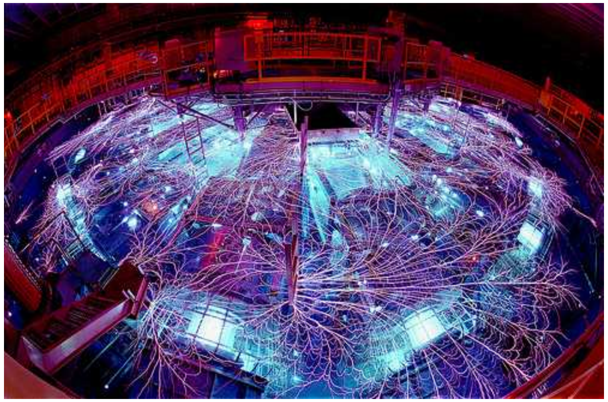
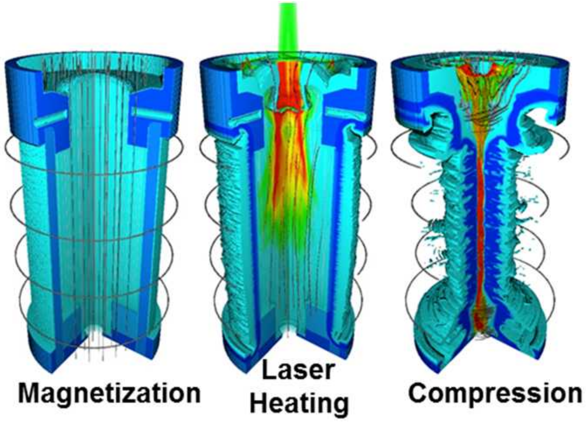




Measuring magnetic fields in Magnetized Liner Inertial Fusion: Past successes and future opportunities

Matthew Gomez
for the MagLIF team

Sandia National Laboratories

4th Magnetic Fields in Laboratory High Energy Density Plasmas Meeting, Princeton, NJ, November 11, 2015

This work represents the effort of a large team

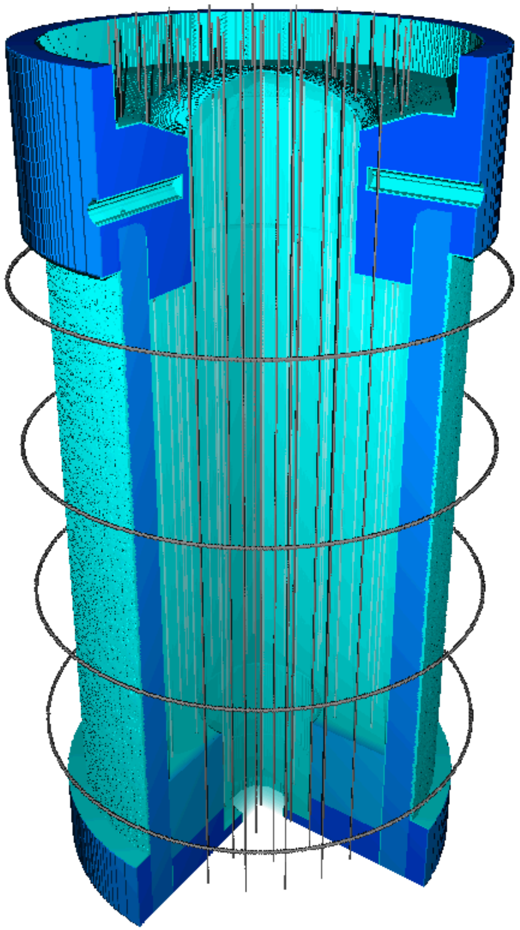
A. B. Sefkow, S. A. Slutz, R. D. McBride, D. E. Bliss, S. B. Hansen,
P. F. Knapp, P. F. Schmit, M. H. Hess, C. A. Jennings, D. C. Lamppa,
B. Hutsel, T. J. Awe, M. Geissel, A. J. Harvey-Thompson,
K. J. Peterson, E. C. Harding, K. D. Hahn, C. L. Ruiz, D. B. Sinars,
I. C. Smith, D. C. Rovang, G. A. Chandler, M. R. Martin, J. L. Porter,
G. A. Rochau, and more…

Sandia National Laboratories, Albuquerque, NM 87185 USA

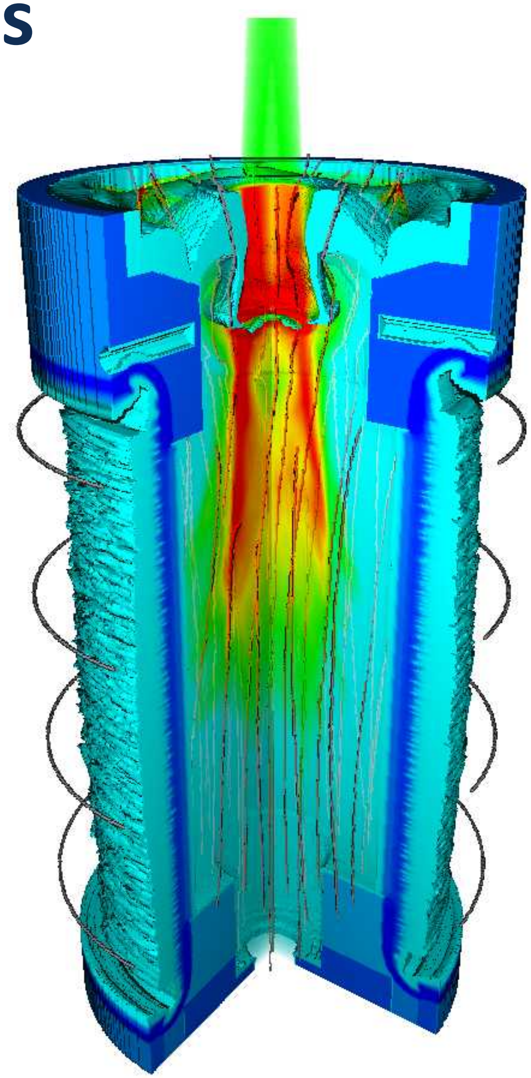
B.E. Blue, D.G. Schroen, K. Tomlinson

General Atomics, San Diego, CA 92186 USA

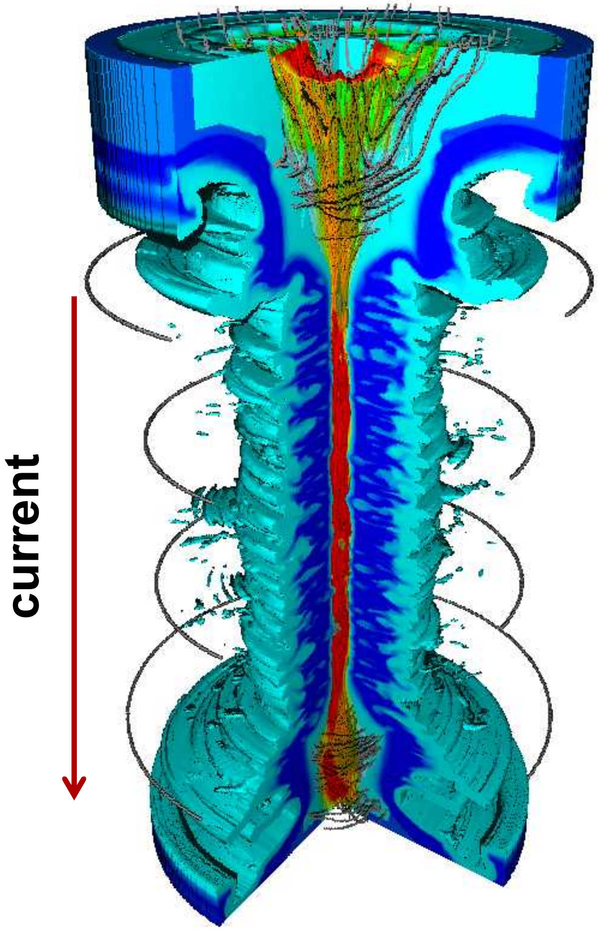
MagLIF relies on three stages to produce fusion conditions



Axial magnetization



Laser Heating



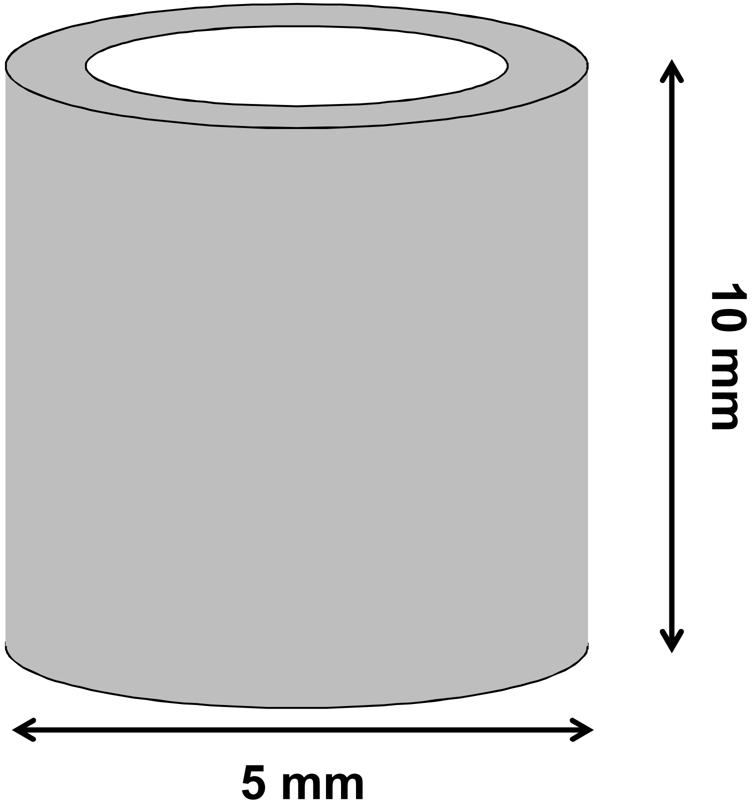
Magnetically-driven compression

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

Outline

- Magnetic field outside the target
  - Drive current pulse shape and amplitude
- Magnetic field inside the target
  - Flux compression measurements in vacuum
  - Magnetic field x radius inference at stagnation
- Interesting areas for future measurements

Measuring the drive field is a common problem to all magnetically-driven systems



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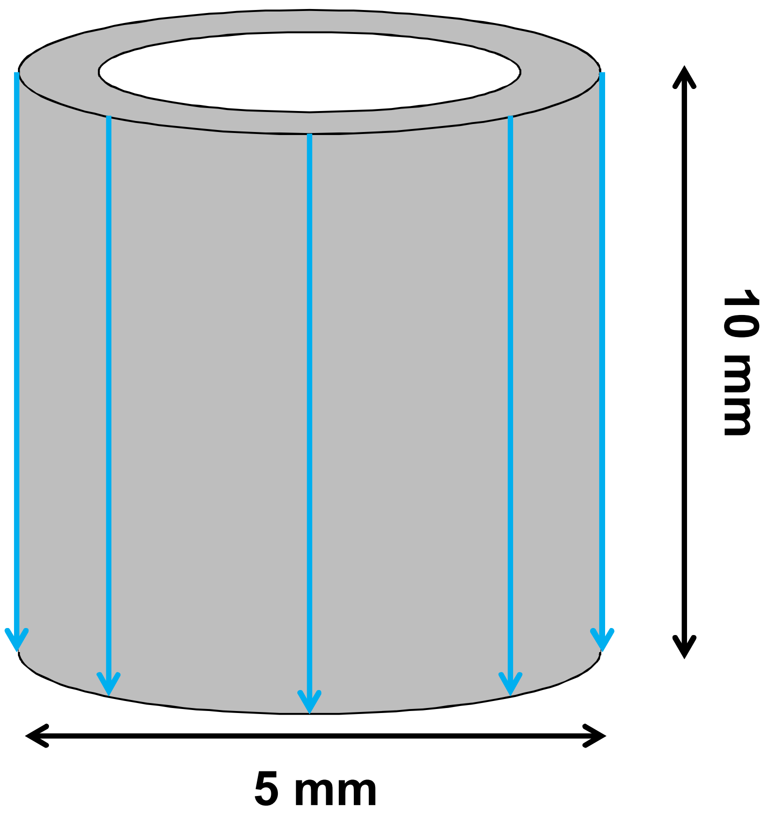
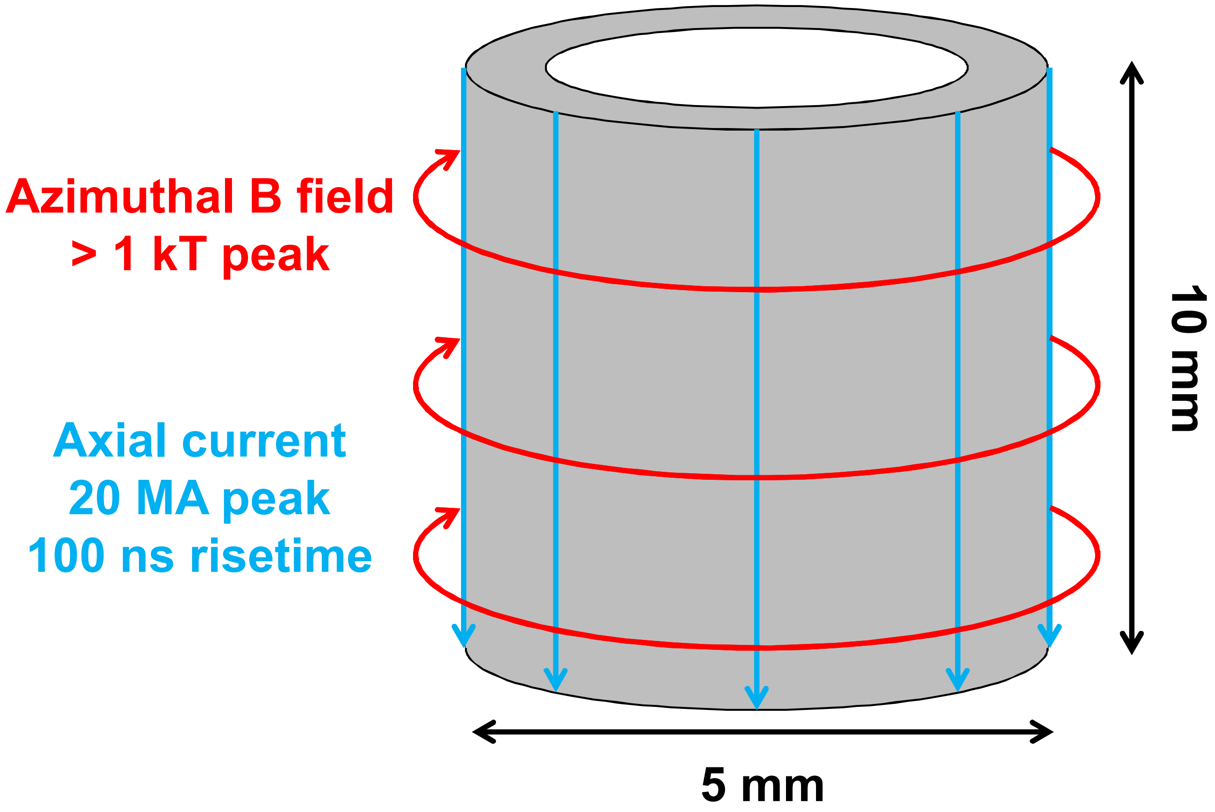


Axial current
20 MA peak
100 ns risetime

Measuring the drive field is a common problem to all magnetically-driven systems



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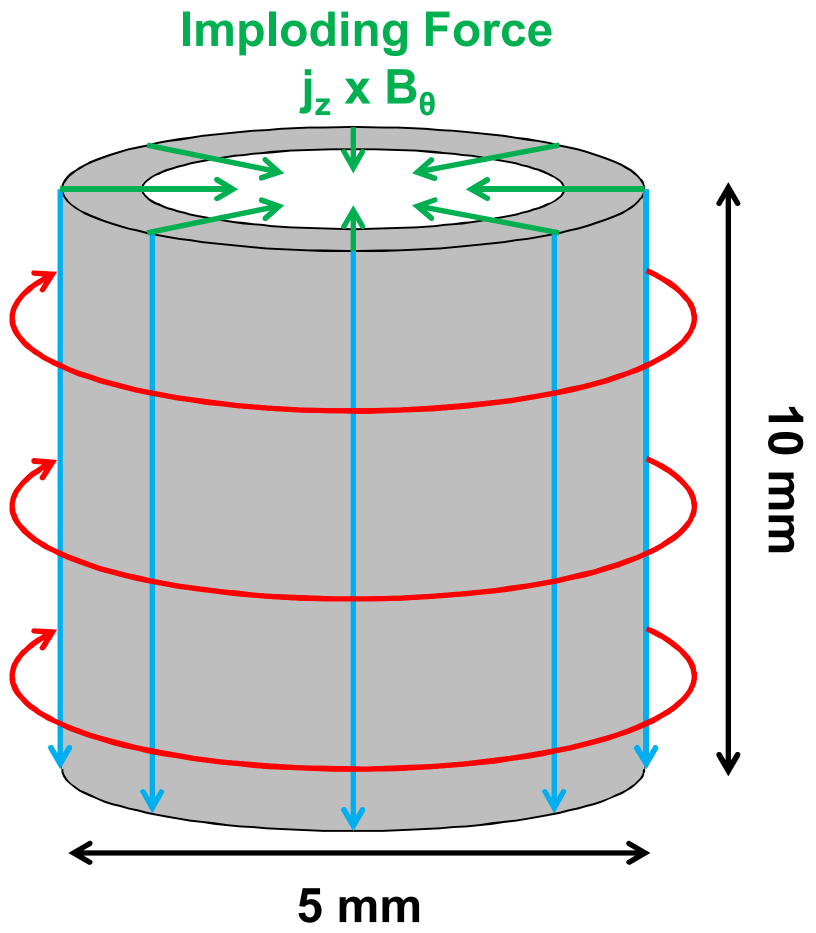
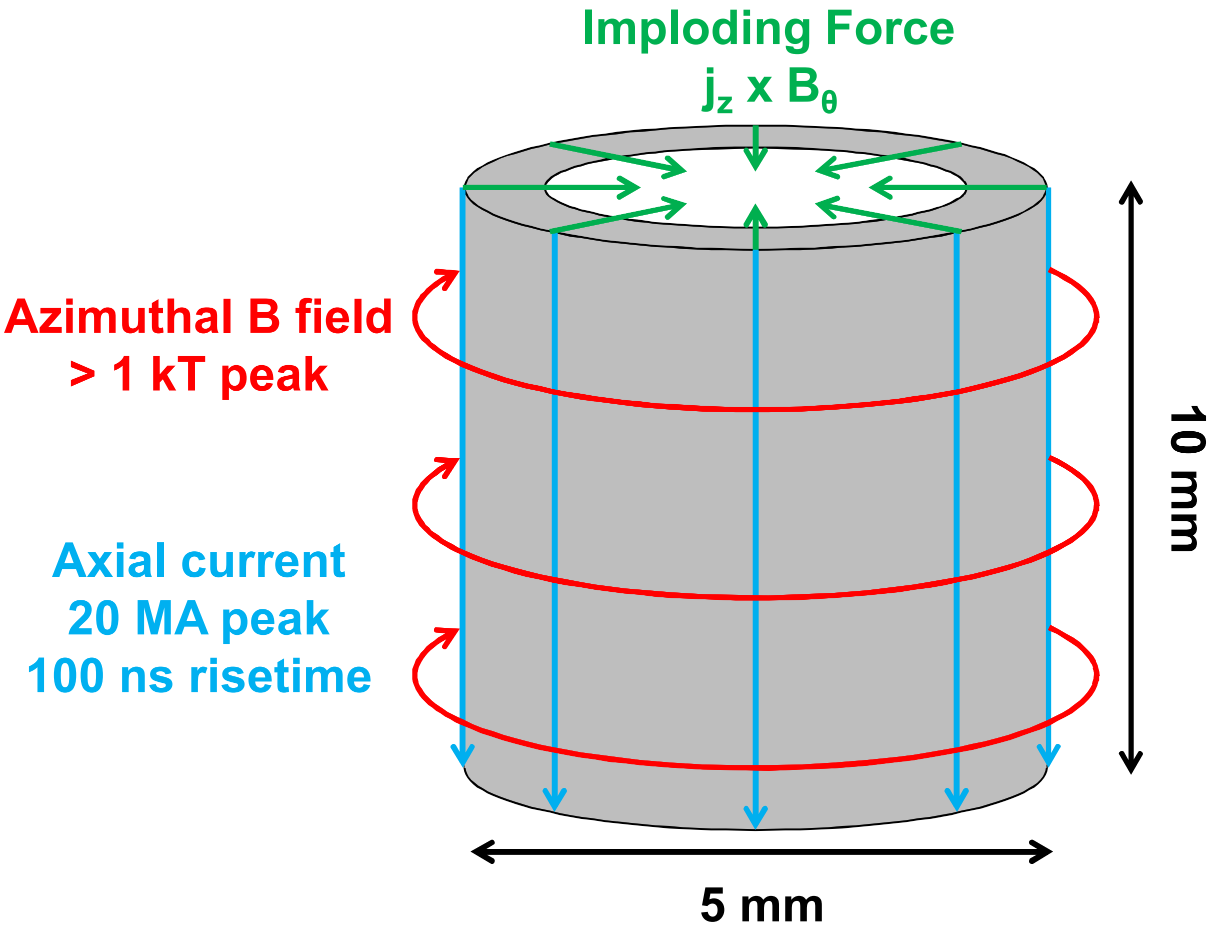


Measuring the drive field is a common problem to all magnetically-driven systems

Simulations of these complex experiments rely on a good understanding of the initial conditions and the drive

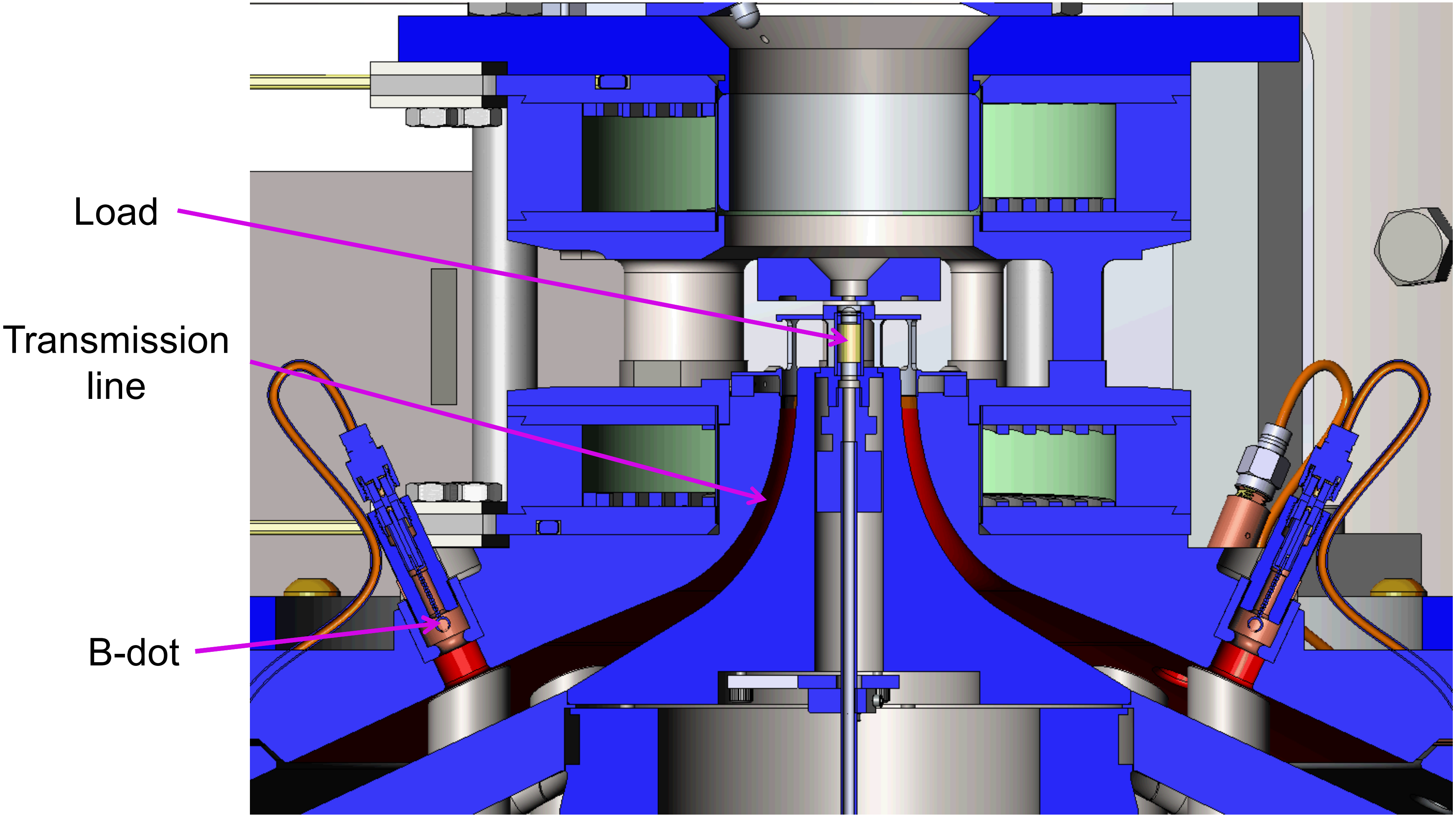
Ideally we want to know the amplitude, shape, and distribution of the drive current



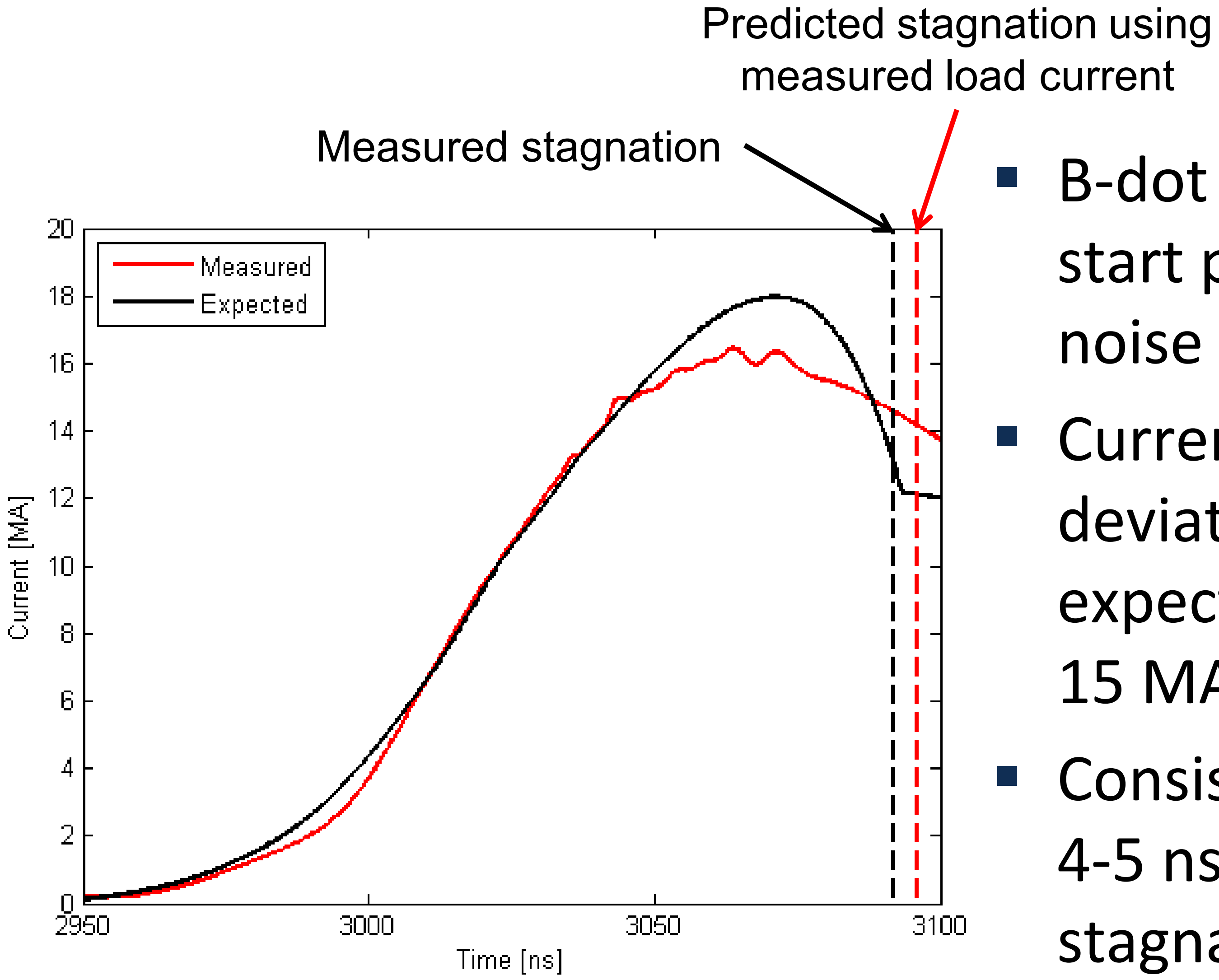
We have struggled to make an accurate drive current measurement in MagLIF

- Typically on Z we field B-dot monitors at R = 6 cm to determine the load current
  - Final A-K gap in MagLIF experiments may have losses not monitored by these probes
    - We'd like to move the measurement closer to the load
  - In MagLIF experiments, these monitors start to fail around halfway through the current pulse
    - Monitors indicate LOWER current than expected and are not consistent with timing of stagnation
- We are exploring other options to monitor load current

Ideally probes would monitor B-field directly on the target, but often this is not practical

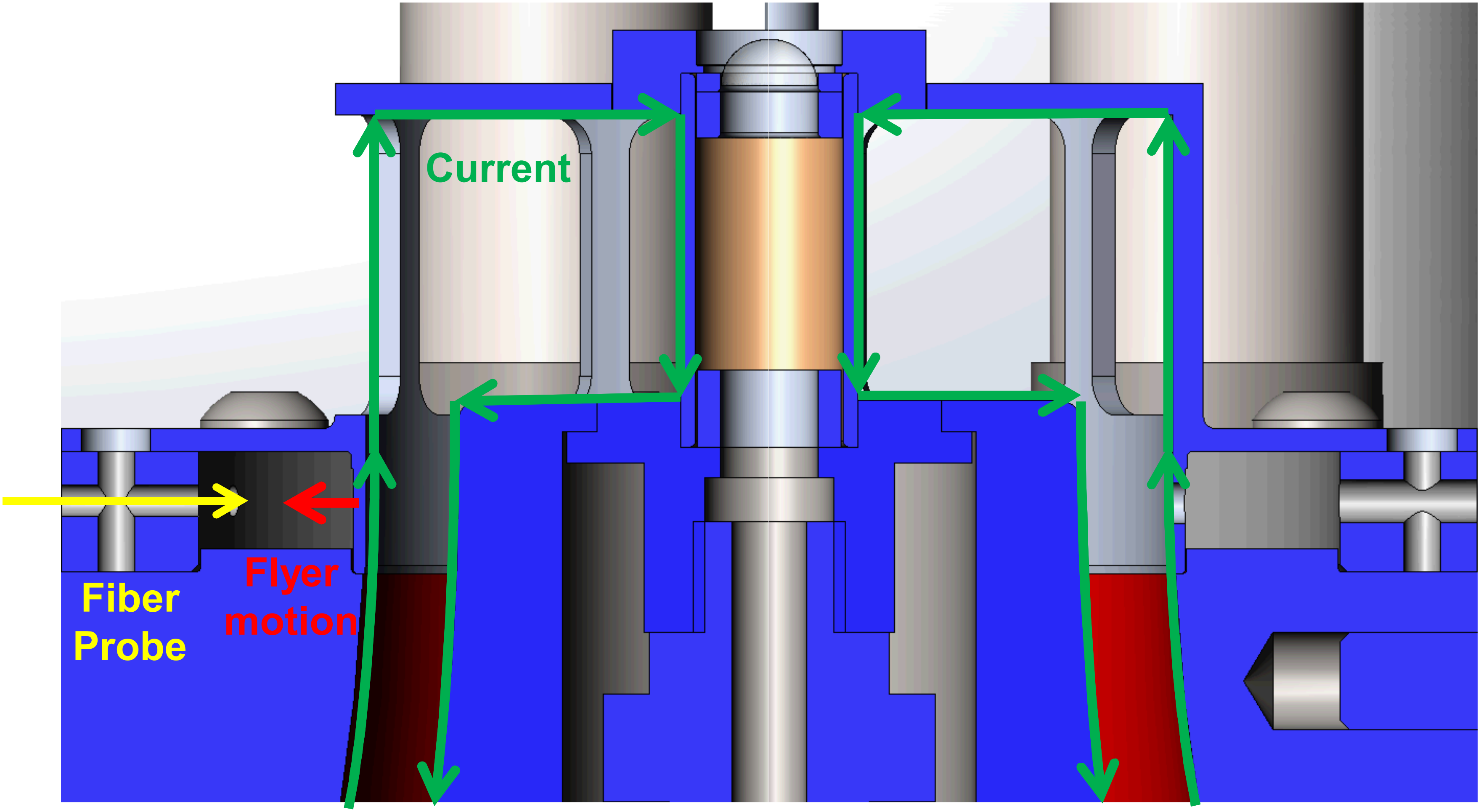


Measured load currents are not consistent with observed stagnation times



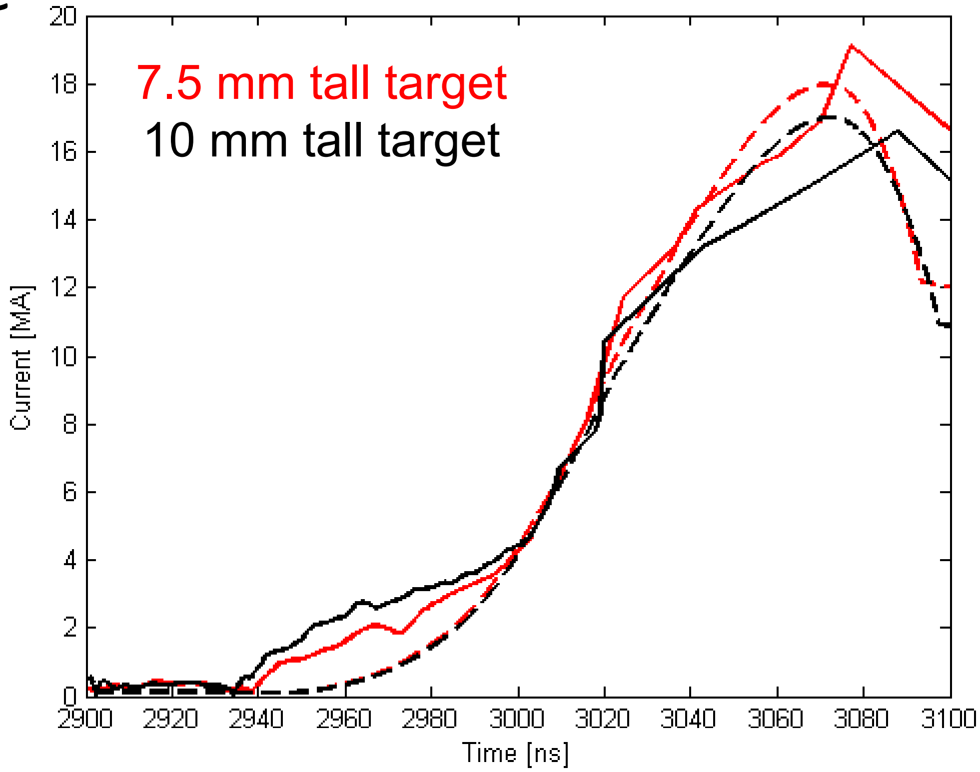
- B-dot monitors start picking up noise around 10 MA
- Current significantly deviates from expected value by 15 MA
- Consistent with a 4-5 ns delay in stagnation

VISAR and PDV probes are used to monitor flyer velocity as a function of time



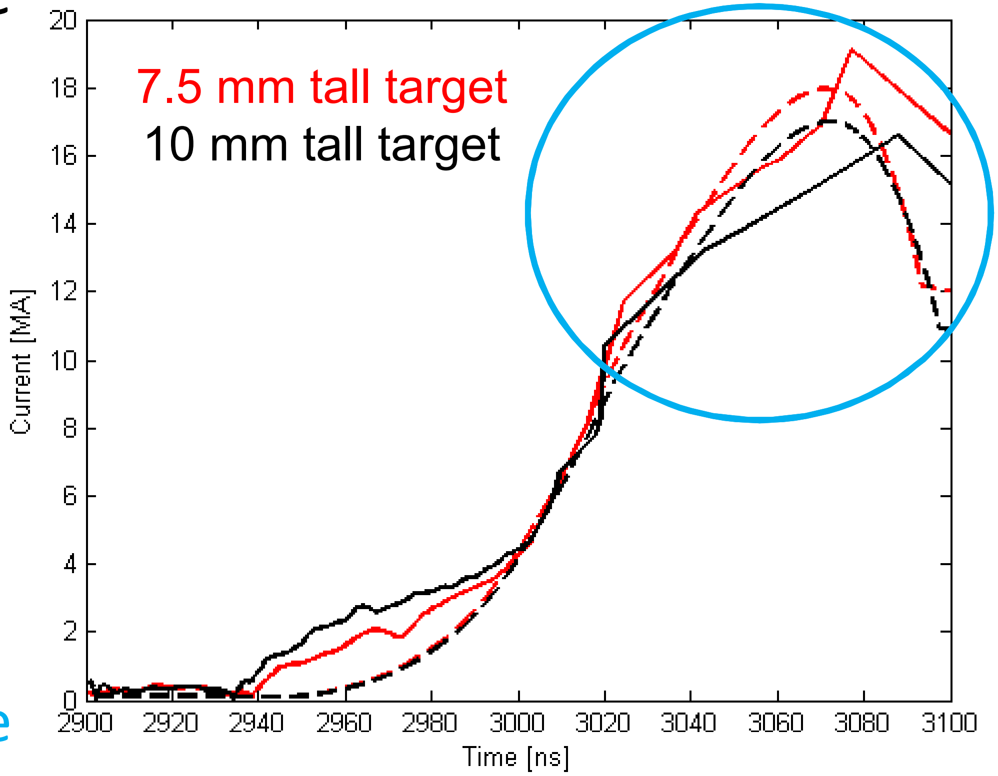
Flyer-baser measurements have potential but need improvement

- We observe a difference in peak load current for different height targets as expected



Flyer-baser measurements have potential but need improvement

- We observe a difference in peak load current for different height targets as expected
- Iterative MHD simulations to match flyer velocity
  - Unfolds take a long time and are not yet complete



Flyer-baser measurements have potential but need improvement

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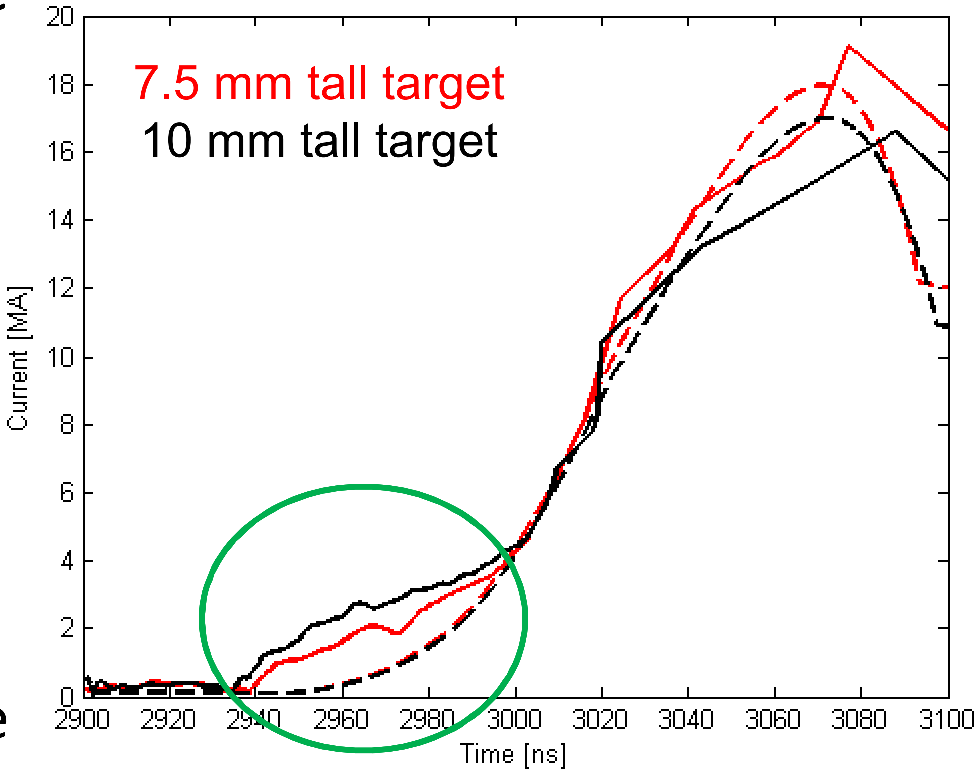
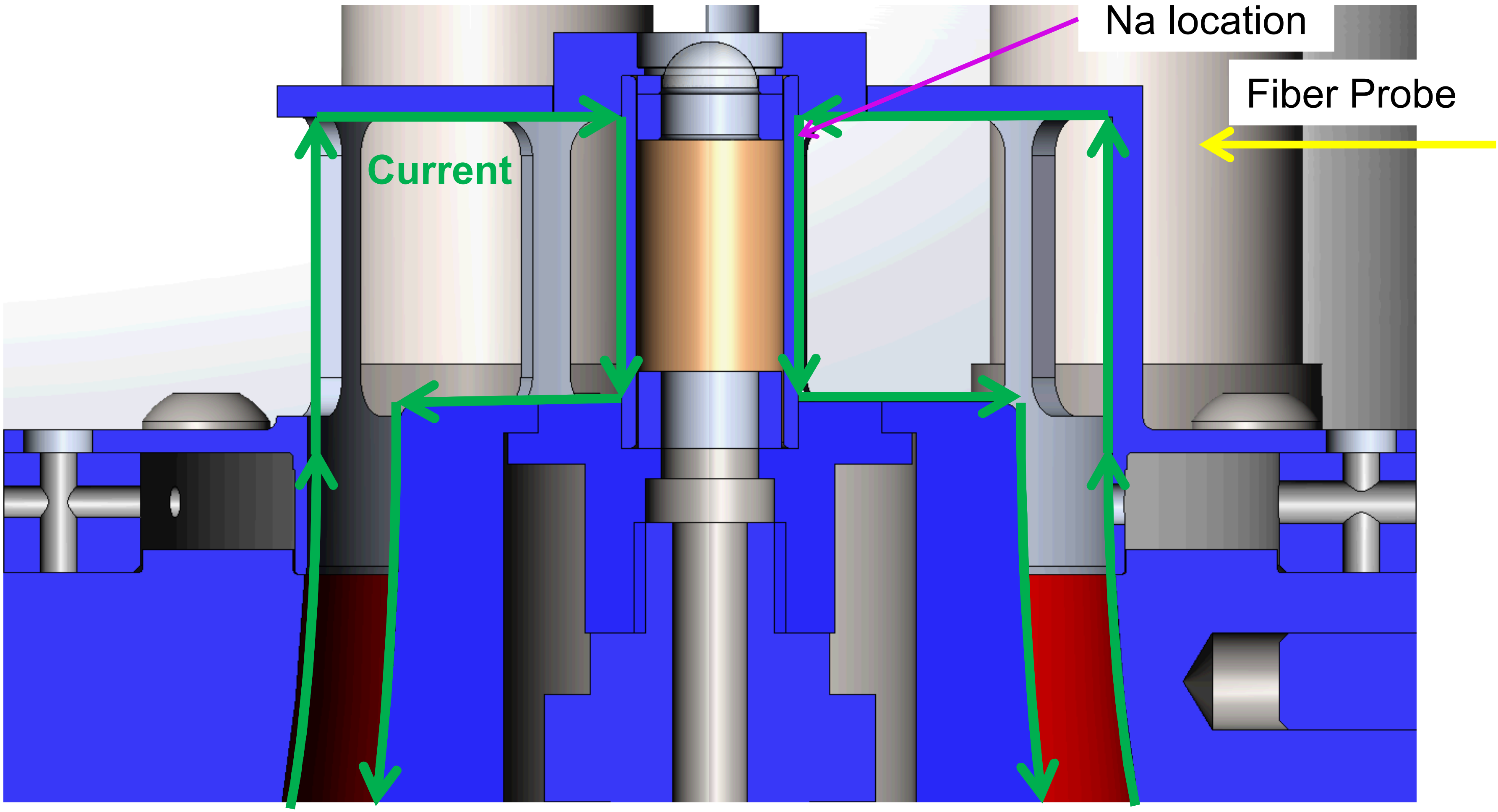
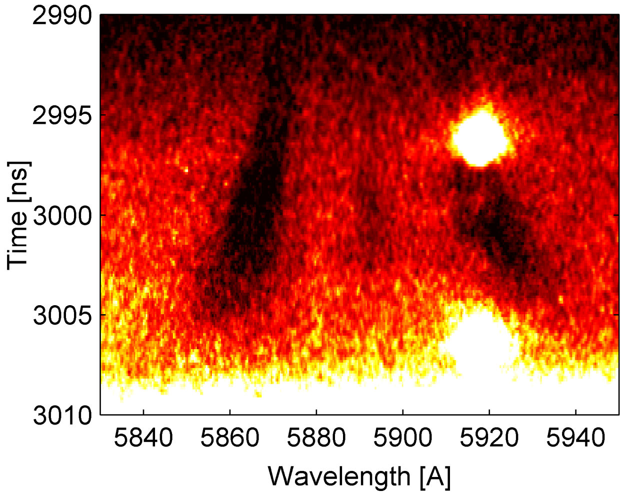


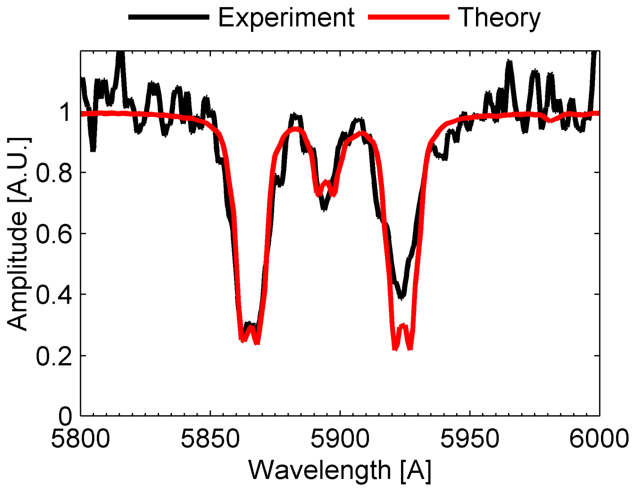
Discrepancy at early times possibly due to electron bombardment of flyer

Visible spectroscopy was used to monitor spectral line splitting to infer load current



Line splitting successfully observed at early times, but signal lost well before peak current

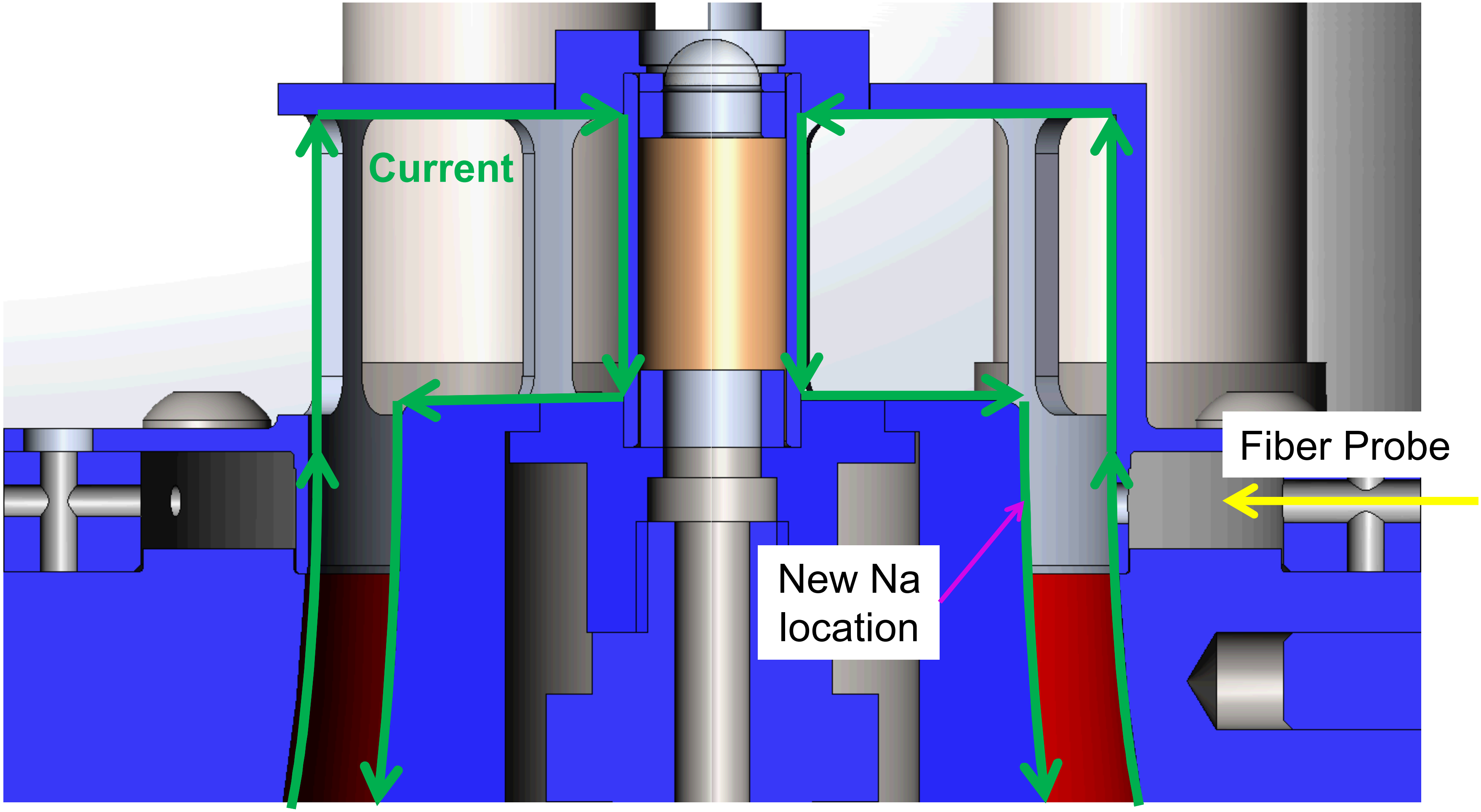




- Probe views target surface
- Using neutral sodium doublet at ~589 nm
- Absorption features lost by around 5 MA (250 T)
- Moving measurement from R = 2.5 to 10 mm
  - 20 MA ~ 250 T

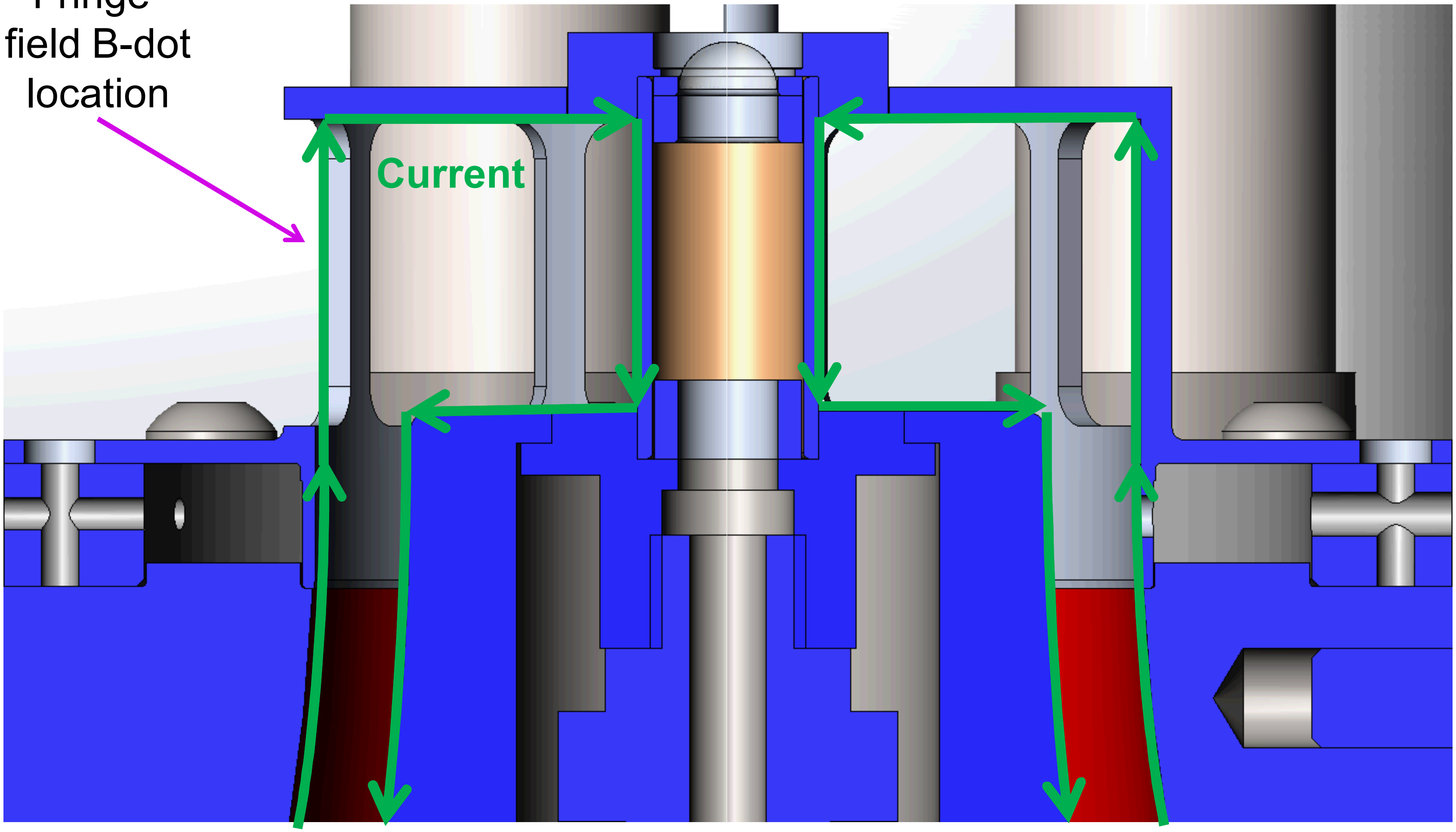
M. R. Gomez et al., Rev. Sci. Instrum. **83**, 11E609 (2014).

New dopant location may allow B-field measurement through peak current



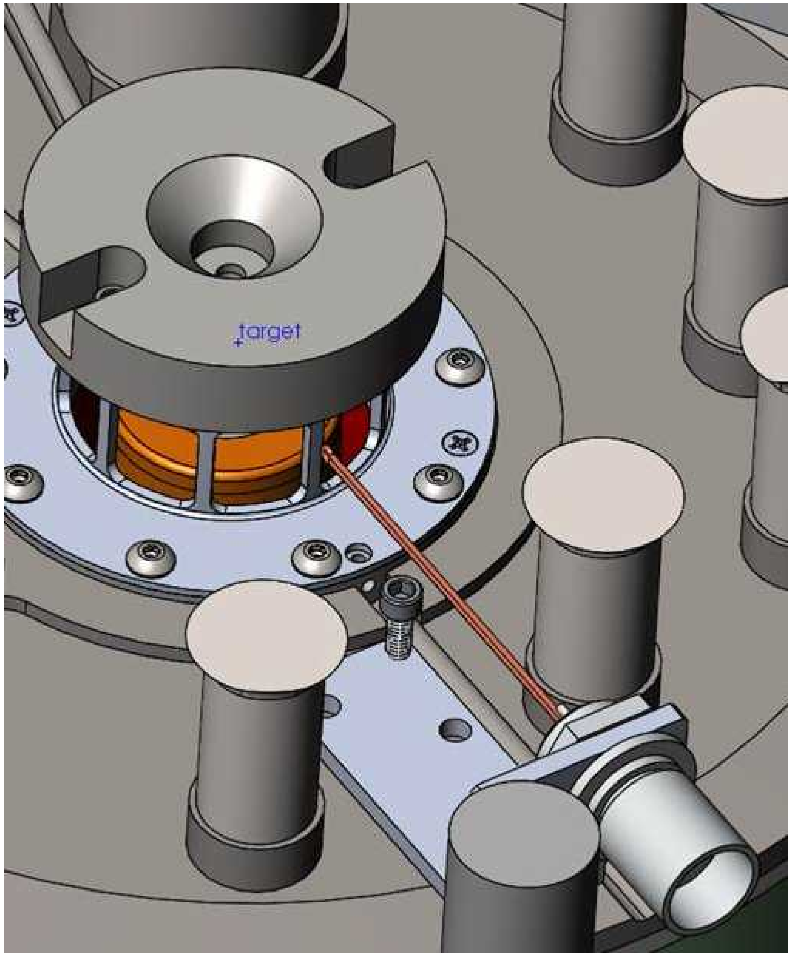
Fringe field B-dots may be difficult to field but provide a true load current measurement

Fringe-field B-dot location



B-dots outside the return can may provide an accurate current pulse shape

- Goal is to monitor the B-field time-history outside the return can
  - Trace can be scaled to match standard B-dots at early times
  - Check against stagnation time to verify
- We will first test these probes in January



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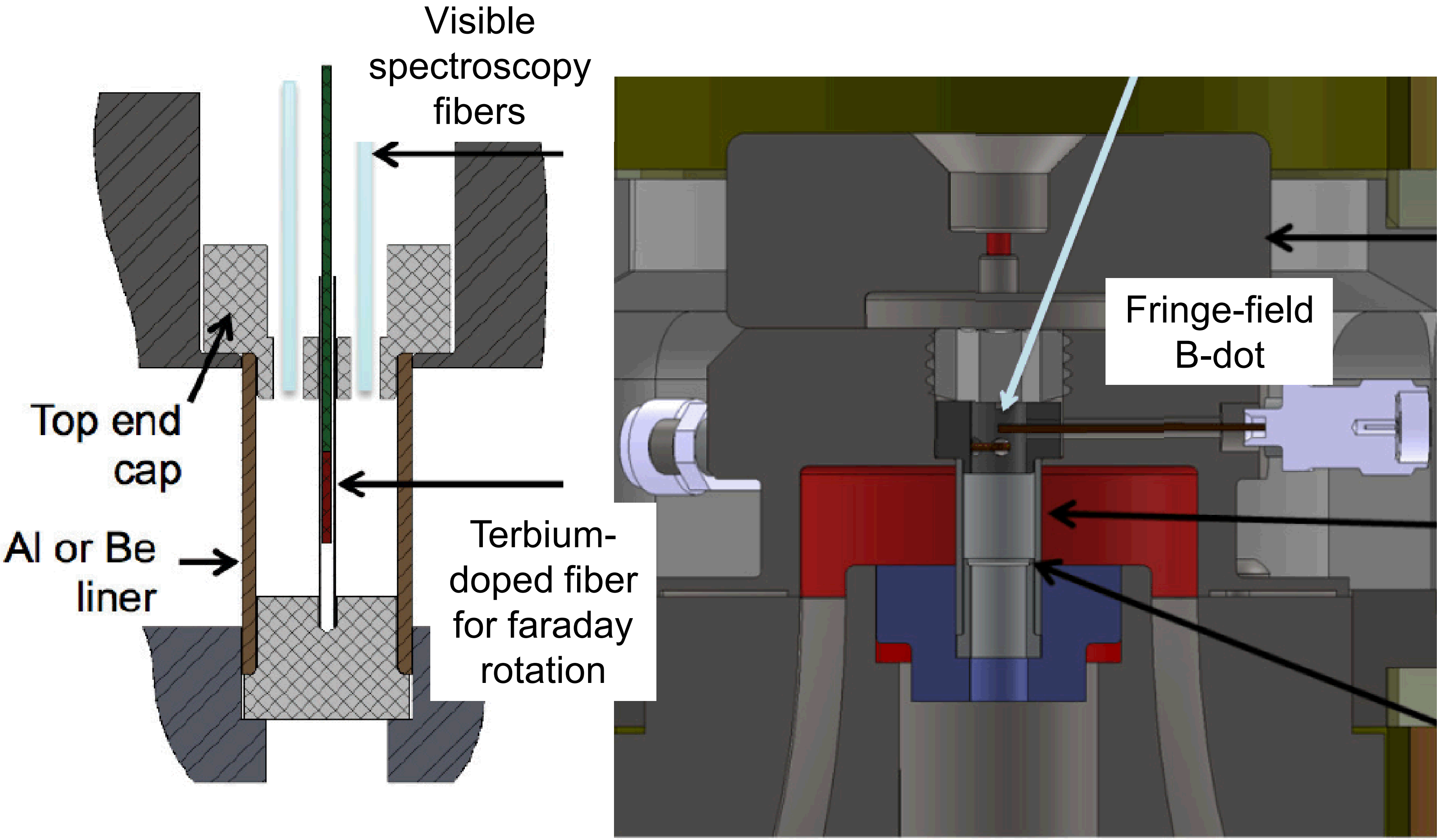
Several techniques have measured vacuum flux compression at early times



Visible spectroscopy fibers

Top end cap

Al or Be liner

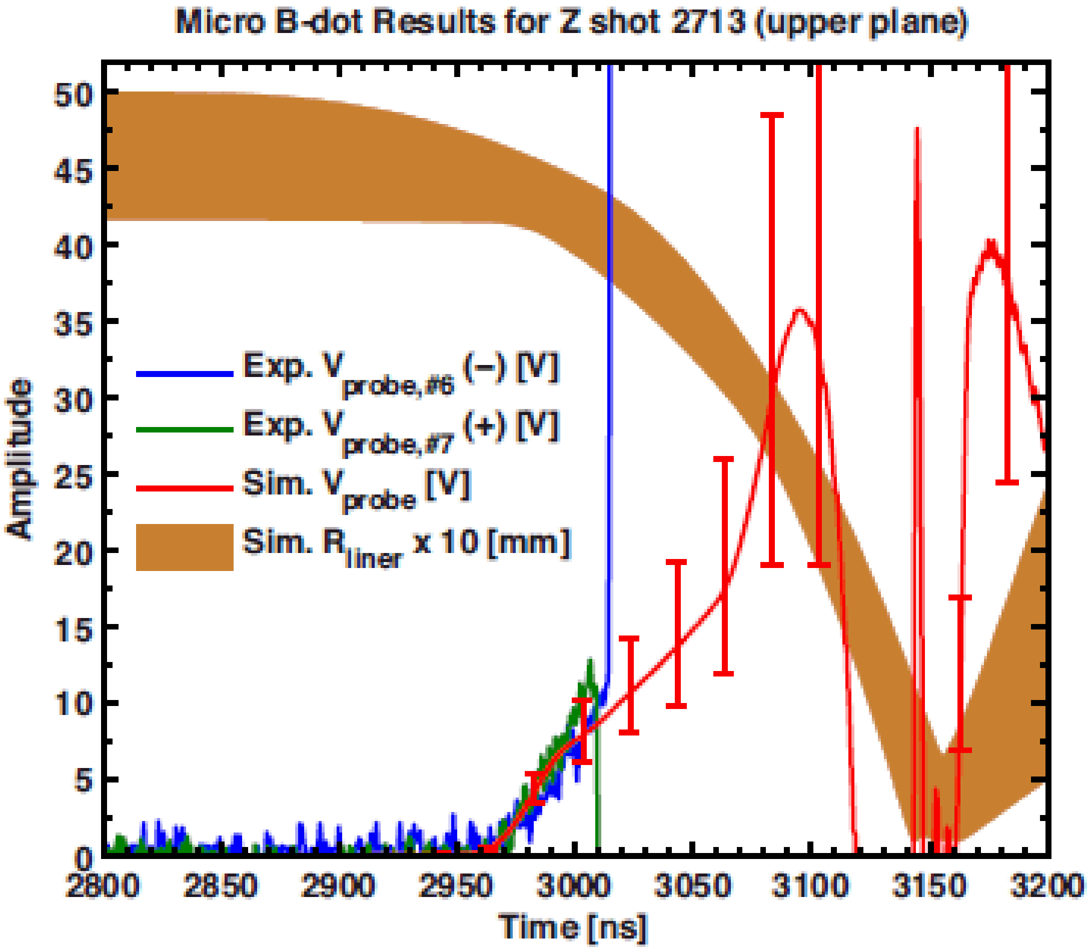
Terbium-doped fiber for faraday rotation

Fringe-field B-dot

R. D. McBride et al., SAND2015-9860 (2015).

We had limited success measuring the fringe field using B-dots

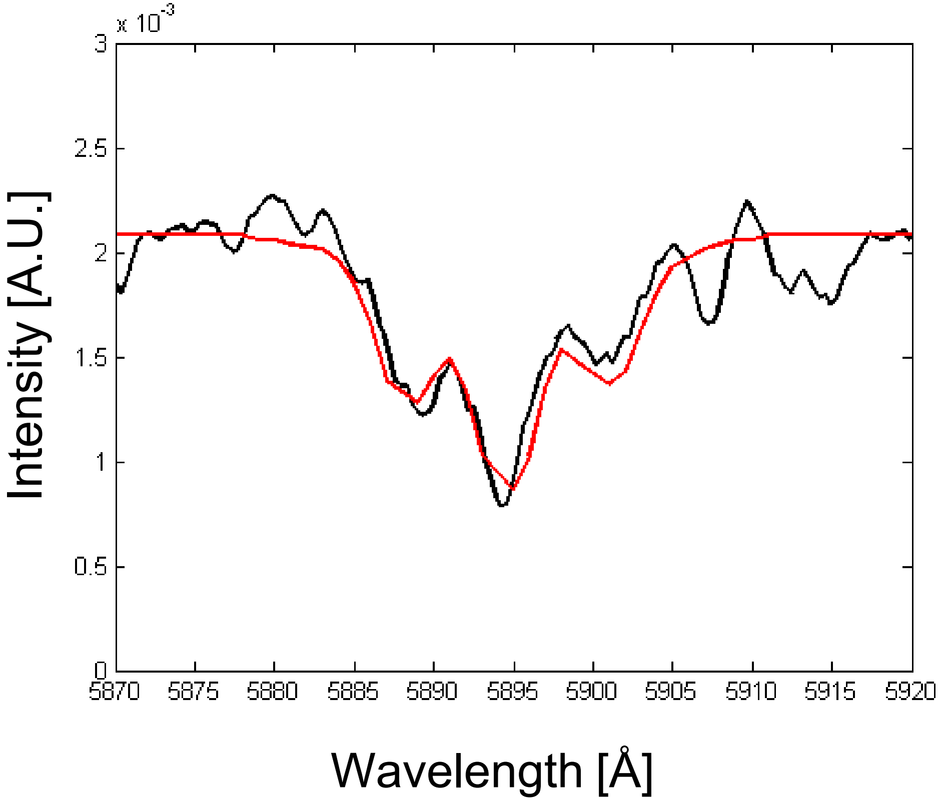
Micro B-dot Results for Z shot 2713 (upper plane)



- Small changes in probe location significantly affect signal amplitude
- Probes fail relatively early in the implosion
- CR = 1.12
- B_z = 12.5 T

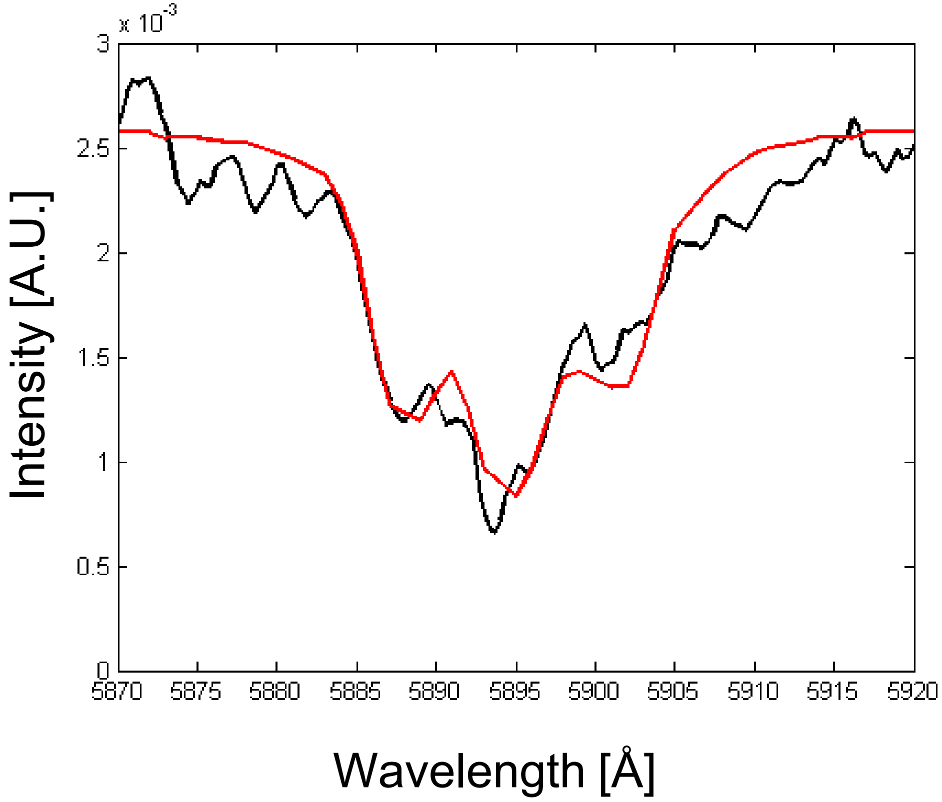
R. D. McBride et al., SAND2015-9860 (2015).

Line splitting briefly worked, but was quickly swamped by line broadening



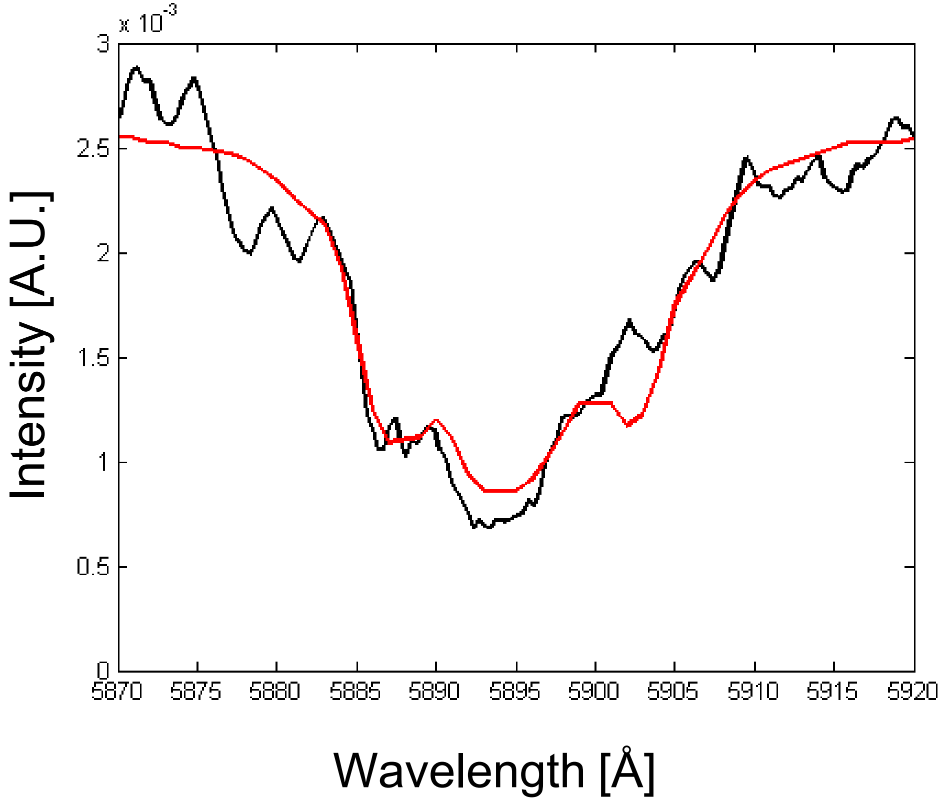
- Time = 3063.5 ns
- Predicted CR = 1.28
- Expected B = 16 T
- Inferred B = 20 T
- Inferred ρ = 1e17/cc

Line splitting briefly worked, but was quickly swamped by line broadening



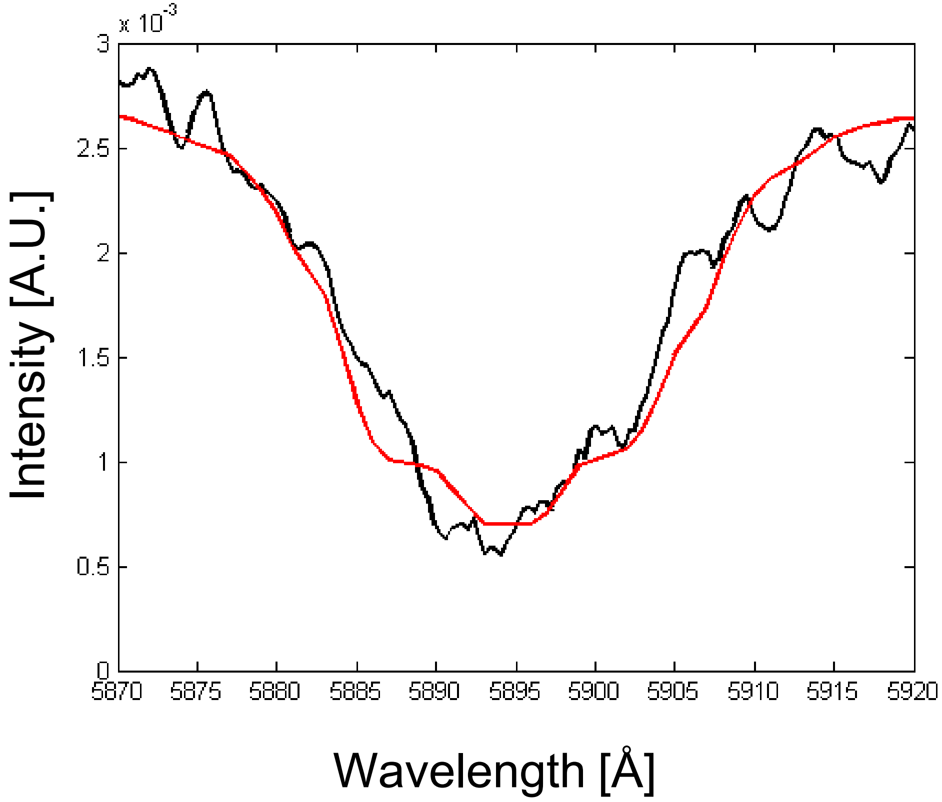
- Time = 3066.0 ns
- Predicted CR = 1.33
- Expected B = 18 T
- Inferred B = 23 T
- Inferred ρ = 3e17/cc

Line splitting briefly worked, but was quickly swamped by line broadening



- Time = 3067.4 ns
- Predicted CR = 1.37
- Expected B = 19 T
- Inferred B = 25 T
- Inferred ρ = 6e17/cc

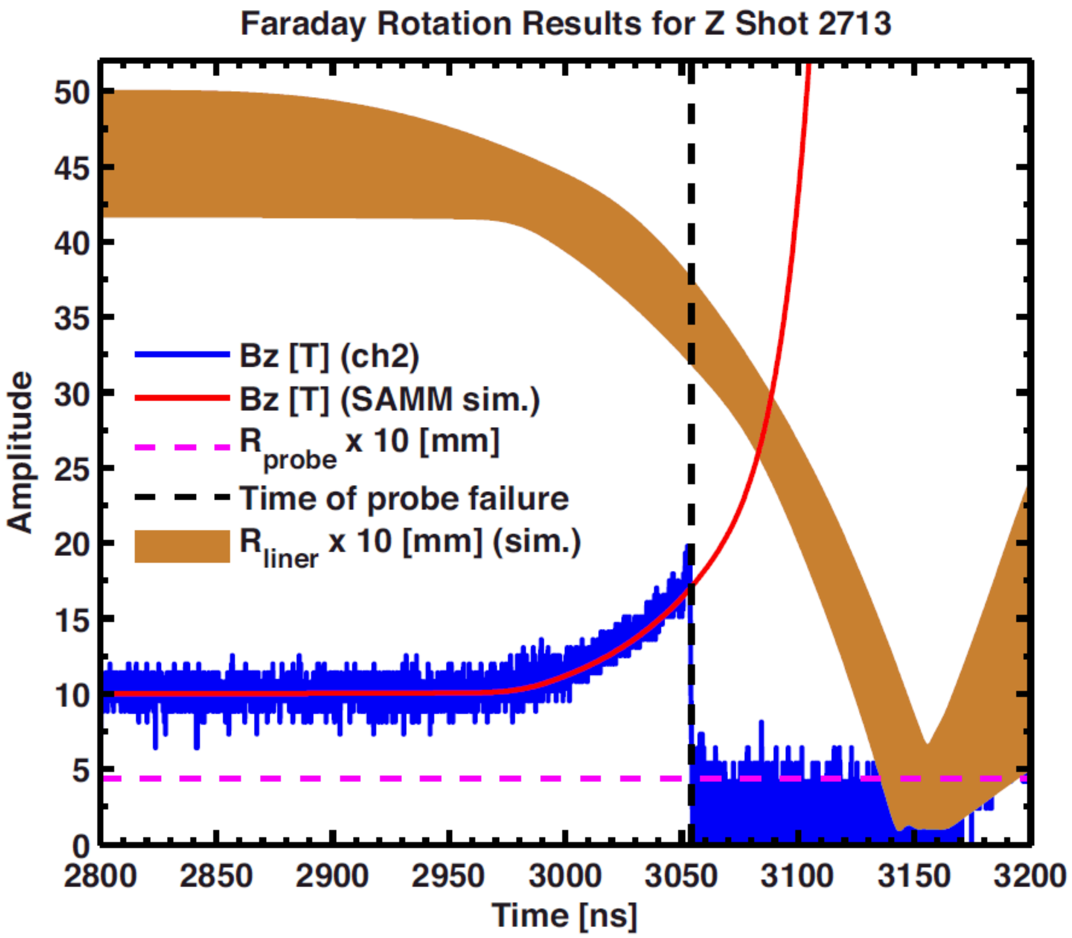
Line splitting briefly worked, but was quickly swamped by line broadening



- Time = 3068.7 ns
- Predicted CR = 1.41
- Expected B = 20 T
- Inferred B = 30 T
- Inferred ρ = 1.5e18/cc

Faraday rotation shows promise for a moderate convergence measurement

- Continuous measure of B field
- Probe fails at roughly CR = 1.3
- We believe we understand cause of failure and have a way to resolve it
- Possible to measure to CR ~ 10



R. D. McBride et al., SAND2015-9860 (2015).

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The MagLIF experiments utilize deuterium gas as the fusion fuel

- Primary reactions

D + D → He3 + n 2.45 MeV 50%

D + D → P + T 1.01 MeV 50%

- Secondary reactions

D + T → He4 + n 14.1 MeV (11-17 MeV)

- Quantity and spectrum of secondary reactions gives us some insight into the fuel conditions at stagnation[*]

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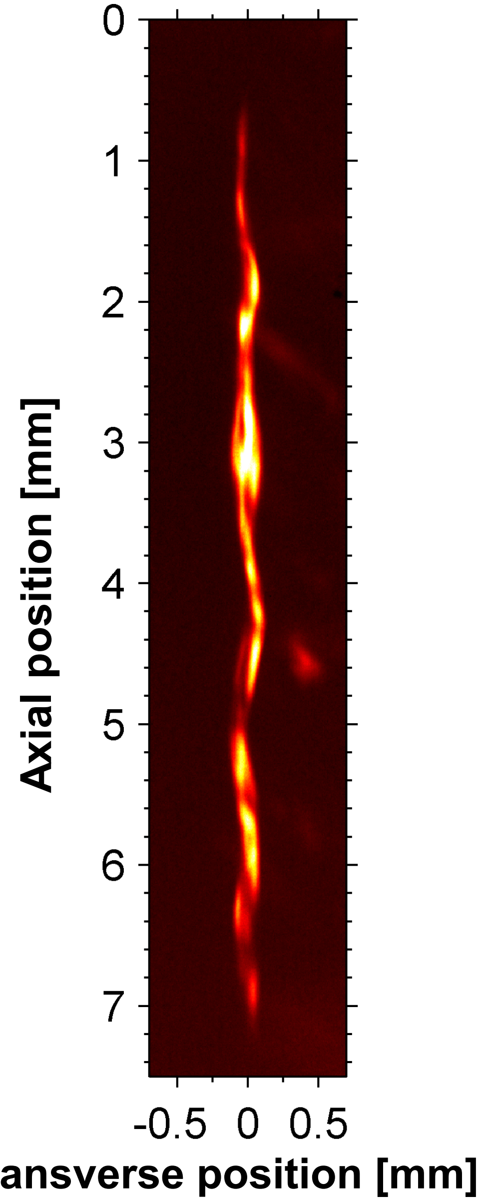
[*] M. D. Cable and S. P. Hatchett, J. Appl. Phys. 62, 2233 (1987).

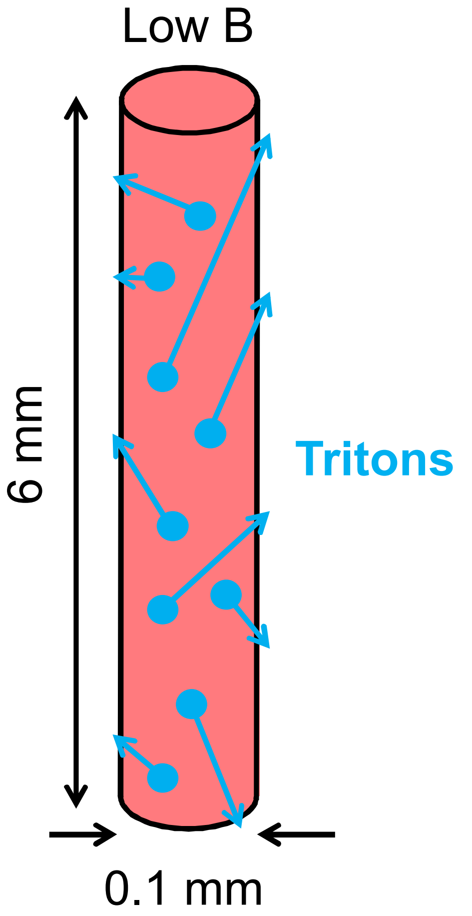
X-ray emission at stagnation indicates a high aspect ratio (h/r) column

- Emission region does not define the fuel-liner boundary
  - defines the hottest region of the fuel
- Emission FWHM is 50-110 µm
- Emission height is approximately 80% of target height



M. R. Gomez et al., Phys. Rev. Lett. 113, 155003 (2014).

Magnetic flux compression demonstrated through secondary neutron yield and spectra



$\rho R \sim 2$ mg/cm^2
$\rho Z \sim 200$ mg/cm^2

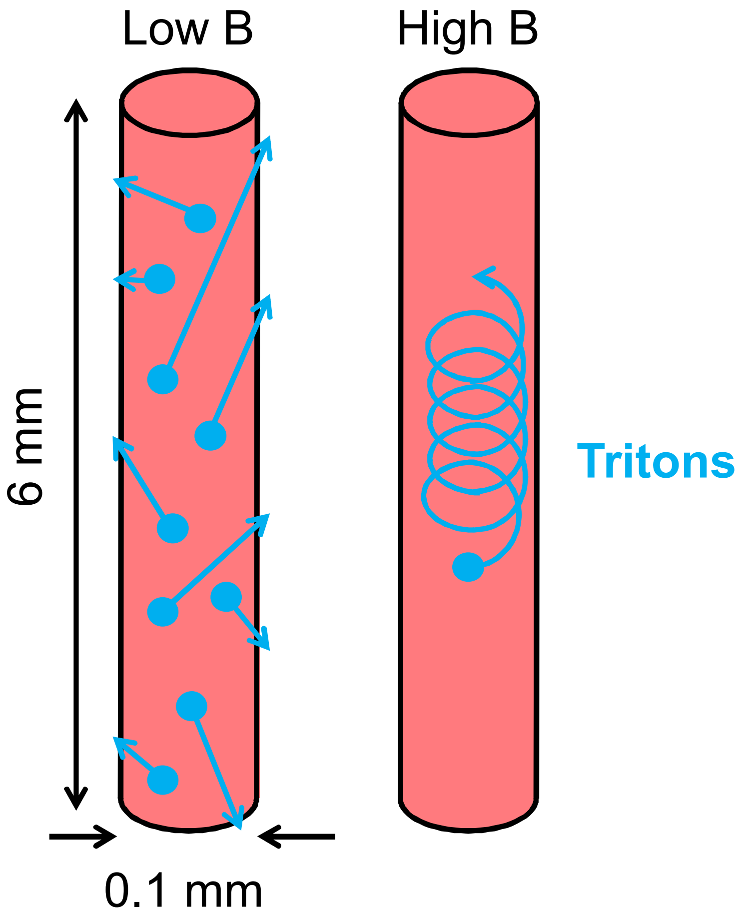
In a high aspect ratio cylinder the effective areal density of the fuel is approximately the radial areal density

For $\rho R \sim 2$ mg/cm^2

DD/DT yield ratio > 1000

P. F. Schmit, et al., Phys. Rev. Lett. **113**, 155004 (2014). P. F. Knapp, et al., Phys. Plasmas **22**, 056312 (2015).

Magnetic flux compression demonstrated through secondary neutron yield and spectra



$\rho R \sim 2$ mg/cm^2
$\rho Z \sim 200$ mg/cm^2

In a highly magnetized cylinder the effective areal density of the fuel becomes much larger because the tritons cannot escape radially.

$\rho R \Rightarrow \rho Z \sim 200$ mg/cm^2

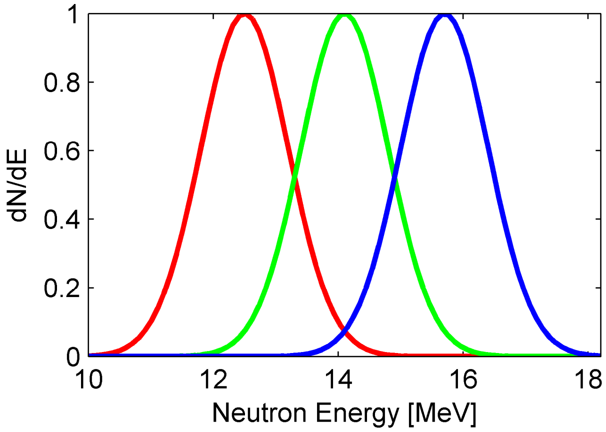
DD/DT yield ratio < 100

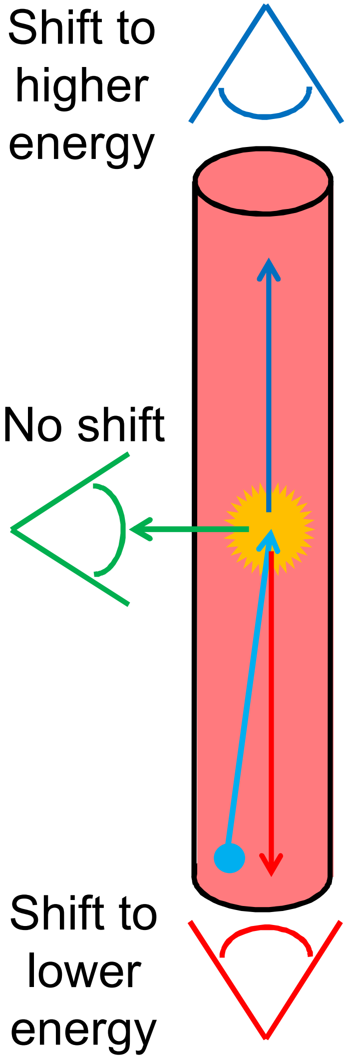
We observed DT yields as high as 5e10
DD/DT ~ 50-100

P. F. Schmit, et al., Phys. Rev. Lett. **113**, 155004 (2014). P. F. Knapp, et al., Phys. Plasmas **22**, 056312 (2015).

DT NTOF spectrum can also be used to infer magnetization at stagnation

For low B
DT reactions primarily
occur for tritons traveling
along the Z axis

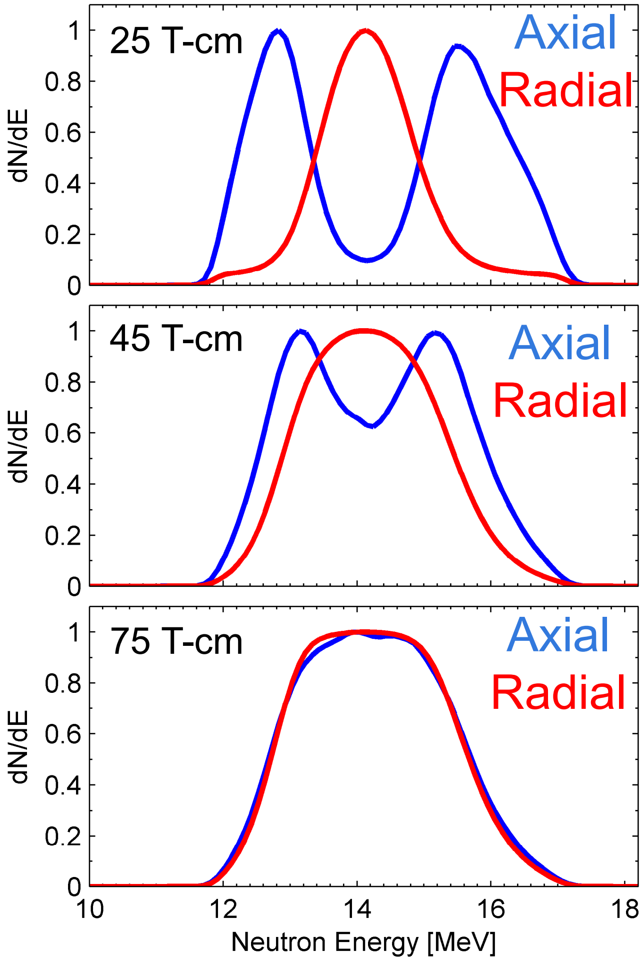




Shift to higher energy

No shift

Shift to lower energy

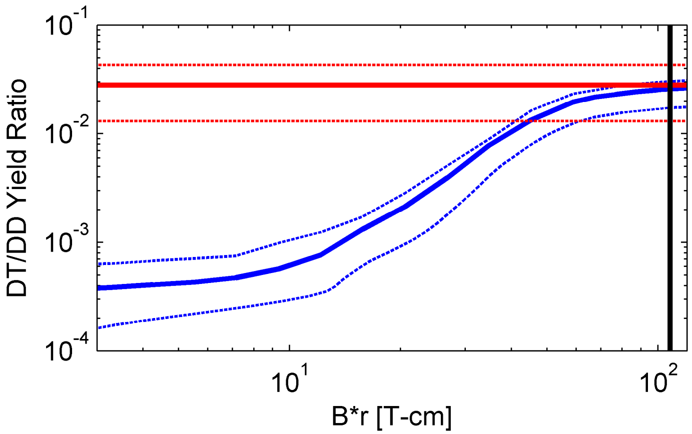


P. F. Schmit, et al., Phys. Rev. Lett. **113**, 155004 (2014). P. F. Knapp, et al., Phys. Plasmas **22**, 056312 (2015).

Yield ratio and secondary neutron spectra indicate magnetic flux compression in MagLIF

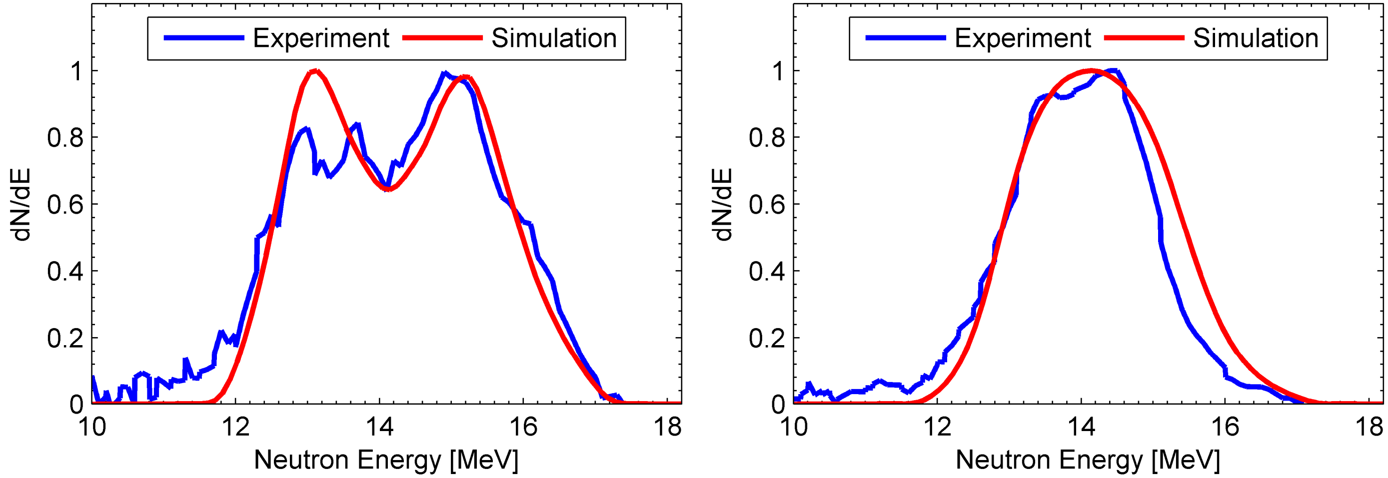
Measured

Calculated



Y_{DT}/Y_{DD} is consistent with
BR ≈ 30-40 T-cm

For ideal flux compression and 0.1 mm diameter at stagnation BR_{max} = 108 T-cm



NTOF spectra are
consistent with
BR ≈ 30-40 T-cm

P. F. Schmit, et al., Phys. Rev. Lett. **113**, 155004 (2014). P. F. Knapp, et al., Phys. Plasmas **22**, 056312 (2015).

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Interesting areas for future measurements

- Outside the liner
  - High fidelity measurements of the current near the load
  - Magnetic field measurements at the liner surface
    - Orientation
    - Spatial distribution
- Inside the liner
  - Vacuum flux compression at high convergence
  - Magnetic field in the fuel from T_{laser} until $T_{stagnation}$
  - Spatially-resolved magnetic field at stagnation