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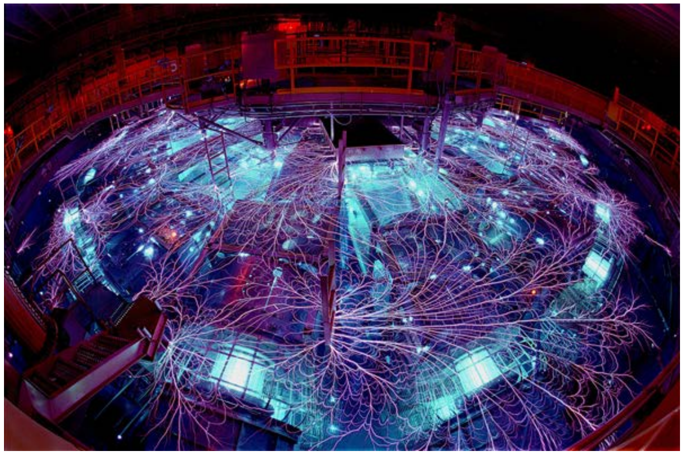

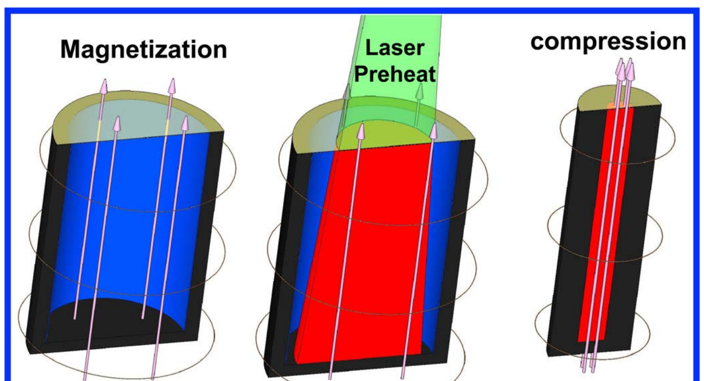

Experiments on Liner Dynamics and Magnetic Flux Compression for MagLIF

R. D. McBride, K. J. Peterson, T. J. Awe, D. B. Sinars, M. R. Gomez, S. B. Hansen, C. A. Jennings, S. A. Slutz, M. R. Martin, R. W. Lemke, D. E. Bliss, P. F. Knapp, P. F. Schmit, D. C. Rovang, and M. E. Cuneo

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Symposium on Fusion Engineering (SOFE)

Austin, Texas, , 2013

U.S. DEPARTMENT OF ENERGY

NNSA National Nuclear Security Administration

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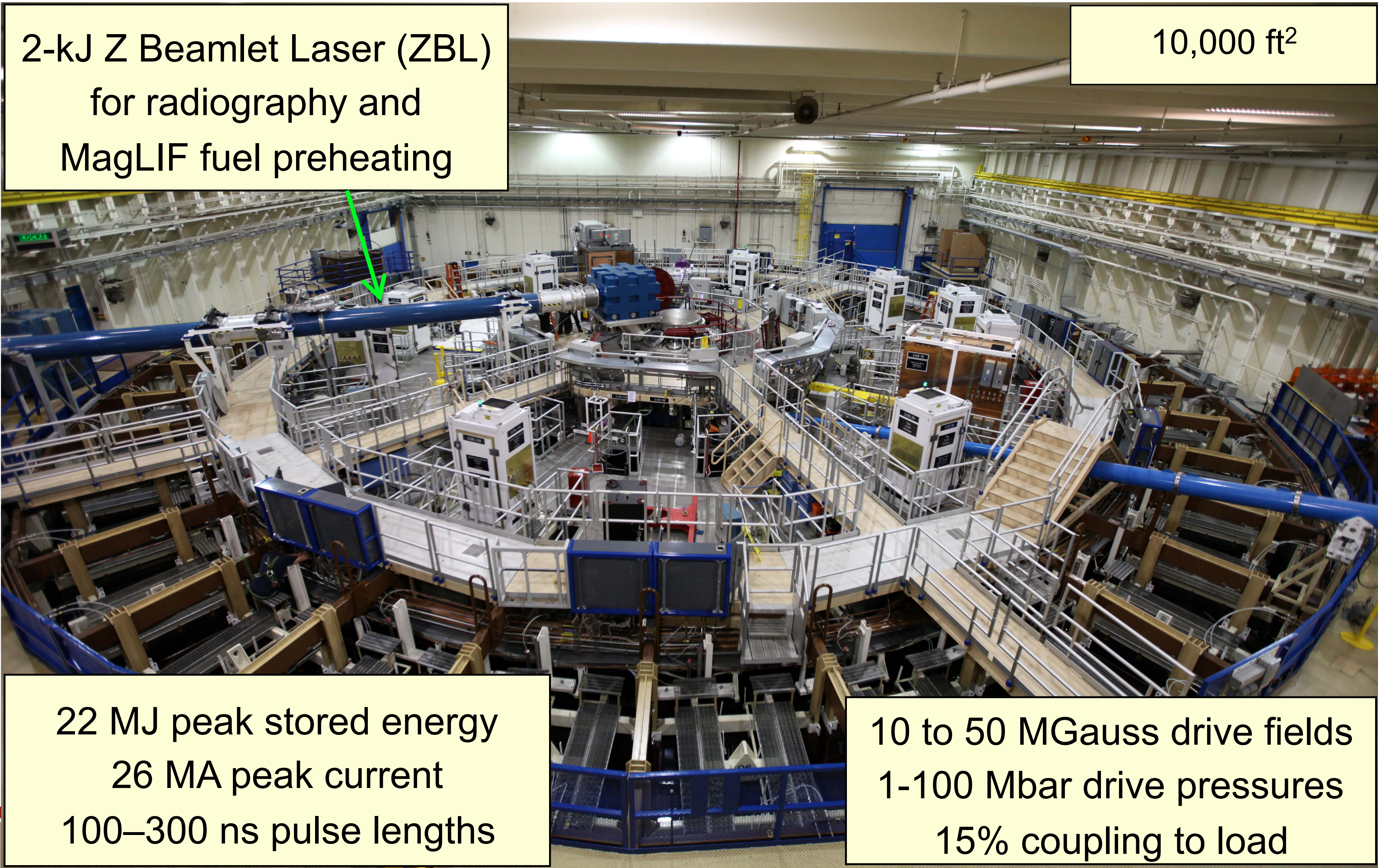
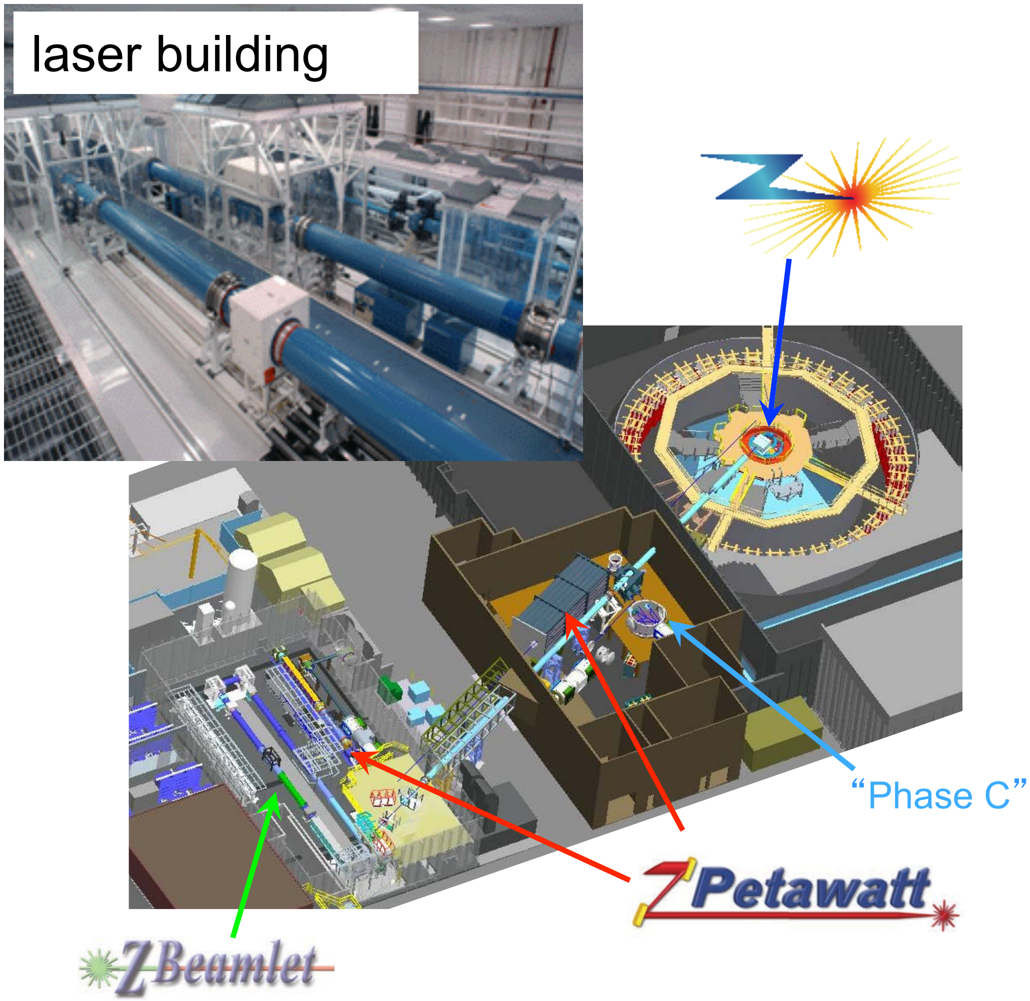
The Z pulsed-power facility combines a compact MJ-class target physics platform (the Z accelerator) with a TW-class laser (ZBL)



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



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).

We are working toward the evaluation of a new Magnetized Liner Inertial Fusion (MagLIF)* concept

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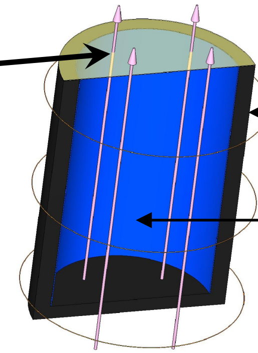
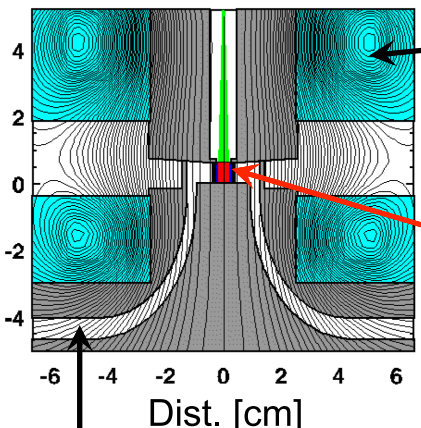
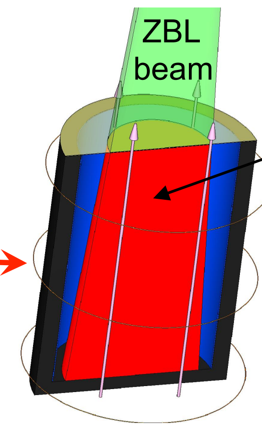
1. A 10–50 T axial magnetic field (B_z) is applied to inhibit thermal conduction losses and to enhance alpha particle deposition

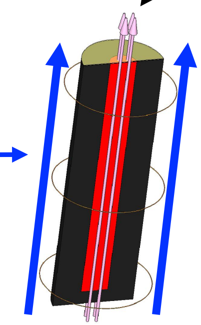




2. ZBL preheats the fuel to ~100–250 eV to reduce the required compression to CR≈20–30



3. Z drive current and B_θ field implode the liner (via z-pinch) at 50–100 km/s, compressing the fuel and B_z field by factors of 1000

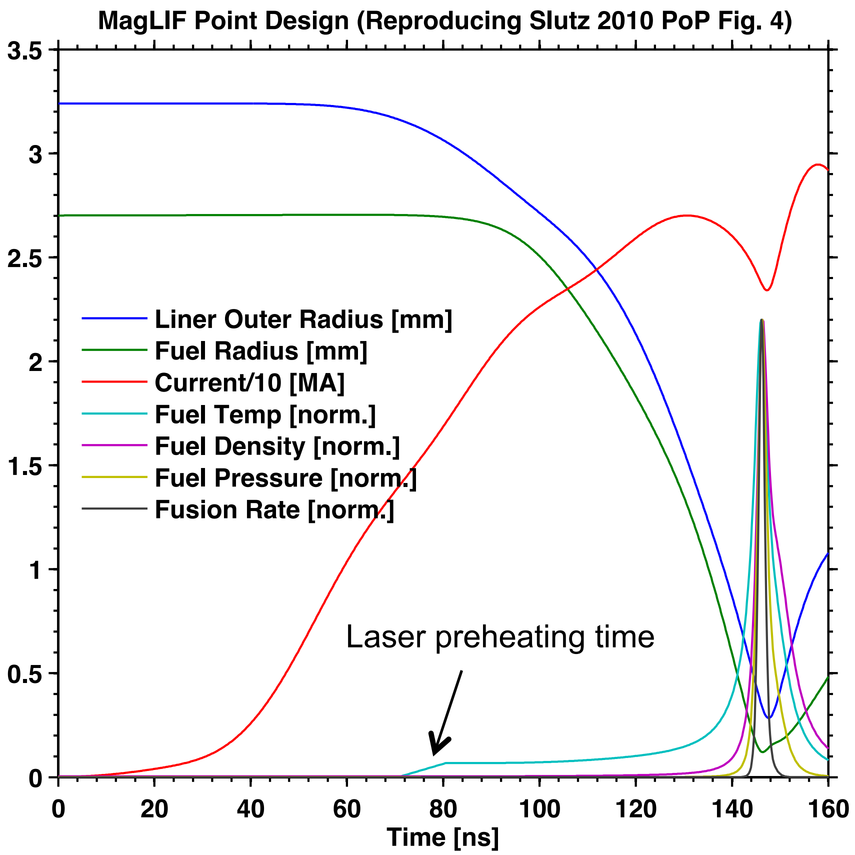


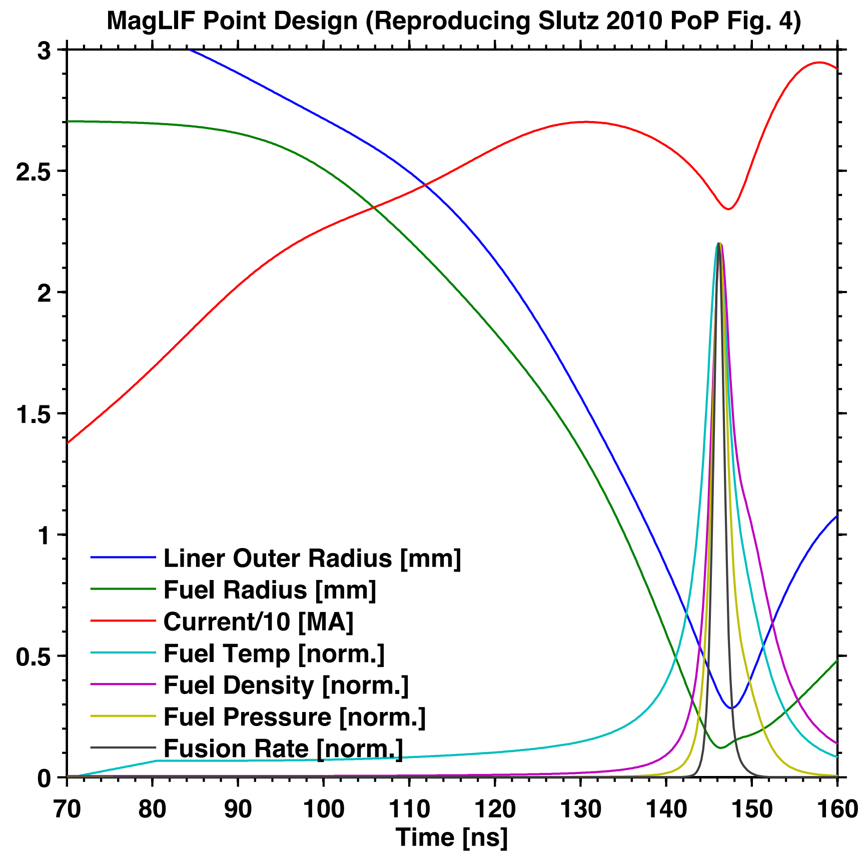
With DT fuel, simulations indicate scientific breakeven may be possible on Z (fusion energy out = energy deposited in fusion fuel)

* S. A. Slutz *et al.*, PoP 17, 056303 (2010). S. A. Slutz and R. A. Vesey, PRL 108, 025003 (2012).

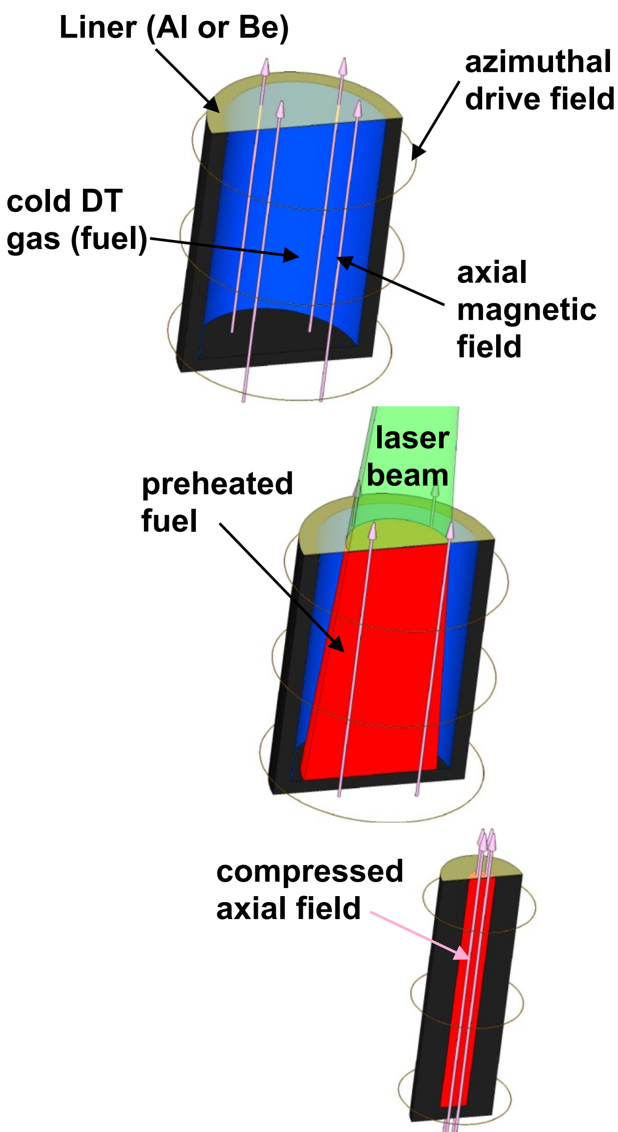
MagLIF Timing Overview

~ 100-ns implosion times
~ adiabatic fuel compression (thus preheating the fuel is necessary)
~ 5-keV fuel stagnation temperatures
~ 1-g/cc fuel stagnation densities
~ 5-Gbar fuel stagnation pressures



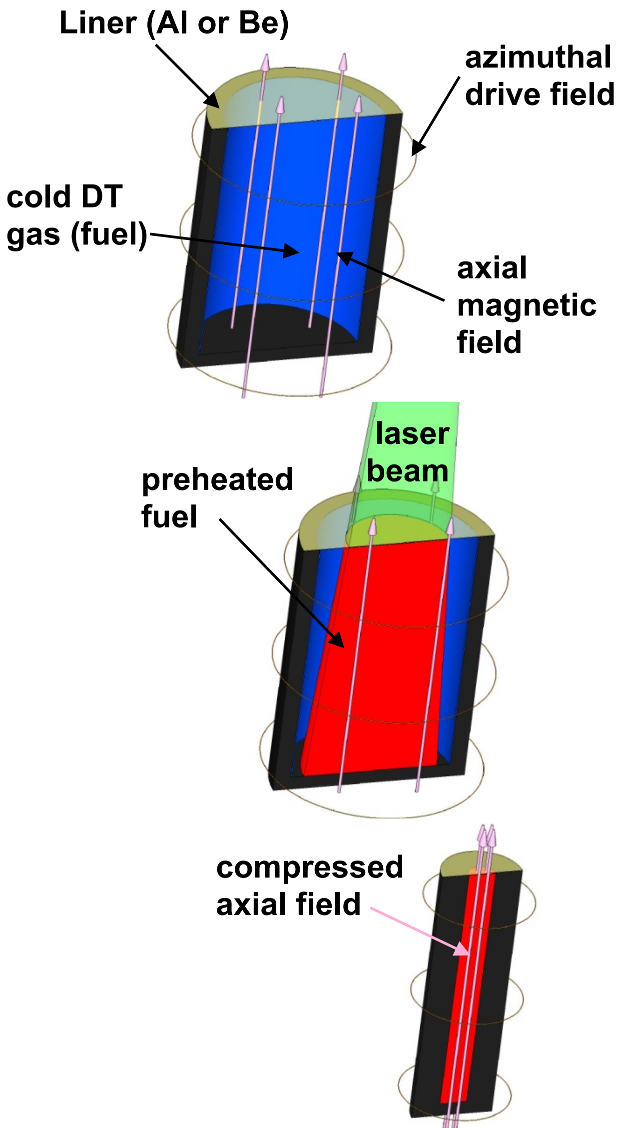


Sandia plans to address key science and engineering research questions related to MagLIF in the next 3-5 years



- Research can be subdivided into several broad categories:
  - Liner implosion dynamics
  - Fuel preheating
  - Impact of fuel magnetization
  - Fuel assembly & stagnation
- MagLIF requires new capabilities to address some of these issues
- MagLIF leverages and benefits ongoing ICF/Science campaign research on Z, NIF, and OMEGA

Sandia plans to address key science and engineering research questions related to MagLIF in the next 3-5 years



- Liner implosion dynamics
- Fuel preheating
- Impact of fuel magnetization
- Fuel assembly & stagnation

2D LASNEX simulations of MagLIF suggest an optimum at an aspect ratio (AR) of 6*

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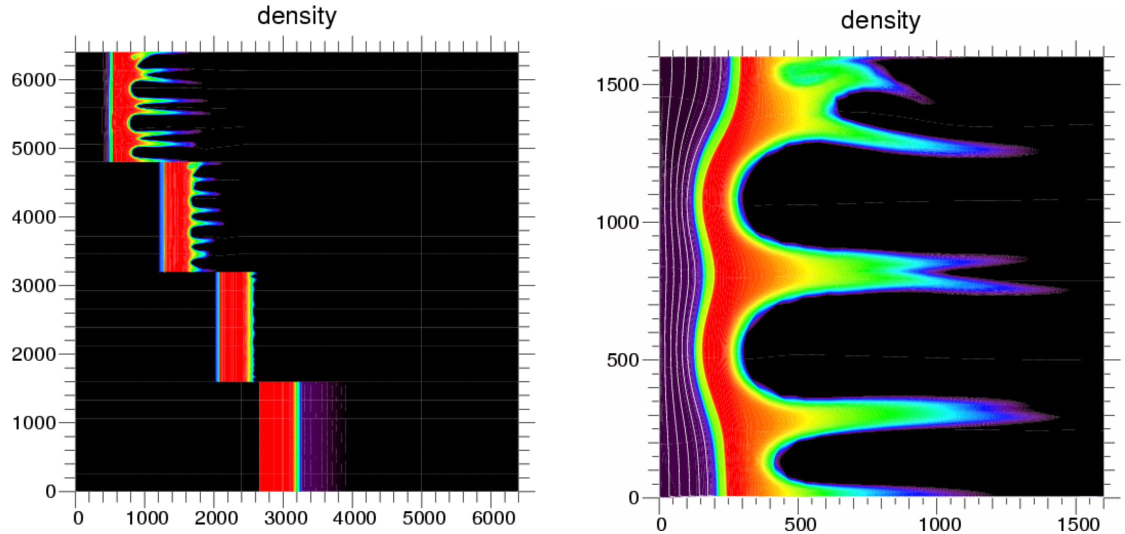
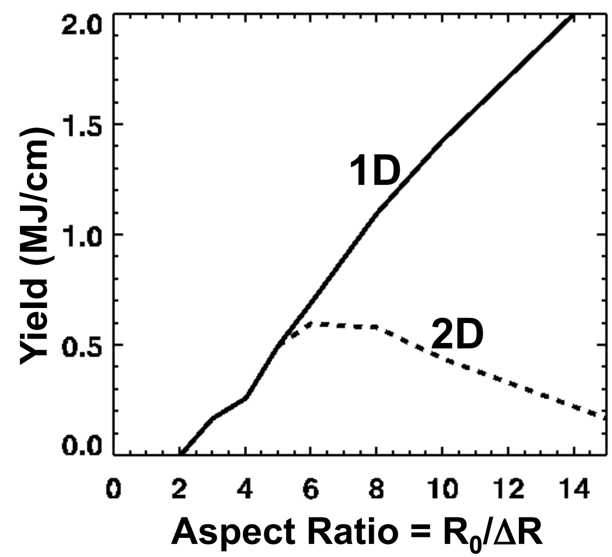
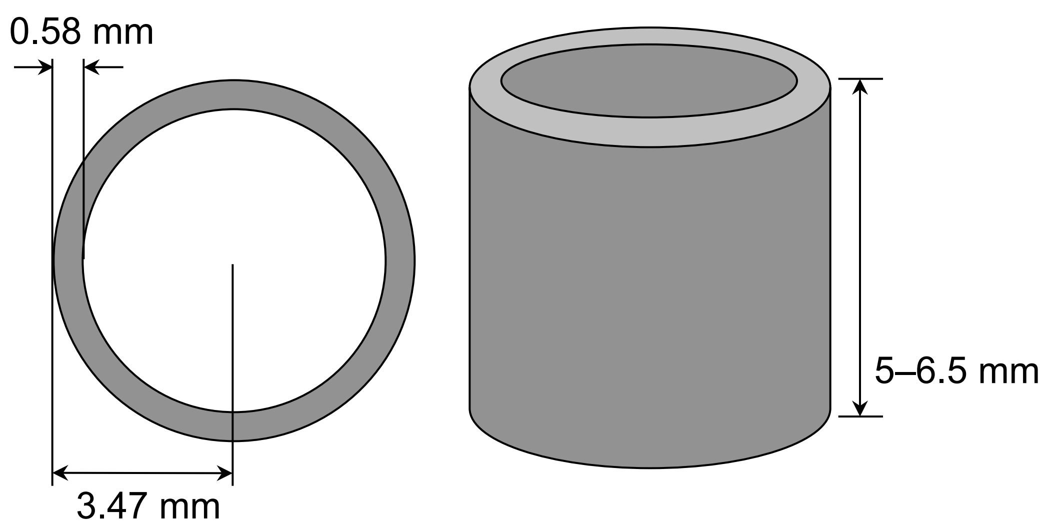






$$AR \equiv \frac{R_{outer,0}}{\Delta R_0}$$

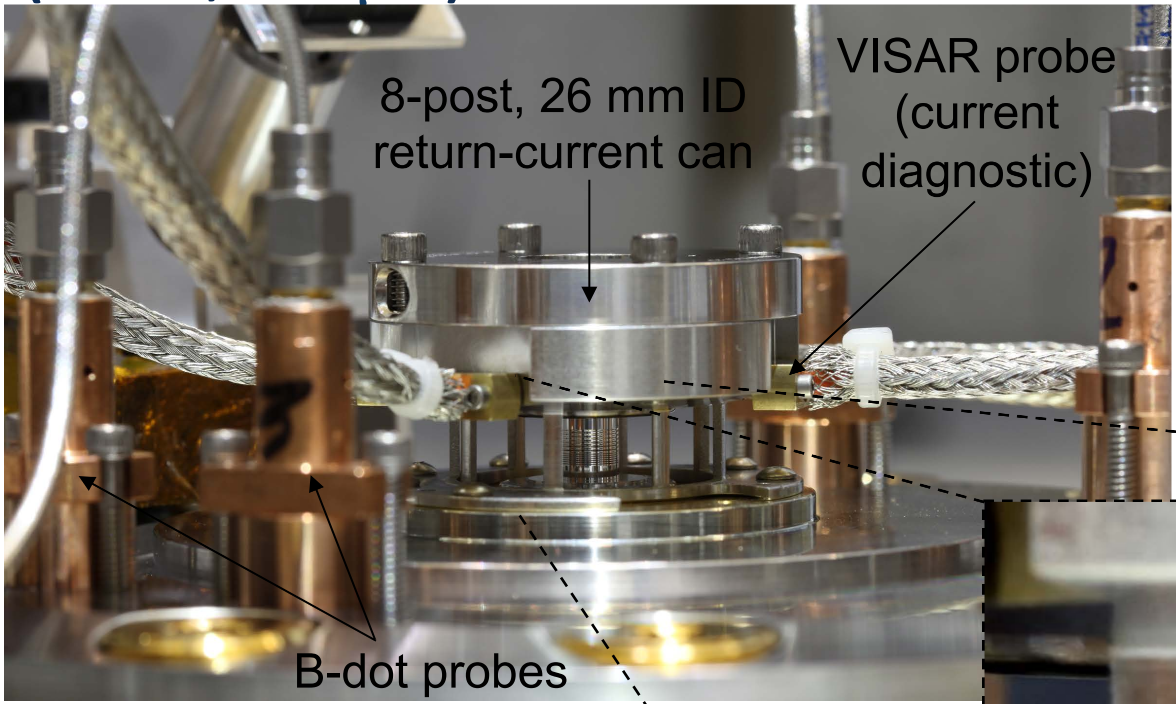
* S. A. Slutz *et al.*, Phys. Plasmas 17, 056303 (2010).

We have already done significant work to date on liner implosion dynamics that is relevant to MagLIF

- We will now briefly summarize several recent MagLIF-relevant liner dynamics publications:

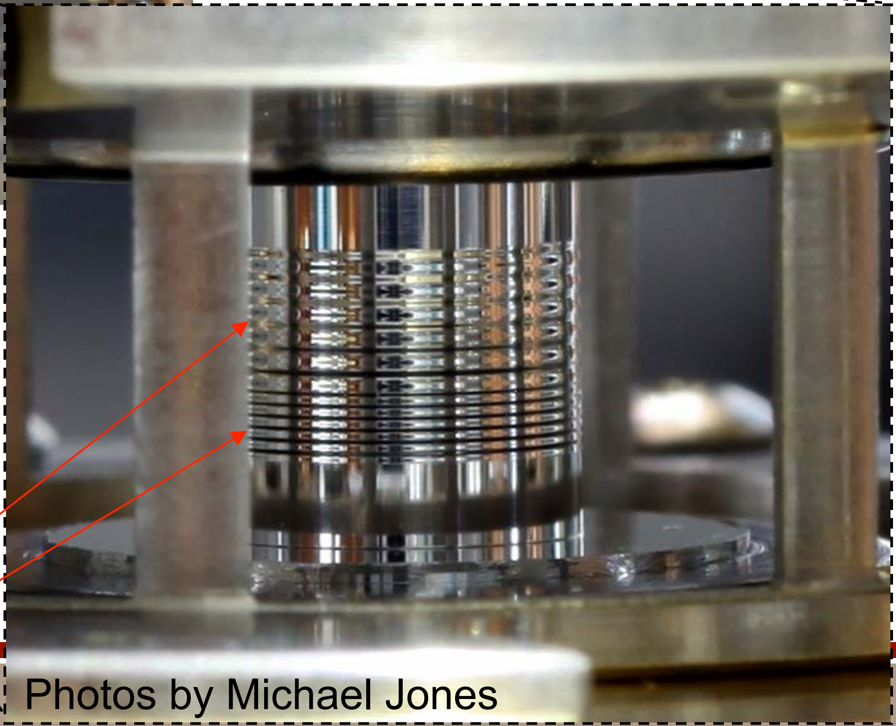
  - D.B. Sinars *et al.*, Phys. Rev. Lett. **105**, 185001 (2010).
  - D.B. Sinars *et al.*, Phys. Plasmas **18**, 056301 (2011).
  - M.R. Martin *et al.*, Phys. Plasmas **19**, 056310 (2012).
  - R.D. McBride *et al.*, Phys. Rev. Lett. **109**, 135004 (2012).
  - R.D. McBride *et al.*, Phys. Plasmas **20**, 056309 (2013).
  - K.J. Peterson *et al*., Phys. Rev. Lett. **112**, 135002 (2014).
  - K.J. Peterson *et al.*, Phys. Plasmas **19**, 092701 (2012).
  - K.J. Peterson *et al.*, Phys. Plasmas **20**, 056305 (2013).
  - T.J. Awe *et al*. Phys. Rev. Lett. **111**, 235005 (2013).
  - T.J. Awe *et al*. Phys. Plasmas **21**, 056303 (2014).
  - P.F. Knapp *et al*., manuscript in preparation (2015).

We tested MRT growth predictions in controlled experiments on Z using Al liners with small sinusoidal perturbations (λ=200, 400-μm)

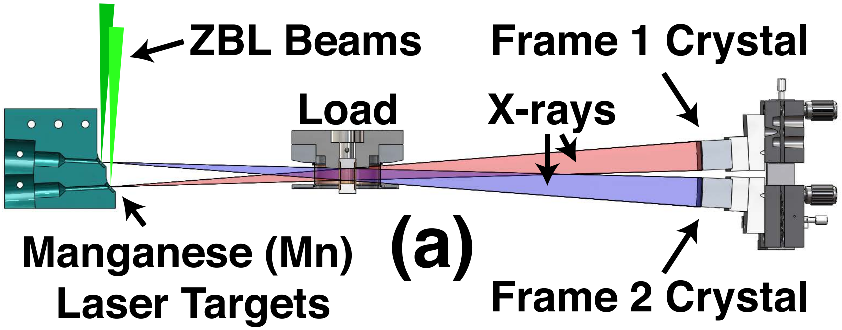


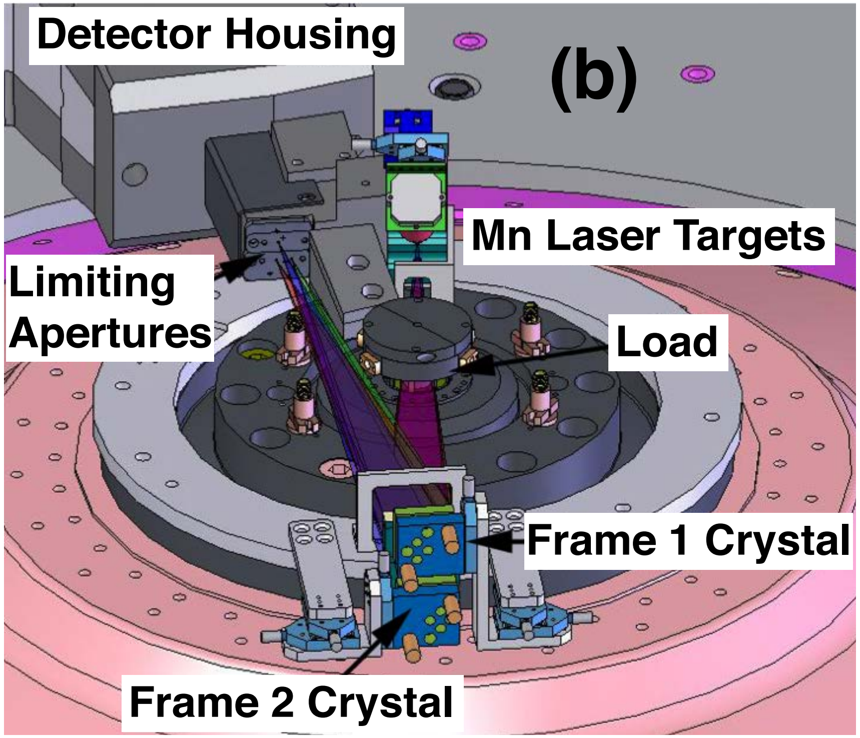
- Solid cylindrical liner (Al 1100 alloy)
- 6.5 mm tall, 6.34 mm diameter, AR=10
- 10 nm surface finish (diamond-turned)
- 12 sinusoidal perturbations

Targets made by General Atomics



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



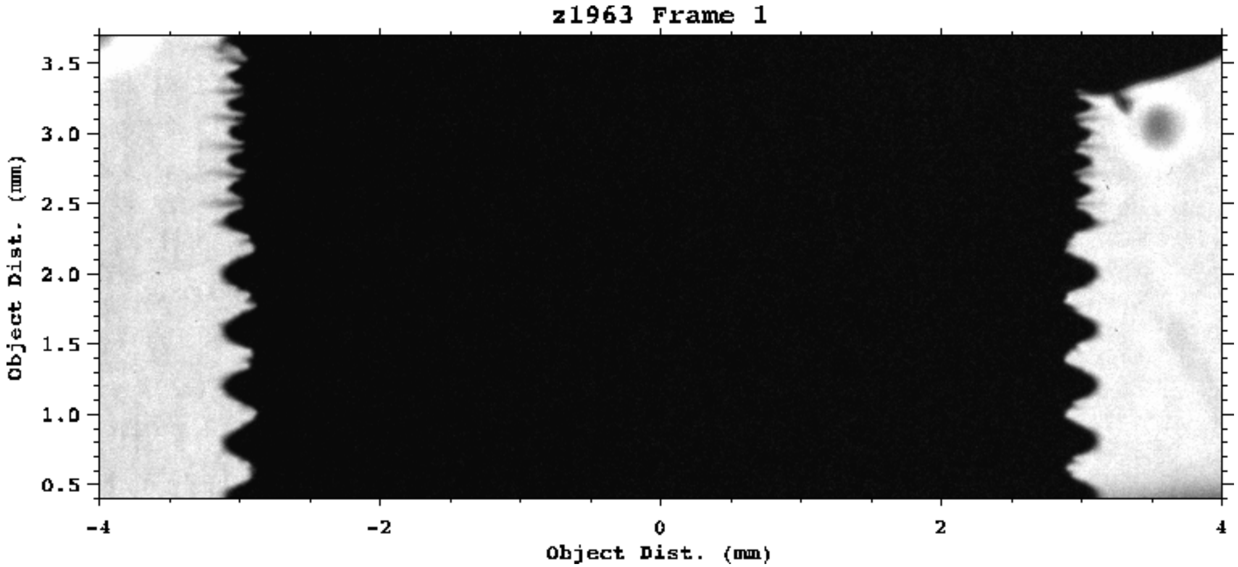


- Spherically-bent quartz crystals (22<u>4</u>3)
- Monochromatic (~0.5 eV bandpass)
- 15 micron resolution (edge-spread)
- Large field of view (10 mm x 4 mm)
- We can see through imploding beryllium (not so for aluminum and other higher-opacity materials)

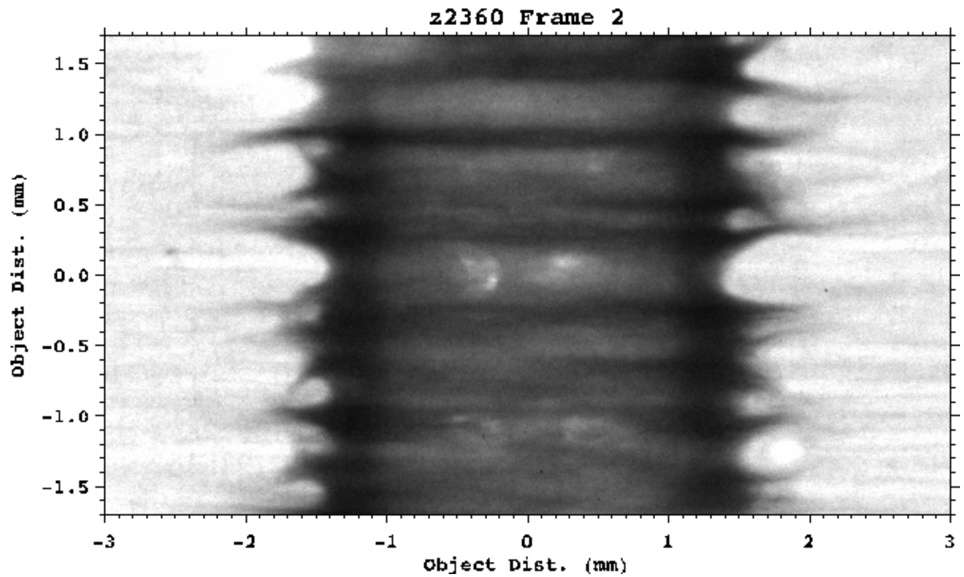
- **Original concept**
  - S.A. Pikuz *et al.*, RSI (1997).
- **1.865 keV backlighter at NRL**
  - Y. Aglitskiy *et al.*, RSI (1999).
- **Explored as NIF diagnostic option**
  - J.A. Koch *et al.*, RSI (1999).
- **Single-frame 1.865 keV and 6.151 keV implemented on Z facility**
  - D.B. Sinars *et al.*,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

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

The lower opacity of beryllium at 6.151 keV allows us to take penetrating radiographs of the liner implosions



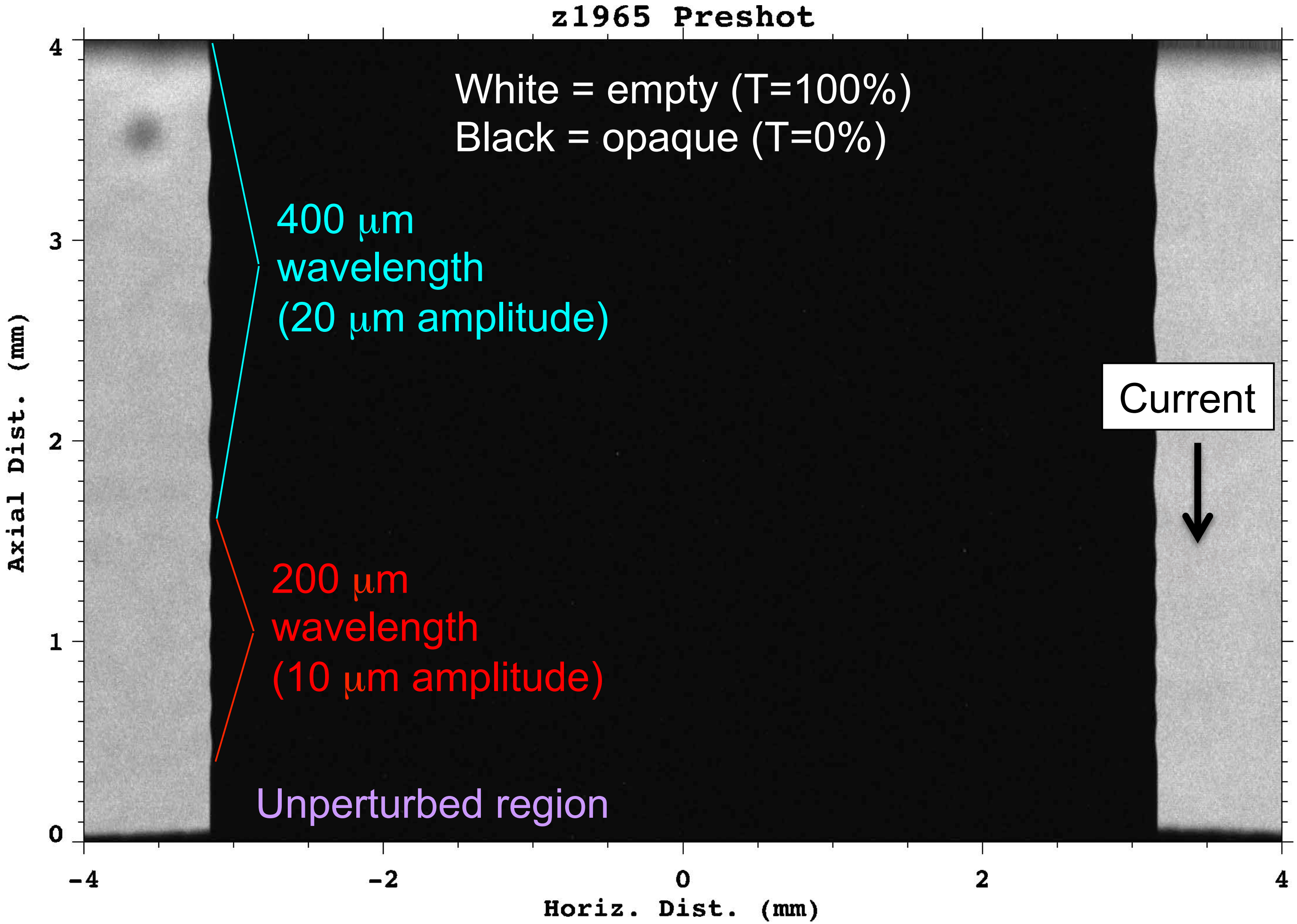
High opacity of Al means that we only see the edge of the liner



Lower opacity of Be means that we can see through the liner and the “spikes” show up as dark bands

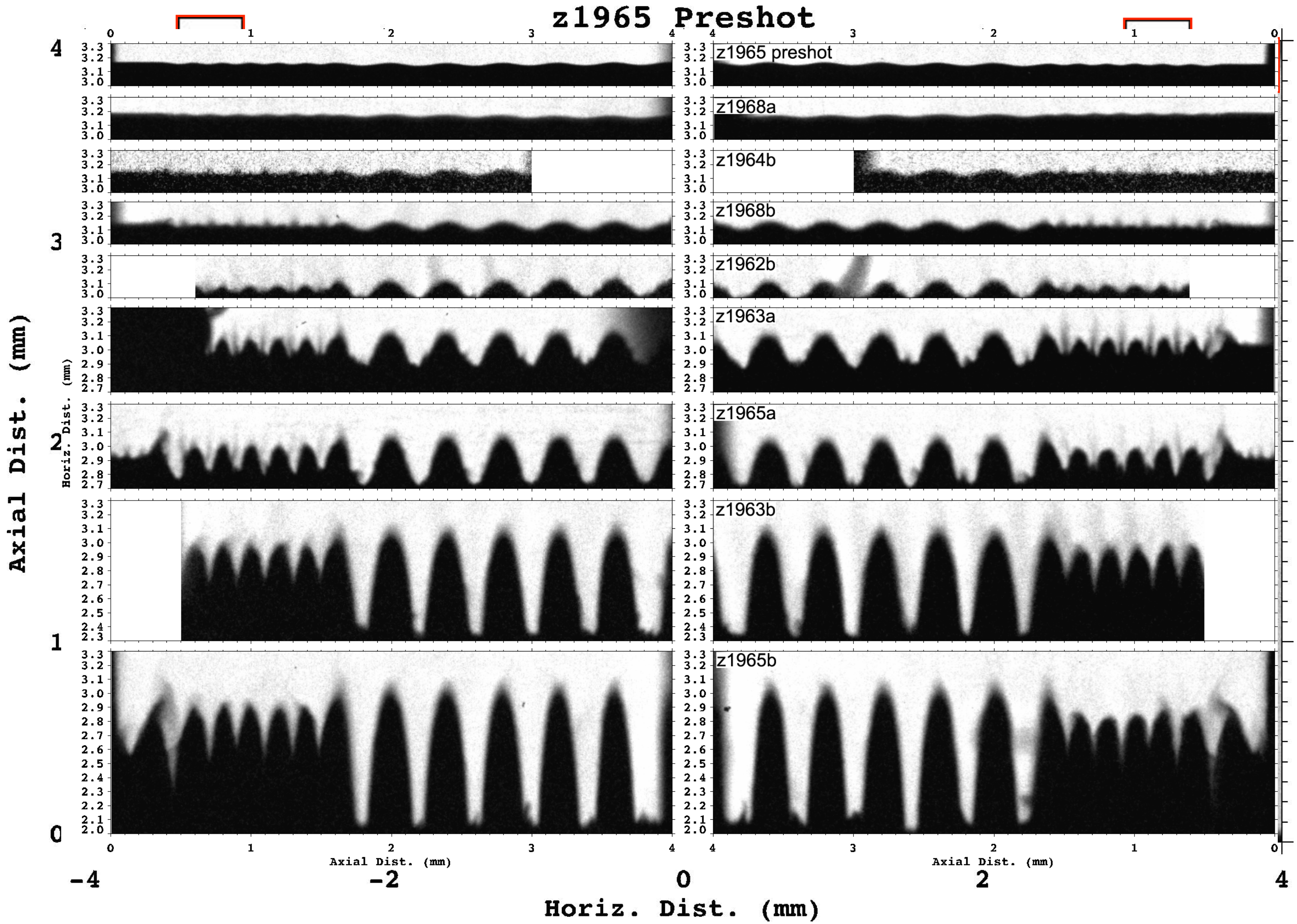
Machining of beryllium targets is done at General Atomics in La Jolla, CA

Example 6.151 keV radiograph (Pre-shot)



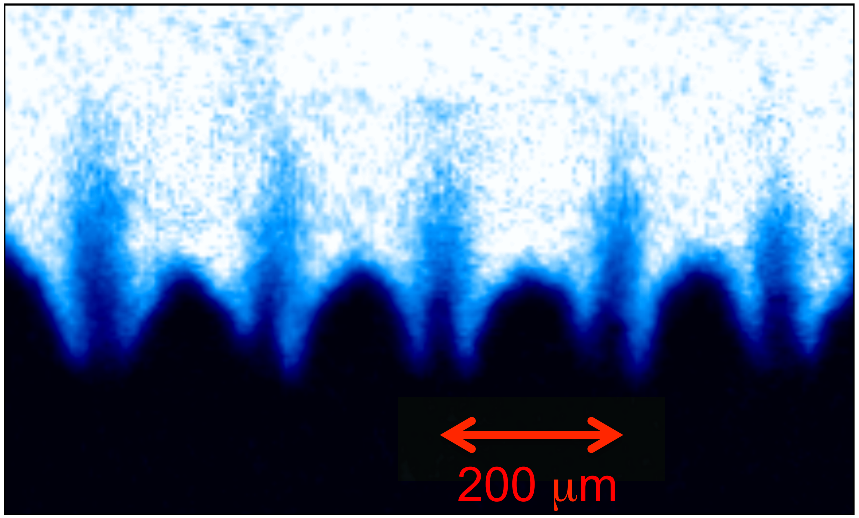
D.B. Sinars *et al.*, Phys. Rev. Lett. (2010); D.B. Sinars *et al.*, Phys. Plasmas (2011).

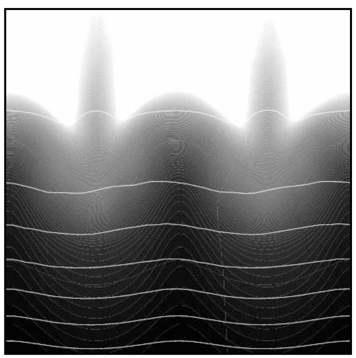
Zooming in, we see ablation, jetting, and small-scale instabilities in addition to the seeded instability growth



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

We observe excellent agreement between simulation and experiment in single-mode MRT growth experiments, *using the same methodology as used in MagLIF calculations*

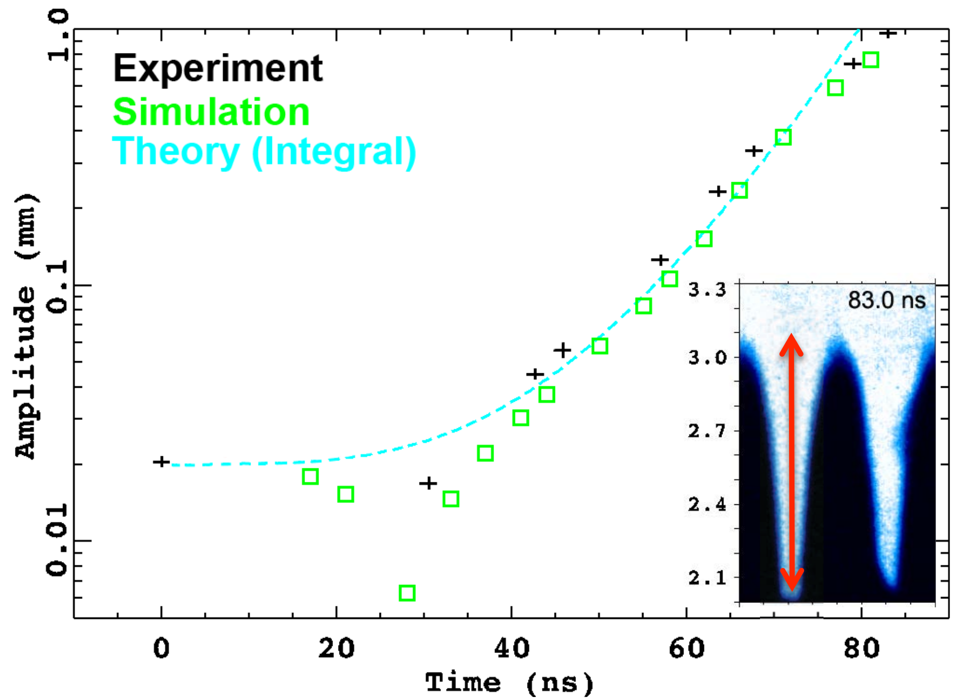




Ablated material coalesces in valleys to form jets visible in the radiographs

Simulated density map with rB_θ contours

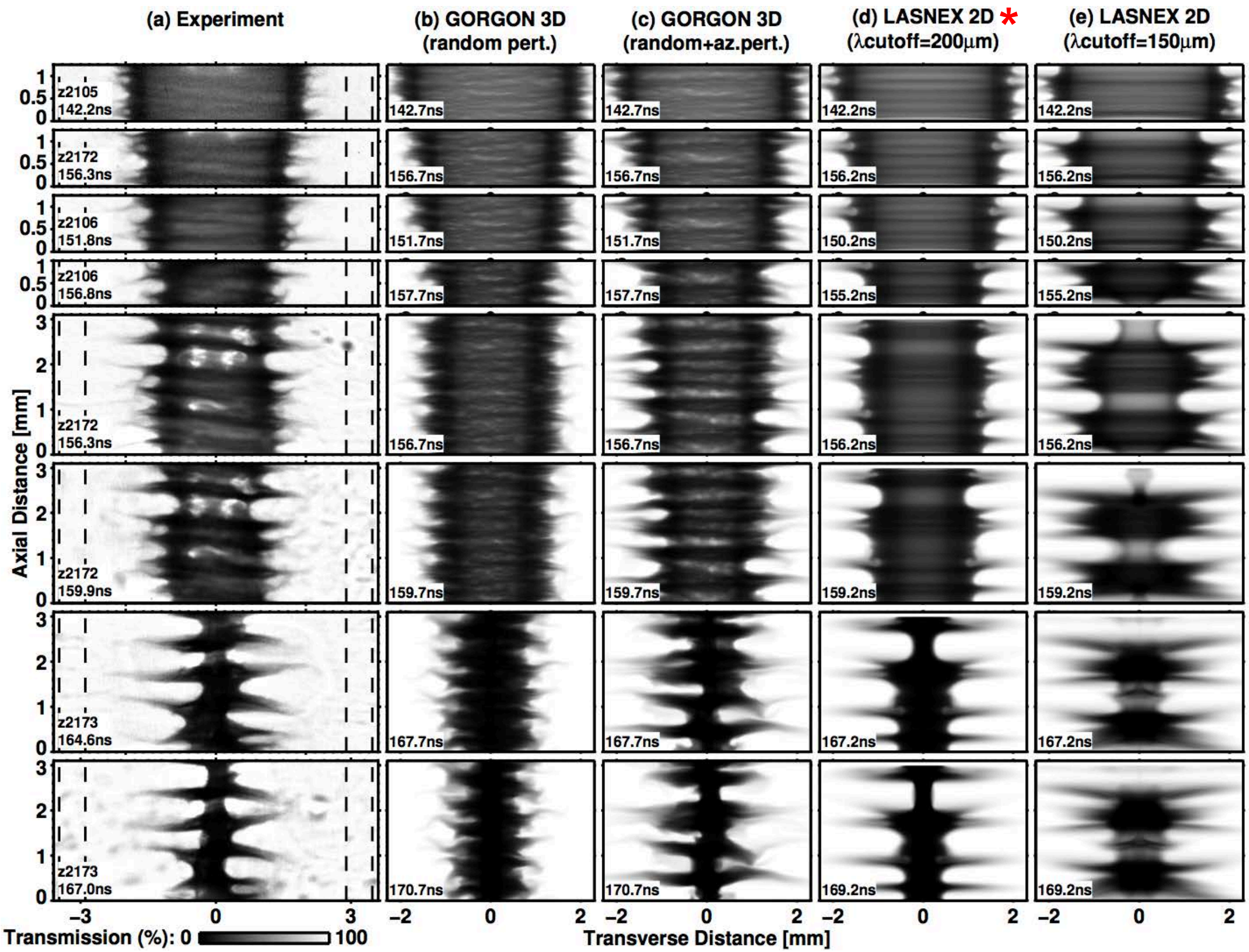
LASNEX: T_{jets} ~30 eV; T_{valley} ~100 eV



- **Fine-structure details such as jetting and ablation were successfully predicted**
- **Amplitude of the resulting growth versus time was also predicted, and matches that expected by theory**

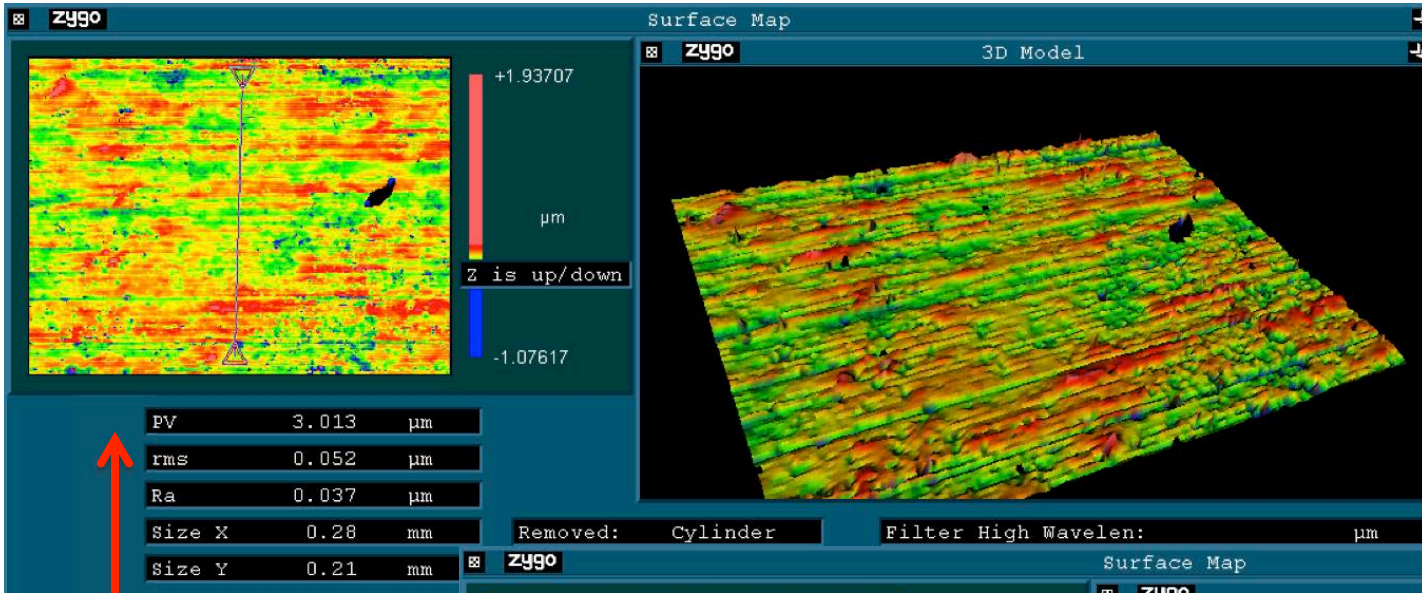
D.B. Sinars *et al.*, Phys. Rev. Lett. (2010); D.B. Sinars *et al.*, Phys. Plasmas (2011).

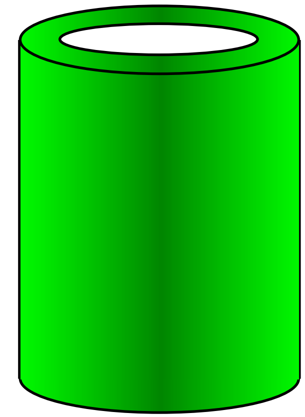
Beryllium experiments show surprisingly correlated instability growth



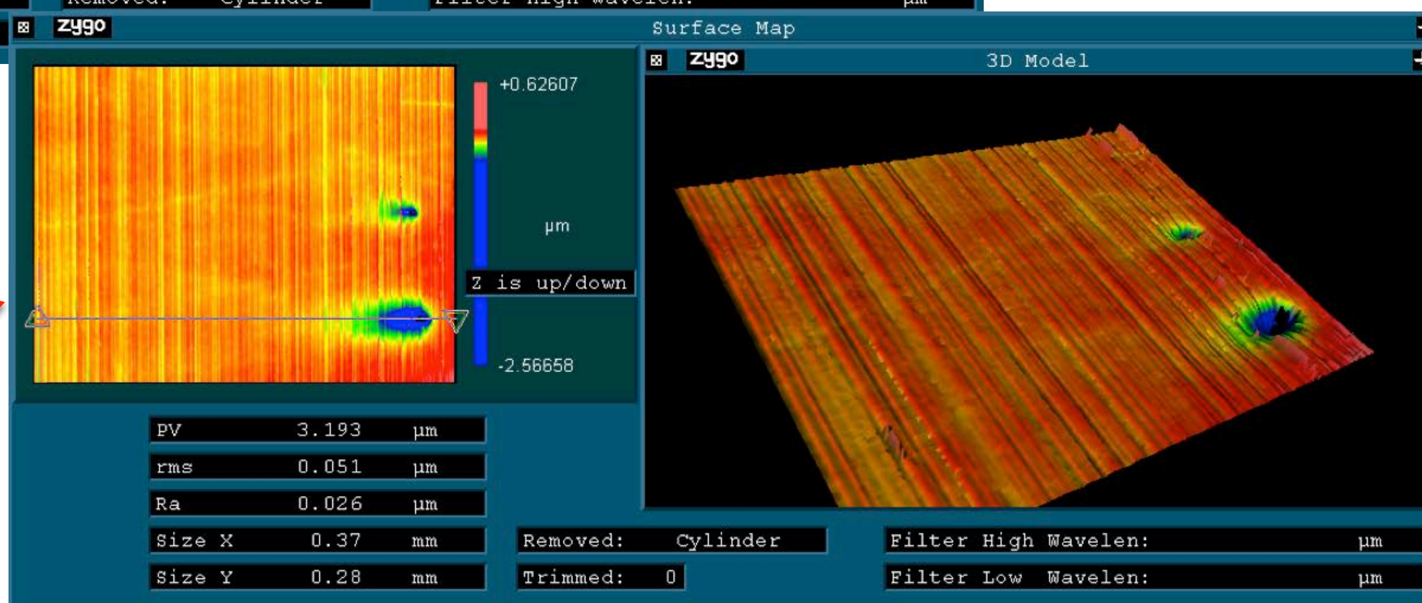
R.D. McBride *et al.*, Phys. Rev. Lett. 109, 135004 (2012).

Our liners are diamond-turned on a lathe to provide smooth surfaces, but this process leaves azimuthally-correlated tool marks





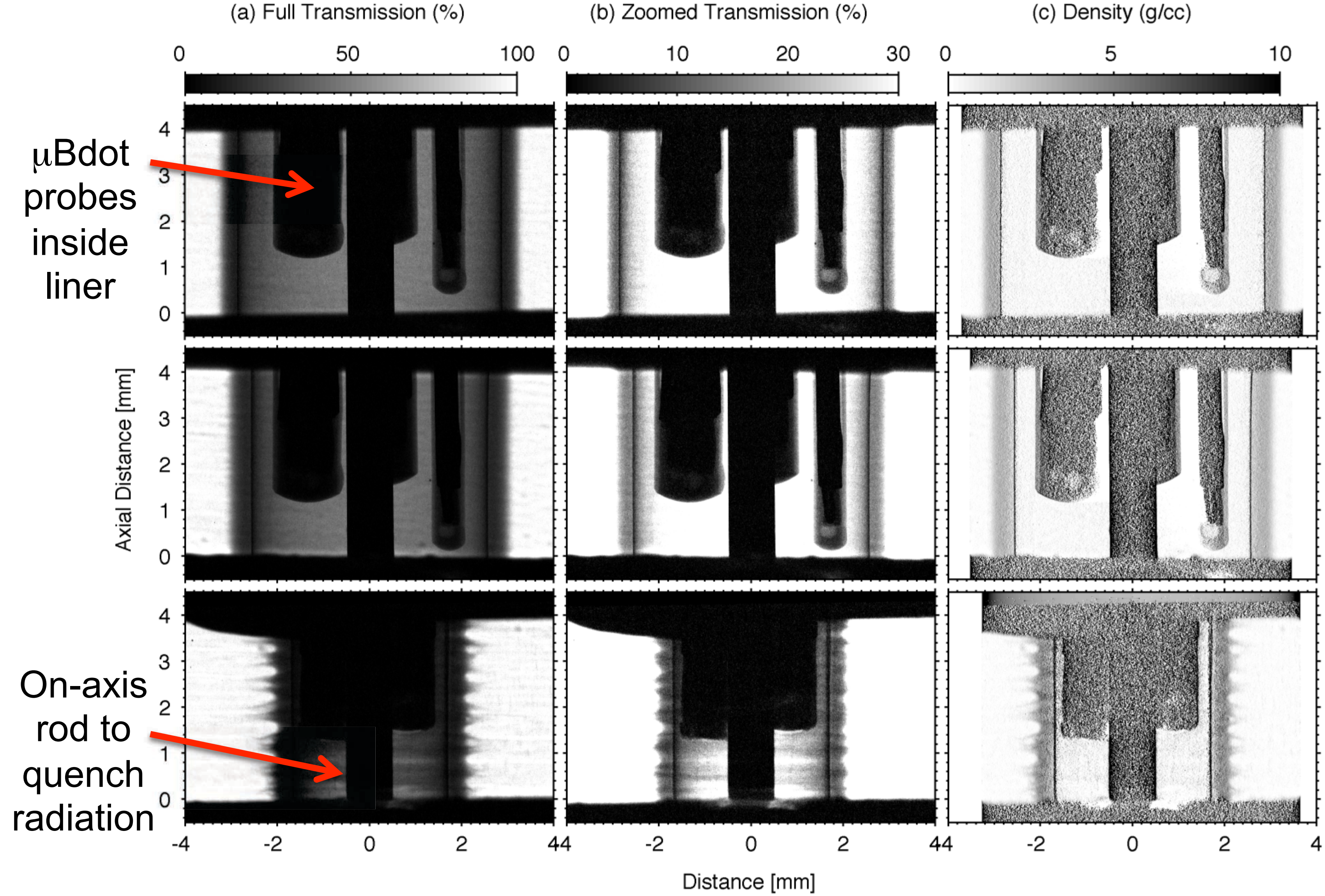
Standard process
(50 nm RMS)



After axial polishing process applied
(50 nm RMS)

We have just started investigating whether a different surface structure affects the results

Recent experiments used 2 μm Al just inside the Be liner to enhance the contrast of the liner's inner surface*

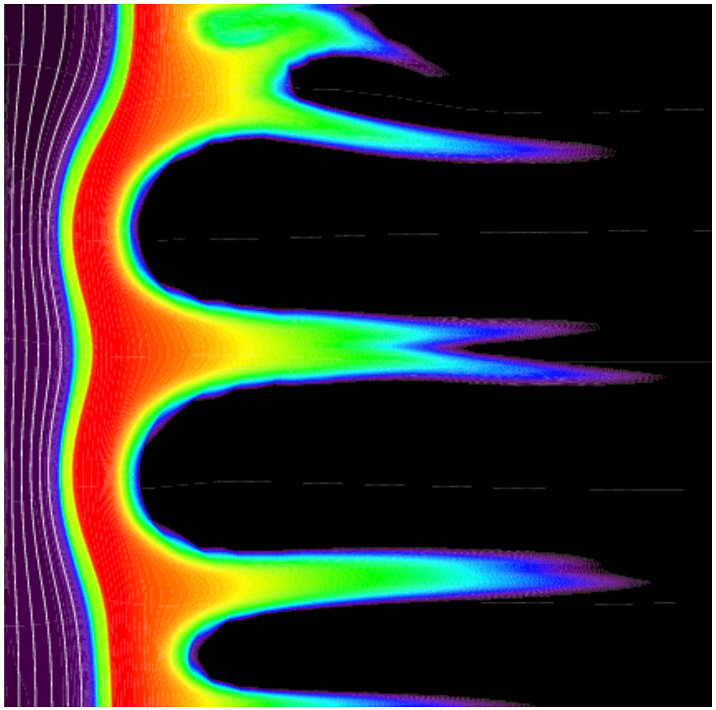


*Thin Al layer to enhance contrast suggested by D.D. Ryutov

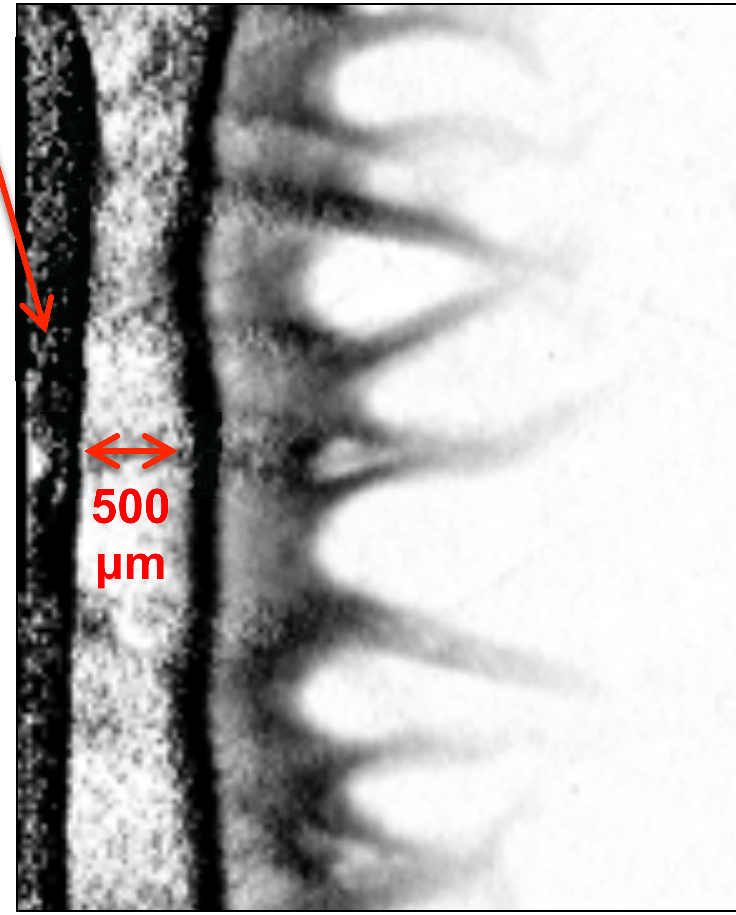
R. D. McBride et al., Phys. Plasmas **20**, 056309 (2013).

Radiographs at a convergence ratio of ~5 show remarkably good stability for inner liner surface

Note: MagLIF requires final compression to on-axis rod



LASNEX 2D from
S. A. Slutz, *et al*., PoP (2010)



Experiment

R. D. McBride et al., Phys. Plasmas **20**, 056309 (2013).

Electrothermal instabilities occur when material conductivity is dependent on temperature

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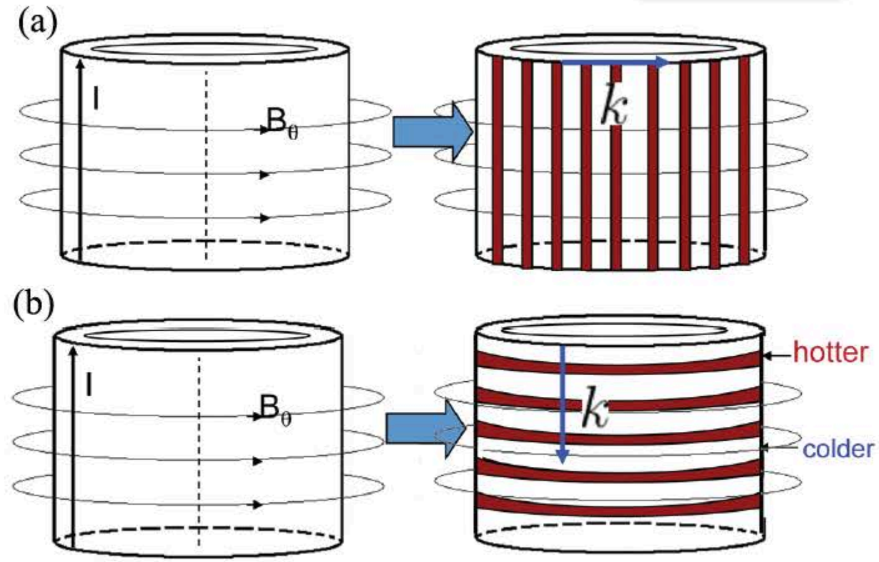
Theory



Filamentations

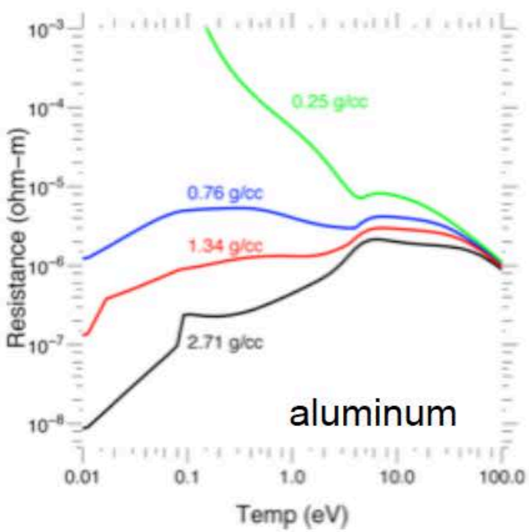
$$\frac{d\eta(T)}{dT} < 0$$

- High temperature (>10 eV) plasmas
- This is commonly the situation that occurs when the term *"electrothermal instabilities"* is referred to in the literature

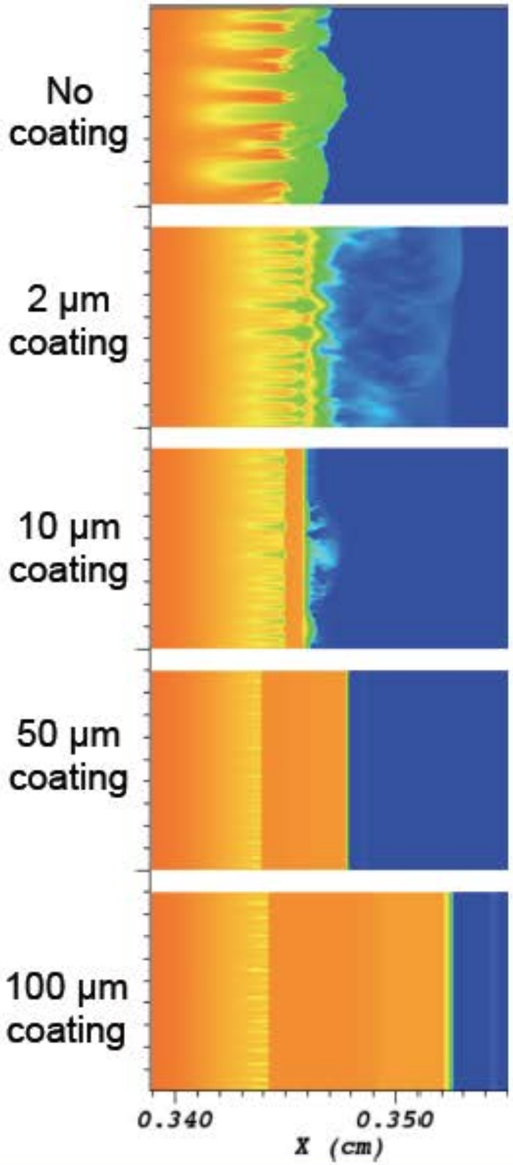
Striations

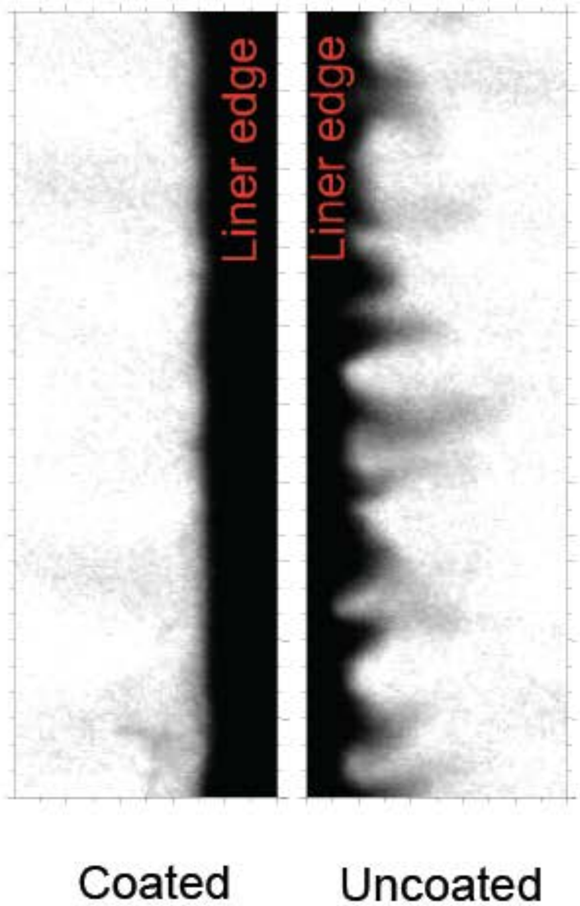
$$\frac{d\eta(T)}{dT} > 0$$

- Also sometimes referred to as thermal *"overheat"* instabilities
- Occurs in condensed states of metals
- Focus of remainder of talk



Relatively thick insulating coatings suppress liner instabilities that are seeded by the electro-thermal instability*

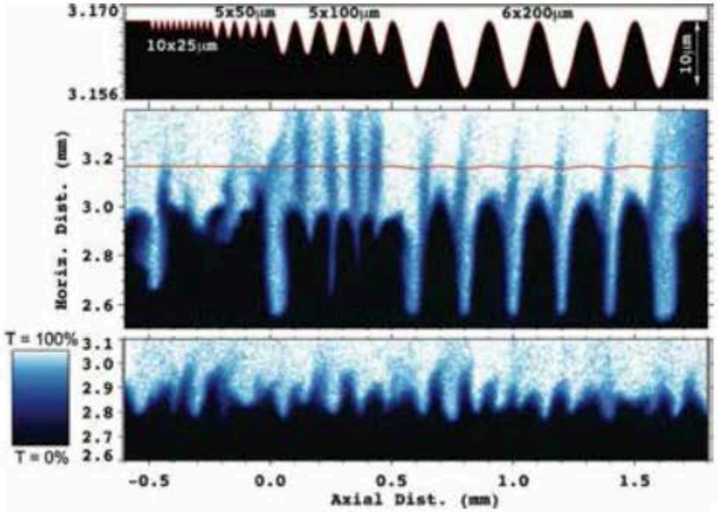




New data from K.J. Peterson *et al.*, manuscript in preparation

* K.J. Peterson *et al.*, Phys. Plasmas 19, 092701 (2012); K.J. Peterson *et al.*, Phys. Plasmas 20, 056305 (2013).

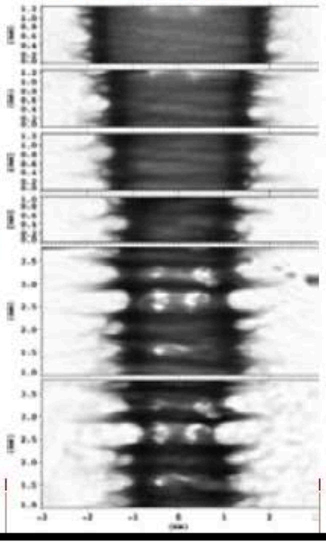
We have made progress in understanding the seed for liner instability growth and in mitigating this growth, which may open up design space for MagLIF



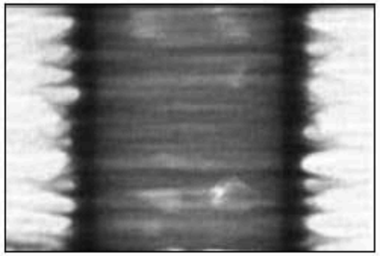
Ao = 25,000 to 200,000 nm

Ao = 60 nm

McBride PRL data

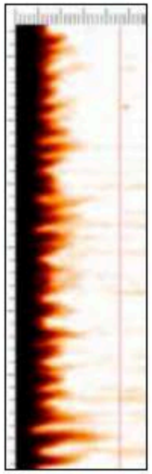


Axially-polished liner growth

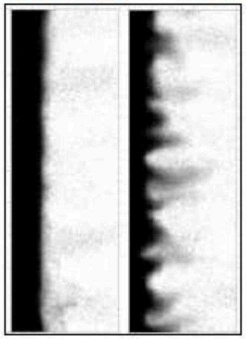


Changing the character of the surface did not change the observations

Based on a hypothesis that instabilities seeded by electro-thermal instability, we have developed a mitigation strategy

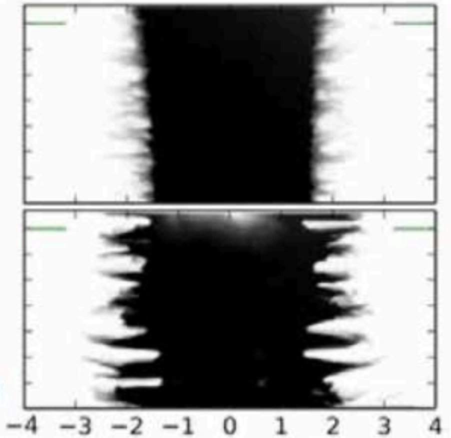


Suppressed growth using CH overcoat



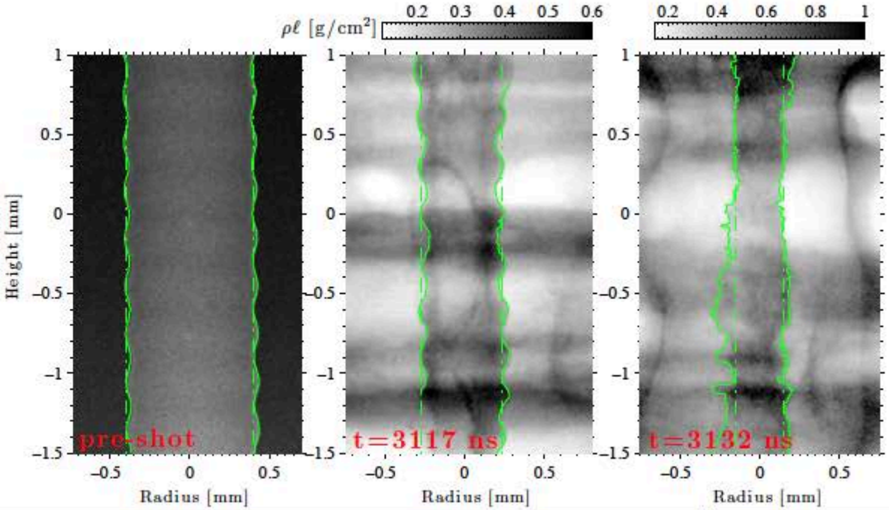
Rod

Liner implosion



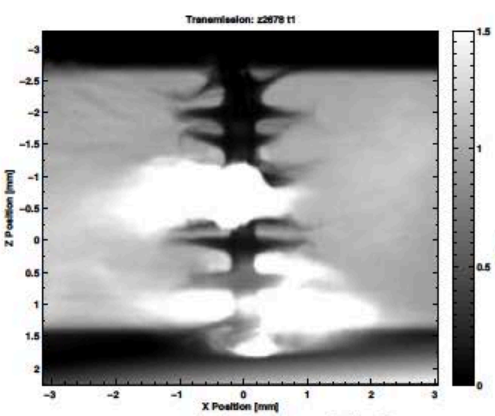
Data collected during past year appears to support the mitigation idea

In the last year we began studying deceleration instabilities, high-density compression, and high CR compression



- A Be, liquid D2 filled liner is imploded onto an on-axis rod with a sinusoidal perturbation
- The liner launches a shock in the D2 which strikes the rod/fuel interface (1st image after shock)
- Shock reflects off the axis and re-shocks the Be/D2 interface (2nd)

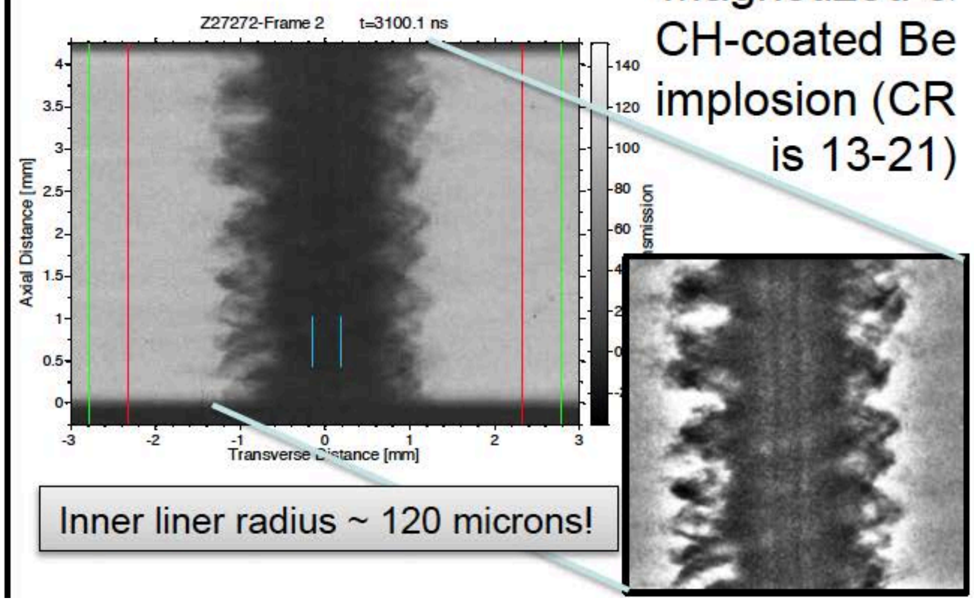
Current pulse shaping to compress liquid D2 to extreme densities



$$CR \approx 19$$
$$\langle \rho \rangle = 60\ \mathrm{g/cm^3}$$
$$\langle \rho R \rangle = 0.5\ \mathrm{g/cm^2}$$

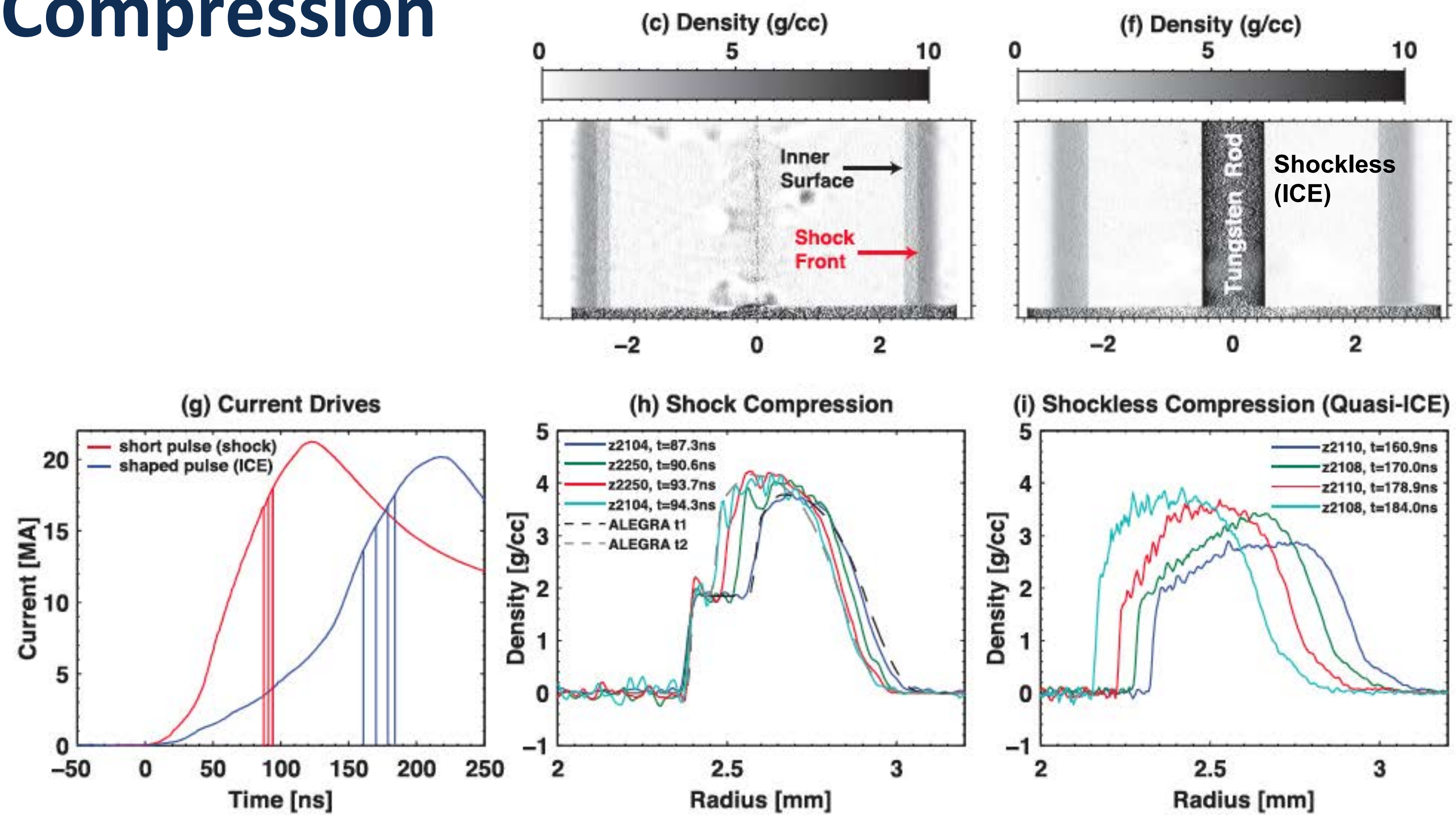
$$r_{stag} = 110 - 170\ \mu\mathrm{m}$$

Magnetized & CH-coated Be implosion (CR is 13-21)



Inner liner radius ~ 120 microns!

Shock vs. Shockless (Quasi-Isentropic) Compression



R. D. McBride et al., Phys. Plasmas **20**, 056309 (2013).

Most Recent Be ICE to >5 Mbar

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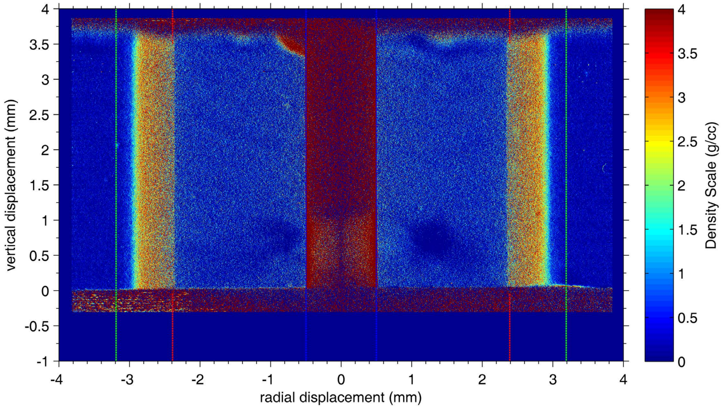
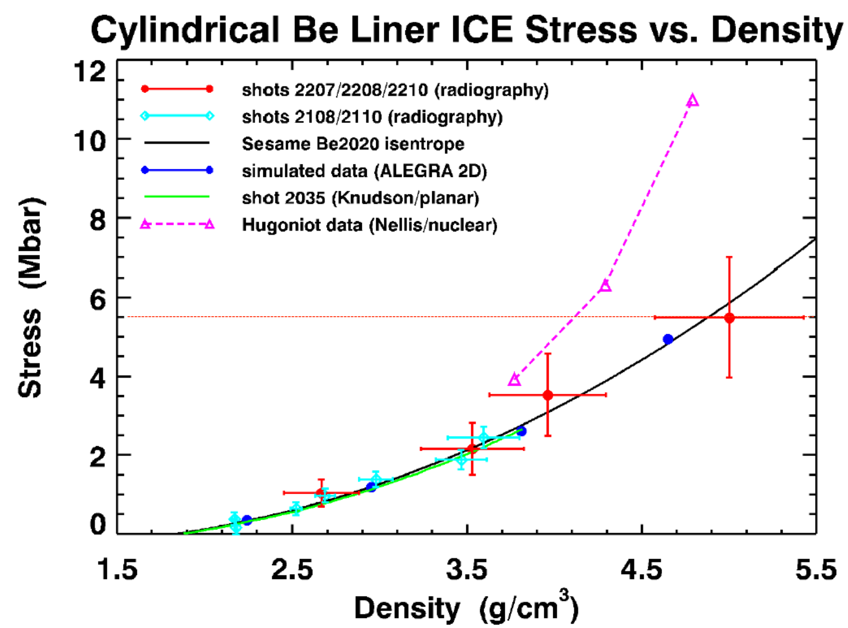


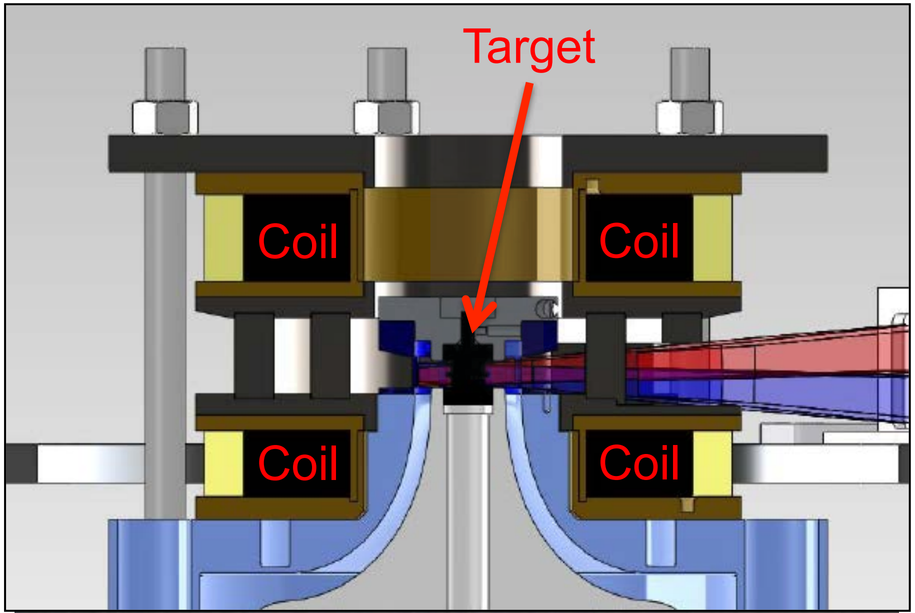
$$\frac{\partial(rv)}{\partial m} = \frac{1}{2\pi}\frac{D}{Dt}\left(\frac{1}{\rho}\right),$$

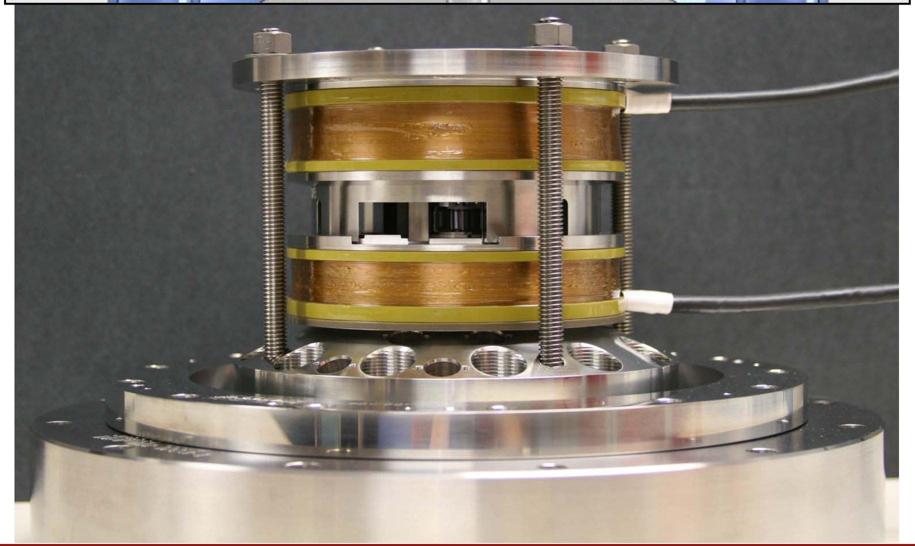
$$\frac{\partial P_T}{\partial m} = -\frac{1}{2\pi r}\frac{Dv}{Dt}.$$



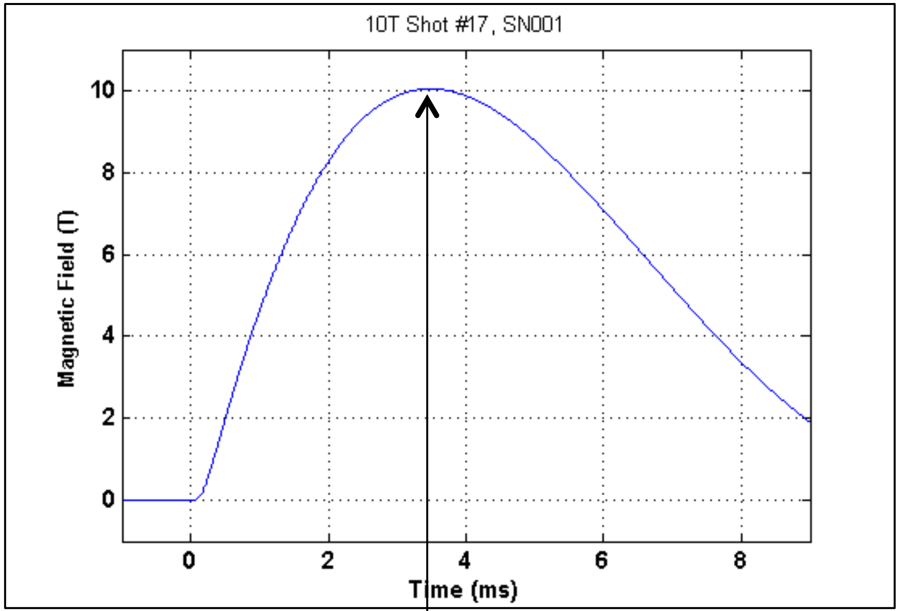
EOS unfolds by
M. R. Martin

Prototype coils have been demonstrated that generate 10 T axial fields over a several cm^3 volume for MagLIF with full diagnostic access





10 Tesla point design



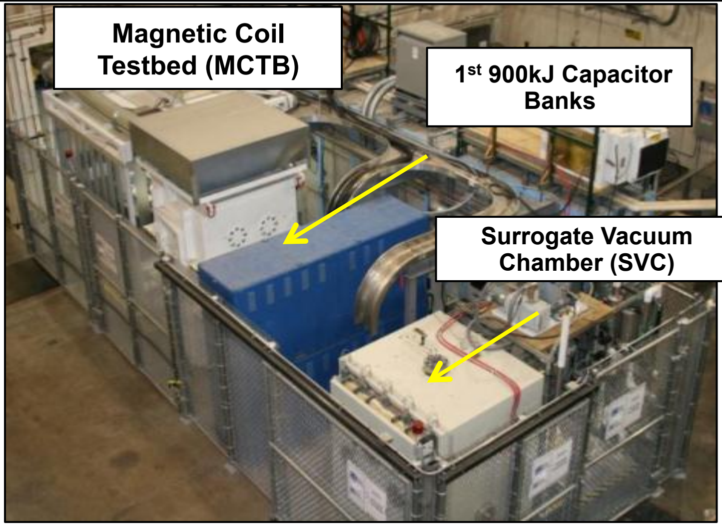
Time to peak field = 3.49 ms

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

An 8 mF, 15 kV, 900 kJ capacitor bank has been installed on Z to drive the coils

- Two identical units (repurposed from ion beam facilities) allows for high-fidelity surrogacy testing in separate test facility
- We believe 900 kJ is enough to meet our short and long term goals (30 T)

The SITF Testbed in Bldg. 970



Commissioning of coils in the Z chamber completed in Feb. 2013

Photo of capacitor bank w/o covers; with covers

D.C. Rovang *et al.*, see http://www.sandia.gov/pulsedpower/maglifpres/Agenda.html

Debris from MagLIF experiments must be carefully managed (several MJ energy release equivalent to few sticks of dynamite)

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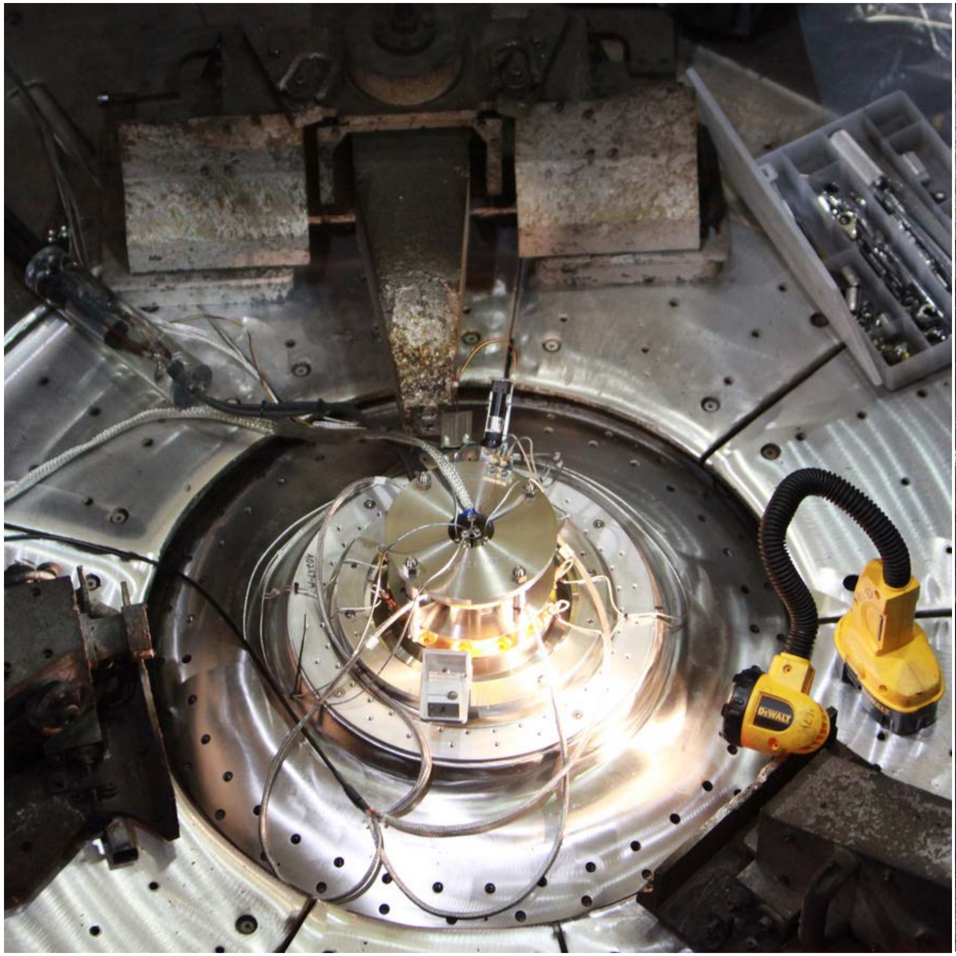
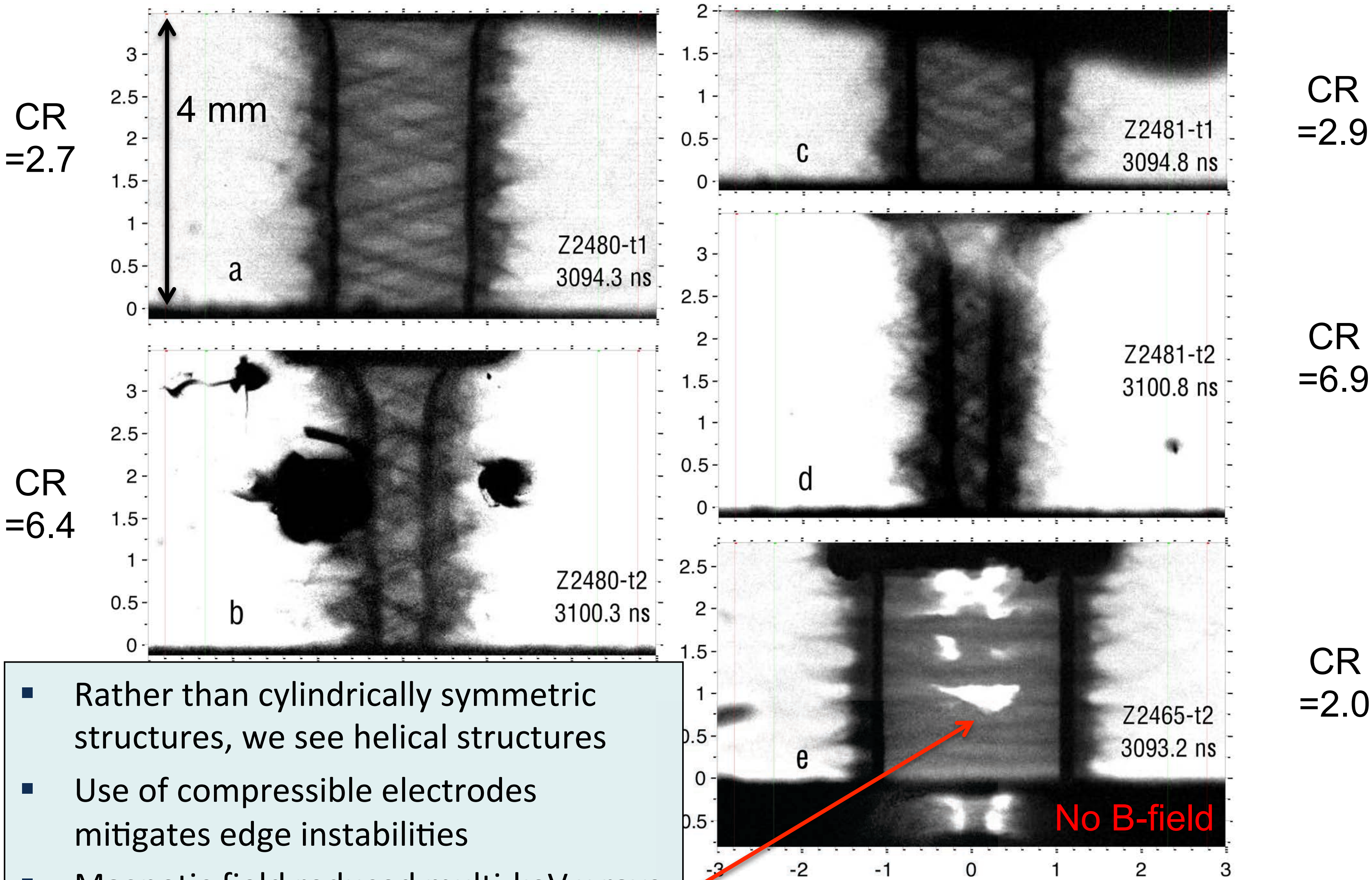


Pre-shot photo of coils & target hardware

Post-shot photo

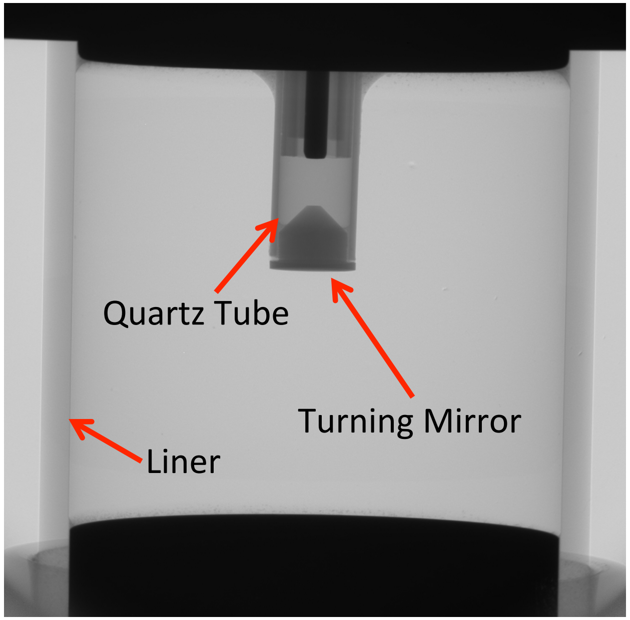
The addition of a 7-10 T axial magnetic field produces a dramatic change in the structure of the liner instabilities

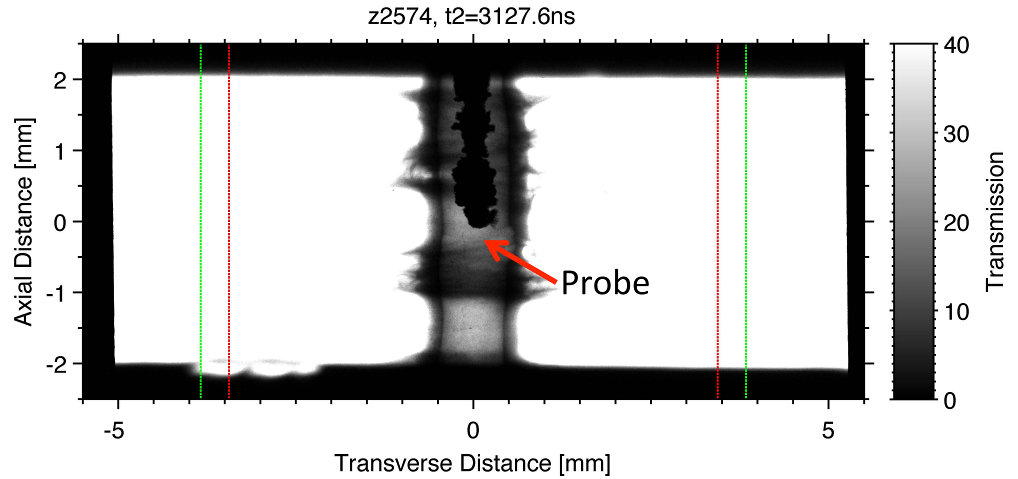


- Rather than cylindrically symmetric structures, we see helical structures
- Use of compressible electrodes mitigates edge instabilities
- Magnetic field reduced multi-keV x rays associated with late-time instabilities

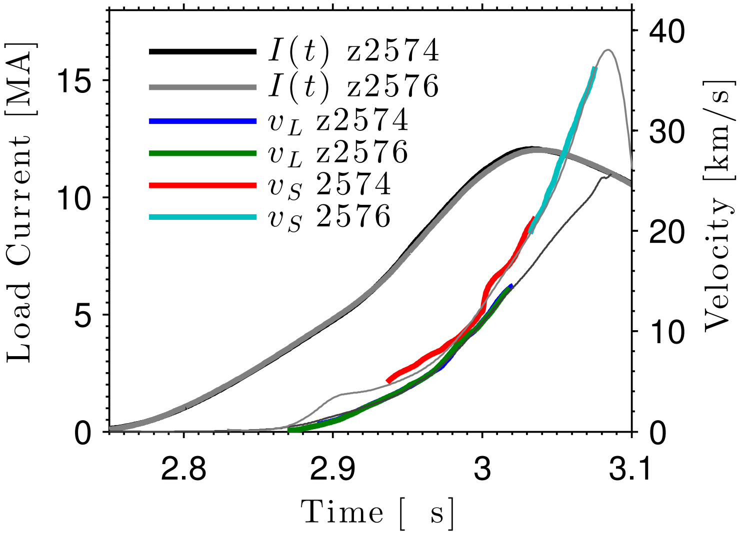
T. J. Awe *et al.*, manuscript in preparation (2013).

Platform development for high pressure deceleration & stagnation dynamics

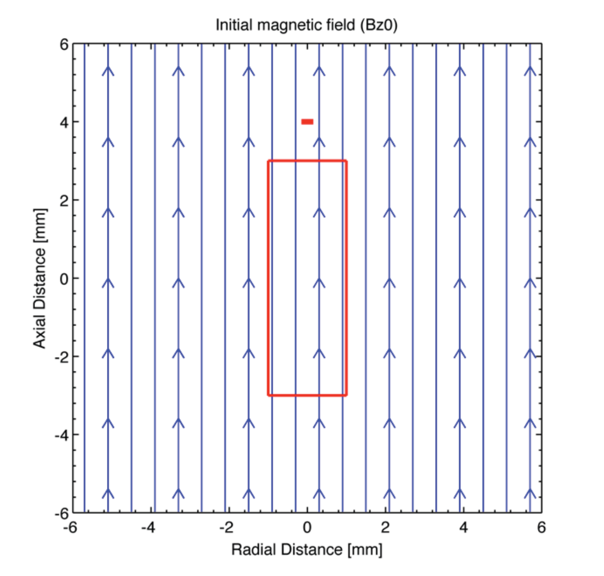


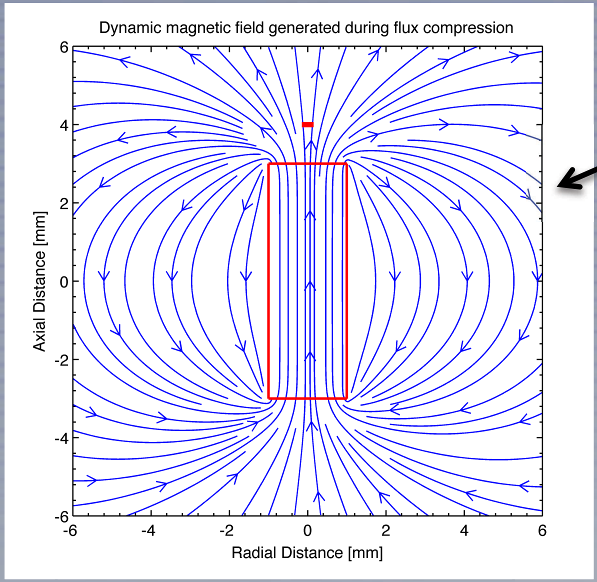


- Successfully measured the liner velocity and the D2 shock velocity
- Peak measured velocity ~40 km/s
- Equipment available to extend velocity range to 80-90 km/s
- Able to infer average post-shock state during run-in phase of ρ=1.5 g/cc, P=2 Mbar
- (~2 Gbar stagnation pressure inferred from radiography)

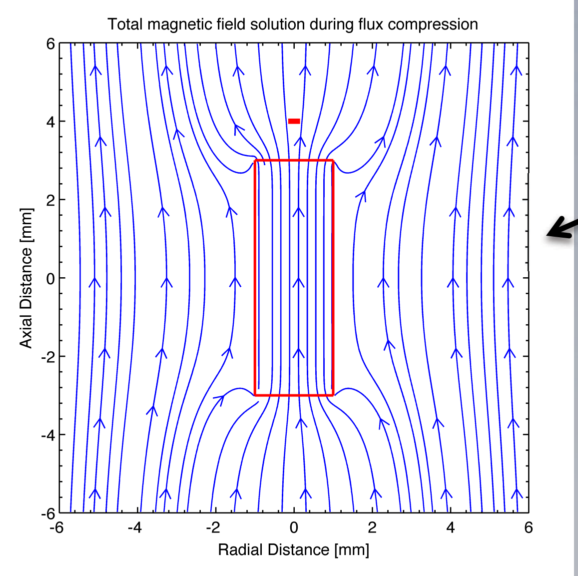


Vacuum Magnetic Flux Compression:



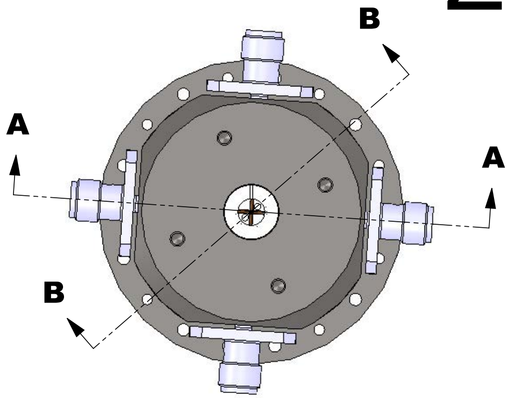


Bdot probes detect dynamic field

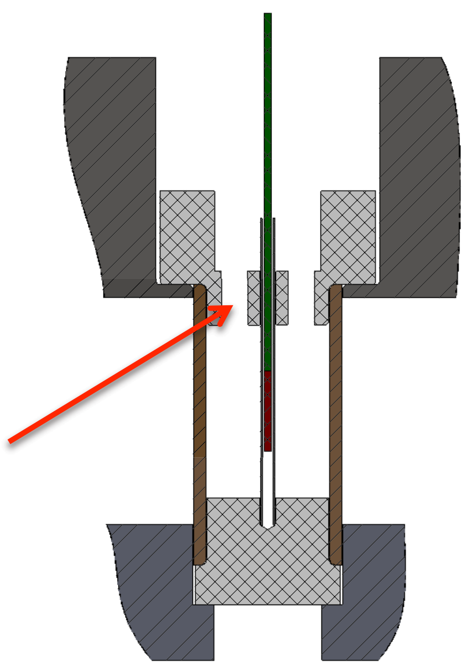


Faraday rotation and Zeeman spectroscopy measure total field

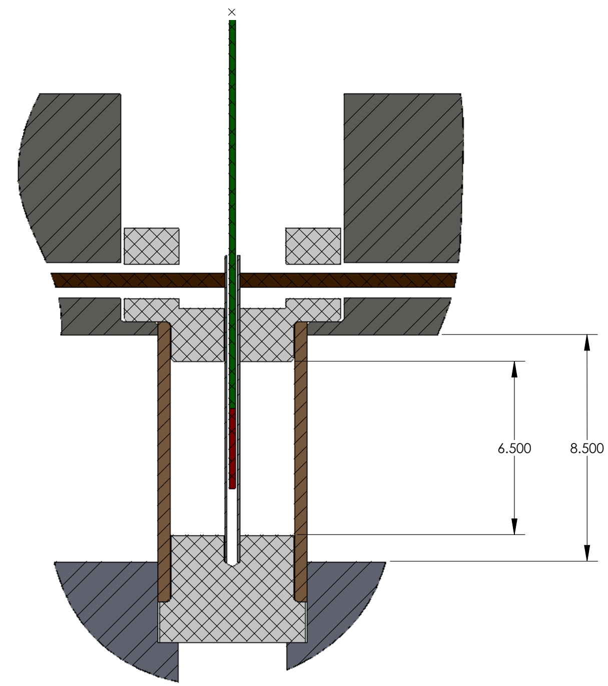
Z Shot 2592 Target design



- Used MagLIF-relevant dimensions and implosion time
- Faraday rotation fiber on axis
- 2 SVS fibers in top end cap
- 4 micro Bdots in top end cap

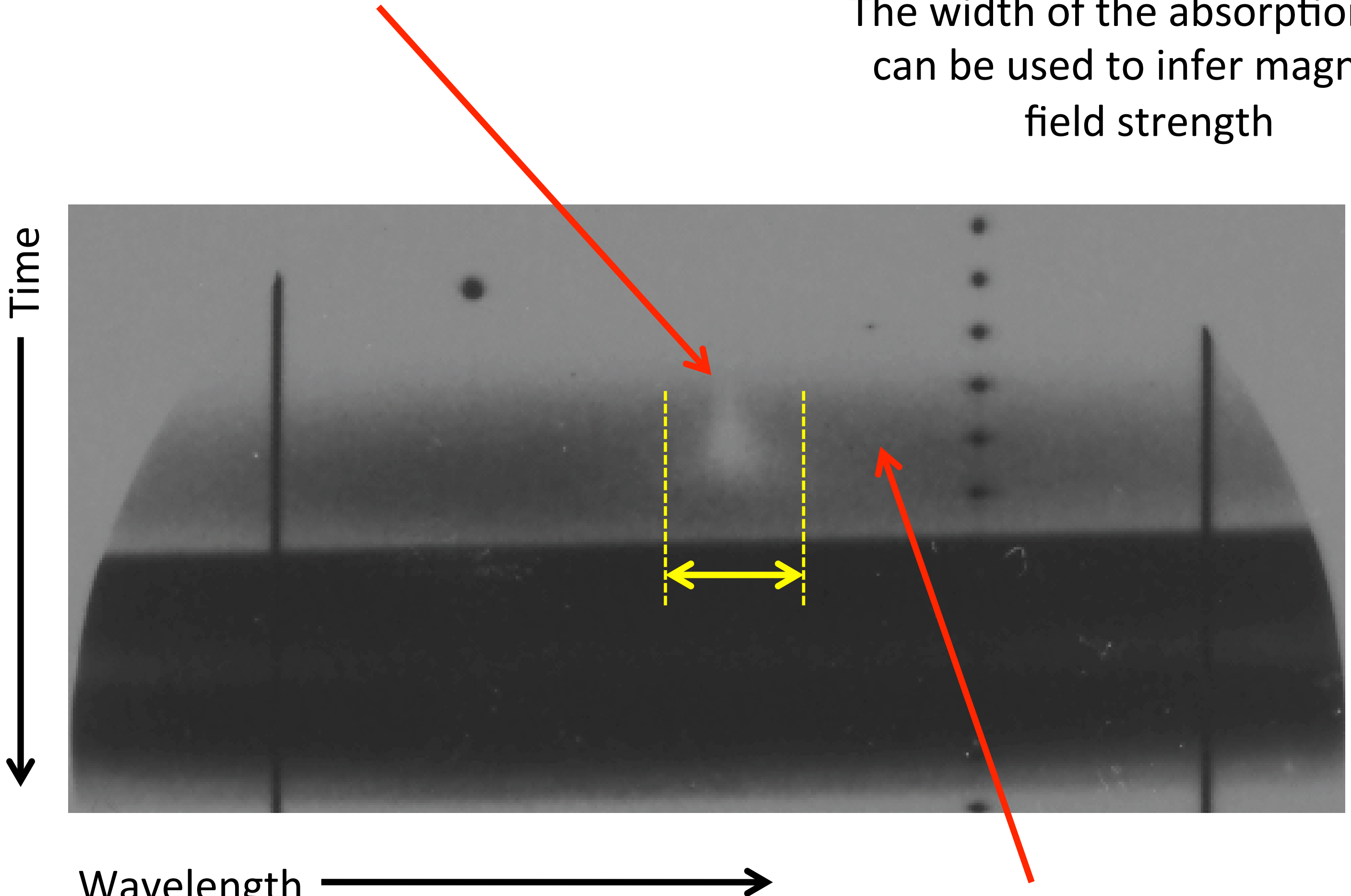


SECTION B-B
SCALE 8 : 1



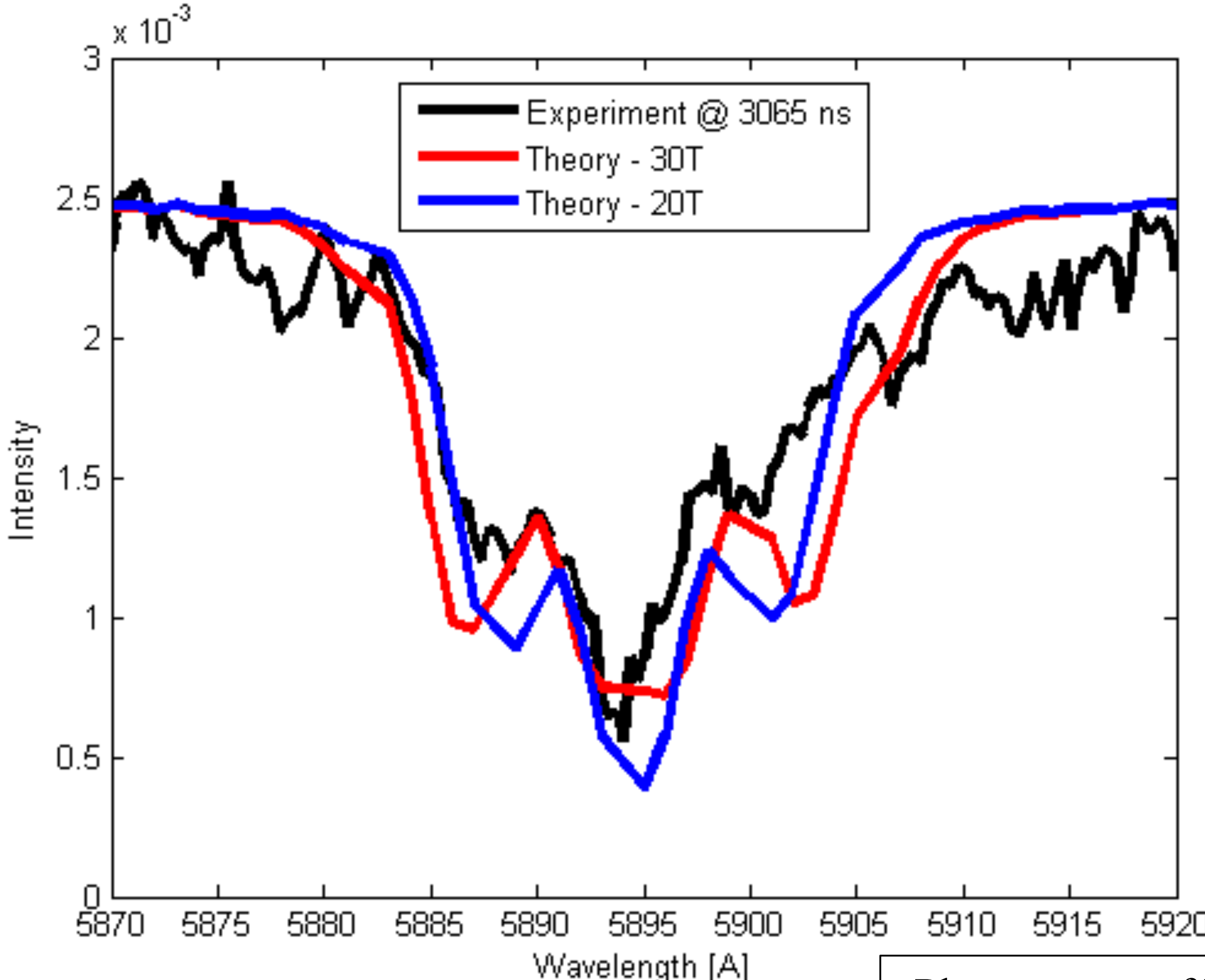
SECTION A-A
SCALE 8 : 1

Zeeman effect was observed in the SVS spectra from z2592 indicating flux compression



Slide courtesy of Matt Gomez

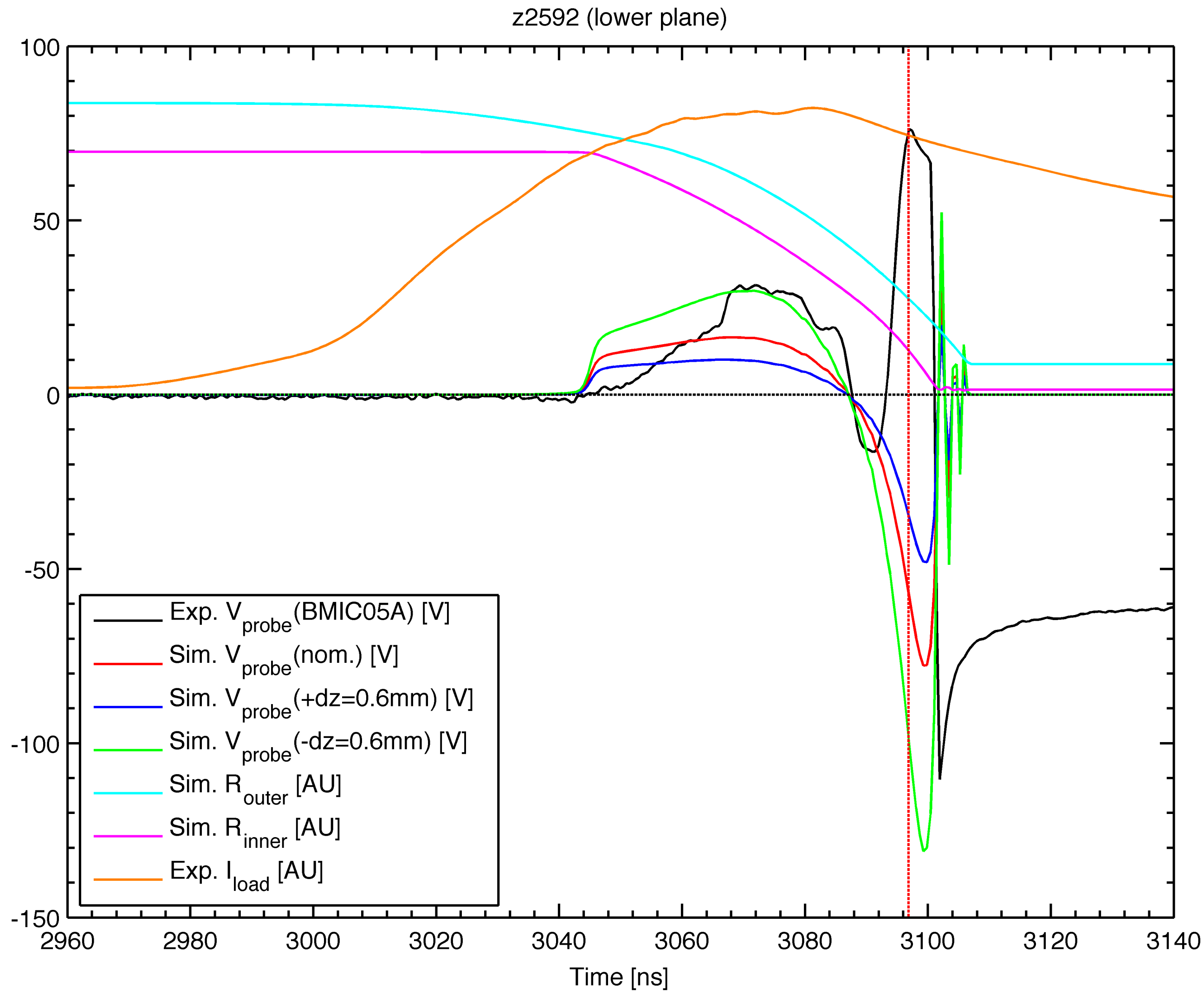
Zeeman effect was observed in the SVS spectra from z2592 indicating flux compression



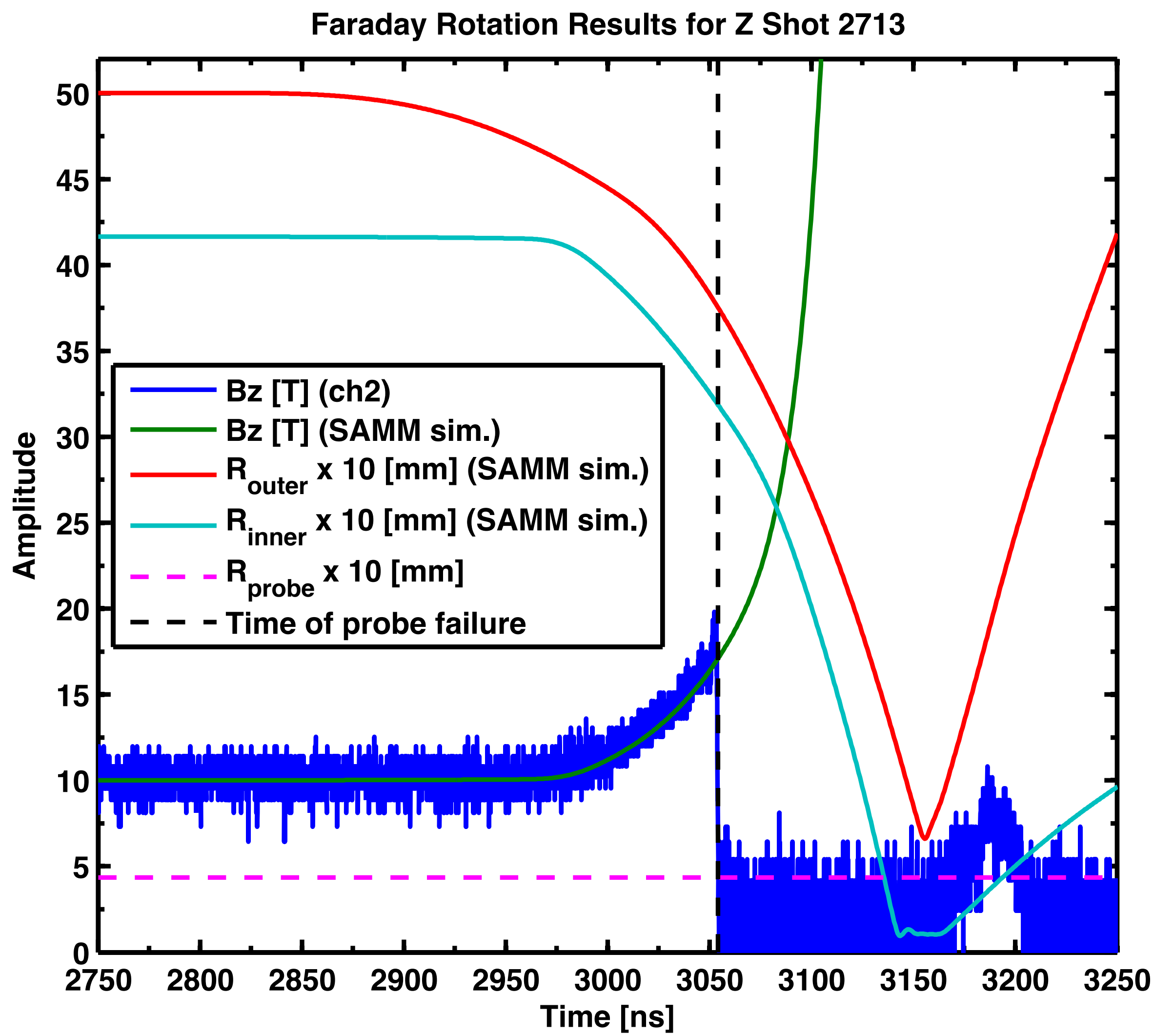
Plot courtesy of Matt Gomez & Stephanie Hansen

z2592 micro-Bdot Results

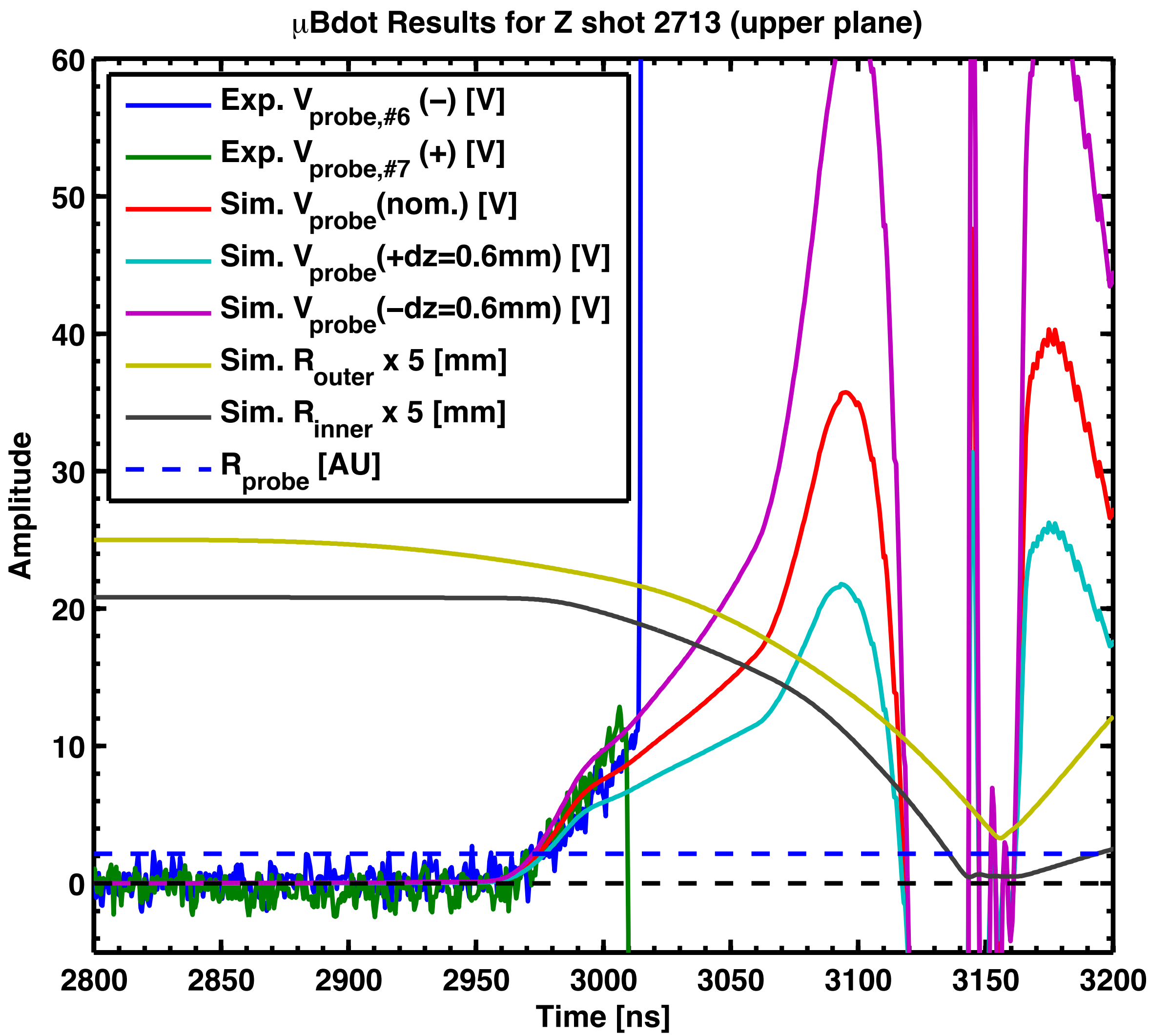
- One single-ended probe, BMIC05 (black curve), gave a good signal that agrees well with a simple simulation (its differential-pair partner, BMIC08, did not survive however)
- The red vertical dashed line indicates the time when the liner hits the outer radius of the on-axis Faraday probe housing, and thus marks the end of the flux compression experiment



Faraday Rotation Results (Z Shot 2713)



Micro-Bdot Results (Z Shot 2713)



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

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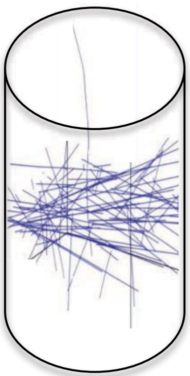

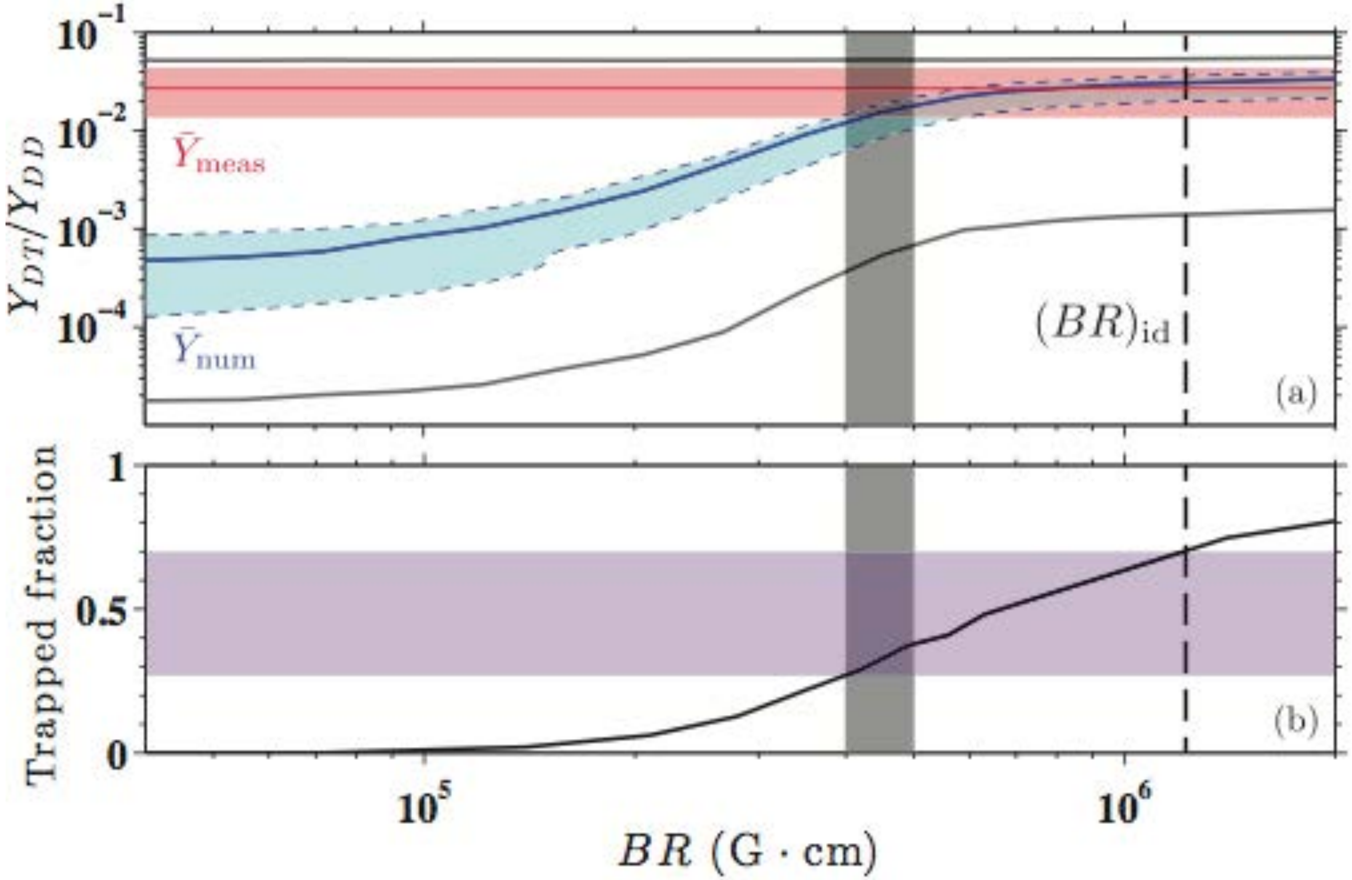

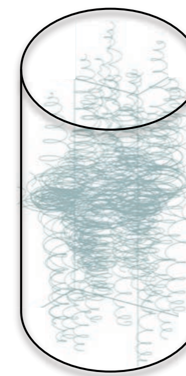

Magnetized tritons implies magnetized electrons:

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

Magnetized tritons implies magnetized alpha particles:

$$r_t \approx 1.1 r_\alpha$$

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

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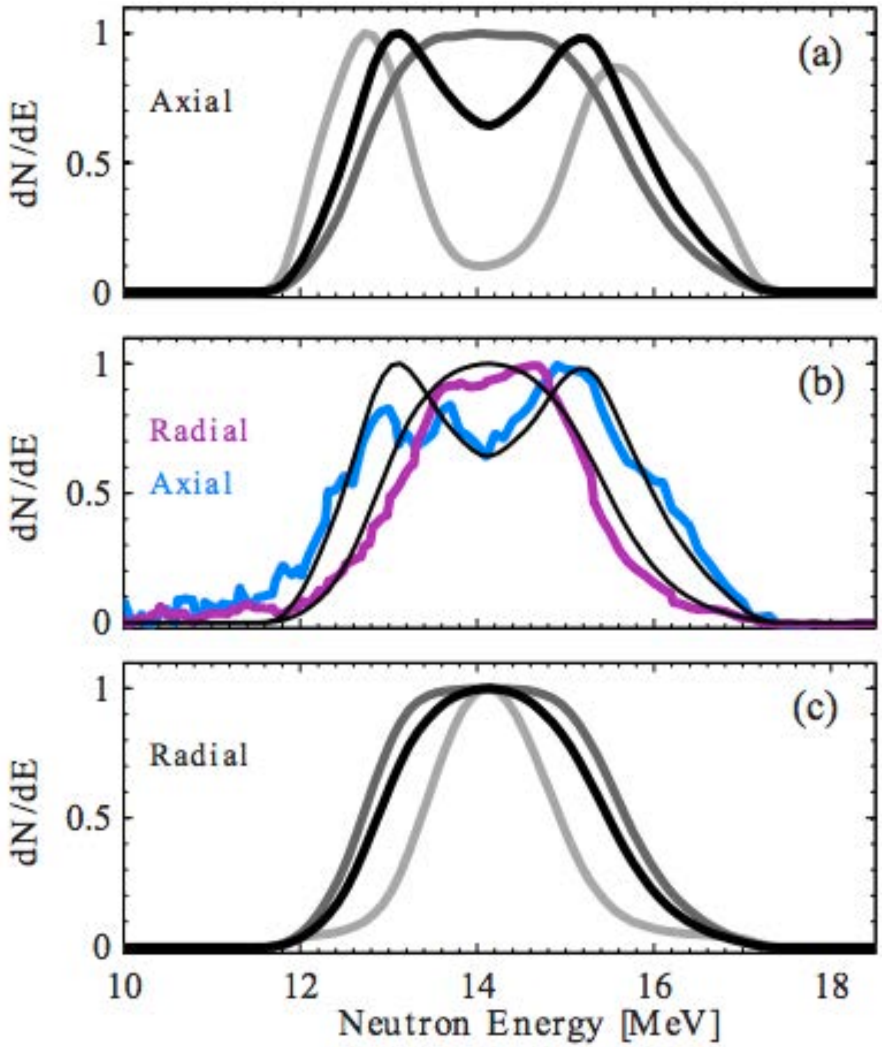

2.5e5 G-cm
4.5e5 G-cm
7.5e5 G-cm

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 *et al.*, PRL **113**, 155004 (2014); P.F. Knapp *et al*. PoP **22**, 056312 (2015).