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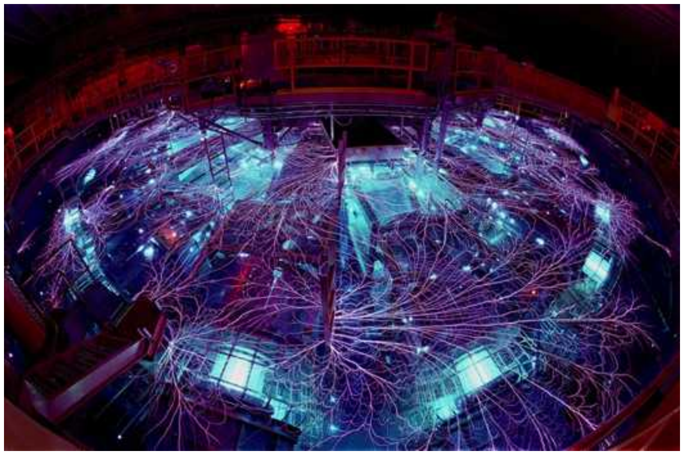

# Results, Progress, and Plans for Magnetized Liner Inertial Fusion (MagLIF) on Z

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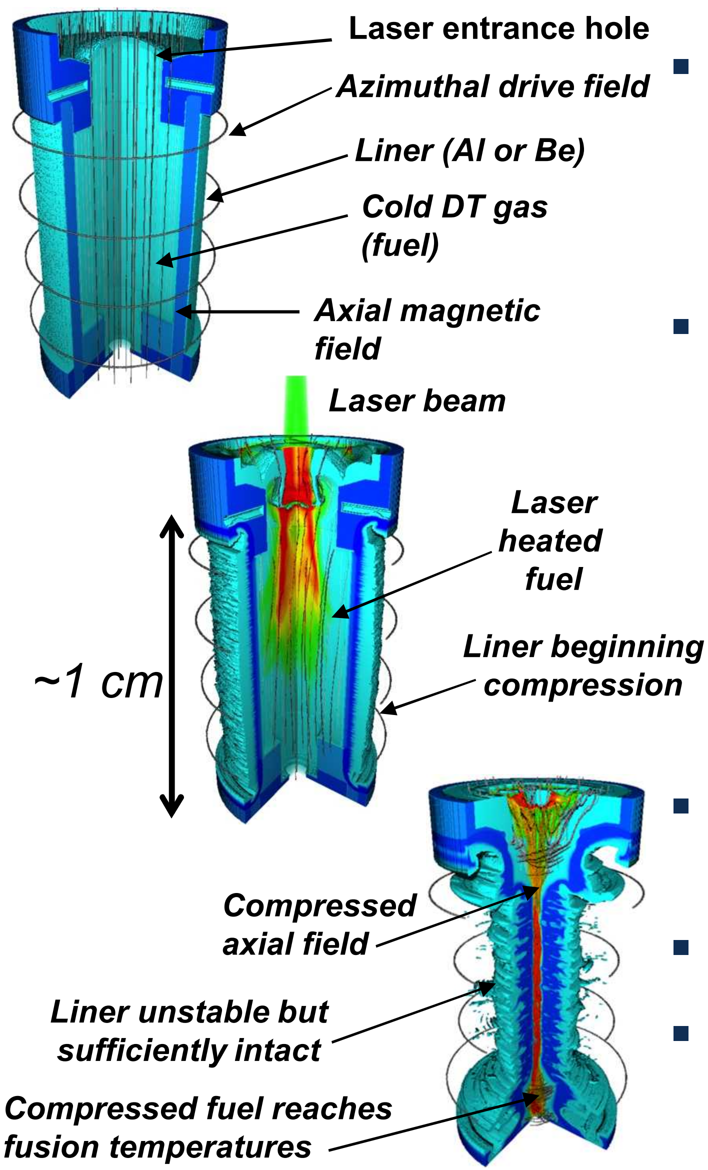
# Abstract

The magnetized liner inertial fusion (MagLIF) concept is a promising approach to achieving large fusion yields on the Z facility. By utilizing pre-magnetized and pre- heated fusion fuel, the required implosion velocity, convergence, and stagnation pressure required to achieve fusion conditions is substantially reduced.

The first integrated MagLIF experiments have obtained DD neutron yields as high as 2e12 and plasma temperatures of 3-4keV. These experiments incorporated both pre- magnetized and preheated fusion fuel and demonstrated dramatic improvement in fusion performance over previous experiments with identical targets that did not incorporate both of these design elements.

In this paper, we present results and plans for both integrated and focused MagLIF experiments that investigate a number of key physics issues including, liner instabilities (electrothermal, magneto-Rayleigh-Taylor, deceleration Rayleigh-Taylor, etc.), laser energy coupling to the fusion fuel, magnetic flux compression, and suppression of electron heat transport by the axial magnetic field.

# We are working toward the evaluation of a new Magnetized Liner Inertial Fusion (MagLIF)* concept

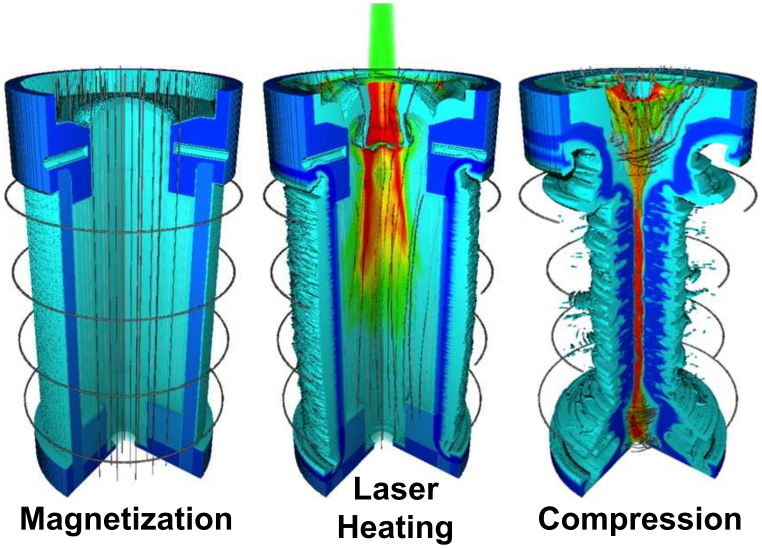



- **An initial 30 T axial magnetic field is applied**
  - **Inhibits thermal conduction losses**
  - **May help stabilize implosion at late times**
- **During the ~100 ns implosion, the fuel is heated using the Z-Beamlet laser (about 6 kJ in designs)**
  - **Preheating to ~300 eV reduces the compression needed to obtain fusion temperatures to 23 on Z**
  - **Preheating reduces the implosion velocity needed to ~100 km/s, allowing us to use thick liners that are more robust against instabilities**
- **~50-250 kJ energy in fuel; 0.2-1.4% of capacitor bank (Pulsed power is very energy efficient!)**
- **Stagnation pressure required is ~5 Gbar**
- **100 kJ yield may be possible on Z using DT Early experiments would use DD fuel**



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

# Our path to studying the underlying science is a mixture of focused and integrated experiments to address key physics

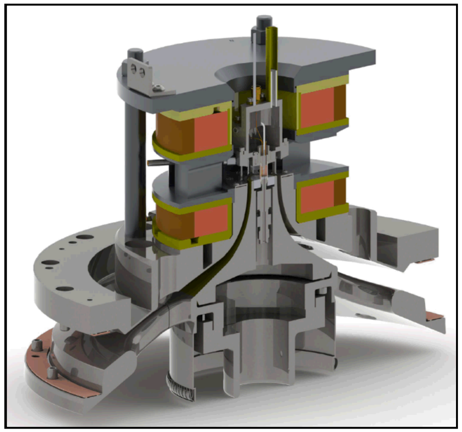



- Key target design elements
  - Liner compression
  - Magnetization
  - Laser heating
  - Fuel layering & burn

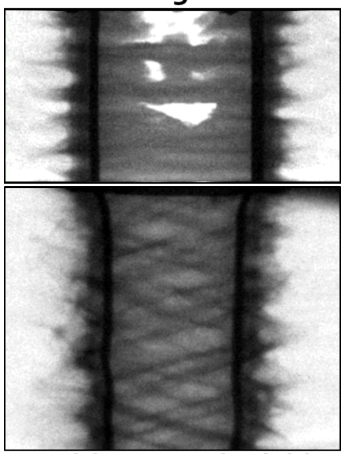
- Key physics uncertainties
  - Liner instabilities
    - Electro-thermal
    - Magneto-Rayleigh-Taylor
    - Deceleration RT
    - Impact of 3D fuel assembly
  - Liner/fuel interactions & mix
  - Laser-window and laser-fuel scattering, absorption, uniformity
  - Suppression of electron heat transport in dense plasma by magnetic fields
  - Magnetic flux compression
  - Magnetized propagating burn

Experiments to address the key physics will be done on the Z pulsed power facility and the Z-Beamlet and Omega(-EP) lasers.

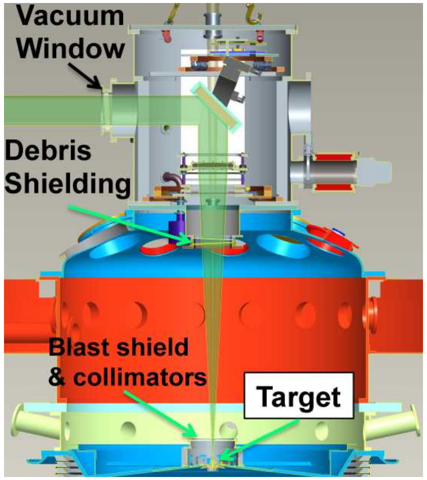
# We completed the supporting infrastructure needed to support our first magnetized and laser-heated MagLIF tests in 2013 and obtained interesting results



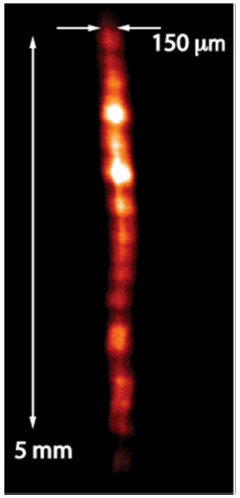
**Developed experimental platform (Dec. '12-Feb. '13)**




**Commissioned 10 T ABZ system; 1st axially-magnetized liner implosions (Feb. '13)**




**Commissioned new Final Optics Assembly and 2 kJ laser heating (Aug. '13)**




3123 eV imager data from z2584

**1st successful integrated MagLIF experiments (Nov.-Dec. '13)**

Multi-year efforts

# Fundamental liner instability experiments represent an important example of a sustained focused science effort—we are transitioning from experiments on initiation/acceleration stages to deceleration stage

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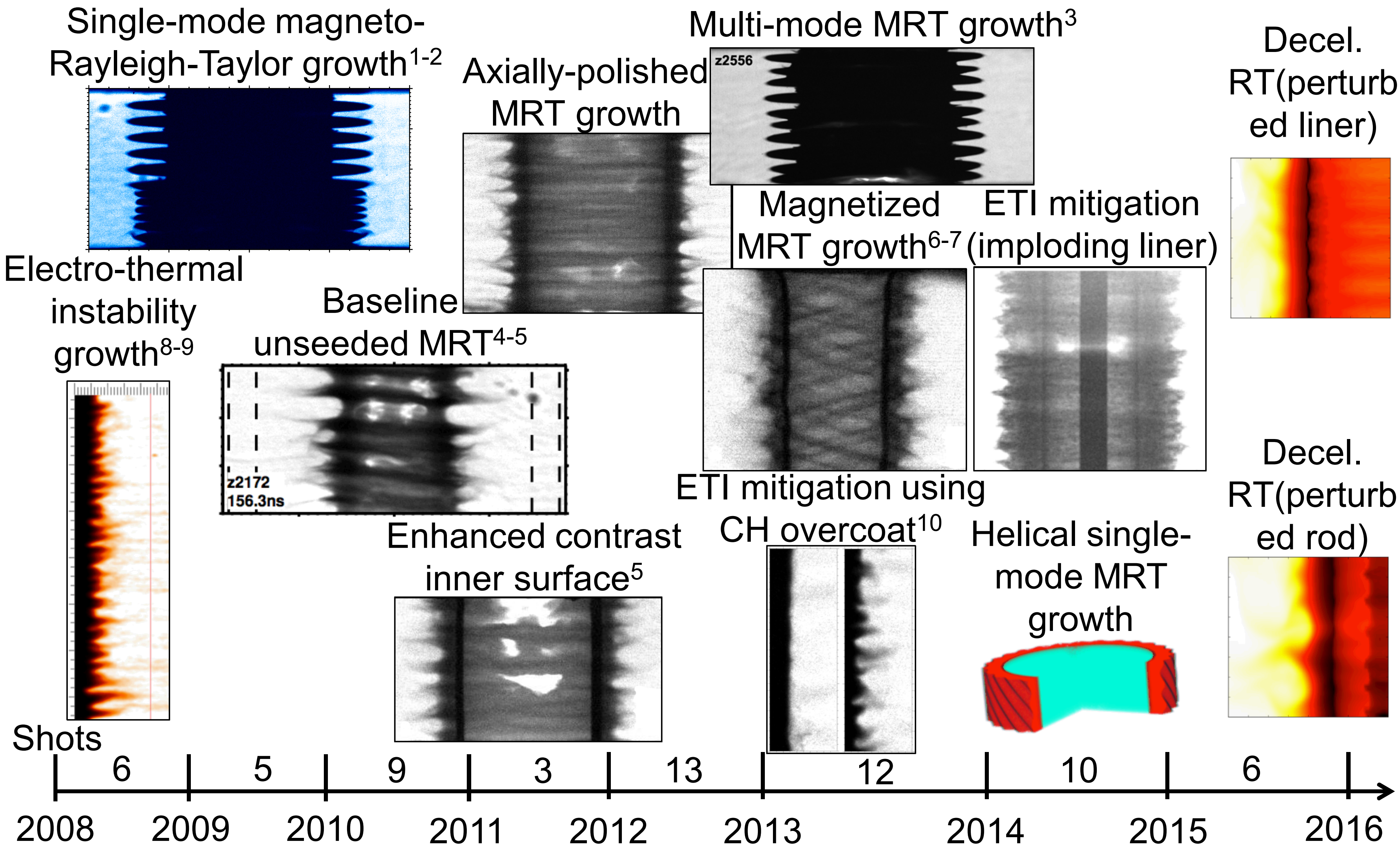
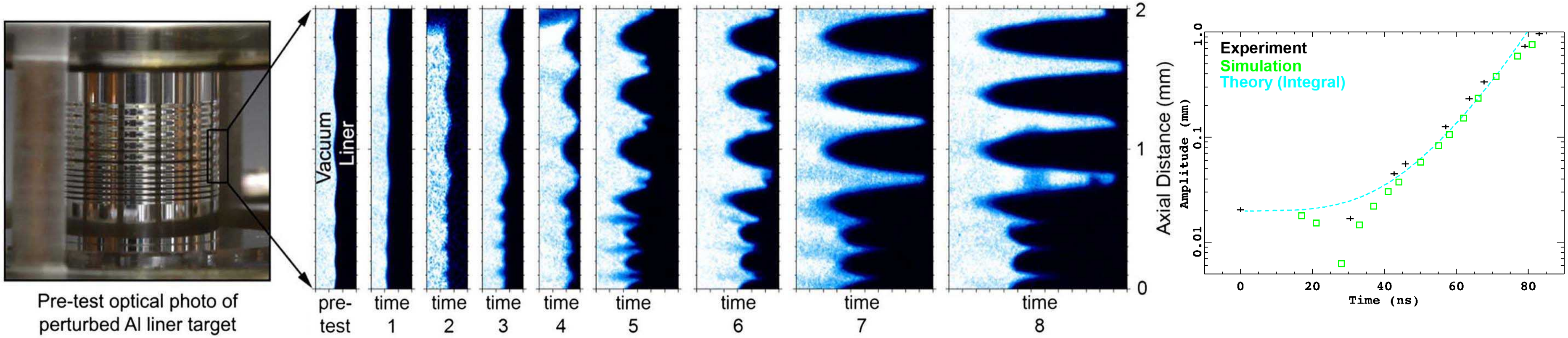



Publications to date include 4 PRLs, 5 PoPs, more in prep.

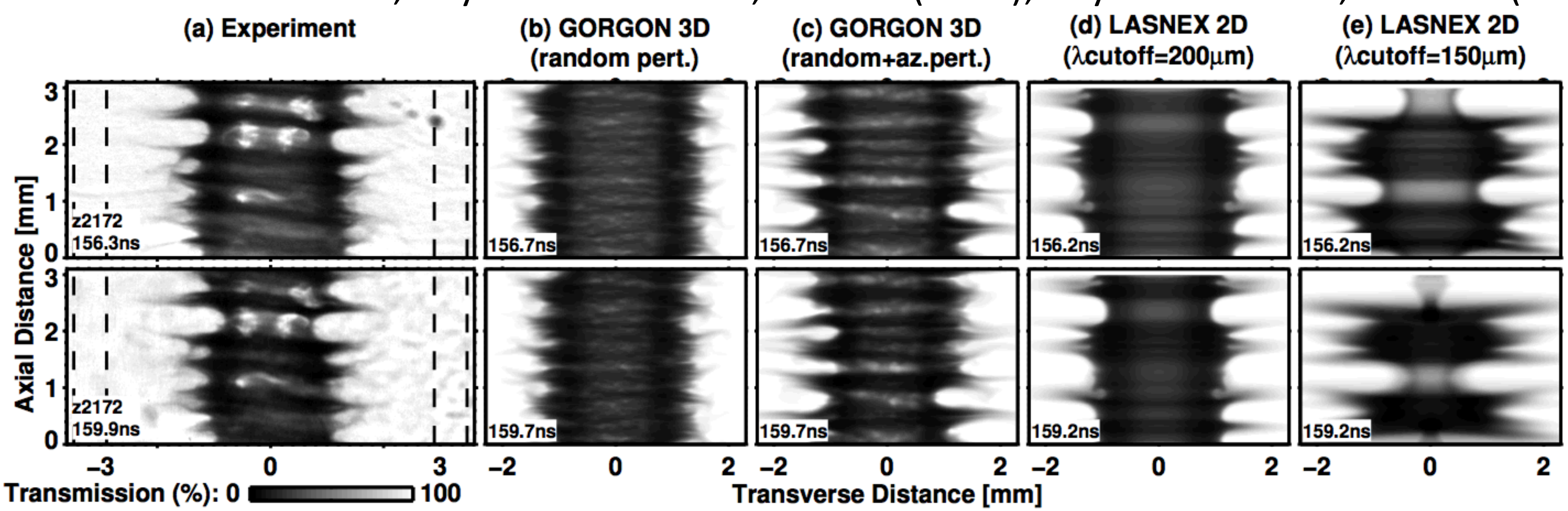
# We have been studying the liner instabilities in MagLIF relevant targets during the last several years

- D.B. Sinars *et al.*, Phys. Rev. Lett. 105, 185001 (2010); Phys. Plasmas 18, 056301 (2011).




Pre-test optical photo of perturbed Al liner target

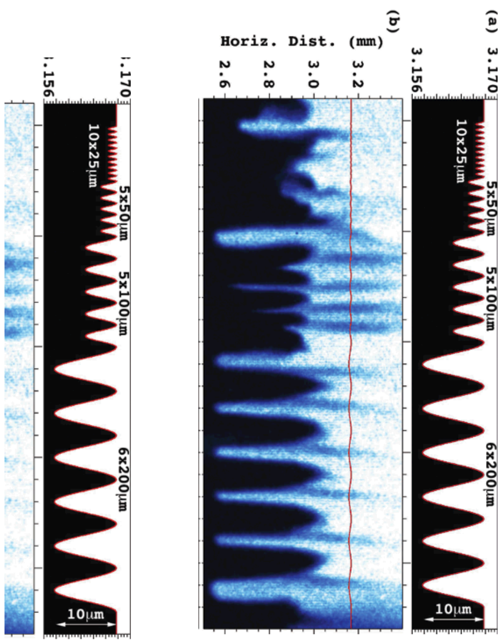
- R.D. McBride *et al.*, Phys. Rev. Lett. 109, 135004 (2012); Phys. Plasmas 20, 056309 (2013).



# Surface roughness and small defects do not appear to be the seed for MRT instability growth as in radiative driven laser ICF targets

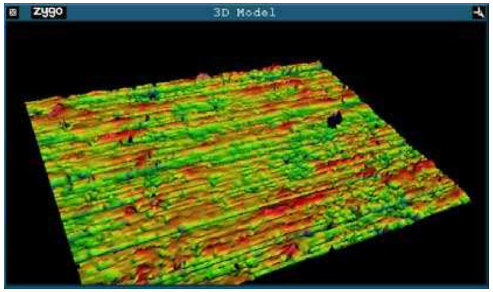
Axially polished liner experiments suggest symmetry is not sensitive to surface characteristics

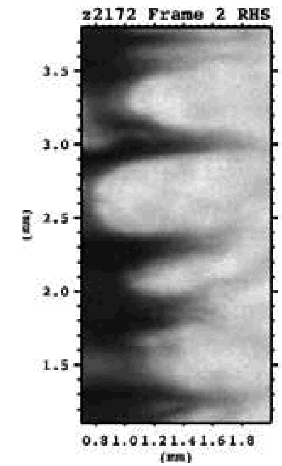
Observed Instability growth is not linearly proportional to the amplitude of the initial perturbations.



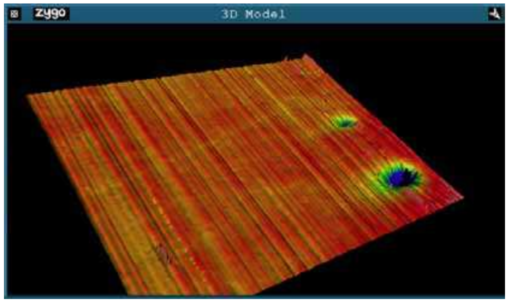

Ao = 60 nm

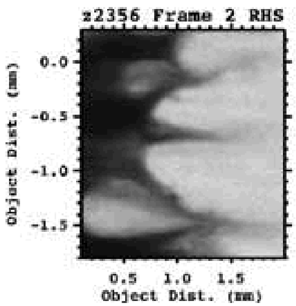
Standard Process
(50 nm RMS)




axial machining and polishing
(50 nm RMS)

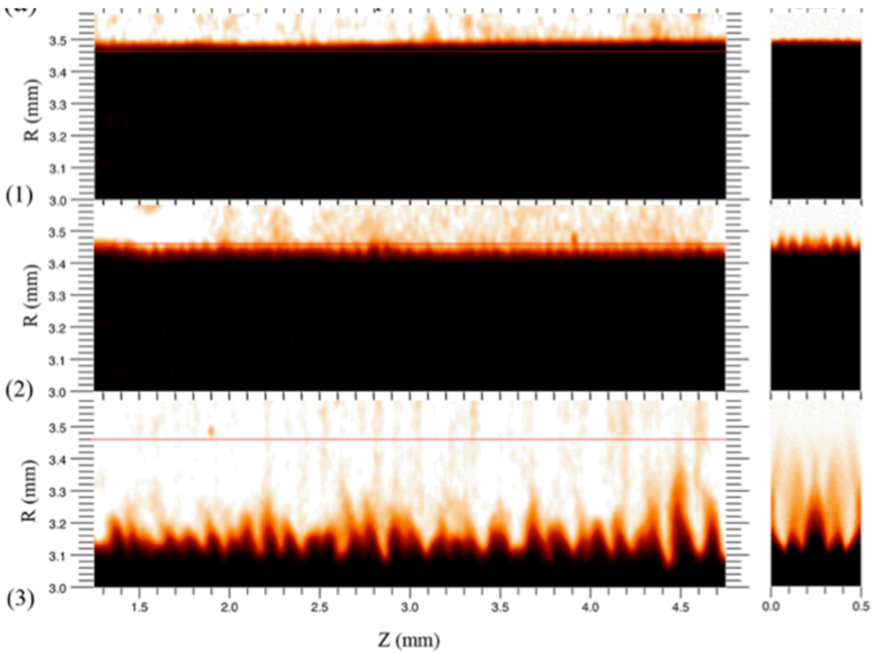


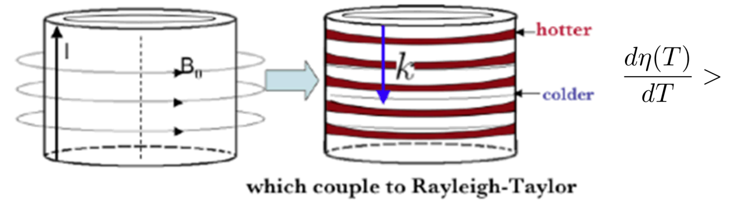



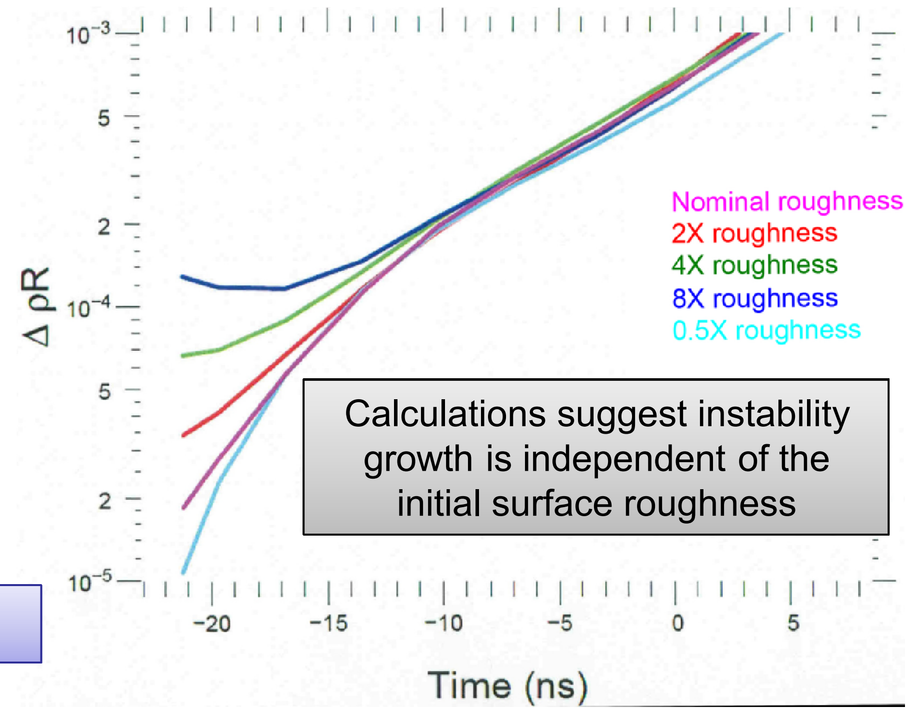

**Symmetry may generally be worse for axially-polished liners**

# Our modeling of electrothermal instabilities agrees well with observed instability growth in solid Al liners

Experimental (left) & simulated (right) radiographs




Calculations suggest instability growth is independent of the initial surface roughness

## Estimated MRT Only Perturbation Growth

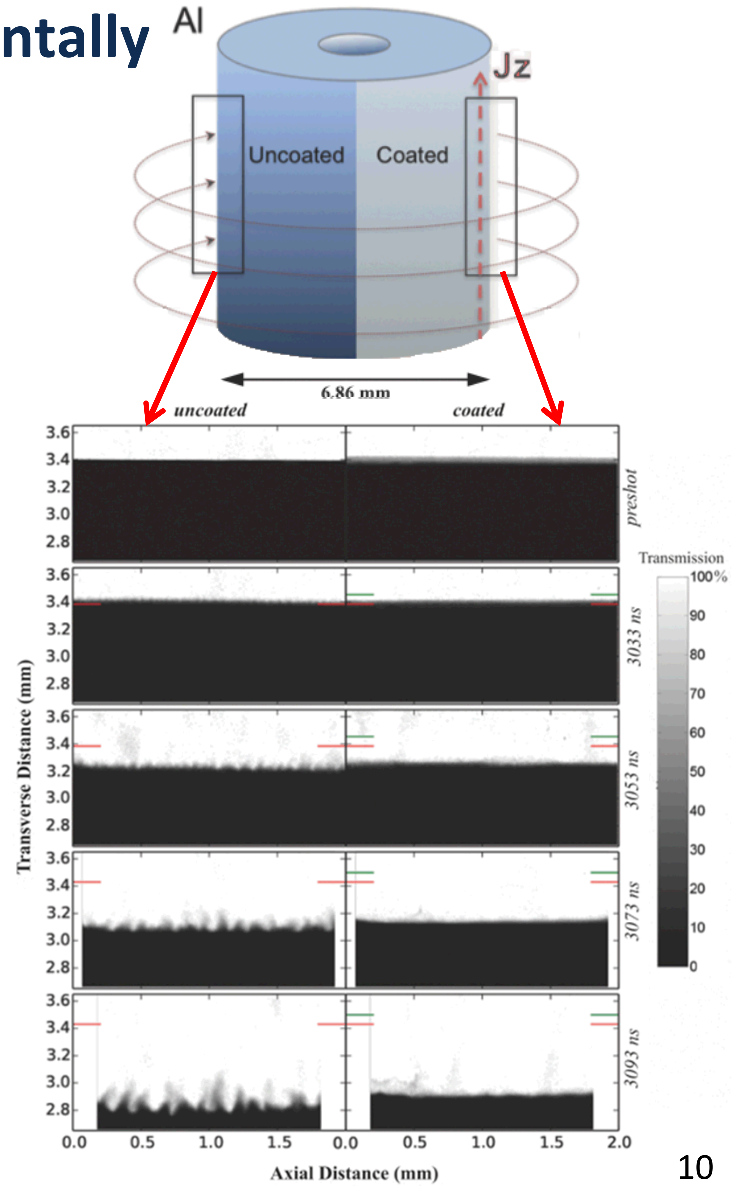
| Time | Est. MRT (λ=100 μm) | $h=0.06Agt^2$ | Observed |
|---|---|---|---|
| A | 0.36 μm | 6.2 μm | 13 ± 7 μm |
| B | 24 μm | 41 μm | 80 ± 7 μm |

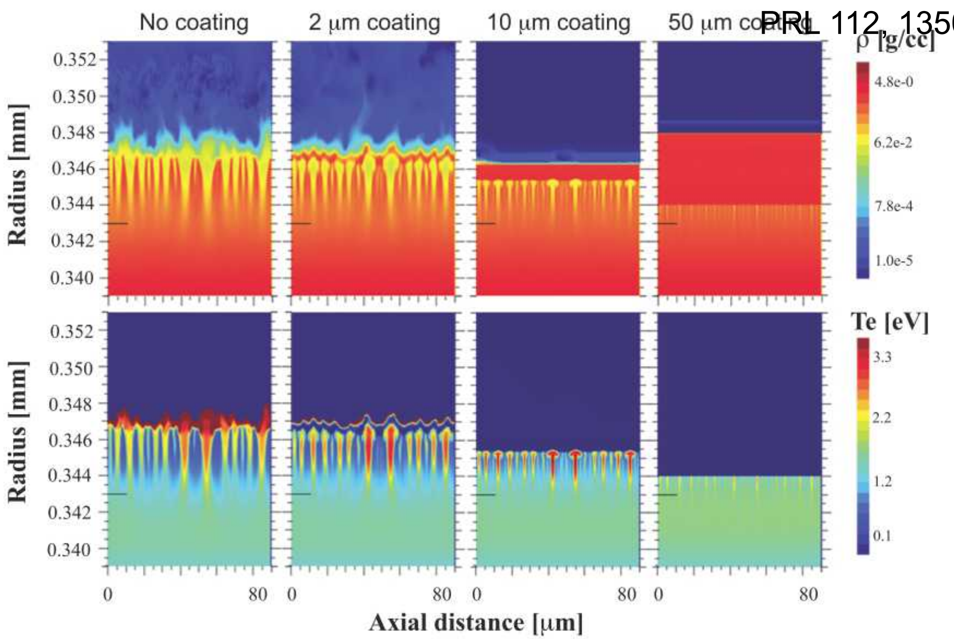
Note that the change from cylindrical to helical perturbations with the addition of an axial magnetic field may also be consistent with ETI seeding hypothesis

*K.J. Peterson *et al.*, Phys. Plasmas (2012); K.J. Peterson *et al.*, Phys. Plasmas 20, 056305 (2013).

# Simulations predicted that we could mitigate the impact of the electrothermal instability by tamping out the density variations—this was confirmed experimentally

- No ETI growth in plastic coating
  - Carries very little current
  - Theoretically ETI stable
- Experimental radiographs of coated and uncoated halves of a solid rod target confirm idea



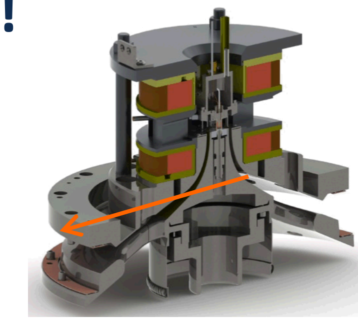




PRL 112, 135002 (2014)

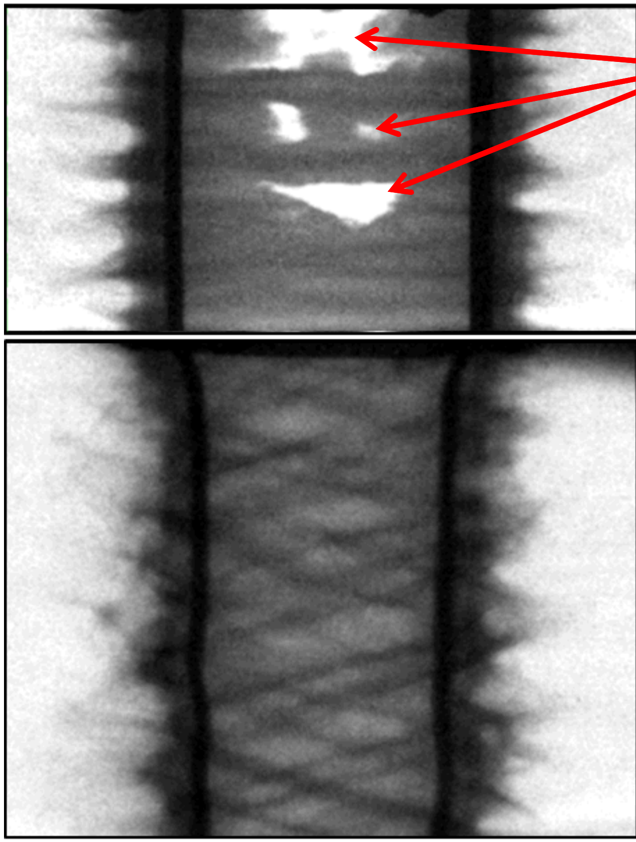


K.J. Peterson *et al.*, Physical Review Letters 112, 135002 (2014)

# Adding an axial magnetic field reduces hard x rays and hot spots, and changes the liner instability structure from cylindrical to helical—evidence it is doing something!

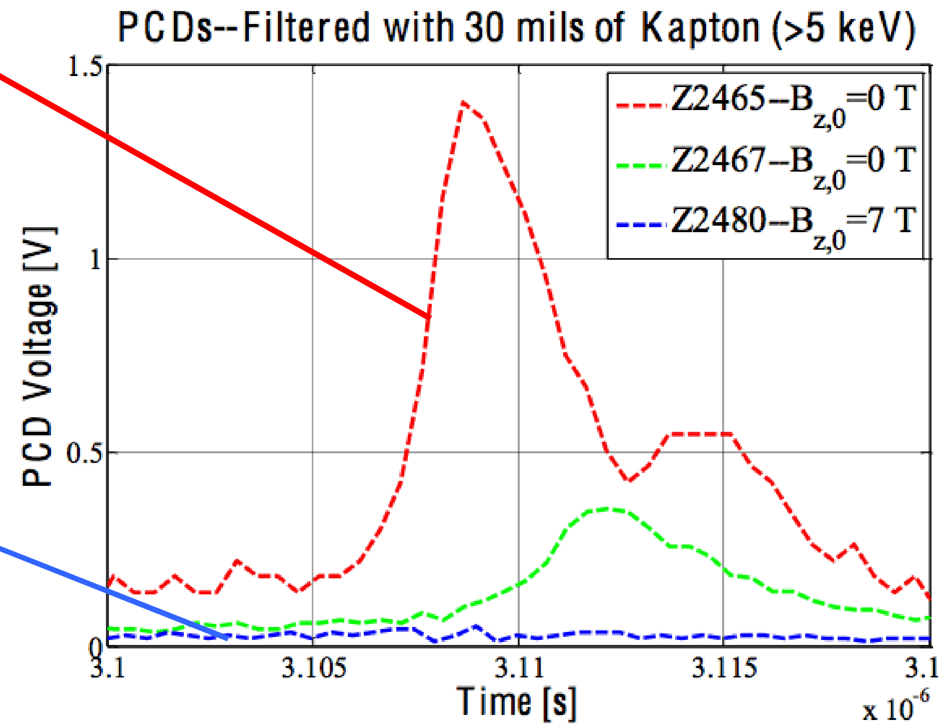


Without Magnetic Field



With Magnetic Field

Time-integrated self-emission from liner implosion at 6151 eV; missing in shots with axial field



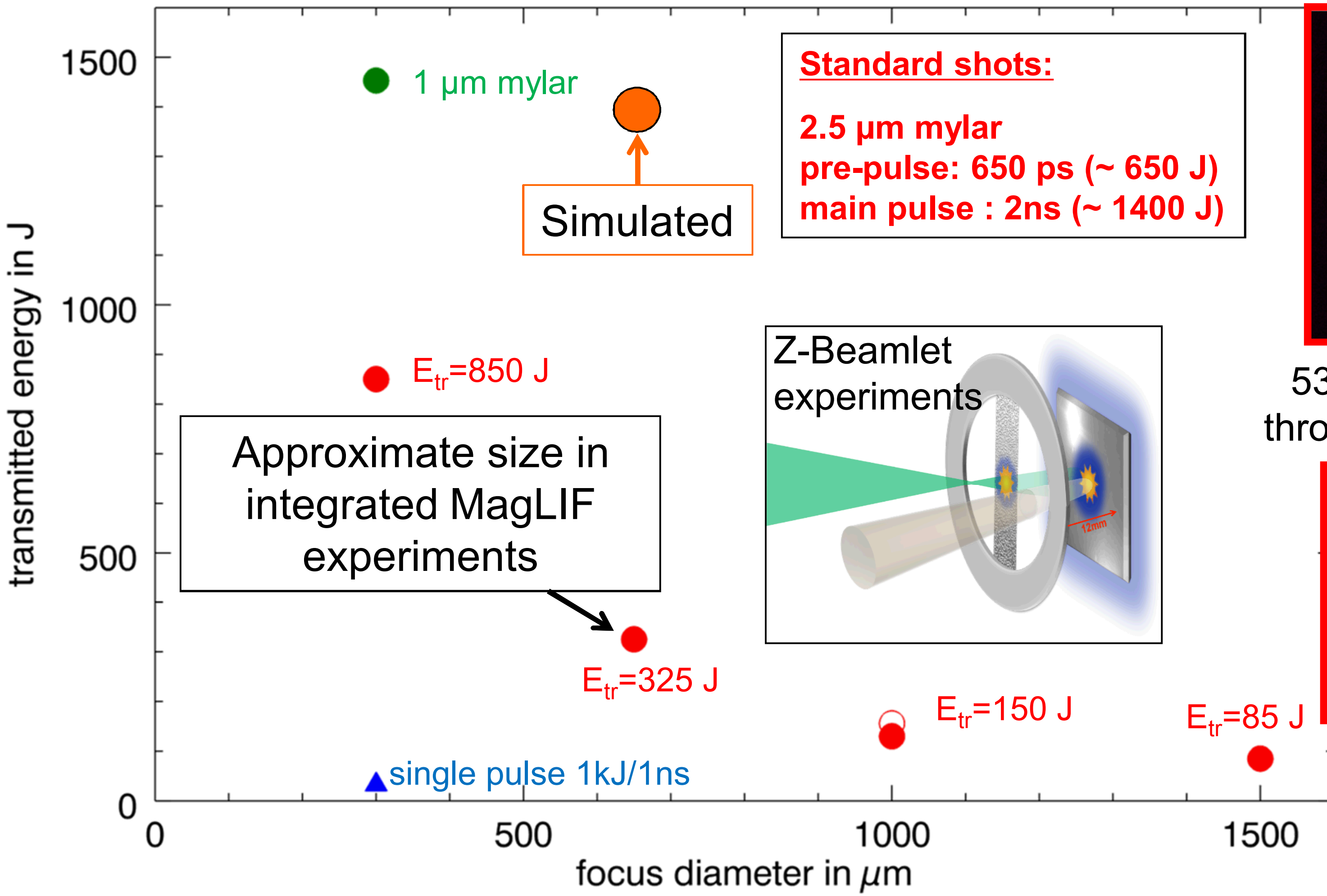

If magnetic flux roughly conserved the additional magnetic pressure from the axial field will suppress micro-pinching—this is indirect evidence for flux compression



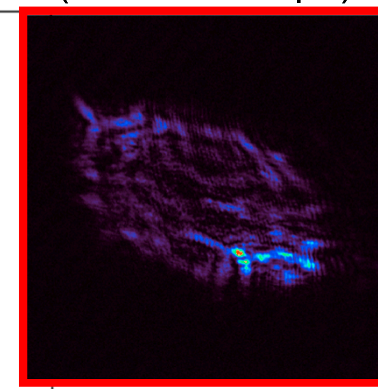
T.J. Awe *et al.*, Phys. Rev. Lett. (2013); *ibid.*, Phys. Plasmas (2014).

# We have found that laser coupling through few micron thick foils using Z-Beamlet is different than we predicted with simulations using a smooth beam

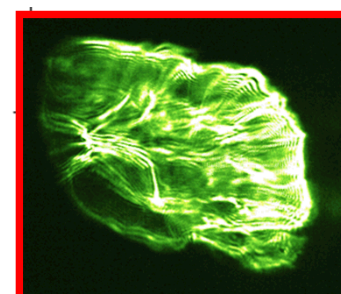
## Calorimeter Measurements

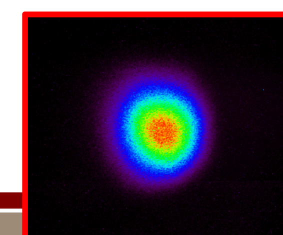



Beam profile for 800 μm diam. (no main amps)



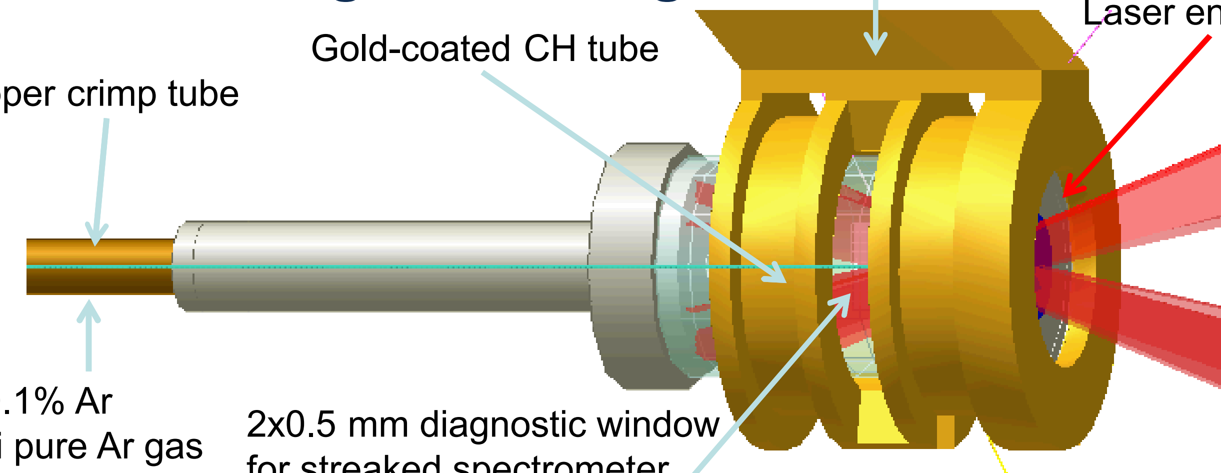
532 nm transmission through foil during pulse





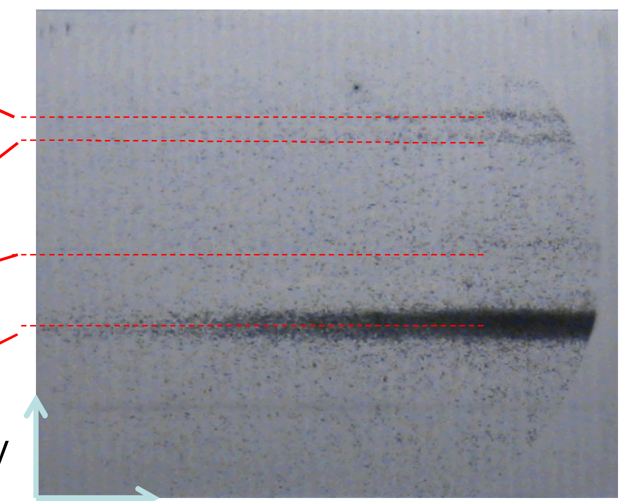
* See Geissel Matthias Poster (this session)

# We just completed our first Omega EP experiments at the University of Rochester to look at the effect of magnetic fields on laser heating and cooling




- Sandia's first MagLIF-related ICF experiments on Omega-EP produced data!
  - Represented a number of "firsts" for the EP facility (e.g., gas fill, diagnostics)— they were extremely helpful
- Results may suggest magnetized plasmas reached higher temperatures as predicted but more shots are needed to confirm.
- First shots also showed poor laser energy coupling through foil until pulse lengthened

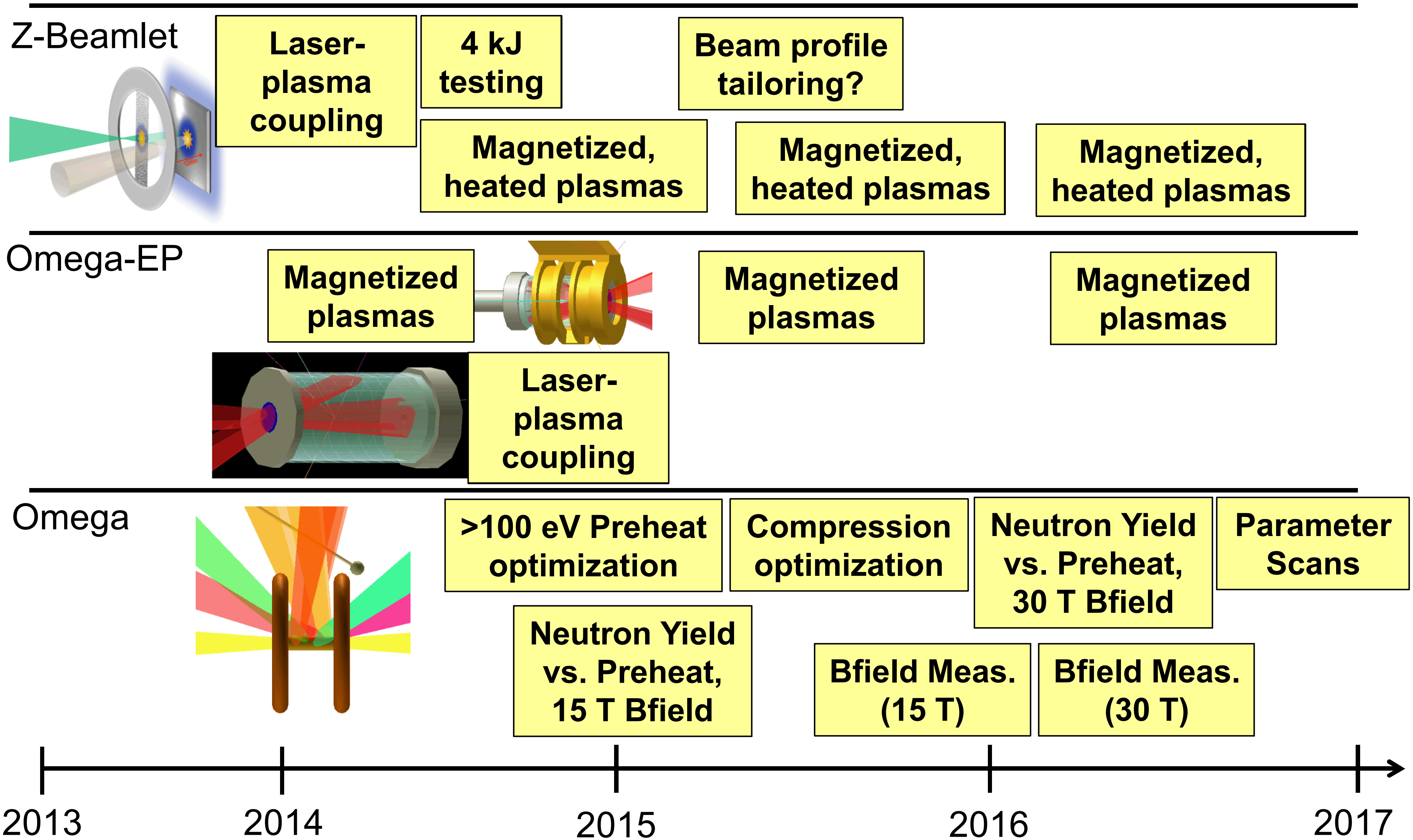
Shot 4 – 48054 – 74 psi D2 magnetized



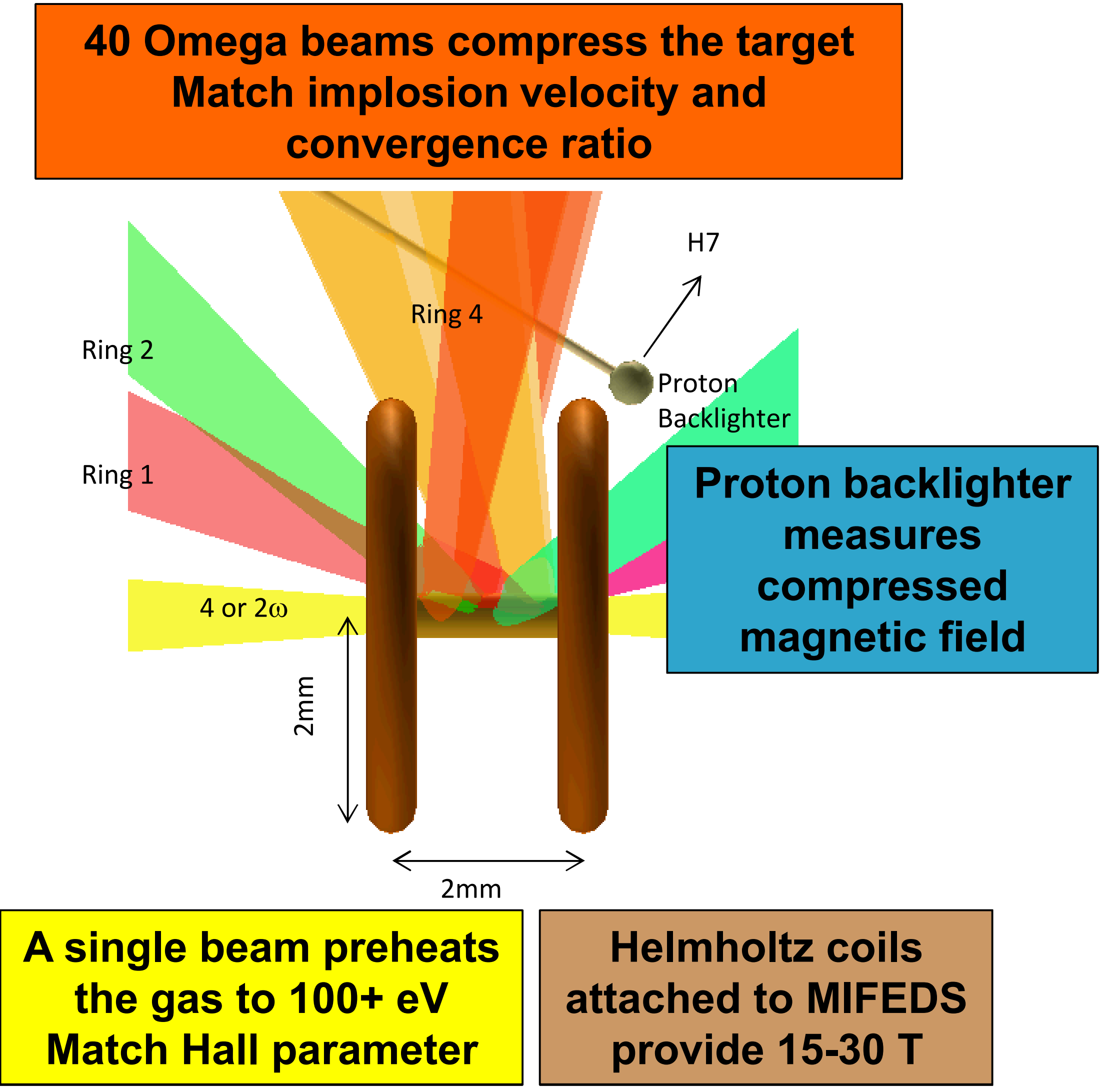



Unmagnetized target did not produce Ar lines

# Laser-based experiments will be an important part of our focused science efforts going forward—the specific plan is evolving as each platform matures.



# We are starting a collaboration with LLE scientists to create and study scaled MagLIF targets on Omega



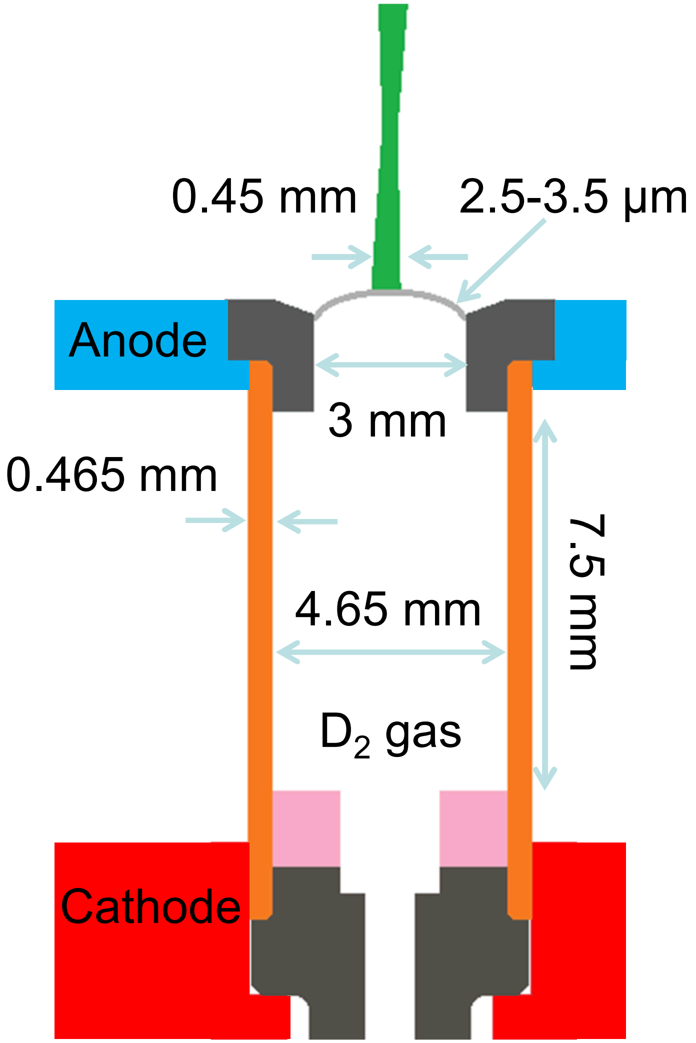

| $B_0$ (T) | Preheat $T_0$ (eV) | Yield ($10^{10}$) | $T_{ion}$ (keV) |
|---|---|---|---|
| 0 | 0 | 0.0667 | 0.77 |
| 0 | 100 | 0.325 | 1.08 |
| 15 | 0 | 0.277 | 1.43 |
| 15 | 100 | 8.63 | 4.94 |
| 30 | 0 | 0.444 | 1.80 |
| 30 | 100 | 12.6 | 5.67 |

Independent modeling using LLE simulation tools (LILAC, DRACO) predicts increase in yield and temperature when both laser heating and magnetization used

May be possible to get 6-9 shot days in 3 years (up to ~90 shots!)

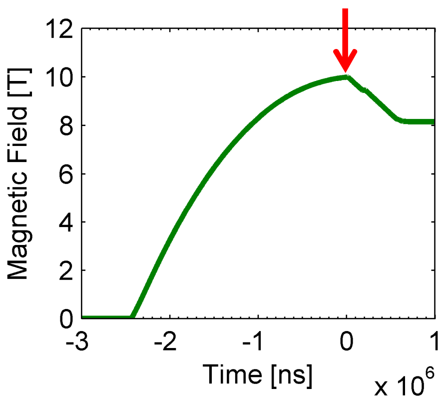
# The target design for our initial experiments incorporates the knowledge gained from focused experiments and extensive simulations

- **Beryllium liner with aspect ratio 6**
  - **Thick liner is more robust to instabilities**
  - **Still allows diagnostic access > 5 keV**
- **Top and bottom implosion cushions**
  - **Mitigates wall instability**
- **Standoff between LEH and imploding region**
  - **Avoid window material mixing with fuel**
- **Exit hole at bottom of target**
  - **Avoid interaction with bottom of target**



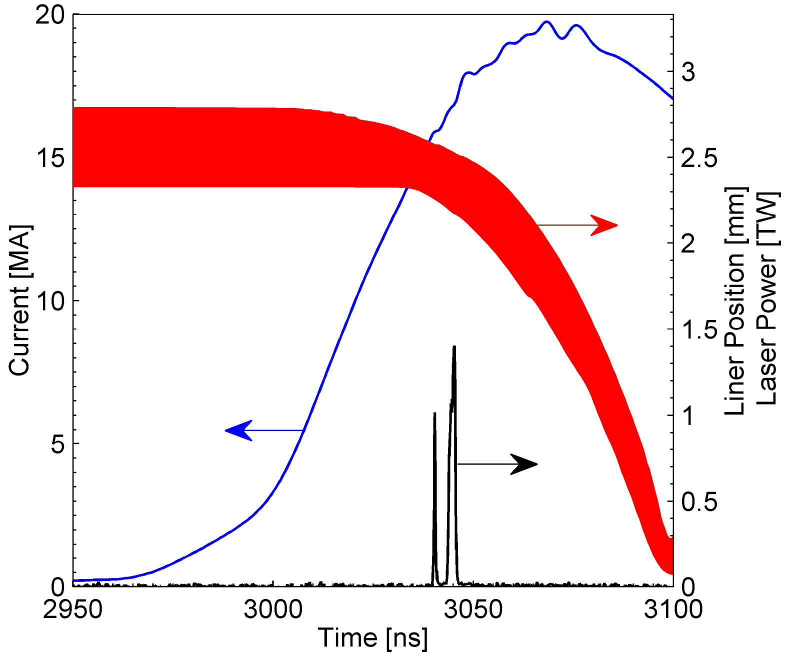
# Initial experiments were conducted at I = 19 MA, B = 10 T, and Laser = 2.5 kJ

Time of experiment



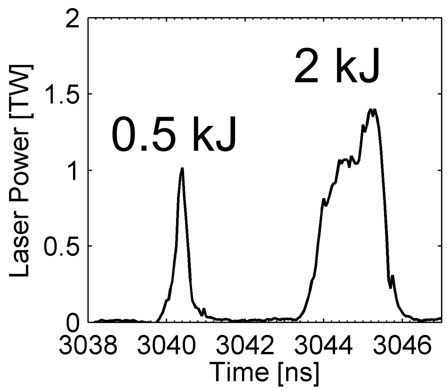

Magnetic field risetime is approximately 2 ms

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



# Comparison of 1D and 2D HYDRA calculations of near-term Z experiments (19 MA, 10 T, 2 kJ)

| Parameter | 1D ideal | 2D integrated |
|---|---|---|
| • $E_{gas}^{abs}$ | 2.20 kJ | 1.74 kJ |
| • $m_{loss}$ | 0% | 43% |
| • $\Phi_{loss}$ | 36% | 38% |
| • $CR_{2D}$ | 28 ($r_{stag}$ 84 μm) | 37 ($r_{stag}$ 63 μm) |
| • $T_i^{peak}$ | 5.0 keV | 6.5 keV |
| • $\langle T_i \rangle^{DD}$ | 2.9 keV | 3.2 keV |
| • $\rho_{gas}^{stag}$ | 0.6 g cm$^{-3}$ | 0.5 g cm$^{-3}$ |
| • $\rho R_{liner}^{stag}$ | 1.0 g cm$^{-2}$ | 0.9 g cm$^{-2}$ |
| • $p^{stag}$ | 2.5 Gbar | 2.2 Gbar (peak in bottle) |
| • $B_z^f r_{stag}$ | 4.1e5 G cm ($r_{stag}/r_\alpha$ 1.5) | 5.3e5 G cm ($r_{stag}/r_\alpha$ 2.0) |
| • $Y_n^{DD}$ | 2.6e14 (in 7.5mm) | 6.1e13 (24% of 1D) |
| • $Y_n^{DD}/Y_n^{DT}$ | 23 | 44 |
| • $t_{burn}^{FWHM}$ | 3.2 ns | 2.1 ns |

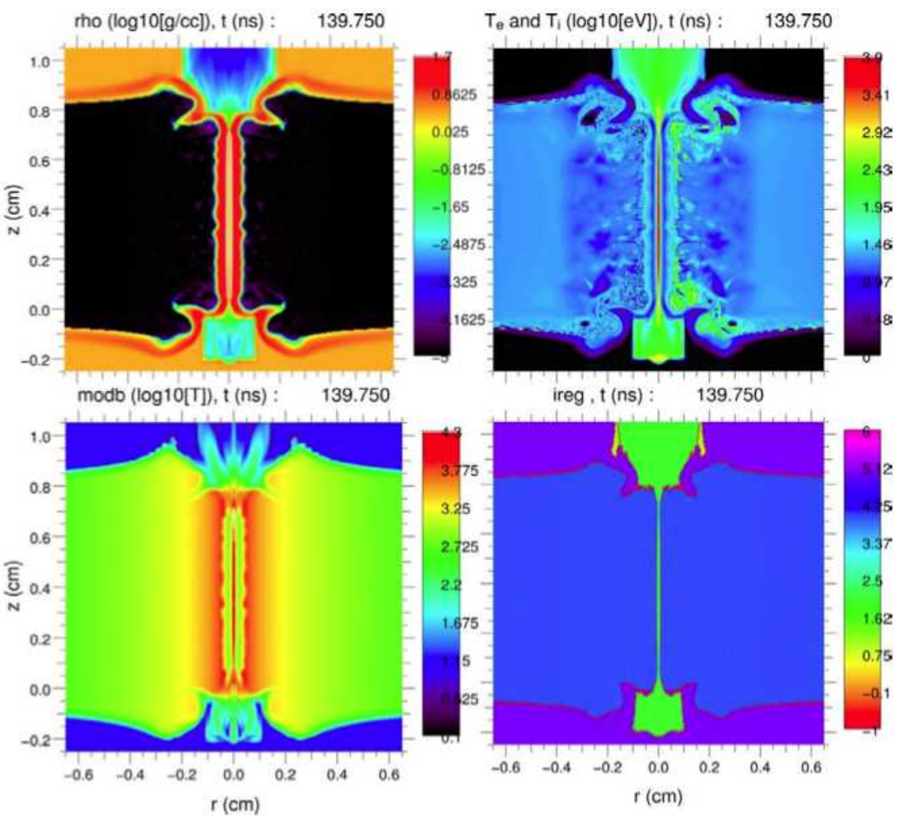
Note: A unique property of magnetic drive is increasing pressure with decreasing radius. If less energy is coupled to fuel, target converges farther in simulations until plasma pressure is sufficient to stop the implosion.



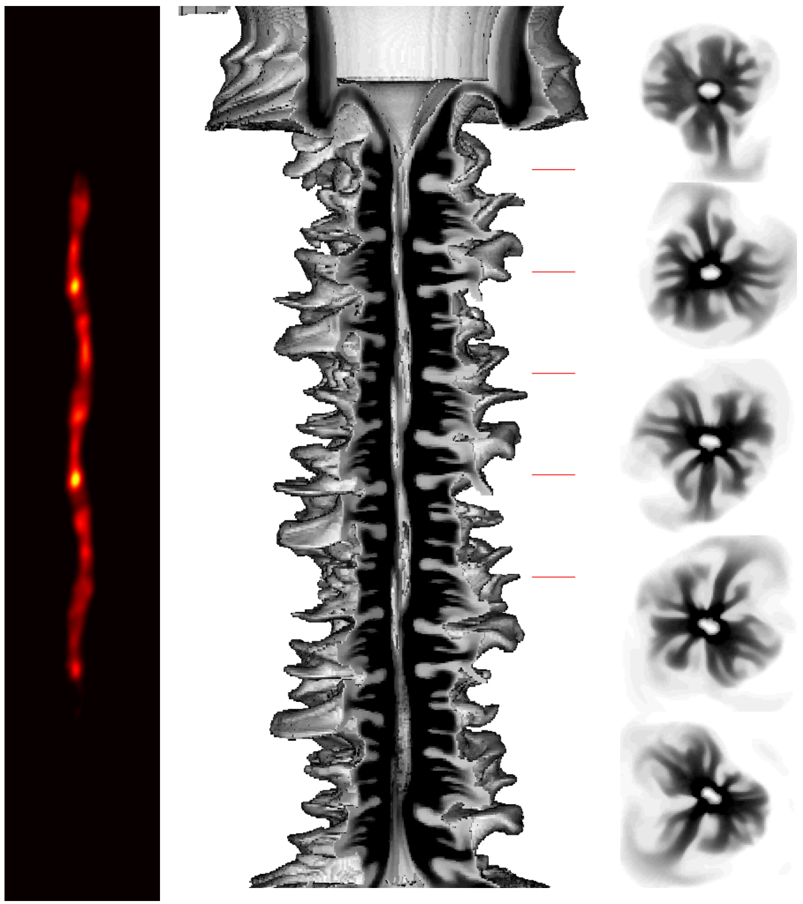
A.B. Sefkow, S.A. Slutz *et al.*, submitted to Phys. Plasmas (2014).

# We are actively working to improve simulation models and benchmarking results to experimental data

2D Integrated Hydra Simulations[1]



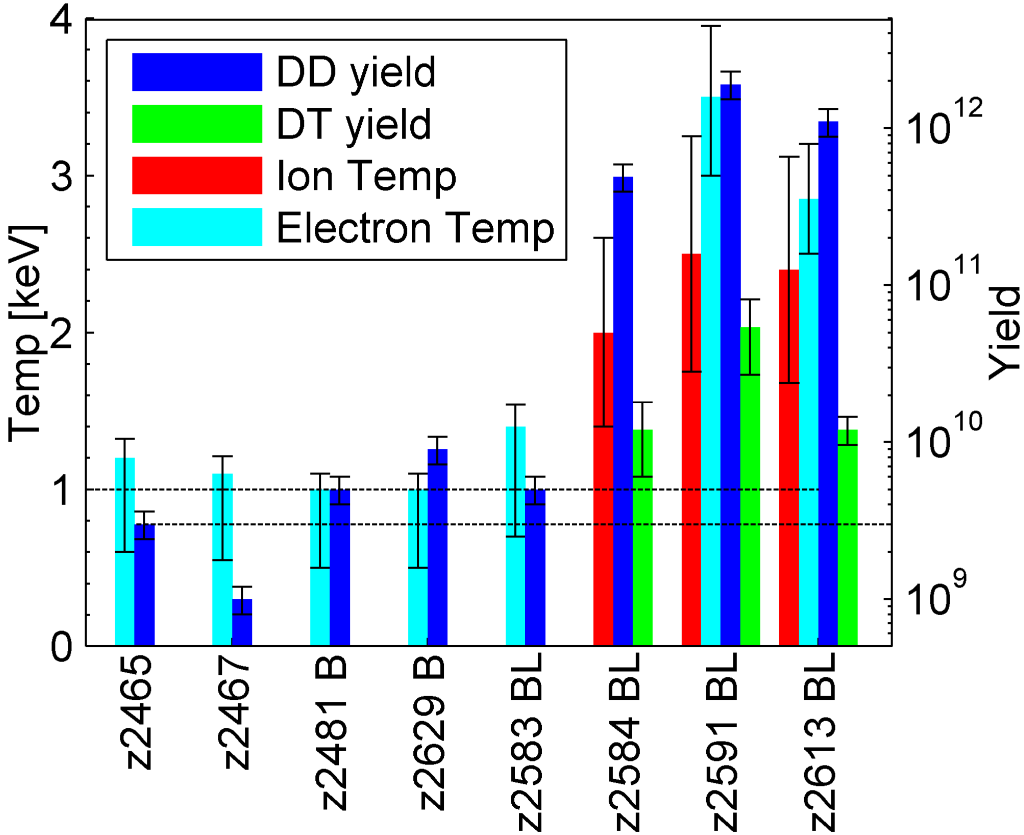

3D GORGON Simulations[2]





[1]A.B. Sefkow, S.A. Slutz *et al.*, submitted to Phys. Plasmas (2014), [2]Chris Jennings simulations

# Significant neutron yield, ion temperature, and electron temperatures are only seen when both magnetization and preheat are present, as expected for a 70-100 km/s implosion

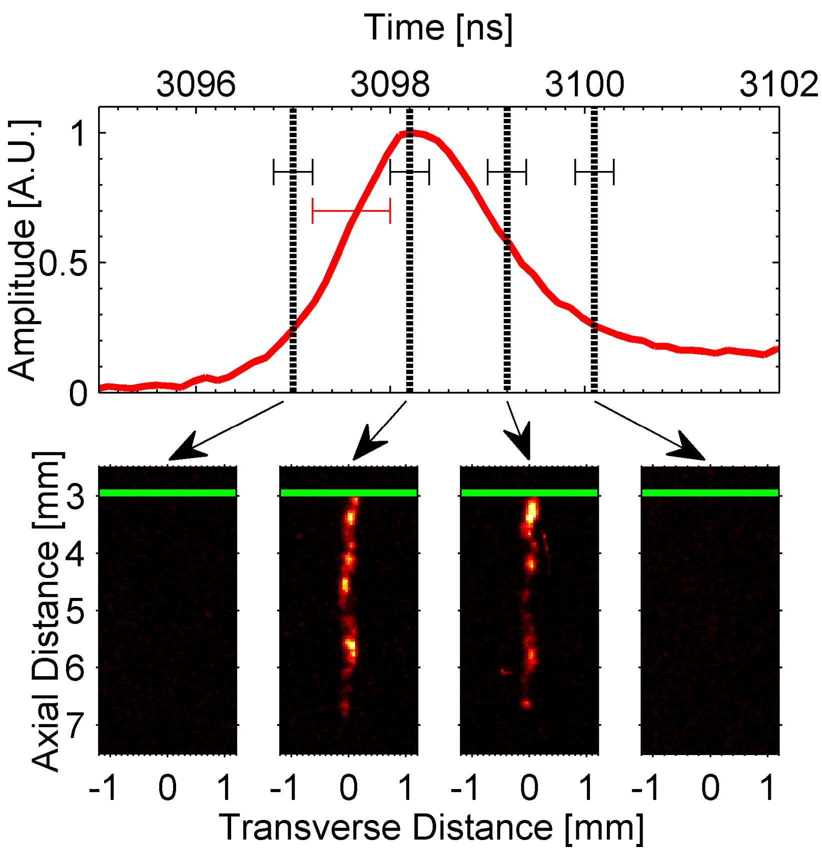


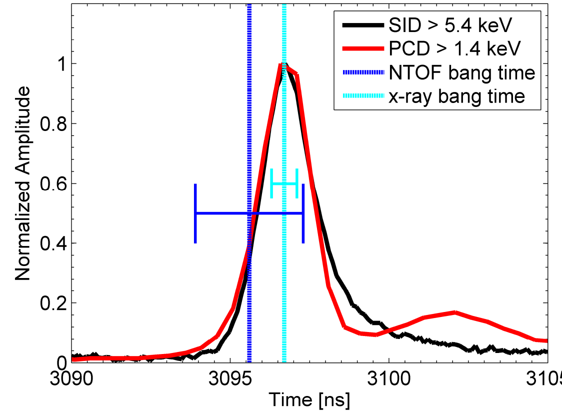

- **Experiments with $T_{electron} \approx 1$ keV have negligible DD yield**
- **For $T_i \approx T_e > 2$ keV, significant yield is observed**
- **Measurable DT yield is observed only on experiments with high DD yield**

Analytic estimates of DD yields are consistent with volume inferred from images (2-4.7e-5 $cm^3$), x-ray duration (2 ns), spectroscopy/radiation-inferred density (0.2-0.6 $g/cm^3$) and temperature (2-3.5 keV)


M.R. Gomez, S.A. Slutz, A.B. Sefkow *et al.*, manuscript in preparation (2014).

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



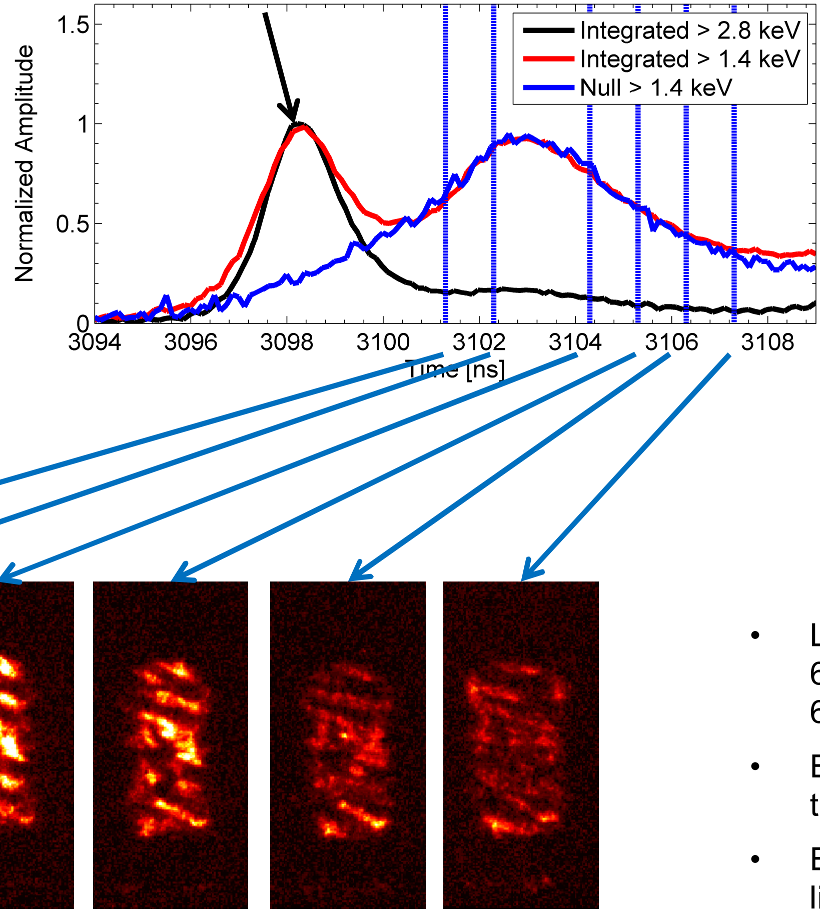

- **Narrow x-ray signature and emission column only observed on experiments with significant neutron yield**
- **X-ray burst has high energy components**
- **X-ray bang time and NTOF bang time agree within the uncertainty of the measurements**
- **Emission column is observed only during the peak in the x-ray signal**
- **Stagnation column width is at the resolution limit of the instrument (~150 microns)**

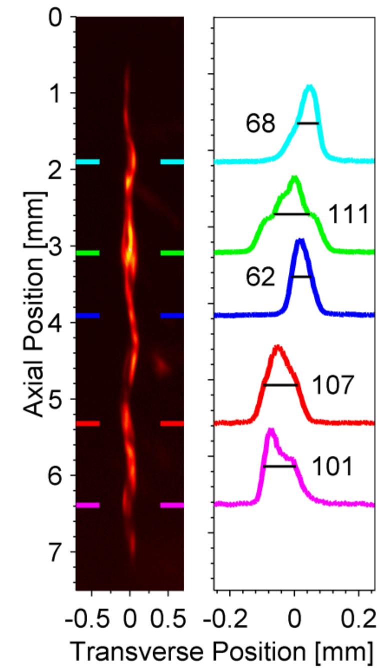


M.R. Gomez, S.A. Slutz, A.B. Sefkow *et al.*, manuscript in preparation (2014).

# High energy x-ray signal and a narrow stagnation emission is only observed when *both* magnetization and preheat are present

- Liner emission is observed in all experiments
- Liner emission is at a lower photon energy ( < 2.8 keV)
- Liner emission is getting larger at late times



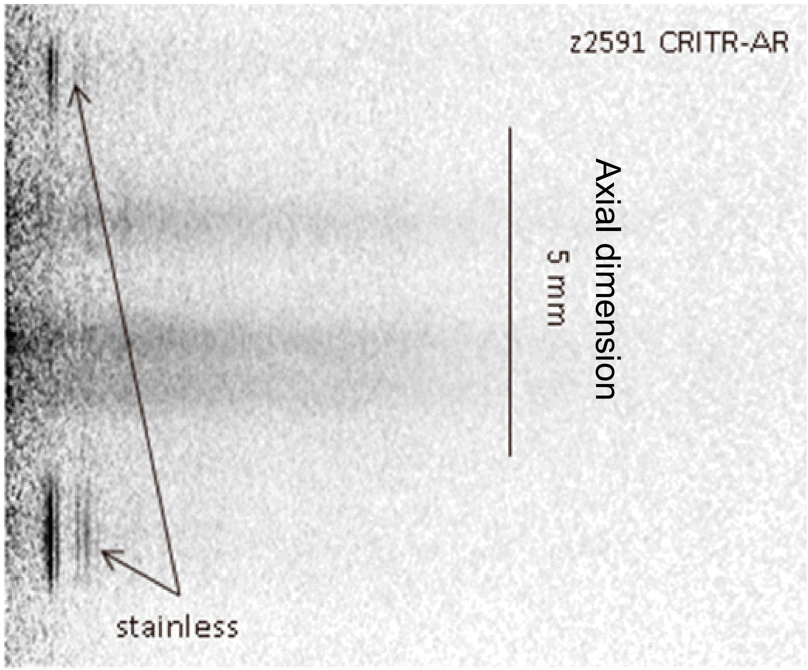



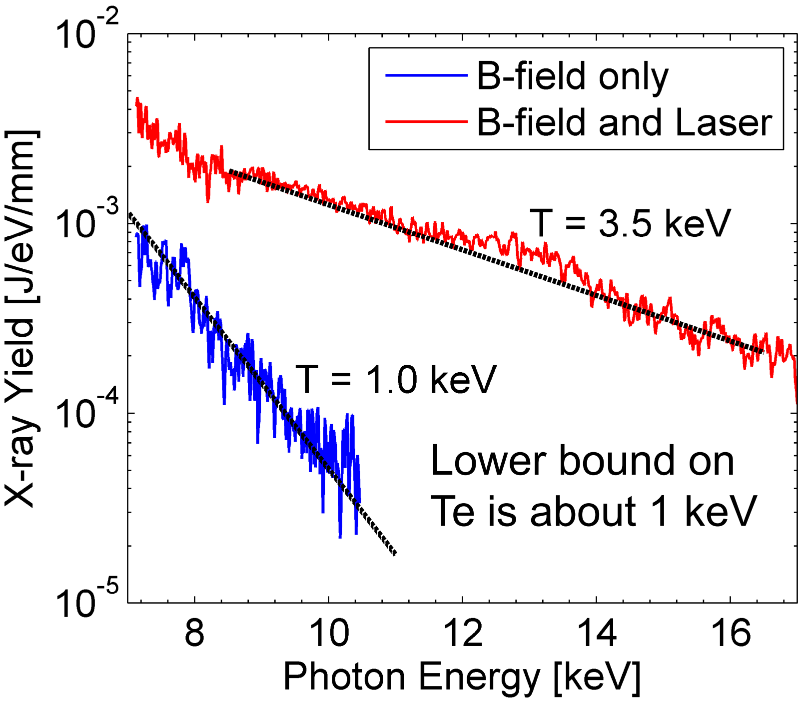

- Lineouts of stagnation column vary from 60 to 120 μm FWHM (resolution is about 60 microns)
- Emission is observed from about 6 mm of the 7.5 mm axial extent
- Emission region does not define the fuel-liner boundary, but defines the hottest region of the fuel
- Stagnation column is weakly helical with 1.3 mm wavelength and 0.05 mm offset

# 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 lines from stainless steel (Fe, Cr, Ni) appear at the anode and cathode, but minimal high-Z contamination is observed in hot central regions

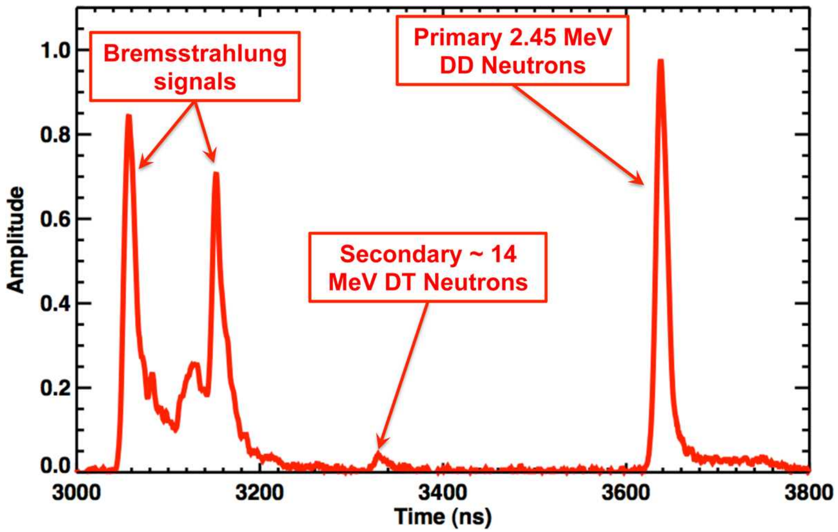
The slope of the high-energy continuum emission implies Te ~ 1.5 keV at the anode and cathode, and T ~ 3.5 keV in the central regions

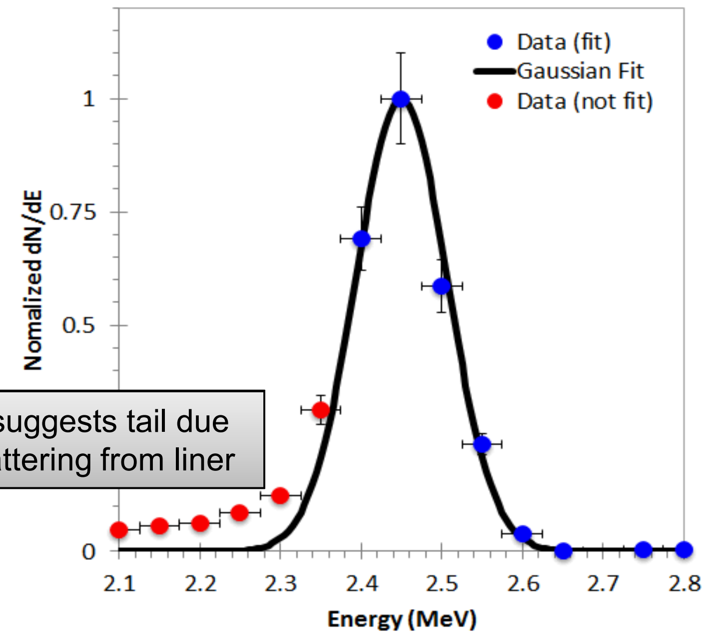



M.R. Gomez, S.A. Slutz, A.B. Sefkow *et al.*, manuscript in preparation (2014).

# Neutron diagnostics indicate these experiments produced both primary (2.45 MeV) and secondary (14 MeV) neutrons with ion temperatures >2 keV at stagnation




"Secondary" 14 MeV neutrons can be produced by 1 MeV tritons interacting with D fuel

$$D + D \xrightarrow{50\%} 0.8\text{ MeV } He^3 + 2.5\text{ MeV n}$$
$$\xrightarrow{50\%} 1.0\text{ MeV T} + 3.0\text{ MeV p}$$

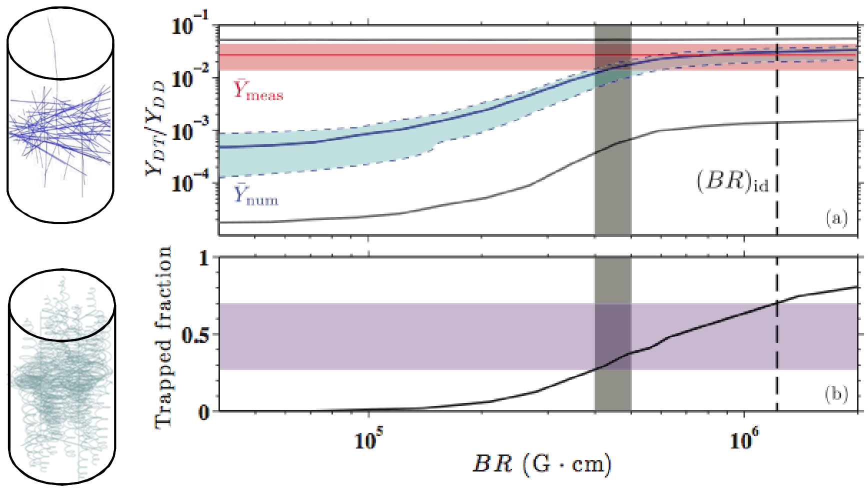
One triton is produced for every 2.45 MeV neutron that is produced

Note: Significant ~0.1-10 MeV bremsstrahlung produced by facility induces a background activation "yield"—e.g., shots with no fusion fuel produce ~5e9 "DD yield"

- **DD neutron peak observed in experiments with significant yield (>1e10)**
- **Gaussian profile fit to high energy side of peak to determine ion temp**
- **Ion temperatures were between 2 and 2.5 keV for high yield experiments**

# Secondary nuclear reactions and time-of-flight data suggest that the fuel is magnetized

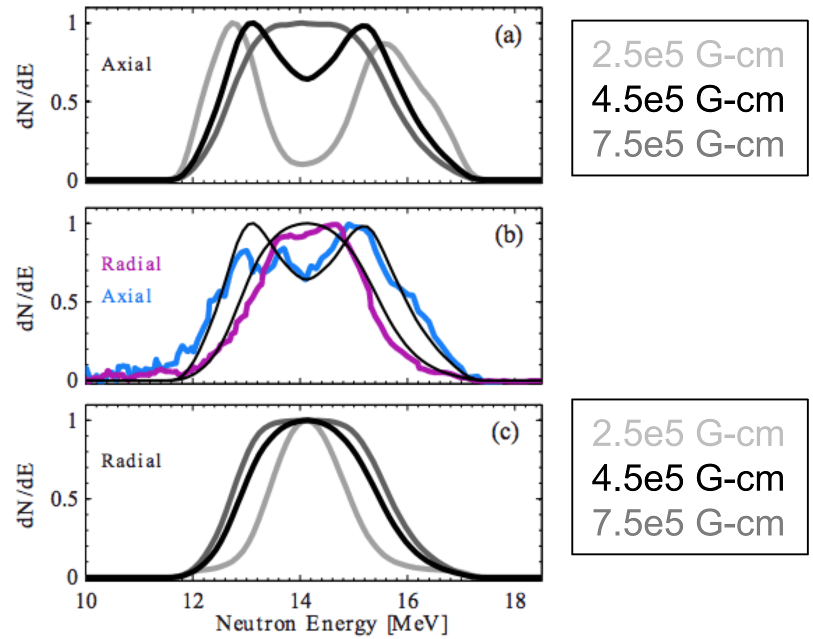
As the triton's Larmor radius becomes comparable to the plasma radius there is a significant enhancement in the DT/DD yield ratio as the effective path length increases




Magnetized tritons implies magnetized electrons: $\omega_{ci}\tau_{ie} \approx \omega_{ce}\tau_{ee}$

Magnetized tritons implies magnetized alpha particles: $r_t \approx 1.1 r_\alpha$

Neutron time-of-flight data is also consistent with the fusing particles being magnetized




nTOF spectra consistent with ~4.5e5 G-cm

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



* See Paul Schmit's Poster (this session)

# Poor laser-energy coupling in these targets is simulated to dramatically decrease yields

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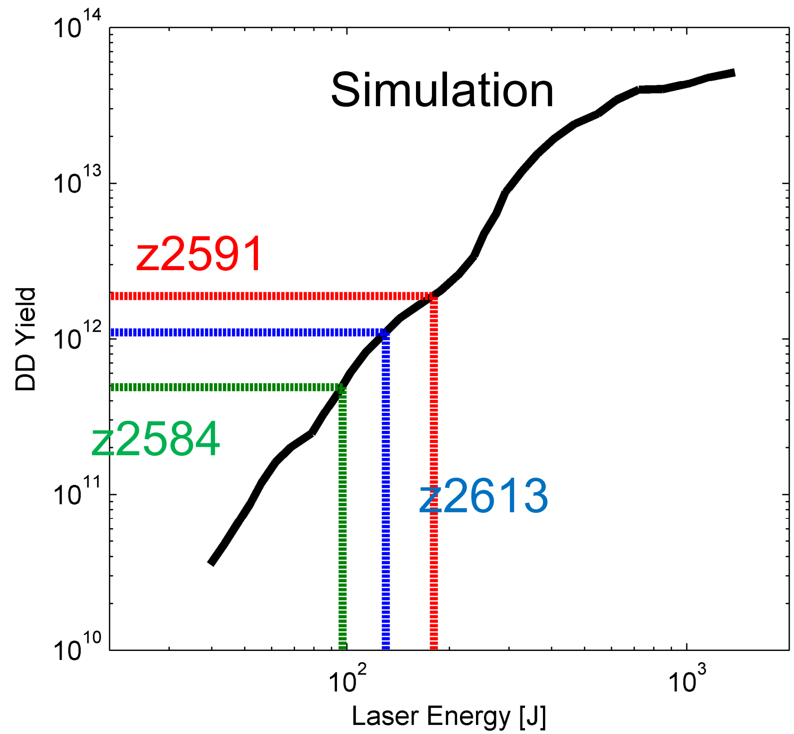
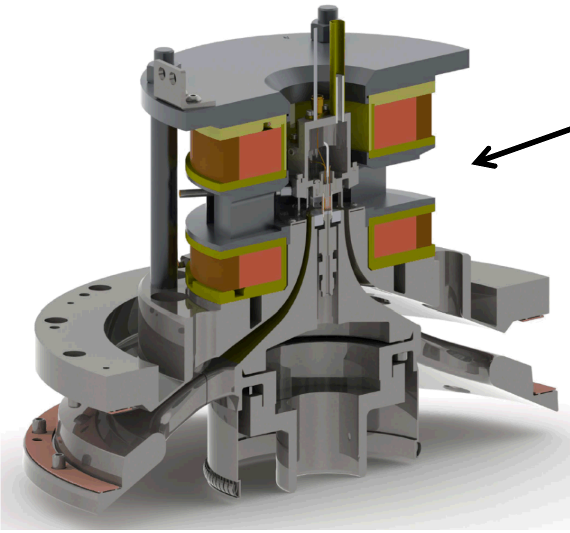
- Separate laser transmission measurements suggest that the majority of the laser energy does not make it through the foil (<400 J)
- Modeled this way in HYDRA, measured yields are consistent with about 200 J of laser energy coupled into the fuel
- We are actively working on this issue in Z, Z-Beamlet, and Omega-EP experiments
- Likely not only issue—we have not evaluated other topics contributing to reduced yield (e.g., Be mix, worse heat transport suppression than modeled, non-uniform assembly)



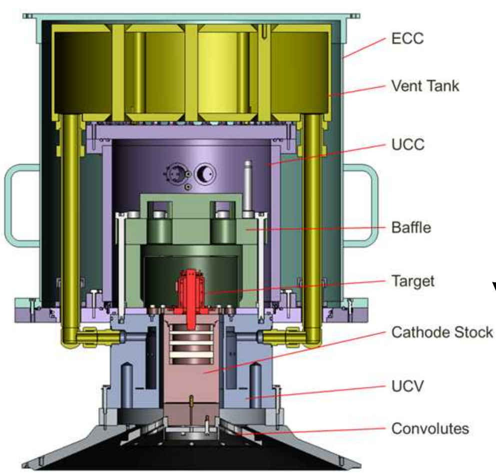

**Experiments will be conducted in near future to test improvements in laser coupling with "smoothed beams"**

# To demonstrate our understanding of the underlying science, we plan to improve our experimental capabilities to permit performance scaling experiments on Z by the end of FY15

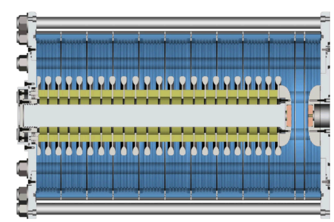


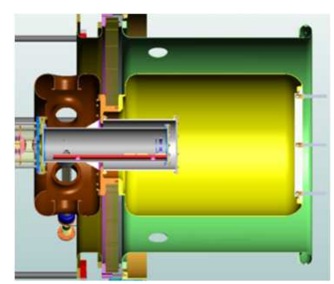
**Increase B-field from 10 T to 30 T**

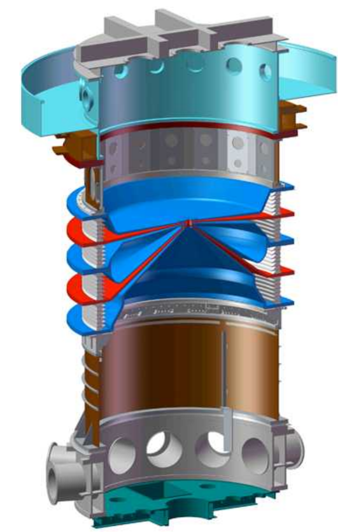

**Increase laser energy from 2 kJ to >6 kJ**




**Increase current from 20 MA to 25 MA**







**Begin designs for DT fill capability on Z (no DT before end of FY15)**

# We are pursuing two parallel technology development paths to achieve 30 T fields on Z in 2015 in support of our scientific studies and performance scaling experiments

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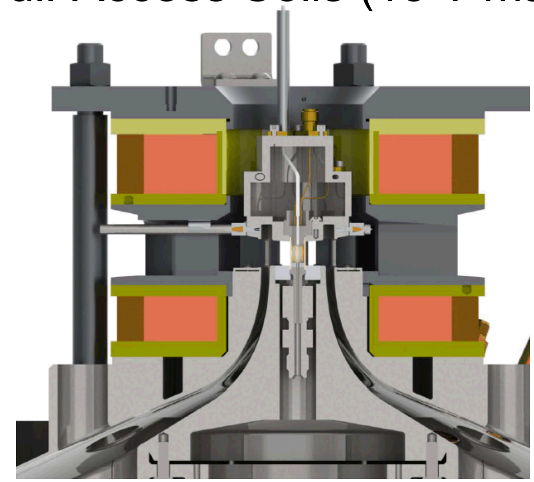
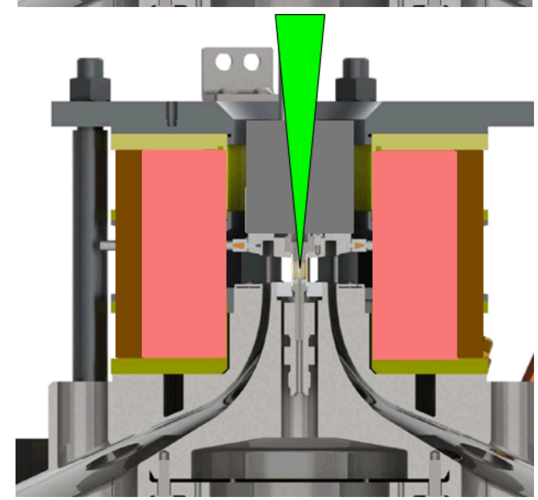
- Most direct path to 30 T is to trade off radial diagnostic access for increased coil volume
- Have successfully tested the full-access coil configuration to 15 T in laboratory—peak stresses on those coils exceed those in our 30 T no-access coil designs
- Currently incorporating additional state-of-the-art high-field coil technologies (e.g., internally reinforced magnets, high strength conductors)
- Working in parallel with National High Magnetic Field Laboratory at Los Alamos to build an independent 30 T prototype by end of FY14—they have also reviewed our designs and concur

Full-Access Coils (15 T max)

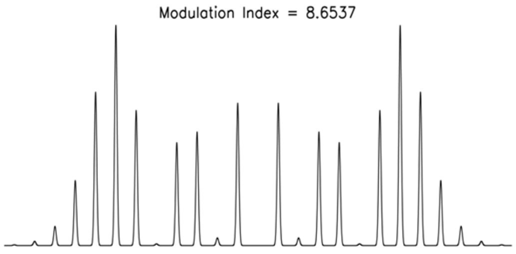




No-Access Coils (30-40 T max)

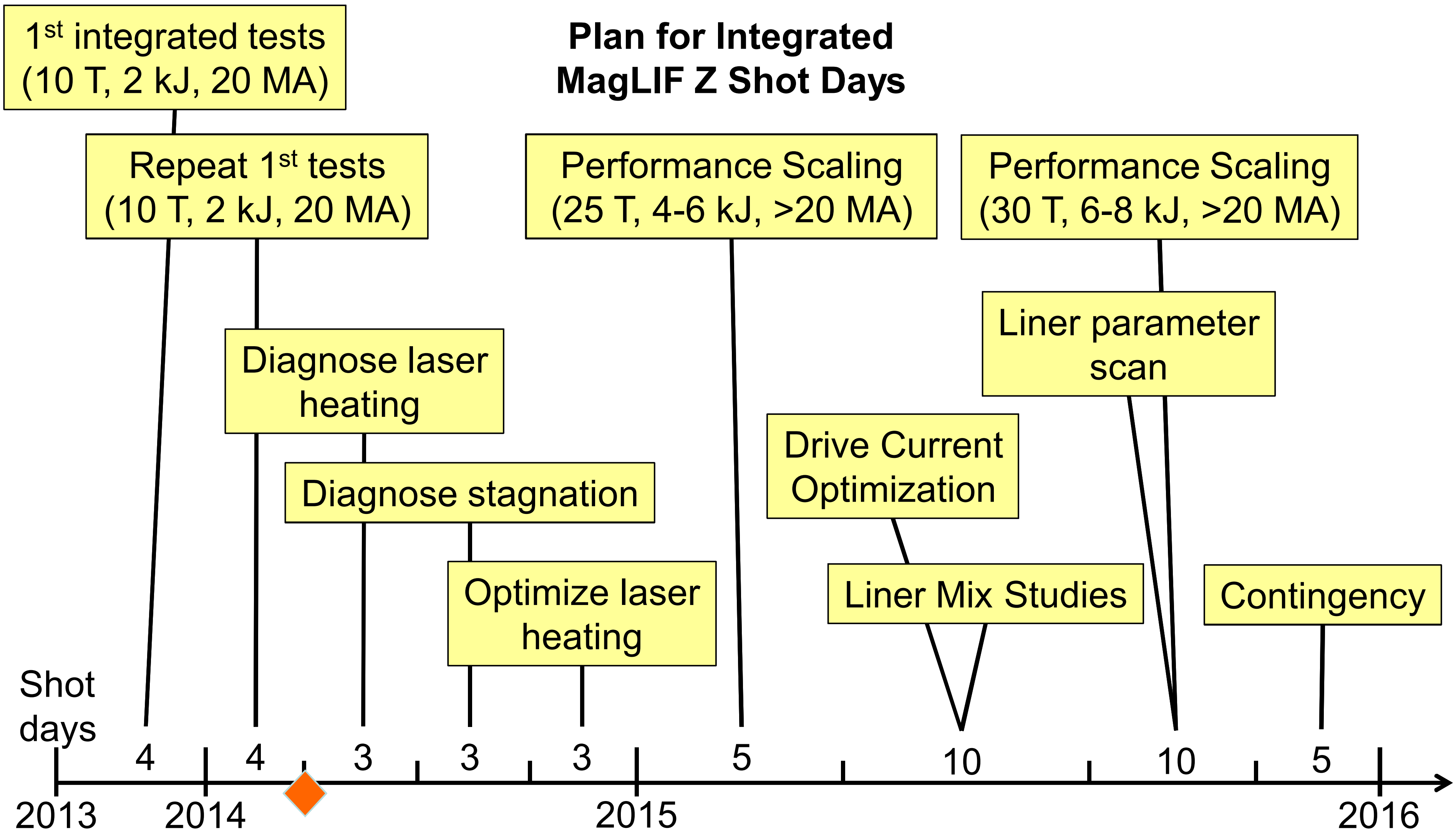
# We have just finished upgrading Z-Beamlet from 2 kJ to 4 kJ to support MagLIF/DMP experiments—additional upgrades to increase energy to 6-8 kJ is now underway

- 4 kJ upgrade increased the bandwidth of the laser to suppress SBS and allowed us to go from 2 ns pulses to 4 ns pulses at existing ~1 TW power levels.




- Upgrade to 6-8 kJ is planned to be completed by the end of 2014. Some of the long-lead time components exist from the original “Beamlet” system Sandia inherited from LLNL in late 1990s, but were never installed. Other components have to be purchased or modernized.
  - Install and optimize adaptive optic for improved beam wave front
  - Procure/replace some damaged optics in beam transport system (related to improving beam wave front)
  - Install booster amplifiers and associated pulsed power

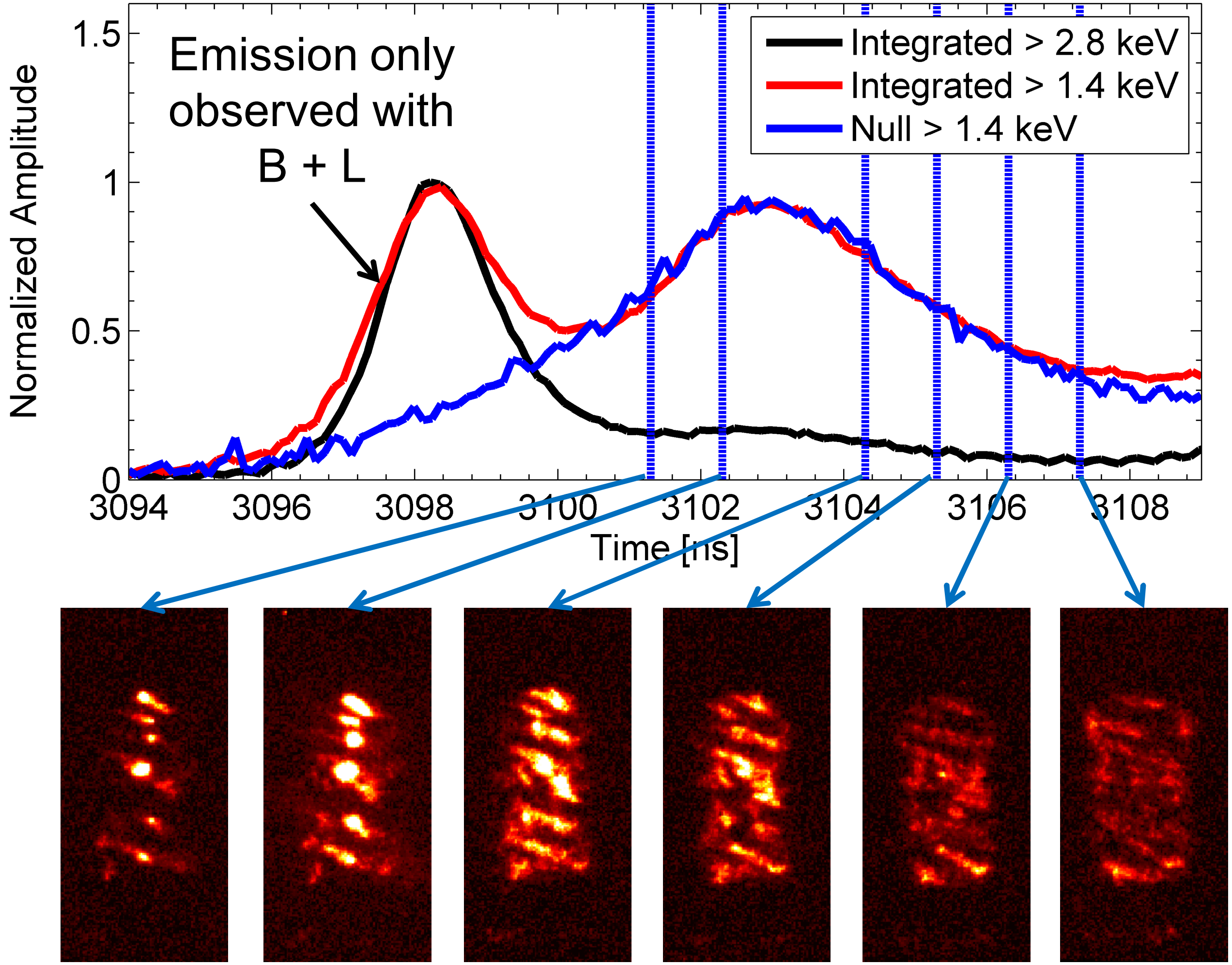
# Our proposed 2015 Z shot distribution strives to mature our understanding of MagLIF by the end of FY15 (go from 5 to >40 experiments)



# Backups

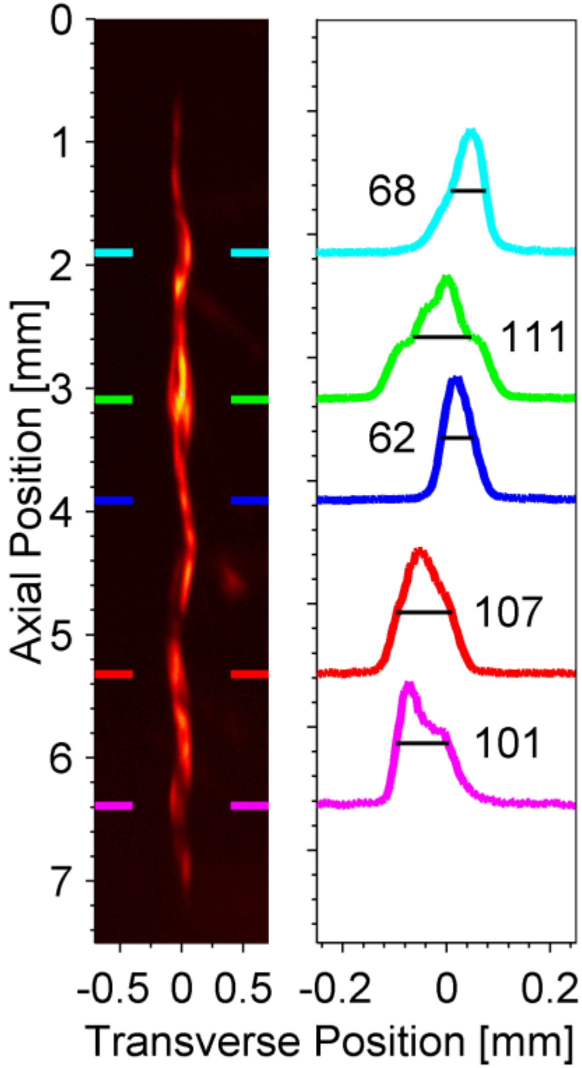
# High energy x-ray signal and a narrow stagnation emission is only observed when *both* magnetization and preheat are present

- **Liner emission is observed in all experiments**
- **Liner emission is at a lower photon energy ( < 2.8 keV)**
- **Liner emission is getting larger at late times**



# High resolution images of the x-ray emission from the hottest part of the fuel show a relatively stable stagnation column

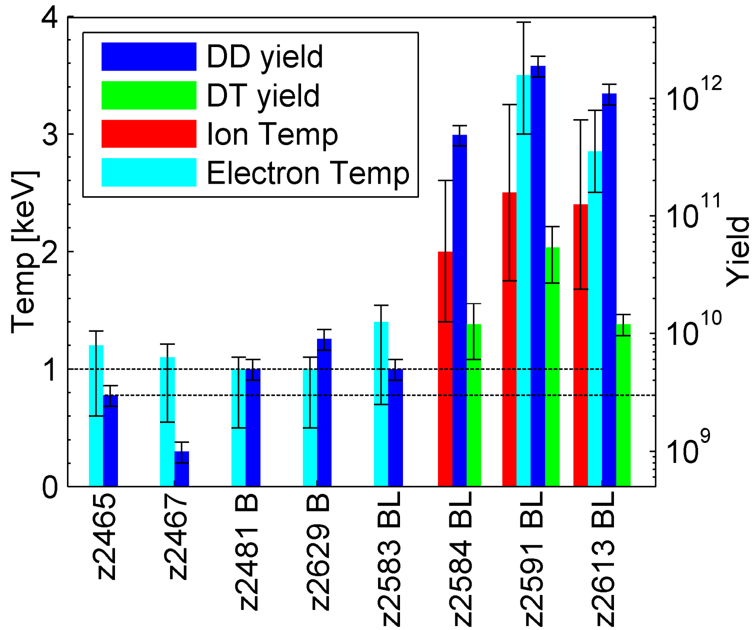
- **Lineouts of stagnation column vary from 60 to 120 µm FWHM (resolution is about 60 microns)**
- **Emission is observed from about 6 mm of the 7.5 mm axial extent**
- **Emission region does not define the fuel-liner boundary, but defines the hottest region of the fuel**
- **Stagnation column is weakly helical with 1.3 mm wavelength and 0.05 mm offset**

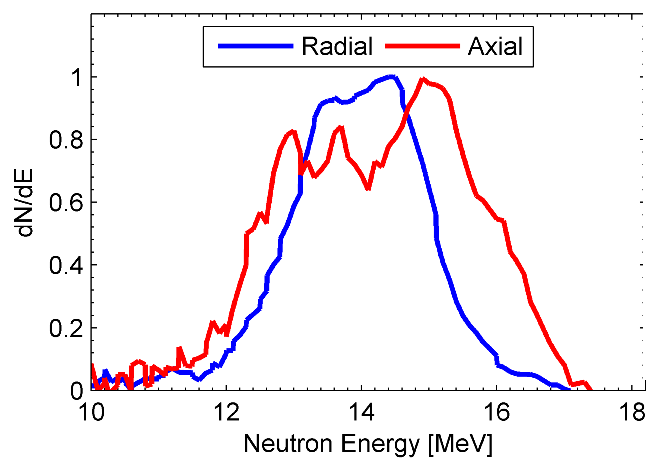


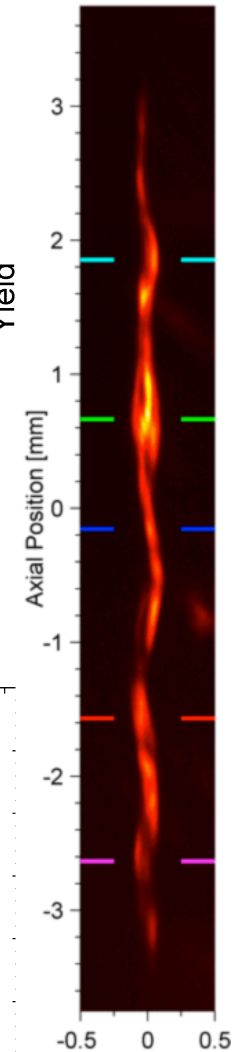
# We obtained promising initial results with MagLIF and seek to mature our understanding significantly for the National ICF Path Forward Review in FY15

Sandia National Laboratories

- We achieved DD yields up to 2e12 (~0.3 kJ DT equivalent) in our first integrated tests of Magnetized Liner Inertial Fusion (MagLIF)
- A variety of data were collected that appear to show a <150 μm diameter, ~3 keV, highly magnetized plasma was produced—remarkable for a 70-100 km/s implosion!
- 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

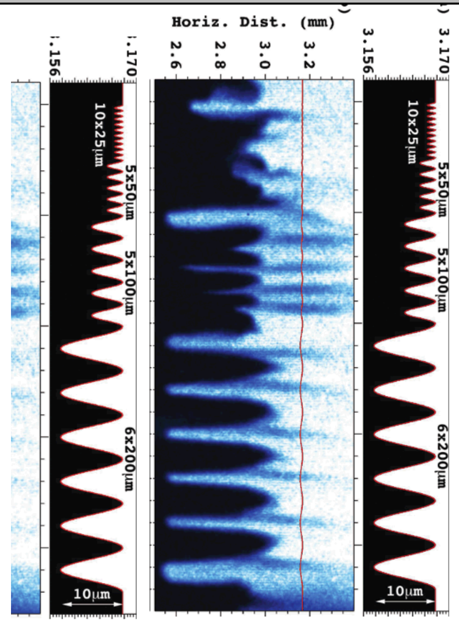


# Surface roughness and small defects do not appear to be the seed for MRT instability growth, but rather electrothermal instabilities

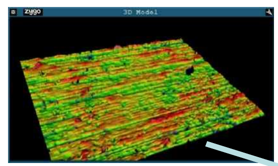
Observed Instability growth is not linearly proportional to the amplitude of the initial perturbations.

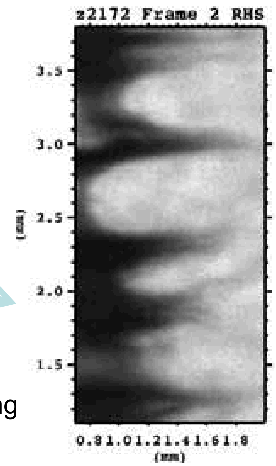



Ao = 60 nm

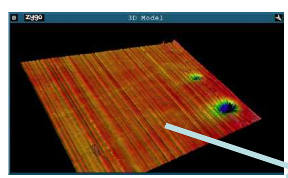
Azimuthal symmetry is **not** sensitive to surface characteristics

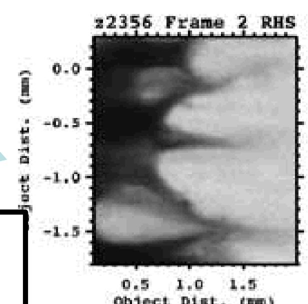
Standard Process
(50 nm RMS)





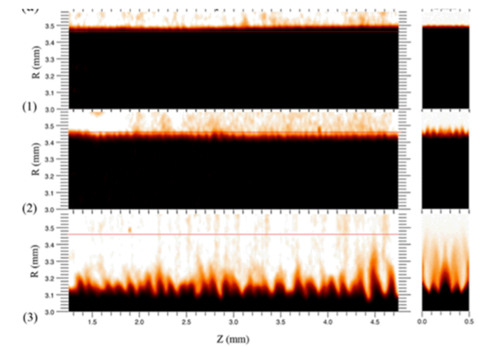

axial machining and polishing
(50 nm RMS)

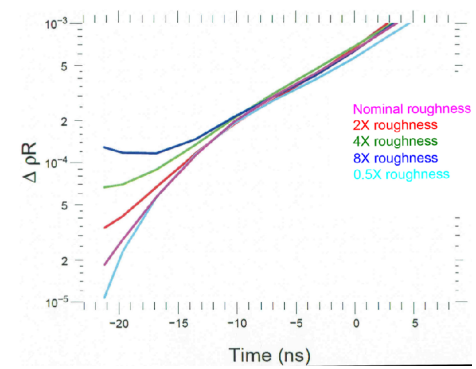


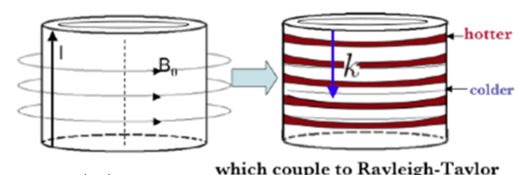



**Symmetry may generally be worse for axially-polished liners**

Electrothermal instabilities may be the dominant seed for MRT




$$\frac{d\eta(T)}{dT} > 0$$