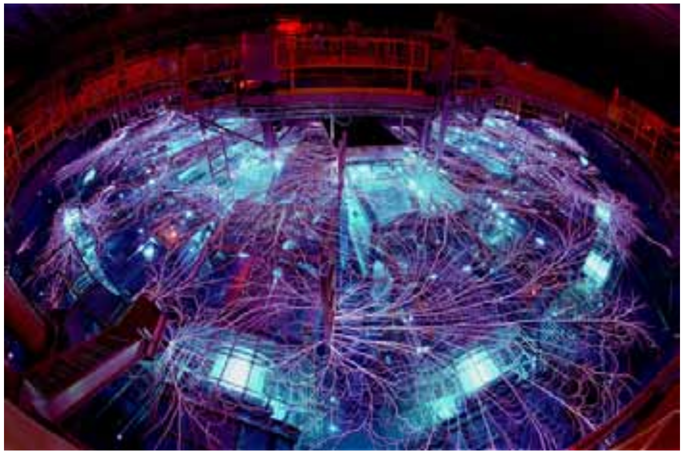
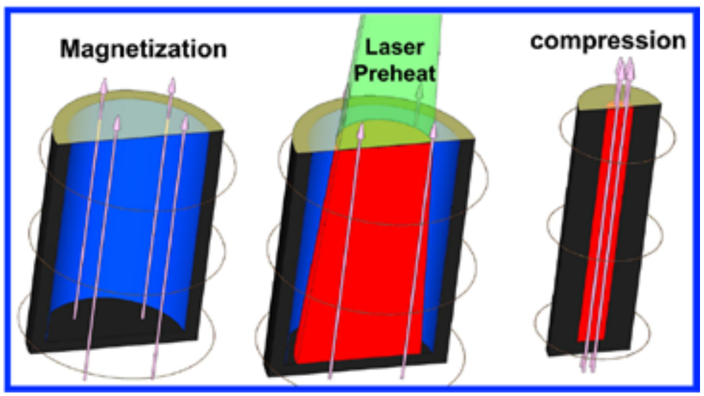
SAND2013-7354C

Exceptional service in the national interest

Sandia National Laboratories





Inertial Confinement Fusion Experiments on the Sandia Z Facility Using Magnetically-Driven Targets

Daniel B. Sinars

Sandia National Laboratories, Albuquerque, NM, USA

Inertial Fusion Sciences and Applications conference,
September 9-13, Nara, Japan

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.

Many people contributed to this work!

Sandia National Laboratories

Inertial Confinement Fusion Experiments on the Sandia Z Facility Using Magnetically-Driven Targets*

D.B. SINARS[1], M.C. HERRMANN[1], M.E. CUNEO[1], C.W. NAKHLEH[1], M.K. MATZEN[1], T.J. AWE[1], B.E. BLUE[2], G.A. CHANDLER[1], P.J. CHRISTENSON[1], G.W. COOPER[1], M. GEISSEL[1], M.R. GOMEZ[1], K.D. HAHN[1], S.B. HANSEN[1], A.J. HARVEY-THOMPSON[1], M.H. HESS[1], C. A. JENNINGS[1], P.F. KNAPP[1], D.C. LAMPPA[1], R.W. LEMKE[1], M.R. MARTIN[1], R. D. MCBRIDE[1], K.J. PETERSON[1], G.A. ROCHAU[1], D.C. ROVANG [1], C.L. RUIZ[1], D.G. SCHROEN[2], A.B. SEFKOW[1], S.A. SLUTZ[1], I.C. SMITH[1], K. TOMLINSON[2], R.A. VESEY[1], E.P. YU[1]

1) Sandia National Laboratories, Albuquerque, New Mexico, USA

2) General Atomics, San Diego, California, USA

dbsinar@sandia.gov

Thanks to many collaborators:

S. A. Slutz,[1] C. A. Jennings,[1] R. W. Lemke,[1] M. R. Martin,[1] D. C. Rovang,[1] J. B. Greenly,[2] D. B. Sinars,[1] M. E. Cuneo,[1] M. C. Herrmann,[1] D. D. Ryutov,[3] B. E. Blue,[4] K. Tomlinson,[4] K. Killebrew,[1,4] D. Schroen,[4] R. M. Stamm,[4] G. E. Smith,[5] J. K. Moore,[5] J.-P. Davis,[1] D. H. Dolan,[1] D. G. Flicker,[1] M. R. Gomez,[1] R. A. Vesey,[1] K. J. Peterson,[1] A. B. Sefkow,[1] C. W. Nakhleh,[1] P. F. Knapp,[1] T. J. Awe,[1] E. C. Harding,[1] T. J. Rogers,[1] A. Laspe,[1] M. R. Lopez,[1] I. C. Smith,[1] B. W. Atherton,[1] M. Savage,[1] W. A. Stygar,[1] J. L. Porter,[1] M. K. Matzen,[1] ***and many more…***

[1]*Sandia National Laboratories, Albuquerque, NM*

[2]*Laboratory of Plasma Studies, Cornell University, Ithaca, NY*

[3]*Lawerence Livermore National Laboratory, Livermore, CA*

[4]*General Atomics, San Diego, CA*

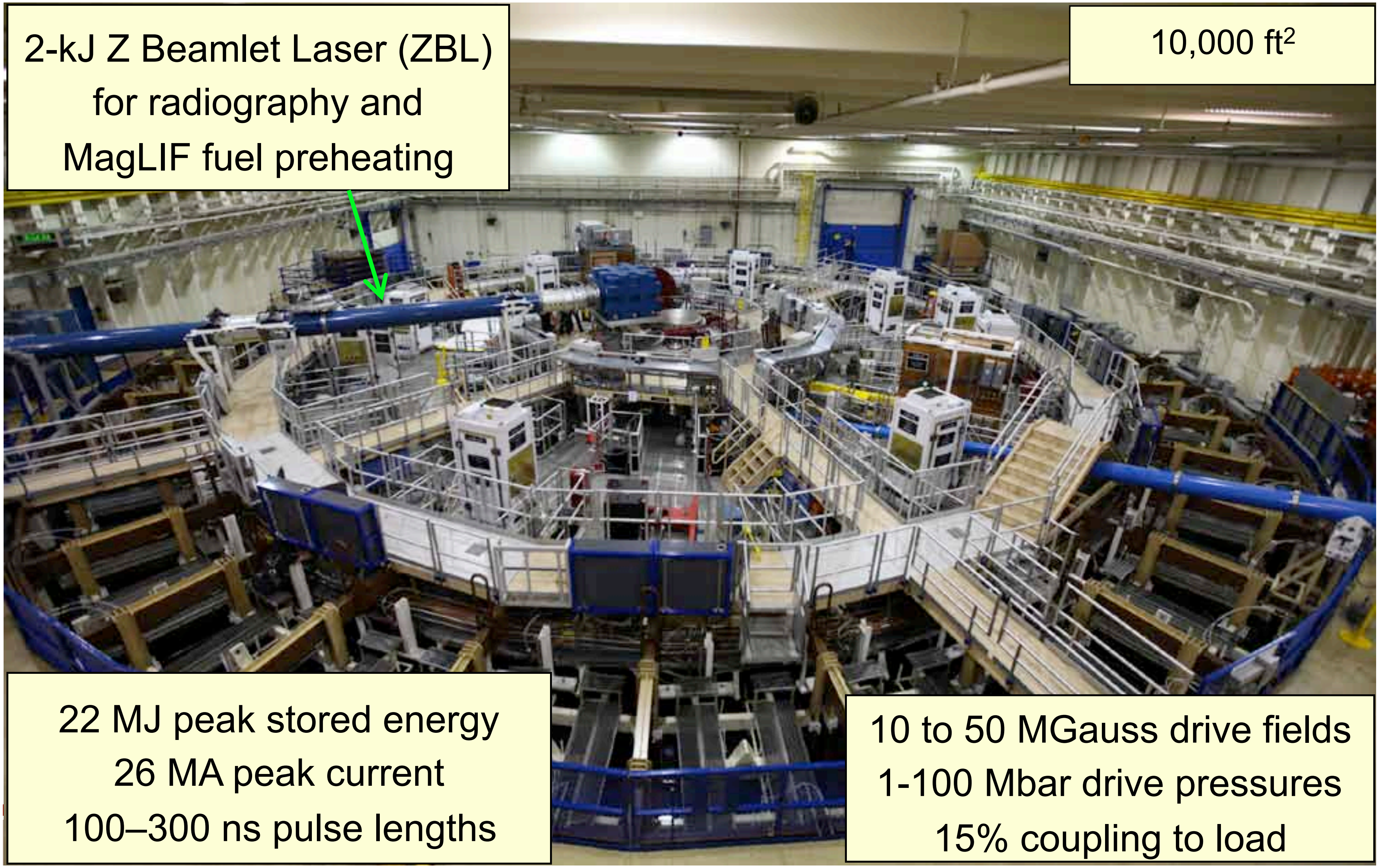
[5]*Raytheon Ktech, Albuquerque, NM*

Outline

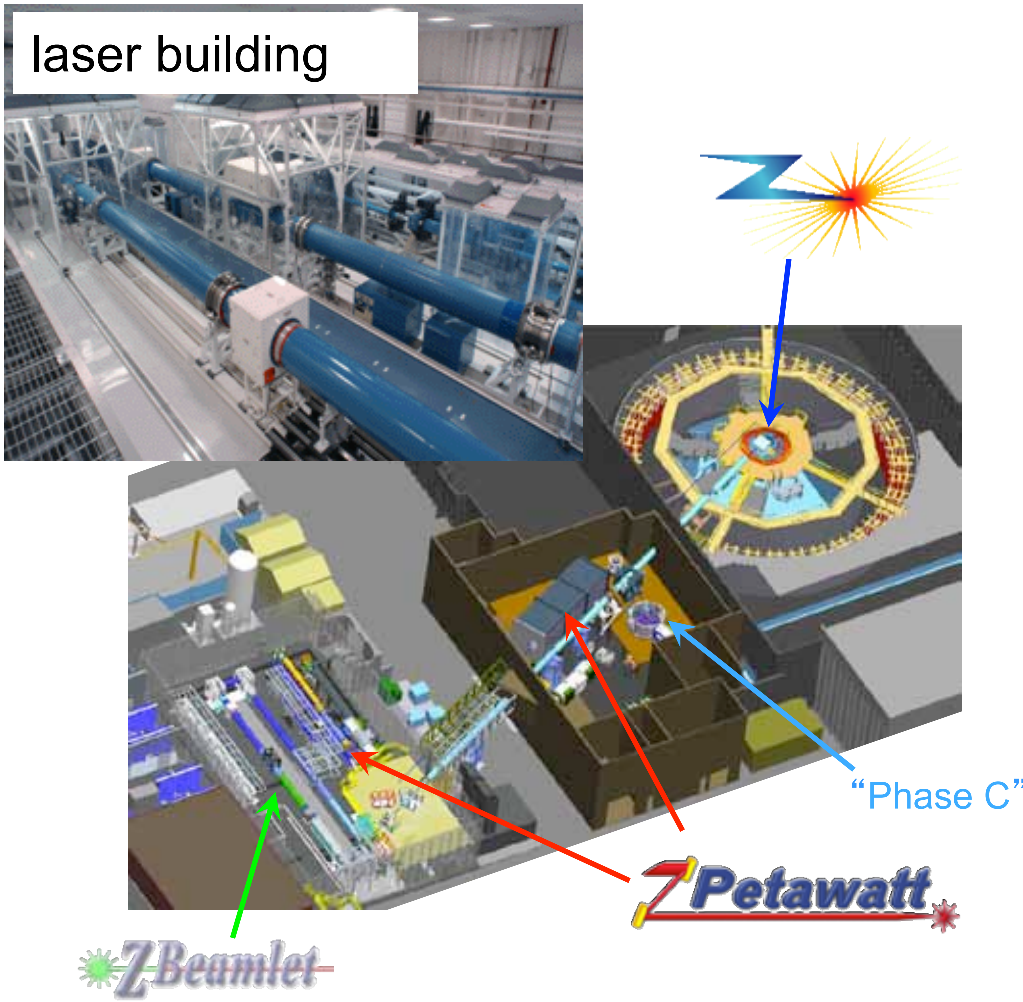
- Introduce Z, Z-Beamlet facility (briefly)
- Introduce MagLIF concept (with movie)
- Highlight progress to date with timeline?
  - Describe ABZ
  - Describe Z-Beamlet + FOA
  - Describe Liner dynamics experiments
  - Describe Standalone Preheat Experiments
  - Describe Roosevelt 1 radiograph results
  - Describe progress measuring magnetic flux compression
- Discuss next two years
  - Integrated MagLIF experiments on August 29, Sept. 3
  - Buildup to 30 T, 6 kJ preheat, higher current, etc.

The Z pulsed-power facility combines a compact MJ-class target physics platform (the Z accelerator) with a TW-class laser (ZBL)

Sandia National Laboratories



The Z-Beamlet Laser (ZBL) at Sandia* can be used to heat fusion fuel and to radiograph liner targets – Facility Scale Size



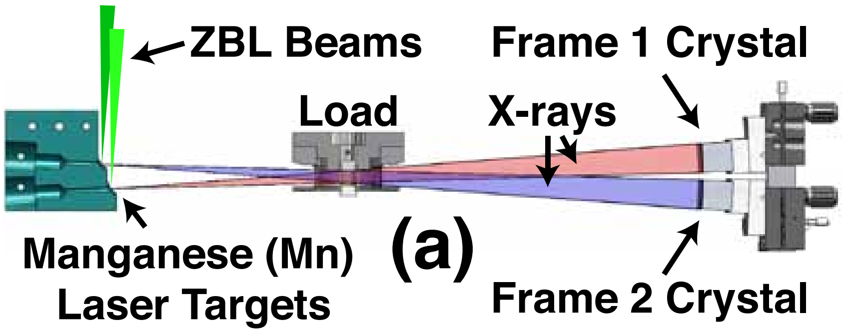
ZBL was originally a prototype laser for the National Ignition Facility (NIF)

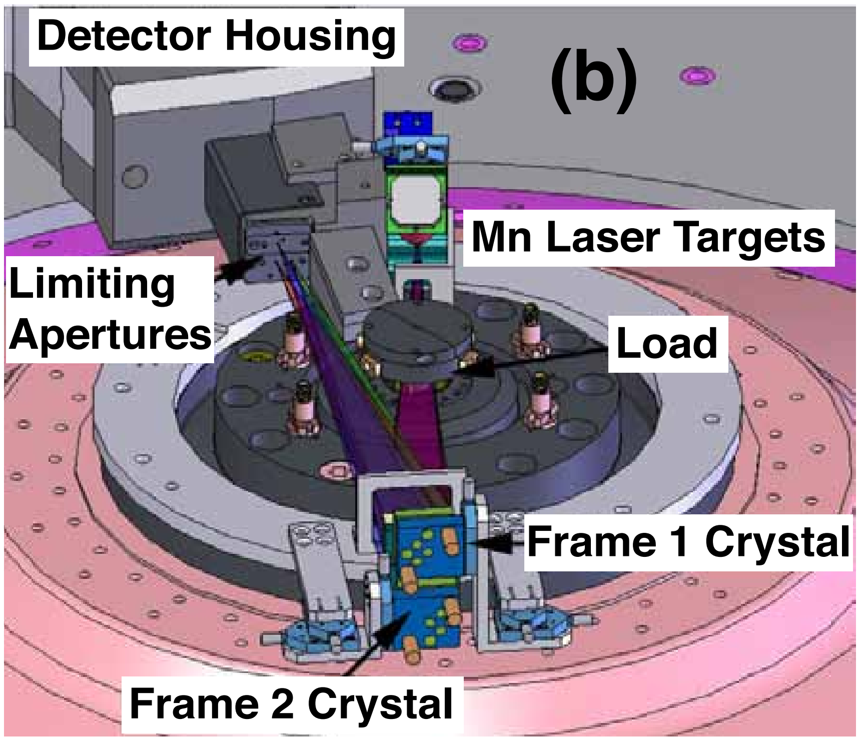
Today ZBL is located at Sandia and is routinely used to deliver ~2.4 kJ of 2ω light in 2 pulses for radiographing Z experiments

Filling out the booster amps would enable longer pulses (5–7 ns) which would extract up to 6 kJ of 1ω, for 4.2 kJ of 2ω. This energy could be used to heat fusion fuel to a few hundred eV.

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

Two-frame monochromatic (6151±0.5 eV) crystal backlighting diagnostic to study liner dynamics on Z*





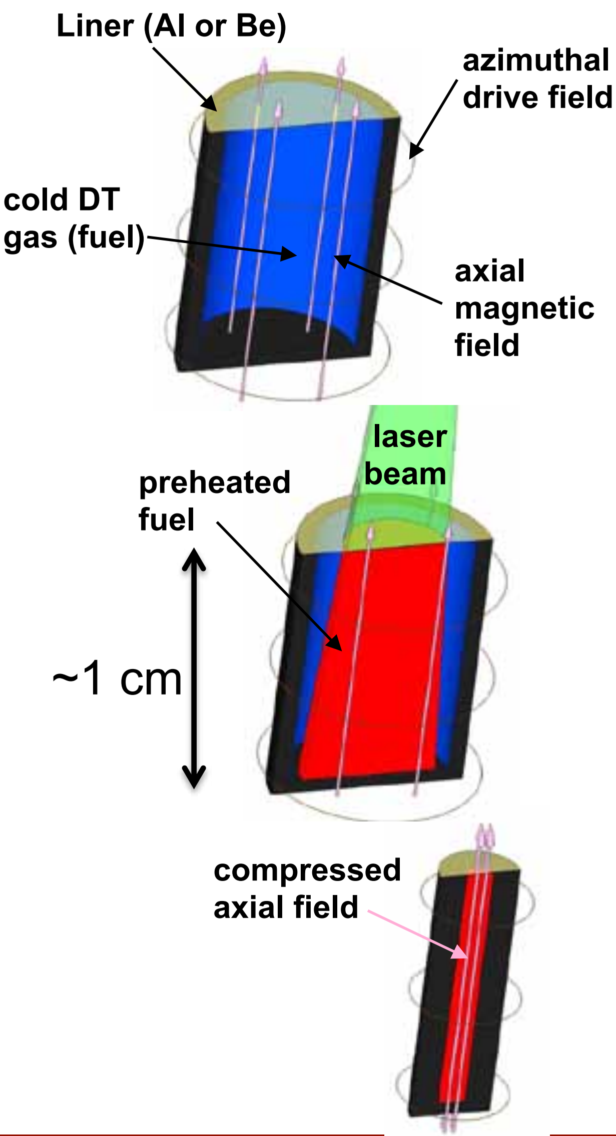
- Spherically-bent quartz crystals (22<u>4</u>3)
- Monochromatic (~0.5 eV bandpass)
- 15 micron resolution (edge-spread)
- Large field of view (10 mm x 4 mm)
- We can see through imploding beryllium (not so for aluminum and other higher-opacity materials)

- **Original concept**
  - S.A. Pikuz *et al.,* RSI (1997).
- **1.865 keV backlighter at NRL**
  - Y. Aglitskiy *et al*., RSI (1999).
- **Explored as NIF diagnostic option**
  - J.A. Koch *et al*., RSI (1999).
- **Single-frame 1.865 keV and 6.151 keV implemented on Z facility**
  - D.B. Sinars *et al*., RSI (2004).
- **Two-frame 6.151 keV on Z facility**
  - G.R. Bennett *et al*., RSI (2008).

* G. R. Bennett *et al*., RSI (2008).

A new final optics assembly was successfully commissioned on Z on August 29

We have made good progress toward evaluating our Magnetized Liner Inertial Fusion (MagLIF)* concept

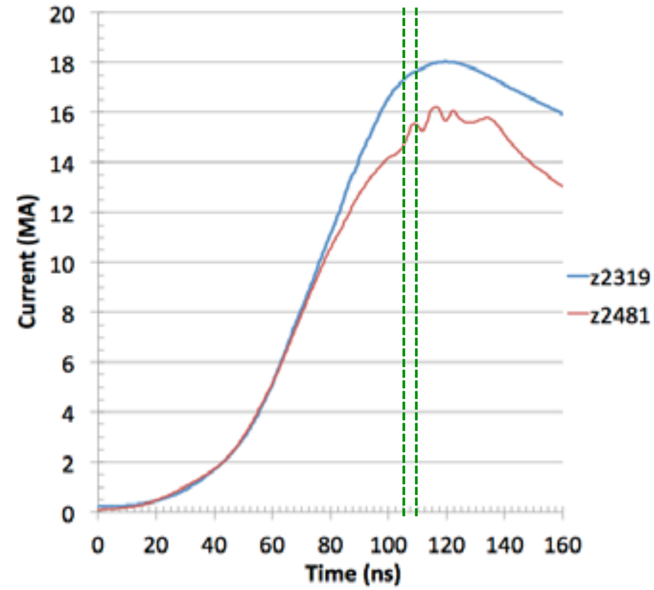


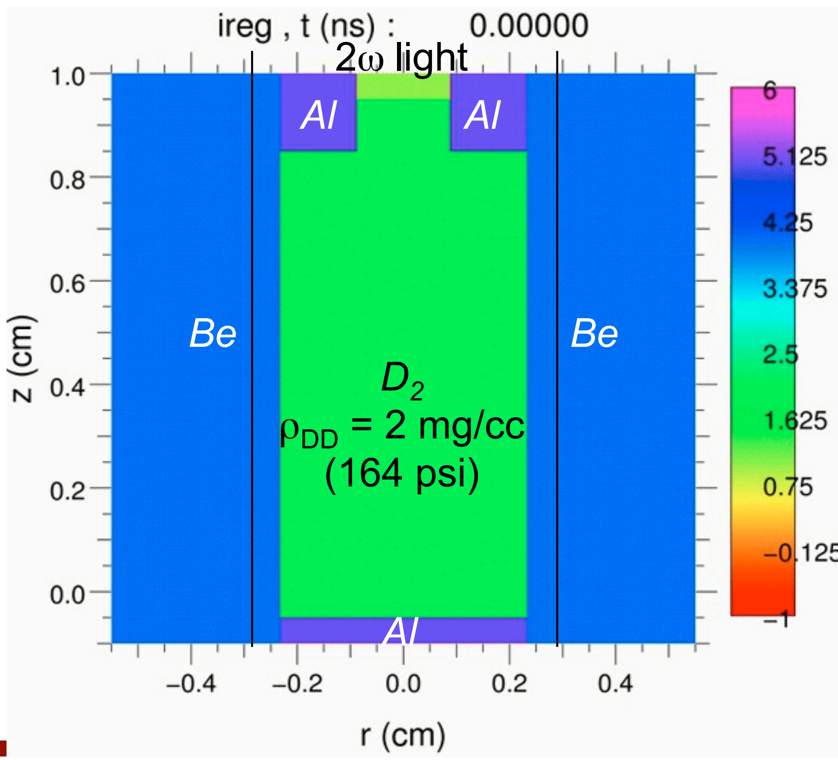
- An initial 30 T axial magnetic field is applied
  - Inhibits thermal conduction losses
  - Enhances alpha particle energy deposition
  - May help stabilize implosion at late times
- During implosion, the fuel is heated using the Z-Beamlet laser (about 6 kJ)
  - Preheating reduces the compression needed to obtain ignition temperatures to about 25 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
- It may be possible to achieve ~100 kJ yield on Z

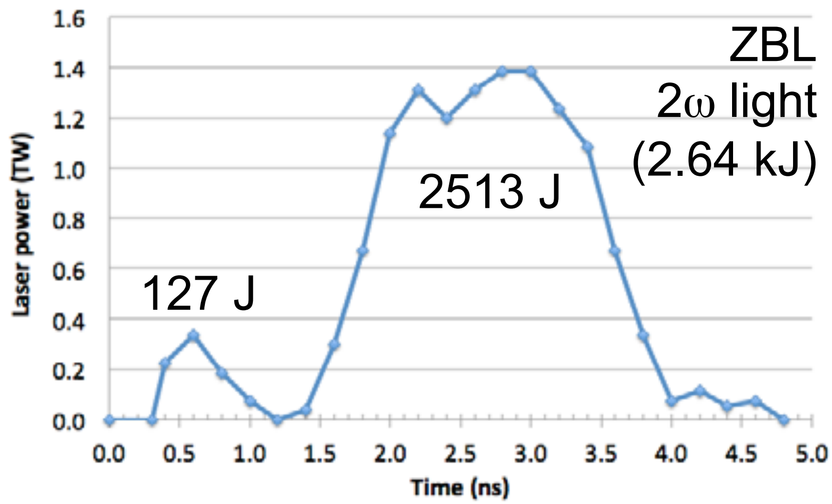
*S.A. Slutz *et al.*, Phys. Plasmas 17, 056303 (2010). S.A. Slutz and R.A. Vesey, Phys. Rev. Lett. (2012).

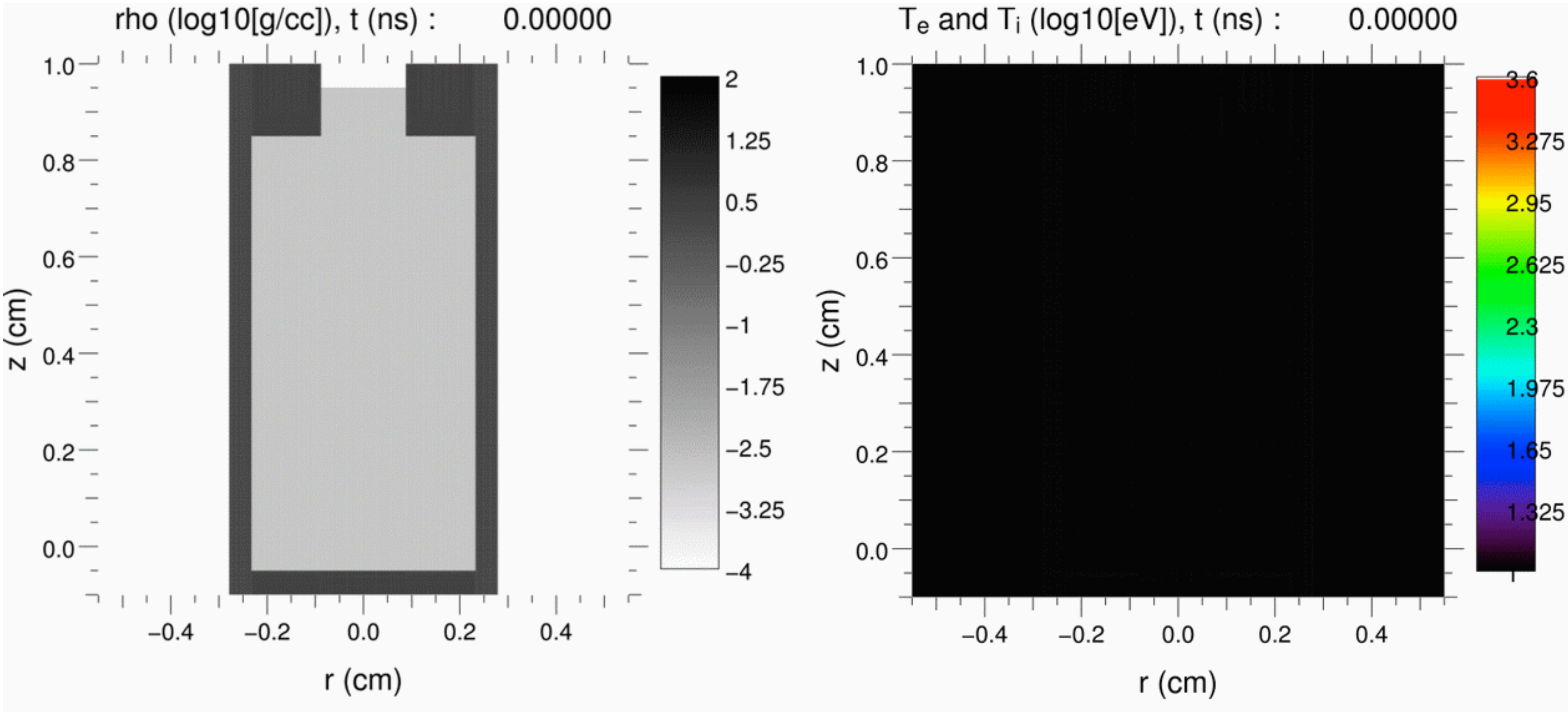
Fully integrated HYDRA simulation with DD fuel, B_z=10T, I_{max}=18 MA, E_{laser}=2.64 kJ

- B_z^0 = 10 T, D_{LEH} = 1.76 mm, Δz_{gas} = 1 cm, Δz_{imp} = 9 mm
- ρ_{gas} = 2 mg/cc, Δz_{win} = 2.47 μm (1.24 μm deformed)
- Roosevelt 1 *Be* liner, Z=6, 138 mg/cm
- Imposing I(t) from z2319 (no B_z, not 9 mm load)
- The 2ω diameter at the LEH window is D_{laser}= 800 μm
- Peak power of 1.4 TW, irradiance ~1-2e14 W cm^{-2}
- ZBL fires at 105 ns (+45 ns from t_{5MA}, -47 ns from t_{stag})

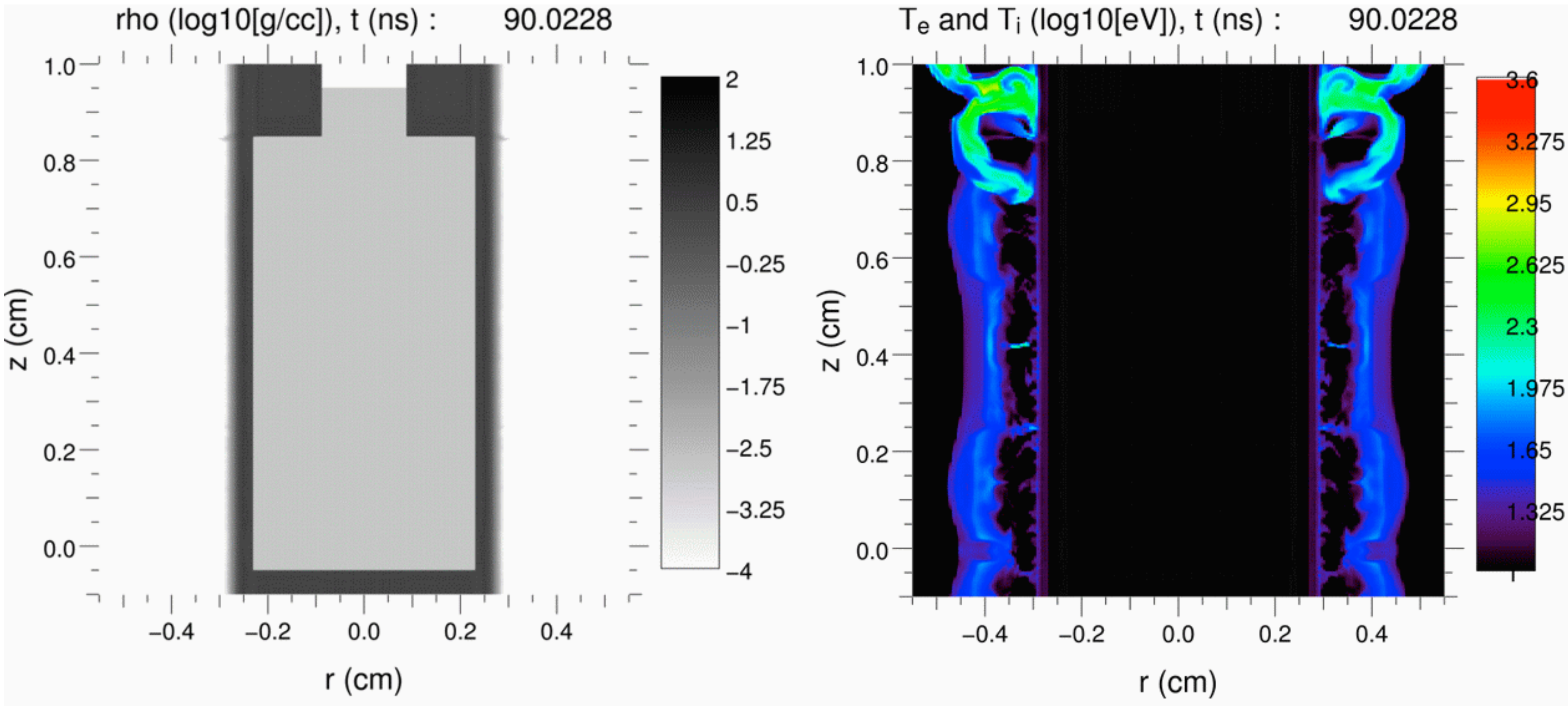




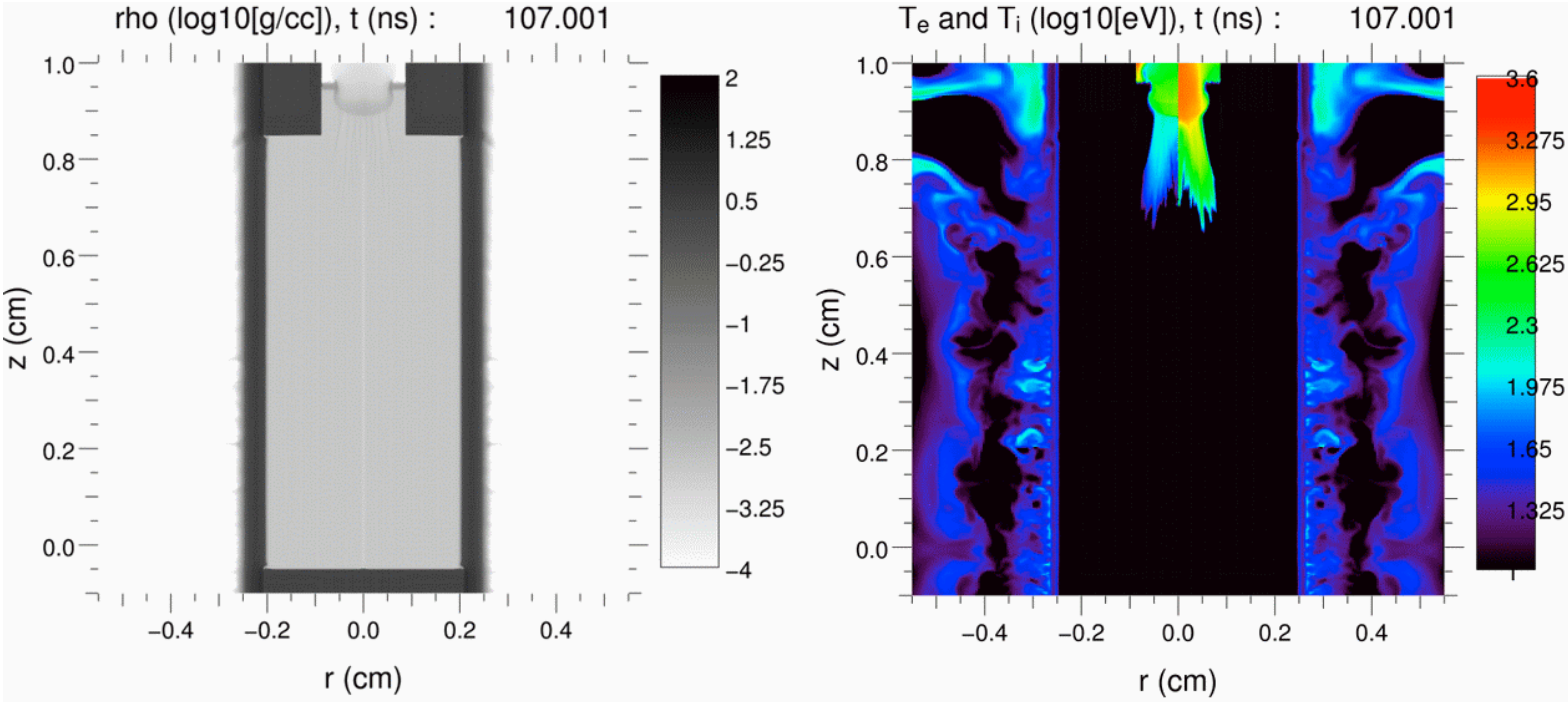




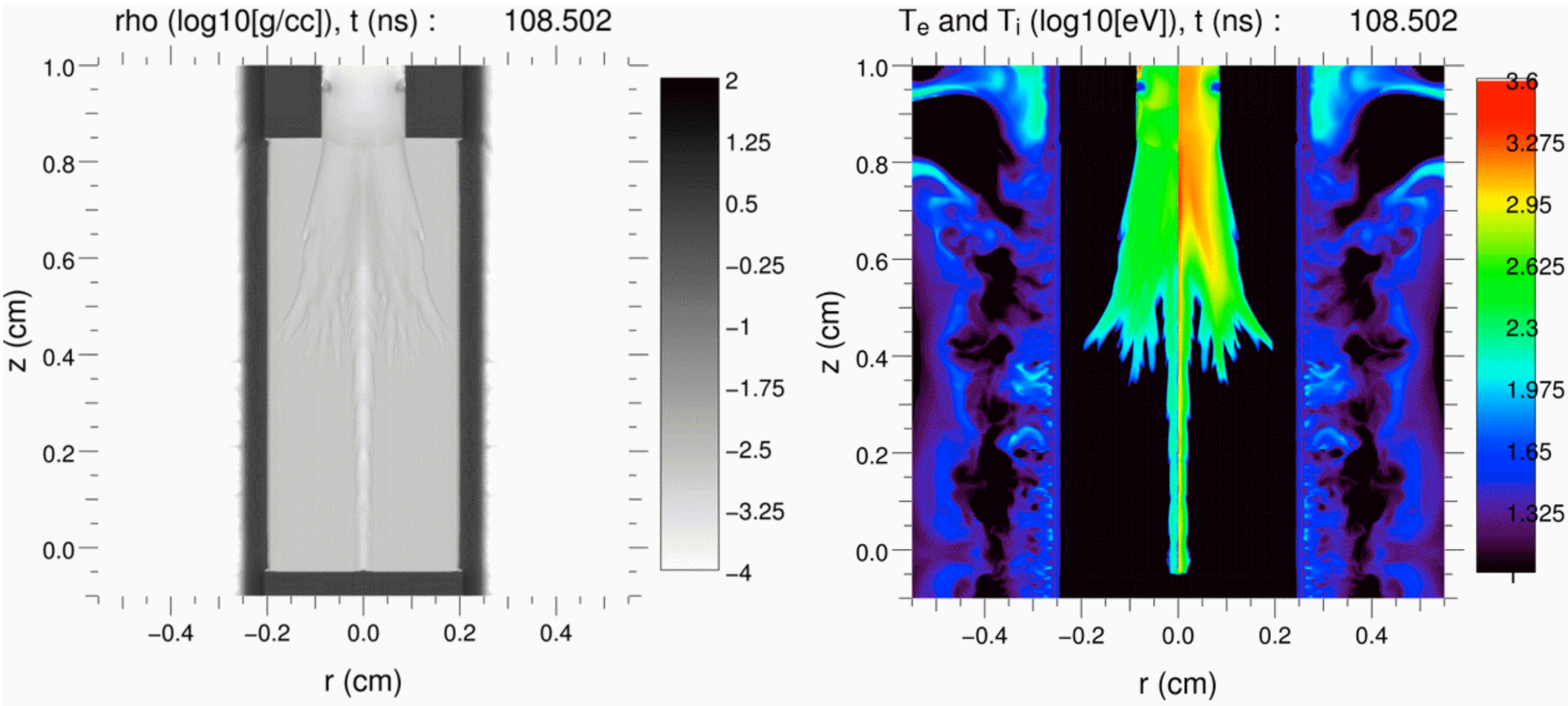
rho (log10[g/cc]), t (ns) : 0.00000
1.0
0.8
0.6
0.4
0.2
0.0
z (cm)
−0.4
−0.2
0.0
0.2
0.4
r (cm)
2
1.25
0.5
−0.25
−1
−1.75
−2.5
−3.25
−4
Te and Ti (log10[eV]), t (ns) : 0.00000
3.6
3.275
2.95
2.625
2.3
1.975
1.65
1.325



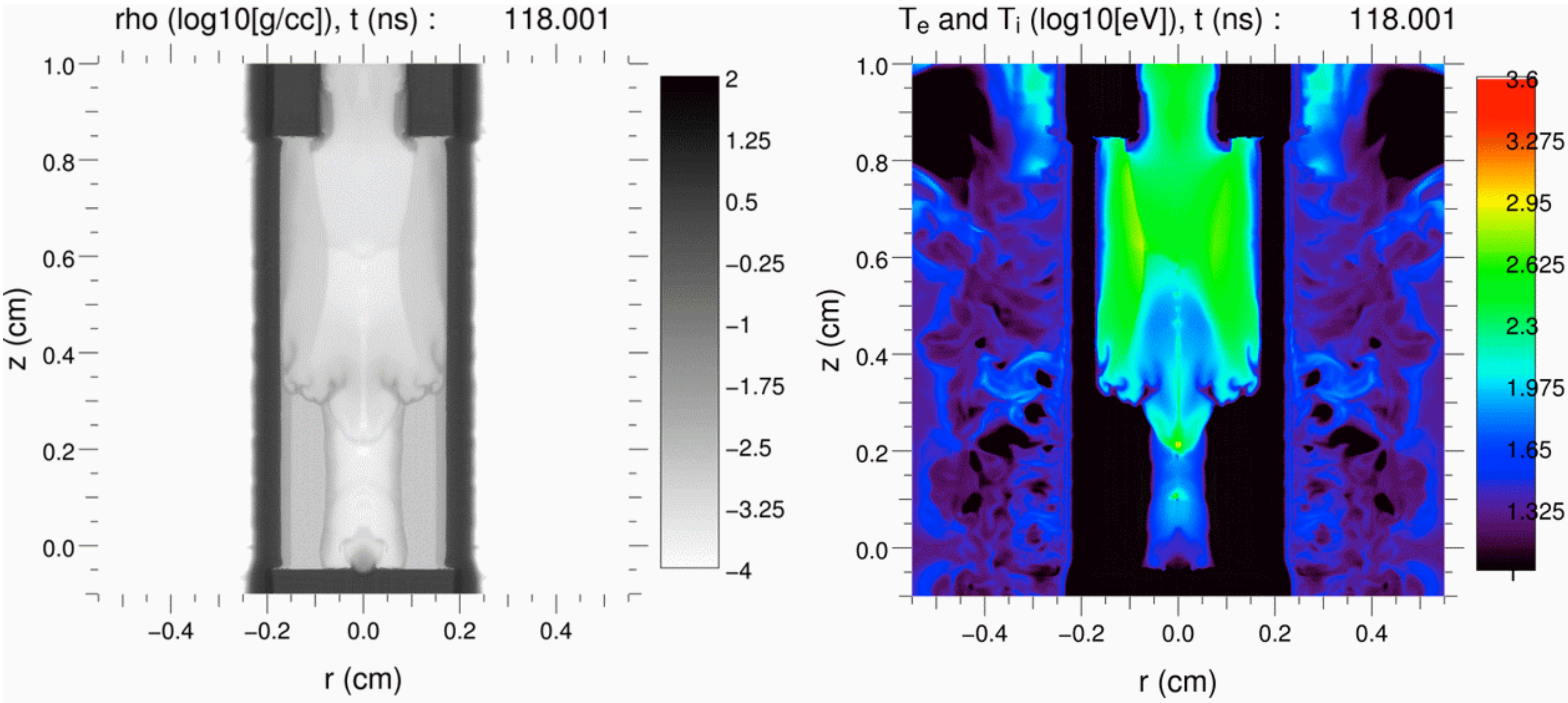
rho (log10[g/cc]), t (ns) : 90.0228
z (cm)
r (cm)
2
1.25
0.5
−0.25
−1
−1.75
−2.5
−3.25
−4
Te and Ti (log10[eV]), t (ns) : 90.0228
z (cm)
r (cm)
3.6
3.275
2.95
2.625
2.3
1.975
1.65
1.325

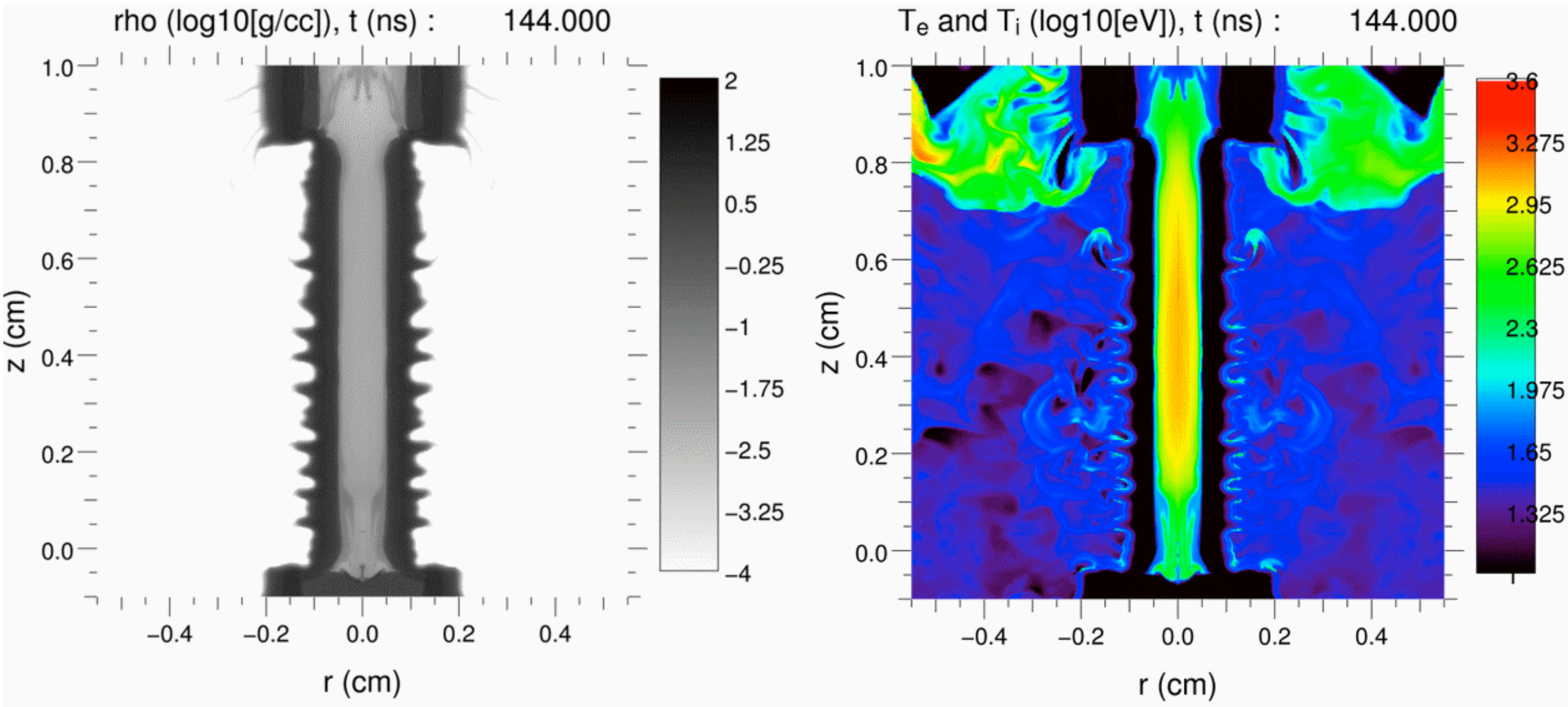


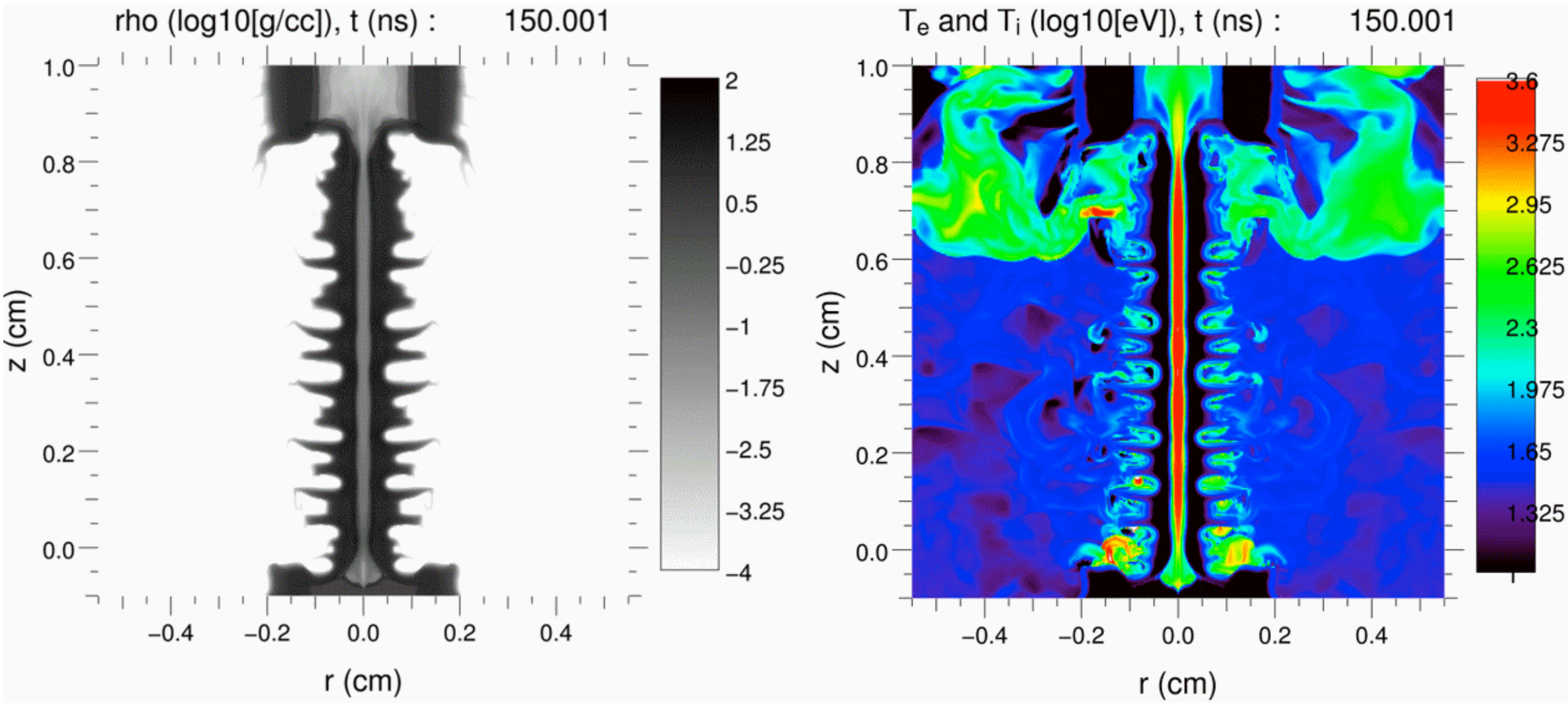
rho (log10[g/cc]), t (ns) : 107.001
z (cm)
r (cm)
2
1.25
0.5
−0.25
−1
−1.75
−2.5
−3.25
−4
Te and Ti (log10[eV]), t (ns) : 107.001
z (cm)
r (cm)
3.6
3.275
2.95
2.625
2.3
1.975
1.65
1.325

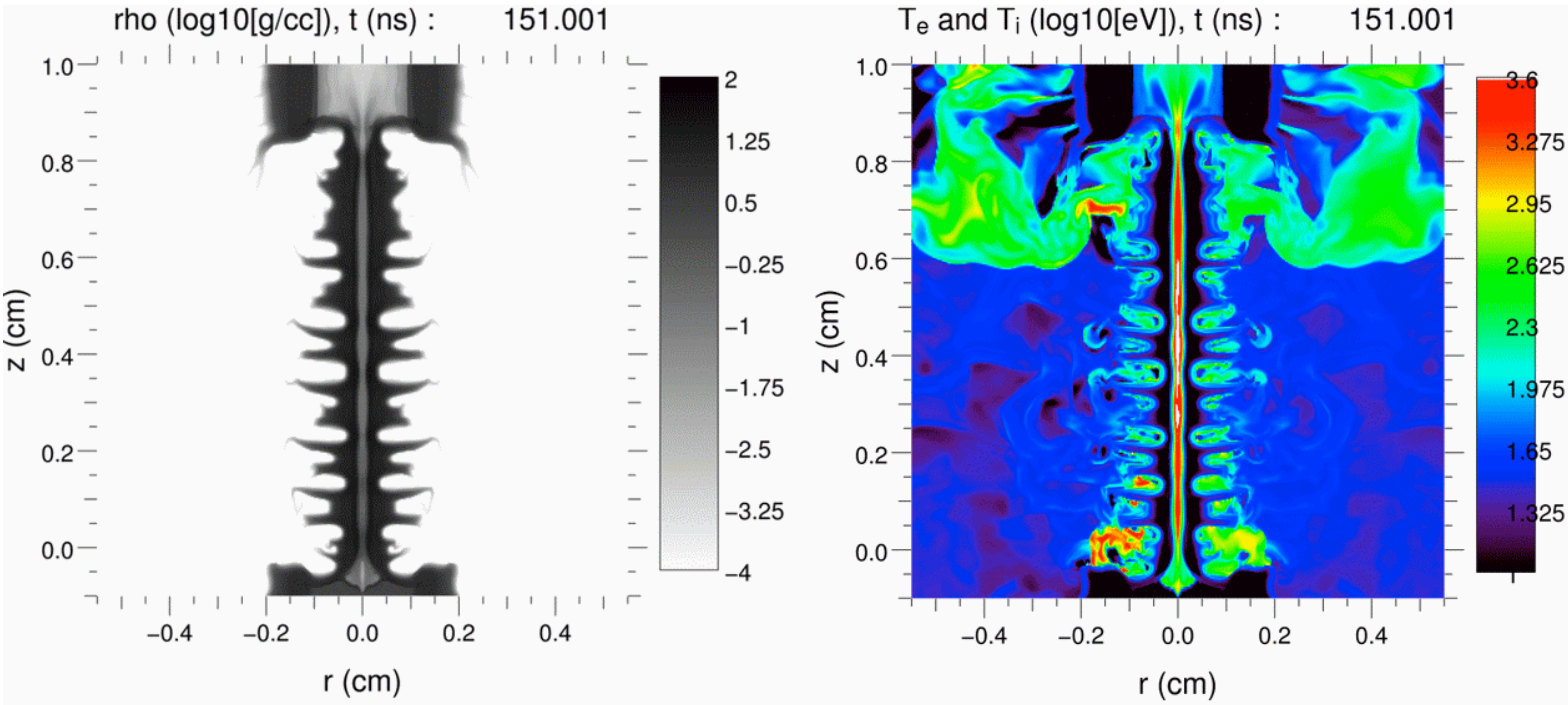


rho (log10[g/cc]), t (ns) : 108.502
z (cm)
r (cm)
1.0
0.8
0.6
0.4
0.2
0.0
−0.4
−0.2
0.0
0.2
0.4
2
1.25
0.5
−0.25
−1
−1.75
−2.5
−3.25
−4
Te and Ti (log10[eV]), t (ns) : 108.502
3.6
3.275
2.95
2.625
2.3
1.975
1.65
1.325


rho (log10[g/cc]), t (ns) : 118.001
z (cm)
r (cm)
1.0
0.8
0.6
0.4
0.2
0.0
−0.4
−0.2
0.0
0.2
0.4
2
1.25
0.5
−0.25
−1
−1.75
−2.5
−3.25
−4
T_e and T_i (log10[eV]), t (ns) : 118.001
3.6
3.275
2.95
2.625
2.3
1.975
1.65
1.325


rho (log10[g/cc]), t (ns) : 144.000
z (cm)
r (cm)
2
1.25
0.5
−0.25
−1
−1.75
−2.5
−3.25
−4
Te and Ti (log10[eV]), t (ns) : 144.000
z (cm)
r (cm)
3.6
3.275
2.95
2.625
2.3
1.975
1.65
1.325


rho (log10[g/cc]), t (ns) : 150.001
z (cm)
r (cm)
T_e and T_i (log10[eV]), t (ns) : 150.001
z (cm)
r (cm)



rho (log10[g/cc]), t (ns) : 151.001
z (cm)
r (cm)
2
1.25
0.5
−0.25
−1
−1.75
−2.5
−3.25
−4
Te and Ti (log10[eV]), t (ns) : 151.001
3.6
3.275
2.95
2.625
2.3
1.975
1.65
1.325

We have installed an 8 mF, 15 kV, 900 kJ capacitor bank on Z to drive 10-30 T axial fields over a several cm^3 volume for MagLIF

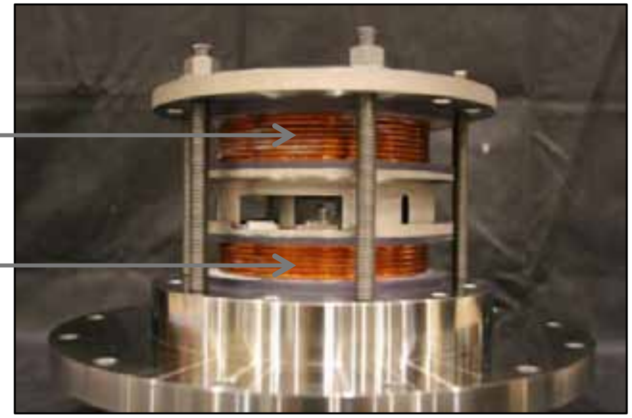
Sandia National Laboratories

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

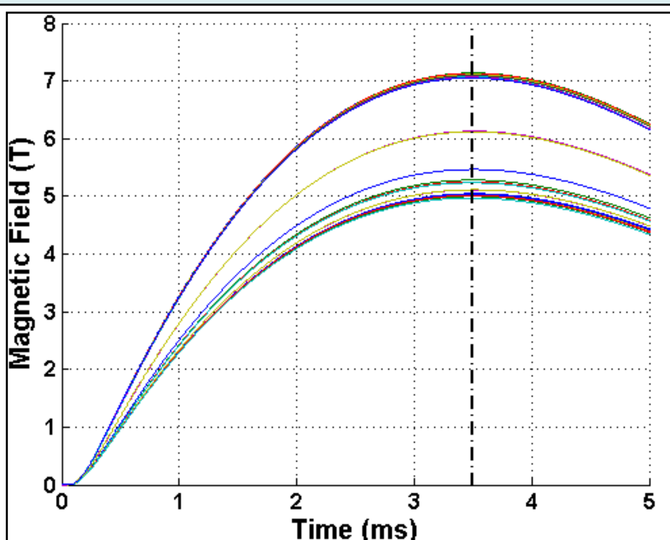
MagLIF prototype assembly with test windings of coils

80-turn coil

60-turn coil



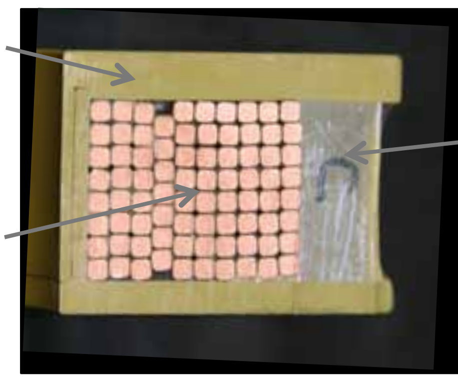
MagLIF on-axis magnetic field data taken at our Systems Integration Test Facility in Bldg. 970



Cross section of 80-turn coil prototype

Torlon housing

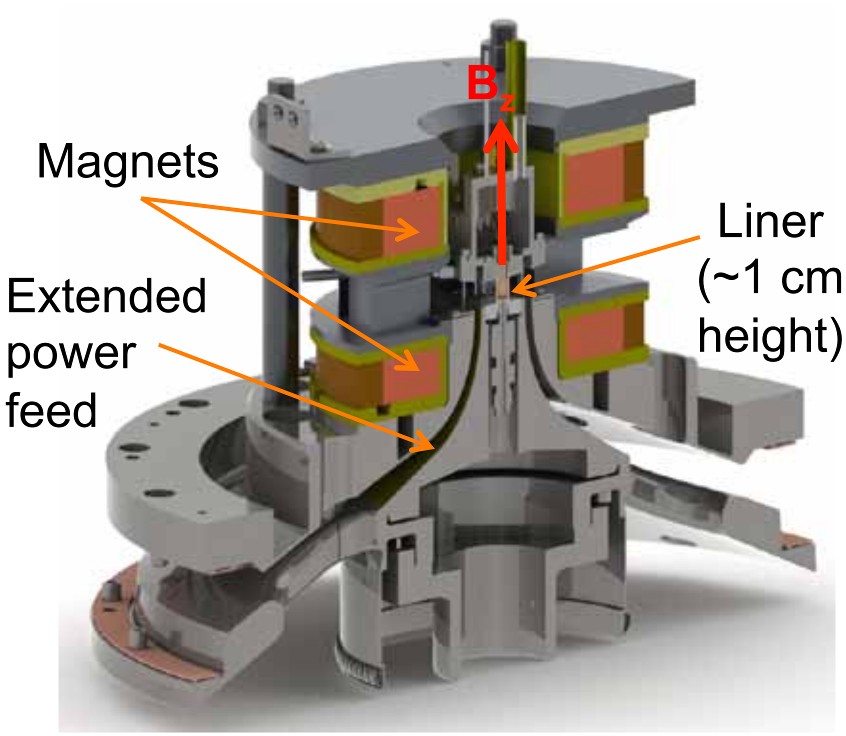
#11 sq. copper wire with double Kapton insulation



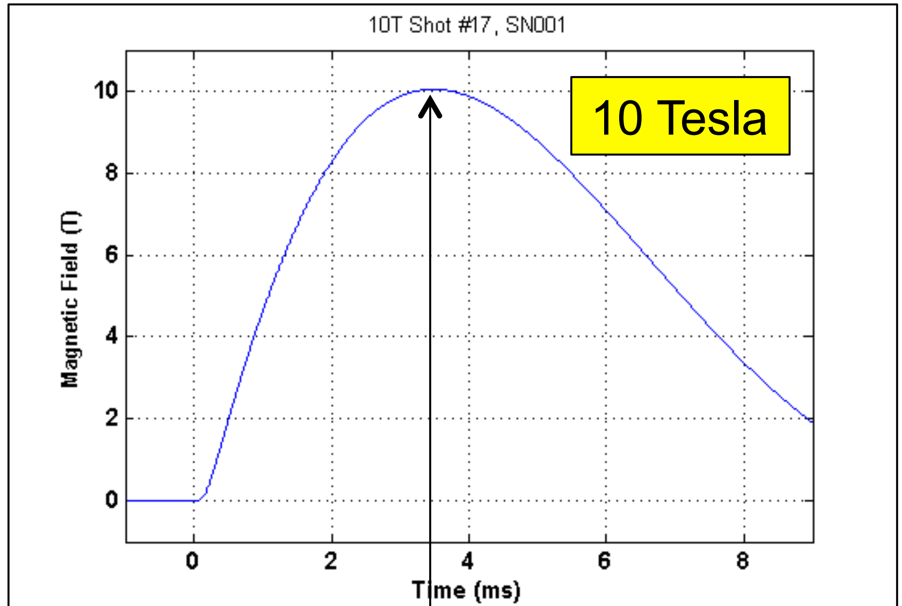
Zylon/epoxy shell provides external reinforcement

Prototype coil development: Jim Puissant, Raytheon-Ktech, Albuquerque
Production coils for Z: Milhous Corporation, Amherst, VA.

Hardware delivers up to 20 MA with no anomalous losses due to axial field. System used on 4 ICF shots on Z to make 7-10 T fields



10 T field coil configuration shown, fields up to 30 T possible by increasing the coil cross section and eliminating the side-on view of liner



Time to peak field = 3.49 ms

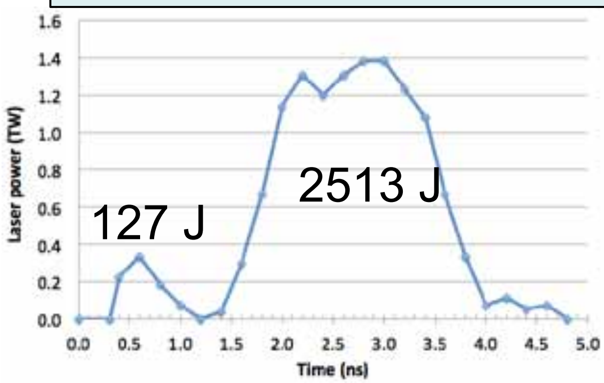
Long time scale needed to allow field to diffuse through the liner without deformation

Energy storage is sufficient to meet our long-term goal of a 30 T field

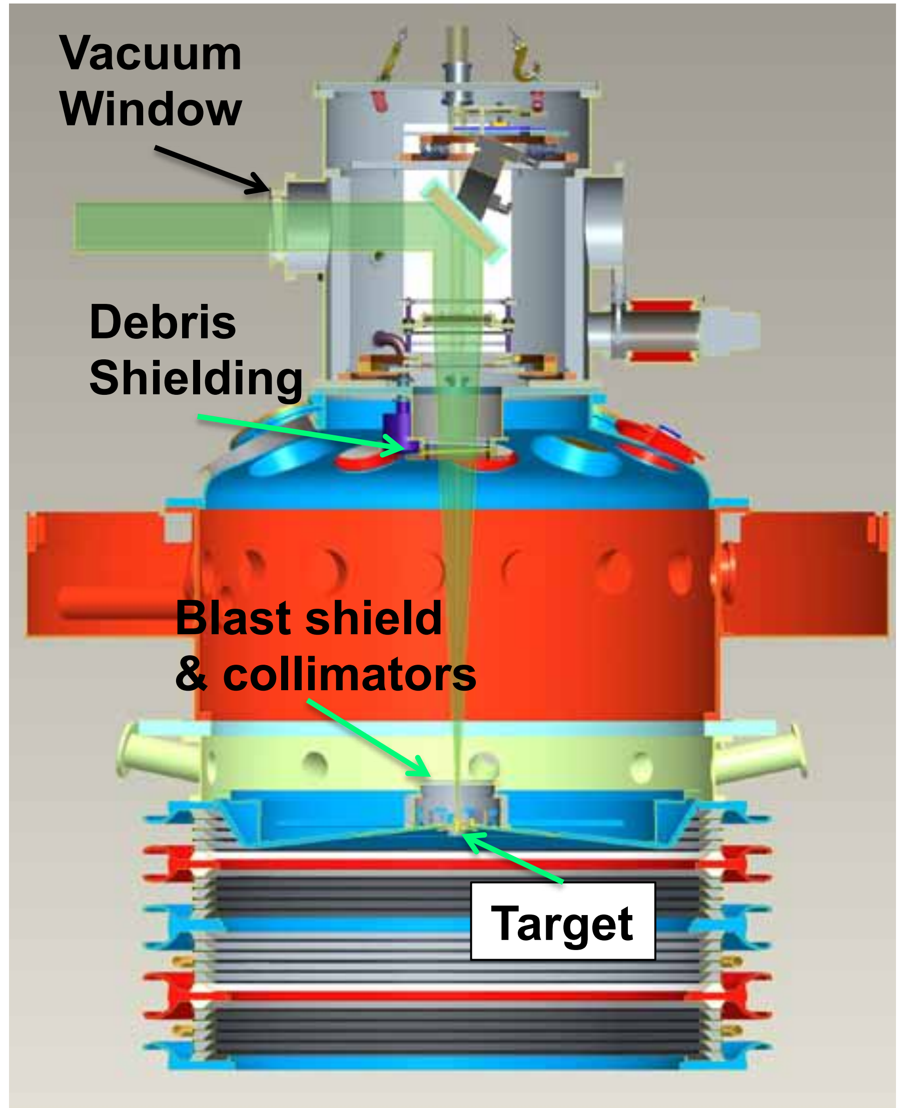
We will begin integrating 2-2.5 kJ laser preheating into Z MagLIF experiments beginning August 2013; 4-6 kJ by 2015

- We are procuring a new Final Optics Assembly optimized for on-axis targeting
- Z-Beamlet is capable of delivering 2-2.5 kJ in a two-part pulse

Example pulse measurement



ZBL
2ω light
(2.64 kJ)



We are making progress on several key areas of physics related to MagLIF using focused experiments

Sandia National Laboratories

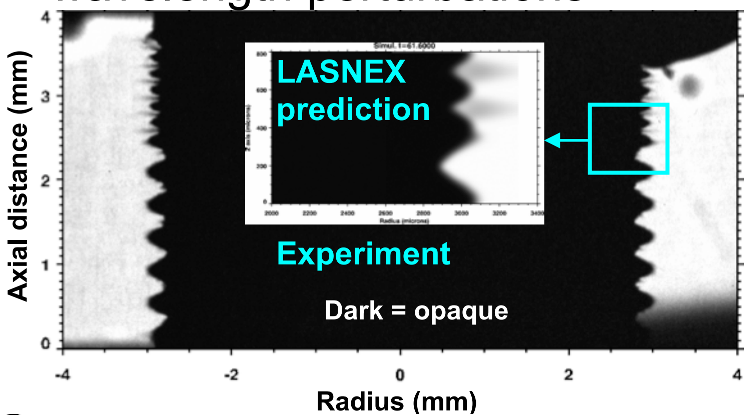
- Initiation of current flow in the liner
  - Control of electro-thermal instability*
  - Measured influence of surface roughness on instability growth*
  - Improving electrical contact between target and load hardware
- Liner stability and symmetry studies
  - Continued testing of predictions for instability growth in fundamental magneto-Rayleigh-Taylor instability studies (multi-mode*, helical)
  - Controlling end effects at top/bottom of liner*
  - Measured liner inner surface at convergence ratio of seven*
  - Discovered unanticipated effect of magnetization on MRT instability structure*
- Preheating in gas-filled targets
  - Measuring energy deposition in magnetized, gas-filled targets on Z*
  - Designing Omega-EP experiments to measure temperature & lifetime*
  - Identifying possible alternate preheating techniques*
- Magnetic flux compression
  - Developing new diagnostics to measure magnetic fields on Z (Bdots*, Optical Faraday rotation, Zeeman splitting*)

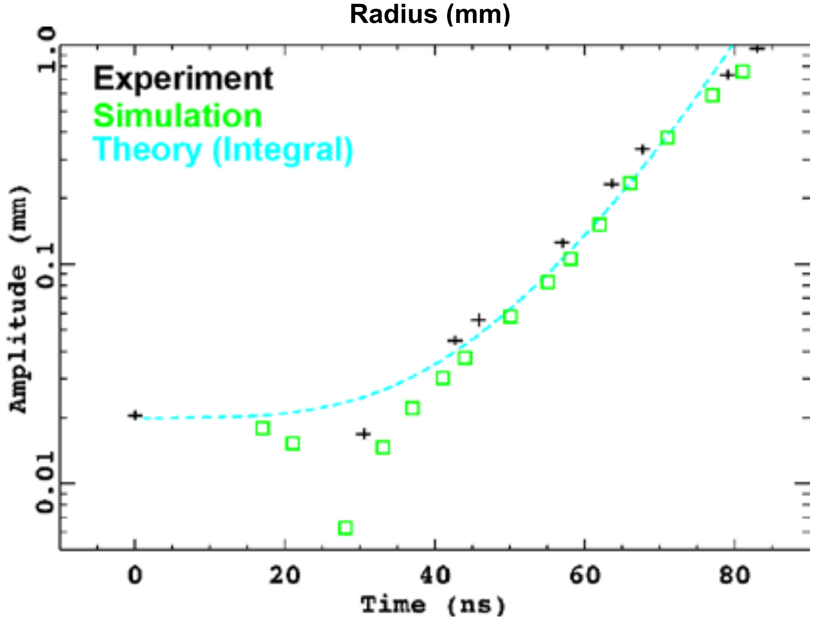
* Highlighted in this presentation

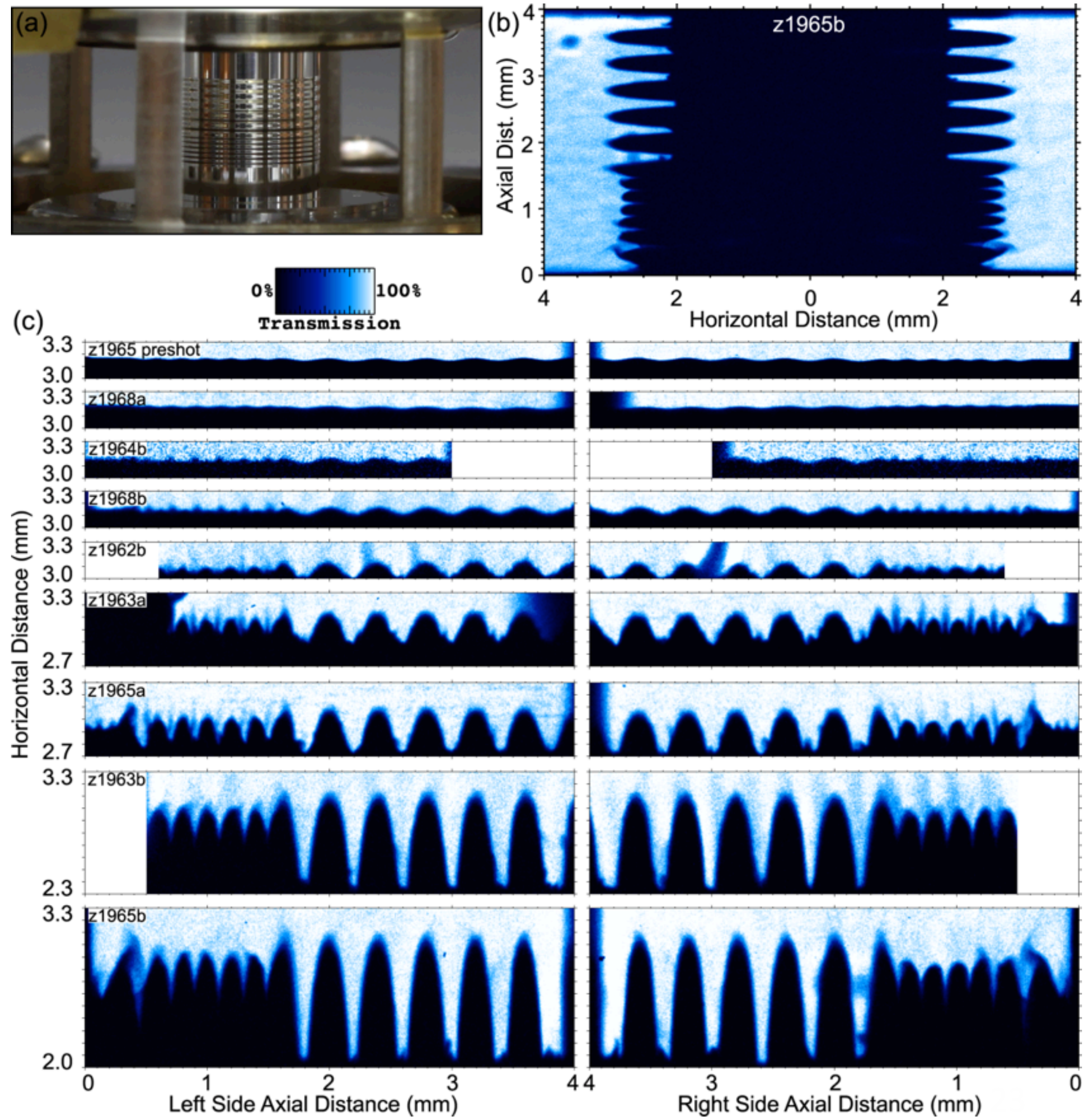
We did controlled experiments as the first critical test of our understanding of the Magneto-Rayleigh Taylor instability

Sandia National Laboratories

Radiographs captured growth of intentionally-seeded 200, 400-μm wavelength perturbations

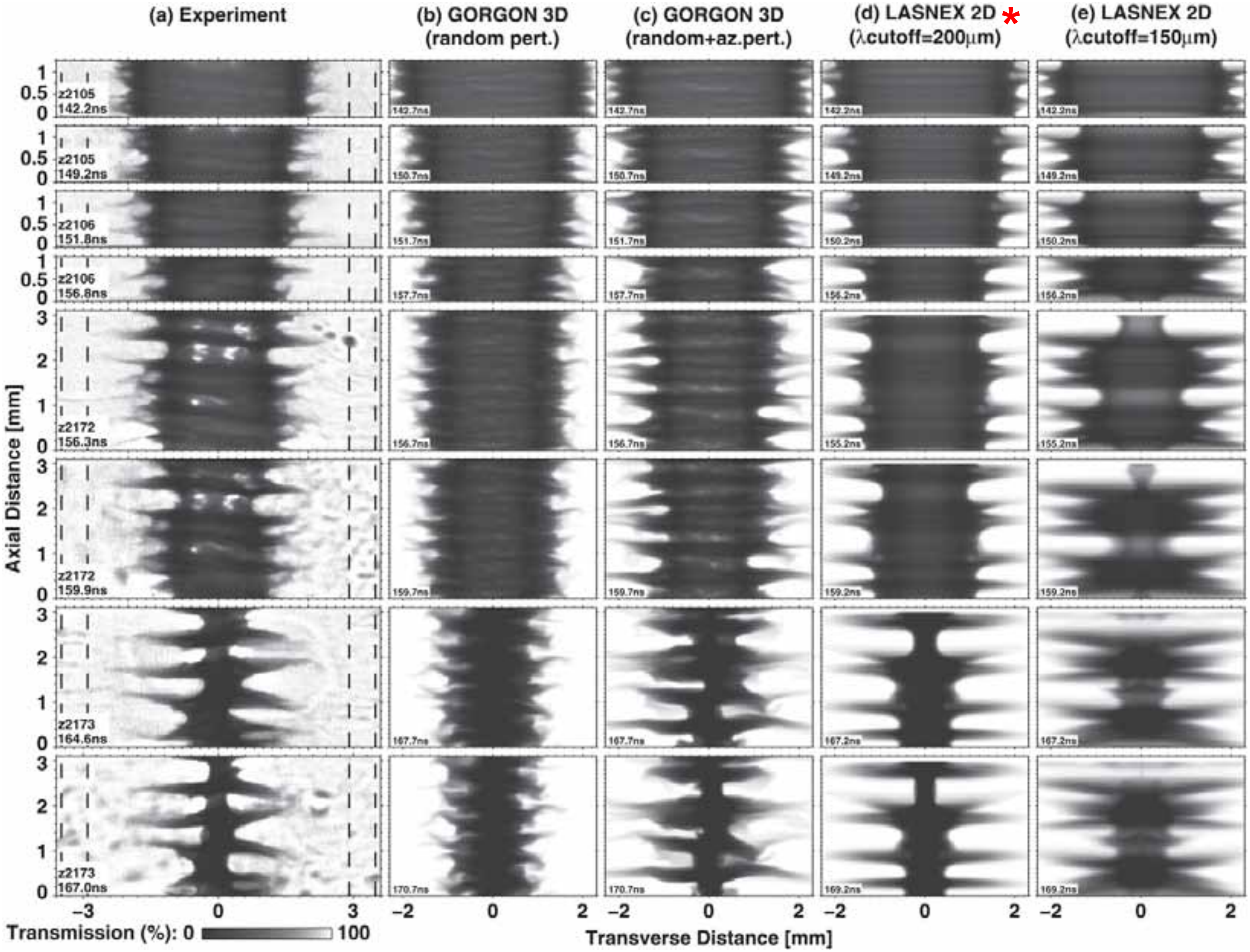






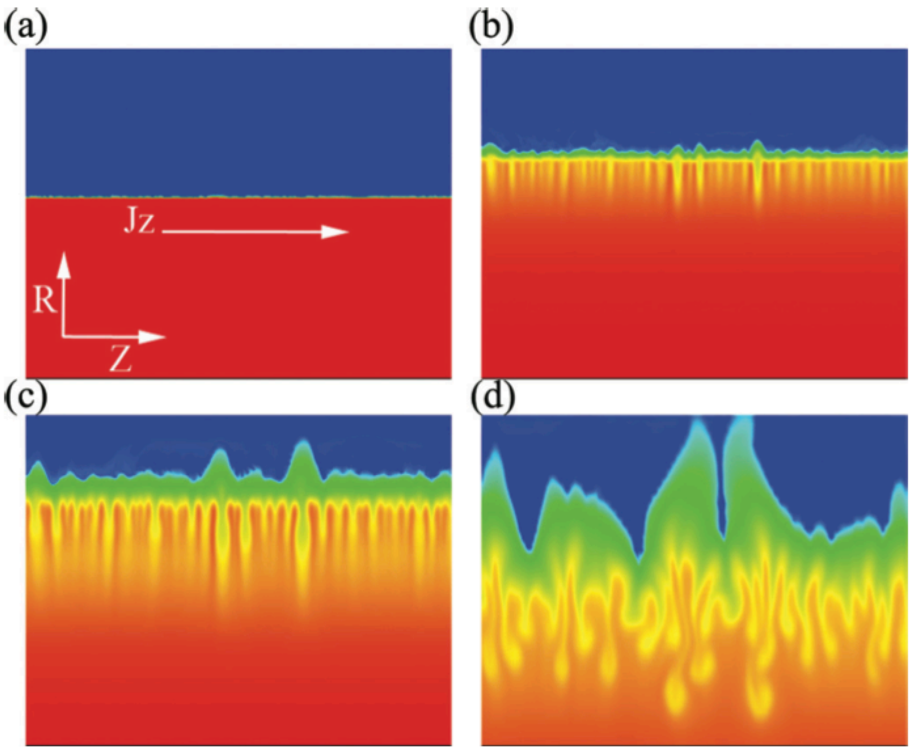
D.B. Sinars *et al.*, Phys. Rev. Lett. (2010); D.B. Sinars *et al.*, Phys. Plasmas (2011).

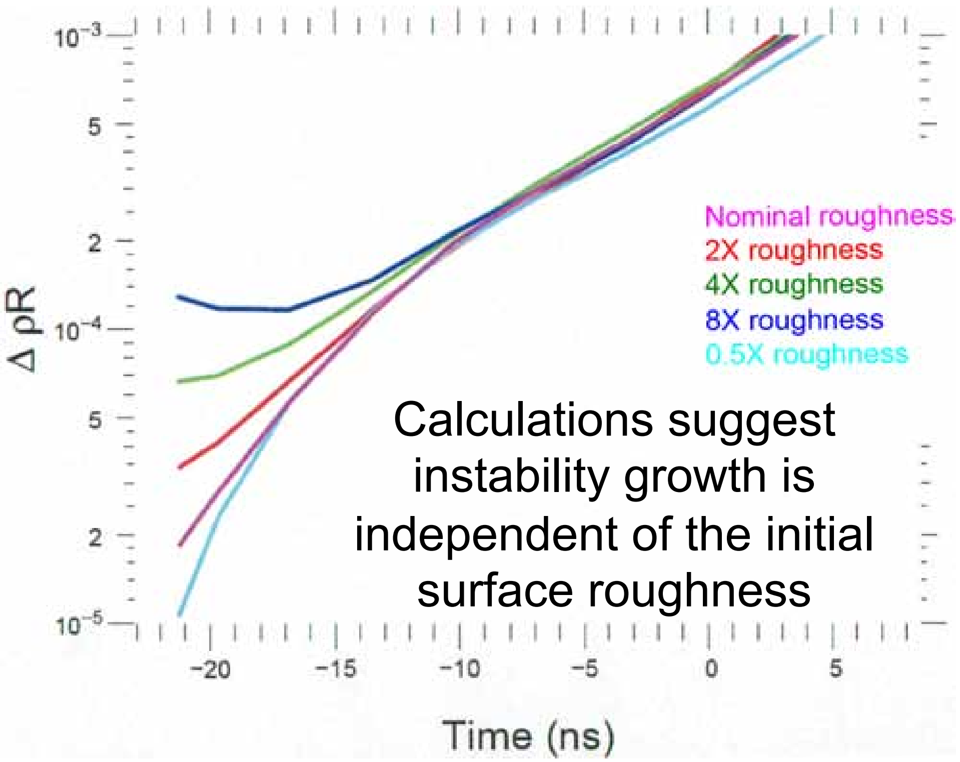
Beryllium experiments show surprisingly correlated instability growth at late times that may imply a highly-correlated initial perturbation



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

The electro-thermal instability is an important mechanism that could seed MRT growth*



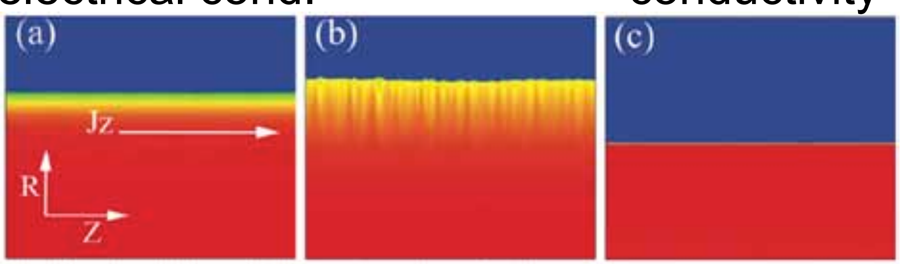


Calculations suggest instability growth is independent of the initial surface roughness

Constant electrical cond.

Nominal

10x thermal conductivity



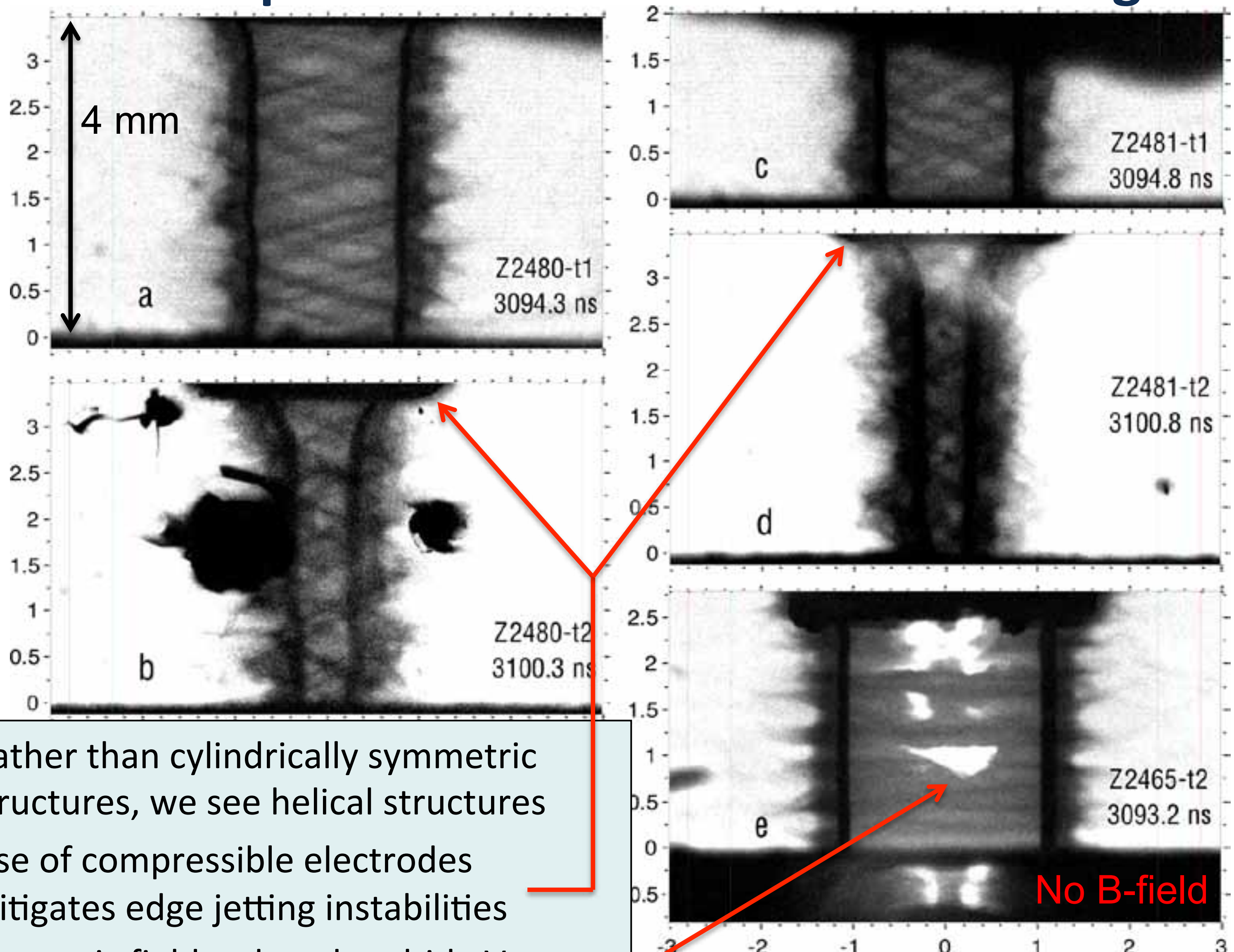
Temperature perturbations give rise to pressure variations which eventually redistribute mass

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

Our first axially-magnetized liner implosion experiments provided us with several new insights

CR =2.7

CR =6.4



CR =2.9

CR =6.9

Highest CR imaged to date

CR =2.0

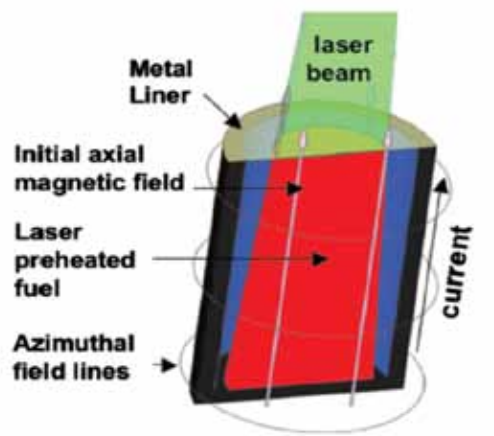
- Rather than cylindrically symmetric structures, we see helical structures
- Use of compressible electrodes mitigates edge jetting instabilities
- Magnetic field reduced multi-keV x rays associated with late-time instabilities

T.J. Awe *et al.*, submitted to Phys. Rev. Lett.

We started testing our preheating model predictions of energy deposition in laser-only experiments

Motivation/aims

We want to ensure that laser preheat energy can be absorbed by MagLIF fuel

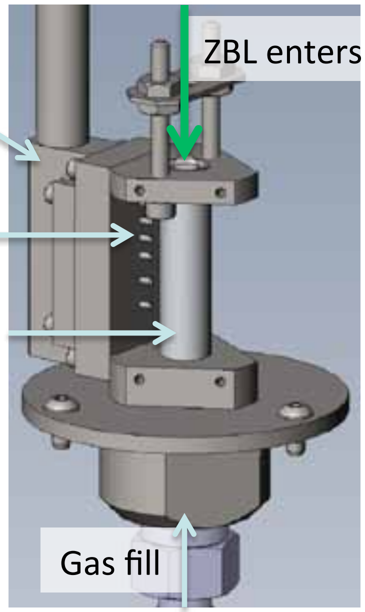


Laser blast wave targets aim to:

1. Reproduce first integrated MagLIF setup as closely as possible
2. Measure laser energy deposition in the fuel by measuring time/velocity of blast wave

Experimental design

ZBL (~2 kJ, 2 ns) enters into thin-walled tube target containing dense D2 gas

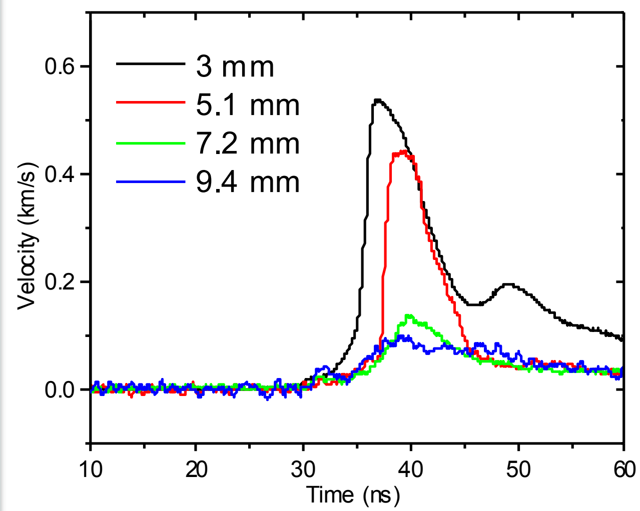


Blast wave in fuel driven by laser energy absorption

Time/velocity of tube wall motion monitored by 21 VISAR probes (3 azimuthal, 7 axial positions)

Results/conclusions

VISAR data shows velocity and time of tube wall motion consistent with laser energy deposition



Data analysis is underway. There is concern that poor beam focal spot quality is affecting transport through the foil

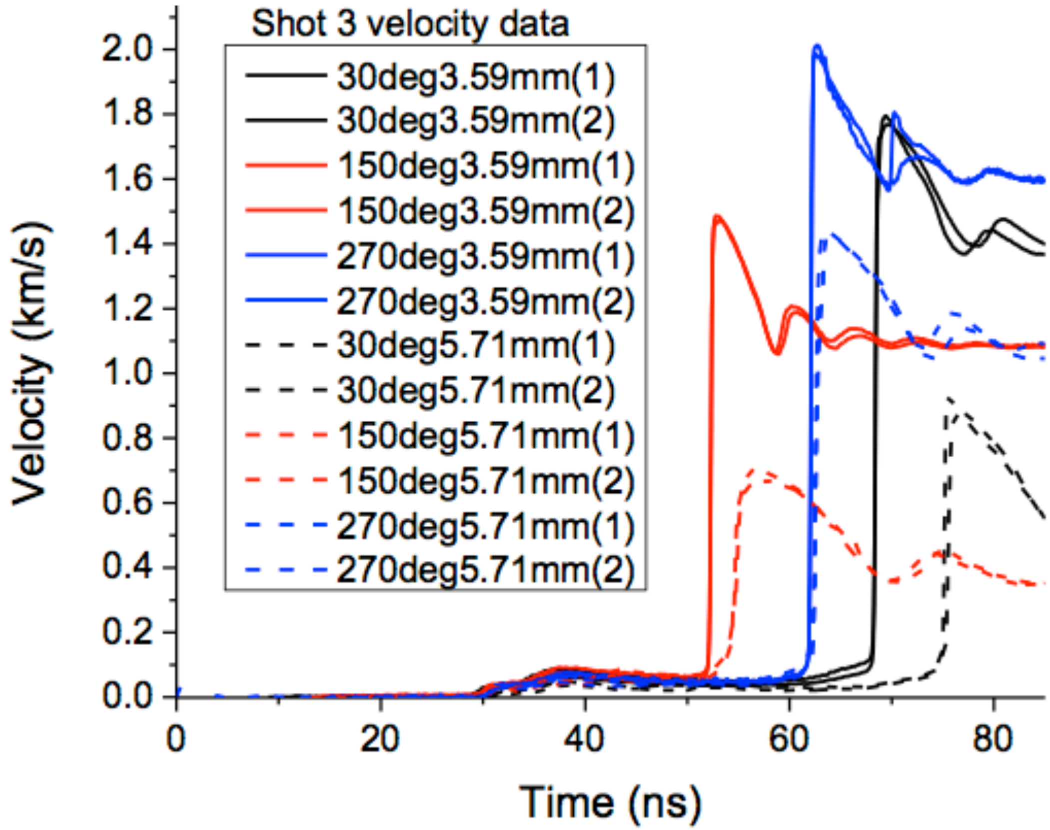
Comparisons to detailed HYDRA and LASNEX simulations are underway

ZBL blast wave tube – shots 3 and 4

- 7 T ABZ fielded on both shots
- Same pulse shape requested as in previous shots
- VISAR, MLM cameras and SiD's were only diagnostics fielded

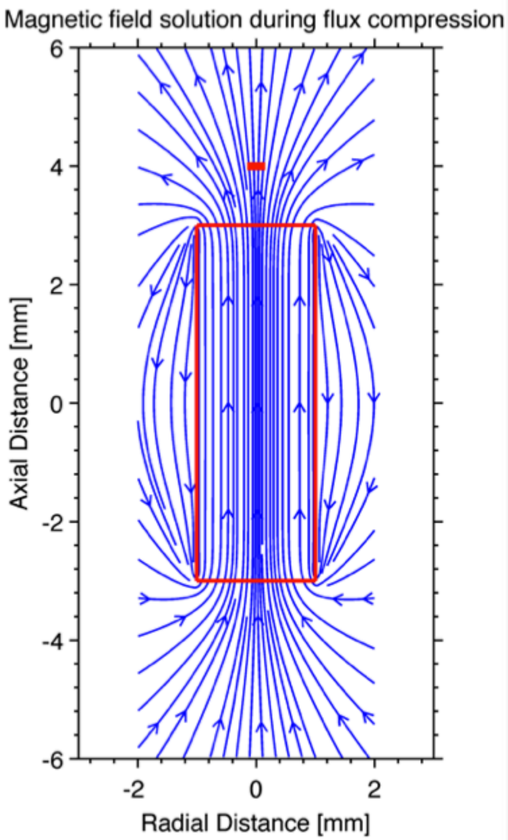
- Shot 3 – laser focused 8 mm above LEH
- Shot 3 – top four fibers on each azimuthal position fielded with 2 sensitivities (typically 0.277, 0.4827 and 0.5062 km/s/fringe)

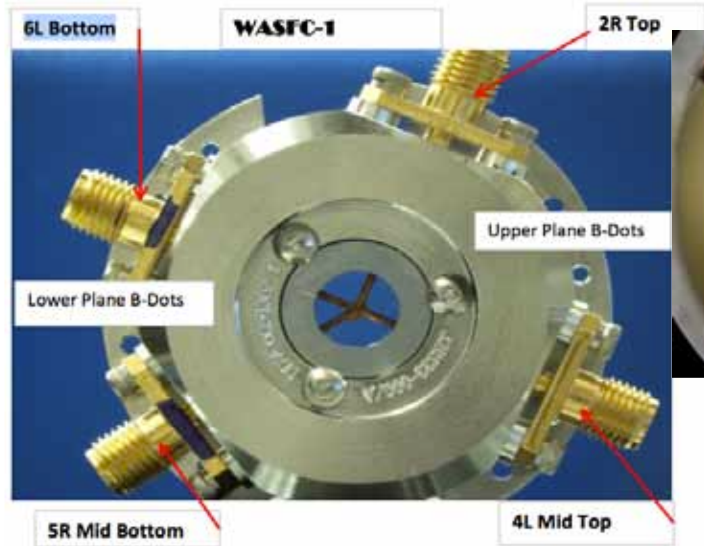
- Shot 4 – laser focused onto LEH (may allow for smaller/thinner LEH)
- Shot 4 – top four fibers on each azimuthal position fielded with 2 sensitivities

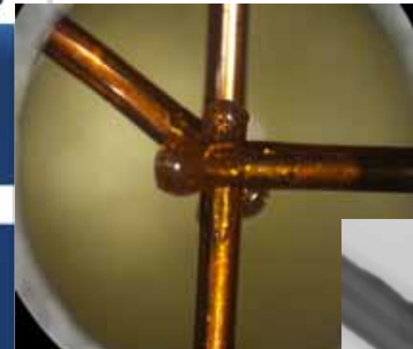


We have made our first measurements of flux compression with Bdot probes above the liner

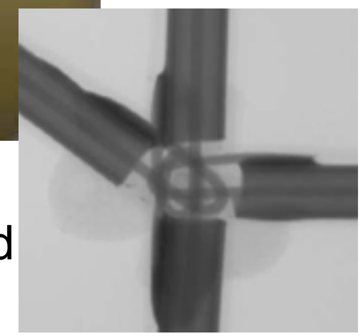
Probes measure the dipole fringing field above the liner



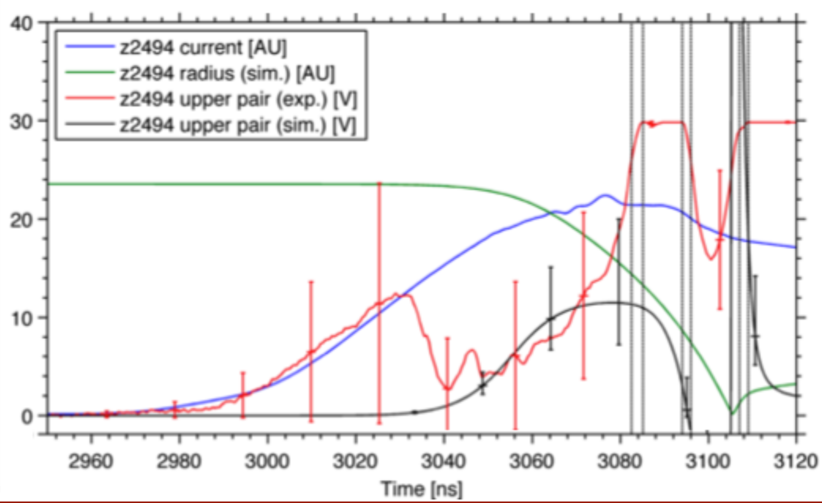




Zoomed Optical Photo



Zoomed X-ray Image of Bdot loops



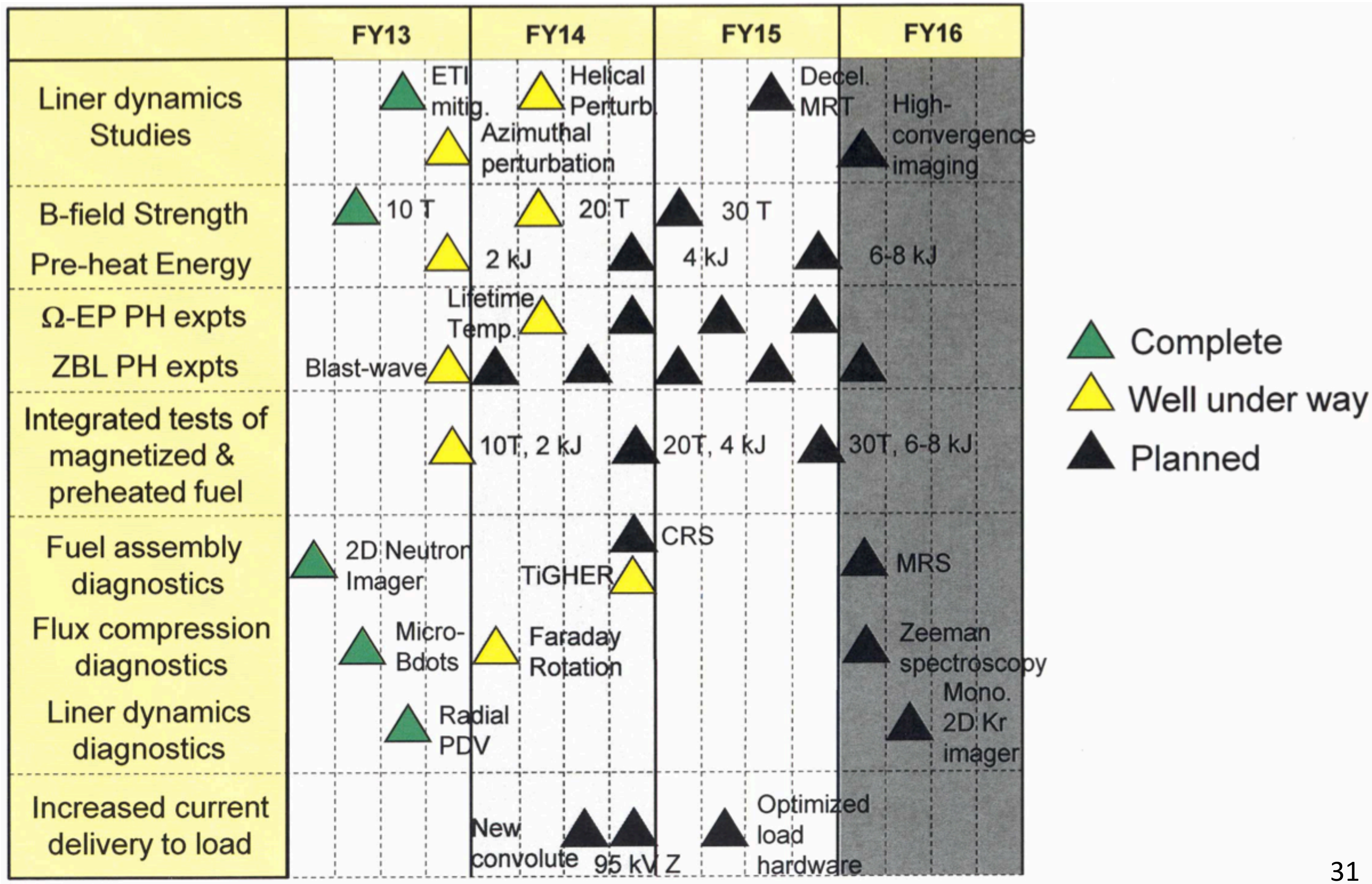
We are improving the data quality, but our first measurements did show evidence of flux compression during the implosion

Bdot probes developed in collaboration with J. Greenly (Cornell U.)

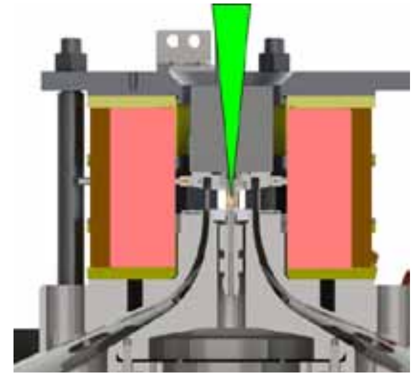
We have made significant progress toward our initial capability goals for testing MagLIF in FY13

- Load hardware compatible with magnetic field coils and laser preheating has been developed and fielded
- Capacitor banks capable of driving up to 30 T fields have been installed on Z
  - We have successfully generated 7-10 T axial magnetic fields on Z
- New final optics assembly commissioned on Z
- First integrated experiments on Z occurred within the last two weeks (August 29, Sept. 3).
  - Demonstrated capability to do these experiments on Z
  - Data analysis is ongoing
  - Initial capabilities deployed in 2013 are not optimal (10 T, 2 kJ, 20 MA)
  - Will expend effort improving these for 2015 (30 T, 6 kJ, >25 MA)

We have developed a 3-year plan that will make significant progress in evaluating Magnetically Driven Implosions by FY15 on a path to 100-kJ equivalent yield



We will continue to improve our capabilities in the next two years to reach more optimal parameters



- Magnetic field strength will be improved from 10 to 30 T by increasing the magnet coil volume while decreasing radial diagnostic access
- Improvements to the stability of the front end of Z-Beamlet (in progress) will enable a 4-ns, ~4 kJ laser pulse
- Installing the booster amplifiers on Z-Beamlet (not needed for original radiography mission) will allow us to reach ~6 kJ
- Continued improvements to Z facility capabilities will allow increased current delivery to the load for multiple programs

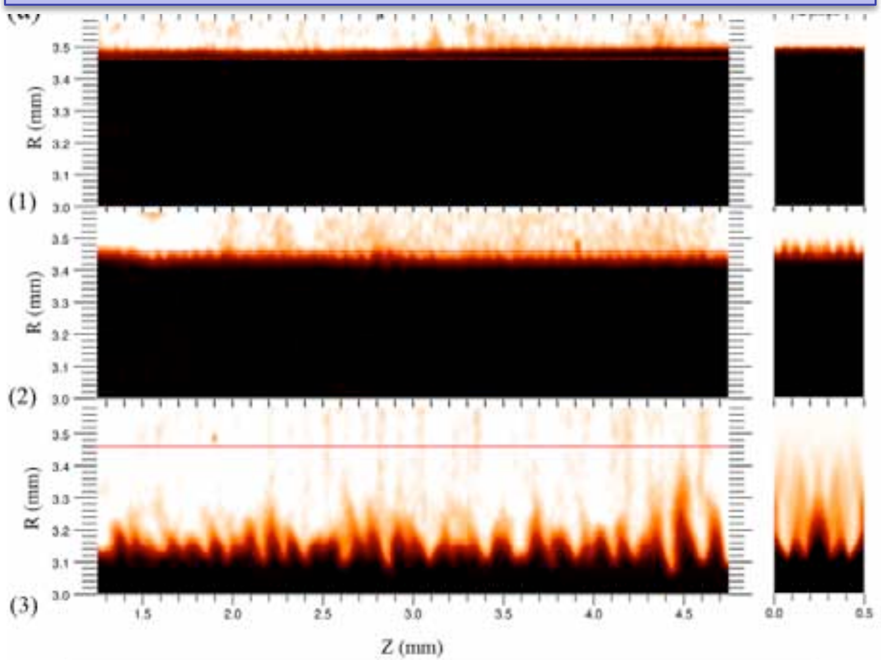
Our goal for 2015 is to identify the promise and key challenges for Magnetized Liner Inertial Fusion

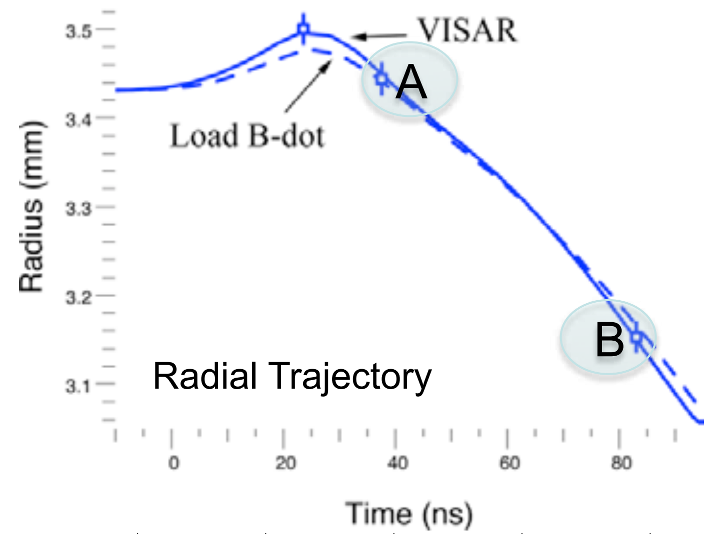
- As noted above, the plan includes focused experiments and instruments to help identify obvious problems with concept
- Our present target design should allow us to quickly identify and measure quantities associated with the key issues, so that we have time to devise and test mitigation strategies by 2015
- In the meantime, we are computationally examining methods that provide more robustness in designs, e.g.,
  - Use thicker, more highly compressible liners (Li, CH vs. Be, Al) for enhanced liner stability and better magnetic flux compression?
  - Use current pulse shaping to sweep up axial magnetic flux with a stable liner that maintains material strength (e.g., AFRL liners)?
  - Use pinch-based methods to preheat the fuel rather than a laser?
  - Use of a laser pre-pulse to ablate and expand the foil containing the gas fuel to below critical density before the main pre-heating pulse?

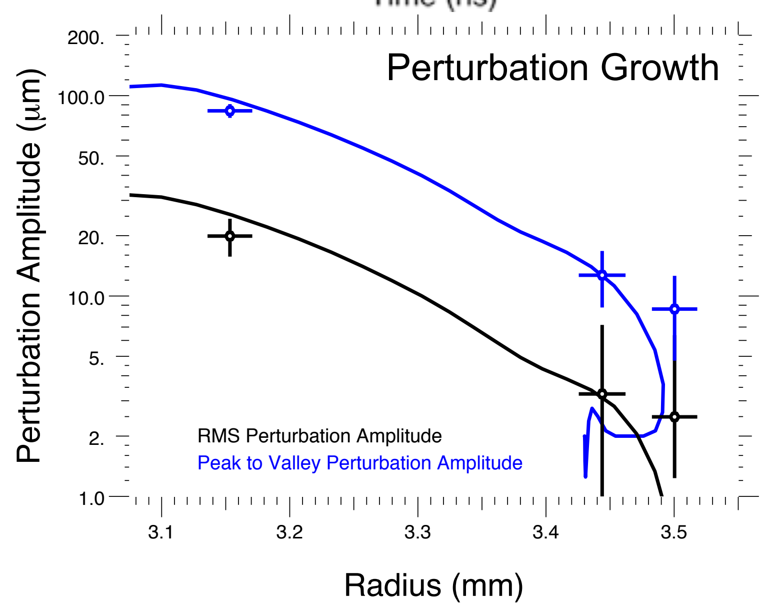
EXTRA

Comparisons between our modeling and experimental instability growth in solid Al liners are promising—the perturbation growth is larger than expected from MRT alone

Experimental (left) & simulated (right) radiographs





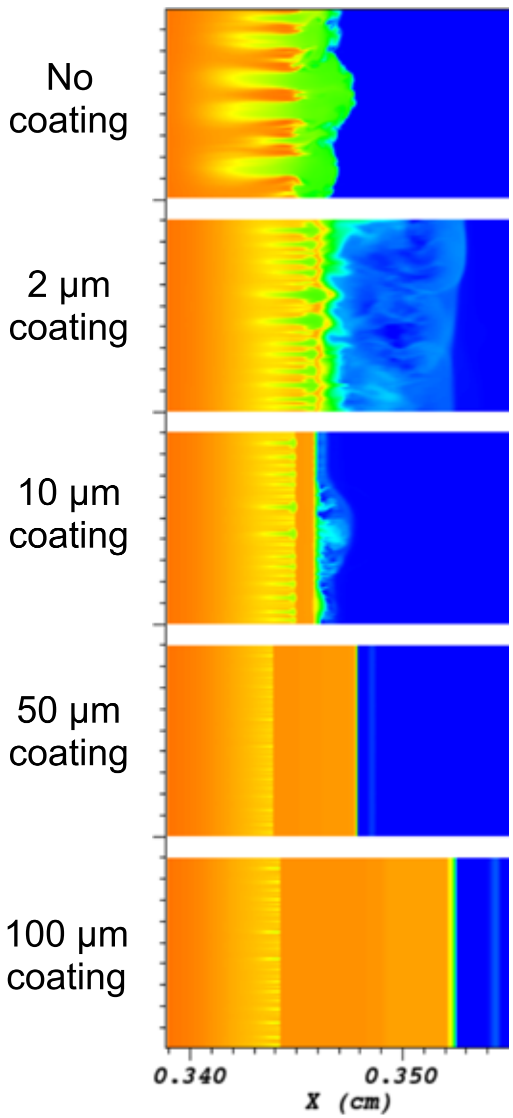


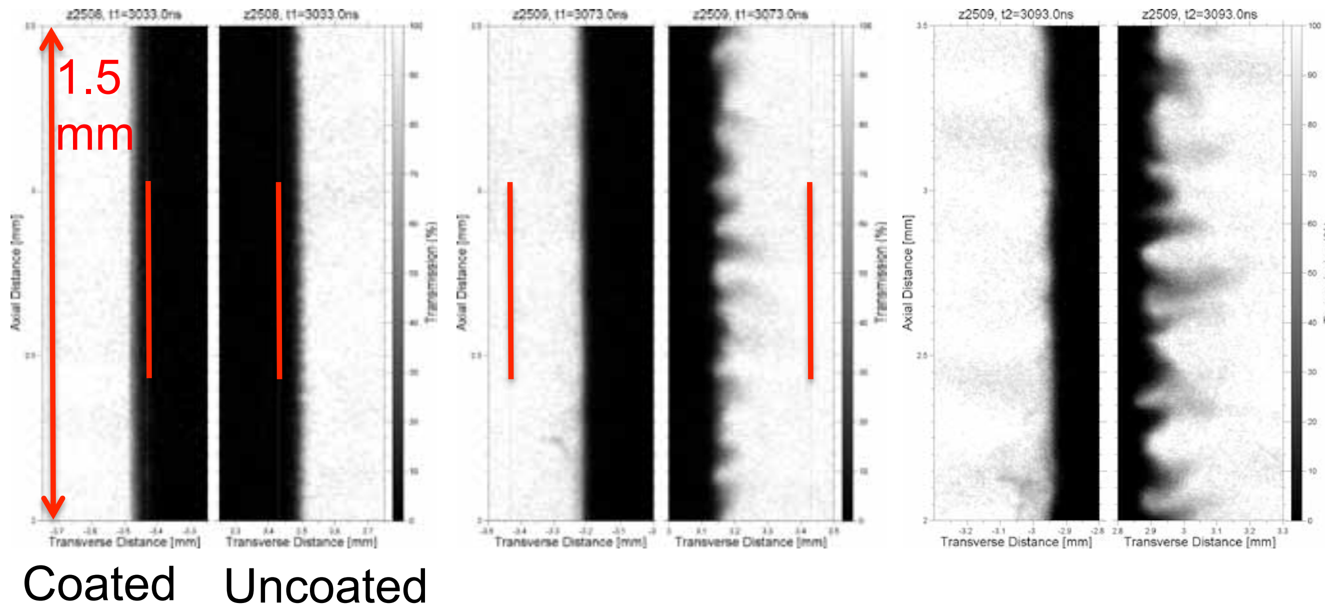
Perturbation Growth Comparison

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

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

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

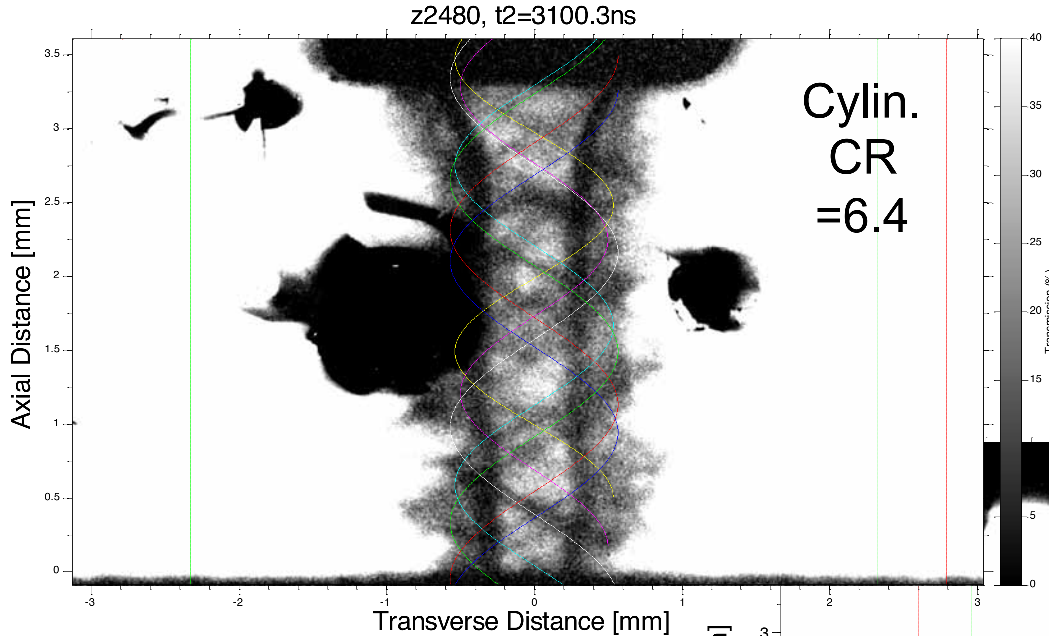


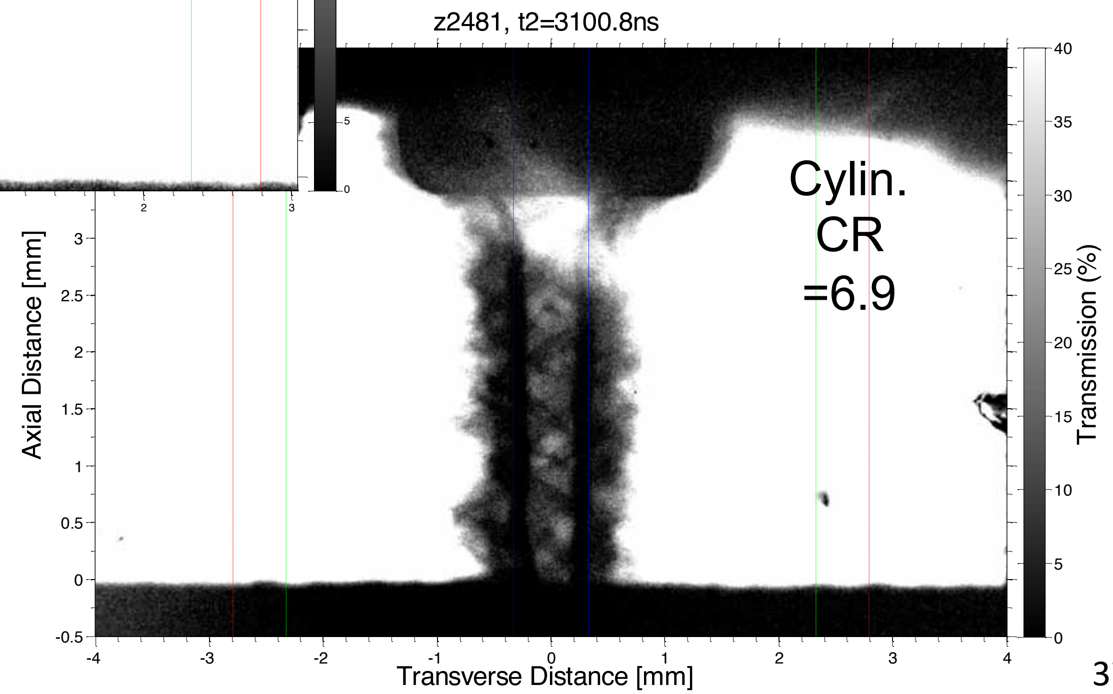


- No ETI growth in plastic coating
  - Carries very little current
  - Theoretically ETI Stable
    (resistivity decreases with increasing temperature)
- Coating does not appear to affect linear ETI growth of temperature perturbations, but it does significantly tamp down the mass redistribution

K.J. Peterson *et al.*, manuscript in preparation

Though the opacity of the converging liners is significant, it is possible to see the inner boundary adjacent to the fuel, which looks reasonably good



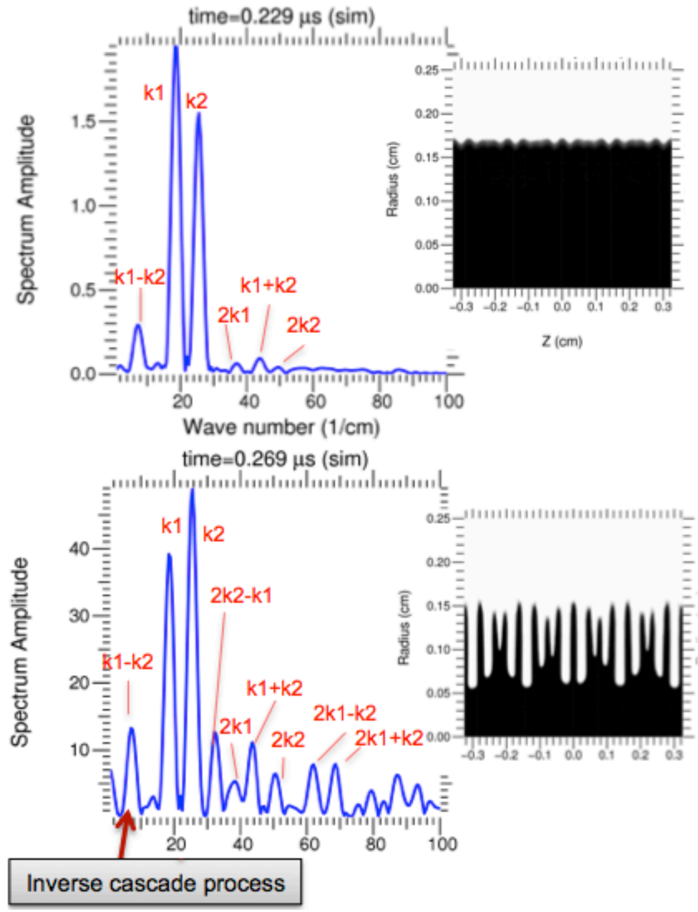


Same images plotted using 0-40% transmission range instead of 0-100%

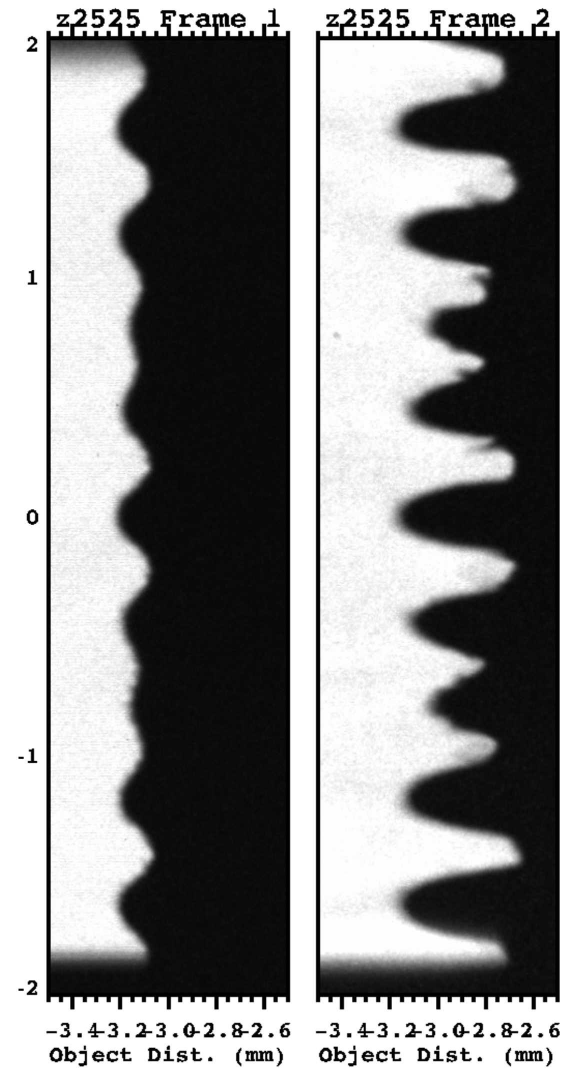
T.J. Awe *et al.*, submitted to Phys. Rev. Lett.

We began studying mode coupling in multi-mode seeded perturbation experiments to test our understanding of multimode MRT instability growth

Two-wavelength structure is machined on outer surface of a cylindrical Al 1100 liner



Additional harmonics are predicted to appear in simulations*



Data show additional short-wavelength features

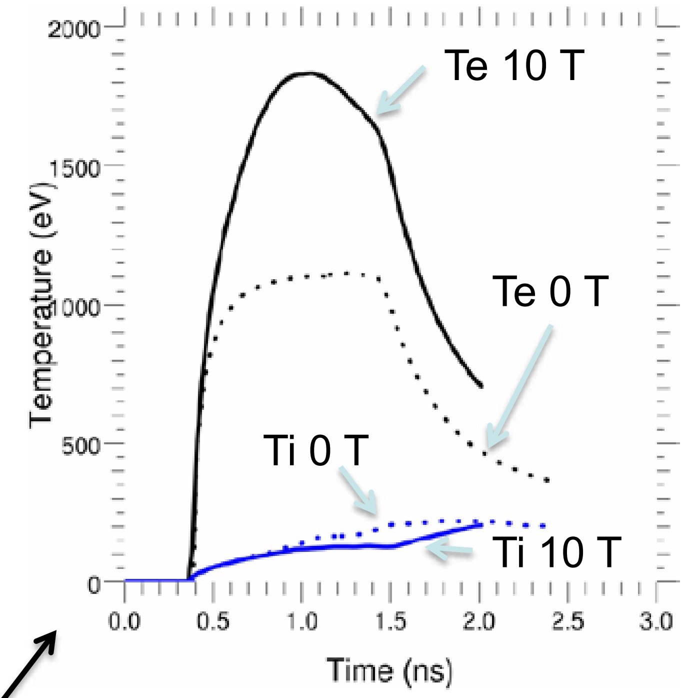
* Idea first noted by M.R. Douglas *et al.*, Phys. Plasmas 5 (1998).

We are designing experiments for Omega-EP to better understand the physics of magnetized & preheated plasma, awarded 2 days on Omega-EP in FY2014 to do this

Sandia National Laboratories

- Previous work used a laser (1ω, 100 J, 1 ns) to heat a magnetized N jet (ne = 1.5e19/cc) with a 12 T peak B field (Froula, PRL 2007)
- Thomson scattering used to determine temperature profile perpendicular to B-field
- They found electron thermal conduction was suppressed according to classic Braginskii models for heat transport

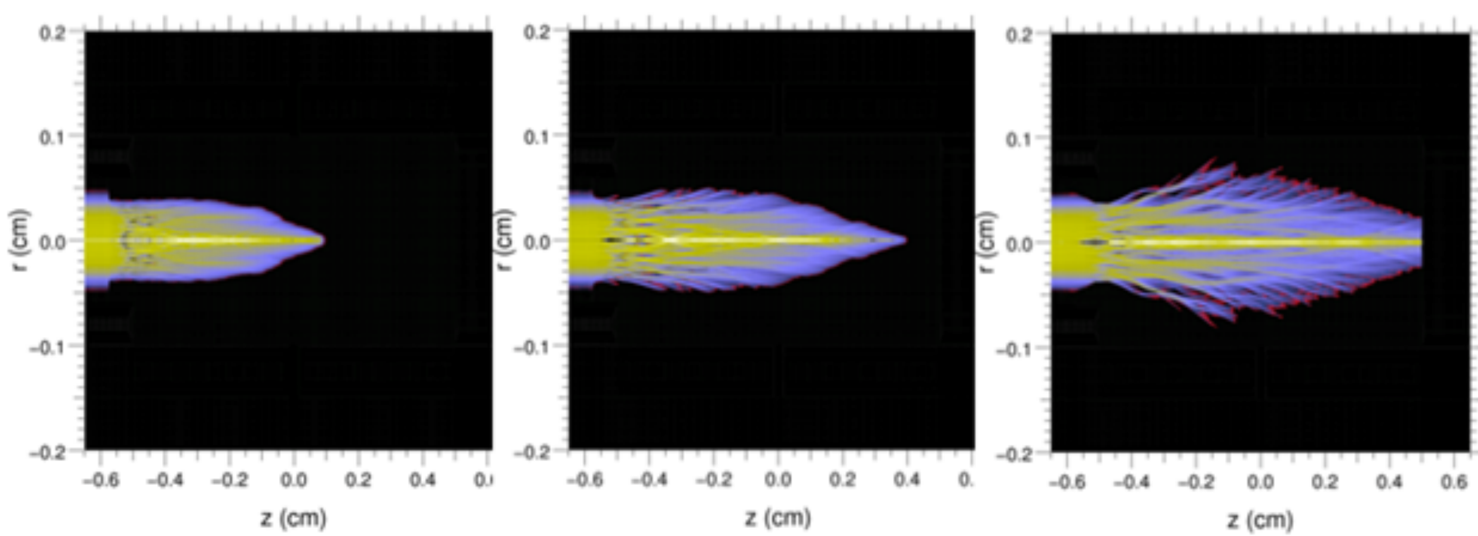
- We propose to extend this in Omega-EP experiments to plasma densities 20x higher, plasma temperatures 5x hotter, using 50x greater laser energy available there
- Effect of 10 T B field on laser-heated plasma dynamics/temperature of laser heated plasma expected to be large/observable
- Near-Braginskii transport under these conditions would be good news for MagLIF!



Ion and electron temperature profiles from HYDRA with and without a 10 T applied B field for a 2mg/cc D2 gas heated with a 3ω laser delivering 2.5 kJ in 1 ns

Z-Beamlet experiments measuring energy deposition are needed because the impact of focal spot quality on filamentation is currently unknown

- Want to absorb 8 kJ of laser energy in ~9 mm long liner filled with ~2 mg/cc D2 without significant energy reaching end of liner
- Lasers propagate in underdense gases in a 'bleaching wave' that travels many times faster than the plasma sound speed
- Intensity variations in beam lead to filamentation which alters the laser energy deposition profile



Hydra sims of laser intensity contours for 2.5 kJ, 1ns, 3ω laser in 2 mg/cc D2 fuel.

The impact of beam quality on laser heating of gasses was demonstrated during preparatory experiments for NIF

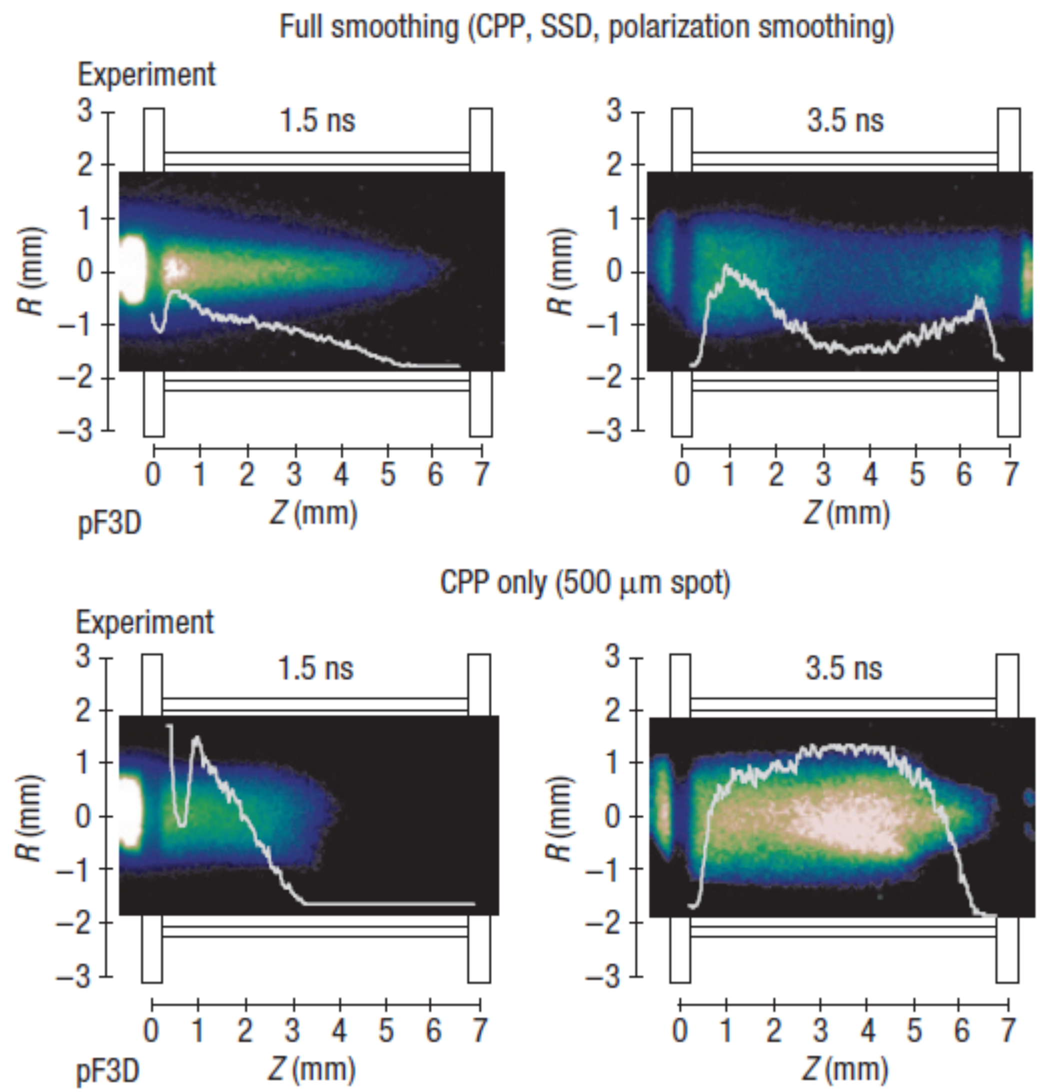
Glenzer et. al., investigated beam propagation through CO2 gas (n_e = 6e20/cc) - relevant to NIF hohlraum

One quadrant of the NIF (16 kJ, 3ω, 3.5 ns, I_0=2e15 W/cm^2) was focused into a 7 mm long gas tube target

Different smoothing resulted in different beam propagation – less smoothing = worse propagation (bad for laser ICF)

We want to absorb as much energy in as shorter distance as possible – want less smoothing?

Also want to have applied B field during experiment



Glenzer et al., Nat. Phys. (2007)

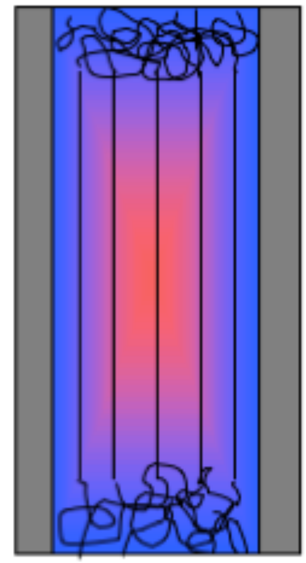
FY15 Experiments on Omega-EP can help us examine the impact of preheating on magnetic field structure

Parallel electron heat flux near cold ends is large and causes distortion of the electron distribution function. This then leads to development of "fire-hose" or "mirror" instabilities if

$$\beta > \left(\frac{n v_{Te} T_e}{q_{\parallel}} \right)^2$$

where $q_{//}$ is axial heat flux. Is satisfied at the distance ~ $L/5$ near each end.

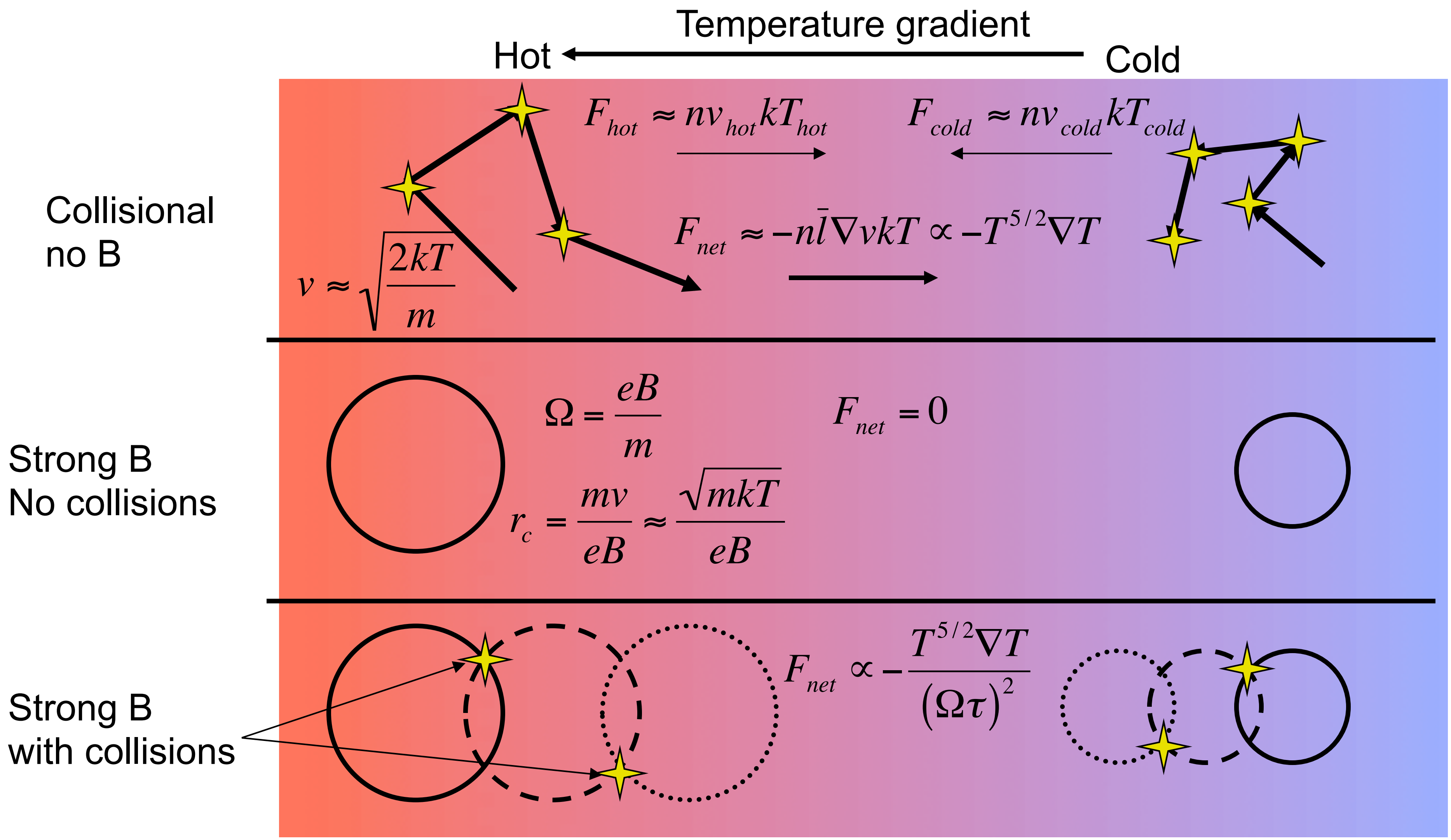
Tangled field is good for suppressing the axial heat loss.



- Detailed estimates suggest that conditions achievable using existing Omega-EP capabilities are nearly ideal for diagnosing existence of tangled field lines using proton radiography*

* D.D. Ryutov (LLNL), 7/16/13 seminar

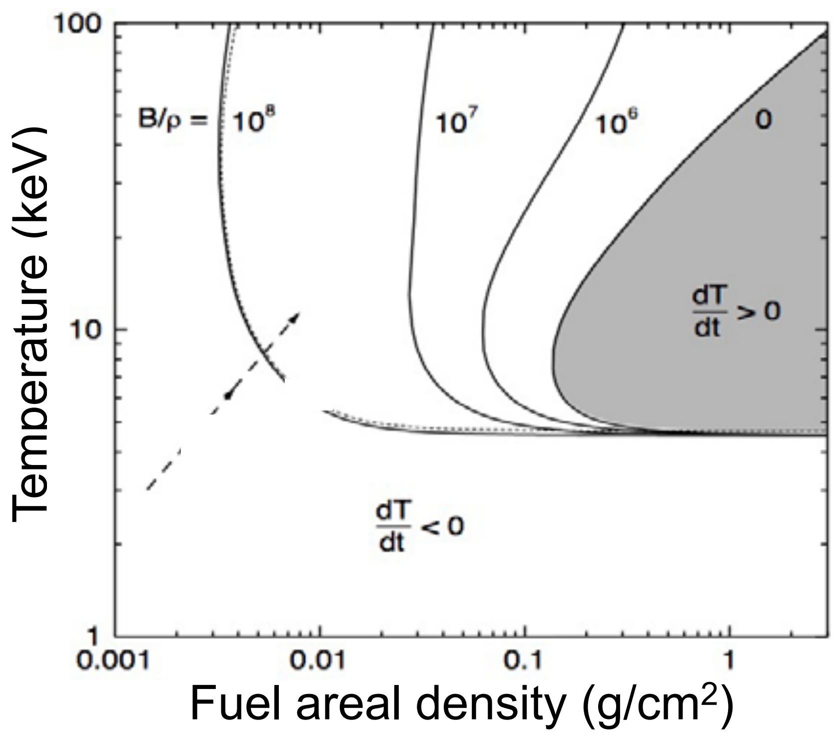
The presence of a magnetic field can strongly affect transport properties, e.g. heat conduction



Energetic particles (e.g., alpha particles) can also be strongly affected by magnetic fields

A large, embedded magnetic field significantly expands the space for fusion self heating

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



Even in non-optimal field-line geometry magnetic fields have had a positive impact on capsule implosions:
P.-Y. Chang *et al.*, Phys. Rev. Lett. (2011)

The ρr needed for ignition can be significantly reduced by the presence of a strong magnetic field
- Inhibits electron conduction
- Enhances confinement of α particles

Lower ρr means low densities are needed (~1 g/cc << 100g/cc)

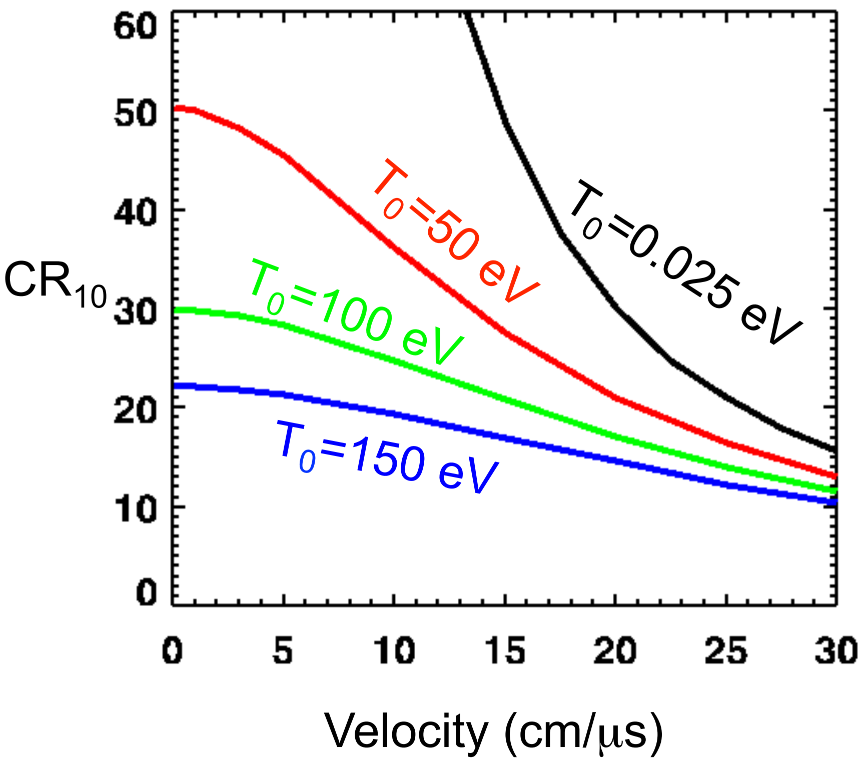
Pressure required for ignition can be significantly reduced to ~5 Gbar (<< 500 Gbar for hotspot ignition)

Large values of B/ρ are needed and therefore large values of B are needed.

B~ 50-150 Megagauss >> B_0 -> flux compression is needed

Preheating the fusion fuel can reduce the velocity and convergence requirements for liner implosions

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

Fuel can be heated to ignition temperature with modest Convergence Ratio when the initial adiabat is large

- adiabat set by implosion velocity (shock) or
- alternatively by fuel preheat in addition to a shock

Preheating the fusion fuel to ~150 eV can allow low-velocity, low-convergence implosions to reach ignition and burn

Rough scaling estimates show how suboptimal parameters lower the yield we would expect

Sandia National Laboratories

Ideal yield from DT, B_z^0 30T, I_{max} 27 MA, E_{laser}~8 kJ : 4e17 cm^{-1}

	Optimistic Reduction factor		*Pessimistic Reduction factor*	
DT to DD hit (at ~8 keV)	80	5.00e15	90	4.44e15
Initial gas energy hit (1.5-2.2 kJ)	3.64	1.38e15	5.33	8.33e14
Low T_i hit on reactivity (~3-4 keV)	7	1.96e14	20	4.17e13
Low I_{max}/E_{drive} (slower, lossy, less PdV)	2.5	7.86e13	4	1.04e13
Losses from low 10T B_z and Nernst	2	3.93e13	3	3.47e12
Burn region dz < 1 cm (~4-6 mm)	1.67	2.36e13	2.5	1.39e12
End losses from 1 cm liner (~0.6-0.7)	1.43	1.65e13	1.67	8.33e11
Non-ideal 2D / 3D effects / Mix / Murphy	5	3.30e12	10	8.33e10

Estimate for experiments: ~10^{11} - few 10^{12} neutrons might be within reach