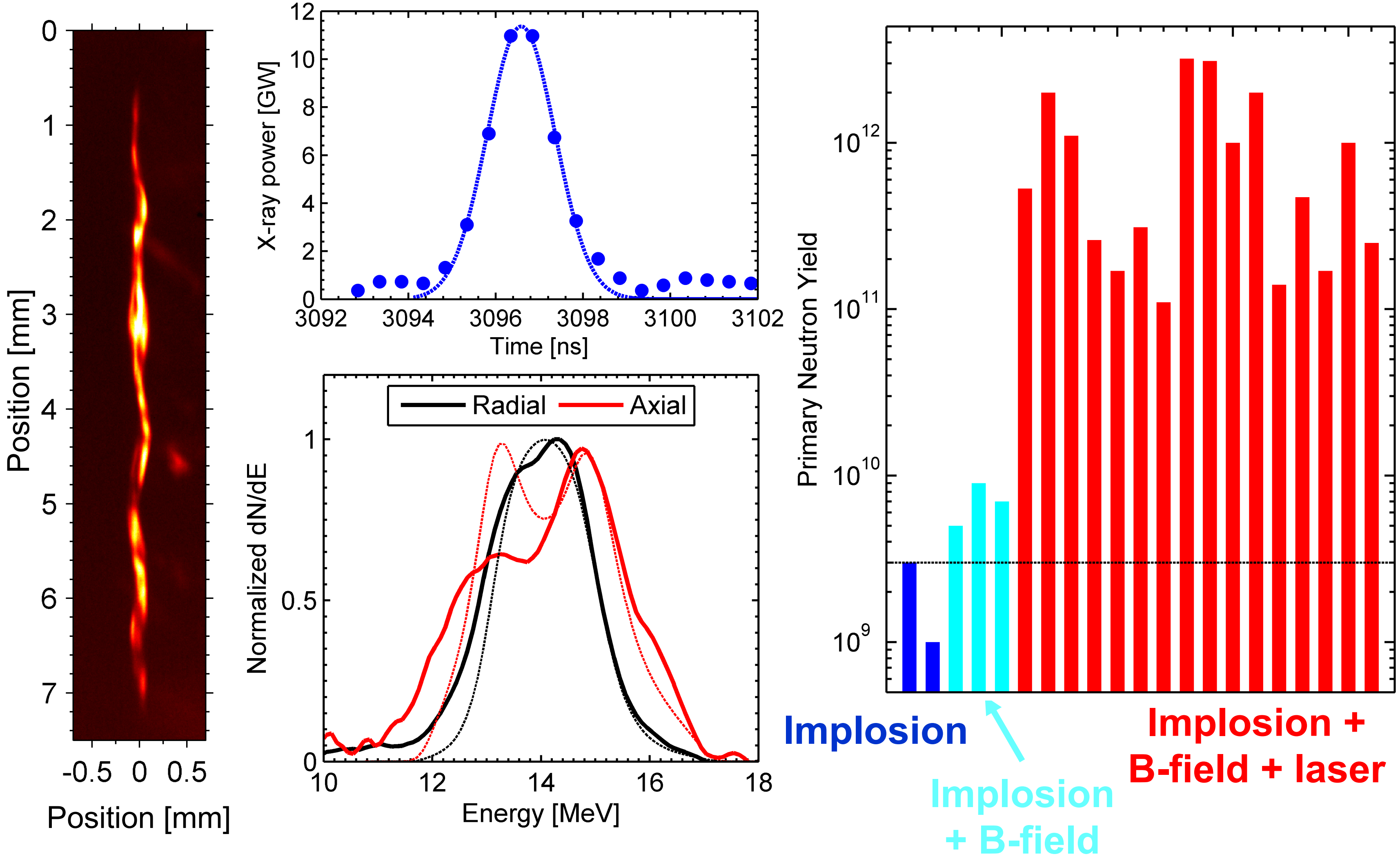
$P_{\text{rad}} \sim r^{-6}$

Over the past year, We have made significant progress in diagnosing and understanding mix in MagLIF implosions on Z using spectroscopy



- **Both window and upper endcap material has been observed to mix into fuel at stagnation**

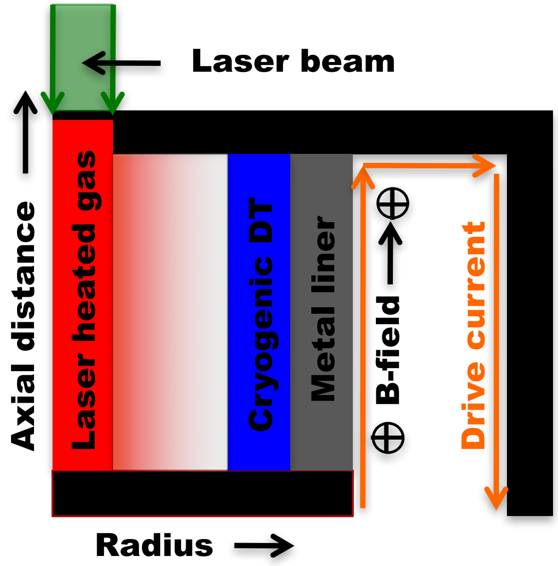
We have demonstrated key aspects of magneto-inertial fusion on Sandia's Z facility



- DT-equivalent yields up to about 1 kJ have been measured
- We are still working on improving our understanding in order to improve performance

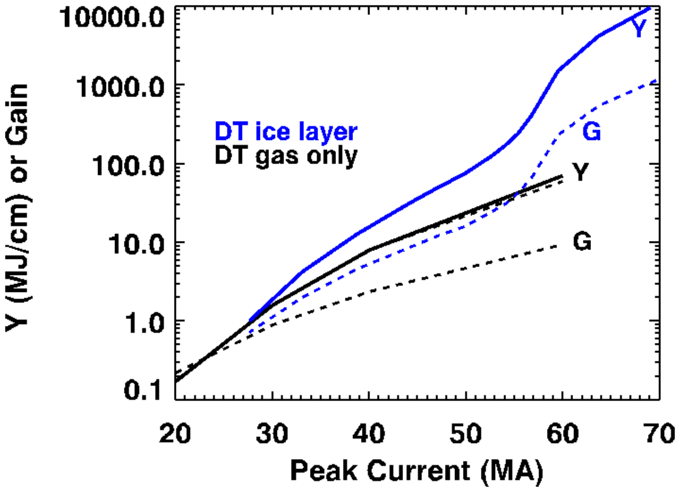
M. R. Gomez, et al., Phys. Rev. Lett. 113, 155003 (2014). P. F. Schmit, et al., Phys. Rev. Lett. 113, 155004 (2014).

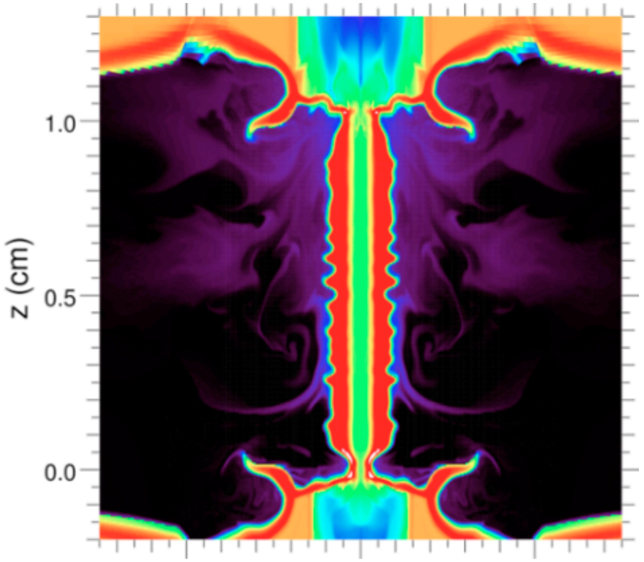
High gain fusion is challenging with MIF targets



- MTF targets are generally designed for volumetric burn with gains ~1-10
- Difficult to ignite DT ice layer
  - Magnetization inhibits deposition of alpha particles in ice
  - Low hot spot density and long confinement times limit fusion power
- 2D Simulations have shown that MagLIF could in principle provide high yield and gain[1] on future accelerators
  - Magnetization must not be too high

1D Lasnex simulations





A 2D integrated Hydra simulation[2] produced ~ 6 GJ

AR_{liner}= 6

ρ_{gas} = 5 mg cm^{-3}

B_z^0 = 8T

E_{laser} = 25 kJ

Peak drive current = 70 MA

1 *Slutz and Vesey PRL 108, 025003 (2012)*

2 *Sefkow, Slutz, Koning et al. PoP 21, 072711 (2014*

MagLIF shows promise as a route to high fusion yields in the laboratory, but we have a long road ahead

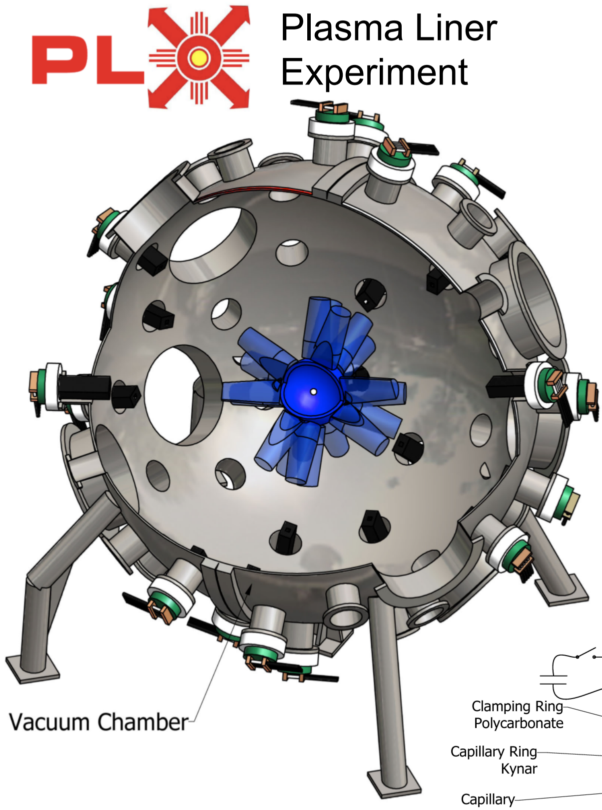
- We have demonstrated the key aspects of the concept:
  - Preheat, compression, magnetic insulation, and trapping of charged fusion products
- Significant challenges remain
  - Sources of fuel contaminants (mix) must be understood and controlled
  - Need to test code predictions of scaling and understanding of critical physics
    - Need higher initial magnetic fields
    - Need to couple more laser energy into the fuel, without generating more mix
    - Need to improve current delivery to target
- High gain may be possible, but large fusion yields can be obtained with relatively low gain

Summary: MTF is not just ICF the addition of a magnetic field

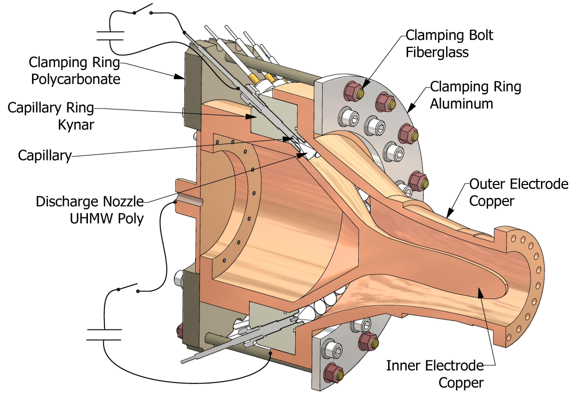
- Lower velocity implosions
  - Less driver power required – less expensive!
  - More massive pushers (liners) leading to longer burn times
  - Lower pressures
- Approximately adiabatic compression (no shocks)
  - ICF targets require exquisite pulse shape control to keep fuel on low adiabat
- Lower density targets
  - reduced radiation rates
  - Bigger targets physically
- Preheat is good!
  - Reduced radial convergence (e.g., < 10)
- Alpha deposition characterized by rB, not ρr
- Inertial confinement provided by liner (not the fuel)
- Low ρ with B → new physics regimes

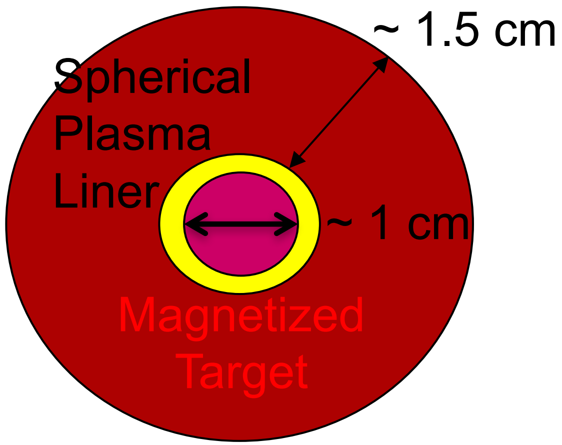
Other MIF examples

A team led by Los Alamos will investigate the compression of a magnetized plasma using the merger of supersonic plasma jets (Plasma Jet Driven Magneto-Inertial Fusion)



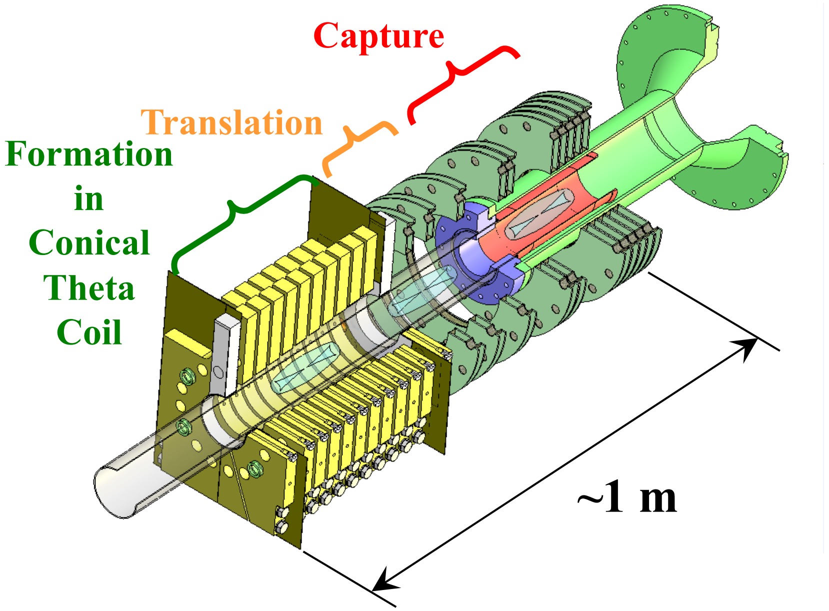
- Xe liner ram pressure (ρv^2) at >50 km/s compresses magnetized target to fusion conditions (~150 Mbar, ~10 keV, 300 ns) -> ~130 MJ yield, G>20
- Desired implosion needs:
  - Cold, fast, highly collisional, high-*Z* liner, i.e., high Mach #
  - Sufficient uniformity (target convergence ratio ~ 10 ×)
  - Liner thickness & profiles optimized for dwell (burn) time & energy gain
- Either high-β magnetized plasmas or merged compact toroids are potentially suitable targets



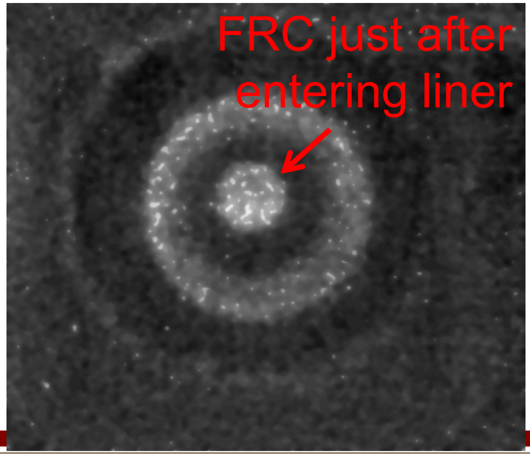


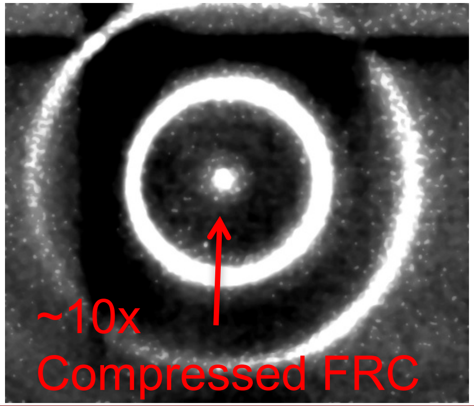
S.C. Hsu *et al.*, Phys Plasmas (2012); Witherspoon *et al.*, RSI (2009); Cassibry *et al.*, Phys Plasmas (2013).

AFRL/LANL led a team that investigated the cylindrical compression of a ~10 cm field-reversed configuration plasma by >10x at >10 microsecond time scales



Formation, translation and capture magnetic coils



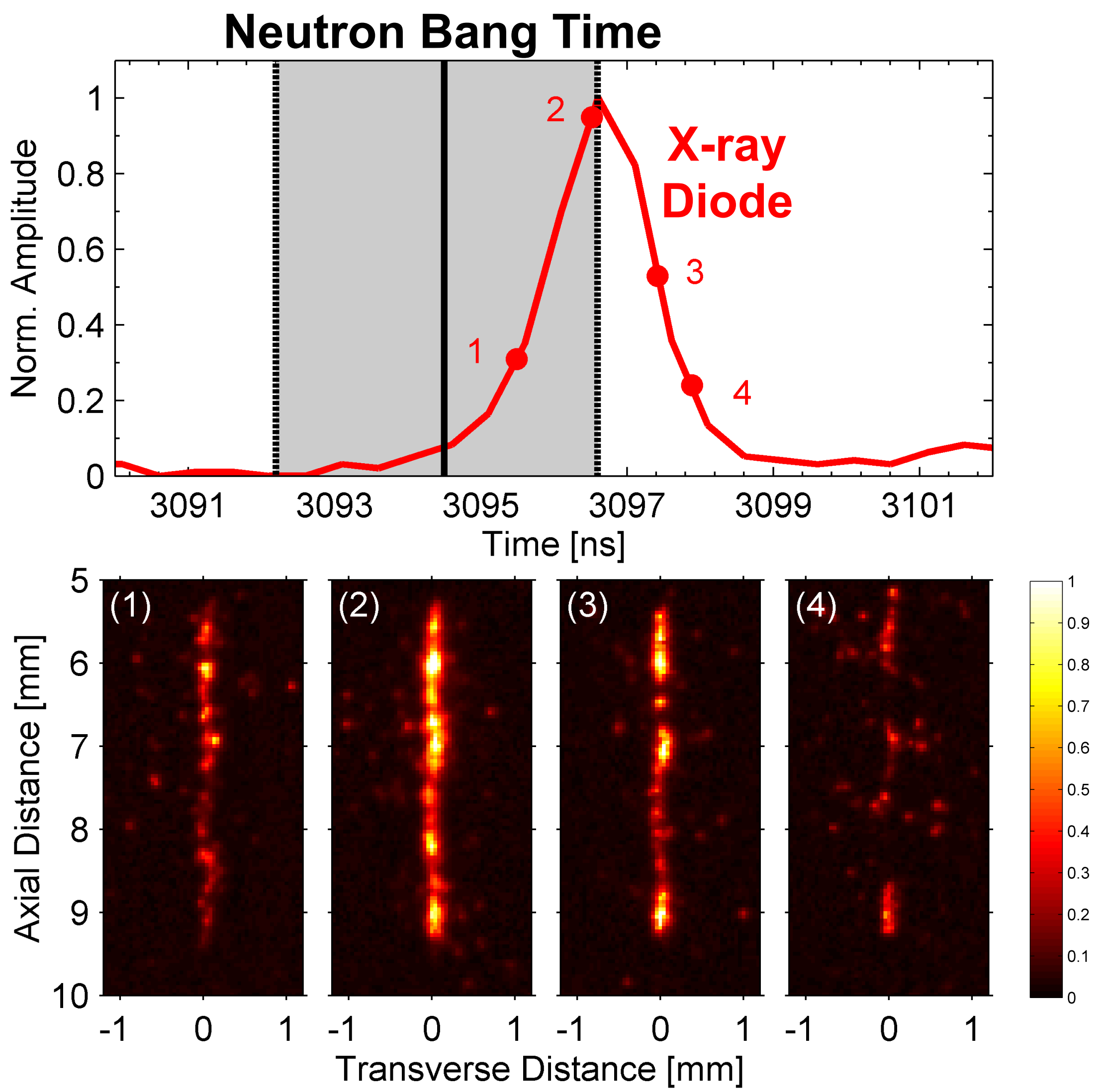


- A compression test was conducted in Oct. 2013.
- Soft x-ray images showed the FRC was compressed to < 0.5 cm diam. (~10x compression), but the plasma was cold (~300 eV based on neutron yield).
- This was the highest density FRC plasma ever created.
- FRC lifetime was too short compared to timescale of compression—stayed cold until the very end of the implosion

J.H. Degnan *et al.* Nuclear Fusion **53**, 093003 (2013).
C. Grabowski *et al.*, IEEE Trans. Plasma Sci. **42**, pp. 1179-1188 (2014).

Backups

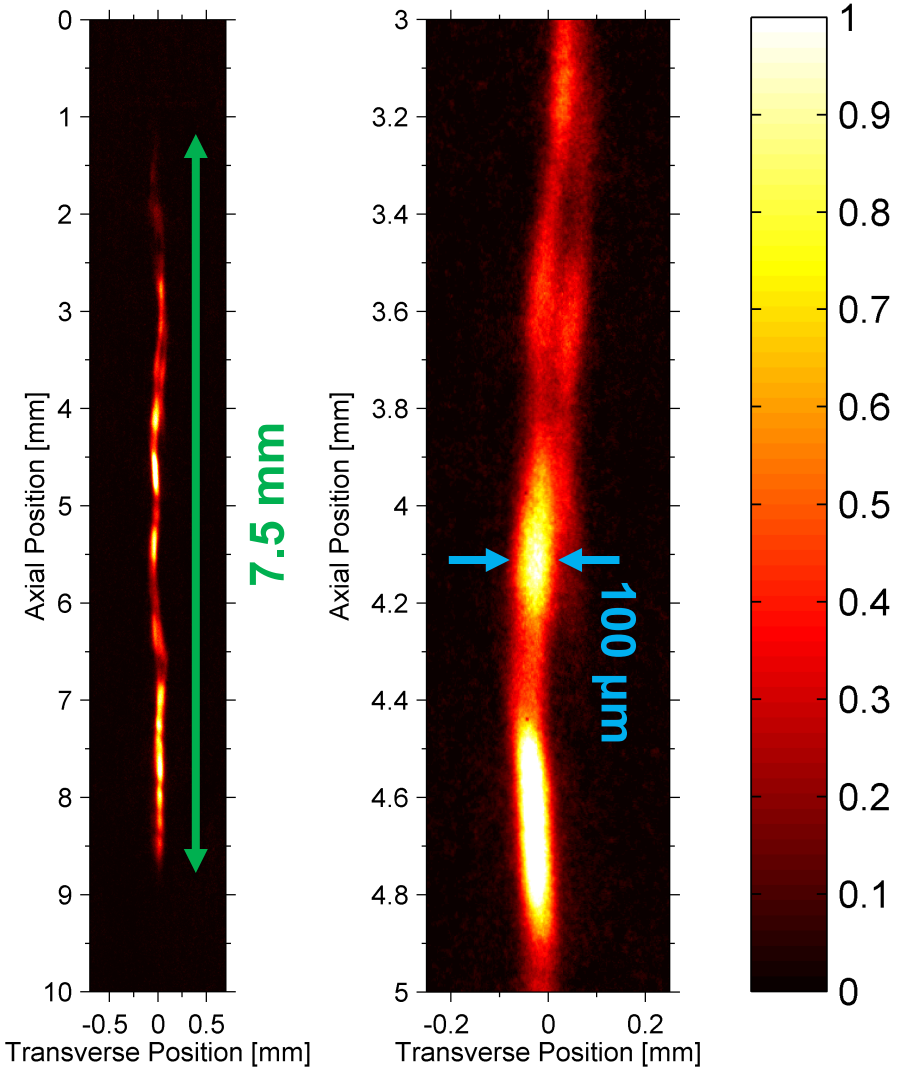
X-ray diodes and time-resolved x-ray pinhole images show the fuel radiating at stagnation



- 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).

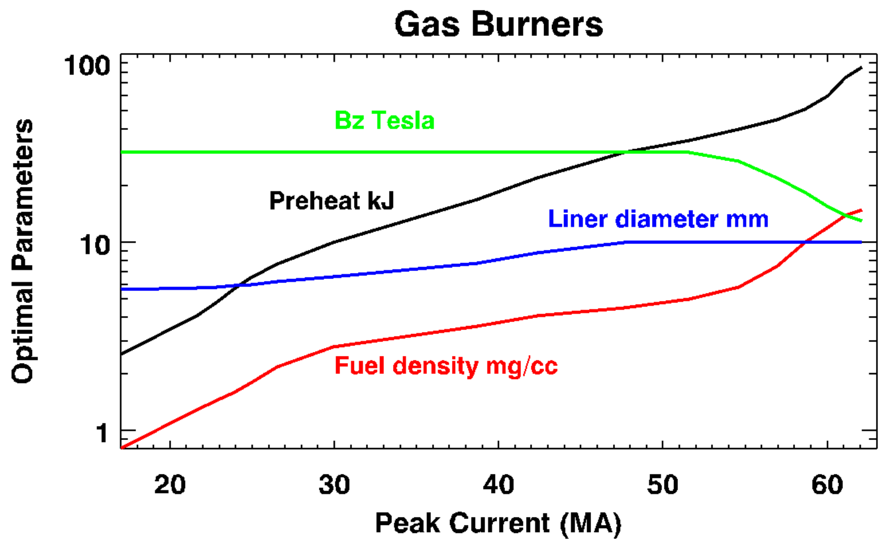
Our spherical crystal imaging system was repurposed to record x-ray emission from the fuel

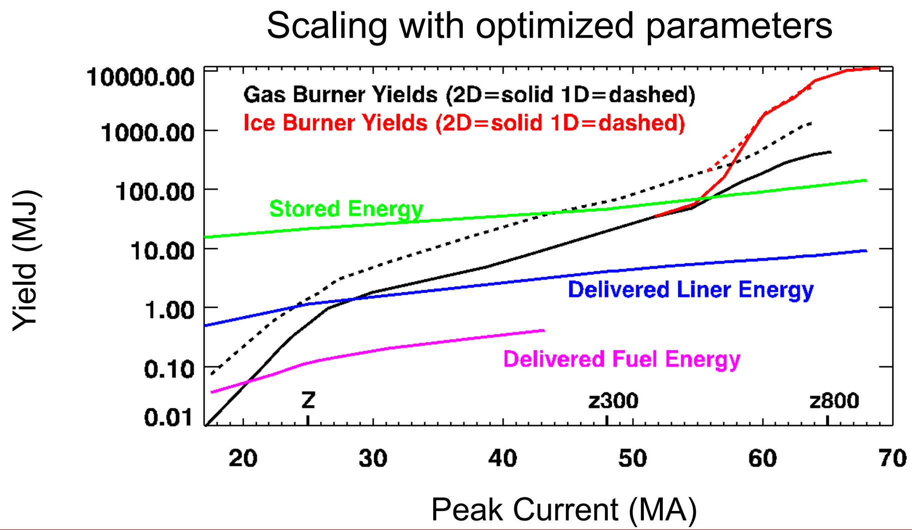


- Hot fuel emission at stagnation gives information about the CR and uniformity of the plasma
- Hot fuel radius is CR ~45
- Helical structure to the emission column
- Intensity fluctuations a combination of emission and opacity variations

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

Our program plan is to develop platforms that enable testing of optimal configurations for scaling





Our present experimental configuration is far from optimal

B-field=10 Tesla (optimum >30 Tesla)

Fuel density=0.7 => **high convergence**

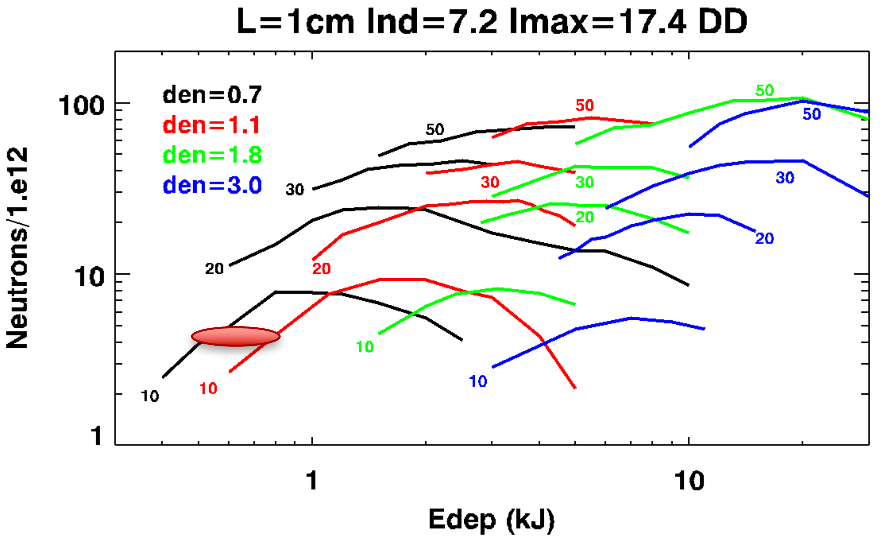
Preheat energy < 1 kJ

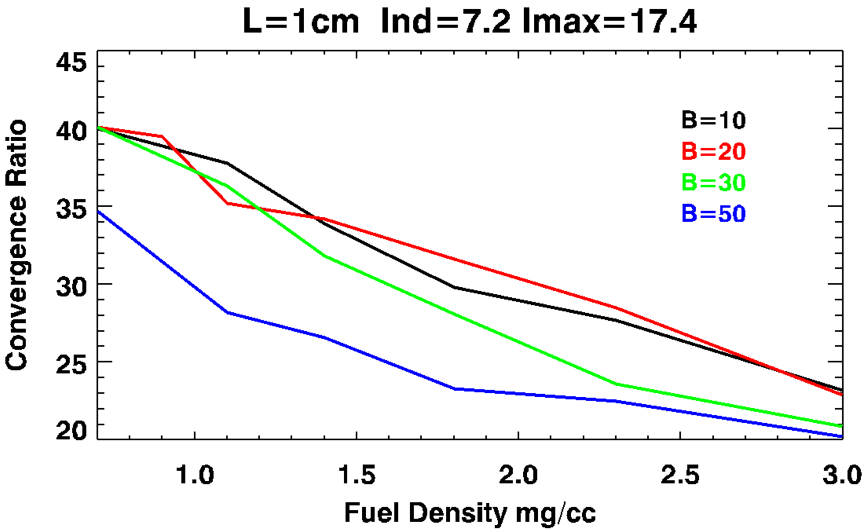
Feed inductance 7.2 nH => **I_{max}~17.4 MA**

Simulations predict favorable scaling of yield with drive current[1] when MagLIF parameters are optimized

[1] S.A. Slutz et al. Phys. Plasmas 23, 022702 (2016)

Higher initial field is required to test predictions of MagLIF scaling to higher yields





- Larger fields increase the burn time
- Higher fuel densities lower convergence
- Lower inductance feed increases current

Larger initial magnetic fields are needed!!

We used pulsed power to create and study *high energy density* (HED) matter

HED conditions are strange on earth, but common in the universe

HED regime (P > 1 Mbar or E > 100 kJ/cm^3)

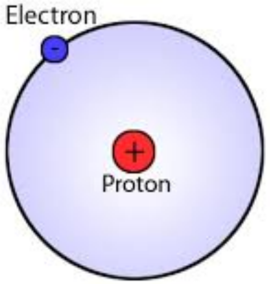
Baseball

10^{-5} Mbar

Dynamite

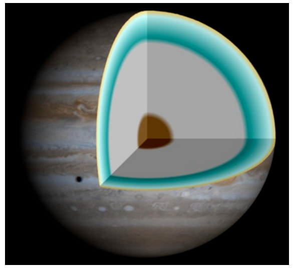
0.1 Mbar

Internal Energy of H atom



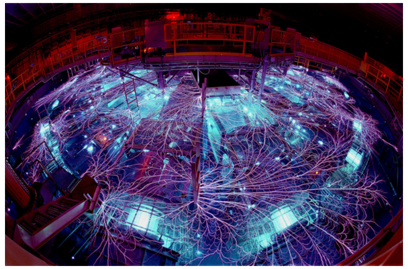
3 Mbar

Metallic H in Jupiter's core



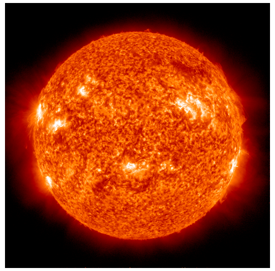
30 Mbar

Z Machine magnetic pressure



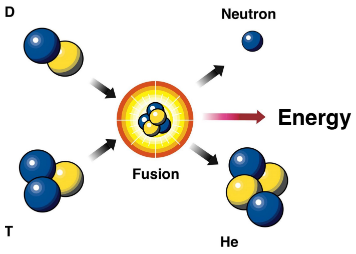
100 Mbar

Center of Sun



250,000 Mbar

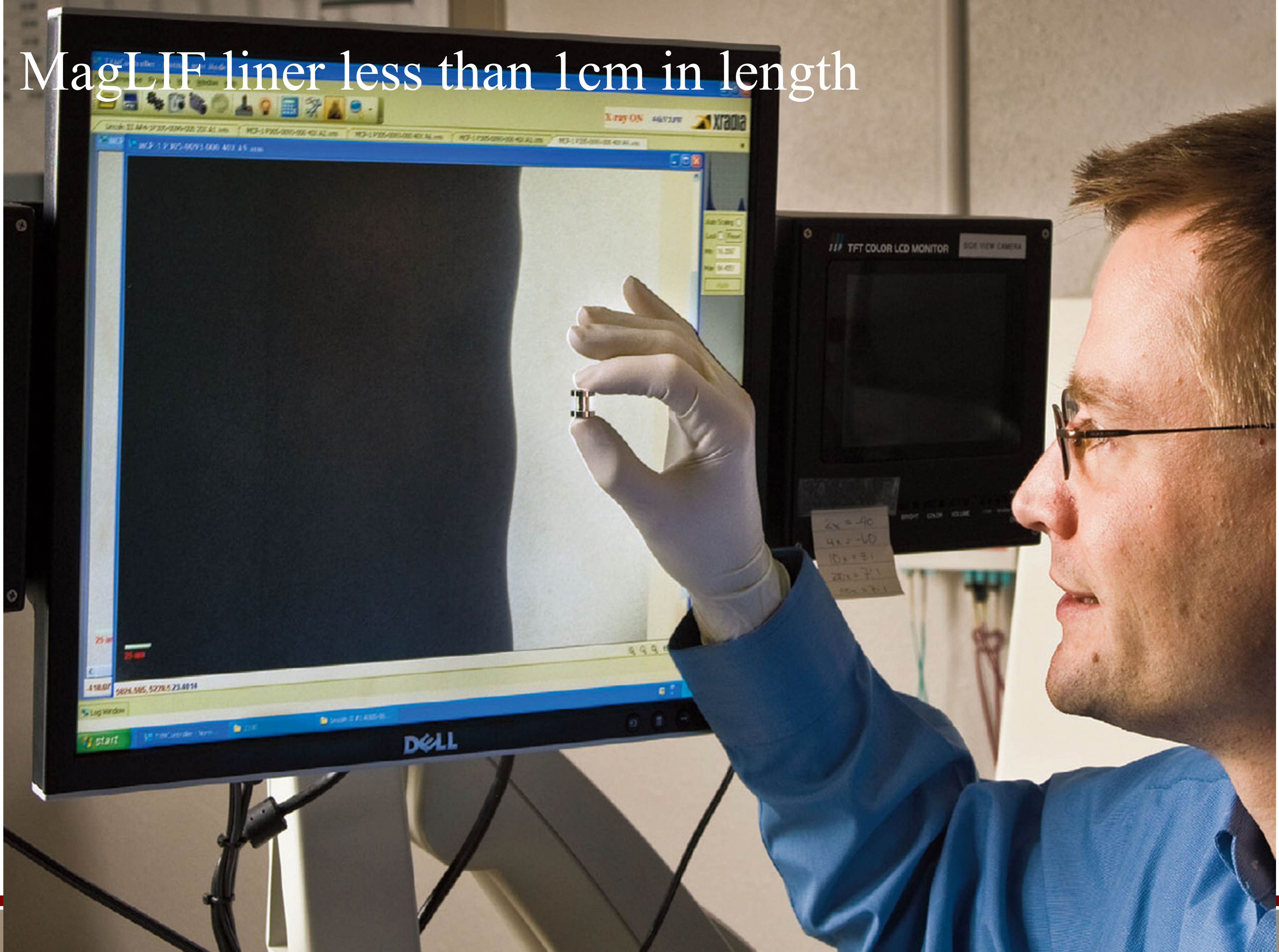
Burning ICF plasma



800,000 Mbar

Z can access the HED regime

MagLIF liner less than 1cm in length



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MagLIF hardware ready to load

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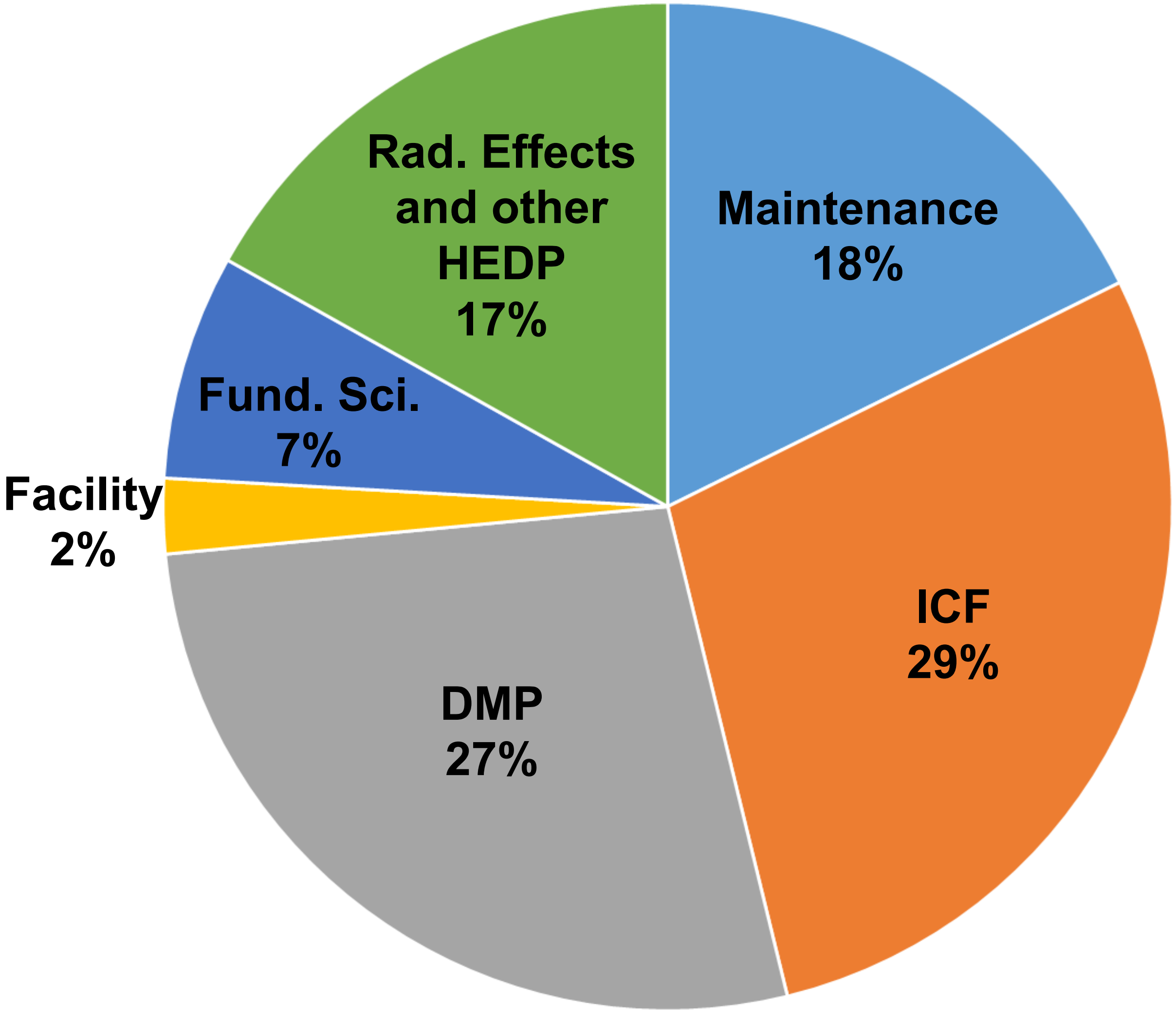
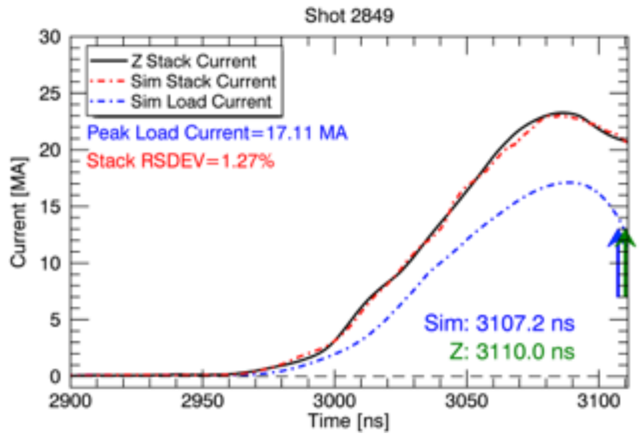
The Z shot allocation is split between a few major efforts

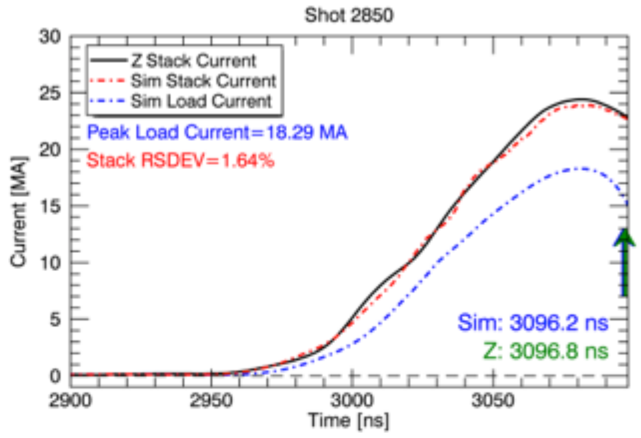


- This is based on our schedule for CY2017
- Approximately 250 working days
- We expect around 160 shots this year
  - Some experiments take more than 1 day to complete
  - We completed an insulator stack rebuild this year (about 20 days)
    - Every few years or so
  - We are rebuilding our transmission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

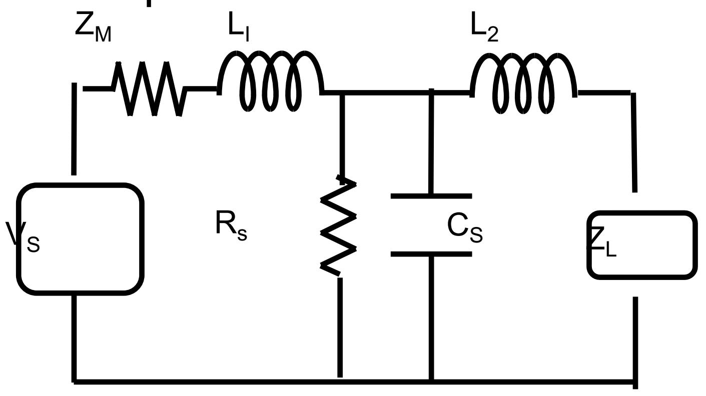
In MDI, the driver and target are strongly coupled

Adding 2.5mm of liner height (0.8nH) decreases peak current ~1MA





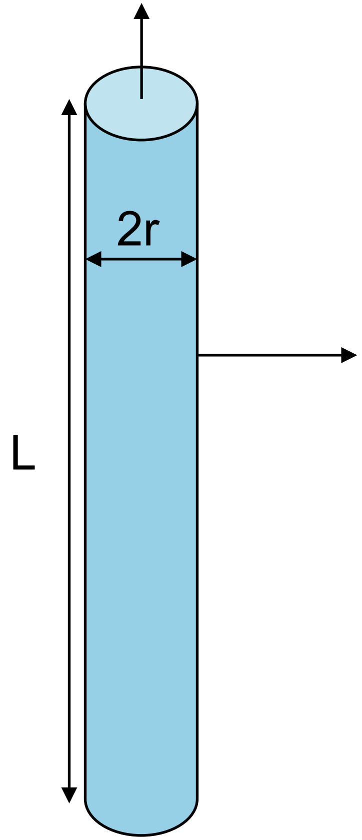
Simple Circuit Model for Z



- Target inductance must be minimized
  - maximizes current delivery
  - minimizes power flow losses
- Current delivery sensitive to both initial inductance and dL/dt

Axial Thermal losses are also expected to be acceptable

Axial loss $$L_{axial} = C\theta^{7/2}\left(A = 2\pi r^2\right)\left(\nabla\theta \sim \theta / L\right)$$



Radial loss $$L_{rad} = C\theta^{7/2}\left(A = 2\pi r L\right)\left(\nabla\theta \sim \theta / r\right)$$

$$L_{rad} / L_{axial} = \left(L / r\right)^2 \sim \left(0.5 / .01\right)^2 = 2500$$

Axial losses have been addressed with fully integrated simulations

In all concepts, the fuel pressure at stagnation is a key metric of progress

Why is Pressure so important for fusion?

$$\langle \sigma v \rangle \equiv \int \int \sigma(|\mathbf{v_1} - \mathbf{v_2}|)|\mathbf{v_1} - \mathbf{v_2}| f(\mathbf{v_1}) f(\mathbf{v_2}) d^3 v_1 d^3 v_2$$

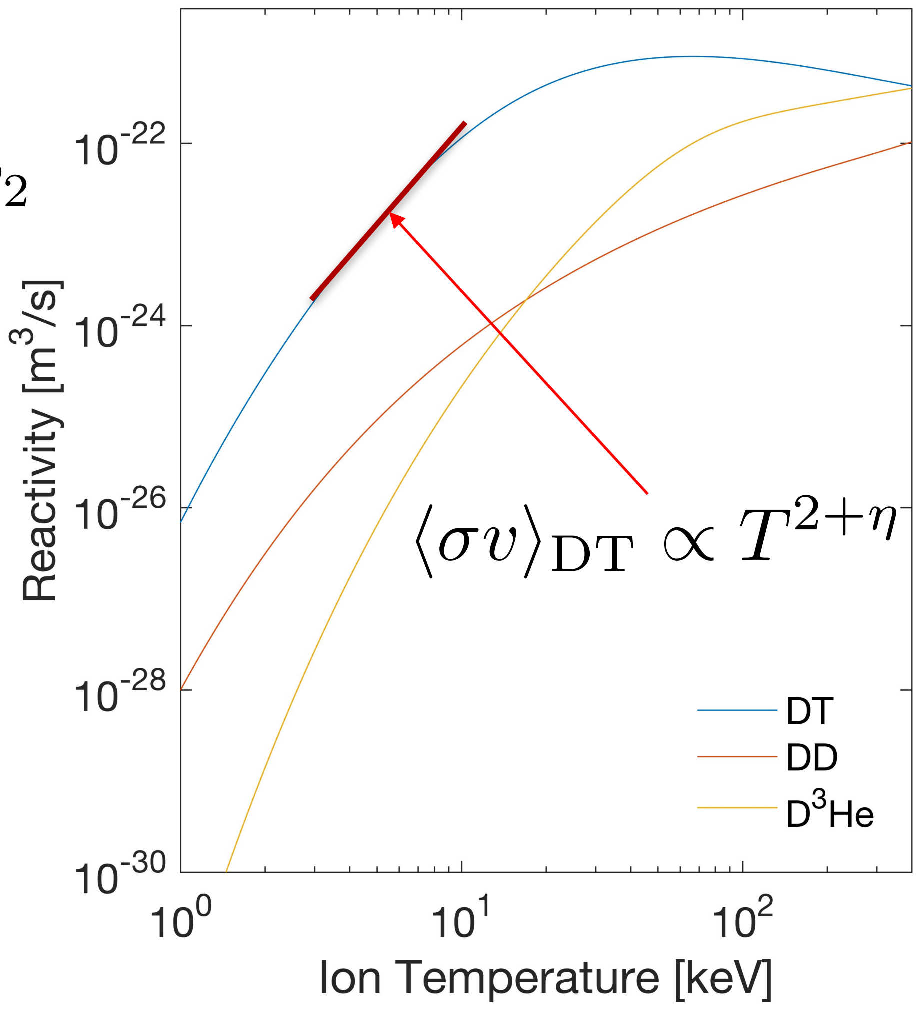
$$f(\mathbf{v}) = \left(\frac{m_i}{2\pi k_b T_i} \right)^{3/2} e^{-\frac{m \mathbf{v} \cdot \mathbf{v}}{2 k_b T_i}}$$

Reaction Rate:

$$\mathcal{R}_{\text{fus}} = n_{\text{D}} n_{\text{T}} \langle \sigma v \rangle V$$

$$\mathcal{R}_{\text{fus}} \propto n^2 T^{2+\eta} \propto P^2 T^\eta, \quad \eta \sim 1$$

Pressure is energy density: $\frac{E_{\text{int}}}{V} = \frac{3}{2} P$



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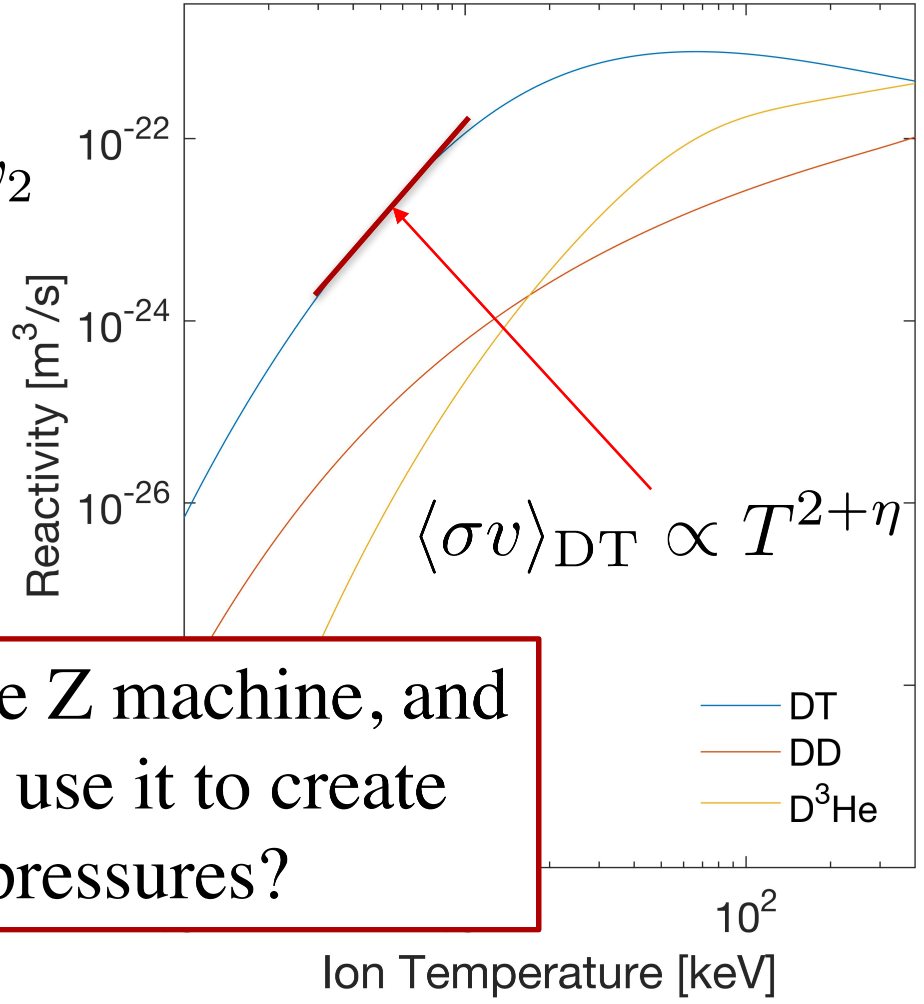
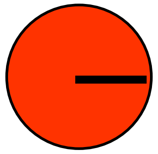


So what is the Z machine, and how do we use it to create high pressures?

For hot spot ignition fusion fuel must be brought to a pressure of a few hundred billion atmospheres



ρ, R, T

For ignition conditions: $\left\{ \begin{array}{l} \rho R \approx 0.4\,\mathrm{g/cm^2} \\ T \approx 5\,\mathrm{keV} \end{array} \right\}$

$$E_{HS} \propto m_{HS} T_{HS} \propto \rho_{HS} R_{HS}^3 T_{HS} \propto \frac{(\rho_{HS} R_{HS})^3 T_{HS}^3}{P_{HS}^2}$$

P_{HS}^2 ~(CR)^6
~(velocity)^6

$$E_{NIF} \sim 15\,\mathrm{kJ} \Rightarrow P \sim 400\ \mathrm{GBar} \qquad R \sim 30\,\mu\mathrm{m} \Rightarrow \text{ and } \rho \sim 130\,g/cm^3$$

This is consistent with detailed calculations

Note: The key challenge for ICF is to make the fuel both ***dense*** and ***hot***. This leads to challenging compression requirements—a NIF capsule has a radial convergence of 35-45x, for a volume compression of ~50,000!

Technological limitations also limit laboratory yield

Imagine hollow shell of fuel:

- Implosion velocity sets drive pressure:

$$M_{\text{shell}} = 4\pi R_0^2 \Delta R_0 \rho_{\text{shell}}$$

$$\dot{V}_{\text{shell}} \sim \frac{u_{\text{imp}}}{t_{\text{imp}}} \sim \frac{u_{\text{imp}}^2}{R_0}$$

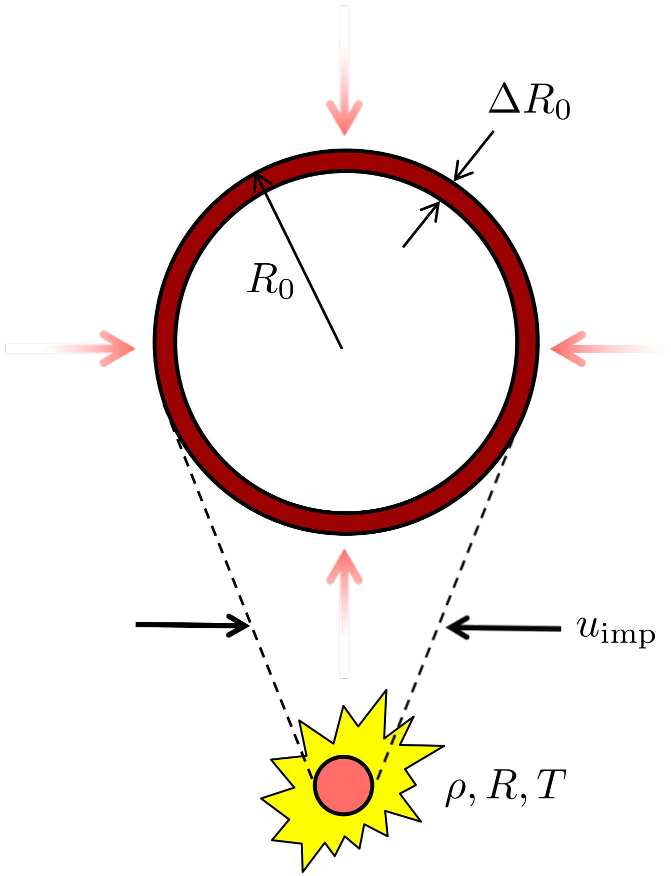
$$P_{\text{drive}} \sim \frac{M_{\text{shell}} \dot{V}_{\text{shell}}}{R_0^2} \sim \frac{\Delta R_0 u_{\text{imp}}^2}{R_0} \equiv \frac{u_{\text{imp}}^2}{A}$$

- Implosion energy converts to heat at stagnation:

$$E_{\text{fuel}} \sim N k_B T \sim M_{\text{shell}} u_{\text{imp}}^2 \sim \frac{(\rho R)^3}{\rho^2} P_{\text{drive}} A \sim \frac{P_{\text{drive}} A^3}{(CR)^6}$$

$A > 1$ (i.e., thin shell) reduces P_{drive} needed

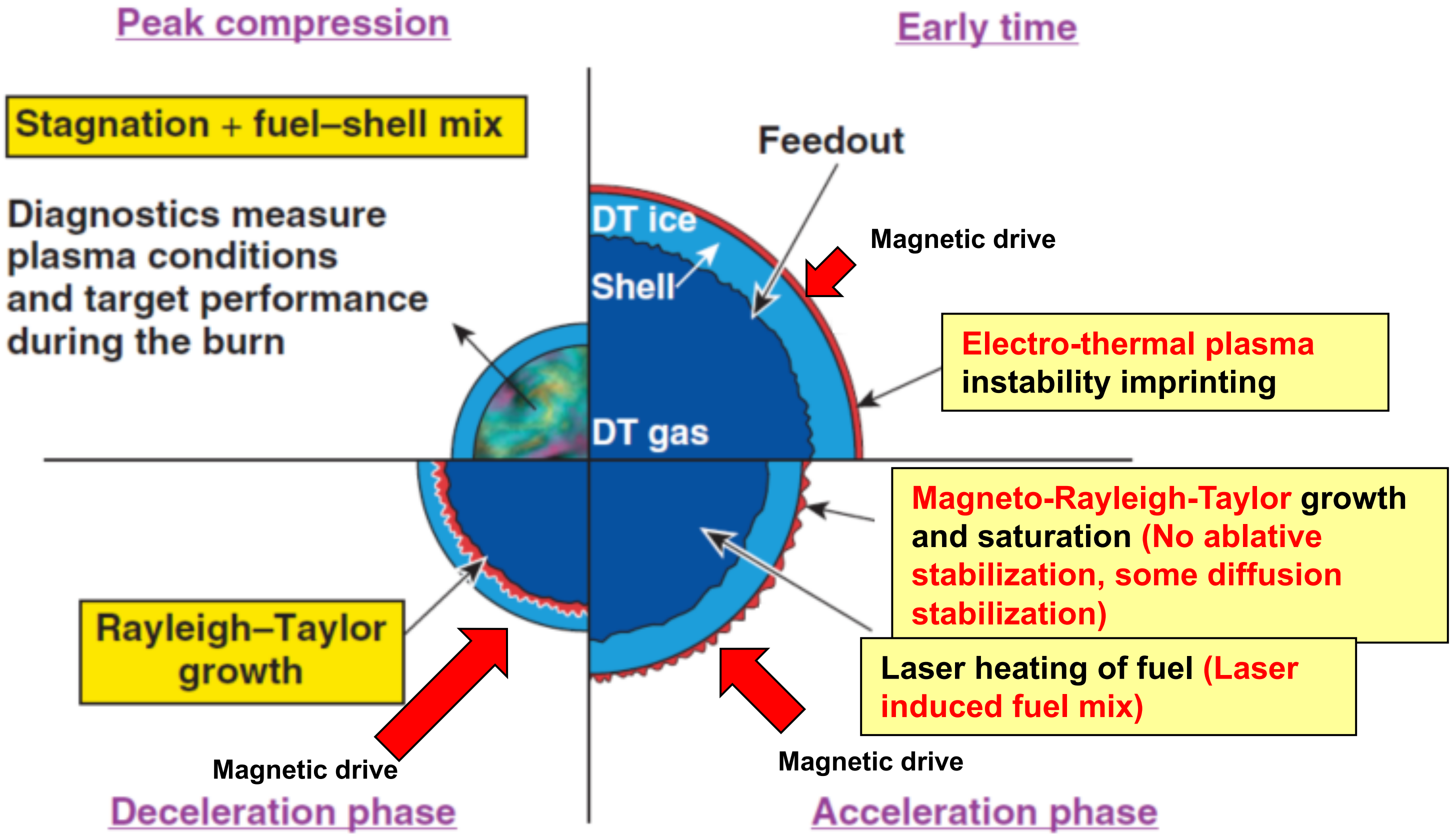
$CR \sim 30 - 40$ set by ρR requirements



- Large compression requires enormous pressures! Limited in the laboratory to O(100 Mbar)

Magnetically driven implosions have similar challenges with respect to ICF instabilities

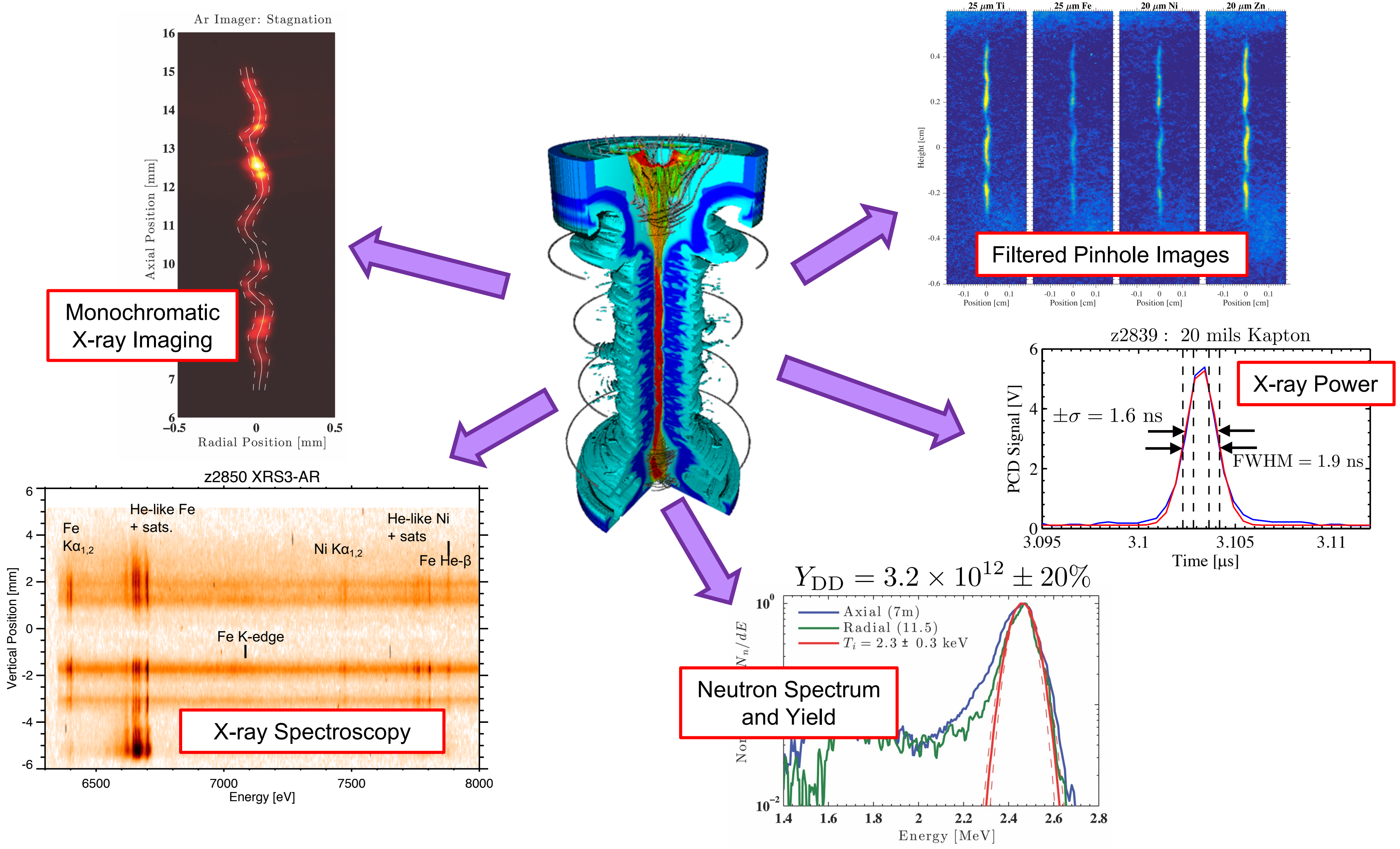
Cylindrical magnetically driven implosions



In both the acceleration and deceleration phases, light fluid is supporting a heavy fluid against "gravity"— the classical Rayleigh–Taylor instability.

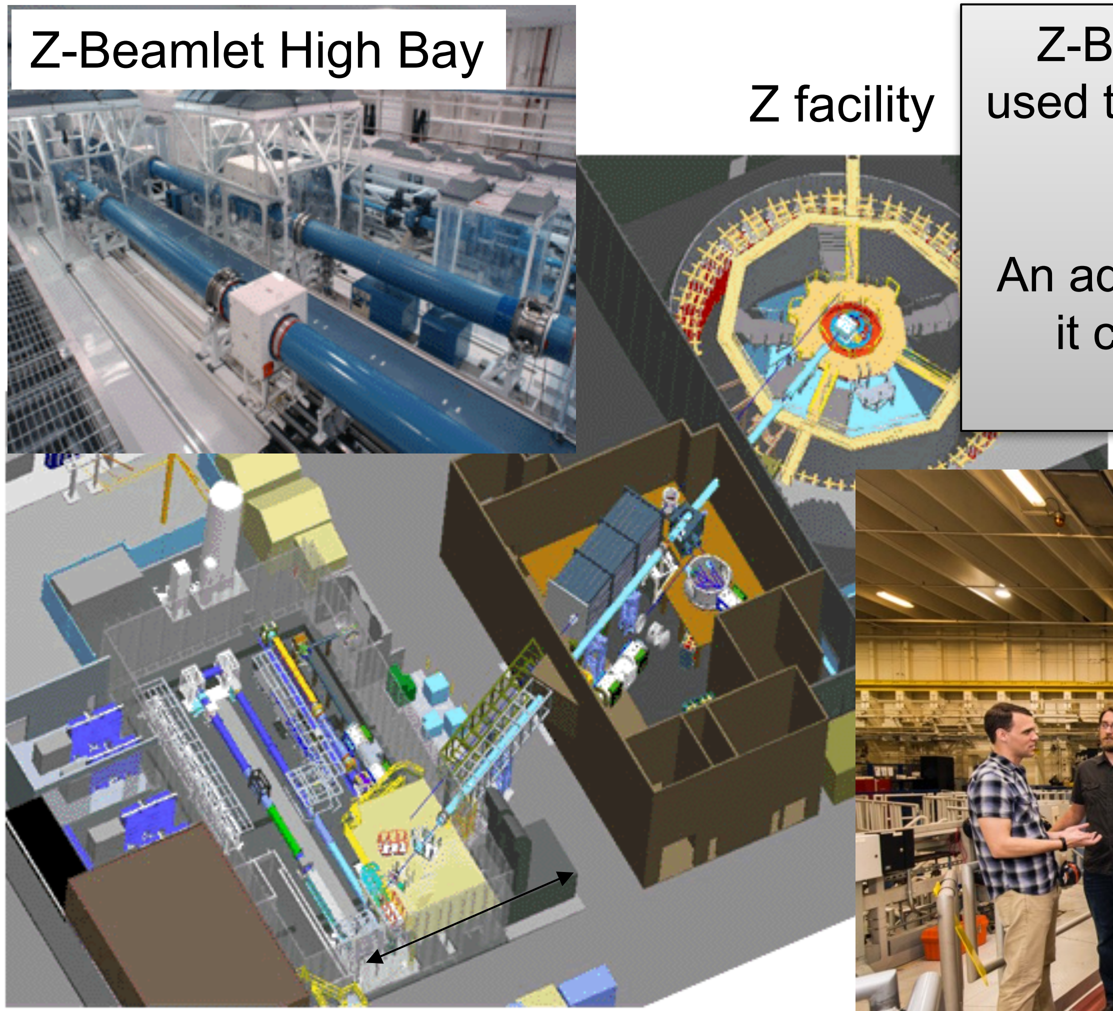
E9886g

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



- Our extensive suite of diagnostics allow us to measure the fuel temperature, density, volume, magnetic field, and burn duration
  - Neutron yield and time-of-flight
  - x-ray imaging and spectroscopy
  - Radiated power and energy

The Z-Beamlet laser at Sandia* is being used to radiograph liner targets and heat fusion fuel



Z facility

Z-Beamlet and Z-Petawatt lasers

Z-Beamlet (ZBL) is now routinely used to deliver up to 4.5 kJ of 2ω light in a 6 ns time window

An advantage of laser heating is that it can be studied and optimized without using Z