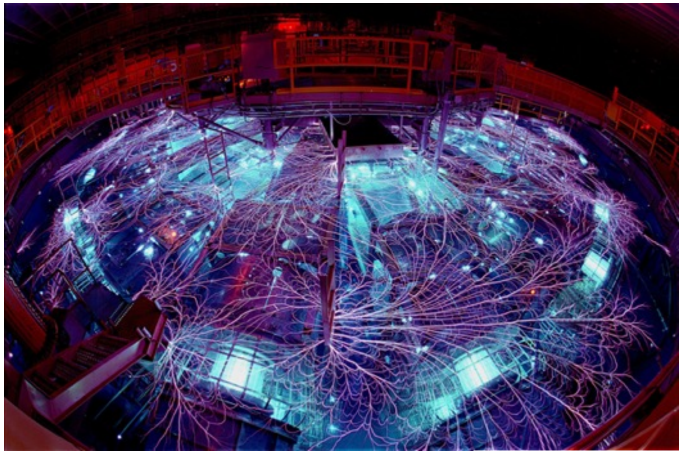
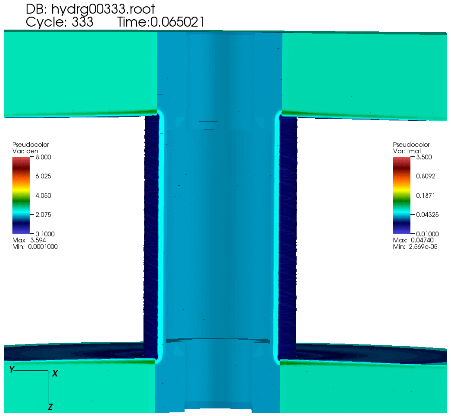
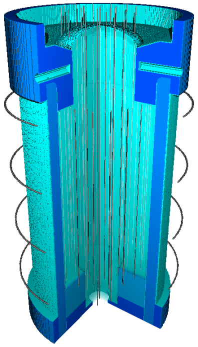






Overview of the Magnetized Liner Inertial Fusion Research Program in the United States*

Kyle Peterson

Manager, Radiation and ICF Target Design

Sandia National Laboratories

U.S. DEPARTMENT OF ENERGY

NNSA National Nuclear Security Administration

Sandia National Laboratories is a multi-program laboratory managed and operated by Sandia Corporation, a wholly owned subsidiary of Lockheed Martin Corporation, for the U.S. Department of Energy's National Nuclear Security Administration under contract DE-AC04-94AL85000.

MagLIF is a broad 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, D.B. Sinars, S.A. Slutz, I.C. Smith, W.A. Stygar, R.A. Vesey, E.P. Yu

Sandia National Laboratories

B.E. Blue, R. Paguio, K. Tomlinson, H. Huang, M.S. Wei

General Atomics

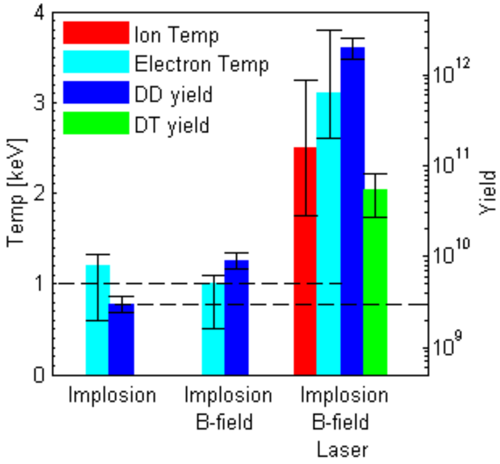
J. Davies, R. Betti, P.-Y. Chang, G. Fiksel, D. Barnak, V. Glebov, E.M. Campbell, A.B. Sefkow

Laboratory for Laser Energetics

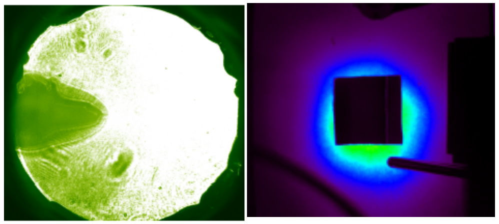
B. Pollock, M.C. Herrmann, J. Moody, D, Strozzi, C. Goyon, S. Khan, D. Hinkel, G. Logan

Lawrence Livermore National Laboratory

Summary

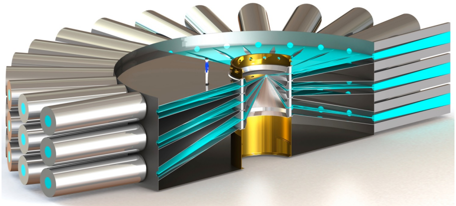


- Initial MagLIF experiments have demonstrated the basic concepts of **preheat**, **fuel magnetization**, and **implosion** to achieve thermonuclear fusion.
    - Max DD fusion yields of ~3E12



- Since our initial experiments, we have focused on understanding the science of MagLIF

- We are also developing several capabilities to test simulation code predictions of MagLIF scaling



Outline of my talk

- Description of Magnetized Liner Inertial Fusion (MagLIF)
- Present State - Experimental results and progress in understanding the science behind MagLIF
- Future - Path forward including current understanding of requirements for ignition and high yield

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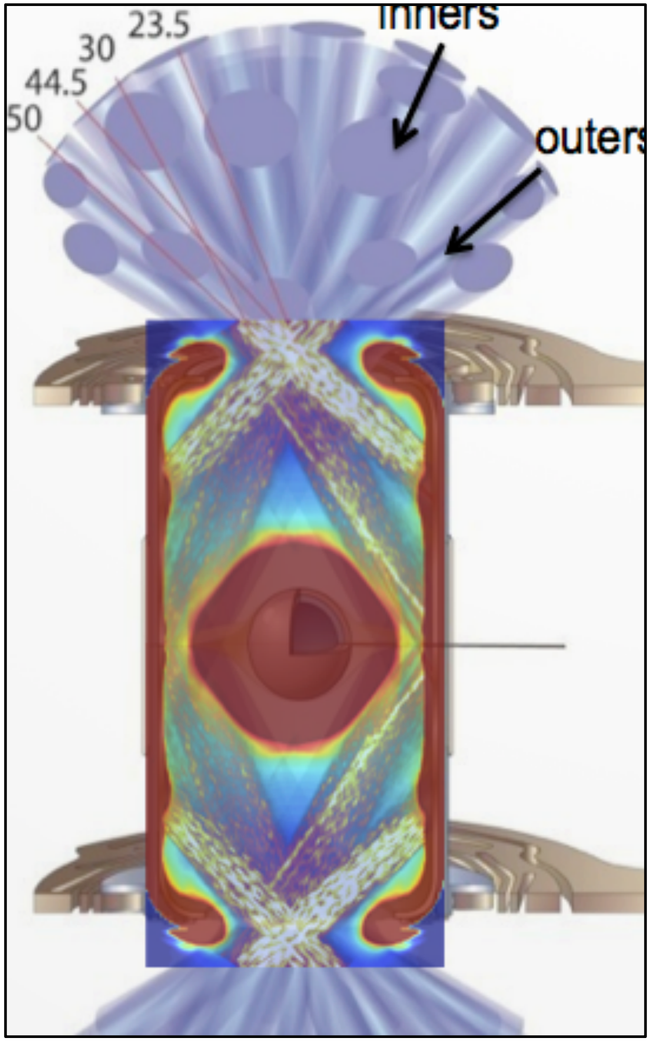
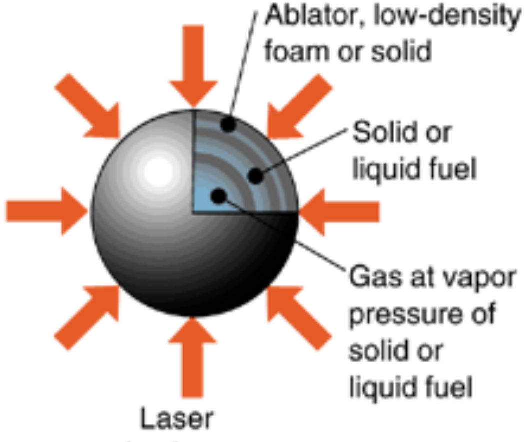
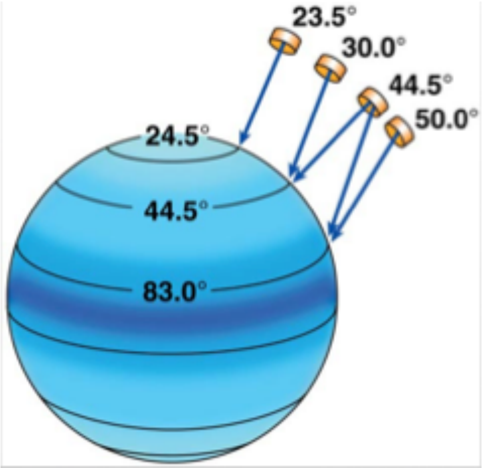
The United States ICF program is pursuing three main approaches to ignition

Radiation-driven implosions

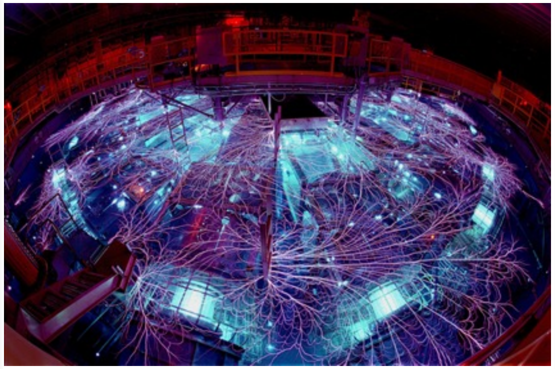


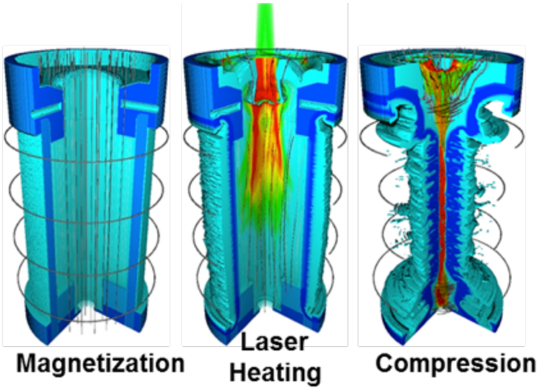
Laser-driven implosions





Magnetically-driven implosions





Focus of today's talk

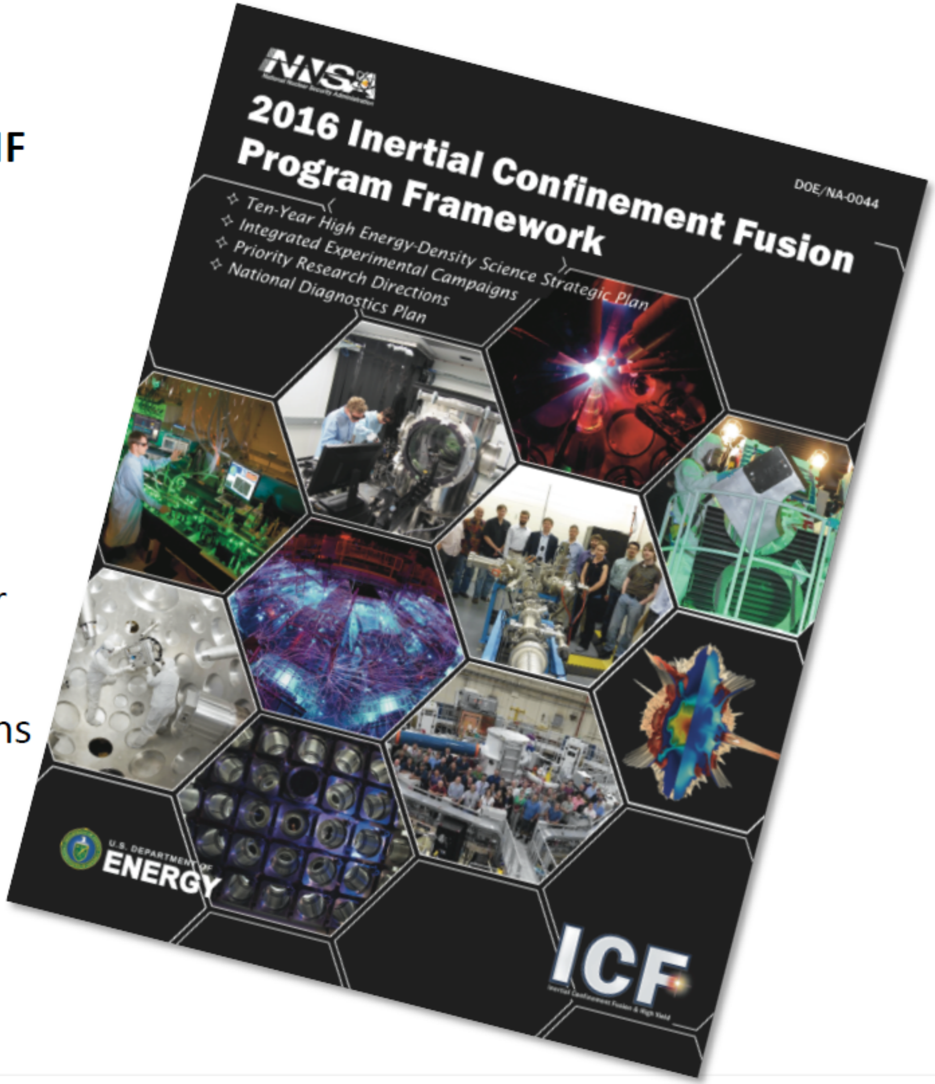
The United States ICF program is pursuing three main approaches to ignition

Radiation-driven implosions

Laser-driven implosions

Magnetically-driven implosions

- We will, by 2020, **determine the efficacy of reaching ignition on the NIF and of achieving credible physics scaling to multi-megajoule fusion yields for each of the three major ICF approaches**
- Organized around four framework elements:
  - 10-year scientific strategic Plan for HED Science for SSP
  - Integrated Experimental Campaigns
  - Priority Research Directions (Science/Diagnostics)
  - Transformative Diagnostics



NNSA

2016 Inertial Confinement Fusion Program Framework

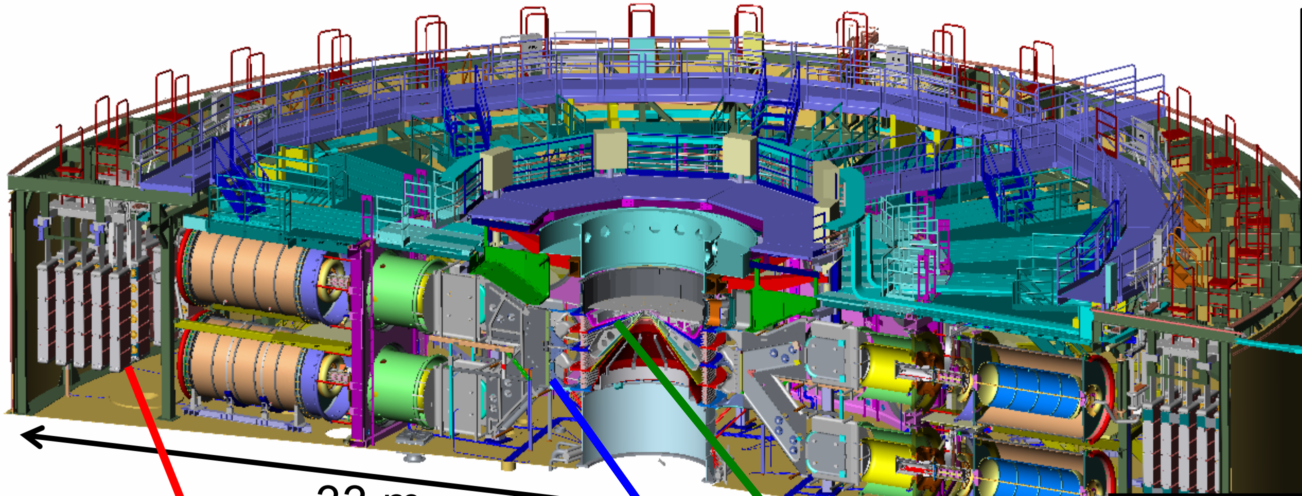
DOE/NA-0044

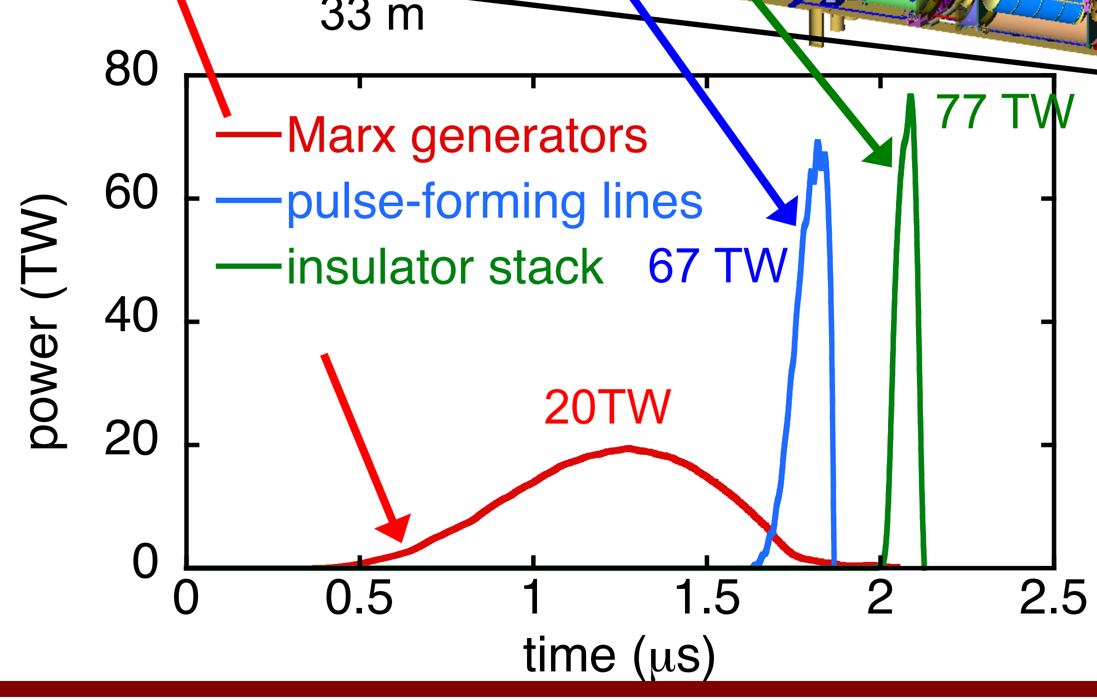
- Ten-Year High Energy-Density Science Strategic Plan
- Integrated Experimental Campaigns
- Priority Research Directions
- National Diagnostics Plan

U.S. DEPARTMENT OF ENERGY

ICF

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

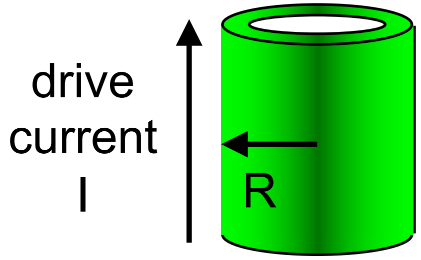




Z today couples ~0.4 MJ out of 20 MJ stored to MagLIF target (0.1 MJ in DD fuel).

Magnetically-Driven Implosion

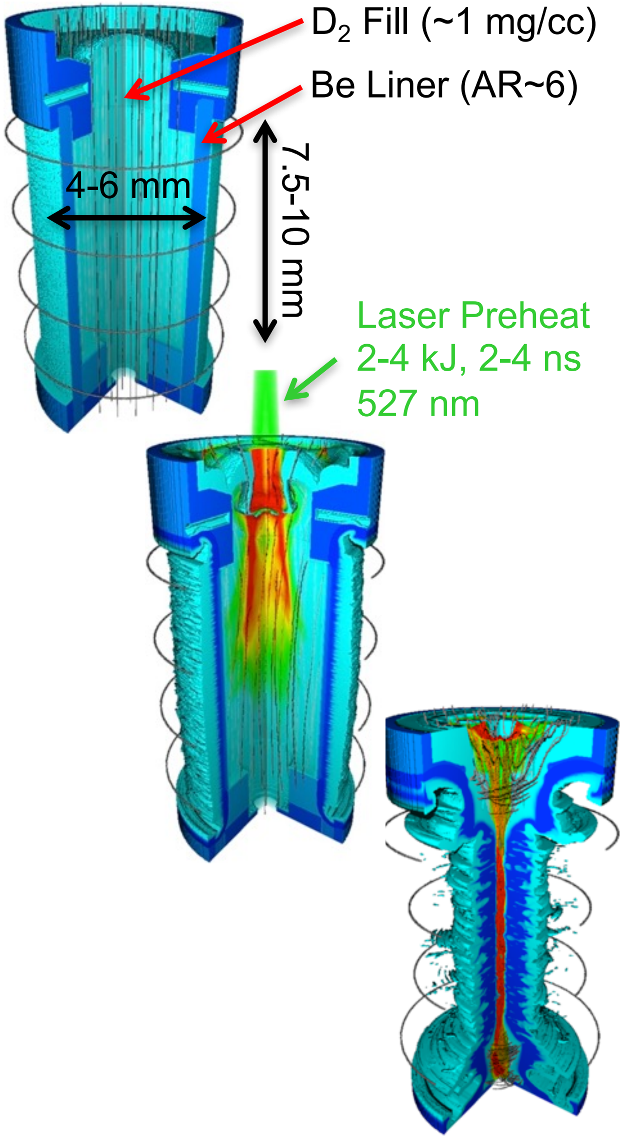
$$P = \frac{B^2}{8\pi} = 105\left(\frac{I_{MA}/26}{R_{mm}}\right)^2 \text{ MBar}$$



100 MBar at 26 MA and 1 mm

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

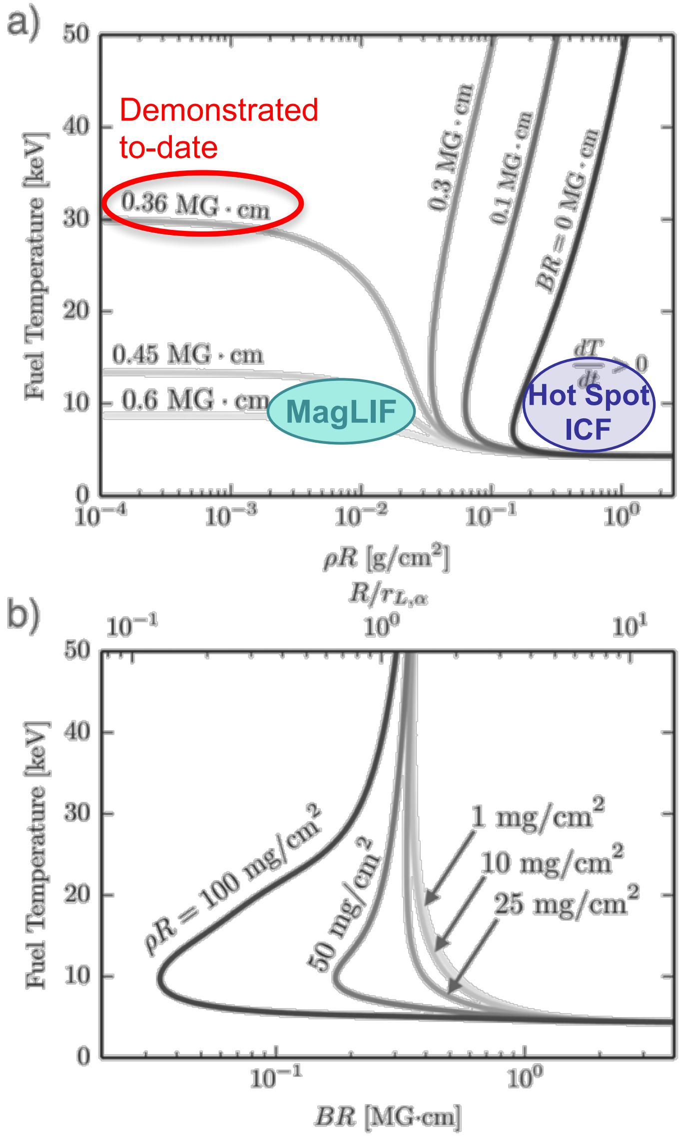
Magnetized Liner Inertial Fusion (MagLIF) is well suited to pulsed power drivers and may reduce fusion requirements

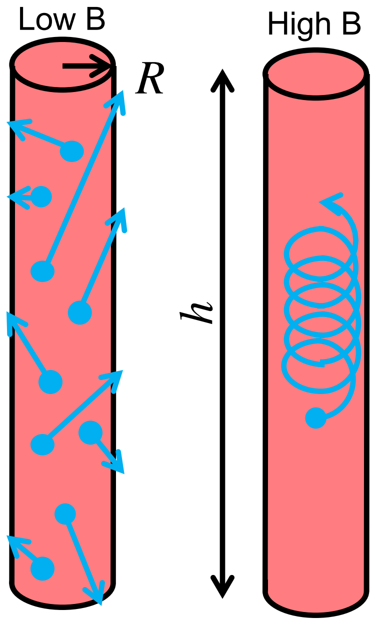


- **Axial magnetization of fuel/liner (B_{z0} = 10-30 T)**
  - Inhibits thermal conduction losses and traps alphas (β: 5~80; $\omega\tau$>200 at stagnation)
- **Laser heating of fuel (2 kJ initially, 6-10 kJ planned)**
  - Reduces radial fuel compression needed to reach fusion temperatures (R_0/R_f about 25, T_0=150-200 eV)
- **Liner compression of fuel (70-100 km/s, ~100 ns)**
  - Low velocity allows use of thick liners ($R/\Delta R$~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 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 α's (tritons) is a function of ***BR***
- At BR>0.5 MG-cm the effects saturate (particles are well confined).
- Measurements to date suggest >0.35 MG-cm

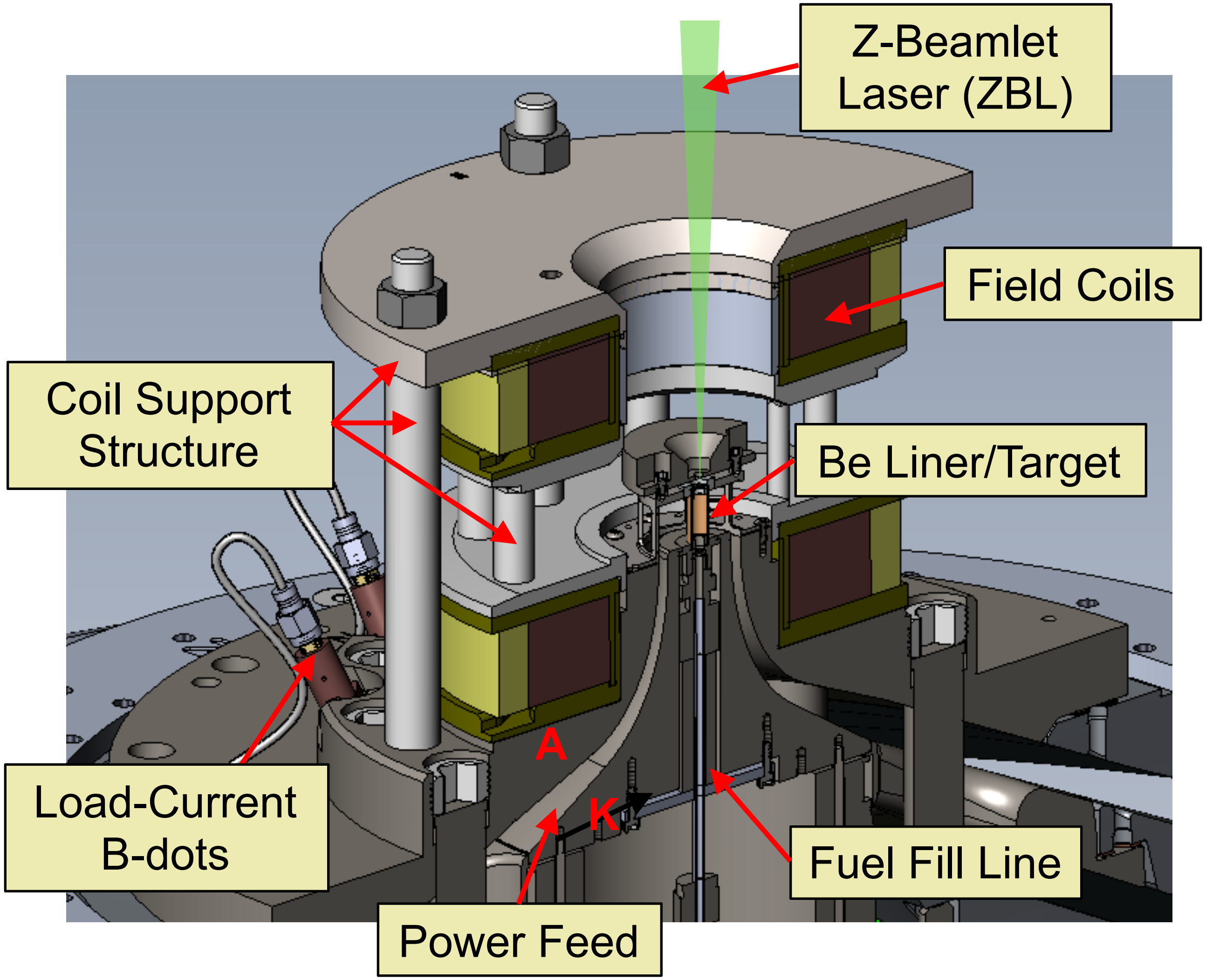
$$\frac{R}{r_\alpha} = \frac{BR\ [T \cdot \mathrm{cm}]}{26.5} = \frac{BR\ [G \cdot \mathrm{cm}]}{2.65e5} \approx 4BR\ [MG \cdot \mathrm{cm}]$$

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

Anatomy of a MagLIF Experiment

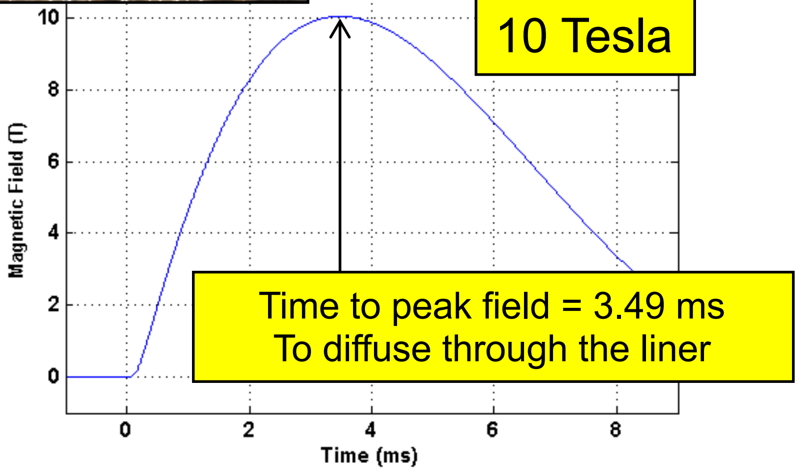
- **Field Coils**: Helmholtz-like coil pair produce a 10-30 T axial field w/ ~3 ms rise time

- **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.

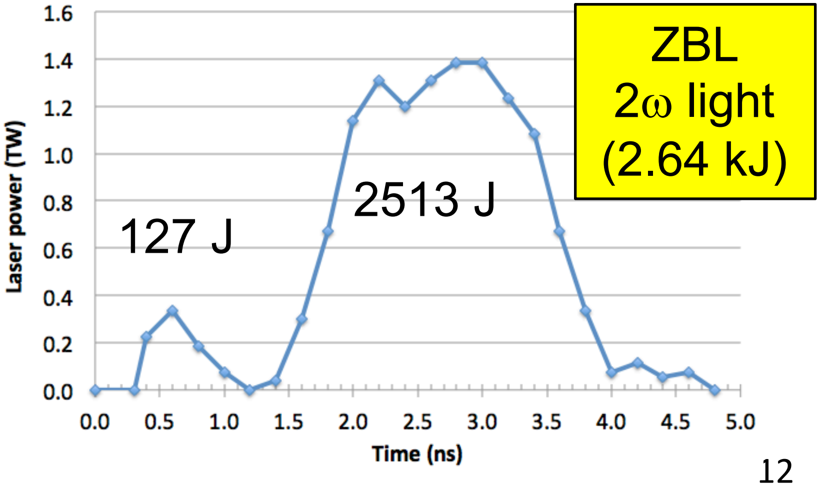
Capacitor bank system on Z
900 kJ, 8 mF, 15 kV



10 Tesla

Time to peak field = 3.49 ms
To diffuse through the liner

Z-Beamlet Vacuum Final Optic Assembly



127 J

2513 J

ZBL
2ω light
(2.64 kJ)

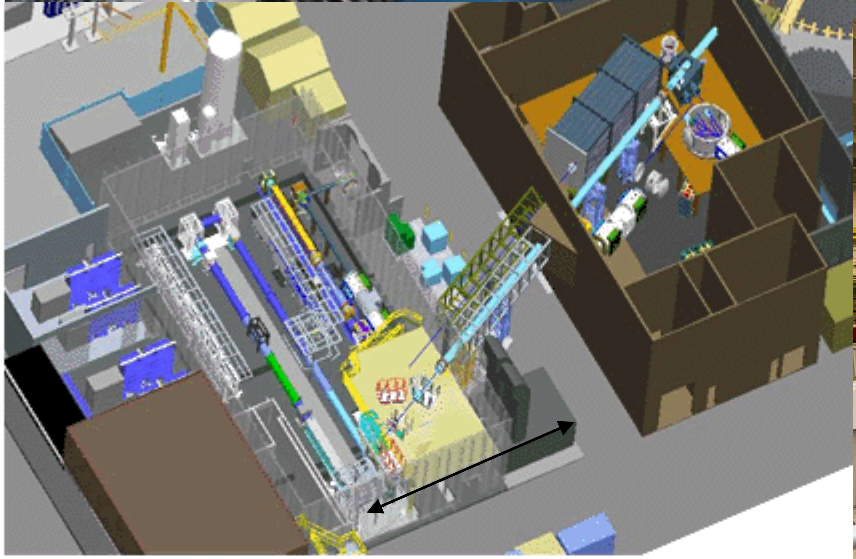
The Z-Beamlet laser at Sandia* is being used to radiograph liner targets and heat fusion fuel


Z-Beamlet High Bay

Z facility

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

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

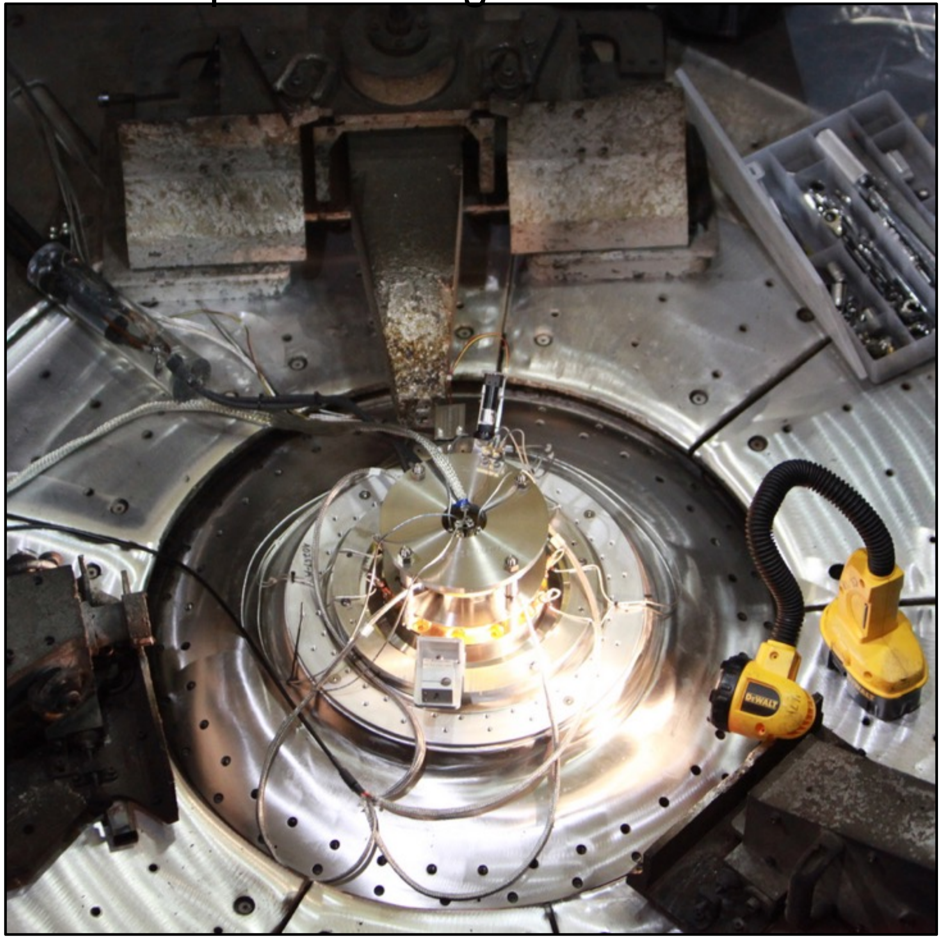

Z-Beamlet and Z-Petawatt lasers

---

* P. K. Rambo *et al.*, Applied Optics 44, 2421 (2005).

Z couples several MJ of energy to the load hardware, ~equivalent to a stick of dynamite, making diagnostic measurements and laser coupling challenging

Pre-shot photo of MagLIF load hardware

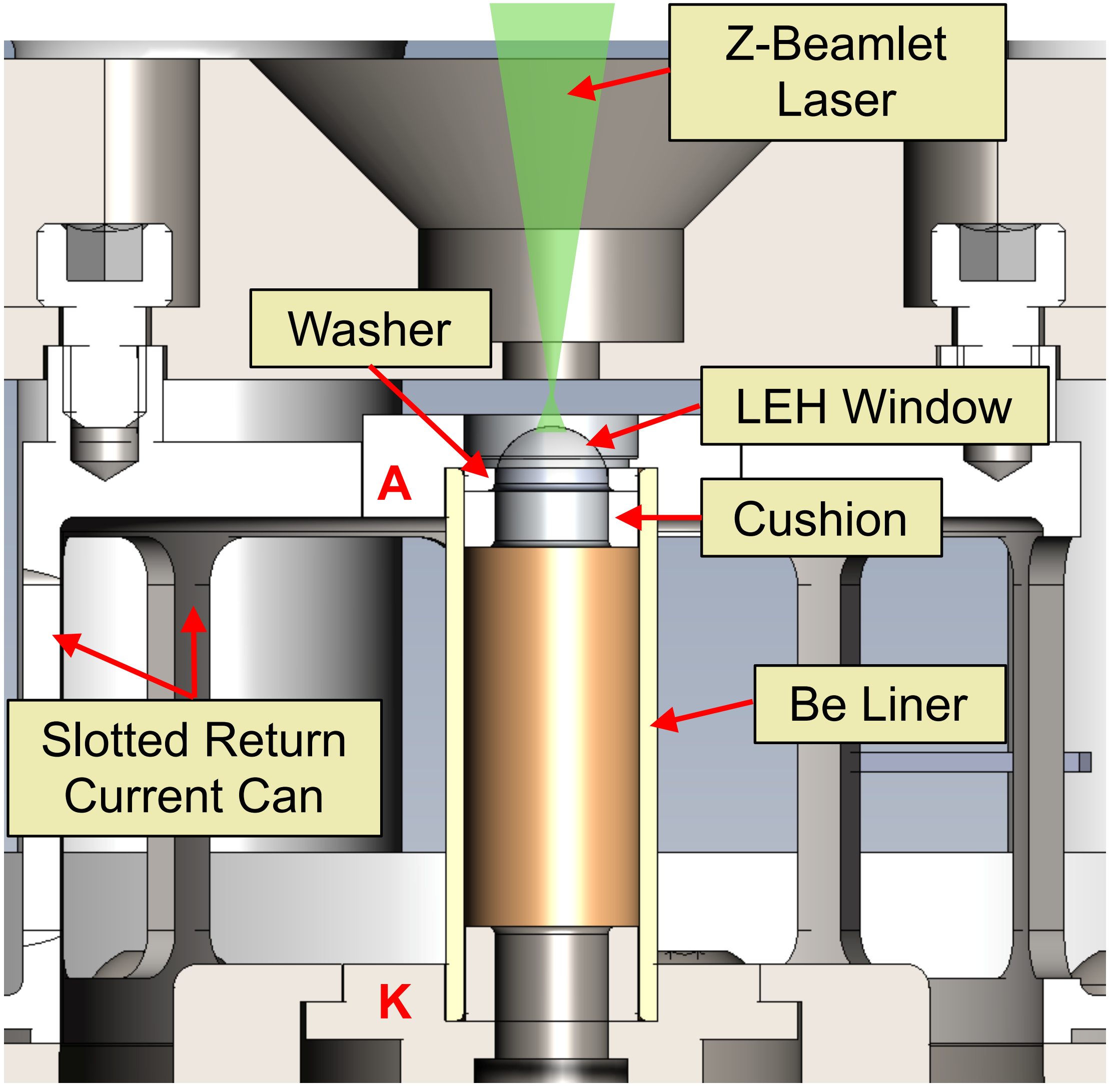


Damage to FOA debris shielding

Post-shot photo

Overview of the existing MagLIF baseline target design

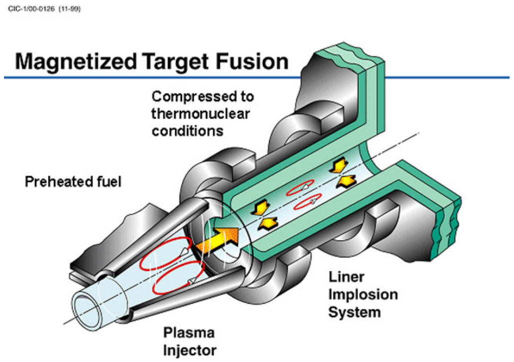
- **Be Liner**: OD = 5.58 mm, ID = 4.65 mm, h = 5–10 mm
- **LEH Window**: 1-3 μm thick plastic window. Supports 60 PSI pure D2 gas fill.
- **Washer**: Metal (Al or Be) washer supporting LEH window
- **Cushion**: Al or Be structure used to mitigate the wall instability. Also reduces LEH window diameter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

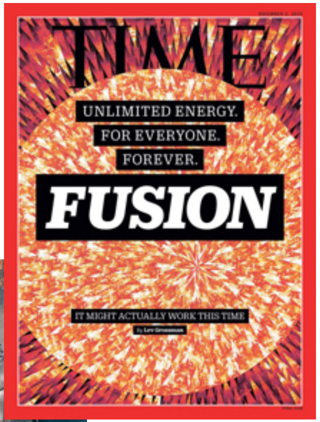


MagLIF has conservative fuel compression characteristics, but relies on largely unvalidated magneto-inertial fusion principles

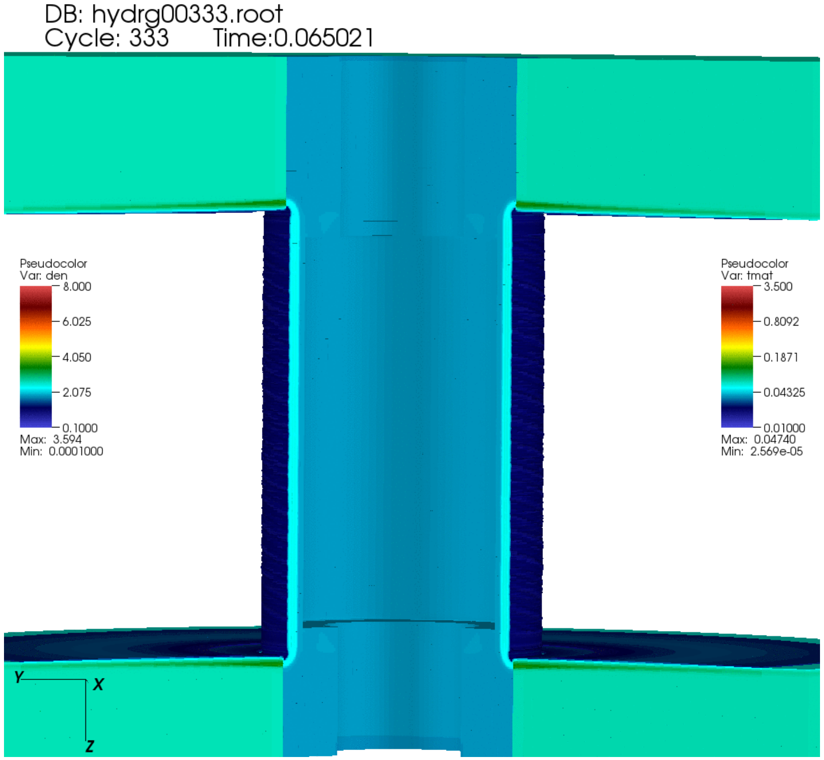
Metric	X-ray Drive on NIF	100 kJ MagLIF on Z
Pressure	~140-160 Mbar	26 MA at 1 mm is 100 Mbar
Force vs. Radius	Goes as R^2	Goes as 1/R
Peak velocity	350-380 km/s	70-100 km/s
Peak IFAR	13-15 (high foot) to 17-20	8.5
Hot spot CR	35 (high foot) to 45	25
Volume Change	43000x (high) to 91000x	625x
Fuel rho-R	>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

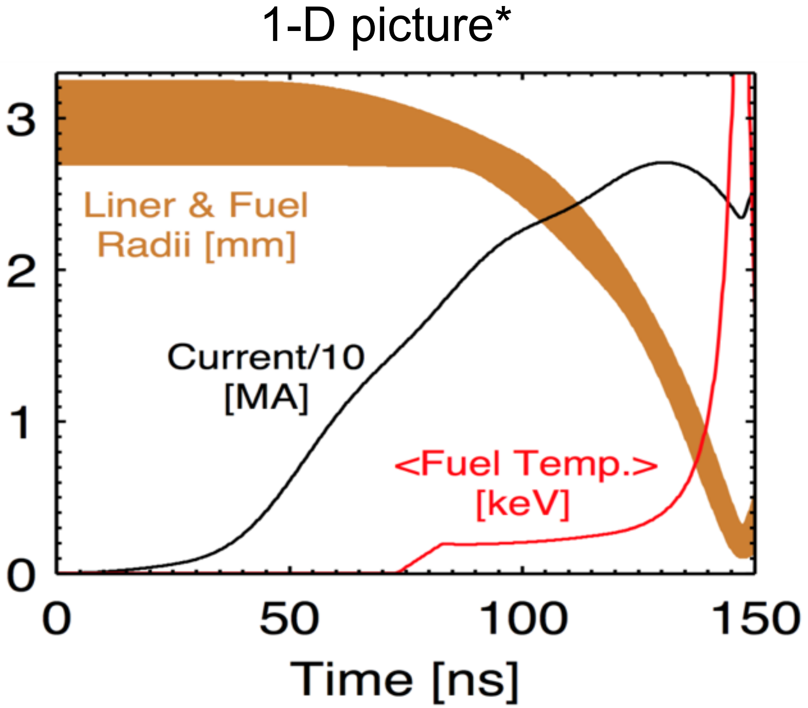
- Low Velocity Implosion
- Low In flight aspect ratio (IFAR)
- Low convergence ratio / volume compression / fuel ρR





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





A. Sefkow

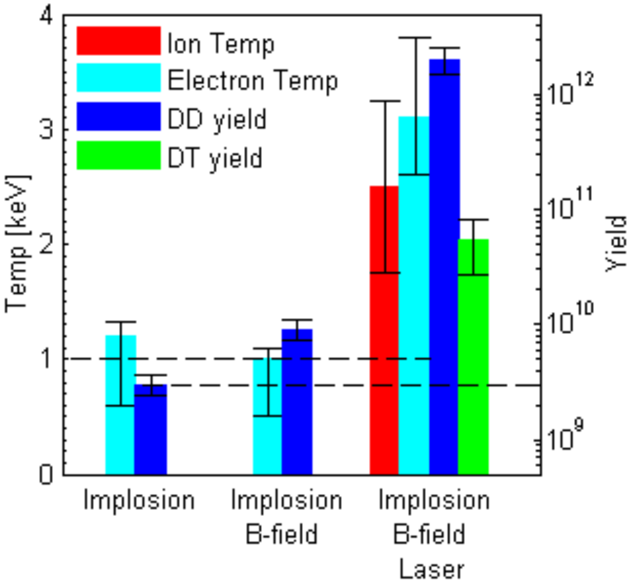
*R. D. McBride and S. A. Slutz, PoP 22, 052708 (2015)

Outline of my talk

- Description of Magnetized Liner Inertial Fusion (MagLIF)
- Present State - Experimental results and progress in understanding the science behind MagLIF
- Future - Path forward including current understanding of requirements for ignition and high yield

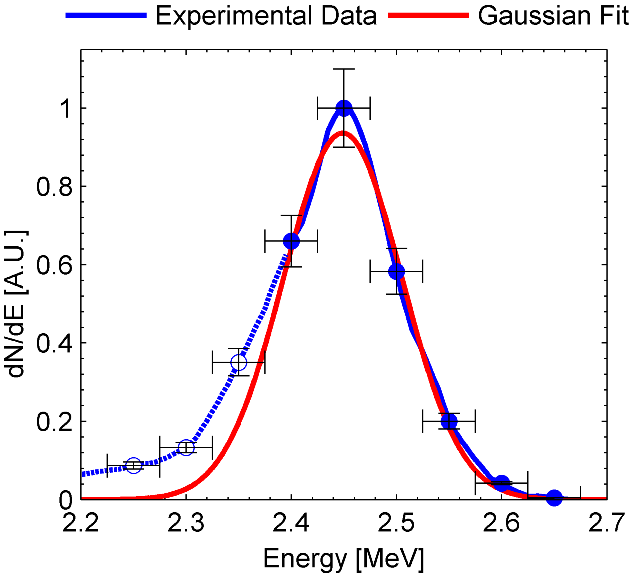
Initial integrated experiments on Z demonstrated that the fundamental concepts of MagLIF work.

Significant yields and temperatures only w/ applied B_z and preheat



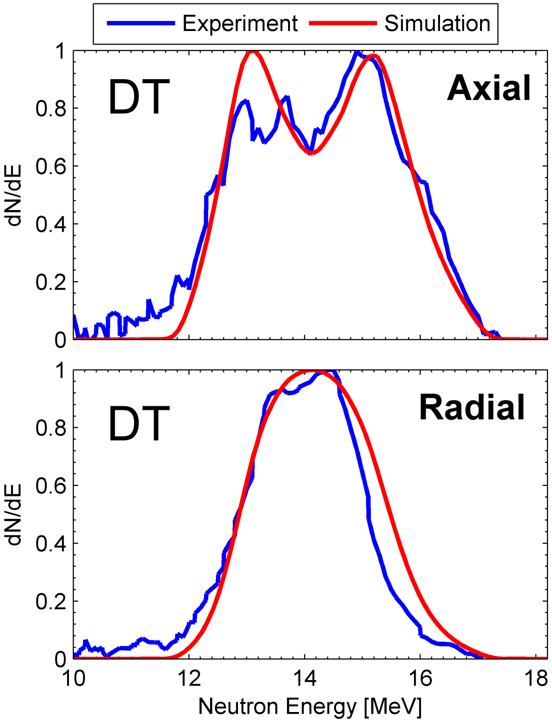
Max DD neutron yield = 3e12
Max ion temp = 2.5 keV

Thermonuclear neutron generation



Isotropic,
‘Near-Gaussian’ DD neutron spectra

Magnetic trapping of charged particles



BR = 0.35 MG-cm

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

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

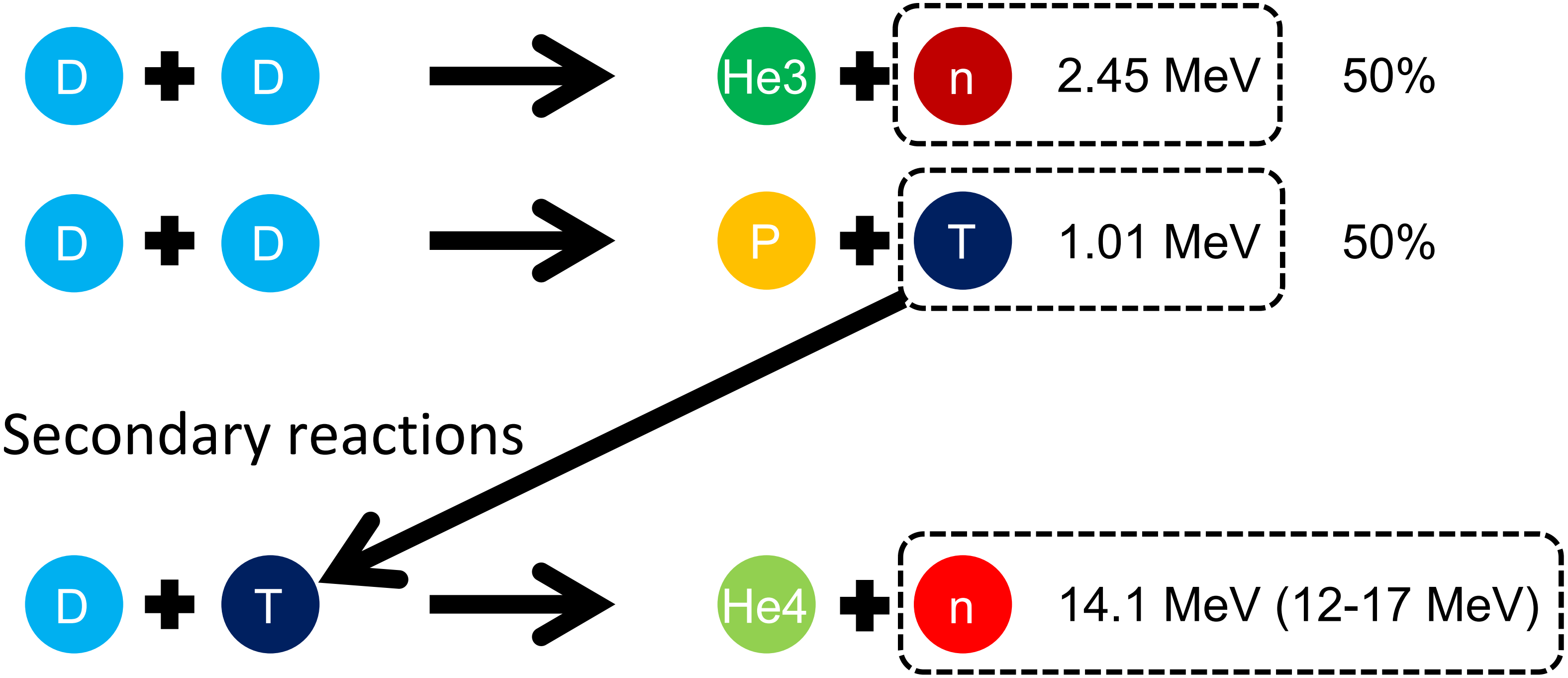
- **Demonstrate target performance over available range of conditions**
  - Primarily accomplished through integration experiments on Z
  - **100 kJ DT yields; P-tau > 5 Gbar-ns; BR > 0.5 MG-cm**

~5% of effort

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

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

- Primary reactions



D + D → He3 + n 2.45 MeV 50%

D + D → P + T 1.01 MeV 50%

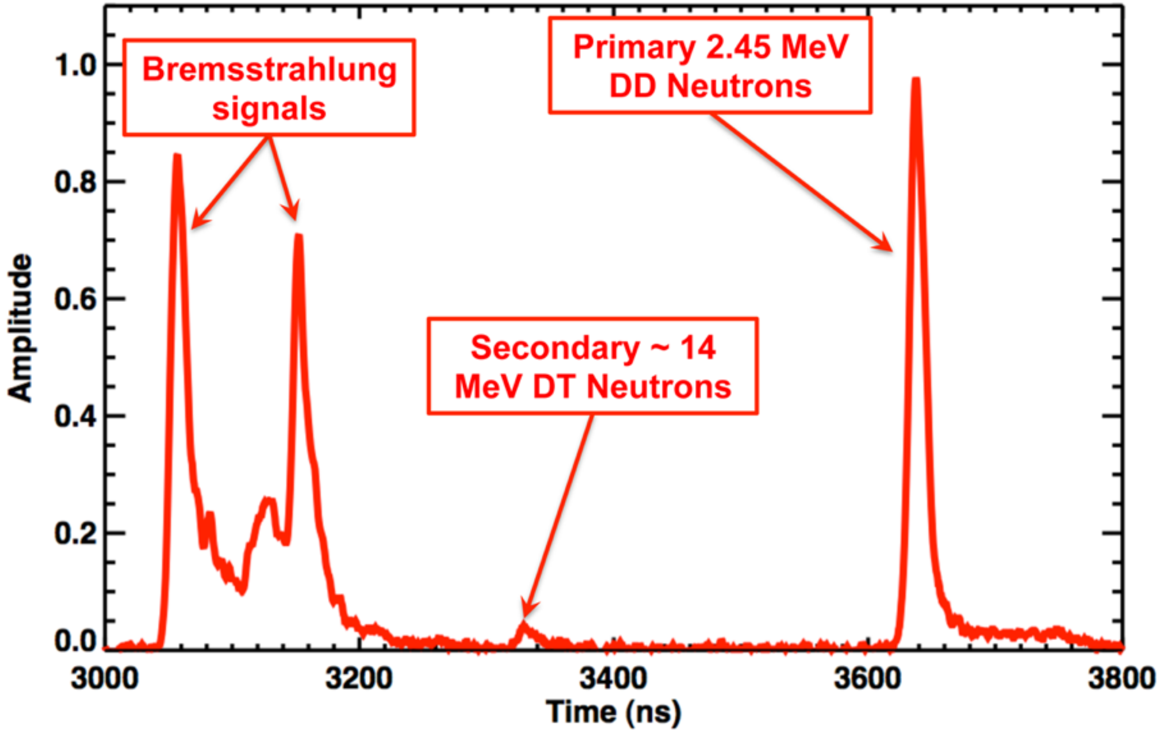
- Secondary reactions

D + T → He4 + n 14.1 MeV (12-17 MeV)

- Triton may still retain fraction of birth energy when reacting

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

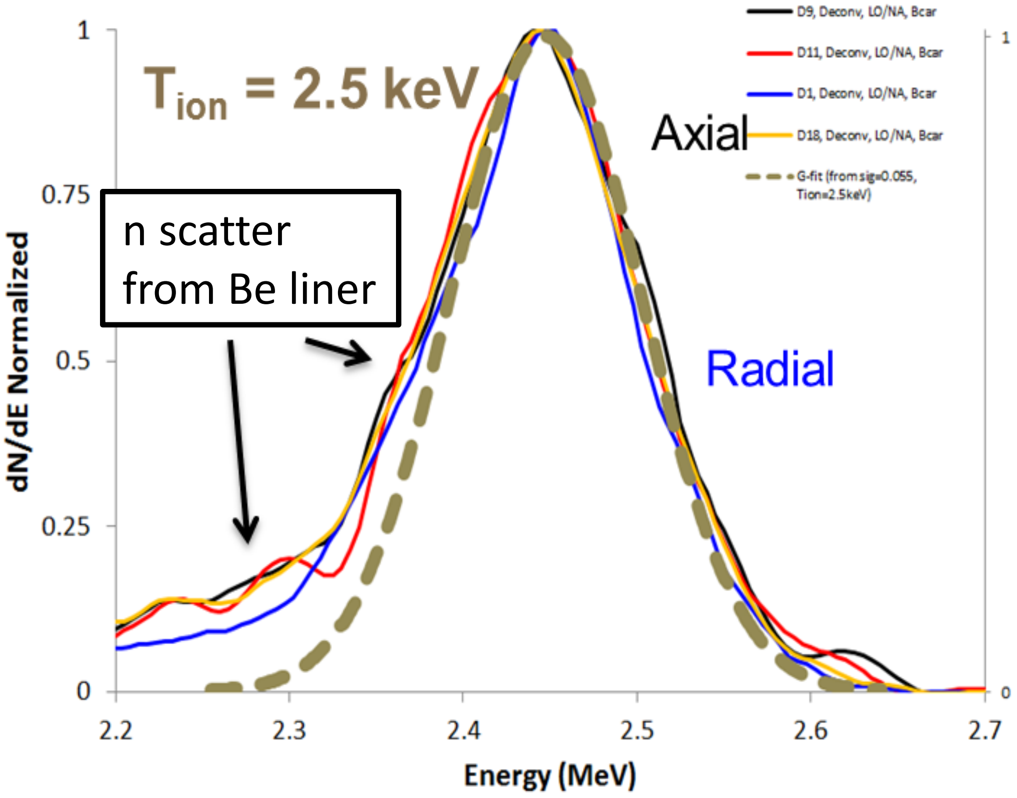
These experiments produced both primary (2.45 MeV) and secondary (14 MeV) neutrons recorded by neutron time-of-flight and activation sample diagnostics (D2 fill only!!!)



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

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}

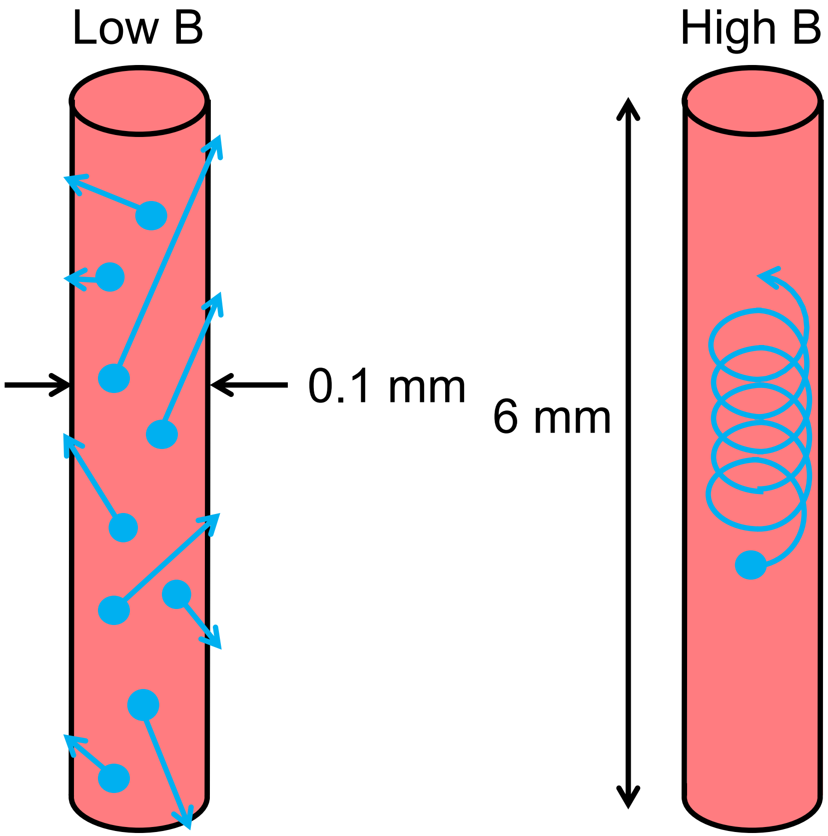


n scatter
from Be liner

- **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**
- Modeling suggests low energy tail due to nBe scattering from liner (0.3-0.9 g/cm^2)

K. Hahn

$\text{Yield}_{DT}/\text{Yield}_{DD}$ can be used to infer magnetization at stagnation


Low B

High B

0.1 mm

6 mm

High aspect ratio cylinder

Most 1 MeV tritons born with trajectory that exits the fuel radially

$\rho \sim 0.4\ \text{g/cm}^3$

$R \sim 0.005\ \text{cm}$
$Z \sim 0.6\ \text{cm}$

$\rho R \sim 0.002\ \text{g/cm}^2$
$\rho Z \sim 0.2\ \text{g/cm}^2$

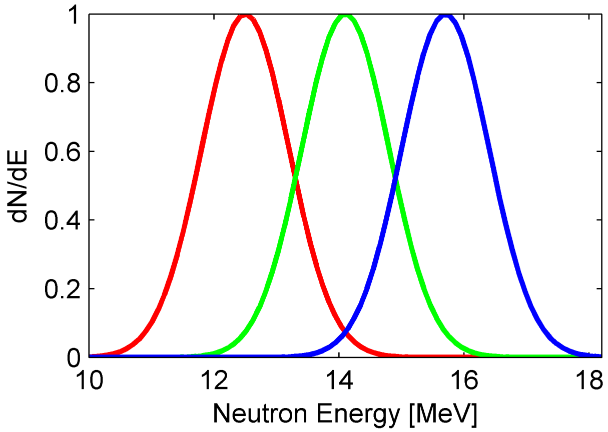
Tritons sample small ρr when B-field is low so DT/DD is low

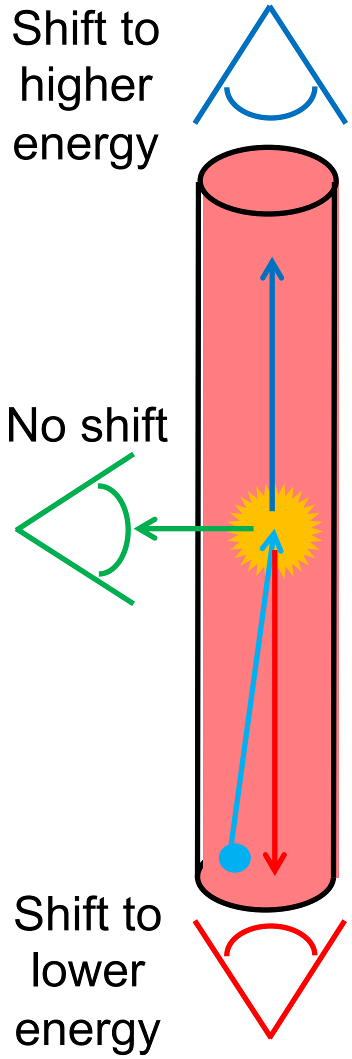
High B-field traps tritons increasing the effective ρr so DT/DD increases

P.F. Schmit *et al.*, Phys Rev Lett (2014); P.F. Knapp *et al.*, Phys. Plasmas (2015).

DT NTOF spectrum can also be used to infer magnetization at stagnation

DT reactions primarily occur for tritons traveling along the Z axis

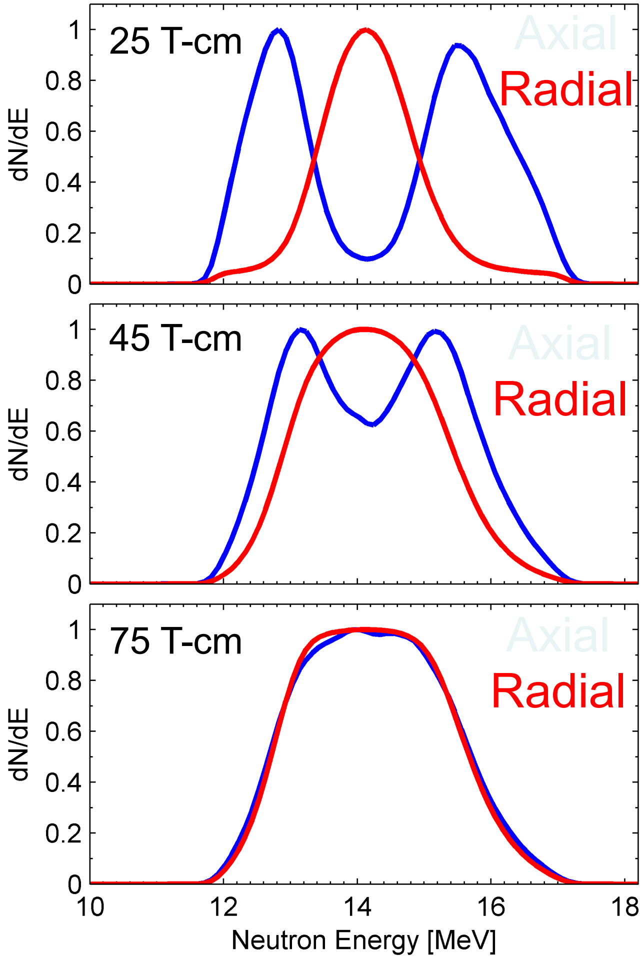




Shift to higher energy

No shift

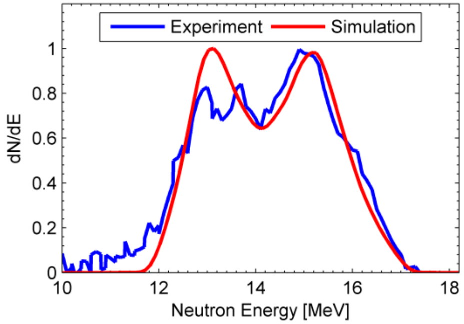
Shift to lower energy

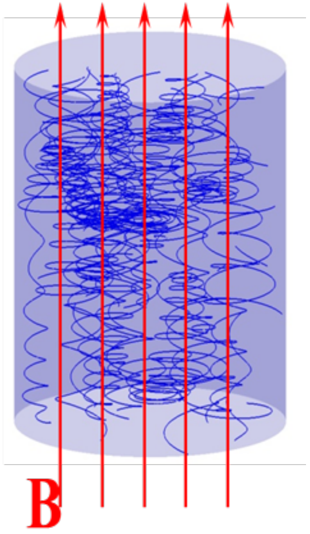


P.F. Schmit *et al.*, Phys Rev Lett (2014); P.F. Knapp *et al.*, Phys. Plasmas (2015).

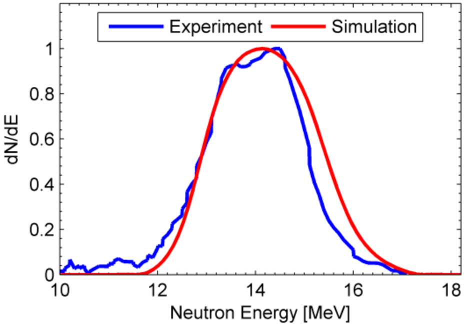
Secondary DT yield and nTOF spectra indicate significant flux compression and resulting fuel magnetization.

Axial DT Spectrum

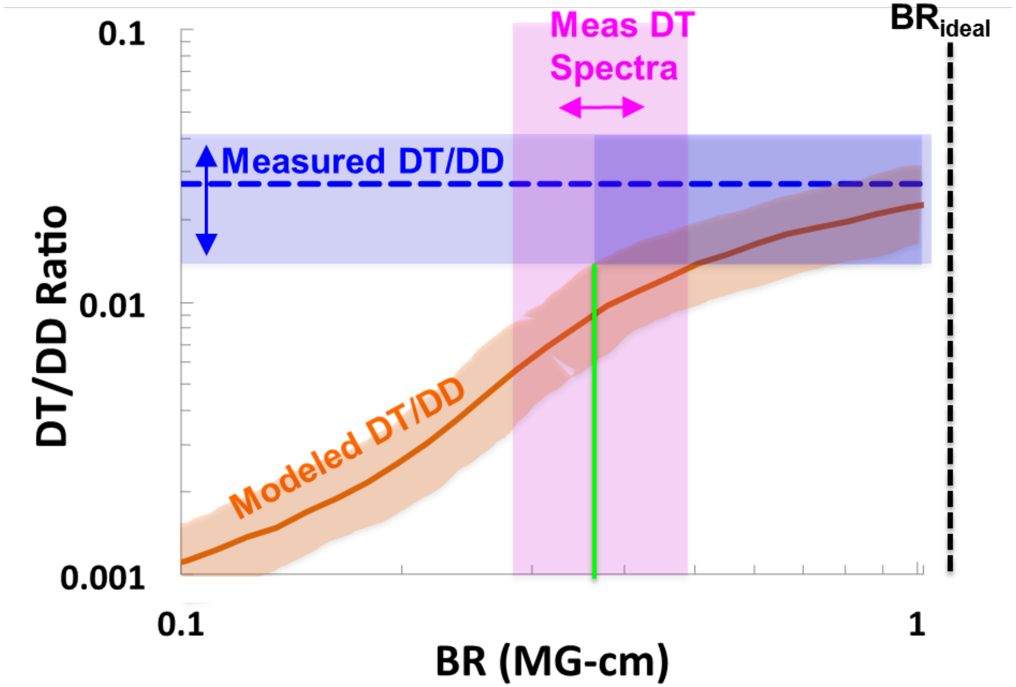




Radial DT Spectrum



DT/DD Yield Ratio



BR = 0.40 +/-18% MG-cm

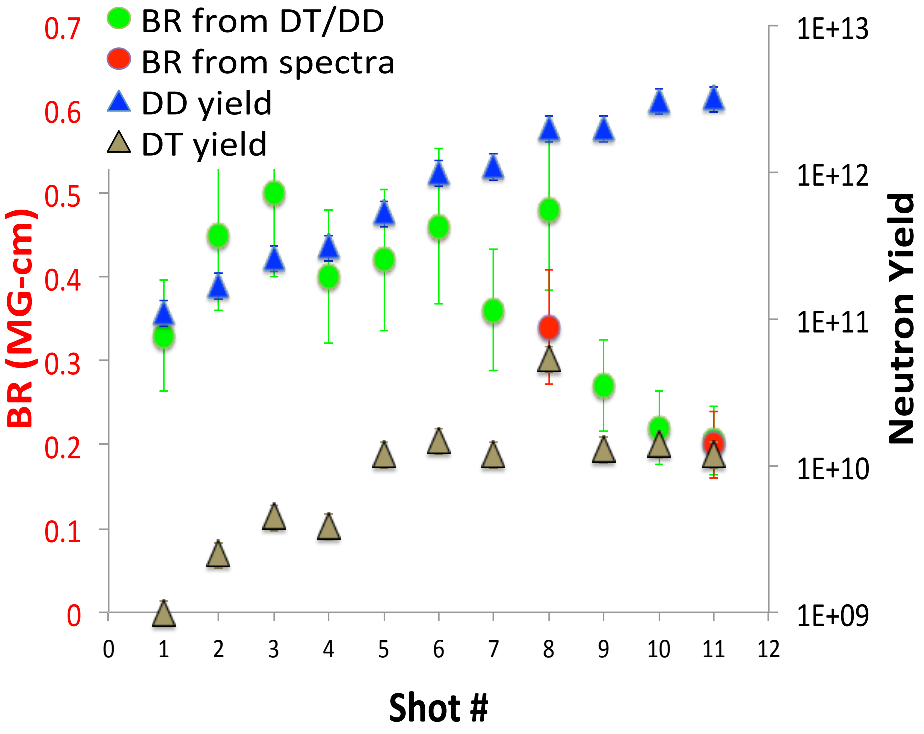
Magnetized T implies magnetized α: $r_t \approx 1.1 r_\alpha$

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

P.F. Schmit *et al.*, Phys Rev Lett (2014); P.F. Knapp *et al.*, Phys. Plasmas (2015).

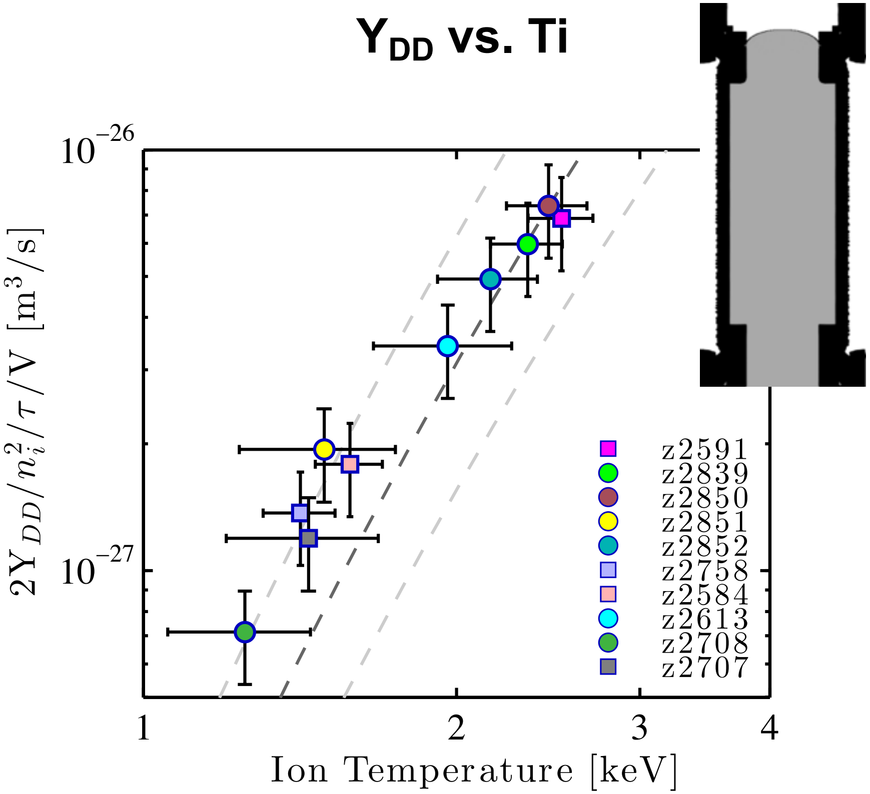
We are starting to collect enough data to study trends in the interplay between the various physical processes of MagLIF.

BR, DD, and DT yield comparisons



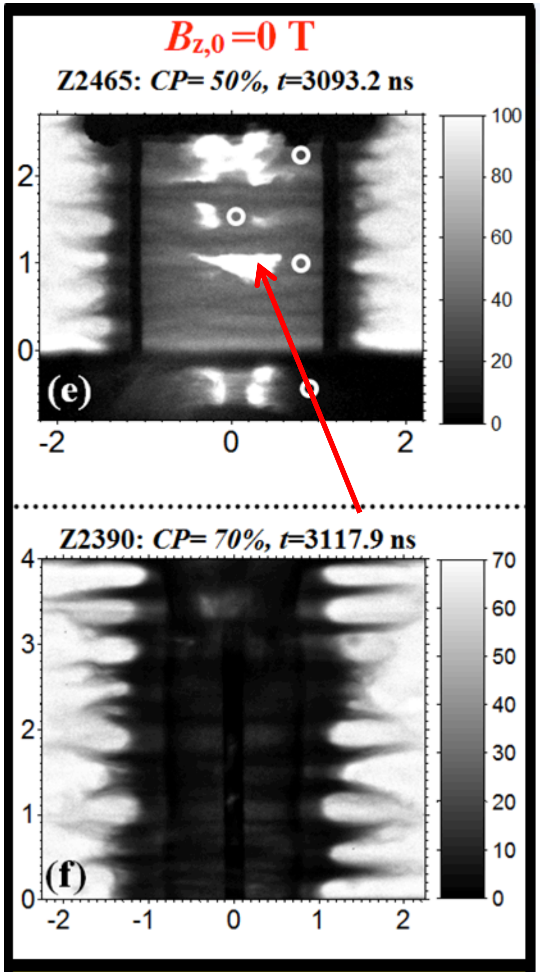
Note: Plot is sorted by increasing DD yield, not time.

Y_{DD} vs. Ti

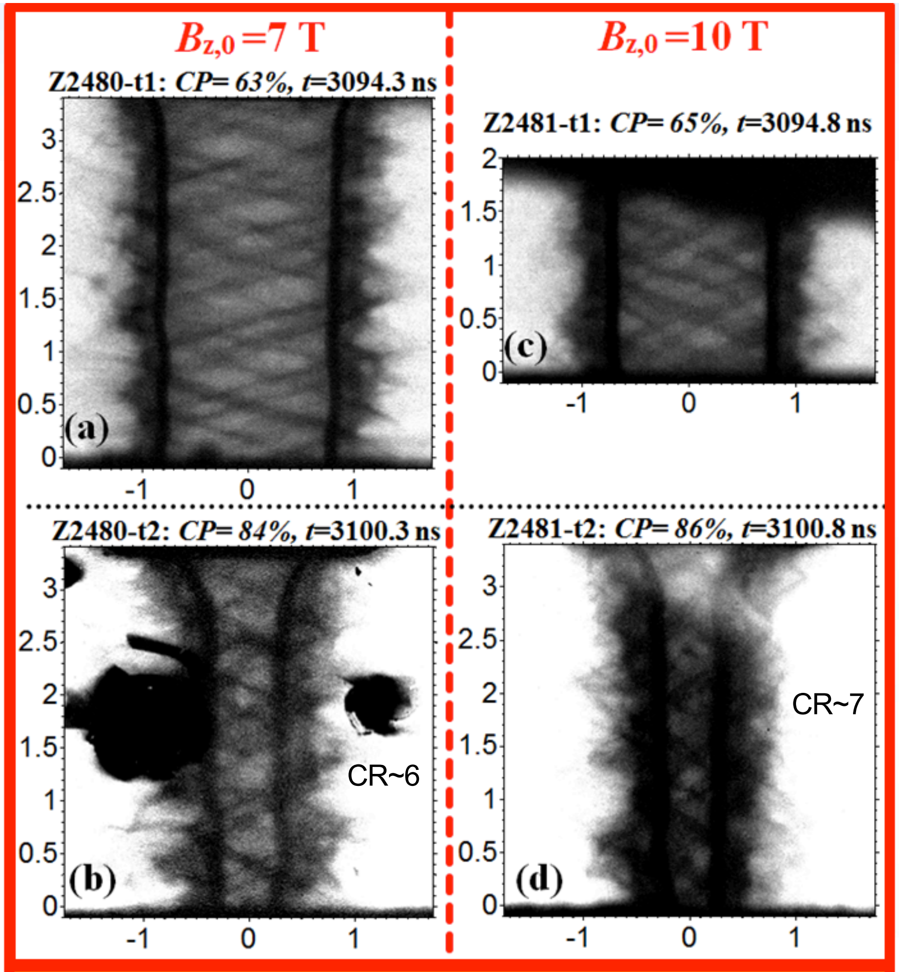


$$Y_{\mathrm{DD}} = \frac{1}{2} n_{\mathrm{D}}^2 \langle \sigma v \rangle_{\mathrm{DD}} V \tau$$

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



Azimuthally correlated MRT



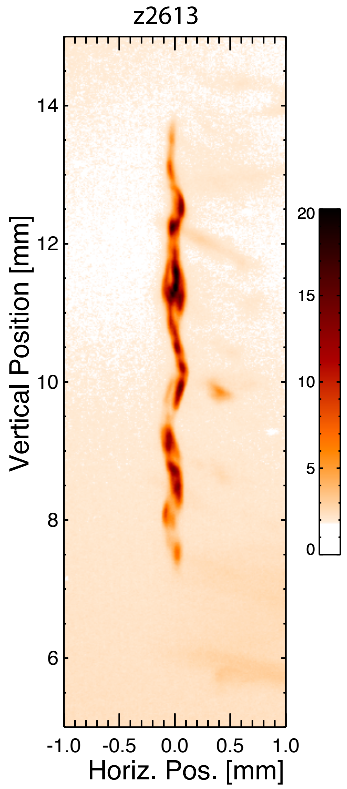
Helix-like instability structure

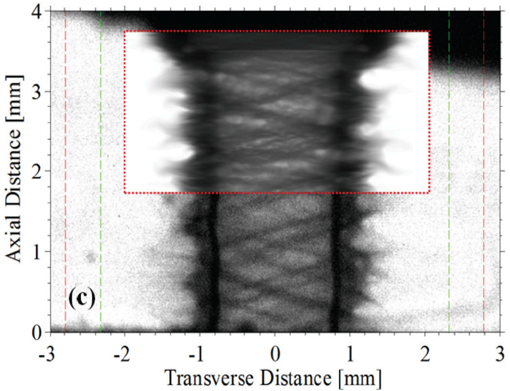
- Rather than cylindrically symmetric structures, we see helical structures
- Magnetic field reduced multi-keV x-rays associated with late-time instabilities

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

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 and consistent with observed helical structure in radiography experiments**



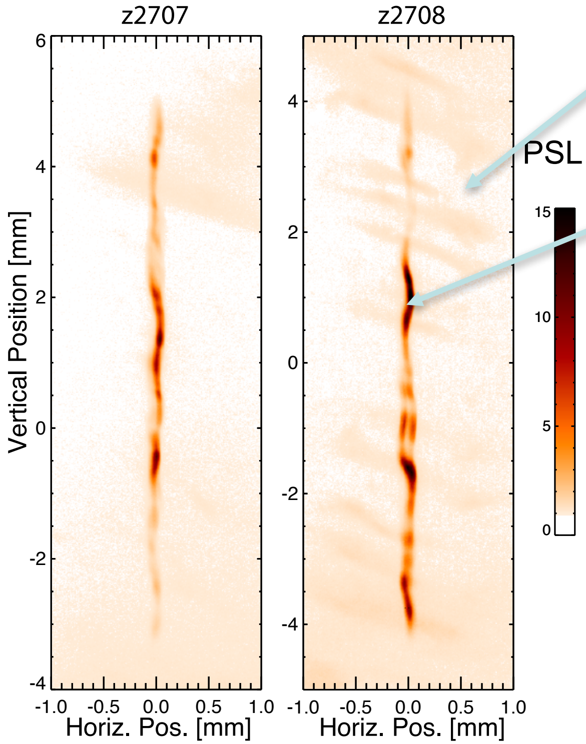


M. R. Gomez et al., PRL **113**, 155003 (2014); E. C. Harding et al., RSI **86**, 043504 (2015).

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

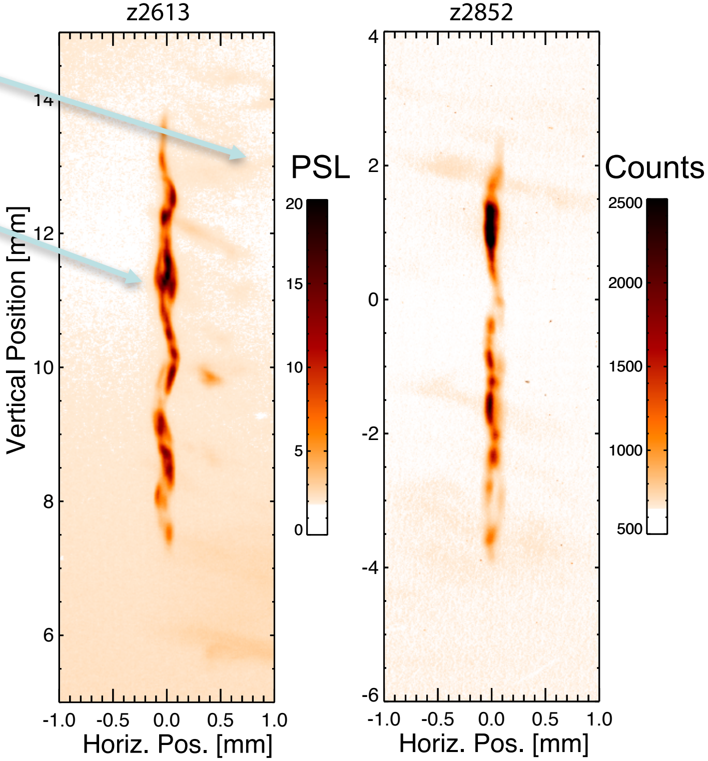


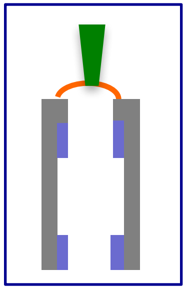
Emission features from Be liner

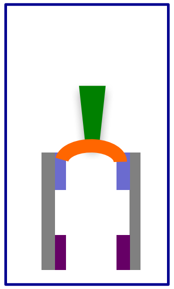
Emission from hot deuterium core

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



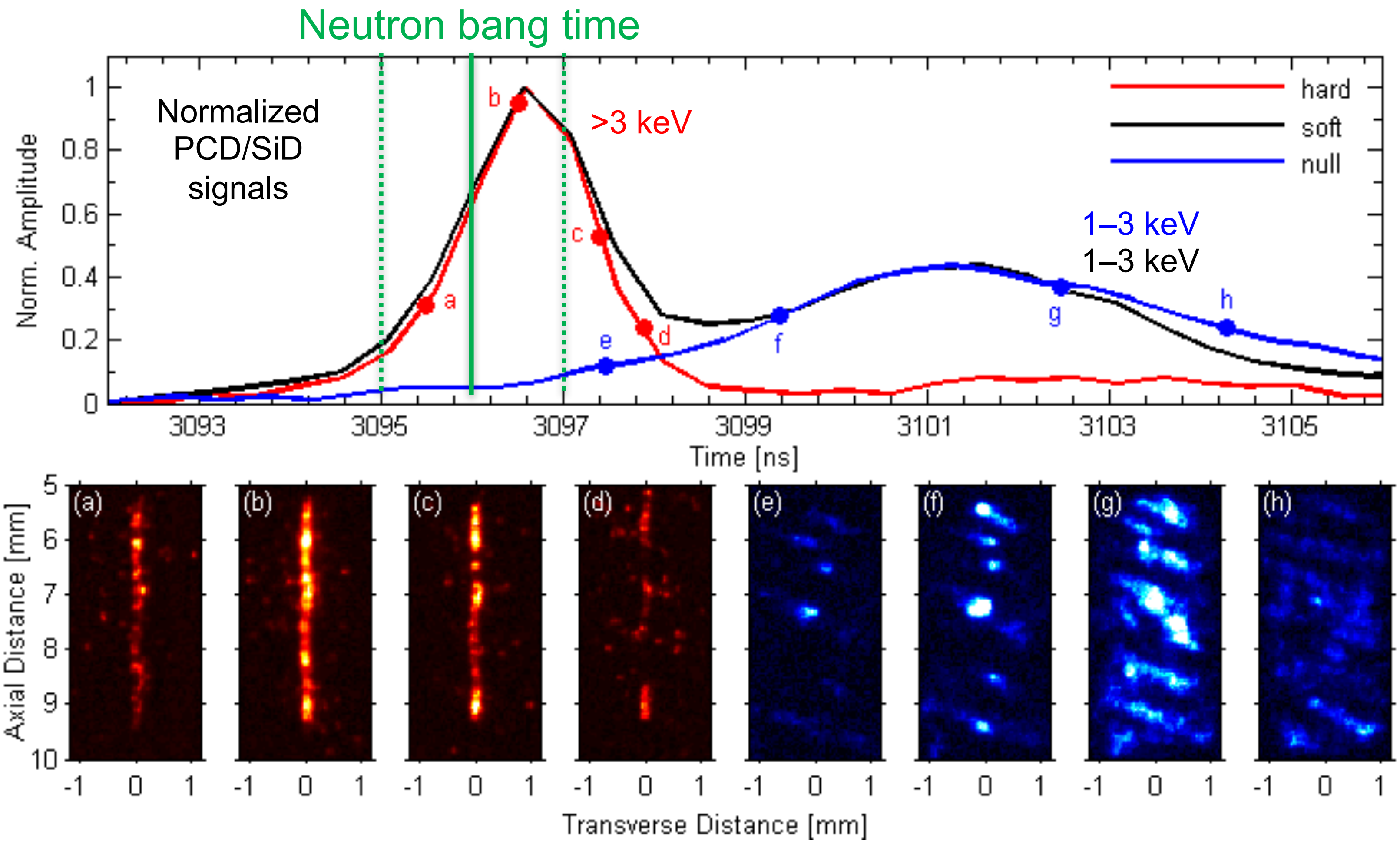




z2707 and 2708 were identical targets.
Long Be liner, thin window, and Al caps

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

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



Neutron bang time

Normalized PCD/SiD signals

>3 keV

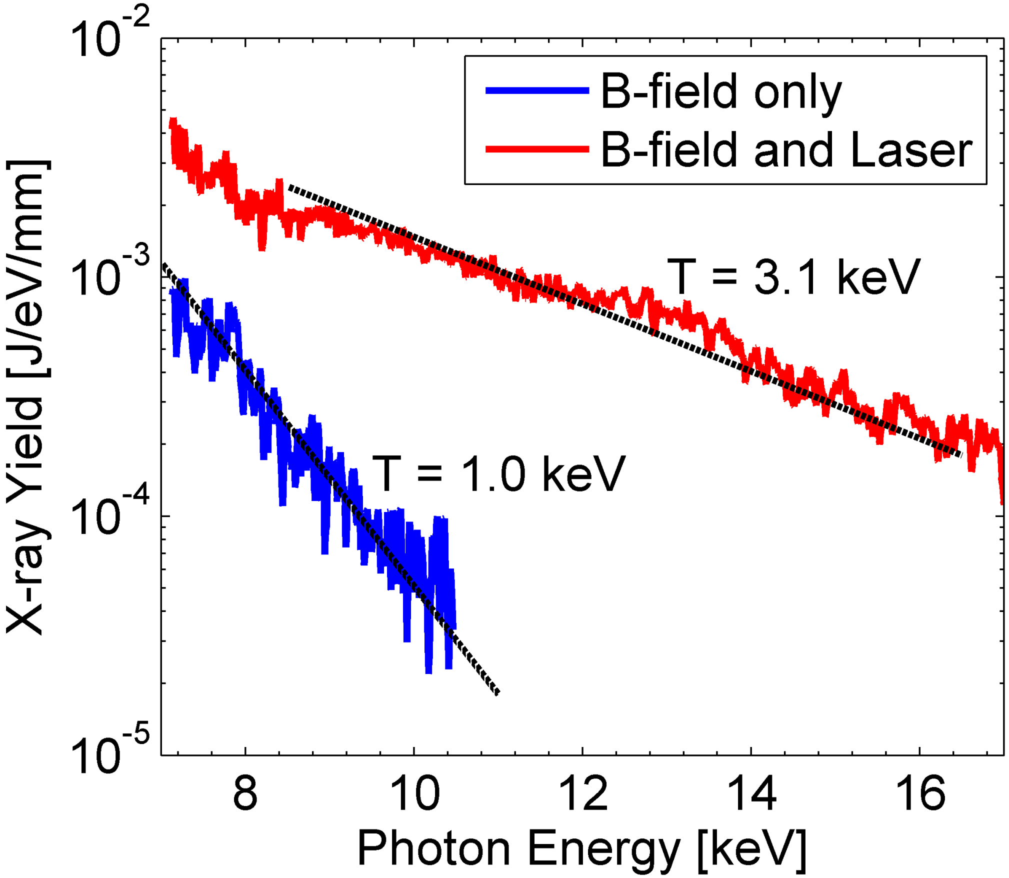
1–3 keV

1–3 keV

- 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).

High-energy continuum x-ray spectra indicate electron temperatures = 2.5-3.1 keV in experiments with laser and B-field



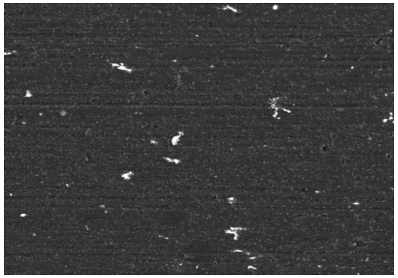
- Electron temperatures inferred from continuum emission
- > 2.5 keV observed on shots with yield
- Approximately 1 keV observed on shots without yield
- Lower bound on measurement with this method is around 1 keV

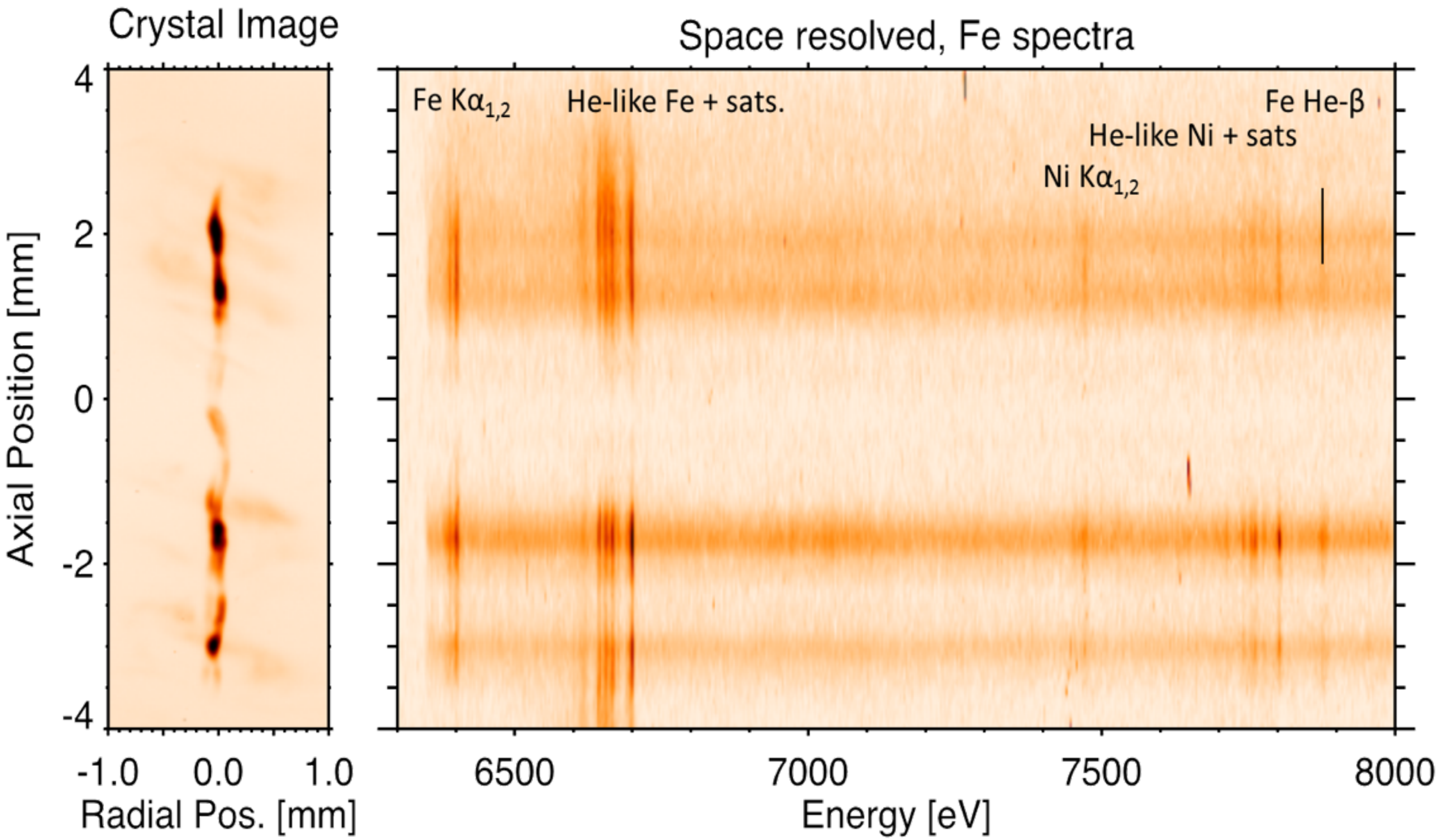
M.R. Gomez *et al.*, Phys. Rev. Lett. (2014); S.B. Hansen *et al.*, Phys. Plasmas (2015).

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

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

SEM image of the Be
liner outer surface

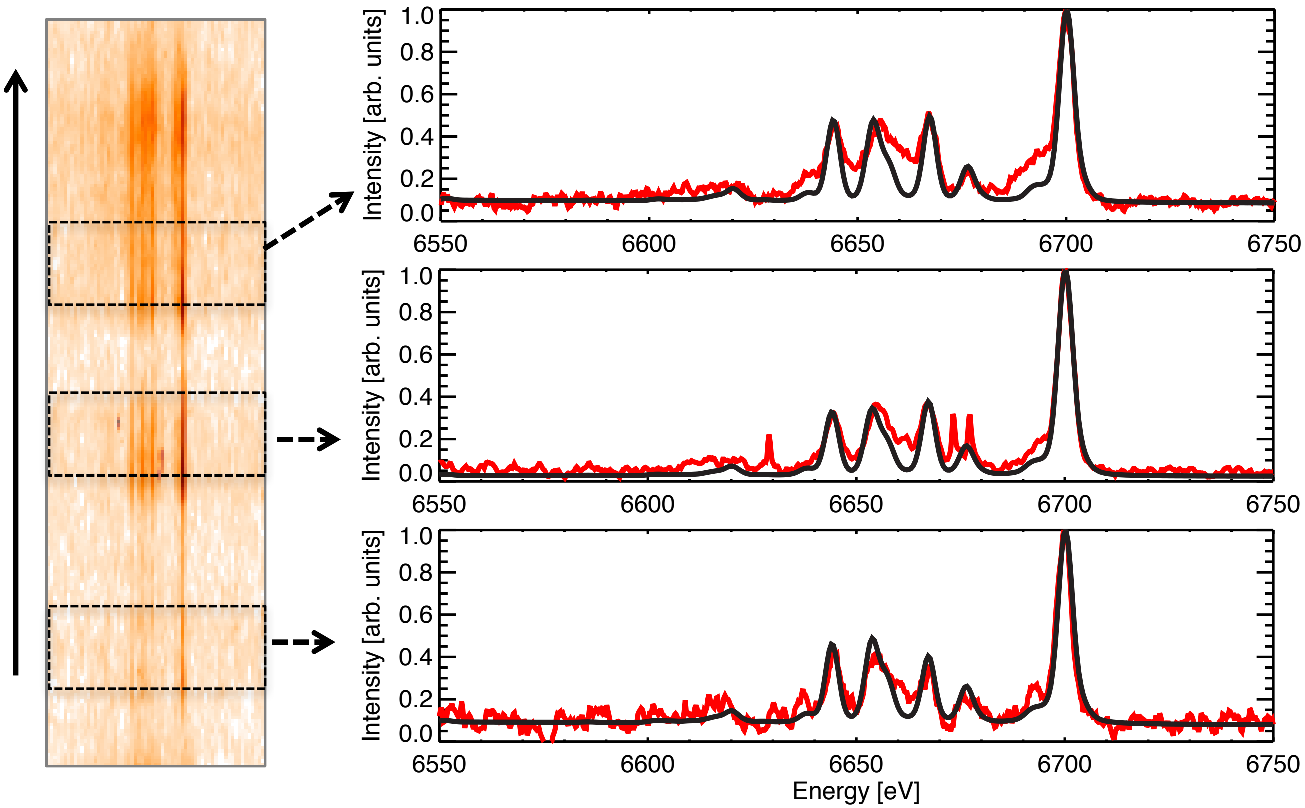




The Fe spectra provide information on the plasma temperature, density, and mix fraction.

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

Preliminary Inferred values



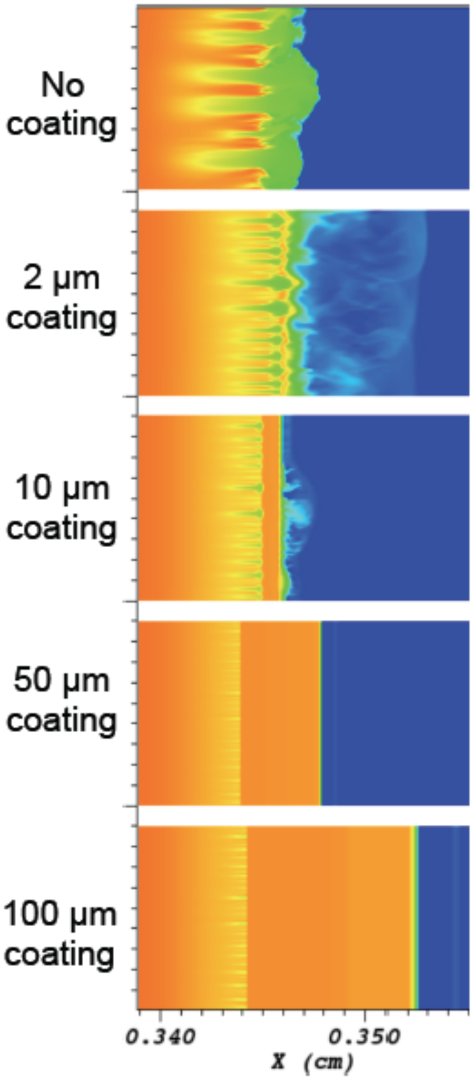
T_e = 1.5 keV
n_e = 1.2e23 cm^{-3}
Be mix ~ 1%

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

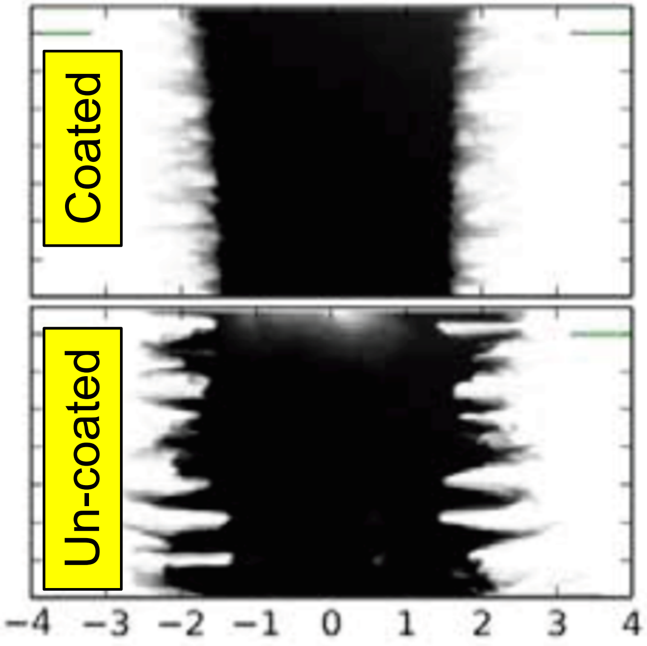
T_e = 1.4 keV
n_e = 2.0e23 cm^{-3}
Be mix ~ 1%

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

The 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



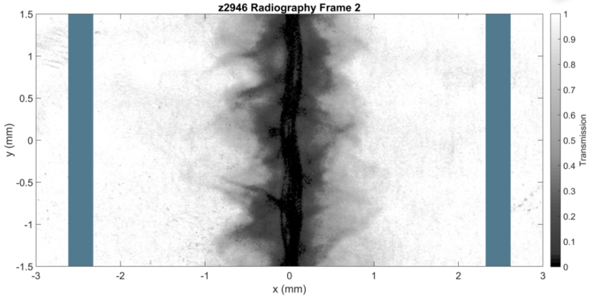
Radiographs of optically thick Al liner instabilities

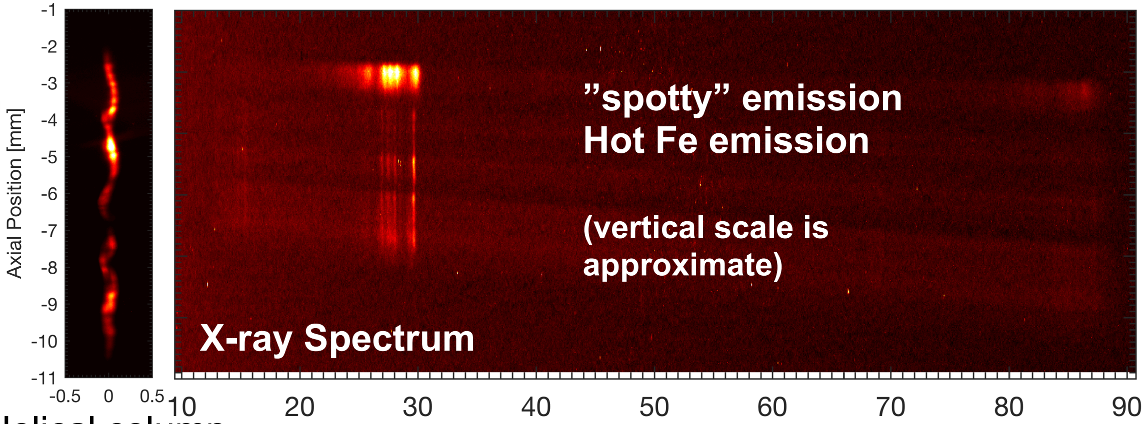
white = transmission
black = absorption

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).

We have demonstrated the ability to impact the stagnation morphology through controlling the implosion

No coating





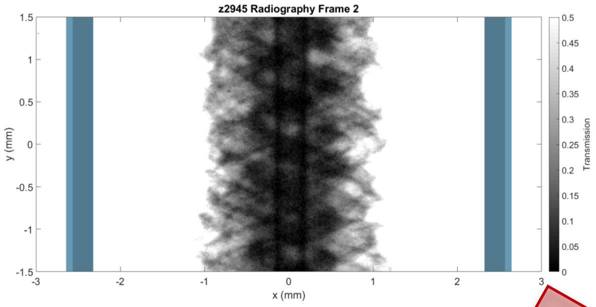
”spotty” emission
Hot Fe emission

(vertical scale is approximate)

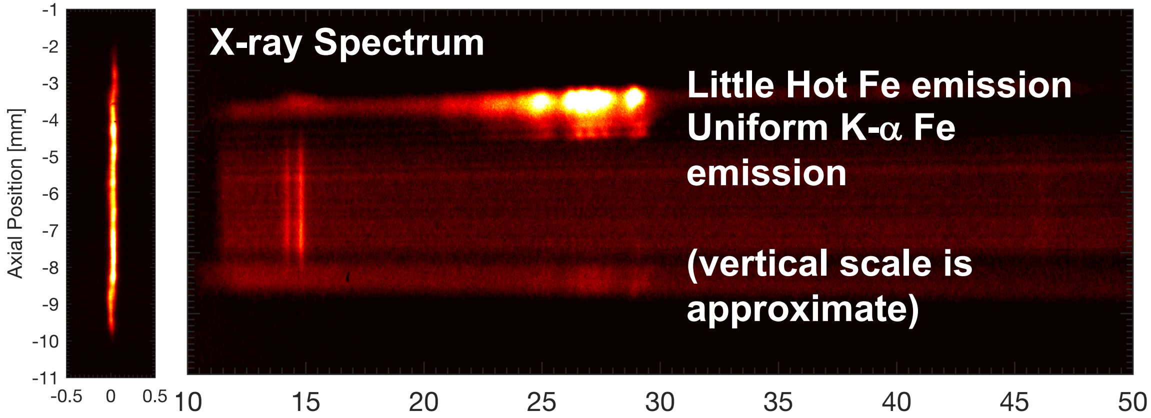
Helical column
Highly variable intensity

Despite ”improved” morphology, neutron yield and ion temperature decreased

Much straighter column
Uniform brightness



w/ dielectric coating



Little Hot Fe emission
Uniform K-α Fe emission

(vertical scale is approximate)

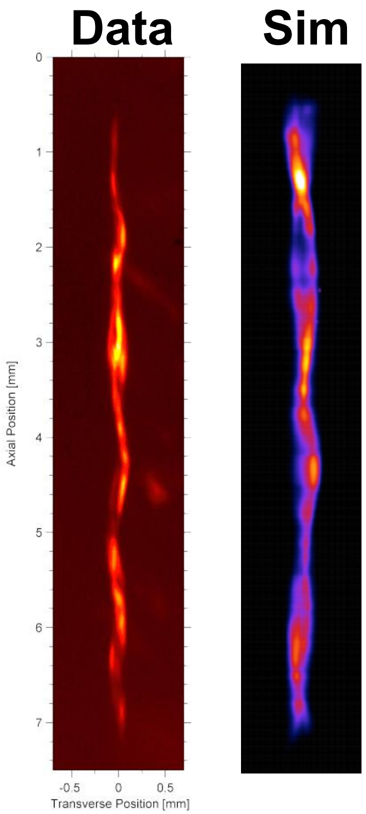
Implosion only experiments

Integrated experiments

Radiographs provided by Tom Awe and Dave Ampleford

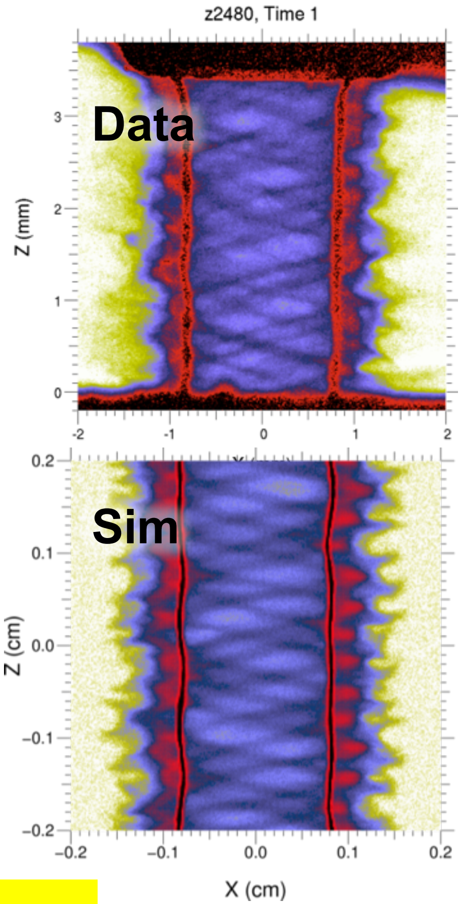
The observables are well modeled by 2-D and 3-D Hydra if we assume ~200 J of laser energy coupled to the target

Imaging



Z2613

Radiography



A. Sefkow

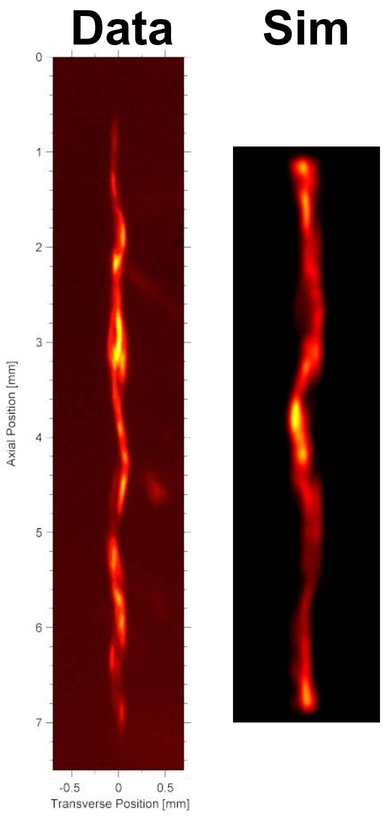
Comparison to z2591 Observables

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
$\langle T_e^{spec}\rangle$	3.0 ± 0.5 keV	2.7 ± 0.5 keV
ρ_{gas}^{stag}	0.3 ± 0.2 g cm^{-3}	0.4 ± 0.2 g cm^{-3}
ρR_{gas}	2 ± 1 mg cm^{-2}	2.6 ± 1.0 mg cm^{-2}
ρR_{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

*Thick window (3.5 micron experiments)

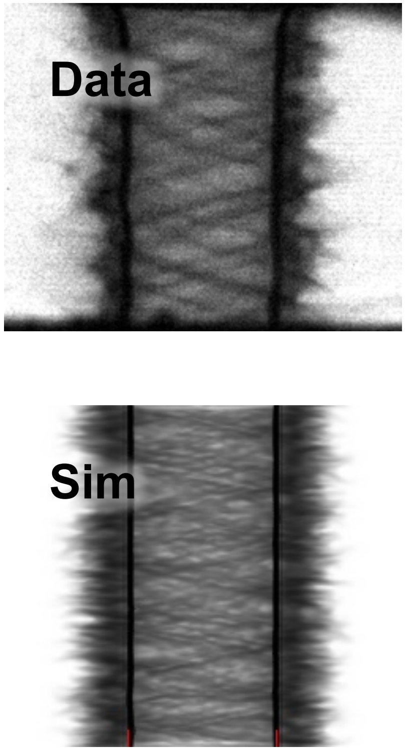
The observables are also well modeled by 3-D GORGON if we assume ~500 J of laser energy coupled to the target

Imaging



Z2613

Radiography

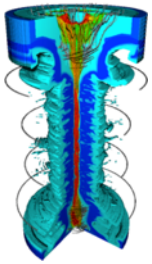


Comparison to z2613 Image

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 ρR 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.

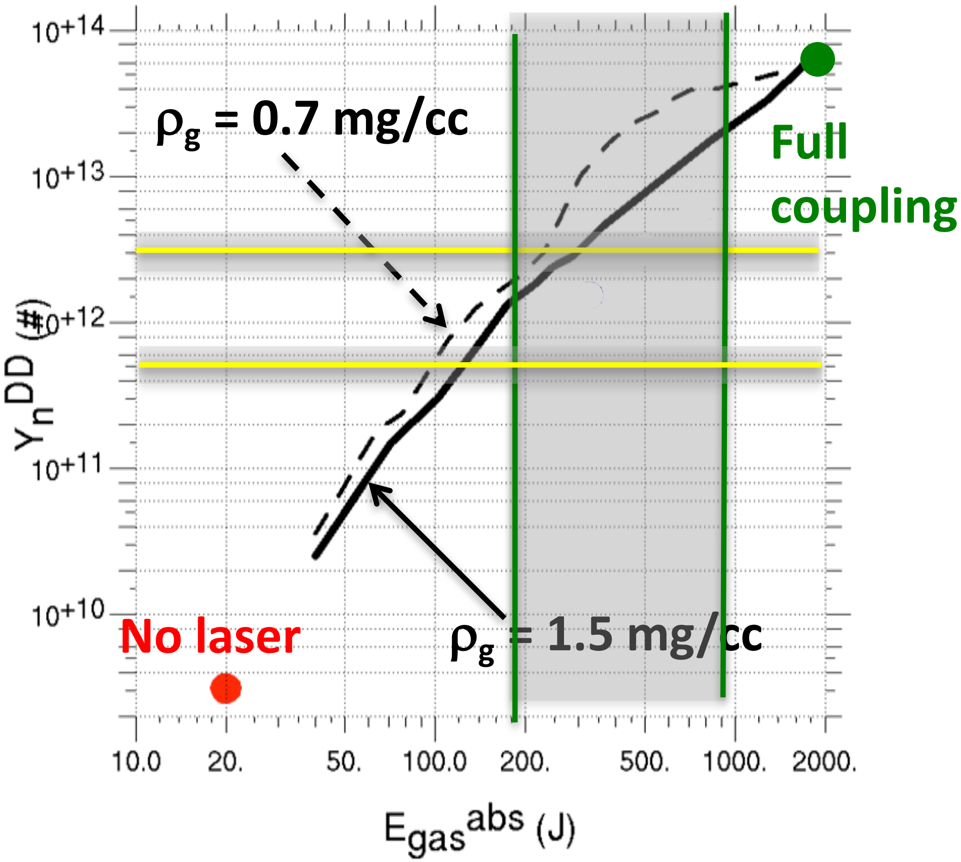


C. Jennings

The main hypotheses for the discrepancies between experiments and models involve preheat, mix, and morphology.

- **Ineffective Preheat**
  - Pecos experiments indicate we are over an intensity cliff
  - Omega and NIF show potential for a predictable preheat condition
- **Radiative cooling from Be walls and/or LEH window**
  - Long interval time (~50ns) between preheat and stagnation
  - Mix may get worse with increased laser energy
- **Liner implosion stability and resulting stagnation morphology**
  - 3-D stagnation column

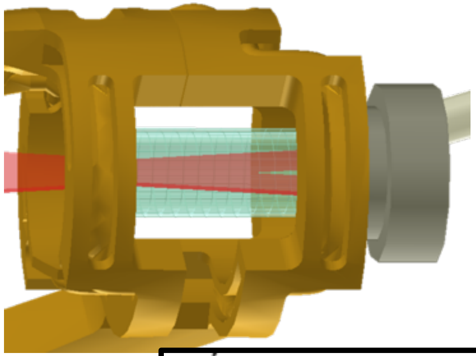
2D Simulated MagLIF Performance



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

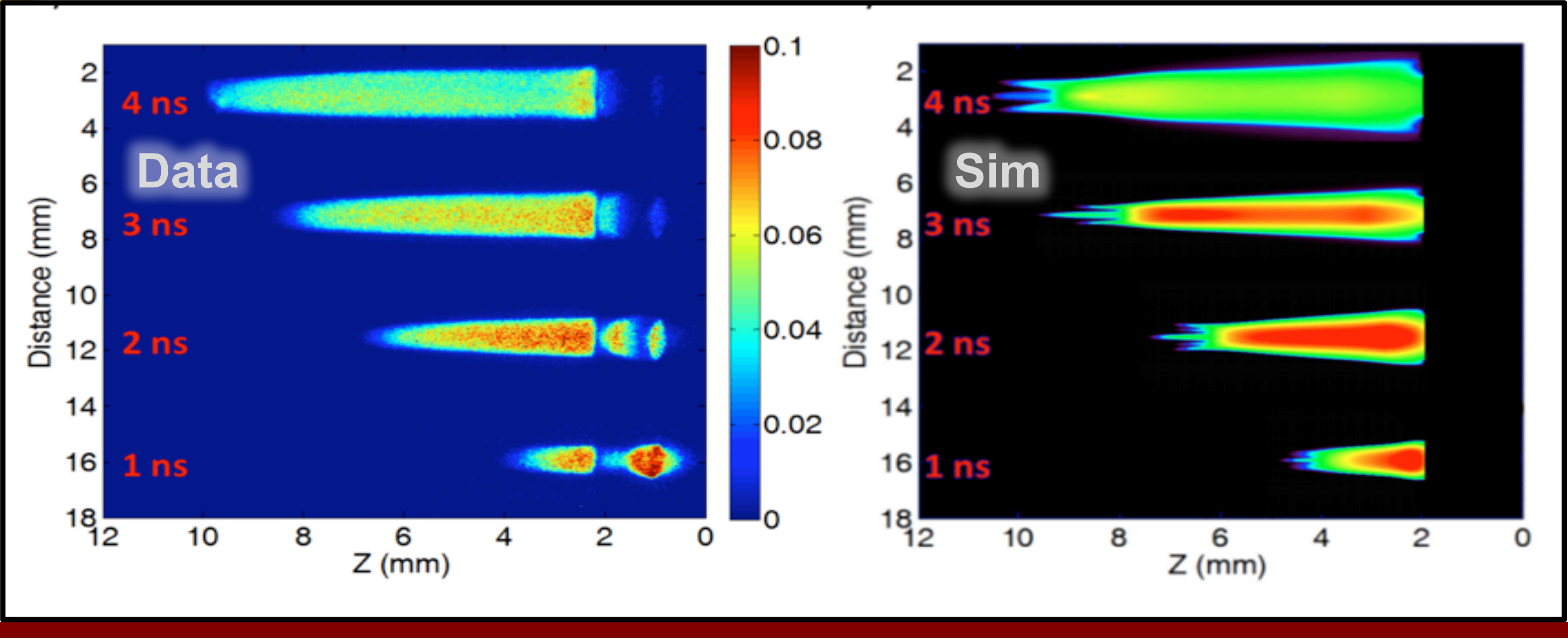
OMEGA-EP experiments are being conducted to develop understanding of laser energy transport & deposition.

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



Current topics of interest for OMEGA-EP Experiments

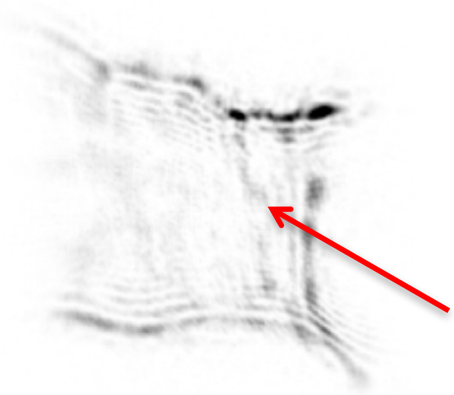
- Effect of LEH thickness
- Effect of gas fill density
- Effect of laser intensity
- Effect of magnetization
- How and where does mix occur?
- At what conditions does LPI become important?



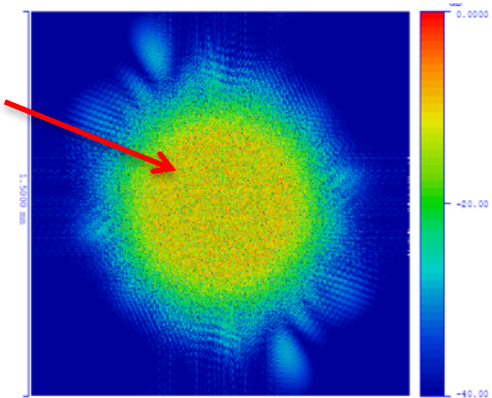
A. Harvey-Thompson et al., (2015)

The Z-Beamlet beam spot quality is one reason that we are not coupling as well to the fusion fuel as predicted

Original MagLIF experiments did not use any beam smoothing techniques adopted by the laser community

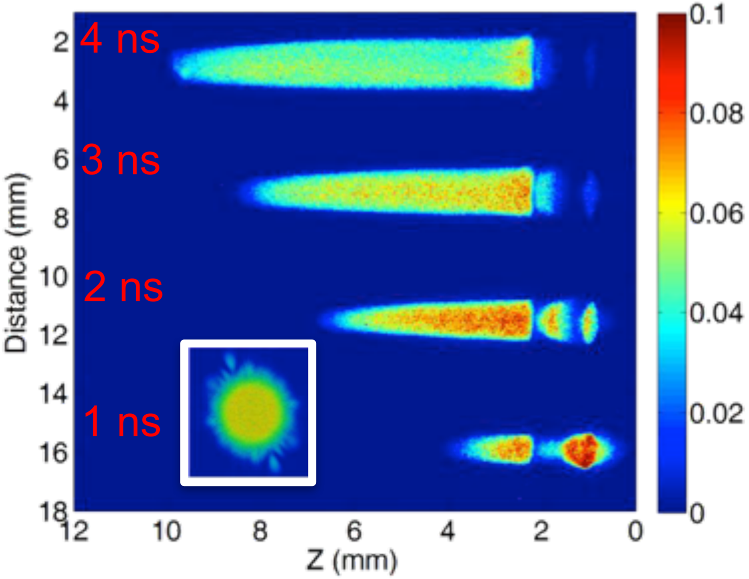


ZBL: No DPP
(representative)

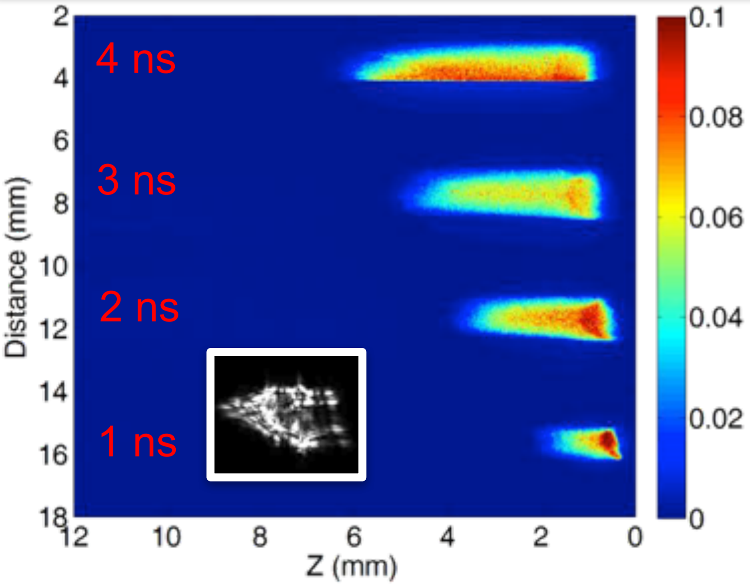


OMEGA-EP
750um DPP

4 ns/3.1 kJ, 2 µm LEH, no prepulse
with DPP (SNL Omega-EP data)

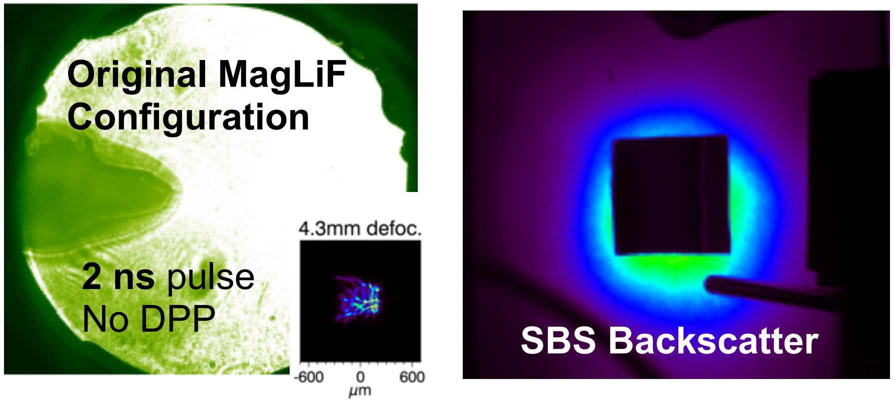


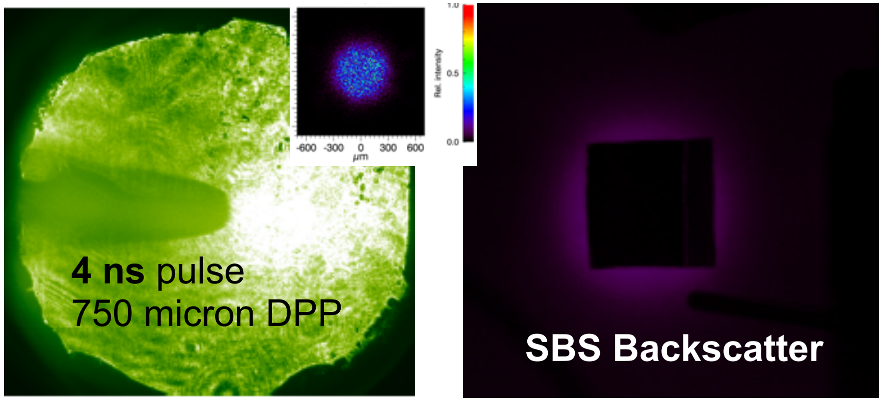
4 ns/2.93 kJ, 2 µm LEH, no prepulse
without DPP (SNL Omega-EP data)



Recent progress on ZBL (PECOS) has demonstrated dramatically lower backscatter losses, higher window transmission, and better simulation predictability

Optical Blastwave Measurements

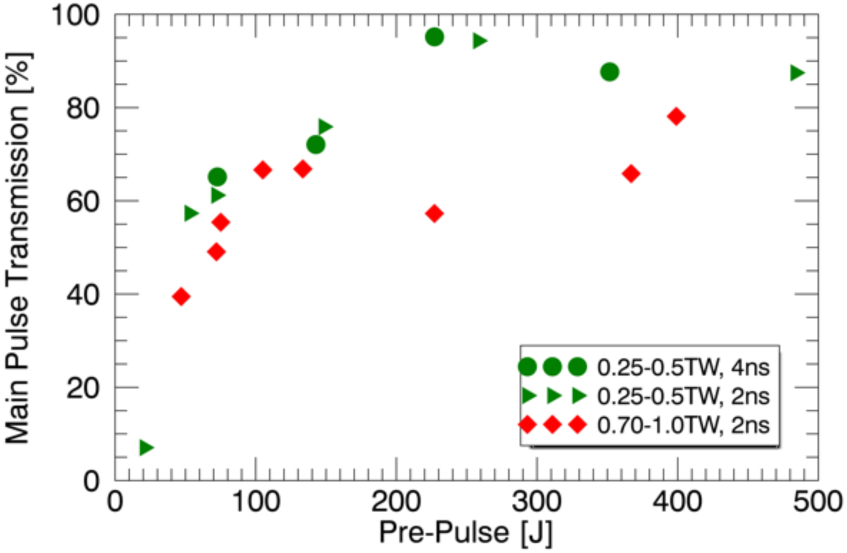




54psi He, 250J/1350J

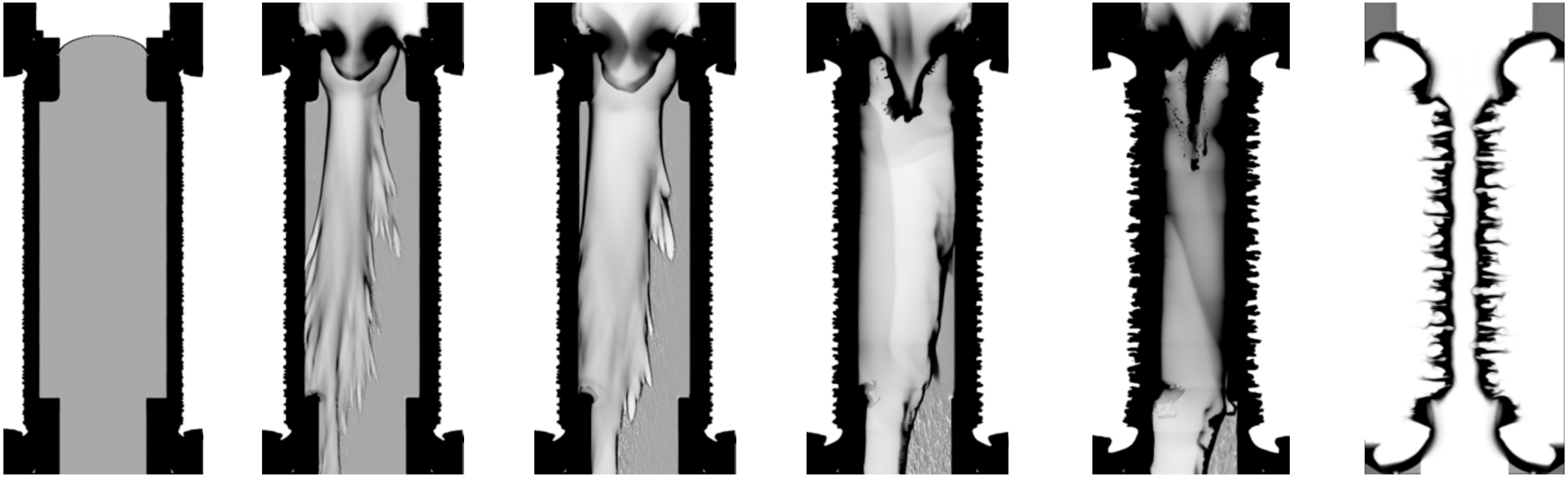
- Dramatically Improved Transmission
- Determined pre-pulse requirements
- Dramatically reduced LPI

LEH Window Transmission



Laser induced mix is currently a topic of focus. Models indicate mix can occur from multiple origins:

- Blast wave from laser preheat causes blowoff from liner wall and endcaps
- Laser can pass through the gas and cause blowoff from the bottom end cap
- Laser can deflect through LEH plasma and hit the liner/endcap causing blowoff
- The exploded LEH window can mix into the gas
- The liner is RT unstable



Laser deflected

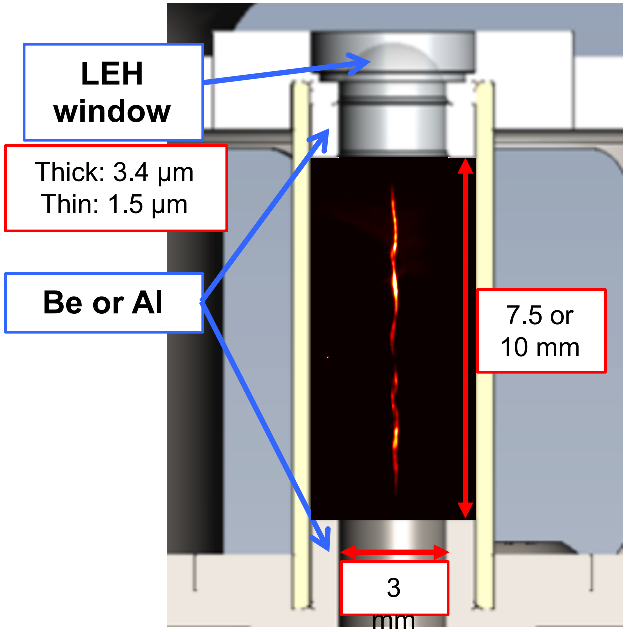
Laser on bottom cap

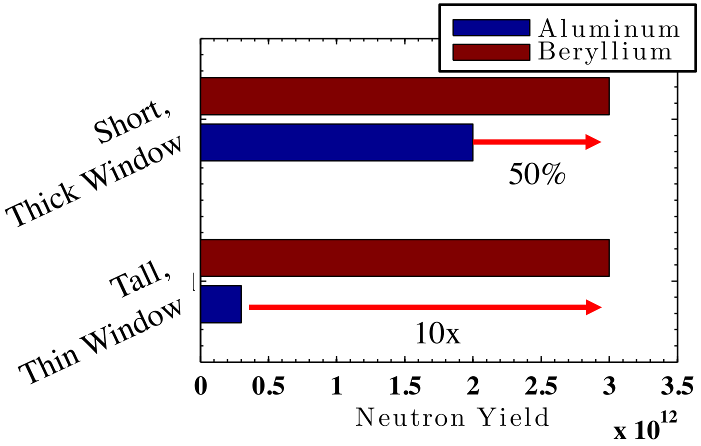
Blast Wave Reflected

LEH window injected

Unstable liner

We are investigating several mix mitigation schemes





Target Design

- Switched from Al to Be end caps
  - Improved yield in both thick and thin windows
  - Improvement is more dramatic in thin-window case
- Laser pulse shape optimization
- Increase height channel height
- Thinner laser entrance windows (cryo)
- Mix Mitigation LIH or frozen DD layers

Experimental Campaigns

- Localized dopant mix studies
  - Integrated MagLIF experiments
  - Laser experiments on OMEGA-EP
- Developing Ne spectroscopy for low Te time history measurements
- Looking into Thomson Scattering solutions

Outline of my talk

- Description of Magnetized Liner Inertial Fusion (MagLIF)
- Present State - Experimental results and progress in understanding the science behind MagLIF
- Future - Path forward including current understanding of requirements for ignition and high yield

Over the next 4-5 years we have an aggressive set of programmatic goals to evaluate the science of MagLIF and establish credible requirements for ignition and high yield.

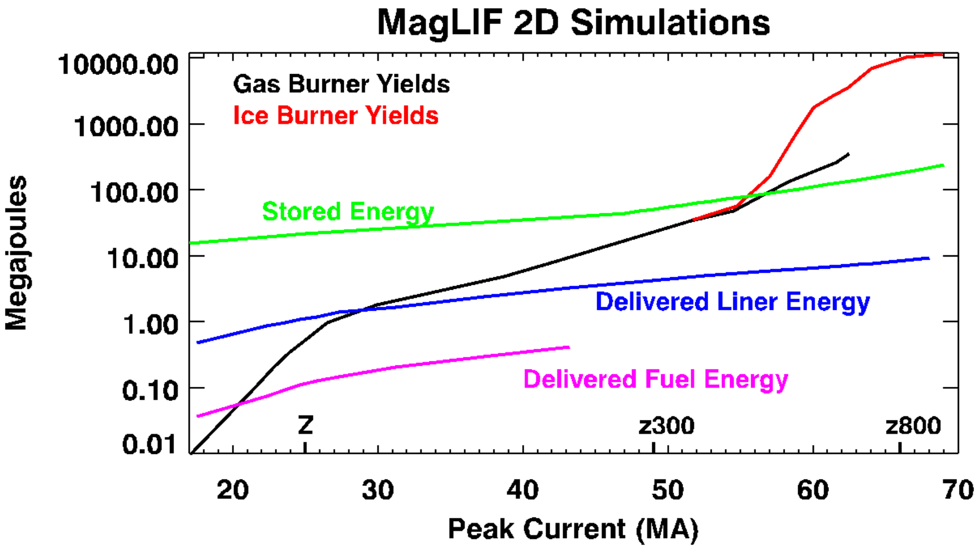
FY17

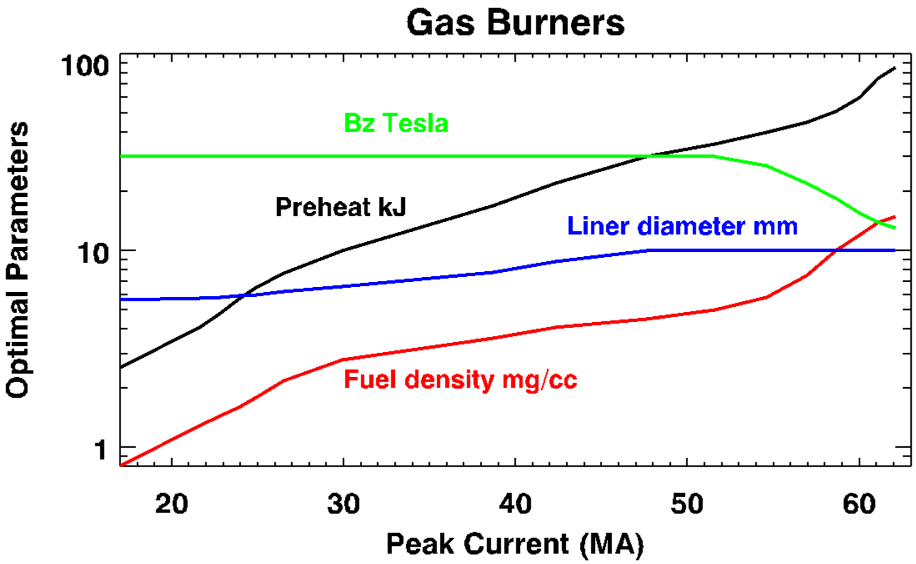
- Develop a methodology for inferring B-r and P-τ as quantitative performance metrics from integrated MagLIF experiments.
- Demonstrate >1 kJ of laser energy coupled to the MagLIF fuel
- Develop and characterize a new MagLIF baseline at ≥20 T, ≥20 MA, and ≥2 kJ
- Quantify the amount and relative origins of Mix
- Develop and characterize an enhanced MagLIF baseline at 30 T, 22-24 MA, and ≥6 kJ
- Provide credible physics extrapolation to ignition
  - **Demonstrate 30 kJ heating on NIF**
  - **Achieve a BR > 0.5 MG-cm ($R/r_\alpha > 2$)**
  - **Achieve fuel pressure > 5 Gbar and $P\tau$ > 5 Gbar-ns**

FY20

We are still working on validating our 2D calculations of MagLIF to understand whether they credibly scale

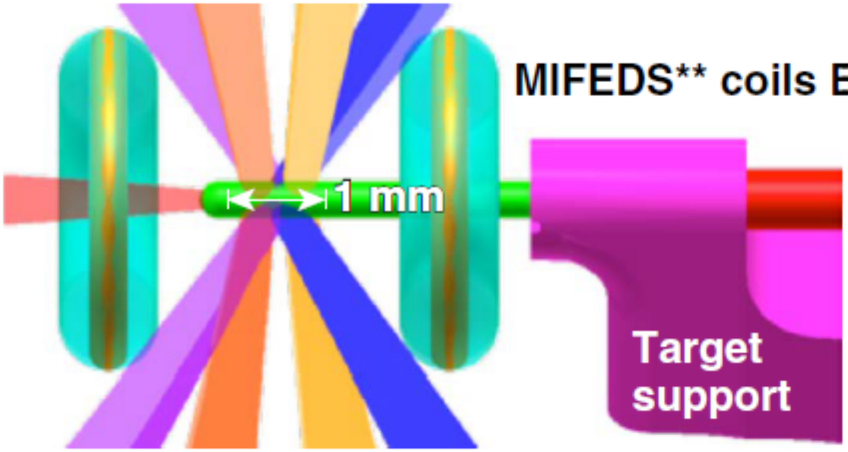
- Today’s MagLIF experiments couple 17-18 MA (~0.4 MJ) to the target
- At **24 MA**, an optimized target design with **30 T** and **>6 kJ** of preheat is predicted to produce **>100 kJ DT yield**
  - Obtaining all of these parameters simultaneously on Z will be a challenge!
- Larger scale designs don’t require larger Bz or scaled liner designs, but do require **higher fuel density** and **more preheat**





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

Laser-driven MagLIF on OMEGA will provide scaling data over a factor of 1000 in energy with more shots and more diagnostics than Z



40 compression beams
SG2 phase plates
up to 15.8 kJ in 1.5 ns

MIFEDS** coils $B_z \sim 10$ T

Preheat beam from P9
200-μm phase plate
up to 395 J in 1.5 ns

Fill-tube
pressure
transducer

	r (mm)	Δr (mm)	$r/\Delta r$	ρ_{fuel} (mg/cm^3)	B_0 (T)	T_0 (eV)	V_{imp} (km/s)	Convergence ratio	T_{max} (keV)
Z *	3.48	0.58	6	3 (DT)	30	250	70	25	8.0
OMEGA	0.30	0.03	10	2.4 (D_2)	10	200	154	26	2.9

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*S. A. Slutz *et al.*, Phys. Plasmas 17, 056303 (2010).
**MIFEDS: magneto-inertial fusion electrical discharge system

We have already demonstrated uniform cylindrical compression over 0.6 mm at a velocity of ~ 150 km/s

<u>**X-ray framing camera data**</u>

0.05 ns temporal resolution

Shell thickness: 20 μm

D_2 density: 1.80 mg/cc

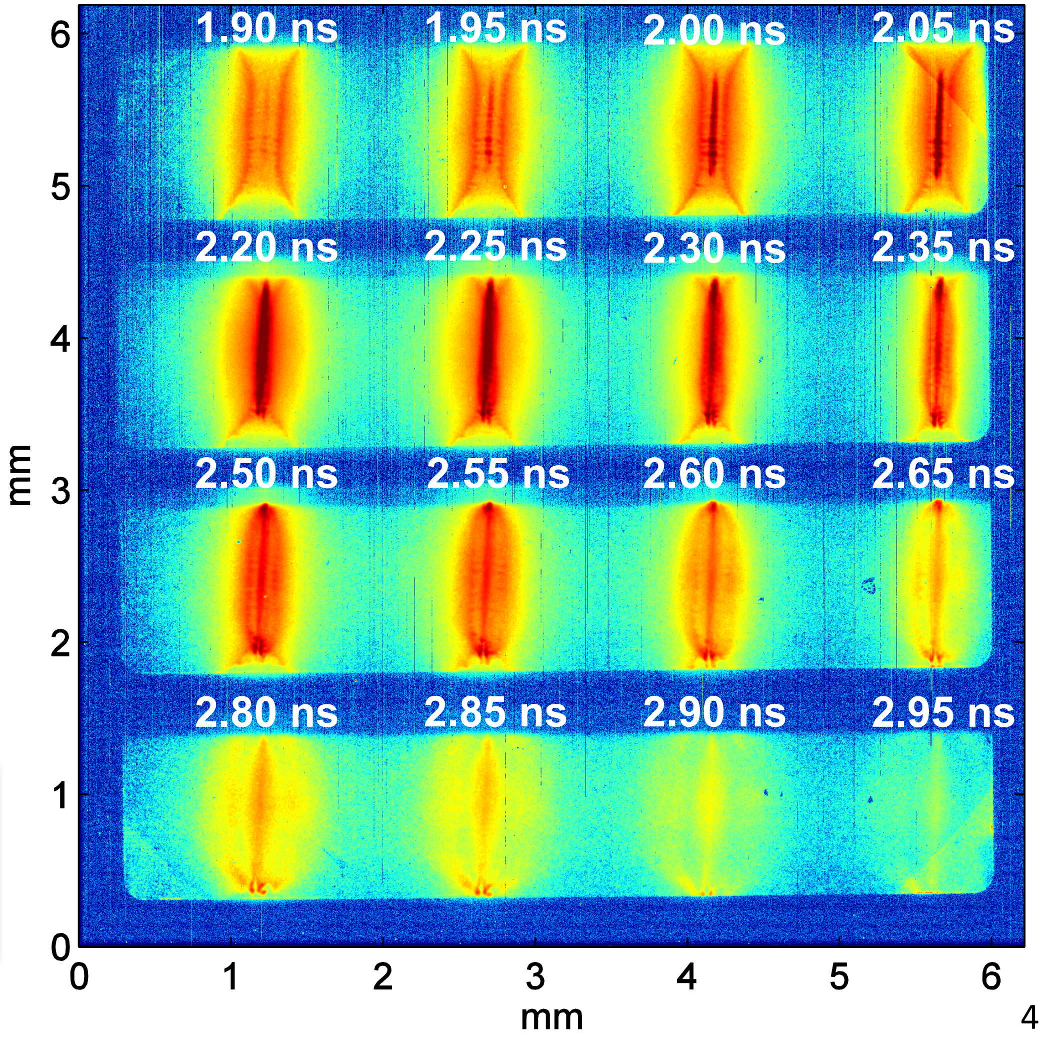
Laser energy: 13.0 kJ

Pulse length: 2.0 ns

Neutron yield: 2.53×10^7

No B, no preheat

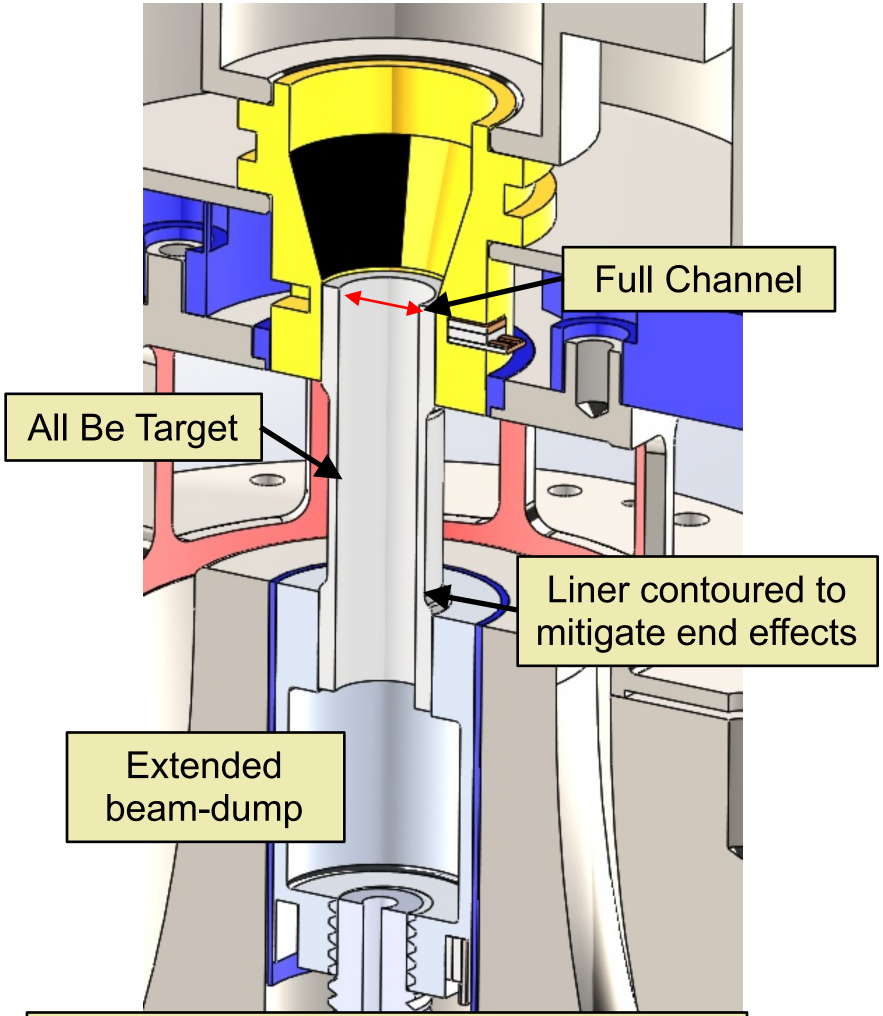
First integrated experiments performed in August:
>30% increase in Ti observed



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

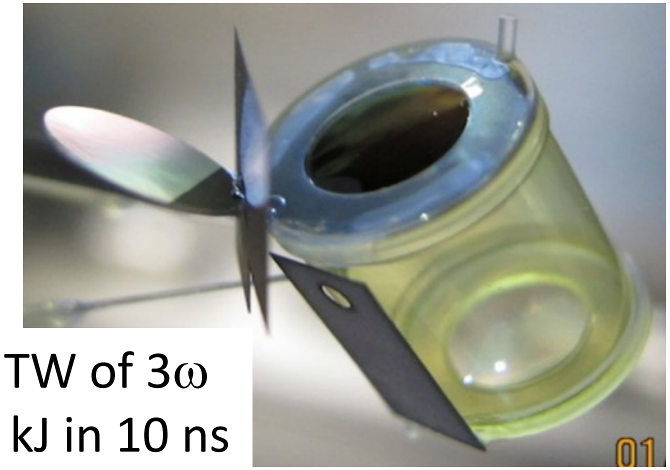
- Same gas density (~0.7 mg/cm^3) at much lower pressure (15 PSI @ 70 K)
- Thinner LEH windows with larger diameter
- Less energy invested in disassembly AND less mass injected into the target
- Bigger window diameter should reduce likelihood of laser interactions with the wall
- Long-term future development:
  - (1) frozen mix mitigation layers
  - (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

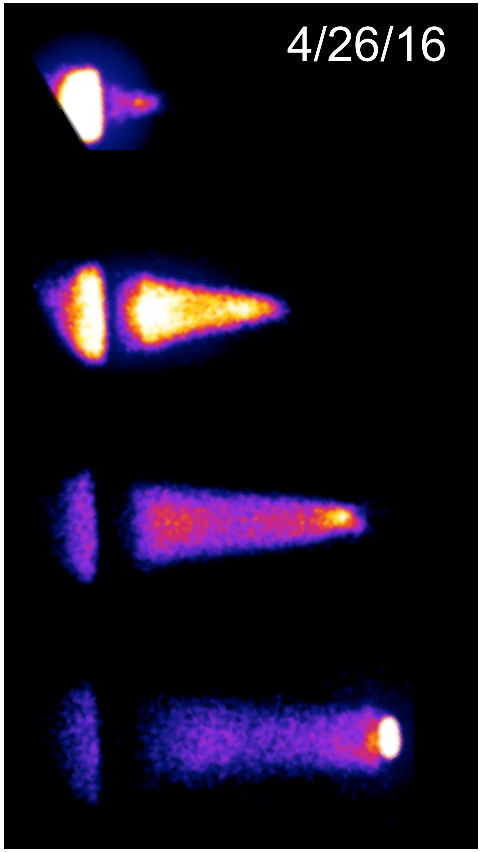
NIF experiments are examining laser transport and deposition at the 30 kJ predicted to be needed for high yields



3 TW of 3ω
30 kJ in 10 ns

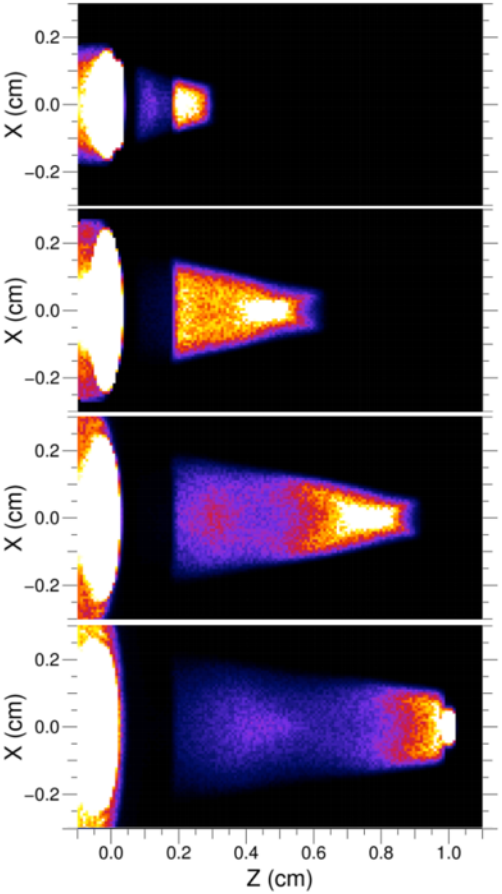
Objective : Measure laser propagation through a 1 cm gas pipe

- 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



GXD Data

4/26/16

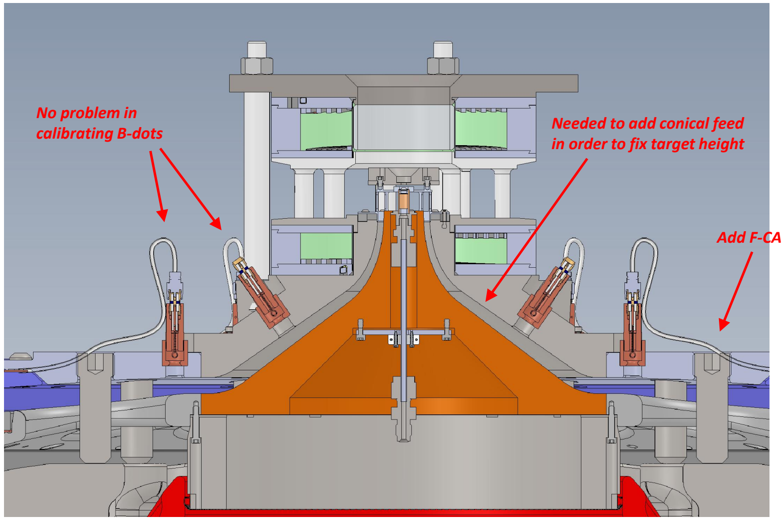


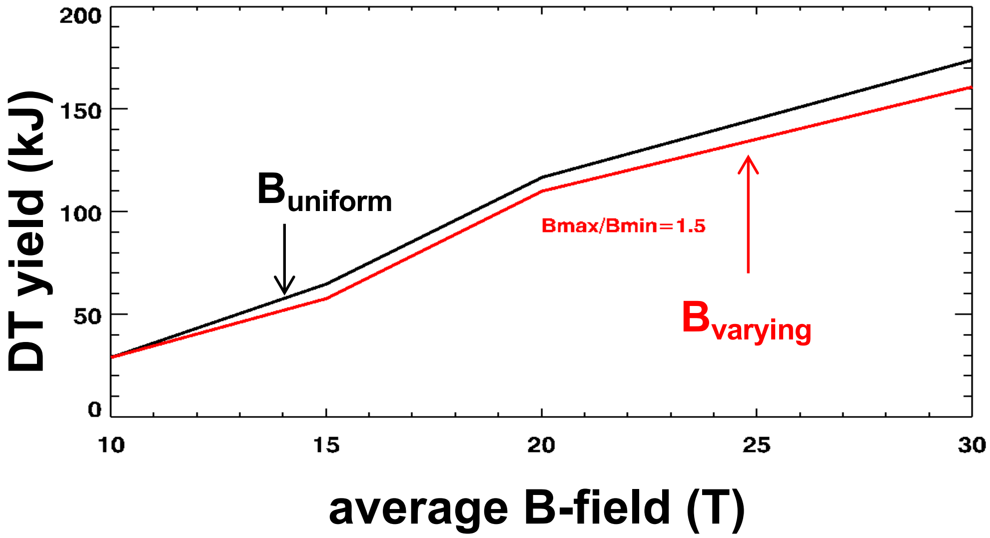
Hydra Sim

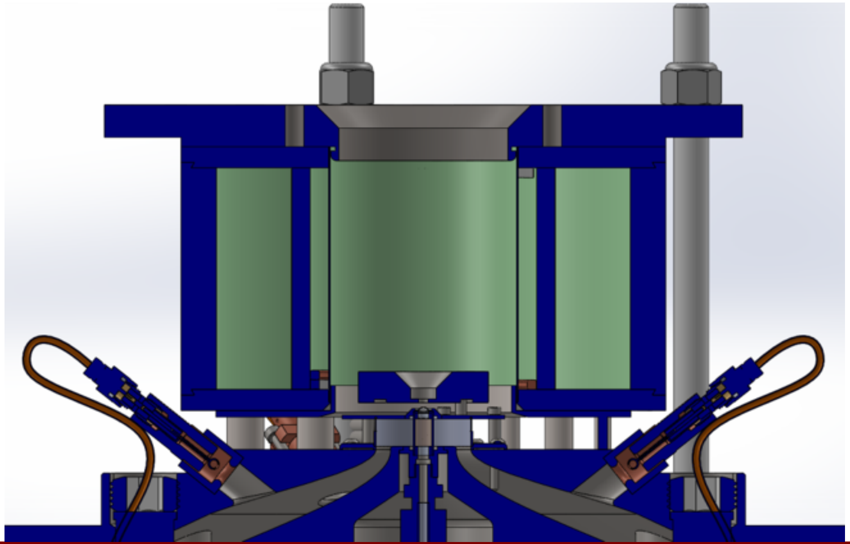
Ultimate Goal: Demonstrate effective MagLIF preheating at higher fuel densities and coupled energies required for scaled targets

We are also exploring new designs to increase the drive current on Z 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.

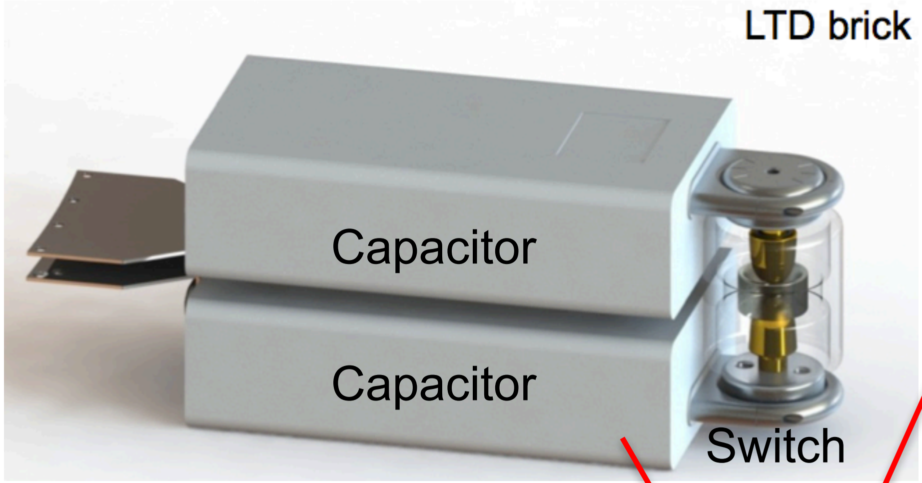


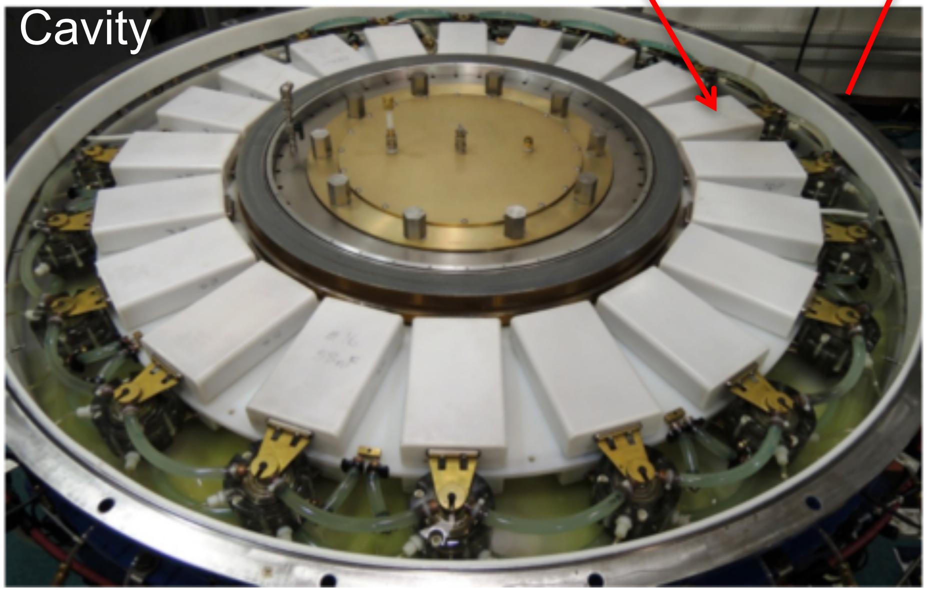


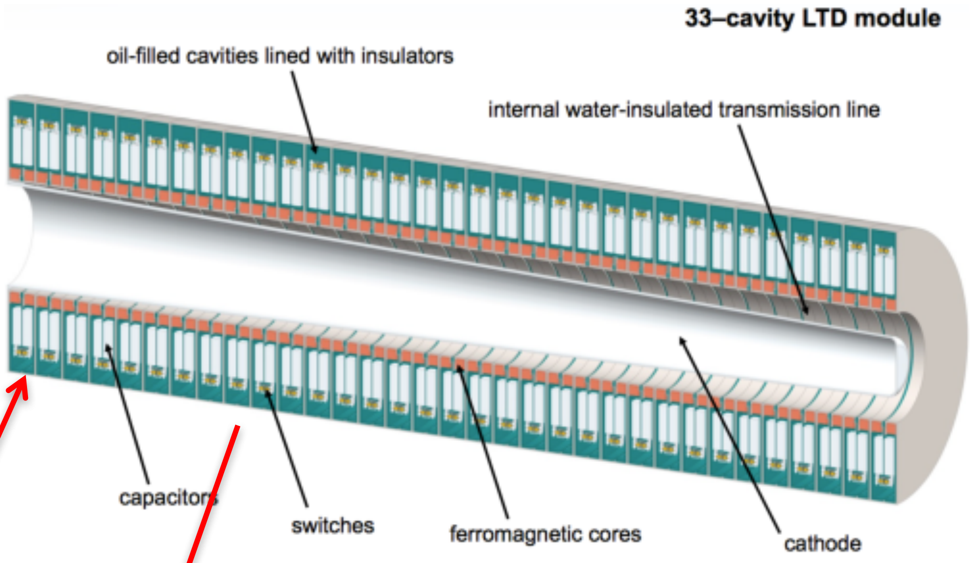


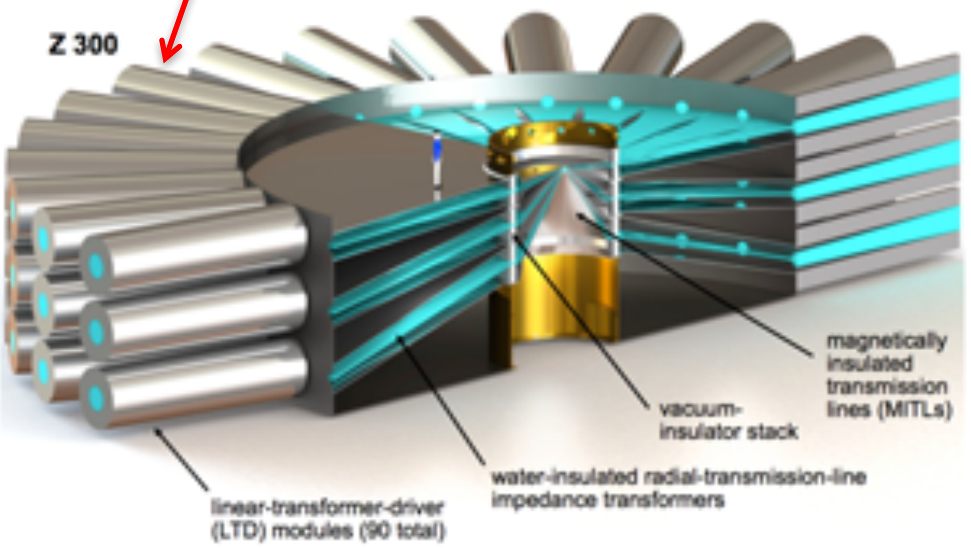
Gomez, Laity, Lamppa, Stygar, Slutz et al.

We are currently testing Linear Transformer Driver (LTD) technology for scaling to next generation pulsed power machines



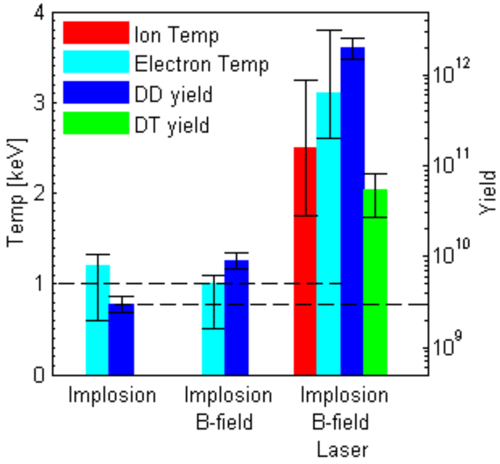




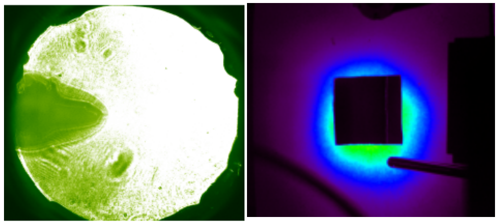


Summary

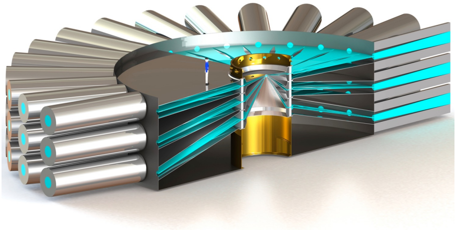
- Initial MagLIF experiments have demonstrated the basic concepts of **preheat**, **fuel magnetization**, and **implosion** to achieve thermonuclear fusion.
  - Max DD fusion yields of ~3E12



- Since our initial experiments, we have focused on understanding the science of MagLIF



- We are also developing several capabilities to test simulation code predictions of MagLIF scaling



Thank you for your attention!

Sandia
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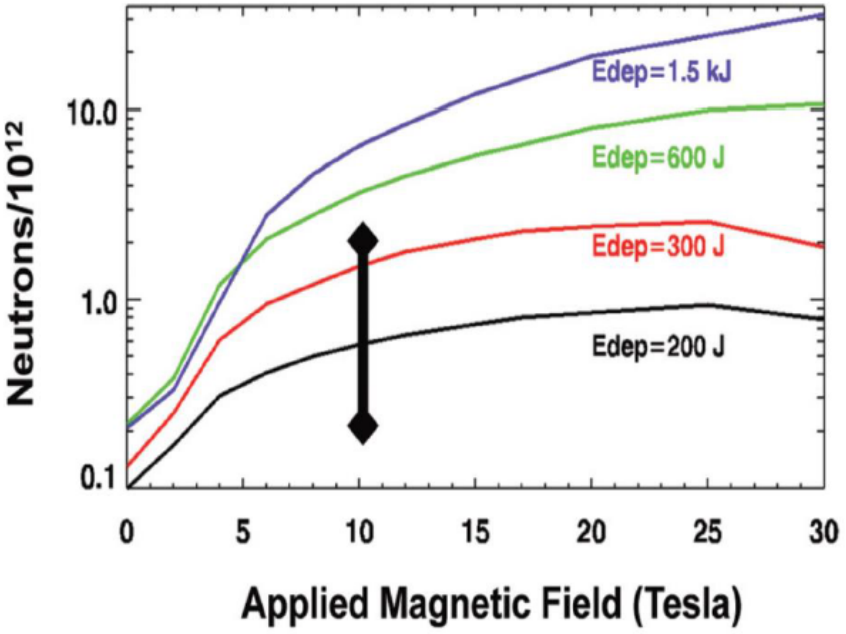
The main hypotheses for the discrepancies between experiments and models involve preheat, mix, and morphology.

- **Ineffective Preheat**
  - Pecos experiments indicate we are over an intensity cliff
  - Omega and NIF show potential for a predictable preheat condition
- **Radiative cooling from Be walls and/or LEH window**
  - Long interval time (~50ns) between preheat and stagnation
  - Mix may get worse with increased laser energy
- **Liner implosion stability and resulting stagnation morphology**
  - 3-D stagnation column

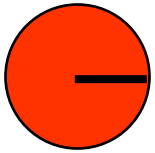
LASNEX Simulations of Rev0 platform*



Even so, we are only ~4x away from the predicted optimum yield for this platform.

- ➢ We need higher gas pressure, preheat, B-field, and current delivery

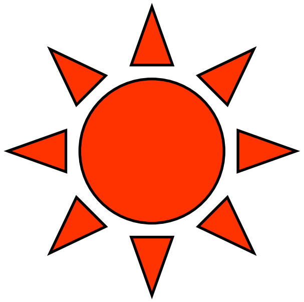
Under extreme conditions a mass of DT can undergo significant thermonuclear fusion before falling apart



ρ, R, T

- Consider a mass of DT with radius R, density ρ, and temperature T
- How does the disassembly time compare with the time for thermonuclear burn?

$$\tau_{disassembly} \sim \frac{R}{c_s} \sim \frac{R}{\sqrt{T}} \qquad \tau_{burn} \sim \frac{1}{n_i \langle \sigma v \rangle} \sim \frac{1}{\rho \langle \sigma v \rangle}$$



- **The fractional burn up of the DT (for small burn up) is:**

$$f_{burn} \approx \frac{\tau_{disassembly}}{\tau_{burn}} \sim \rho R \frac{\langle \sigma v \rangle}{\sqrt{T}}$$

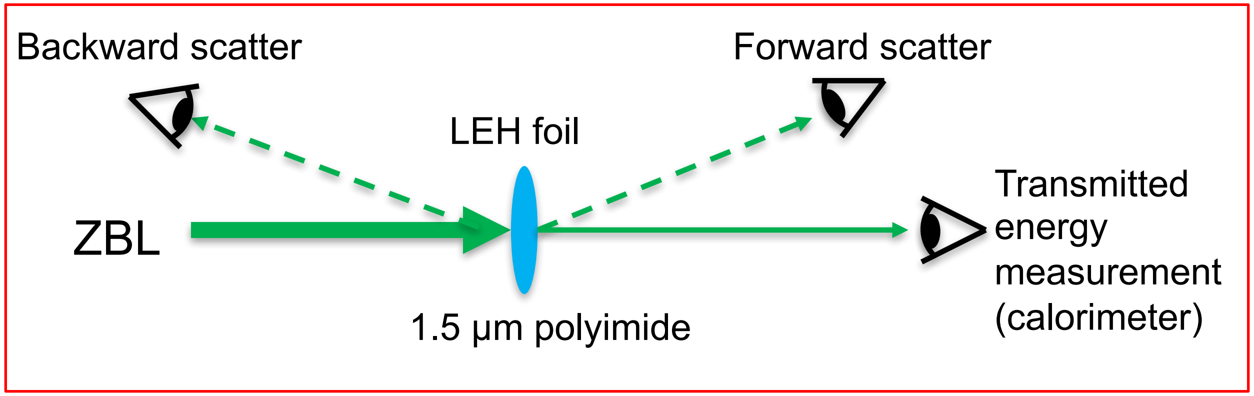
- **At sufficiently high ρR and T the fractional burn up becomes significant and the energy deposited by alpha particles greatly exceeds the initial energy in the fusion fuel (“ignition”)**

- **Typical conditions are:** $\rho R \approx 0.4\,\mathrm{g/cm^2}$

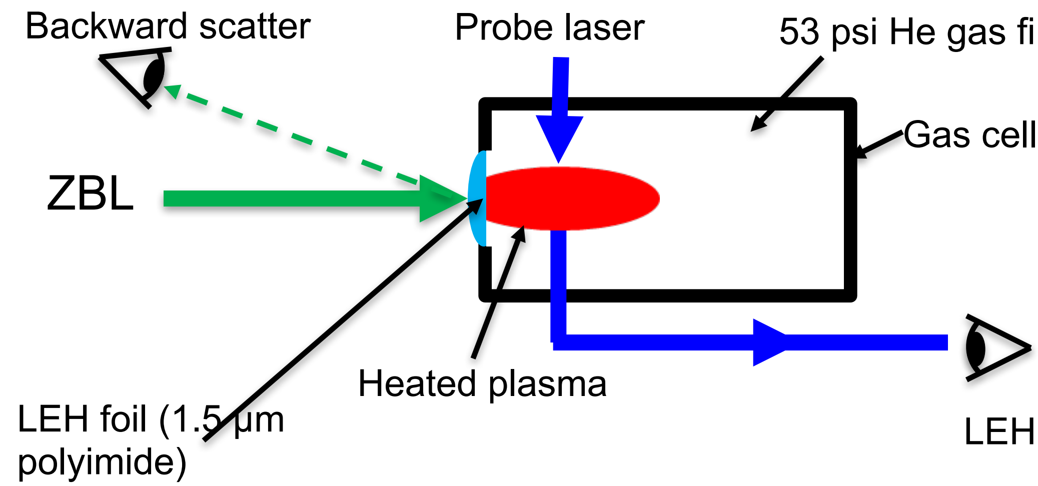
  $T \approx 5\,\mathrm{keV}$ (50,000,000 K)

Laser experiments in PECOS have been critical to provided an improved understanding of laser heating on Z

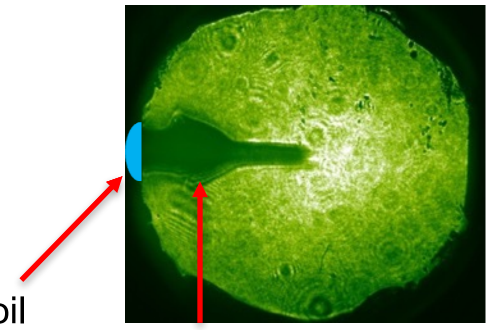
LEH transmission studies



Gas cell experiments

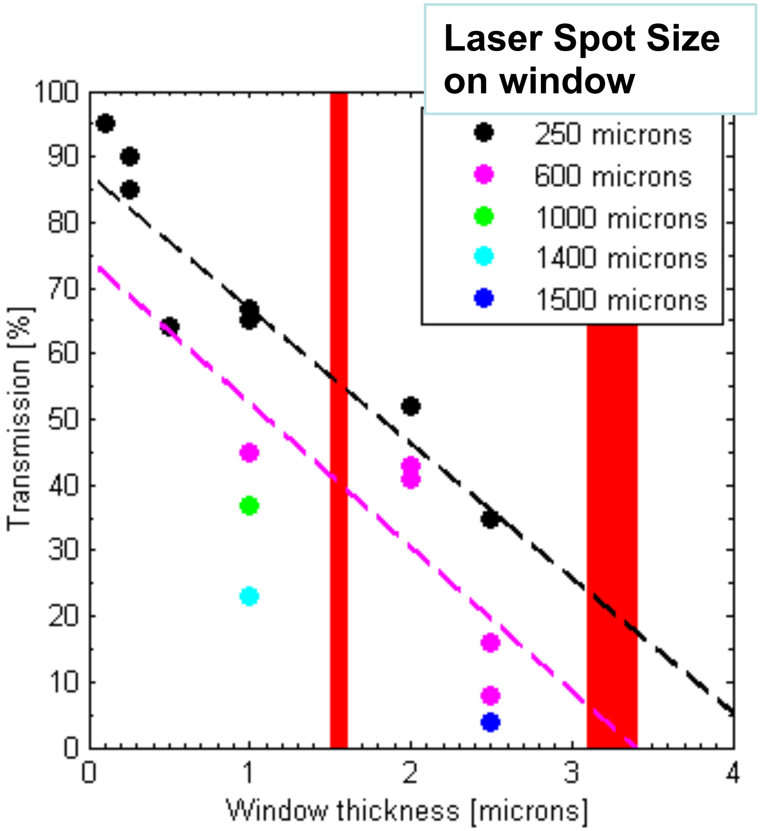


Laser shadowgram



Foil transmission experiments have confirmed poorer than expected laser energy coupling in MagLIF experiments

Transmission as fct. of thickness & spot size



Laser Spot Size on window

Conclusions

400-500 micron spot size

>3 micron thick foil

5-20% transmission

(100-400 J)

400-500 micron spot size

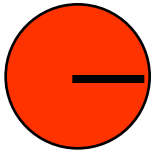
1.5 micron thick foil

40-60% transmission

(0.8-1.2 kJ)

Note: PECOS experiments, 2.5 kJ, No phase plate, flat foil

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



ρ, R, T

For ignition conditions:

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

$$E_{HS} \propto m_{HS} T_{HS} \propto \rho_{HS} R^3_{HS} T_{HS} \propto \frac{(\rho_{HS} R_{HS})^3 T^3_{HS}}{P^2_{HS}}$$

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

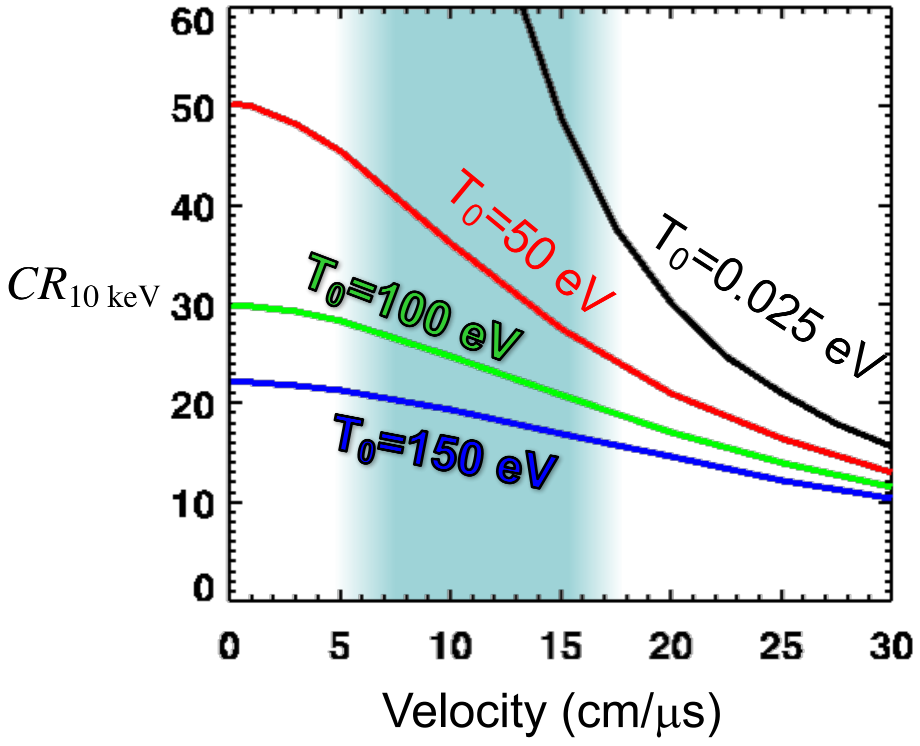
$E_{NIF} \sim 15\,\mathrm{kJ} \Rightarrow P \sim 400\ \mathrm{GBar}$ $\qquad R \sim 30\,\mu\mathrm{m} \Rightarrow$ and $\rho \sim 130\, g/cm^3$

This is consistent with detailed calculations

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

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

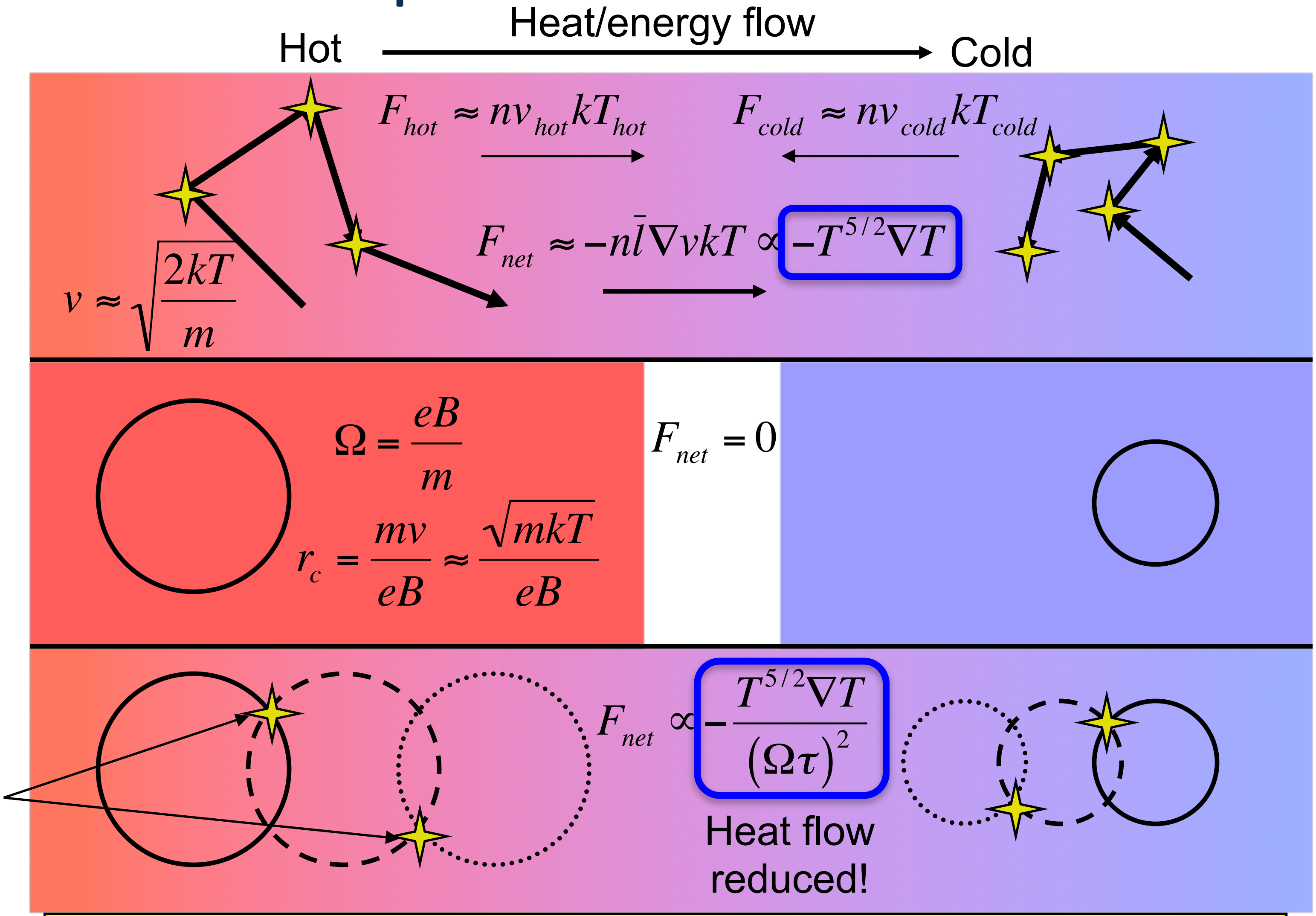
Temperature rise for an ideal adiabatic cylindrical compression

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

- 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

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

Magneto-inertial fusion is based on the idea that energy and particle transport can be reduced by strong magnetic fields, even in collisional plasmas



Collisional
no B

$$F_{hot} \approx n v_{hot} kT_{hot} \longrightarrow$$

$$F_{cold} \approx n v_{cold} kT_{cold} \longleftarrow$$

$$F_{net} \approx -n\bar{l}\nabla v kT \propto \boxed{-T^{5/2}\nabla T} \longrightarrow$$

$$v \approx \sqrt{\frac{2kT}{m}}$$

Strong B
(perpendicular to this slide)
No collisions

$$\Omega = \frac{eB}{m}$$

$$r_c = \frac{mv}{eB} \approx \frac{\sqrt{mkT}}{eB}$$

$$F_{net} = 0$$

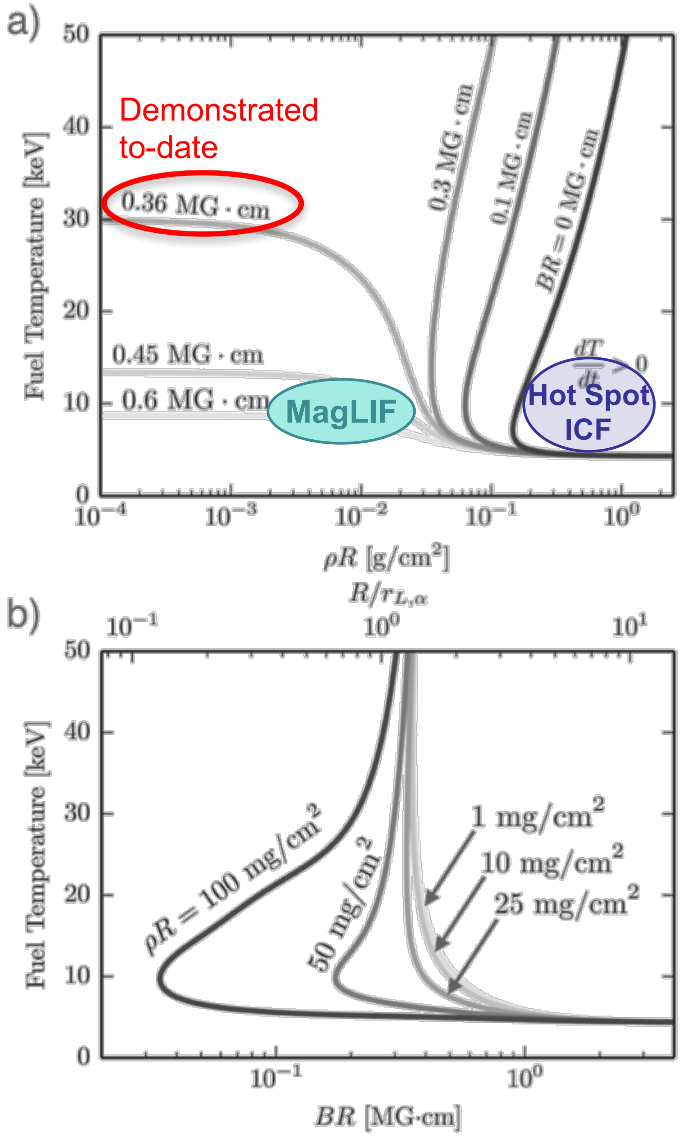
Strong B
with collisions

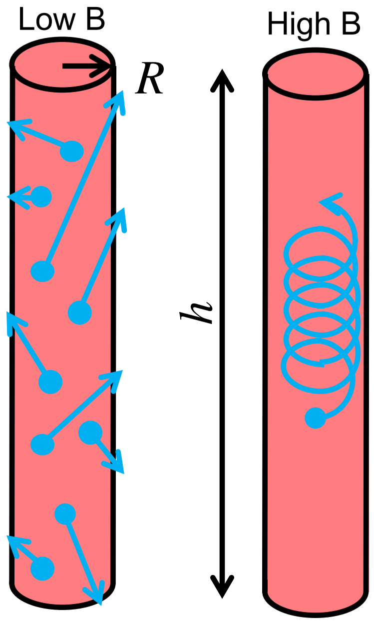
$$F_{net} \propto -\boxed{\frac{T^{5/2}\nabla T}{(\Omega\tau)^2}}$$

Heat flow
reduced!

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

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





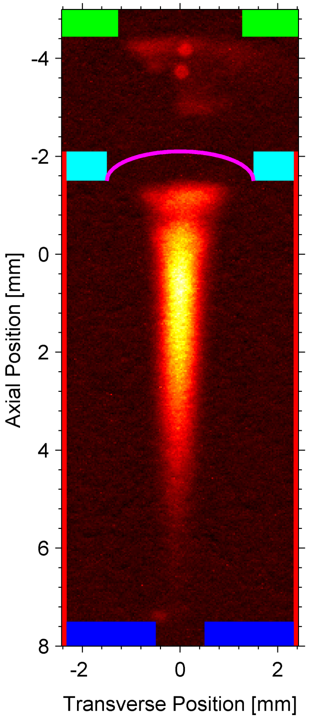
- Fraction of trapped α's (tritons) is a function of ***BR***
- At BR>0.5 MG-cm the effects saturate (particles are well confined).
- Measurements to date suggest >0.3 MG-cm

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

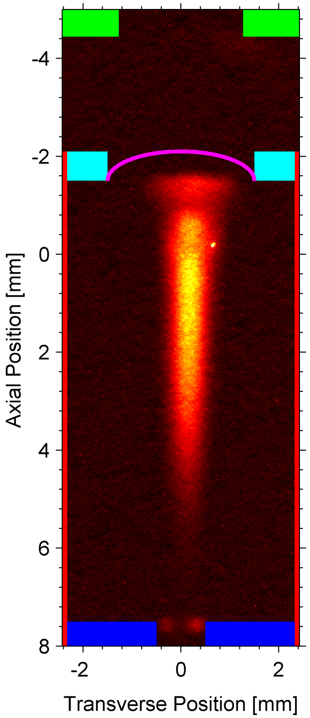
Basko *et al*. Nuclear Fusion 40, 59 (2000); P.F. Knapp *et al.*, Phys. Plasmas (2015).

In January we conducted successful laser heating experiments in Z using phase plates to condition the beam

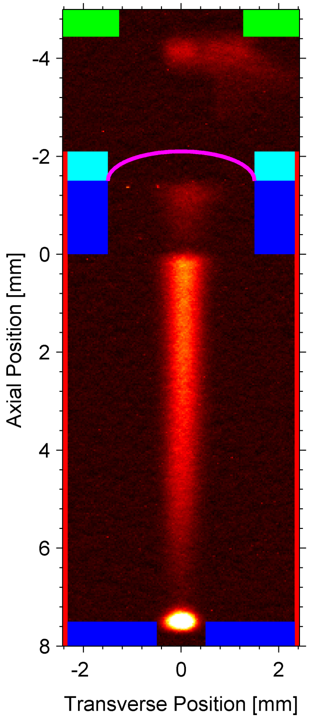
- 0.75 and 1.1 mm distributed phase plates have been procured, coated, conditioned, and characterized. Shots as high as 4 kJ with prepulse have been performed on Z using the DPPs.



H39
0.75 mm PP
2 kJ

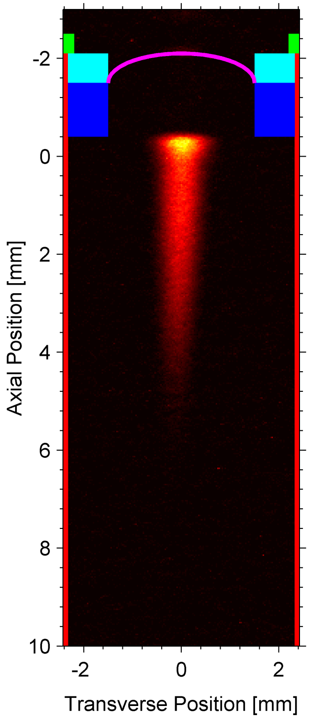


H40
0.75 mm PP
2 kJ

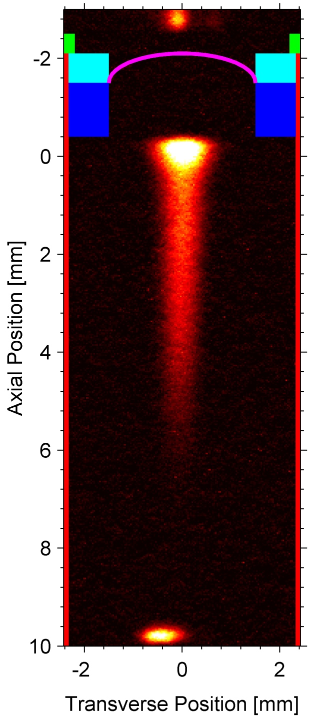


H41
0.75 mm PP
4 kJ

H42
1.1 mm PP
2 kJ



H43
1.1 mm PP
2 kJ



All use D_2 + 0.1% atomic Ar; H39-H42 at 60 PSI; H43 at 45 PSI

This technology can generate about 47 MA, 300 TW in a machine the same size as Z (26 MA, 85 TW)

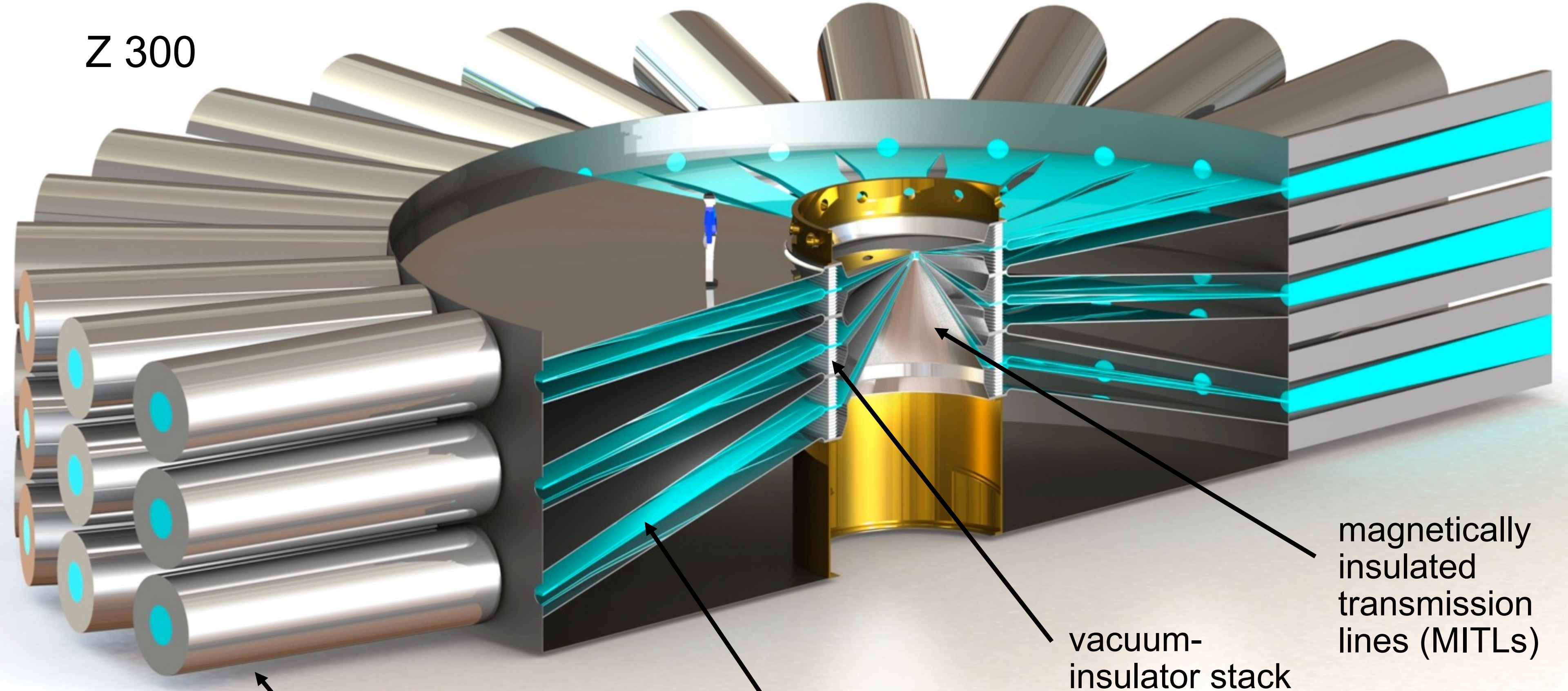
P_{LTDs} = 300 TW
E_{LTDs} = 47 MJ

V_{stack} = 7.5 MV
L_{vacuum} = 14 nH

I_{load} = 50 MA
$\tau_{implosion}$ = 130 ns

$E_{radiated}$ = 11 MJ
diameter = 35 m

η_{x-ray} = 23%



magnetically insulated transmission lines (MITLs)

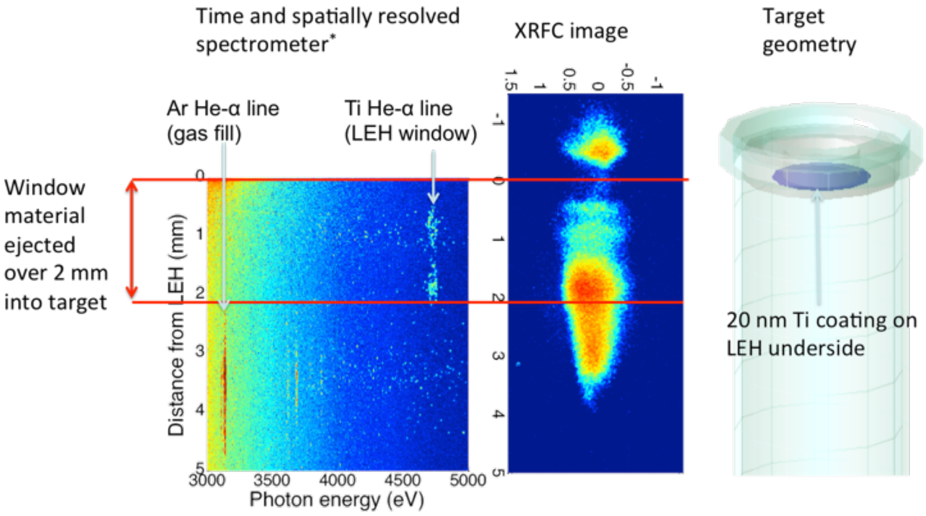
vacuum-insulator stack

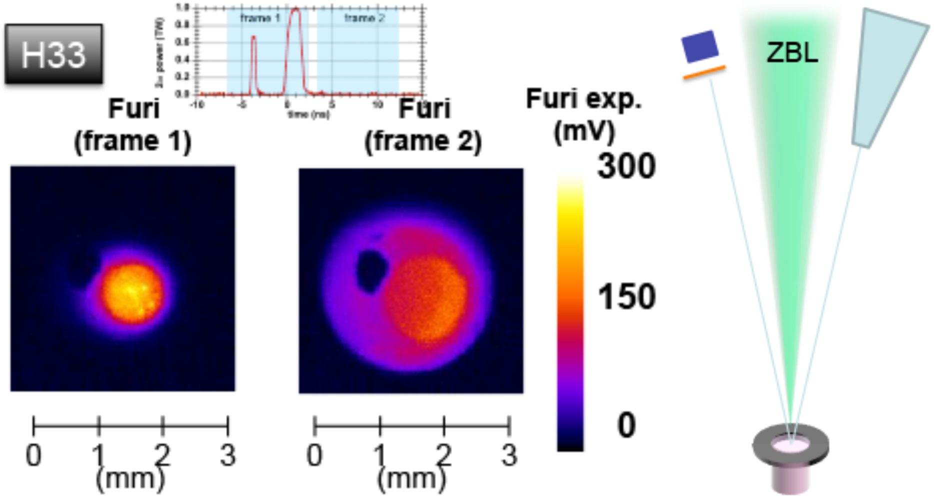
water-insulated radial-transmission-line impedance transformers

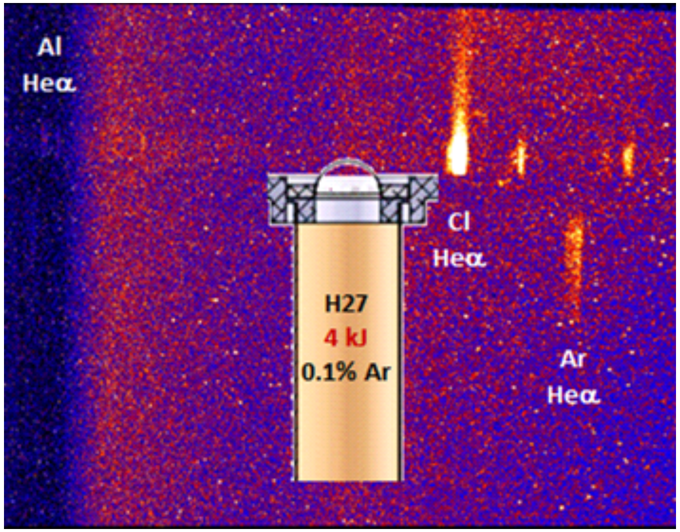
linear-transformer-driver (LTD) modules (90 total)

We have made progress in characterizing and mitigating fuel contamination as a result of the preheating method

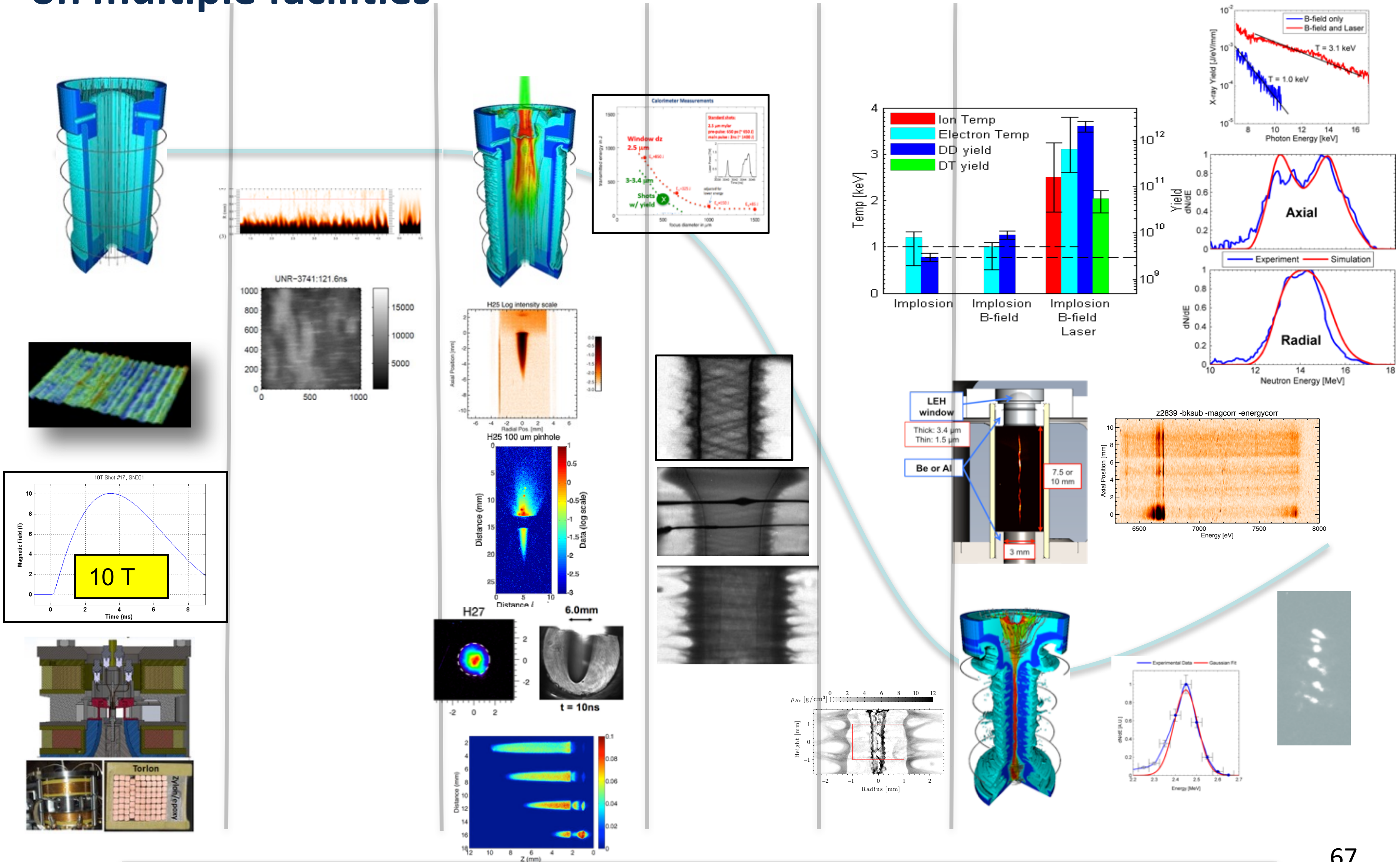
- Window mix using Ti dopant coated on the LEH window at OMEGA-EP
- Localized Cl dopant on the LEH window, Al washers, we are assessing laser-induced mix using ZBL
- Developing time-gated axial imaging and spectroscopy to measure heating on integrated Z shots







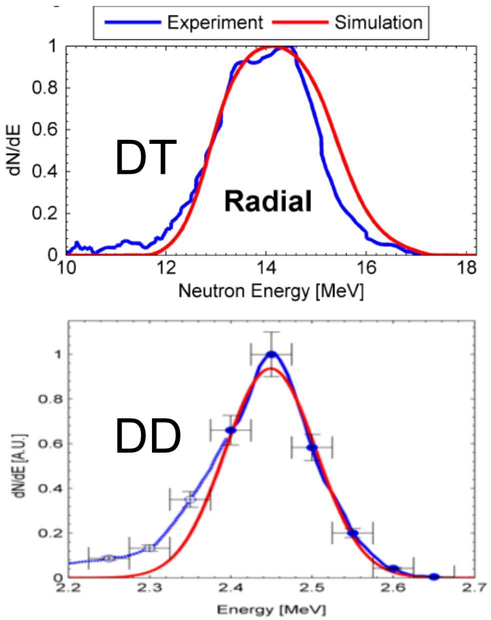
We are collecting data on all phases of MagLIF implosions, on multiple facilities



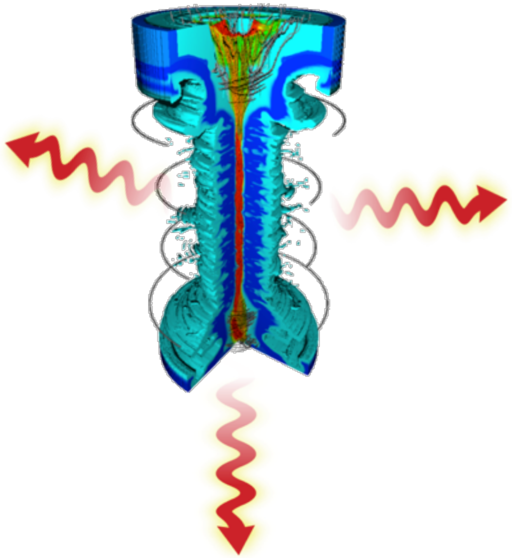
Our current focus is on better understanding of fuel preheating and mix

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

Neutron spectra

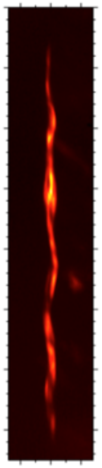


MagLIF Z pinch

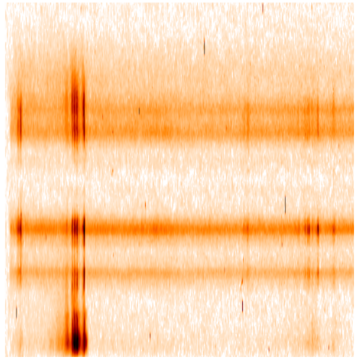


X-ray

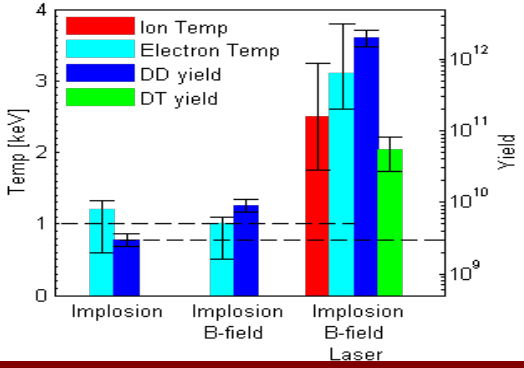
Imaging



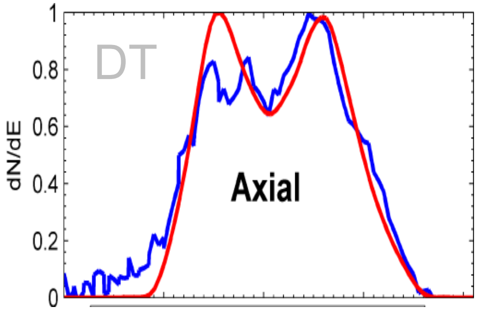
Spectra



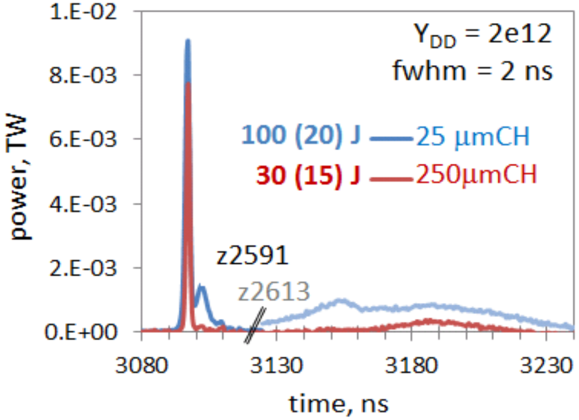
Nuclear Activation



Neutron spectra

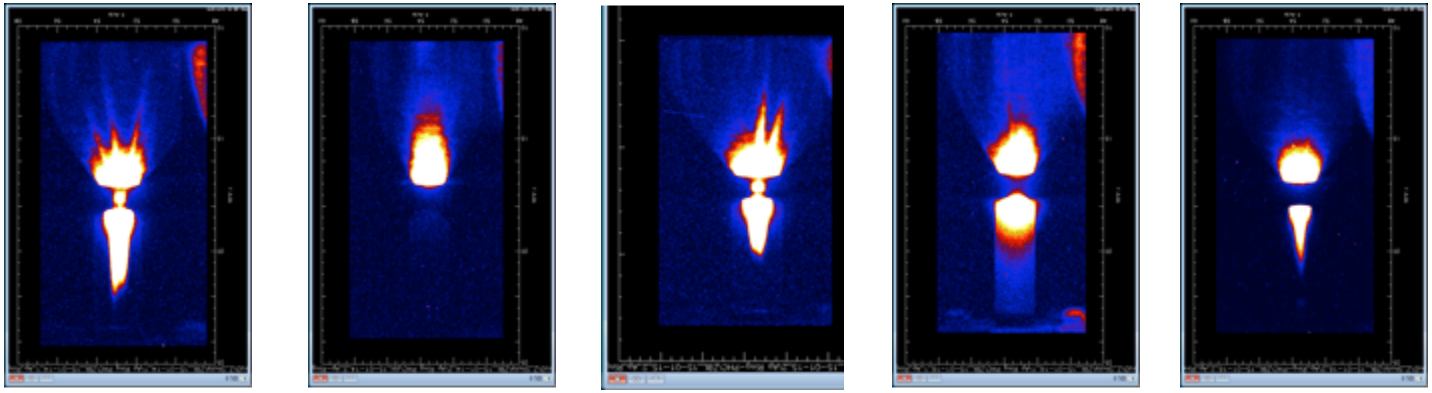


X-ray Power



Laser only experiments on Z (with ~1.8mm DPP) **suggests *significant* window mix**

All pinhole images have similar intensities above washer



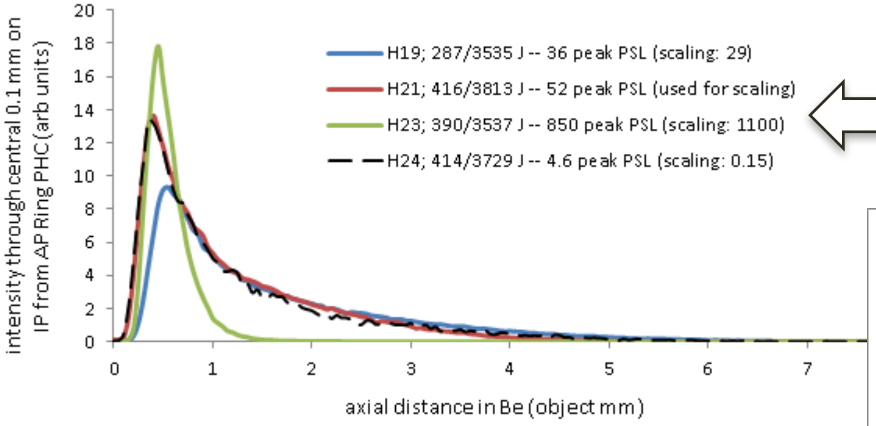
H19
45 psi, 0.5% Ar

H20
50 psi, Pure Ne

H22
60 psi, 0.5% Ar

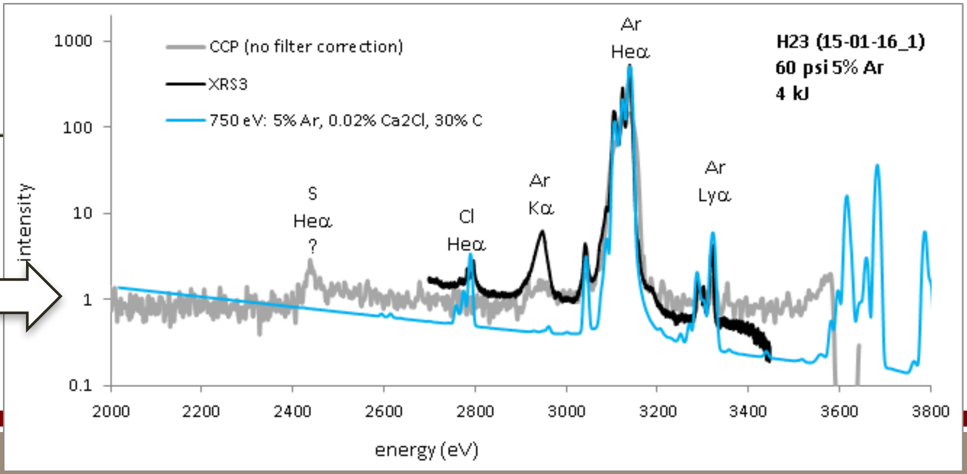
H23
60 psi , 5% Ar

H24
60 psi, pure D2

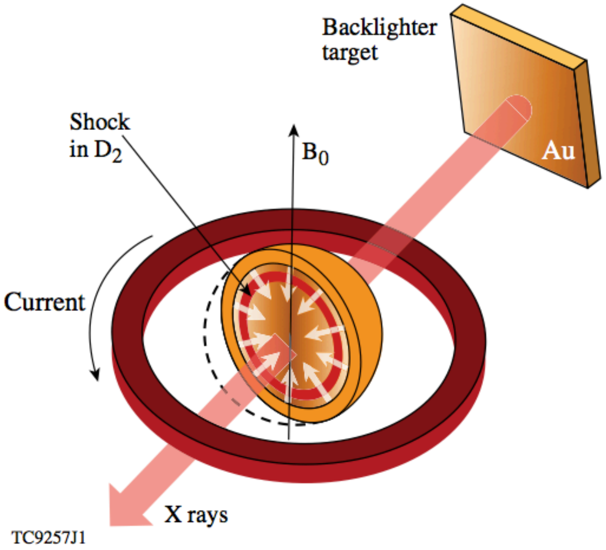


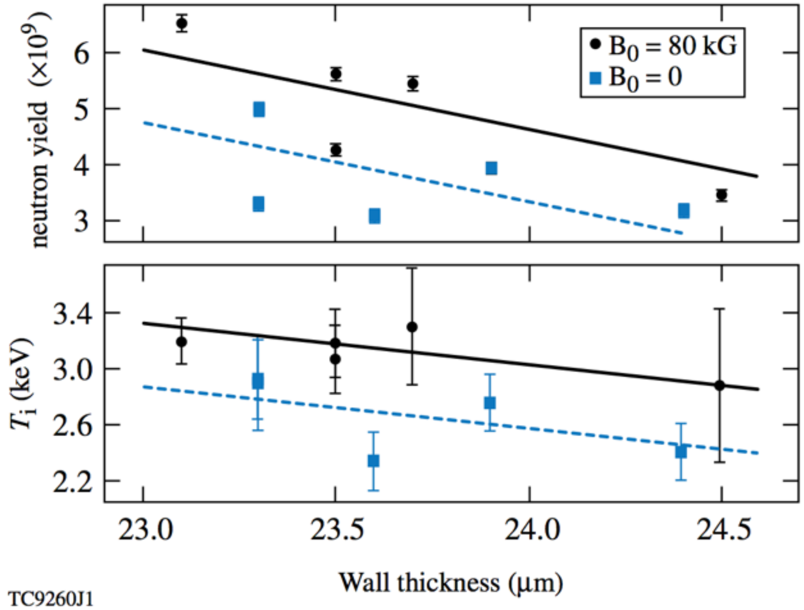
Axial lineouts below washer show similar profiles for low dopant fractions, with intensity scaling that suggests 10% carbon mix in pure D2 case (H22)

XRS3 spectra indicate fill temperatures of 0.6 – 0.8 keV, small (~0.02%) Cl mix fractions, and significant (>20%) low-Z mix



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





- Simple axial field used in a spherical implosion geometry
- Field suppressed electron heat conduction losses along one direction
- The resulting 30% increase in temperature and 15% increase in yield is consistent with rough estimates for heat loss suppression
- This is an example of success with a target that produced fusion yield without magnetization—can we produce yield in targets that wouldn't produce significant yield otherwise? (and gain benefit from doing so?)

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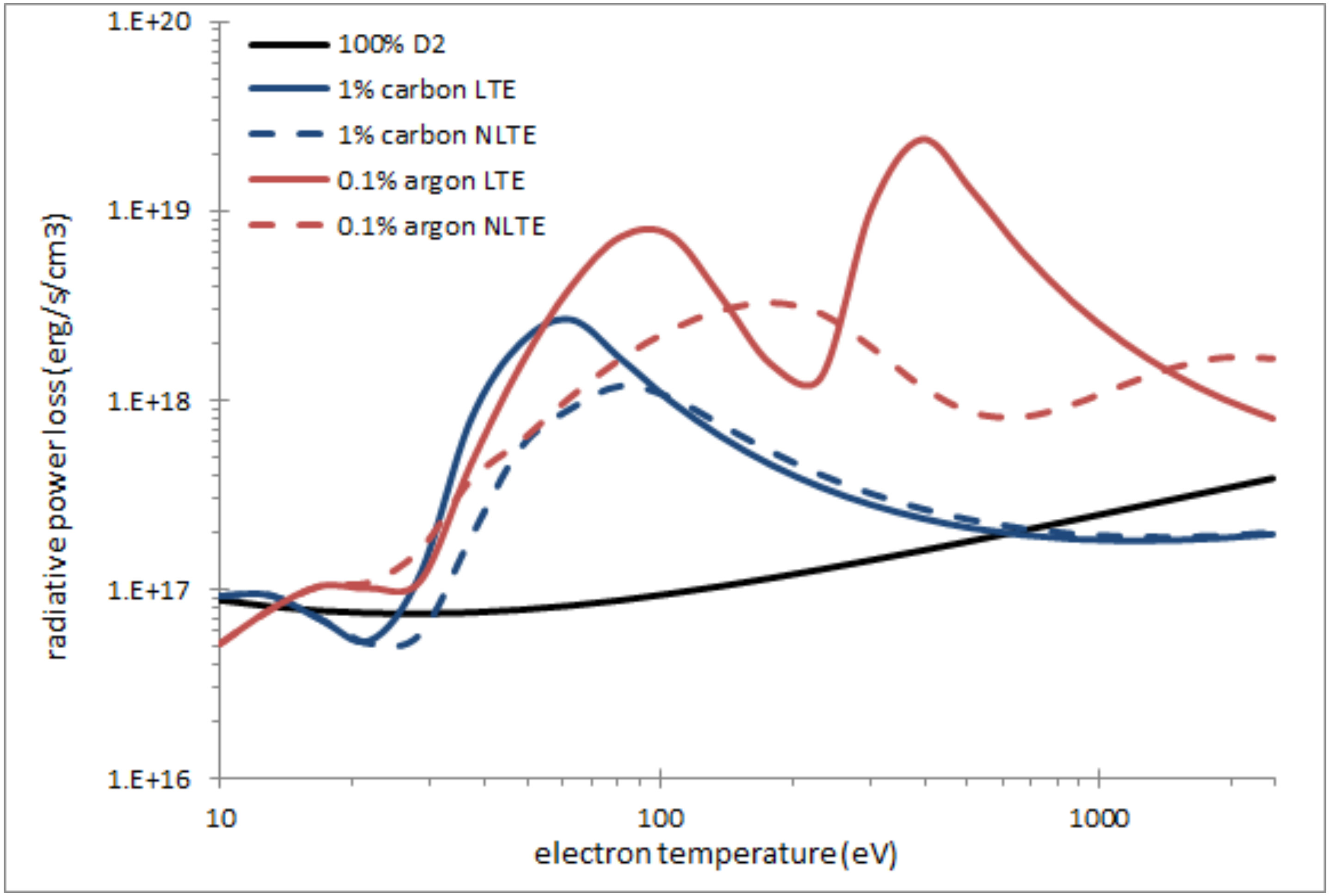
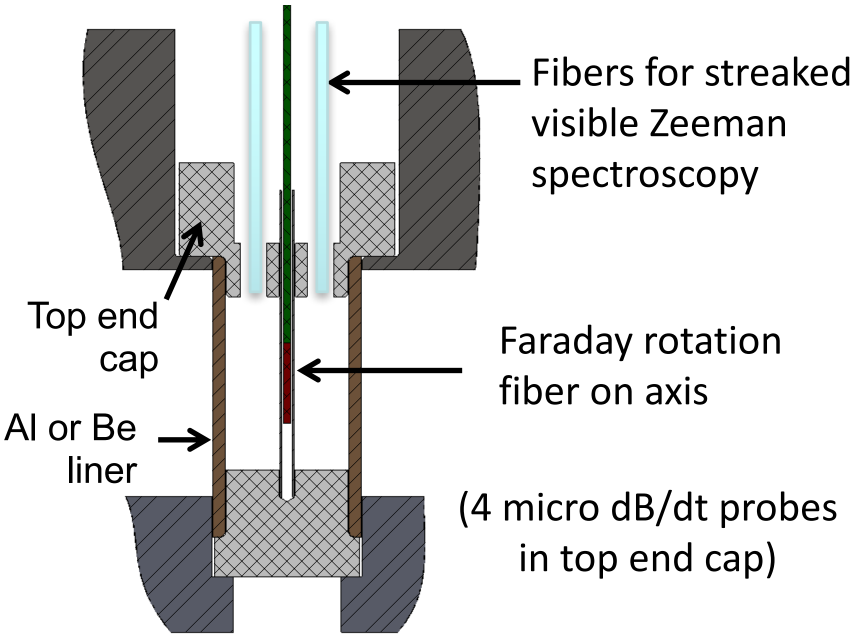
* P.Y. Chang *et al.*, Phys. Rev. Lett. 107, 035006 (2011).


100% D2
1% carbon LTE
1% carbon NLTE
0.1% argon LTE
0.1% argon NLTE
radiative power loss (erg/s/cm3)
1.E+20
1.E+19
1.E+18
1.E+17
1.E+16
10
100
1000
electron temperature (eV)

Magnetic flux compression experiments in November may have directly measured >500 T fields (initial B=17 T)

- Three Z shots (z2882, z2883, z2885) used an on-axis Faraday rotation fiber to measure flux compression in a vacuum-filled liner implosion
- Analysis underway, preliminary work suggests >1000 T
- LDRD-funded initiative; also included micro Bdot development efforts

Platform developed for magnetic flux compression experiments on Z



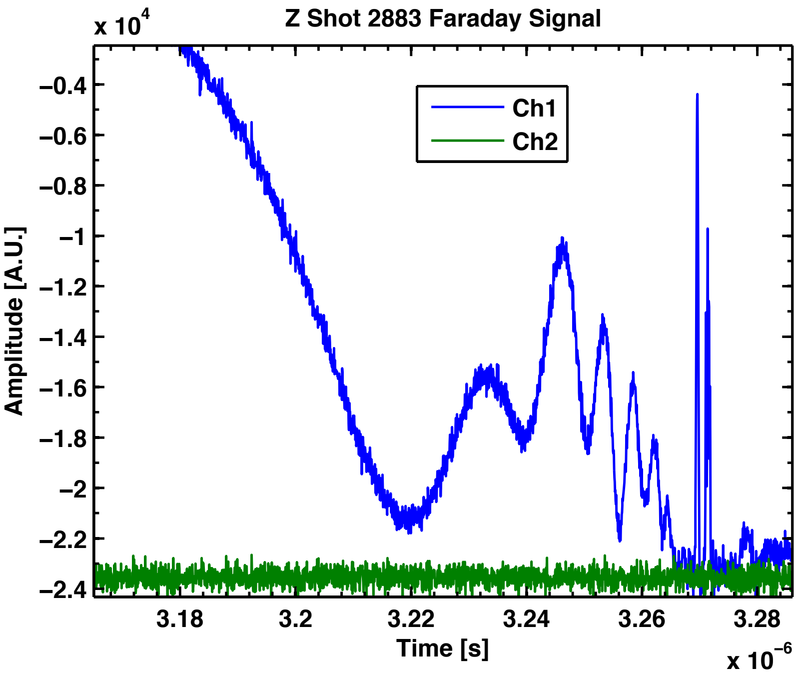
Fibers for streaked visible Zeeman spectroscopy

Top end cap

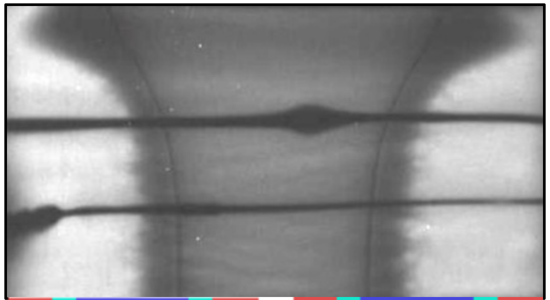
Faraday rotation fiber on axis

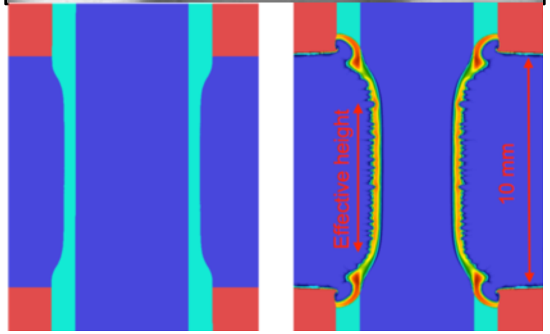
Al or Be liner

(4 micro dB/dt probes in top end cap)



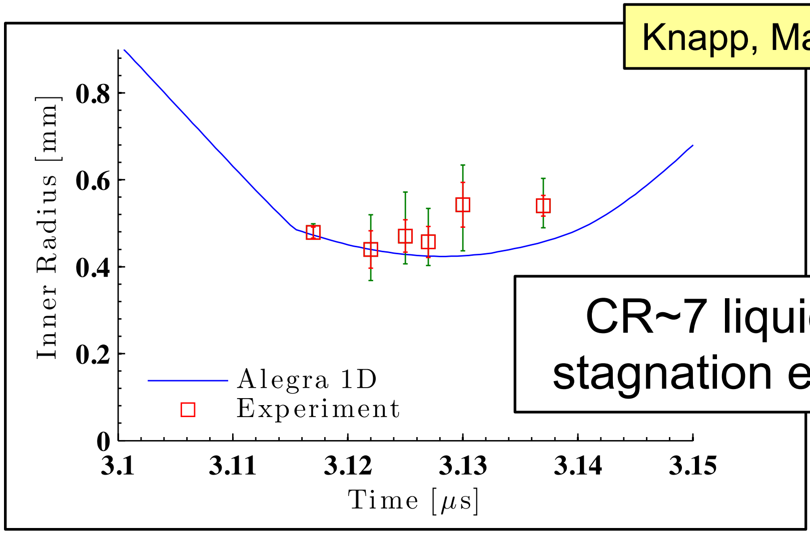
Implosion shots this year will continue to address several of our 5-year objectives





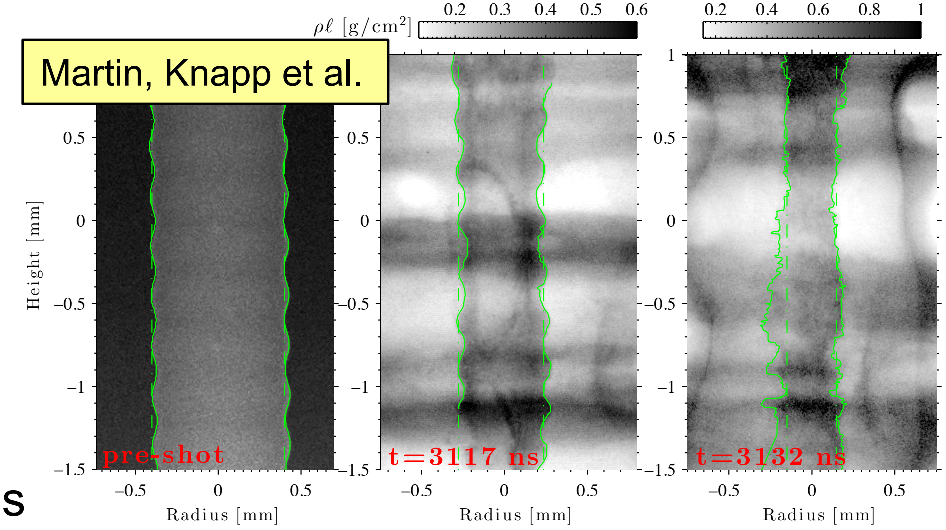
Shaped liners to control electrode/end effects

Sefkow, Ampleford et al.



Knapp, Martin et al.

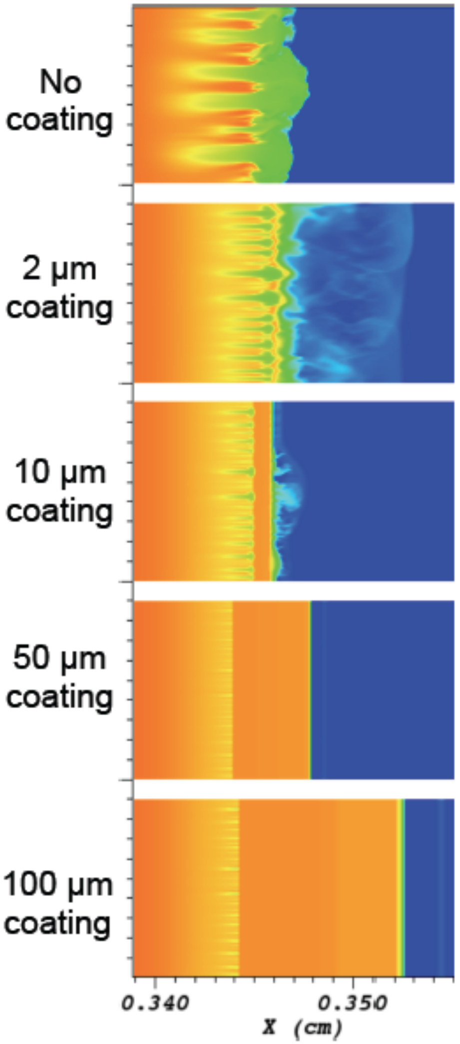
CR~7 liquid D2 “1D” stagnation experiments



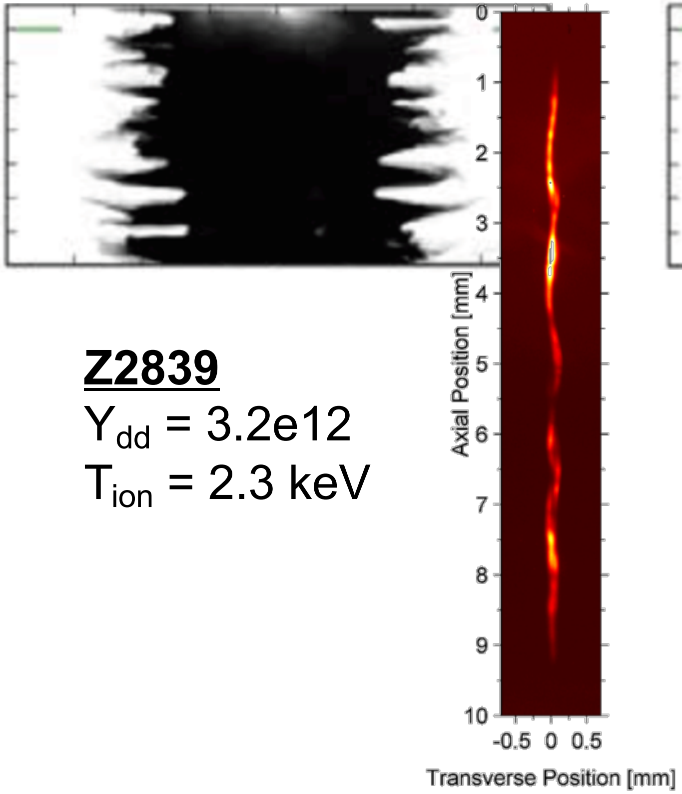
Martin, Knapp et al.

On-axis rods to study deceleration instabilities

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

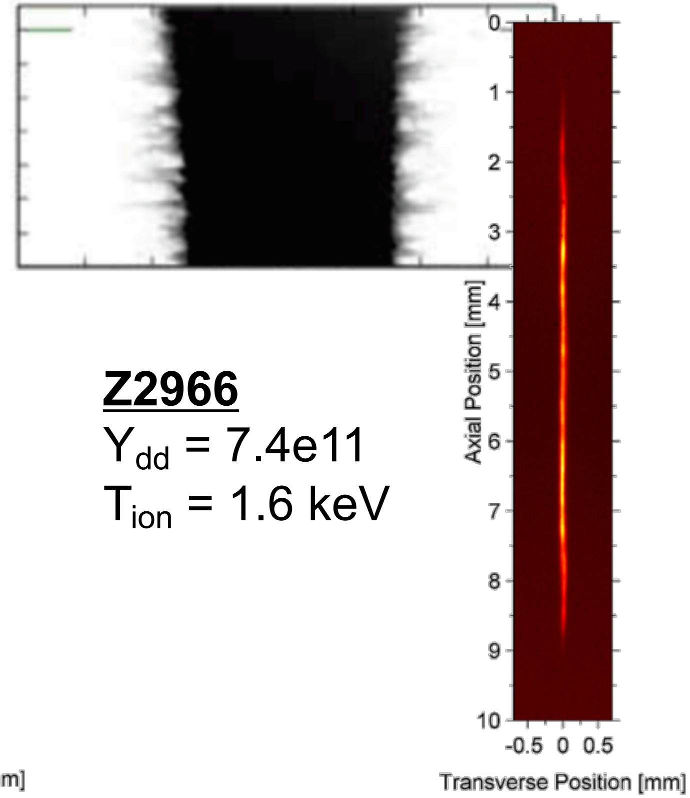


Uncoated Liners



Z2839
Y_{dd} = 3.2e12
T_{ion} = 2.3 keV

Coated Liners



Z2966
Y_{dd} = 7.4e11
T_{ion} = 1.6 keV

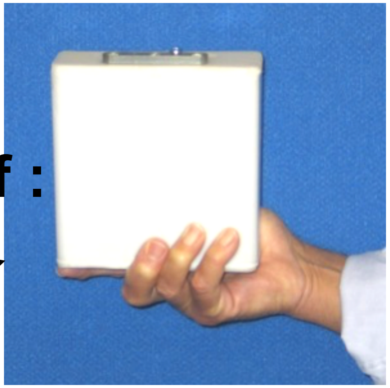
Thick dielectric coatings suppress liner instabilities that are seeded by the electro-thermal instability

New driver technology: The Linear Transformer Driver (LTD) is the biggest advance in pulsed power since the invention of the Marx generator in 1924

An LTD Cavity is the building block of a future high yield facility

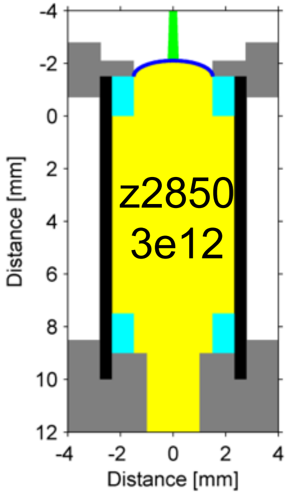
An LTD consists of :

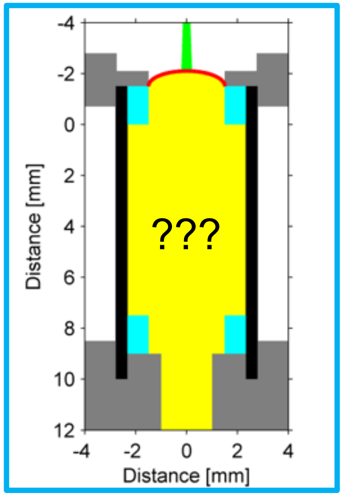
- **Capacitors**
- **Switches**
- **Magnetic cores**

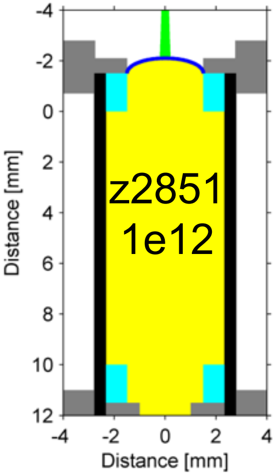


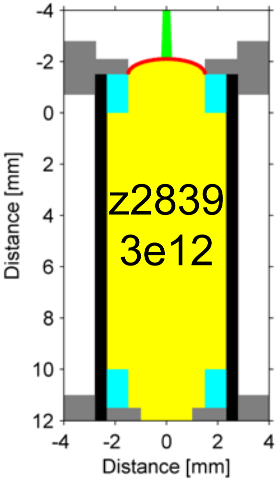
The configuration of our first phase plate test was largely driven by empirical progress with the unconditioned beam

Drive current (target height 10-7.5mm)





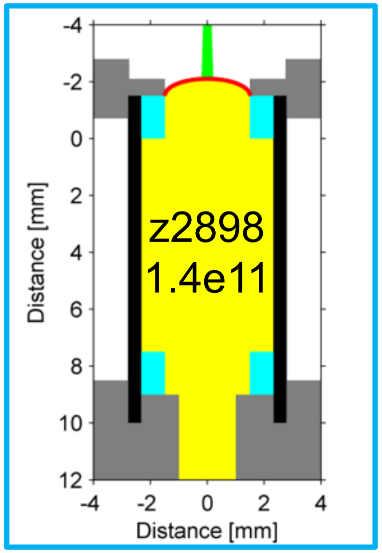




z2899
Pulsed Power Failure

2-3x improvement?

Z2898
+0.75mm DPP



All targets have only Be components in contact with fuel

Laser coupling (window thickness, 3.5mm - 1.7mm)

We believe that we need to demonstrate tritium use on Z to do better science & prepare for the future

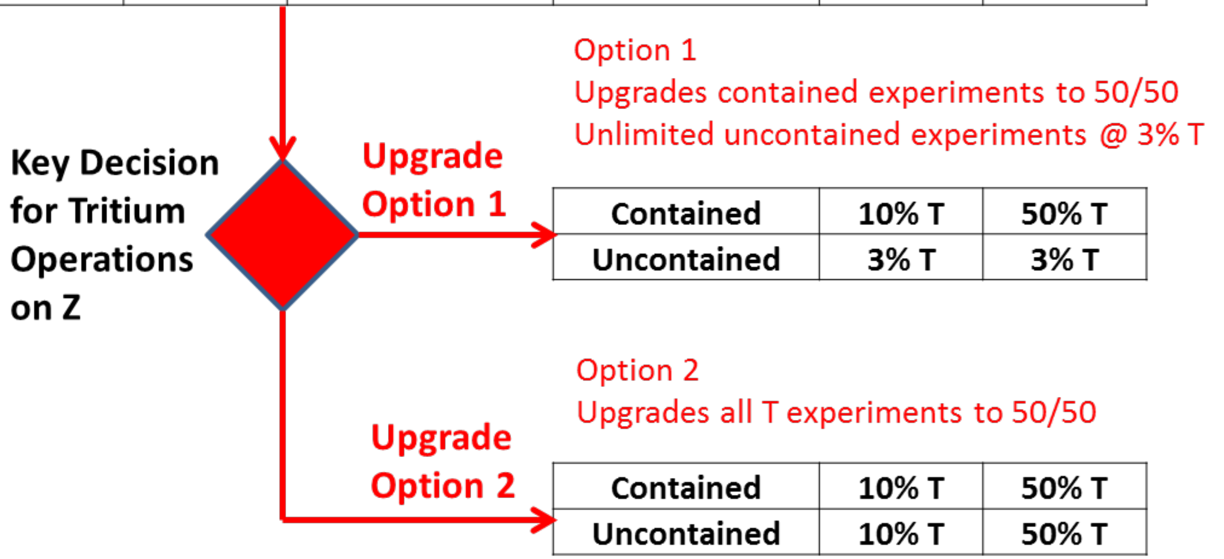
- **Even at small percentages, tritium can enhance our scientific understanding and productivity on Z**
  - In ICF, could leverage more of the diagnostics and experience developed by the larger community that is centered on measuring 14 MeV neutrons, as well as demonstrating understanding in going from pure DD to few %T
  - In effects testing work, could benefit from enhanced yields and changes in energy spectrum to test our understanding of new testing platforms under development
- **We need to develop processes and experience**
  - Tritium has never been used on a large-scale pulsed power facility
  - Multiple missions for any next-step pulsed power facility will likely require the use of tritium
    - Multi-MJ fusion yields for Inertial Confinement Fusion
    - Combined neutron/photon effects testing
    - Science campaign experiments (e.g., boost)
  - Not all of the experience with using tritium on large laser facilities is relevant—we cannot rely solely on those experiences to define requirements for a next-step facility

We plan to work towards a key decision in late 2017 regarding future tritium operations on Z

	2015	2016	2017	2018	2019	2020	2021
Contained	D2, He3	0.1% T	1% T	3% T	3% T	3% T	3% T
Uncontained	D2, He3	D2	0.1% T	1% T	3% T	3% T	3% T

We believe the existing infrastructure would allow an estimated 2- 4 tritium experiments / yr. at up to 3% T

Option 0 would sustain 2 – 4 experiments / yr.
Limited uncontained experiments



Key Decision for Tritium Operations on Z

Upgrade Option 1

Option 1
Upgrades contained experiments to 50/50
Unlimited uncontained experiments @ 3% T

Contained	10% T	50% T
Uncontained	3% T	3% T

Upgrade Option 2

Option 2
Upgrades all T experiments to 50/50

Contained	10% T	50% T
Uncontained	10% T	50% T

Potential systems requiring upgrades for options 1 & 2 include:

- Center section purging/ventilation
- MITL tent
- HVAC
- Neutron shielding
- Tritium dedicated hardware
- Tritium capture system
- Tritium fill station

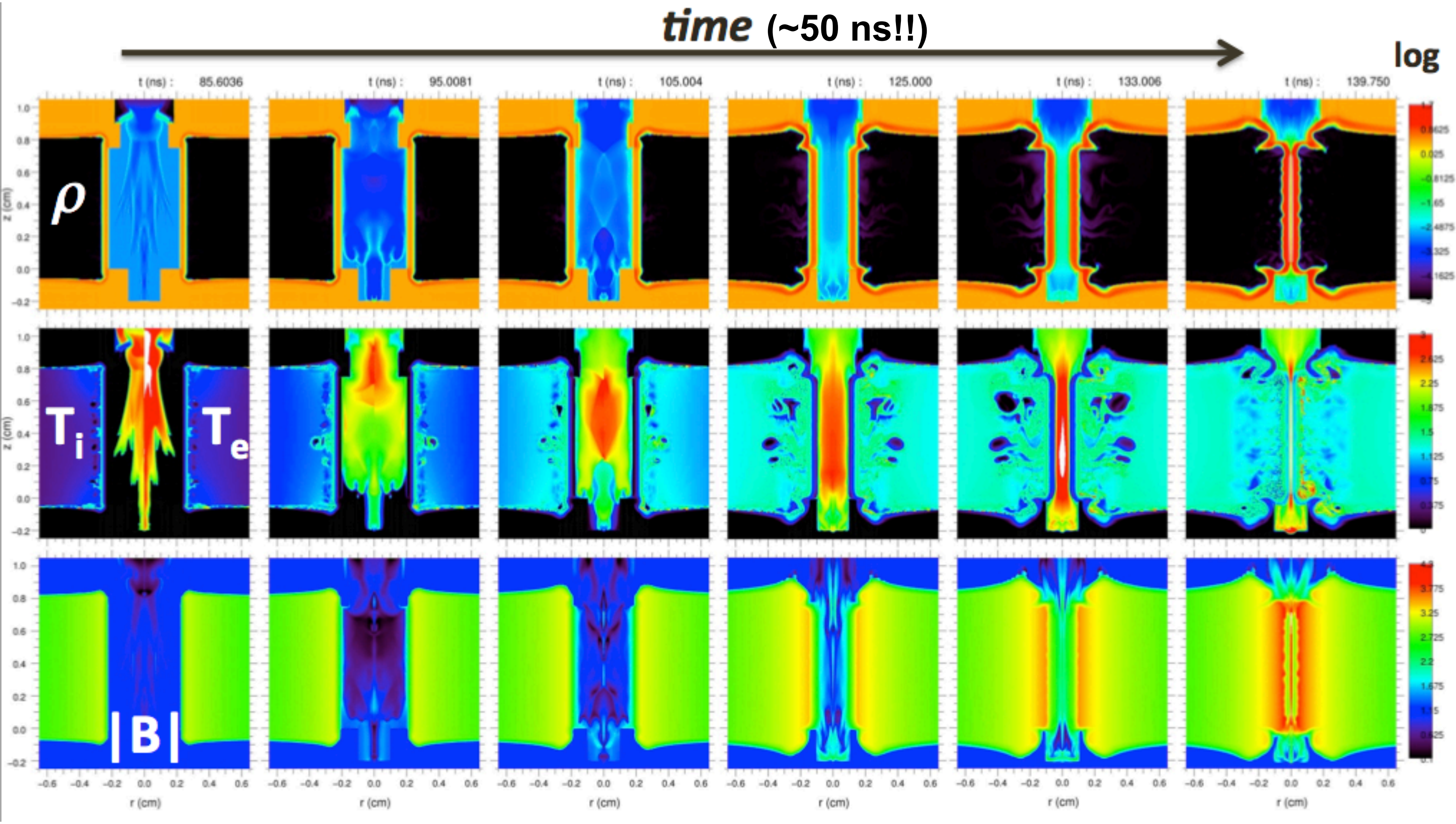
- Tests using light gas surrogates suggest a containment efficiency of 0.98. Measurements of recovery (0.99) and decontamination (0.99) give a combined 0.999998 removal efficiency
- 1st trace tritium test (contained) on Z in August

We have obtained fusion yield from a target that *does not work* without magneto-inertial fusion principles, and we can show that the fusing plasma is highly magnetized

- **New “Magnetized Liner Inertial Fusion” (MagLIF) concept is interesting!**
  - Magnetized (10 T) and laser-heated (2 kJ) cylindrical targets containing only deuterium (no T) reached ~3 keV temperatures and produced fusion yield (up to 2x10^{12} DD)
    M.R. Gomez *et al.*, Phys. Rev. Lett. (2014).
  - Secondary neutron yield (>10^{10} 14 MeV) and spectra demonstrate that the fusing plasma was highly magnetized with BR of 0.4 MG-cm
    P.F. Schmit *et al.*, Phys. Rev. Lett. (2014).
  - Data from multiple laser facilities has confirmed that poor laser coupling to the fuel is a significant issue, and better performance may be possible if poor beam spot quality is an issue.
- **This may have broad implications for the success of many different magneto-inertial fusion ideas, as it validates key principles**
  - Measured BR=0.4 MG-cm close to saturation level of BR>0.5 MG-cm
  - Measured yield remarkable for a 70 km/s implosion—not possible unless magnetization is suppressing at least some electron heat loss

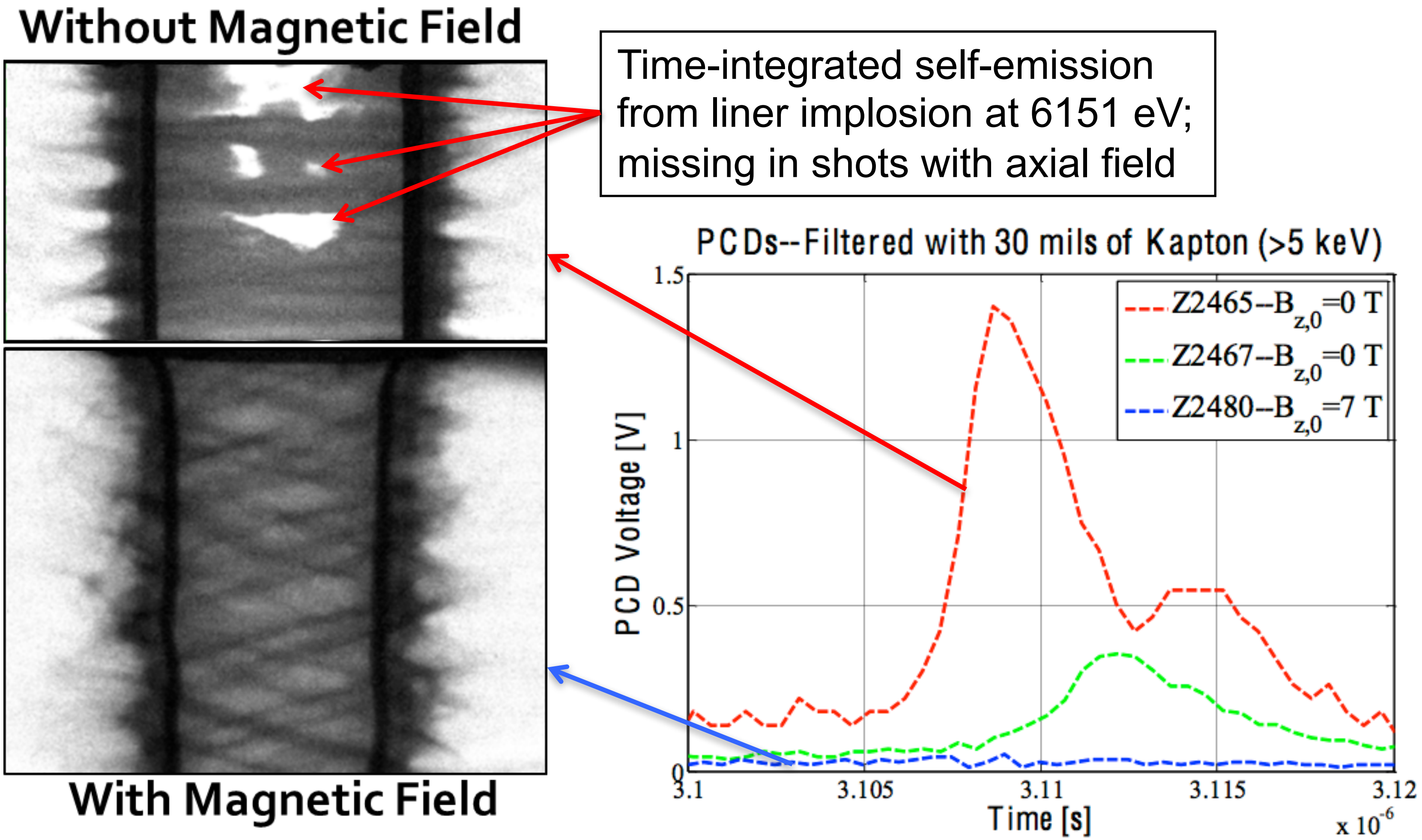
Example fully-integrated HYDRA calculations of near-term Z experiments (19 MA, 10 T, 2 kJ) illustrate the stages of a MagLIF implosion

time (~50 ns!!)



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

Adding an axial magnetic field has noticeable impacts: It reduces hard x rays and hot spots, and fundamentally changes the liner implosion instabilities & compression



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

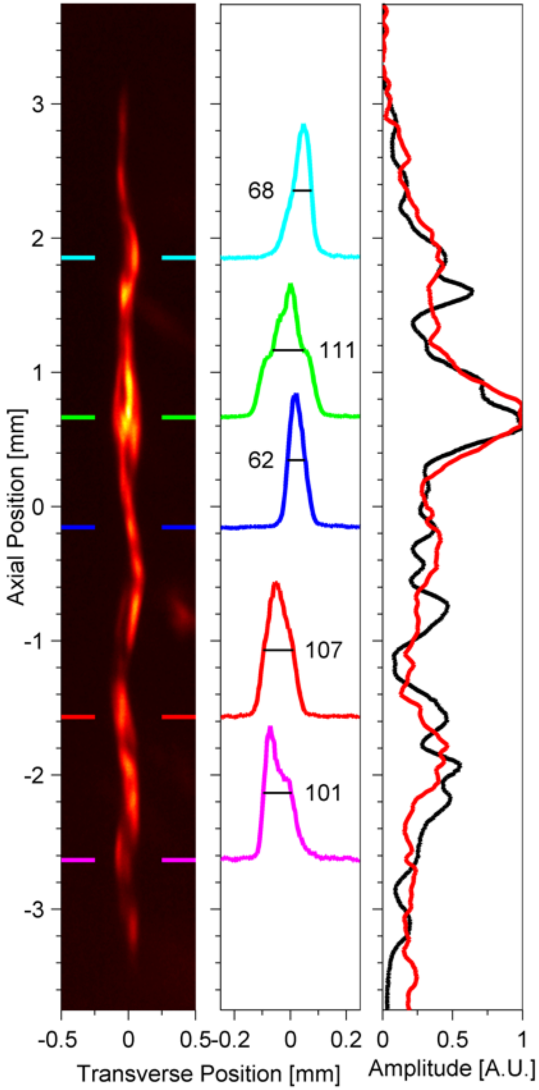
If magnetic flux roughly conserved the additional magnetic pressure from the axial field will suppress micro-pinching—this is indirect evidence for flux compression

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

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

Sandia National Laboratories

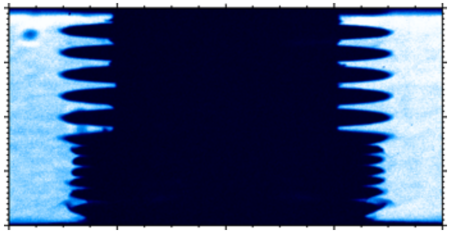
- Lineouts of stagnation column vary from 60 to 120 μm FWHM (resolution about 60 μm)
- Emission is observed from about 6 mm of the 7.5 mm axial extent
- Note that the emission doesn't necessarily define the fuel-liner boundary, but only the hot fuel region
- The stagnation column is weakly helical with 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 >9 keV small).



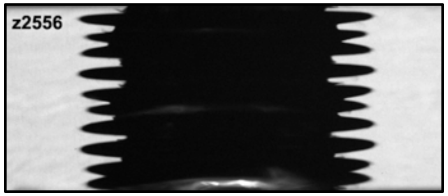
M.R. Gomez *et al.*, Phys. Rev. Lett. (2014); S.B. Hansen *et al.*, Phys. Plasmas (2015).

We have built up a collection of implosion data for testing and validating 2D and 3D magneto-hydrodynamics codes, but we are struggling to keep up with the modeling effort

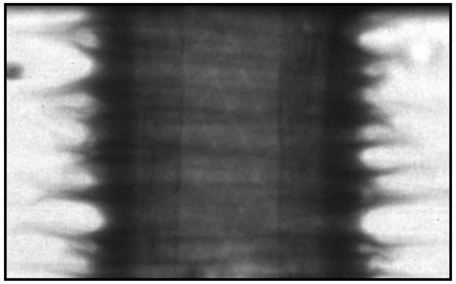
Single-mode magneto-Rayleigh-Taylor growth*



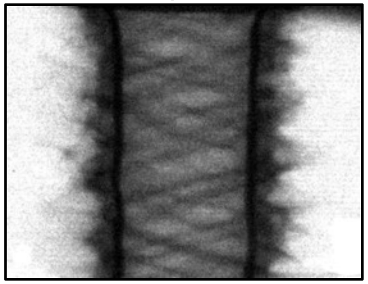
Multi-mode MRT growth

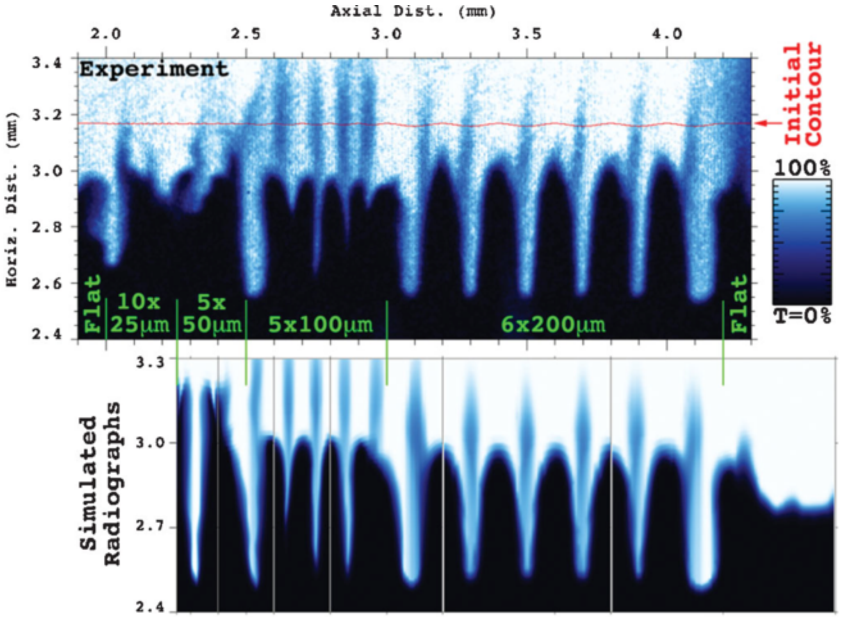


Helically perturbed growth



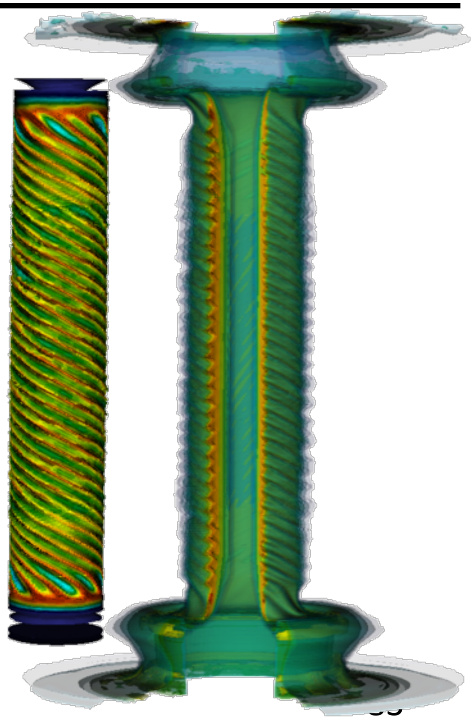
Magnetized MRT growth**





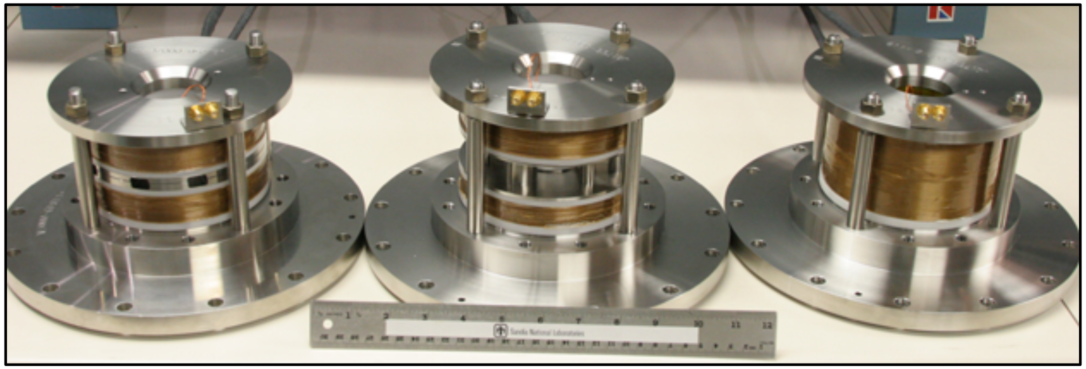
High-resolution 2D modeling can capture early growth down to the ~50-micron scale

Complex HYDRA (or HYDRA+LSP) simulations can capture details but more modeling work is needed

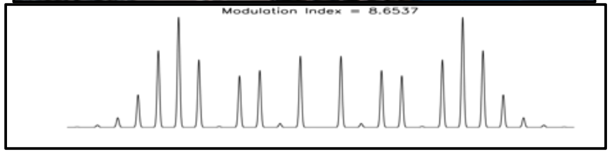


*D.B. Sinars *et al.*, Phys. Rev. Lett. (2010).; ** T.J. Awe *et al.*, Phys. Rev. Lett. (2013).

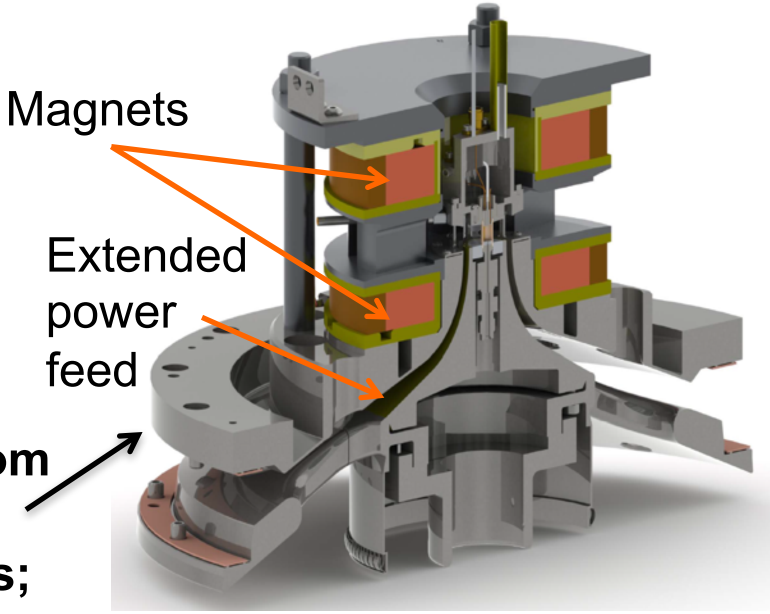
To meet our 5-year goal of demonstrating P-tau>5 Gbar-ns and BR>0.5 MG-cm in a continuous cylindrical plasma, we are working to increase the available drive conditions.



Increase B-field from 10 T to 30 T

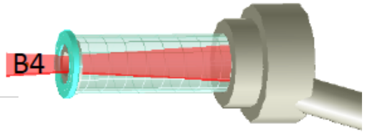


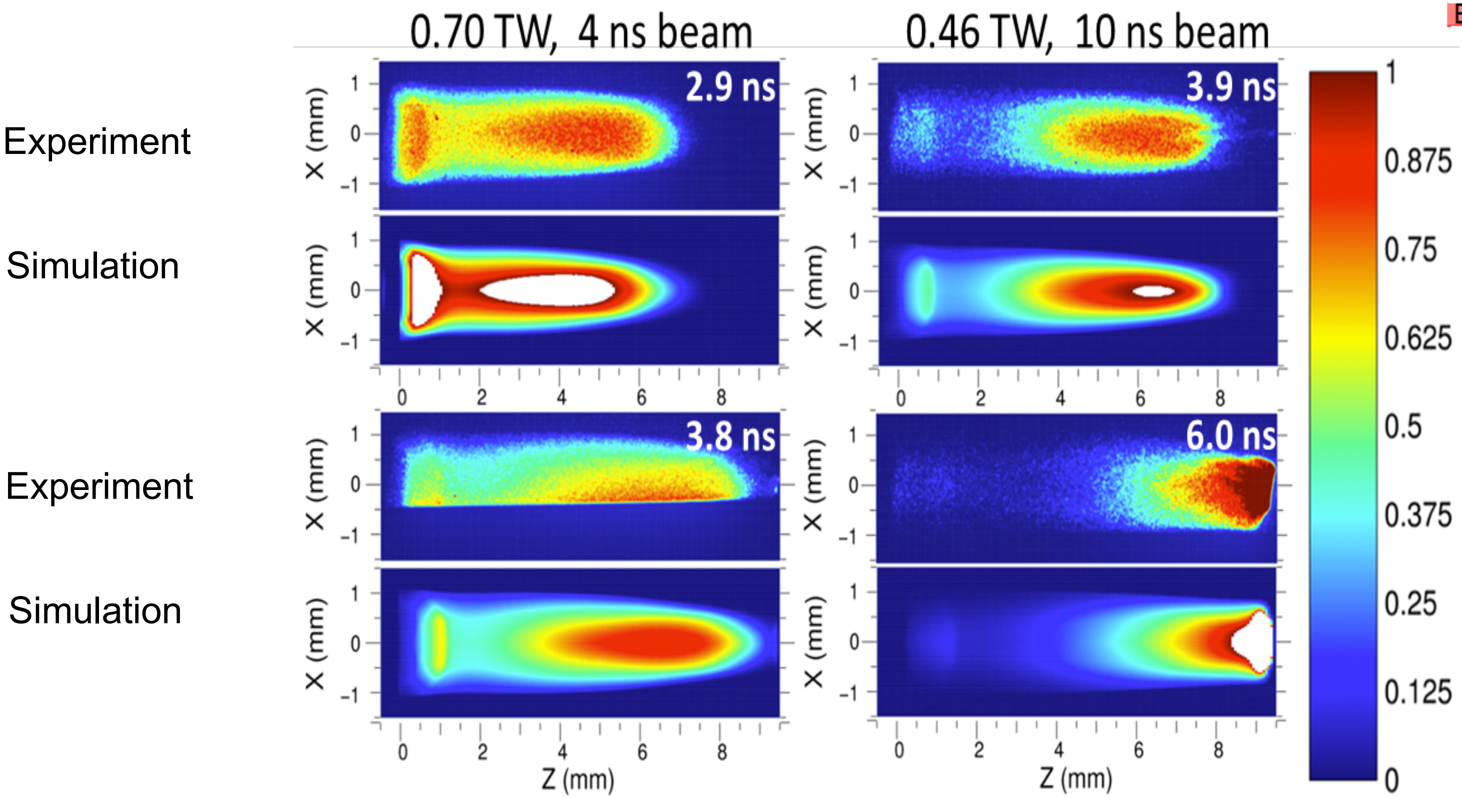
Increase laser energy from 2 kJ to 6-10 kJ; Install phase plates



Increase current from 19 MA to ~25 MA (Z facility upgrades; load hardware optimization)

OMEGA-EP experiments are providing key data at 3ω that cannot be obtained with ZBL

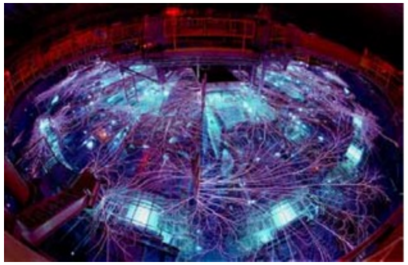




Harvey-Thompson *et al.*, Recently submitted for publication

We are currently exploring target designs and pulsed power architectures that may be on the path to 0.5-1 GJ yields and that also meet the needs of the science campaigns

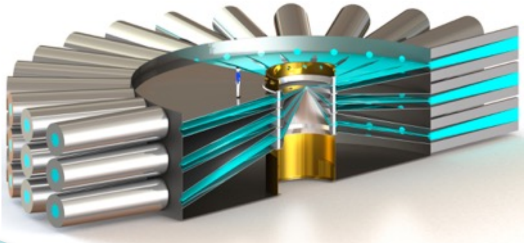
Yield = E_{fuel}?
(~100kJ$_{DT\ eq}$)
Physics Basis for Z300



Z

- 80 TW
- 33 Meter diameter
- 26 MA
- 22 MJ Stored Energy

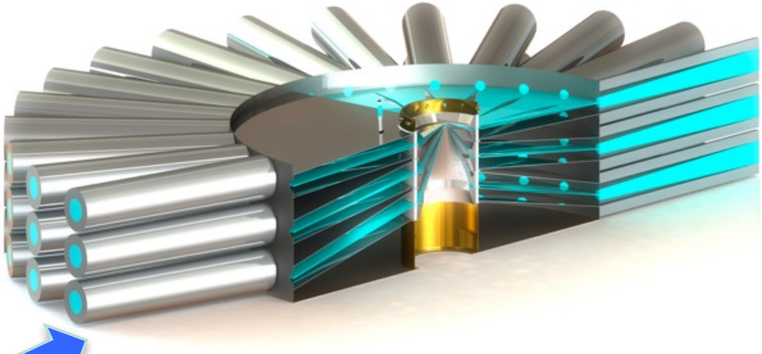
Yield = Etarget?
(About 3-4 MJ)
α-dominated plasmas



"Z300"

- 300 TW
- 35 Meter diameter
- 47 MA
- 47 MJ Stored Energy

Fusion Yield 0.5-1 GJ?
Burning plasmas



"Z800"

- 800 TW
- 52 Meter diameter
- 61 MA
- 130 MJ Stored Energy