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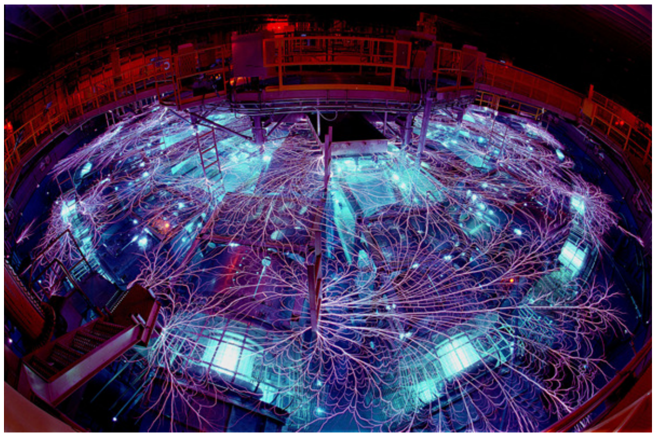

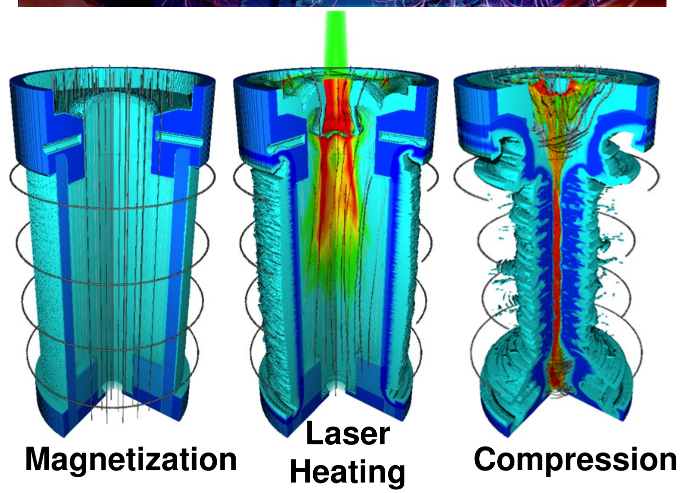


# Analysis of Magnetized Liner Inertial Fusion (MagLIF) experiments on Z

Stephanie Hansen
for the MagLIF team

*Sandia National Laboratories*

*Radiative Properties of Hot Dense Matter*
*Vienna, Austria*
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U.S. DEPARTMENT OF ENERGY

NNSA National Nuclear Security Administration

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# Summary: Magnetized Liner Inertial Fusion (MagLIF) appears to be a promising ICF platform

- Magnetized Liner Inertial Fusion (MagLIF) relaxes the pressure requirements for ignition by imposing an external magnetic field that reduces heat losses and confines charged particles
- Initial integrated experiments have produced $>10^{12}$ DD neutron yields and large secondary DT yields indicating highly effective magnetic confinement
- Focused experiments are helping to increase our fundamental understanding of stability, heating, compression, and confinement
- Spectroscopic analysis of preheat and stagnation plasmas are helping to constrain the simulation tools used for target design
- Future experiments will help us understand initial conditions, platform stability, mix, and scaling

# Many people are contributing to our Magnetized Liner Inertial Fusion (MagLIF) effort:

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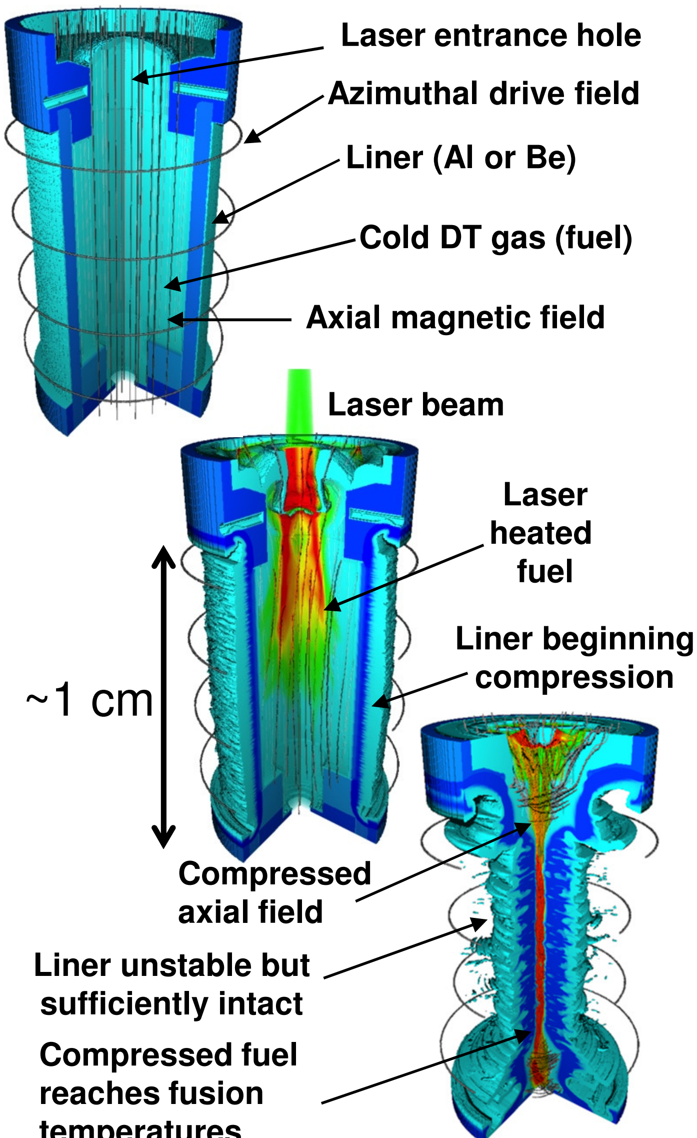
*General Atomics, San Diego, CA 92186 USA*

# We are evaluating a Magnetized Liner Inertial Fusion (MagLIF) concept that may reduce fusion requirements

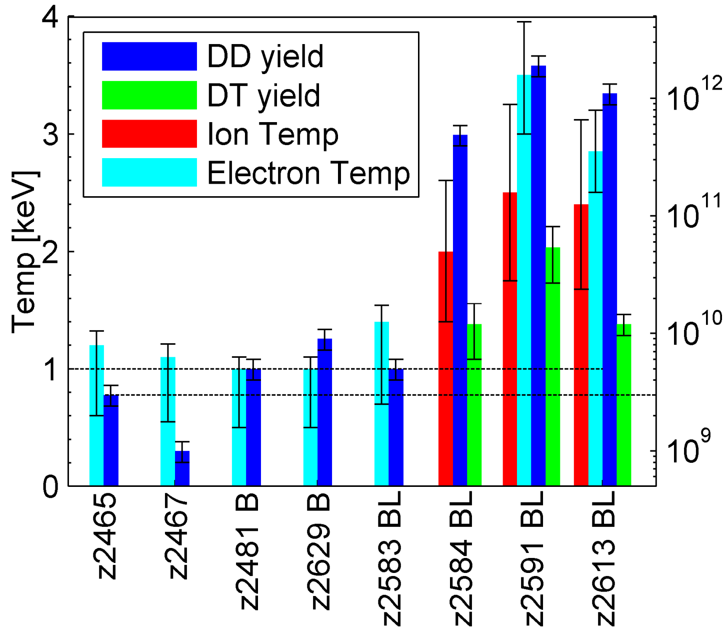


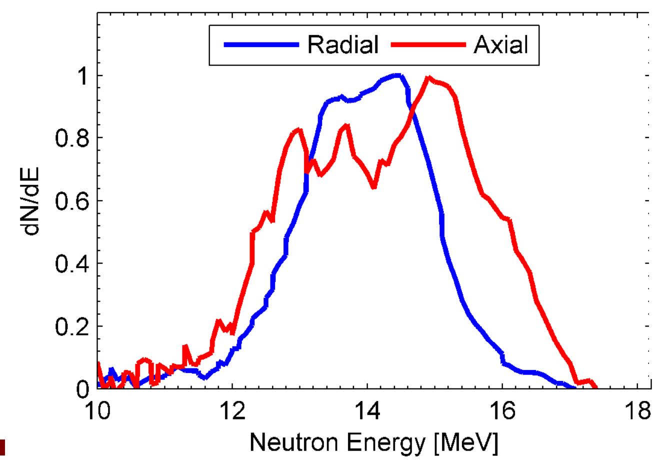

- An applied initial 10-30 T axial magnetic inhibits thermal conduction losses and appears to stabilize implosion at late times
- 30 ns before the implosion begins, the fuel is preheated using 2-6 kJ from the Z-Beamlet laser. Preheating reduces required compression and implosion velocities, increasing stability
- Z's 20 MA current efficiently drives a ~100 km/s implosion, delivering ~1% (100 kJ) of the 10 MJ stored in its capacitor banks *to the fuel*
- Each of these components must be present for the concept to work, and they work together to reduce the stagnation pressure requirement to ~5 Gbar from the ~500 Gbar of traditional ICF
- DD equivalent of 100 kJ DT yield may be possible on Z in the next few years, requiring upgrades that are in progress:
  10 T → 30 T; 2 kJ → >6 kJ; 19 MA → >24 MA

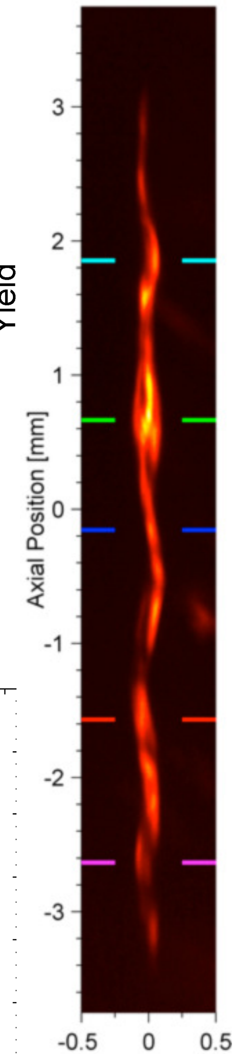
*S.A. Slutz *et al.*, Phys. Plasmas 17, 056303 (2010). S.A. Slutz and R.A. Vesey, Phys. Rev. Lett. (2012).

# We obtained promising initial results with MagLIF and are seeking to increase our understanding

- We achieved DD yields up to 2e12 (~0.3 kJ DT equivalent) in our first integrated tests of MagLIF
- Extensive neutron and x-ray data indicate a <150 μm diameter, ~3 keV, ~0.4 g/cm$^3$, highly magnetized plasma
- We are continuing to build on these results with a balanced combination of focused and integrated experiments
- In parallel, we are improving capabilities to understand how this performance will scale with increasing drive parameters



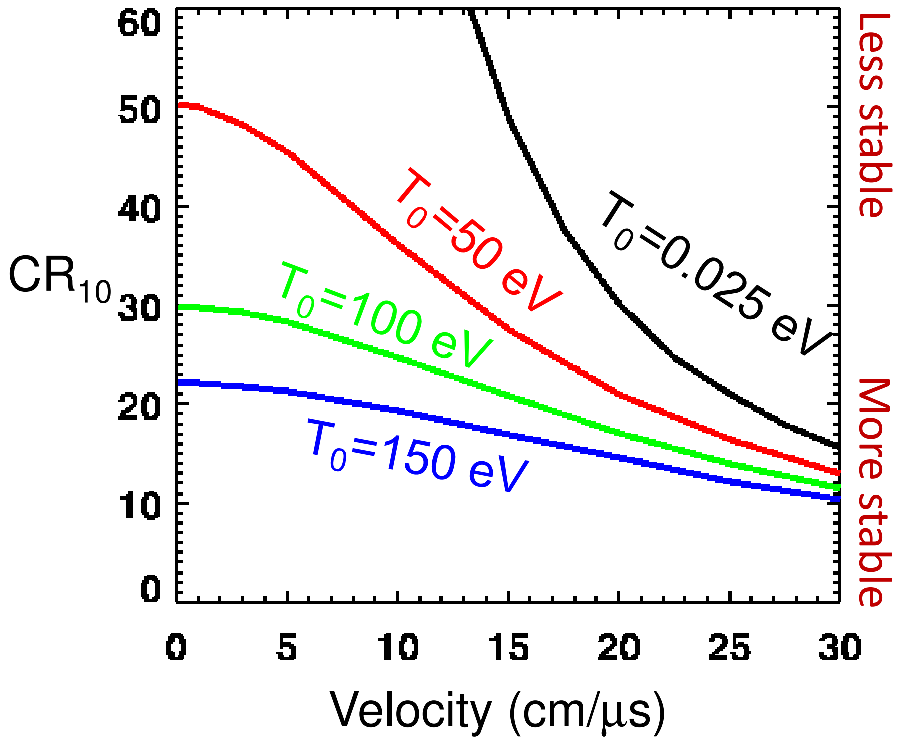






M.R. Gomez, S.A. Slutz, A.B. Sefkow *et al.*, to be published in PRL (2014).

# Typical ICF implosions need high velocities to reach fusion temperatures; laser preheating can reduce velocity requirements




$CR_{10}$ = Convergence Ratio ($R_0/R_f$) needed to obtain 10 keV (ignition) with no radiation losses or conductivity

Heating fuel to ignition temperatures is typically done with a high-velocity shock (or series of shocks)

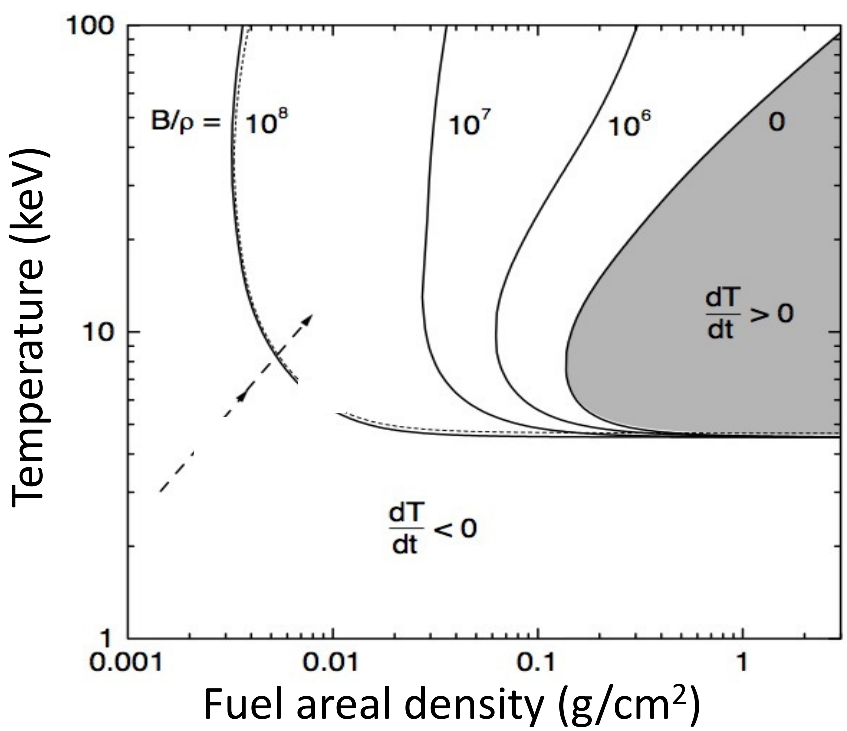
High velocities make it easier to reach fusion temperatures and also reduce the time available for losses (e.g., electron heat conduction or radiation) -- but can lead to uncontrolled instability growth

Heating the fuel prior to the implosion *in the absence of losses* can allow stable, low-velocity, low-convergence implosions to reach ignition temperatures

**Is there a way to reduce losses?**

# A large, embedded magnetic field can significantly reduce electron conduction losses from heated fuel

*Basko et al. *Nuc. Fusion* 40, 59 (2000)




**An external magnetic field can significantly reduce the ρr needed for ignition by inhibiting electron conduction losses**

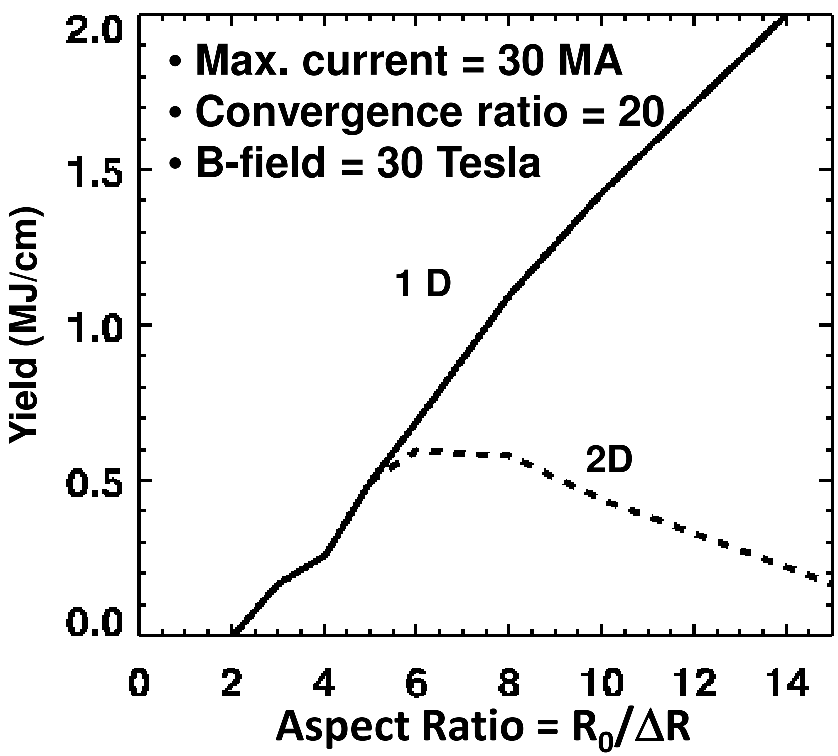
Lower ρr reduces the required final fuel density (e.g., ~1 g/cc << 100g/cc), which also reduces bremsstrahlung radiation losses

This means the stagnation plasma pressure at ignition temperatures is significantly reduced (e.g., ~5 Gbar << ~500 Gbar)

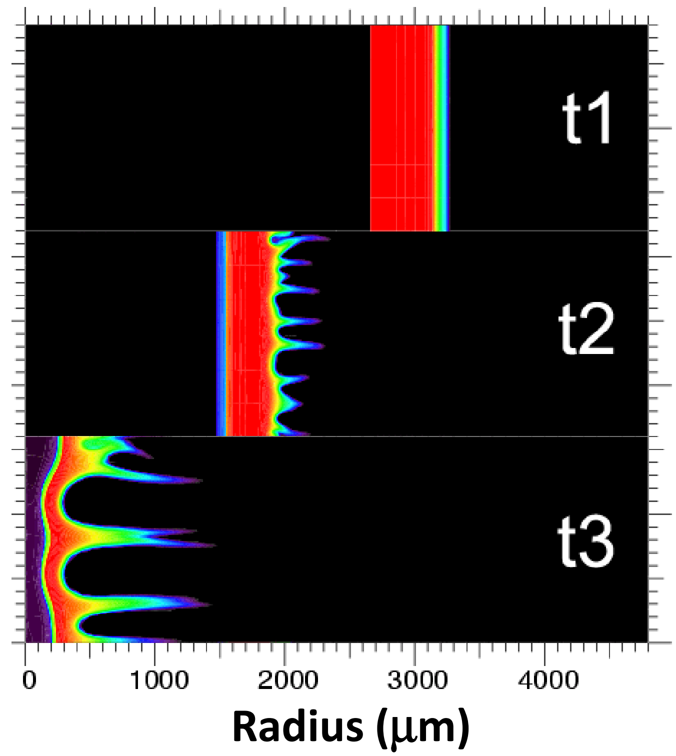
Large values of B/ρ are needed and therefore large values of B are needed: B ~ 10,000 Tesla (>$10^8$ x Earth's B-field)

This field significantly exceeds pulsed coil technology ($B_0$ ~10-30 T), therefore flux compression is needed… and we have an imploding liner to do it.

# Reducing the implosion velocity requirements through fuel heating and magnetization allows us to use thicker liners for more stable implosions




In 2D simulations, the Magneto-Rayleigh-Taylor instability degrades the yield as the aspect ratio is increased, due to decreased liner ρR.

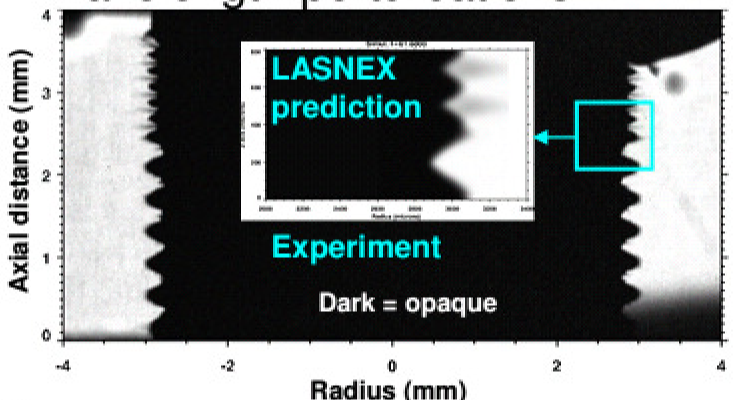


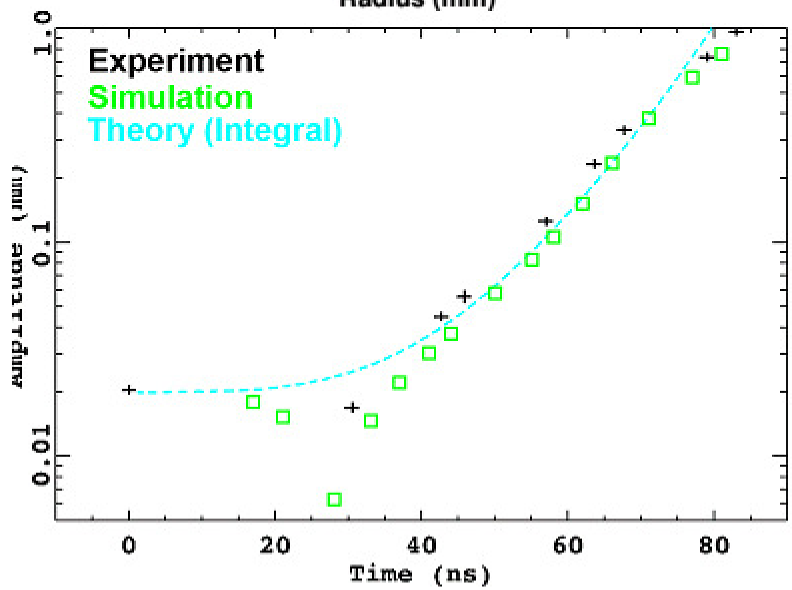

2D simulations of AR=6 Be liner show reasonably uniform fuel compression and sufficient liner ρR at stagnation to inertially confine the fuel

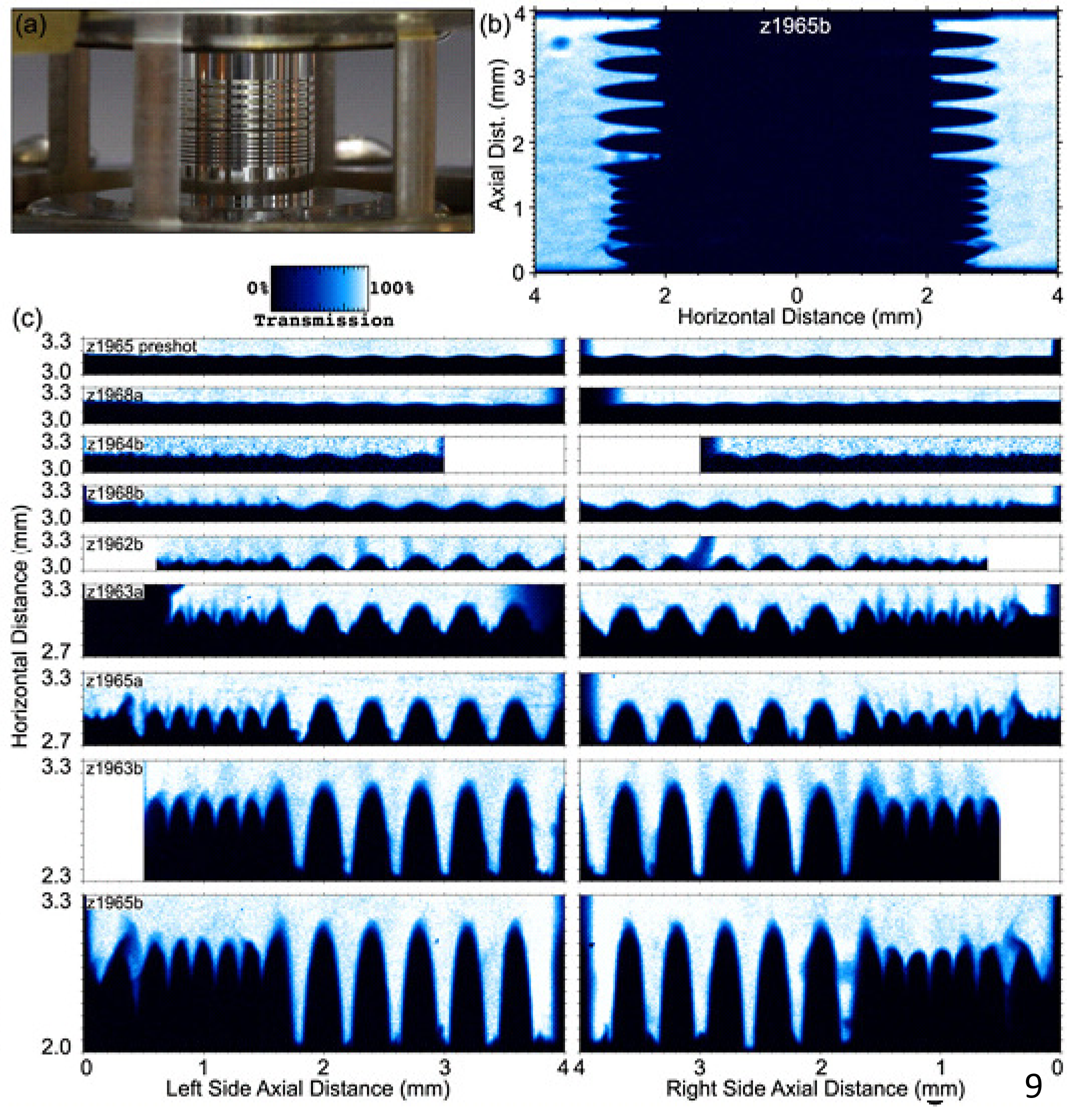
S.A. Slutz *et al.*, Phys. Plasmas 17, 056303 (2010).

# The Magneto-Rayleigh Taylor instability has been extensively studied on Z

Radiographs captured growth of intentionally-seeded 200, 400-µm wavelength perturbations






D.B. Sinars et al. Phys. Rev. Lett. (2010)

# Adding an axial magnetic field appears to enhance liner stability, changing its structure from cylindrical to helical

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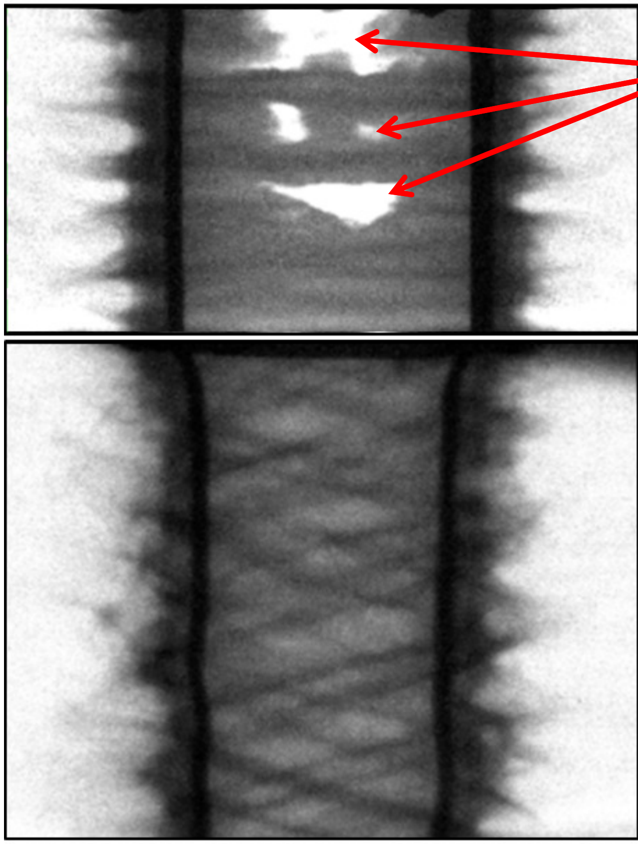
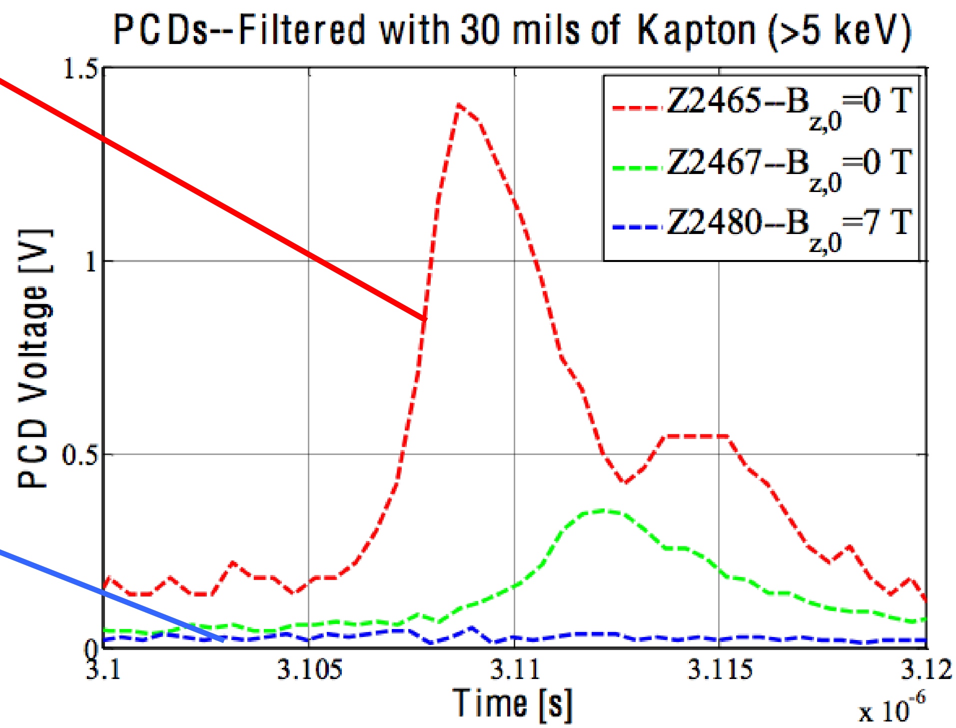
Without Magnetic Field



With Magnetic Field

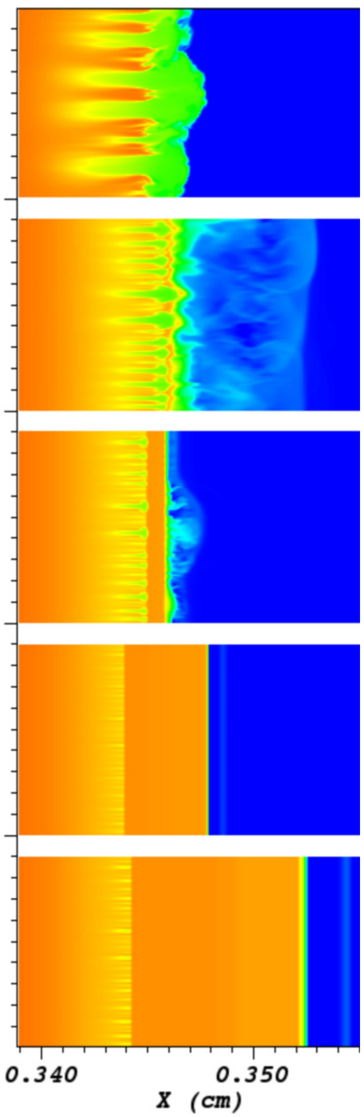
Time-integrated 6 keV self-emission from liner implosion is absent from shots with axial field, indicating suppression of micro-pinching by flux-compressed Bz

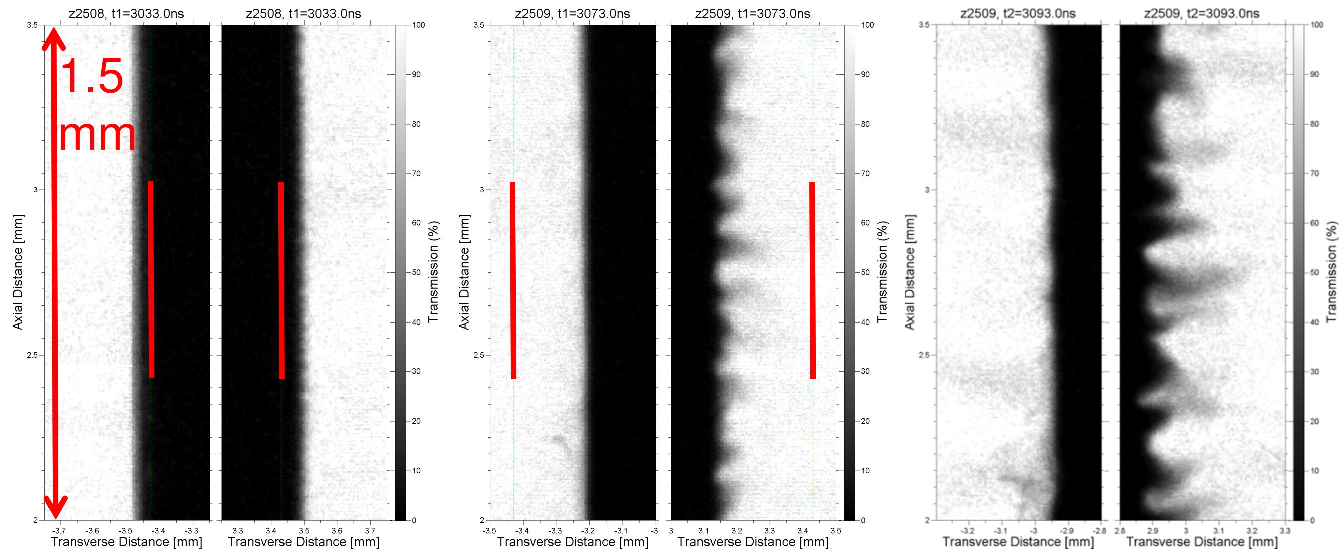





T.J. Awe *et al.*, Phys. Rev. Lett. (2013); *ibid.*, Phys. Plasmas (2014).

# Further enhancement of stability appears possible through mitigation of Electro-thermal instability growth

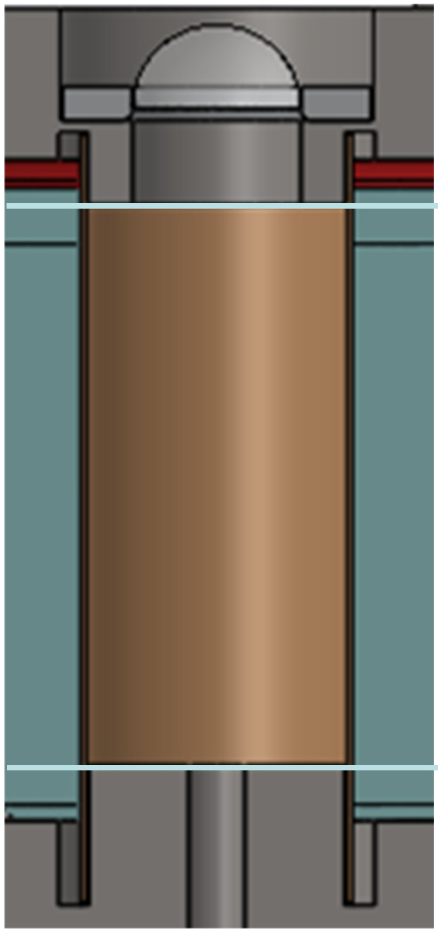


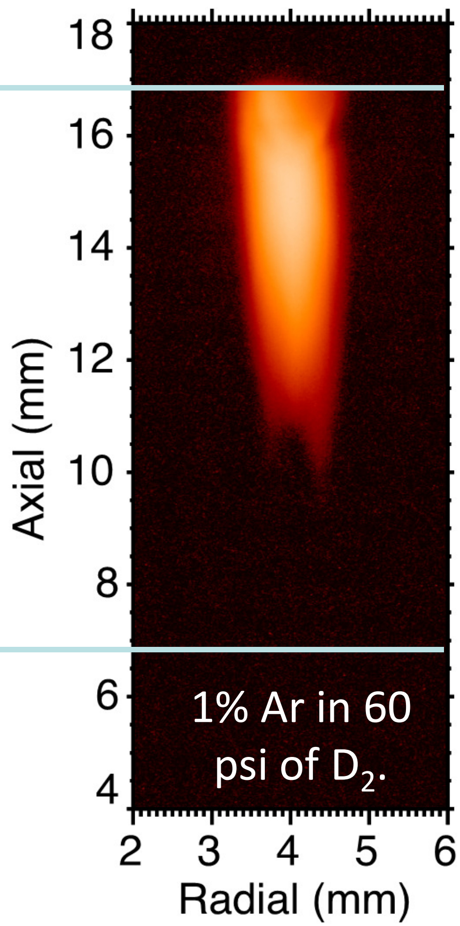

- ETI: regions with higher T have higher resistivity and are heated further; pressure variations eventually redistribute mass
- A plastic coating carries very little current and is theoretically ETI stable, with resistivity that decreases with temperature
- A thin coating significantly reduces the mass redistribution and provides a more stable implosion

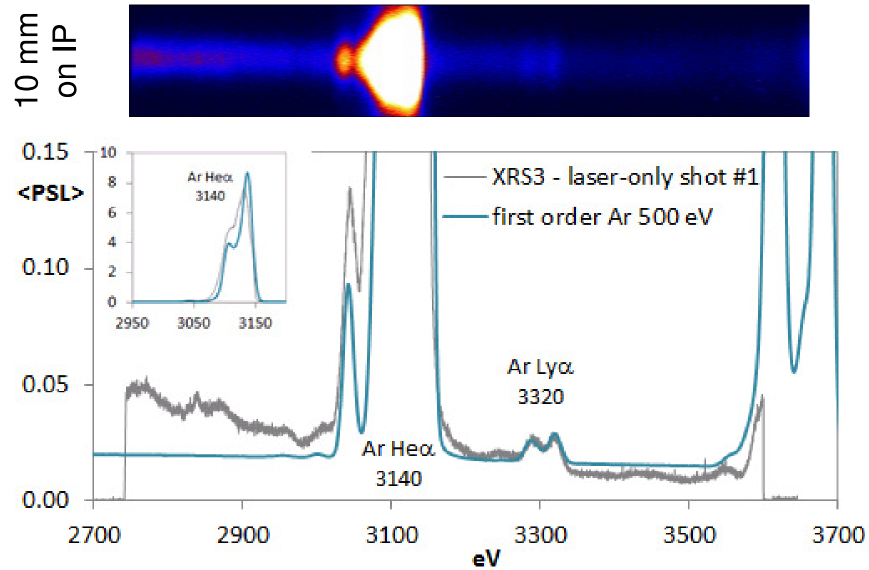
K.J. Peterson, Phys. Plasmas 20, 056305 (2013)

# Focused studies of the laser preheat performance are ongoing at both Z/Beamlet and Omega



2.5 J of laser energy onto a 1.5 μm foil



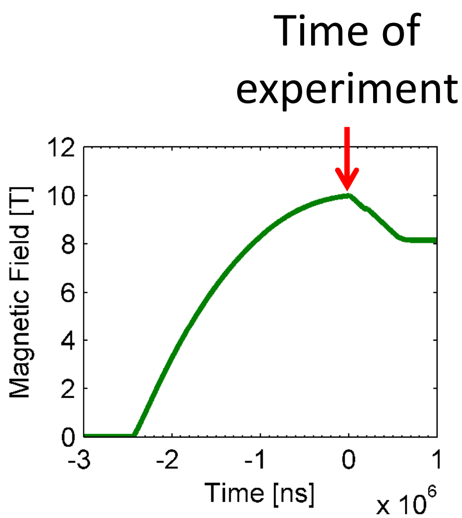

-3.1 keV crystal imager and spectral data* indicate that about half of the 10-mm axial dimension is heated to Te ~ 500 eV

-A laser-only shot with no gas fill and 4.5 kJ laser energy showed Te~600 eV emission from a Cl dopant at the bottom of the target

-X-ray emission from targets at Omega indicated T > 200 eV only with Bz > 0

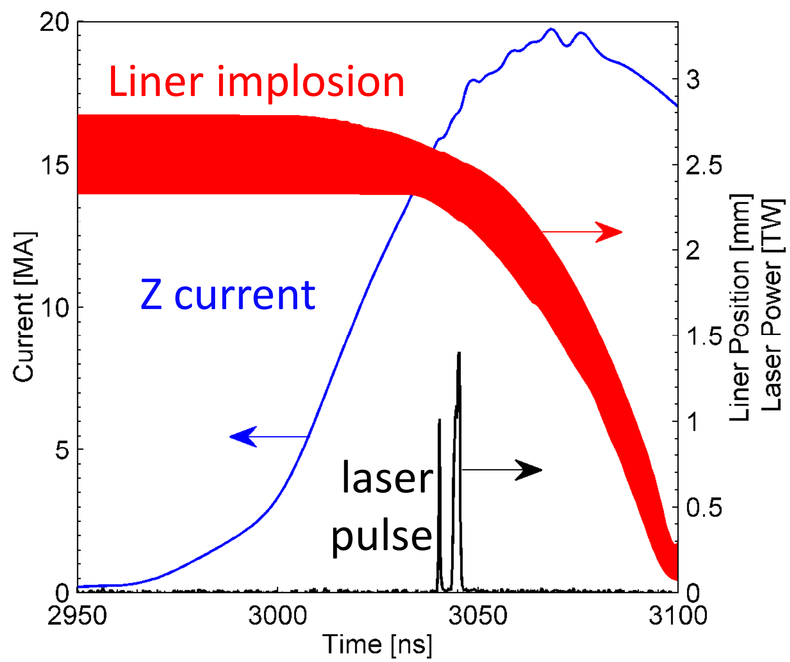
*courtesy Eric Harding and Matt Gomez

# The initial integrated experiments used I = 19 MA, B = 10 T, and Laser = 2.5 kJ



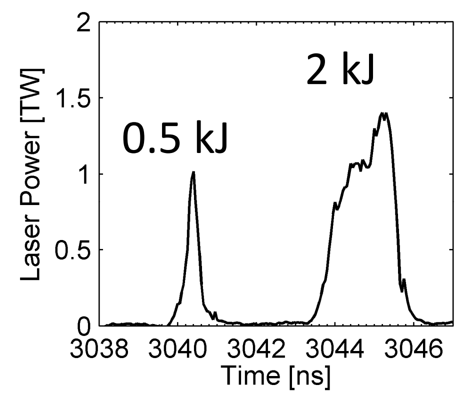

Magnetic field risetime is approximately 2 ms

B is constant over the timescale of the experiment

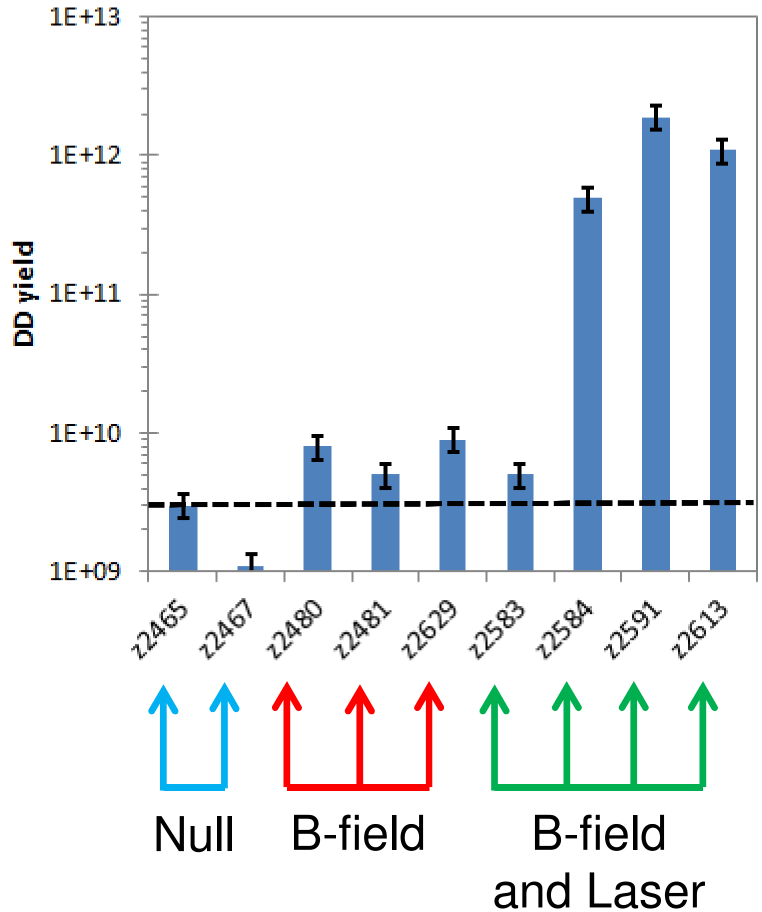



Peak current is 19 MA
Magnetic field is 10 T
Total laser energy is 2.5 kJ

Laser energy is split into 2 pulses:
1st pulse intended to destroy LEH
2nd pulse intended to heat fuel

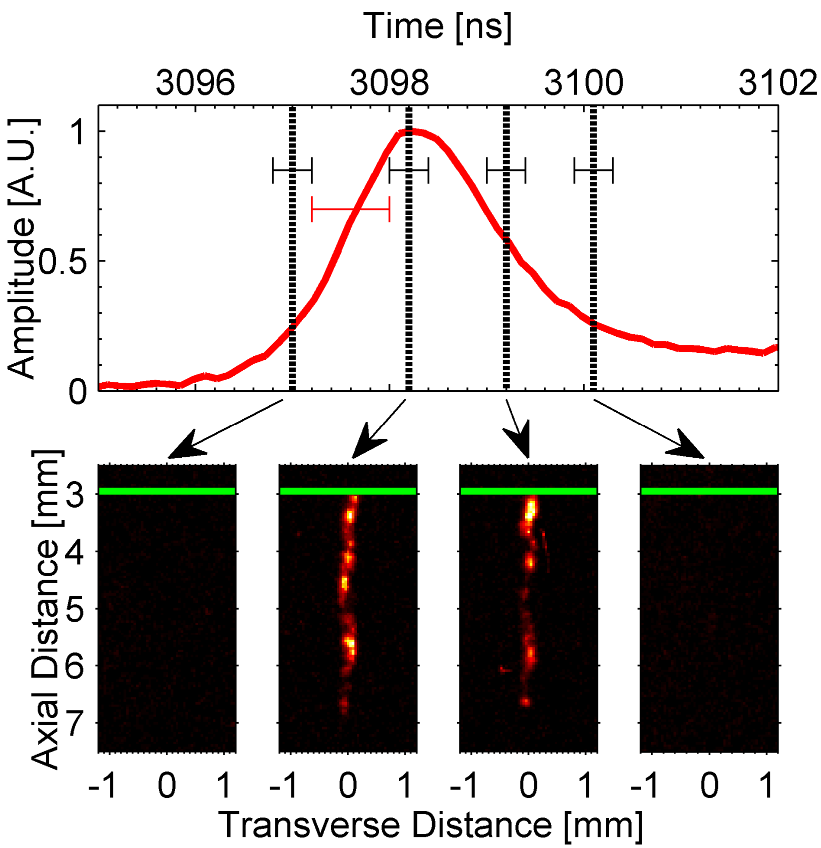


# Z shots producing DD yields in excess of $10^{12}$ were only observed in experiments with laser and B-field




- High yields were only observed on experiments incorporating both applied magnetic field and laser heating
- A series of experiments without laser and/or B-field produced yields at the background level of the measurement
- A high-pressure shot and a shot with high-Z-doped fuel did not produce measurable yield
- Shots in June 2014 with 4 kJ laser energy did not produce measurable yield
- Shots in September 2014 with thinner LEH windows produced few-$10^{11}$ yields

# Time-resolved x-ray pinhole imaging (hν > 2.8 keV) shows a narrow emission column during peak in X-ray signal

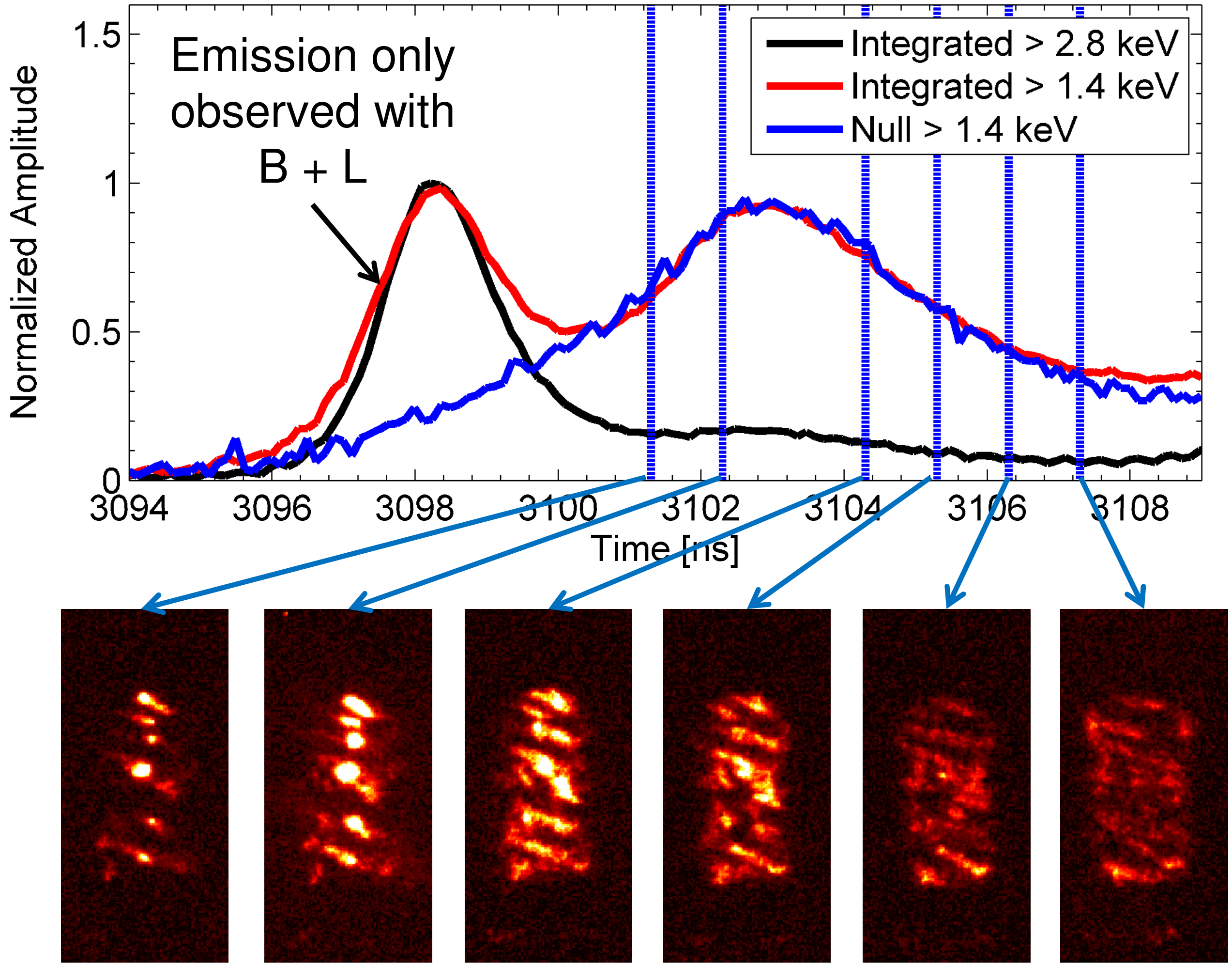



- Emission column is observed only during the peak in the x-ray signal, and only on experiments with high neutron yield
- Stagnation column width is at the resolution limit of this instrument (~150 microns)
- Absolute x-ray powers suggest stagnation density of 0.4 +/- 0.2 $g/cm^3$ and Be mix < 10%

M.R. Gomez, S.A. Slutz, A.B. Sefkow *et al.*, to be published in PRL (2014).

# High energy x-ray signal and narrow emission region are absent in null experiments

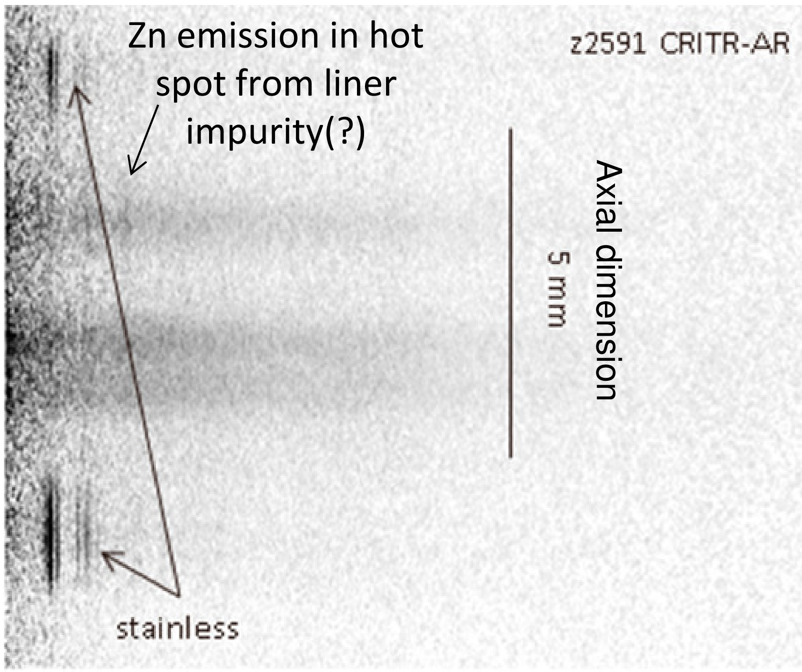
- Liner emission is observed in all experiments
- Liner emission is at a lower photon energy ( < 2.8 keV)
- Liner emission region expands after stagnation & exhibits helical structure



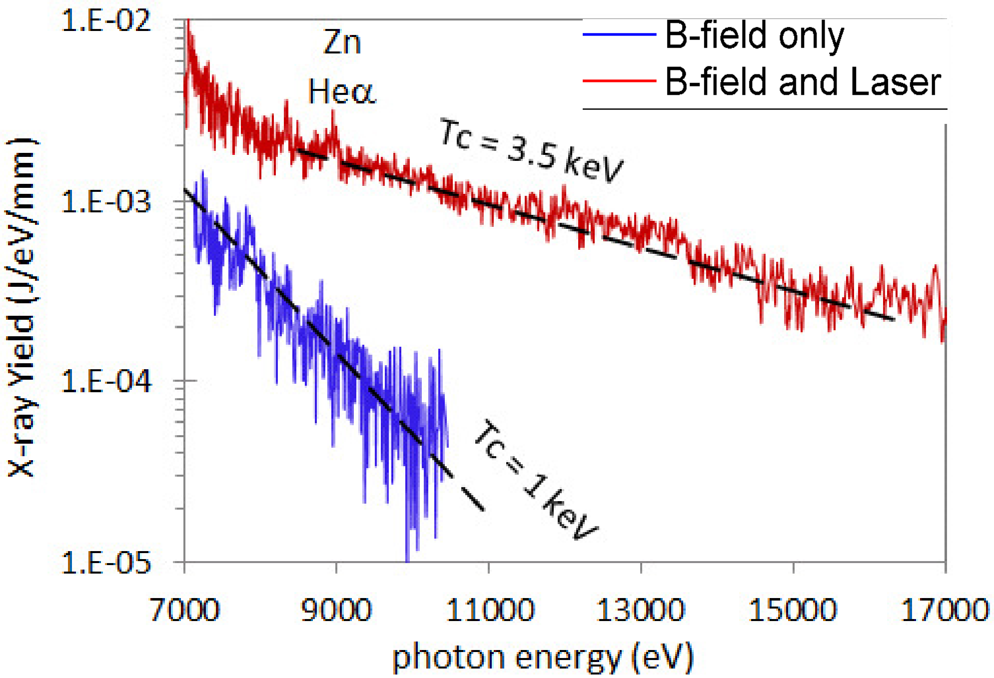

M.R. Gomez, S.A. Slutz, A.B. Sefkow *et al.*, to be published in PRL (2014).

# High-energy spectra show axial variations in temperature and composition, with ~3.5 keV electron temperature in the pinch region—remarkable for a 70-100 km/s implosion!

Emission from high-Z components of stainless steel is consistent with late-time emission yields



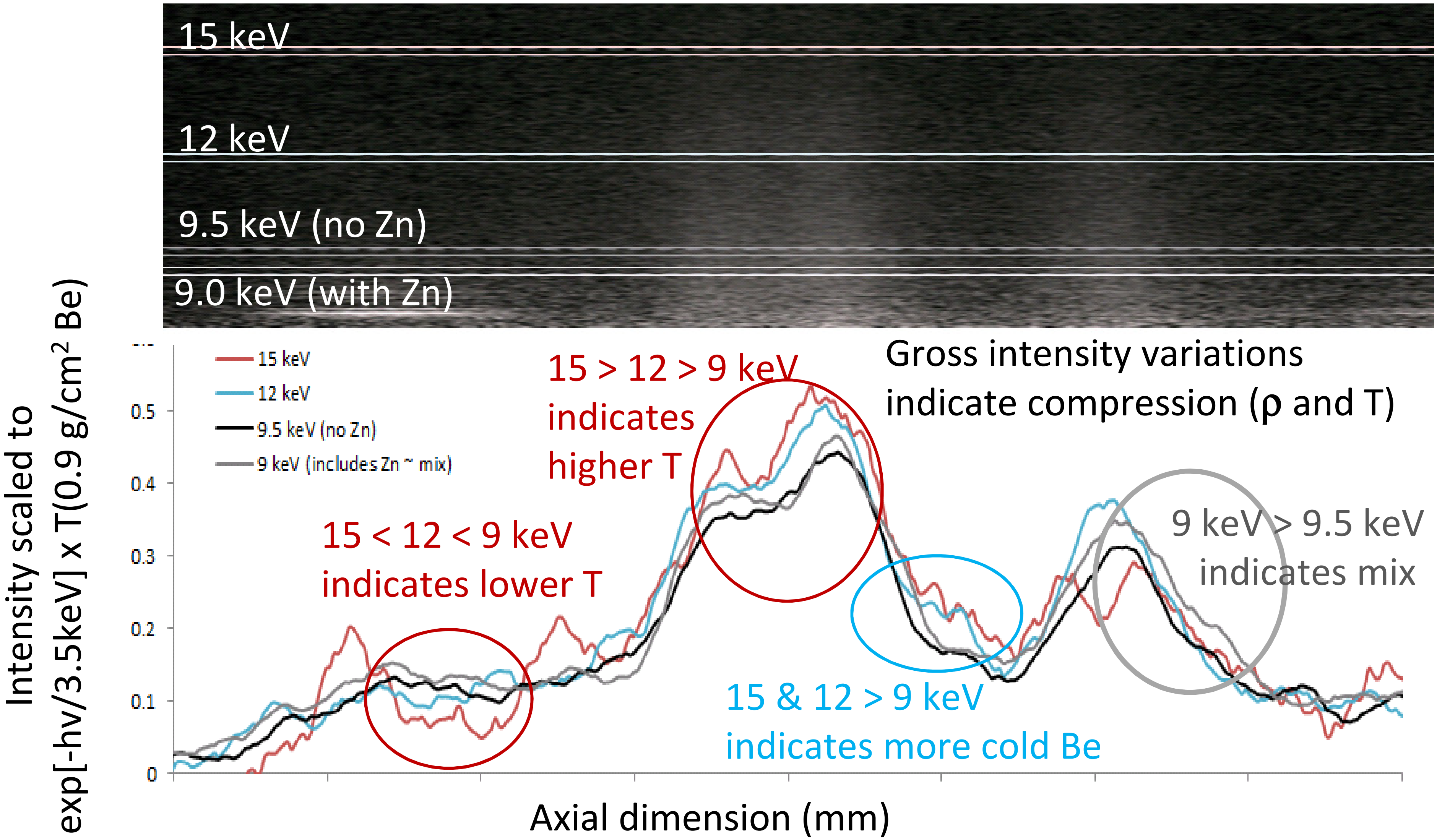

High-energy spectra from hot spots indicate Te ~ 3.0-3.5 keV from high-yield shots and constrain Be mix to < 10%




**The measured Te are close to the Tion obtained from neutron time-of-flight data and tend to scale with the measured neutron yields.**

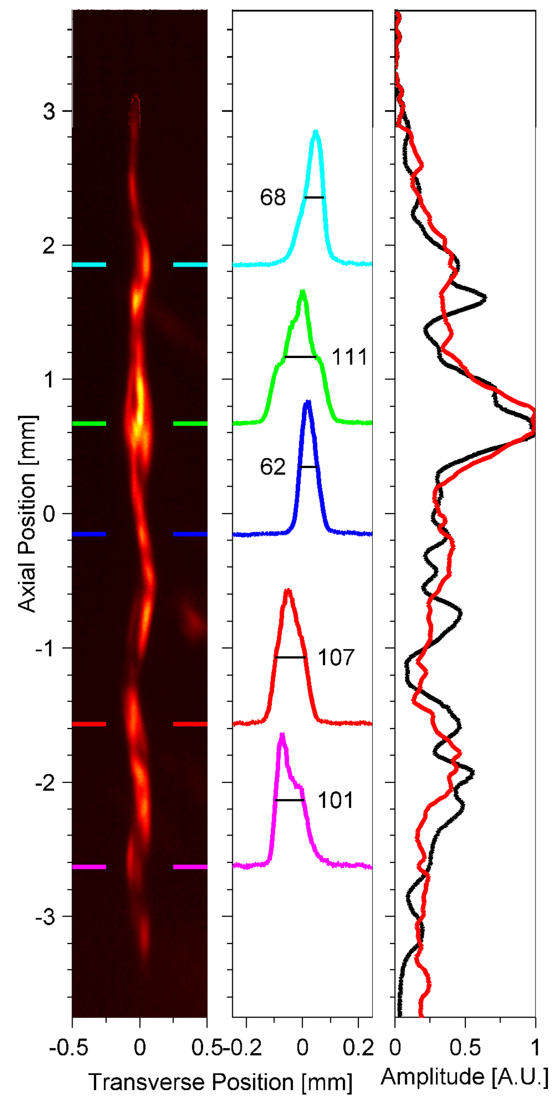
M.R. Gomez, S.A. Slutz, A.B. Sefkow *et al.*, to be published in PRL (2014).

# Lineouts of the high-energy spectrum at different energies can be used to infer axial variations in liner opacity, compression, temperature, and mix



# High-resolution monochromatic imaging of the x-ray emission shows a narrow, hot plasma column with weakly helical structure

- Lineouts of stagnation column vary from 60 to 120 μm FWHM (resolution about 60 μm)
- Emission is observed from about 6 mm of the 7.5 mm axial extent
- Note that the emission doesn't necessarily define the fuel-liner boundary, but only the hot fuel region
- The stagnation column is weakly helical with a wavelength of about 1.3 mm and a 0.05 mm horizontal offset
- Axial lineouts of image (black) agree with 9.3 keV 1D spectrometer lineouts (red), suggesting features are due to emission and not liner opacity (Be opacity is small >9 keV)
- **With $\rho \sim 0.4$ g/cm$^3$ → $\rho r \sim 2$ mg/cm$^2$**




M.R. Gomez, S.A. Slutz, A.B. Sefkow *et al.*, to be published in PRL (2014).

# In addition to the significant ~2x$10^{12}$ DD neutron yields, we measure a remarkable ~5x$10^{10}$ DT neutrons

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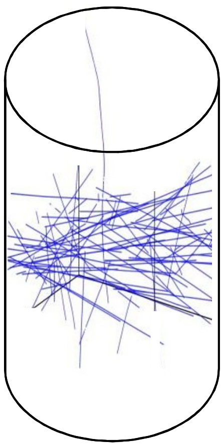
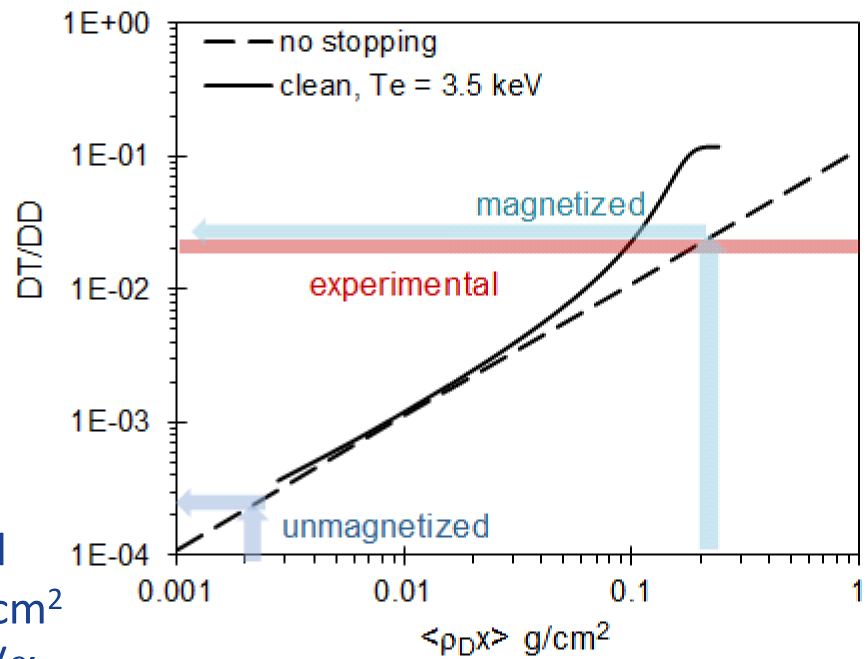
"Secondary" 14 MeV neutrons are produced by 1 MeV tritons interacting with D fuel:

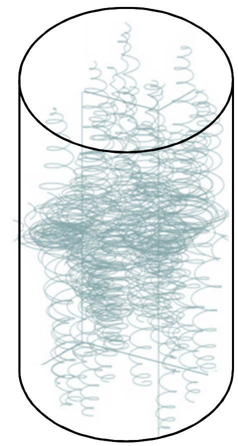
D + D → (50%) **0.8 MeV He$^3$ + 2.5 MeV n**

D + D → (50%) **1.0 MeV T + 3 .0 MeV p**



In an unmagnetized plasma, ρR > 200 mg/cm$^2$ is required for triton/α confinement



In a magnetized plasma, ρR ~ 2 mg/cm$^2$ is sufficient to confine 1 MeV tritons

This demonstration that Bz confines 1 MeV tritons is critically important for MagLIF – which requires magnetic enhancement of thermal confinement and a-deposition – because a field that confines 1 MeV tritons also confines electrons and 3 MeV alphas.

P.F. Schmit, P.F. Knapp, S.B. Hansen *et al.*, to be published in PRL (2014).

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- Focused experiments are helping to increase our fundamental understanding of stability, heating, compression, and confinement
- Spectroscopic analysis of preheat and stagnation plasmas are helping to constrain the simulation tools used for target design
- Future experiments will help us understand initial conditions, platform stability, mix, and scaling

# While fuel dopants lead to radiative losses during preheat that can dud stagnation, interior coatings that mix with fuel at stagnation would be less detrimental.

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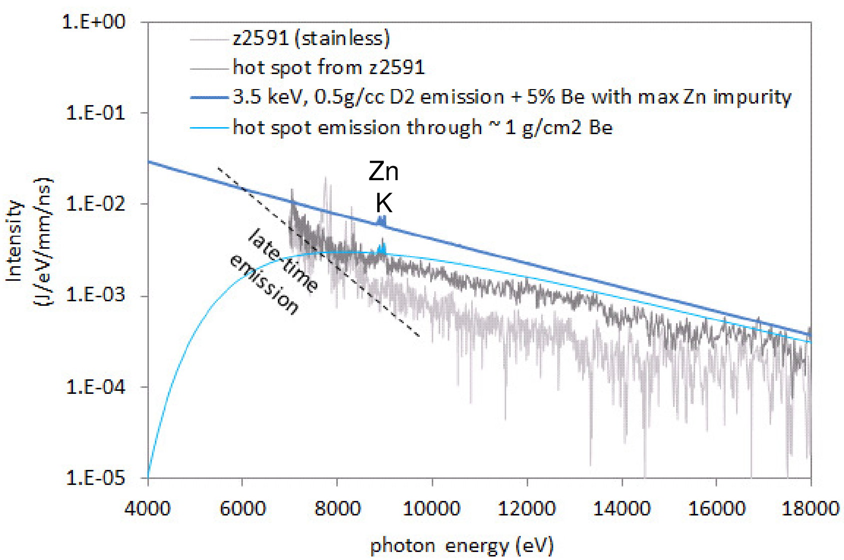
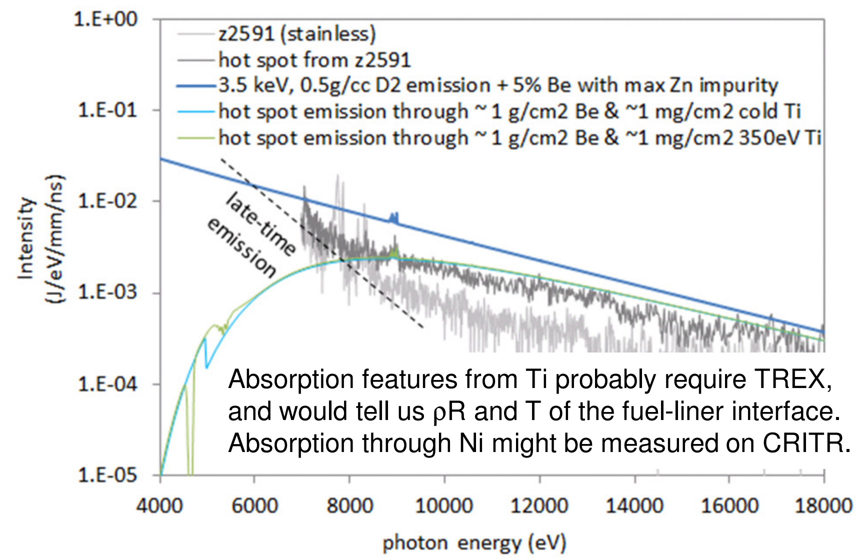
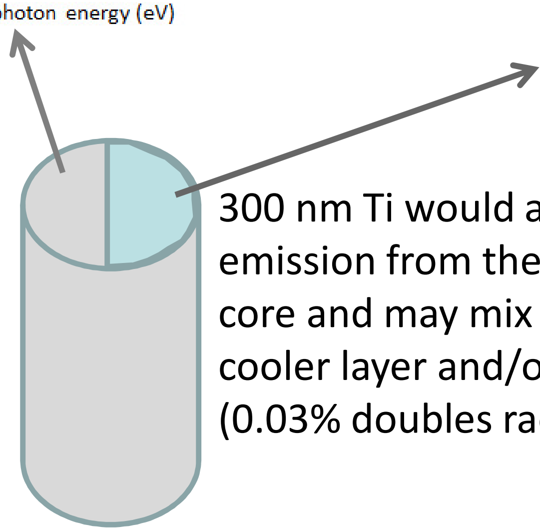
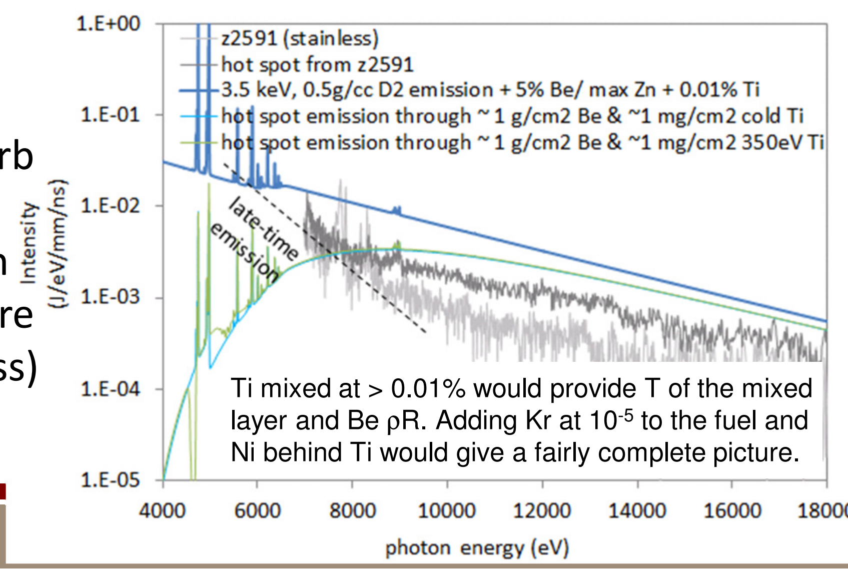


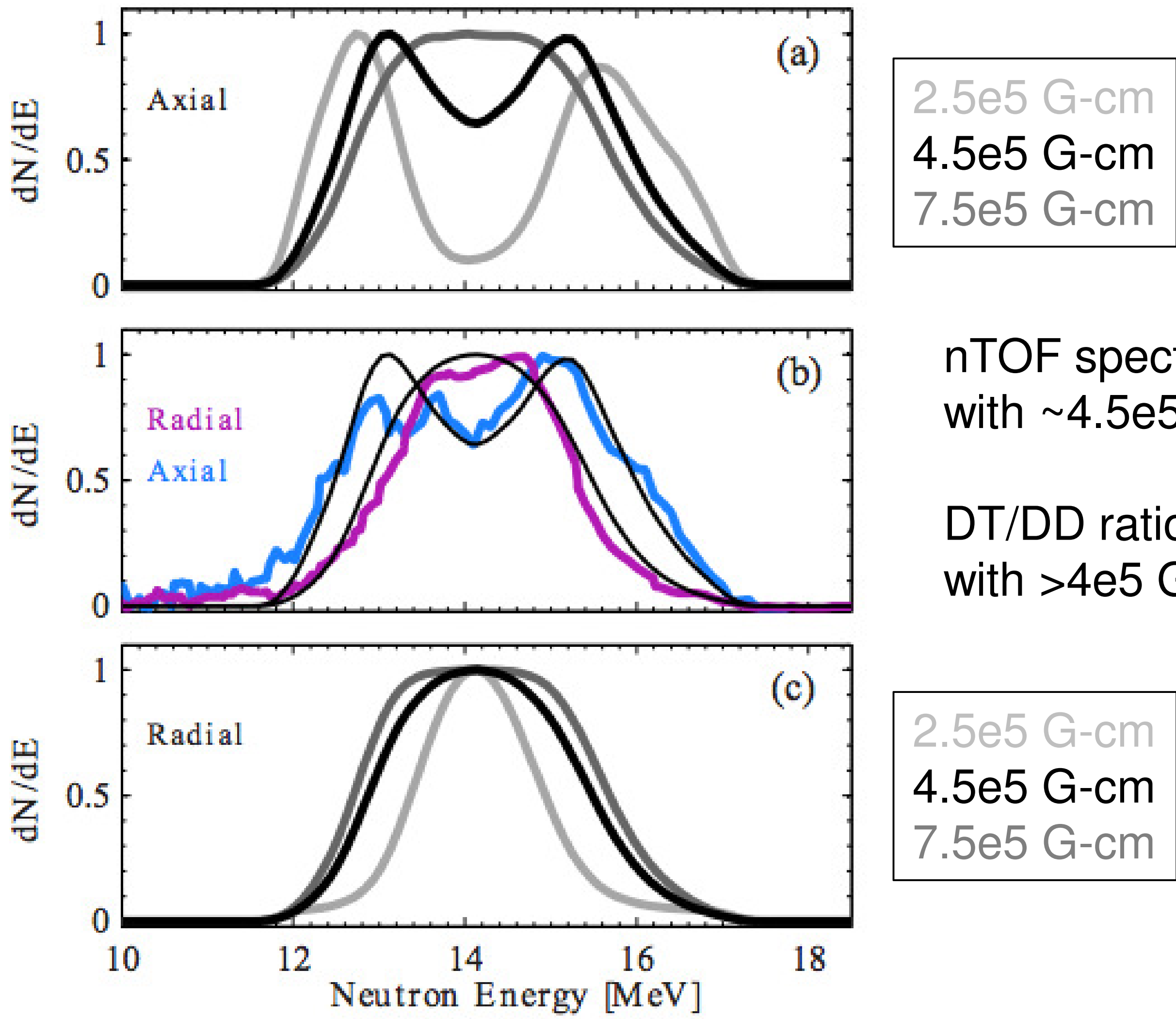

Uncoated Be (< 0.005% Zn) Measured Zn K-shell suggests a hot core surrounded by a slightly cooler layer mixed layer with ~10% Be (~doubles rad loss)



300 nm Ti would absorb emission from the hot core and may mix with cooler layer and/or core (0.03% doubles rad loss)



# Neutron time-of-flight data are consistent with high magnetization




nTOF spectra consistent with ~4.5e5 G-cm

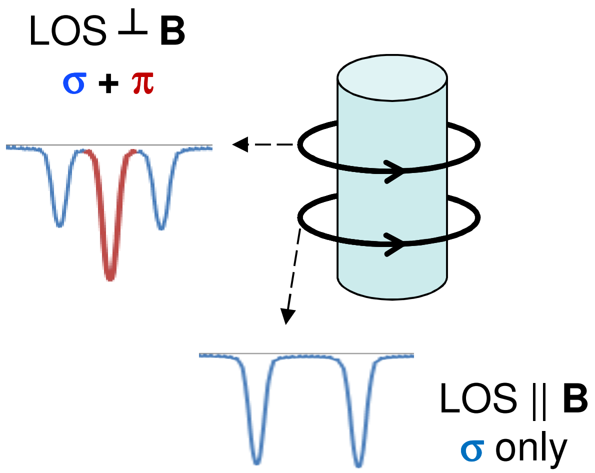
DT/DD ratio consistent with >4e5 G-cm



P.F. Schmit, P.F. Knapp, S.B. Hansen *et al.*, to be published in PRL (2014).

# Zeeman splitting is being used to characterize Z's current drive and flux compression in Magnetized Liner Inertial Fusion (MagLIF) experiments

- Sodium deposits vaporized and backlit by current-carrying surfaces signal both the magnitude and direction of the local magnetic field:




The relative strength of σ and π components indicates field direction