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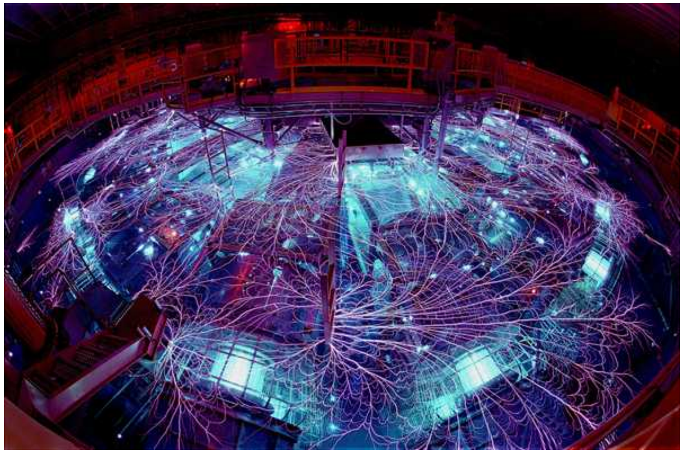

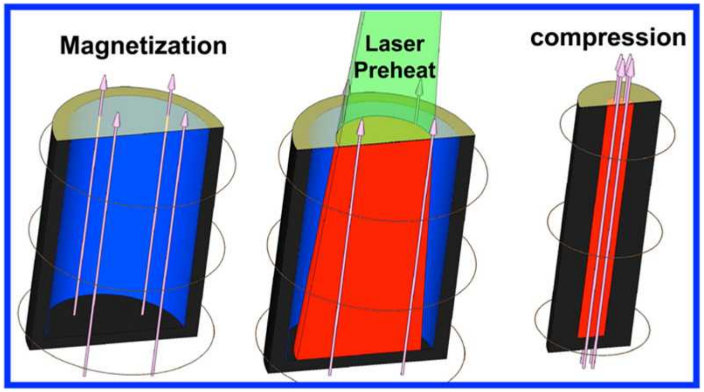


# Magnetic Direct Drive Overview (Magnetized Liner Inertial Fusion)

**Greg Rochau**

**Manager, Radiation and Fusion Experiments**

*Sandia National Laboratories*

*1st Workshop on Addressing Common Challenges in ICF*

*Santa Fe, NM, June 20–24, 2016*

U.S. DEPARTMENT OF ENERGY

NNSA National Nuclear Security Administration

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# MagLIF is a broad national collaboration


T.J. Awe, C.J. Bourdon, G.A. Chandler, P.J. Christenson, M.E. Cuneo, M. Geissel, M.R. Gomez, K.D. Hahn, S.B. Hansen, E.C. Harding, A.J. Harvey-Thompson, M.H. Hess, C.A. Jennings, B. Jones, M. Jones, P.F. Knapp, D.C. Lamppa, J.S. Lash, M.R. Martin, R.D. McBride, L.A. McPherson, T.N. Nagayama, K.J. Peterson, J.L. Porter, G.A. Rochau, D.C. Rovang, C.L. Ruiz, S.E. Rosenthal, M.E. Savage, P.F. Schmit, A.B. Sefkow, D.B. Sinars, S.A. Slutz, I.C. Smith, W.A. Stygar, R.A. Vesey, E.P. Yu

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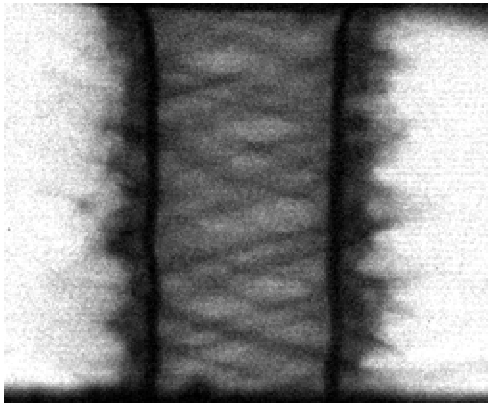
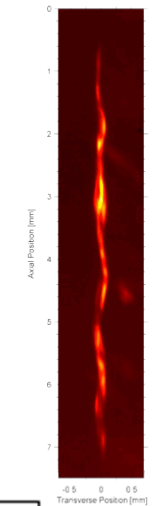
# Summary: Initial experiments have demonstrated the fundamental MagLIF concept, and PRD-led experiments are now focused on understanding the science and future scaling.

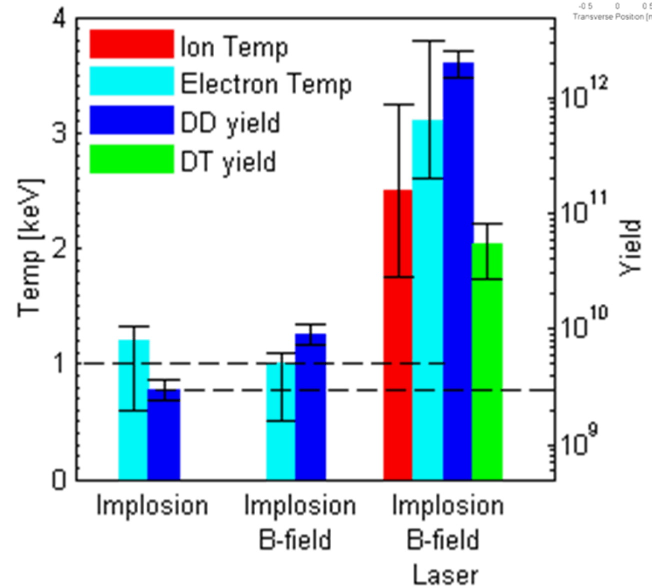
- Magnetic Direct Drive is an efficient way to couple energy to an ICF target.
  - Experiments to date couple ~0.4 MJ to the target

- Initial MagLIF experiments have demonstrated the basic concepts of preheat and fuel magnetization to achieve thermonuclear fusion.
  - Max DD yields of ~3E12

- We have organized our program around 5 Priority Research Directions, and focused experiments will provide the understanding to scale to ignition and high yield.
  - Driver-Target Coupling (Current coupling)
  - Preconditioning (Laser preheat and B-fields)
  - Implosion (Liner stability)
  - Stagnation (Measurements)
  - Modeling, Simulation, & Scaling







# "Magnetic direct drive" is based on the idea that we can efficiently use large currents to create high pressures

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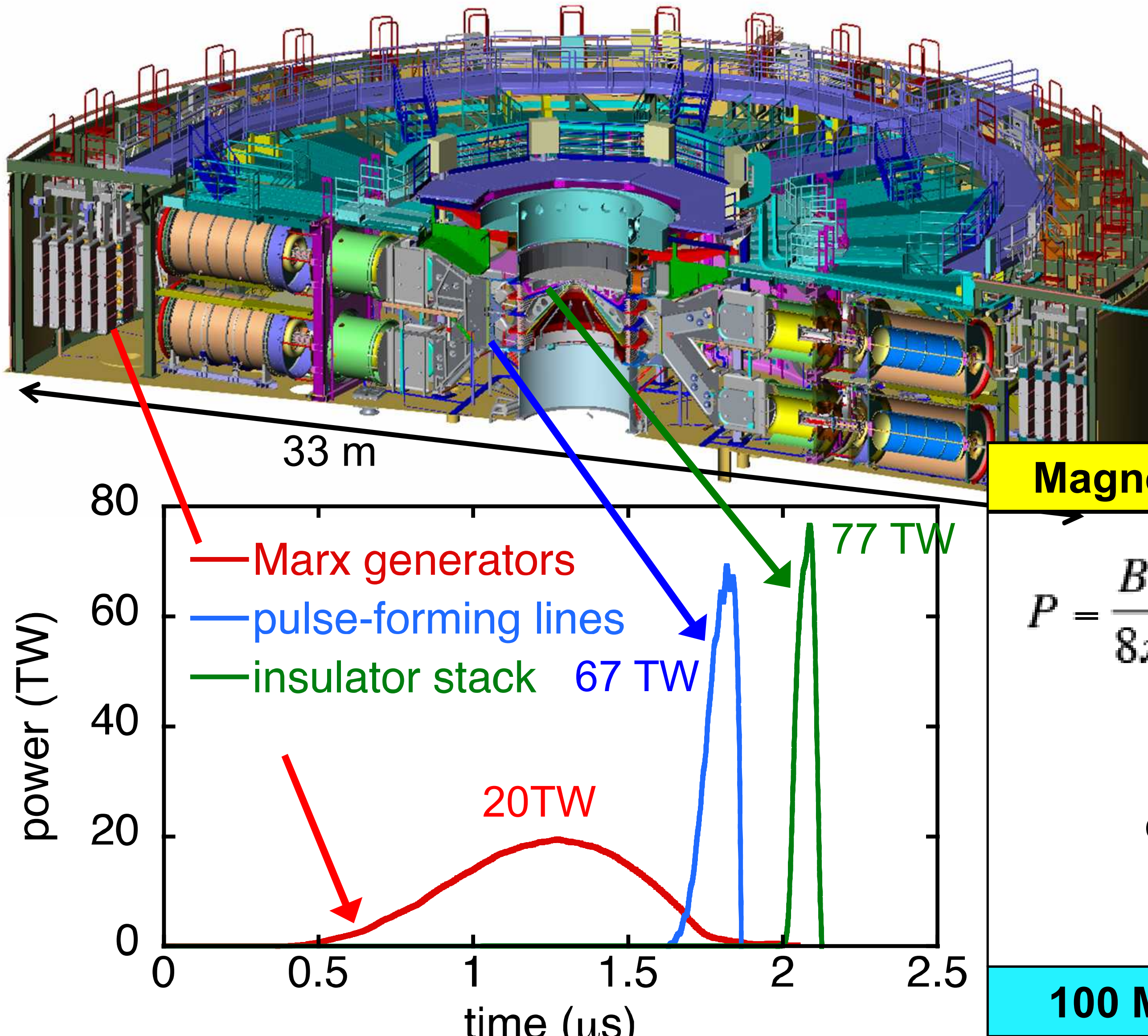
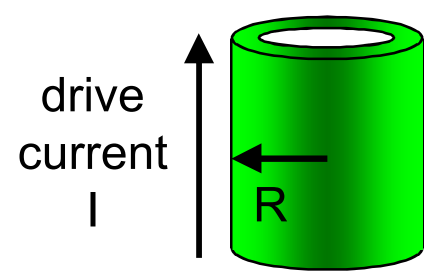
Z today couples ~0.4 MJ out of 20 MJ stored to MagLIF target (0.1 MJ in DD fuel).




**Magnetically-Driven Implosion**

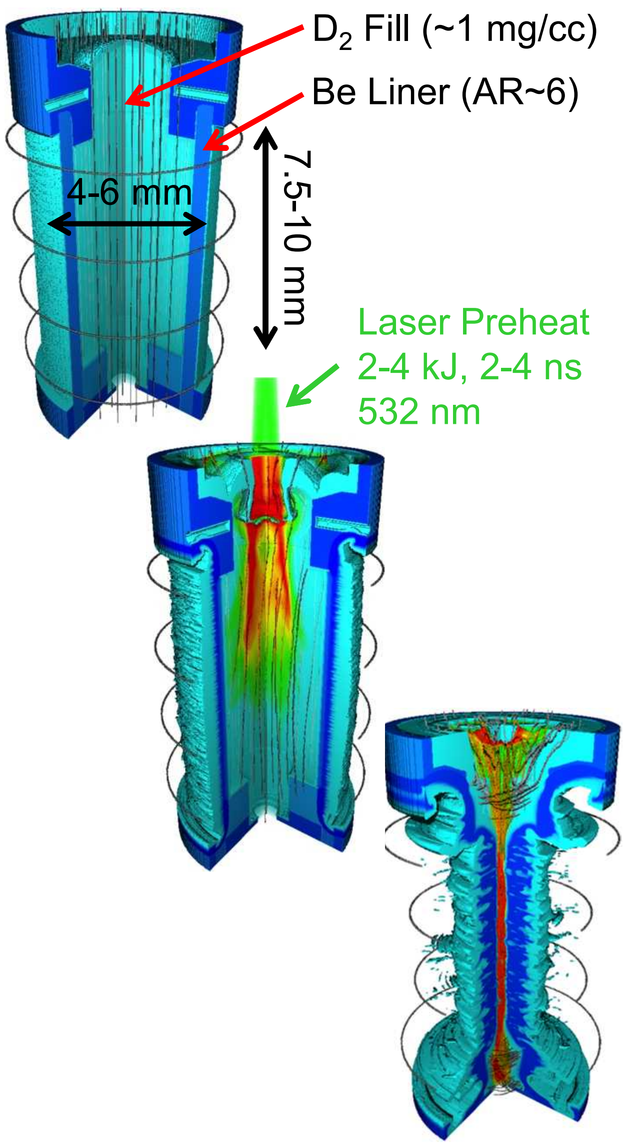
$$P = \frac{B^2}{8\pi} = 105\left(\frac{I_{MA}/26}{R_{mm}}\right)^2 \text{ MBar}$$




**100 MBar at 26 MA and 1 mm**

(1 atm = 1 bar = $10^5$ Pascals)

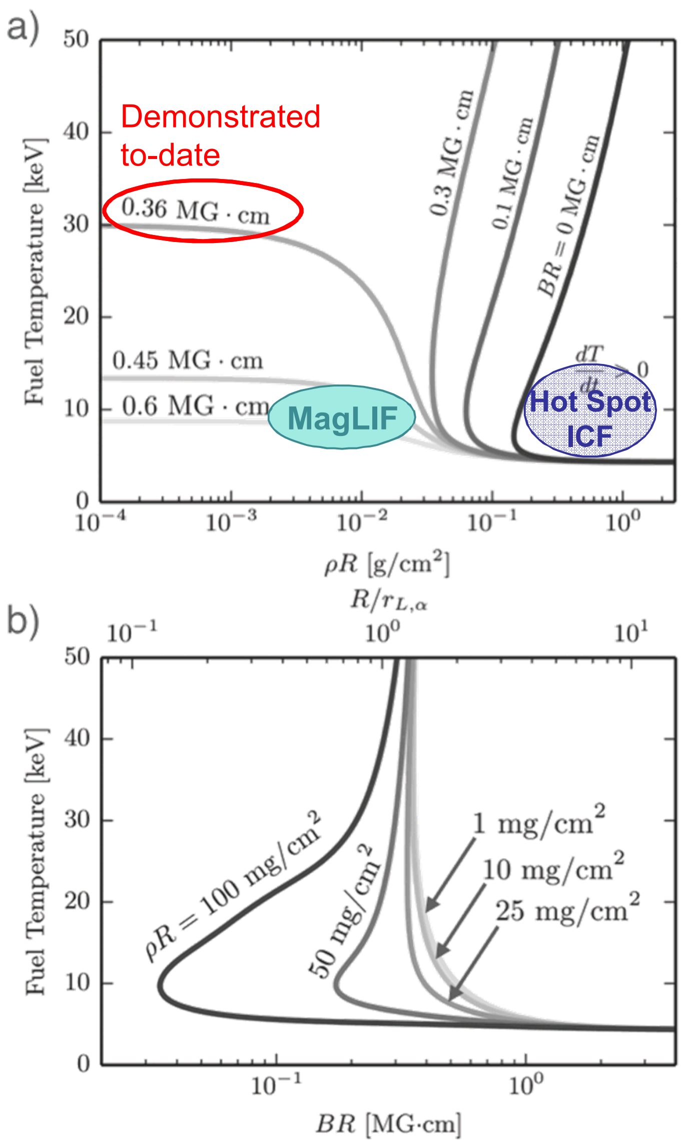
# Magnetized Liner Inertial Fusion (MagLIF) is well suited to pulsed power drivers and may reduce fusion requirements

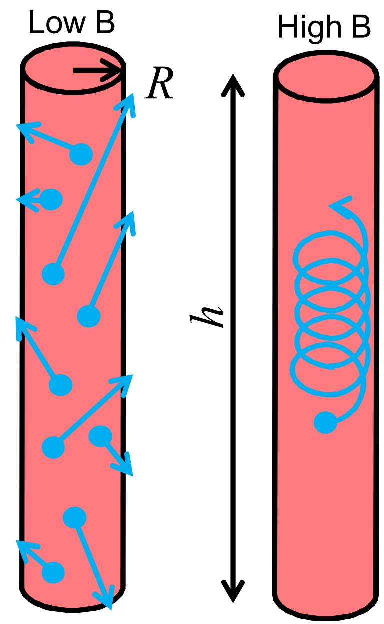



- **Axial magnetization of fuel/liner ($B_{z0}$ = 10-30 T)**
  - Inhibits thermal conduction losses (β: 5~80; ωτ>200)
- **Laser heating of fuel (2 kJ initially, 6-10 kJ planned)**
  - Reduces radial fuel compression needed to reach fusion temperatures ($R_0/R_f$ about 25, $T_0$=150-200 eV)
- **Liner compression of fuel (70-100 km/s, ~100 ns)**
  - Low velocity allows use of thick liners (R/ΔR~6) that are robust to instabilities and have sufficient ρR at stagnation for inertial confinement
- This combination allows fusion at ~100x lower fuel pressure than traditional ICF (~5 Gbar vs. 500 Gbar)
- 2-D Simulations suggest DD equivalent of 100 kJ DT yield may be possible on Z in future
  - Requires upgrades from our present system e.g., 10 T → 30 T; 2 kJ → >6 kJ; 19 MA → >24 MA

S.A. Slutz *et al.*, Phys Plasmas (2010); S.A. Slutz and R.A. Vesey, Phys Rev Lett (2012); A.B. Sefkow *et al.*, Phys Plasmas (2014).

# Magnetization ("BR") reduces rho-R requirements and minimizes electron heat losses



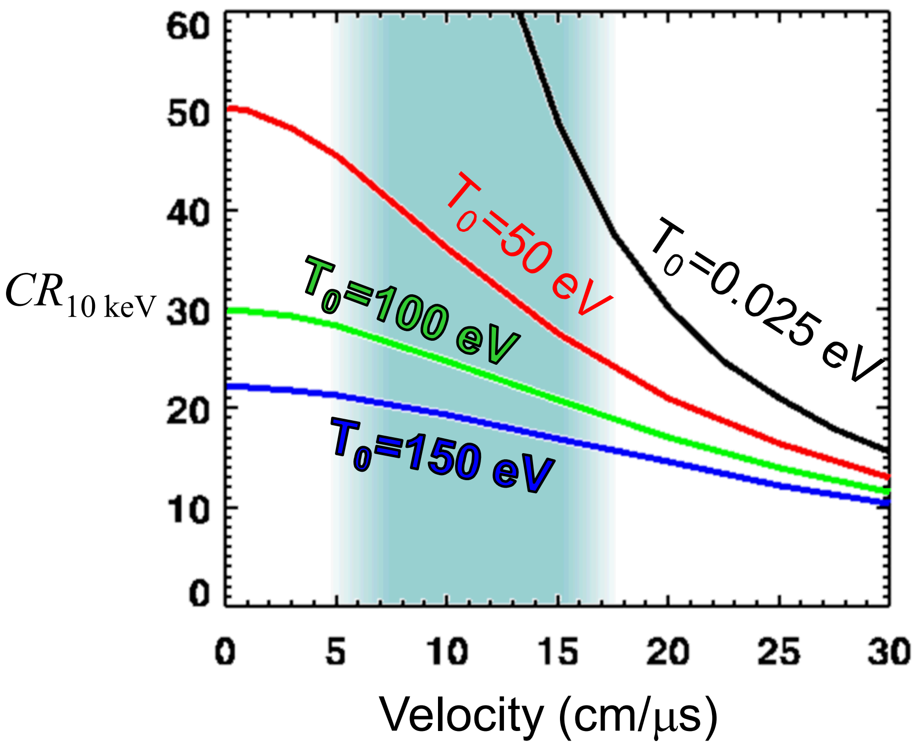

- Fraction of trapped $\alpha$'s (tritons) is a function of ***BR***
- At BR>0.5 MG-cm the effects saturate (particles are well confined).
- Measurements to date suggest >0.3 MG-cm

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

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

# Preheating the fuel reduces the requirements on implosion velocity and convergence

Simulated CR necessary to achieve T = 10 keV*




*Constant velocity cylindrical implosion of $D_2$ gas assuming no radiation or conductivity losses

**Temperature rise for an ideal adiabatic cylindrical compression**

$$T = T_0 \underbrace{(r_0/r_f)}_{CR}{}^{4/3}$$

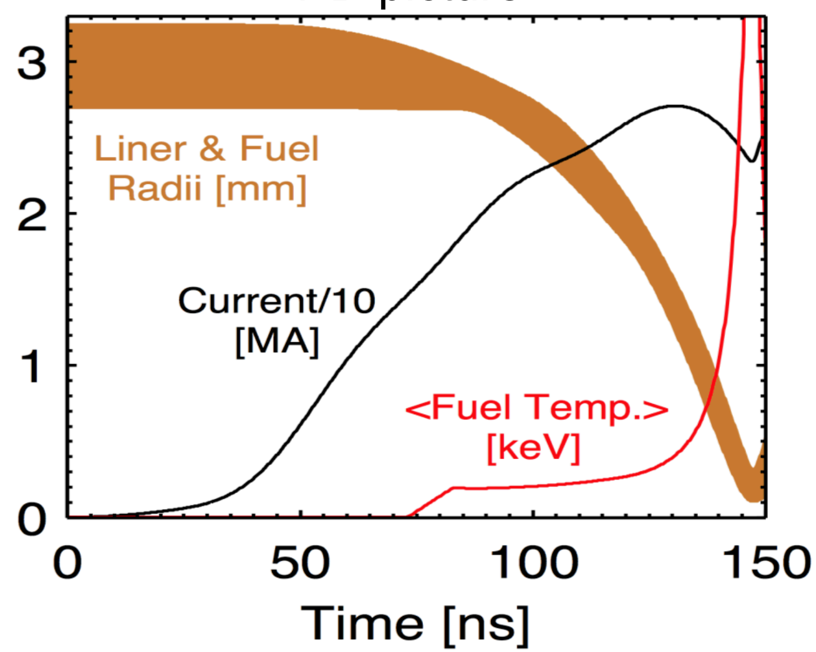
- Laser heating of fuel (6-10 kJ) offers one way to reach pre-compression temperatures of ~200 eV
- Detailed simulations suggest we can reach fusion temperatures at $CR$ = 25

# MagLIF has conservative fuel compression characteristics, but relies on largely unvalidated magneto-inertial fusion principles

| Metric | X-ray Drive on NIF | 100 kJ MagLIF on Z |
|---|---|---|
| **Pressure** | ~140-160 Mbar | 26 MA at 1 mm is 100 Mbar |
| **Force vs. Radius** | Goes as R^2 | Goes as 1/R |
| **Peak velocity** | 350-380 km/s | 70-100 km/s |
| **Peak IFAR** | 13-15 (high foot) to 17-20 | 8.5 |
| **Hot spot CR** | 35 (high foot) to 45 | 25 |
| **Volume Change** | 43000x (high) to 91000x | 625x |
| **Fuel rho-R** | >0.3 g/cm^2 | ~0.003 g/cm^2 |
| **Liner rho-R** | n/a | >0.3 g/cm^2 |
| **BR** | n/a | >0.5 MG-cm |
| **Burn time** | 0.15 to 0.2 ns | 1 to 2 ns |
| **T_ion** | >4 keV | >4 keV |

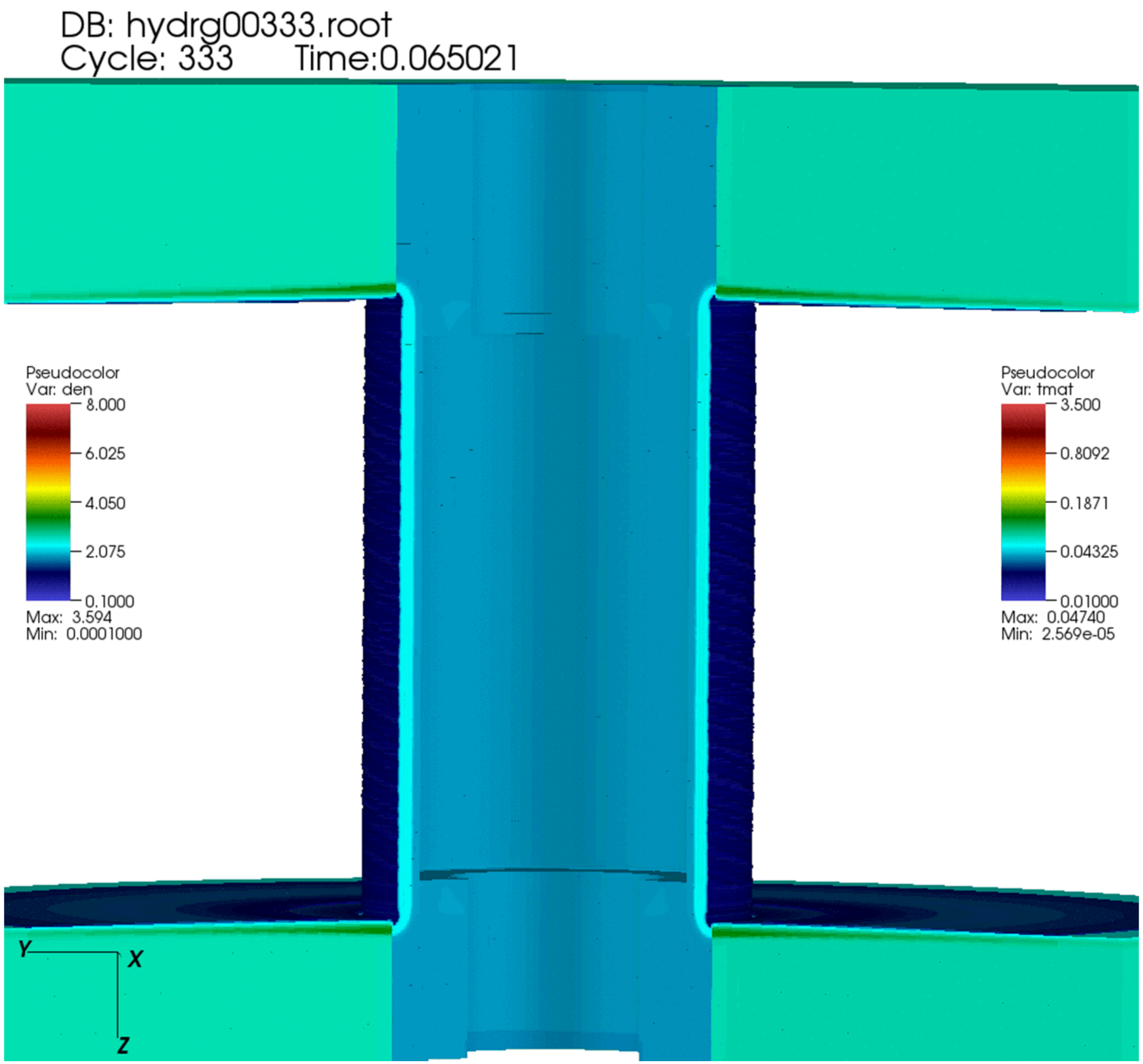
- Low Velocity Implosion
- Low IFAR
- Low convergence ratio / volume compression / fuel ρR

1-D picture




R. D. McBride and S. A. Slutz, PoP 22, 052708 (2015)

# Fully-integrated (Bz+Laser+Z) 3-D HYDRA calculations illustrate the stages of a MagLIF implosion



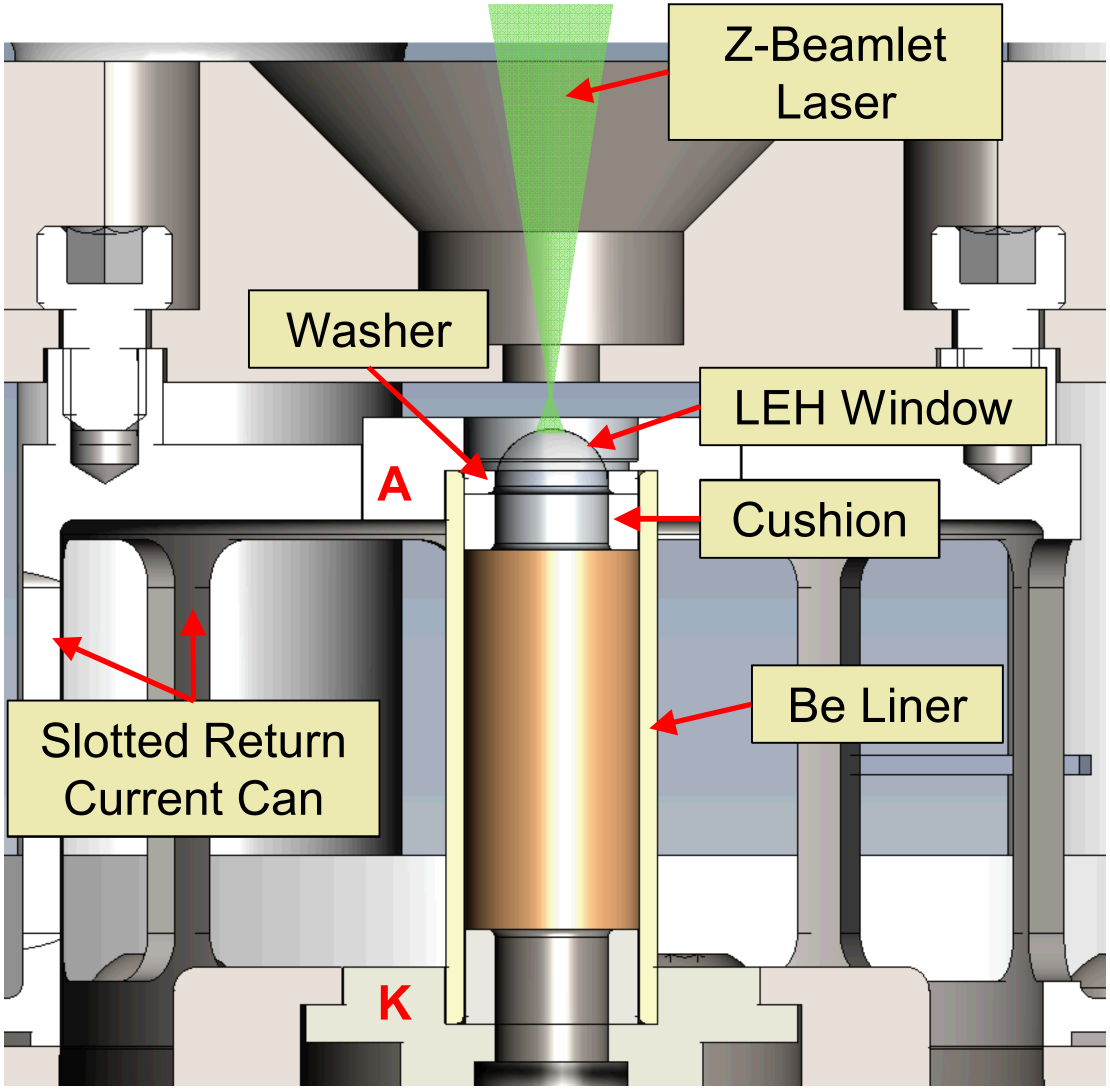

A. Sefkow



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

# Anatomy of a MagLIF Target

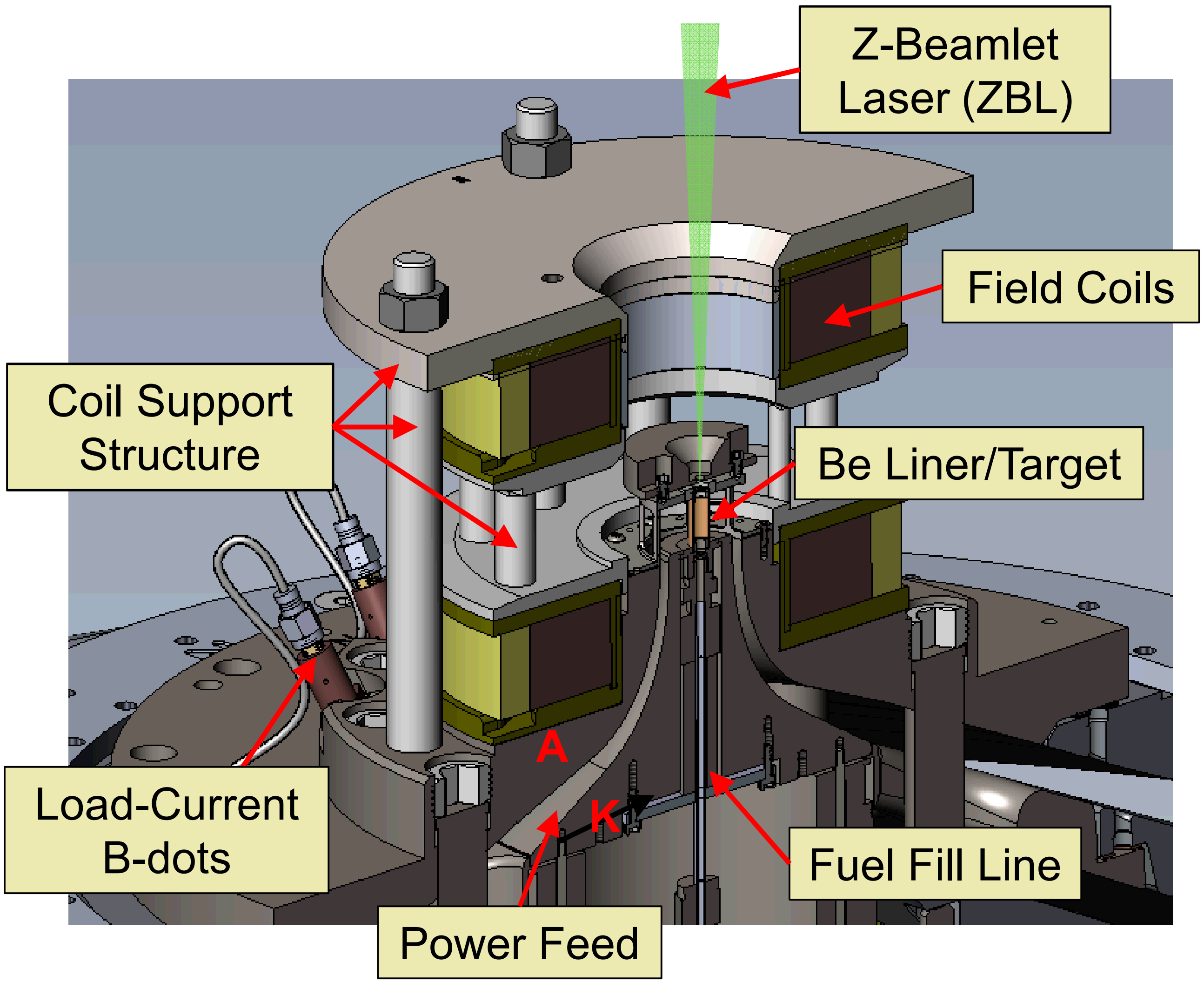
- **Be Liner**: OD = 5.58 mm, ID = 4.65 mm, h = 5–10 mm
- **LEH Window**: 1-3 µm thick plastic window. Supports 60 PSI pure D2 gas fill.
- **Washer**: Metal (Al or Be) washer supporting LEH window
- **Cushion**: Al or Be structure used to mitigate the wall instability. Also reduces LEH window diameter to allow thinner windows
- **Return Can:** Slotted for diagnostic access



# Anatomy of a MagLIF Experiment

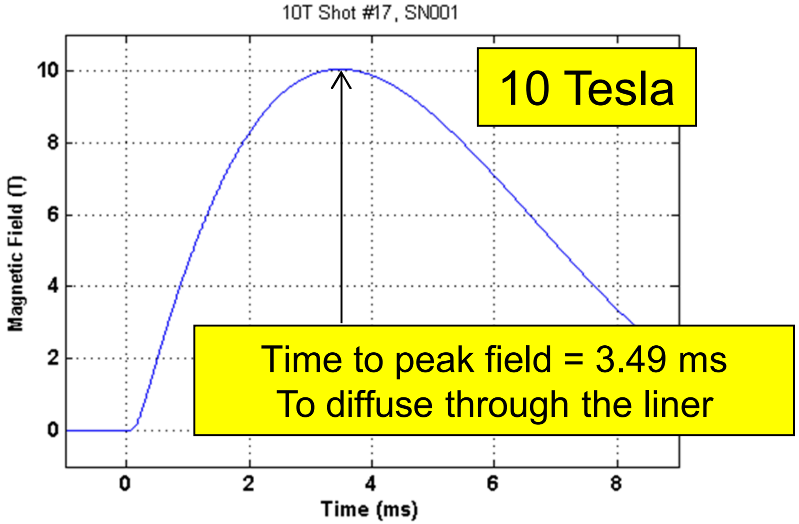
- **Field Coils**: Helmholtz-like coil pair produce a 10-30 T axial field w/ ~3 ms rise time

- **ZBL**: 1-4 kJ green laser, 1-4 ns square pulse w/ adjustable prepulse (prepulse used to help disassemble laser entrance window)

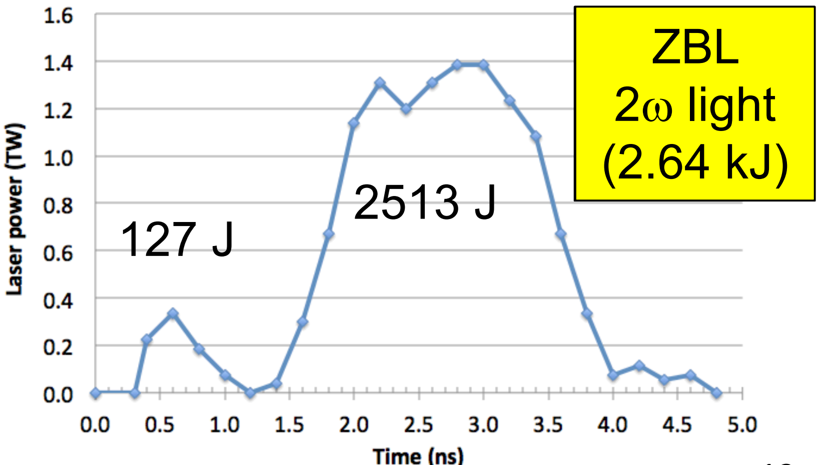


# It took until 2013 to develop the B-field and laser optics subsystems necessary to test the MagLIF concept.

**Capacitor bank system on Z**
**900 kJ, 8 mF, 15 kV**




**Z-Beamlet Vacuum Final Optic Assembly**



# Initial integrated experiments on Z demonstrated that the fundamental concepts of MagLIF work.

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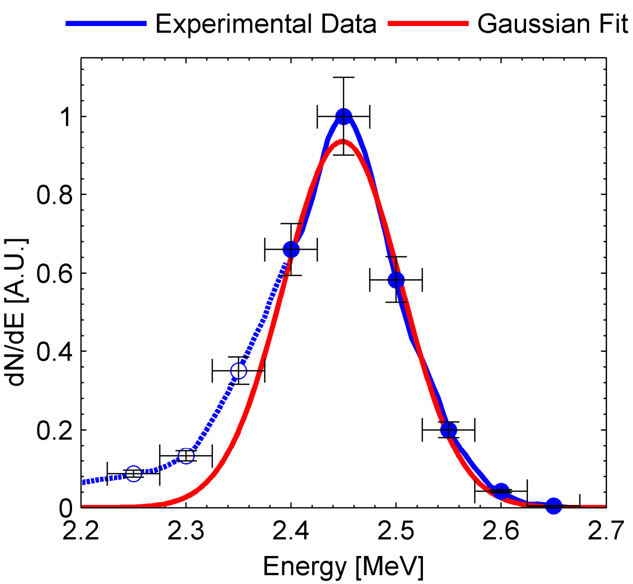
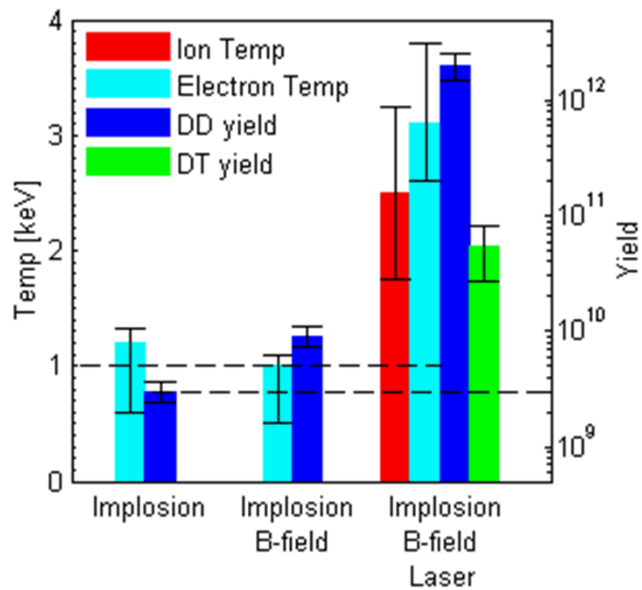
## Thermonuclear neutron generation




Isotropic, 'Near-Gaussian' DD neutron spectra

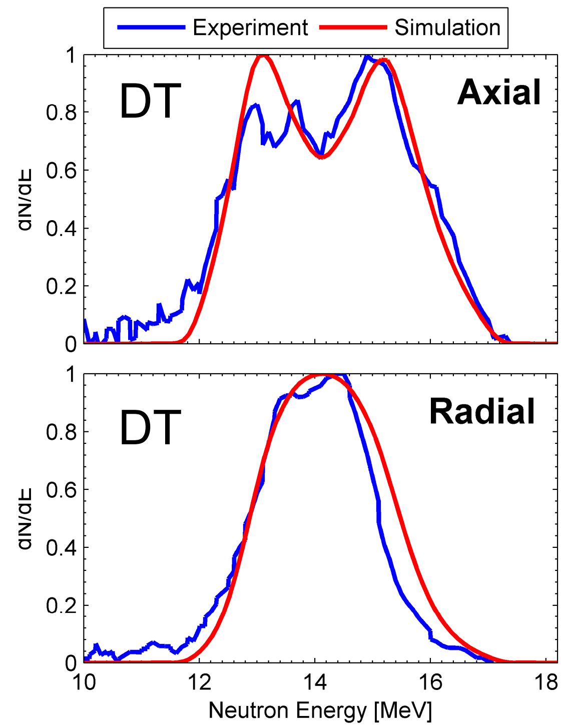
## Significant yields and temperatures




Max DD neutron yield = 3e12

Max ion temp = 2.5 keV

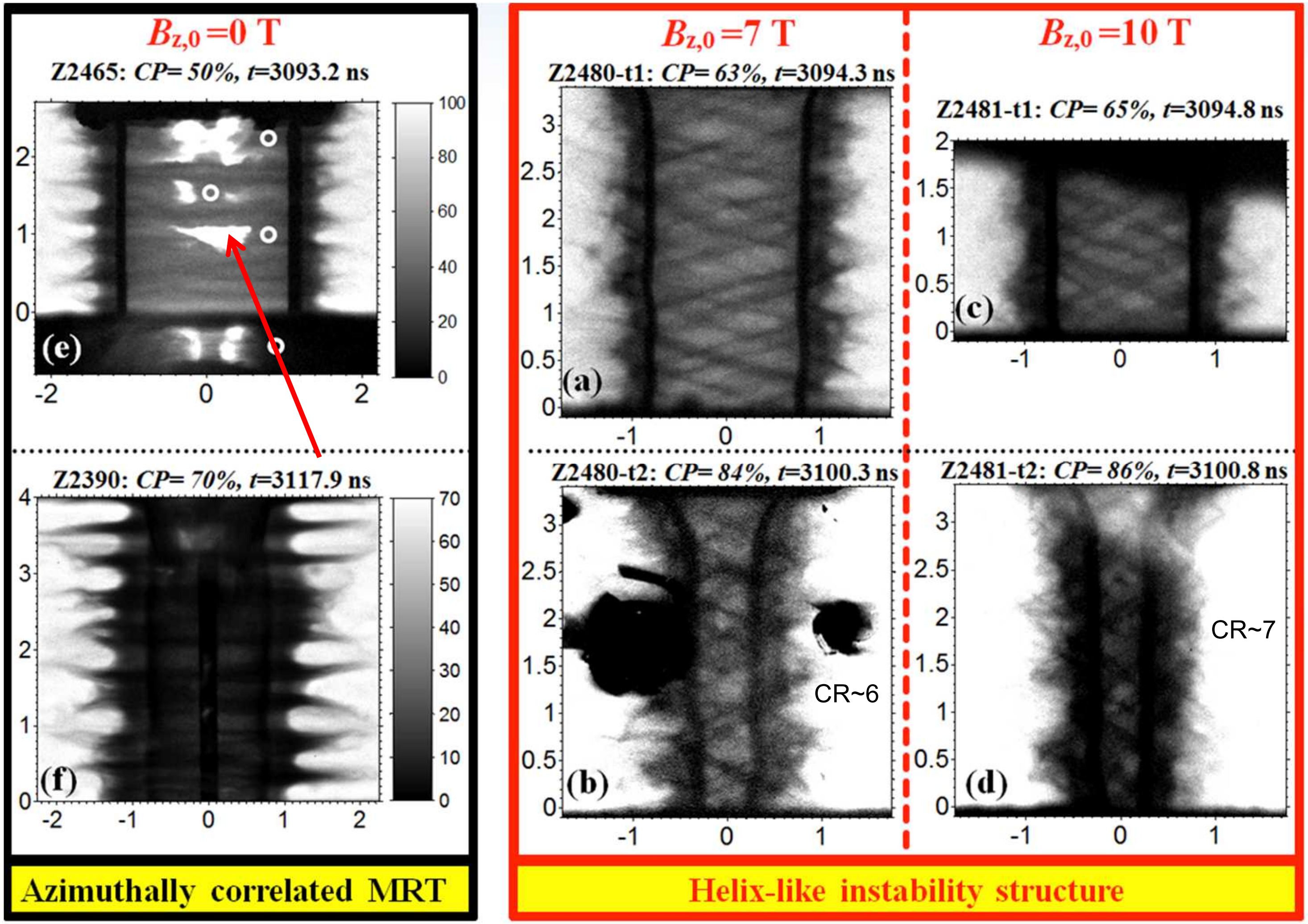
## Magnetic trapping of charged particles




BR = 40 T-cm

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

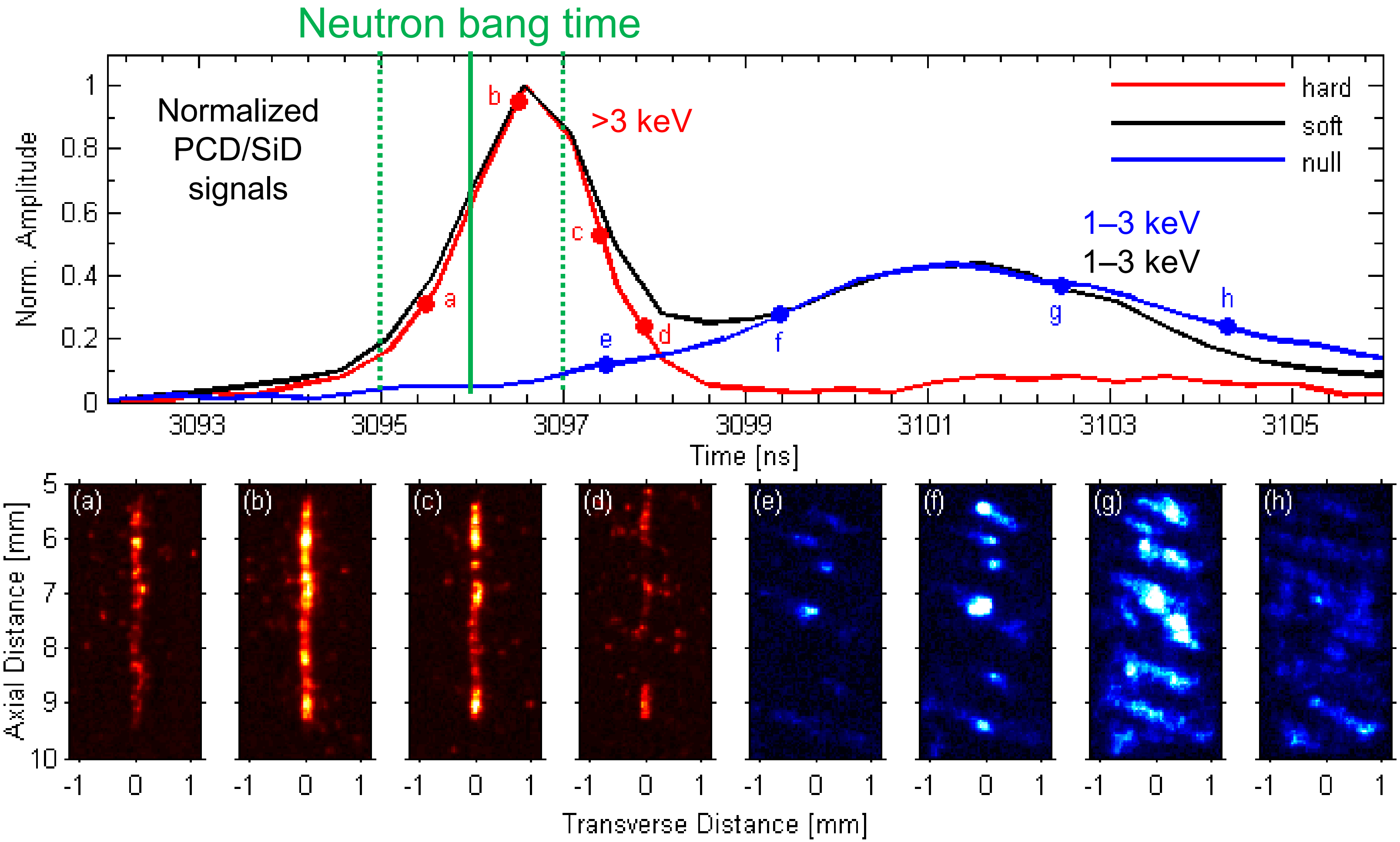
# The addition of a ~10 T axial magnetic field produces a dramatic change in the structure of the liner instabilities




- Rather than cylindrically symmetric structures, we see helical structures
- Magnetic field reduced multi-keV x-rays associated with late-time instabilities

T. J. Awe *et al.*, PRL **111**, 235005 (2013); T.J. Awe *et al*. PoP **21**, 056303 (2014).

# We observe a high-energy x-ray pulse from the stagnation column followed by late-time, lower energy liner emission.

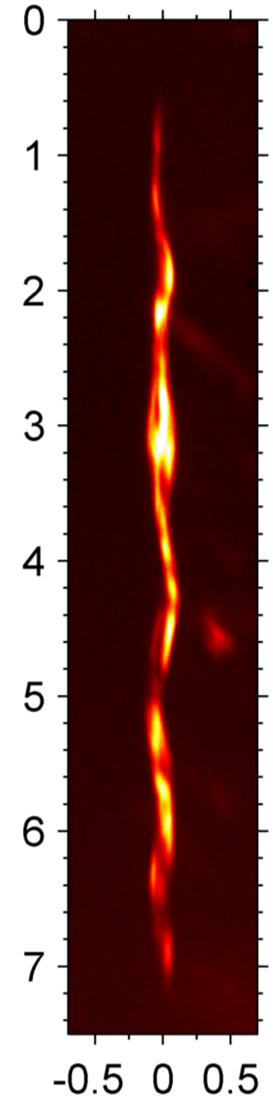



- Narrow x-ray emission column observed at neutron bang time
- Emission from exterior of liner is observed with and without laser and B-field

M. R. Gomez et al., Phys. Rev. Lett. 113, 155003 (2014). M. R. Gomez et al., Phys. Plasmas 22, 056306 (2015).

# X-ray emission from the fuel shows a high aspect ratio stagnation column

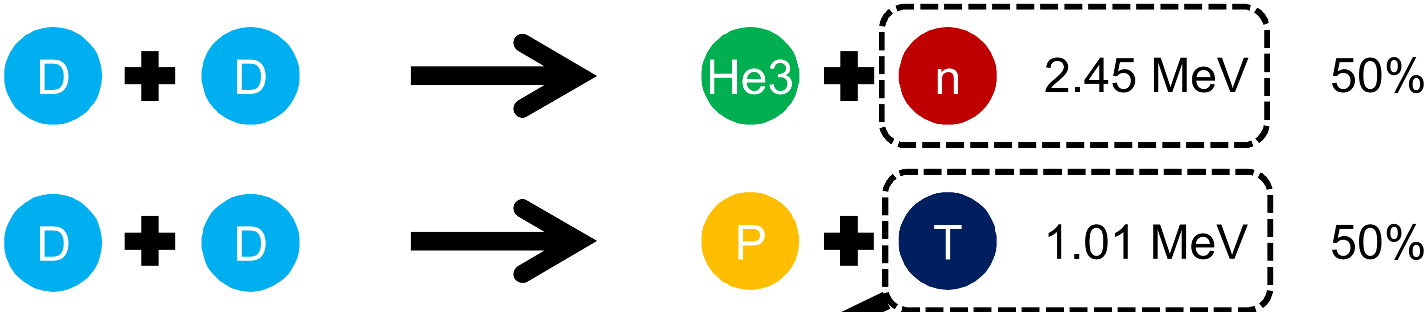
- **Image was produced by a time-integrated x-ray crystal optic system, and it is a combination of 6.2 and 9.4-keV emission**
- **Emission region does not define the fuel-liner boundary, but defines the hottest region of the fuel**
- **Emission FWHM is 50-110 μm**
- **Emission height is > 6mm (approximately 80% of target height)**
- **Axial intensity variations indicate variations in both the fuel conditions (temperature and density) and the liner opacity**
- **Stagnation column appears weakly helical**




M. R. Gomez et al., PRL **113**, 155003 (2014); E. C. Harding et al., RSI **86**, 043504 (2015).

# All of our experiments have used deuterium gas as the fusion fuel

- Primary reactions

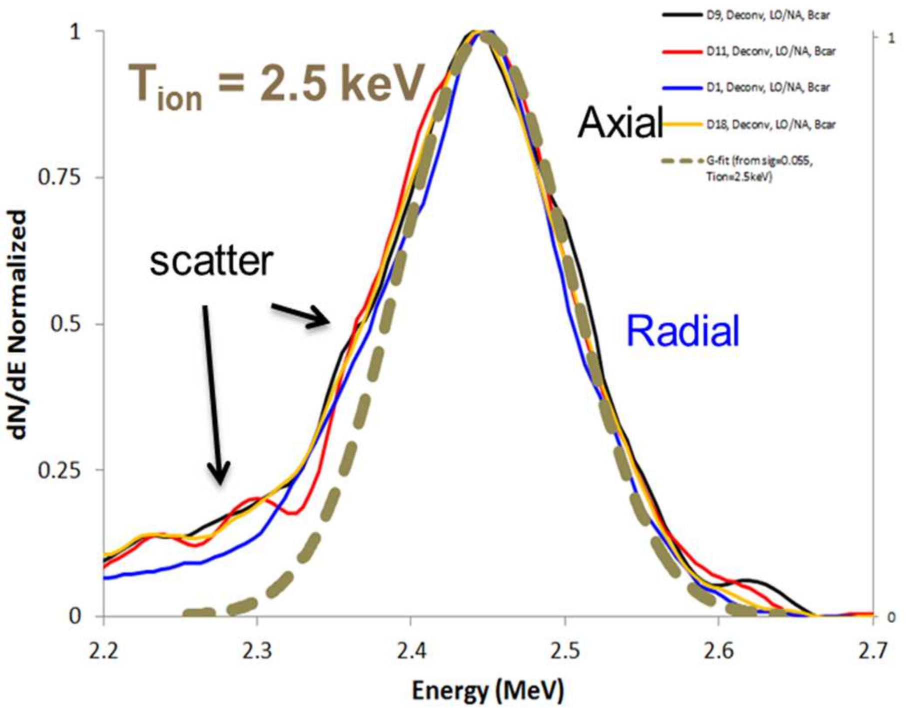



- Secondary reactions


- Triton may still retain fraction of birth energy when reacting

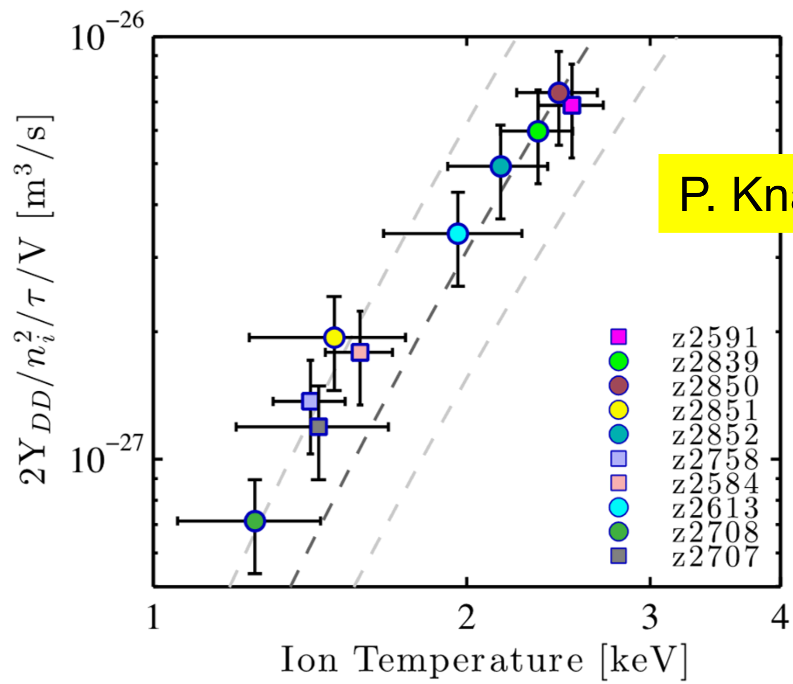
# DD nTOF spectra provide a measure of Tion and yield scales roughly as we expect from a thermonuclear process.

DD nTOF spectra provide one interpretation of $T_{ion}$




K. Hahn

Various targets have spanned a range of ion temperatures and produce yields that are consistent with the thermonuclear cross section




P. Knapp

$$Y_{DD} = \frac{1}{2} n_D^2 \langle \sigma v \rangle_{DD} V \tau$$

# Secondary DT yield and nTOF spectra indicate significant flux compression and resulting fuel magnetization.

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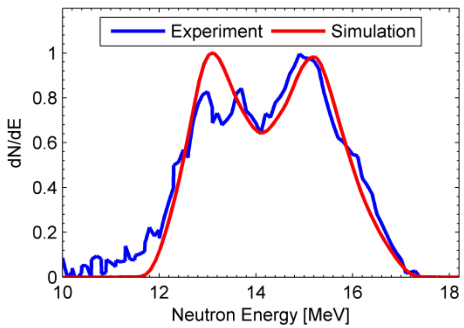
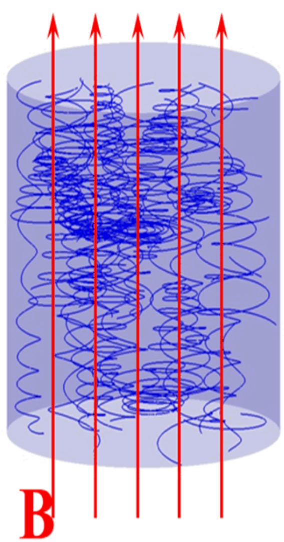
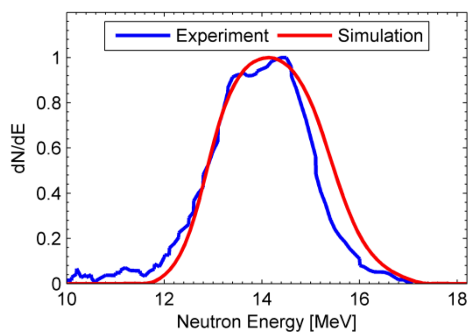
## Axial DT Spectrum

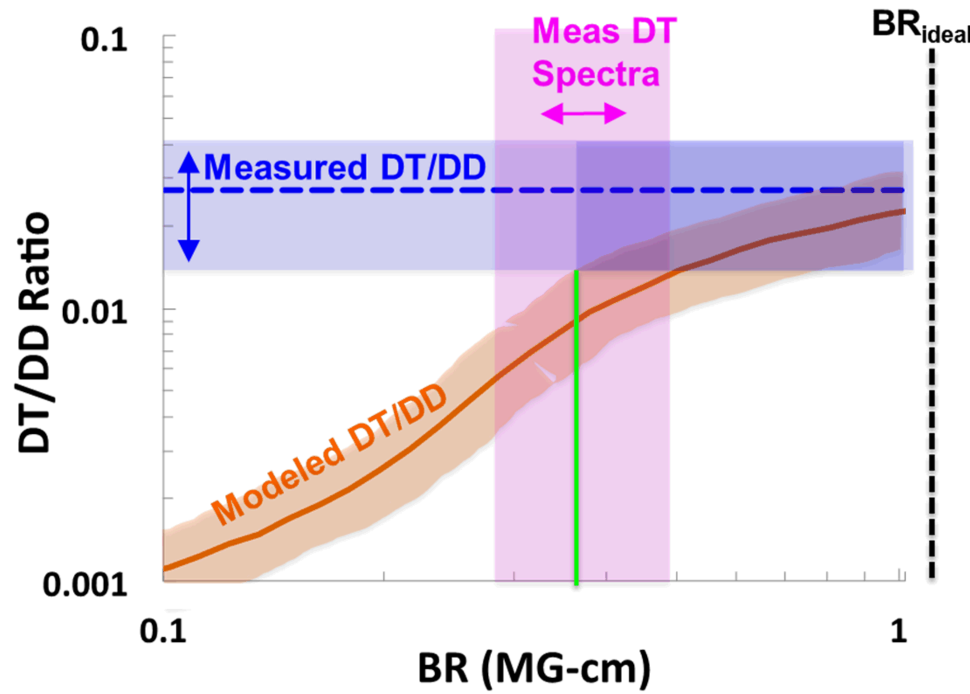



## Radial DT Spectrum




## DT/DD Yield Ratio




**BR = 0.34** +40/-18% **MG-cm**

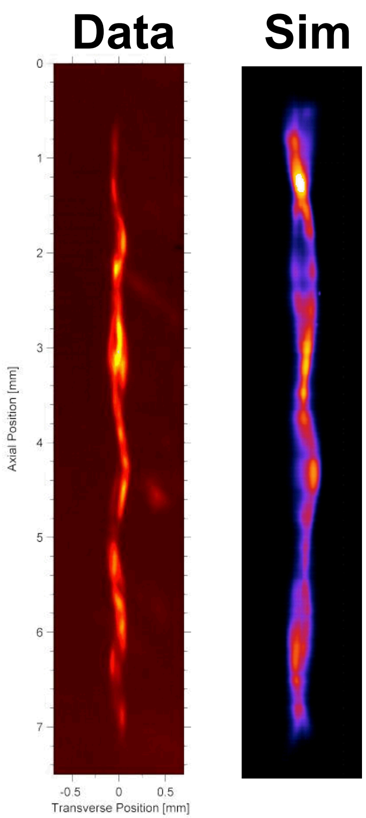
$$r_t \approx 1.1 r_\alpha$$

$$\omega_{ci}\tau_{ie} \approx \omega_{ce}\tau_{ee}$$


P. F. Knapp *et al*. PoP **22**, 056312 (2015).

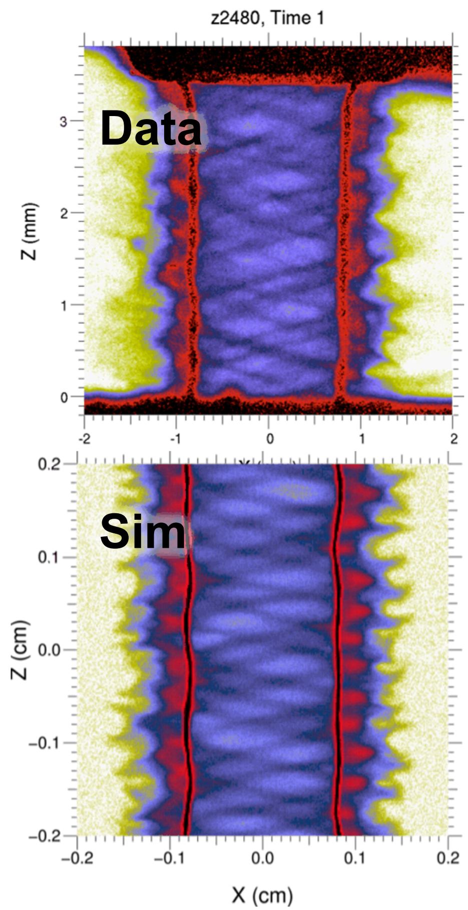
# The observables are well modeled by 2-D and 3-D Hydra if we assume ~200 J of laser energy coupled to the target

## Imaging



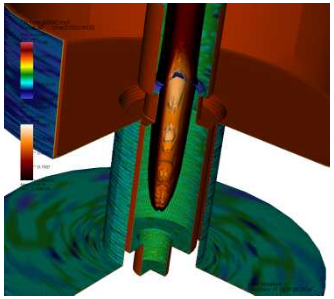

Z2613

## Radiography




## Comparison to z2591 Observables

| Parameter | Measured/inferred | Post-shot simulations |
|---|---|---|
| • $r_{stag}^{hot}$ | 44 ± 13 μm | 40 μm |
| • $\langle T_i \rangle^{DD}$ | 2.5 ± 0.75 keV | 3.0 ± 0.5 keV |
| • $\langle T_{i,e}^{spec} \rangle$ | 3.0 ± 0.5 keV | 2.7 ± 0.5 keV |
| • $\rho_{gas}^{stag}$ | 0.3 ± 0.2 g cm$^{-3}$ | 0.4 ± 0.2 g cm$^{-3}$ |
| • $\rho R_{gas}$ | 2 ± 1 mg cm$^{-2}$ | 2.6 ± 1.0 mg cm$^{-2}$ |
| • $\rho R_{liner}^{stag}$ | 900 ± 300 mg cm$^{-2}$ | 900 mg cm$^{-2}$ |
| • $\langle P^{stag} \rangle$ | 1.0 ± 0.5 Gbar | 1.5 ± 0.3 Gbar |
| • $E_{gas}^{stag}$ | 4 ± 2 kJ | 7 ± 2 kJ |
| • $\langle B_z^f r_{stag} \rangle$ | (4.5±0.5)e5 G cm | 4.8e5 G cm |
| • $Y_n^{DD}$ | (2.0±0.5)e12 | (2.5±0.5)e12 |
| • $Y_n^{DD}/Y_n^{DT}$ | 40 ± 20 | 41-57 |
| • $t_{burn}^{FWHM}$ | 1.5 ± 0.1 ns (x-ray) | 1.6 ± 0.2 ns |

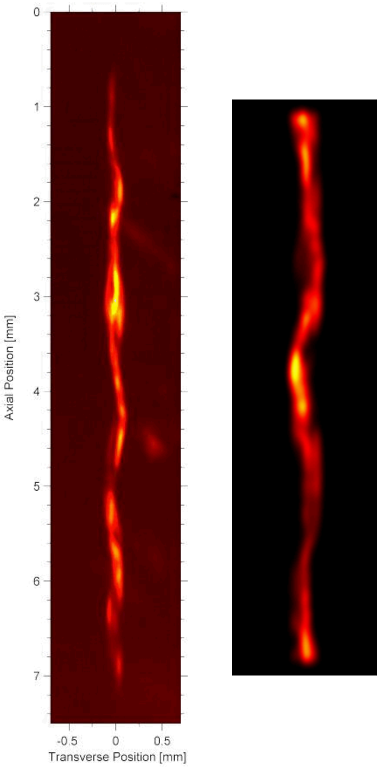


A. Sefkow

# The observables are also well modeled by 3-D GORGON if we assume ~500 J of laser energy coupled to the target

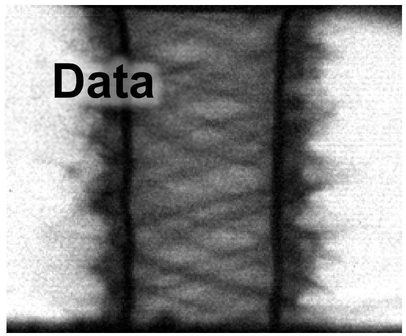
## Imaging

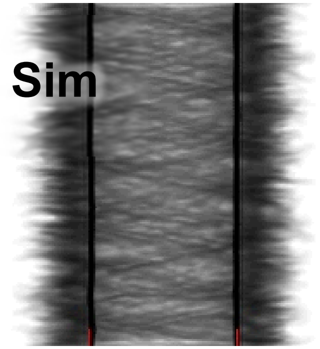
Data Sim




Z2613

## Radiography



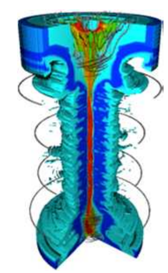




## Comparison to z2613 Image

| Parameter | Measured/inferred | Post-shot simulations |
|---|---|---|
| • FWHM | 91 ± 40 mm | 121 ± 40 mm |

**Sim. Values:**

- Burn weighted, time integrated ion temp: **3.5 keV**
- Continuum emissivity (~9keV) weighted, time integrated electron temperature: **3.3 keV**
- Iron contaminant in Be emissivity weighted, time integrated electron temperature: **1.8 keV**
- Continuum emissivity (~9keV) weighted, time integrated fuel density: **0.33 g cm$^{-3}$**
- DD Yield: **4.e12**
- FWHM neutron pulse: **1.7ns**
- Liner $\rho$R integrated along a single azimuth and axially averaged. Increases from **520 ± 60 mg cm$^{-2}$** to **980 ± 110 mg cm$^{-2}$** over the FWHM of the neutron pulse.



C. Jennings

# Energy coupled to the fuel in separate laser heating experiments appears to be less than originally expected.

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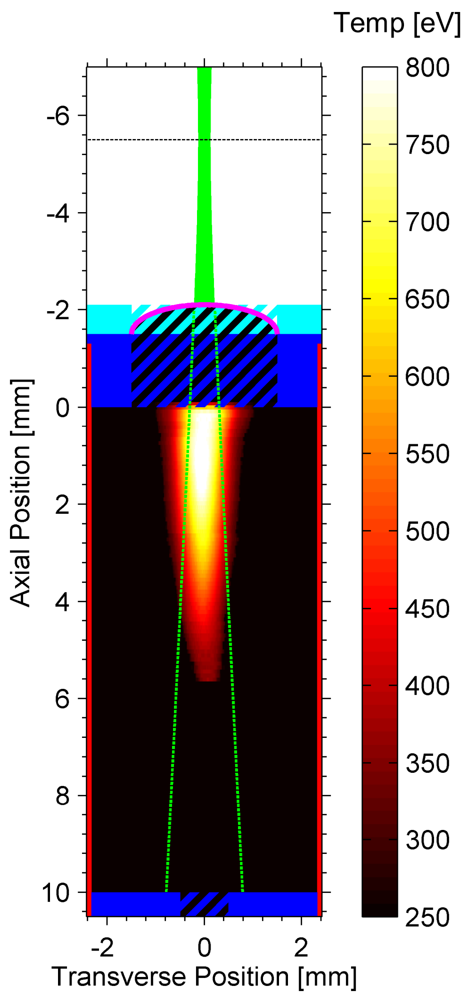
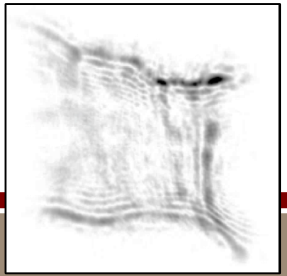



- Predicted greater than 1 kJ would be delivered to fuel
  - Energy inferred from x-ray image is only about 100-300 J
- Self-emission diagnostic is not sensitive to regions below 250 eV
  - There could be hundreds of Joules hidden
  - New target and diagnostic designs are needed to access lower temperature regions
- Energy deposition linearly increases towards the top of the target
  - There is unmeasured energy in the laser entrance channel
- Beam is unconditioned (not a smooth profile) which can substantially affect energy deposition
  - phase plates are under investigation



# After demonstrating the fundamental concept of MagLIF, we are now focusing on understanding the science and developing the requirements for ignition and high yield.

~85% of total effort (Z,Ω,NIF)

- **Study the underlying science of MDDs, emphasizing MagLIF**
  - Primarily accomplished by the Priority Research Direction teams
  - Teams have dedicated experiments on multiple facilities (e.g., Z, Z-Beamlet, Omega, Omega-EP, universities, NIF)

~10% of effort

- **Demonstrate target performance over available range of conditions**
  - Primarily accomplished through integration experiments on Z
  - 100 kJ DT yields (or DD equivalent); P-tau > 5 Gbar-ns + BR > 0.5 MG-cm

~5% of effort

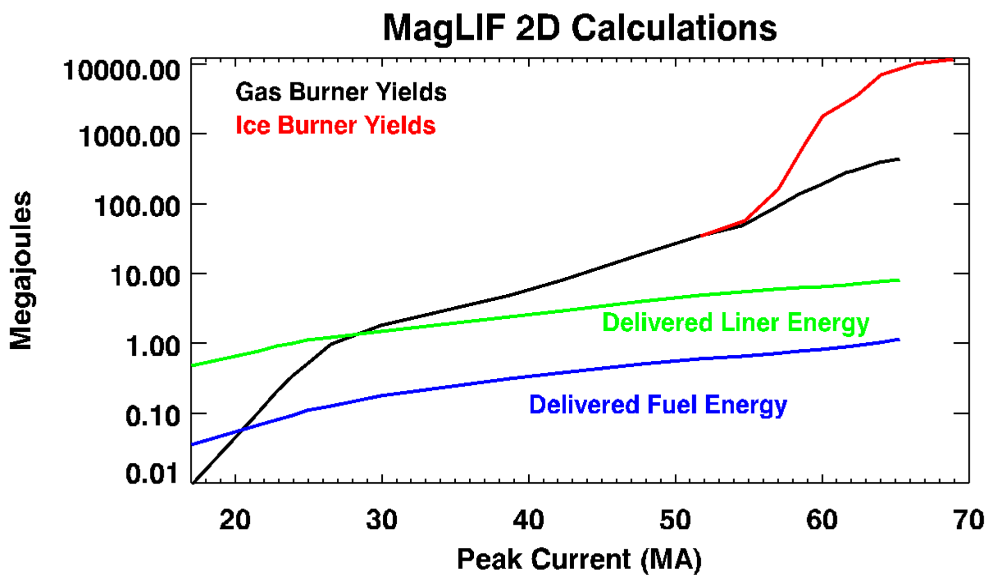
- **Develop a path to ignition and beyond, and assess its credibility**
  - Define credible gas (~5 MJ) and ice burning (~ 1GJ) ignition designs
  - Demonstrate "at-scale" fuel heating on NIF relevant to MagLIF

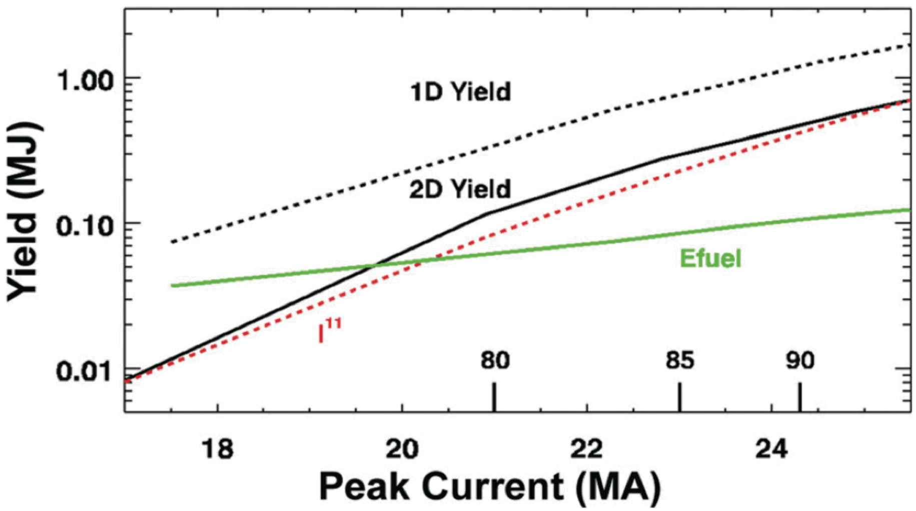
~1% of effort

- **Update the mission needs for ignition and high yield**
  - Why does the nation need a facility capable of ~1 GJ/shot?

# MDD Approach Goal 1: Demonstrate MagLIF target yields over the range of available parameters on Z (up to 24 MA)

- Initial MagLIF experiments coupled 17-18 MA to the target.
- 22-24 MA possible on Z using higher charge voltage & optimized load hardware.
- We will use integrated experiments to determine if predictions of >100 kJ yields are valid
- Significant investments are needed to actually reach 100 kJ (50/50 tritium on Z, 95 kV, higher shot rate)




S.A. Slutz *et al.*, Phys. Plasmas 23, 022702 (2016).

Slutz, Stygar, Gomez et al.

# MDD Approach Goal 2: Demonstrate Pτ>5 Gbar-ns and BR>0.5 MG-cm in the fusing fuel to validate the precepts of magneto-inertial fusion (not just about yield)

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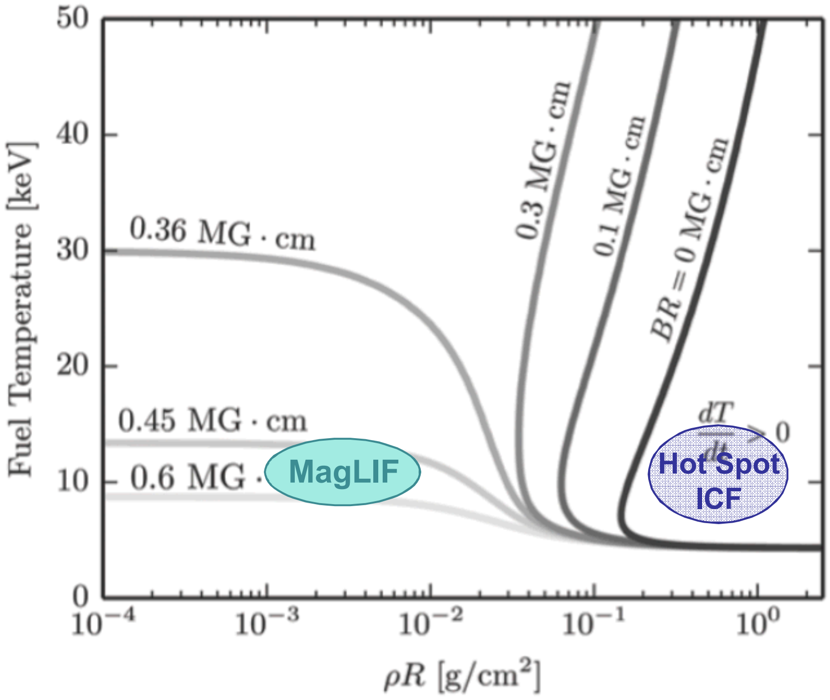
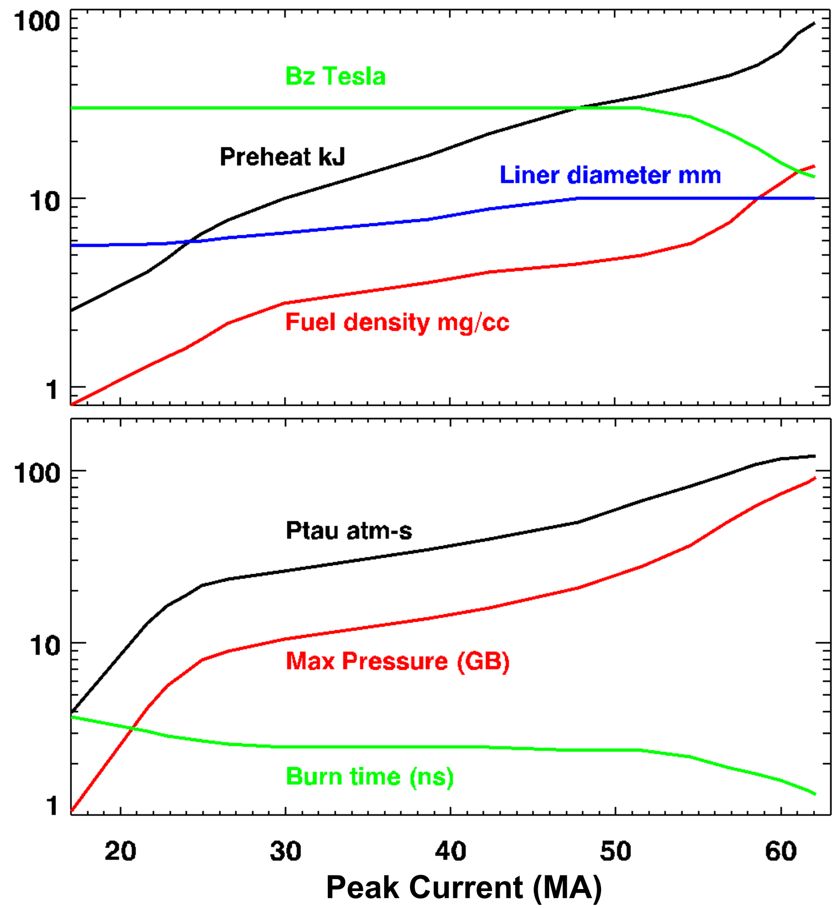
**Alpha Particle Trapping**




Demonstrated >0.3 MG-cm

**LASNEX Simulations**




Demonstrated ~1 Gbar-ns

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

# We established teams and team leaders for the science organized around the Priority Research Directions. They are focused on 5-year science & performance goals.

| Research Group | Team Leaders |
|---|---|
| Driver-Target Coupling | Bill Stygar, Mike Cuneo |
| Target Pre-conditioning | Kyle Peterson |
| Implosion | Ryan McBride |
| Stagnation & Burn | Greg Rochau and Brent Jones |
| Intrinsic & Transport Properties | (treated as subset of next category) |
| Modeling, Simulation, & Scaling | Kyle Peterson and Thomas Mattsson |

- Team leaders responsible for organizing the program of work for each of the research groups, including coordinating national research in each area

- The following slides summarize our progress to date and our key goals for the next five years in these areas

# Over the next five years, we seek to accomplish the following goals related to driver-target coupling:

<u>Scientific goals</u>

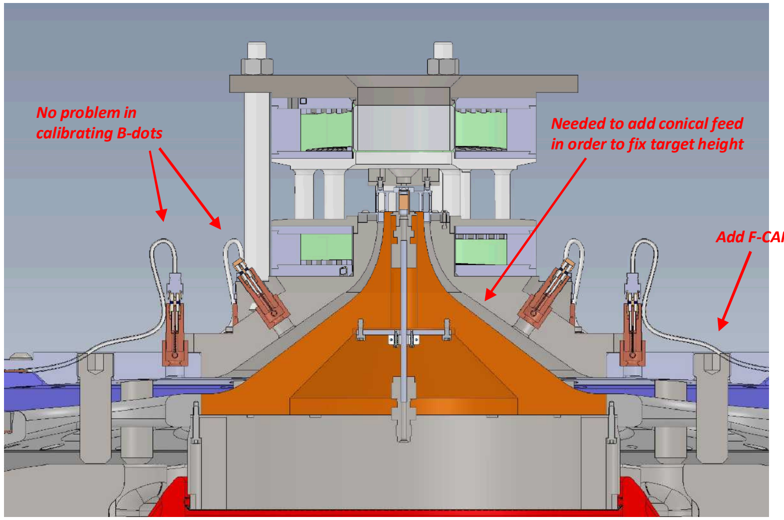
- Develop predictive (~5%) circuit and PIC models of load current coupling.
- Conduct scaled power-flow experiments under conditions similar to those of Z Next.
- Quantify the benefits to ICF loads of current-pulse shaping.
- Quantify the benefits of longer implosions.

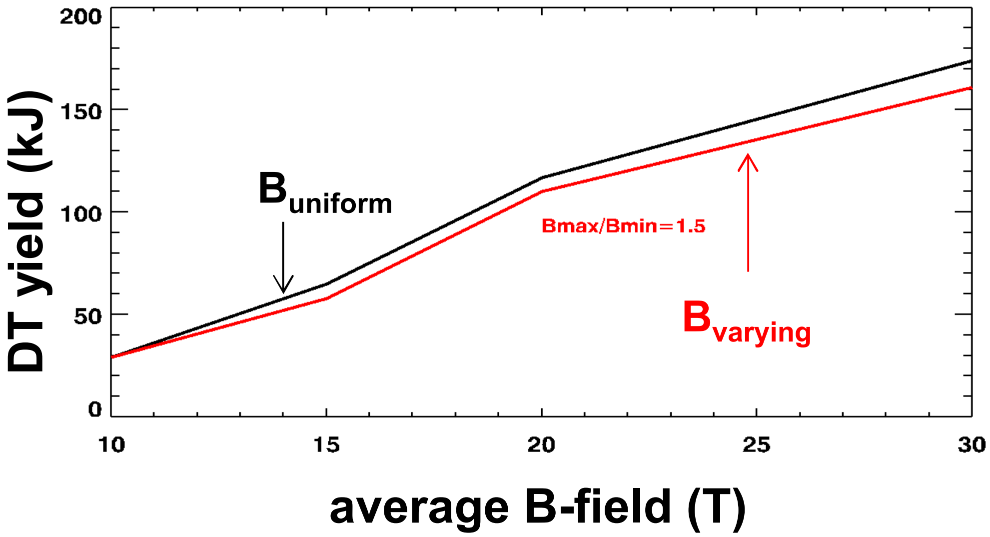
<u>Programmatic goals</u>

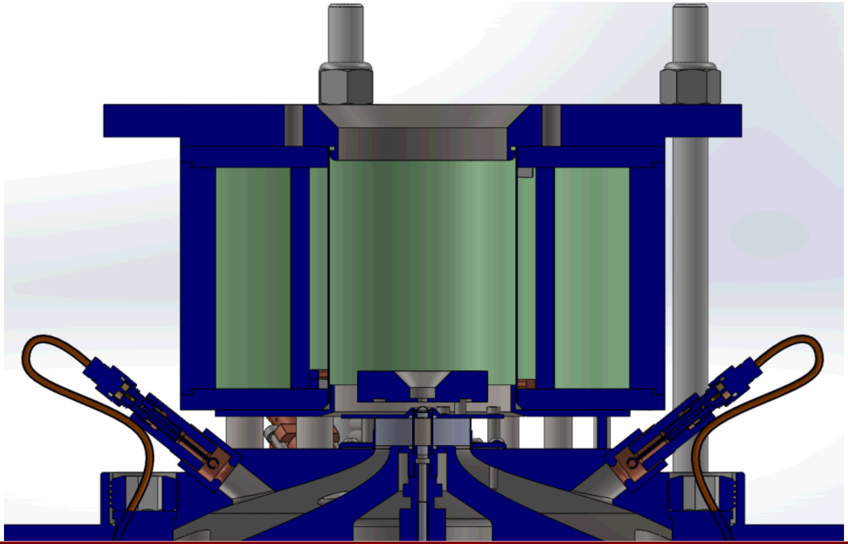
- Deliver 22-24 MA to a MagLIF target on Z.
- Develop a point *pulsed-power* design of a MagLIF target for Z Next that achieves a net target gain of 1 (Likely, Yield ~ $E_{target}$ ~ 3-5 MJ).

# The DTC team is exploring new designs as a way to increase the current and test our predictive circuit models

- Uniform B-field requires high inductance loads that only achieve peak currents of ~18 MA.
- A non-uniform B-field allows lower-inductance hardware.
- Experiments in May demonstrated ~20 MA coupled to a MagLIF target.





Gomez, Laity, Lamppa, Stygar, Slutz et al.

# Over the next five years, we seek to accomplish the following goals related to target pre-conditioning:

**Scientific goals**

- **Demonstrate a method for reproducibly coupling >2 kJ into magnetized fuel**
- **Characterize & mitigate any fuel contamination as a result of the heating method**
- **Minimize the likelihood and impact of laser-plasma interactions**

**Programmatic goals**

- **Improve Z-Beamlet to be capable of a multi-ns, >6 kJ, well-characterized "smoothed" beam profile (including an optimized pulse shape)**
- **Demonstrate 30 kJ heating on the NIF**

# New phase-plates result in deeper laser penetration, but have a negative effect on the target performance; Mix?

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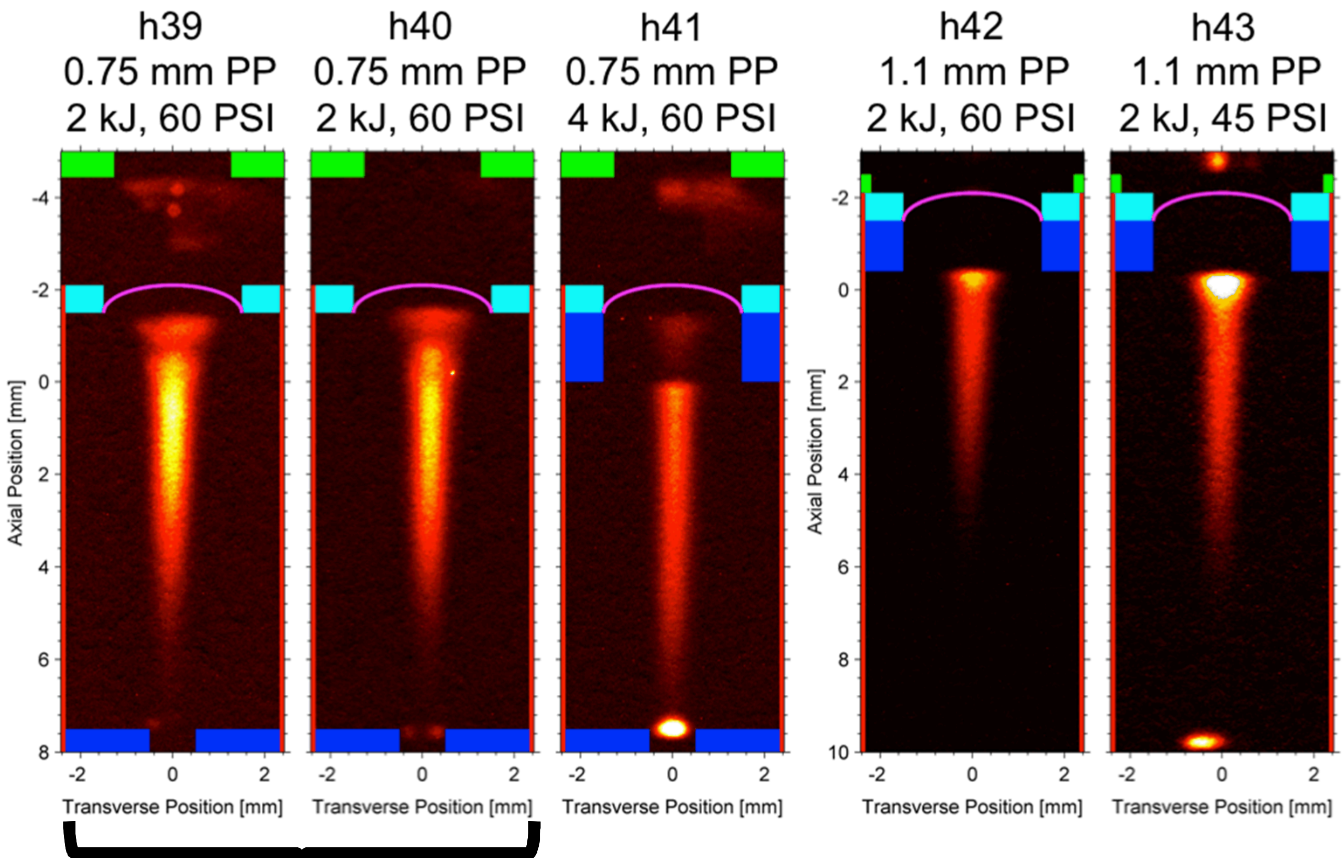
X-ray pinhole camera images of fuel emission

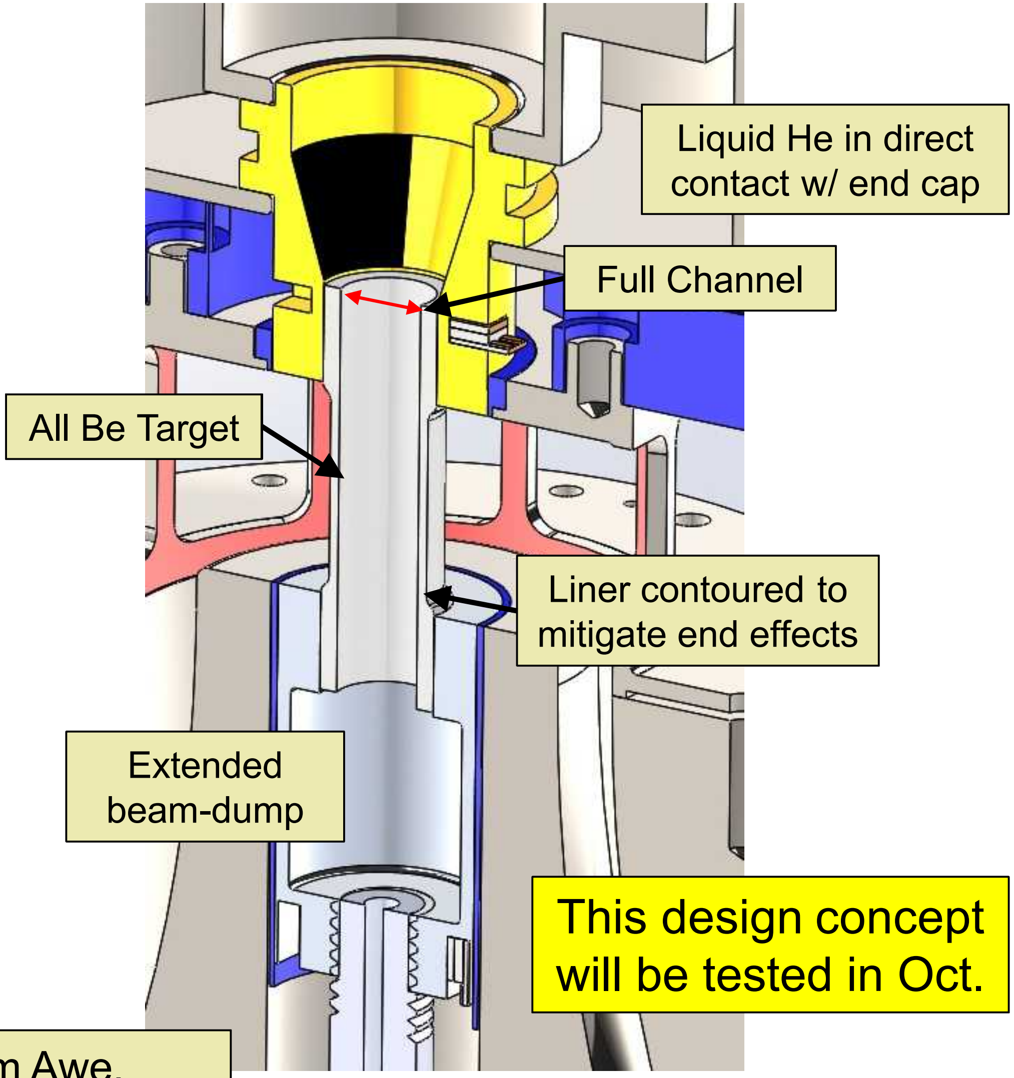



>10x decrease in n-yield
Compared to same pulse-shape w/out phase plate

Target Pre-conditioning

# A cryogenic target has been designed to help mitigate the laser interaction issues

- Why cryogenic?
  - Cooling allows us to get the same gas density (~0.7 mg/cm$^3$) at much lower pressure (15 PSI @ 70 K)
  - This allows for much thinner LEH windows with larger diameter
  - Thinner LEH window allows less energy to be invested in disassembly AND less mass injected into the target
  - Bigger window diameter should reduce likelihood of laser interactions with the wall
  - Also long-term future development: (1) frozen anti-mix layers and (2) frozen fuel layers for high-gain MagLIF

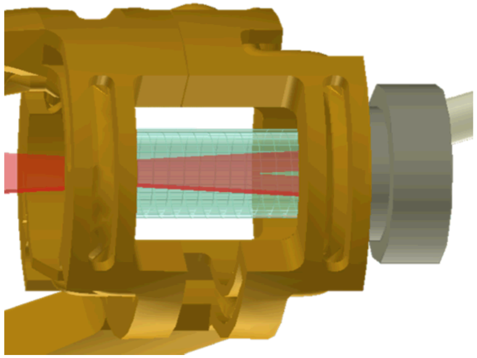



This design concept will be tested in Oct.

Design work done by Tom Awe, Adam Sefkow, and Keegan Shelton

# OMEGA-EP experiments are being conducted to develop understanding of laser energy transport & deposition.

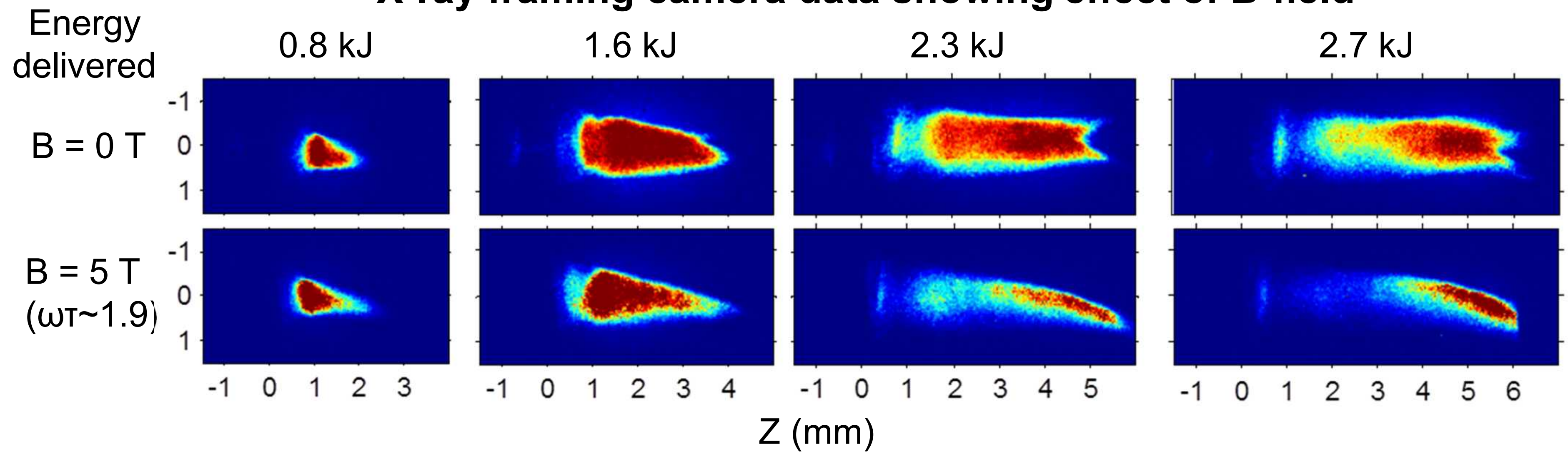
Rexolite (CH) tube
(6.5-10 mm long)



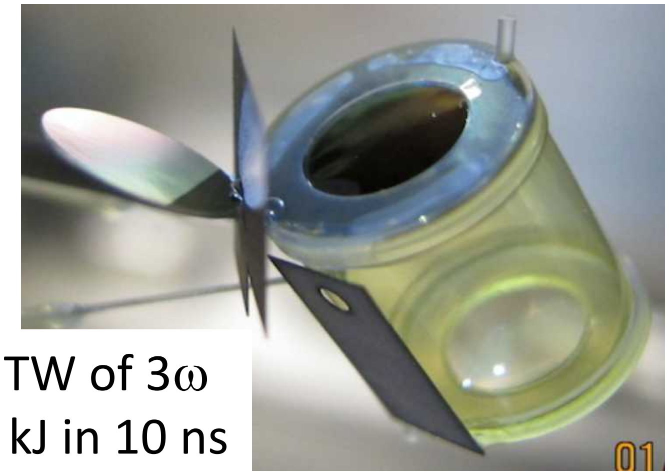
**Current topics of interest for OMEGA-EP Experiments**

- Effect of LEH thickness
- Effect of gas fill density
- Effect of laser intensity
- Effect of magnetization
- How and where does mix occur?
- At what conditions does LPI become important?

**X-ray framing camera data showing effect of B-field**

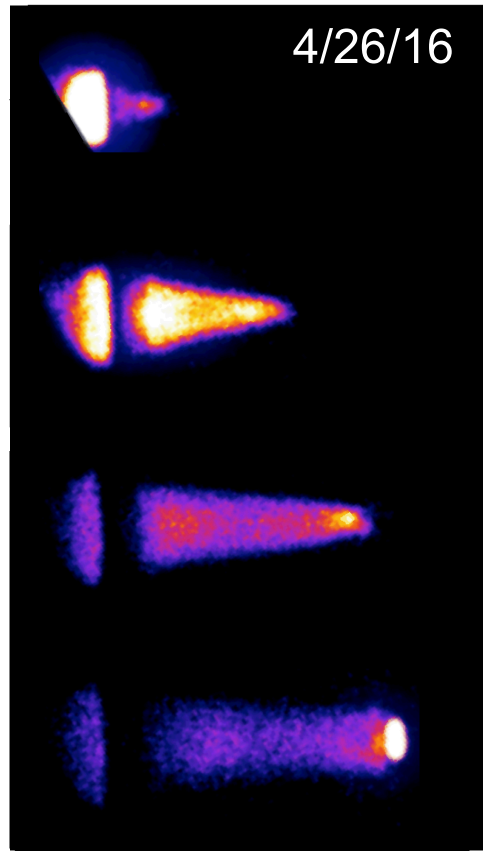


# NIF experiments are targeted at understanding laser transport and deposition at the 30 kJ predicted to be needed for **high yields**

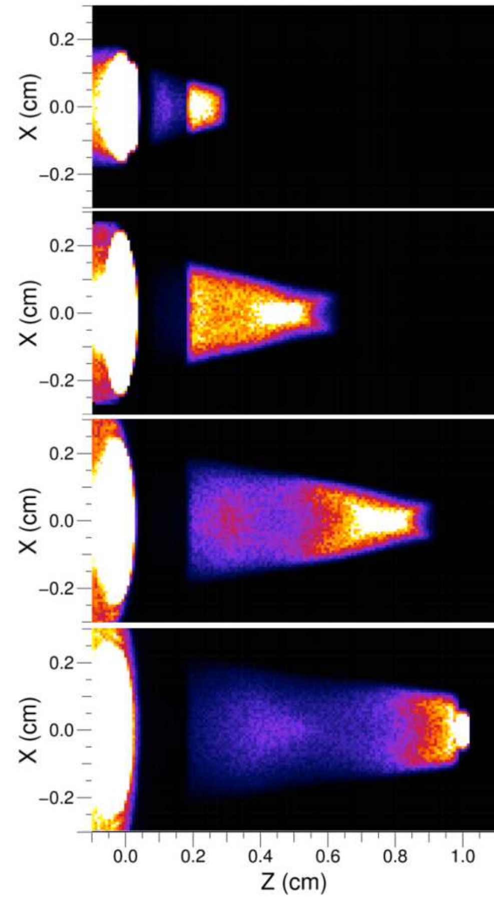



3 TW of 3ω
30 kJ in 10 ns

**GXD Data**




**Hydra Sim**




Objective : Measure laser propagation through a 1 cm gas pipe

- 1 cm long by 0.845 cm gas pipe
- Gas fill: 1 atm of $C_5H_{12}$ at room temp., doped with 1% *Ar*
- 100 μm thick epoxy tube
- 0.75 μm polyimide LEH window

# We have made inexpensive improvements to Z-Beamlet to support MagLIF experiments in the near term

- Activated Booster Amplifier
  - Added 400J of 2ω energy (4.5kJ total)
- Upgraded Final Optics Assembly (FOA)
  - Motorized up/down motion of focusing lens
- Activating co-injection to combine ZBL with sub-aperture (16 cm dia.) ZPW laser in long-pulse (2ns) mode
- Commissioning applied B-field system for laser experiments in Phase C target area
  - Integrated system into Phase C target area
  - Working reliably at 4 – 8 Tesla

# Over the next five years, we seek to accomplish the following goals related to magnetic implosions:

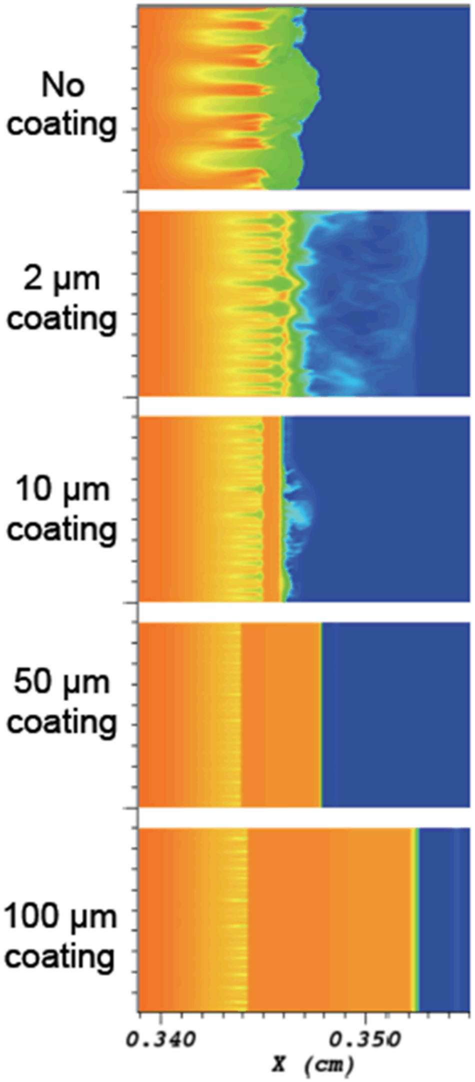
- **Determine the dominant seeds for observed acceleration and deceleration instabilities, and strategies to mitigate against them**

- **Demonstrate the ability to model the evolution of 2D & 3D instability structures in codes used to predict the integrated target performance**

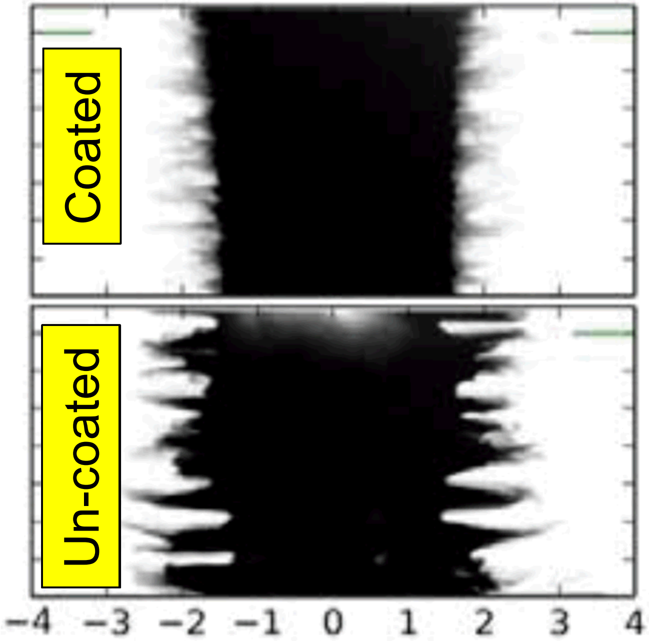
- **Measure the spatial distributions for temperature, density, $B_z$, and any contaminants in the fuel after heating and through at least CR=5**

- **Experimental demonstration of a magnetized liner implosion resulting in a diagnosable, ignition-relevant stagnation pressure-tau product of > 5 Gbar ns**

# The electro-thermal instability can seed the MRT instability, and can be mitigated using dielectric coatings




Thick dielectric coatings suppress liner instabilities that are seeded by the electro-thermal instability

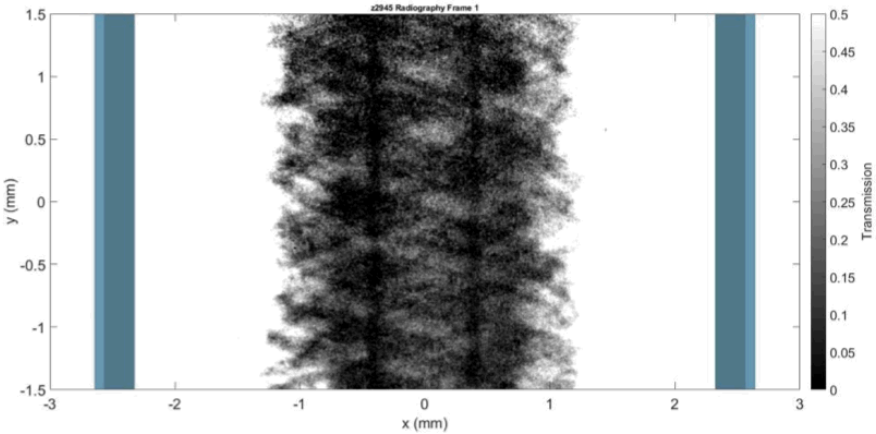


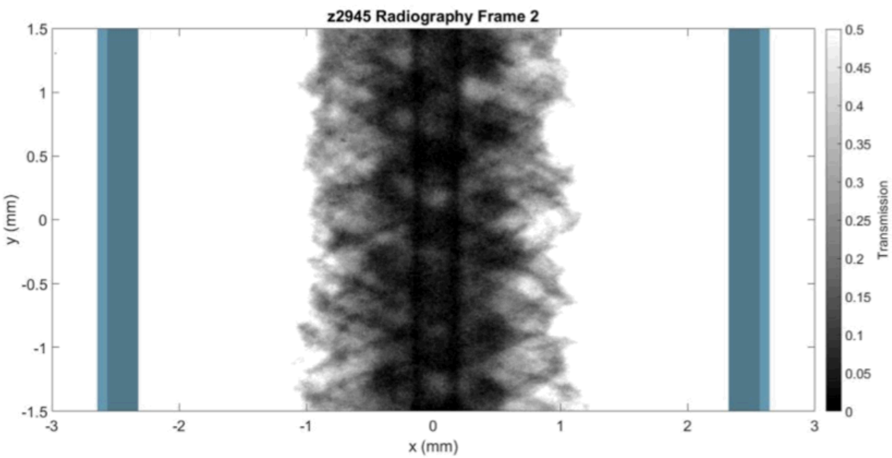


K. J. Peterson *et al*., Phys. Plasmas **19**, 092701 (2012);
K. J. Peterson *et al*., Phys. Plasmas **20**, 056305 (2013);
K. J. Peterson *et al*., Phys. Rev. Lett. **112**, 135002 (2014).

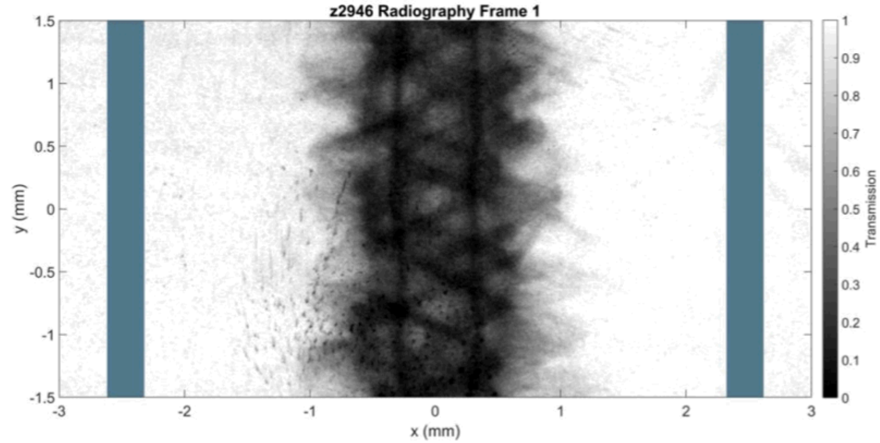
# Late time radiography demonstrates that high aspect ratio liners can achieve more stable implosions with coatings

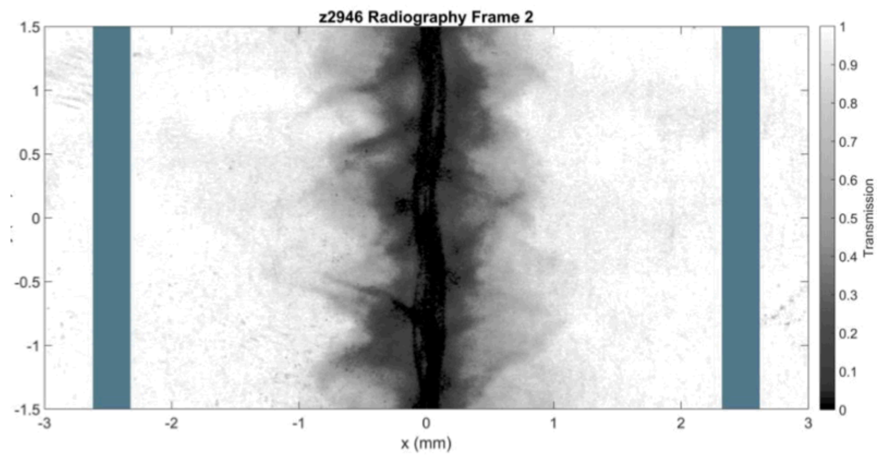
## Coated liner




## Uncoated liner




Ampleford, Rosenthal, Jennings et al.

Implosion

# Other implosion experiments this year are exploring our ability to diagnose and control liner implosions

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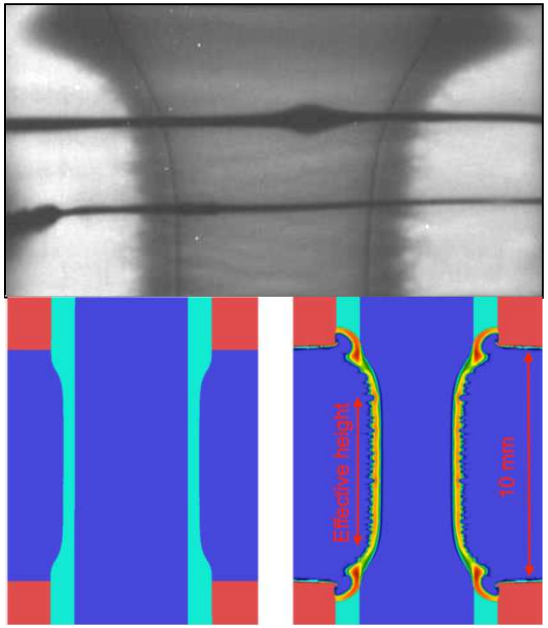
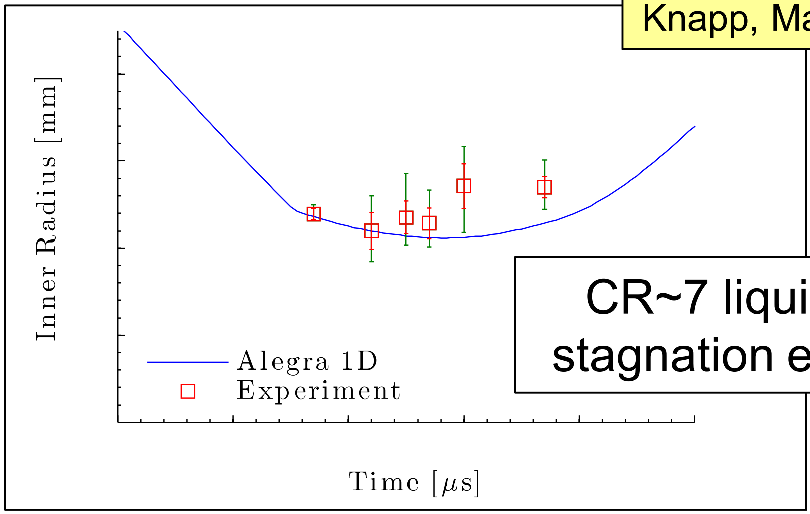



Shaped liners to control electrode/end effects

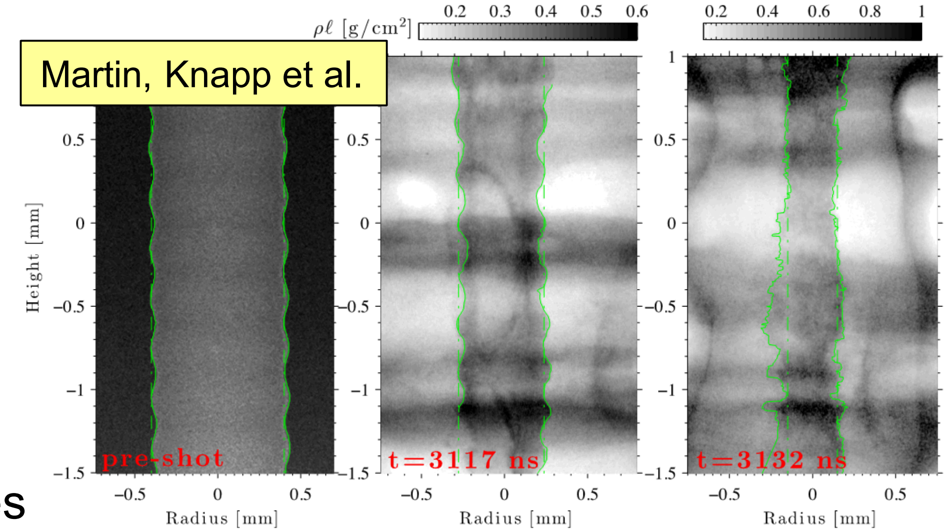
Sefkow, Ampleford et al.

Knapp, Martin et al.




CR~7 liquid D2 "1D" stagnation experiments

Martin, Knapp et al.




On-axis rods to study deceleration instabilities

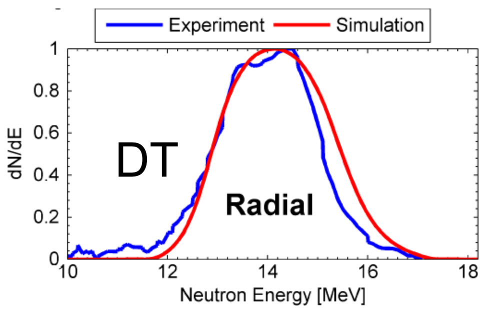
# Over the next five years, we seek to accomplish the following goals related to stagnation and burn:

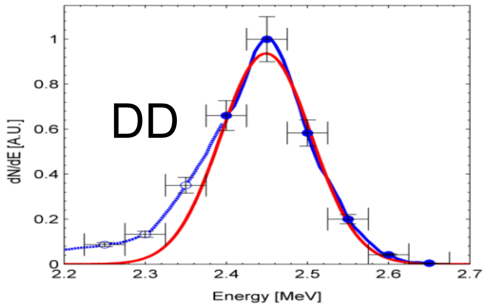
- **Achieve a burn-averaged ion temperature of >4 keV (robust burn threshold)**
- **Achieve a BR > 0.5 MG-cm ($R/r_\alpha > 2$)**
- **Achieve fuel pressure > 5 Gbar and $P\tau$ > 5 Gbar-ns**
- **Minimize and mitigate against radiation loss from high-Z contamination**
- **Demonstrate a continuous, nearly uniform stagnation column at CR>20**
- **Determine the non-thermal component of the fusion yield.**

**Implicit in these goals is developing the ability to make these measurements, which is where we are spending a lot of effort today**

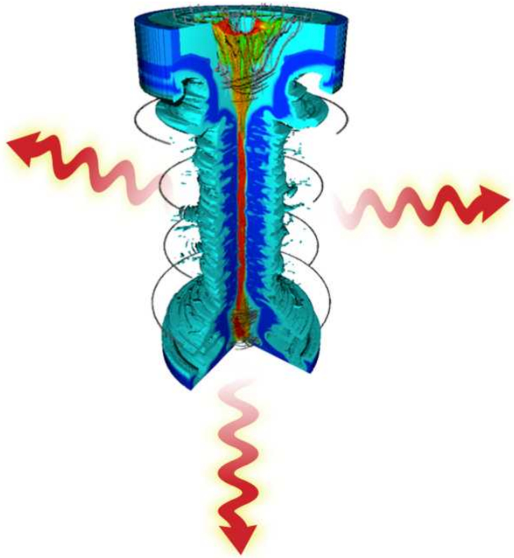
# We use a combination of x-ray and neutron diagnostics to assess the performance of MagLIF implosions.

## Neutron spectra



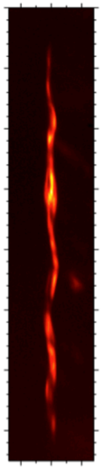




## MagLIF Z pinch

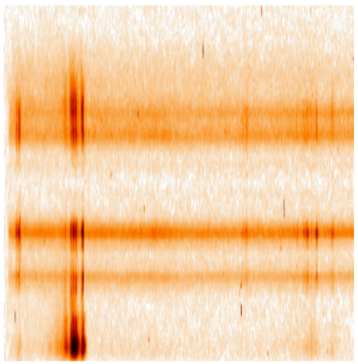


## X-ray

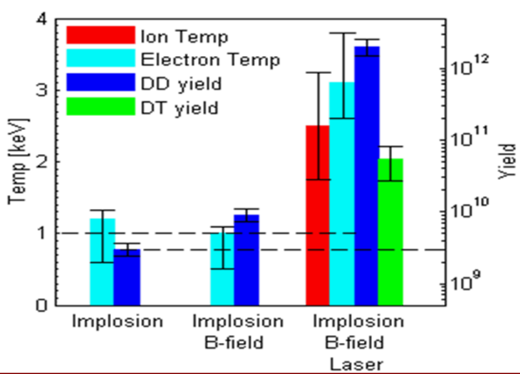
### Imaging



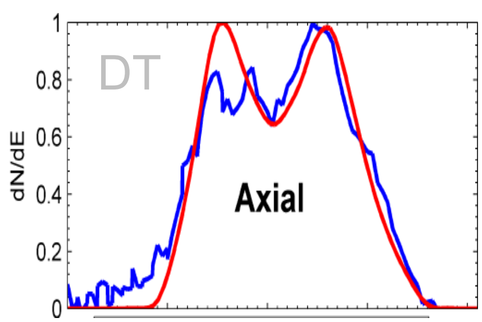
### Spectra



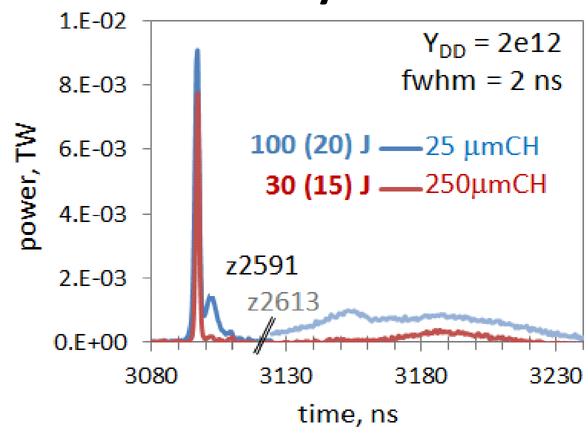
## Nuclear Activation




## Neutron spectra



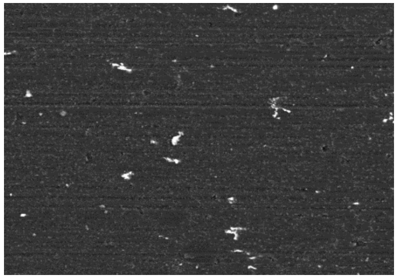

## X-ray Power

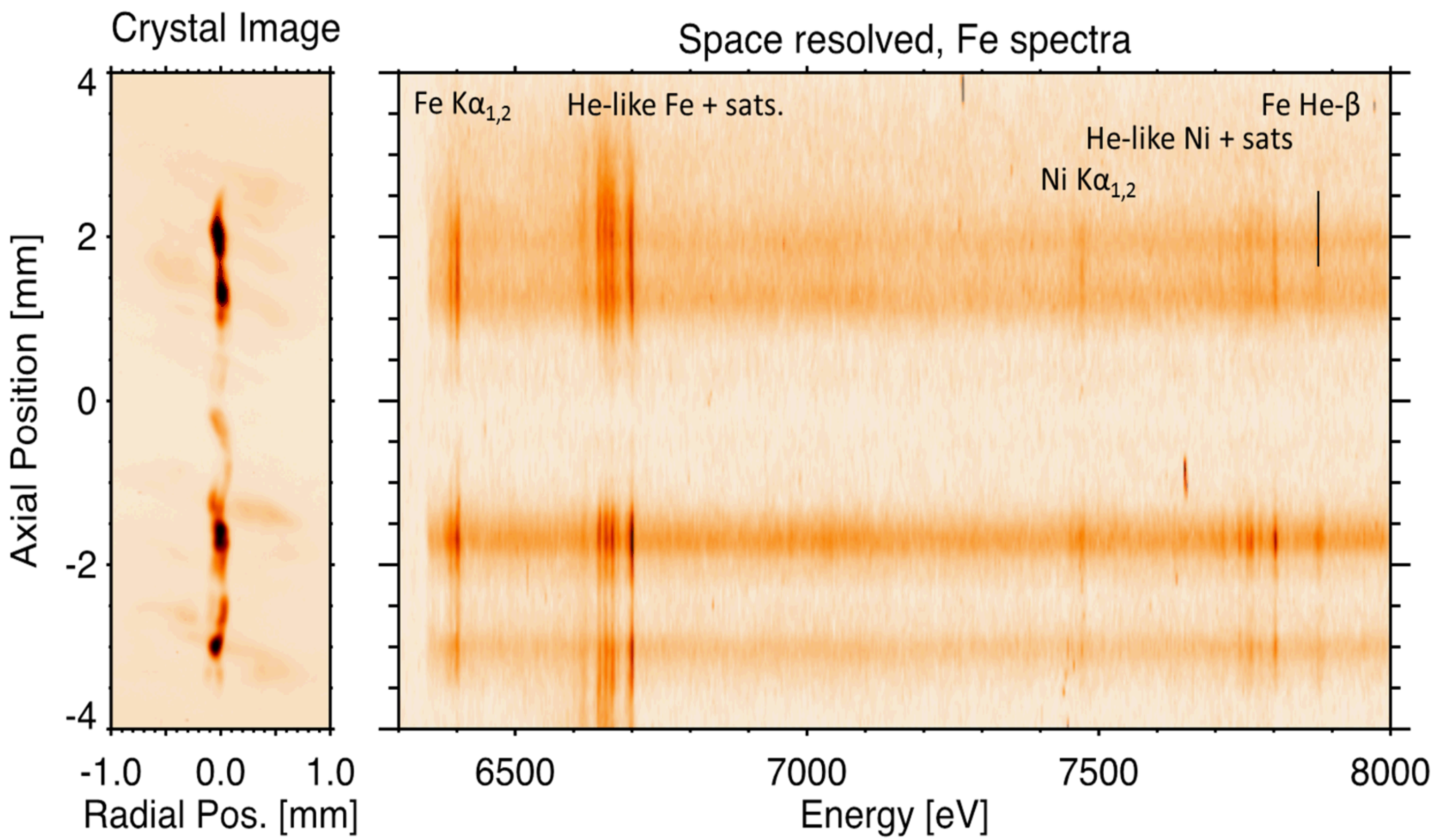


# Fe impurities from the Be liner/endcap mix into the stagnation column and provide an axially-resolved diagnostic of the plasma.

MagLIF liner machined out of S65 Be (100 ppm Fe)

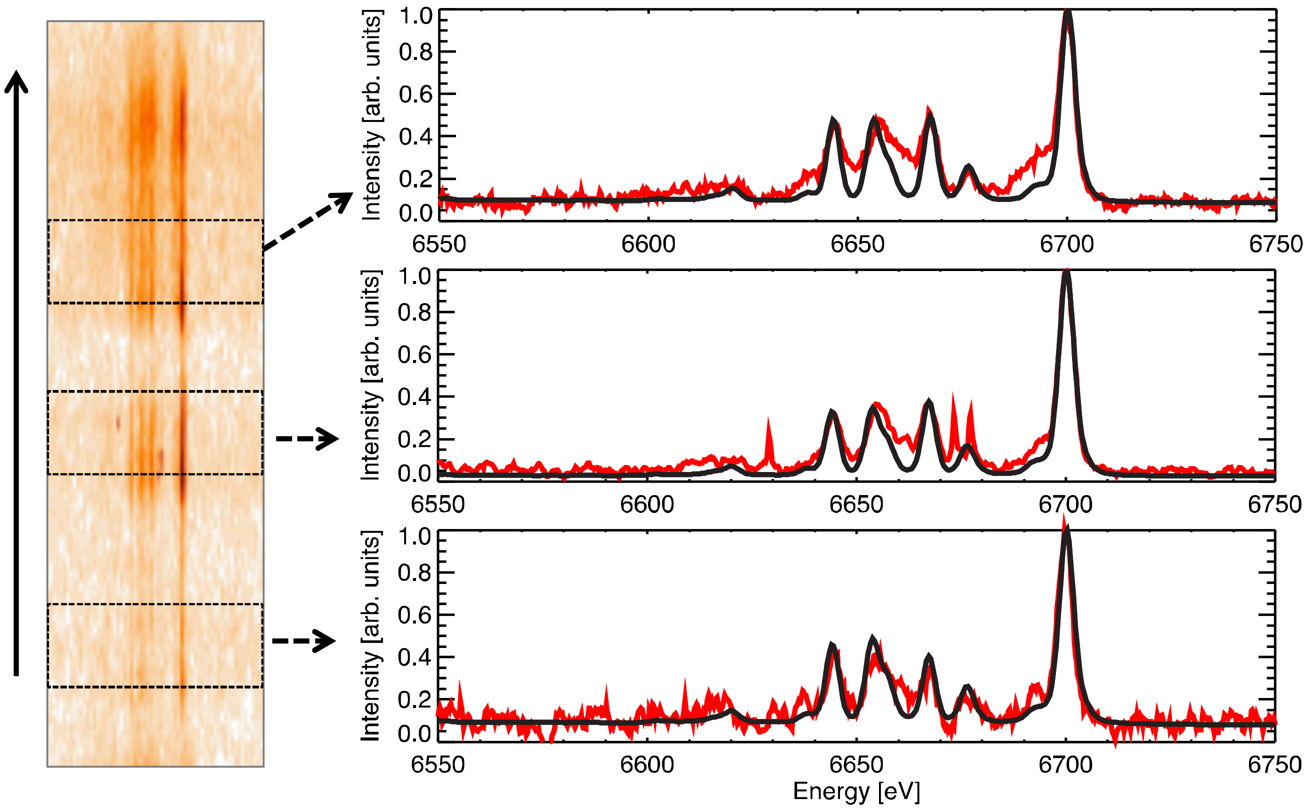
SEM image of the Be liner outer surface





# The Fe spectra can provide information on the plasma temperature, density, and mix fraction.

**Experimental spectra fitted with PrismSPECT simulations using E/ΔE = 3000.**




Preliminary Inferred values

**$T_e$ = 1.5 keV**
**$n_e$ = 1.2e23 $cm^{-3}$**
**Be mix ~ 1%**

**$T_e$ = 1.6 keV**
**$n_e$ = 1.7e23 $cm^{-3}$**
**Be mix ~ 3%**

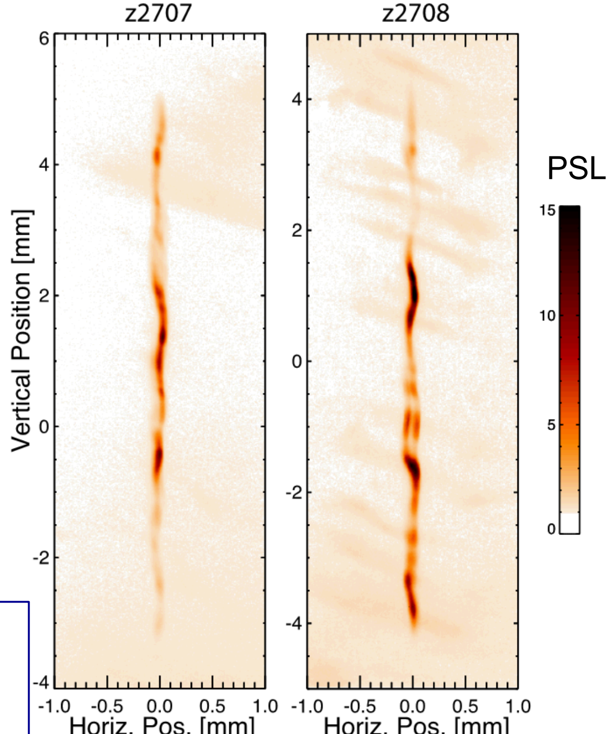
**$T_e$ = 1.4 keV**
**$n_e$ = 2.0e23 $cm^{-3}$**
**Be mix ~ 1%**

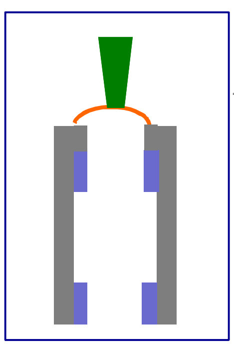
Much more work needs to be done to validate the model assumptions

# The emission morphology from nearly identical targets can vary, but DD yields are similar.

$Y_{dd}$ = 2.8e11
$I_{var}$ = 0.87
$I_{ave}$ = 2.1 PSL

$Y_{dd}$ = 1.8e11
$I_{var}$ = 0.716
$I_{ave}$ = 5.0 PSL

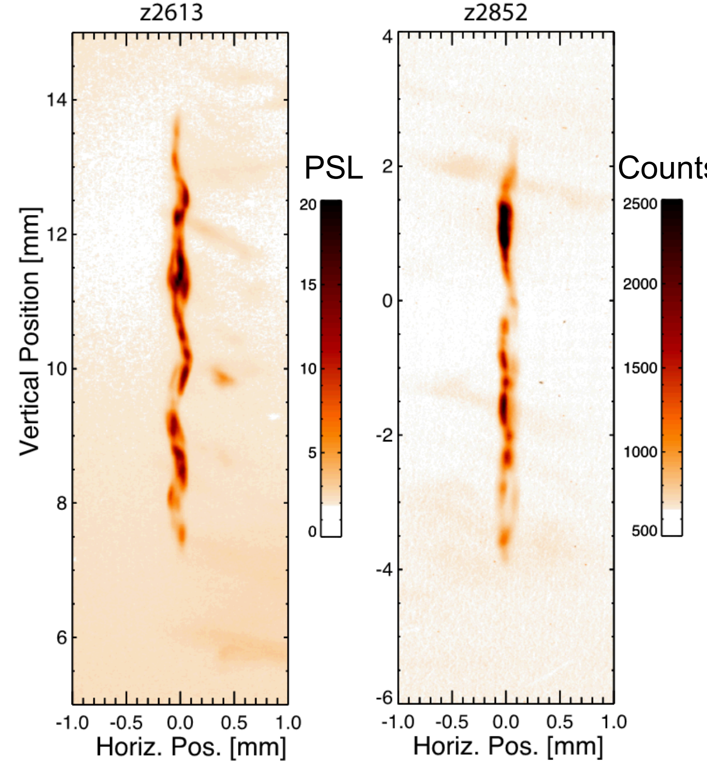


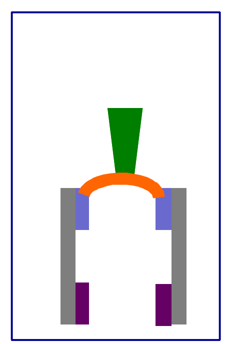



**z2707 and 2708 were identical targets.**
Long Be liner, thin window, and Al caps

$Y_{dd}$ = 1.1e12
$I_{var}$ = 0.541
$I_{ave}$ = 5.3 PSL

$Y_{dd}$ = 2.0e12
$I_{var}$ = 1.0
$I_{ave}$ = 528 counts



**z2613 and 2852 were nearly identical.**
Both were short liners with thick windows.
z2613: Al top cap, Nylon bottom, 2 mm exit hole
Z2852: Al top cap, Be bottom, 3 mm exit hole

# Recent experiments have demonstrated the efficacy of dielectric coatings on improving the stagnation morphology.

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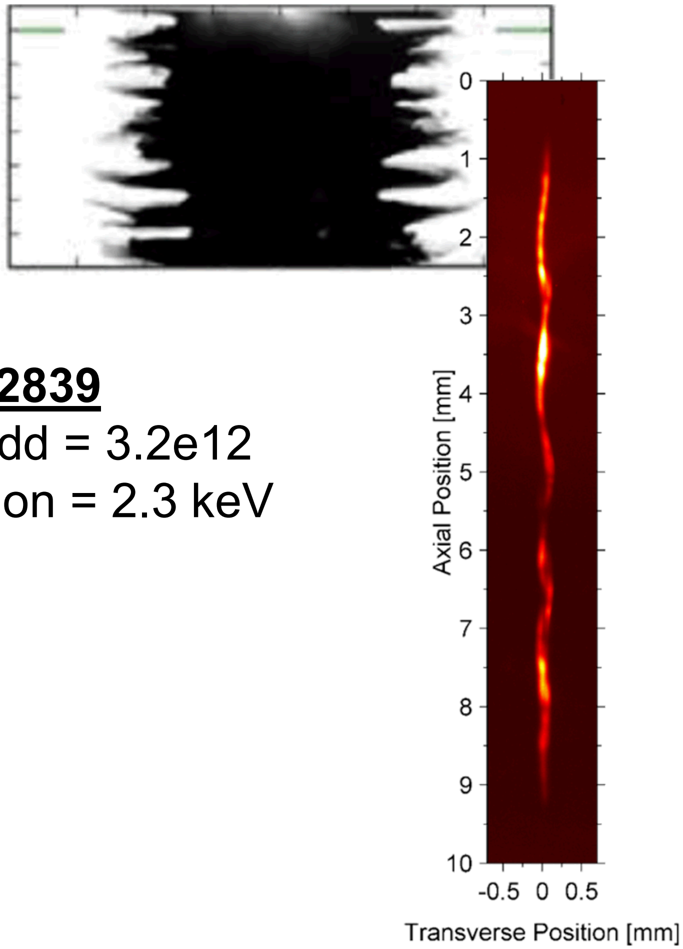
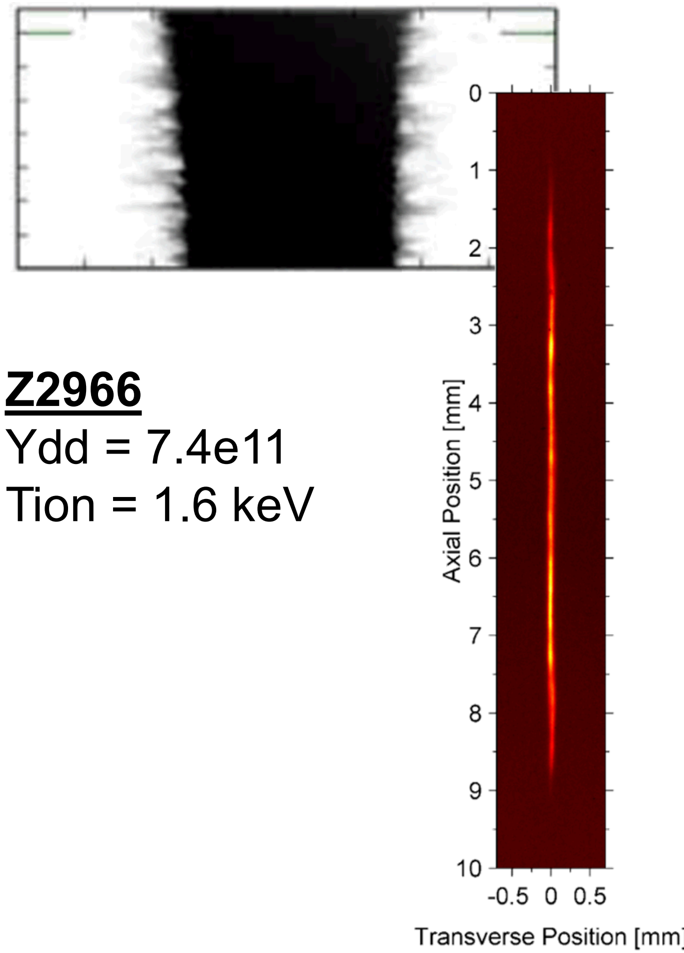
**Uncoated Liners**




**Z2839**
Ydd = 3.2e12
Tion = 2.3 keV

**Coated Liners**




**Z2966**
Ydd = 7.4e11
Tion = 1.6 keV

More work is needed to understand exactly why the column is more uniform

# We are starting to collect enough data to study trends in the interplay between the various physical processes of MagLIF.

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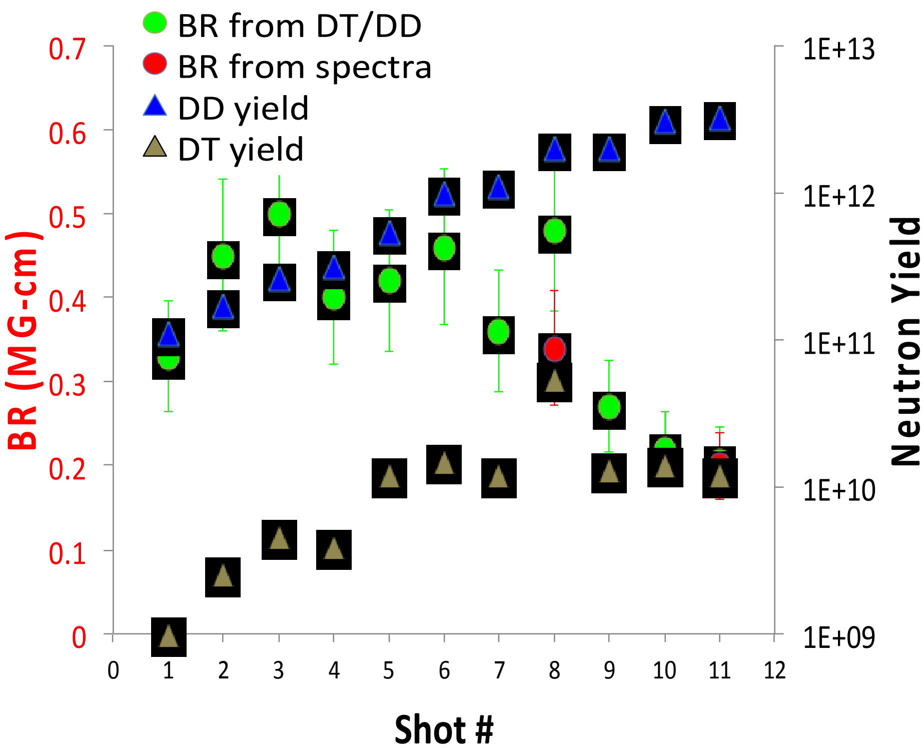
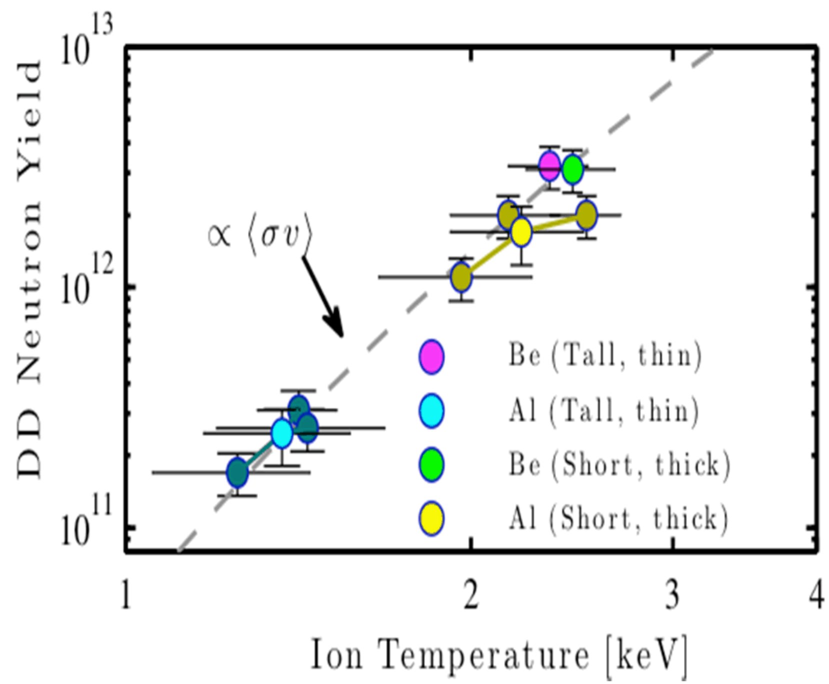
## BR, DD, and DT yield comparisons




Note: Plot is sorted by increasing DD yield, not time.

## $Y_{DD}$ vs. Ti

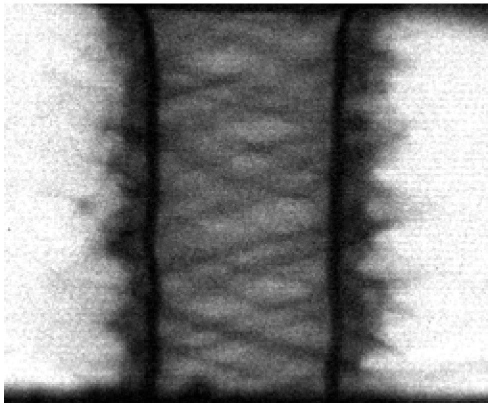


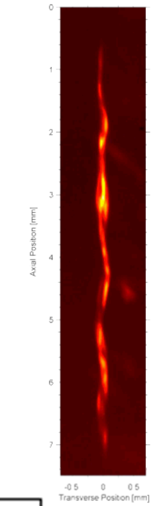
# <u>Summary</u>: Initial experiments have demonstrated the fundamental MagLIF concept, and PRD-led experiments are now focused on understanding the science and future scaling.

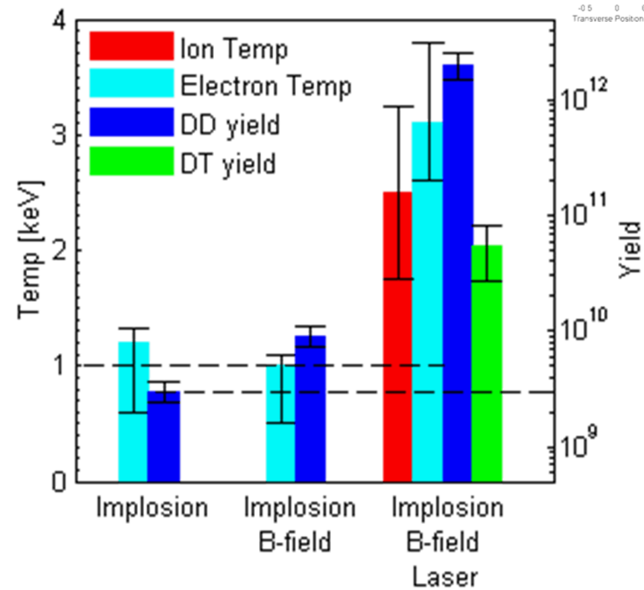
- Magnetic Direct Drive is an efficient way to couple energy to an ICF target.
  - Experiments to date couple ~0.4 MJ to the target

- Initial MagLIF experiments have demonstrated the basic concepts of preheat and fuel magnetization to achieve thermonuclear fusion.
  - Max DD yields of ~3E12

- We have organized our program around 5 Priority Research Directions, and focused experiments will provide the understanding to scale to ignition and high yield.
  - Driver-Target Coupling (Current coupling)
  - Preconditioning (Laser preheat and B-fields)
  - Implosion (Liner stability)
  - Stagnation (Measurements)
  - Modeling, Simulation, & Scaling







# Extra