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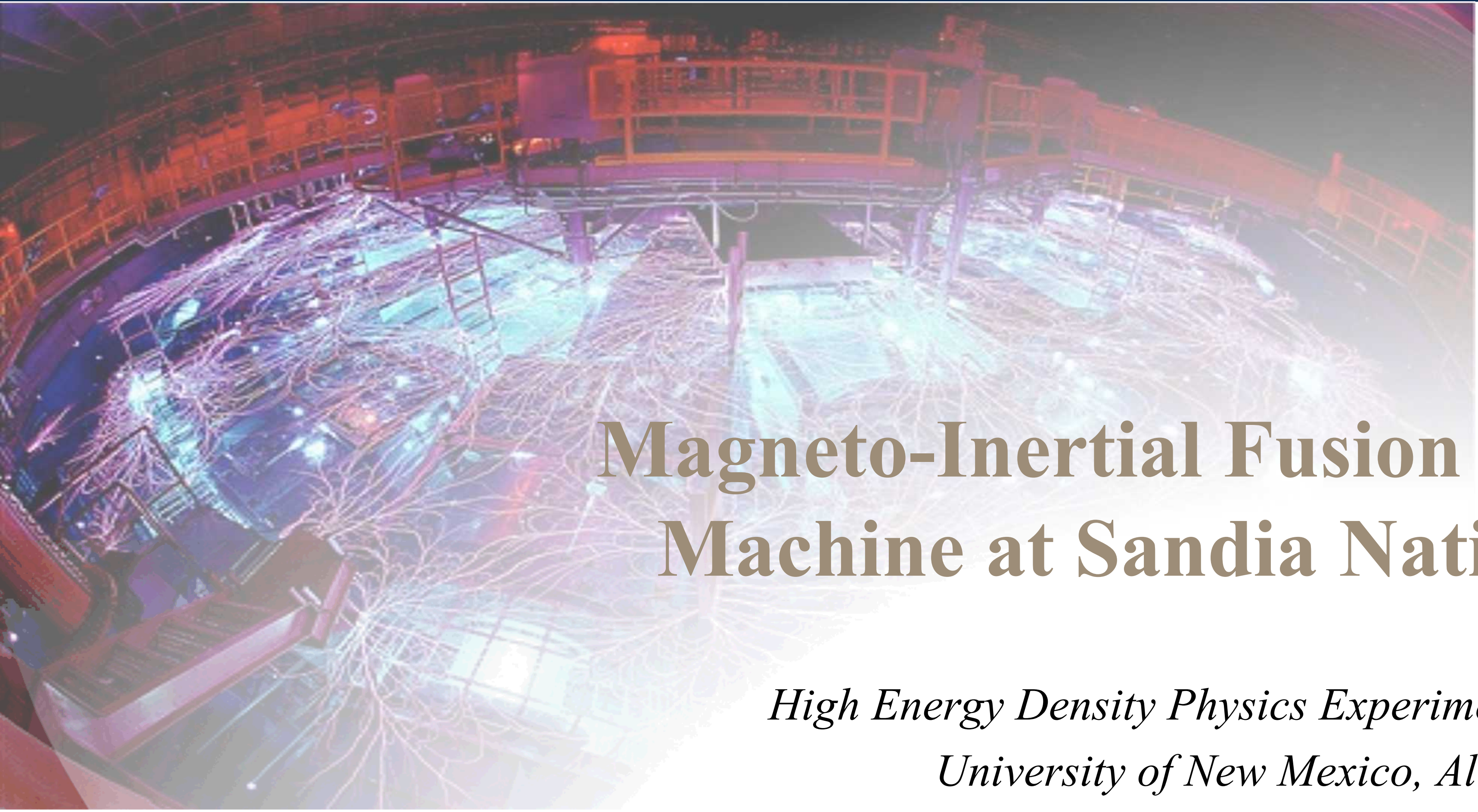

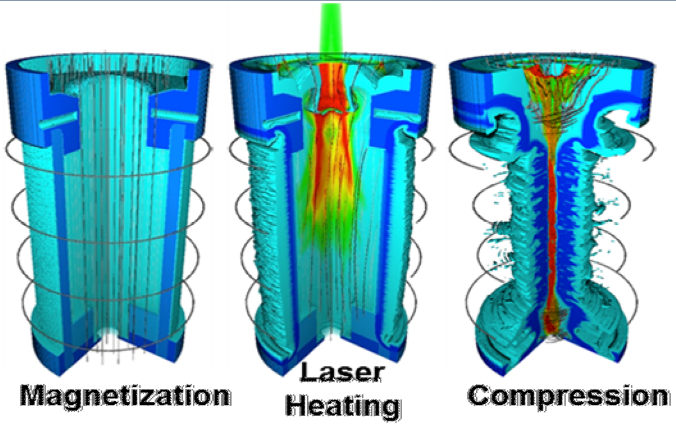

Magneto-Inertial Fusion Research on the Z Machine at Sandia National Laboratories

Patrick Knapp

High Energy Density Physics Experiments, Sandia National Laboratories

University of New Mexico, Albuquerque NM, February 21, 2017

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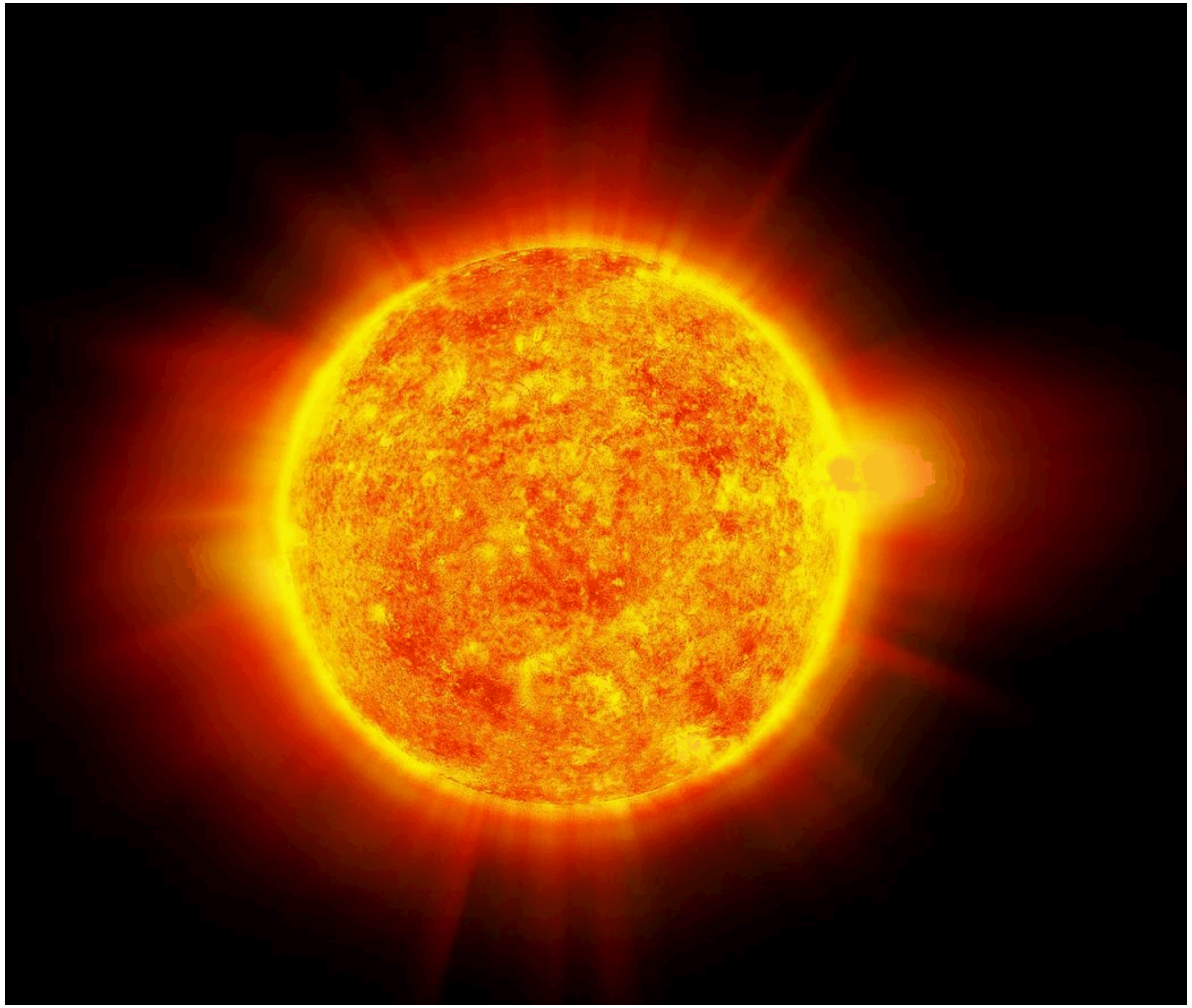
Thermonuclear fusion powers the stars…



- 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

What makes thermonuclear fusion such an attractive energy source?

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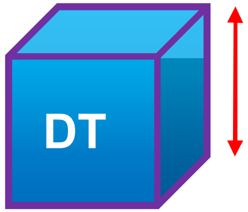
$$Y_{\text{fus}} = Q n_1 n_2 \langle \sigma v \rangle V \tau$$



1 mm

$\tau = 10\ \mu\text{s}$

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

$$1\ \text{ton} = 4\ \text{GJ}$$

DT fuel

$$\langle \sigma v \rangle|_{4\text{keV}} = 6 \times 10^{-18}\ \text{cm}^3/\text{s}$$

$$n_{\text{DT,solid}} \sim 10^{23}\ \text{cm}^{-3}$$

$$Q = 17.6\ \text{MeV}$$

$$Y_{\text{fus}} = Q10^{20} \approx 3 \times 10^{8}\ \text{J}$$

$$Y_{\text{fus}} \sim 0.1\ \text{ton!!}$$

- This is a tremendous amount of energy contained in an incredibly small volume
- ~80% of the energy is in neutrons, the remainder is in the charged α particles
- But there is (at least) one significant problem…

What makes thermonuclear fusion such an attractive energy source?

$$\mathrm{Y_{fus}} =$$

on K

$$\langle \sigma v \rangle|_{4\mathrm{keV}} =$$

$$n_{\mathrm{DT,sol}}$$

$$Q =$$

$$\mathrm{Y_{fus}} = Q$$

e

$$\mathrm{Y_{fus}}$$

We can't confine the fuel for 10 μs!

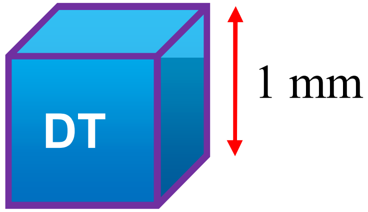
$$P_{\mathrm{fuel}} = 2 n_{\mathrm{DT}} T_i \sim 1 \ \mathrm{Gbar} = 10^9 \ \mathrm{atm}$$

$$\tau_{\mathrm{disassembly}} \approx \sqrt{\frac{R}{a}}$$

$$a = \frac{2 P_{\mathrm{fuel}}}{n_{\mathrm{DT}} m_{\mathrm{DT}} R} = \frac{2 P_{\mathrm{fuel}}}{\rho R}$$

$$a \sim 10^{15} \ \mathrm{m/s^2}$$

$$\tau_{\mathrm{disassembly}} \sim 10^{-9} \ \mathrm{s}$$



$$\mathrm{Y_{fus}} \sim 10^{-5} \ \mathrm{ton!!}$$

How do we overcome the confinement problem?

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

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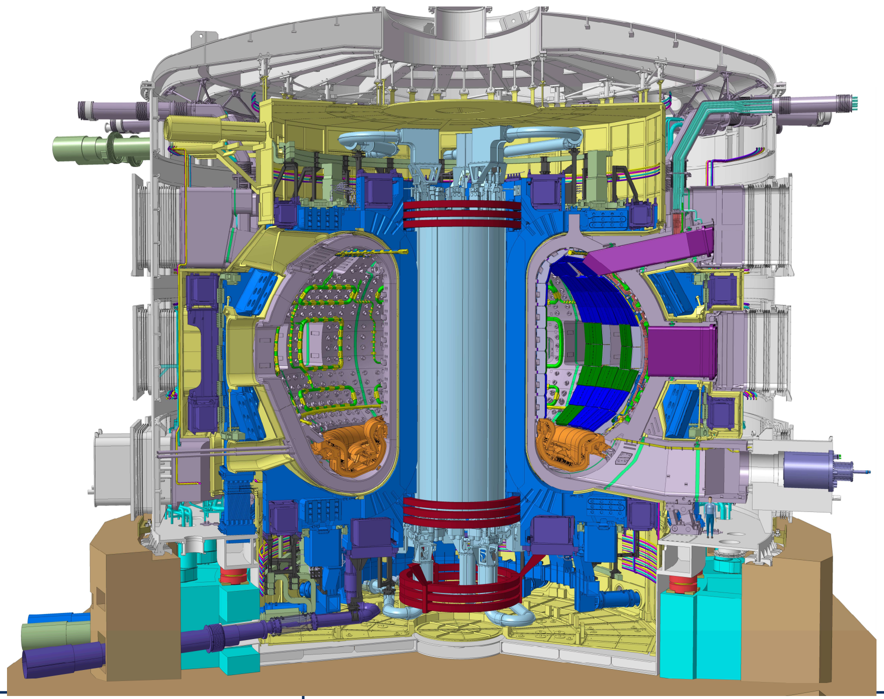
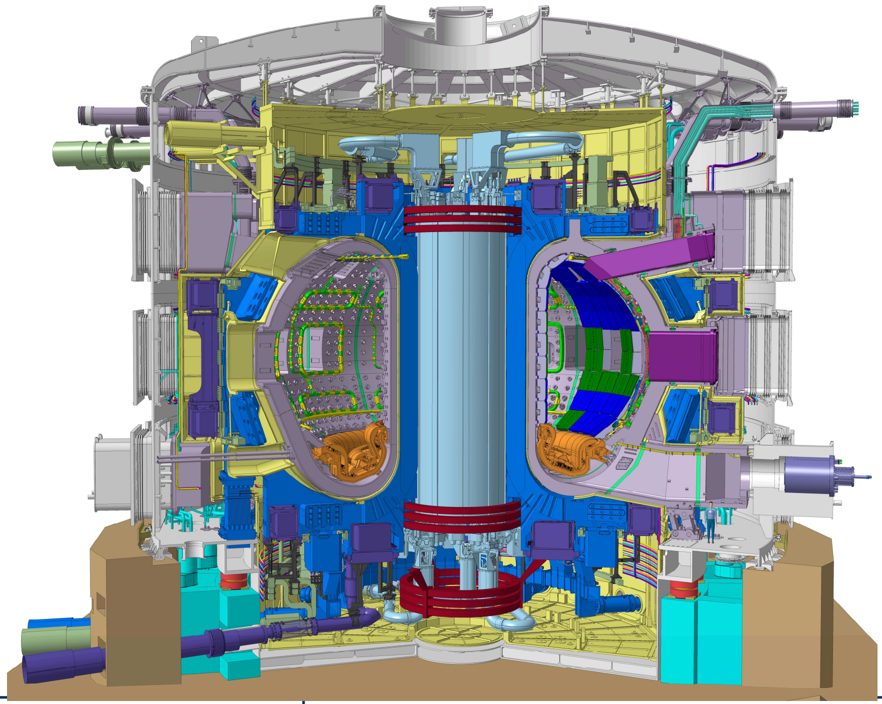
ITER



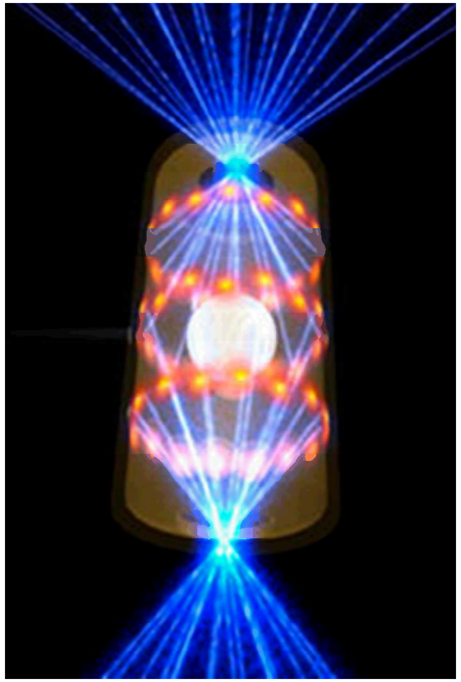
Density	1 x 10^{14} cm^{-3}		
Volume	8 x 10^{8} cm^{3}		
Duration	300-500 s		
Magnetic field	100 kG		

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

ITER

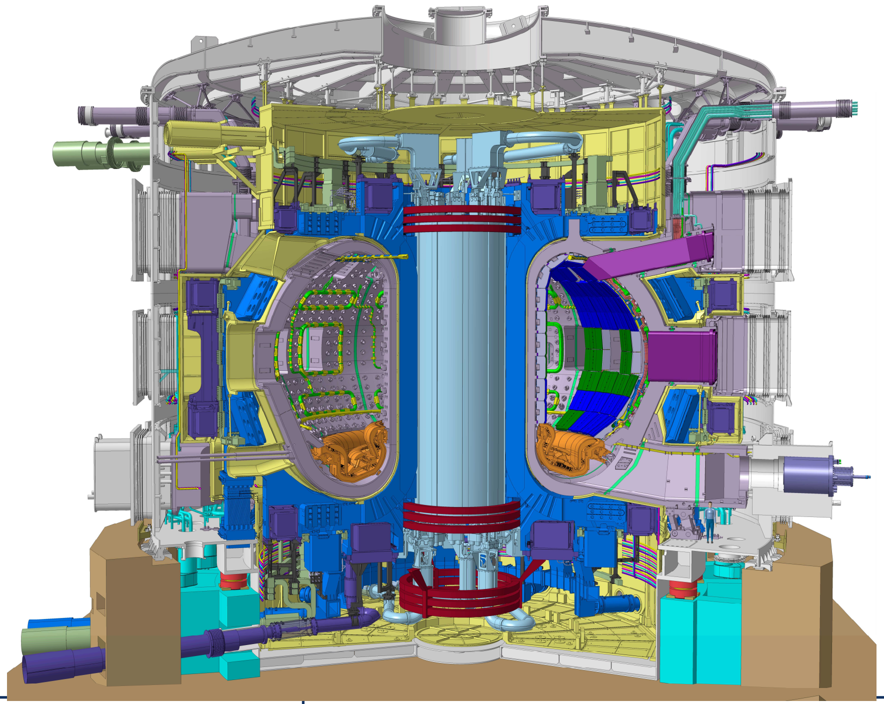
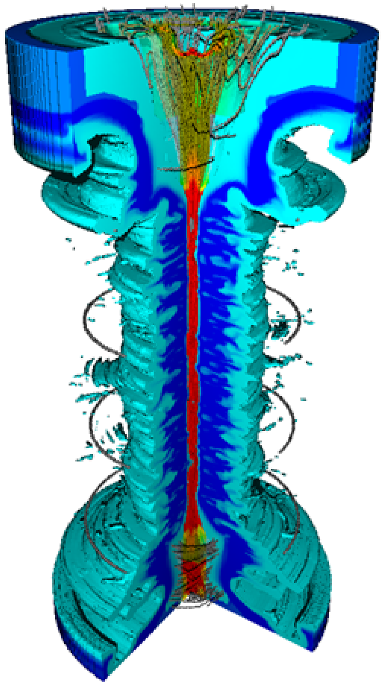
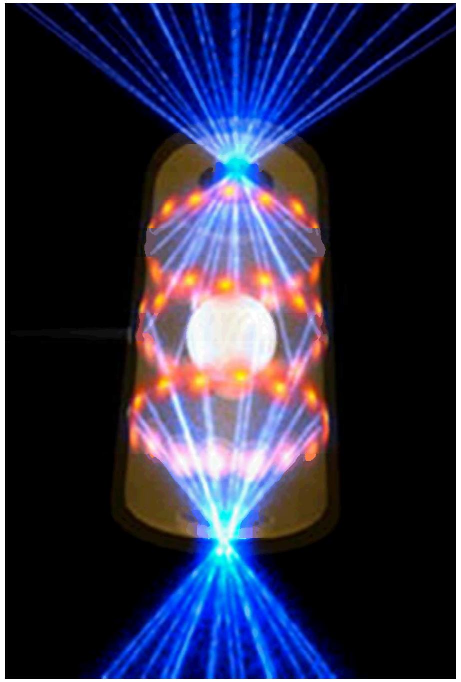


NIF hohlraum



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

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

ITER	MIF concept	NIF hohlraum
		

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

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

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Why is Pressure so important for fusion?

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

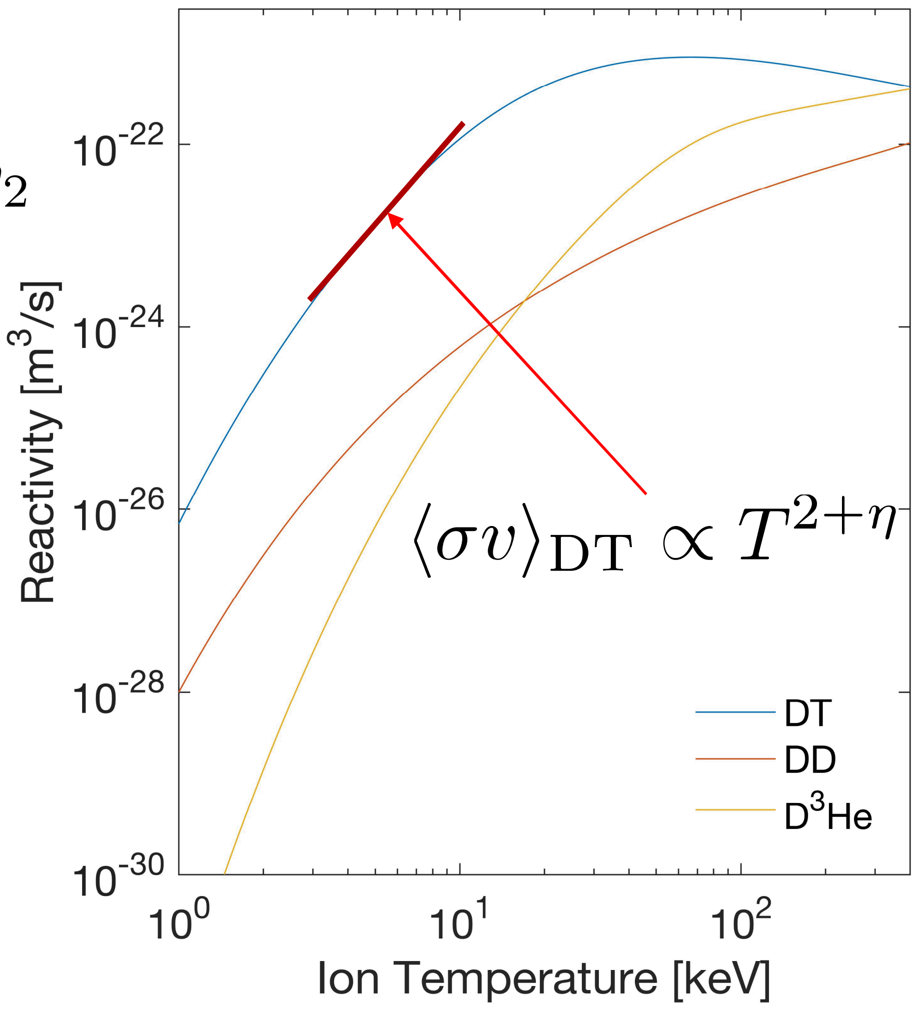
$$f(\mathbf{v}) = \left(\frac{m_i}{2\pi k_b T_i} \right)^{3/2} e^{-\frac{m\mathbf{v}\cdot\mathbf{v}}{2k_bT_i}}$$

Reaction Rate:

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

$$\mathcal{R}_{\mathrm{fus}} \propto n^2 T^{2+\eta} \propto P^2 T^\eta$$

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



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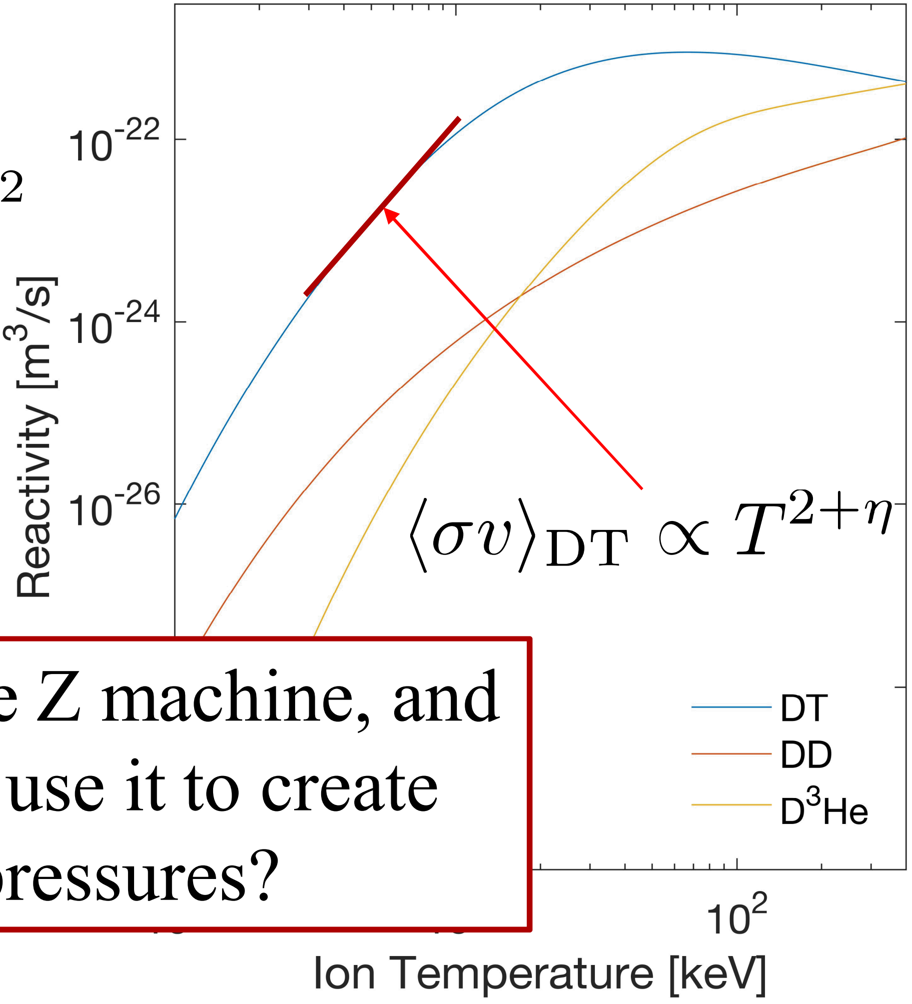
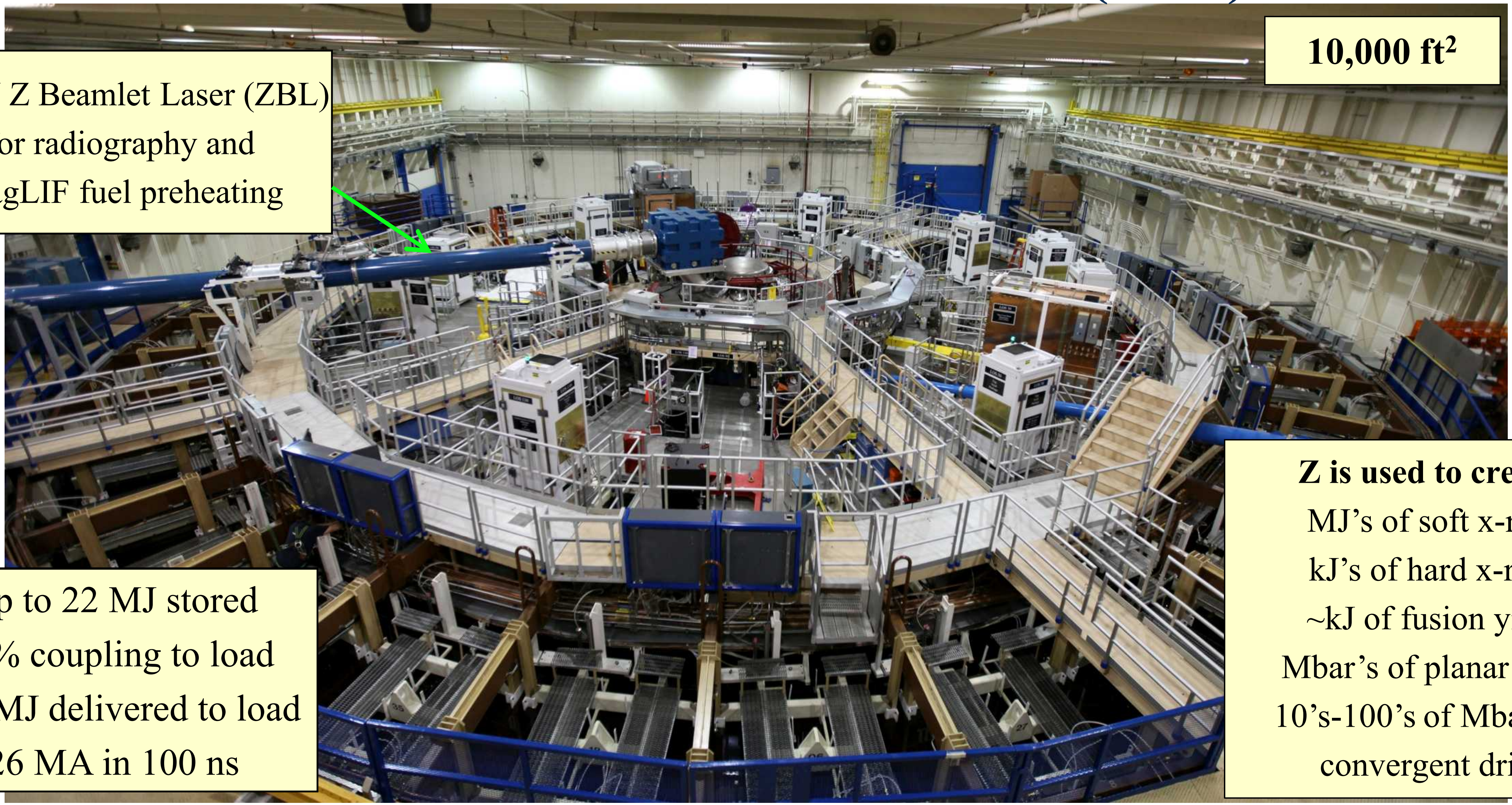


So what is the Z machine, and how do we use it to create high pressures?

The Z facility combines the multi-MJ Z pulsed-power accelerator with the multi-kJ Z Beamlet Laser (ZBL)



10,000 ft^2

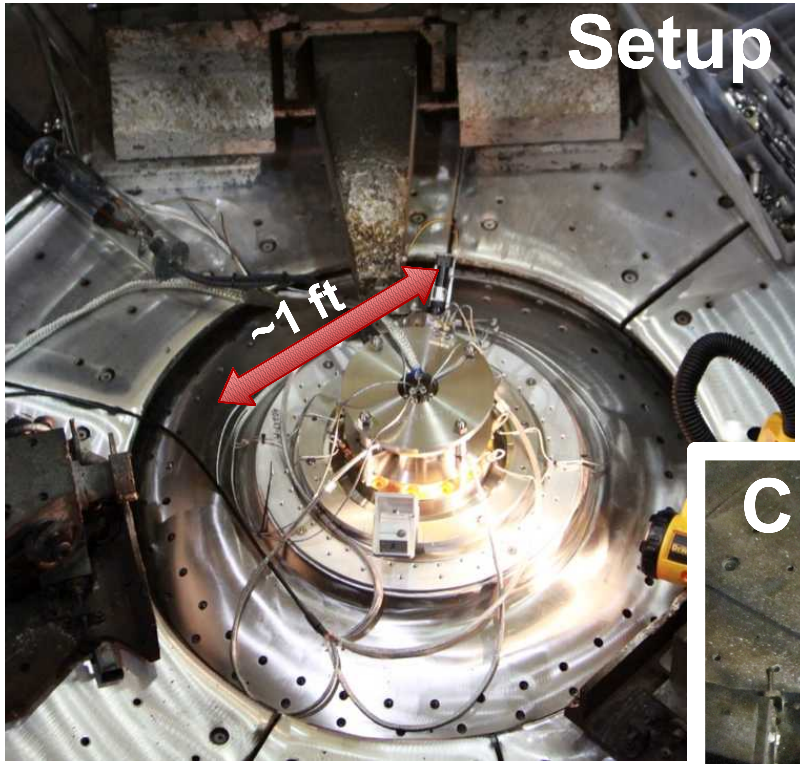
1–4 kJ Z Beamlet Laser (ZBL) for radiography and MagLIF fuel preheating

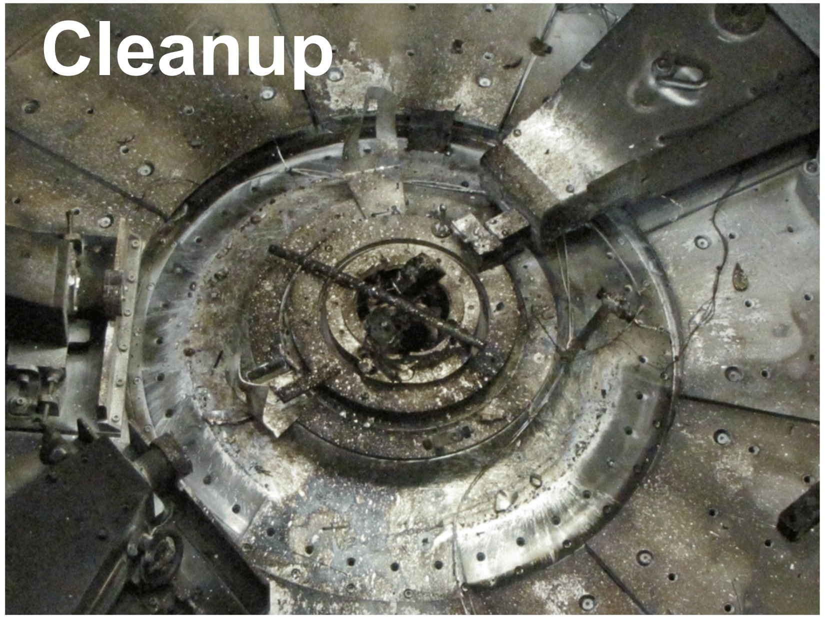
Up to 22 MJ stored
15% coupling to load
1–3 MJ delivered to load
26 MA in 100 ns

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

Z is a fun and challenging place to conduct high impact experiments

- Shot rate of ~1/day
- ~150 shots/year



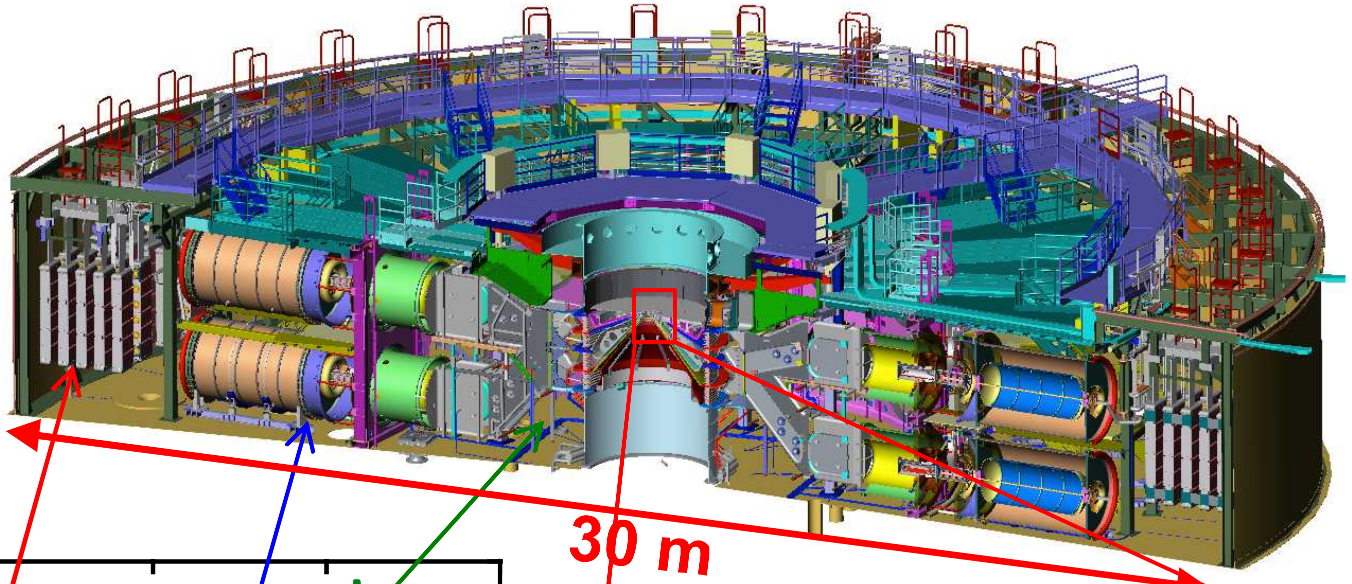


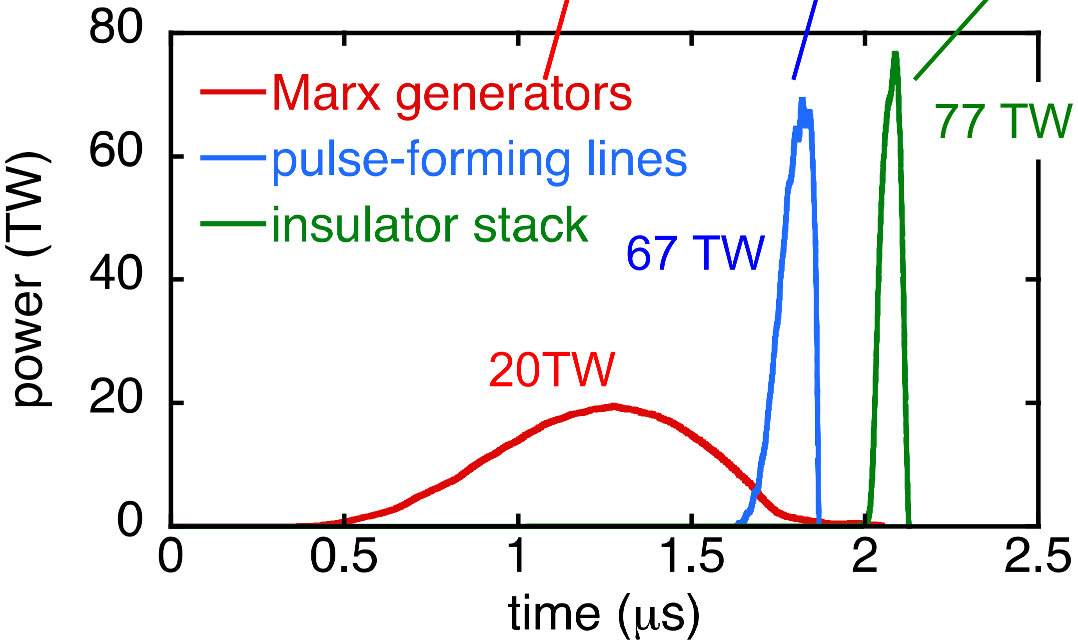
- MJ’s of magnetic energy to the load
- Equivalent to detonating a few sticks of dynamite
- Harsh debris, shock, and radiation environment make fielding experiments unique and challenging

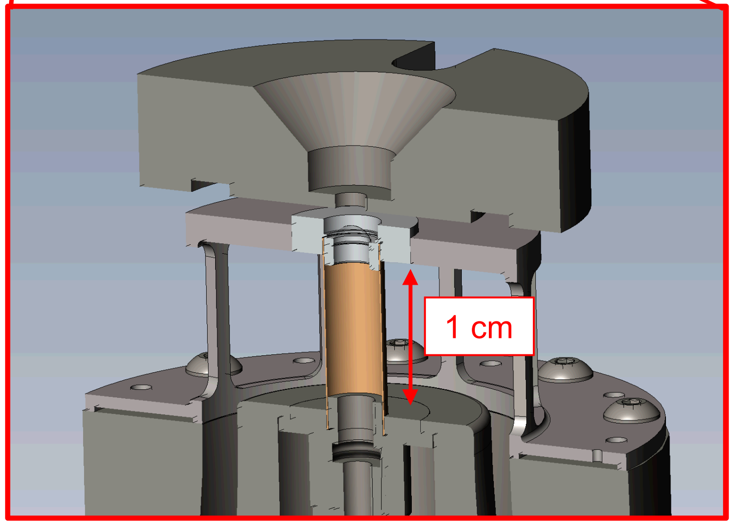
Pulsed-power is all about energy compression in both space and time

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

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







Magnetically-Driven Cylindrical Implosions are Efficient: Implosion Drive Pressure is Divergent!

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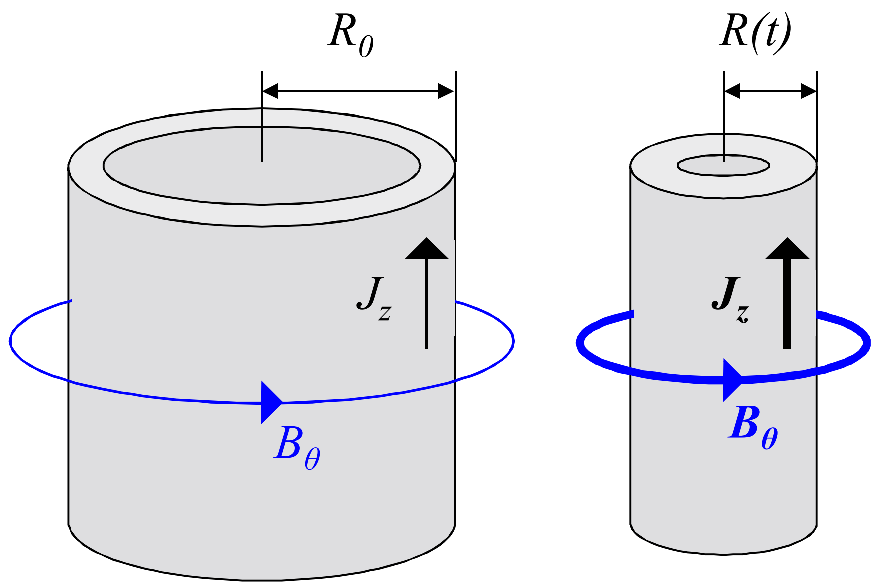
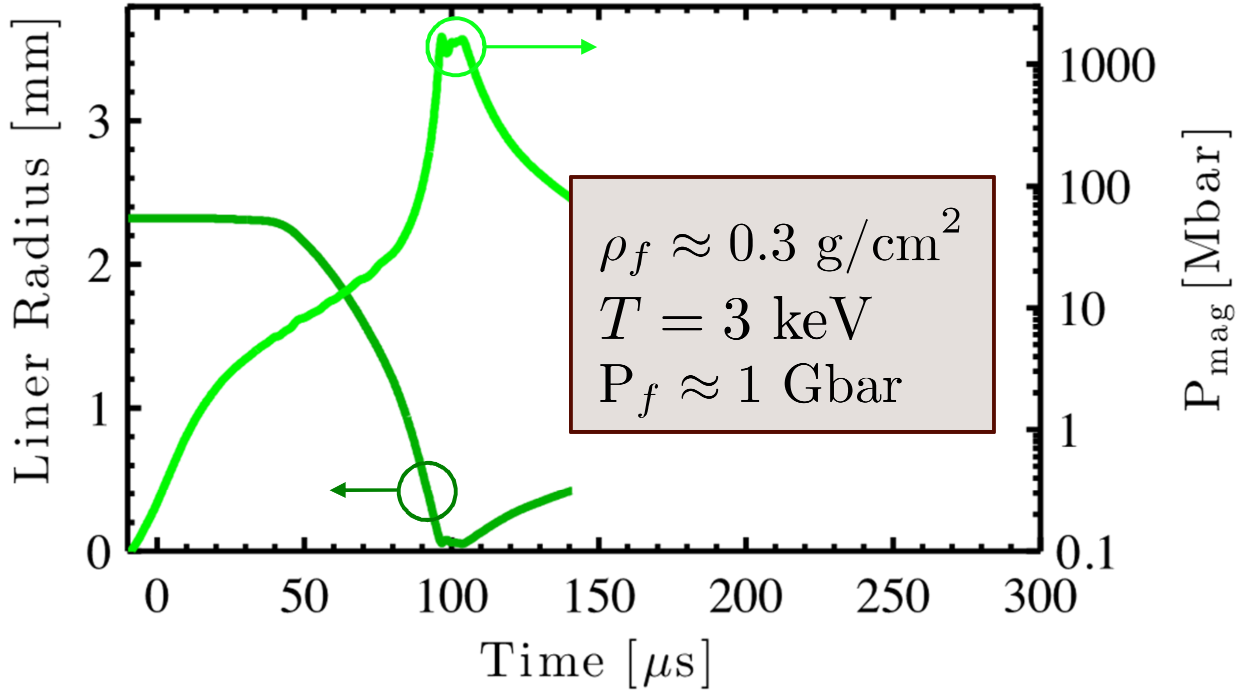
$$P = \frac{B^2}{2\mu_o} = 140 \cdot \left(\frac{I_{[\mathrm{MA}]}/30}{R(t)_{[\mathrm{mm}]}} \right)^2 \quad [\mathrm{Mbar}]$$

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





By varying the magnetic pressure pulse shape, liner dimensions, and duration of drive, Z can access a wide variety of end states

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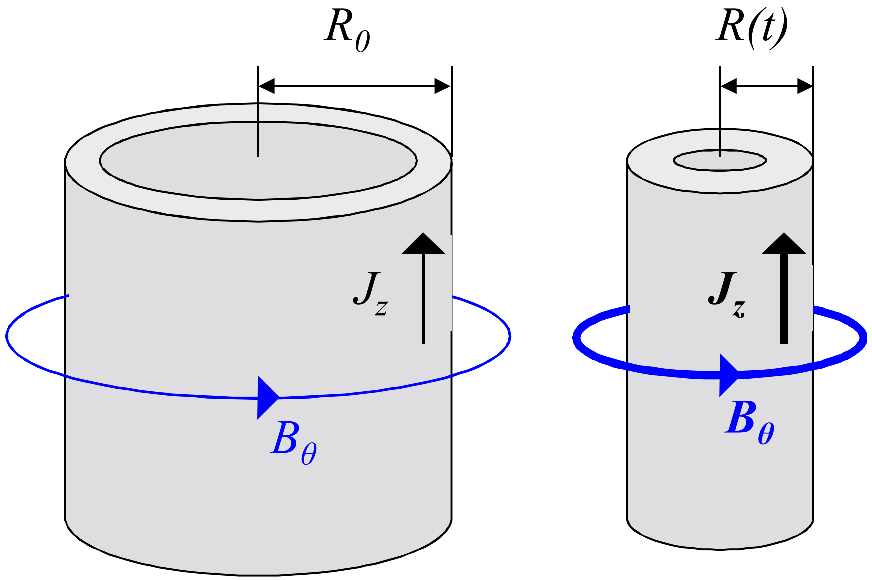

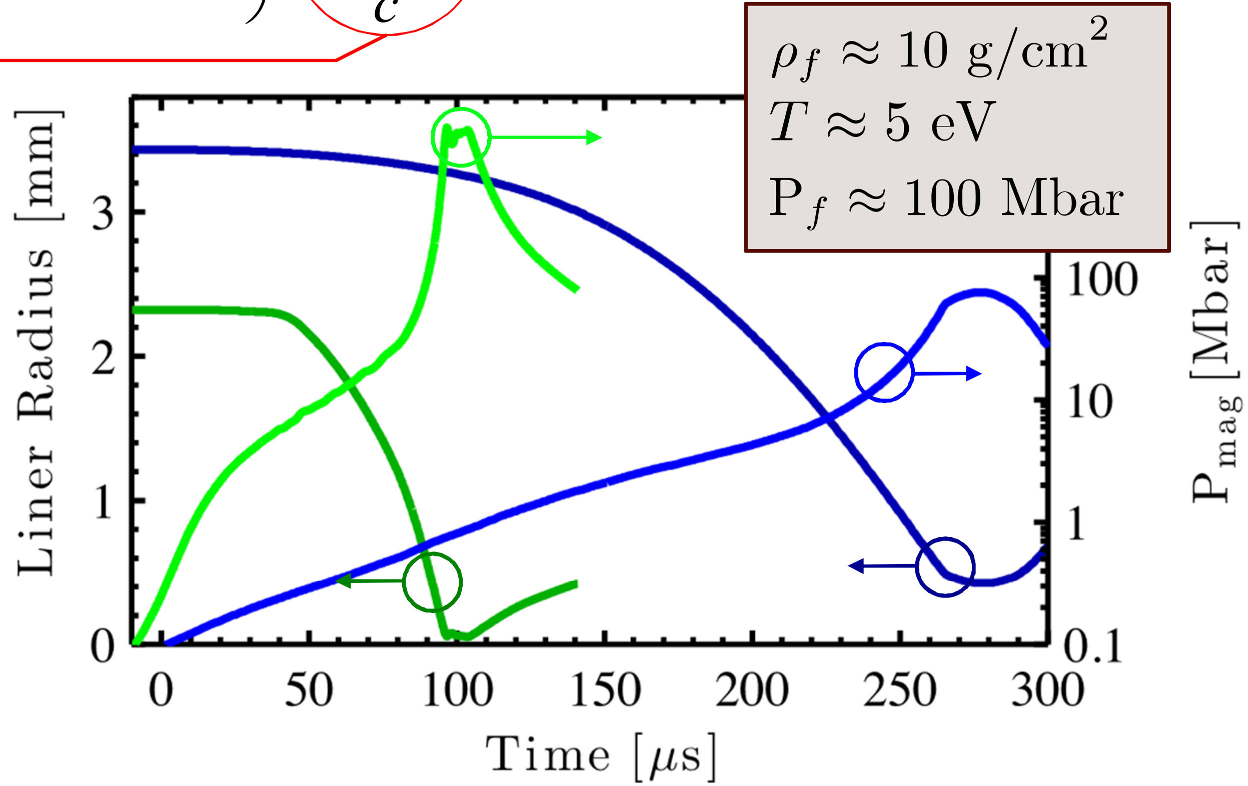

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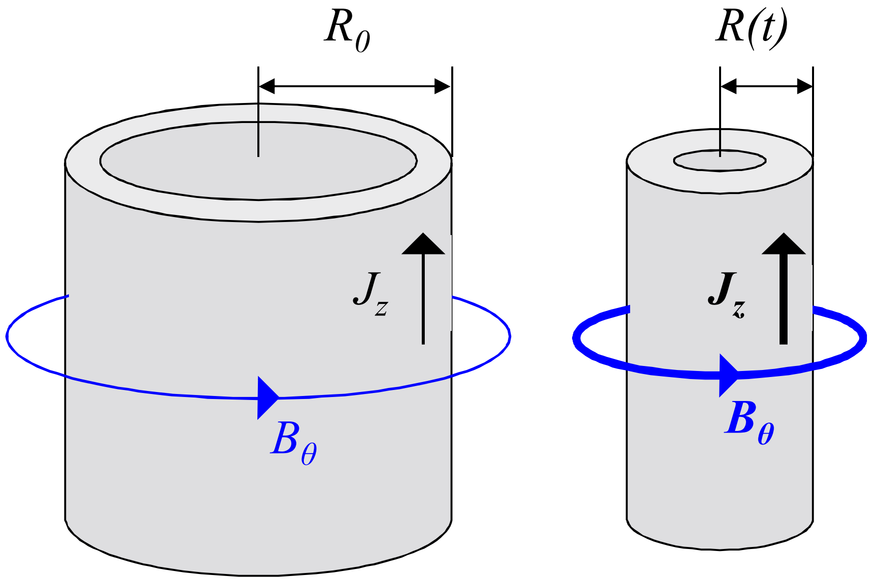
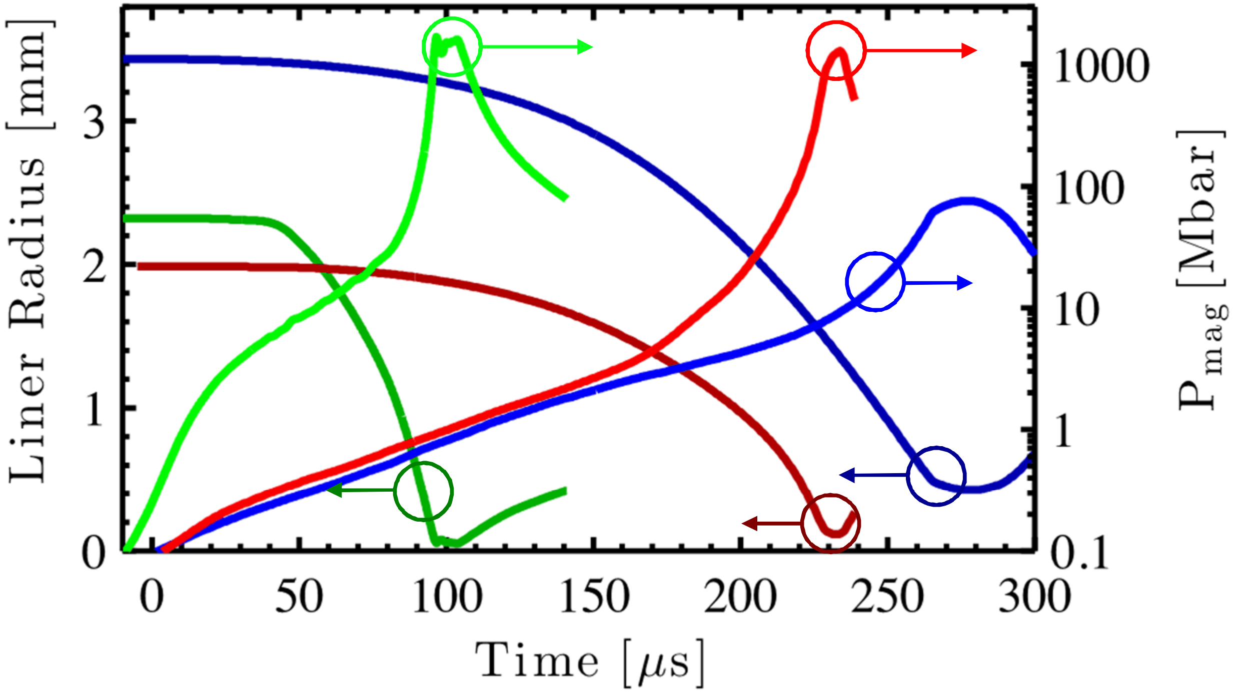
$$\rho\left(\frac{\partial \mathbf{u}}{\partial t} + (\mathbf{u}\cdot\nabla)\mathbf{u}\right) = \frac{\mathbf{J}\times\mathbf{B}}{c} - \nabla P$$

$\rho_f \approx 60\ \text{g/cm}^2$
$T \approx 10\ \text{eV}$
$P_f \approx 2\ \text{Gbar}$





By varying the magnetic pressure pulse shape, liner dimensions, and duration of drive, Z can access a wide variety of end states

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

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

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

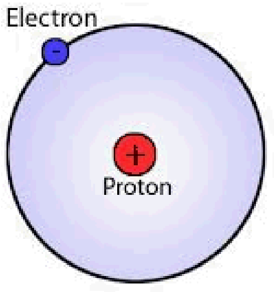
Baseball

10^{-5} Mbar

Dynamite

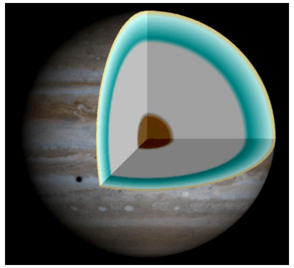
0.1 Mbar

Internal Energy of H atom



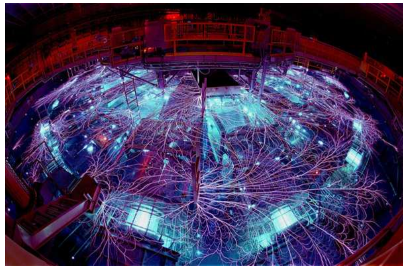
10 Mbar

Metallic H in Jupiter’s core



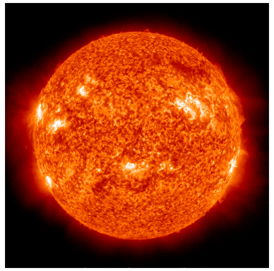
30 Mbar

Z Machine magnetic pressure



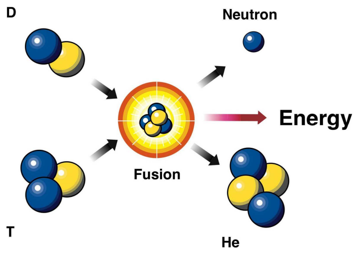
100 Mbar

Center of Sun



250,000 Mbar

Burning ICF plasma



800,000 Mbar

Z can access the HED regime

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

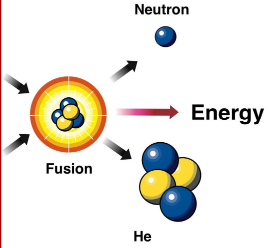
HED conditi
earth, but c
universe

Baseball

10^{-5} Mbar

- 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

rning ICF
plasma



00,000
Mbar

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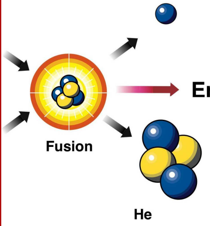
HED conditi
earth, but c
universe

Baseball

10^{-5} Mbar

- 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

rning ICF
plasma



00,000
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HED conditi
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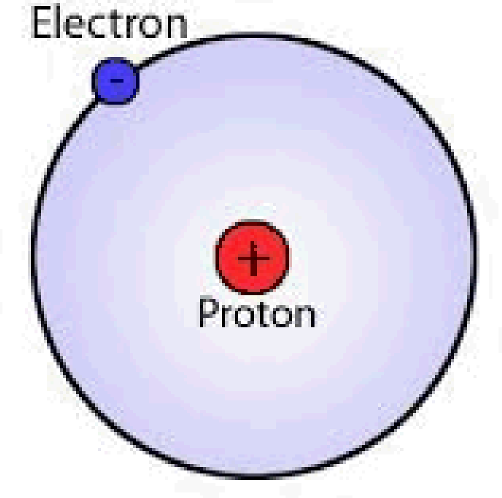
Baseball

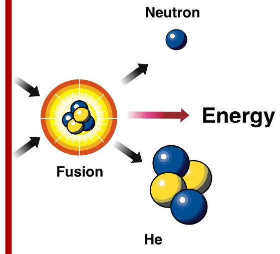
10^{-5} Mbar

Internal Energy of H atom



- The electron is bound to the proton with an energy of 13 eV
- The atomic radius is 53 pm
  - Volume ~10^{-25} cm^3
- Energy density ~ 1,000 kJ/cm^3

rning ICF
plasma



300,000
Mbar

Z can access the HED regime

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HED conditions a
earth, but comm
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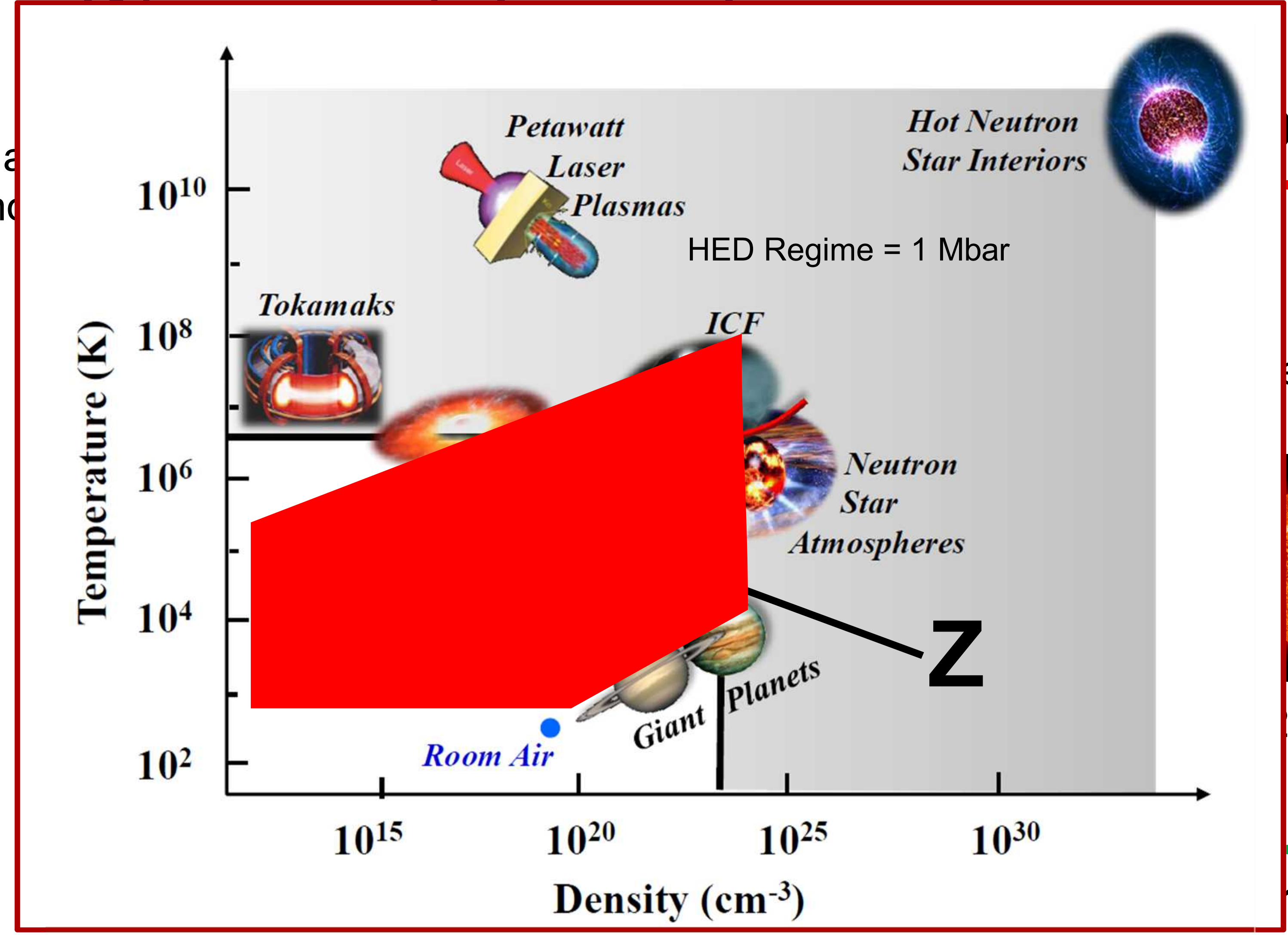
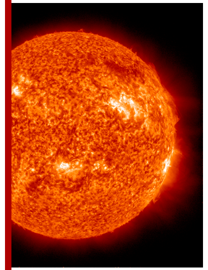
0 kJ/cm^3)

Baseball

10^{-5} Mbar

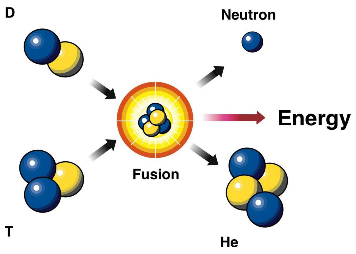


enter of Sun



50,000 Mbar

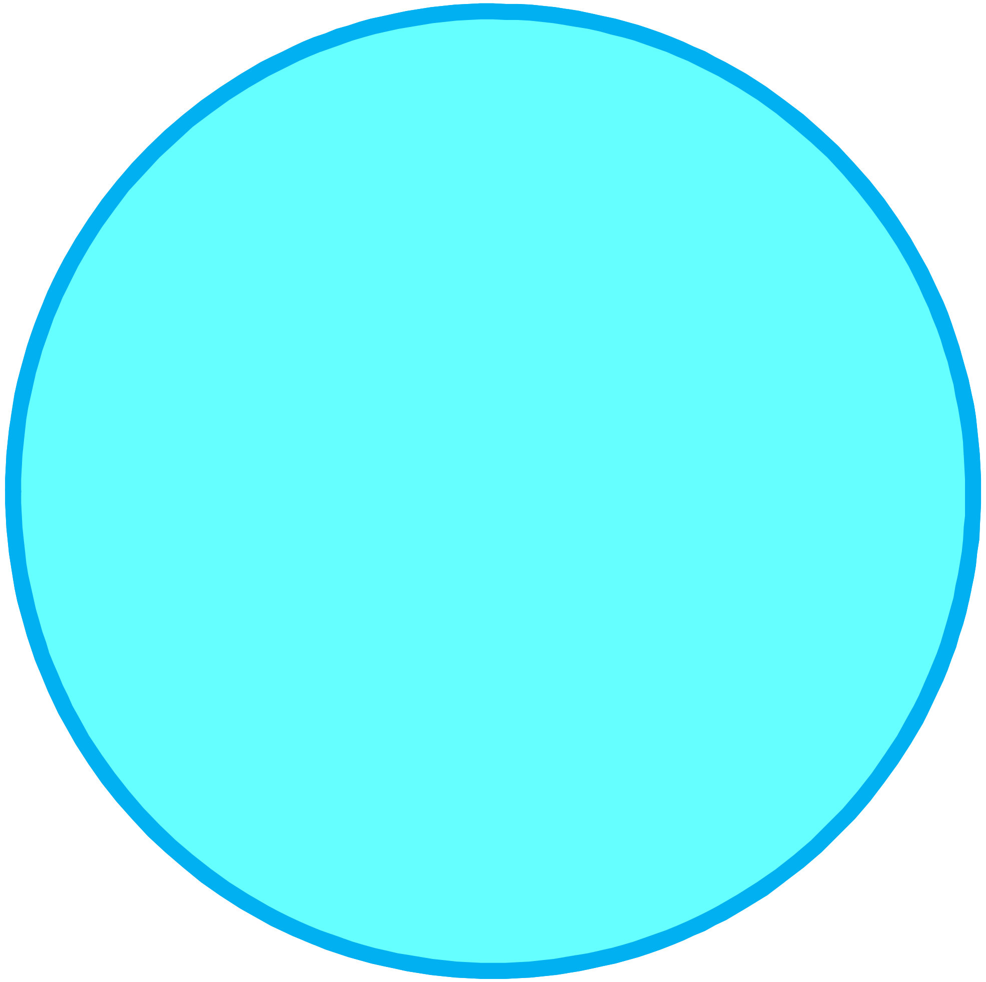
Burning ICF plasma



800,000 Mbar

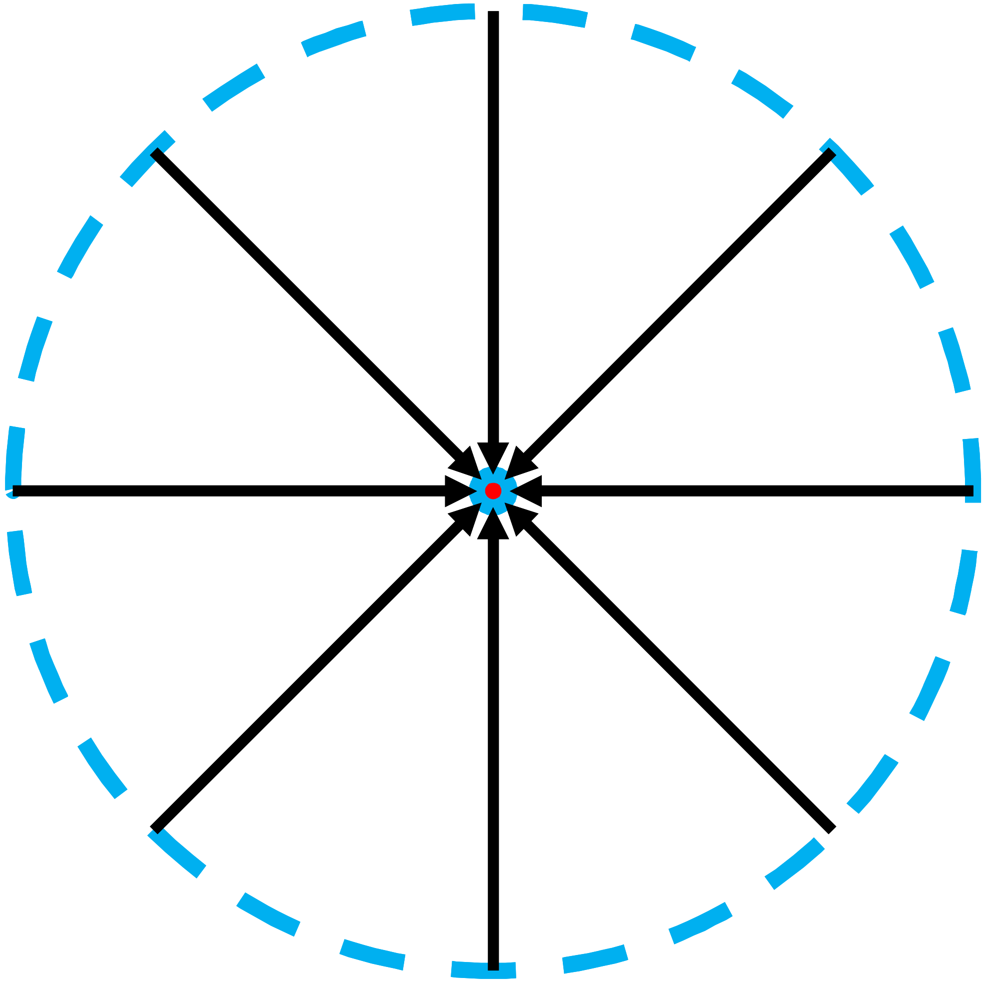
regime

A quick review of traditional ICF will help us understand MIF



- Start with a sphere containing DT

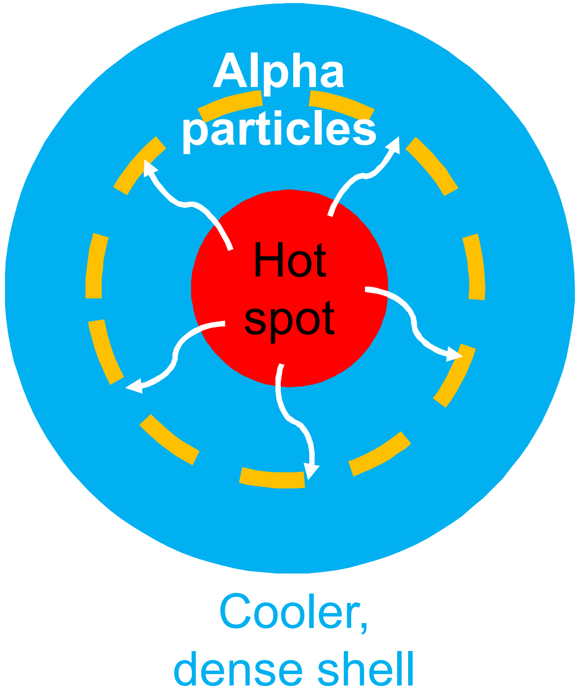
A quick review of traditional ICF will help us understand MIF



- 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)

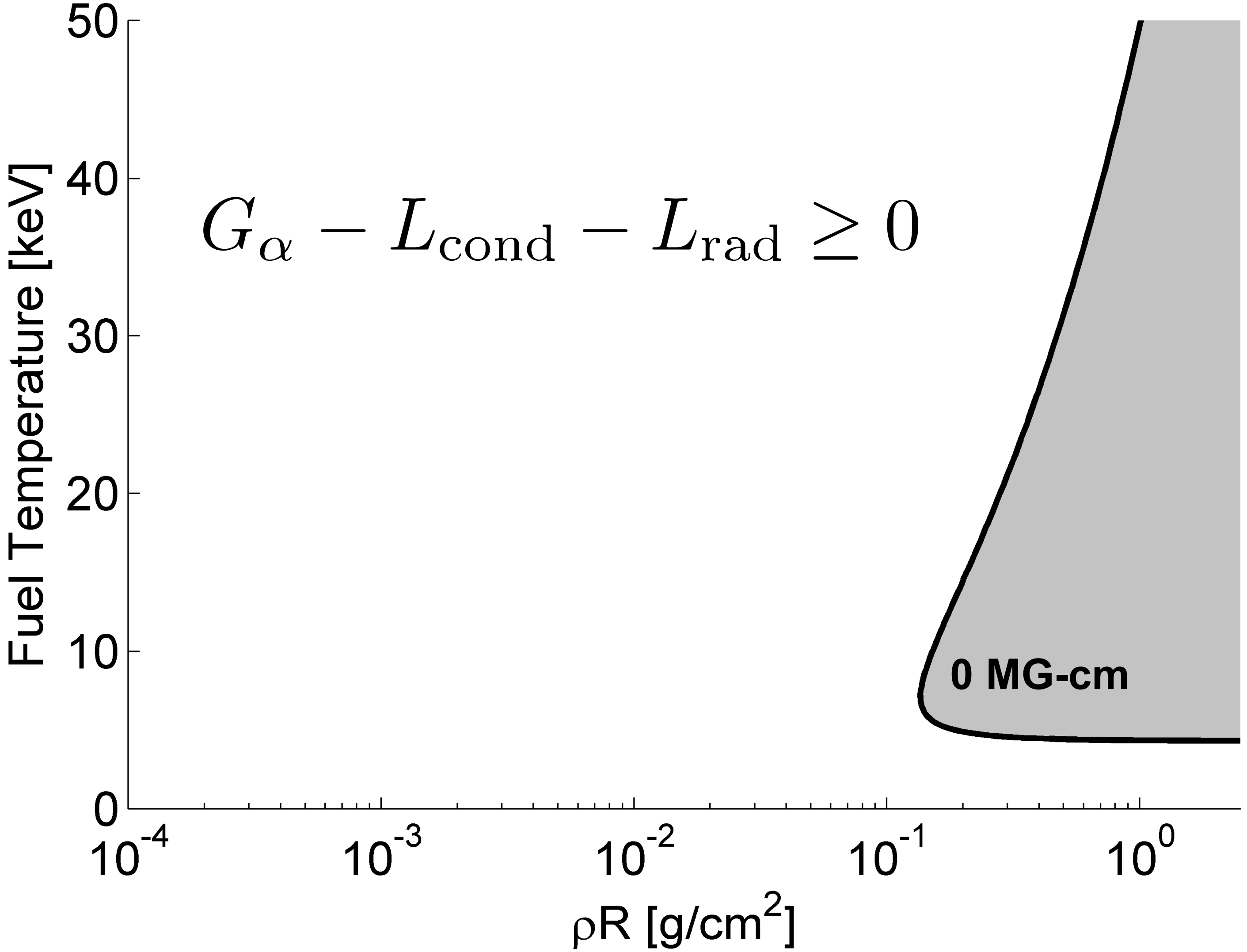
A quick review of traditional ICF will help us understand MIF

Zooming in



- Start with a sphere containing DT
- Implode the sphere
  - Compress radius by 30 (volume by 27,000)
  - Series of shocks heat the center (hot spot)
- Fuel in hot spot undergoes fusion
  - Fusion products heat surrounding dense fuel
- With a favorable power balance, a chain reaction occurs
  - For parameters of interest on the NIF, this requires $P_{HS} > 300$ Gbar and $\rho_{cold} > 1000$ g/cm^3

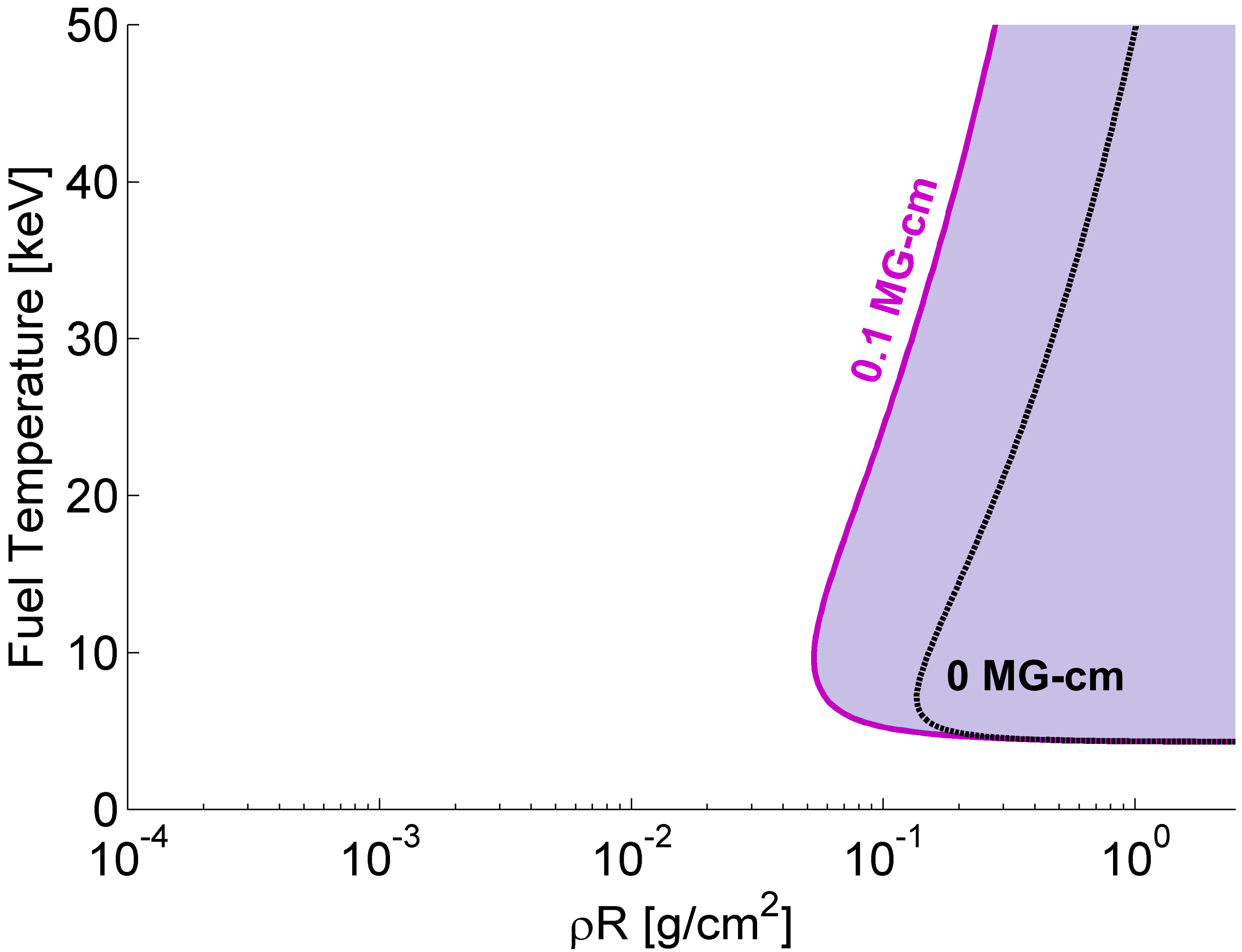
ICF has requirements on fuel temperature and areal density for gains to exceed losses



- 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).

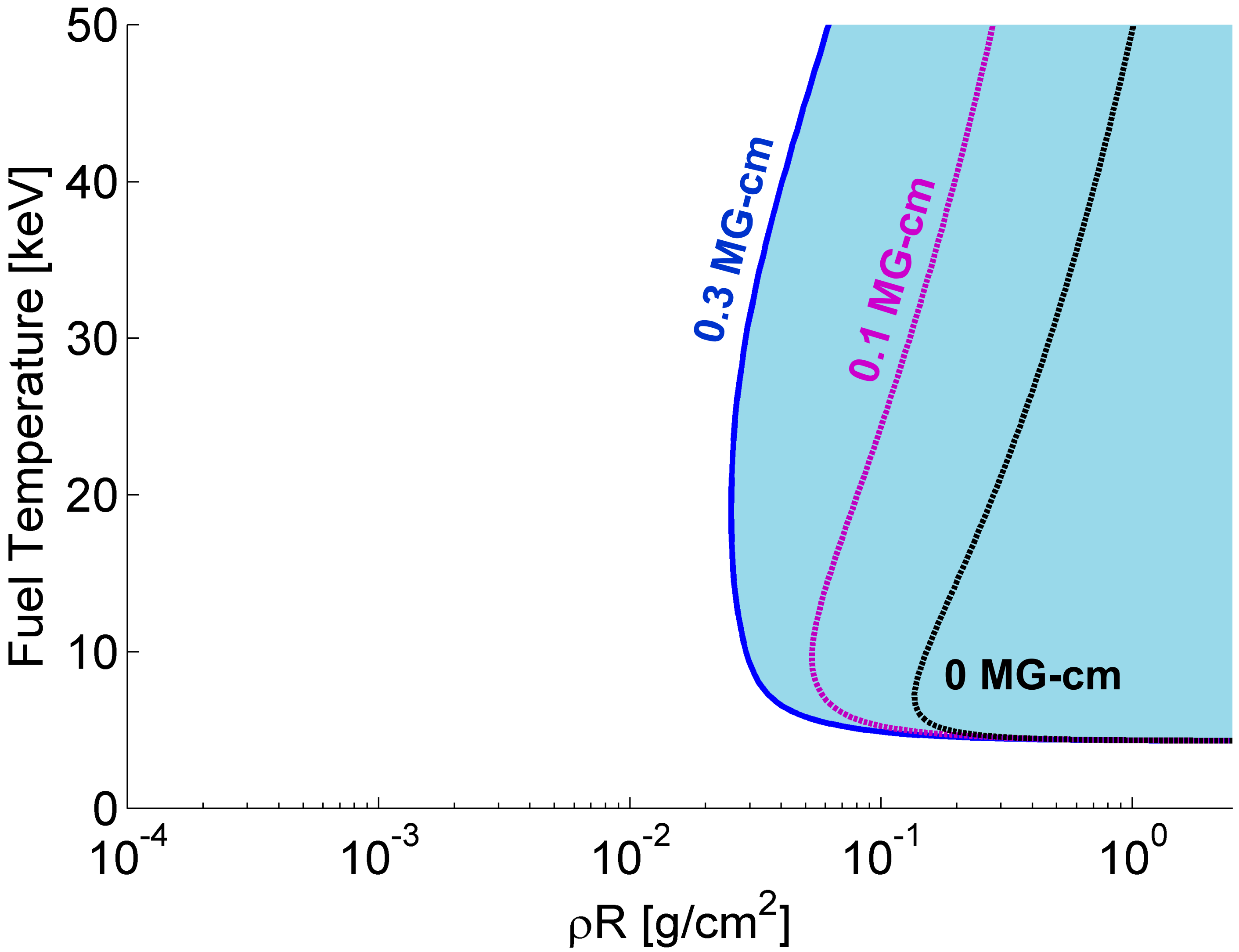
Magneto-inertial fusion (MIF) utilizes magnetic fields to relax the stagnation requirements of ICF



- 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).

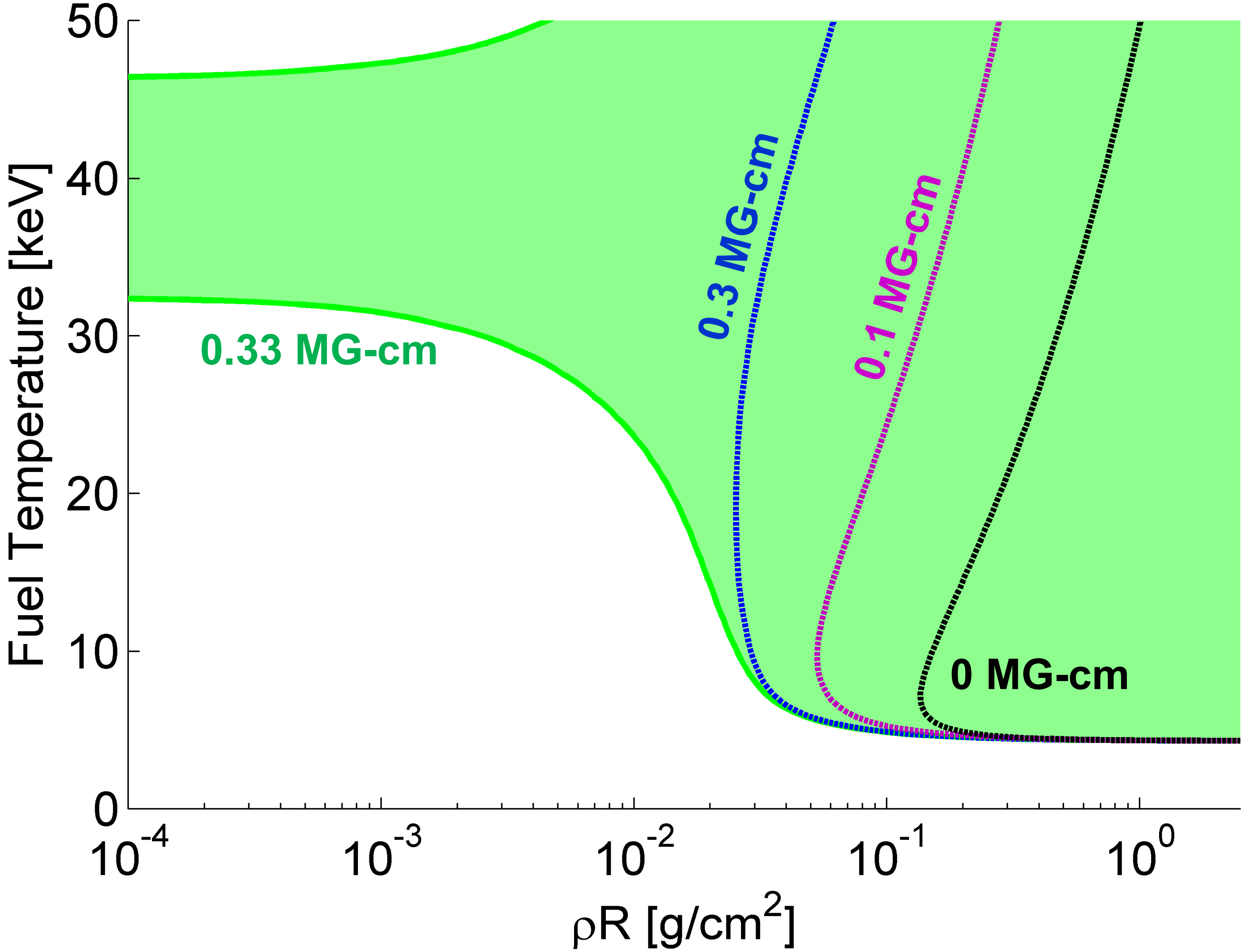
Magneto-inertial fusion (MIF) utilizes magnetic fields to relax the stagnation requirements of ICF



- 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).

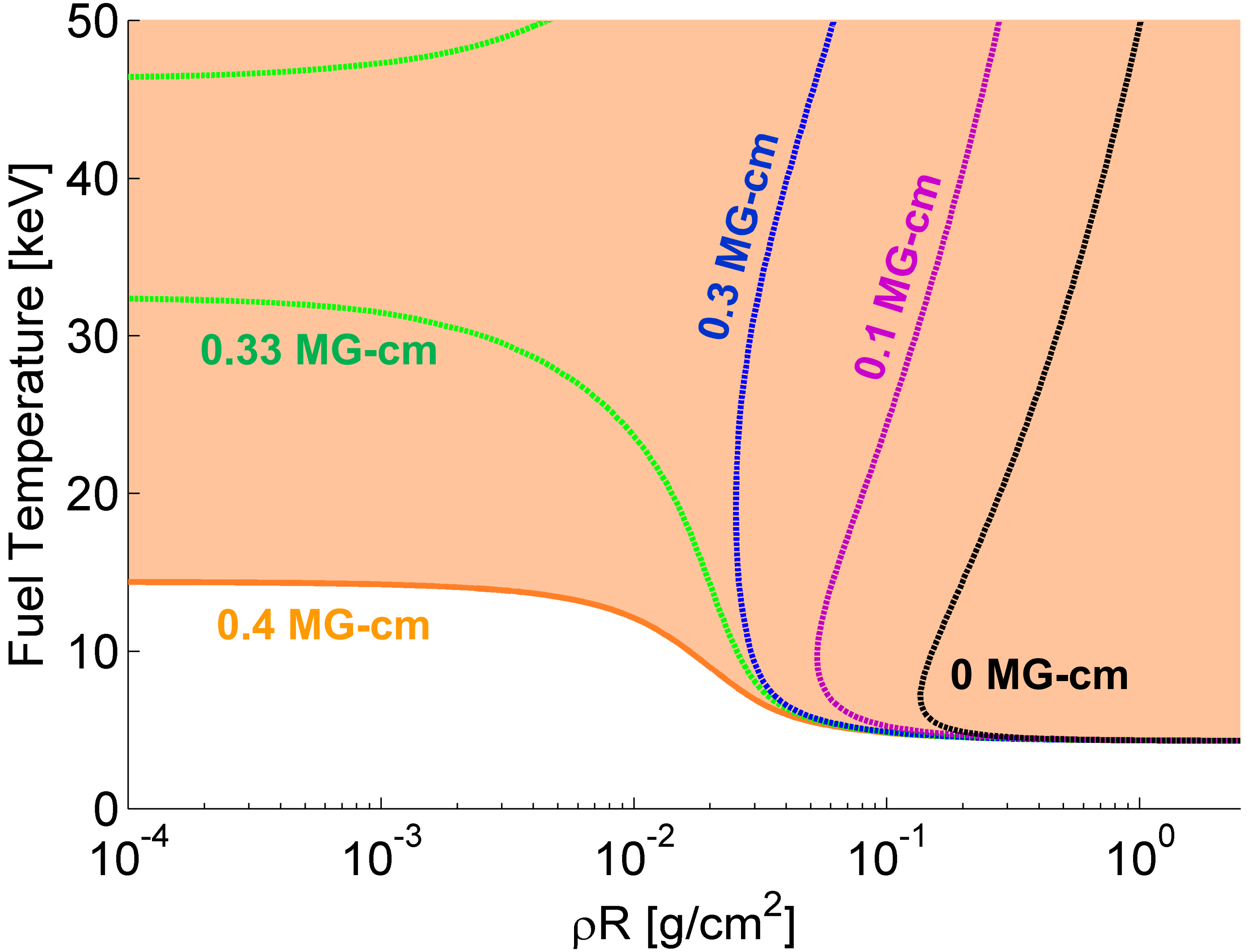
Magneto-inertial fusion (MIF) utilizes magnetic fields to relax the stagnation requirements of ICF



- 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).

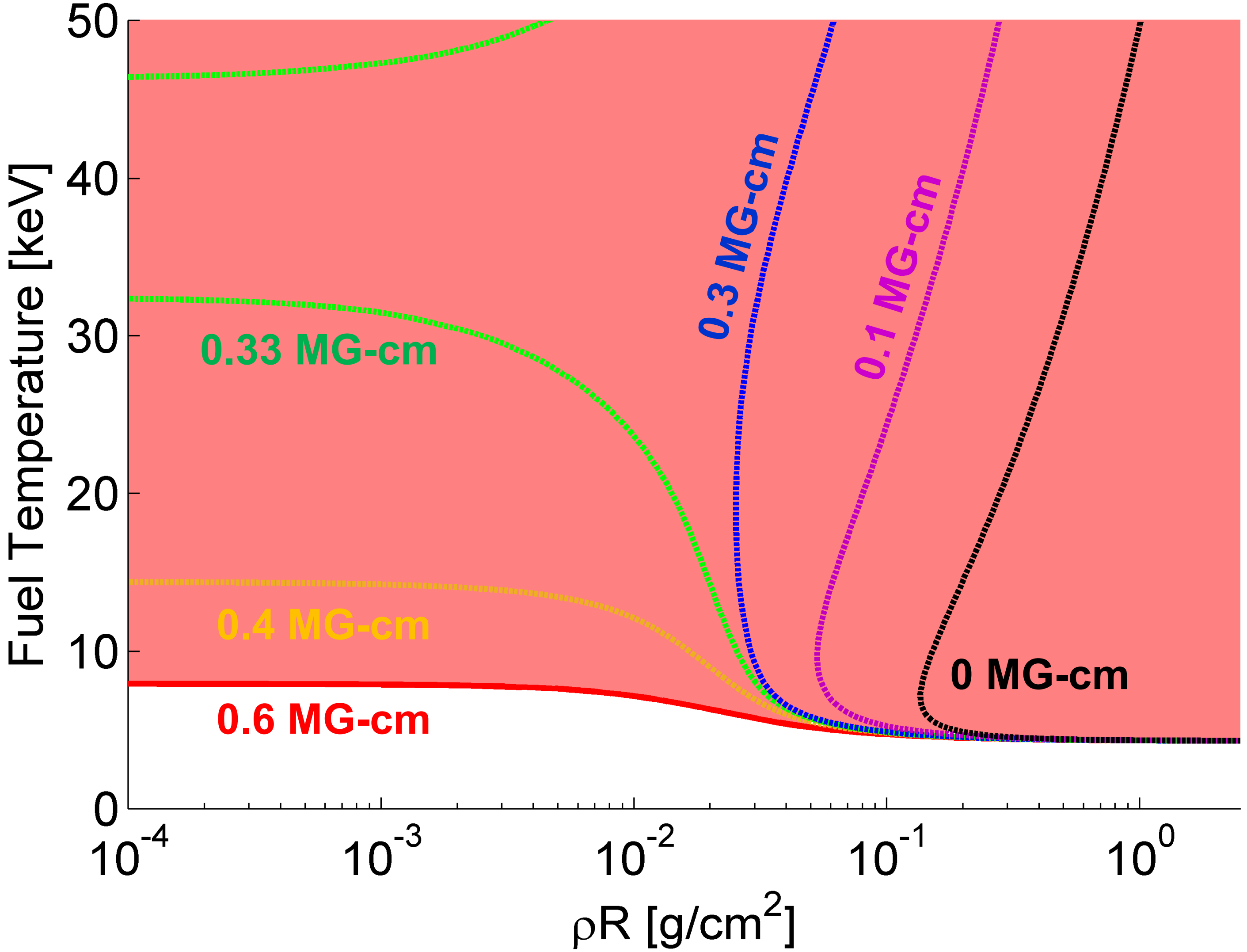
Magneto-inertial fusion (MIF) utilizes magnetic fields to relax the stagnation requirements of ICF



- 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).

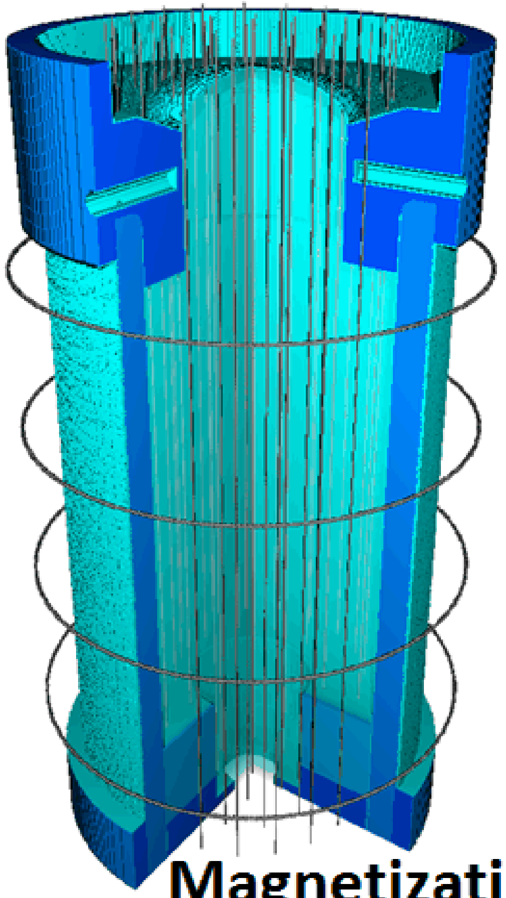
Magneto-inertial fusion (MIF) utilizes magnetic fields to relax the stagnation requirements of ICF



- 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).

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
  - D2 gas ~ mg/cc (n_e/n_{crit} < 0.1)
- Axial magnetic field is applied to target
  - 10-30 T
  - ~ 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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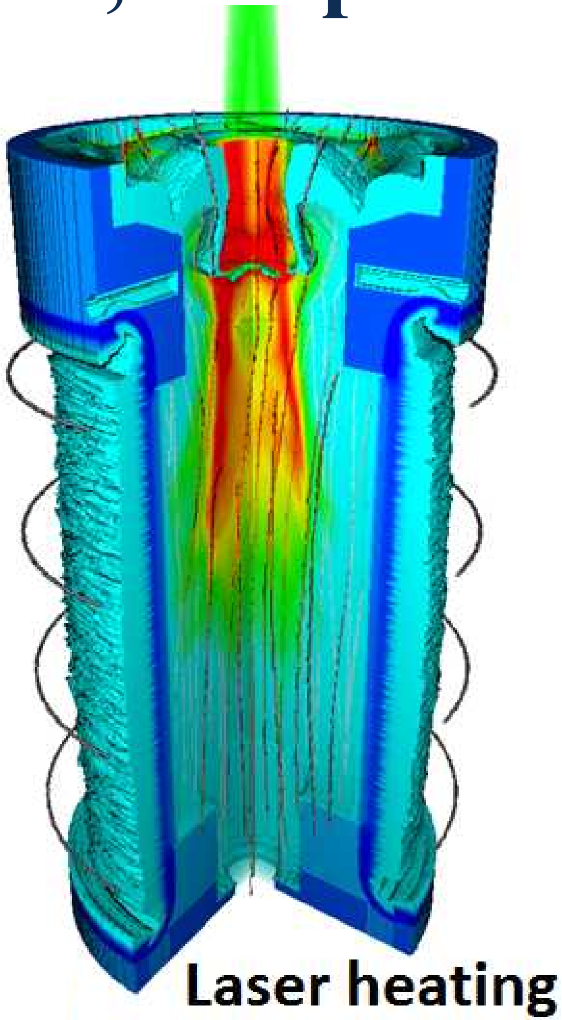
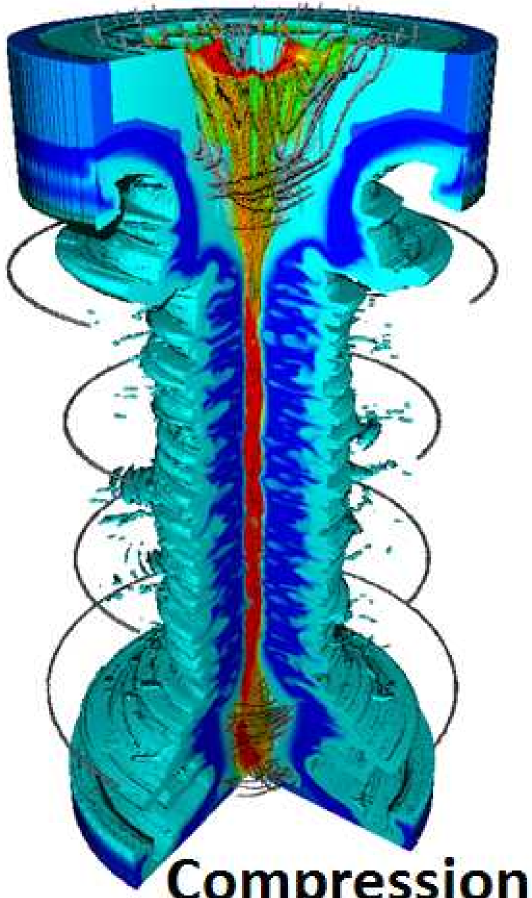


Stage 2: Laser Heating

- **Liner begins to compress**
  - **OD is moving but ID is stationary**
- **Laser heats the fuel**
  - $T_e \sim$ **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)
[2] A.B. Sefkow, *et al.*, Phys. Plasmas, **21** 072711 (2014)

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

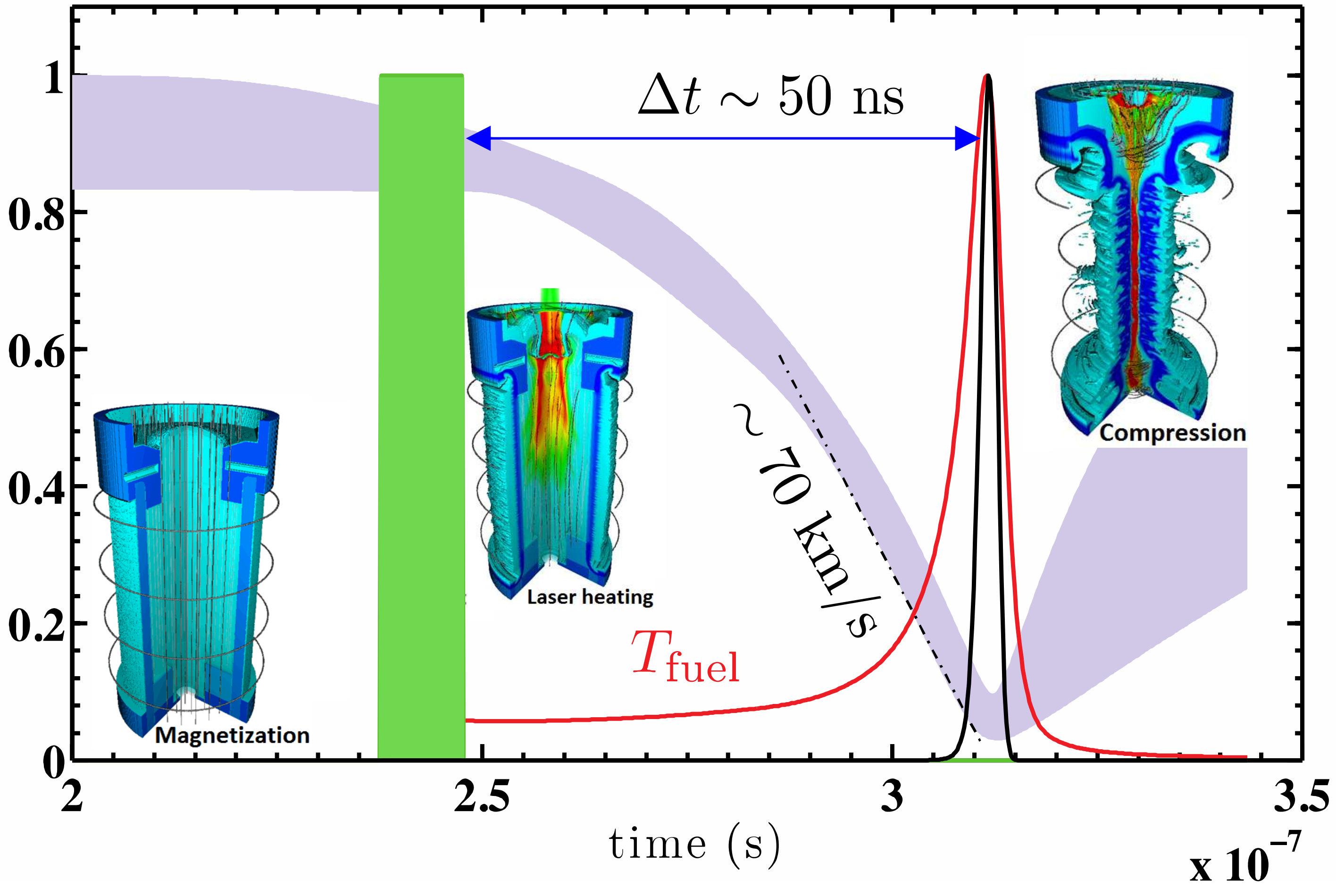


Stage 3: Compression

- **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)

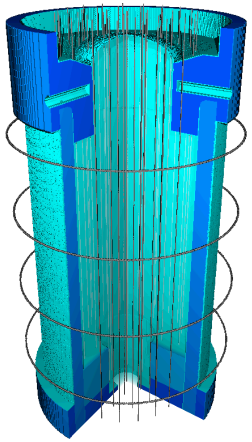
Magnetization and preheat reduce peak velocity required for ignition compared to traditional ICF



- Magnetization confines 3.5 MeV α-particles at lower ρR
- Preheating + magnetization allows ignition temperature to be reached at a lower implosion velocity
- Calculations show MagLIF scales to high yield and gain*

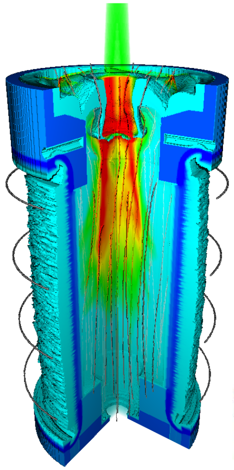
[1] S. A. Slutz, *et al.*, Phys. Plasmas **17** 056303 (2010)
[2] S. A. Slutz. and R.A. Vesey, PRL **108**, 025003 (2012)

MagLIF experiments are complicated to field and analyze



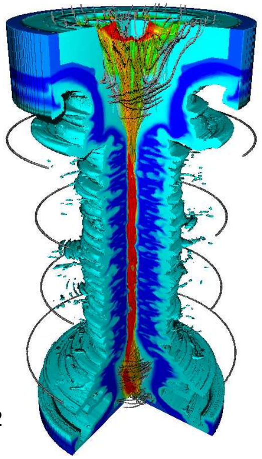
Magnetization

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



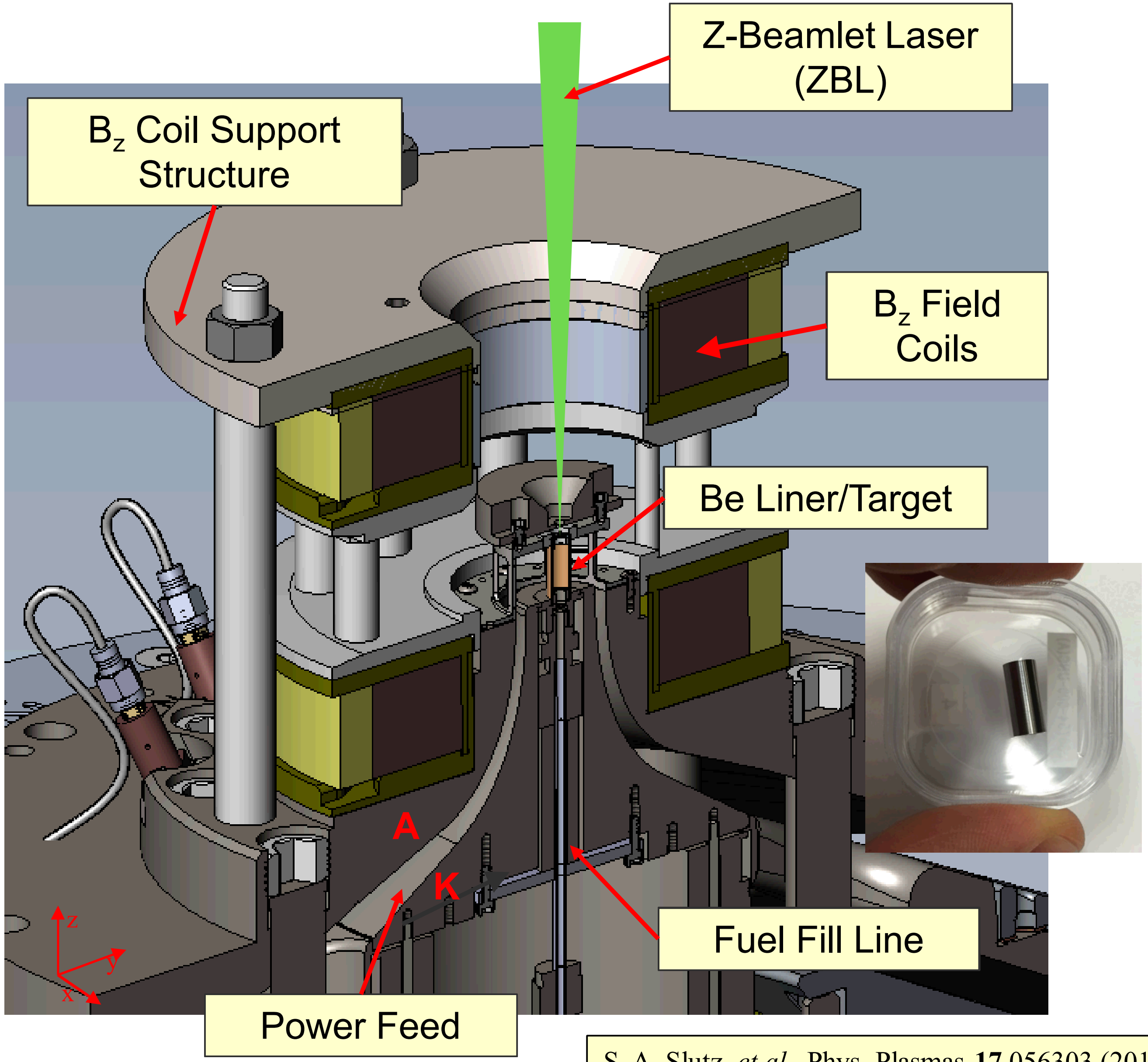
Laser Heating

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



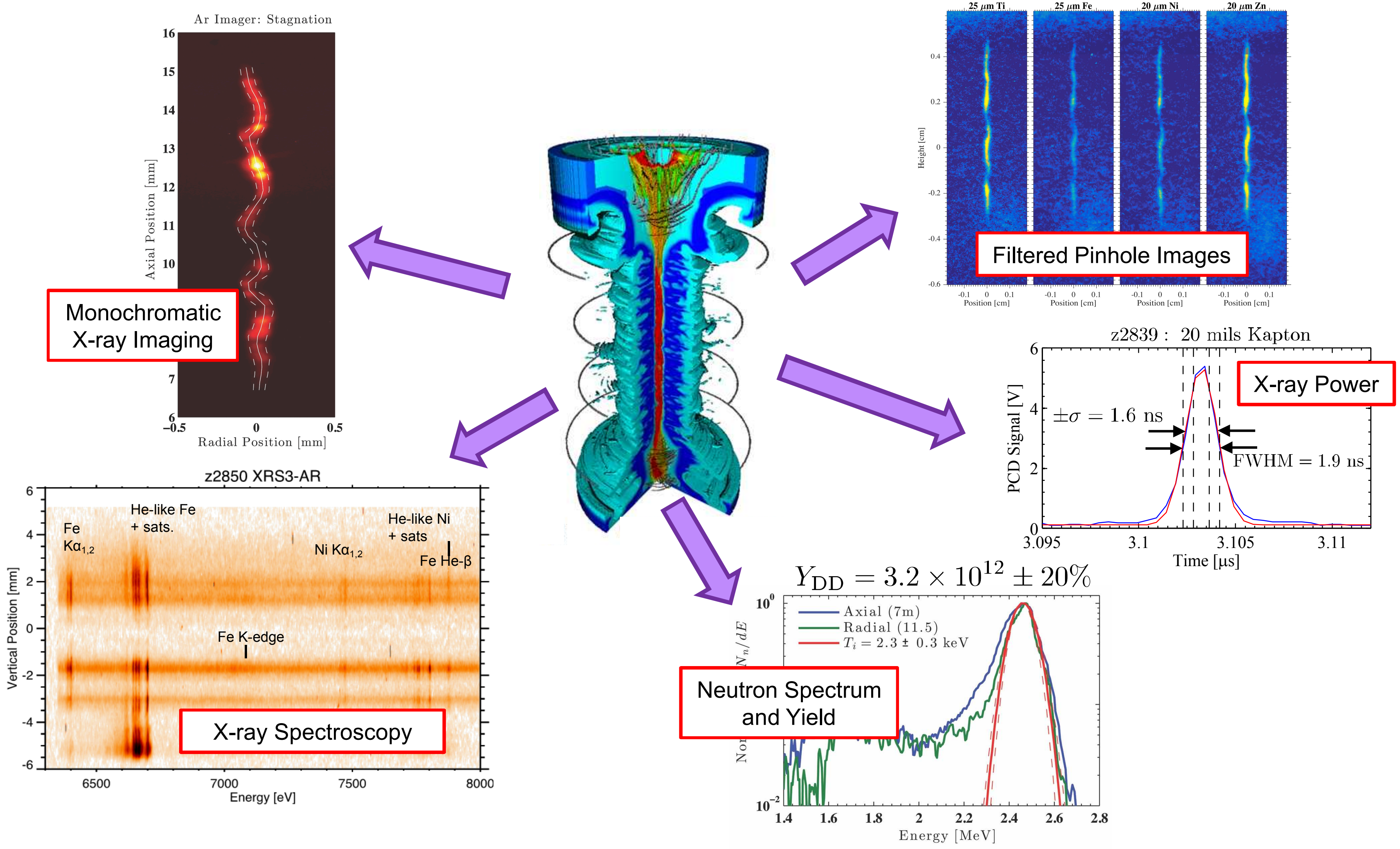
Implosion and Stagnation

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



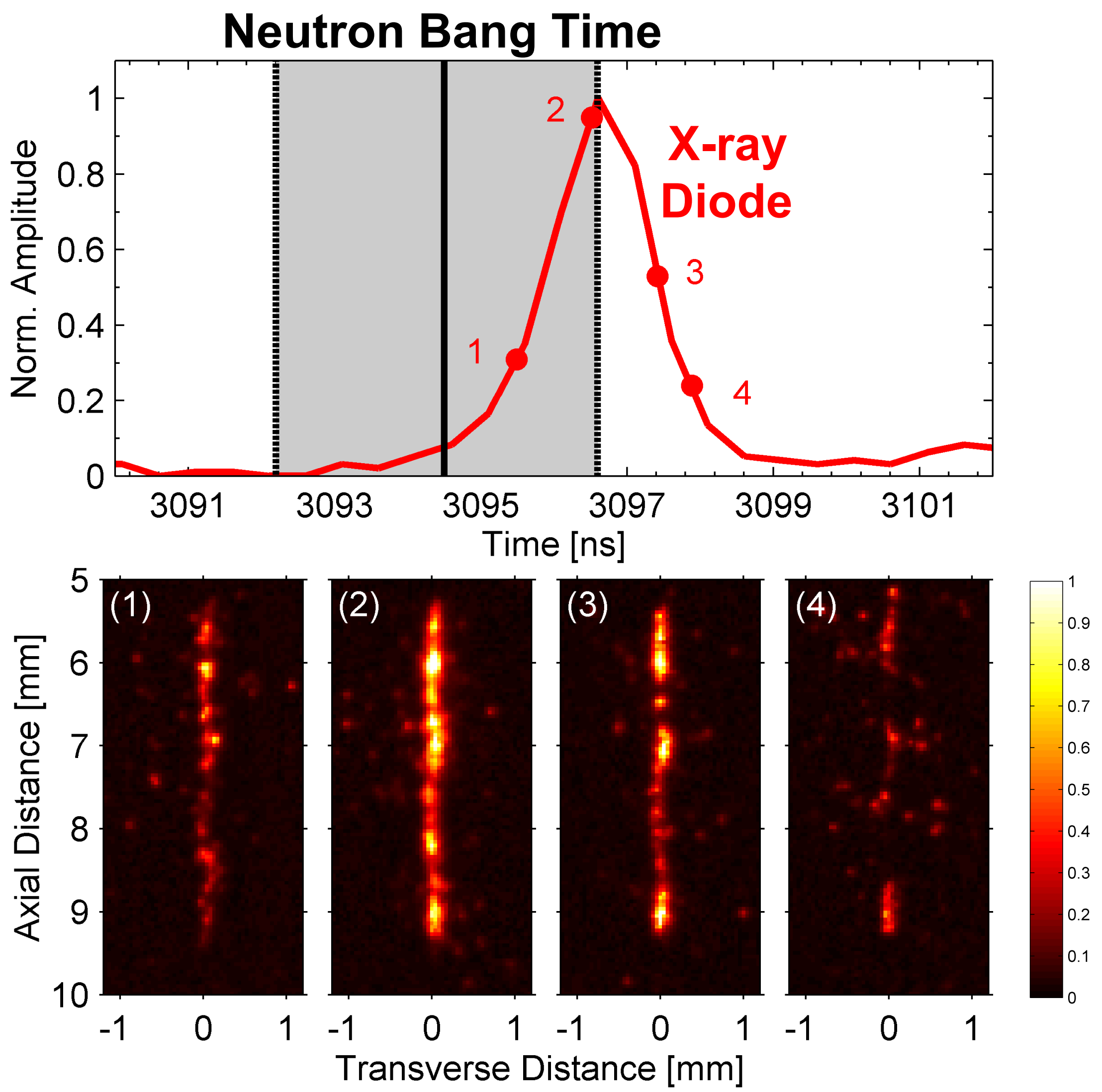
S. A. Slutz, *et al.*, Phys. Plasmas **17** 056303 (2010)
A.B. Sefkow, *et al.*, Phys. Plasmas, **21** 072711 (2014)

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

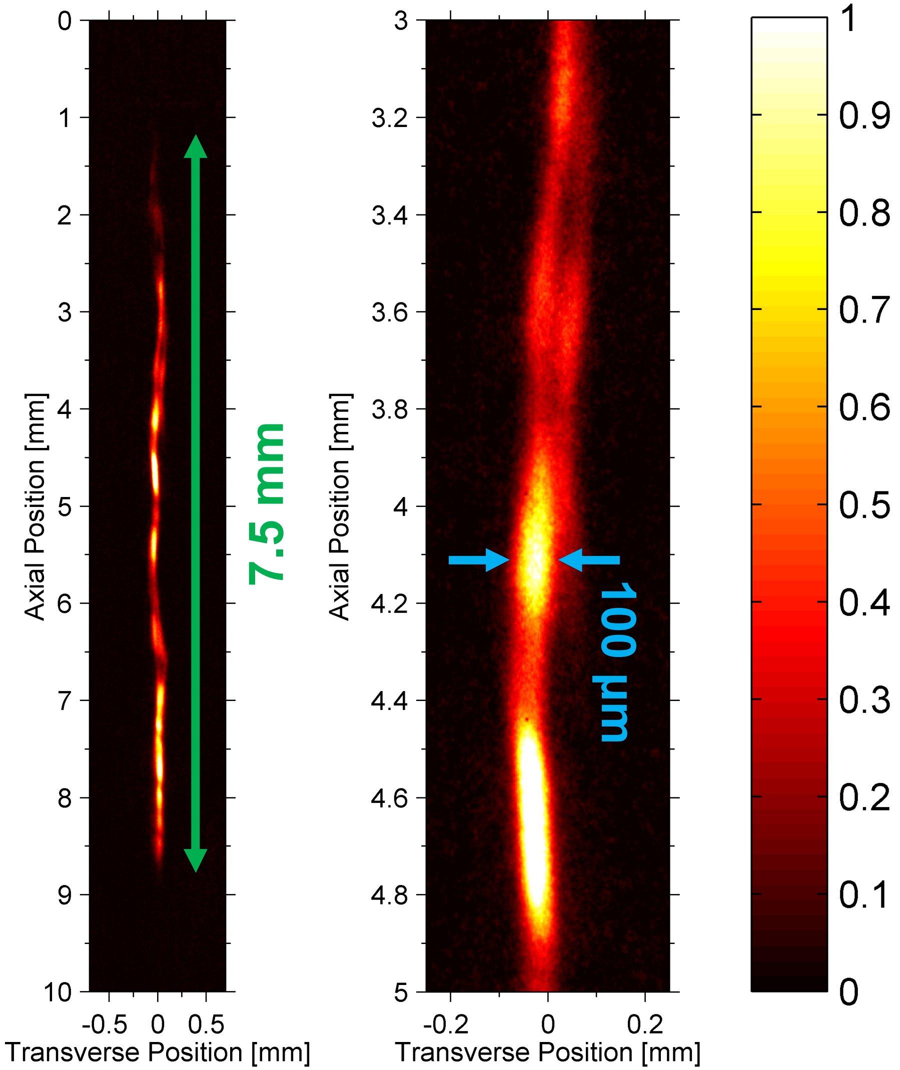
X-ray diodes and time-resolved x-ray pinhole images show the fuel radiating at stagnation



- 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).

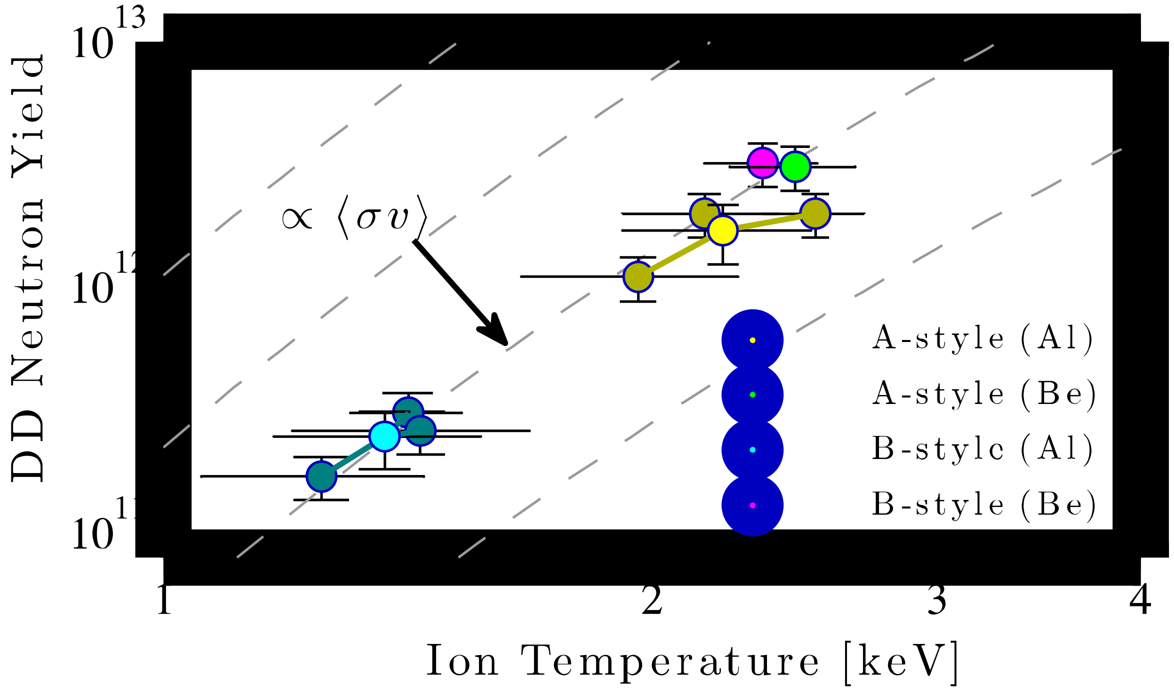
Our spherical crystal imaging system was repurposed to record x-ray emission from the fuel



- 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



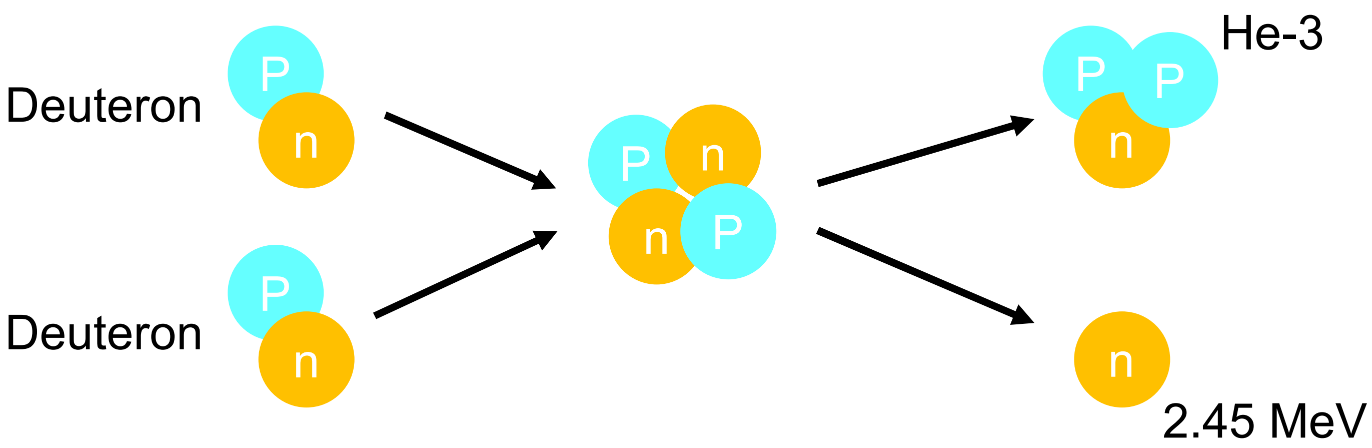
- Yield and ion temperature are related by the fusion reaction rate
- Experimental values roughly follow the trajectory of the fusion reaction rate
- This is expected for a thermonuclear plasma

Despite early success, there are a number of unknowns

- According to the models, we have a lot of room for improvement
  - Current best yield is 4×10^{12} DD neutrons
  - Think $>10^{14}$ DD neutrons in possible on Z
- What keeps *me* up at night?
  - Can we keep the fuel clean enough to stay hot?
  - Will instabilities shred the liner before it can compress the fuel?
  - Can we effectively heat the fuel with a laser?
  - Can we efficiently compress the magnetic field to the required strength?

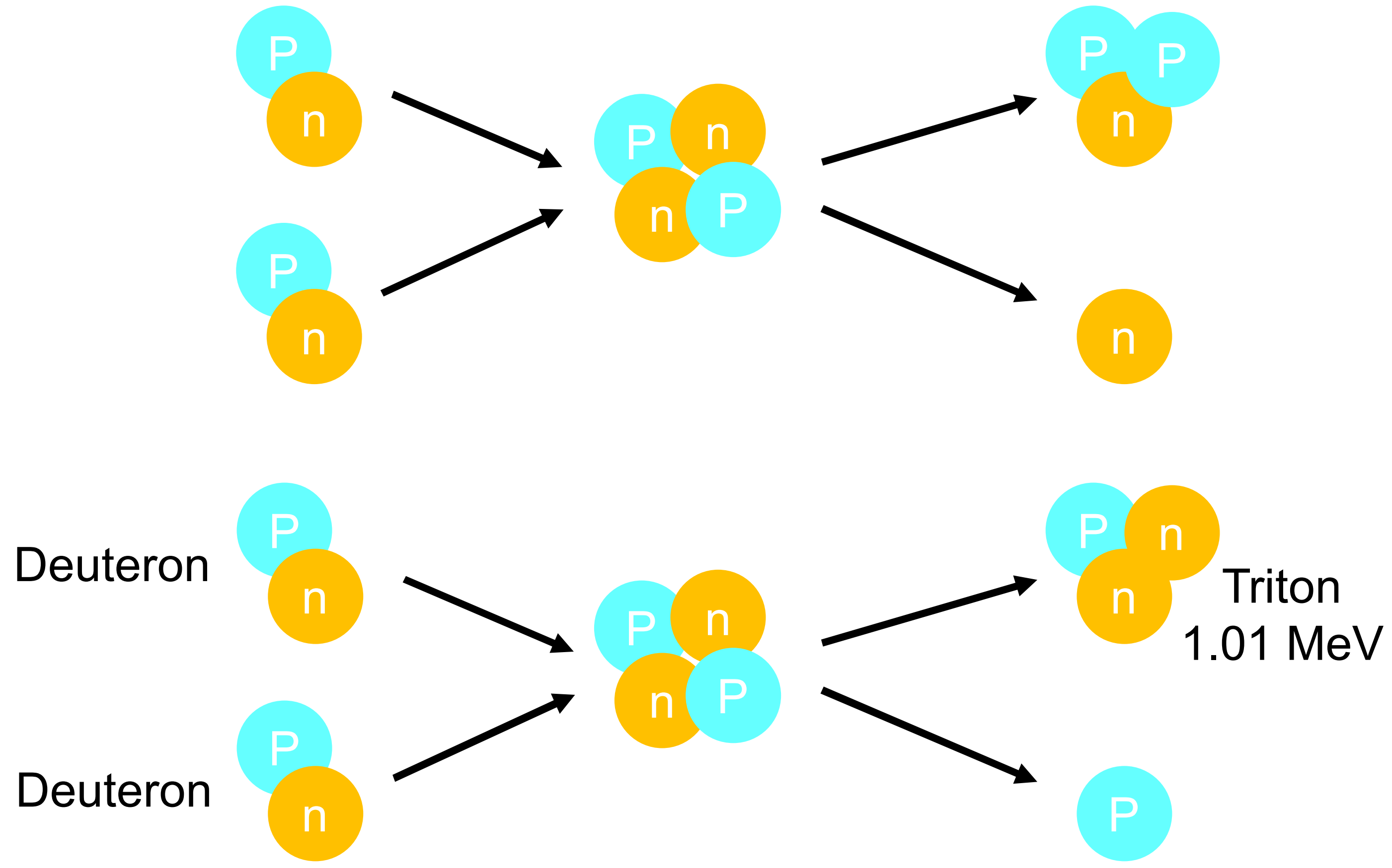
The fuel in these experiments is deuterium gas: one branch produces a neutron…

Primary Reactions

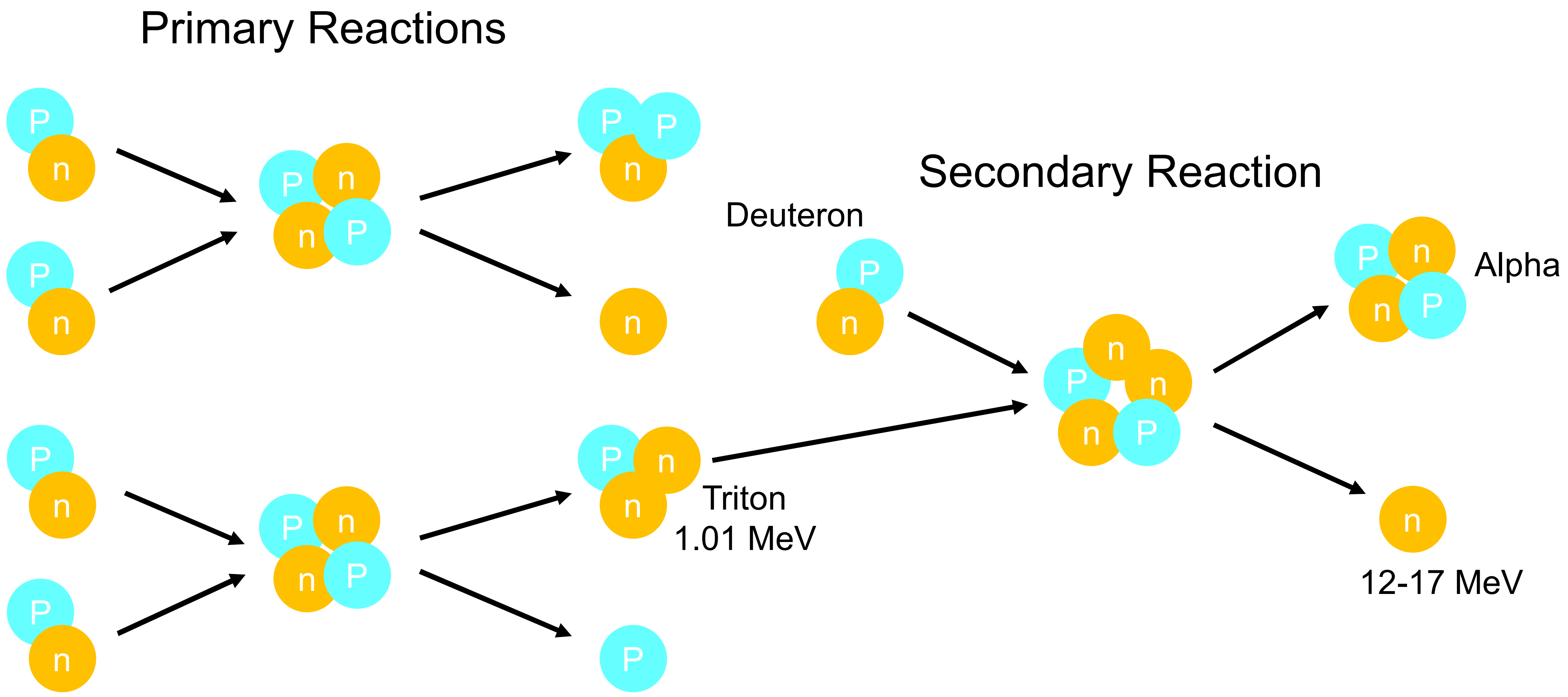


…and the other branch produces a triton…

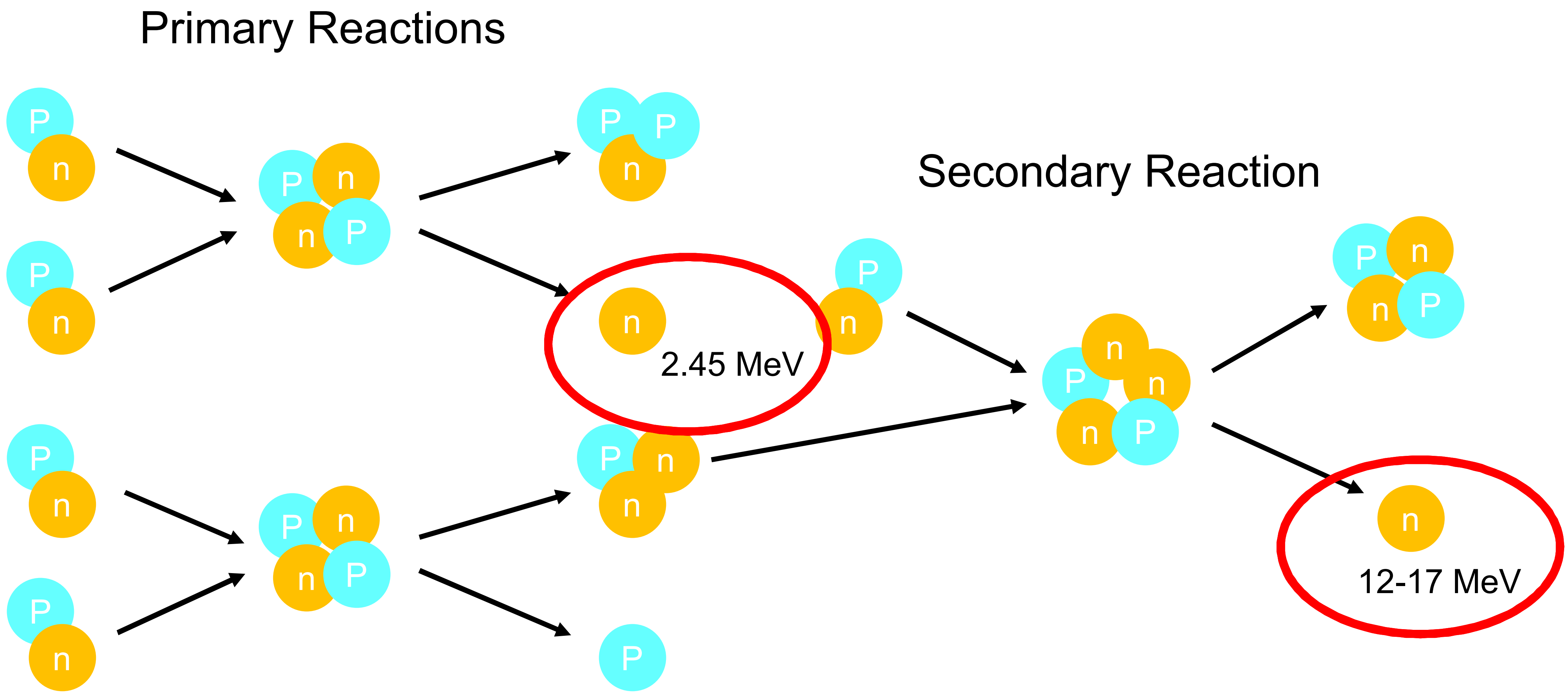
Primary Reactions



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



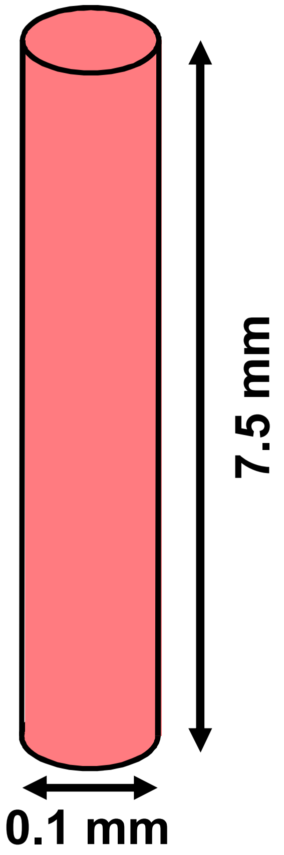
We measure both the primary and secondary neutrons



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

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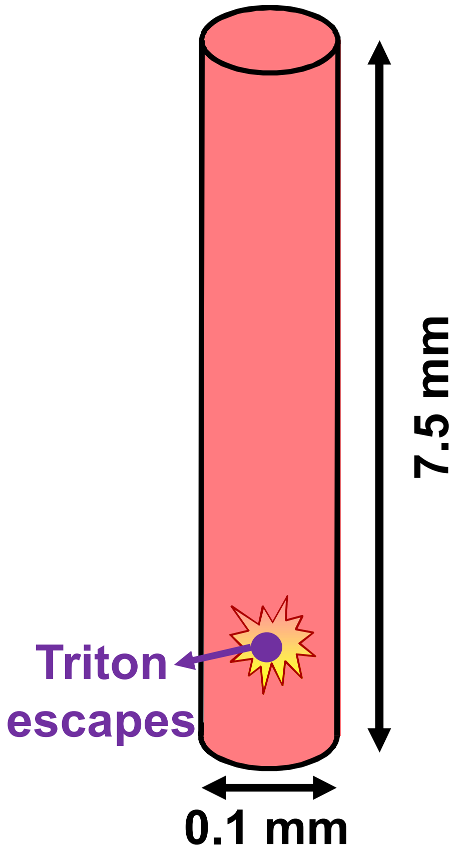
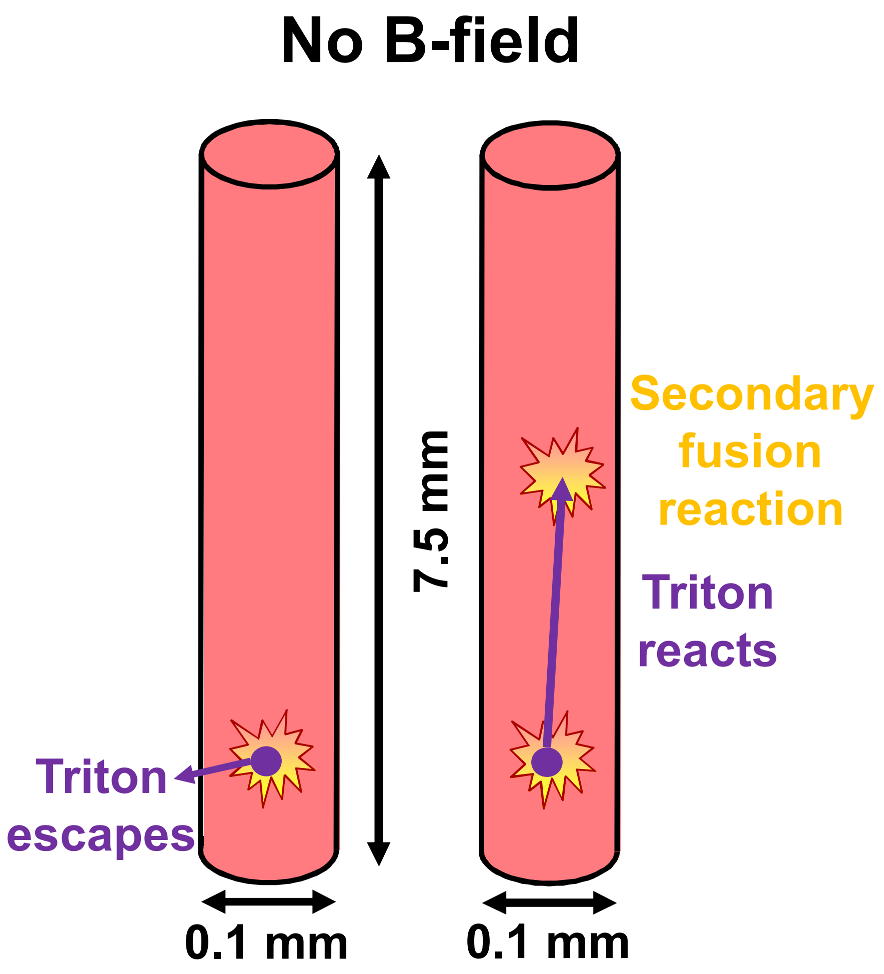


- High aspect ratio stagnation geometry
  - Height >> radius

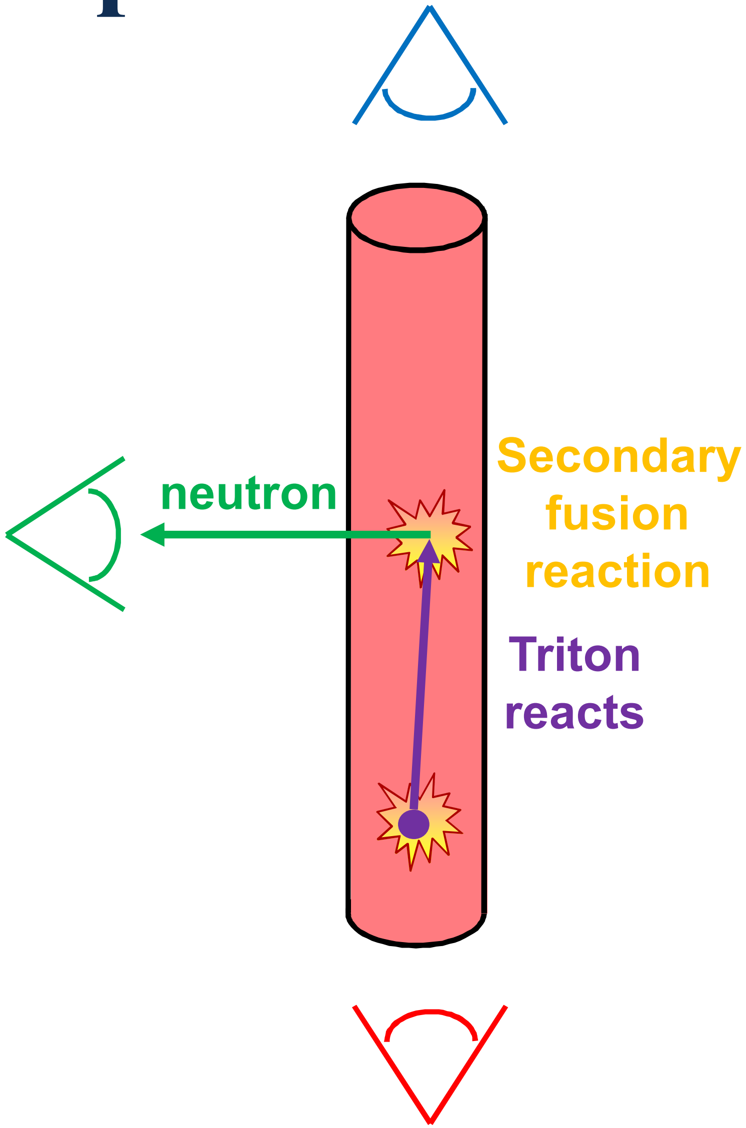
- Consider 2 cases:
  - 1) Triton is created traveling radially
    - Very little probability of interacting prior to escaping

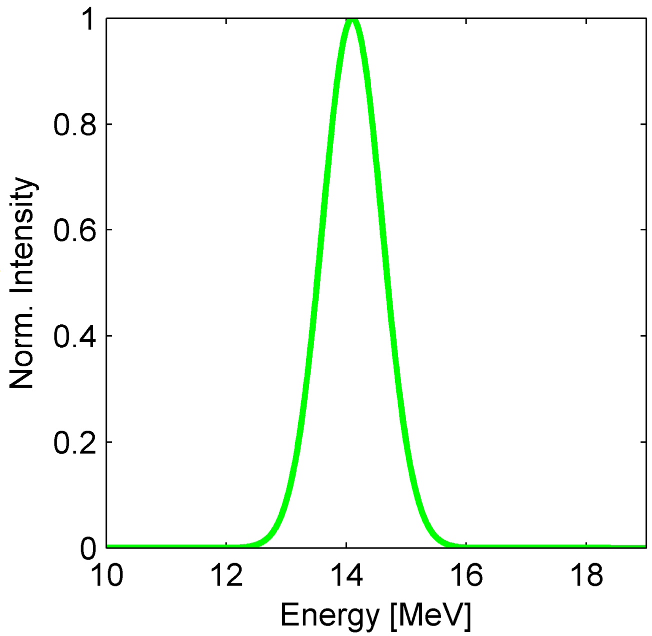
Secondary neutrons are produced when primary tritons react before exiting the fuel



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

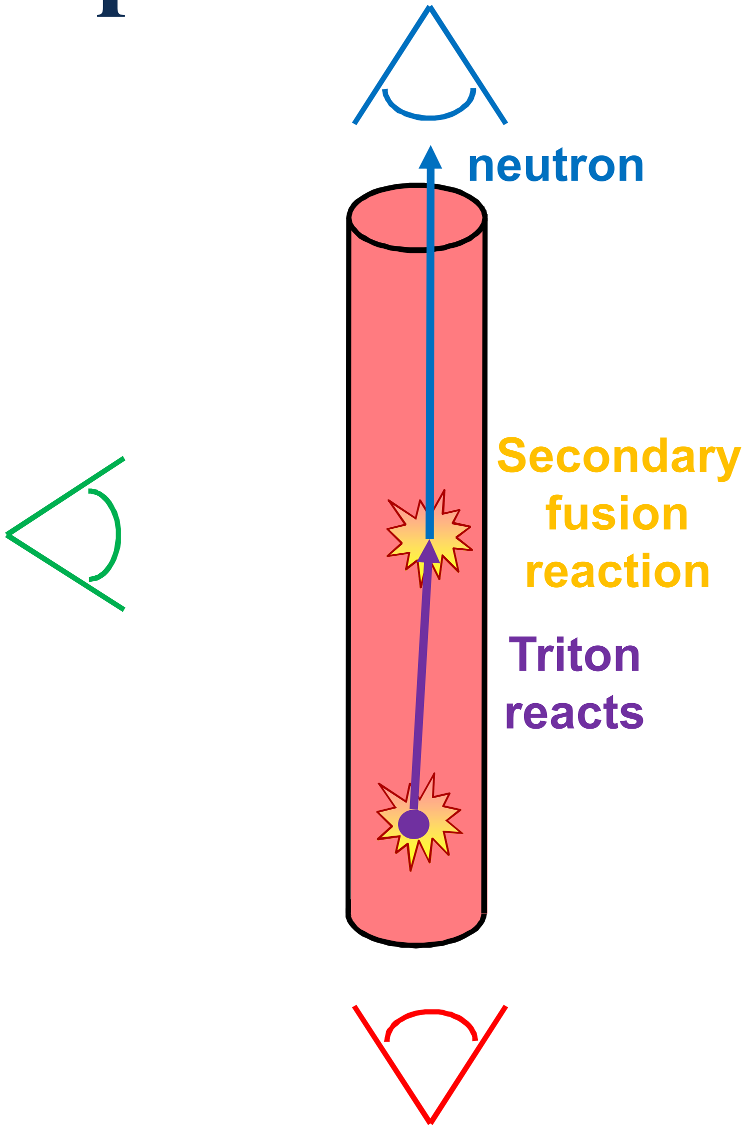
The secondary neutron energy spectra are not expected to be isotropic

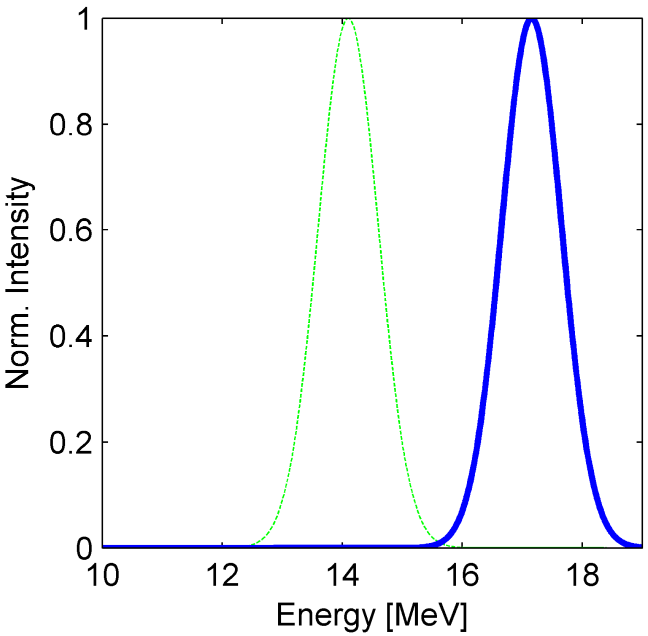




- Consider 3 detector locations:
  - Radial
    - Neutrons at nominal energy

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

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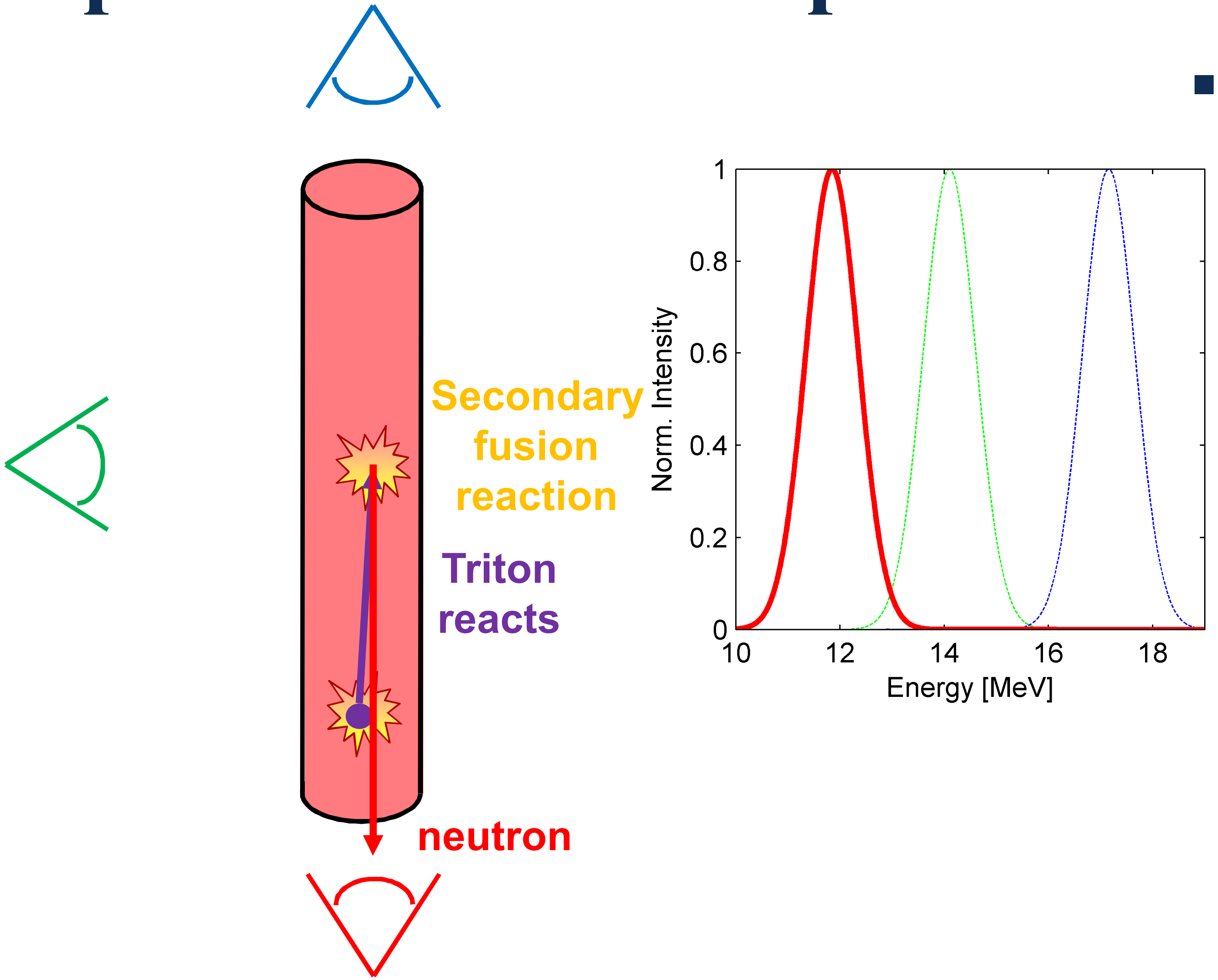

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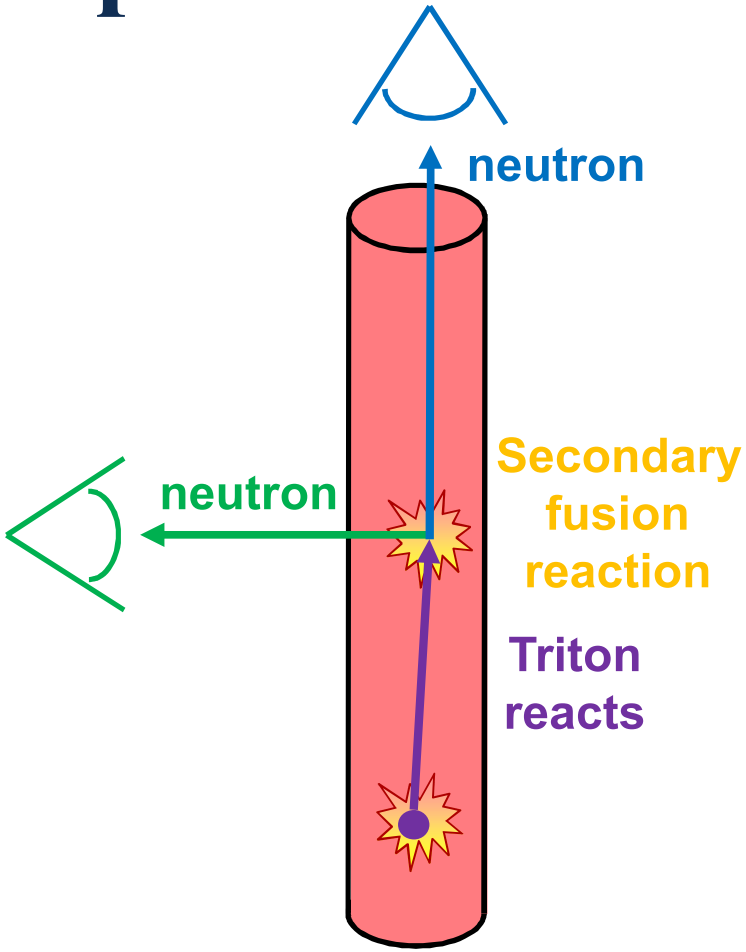
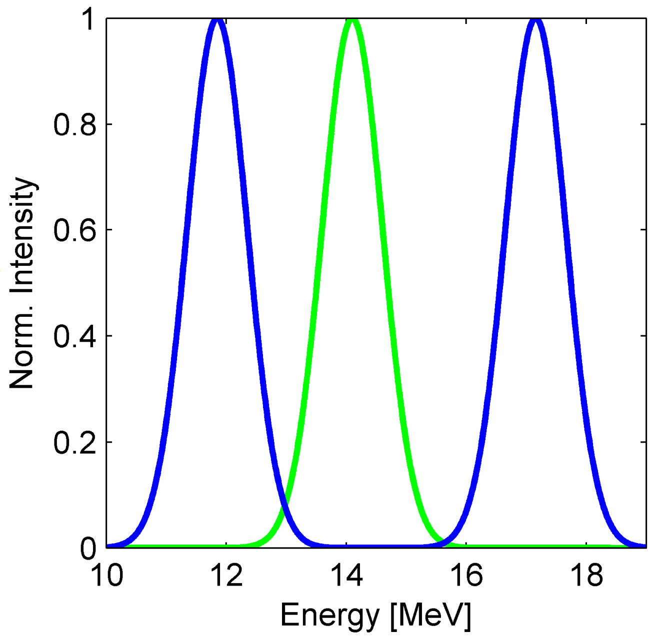
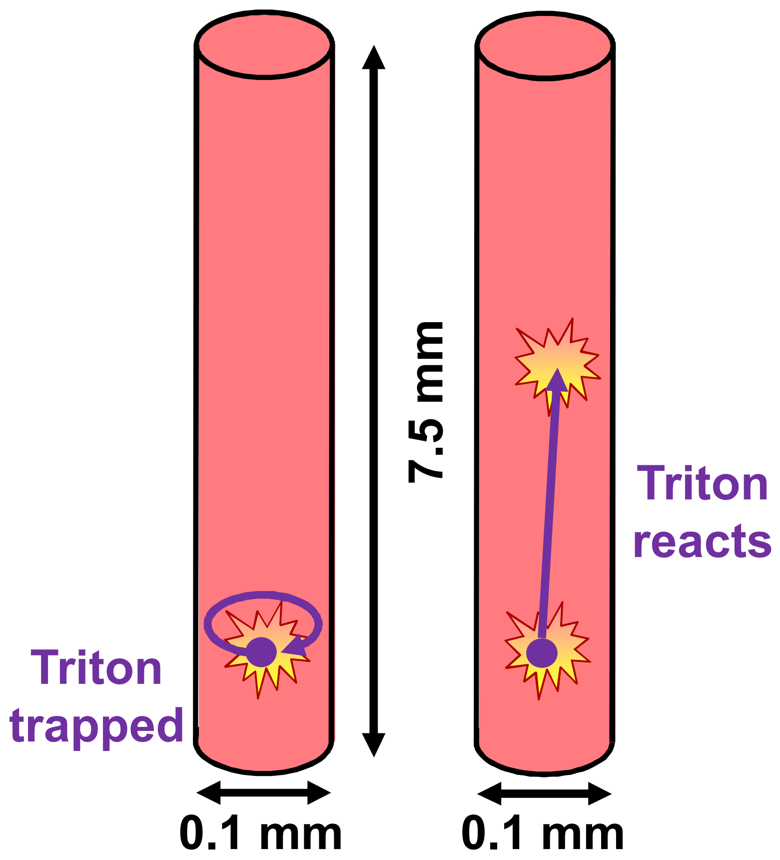




- Consider 3 detector locations:
  - Radial
    - Neutrons at nominal energy
  - Axial (triton moving towards)
    - Neutrons shifted to higher energy
  - Axial (triton moving away)
    - Neutrons shifted to lower energy
- Axial detectors will have double peaked structure

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

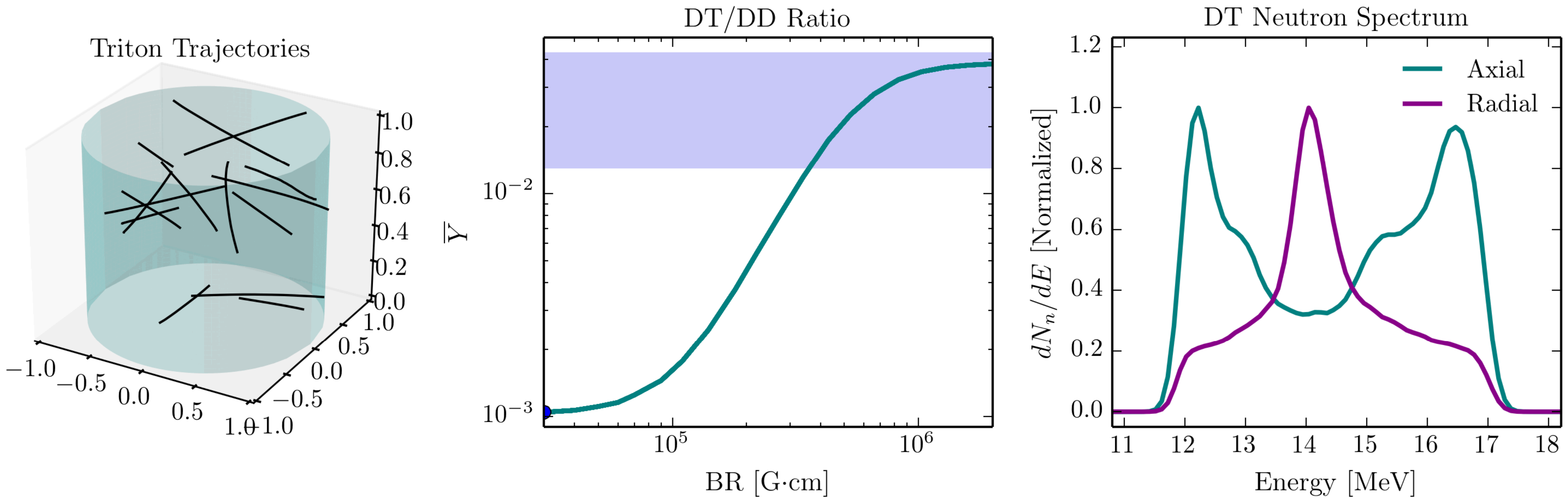
High B-field



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

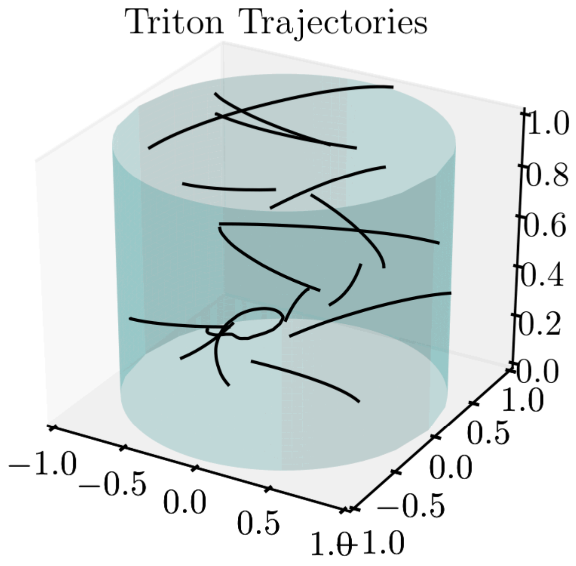
Magnetizing the tritons modifies their trajectories, imprinting on DT spectrum

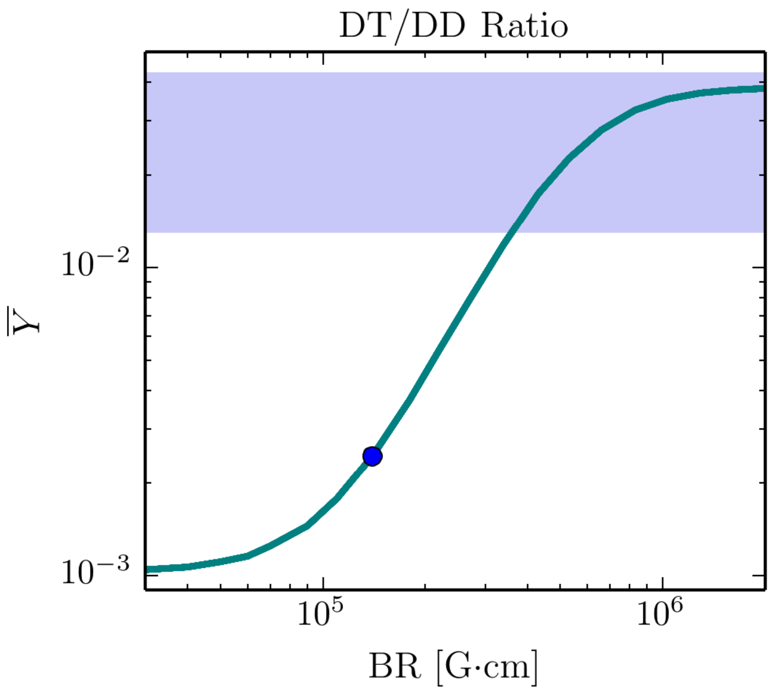


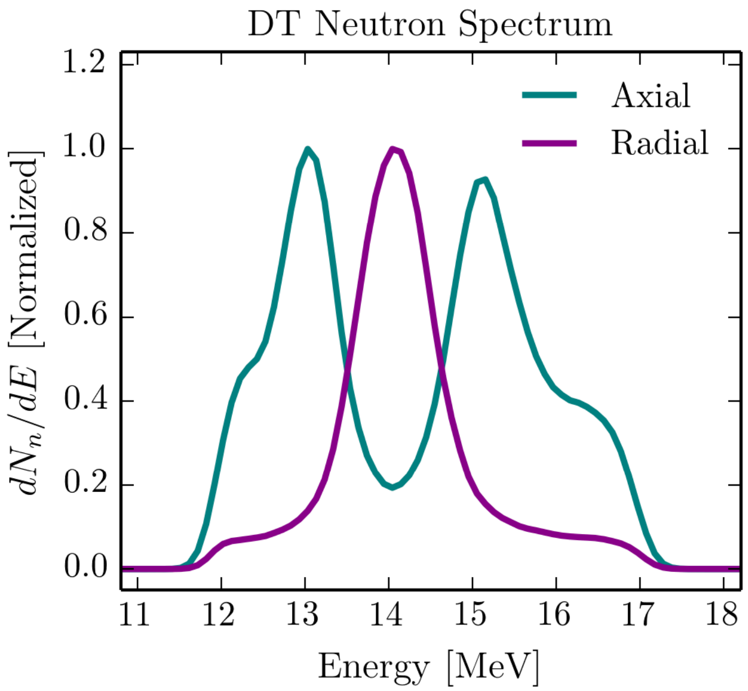
- Magnetization serves to:
  - Trap tritons
  - Direct them axially
  - Execute helical orbits
- Axial redirection forces tritons to see ρZ instead of ρR
  - ρZ = AR*ρR, AR>>1
  - broadens the velocity distribution of tritons that have a significant probability of reaction

At large *BR*, helical orbits induce Doppler splitting in the radial view

Magnetizing the tritons modifies their trajectories, imprinting on DT spectrum







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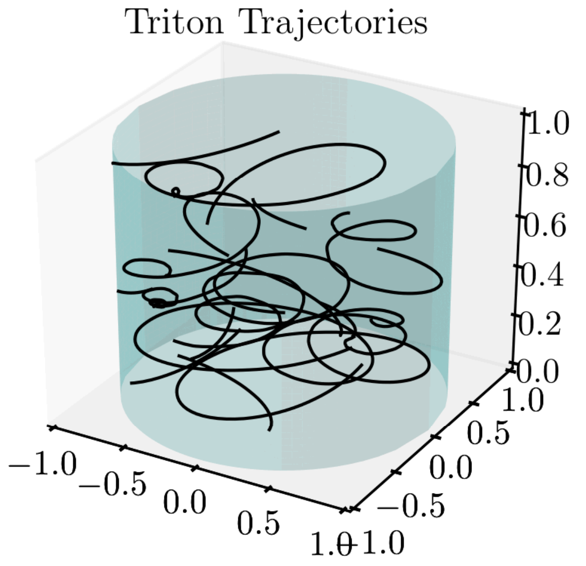

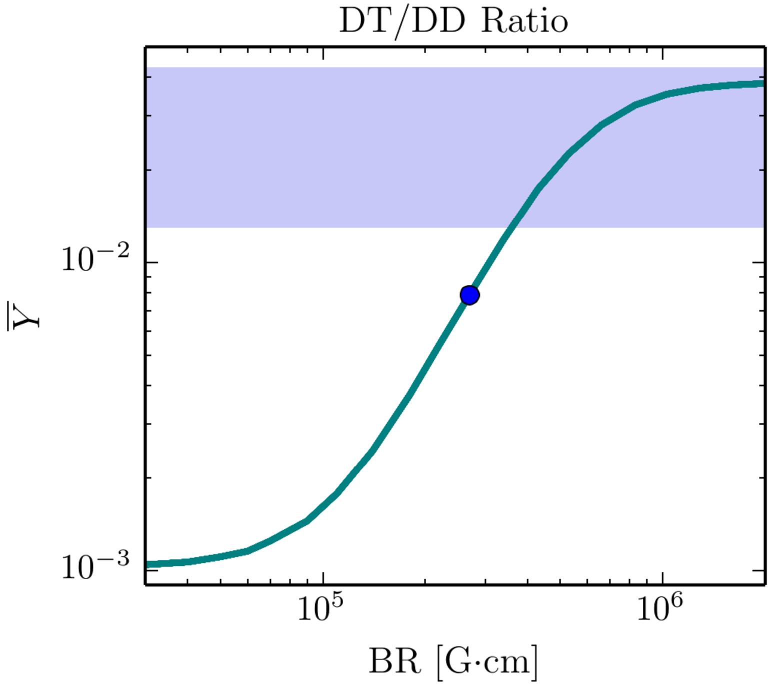

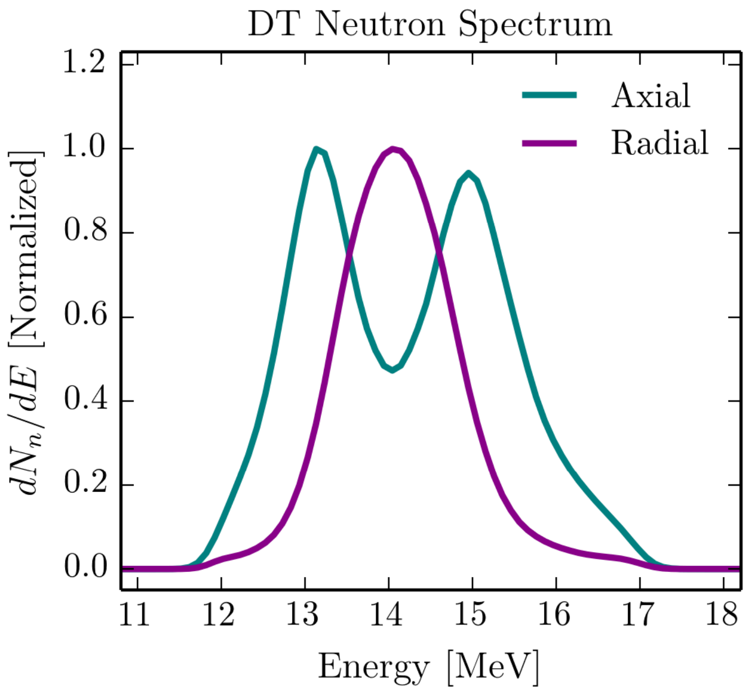

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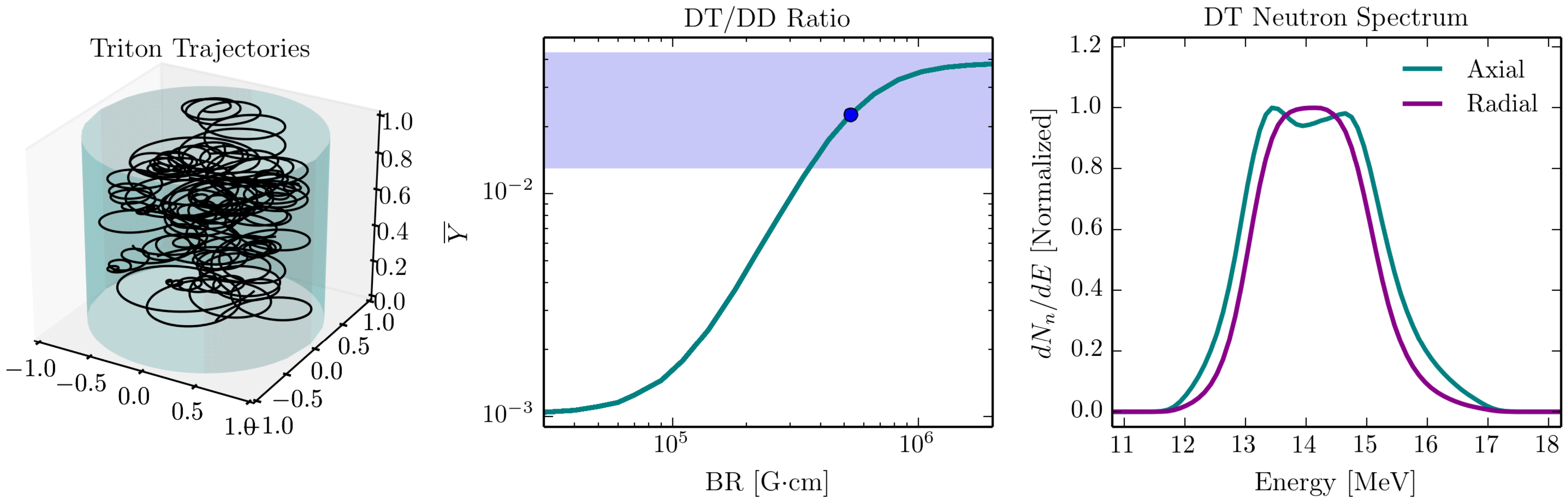

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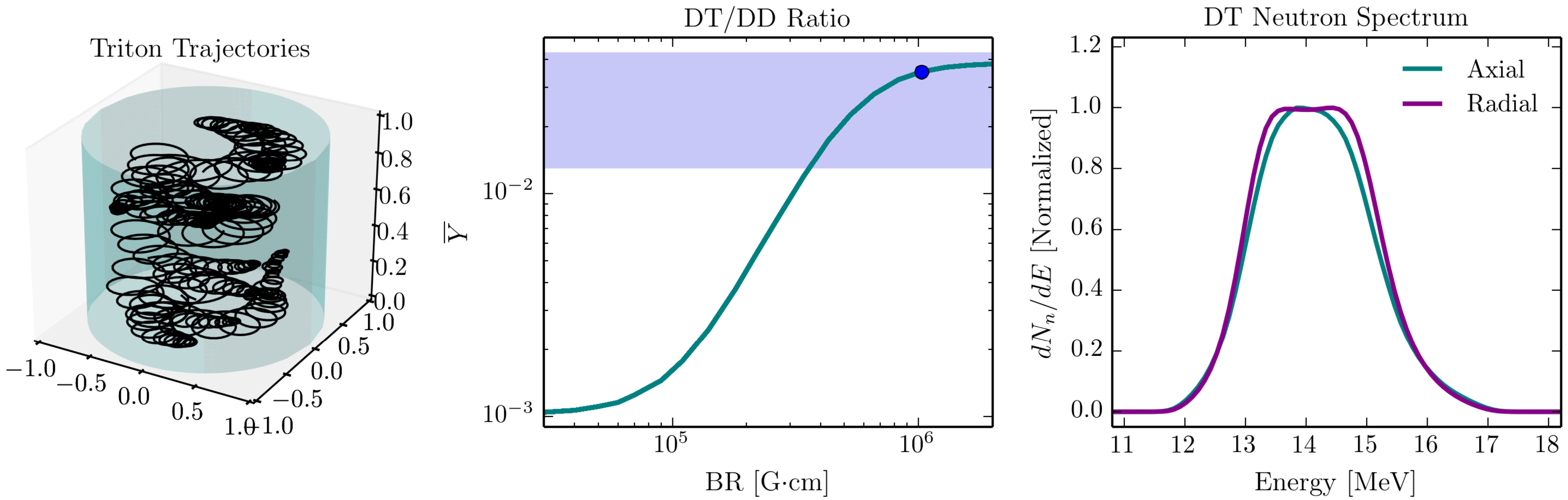

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DT Spectra are used in conjunction with measured DT/DD ratio to constrain the stagnation *BR*

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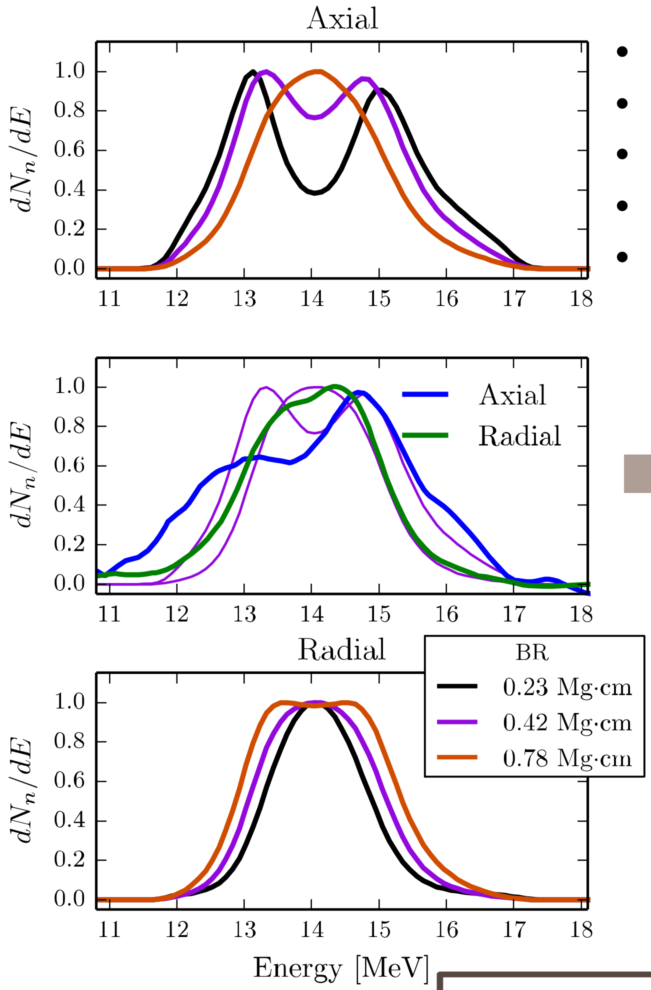
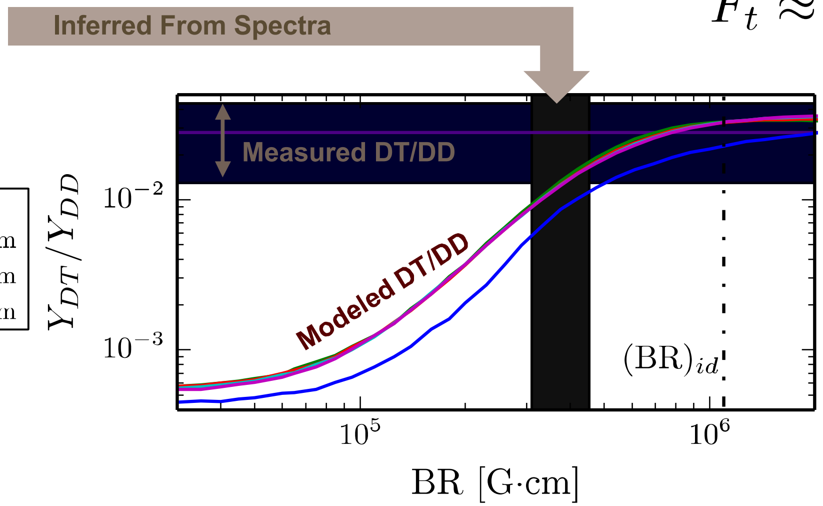


- $T_i \sim T_e$=3.1 keV
- ρ=0.5 g/cc
- R=50–100 µm
- ρR=2-5 mg/cm^2
- ρZ~0.3 g/cm^2

- 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

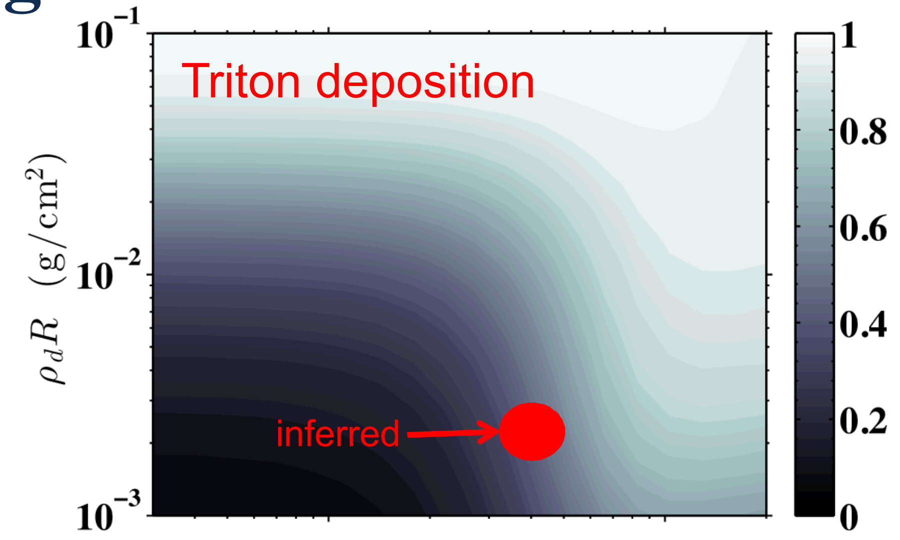
$$BR \sim 4 \times 10^5 G \cdot \mathrm{cm} \rightarrow \frac{R}{r_\alpha} \sim 1.5 - 2$$

$$r_\alpha \approx 1.07 r_t$$

- Magnetizing fast tritons implies electrons are magnetized as well

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

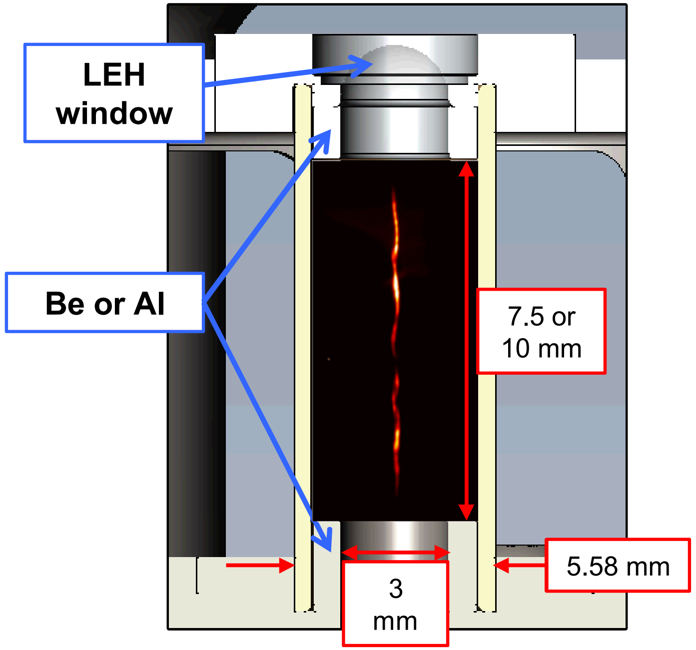
MagLIF works! We were able to compress flux, preheat the plasma and keep it hot and magnetize the burn products!

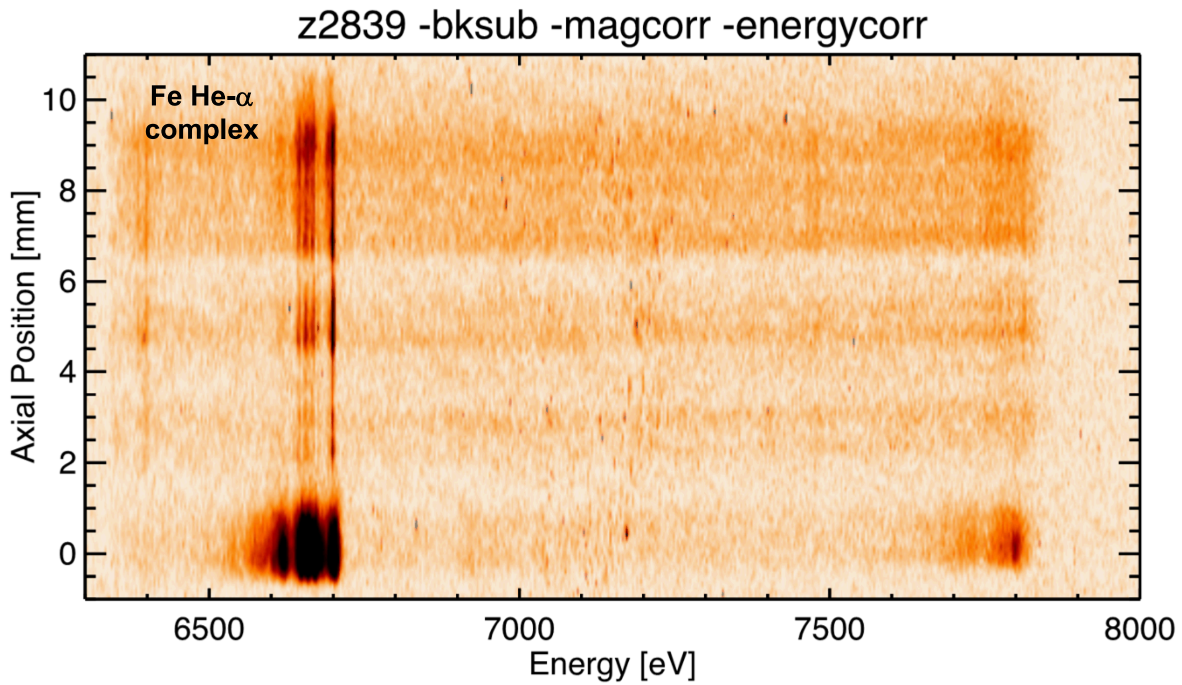


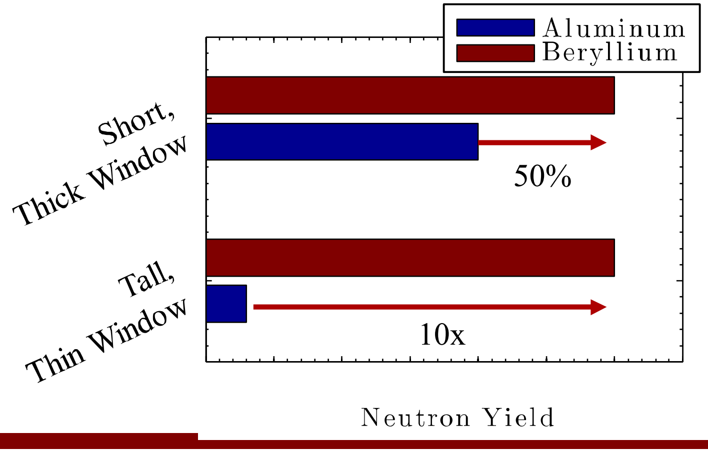
Alpha deposition

scaled

X-ray spectroscopy has allowed us to determine that "mix" is a significant limiting factor



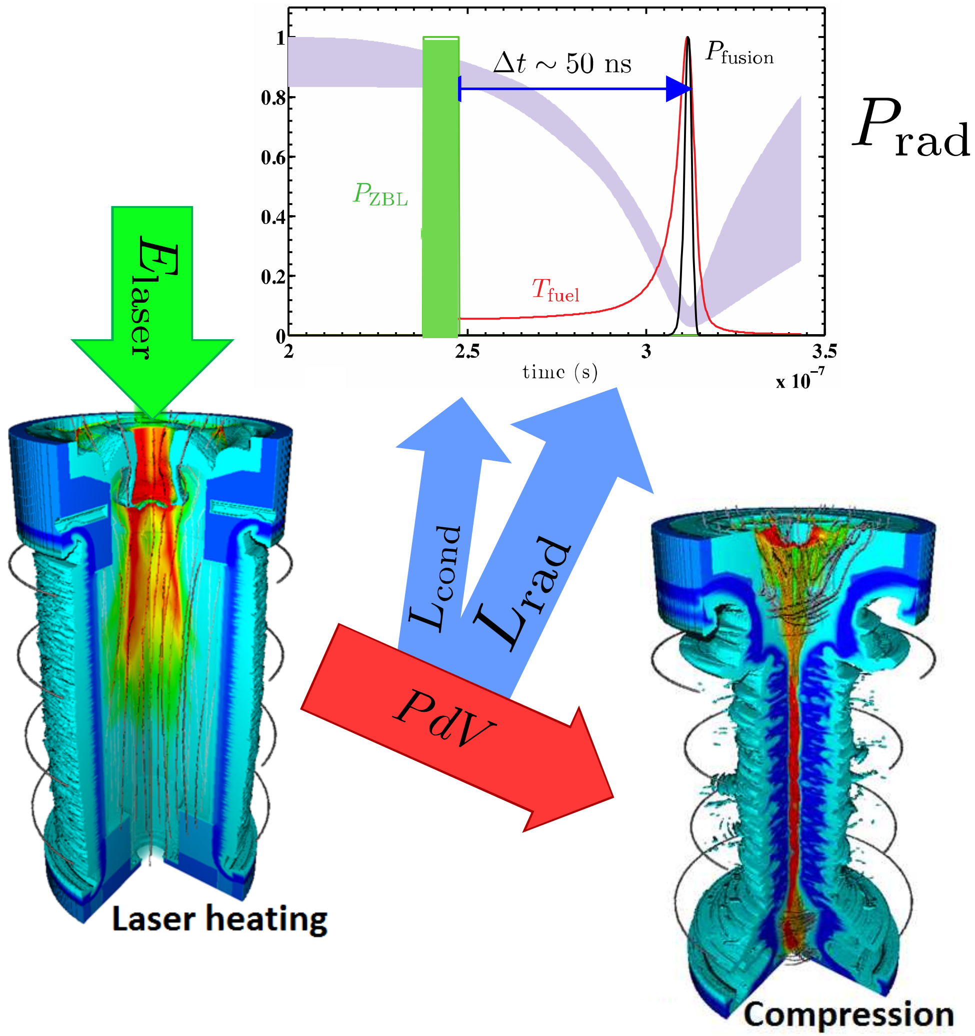




- Spherical crystal image shows a narrow plasma column (r=50µm) with a slight helical structure
- High spectral resolution, high sensitivity spectroscopy shows us Fe impurities mixed into the fuel
- This allows us to determine T_e=1.5-2 keV, n_e=1e23 cm^{-3} and f_{mix}=0.5-1%
- Mix from Be is at a significant, but manageable level

E.C. Harding et al., Rev. Sci. Inst. 86, 043504 (2015)

Mix degrades performance by enhancing losses due to radiation

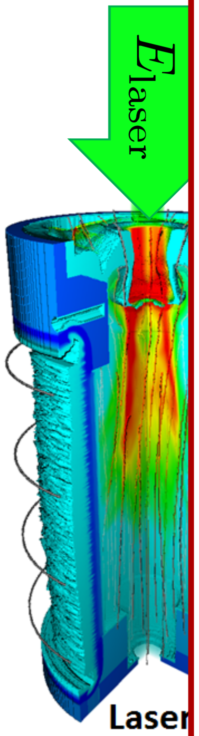


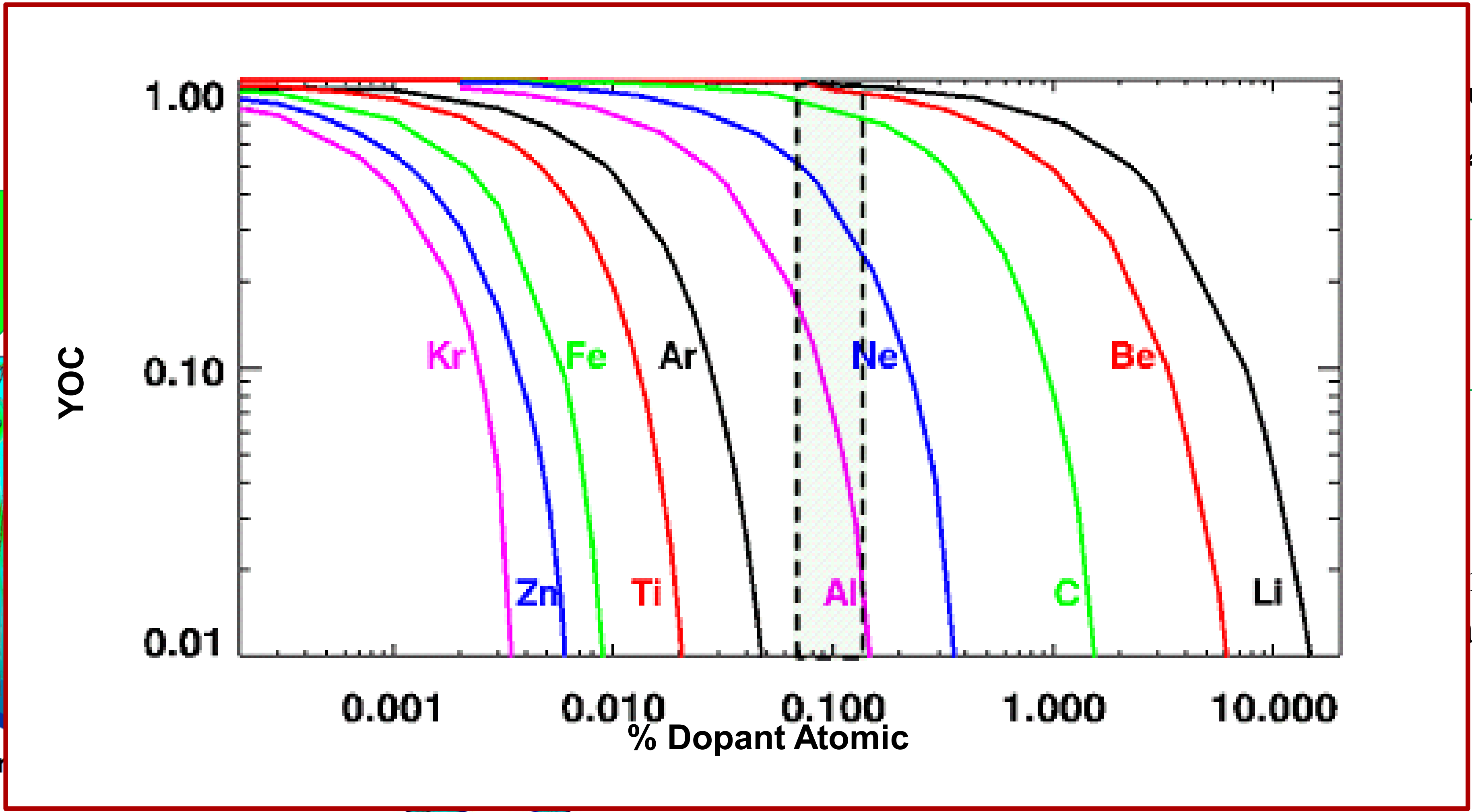
$$P_{\rm rad} = A_{f-f} 2V \square \int_0^1 \tilde{r} d\tilde{r} \frac{g_{\rm FF}\langle Z \rangle}{(1+\langle Z \rangle)^2} \sum_i \square \frac{e^{-h\nu/T}}{T^{5/2}}$$

$$\tilde{j}_i \equiv \frac{j_i}{j_{\rm D}} = \square + \frac{A_{f-b} \square}{A_{f-f}\ T} e^{RyZ_i^2/T}$$

- f is the mix fraction
- Z is the charge of the mix species
- If contaminants get into the hot spot early, they have a long time to radiate heat away before stagnation
- The radiated power increases like P^2
- Pressure increases like $(r/r_o)^{2\frac{5}{3}}$

Mix degrades performance by enhancing losses due to radiation





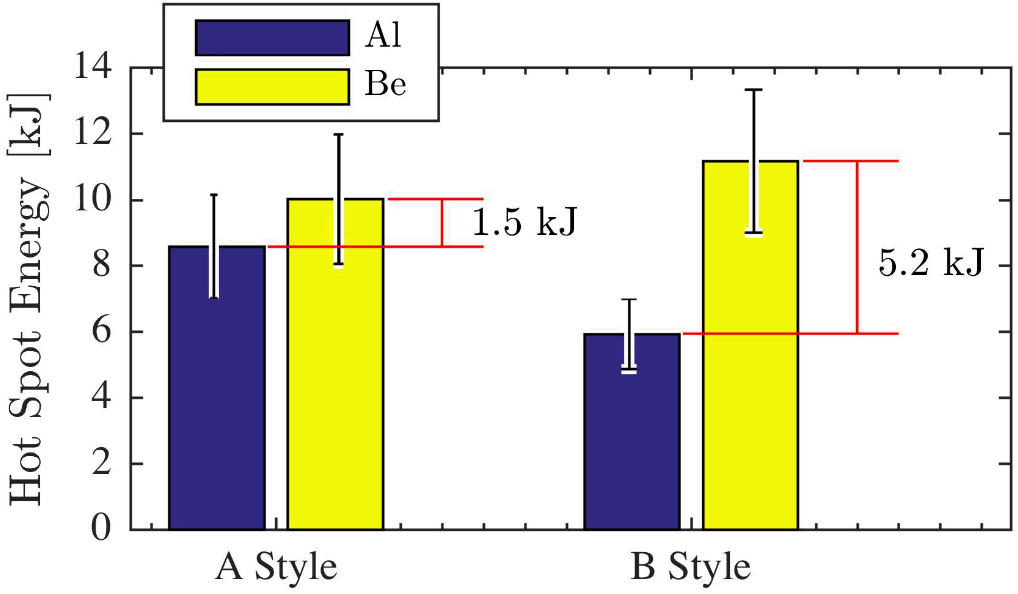
$$\sum_i \quad \frac{e^{-h\nu/T}}{T^{5/2}}$$

$$e^{RyZ_i^2/T}$$

rly, they have a long
tion

Looking at the hot spot energy shows that we lose a significant amount of energy to mix

$$^{*}E_{\mathrm{HS}} = \frac{3}{2} P_{\mathrm{HS}} V = \frac{3}{2}(\langle Z \rangle + 1)\sqrt{\frac{Y_{\mathrm{DD}} V}{\tau \int_0^1 \tilde{r} d\tilde{r} \langle \sigma v \rangle_{\mathrm{DD}} / T^2}}$$



Lose up to ~50% of our energy to mix!!
More when considering window mix as well

Magnetic insulation

$$E_{\mathrm{HS}} = E_{\mathrm{las}} + PdV - E_{\mathrm{rad}} - E_{\mathrm{cond}} \rightarrow 0$$

For same style targets:

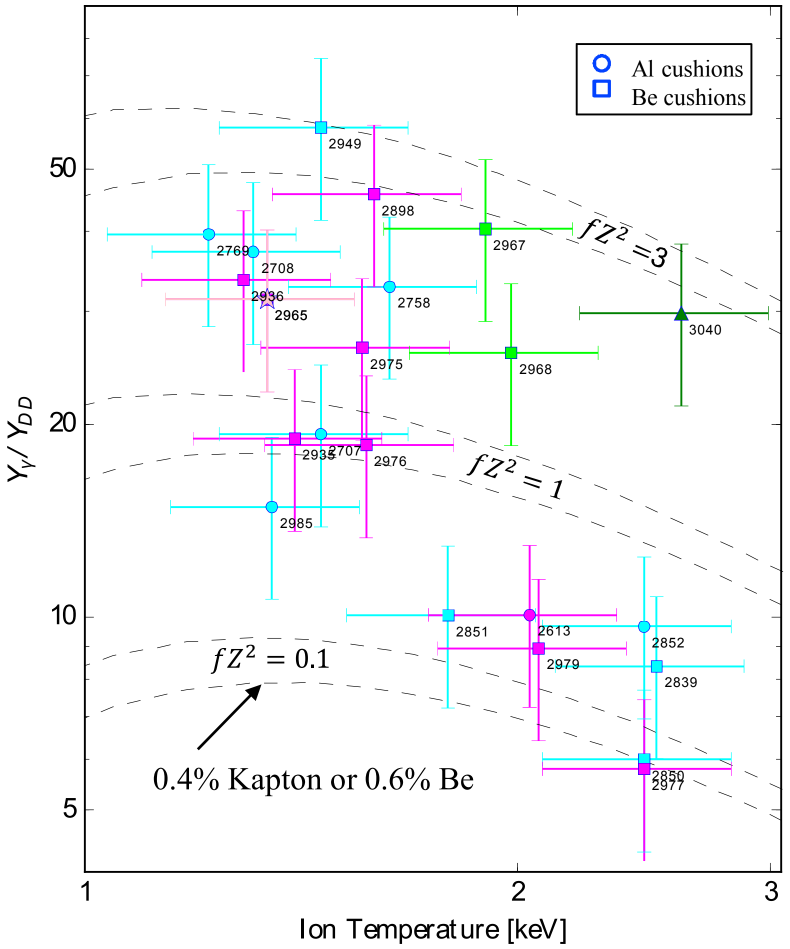
$$E_{\mathrm{las}} \rightarrow \mathrm{Const.}$$
$$PdV \rightarrow \mathrm{Const.}$$

The difference between inferred E_{HS} for like-targets is due entirely to the different radiative properties of Al and Be

$$\Delta E_{\mathrm{HS}} = \Delta E_{\mathrm{rad}} = E_{\mathrm{rad}}^{\mathrm{Al}} - E_{\mathrm{rad}}^{\mathrm{Be}}$$

*S. P. Regan et al. Phys. Rev. Lett. **117**, 025001

Looking at the ensemble of data, we are able to see some trends and some potential avenues for improvement



$$\frac{Y_\gamma}{Y_{\rm DD}} \propto \int_0^\infty \mathcal{F}_{\rm Tx}(h\nu) e^{-\tau_\nu^\ell} \langle Z \rangle \frac{e^{-h\nu/T}}{\langle \sigma v \rangle} \sum f_i \frac{j_i}{j_{\rm D}} \frac{dh\nu}{\sqrt{h\nu}}$$

$$\frac{j_i}{j_{\rm D}} = Z_i^2 + \frac{A_{f-b}}{A_{f-f}} \frac{Z_i^4}{T} e^{Ry Z_i^2/T}$$

- Attempts to increase the amount of laser energy coupled to the gas have led to signatures of higher mix
- Replacing Al fuel-facing components with Be improves performance
- Coupling more current to the load tends to improve neutron yield and temperature

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
- We have many improvements to make
  - We must solve the mix problem
  - Couple more laser energy into the fuel, without generating more mix
- There is a lot of room for improvement in diagnostics and analysis
  - Interpreting neutron diagnostics on Z is extremely challenging
- We have a ton of work to do and not enough people to do it!

Fusion energy is a worthy goal, but it is a long ways away. There are other exciting things we can do with large laboratory fusion yields

- Excited state nuclear physics
  - Multi-neutron reactions are possible with high enough neutron flux
- The astrophysical r-process may be within reach
  - The theorized process that allows high atomic number elements to be created in supernovae
- We can study other fusion reactions, particularly those of importance to stellar energy balance and evolution (^{3}He-^{3}He and the p-p cycle, parts of the CNO cycle, etc.)
- Neutron and photon fluxes similar to those present in stellar cores can be created
- Behavior of materials under intense neutron and x-ray radiation
  - Important for fusion reactor development and space travel

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

Sandia National Laboratories

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