SAND2014-19320C

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Magnetic Flux Compression Experiments on the Z Pulsed-Power Accelerator

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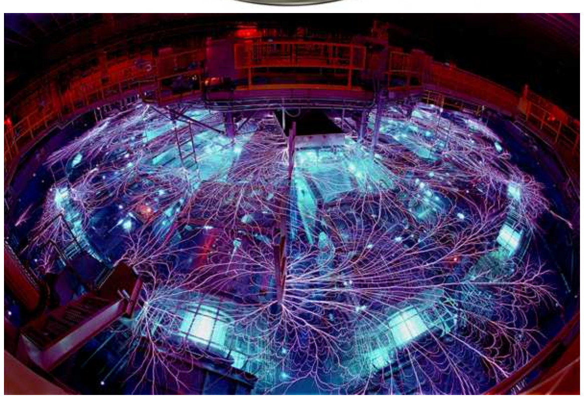
APS Division of Plasma Physics
New Orleans, October 28, 2014



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)

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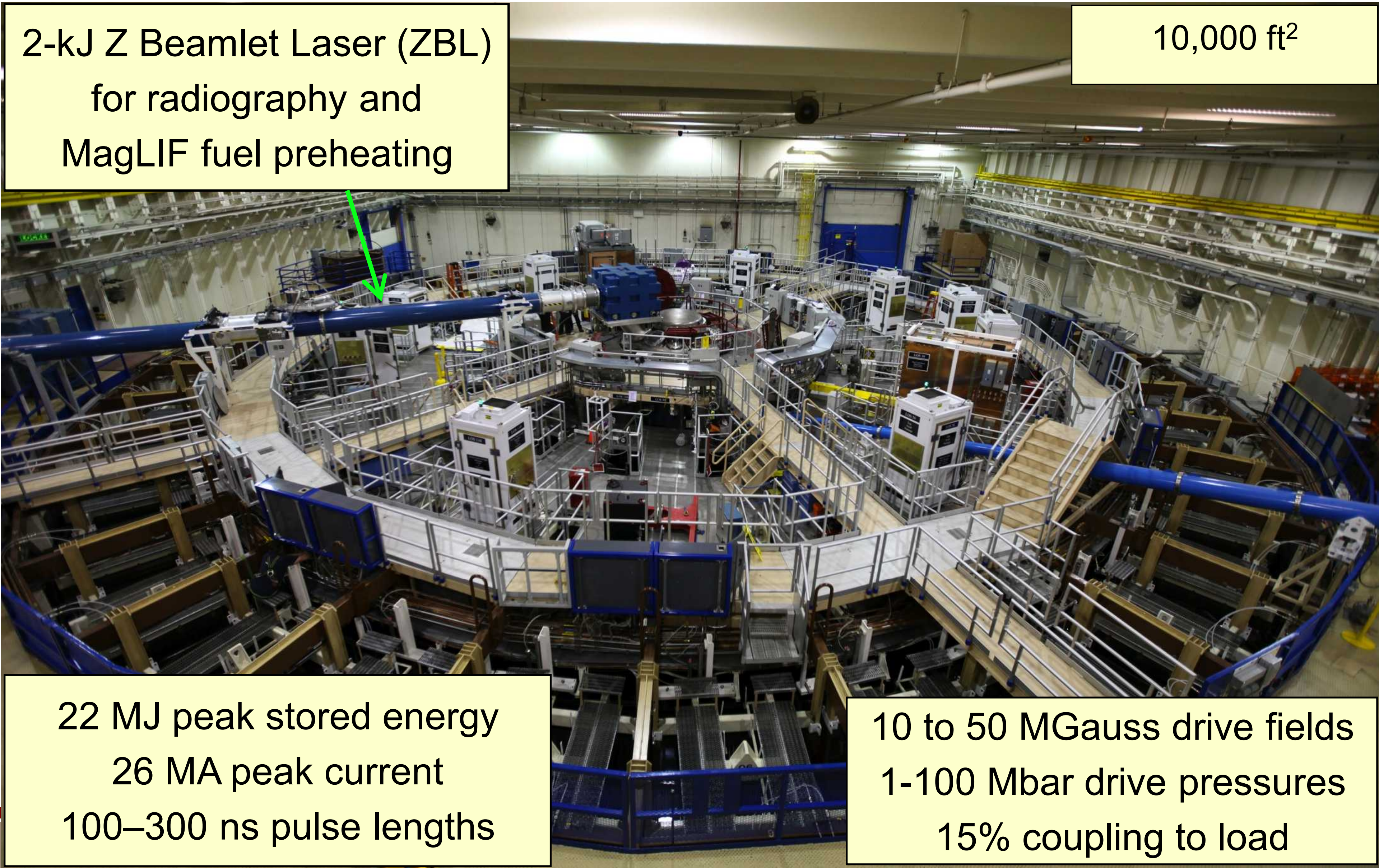


2-kJ Z Beamlet Laser (ZBL) for radiography and MagLIF fuel preheating

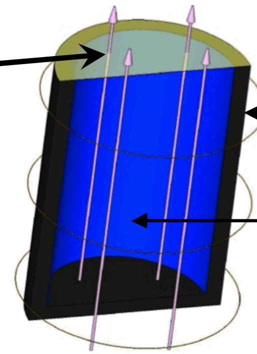
10,000 ft^2

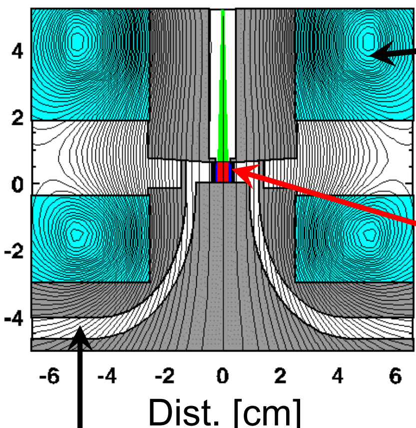
22 MJ peak stored energy
26 MA peak current
100–300 ns pulse lengths

10 to 50 MGauss drive fields
1-100 Mbar drive pressures
15% coupling to load

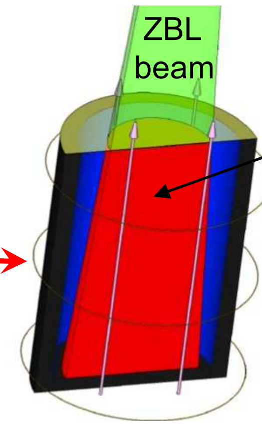
We are working toward the evaluation of a new Magnetized Liner Inertial Fusion (MagLIF)* concept

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

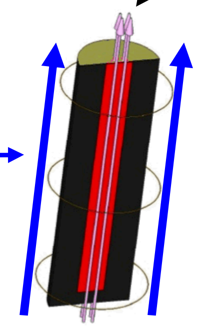




2. ZBL preheats the fuel to ~100–250 eV to reduce the required compression to CR≈20–30



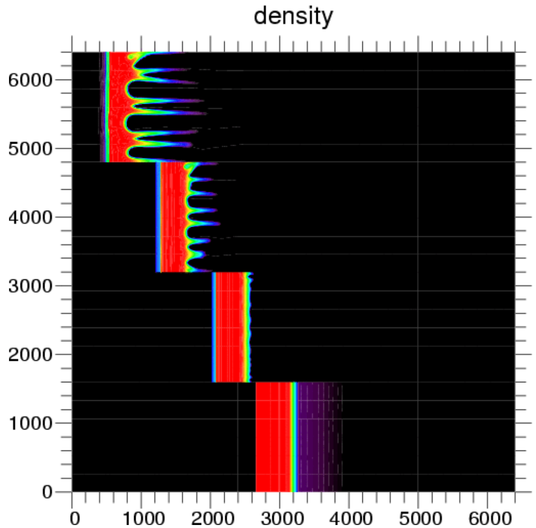
3. Z drive current and B_θ field implode the liner (via z-pinch) at 50–100 km/s, compressing the fuel and B_z field by factors of 1000

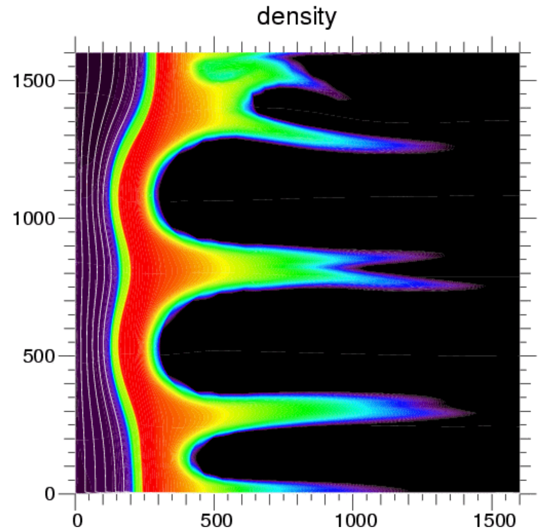


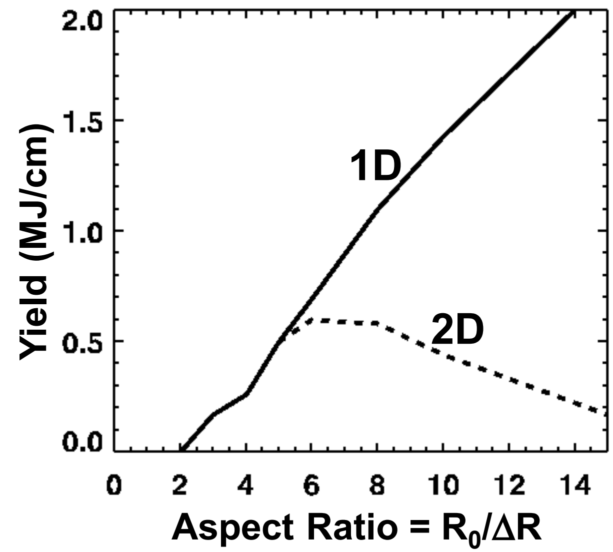
With DT fuel, simulations indicate scientific breakeven may be possible on Z (fusion energy out = energy deposited in fusion fuel)

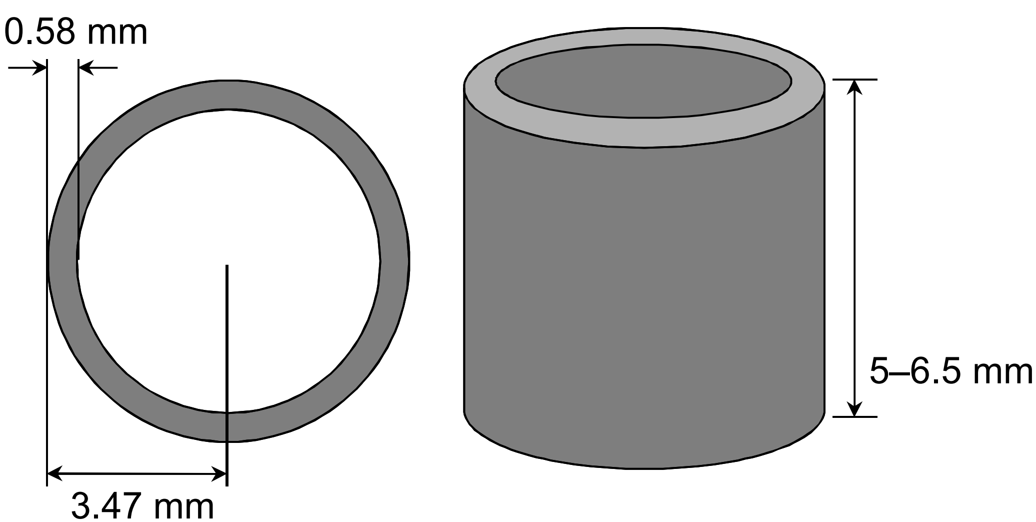
* S. A. Slutz *et al.*, PoP 17, 056303 (2010). S. A. Slutz and R. A. Vesey, PRL 108, 025003 (2012).

1D & 2D simulations of MagLIF suggest 1D-like behavior up to an aspect ratio of 6*









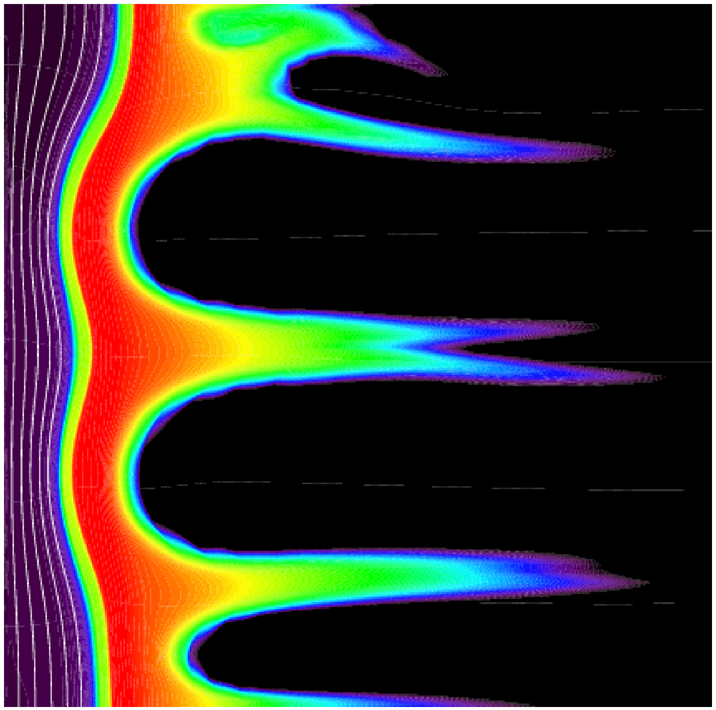
$$\mathrm{AR} \equiv \frac{R_{outer,0}}{\Delta R_0}$$

Thus, we restrict the range of validity of our 1D semi-analytic model to liners with AR ≤ 6

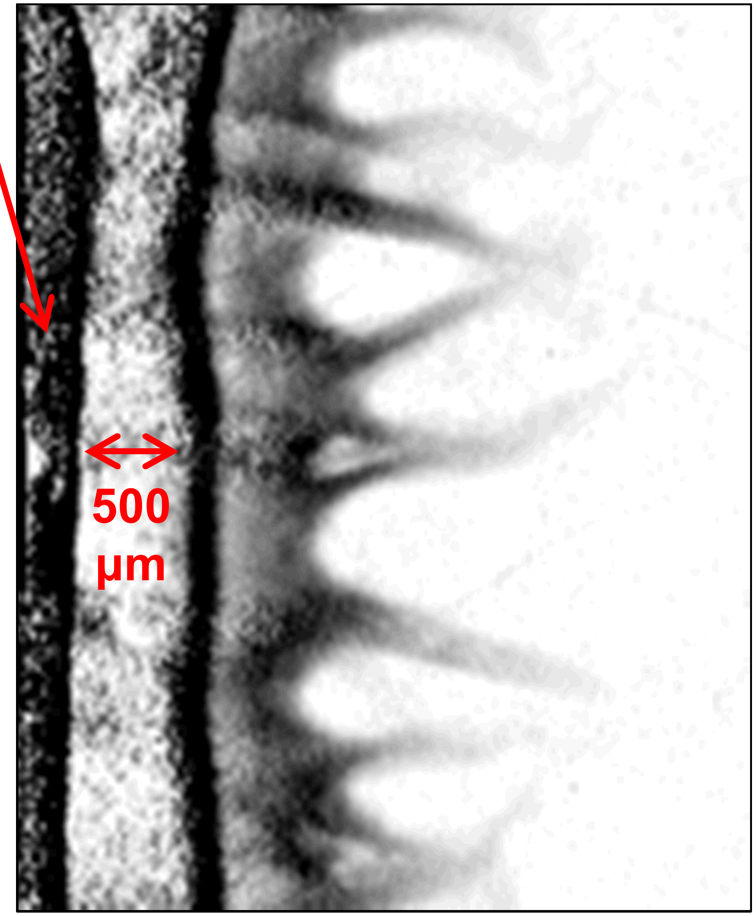
* S. A. Slutz *et al.*, Phys. Plasmas 17, 056303 (2010).

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

Note: MagLIF requires final compression to on-axis rod



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

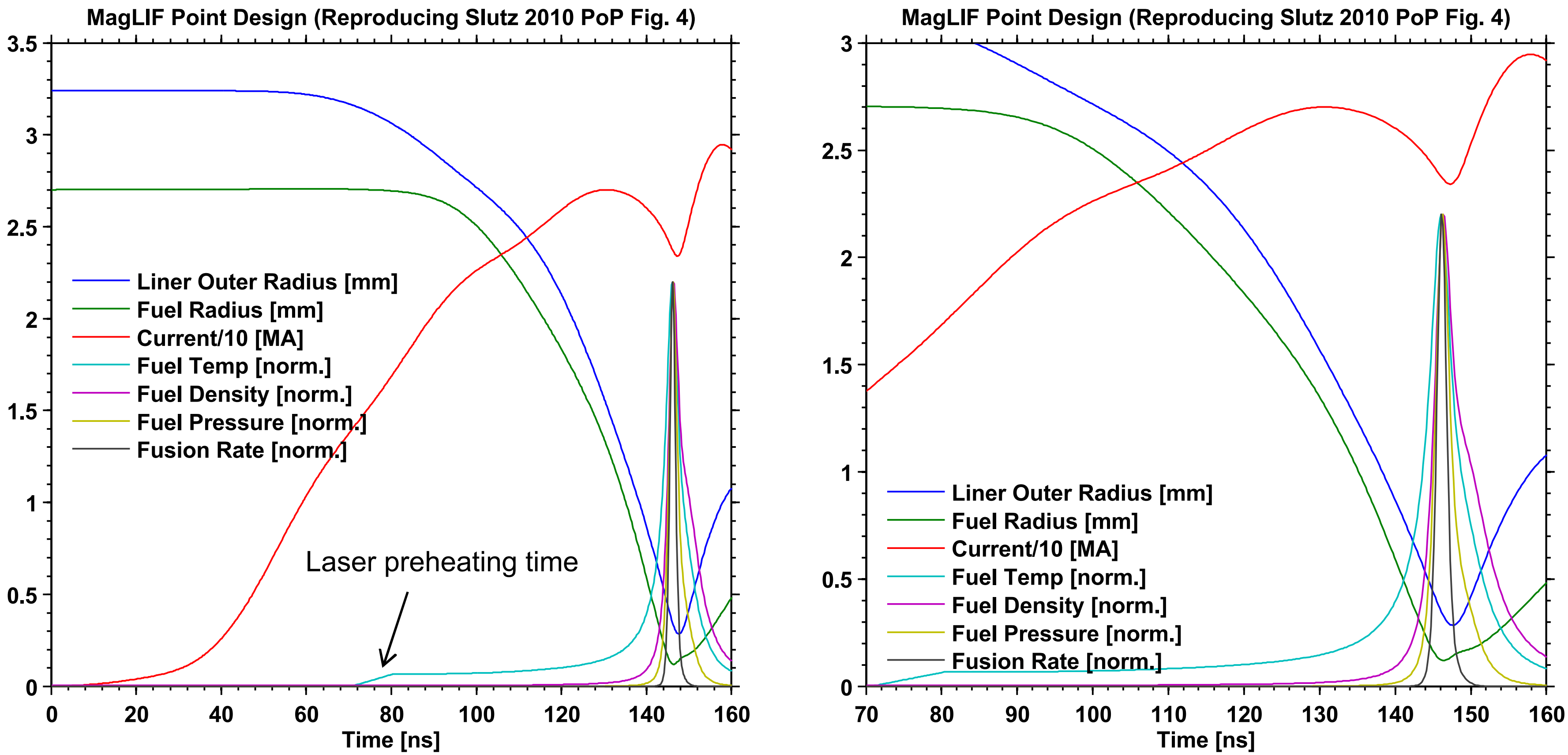


Experiment*

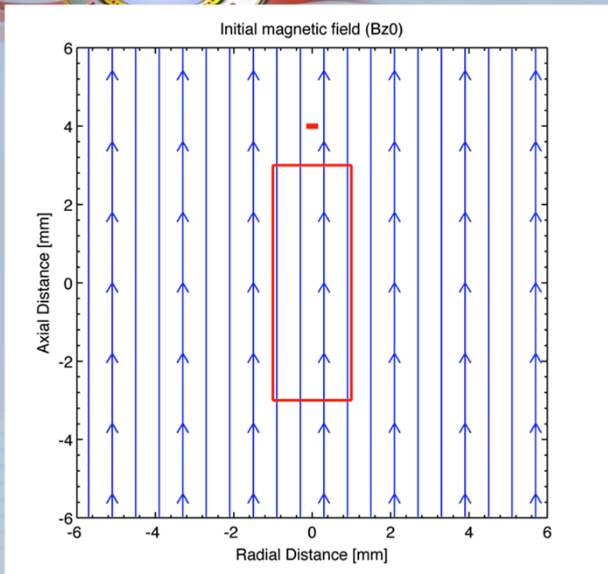
* R. D. McBride et al., Phys. Plasmas **20**, 056309 (2013).

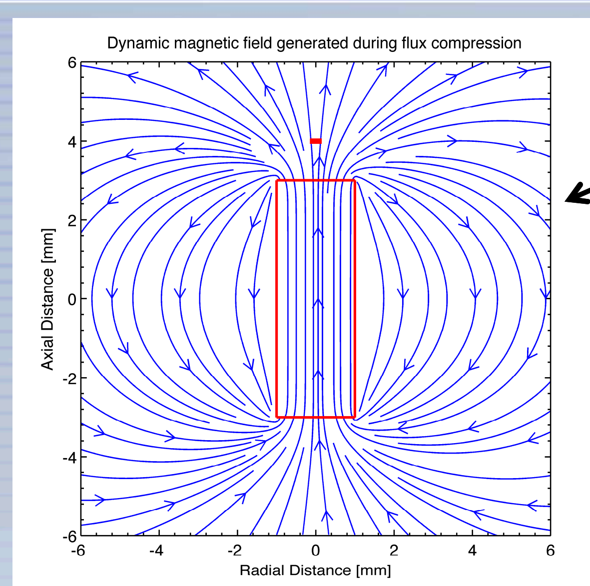
MagLIF Timing Overview

~ 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

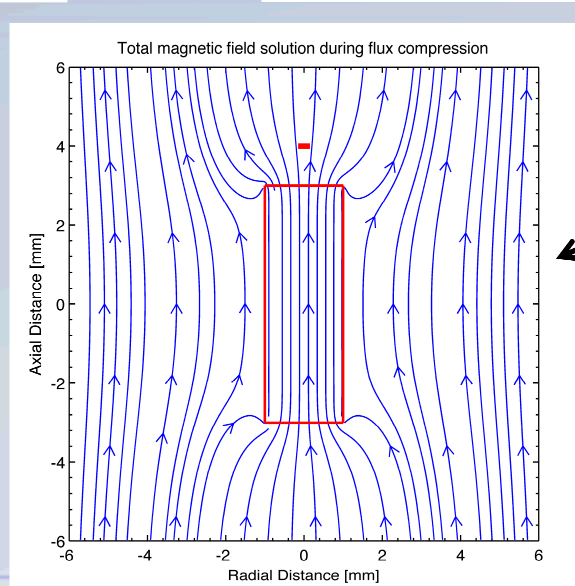


Vacuum Magnetic Flux Compression:





Bdot probes detect dynamic field



Faraday rotation and Zeeman spectroscopy measure total field

Laboratory Directed Research & Development (LDRD) Project Established for Implementing and Diagnosing Magnetic Flux Compression on Z

Sandia National Laboratories

- LDRD for FY13–15

- Objectives:
  - To evaluate and test on Z the most promising diagnostic methods that have been proven to work on smaller-scale facilities, including:
    - Zeeman spectroscopy
    - Miniature dB/dt probes
    - Faraday rotation
  - To validate physics such as the Nernst thermoelectric effect (included in many MHD codes used at Sandia):

B_z flux loss due to the Nernst thermoelectric effect (Braginskii) → $\dot{\Phi}_{B_z} = -2\pi r_g f(\omega\tau) \frac{dT_g}{dr}$

A pulsed coil system to supply a seed Bz field on Z has been successfully developed and deployed

- Development work led by Dean Rovang, Derek Lamppa, Marc Jobe, Albert Owen, John McKenney, Mike Cuneo, et al.
- Initial prototyping and testing of the pulsed coil system (capacitor banks, controllers, coils, supporting hardware, etc.) was completed at the Systems Integration Test Facility (SITF) in the medium bay of building 970
- The system was successfully integrated into the Z facility thanks to the efforts of many folks in 1670
- The first Z shot with Bz was fired on February 28, 2013
- So far we have performed 6 experiments on Z that involved flux compression (4 dedicated and 2 ride-along/MagLIF-development shots)

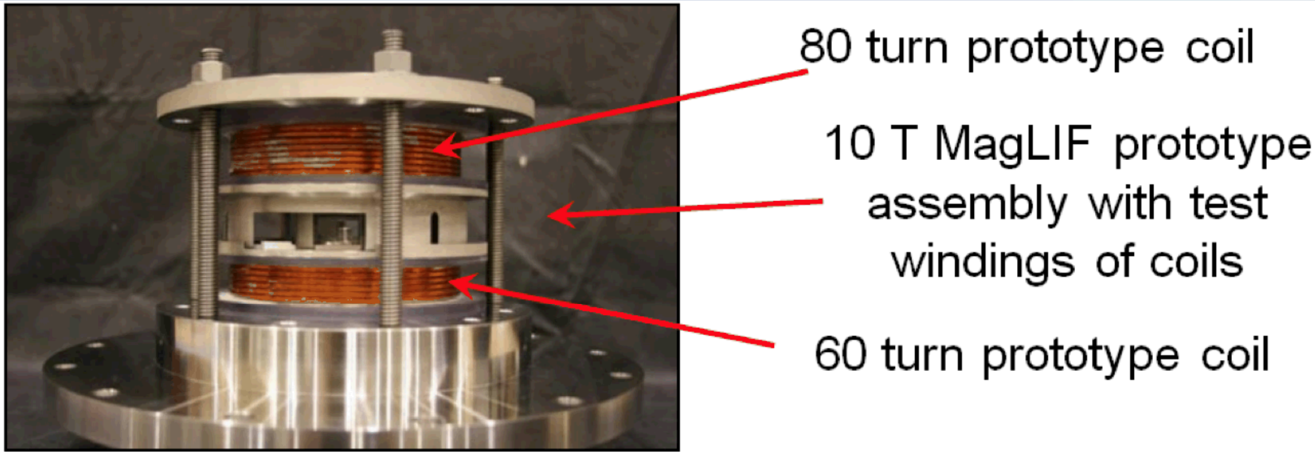
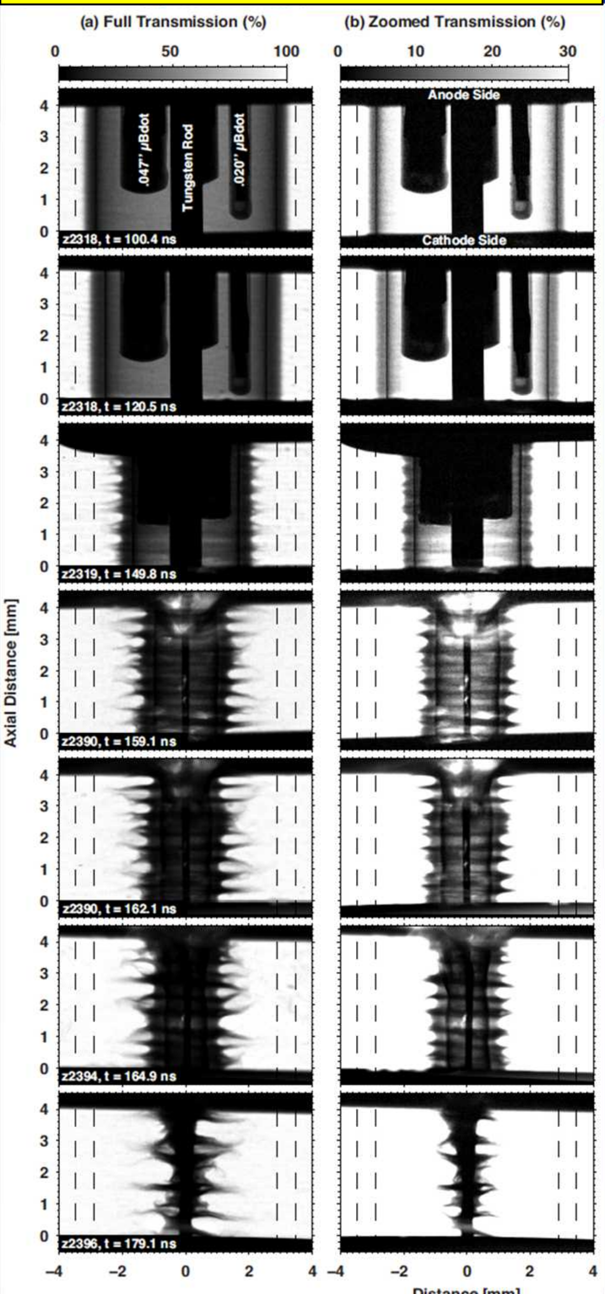


Figure 1. Prototype Helmholtz coil system for flux-compression experiments on Z. Up to 10 T of seed Bz field have already been generated and measured directly with B-dot probes at the SITF.

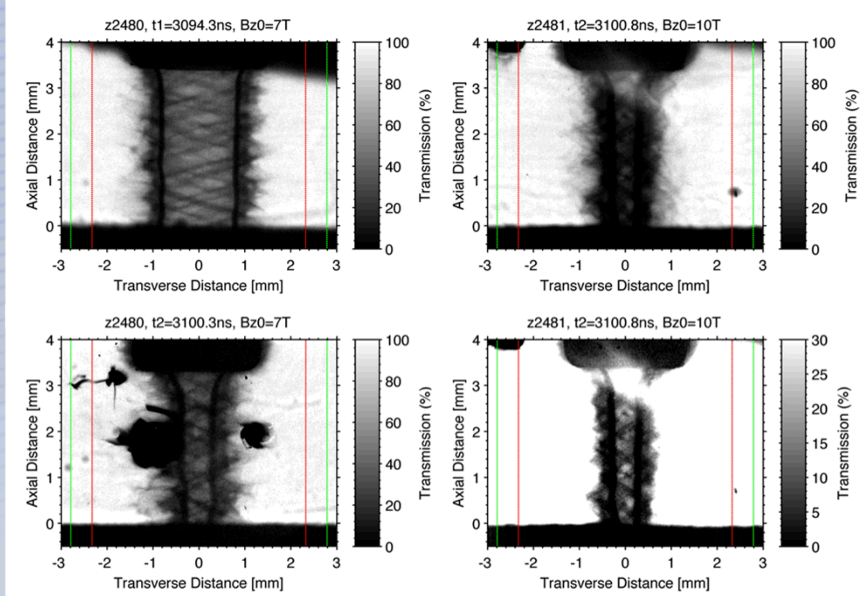
From these first B_z shots, exciting, unexpected results:

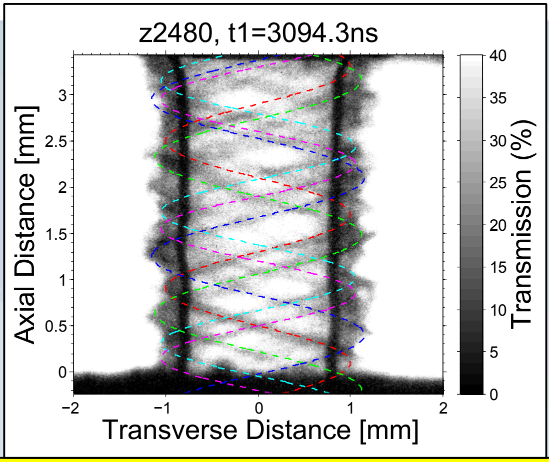
No Applied B_z



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

With Applied B_z





T. J. Awe *et al.*, Phys. Rev. Lett. (2012).

LDRD Status Overview

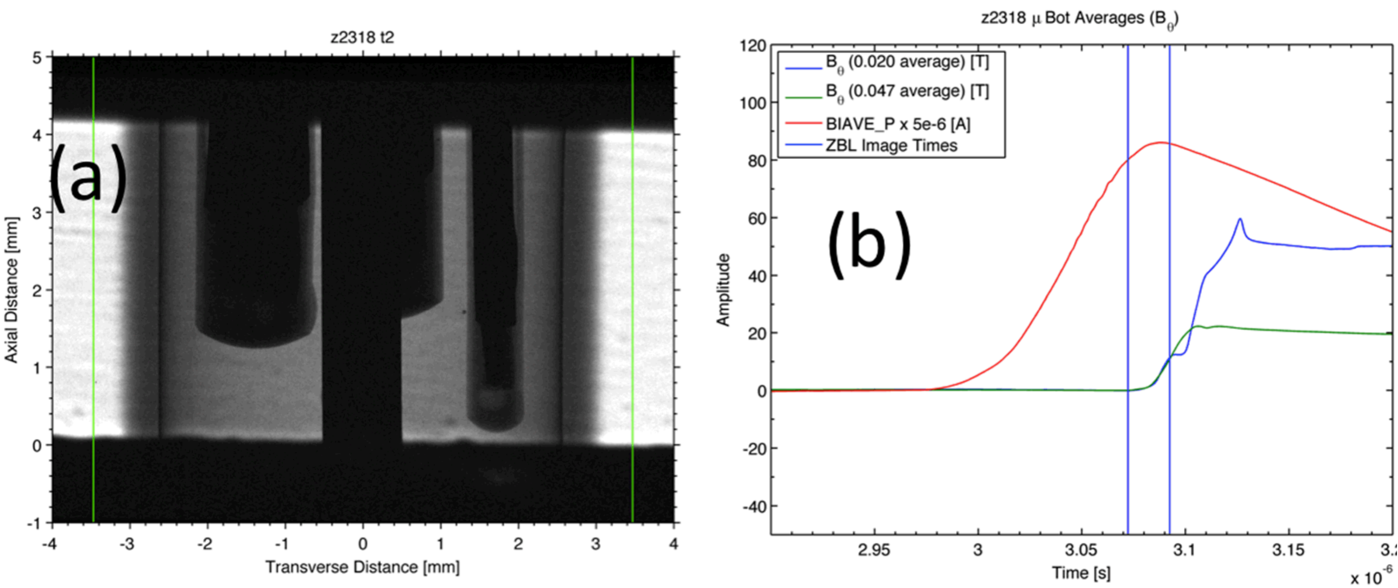
Sandia National Laboratories

- Developing 3 independent probe-based diagnostic techniques for measuring vacuum flux compression on Z with the fidelity needed to assess the physics of flux loss due to resistive diffusion into the wall of a fast imploding liner
- These 3 vacuum flux compression diagnostic techniques are:
  - Small B-dot assemblies for both the dynamic fringe fields above the imploding liner as well as the intense dynamic fields down inside the imploding liner
  - Streaked visible Zeeman spectroscopy for the fields down inside the imploding liner
  - Fiber-based Faraday rotation for the fields down inside the imploding liner
- For experiments with hot plasma gradients (e.g., fully-integrated MagLIF experiments on Z), we are beginning to assess the feasibility of using recent advances in neutron analysis techniques on Z data to hopefully get at the physics of the Nernst effect (e.g., flux redistribution and possibly enhanced flux loss)
- Synthetic diagnostic output being developed for use with advanced MHD simulation codes (e.g., GORGON, HYDRA, LASNEX, ALEGRA)

Micro-Bdots are a simple low-cost, low-risk first approach

- Not expected to survive a rise of 100's of MGauss in 10's of ns
- Though could provide the initial compression trajectory
- And could be used in low-seed-field, proof-of-principle flux compression experiments to cross-calibrate other more sophisticated diagnostics

- Approved diagnostic on Z
- Fabricated for us by John Greenly at Cornell University
- Fielded (successfully) for first time on Z during Washington-1 shot series (March 2012) – results shown here for measuring Z's B_θ drive field that penetrated the imploding liner's vacuum-filled interior:



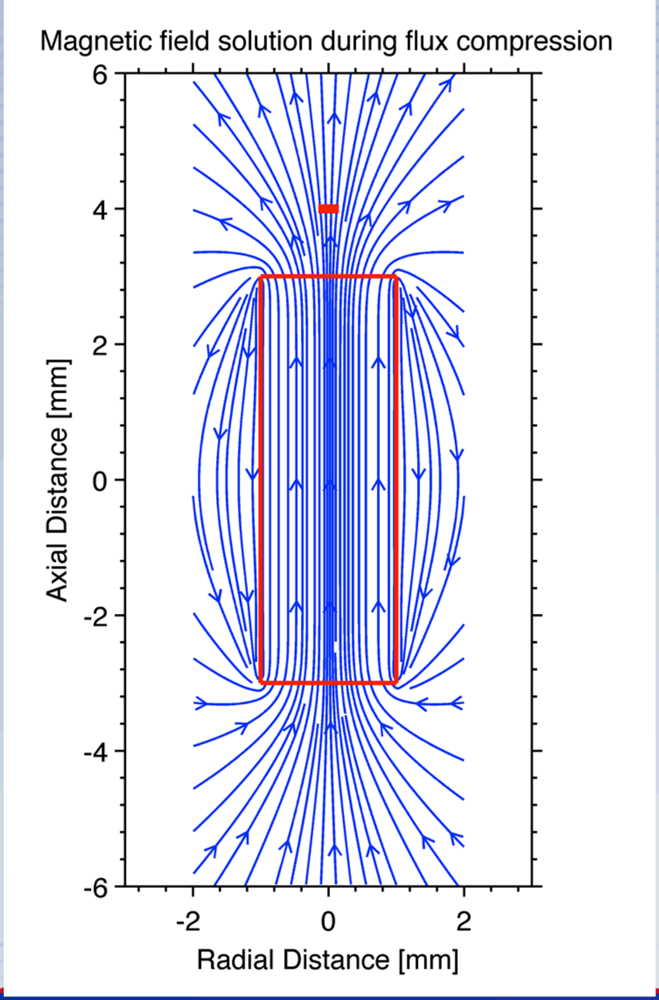
- Easily reconfigured to measure B_z instead of B_θ, e.g., hover probe tip on-axis just above imploding liner to measure compressed Bz streaming out of the top of the imploding liner (this is a non-perturbative configuration)

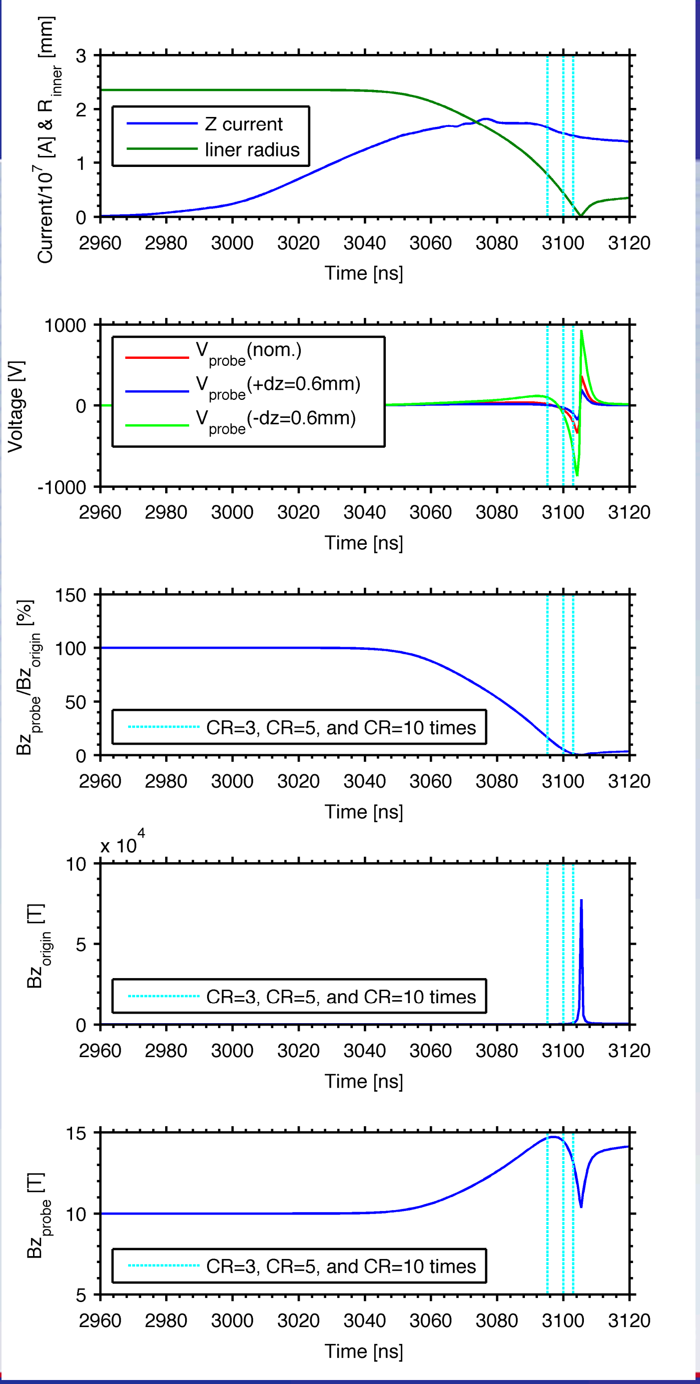
R. D. McBride *et al.*, Phys. Plasmas 20, 056309 (2013).

Figure 3. (a) ZBL radiograph of imploding solid beryllium liner on Z showing the micro-Bdot probes fielded within the liner's vacuum-filled interior. (b) B-theta signals detected and measured by probes prior to and during the implosion.

Field solvers developed and coupled to simple implosion models

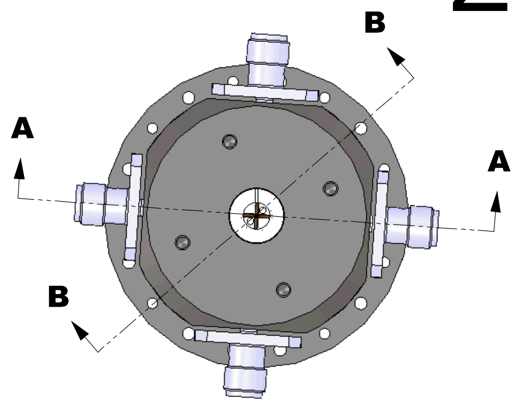
- Needed to understand how the measurements made just above the top implosion plane of the liner translate to magnetic field conditions within the imploding volume of the liner



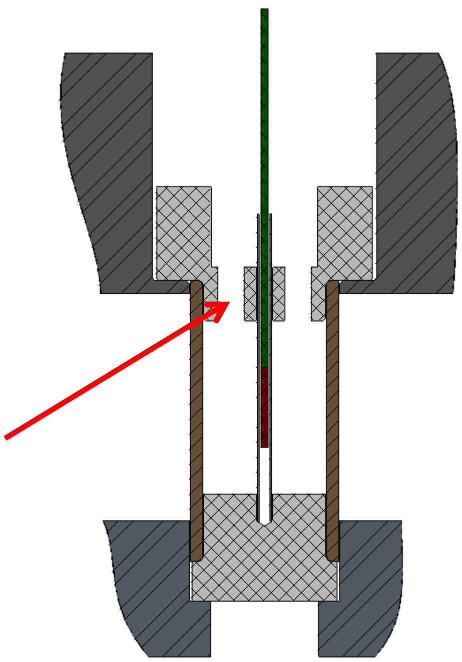


LABORATORY DIRECTED RESEARCH & DEVELOPMENT

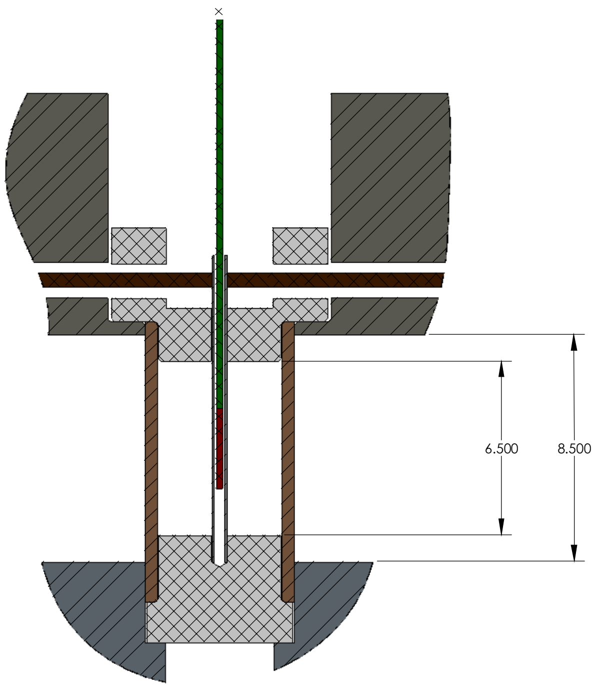
Z Shot 2592 Target design



- 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



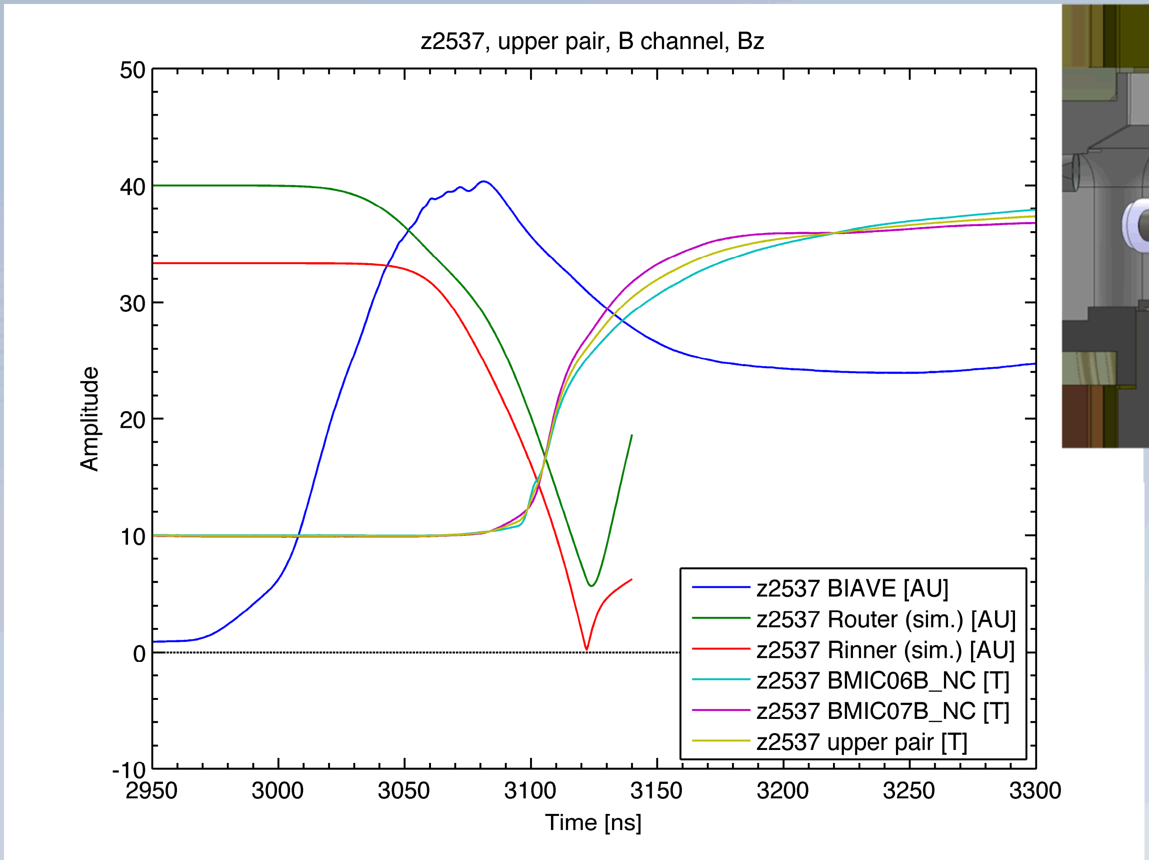
SECTION B-B
SCALE 8 : 1

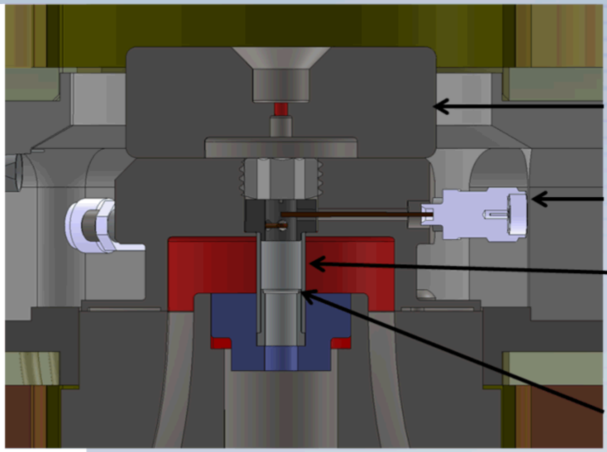


SECTION A-A
SCALE 8 : 1

Micro-Bdot Progress:

- Good clean signals obtained with micro-Bdots on previous Z shot 2537



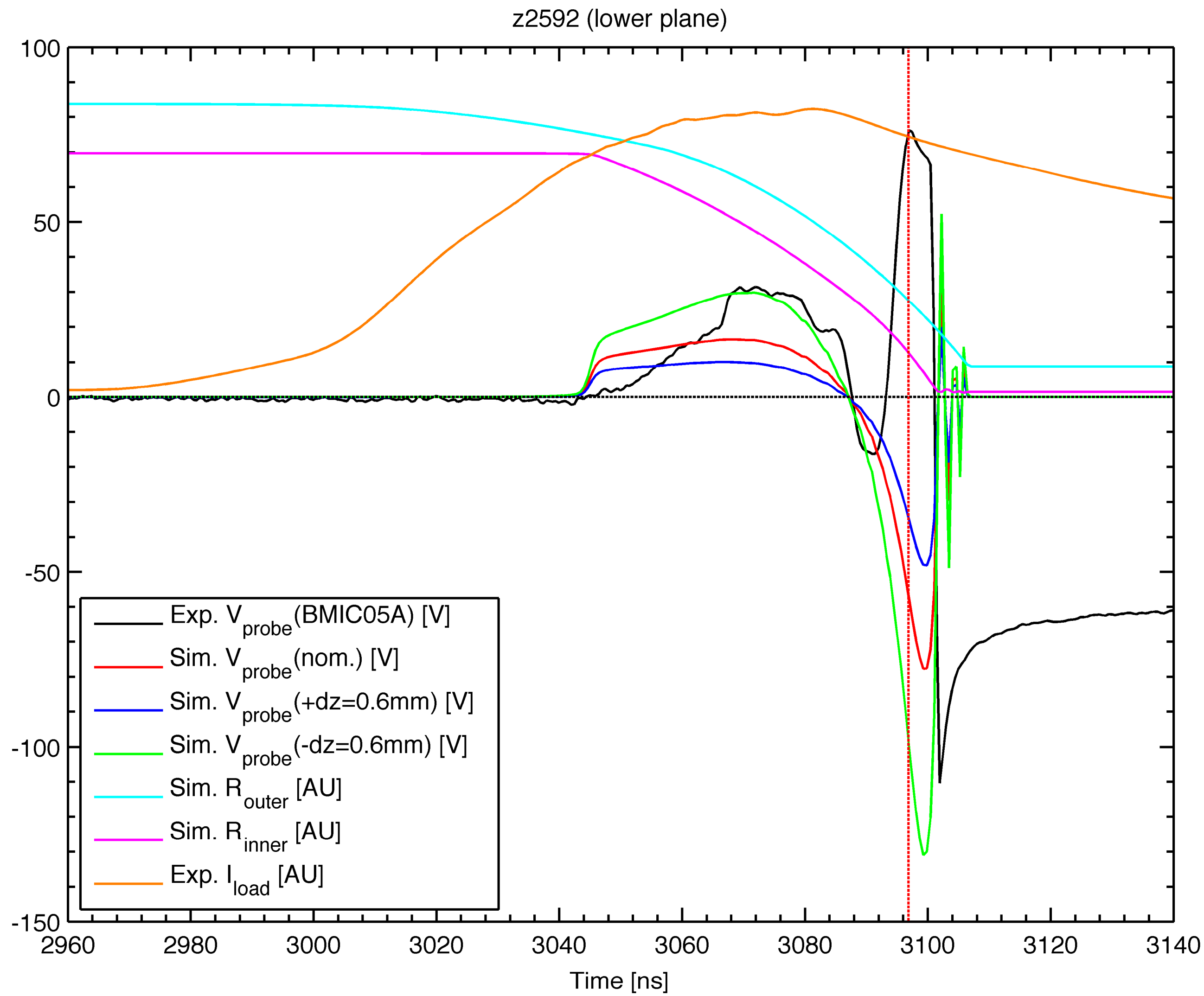


- Probe development in collaboration with John Greenly at Cornell University

z2592 micro-Bdot Results

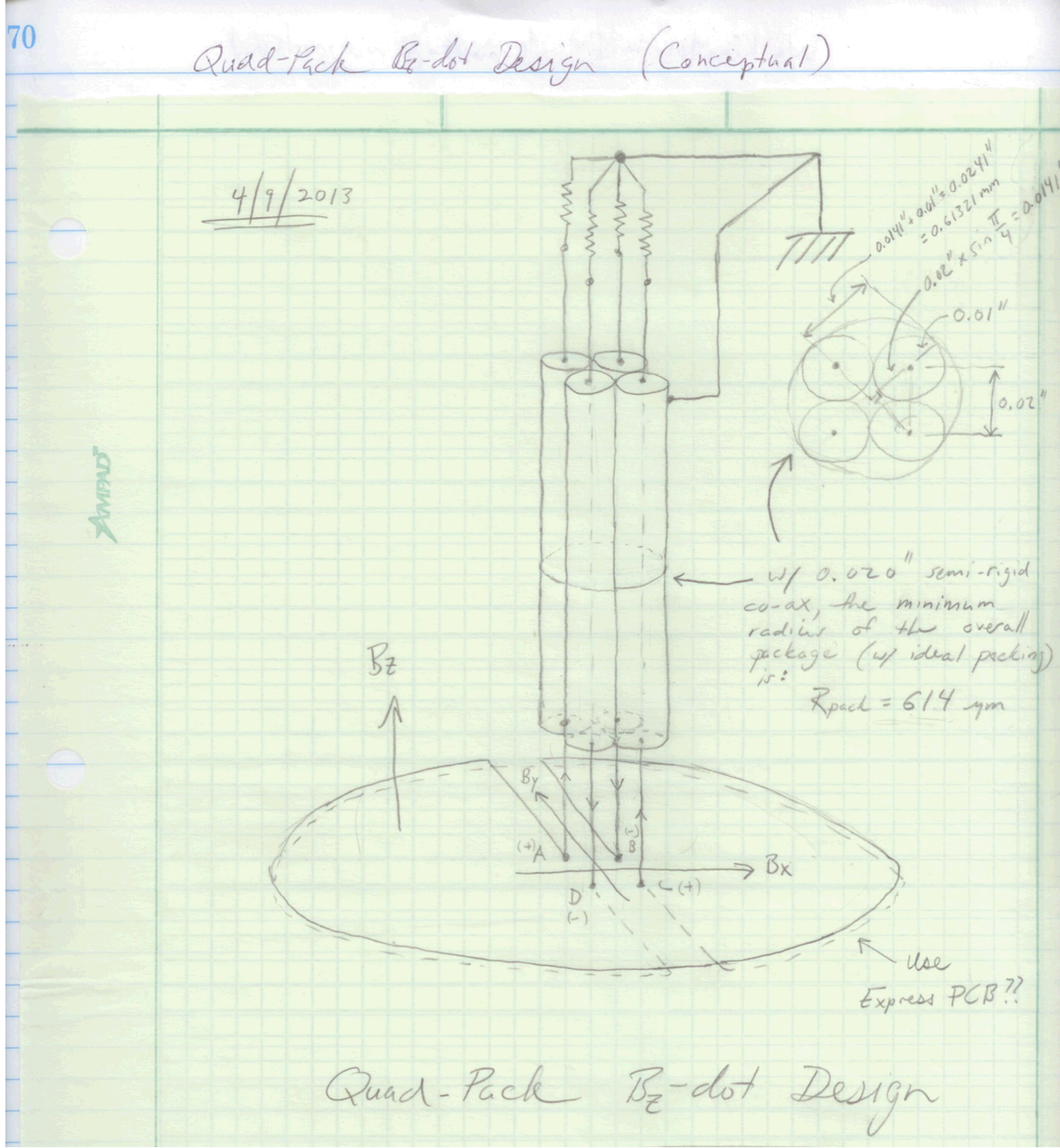
- One single-ended probe, BMIC05 (black curve), gave a good signal that agrees well with a simple simulation (its differential-pair partner, BMIC08, did not survive however)

- 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

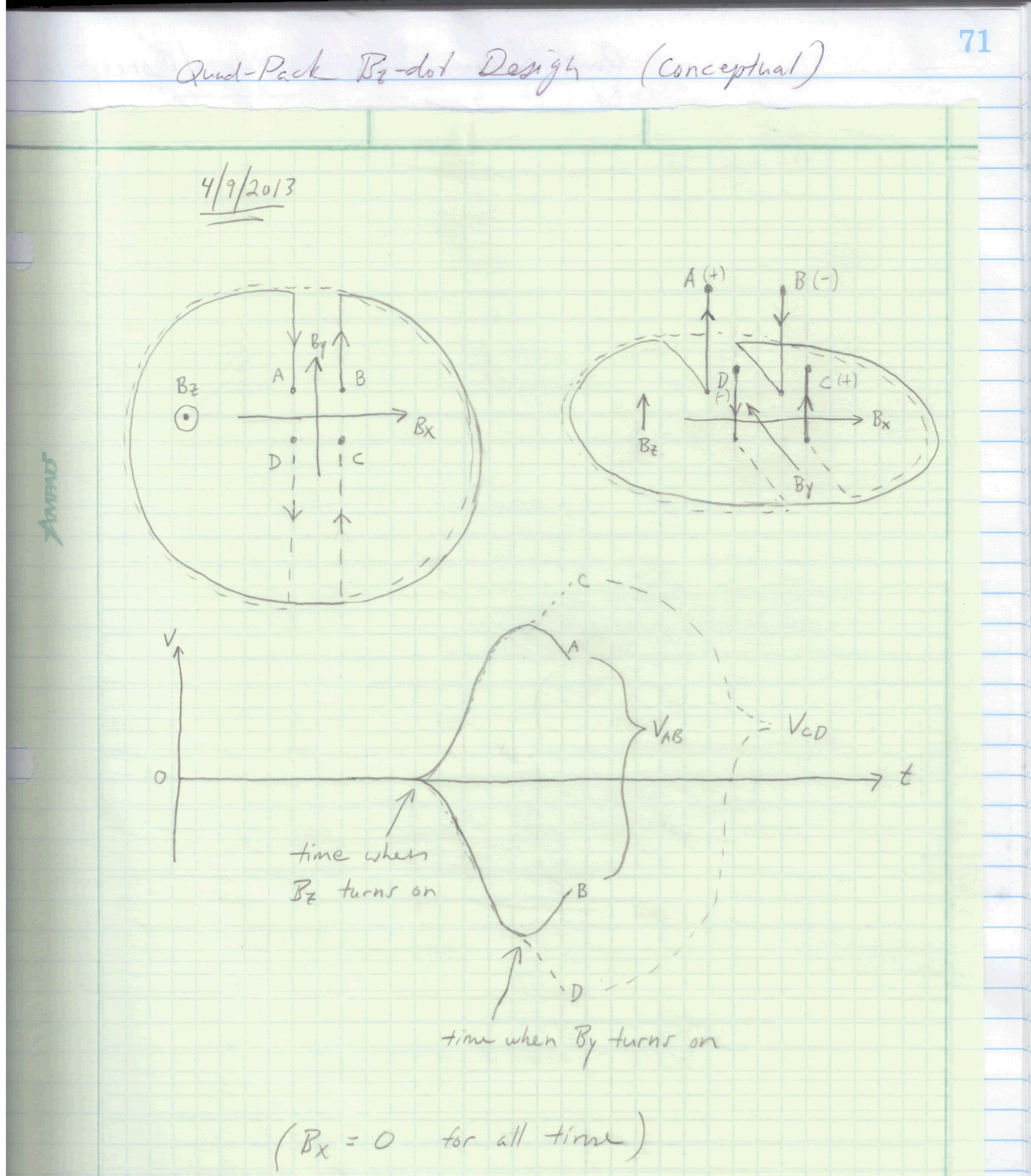


New true Bz-dot probe developments:

New “Quad-Pack” Bz-dot package design by R. D. McBride at SNL



The Quad-Pack could also measure and/or reject Br-dot and Bθ-dot components



Quad-Pack development & fabrication in progress in collaboration with Centers 5400 (Marc Jobe & Derek Lamppa) and 1700 (Lu Fang)

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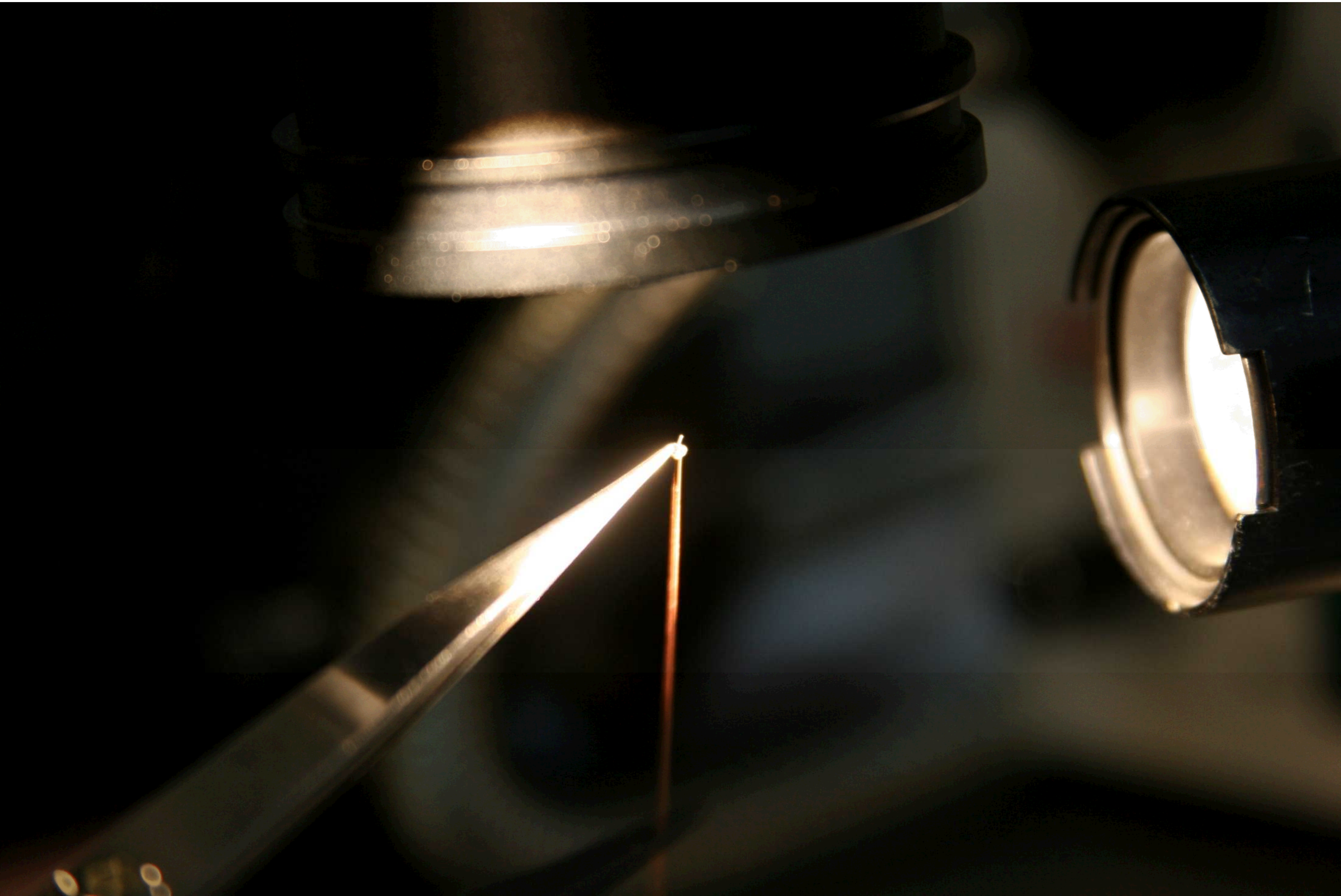

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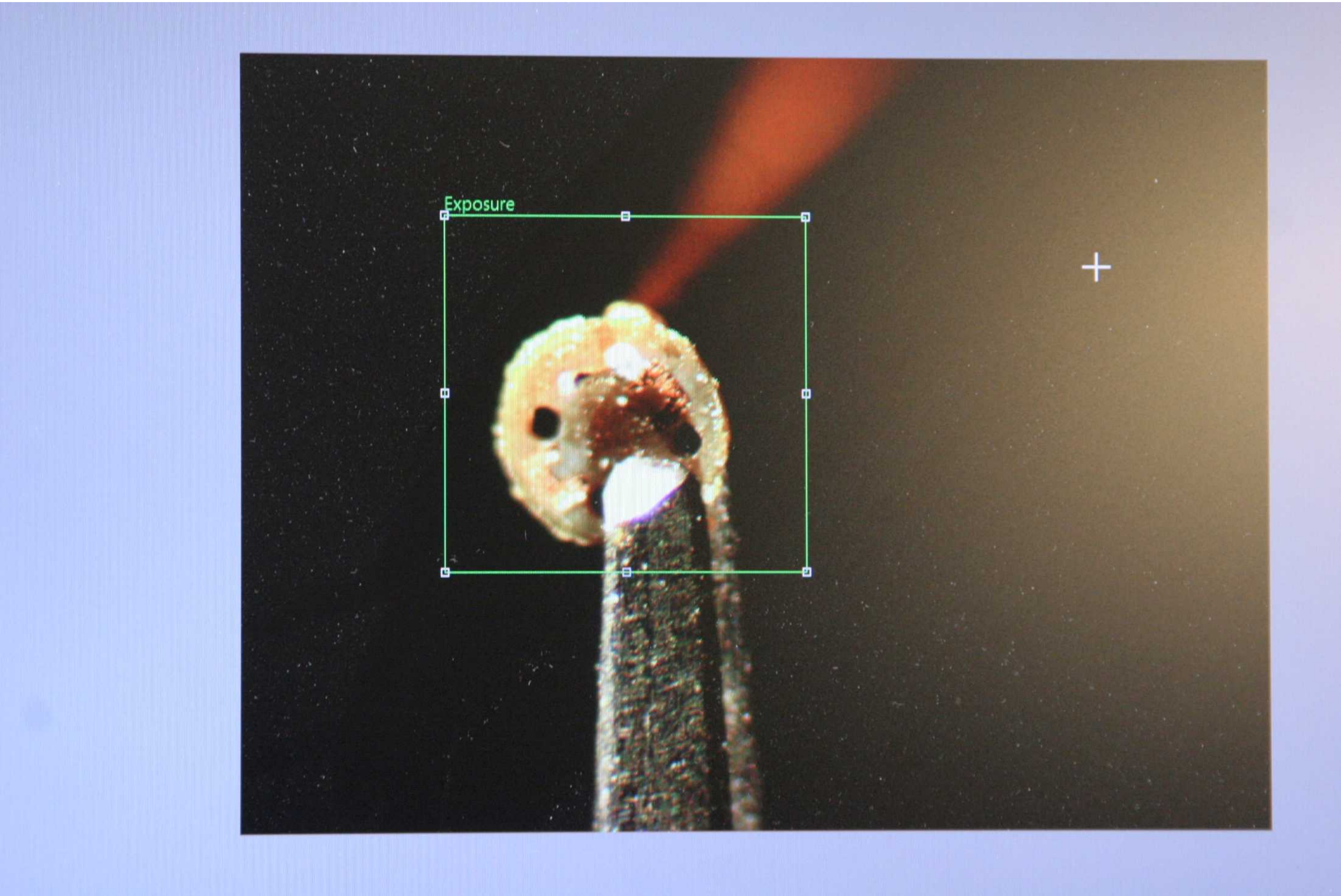
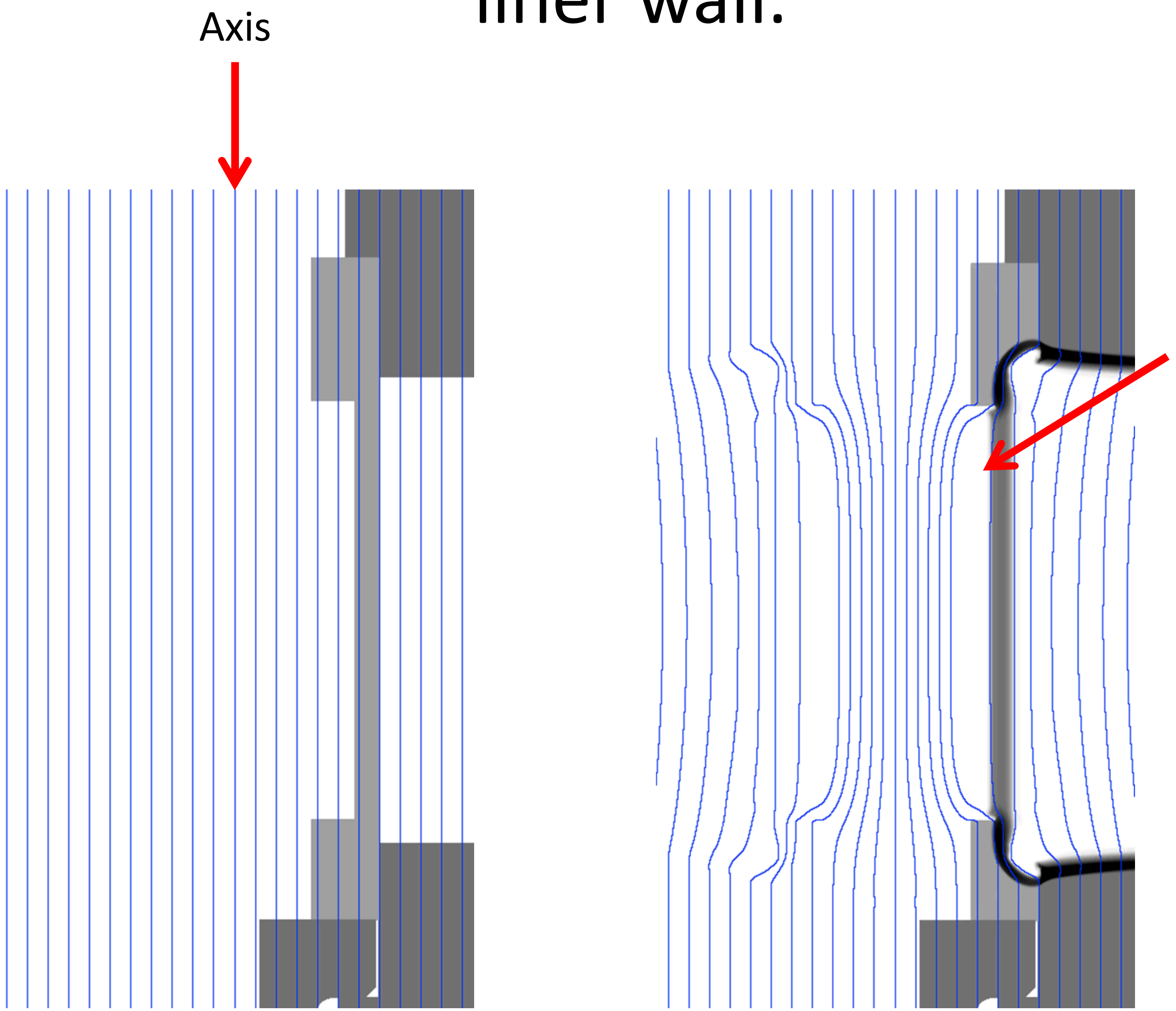


Vacuum liner, standard point design dimensions. Flux initially compressed by blow off plasma from inside liner wall.

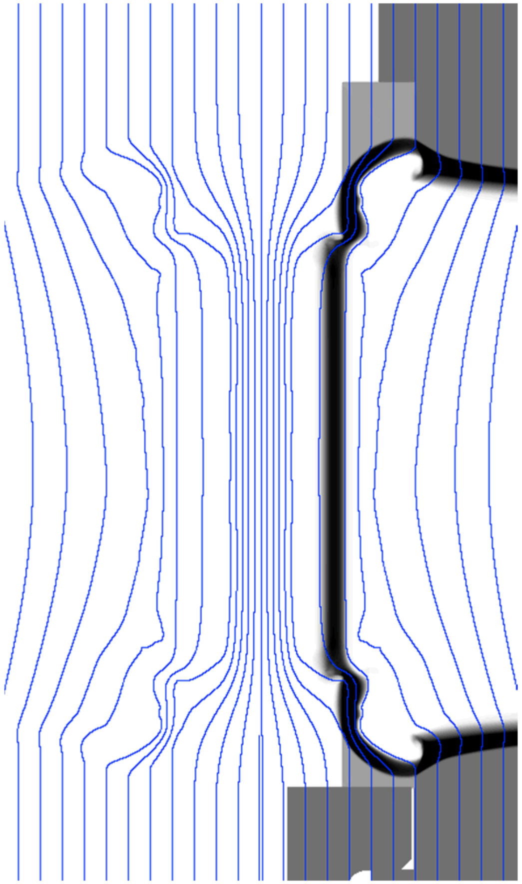


Flux compression from blow off plasma.

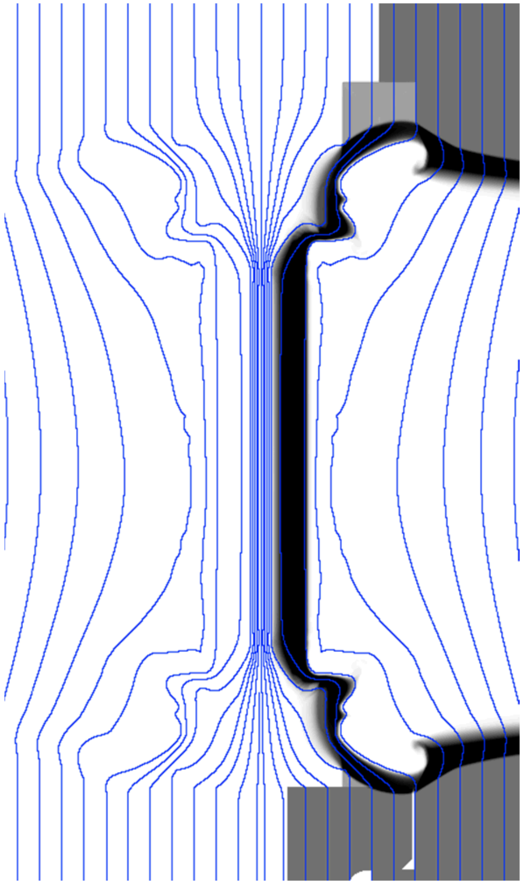
Can confuse results. Not sure how well code captures this.

By late time low density blow off compresses back to liner surface

3080ns



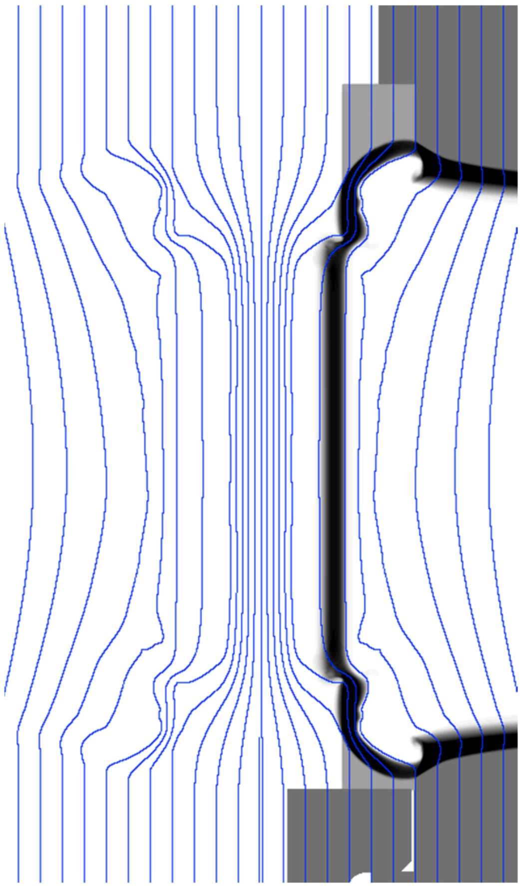
3092ns



Low density blow-off can stagnate against field in calculations. In reality this might be more unstable.

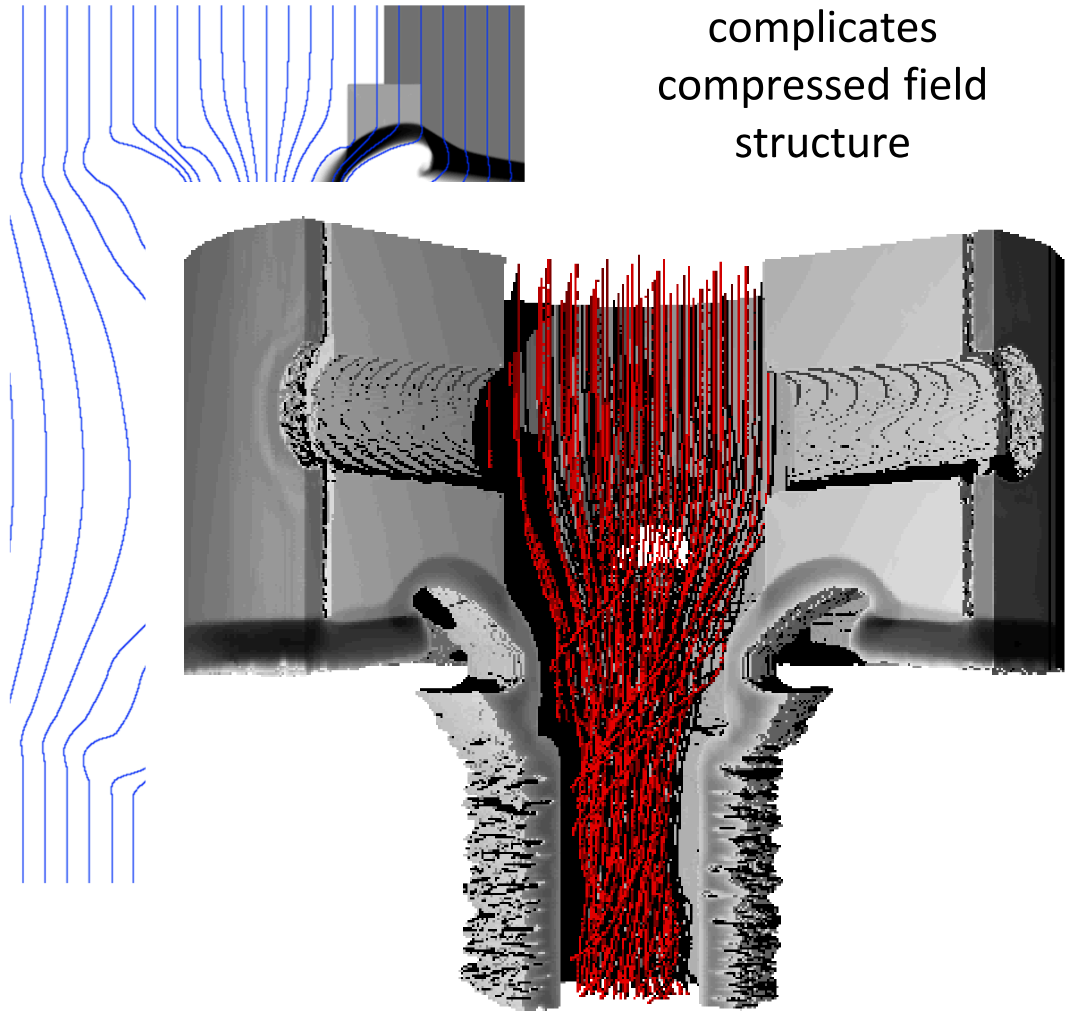
By late time low density blow off compresses back to liner surface

3080ns

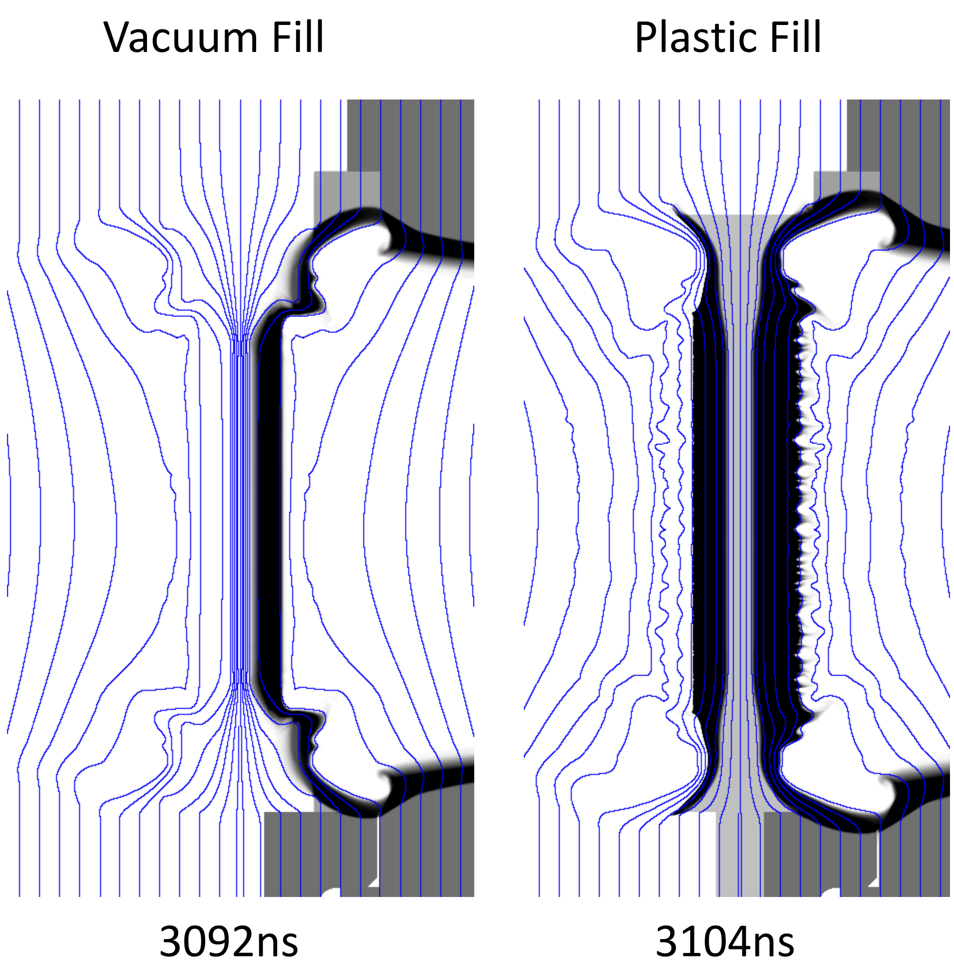


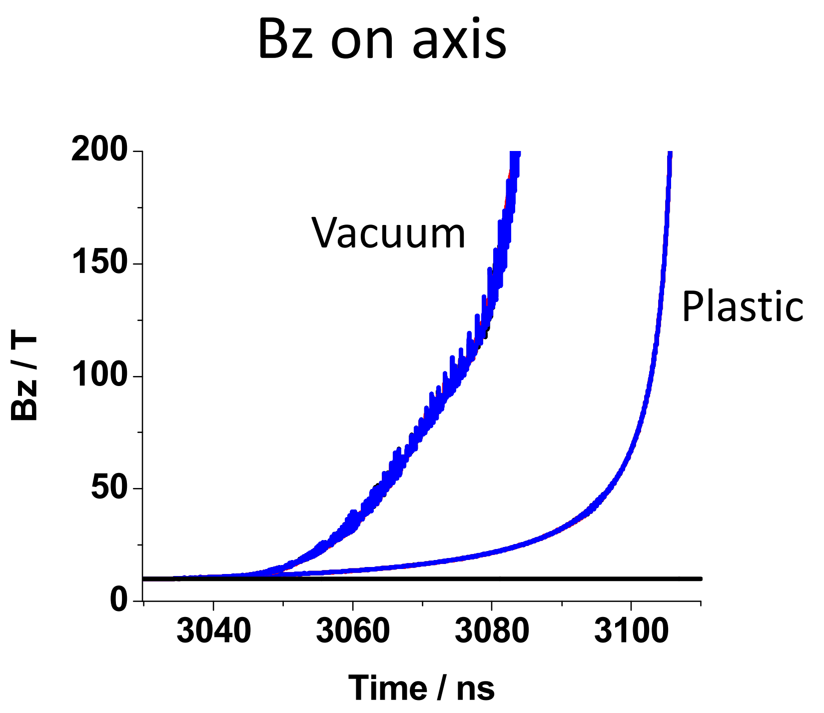
3092ns

Azimuthal current carried by blow off adds complicates compressed field structure

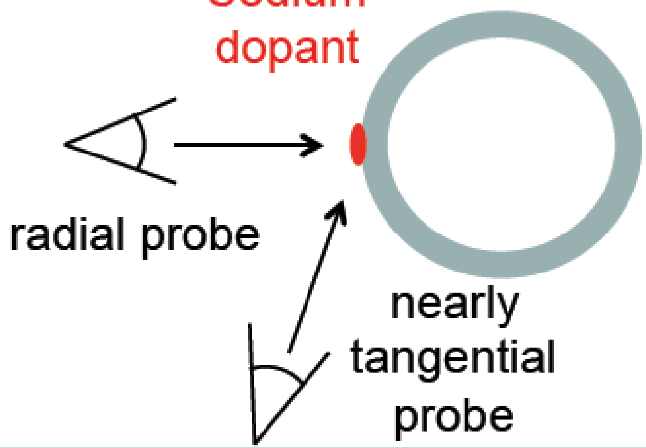


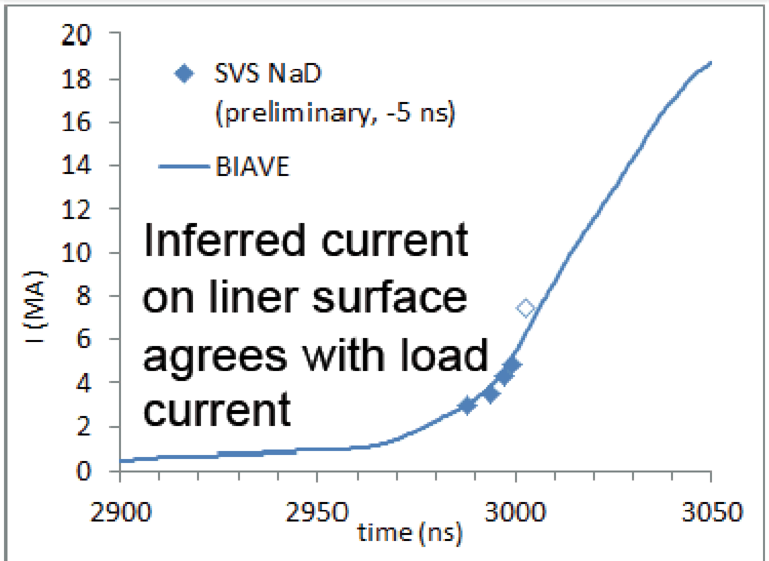
Both vacuum and plastic filled liners can compress flux over timescales relevant to MagLIF



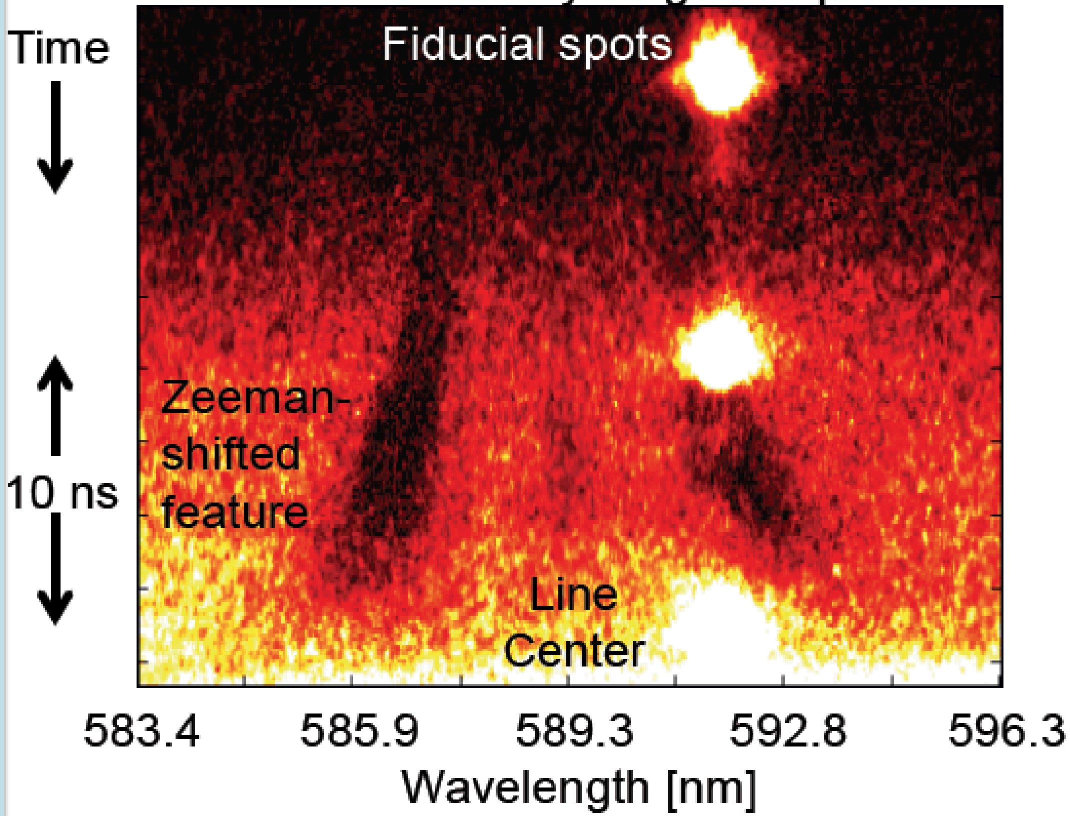


Possibility of measuring flux compressed Bz field using Streaked Visible Zeeman Spectroscopy





Data from nearly tangential probe

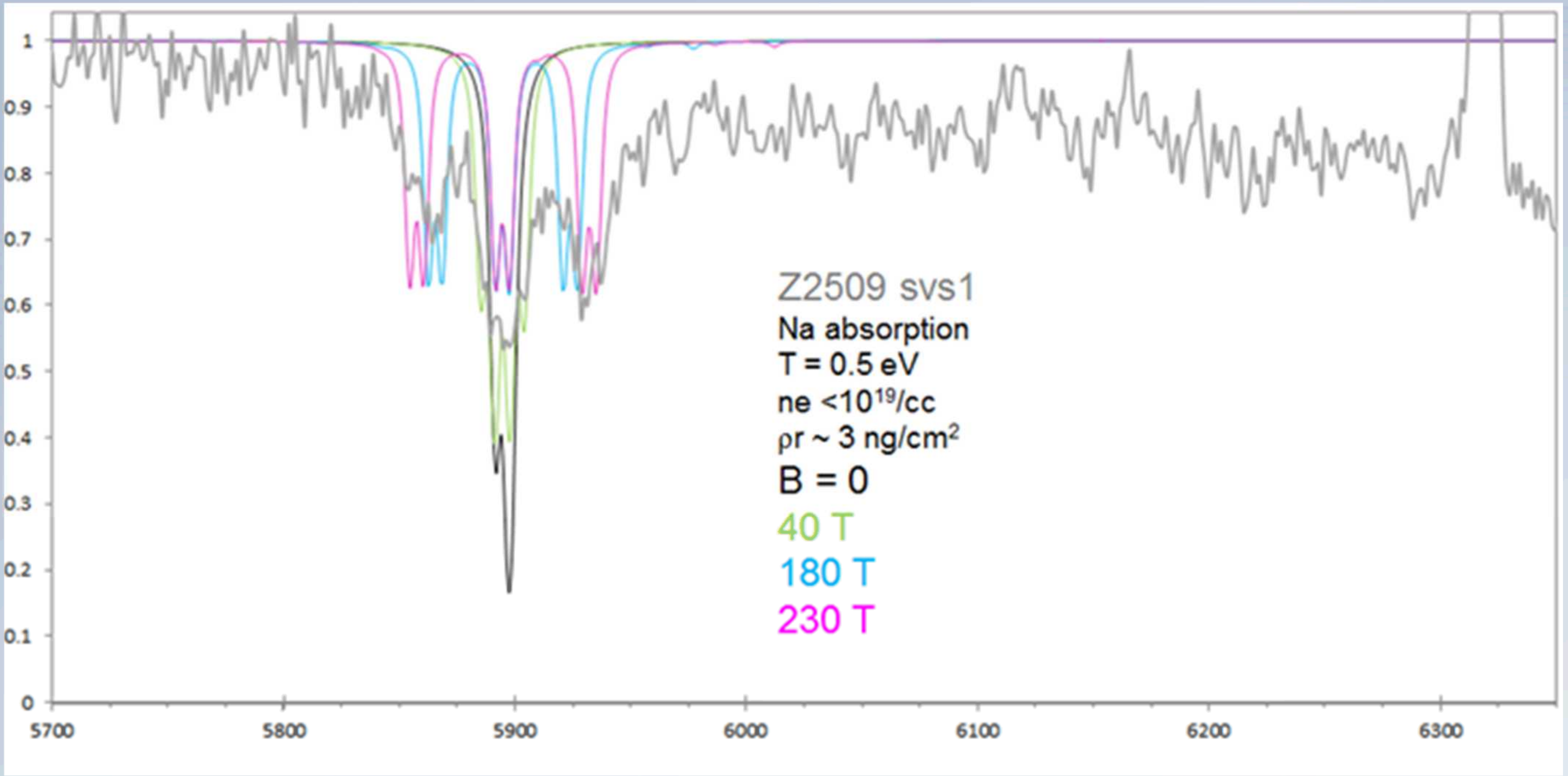


Time-dependent Zeeman splitting of neutral sodium line seen in absorption—splitting is proportional to magnetic field strength

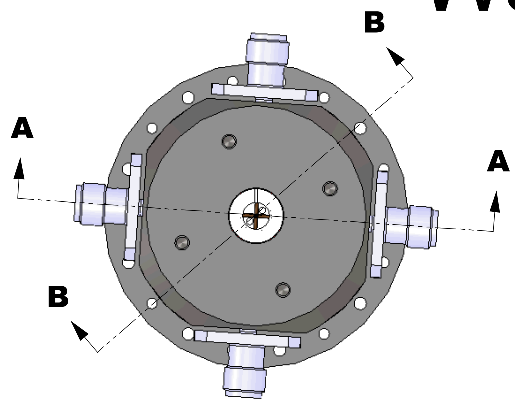
* Data analysis and data from M.R. Gomez, S.B. Hansen

Zeeman Spectroscopy Progress: Splitting observed in Na *absorption* lines

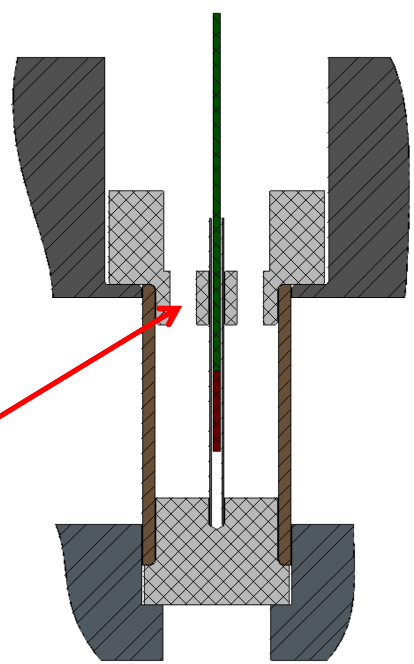
- Work being led by Matt Gomez and Stephanie Hansen



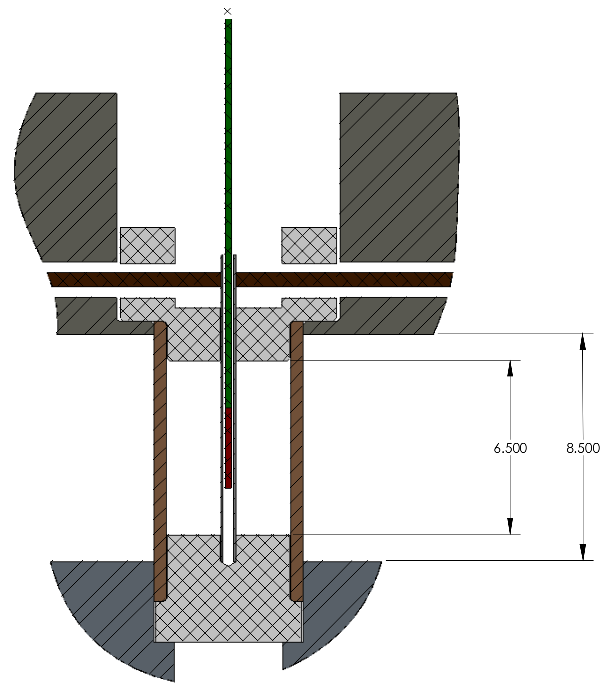
Washington-5 Target design



- 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

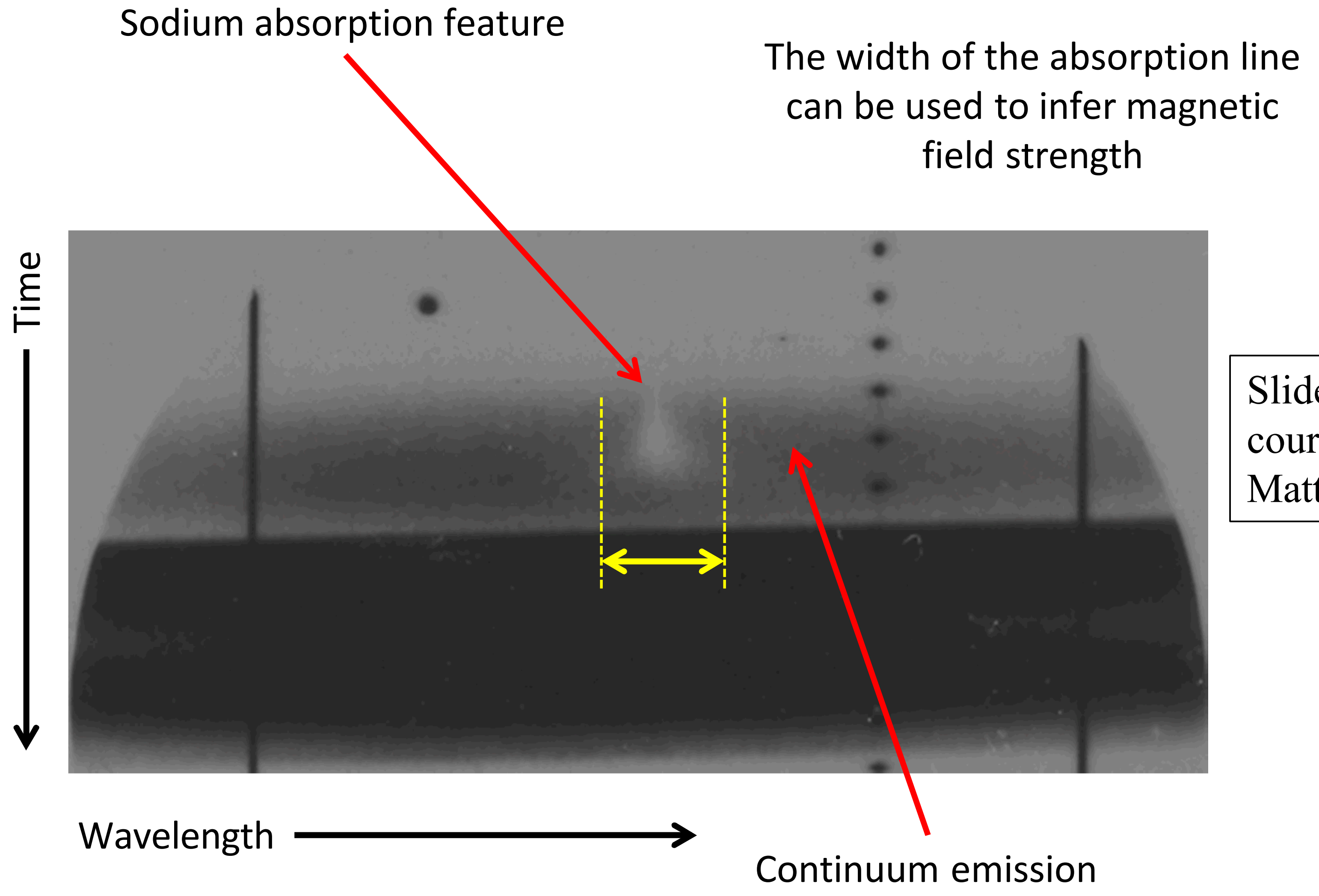


SECTION B-B
SCALE 8 : 1



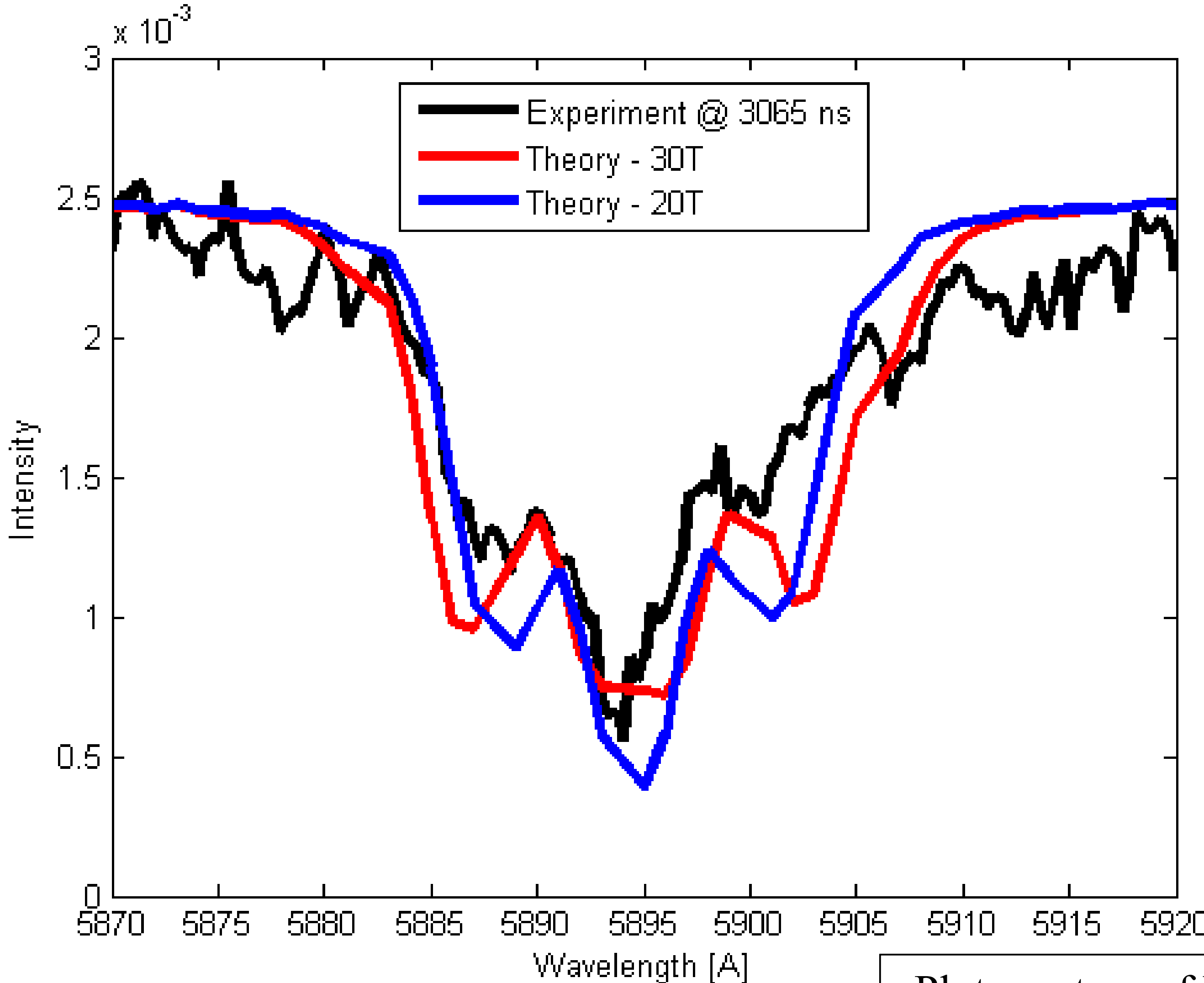
SECTION A-A
SCALE 8 : 1

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

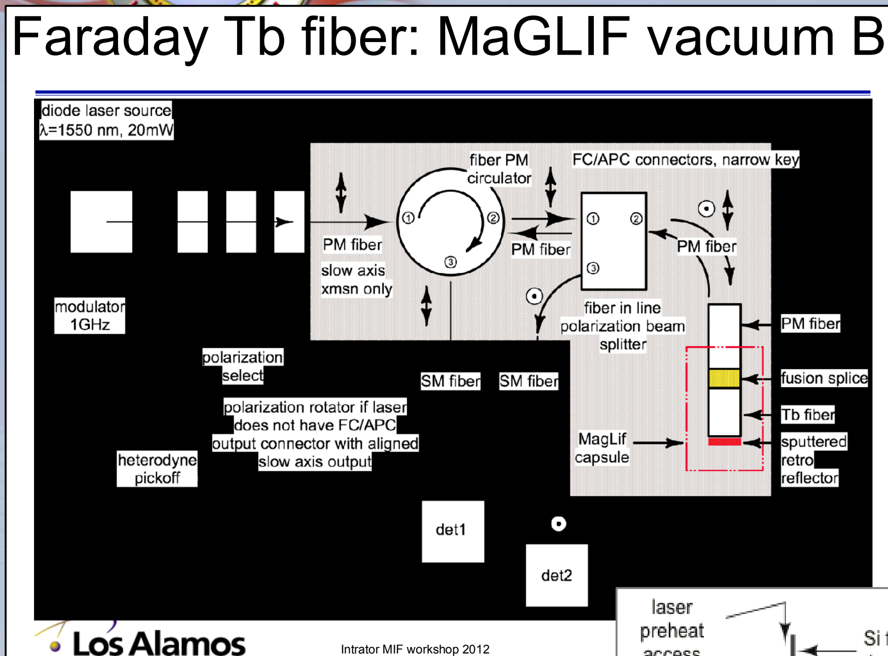


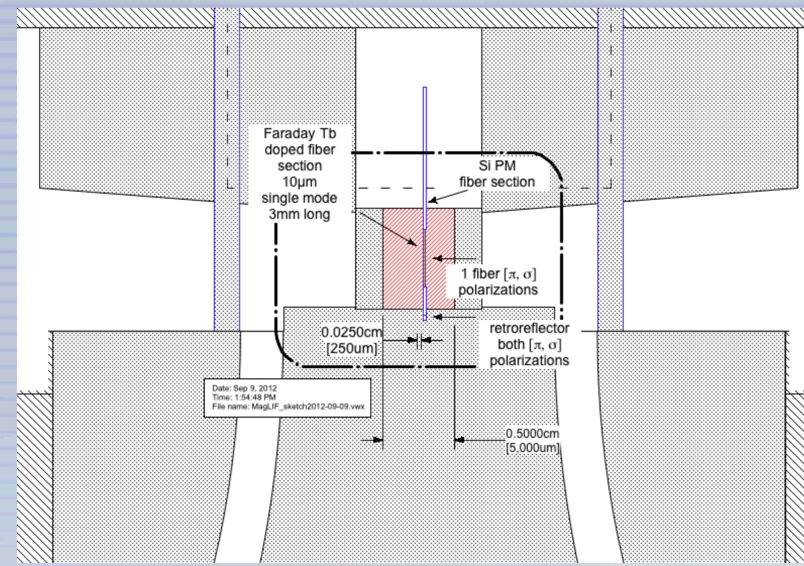
Plot courtesy of Matt Gomez & Stephanie Hansen

Fiber Faraday Rotation

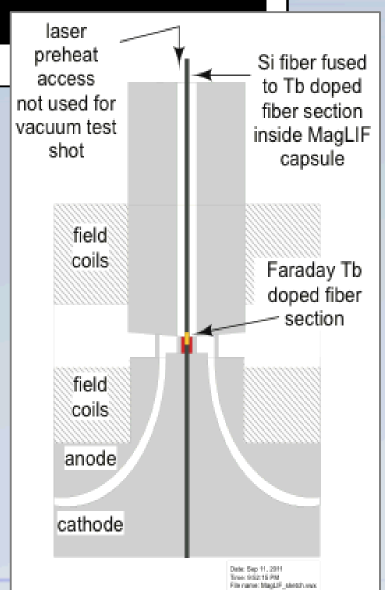
- Designed in collaboration with Tom Intrator and Tom Weber from LANL and Dave Bliss from SNL to evaluate the use of this technique on Z
- This technique uses a magneto-optic fiber placed along the axis of the imploding liner
- Knowledge of the fiber's Verdet constant circumvents the need for an independent plasma density measurement in determining the magnetic field
- Fiber Faraday rotation methods have been used to measure up to 1100 T (11 MGauss) in American-Russian collaborative experiments in 1993 using Russian MC1 explosively-driven magnetic flux compression generators
- This LDRD has enabled us to begin to evaluate this technique on Z

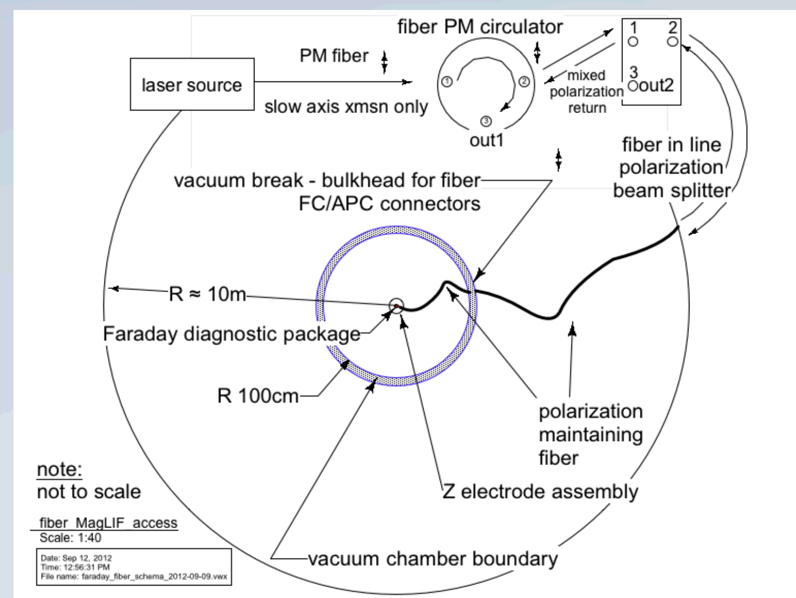
Fiber Faraday Rotation Progress: Design completed and bench-tested at LANL, SITF, and Z





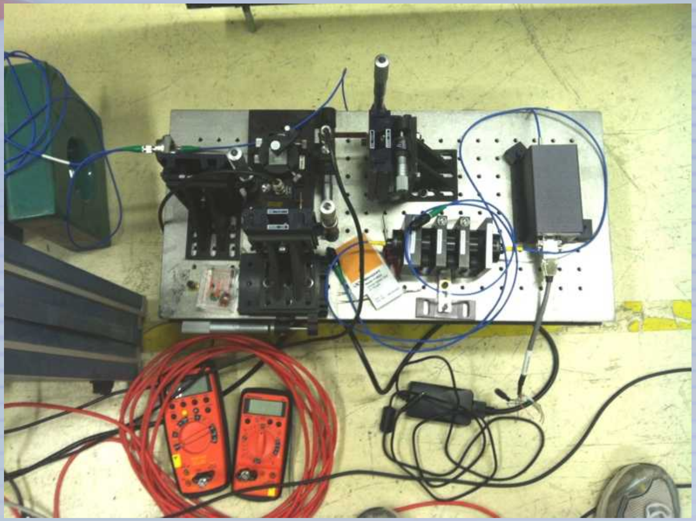
- Tom presented his design and preliminary bench-testing results at the Diagnostics User Group Meeting at LLNL on May 21-23, 2013

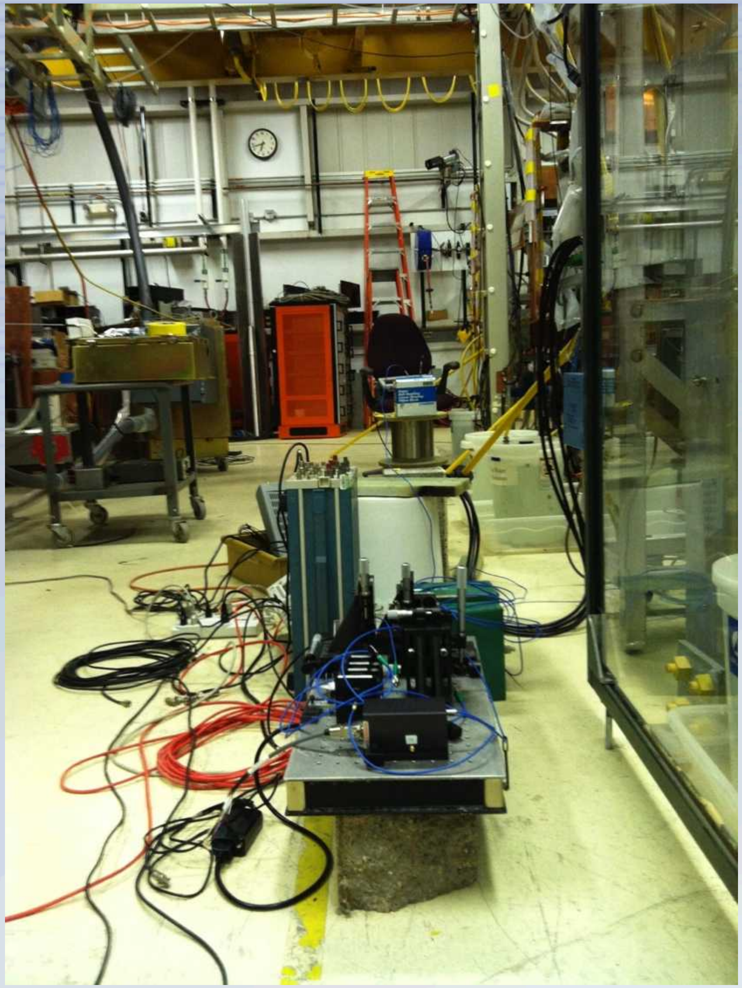




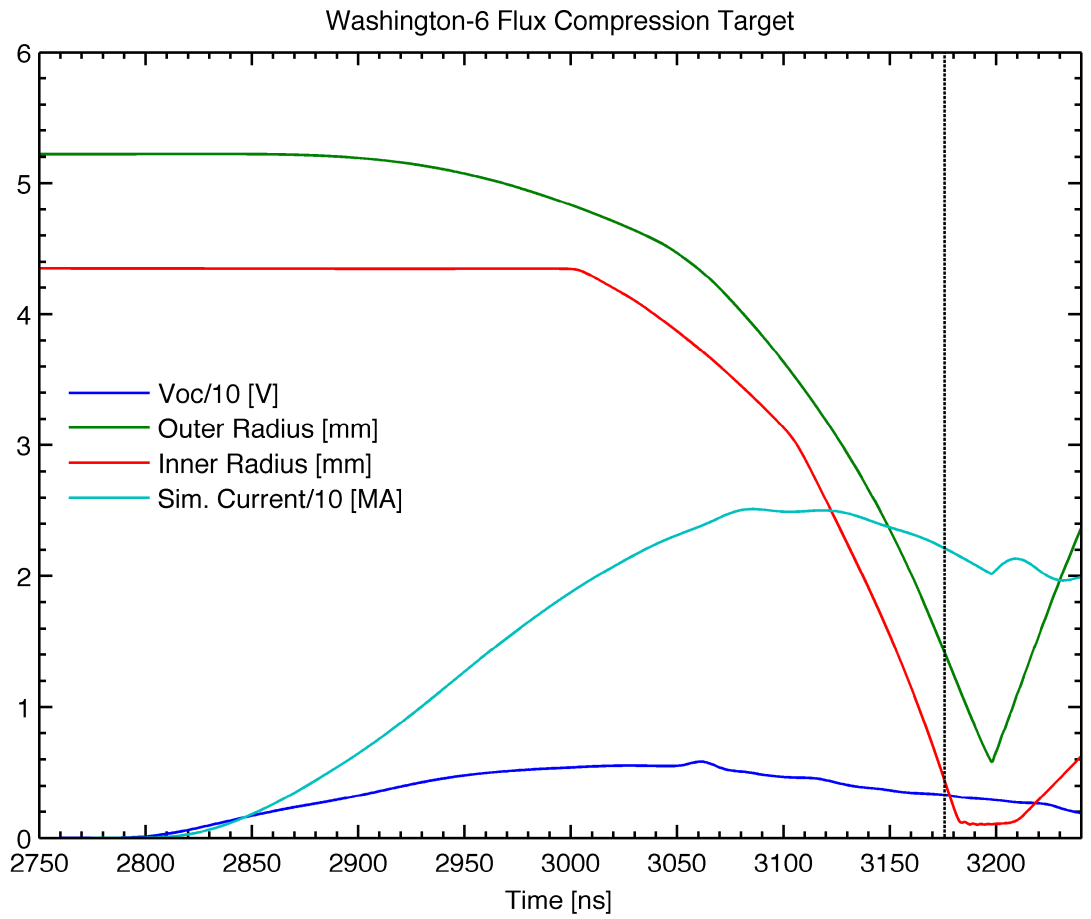
LDRD
LABORATORY DIRECTED RESEARCH & DEVELOPMENT

Fiber Faraday Rotation Progress: Design completed and bench-tested at LANL, SITF, and Z





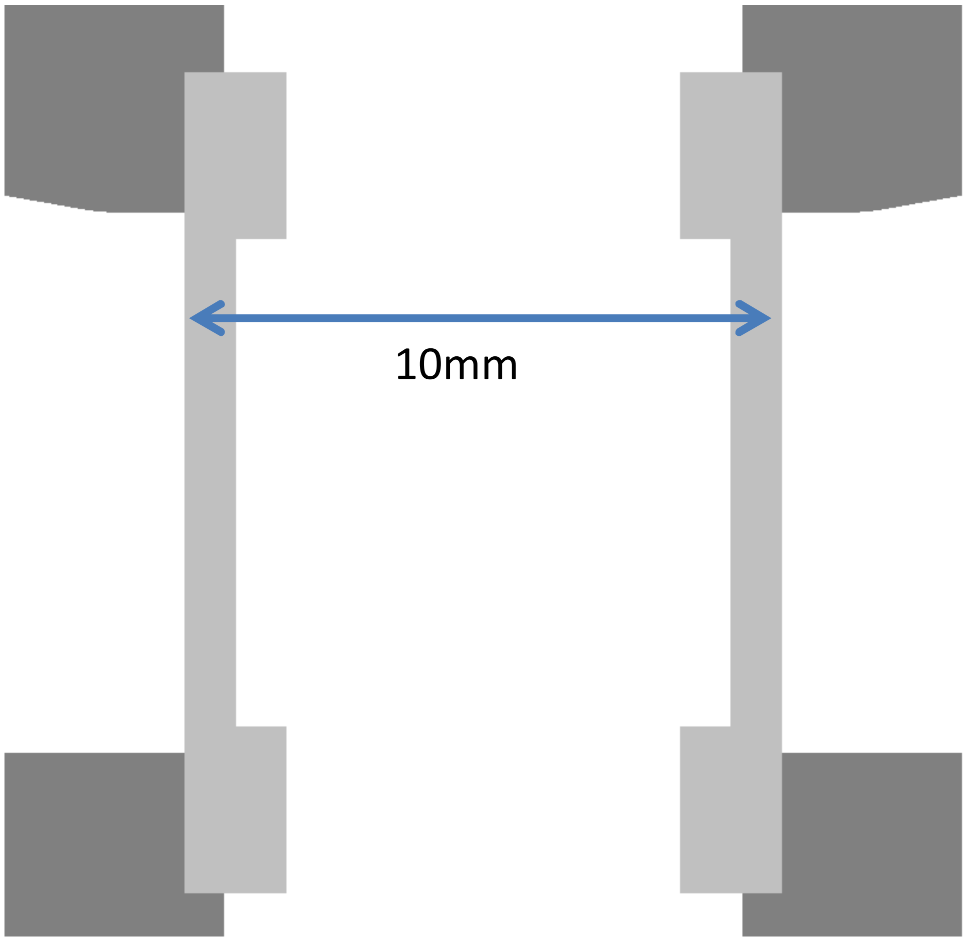
Utilize Z in long-pulse mode to implode larger liners and fit larger/more probes

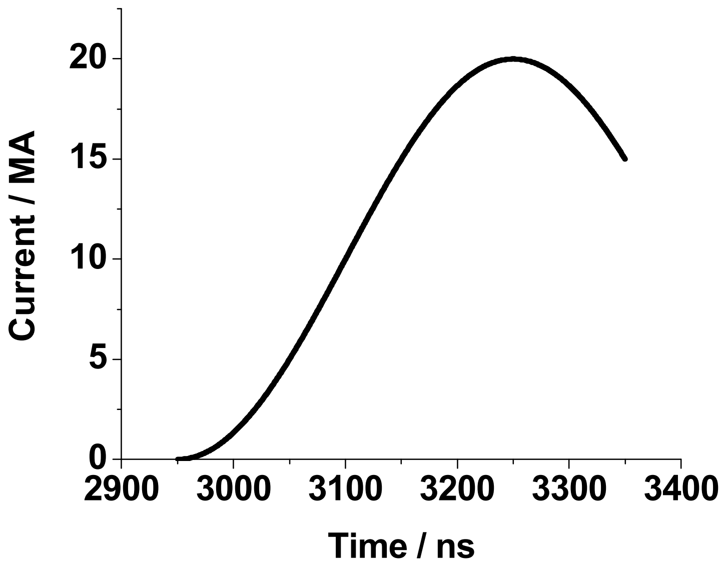


*We will use Z in long-pulse mode to implode a larger-radius AR=6 liner ($R_{in,0}$ = 4.35 mm), thus providing more space for larger on-axis probes, while not sacrificing implosion convergence (CR~10 obtainable)

Can implode much larger, same aspect ratio liner in long pulse (lots more space to work with)

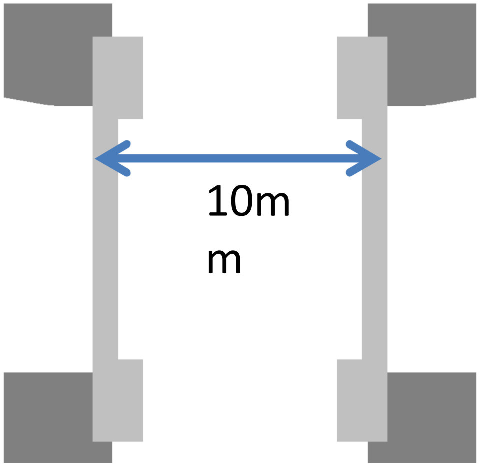
Proposed long pulse load parameters

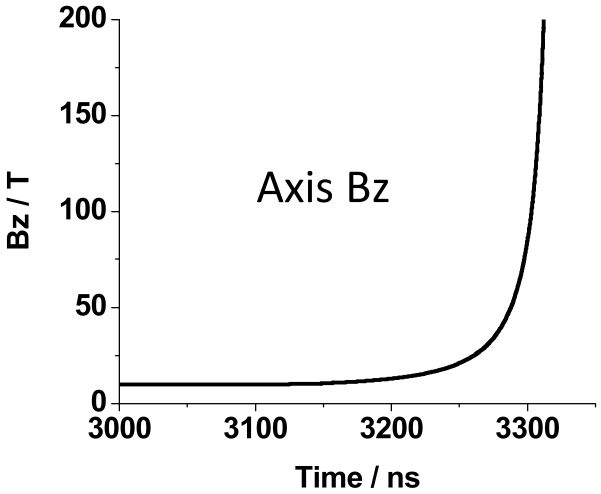




Long pulse can compress flux inside large initial liner

- No indication of plasma blow off from inside liner surface
- Probably not shocking up as strongly

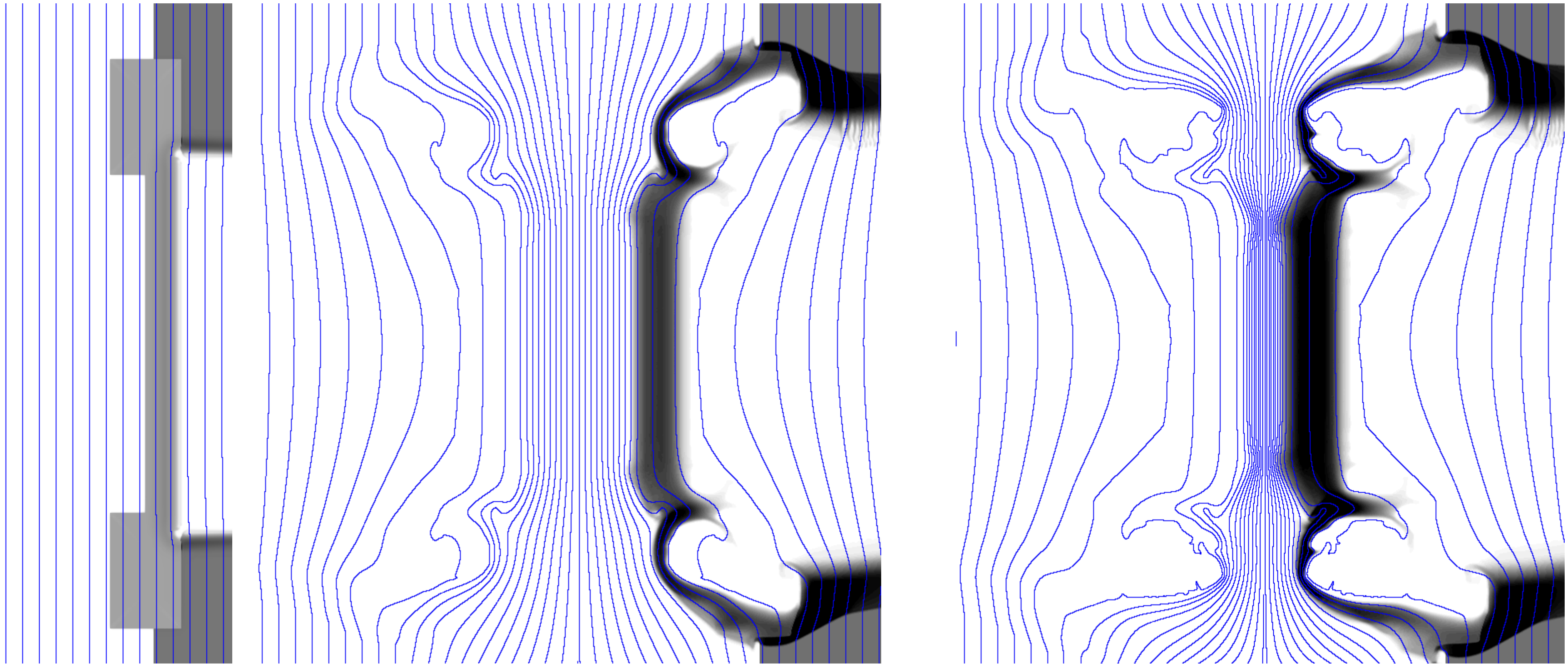




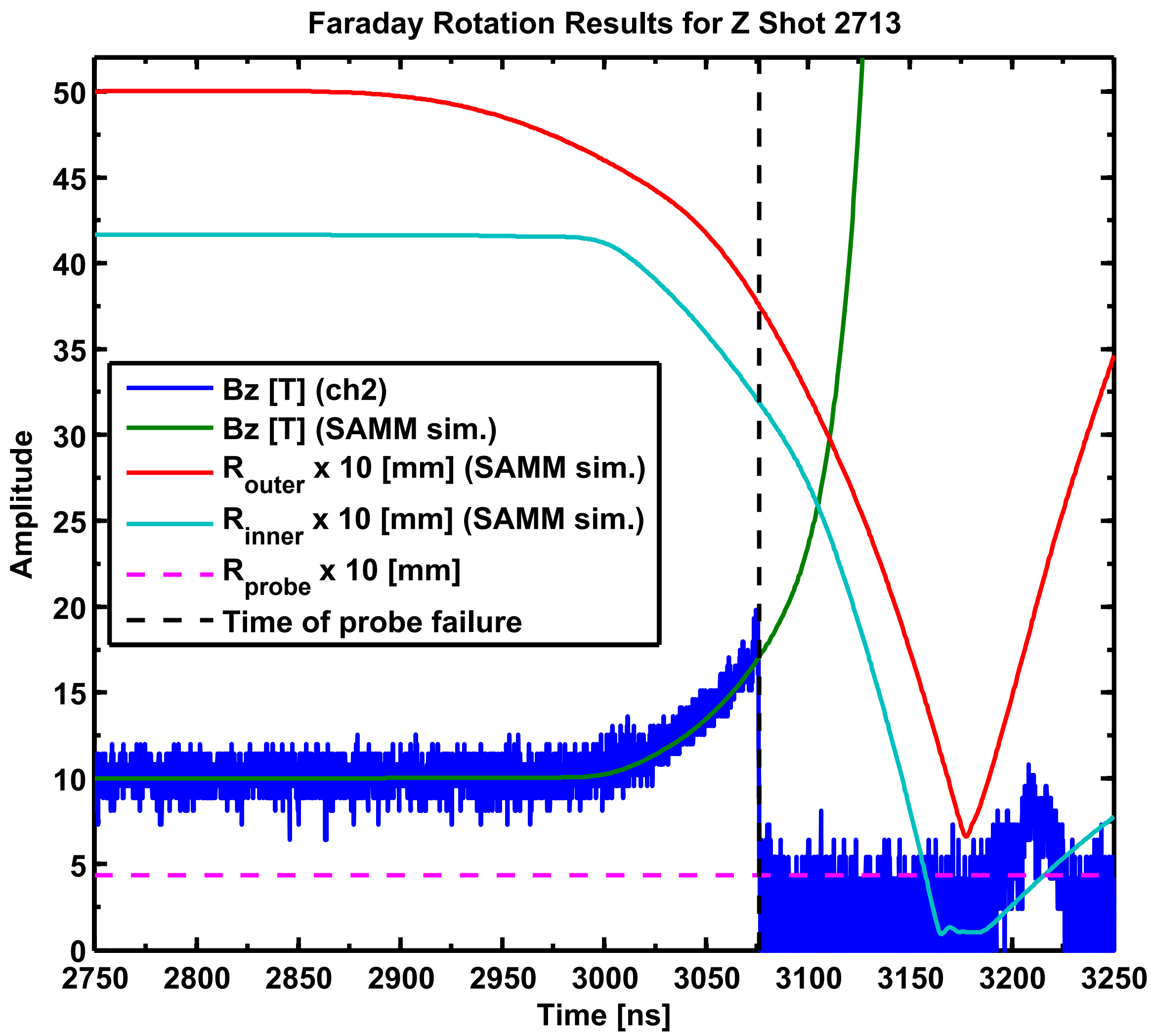
3100ns

3300ns

3320ns



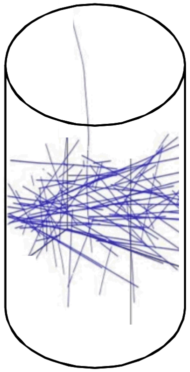
Faraday Rotation Results (Z Shot 2713)

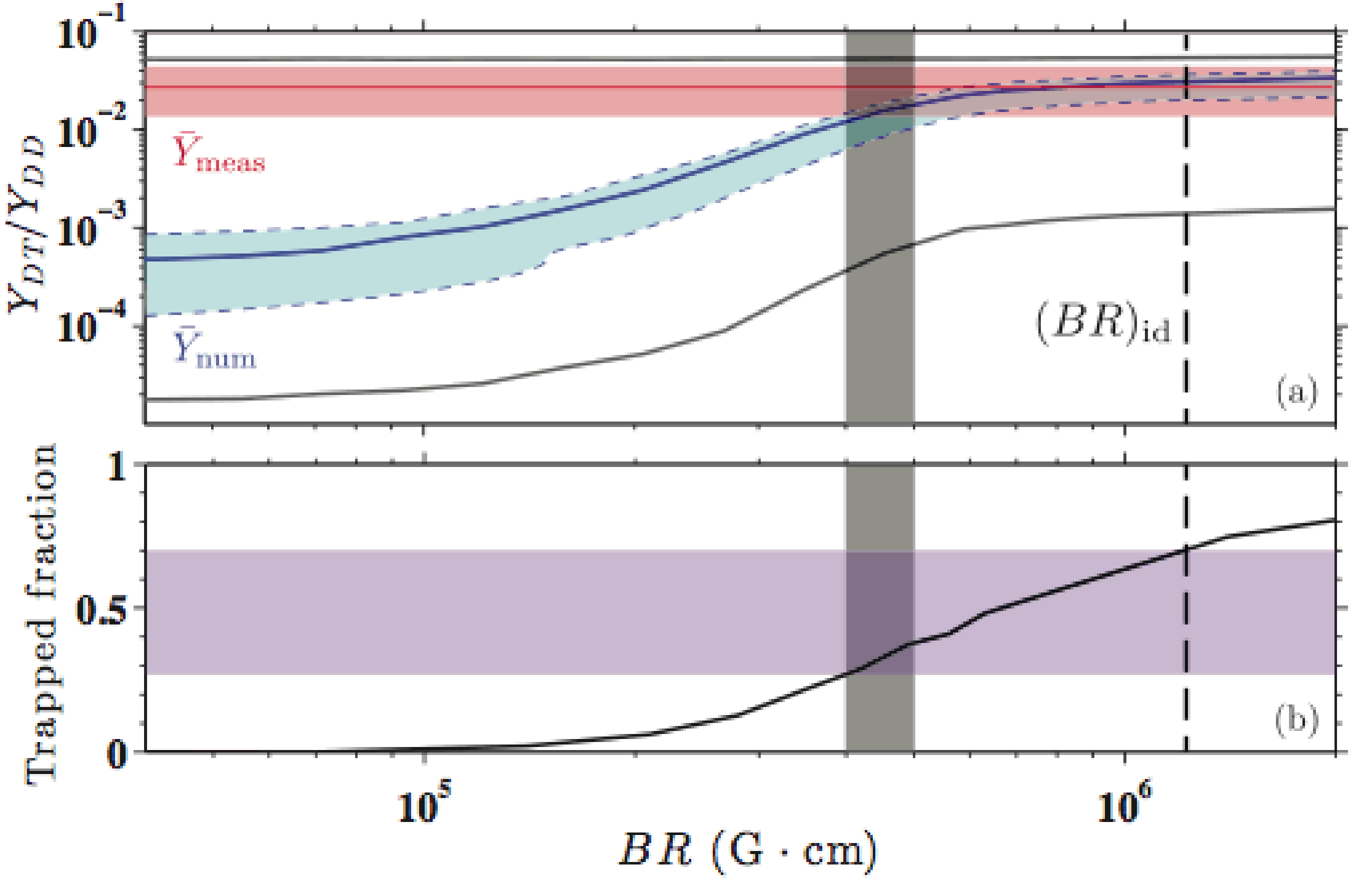


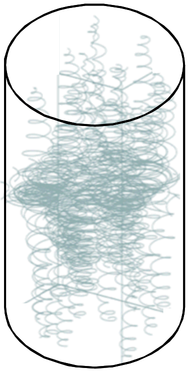
Looking toward the future: How to measure flux compression in a fully integrated MagLIF experiment to get at Nernst physics?

- An exciting development in the analysis of neutron DT/DD yield ratios and secondary DT-reaction neutron spectra from NTOF detectors could help with this very difficult problem
- Development of this new technique led by Paul Schmit and Patrick Knapp
- Looking to design experiments in CY2015 to leverage this new technique

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:

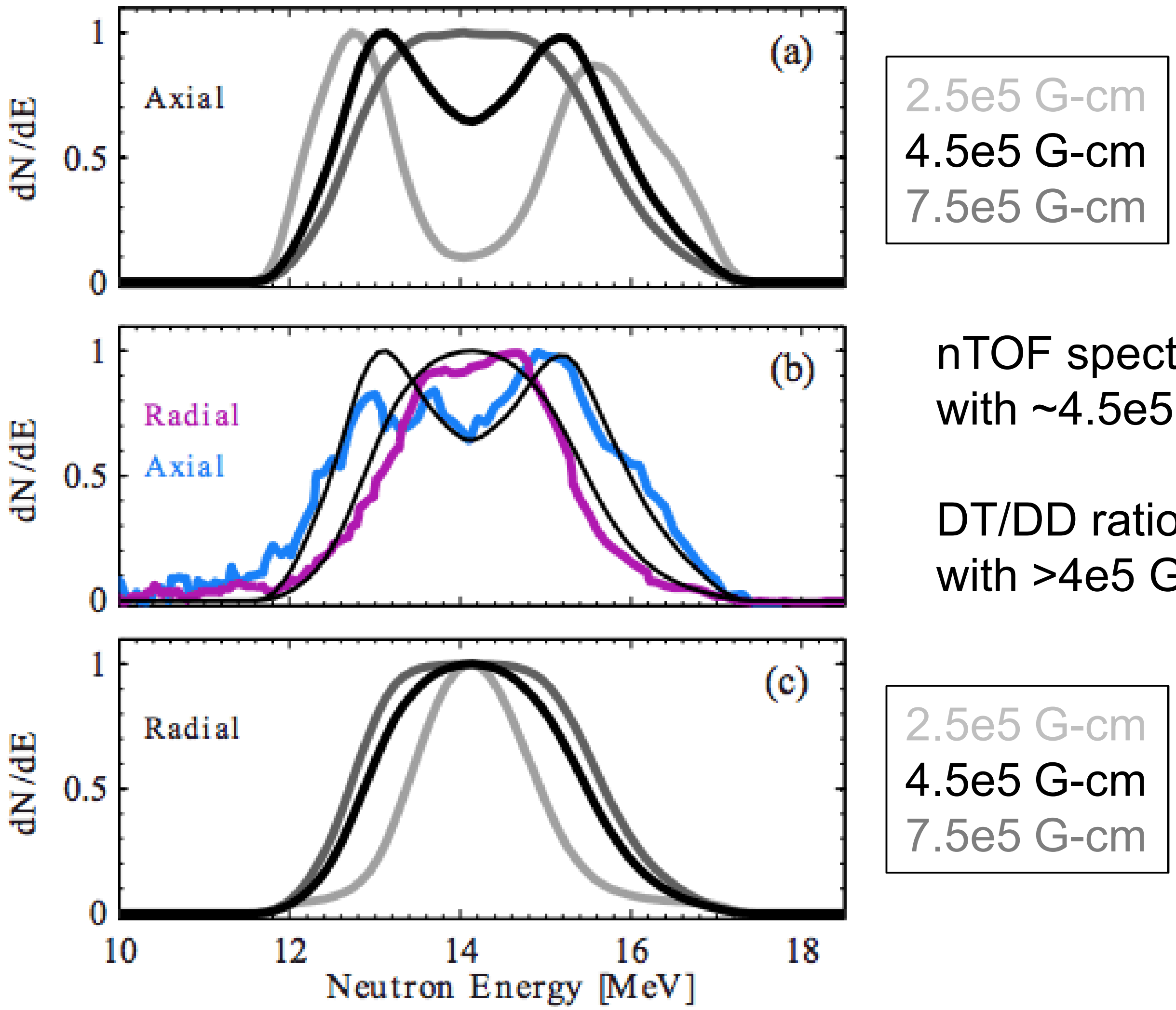
$$\omega_{ci}\tau_{ie} \approx \omega_{ce}\tau_{ee}$$

Magnetized tritons implies magnetized alpha particles:

$$r_t \approx 1.1 r_\alpha$$

P.F. Schmit, P.F. Knapp *et al.*, PRL **113**, 155004 (2014).

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



nTOF spectra consistent with ~4.5e5 G-cm

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

P.F. Schmit, P.F. Knapp *et al.*, PRL **113**, 155004 (2014).