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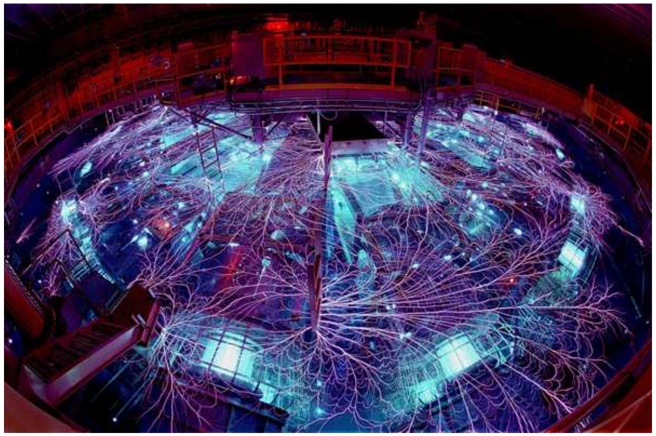

Progress on Magnetically Driven Implosions for Inertial Confinement Fusion at Sandia

Daniel B. Sinars, 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.C. Herrmann, M.H. Hess, C.A. Jennings, B. Jones, M. Jones, R.J. Kaye, P.F. Knapp, D.C. Lamppa, M.R. Lopez, M.R. Martin, R.D. McBride, L.A. McPherson, J.S. Lash, 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, S.A. Slutz, I.C. Smith, W.A. Stygar, R.A. Vesey, E.P. Yu, B.E. Blue*, D.G. Schroen*, K. Tomlinson*

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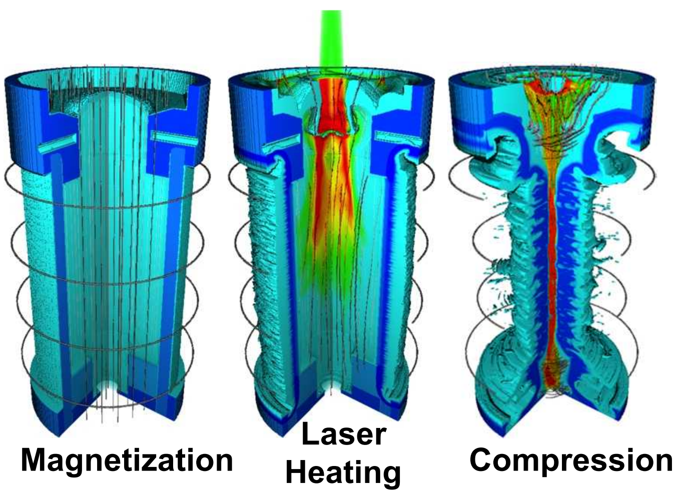
** General Atomics, San Diego, CA 92186 USA*



U.S. DEPARTMENT OF ENERGY

NNSA National Nuclear Security Administration

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We obtained promising initial results in our first magneto-inertial fusion experiments on the 26 MA Z pulsed power facility at Sandia

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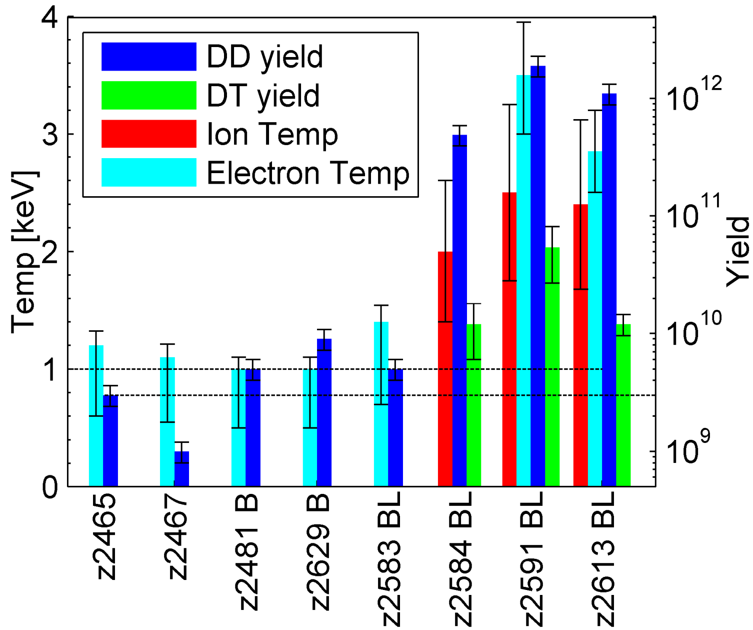
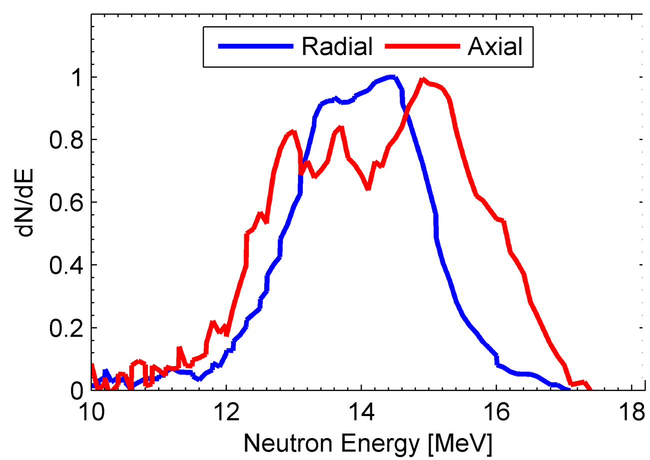
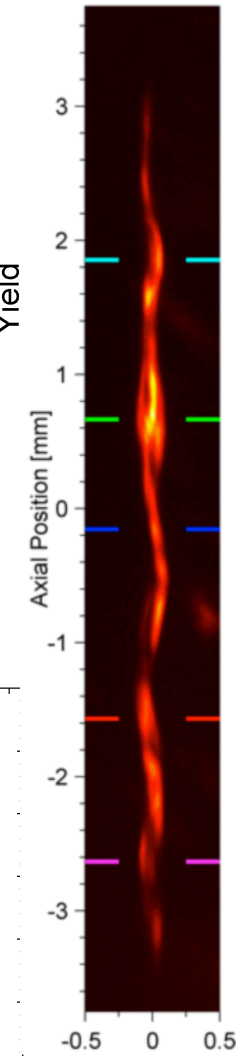
- We achieved DD yields up to 2e12 (~0.3 kJ DT equivalent) in our first integrated tests of Magnetized Liner Inertial Fusion (MagLIF)
- A variety of data were collected that appear to show a <150 μm diameter, ~3 keV, highly magnetized plasma was produced—remarkable for a 70-100 km/s implosion!
- We are continuing to build on these results with a balanced combination of focused and integrated experiments
- In parallel we are improving capabilities to understand how this performance will scale with increasing drive parameters







The Sandia Z pulsed power facility uses magnetic pressure to efficiently couple energy to imploding liner targets

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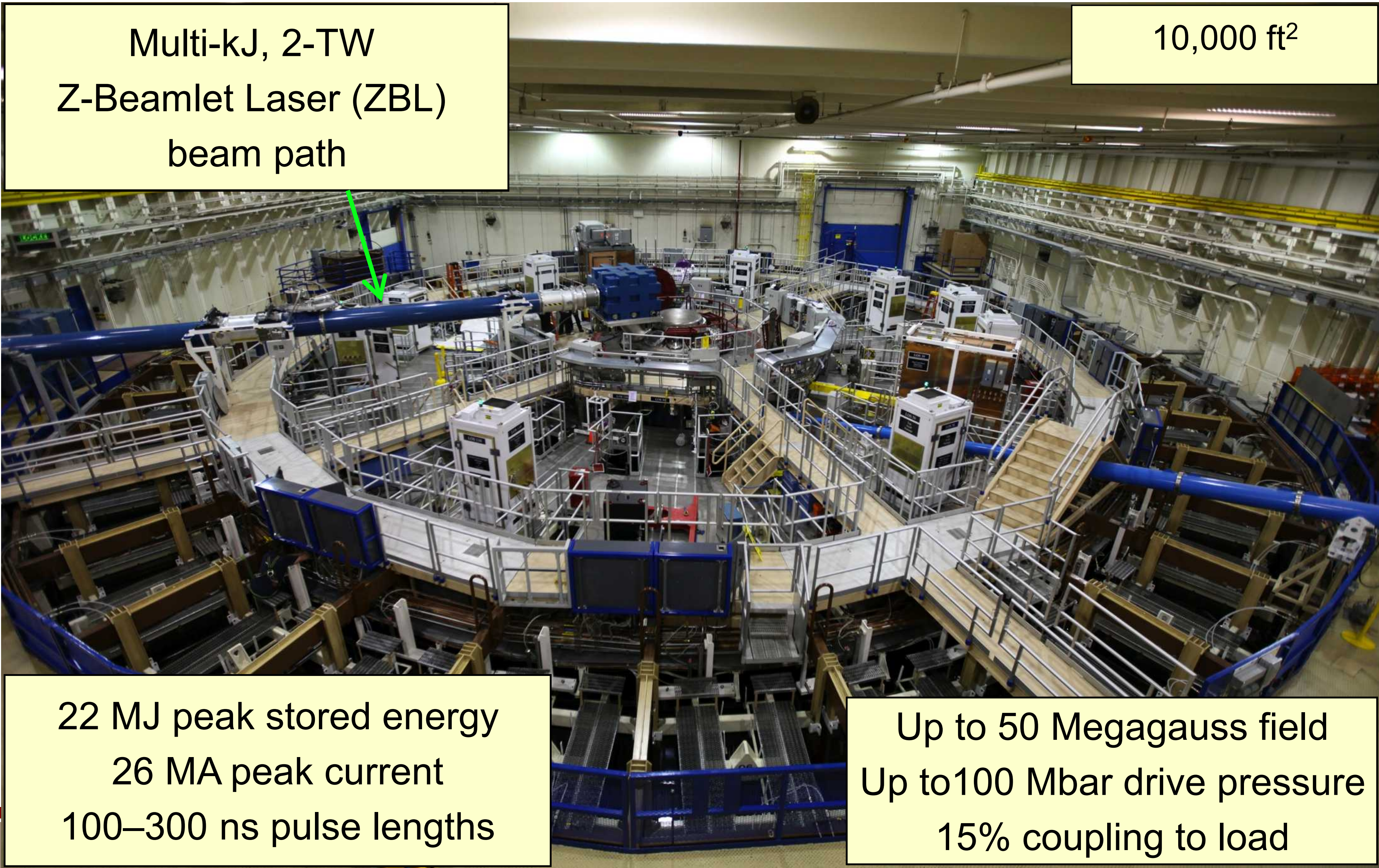
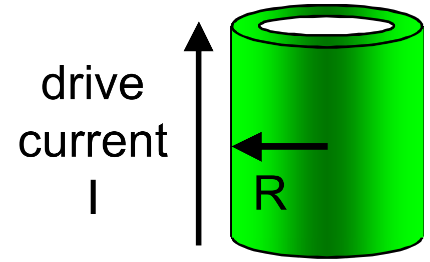


Magnetically driven implosions may be a compelling path to significant fusion yields (>10s MJ), but a lot of work is needed to show that this is credible

- Magnetic fields created by pulsed power can create the large drive pressures (high energy density) needed for fusion
- Approach is fundamentally different than laser-driven target compression with unique physics, risks, and benefits
- Magnetic fields can also make laboratory fusion easier, e.g., strong fields can affect charged particles (electrons, alphas) and thus plasma heat transport and confinement properties

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

- Magnetically-driven targets driven by pulsed power drivers are energy efficient and could be a practical and cost-effective path to achieving significant fusion yields (>10s MJ). Z today couples ~0.5 MJ out of 20 MJ stored to MagLIF target (0.1 MJ in DD fuel).

The presence of a magnetic field can strongly affect transport properties, e.g. electron heat conduction

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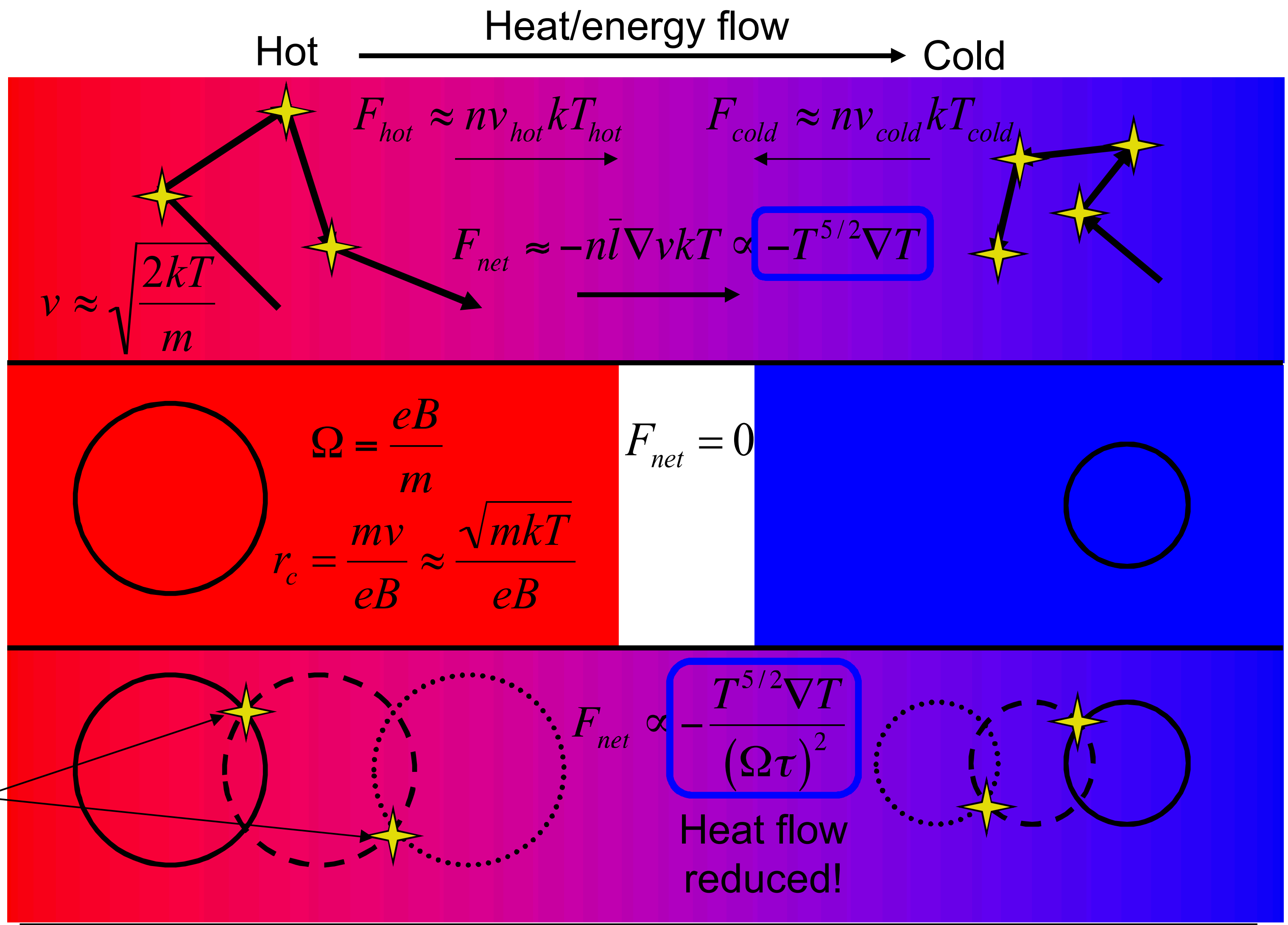
Collisional no B

Strong B (perpendicular to this slide) No collisions

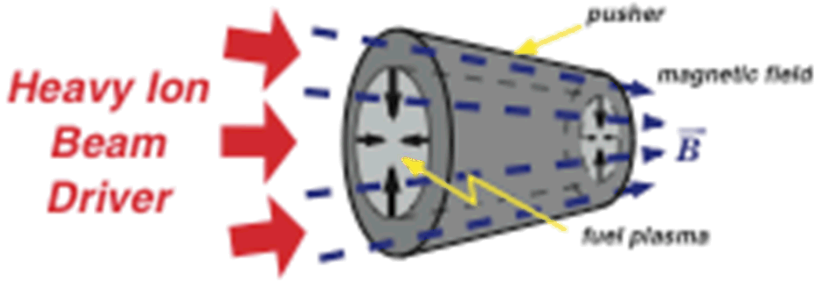
Strong B with collisions



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

Many groups want to use magnetic fields to relax inertial fusion stagnation requirements

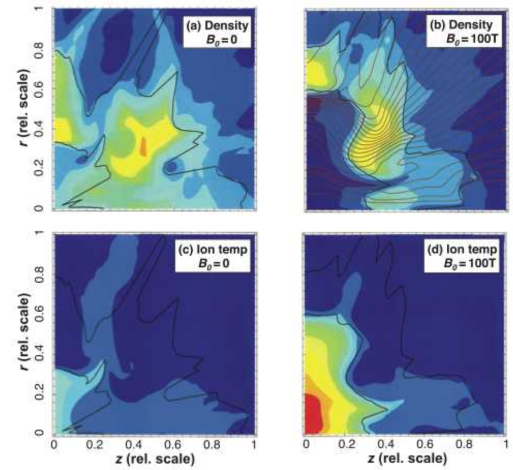
Max Planck/ITEP



Basko, Kemp, Meyer-ter-Vehn, *Nucl. Fusion* **40**, 59 (2000)
Kemp, Basko, Meyer-ter-Vehn, *Nucl. Fusion* **43**, 16 (2003)

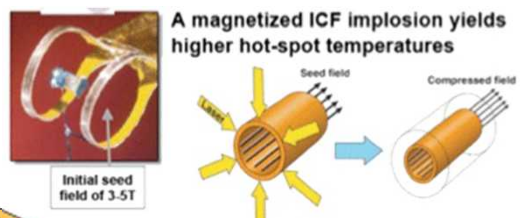
LLNL

(Perkins et al., Phys Plasmas 2013)

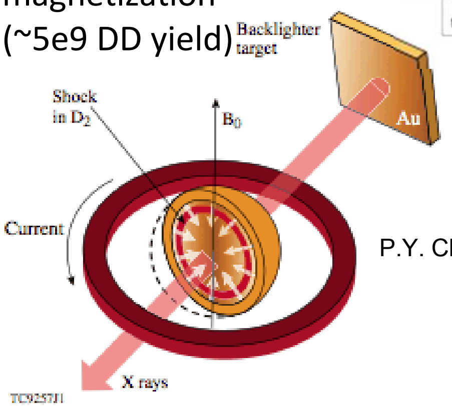


University of Rochester/LLE

2011 Demonstration of enhanced fusion yield with magnetization (~5e9 DD yield)



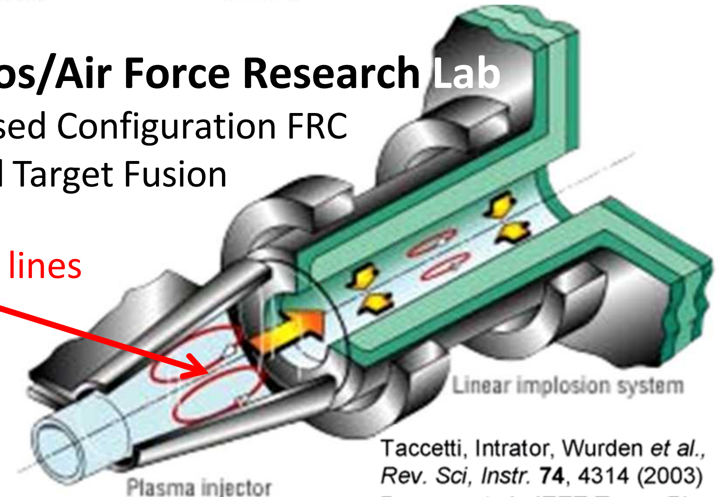
Gotchev *et al.*, *Rev. Sci. Instr.* **80**, 043504 (2009)



P.Y. Chang *et al.*, PRL (2011).

Los Alamos/Air Force Research Lab

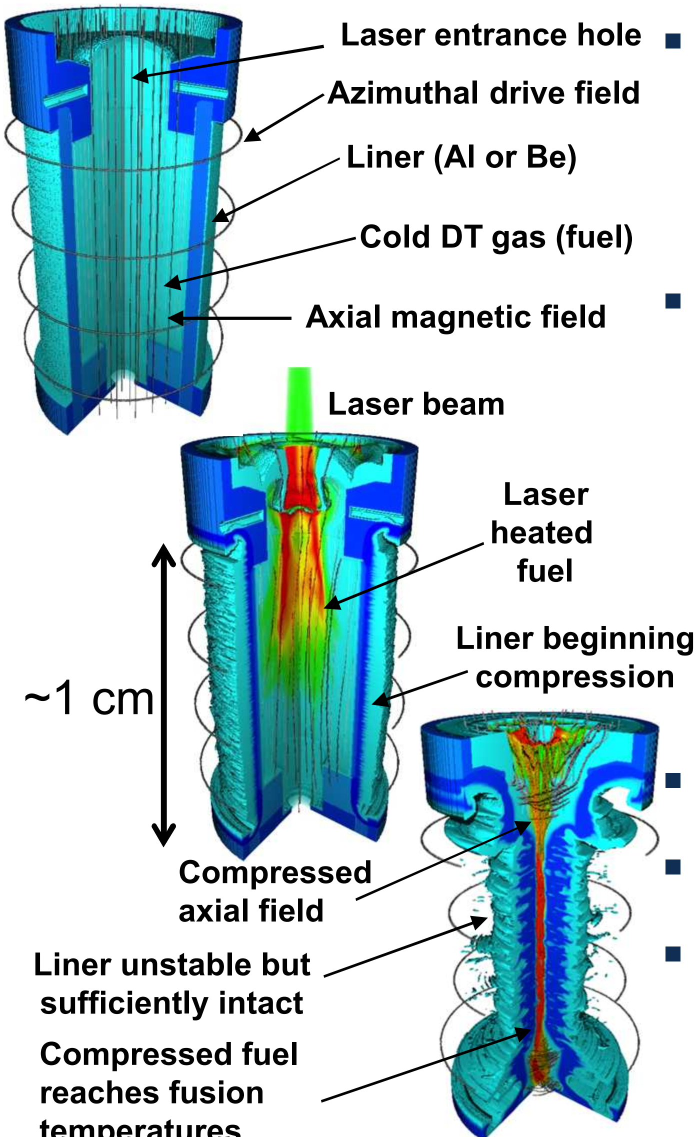
Field Reversed Configuration FRC
Magnetized Target Fusion
Shiva Star
closed field lines
FRC



Taccetti, Intrator, Wurden *et al.*, *Rev. Sci, Instr.* **74**, 4314 (2003)
Degnan *et al.*, *IEEE Trans. Plas. Sci.* **36**, 80 (2008)

and many others…

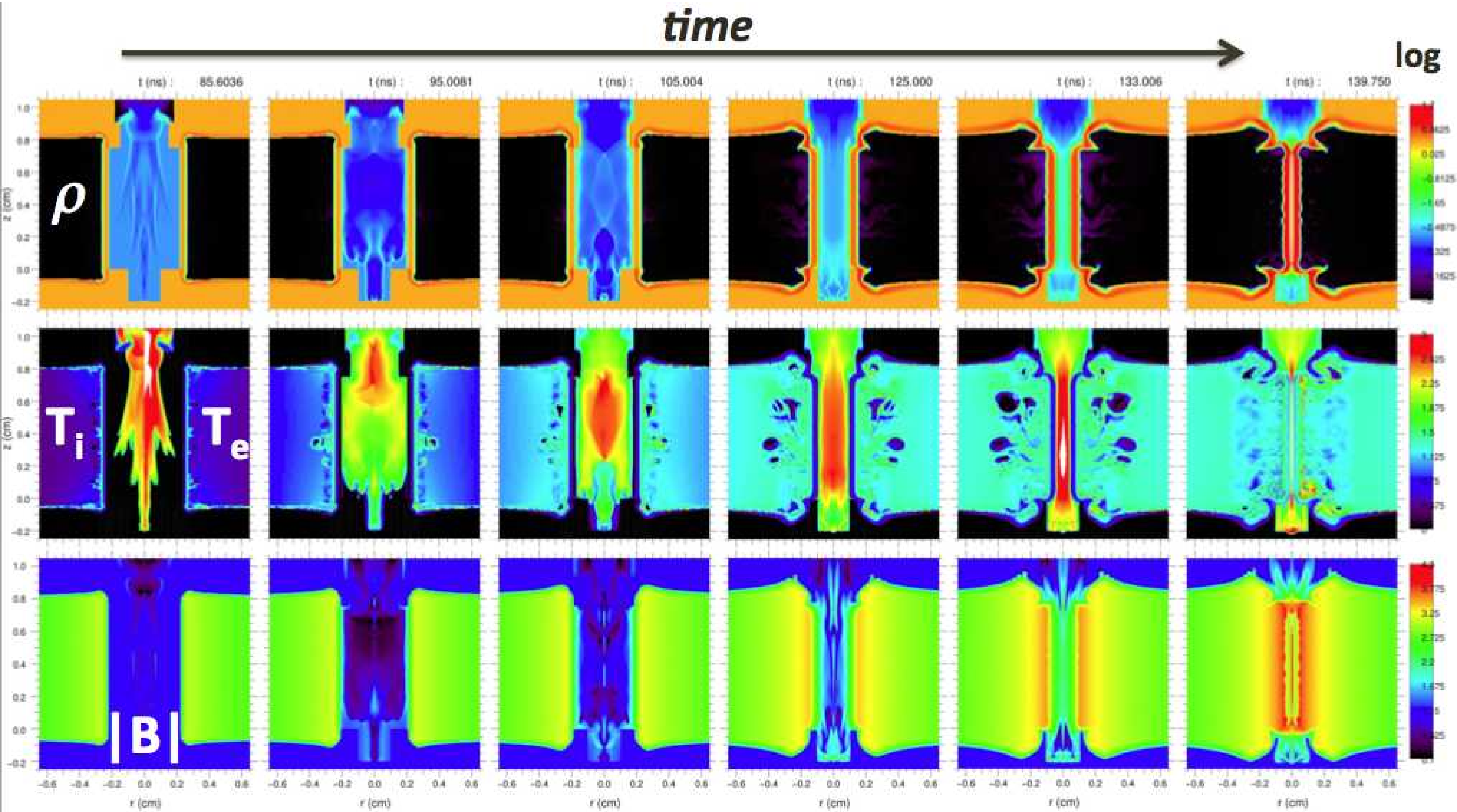
We are evaluating a Magnetized Liner Inertial Fusion (MagLIF)* concept that may reduce fusion requirements



- An initial 30 T axial magnetic field is applied
  - Inhibits thermal conduction losses
  - Appears to stabilize implosion at late times
- During the ~100 ns implosion, the fuel is heated using the Z-Beamlet laser (about 6 kJ in designs)
  - Preheating to ~300 eV reduces the compression needed to obtain fusion temperatures to 23 on Z
  - Preheating reduces the implosion velocity needed to ~100 km/s, allowing us to use thick liners that are more robust against instabilities
- ~50-250 kJ energy in fuel; 0.2-1.4% of capacitor bank
- Stagnation pressure required is ~5 Gbar
- DD equivalent of 100 kJ DT yield may be possible on Z in the next few years—this will require enhanced drive upgrades that are in progress, e.g., 10 T → 30 T; 2 kJ → >6 kJ; 19 MA → >24 MA

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

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



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

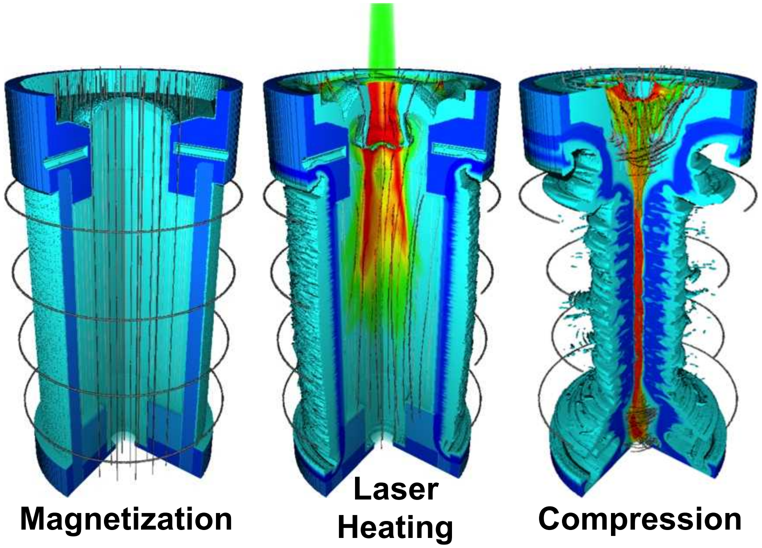
Comparison of 1D and 2D HYDRA calculations of near-term Z experiments (19 MA, 10 T, 2 kJ)

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

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

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

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



- Key target design elements
  - Liner compression
  - Magnetization
  - Laser heating

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

Experiments to address the key physics are planned for the Z pulsed power facility and the Z-Beamlet and Omega (and Omega-EP) lasers.

Prior to the integrated experiments, a series of focused experiments were conducted to develop and test the critical components of MagLIF

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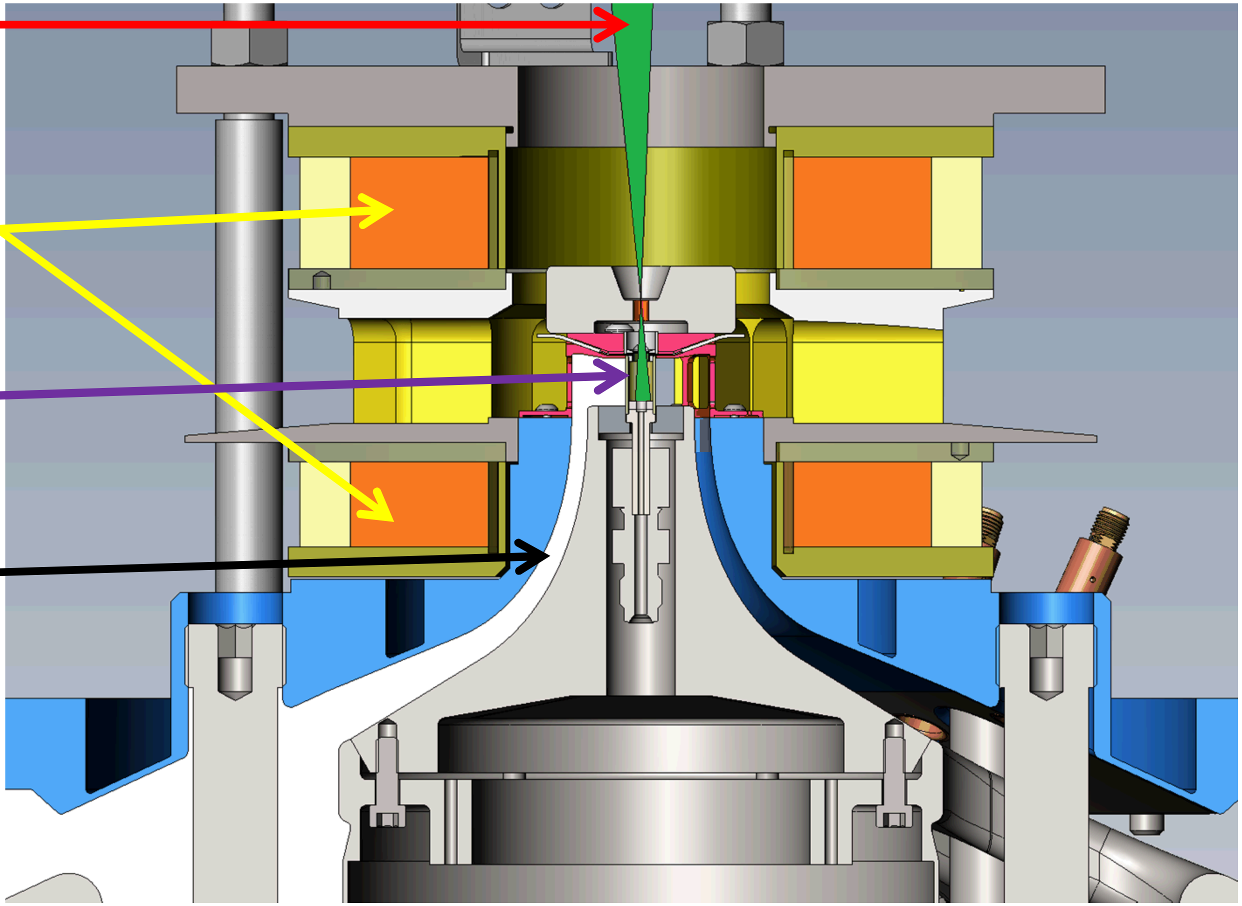
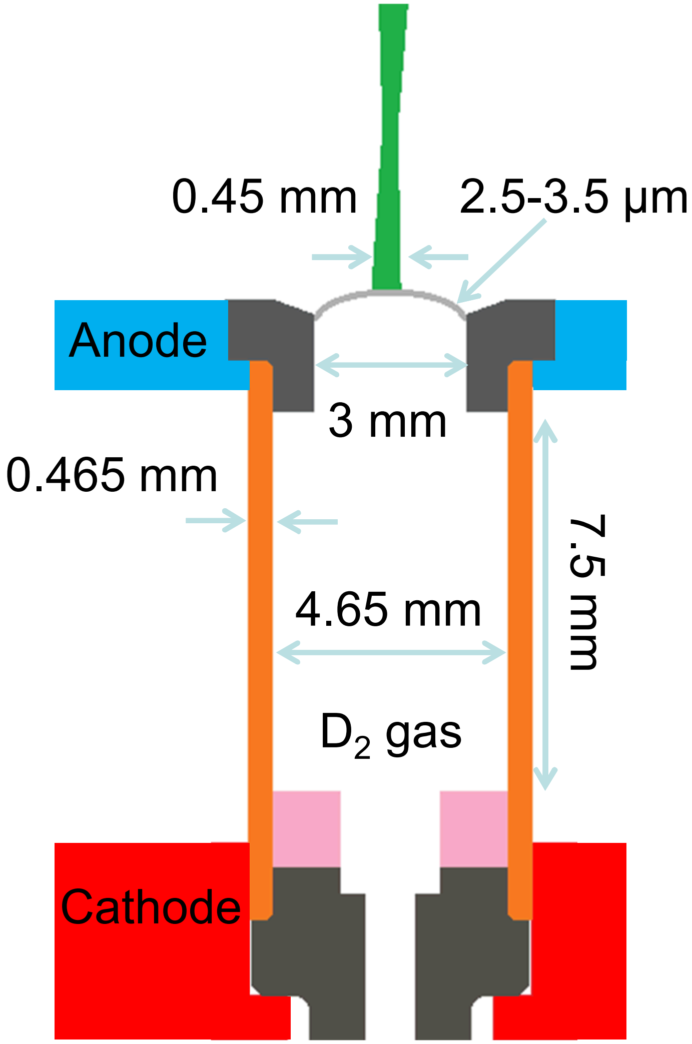
- Laser preheat
  - >10 laser-only experiments
- Applied magnetic field
  - >10 experiments
- Liner Stability
  - >40 experiments
- Modified power flow
  - Geometry scan to minimize losses
  - >20 experiments
- Fully integrated shots
  - 5 Z + ZBL shots



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

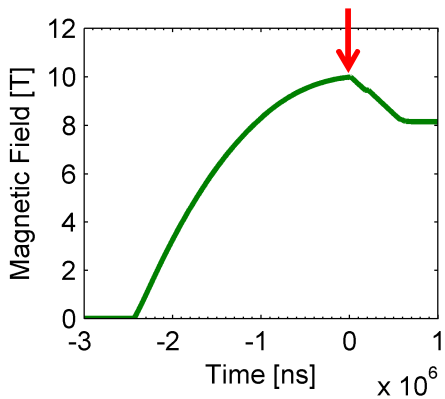
- **Beryllium liner with ΔR/R = 6**
  - **Thick liner is more robust to instabilities**
  - **Still allows diagnostic access > 5 keV**
- **Top and bottom implosion cushions**
  - **Mitigates wall instability**
- **Standoff between LEH and imploding region**
  - **Avoid window material mixing with fuel**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



M.R. Gomez, S.A. Slutz, A.B. Sefkow *et al.*, submitted to Physical Review Letters (2014).

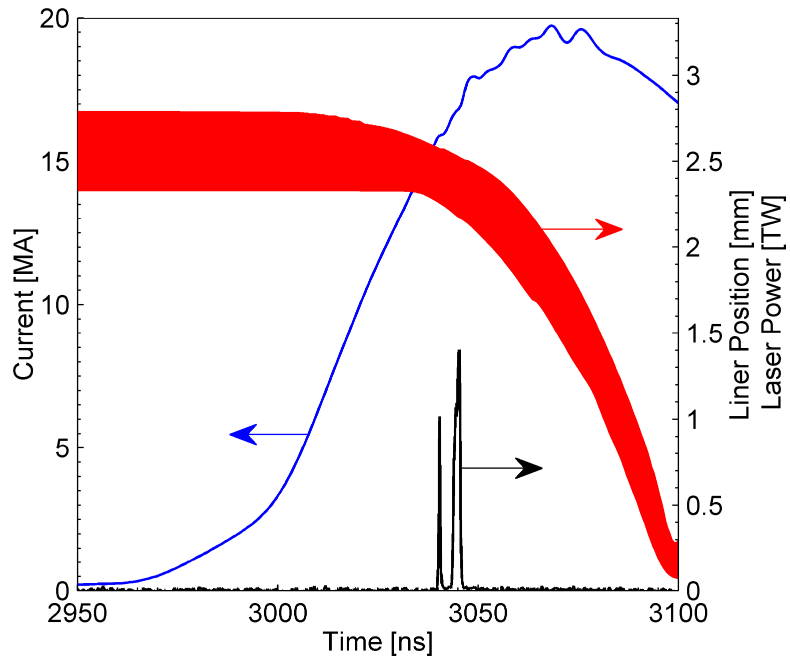
Initial experiments were conducted on Z at I = 19 MA, B = 10 T, and Laser = 2.5 kJ

Time of experiment



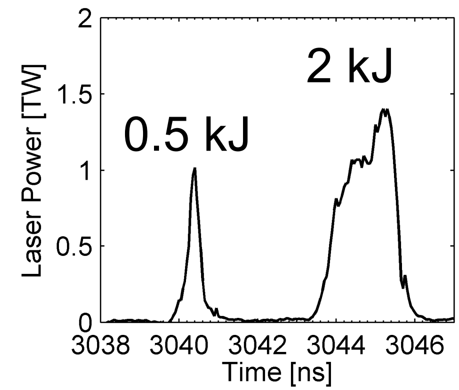
Magnetic field risetime is approximately 2 ms

B is constant over the timescale of the experiment

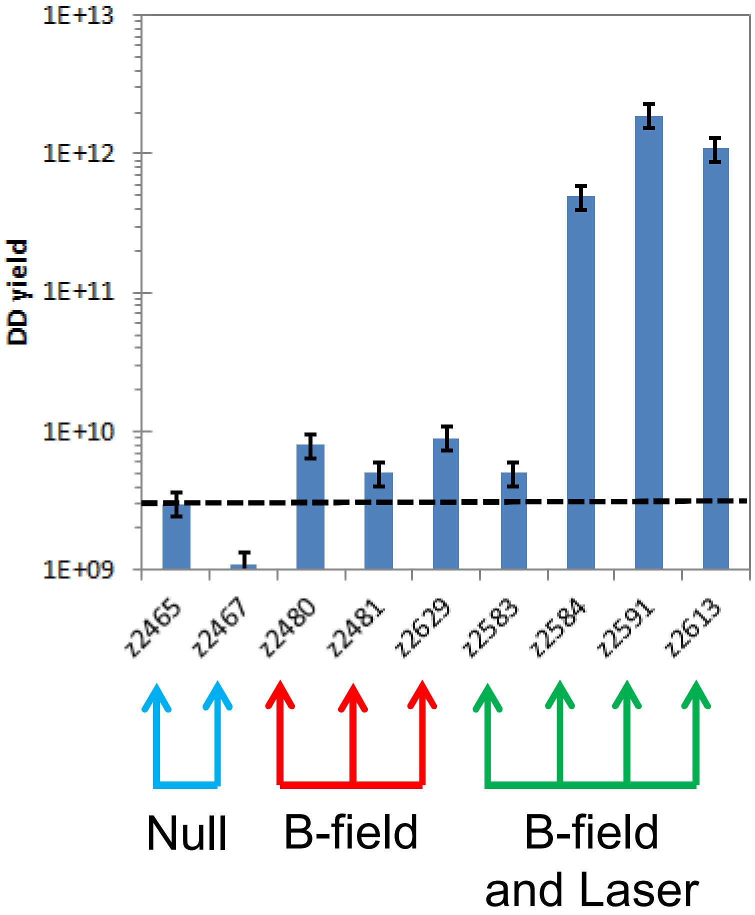


Peak current is 19 MA
Magnetic field is 10 T
Total laser energy is 2.5 kJ

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



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

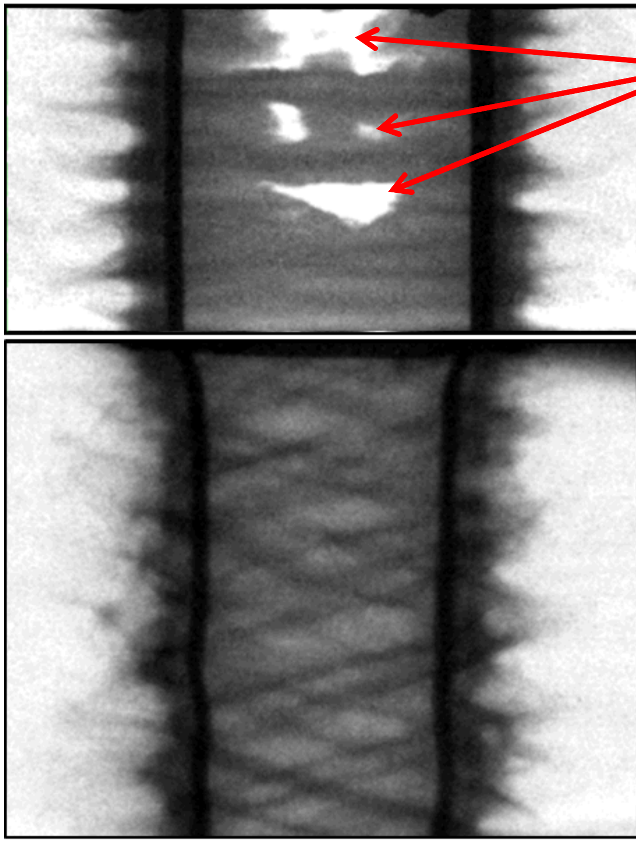


- **High yields were only observed on experiments incorporating both applied magnetic field and laser heating**
- **A series of experiments without laser and/or B-field produced yields at the background level of the measurement**
- **Result of z2583 is not well understood nor reproduced at this time (used higher fill density)**

M.R. Gomez, S.A. Slutz, A.B. Sefkow *et al.*, submitted to Physical Review Letters (2014).

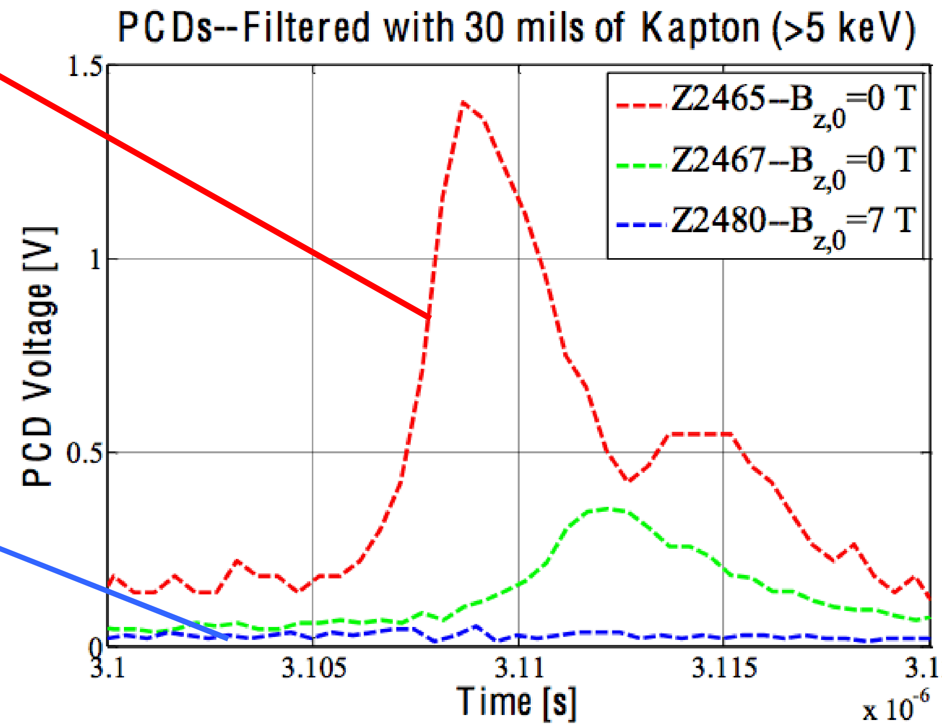
Adding an axial magnetic field changes the liner instability structure from cylindrical to helical and reduces hard x rays and hot spots, suggestive of improved stability

Without Magnetic Field



With Magnetic Field

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



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

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

A narrow (<2 ns FWHM) peak is seen on PCD and Si Diode signals when laser heating is added a magnetized liner target. Timing is consistent with NTOF bang time estimate

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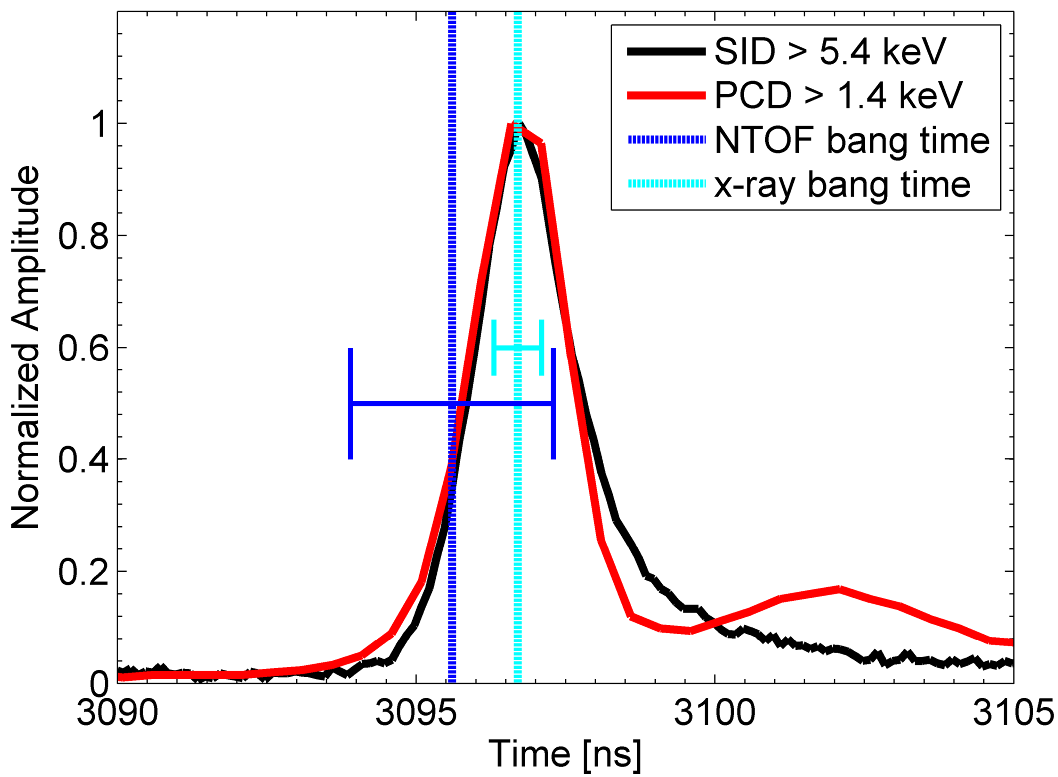
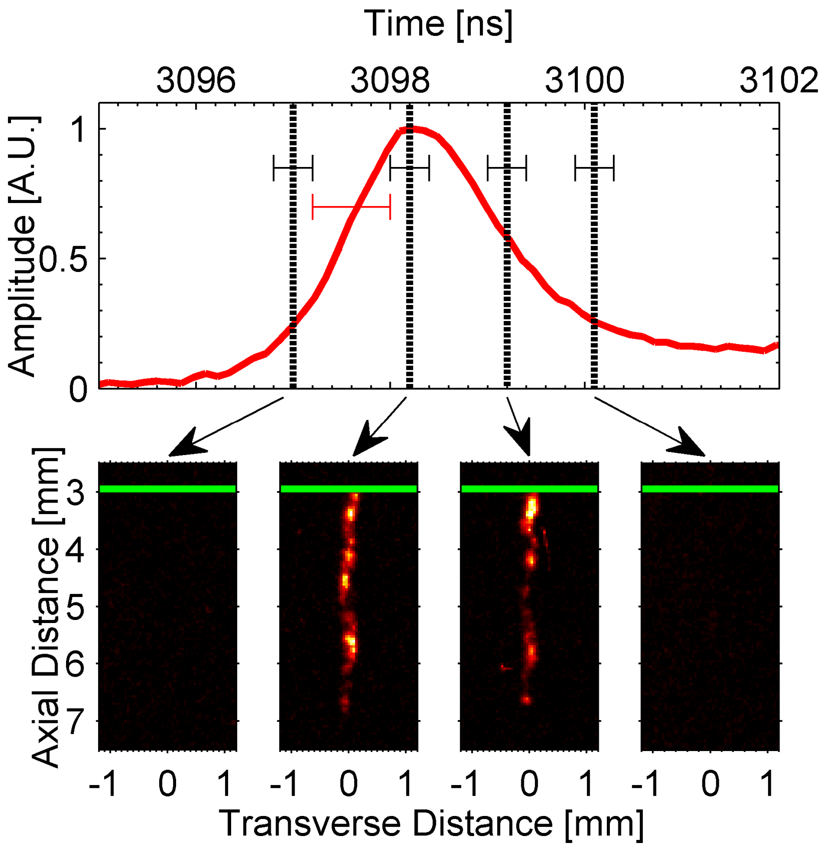


- **Narrow x-ray signature only observed on experiments with significant neutron yield**
- **X-ray burst has high energy components**
- **X-ray bang time and NTOF bang time agree within the uncertainty of the measurements**

M.R. Gomez, S.A. Slutz, A.B. Sefkow *et al.*, submitted to Physical Review Letters (2014).

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

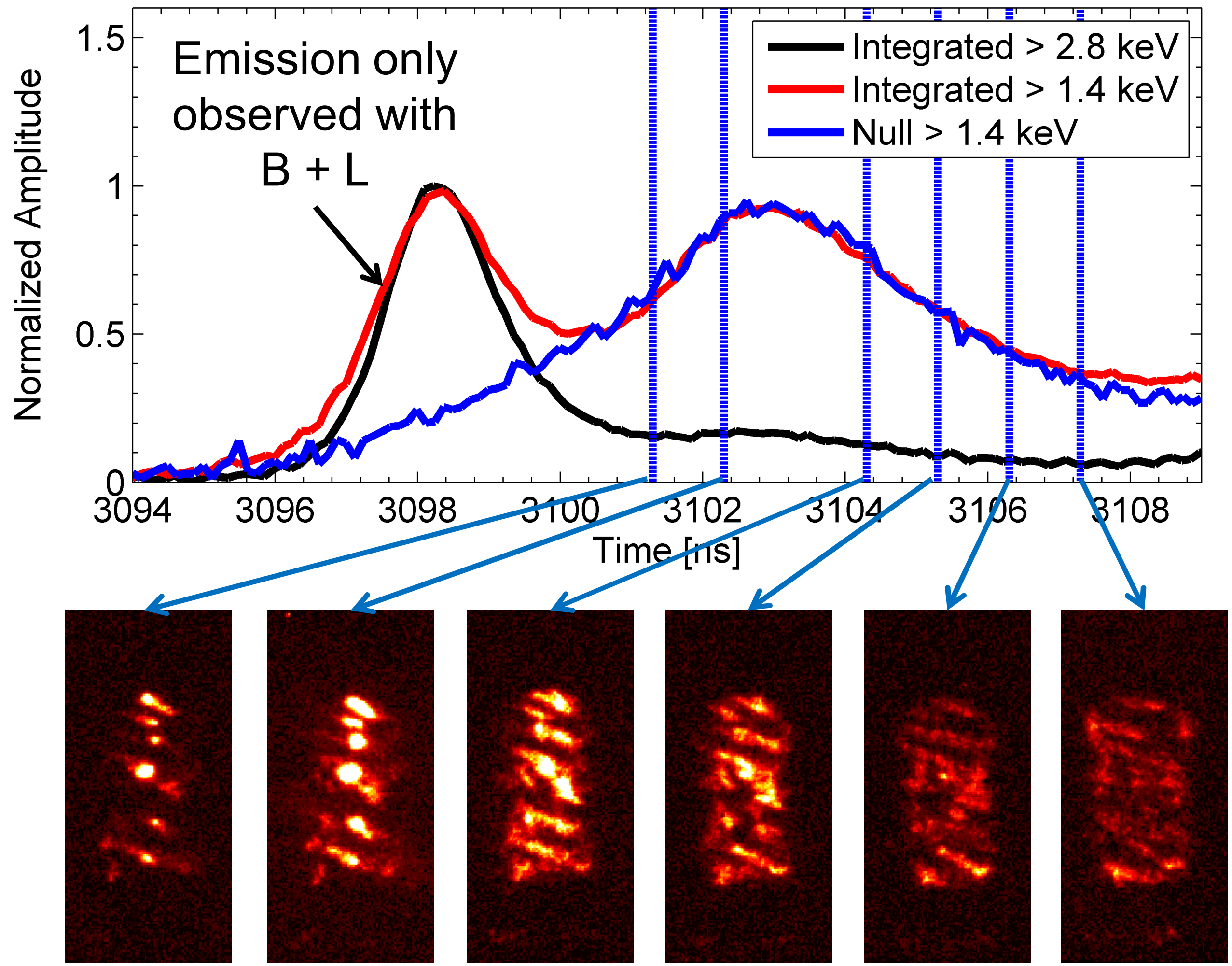


- **Emission column is observed only during the peak in the x-ray signal**
- **Emission column is only observed on experiments with high neutron yield**
- **Stagnation column width is at the resolution limit of this instrument (~150 microns)**

M.R. Gomez, S.A. Slutz, A.B. Sefkow *et al.*, submitted to Physical Review Letters (2014).

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

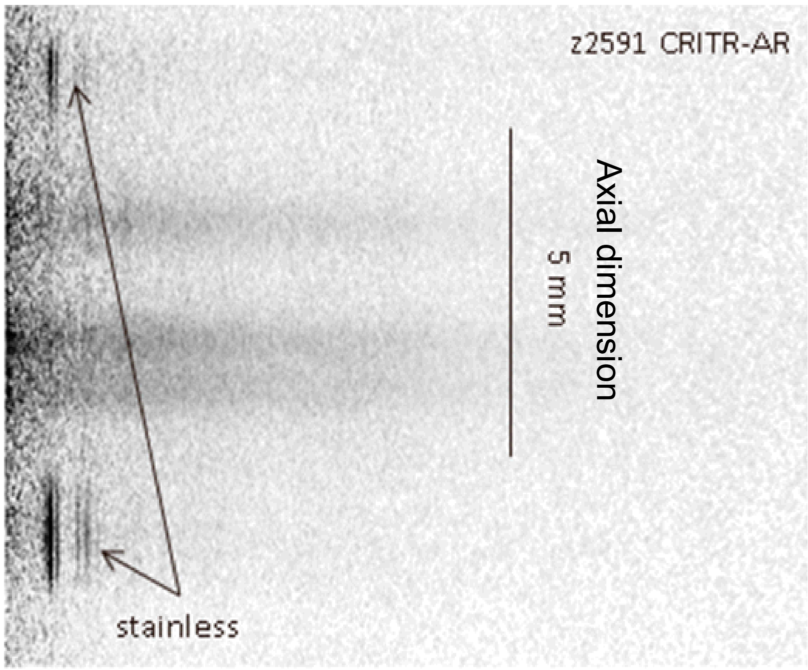
- **Liner emission is observed in all experiments**
- **Liner emission is at a lower photon energy (< 2.8 keV)**
- **Liner emission is getting larger at late times**



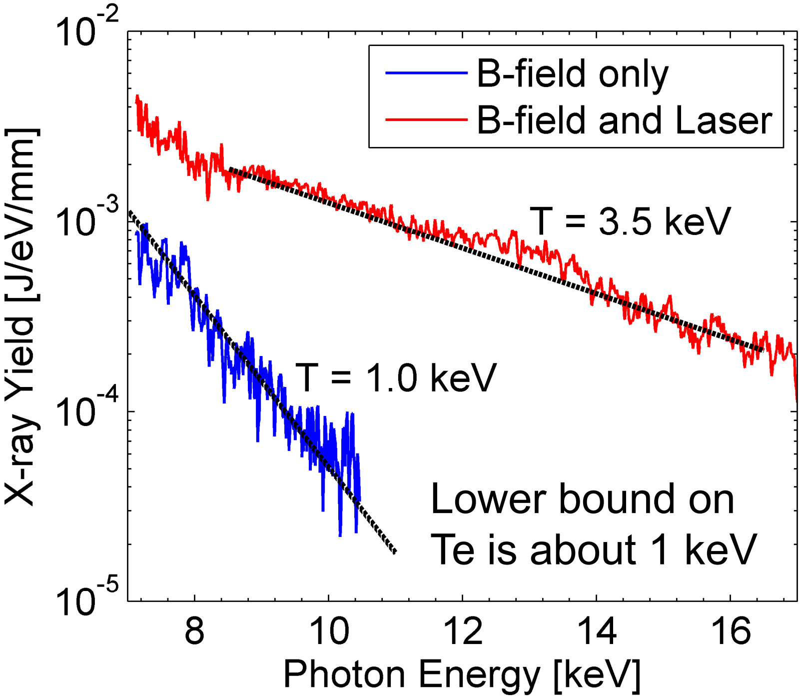
M.R. Gomez, S.A. Slutz, A.B. Sefkow *et al.*, submitted to Physical Review Letters (2014).

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

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



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



The electron temperatures measured by spectroscopy agree with the ion temperatures indicated by neutron time-of-flight data

M.R. Gomez, S.A. Slutz, A.B. Sefkow *et al.*, submitted to Physical Review Letters (2014).

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

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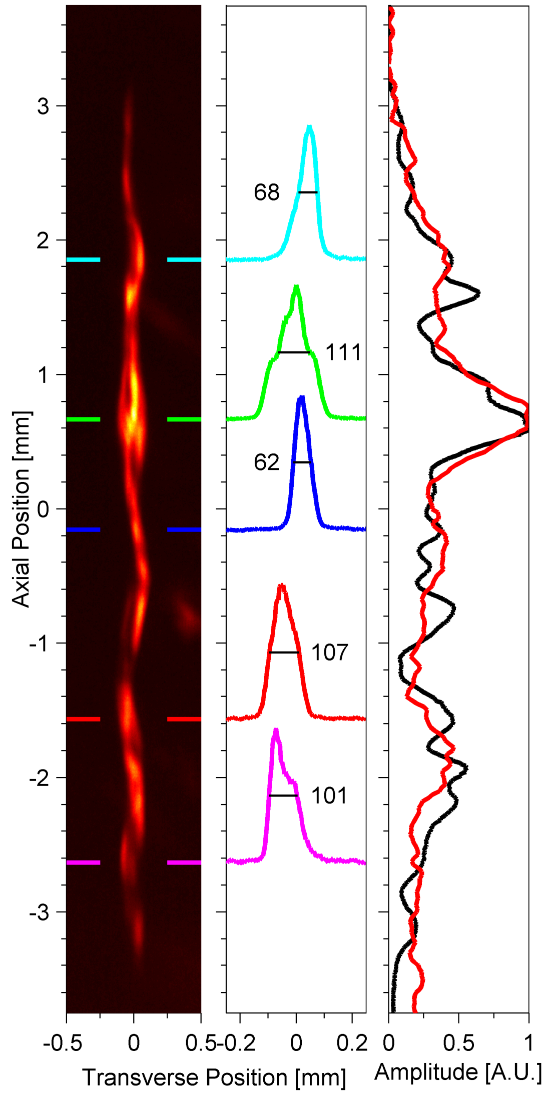
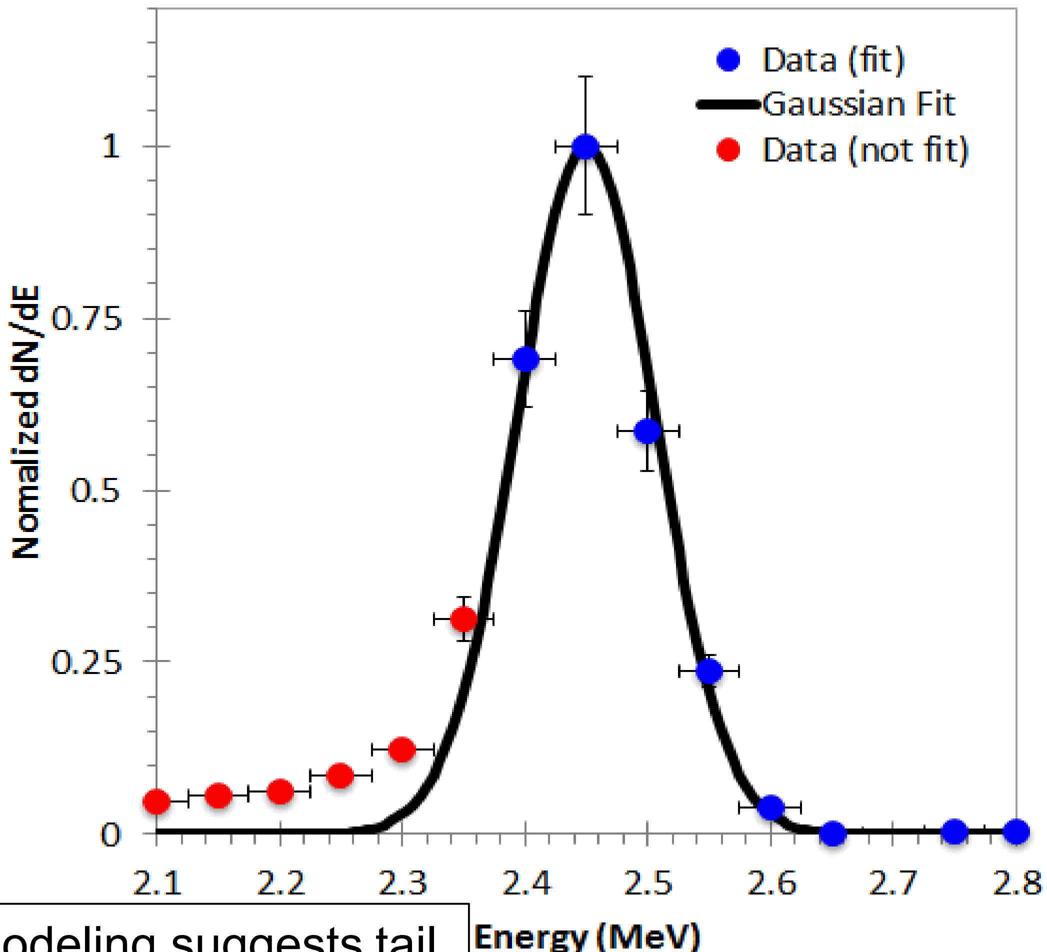
- **Lineouts of stagnation column vary from 60 to 120 μm FWHM (resolution about 60 μm)**
- **Emission is observed from about 6 mm of the 7.5 mm axial extent**
- **Note that the emission doesn't necessarily define the fuel-liner boundary, but only the hot fuel region**
- **The stagnation column is weakly helical with a wavelength of about 1.3 mm and a 0.05 mm horizontal offset**
- **We are currently investigating whether we can use 8-20 keV x-ray spectroscopy data to constrain role of Be opacity on image**



DD Neutron Time of Flight spectra indicate ion temperatures greater than 2 keV at stagnation



Modeling suggests tail due to nBe scattering from 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

M.R. Gomez, S.A. Slutz, A.B. Sefkow *et al.*, submitted to Physical Review Letters (2014).

The secondary "DT" neutrons produced by DD-fuel targets provide useful information about the plasma that is relevant for fusion

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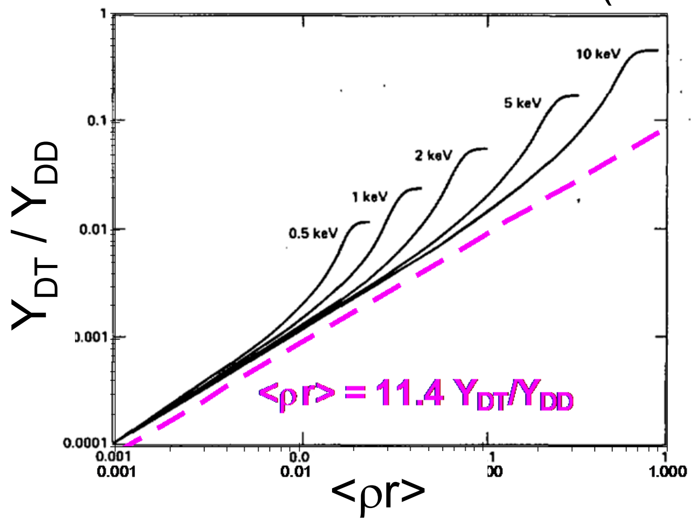
"Secondary" 14 MeV neutrons can be produced by 1 MeV tritons interacting with D fuel

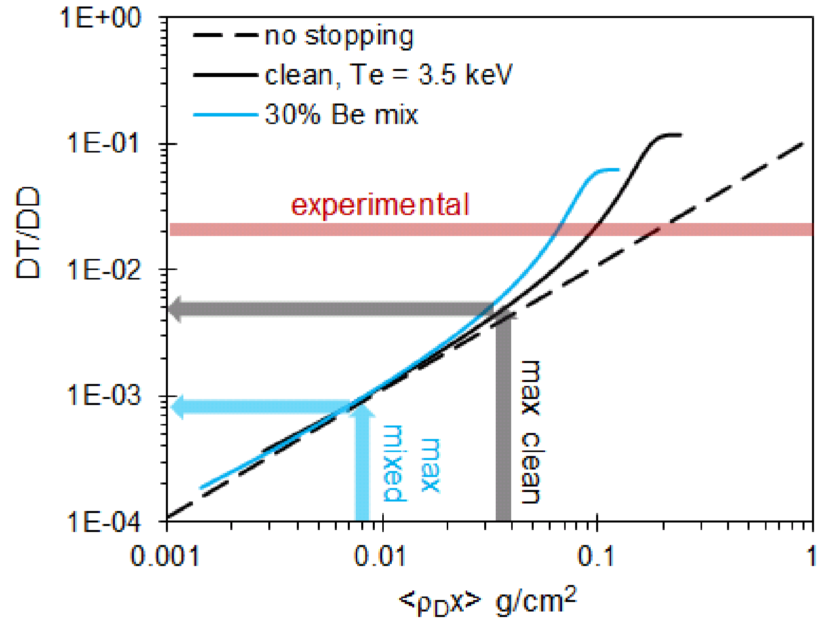
$$\mathbf{D + D} \xrightarrow{50\%} \mathbf{0.8\ MeV\ He^3 + 2.5\ MeV\ n}$$
$$\xrightarrow{50\%} \mathbf{1.0\ MeV\ T + 3.0\ MeV\ p}$$

$$\mathbf{D + T \rightarrow 3.6\ MeV\ \alpha + 14\ MeV\ n}$$

M.D. Cable and S.P. Hatchett (1987).



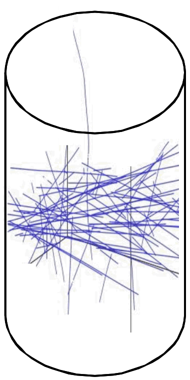
DT/DD ratio α plasma areal density—fusion probability increases through electron drag slowing of 1 MeV T

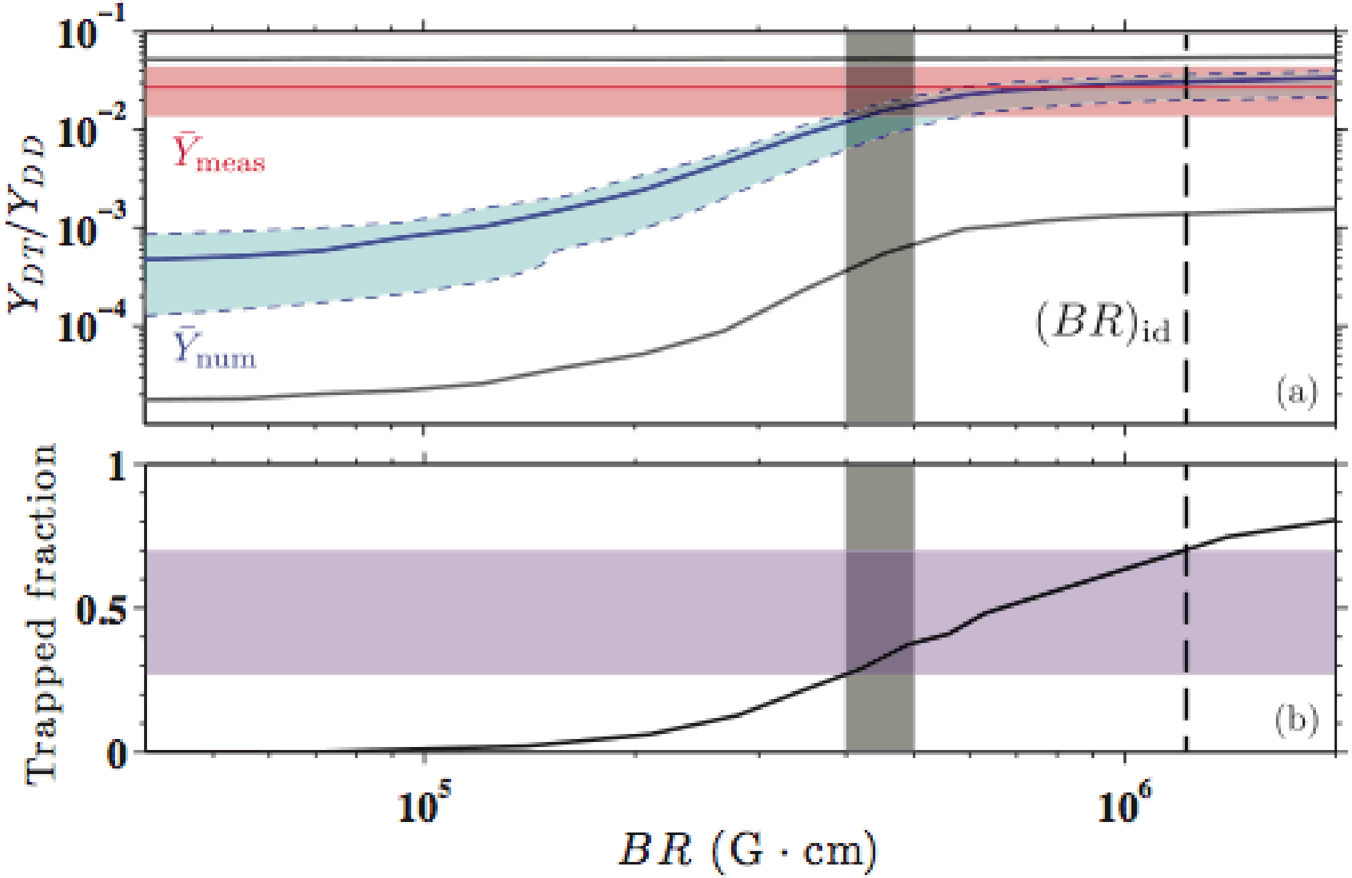


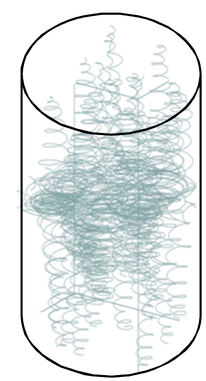
We observe a much higher yield than it is possible to achieve even with no-loss, >100x radial convergence implosions!

P.F. Schmit, P.F. Knapp *et al.*, submitted to Physical Review Letters (2014).

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







Magnetized tritons implies magnetized electrons:

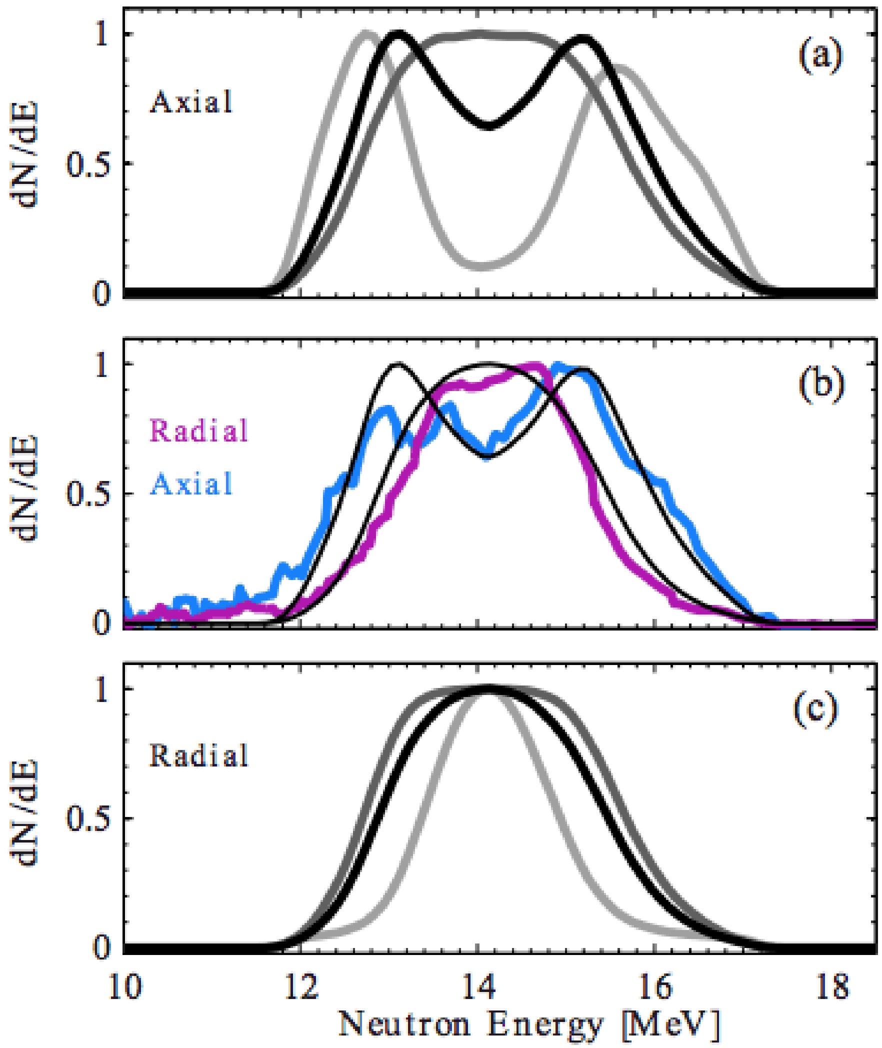
$$\omega_{ci}\tau_{ie} \approx \omega_{ce}\tau_{ee}$$

Magnetized tritons implies magnetized alpha particles:

$$r_t \approx 1.1 r_\alpha$$

P.F. Schmit, P.F. Knapp *et al.*, submitted to Physical Review Letters (2014).

Our neutron time-of-flight data are also consistent with the fusing particles being magnetized



2.5e5 G-cm
4.5e5 G-cm
7.5e5 G-cm

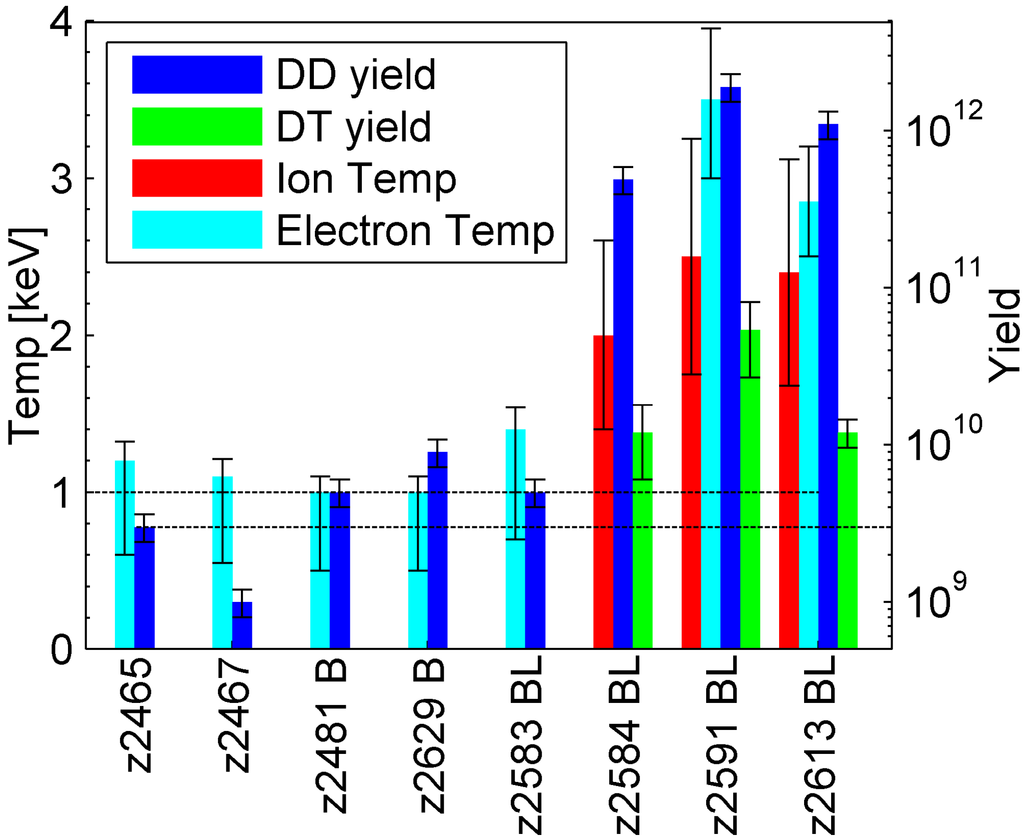
nTOF spectra consistent with ~4.5e5 G-cm

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

2.5e5 G-cm
4.5e5 G-cm
7.5e5 G-cm

P.F. Schmit, P.F. Knapp *et al.*, submitted to Physical Review Letters (2014).

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

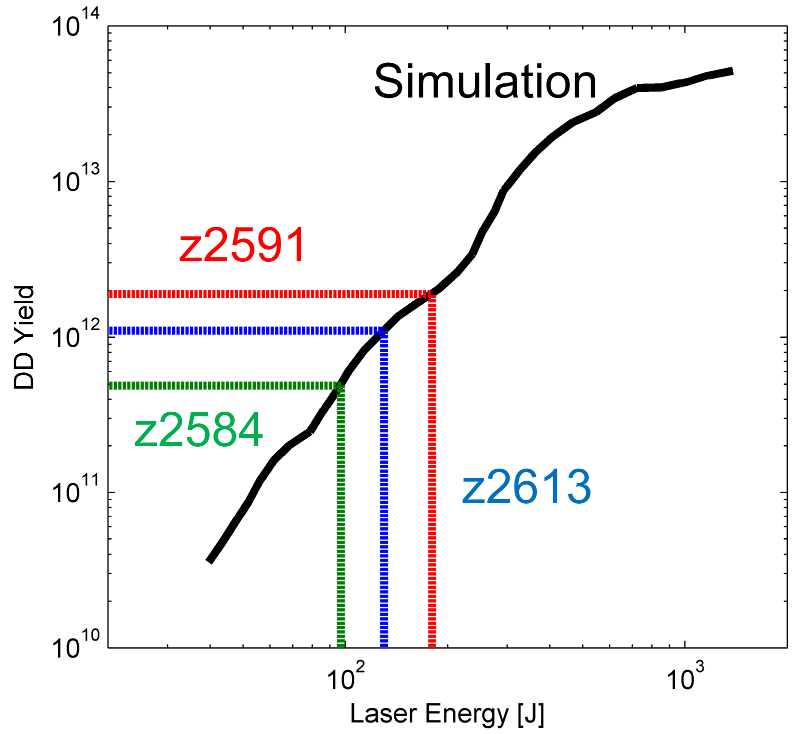


- **Experiments with $T_{electron} \approx 1$ keV have negligible DD yield**
- **For $T_i \approx T_e > 2$ keV, significant yield is observed**
- **Measurable DT yield is observed only on experiments with high DD yield**

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

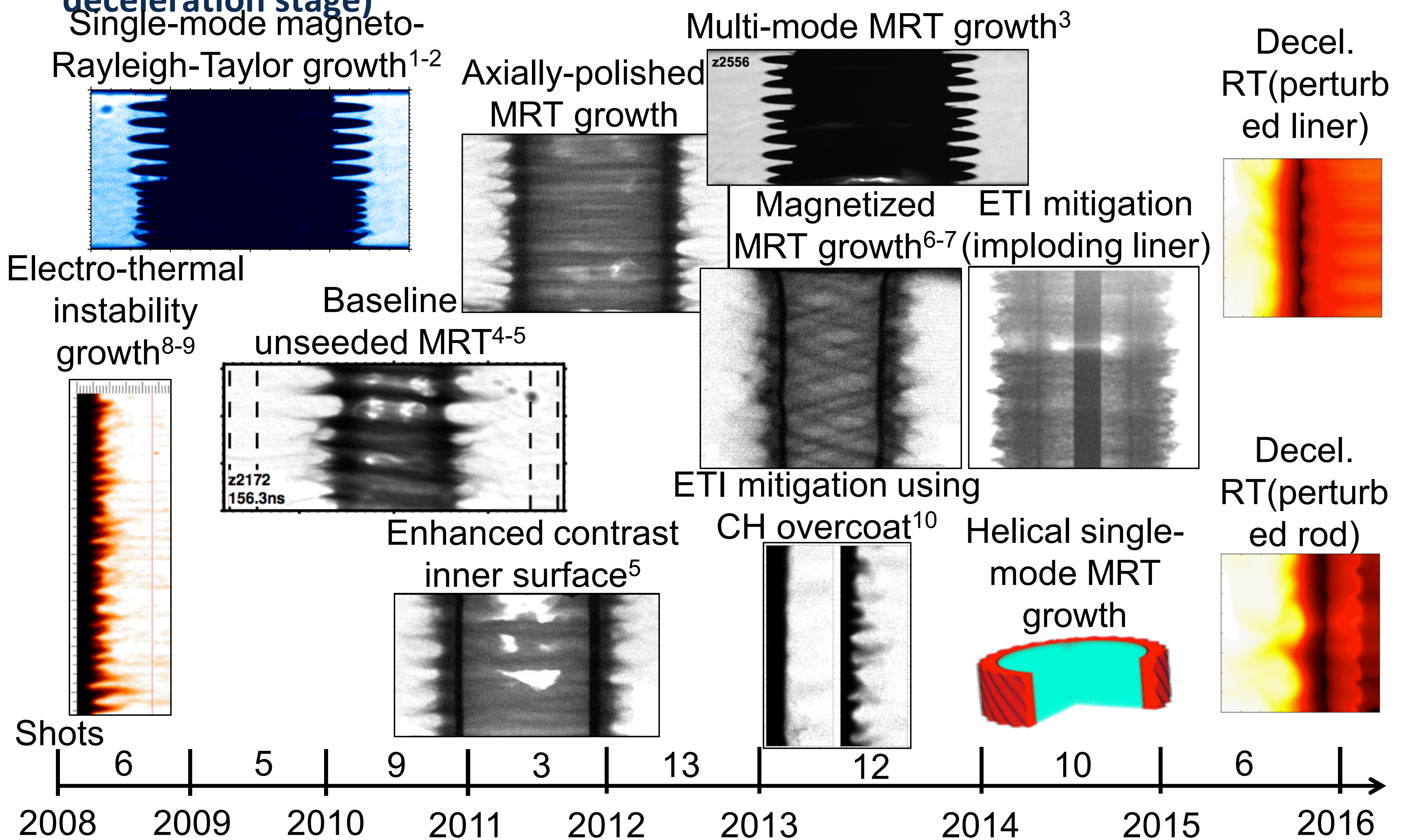
Our laser heating of MagLIF targets has not yet been optimized and improvements may be possible

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



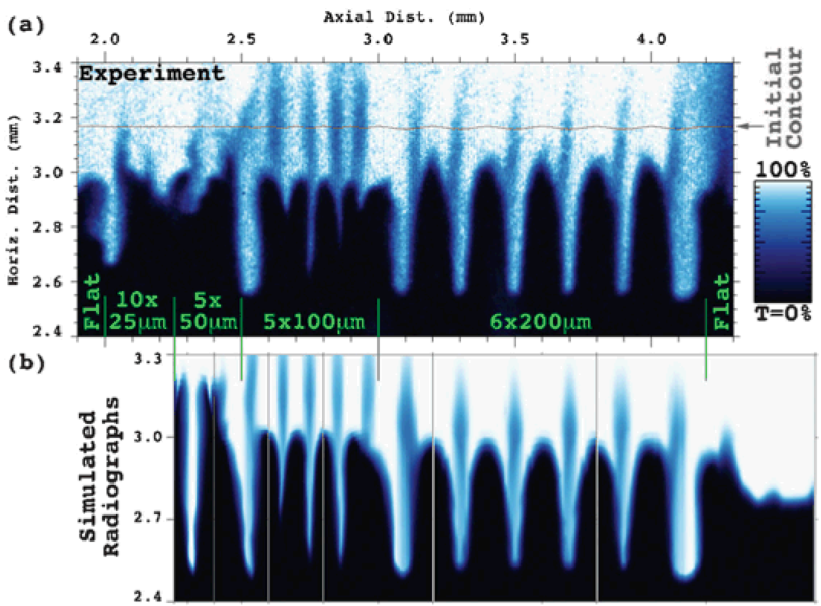
Experiments will be conducted in near future to test improvements in laser coupling with "smoothed beams"

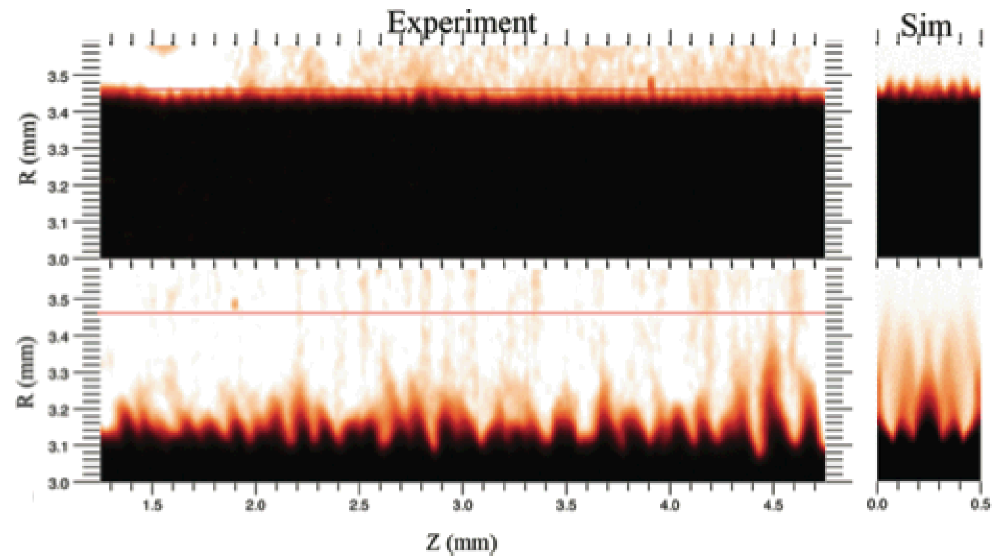
Our biggest uncertainty in 2008 was our ability to model liner dynamics—we have made studying this a high priority for Z experiments and will continue to do so going forward (emphasizing deceleration stage)

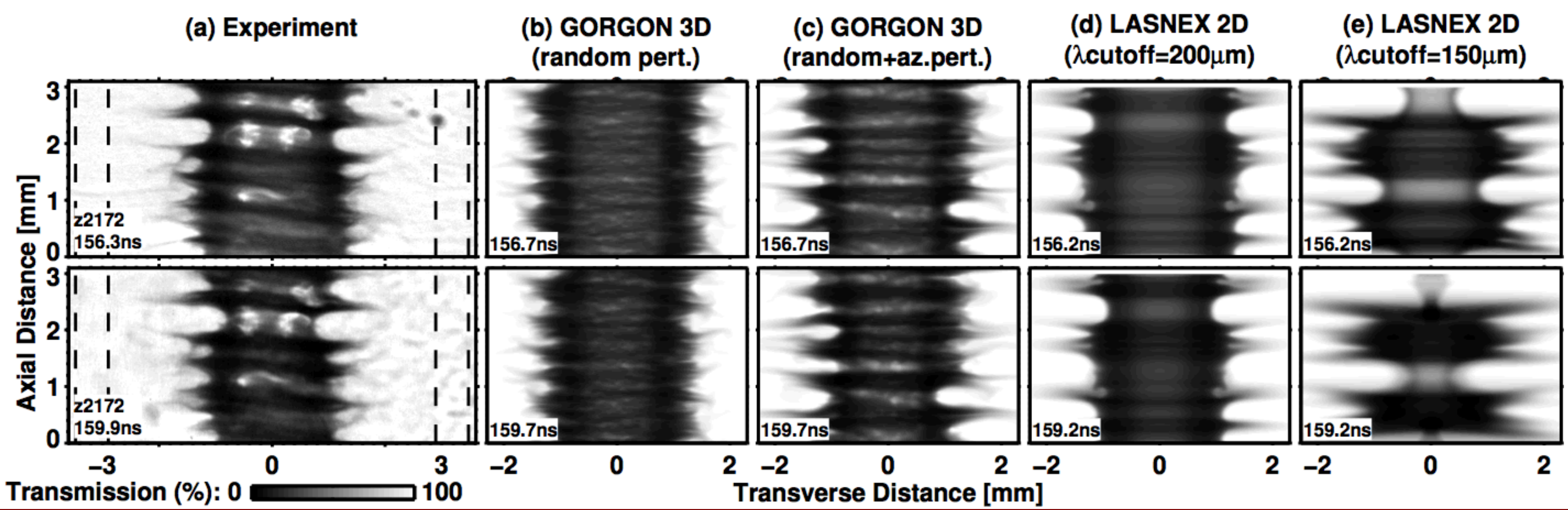


Publications to date include 4 PRLs, 5 PoPs, more in preparation

While a high-resolution simulation of the initiation through implosion is impractical, detailed modeling can match the data. Low-resolution predictions that match the data remain promising for MagLIF.



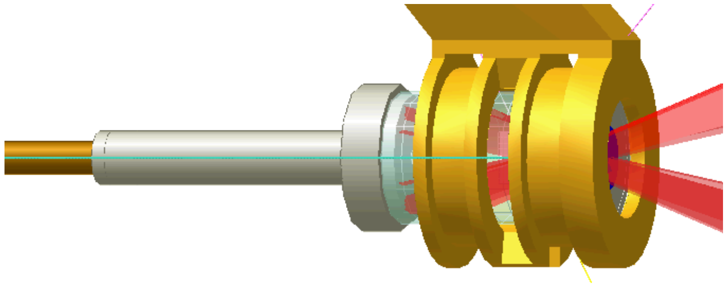




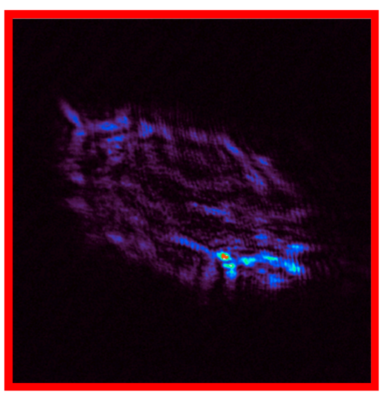
1 D.B. Sinars *et al.*, PRL (2010); 2 K.J. Peterson *et al.*, PoP (2012); 3 R.D. McBride *et al.*, PRL (2012).

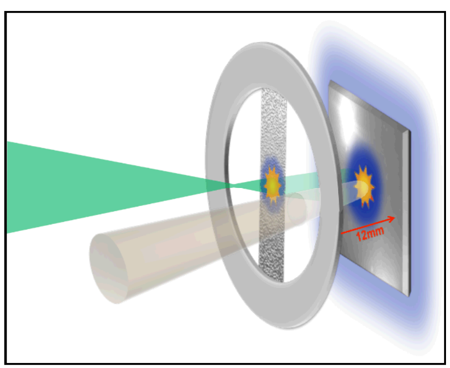
We are using laser facilities to study other key physics underlying magnetized liner inertial fusion

Magnetized and un-magnetized laser heating experiments on Omega-EP



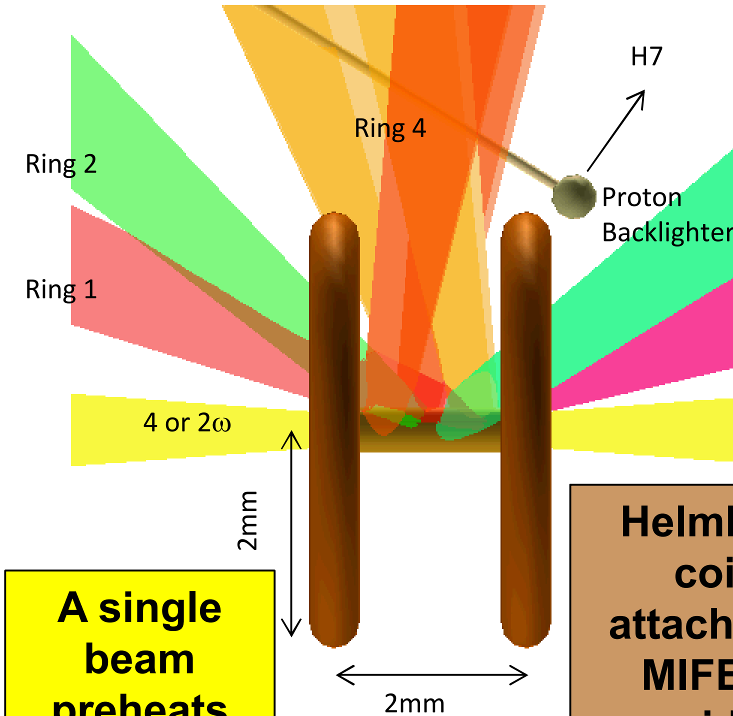
Foil transmission measurements using Z-Beamlet laser at Sandia





Scaled MagLIF experiments using the Omega laser at University of Rochester

40 Omega beams compress the target



A single beam preheats the gas to 100+ eV

Helmholtz coils attached to MIFEDS provide 15-30 T

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

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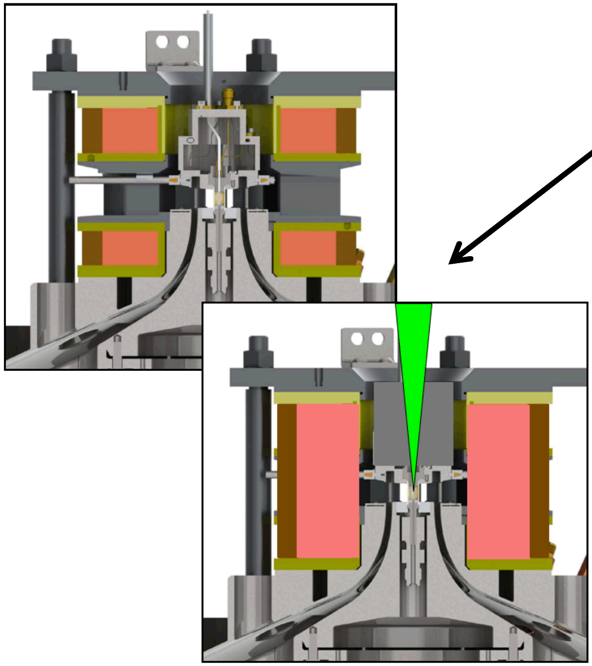
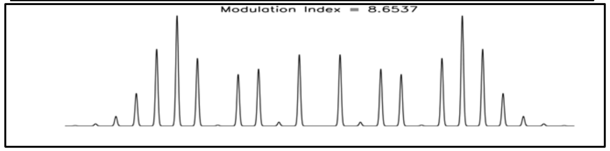


Increase B-field from 10 T to 30 T

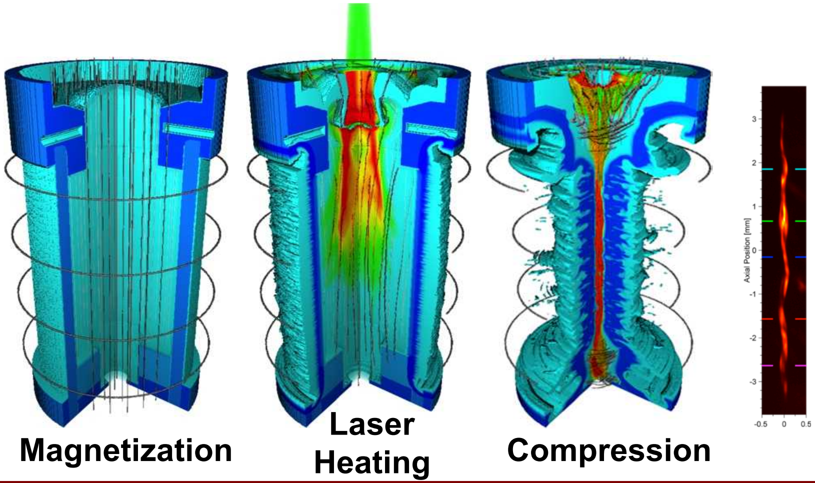
Increase laser energy from 2 kJ to >6 kJ

Increase current from 20 MA to 25 MA

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

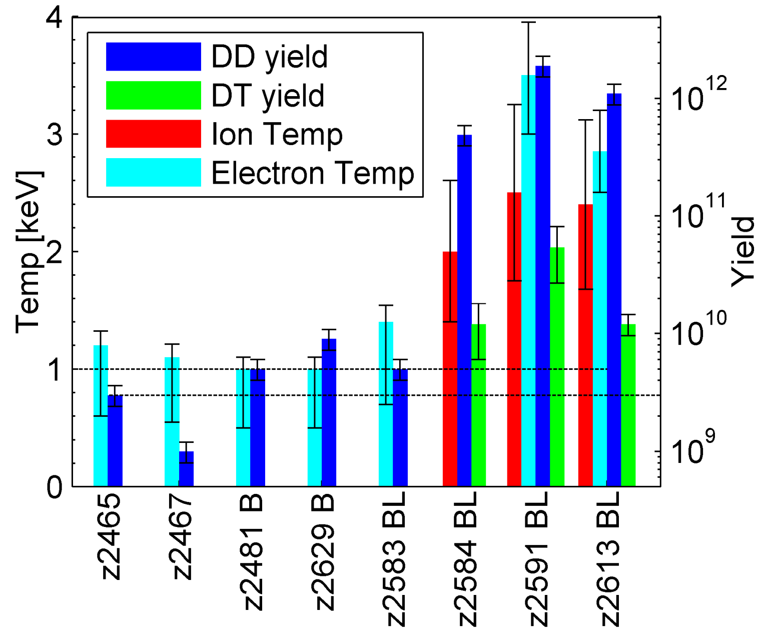


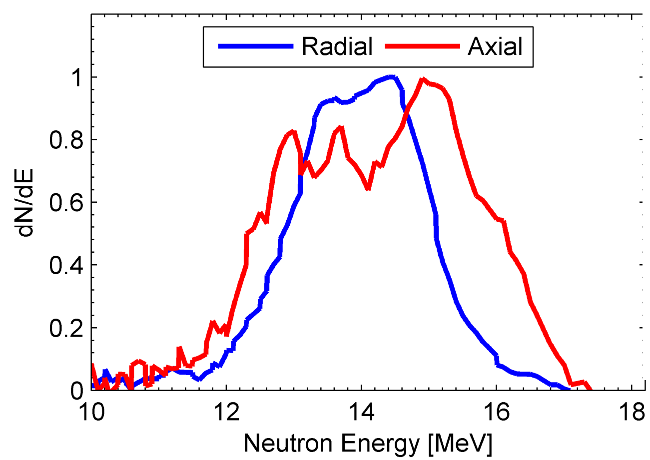
Increase database from 5 to >40 integrated MagLIF experiments, with a mix of scaling and science-focused experiments

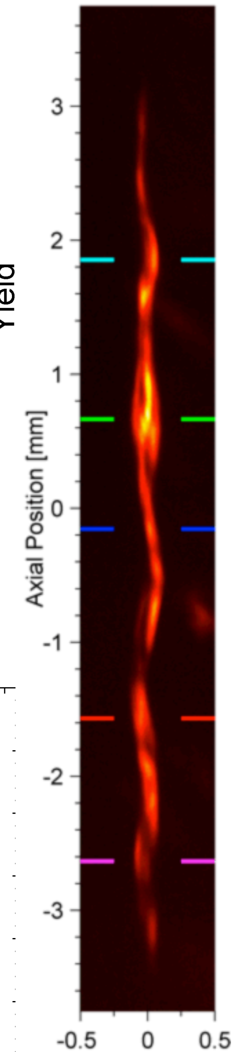


We obtained promising initial results in our first magneto-inertial fusion experiments on the 26 MA Z pulsed power facility at Sandia

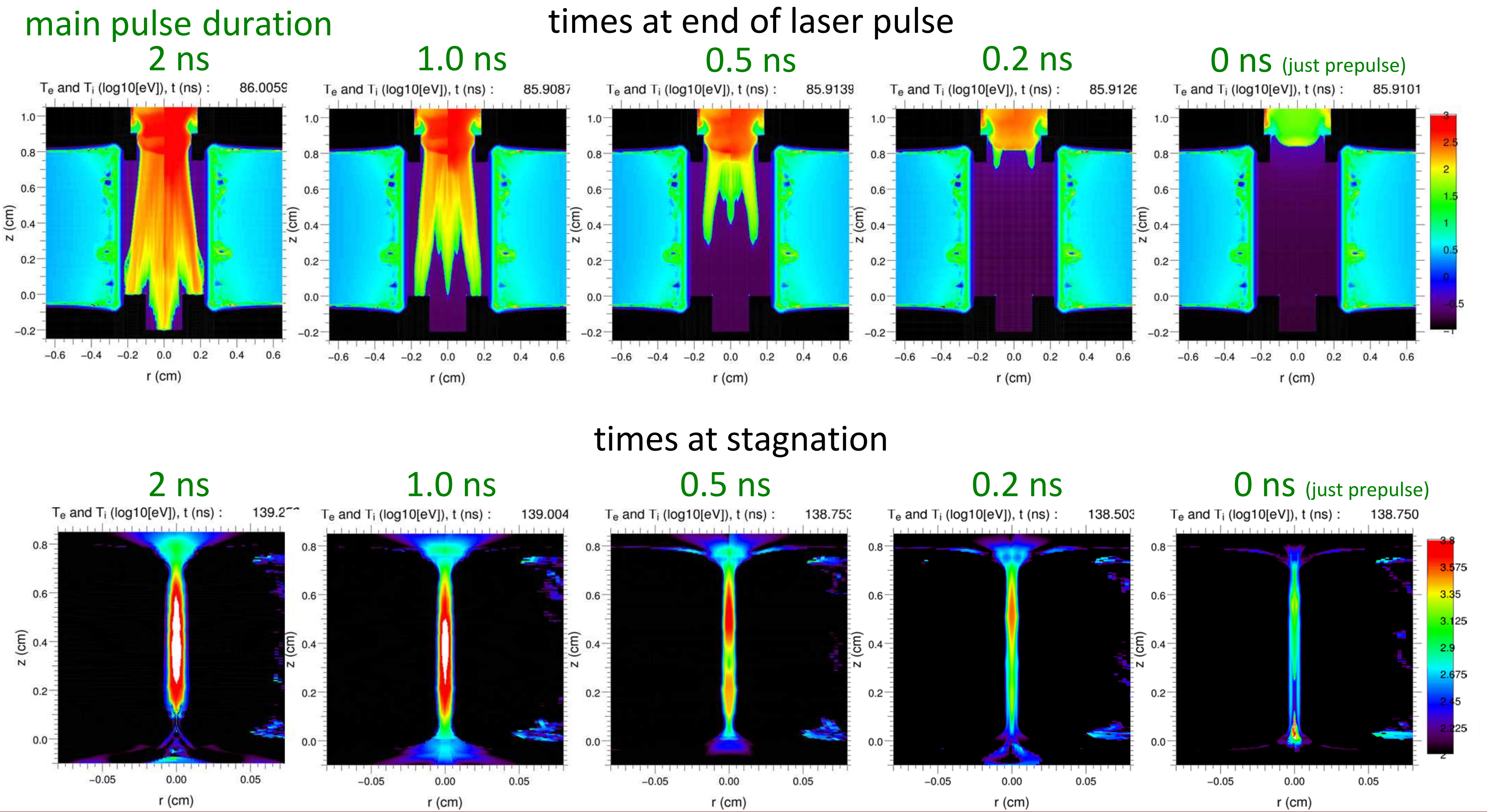
- We achieved DD yields up to 2e12 (~0.3 kJ DT equivalent) in our first integrated tests of Magnetized Liner Inertial Fusion (MagLIF)
- A variety of data were collected that appear to show a <150 μm diameter, ~3 keV, highly magnetized plasma was produced—remarkable for a 70-100 km/s implosion!
- We are continuing to build on these results with a balanced combination of focused and integrated experiments
- In parallel we are improving capabilities to understand how this performance will scale with increasing drive parameters







Pre-shot 2D calculations predicted yields in the mid-10^{13} range—one hypothesis for 0.5-2e12 yields is poor laser coupling. To estimate the impact of this, a series of HYDRA calculations artificially shortened the laser pulse duration.



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

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

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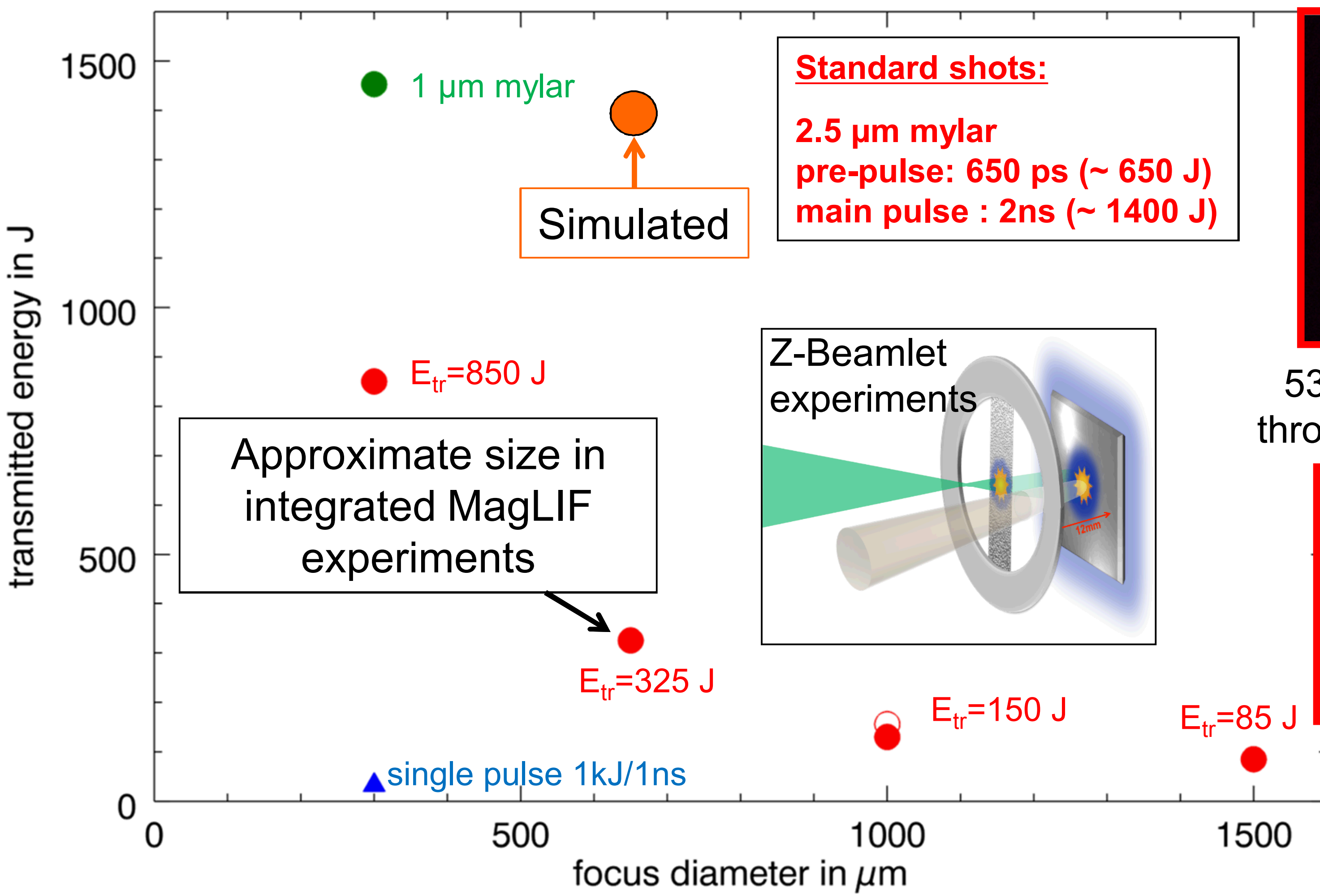
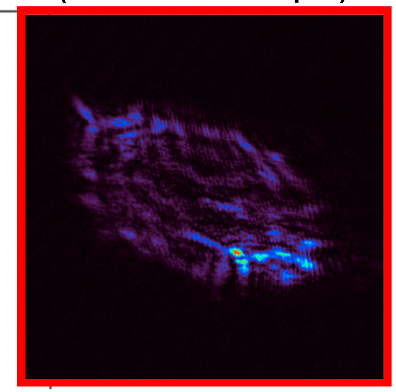
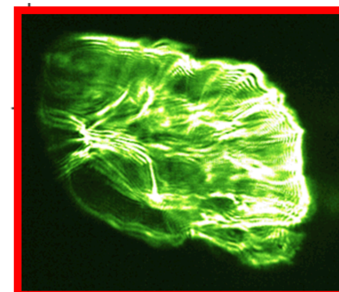
Calorimeter Measurements

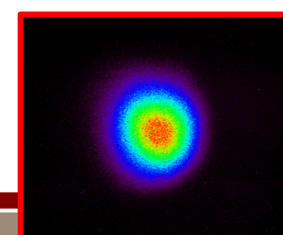


Beam profile for 800 μm diam. (no main amps)



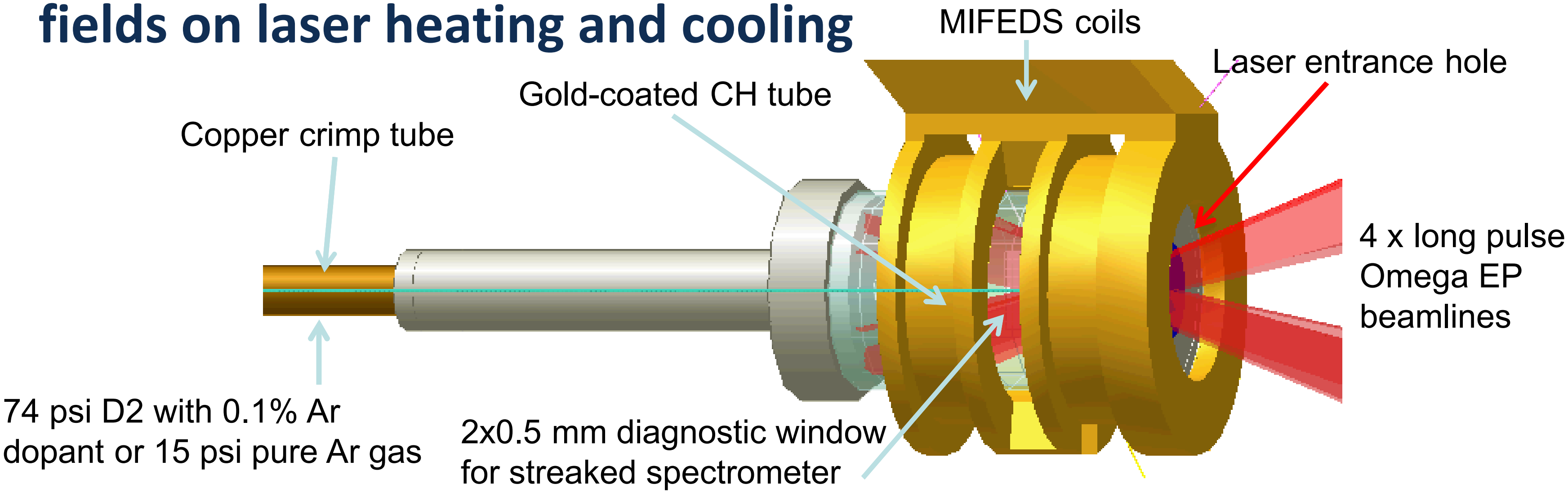
532 nm transmission through foil during pulse





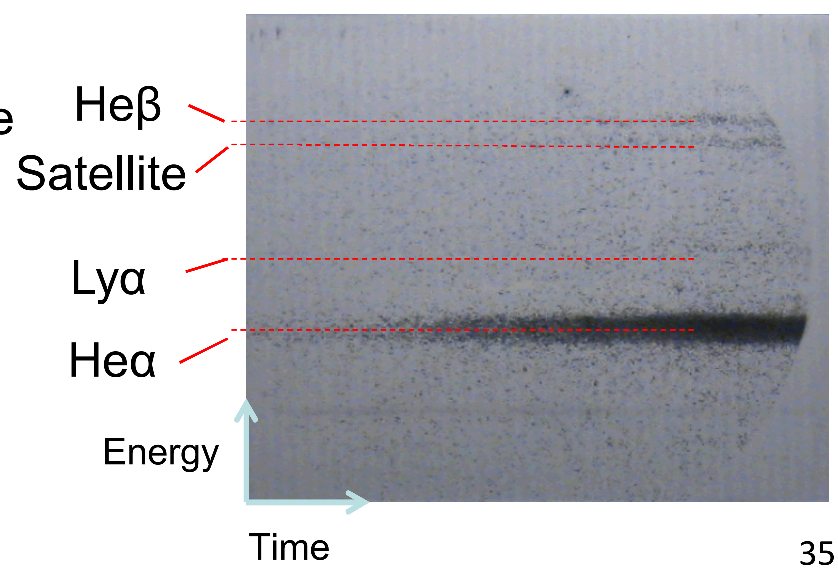
We are studying beam smoothing in near term using thin foils above LEH

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



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

Shot 4 – 48054 – 74 psi D2 magnetized



Unmagnetized target did not produce Ar lines

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

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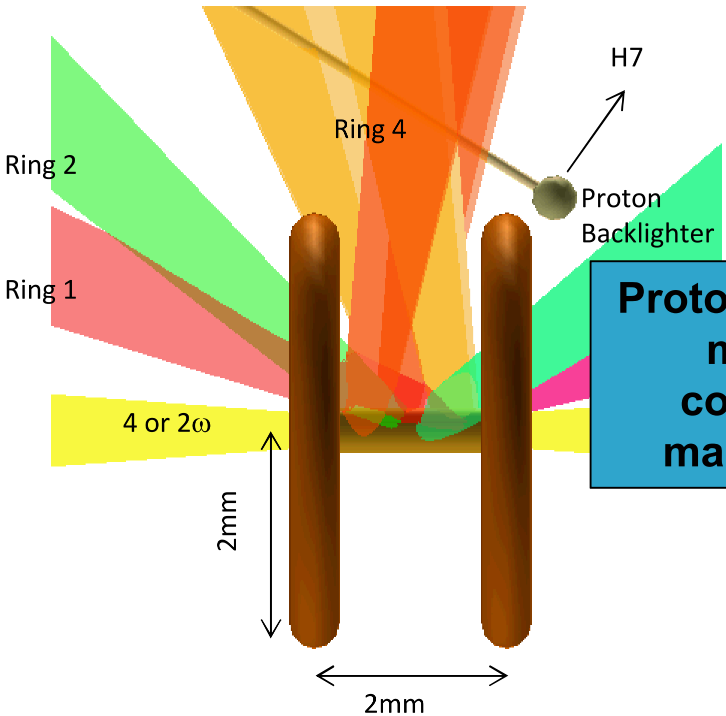
FSC

40 Omega beams compress the target
Match implosion velocity and convergence ratio



Proton backlighter measures compressed magnetic field

A single beam preheats the gas to 100+ eV
Match Hall parameter

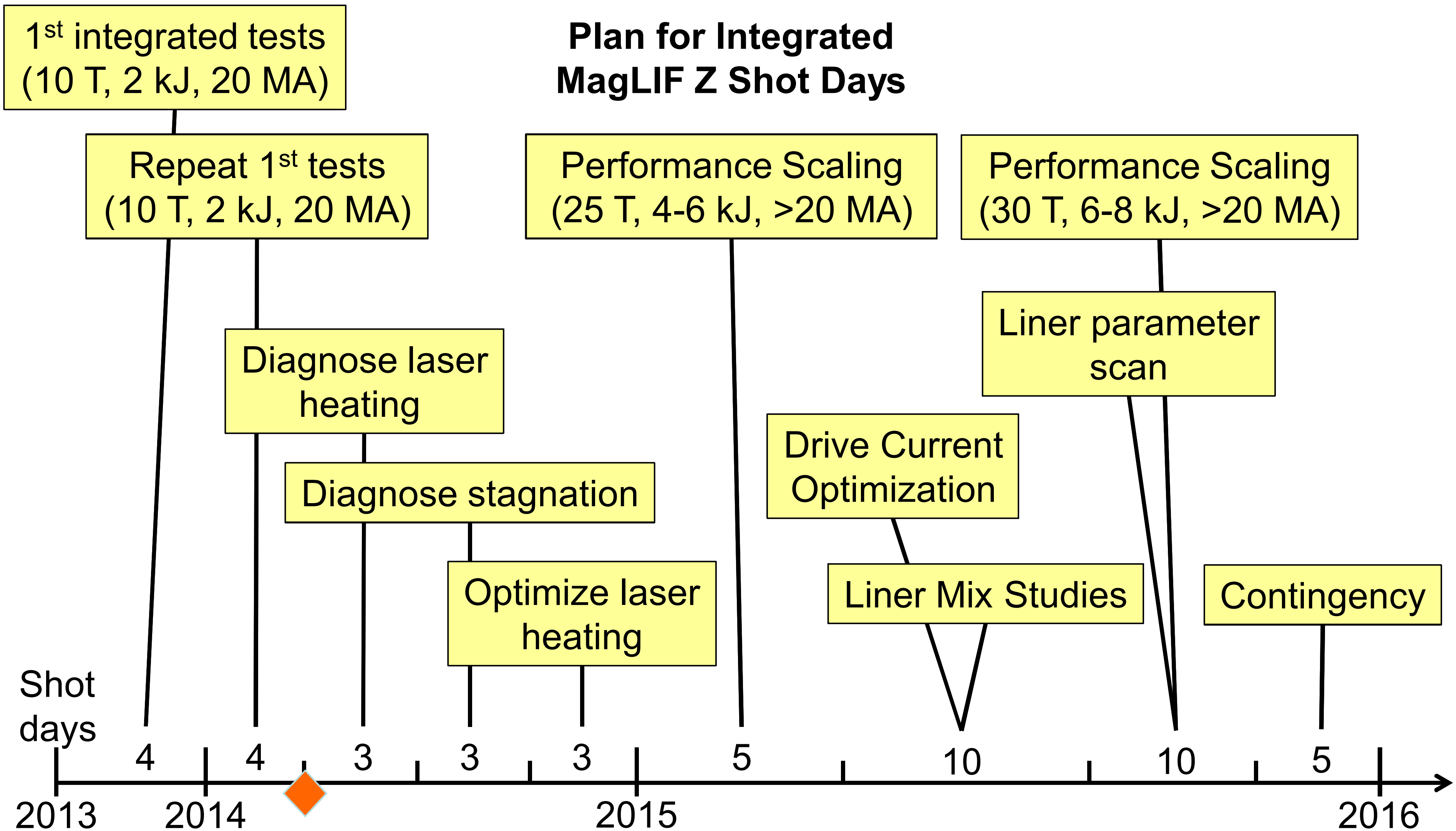
Helmholtz coils attached to MIFEDS provide 15-30 T

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

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

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

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



Magnetically Driven Implosions are one of three main paths forward identified by the National ICF program and NNSA its 2012 "Path Forward" document

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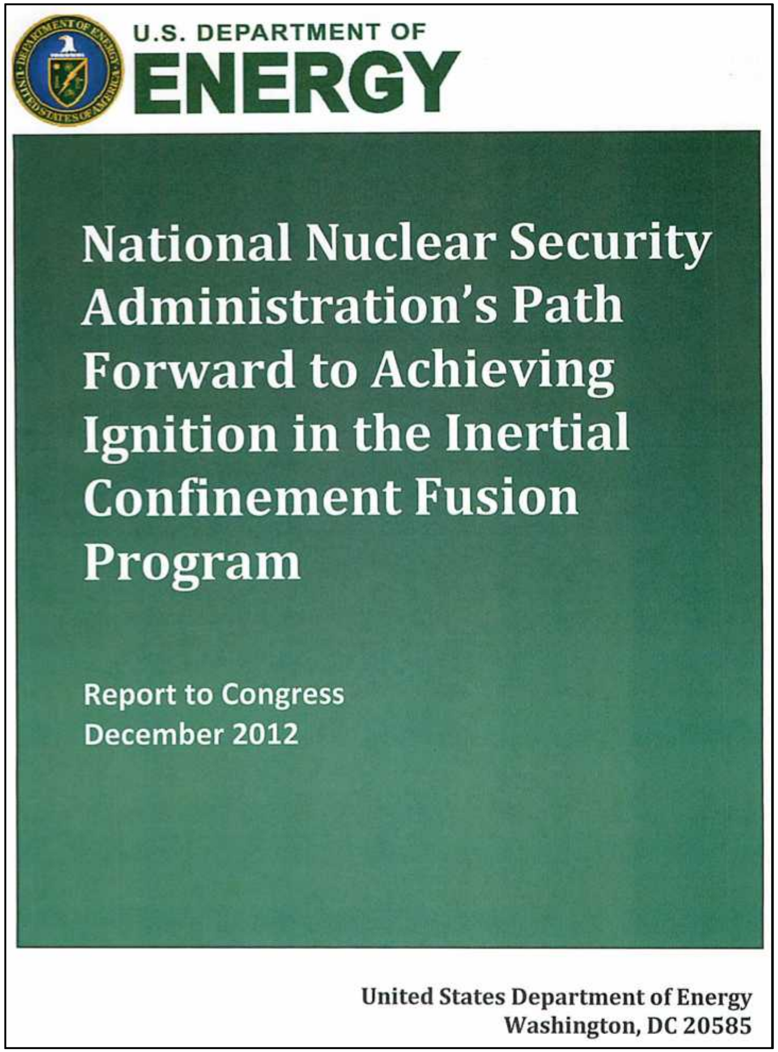
- "To date there is no compelling scientific information suggesting that the indirect drive approach cannot achieve ignition. Because the ***indirect drive approach*** has the closest relevance to nuclear weapons physics, this ***will remain the mainline approach for ignition*** either until it achieves ignition or until there is sufficient scientific understanding supporting a conclusion that priorities should be reset to favor an alternative approach."
- "This strategy is balanced to provide multiple paths to success. Polar Direct Drive (PDD) and ***Magnetically Driven Implosions (MDI) offer an alternative path to ignition based on current understanding***."
- ***"NNSA will continue to support research and technology development for both PDD and MDI fusion in parallel with developing an understanding of indirect drive ignition."***


U.S. DEPARTMENT OF
ENERGY

National Nuclear Security Administration's Path Forward to Achieving Ignition in the Inertial Confinement Fusion Program

Report to Congress
December 2012

United States Department of Energy
Washington, DC 20585

By the end of FY15 we will have several critical new capability upgrades, increased the number of integrated MagLIF tests from 5 to >40, done initial MagLIF scaling studies, and tackled deceleration RT

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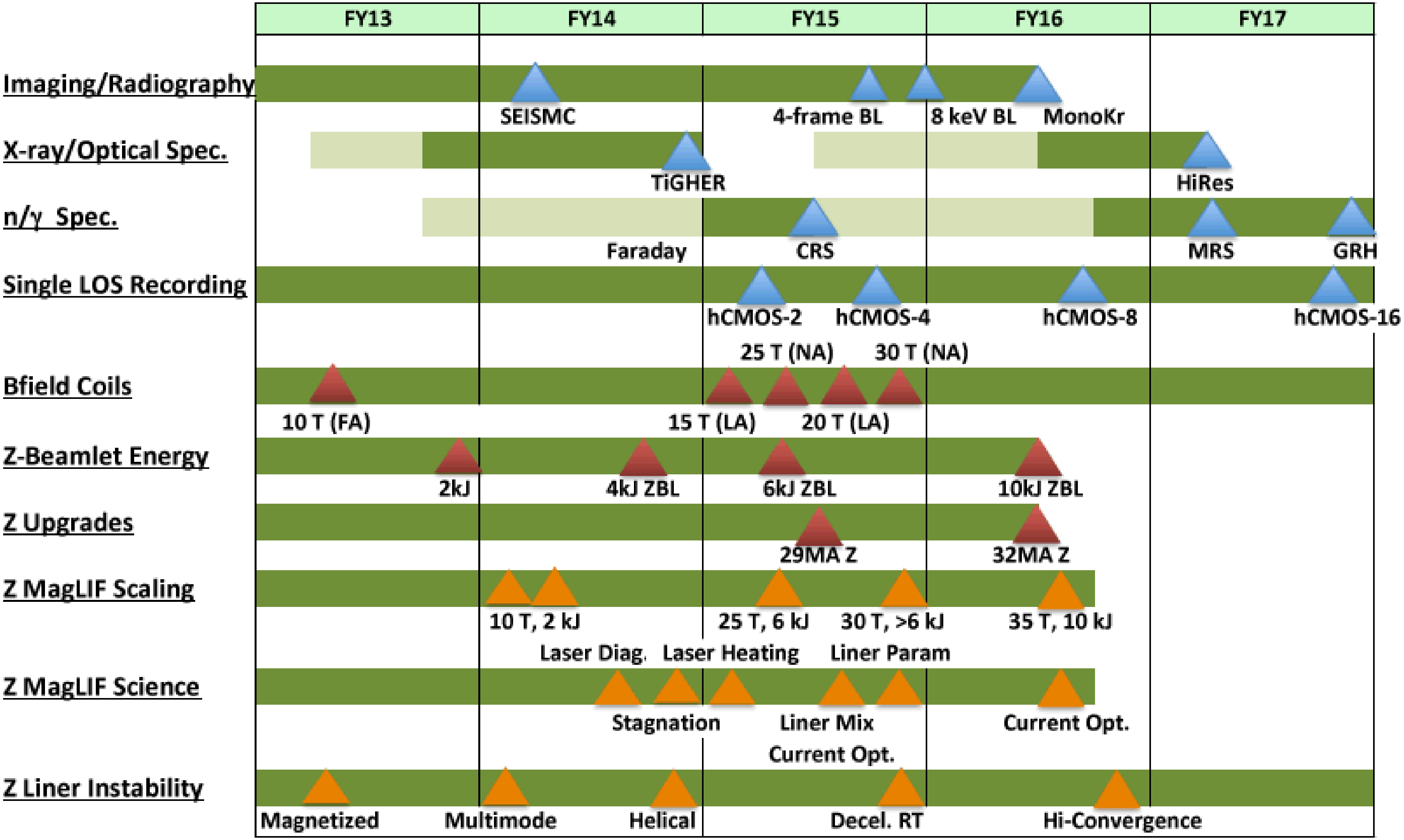
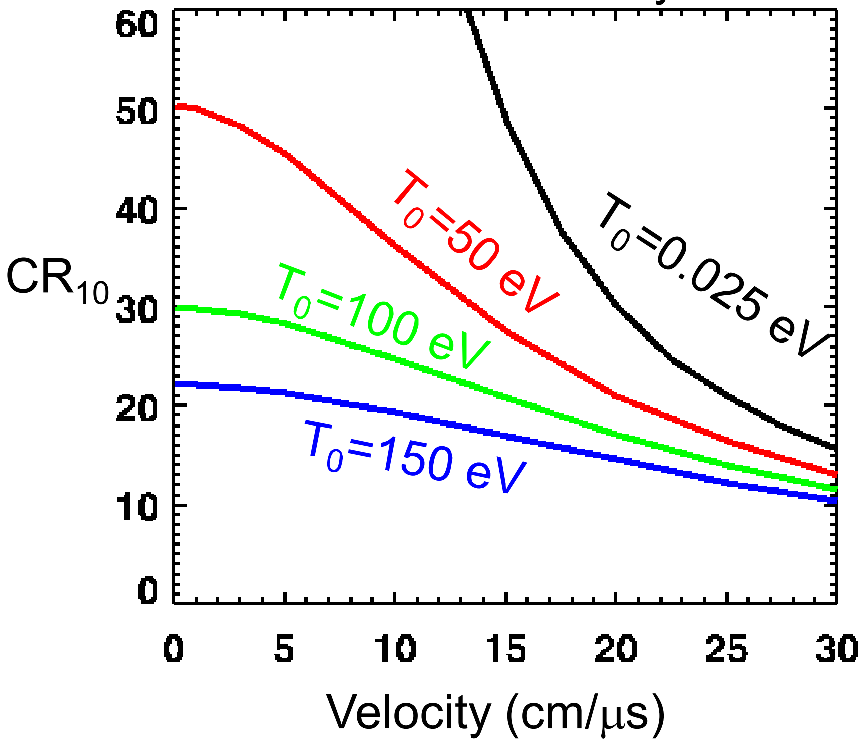


Not shown: In FY14-FY16 we will execute Z-Beamlet, Omega, & Omega-EP expts.

Typical ICF implosions need high velocities to reach fusion temperatures—starting the implosion with heated fuel potentially reduces requirements

Lasnex simulation with constant velocity



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

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

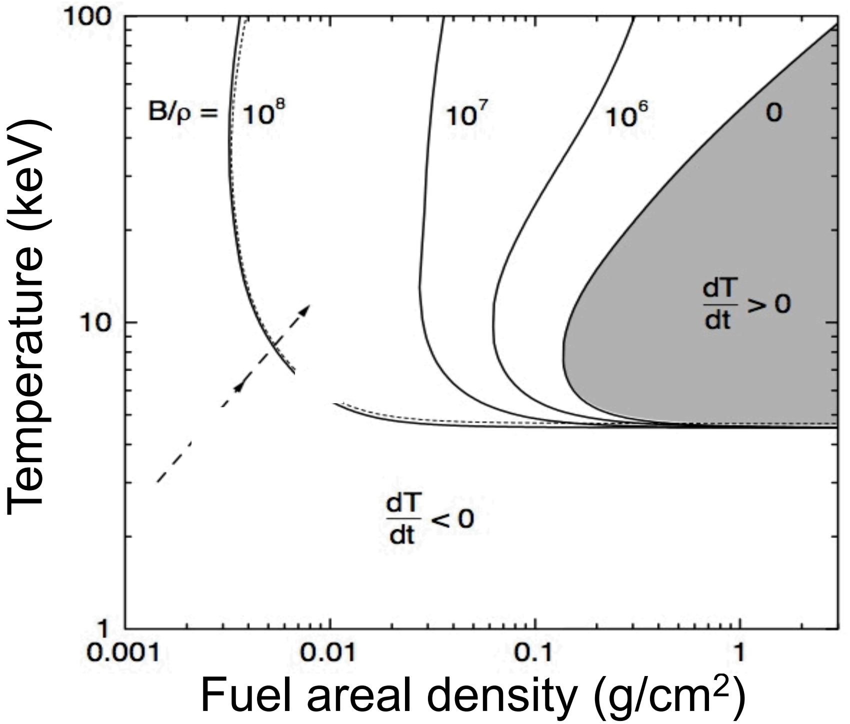
High velocities make it easier to reach fusion temperatures and also reduce the time available for losses (e.g., electron heat conduction or radiation)

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

Is there a way to reduce losses?

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

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



The □r needed for ignition can be significantly reduced by the presence of a strong magnetic field largely through inhibiting electron conduction

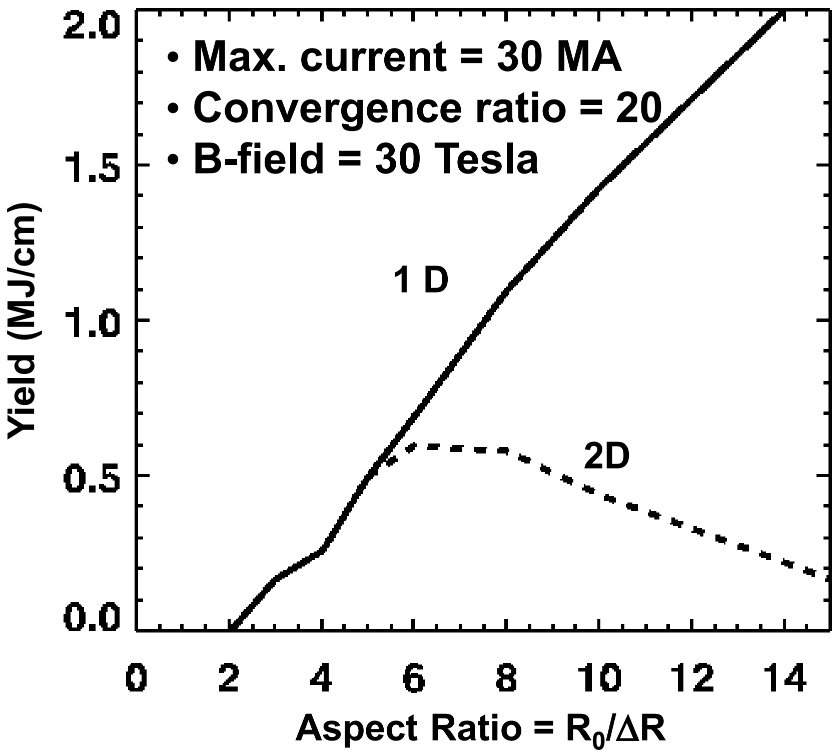
Lower □r reduces the required final fuel density (e.g., ~1 g/cc << 100g/cc), which also reduces bremsstrahlung radiation losses

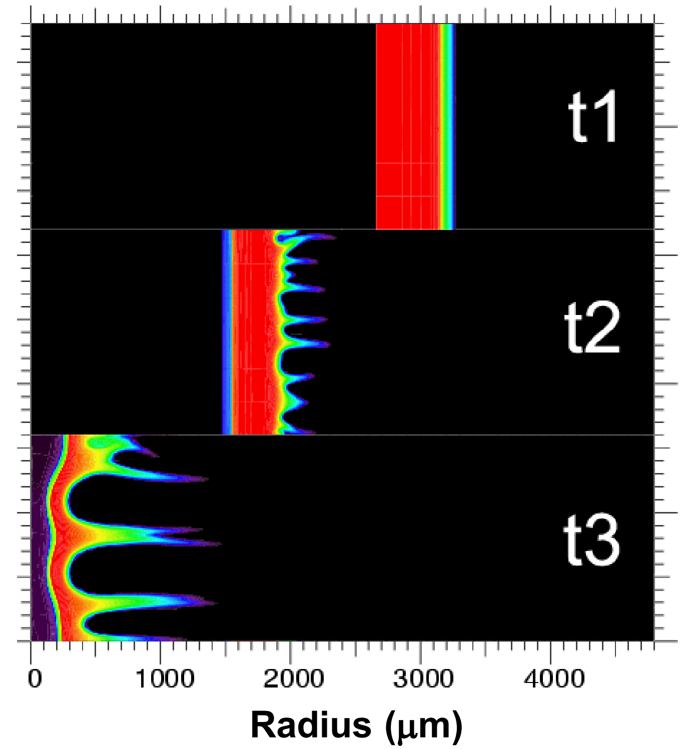
This means the stagnation plasma pressure at ignition temperatures is significantly reduced (e.g., ~5 Gbar << ~500 Gbar for hot spot ignition)

Large values of B/□ are needed and therefore large values of B are needed, B ~ 10,000 Tesla (Earth's B-field is ~0.00003 Tesla)

This field significantly exceeds pulsed coil technology (B_0 ~10-30 T), therefore flux compression is needed

Reducing the implosion velocity requirements through fuel heating and magnetization allows us to use thicker, more massive liners to compress the fuel that are more stable





• The Magneto-Rayleigh-Taylor instability degrades the yield as the aspect ratio is increased (due to decreased liner ρR)

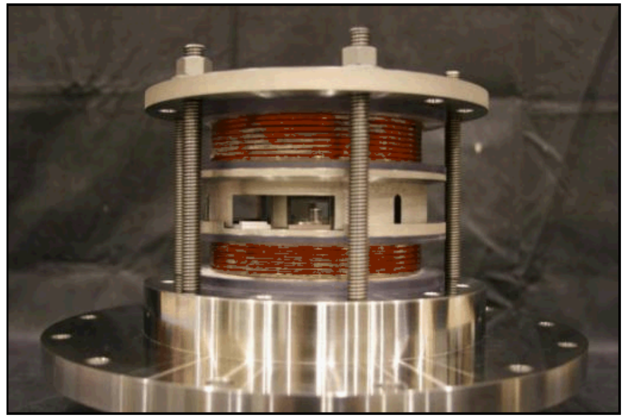
• Simulations of AR=6 Be liner show reasonably uniform fuel compression and sufficient liner ρR at stagnation to inertially confine the fuel—important because fuel density is low!

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

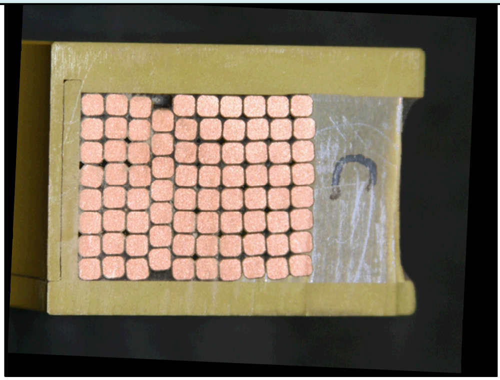
We have successfully implemented 10 T axial fields over a several cm^3 volume for MagLIF and the capacitor bank is capable of driving 30 T field coils under development

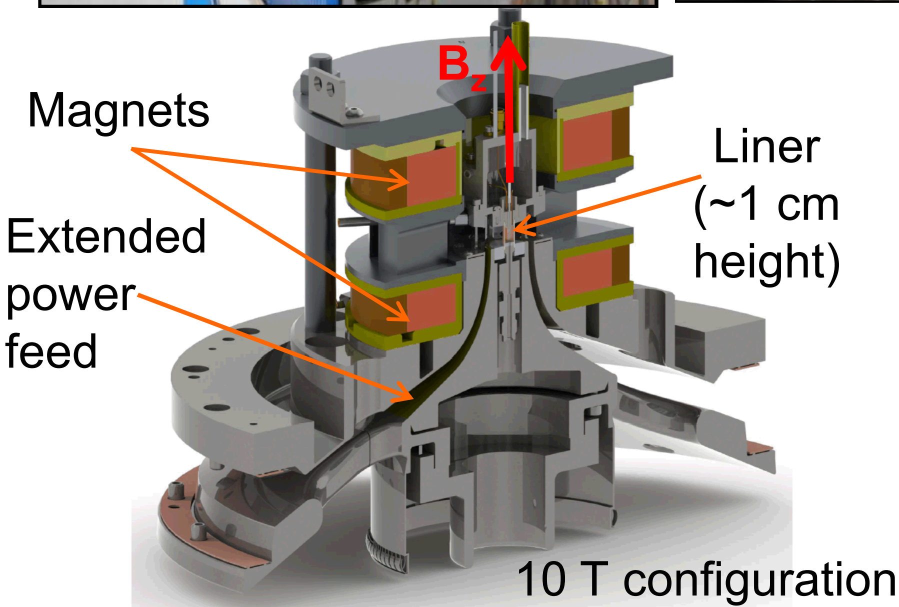
Capacitor bank system on Z
900 kJ, 8 mF, 15 kV (Feb. 2013)

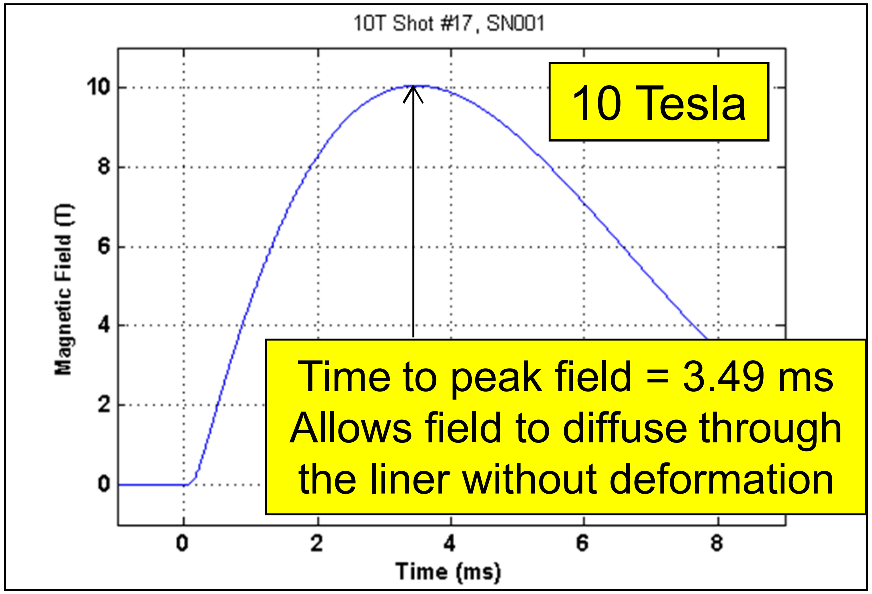
Example MagLIF coil assembly with copper windings visible



Cross section of coil showing Cu wire, Torlon housing, and Zylon/epoxy reinforcement







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

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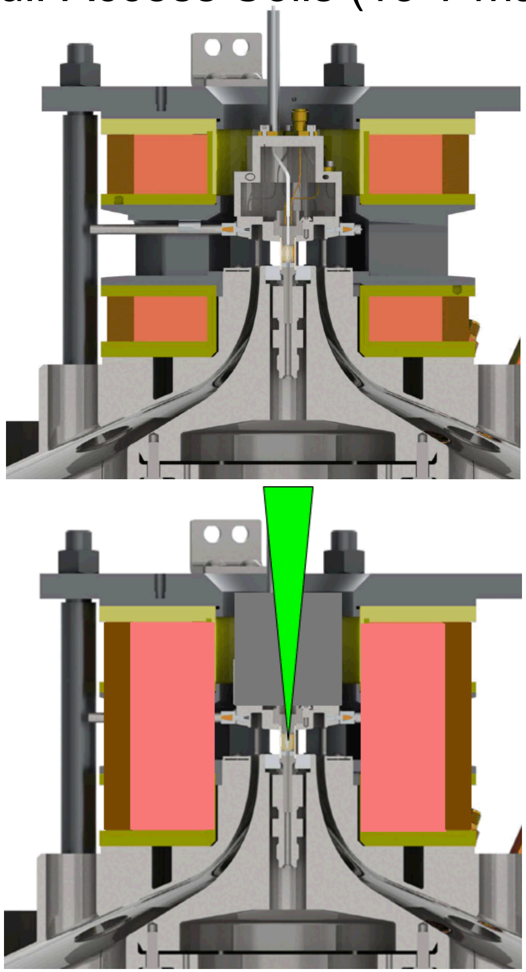
- Most direct path to 30 T is to trade off radial diagnostic access for increased coil volume
- Have successfully tested the full-access coil configuration to 15 T in laboratory—peak stresses on those coils exceed those in our 30 T no-access coil designs
- Currently incorporating additional state-of-the-art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

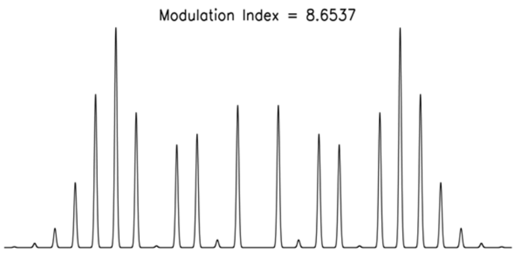
Full-Access Coils (15 T max)



No-Access Coils (30-40 T max)

We are in the process of upgrading Z-Beamlet from 2 kJ to 4 kJ to support MagLIF/DMP experiments—additional upgrade to 6-8 kJ will start in June

- Upgrade to 4 kJ to be completed by June 2014. This upgrade increases the bandwidth of the laser to suppress SBS and allows us to go from 2 ns pulses to 4 ns pulses at existing ~1 TW power levels. (Note: NOVA lost lens to SBS in 1990s—want to avoid!)



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

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

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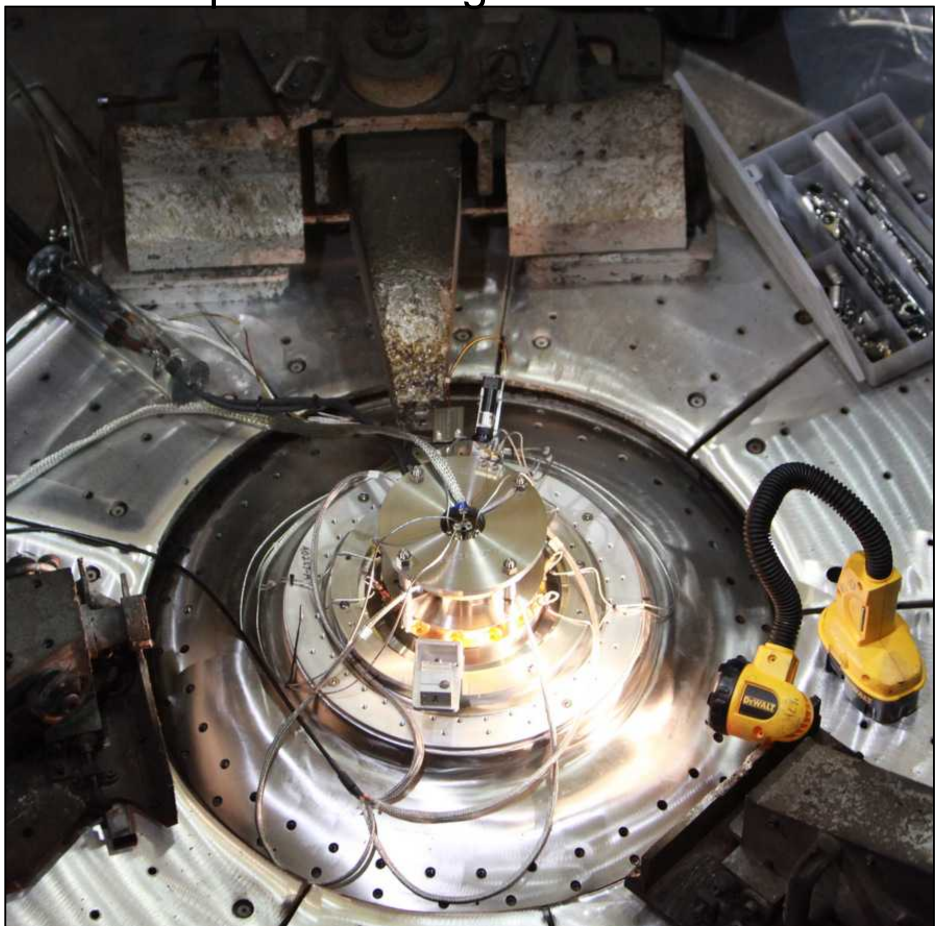
Damage to FOA debris shielding

Pre-shot photo of MagLIF load hardware



Post-shot photo