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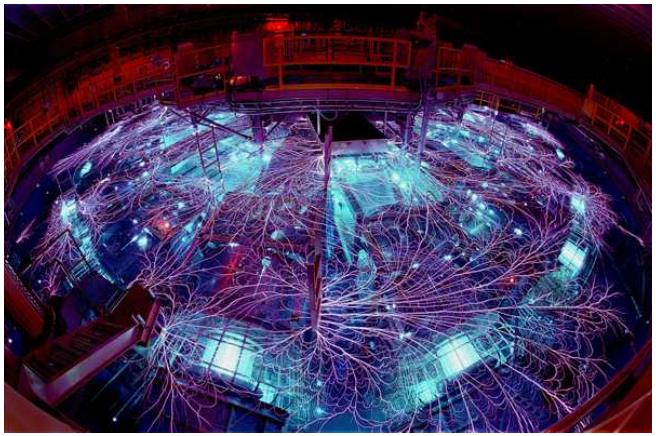

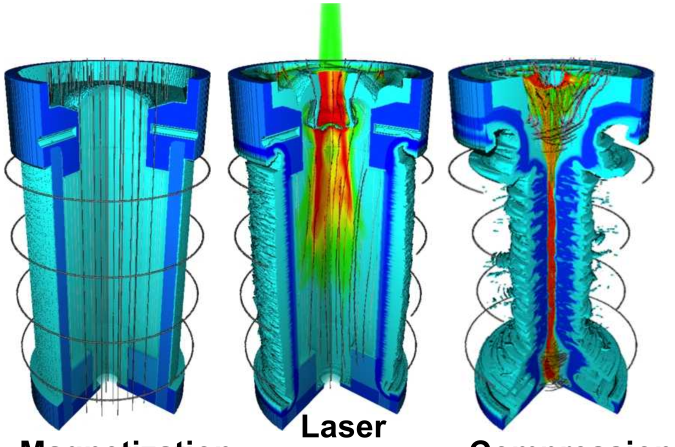

Magnetized Liner Inertial Fusion (MagLIF) Research: A Promising Beginning

Stephanie B. Hansen
for the MagLIF team
Sandia National Laboratories

SCCS workshop
July 27 – Aug 1, 2014

U.S. DEPARTMENT OF ENERGY
NNSA National Nuclear Security Administration

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We have a great team of scientists and engineers contributing to the work being shown today

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The Sandia Z pulsed power facility uses magnetic pressure to efficiently couple energy to drive relatively large targets for a wide variety of stockpile stewardship applications

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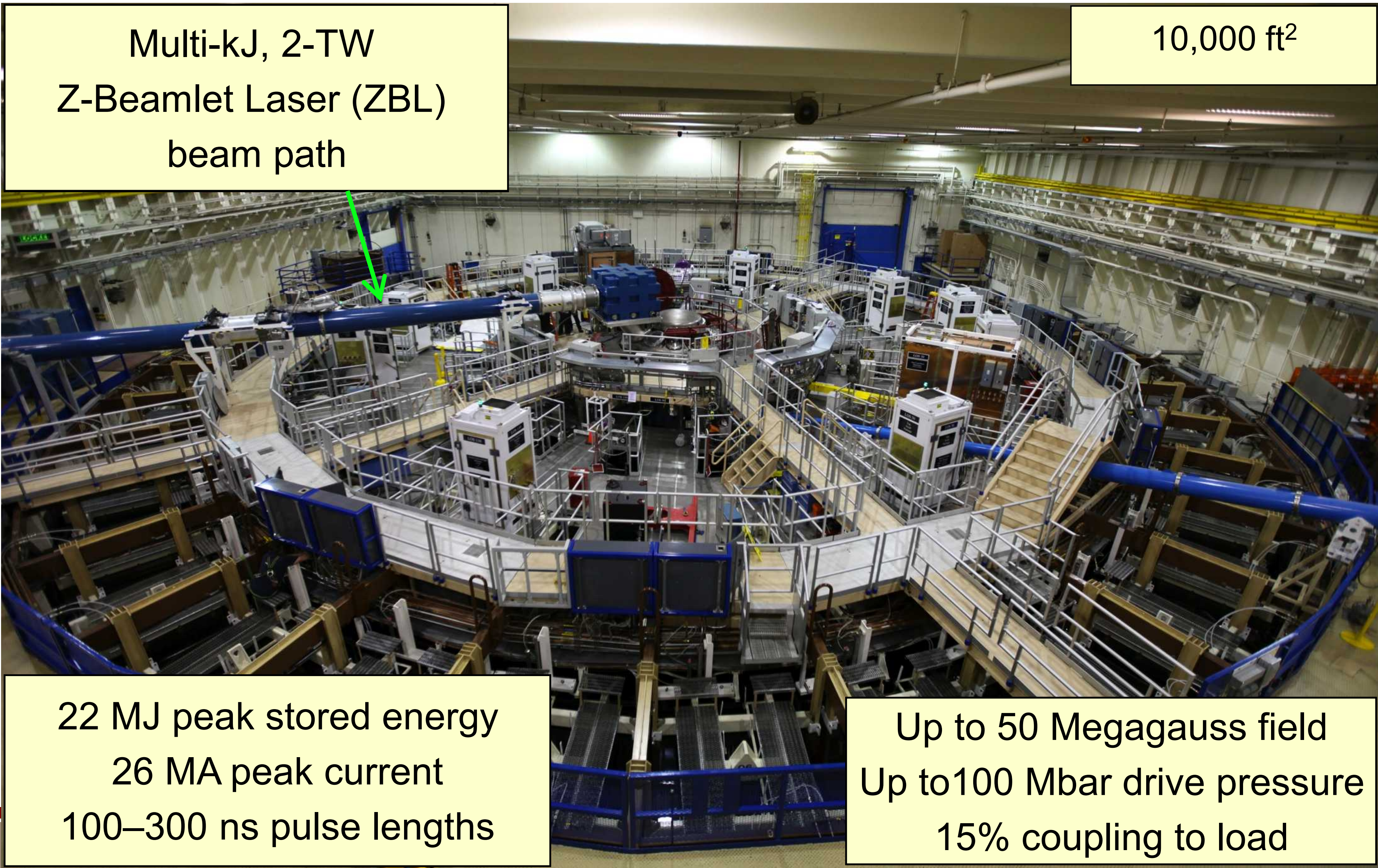
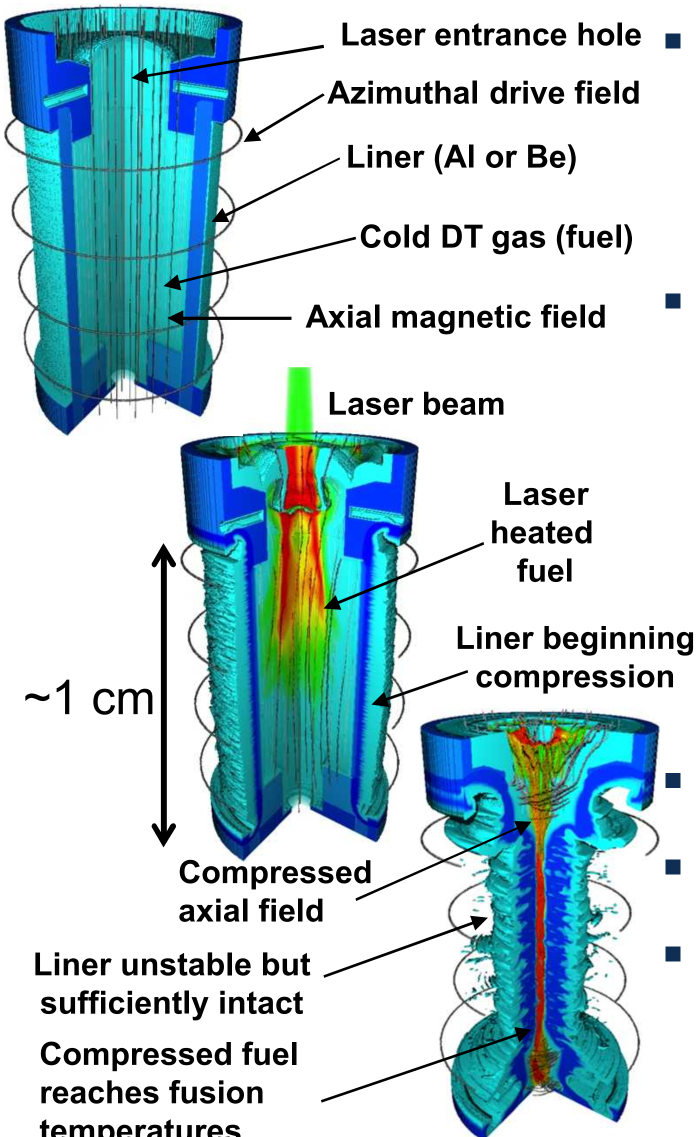


We are evaluating a Magnetized Liner Inertial Fusion (MagLIF)* concept that may reduce fusion requirements



- 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).

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

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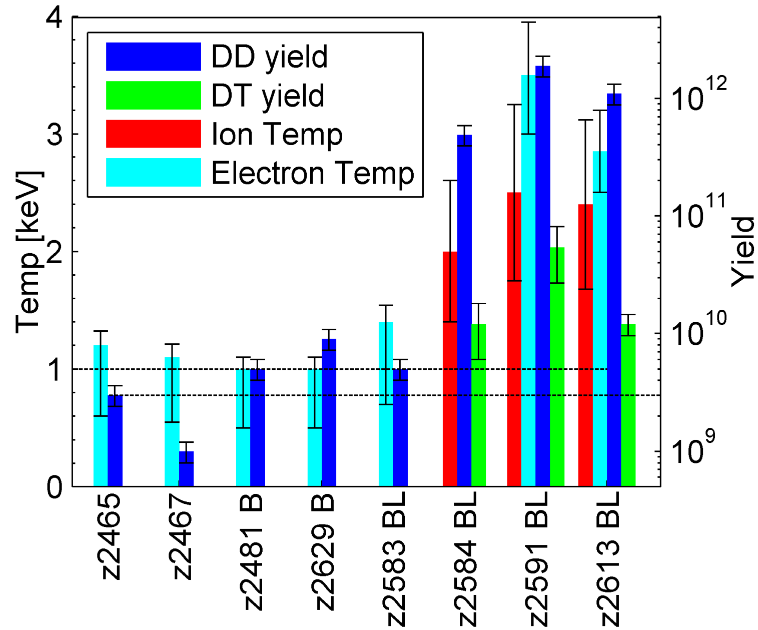
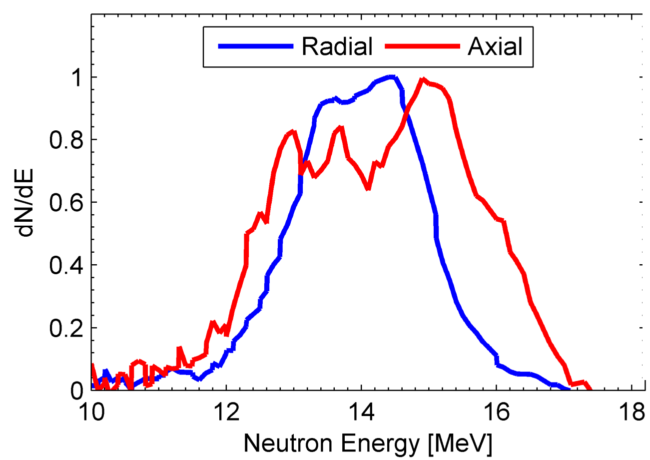
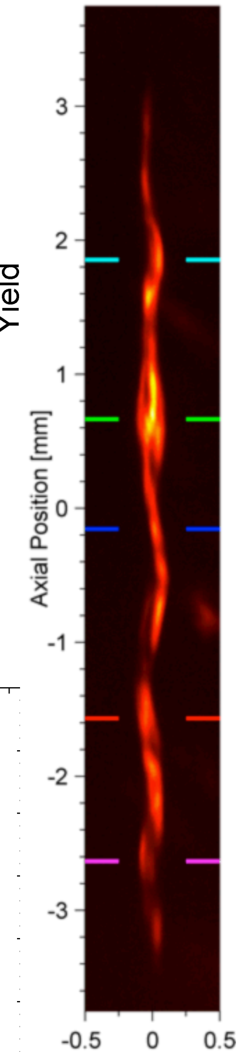
- We achieved DD yields up to 2e12 (~0.3 kJ DT equivalent) in our first integrated tests of Magnetized Liner Inertial Fusion (MagLIF)
- A variety of data were collected that appear to show a <150 μm diameter, ~3 keV, highly magnetized plasma was produced—remarkable for a 70-100 km/s implosion!
- We are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







MagLIF combines three complementary design elements into a single target that appears capable of 100 kJ yields on Z in 2D simulations

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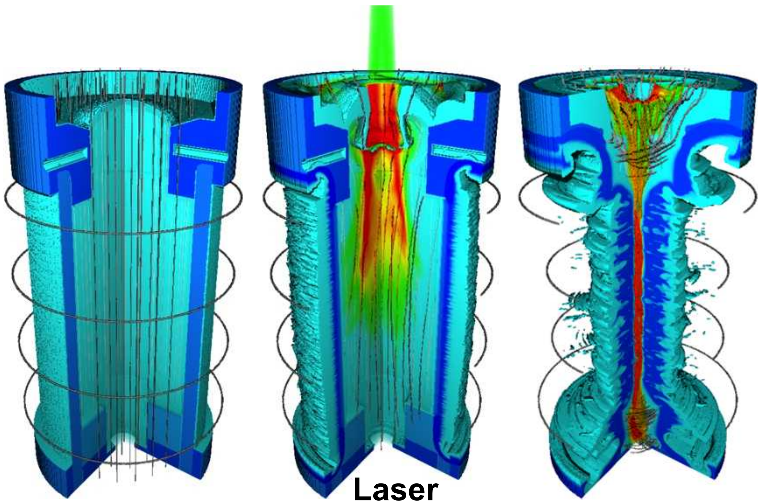


- Key target design elements
  - Magnetization
  - Laser heating
  - Liner compression

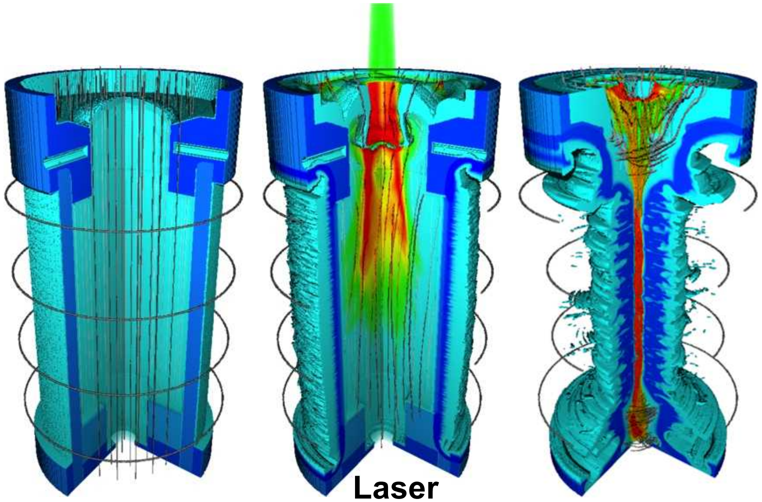
- 30 Tesla initial magnetic field
- Laser heating of ~3 mg/cm^3 fuel produces initial ~250 eV plasma
- Thick (AR=6) Be liner with R_0=2.7 mm, h=5 mm, peak velocity ~100 km/s for a 27 MA peak current drive

- At stagnation the fuel absorbs 120 kJ, reaches 8 keV and ~0.5 g/cm^3, and is highly magnetized at 13500 Tesla (Note: Fuel β varies from ~80 during heating to ~5 at stagnation—plasma pressure always dominates)
- Yields >100 kJ predicted in 2D

Similar predictions are obtained using multiple codes – but a key uncertainty is the effect of high magnetic fields on thermal transport and stopping powers.

Detailed designs in 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



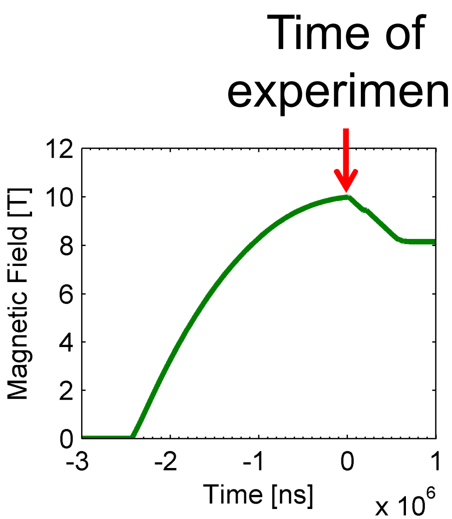
- Key target design elements
  - Liner compression
  - Magnetization
  - Laser heating

- 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
  - Magnetized burn

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

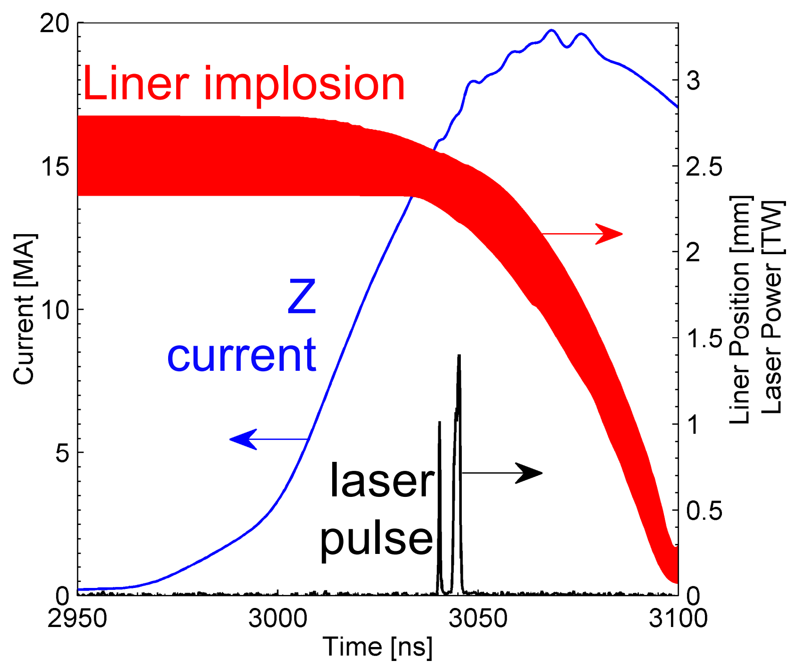
Collaborative experiments on NIF may be helpful too!

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



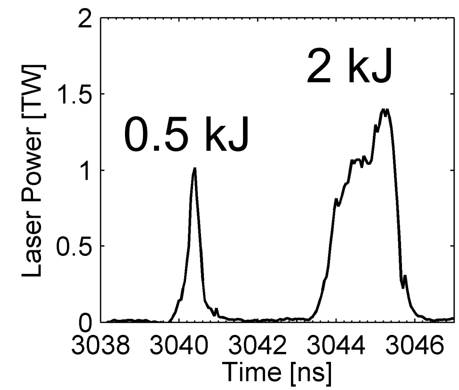
Magnetic field risetime is approximately 2 ms

B is constant over the timescale of the experiment

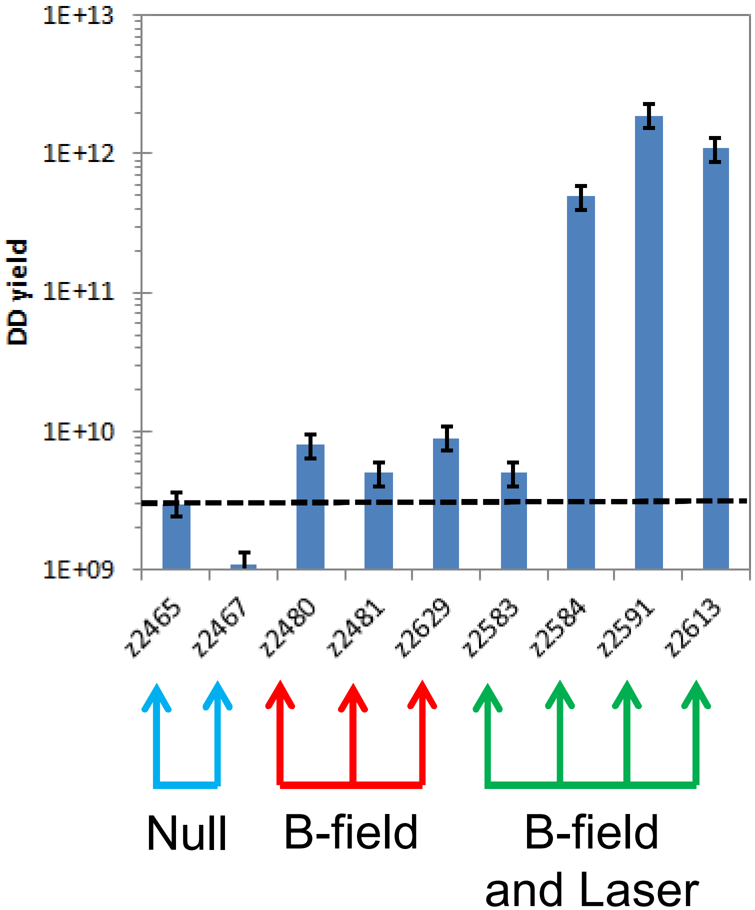


Peak current is 19 MA
Magnetic field is 10 T
Total laser energy is 2.5 kJ

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



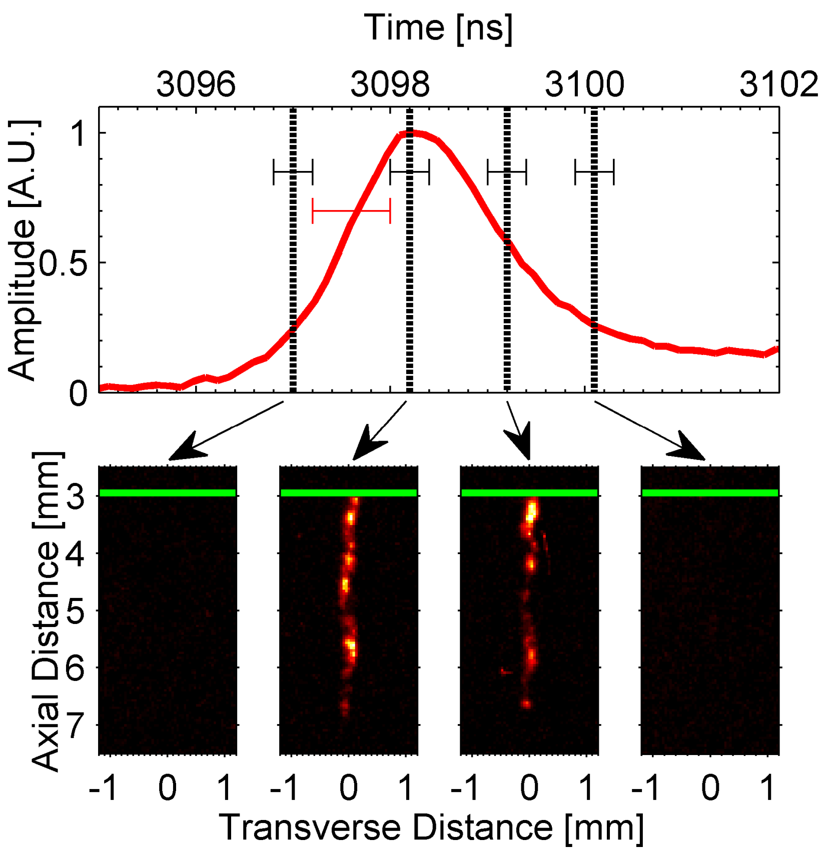
Z shots producing DD yields in excess of 10^{12} were only observed in experiments with laser and B-field



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

M.R. Gomez, S.A. Slutz, A.B. Sefkow *et al.*, submitted (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 (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!

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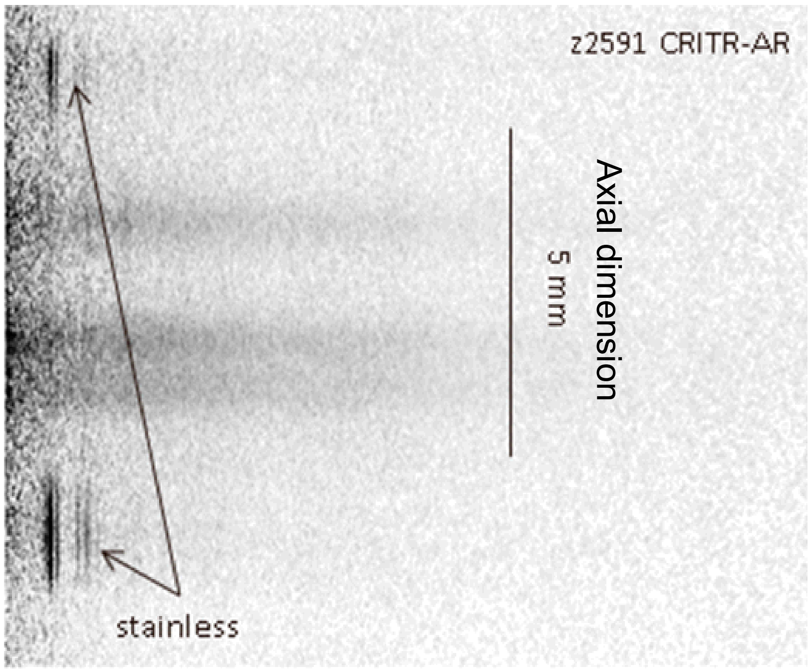
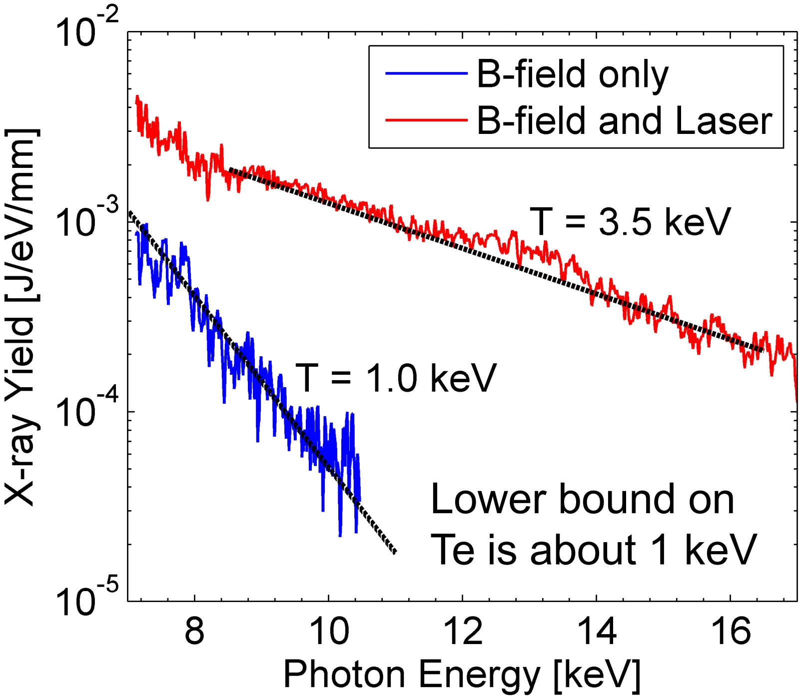
Emission lines from stainless steel (Fe, Cr, Ni) appear at the anode and cathode, but minimal high-Z contamination is observed in hot central regions



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

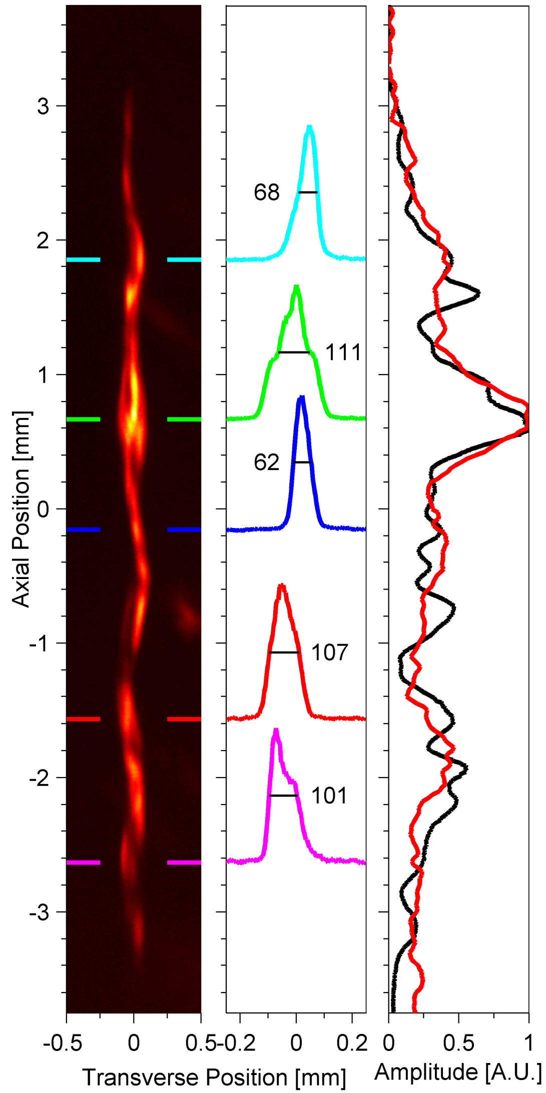


The measured electron temperature is close to the ion temperature obtained from neutron time-of-flight data; x-ray emission yields are consistent with fuel ρ ~ 0.4 g/cm^3

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

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

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



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

In addition to the significant ~2x10^{12} DD neutron yields, we measure a remarkable ~5x10^{10} DT neutrons

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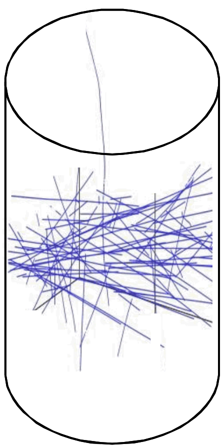
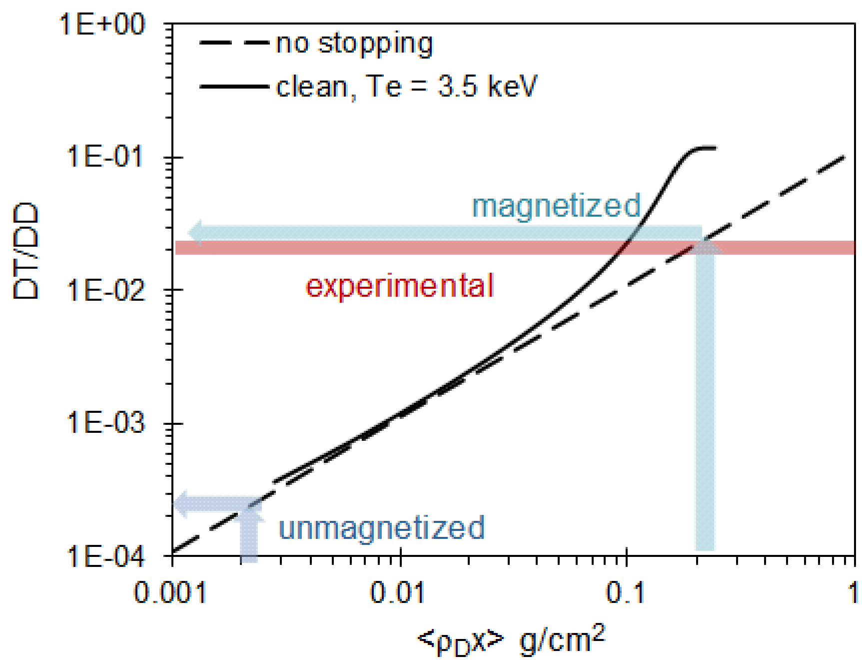
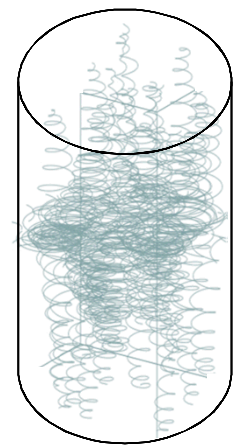
"Secondary" 14 MeV neutrons can be produced by 1 MeV tritons interacting with D fuel

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





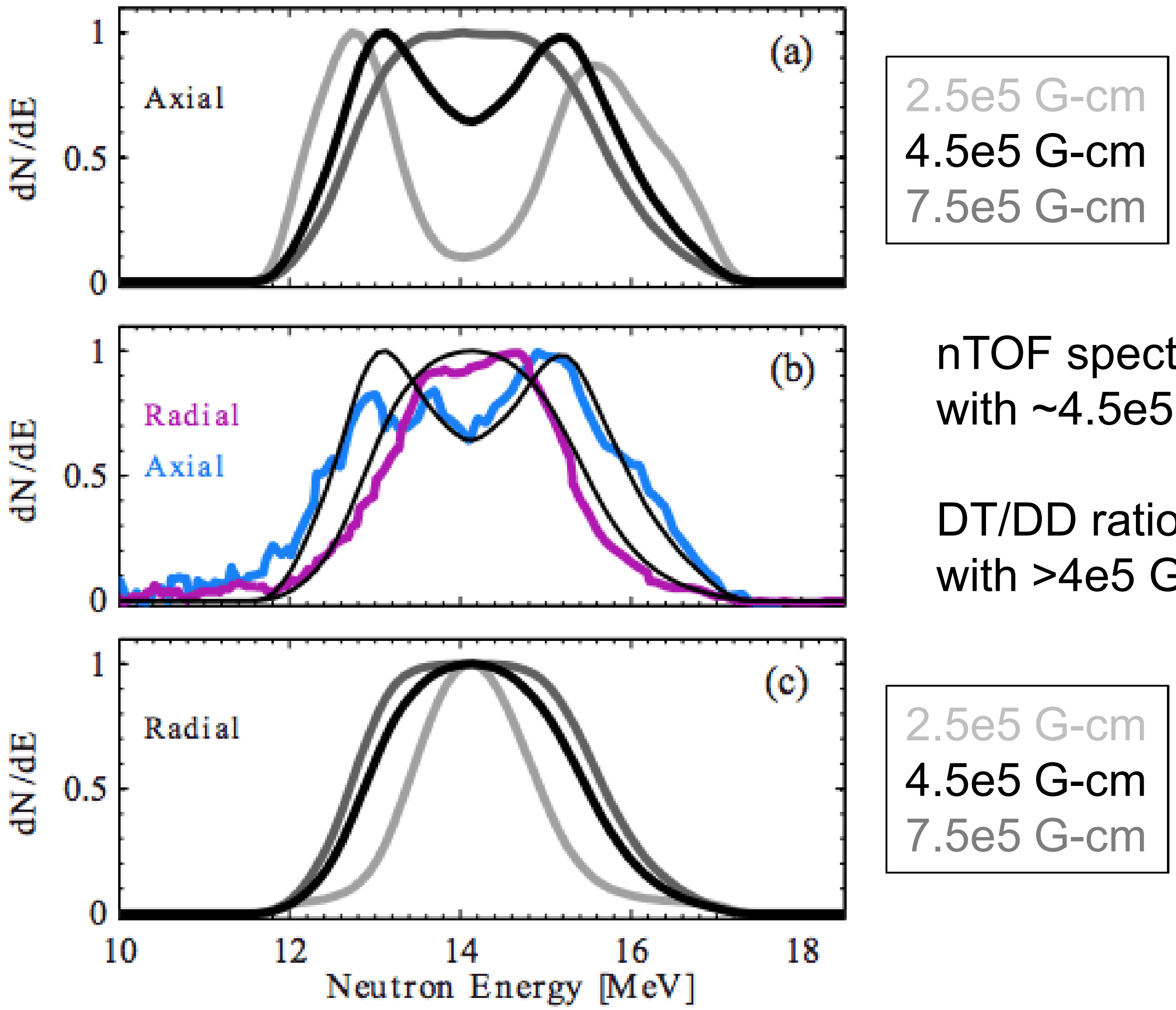


Unmagnetized plasmas must reach pressures of ~500 Gbar and ρR > 0.2 g/cm^2 to achieve the α-particle confinement required for ignition

In magnetized plasmas, thermal confinement and α-deposition are both enhanced by B, reducing pressure and ρR requirements by factors of ~100.

A field that confines tritons confines electrons -- and will confine alphas!

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



nTOF spectra consistent with ~4.5e5 G-cm

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

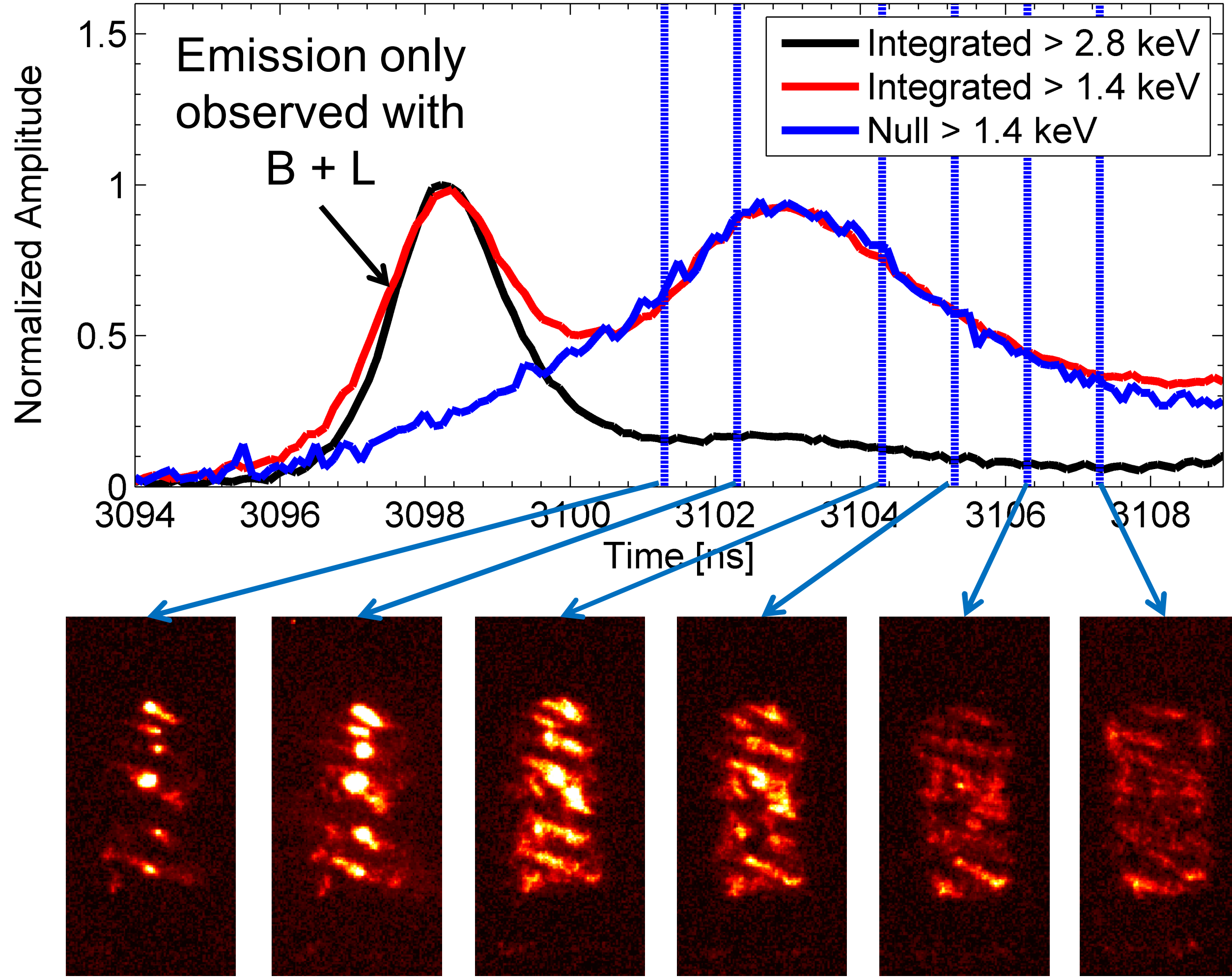
P.F. Schmit, P.F. Knapp *et al.*, submitted (2014).

Summary

- Results from initial MagLIF experiments have been encouraging, with significant DD and DT yields and strong evidence for good stability, confinement, and scaling
- A helical stagnation column with T~3 keV, r~0.4 g/cc, r ~ 50 um, and Bz ~ 10 kT is consistent with an extensive collection of neutron and x-ray data
- Both integrated and focused experiments are ongoing
- Better understanding of how high magnetic fields affect thermal transport and stopping power will increase confidence in our predictions for yield scaling with increasing current, external field, and laser power

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.*, manuscript in preparation (2014).

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

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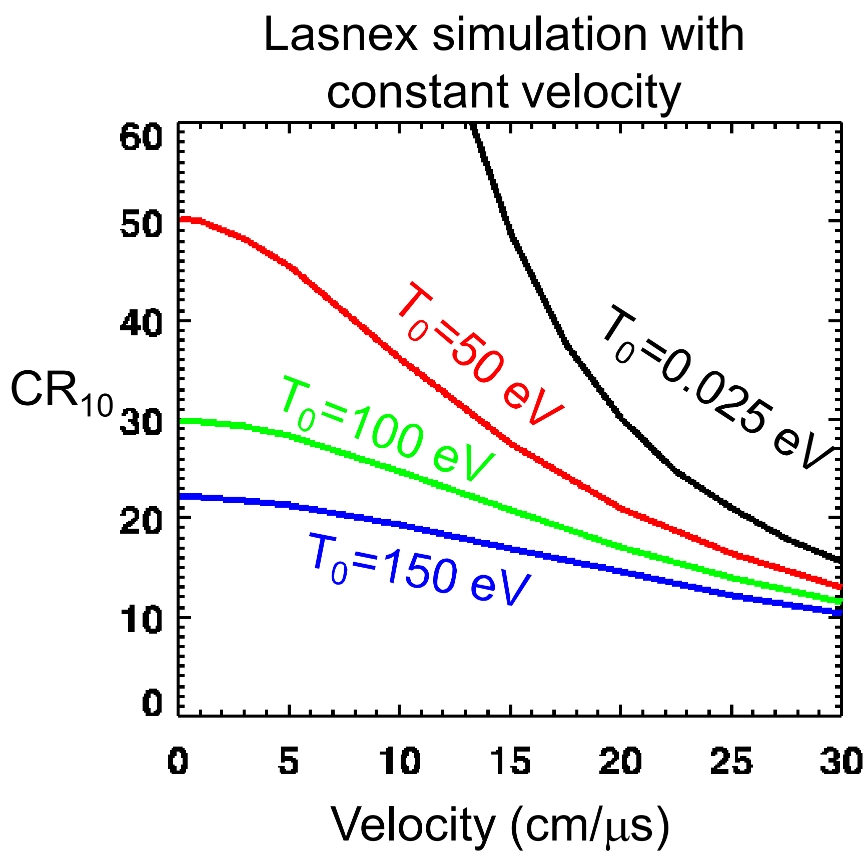


CR_{10} = Convergence Ratio (R_0/R_f) needed to obtain 10 keV (ignition) with no radiation losses or conductivity

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

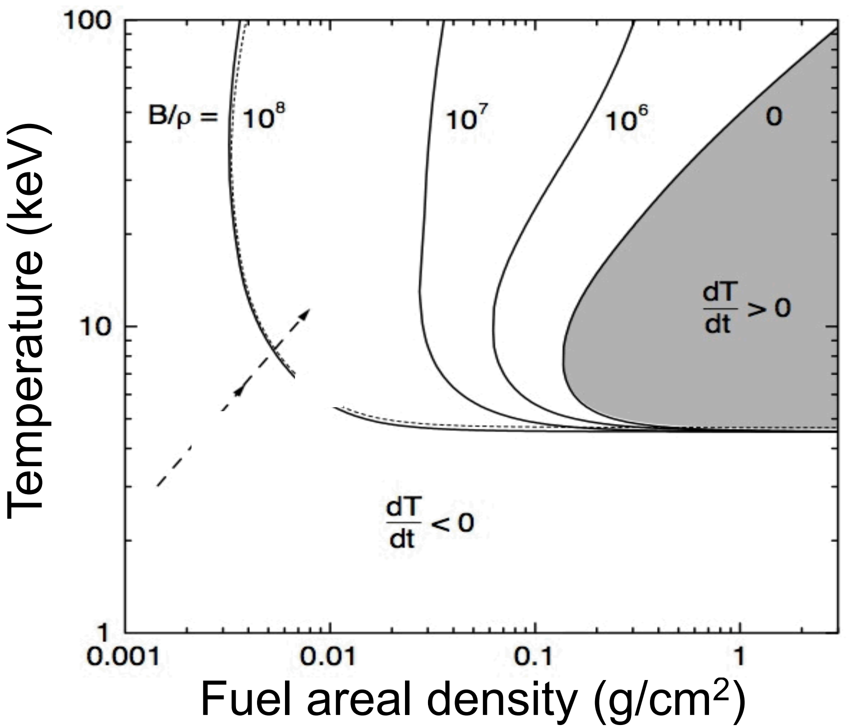
High velocities make it easier to reach fusion temperatures and also reduce the time available for losses (e.g., electron heat conduction or radiation)

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

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

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

Large values of B/ρ 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

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

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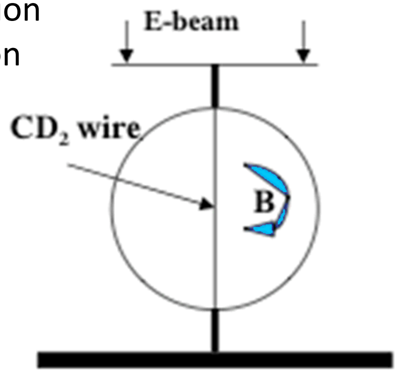
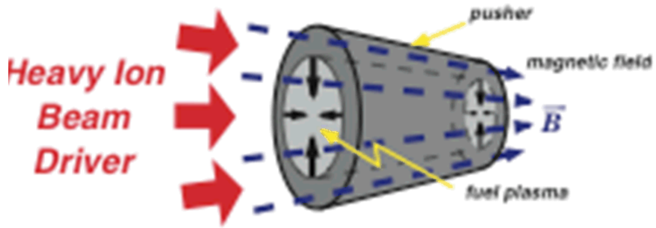
SNL Phi Target

1982 Demonstration of enhanced fusion yield with magnetization (~1e6 DD yield)



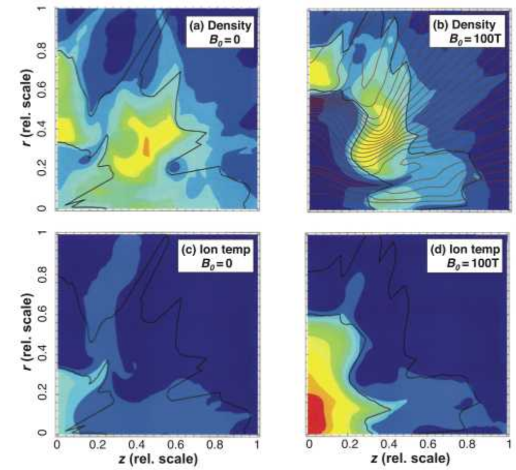
Max Planck/ITEP



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

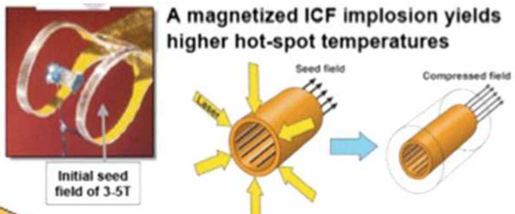
LLNL

(Perkins et al., Phys Plasmas 2013)

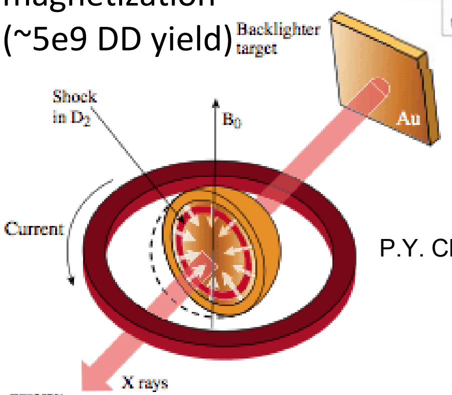


University of Rochester/LLE

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



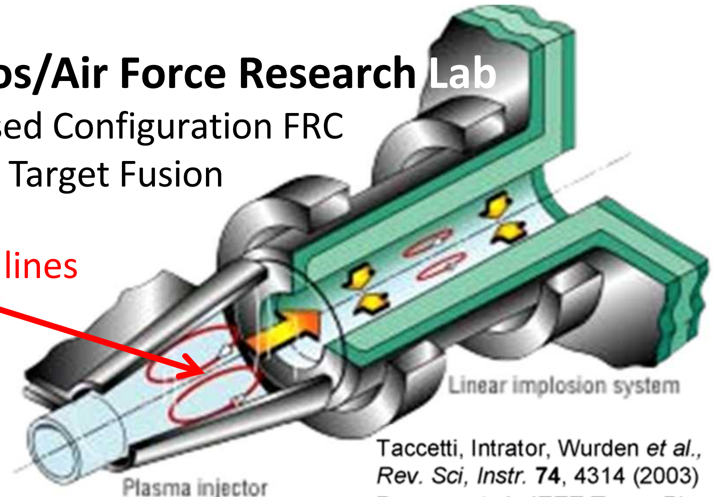
Gotchev *et al.*, *Rev. Sci. Instr.* **80**, 043504 (2009)



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

Los Alamos/Air Force Research Lab

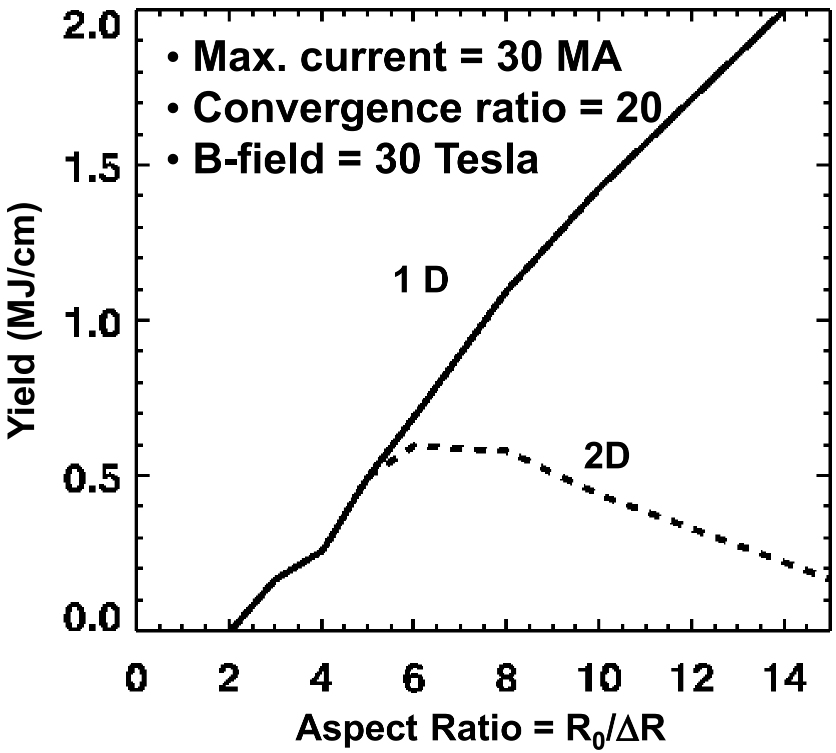
Field Reversed Configuration FRC
Magnetized Target Fusion
Shiva Star
closed field lines
FRC



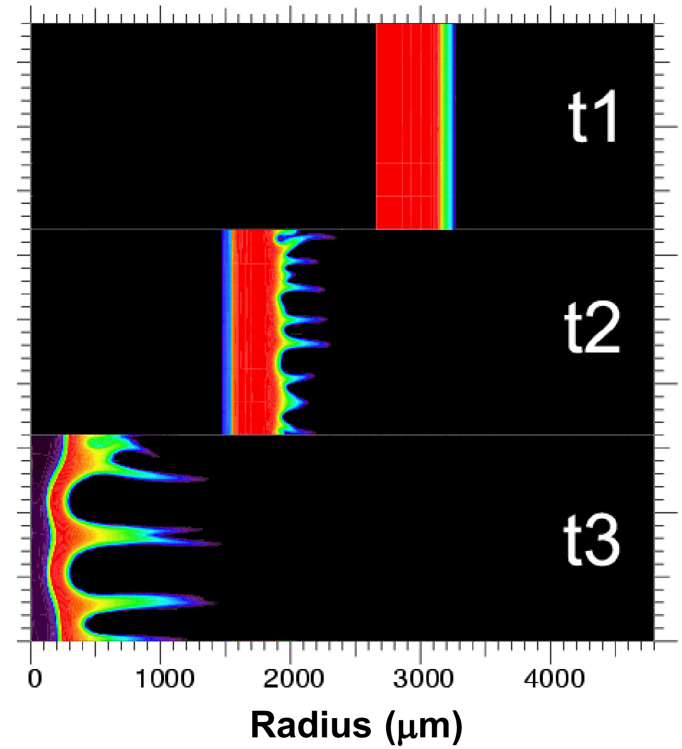
Taccetti, Intrator, Wurden *et al.*, *Rev. Sci, Instr.* **74**, 4314 (2003)
Degnan *et al.*, *IEEE Trans. Plas. Sci.* **36**, 80 (2008)

and many others…

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)

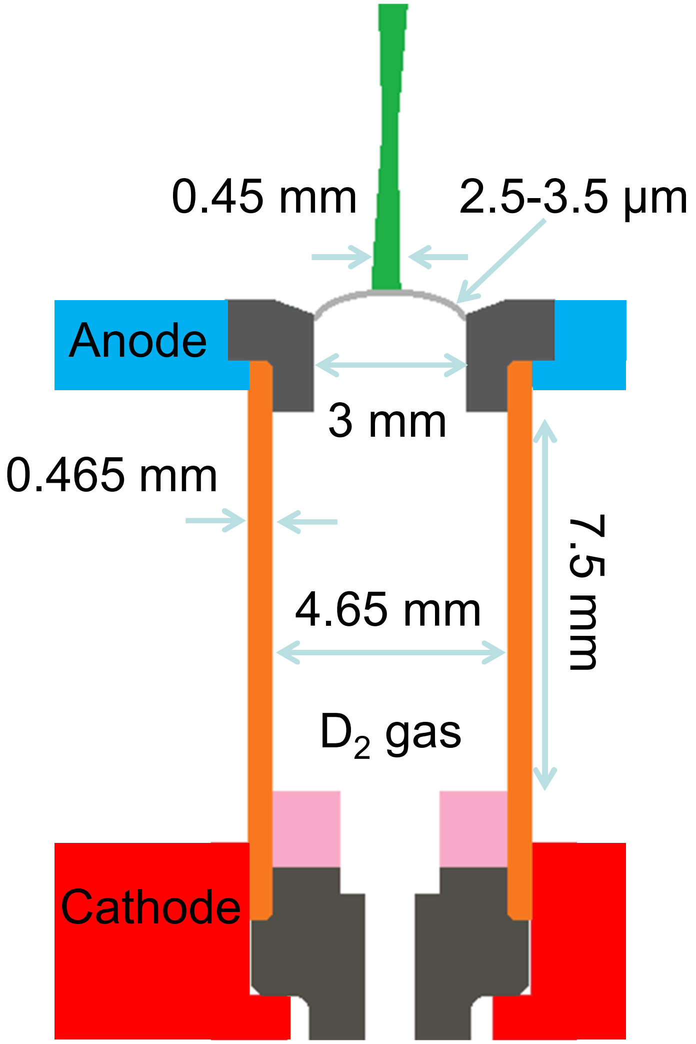


- Simulations of AR=6 Be liner show reasonably uniform fuel compression and sufficient liner ρR at stagnation to inertially confine the fuel—important because fuel density is low!

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

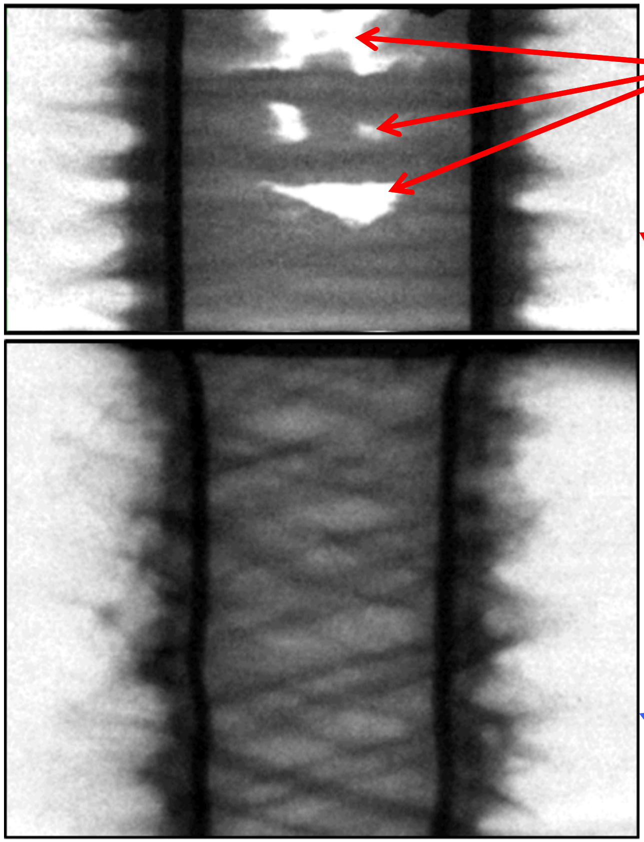
The target design for our initial experiments incorporates the knowledge gained from focused experiments and extensive simulations

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



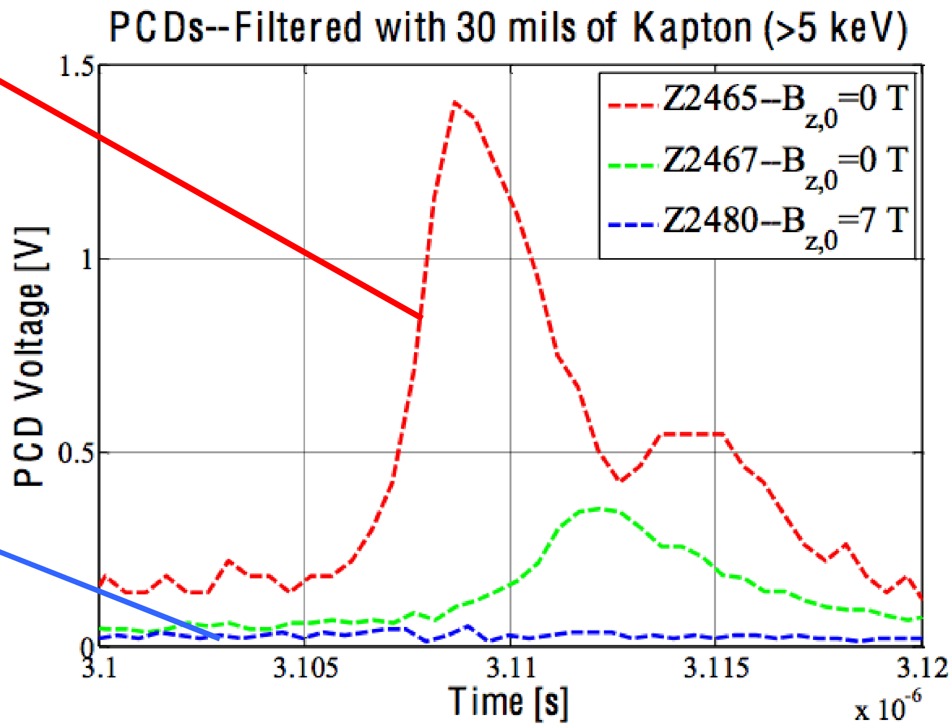
Adding an axial magnetic field reduces hard x rays and hot spots, and changes the liner instability structure from cylindrical to helical—evidence it is doing something!

Without Magnetic Field



With Magnetic Field

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



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

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