Direct Measurement of Magnetic Flux Compression on the Z Pulsed-Power Accelerator

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The Magnetized Liner Inertial Fusion (MagLIF)* concept seeks to reduce requirements on implosion velocity and pressure by using a magnetic field.

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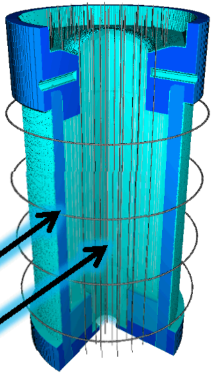
1. A 10–50 T axial magnetic field is applied (~3-ms rise time) to inhibit thermal conduction losses and to enhance alpha particle deposition.

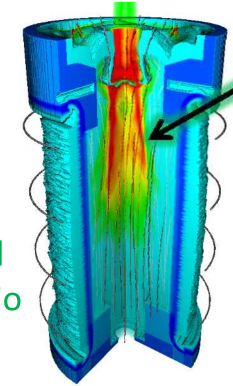
Liner (Li, Be, or Al)

Cold DD or DT gas (fuel)



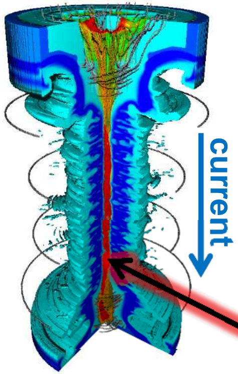
The magnetic field helps to:

- Thermally insulate hot fuel from a cold pusher
- Increase confinement of hot fusion products
- Possibly stabilize the liner implosion



ZBL preheated fuel

2. ZBL preheats the fuel to ~100–250 eV, reducing the required final convergence ratio to CR 20–30.

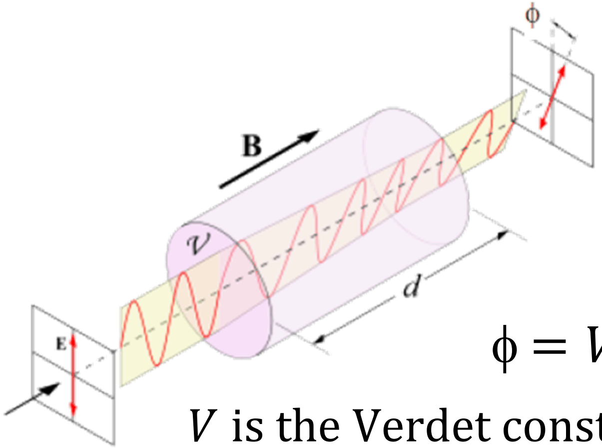


3. The Z-pinch drive current implodes the liner at 50–100 km/s, compressing the fuel and Bz field by factors of 1000.

Compressed B_z

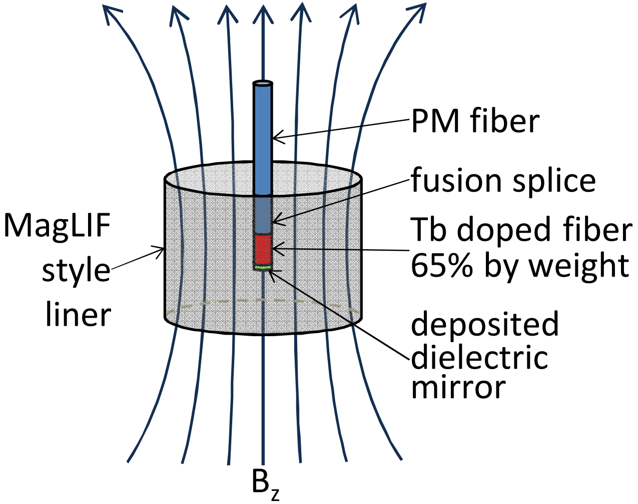
Flux compression is a critical component of MagLIF, required to confine hot fusion products, B·r = 0.5 T·m

We used a terbium-doped fiber as the magneto-sensitive element of the probe



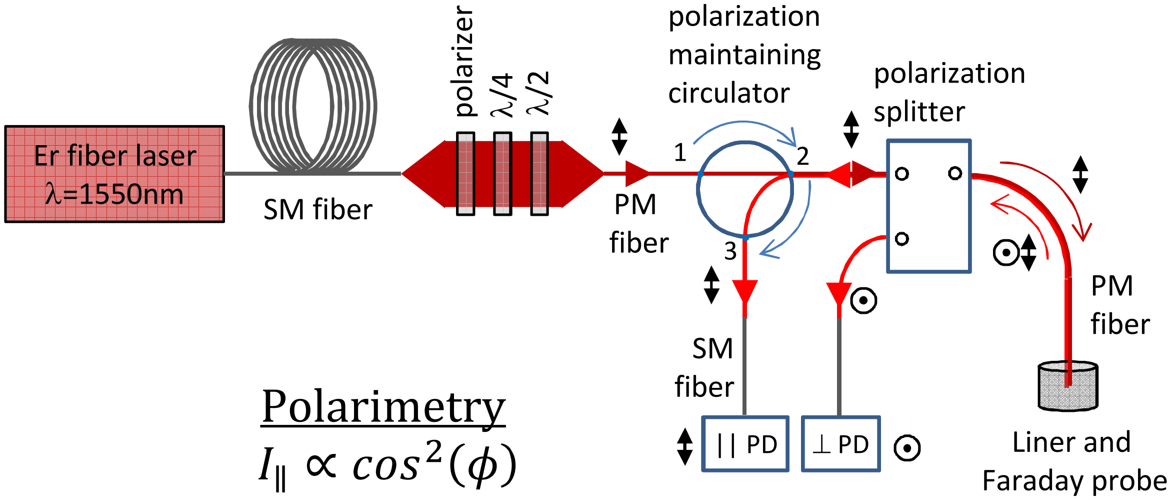
$$\phi = VBd$$

V is the Verdet constant



- The Verdet Constant of our 65% Tb fiber (by weight) at λ = 1550 nm is -8.2 rad/T/m
- All Tb-doped fiber probes were calibrated at Sandia’s Systems Integration Test Facility
- Overall Calibration of all probes: 20±1 T/radian

The Faraday system on Z utilizes commercial off-the-shelf fiber optics components from optical communication industry



Polarimetry

$$I_{\parallel} \propto cos^2(\phi)$$

$$I_{\perp} \propto sin^2(\phi)$$

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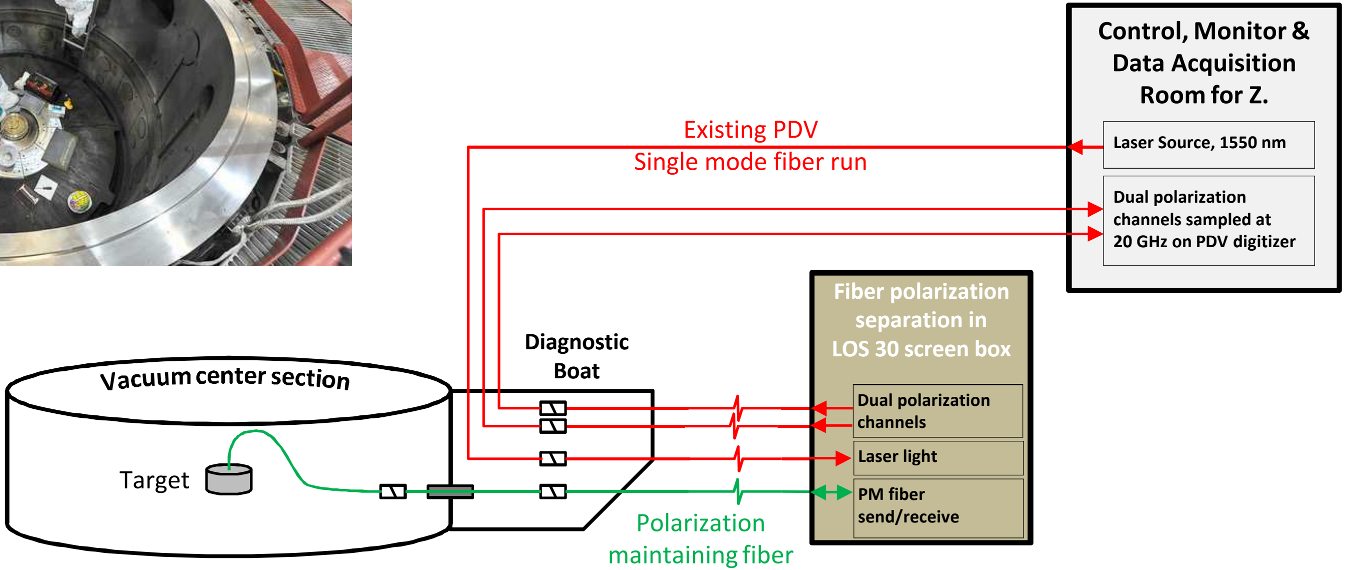
The Faraday rotation diagnostic uses existing infrastructure (PDV) combined with new polarization maintaining fiber components



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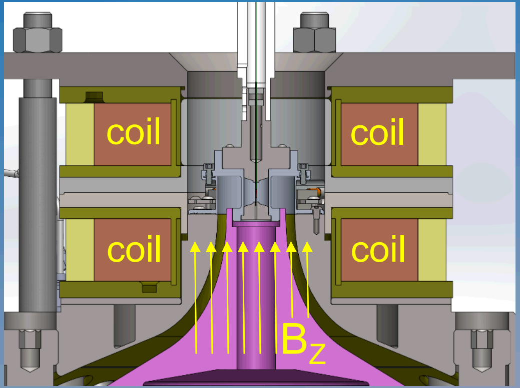
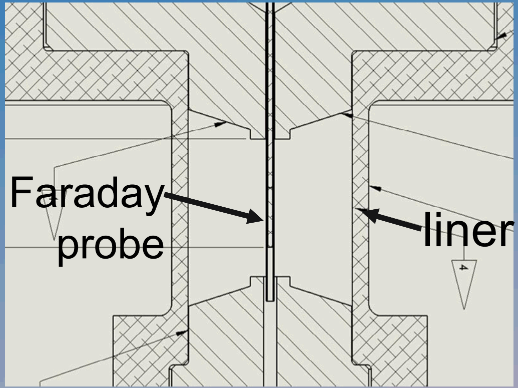
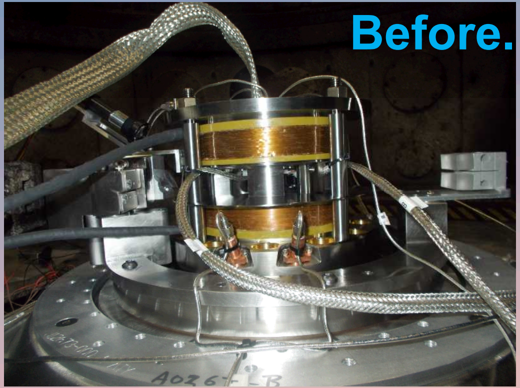
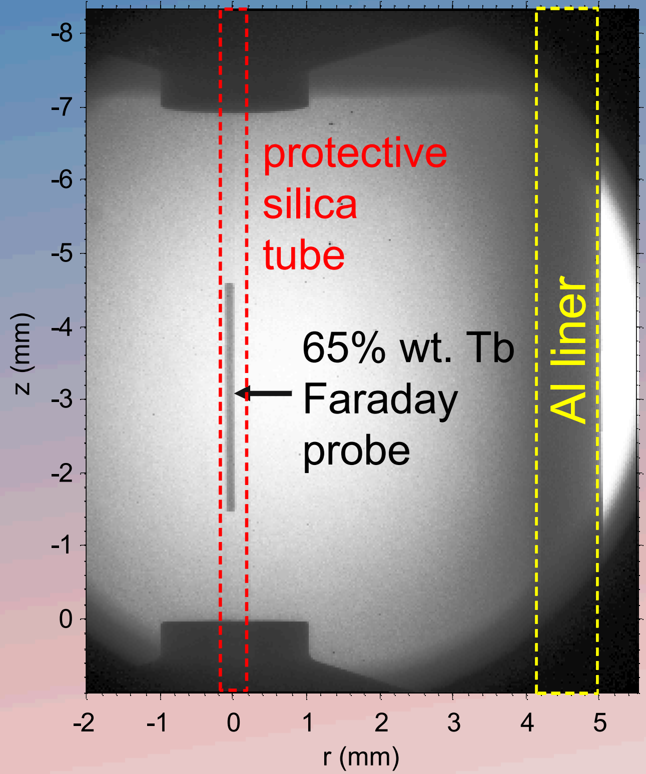
Images and drawings of the load hardware shows configuration of the applied B_Z coil pair, imploding liner, and Faraday probe.



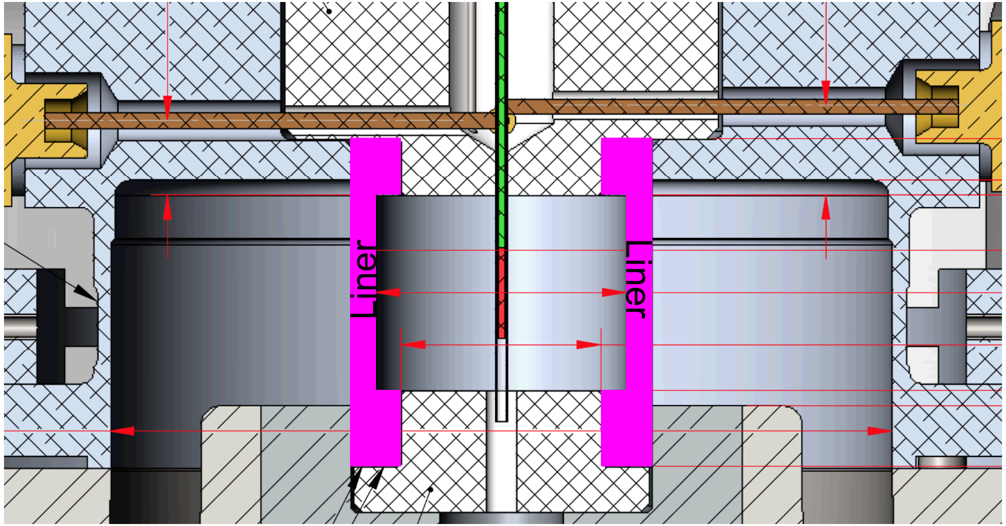


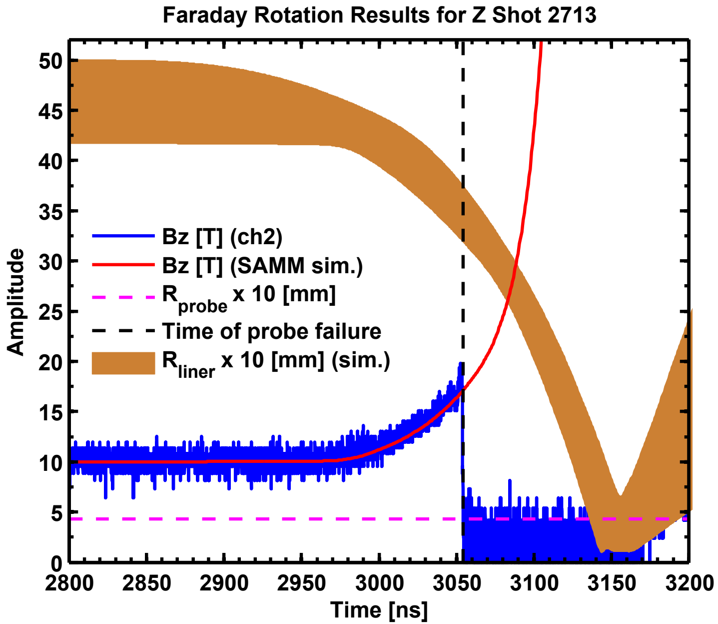




Lessons Learned: Premature failures with a previous target design were initially a mystery

Faraday probe failed ~60 ns into implosion





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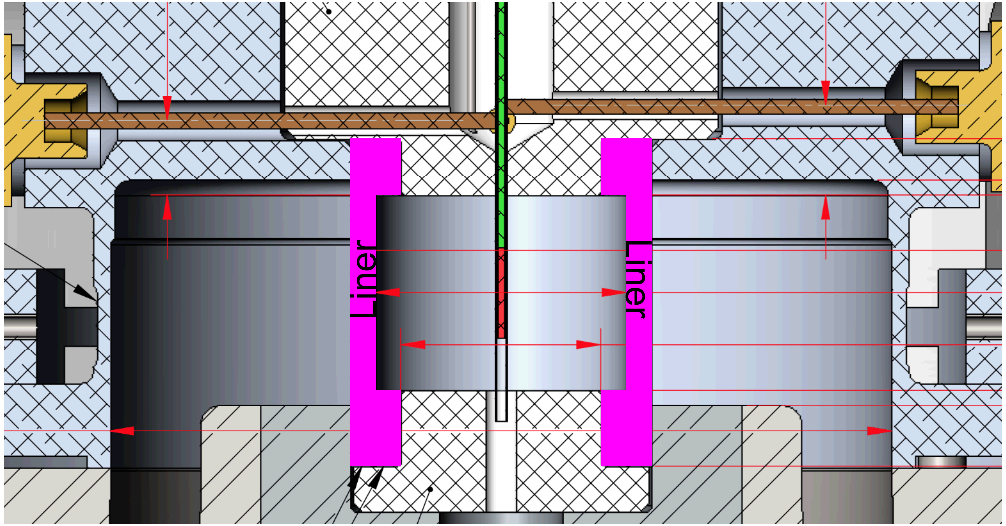
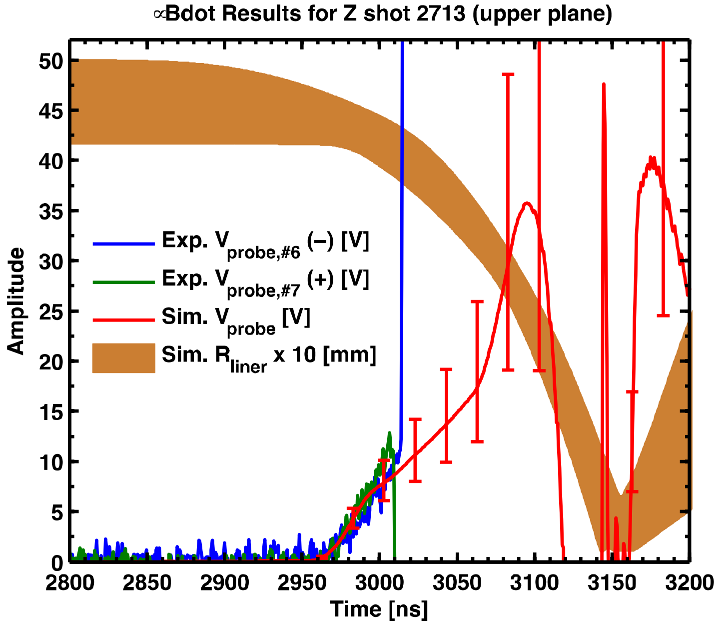


…but micro B-dot probes failed even earlier, roughly 40 ns into implosion



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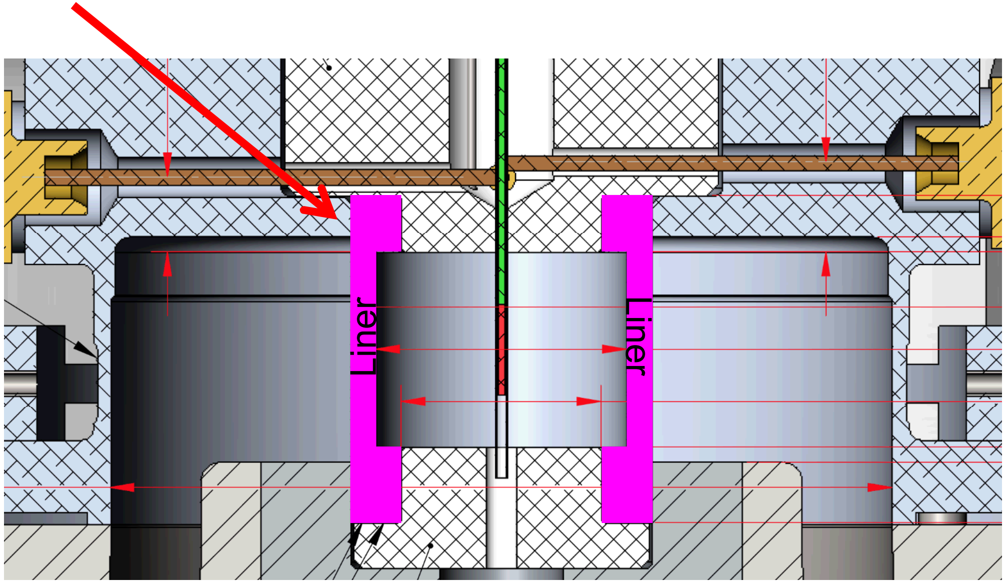
Lessons Learned – Premature failures with a previous target design led to new hypothesis:

- The 100-micron tolerance gap between liner body and upper electrode likely allowed magnetic field to propagate up into the dielectric end-cap
  - This first crushed the micro B-dot cable
  - The field then propagated down the micro B-dot feed-through channel, crushing the Faraday fiber at a slightly later time



Lessons Learned: New target design now successfully tested

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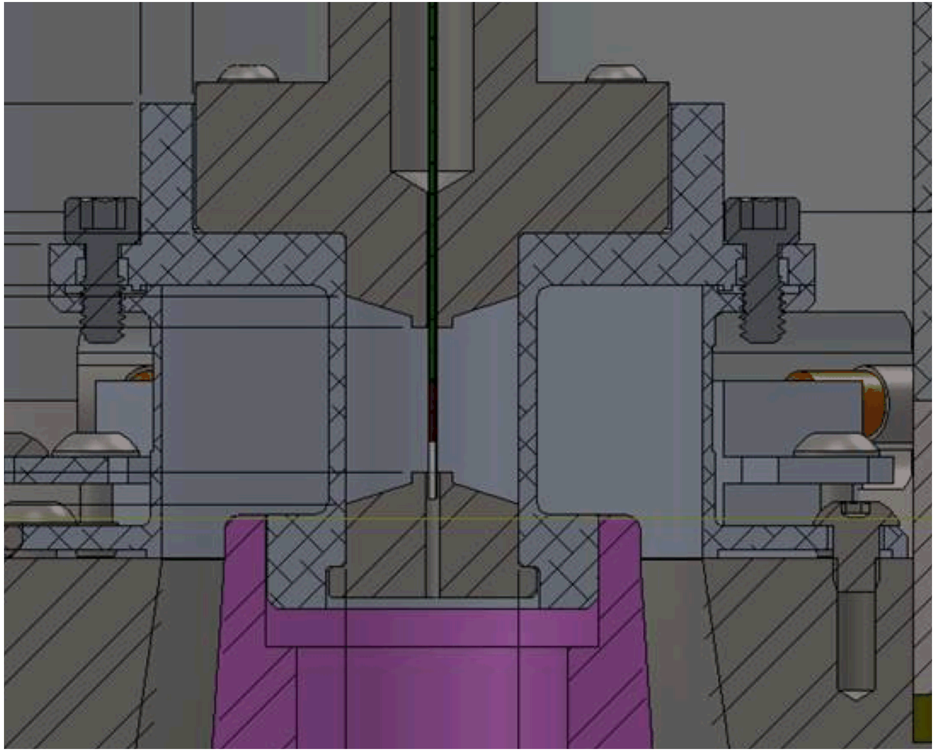
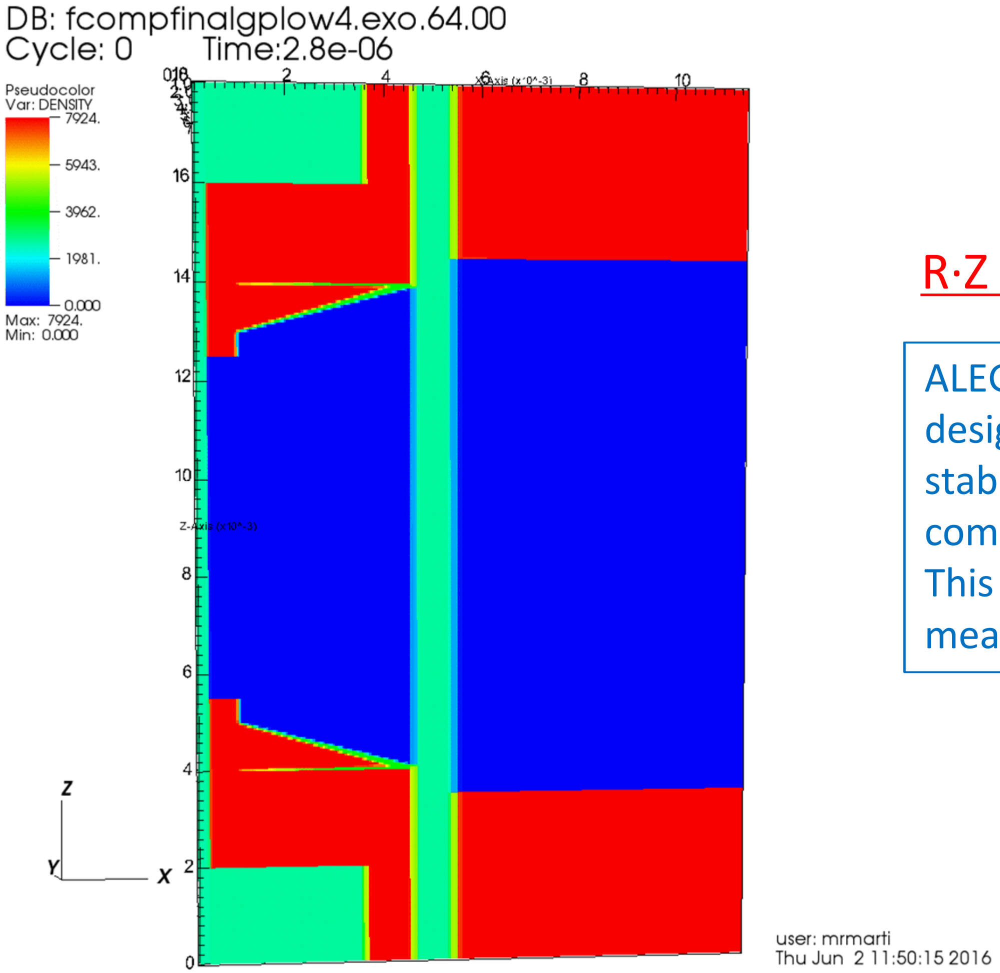
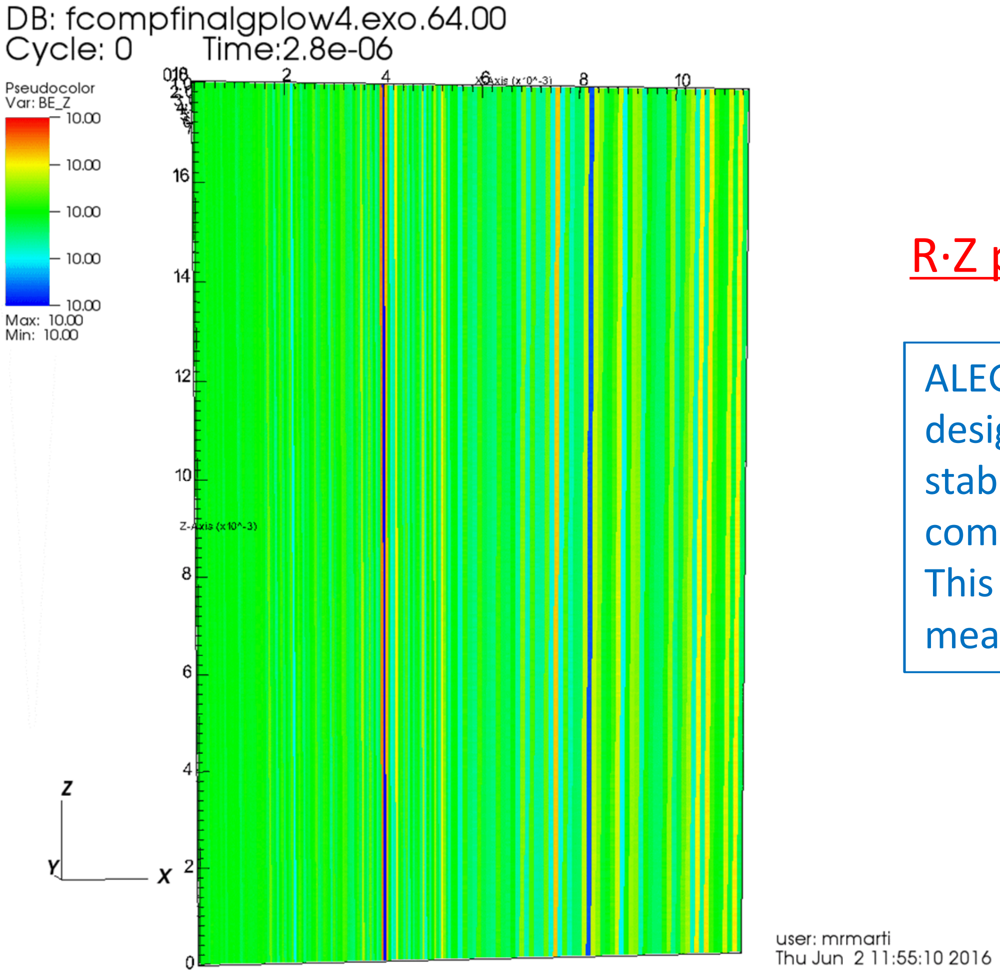
- **Monolithic liner-electrode design ("dumbbell" design)**
- **Angled stainless steel glide planes for reinforced stability**
- **Faraday probe only (i.e., no micro B-dots)**





R·Z plot of density versus time

ALEGRA-2D simulations used to design an Al liner that implodes in a stable 1D manner and remains in a compressed solid state until impact. This simulation is run with the measured load current from Z2882.



R·Z plot of B_Z versus time

ALEGRA-2D simulations used to design an Al liner that implodes in a stable 1D manner and remains in a compressed solid state until impact. This simulation is run with the measured load current from Z2882.

SAMM* 1D calculation of the liner's inner surface trajectory, magnetic field, and Faraday signal for Z2883

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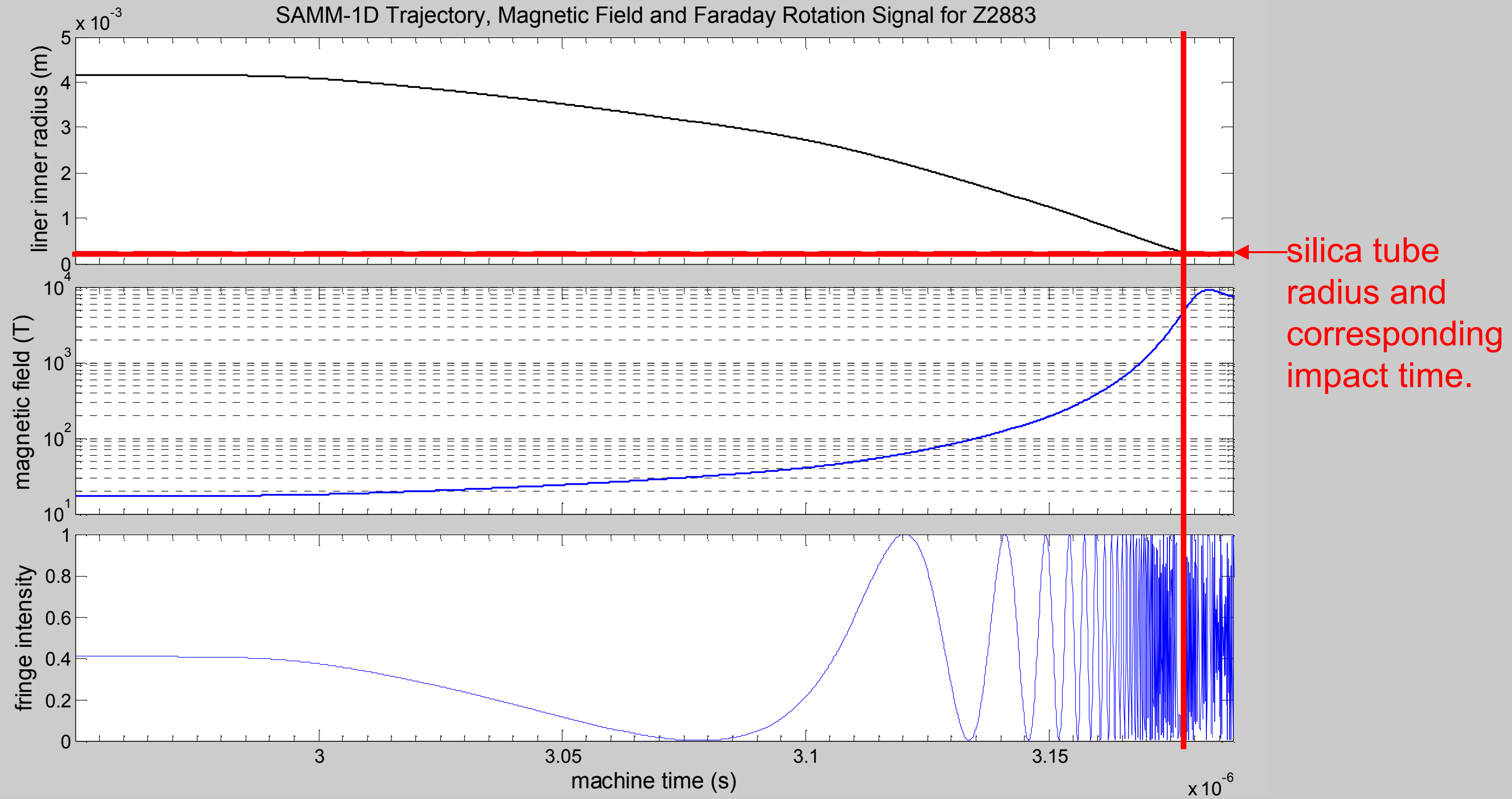
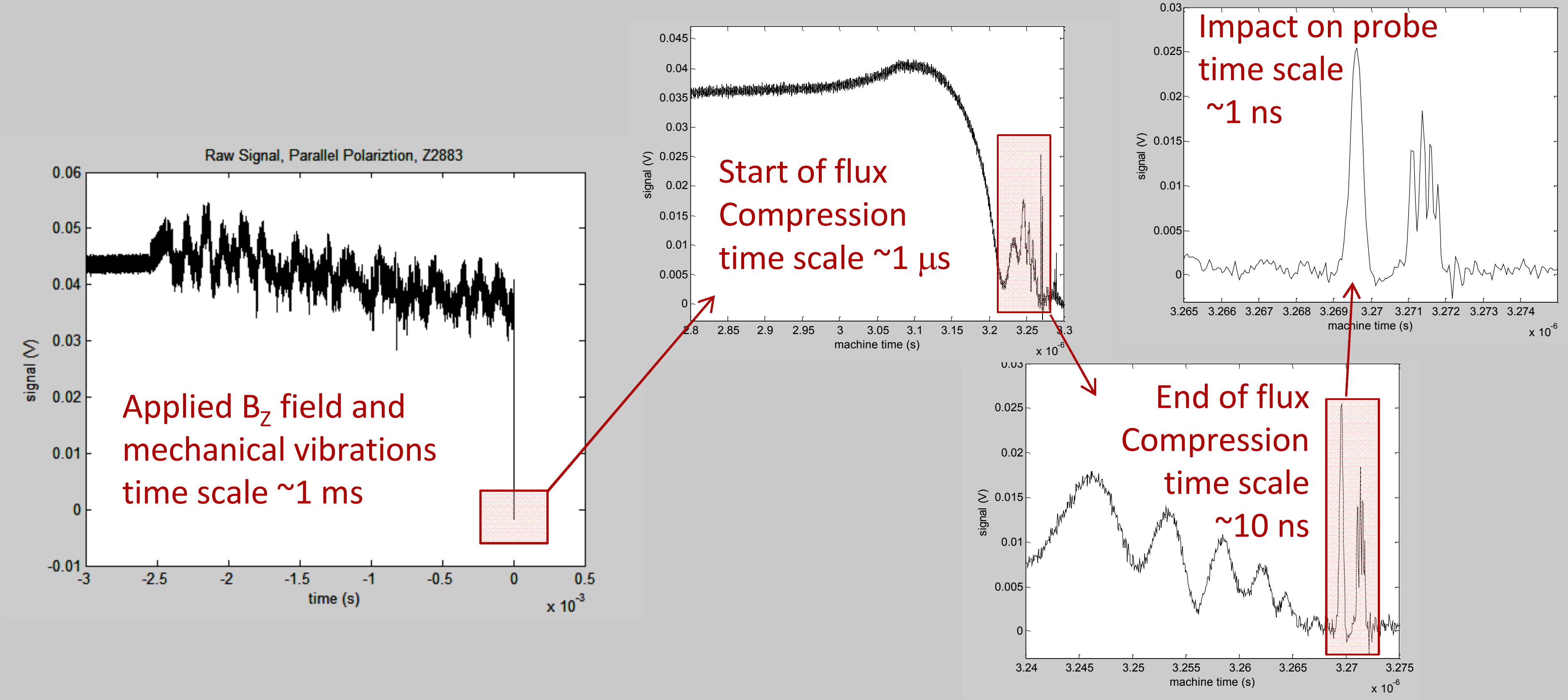
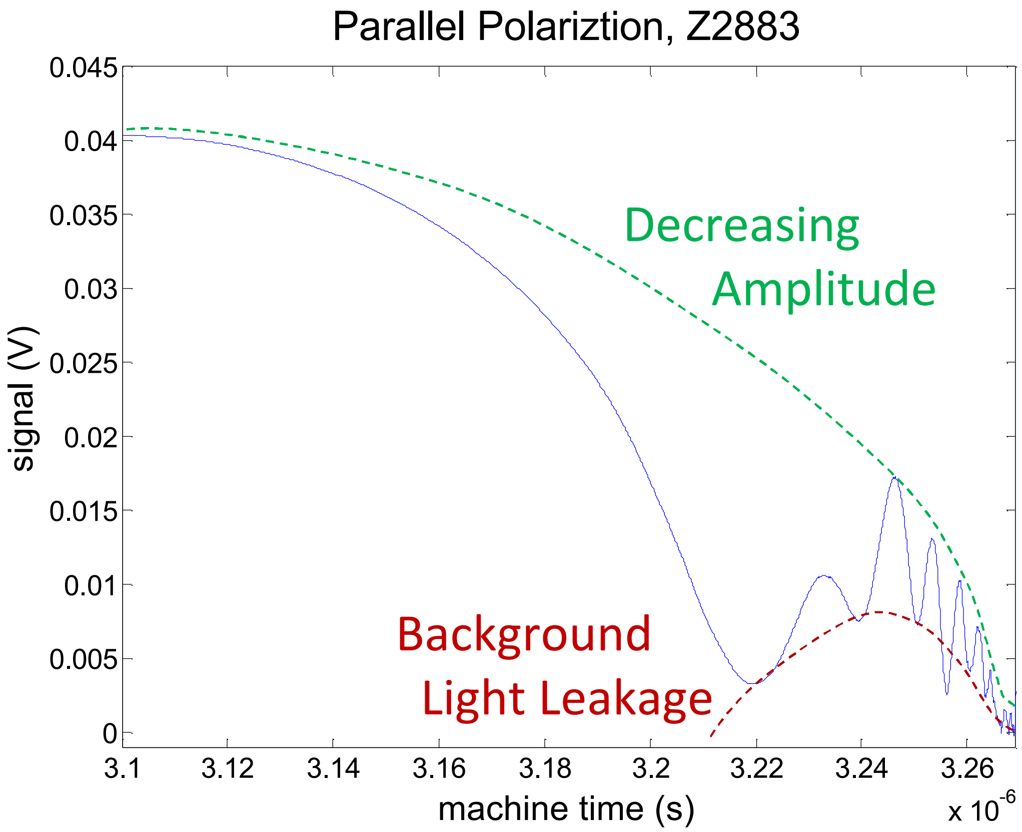


The Faraday channels are digitized at 20 GHz over a 10 ms window to record the entire applied B_Z (17.2 T) pulse and ensuing flux compression.



The filtered Faraday rotation signal shows oscillations of increasing frequency, decreasing amplitude and a varying background offset



Shift and scale oscillations between each peak and valley to create a signal that varies from 0 to 1 to get polarization rotation angles

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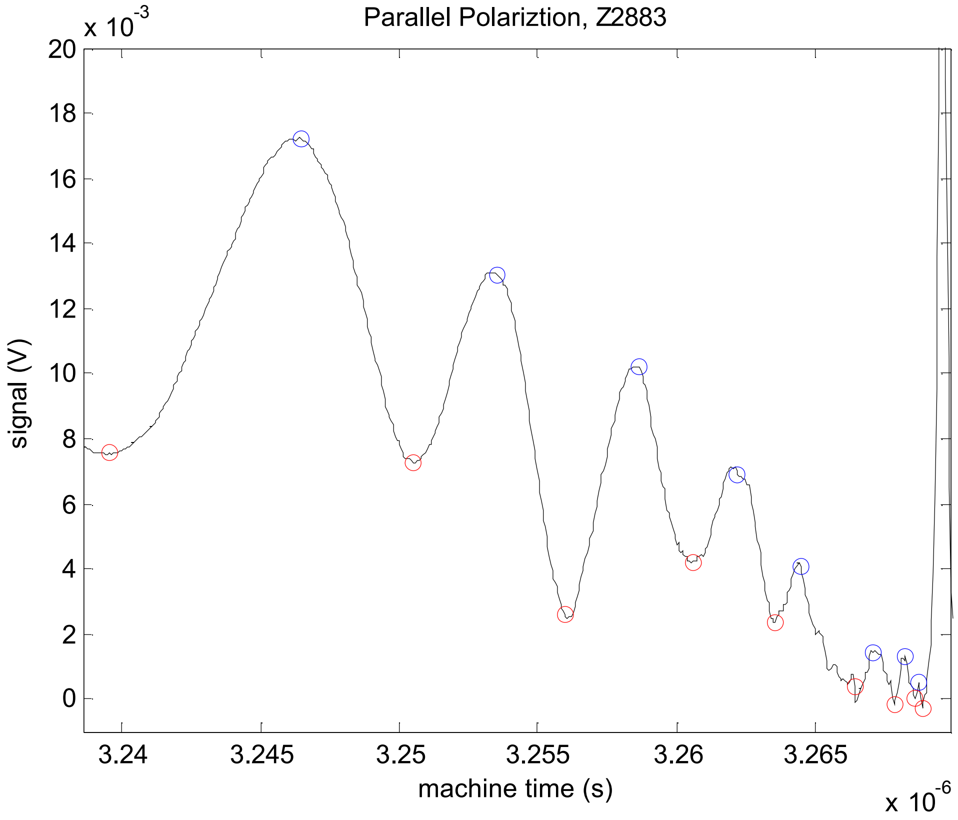
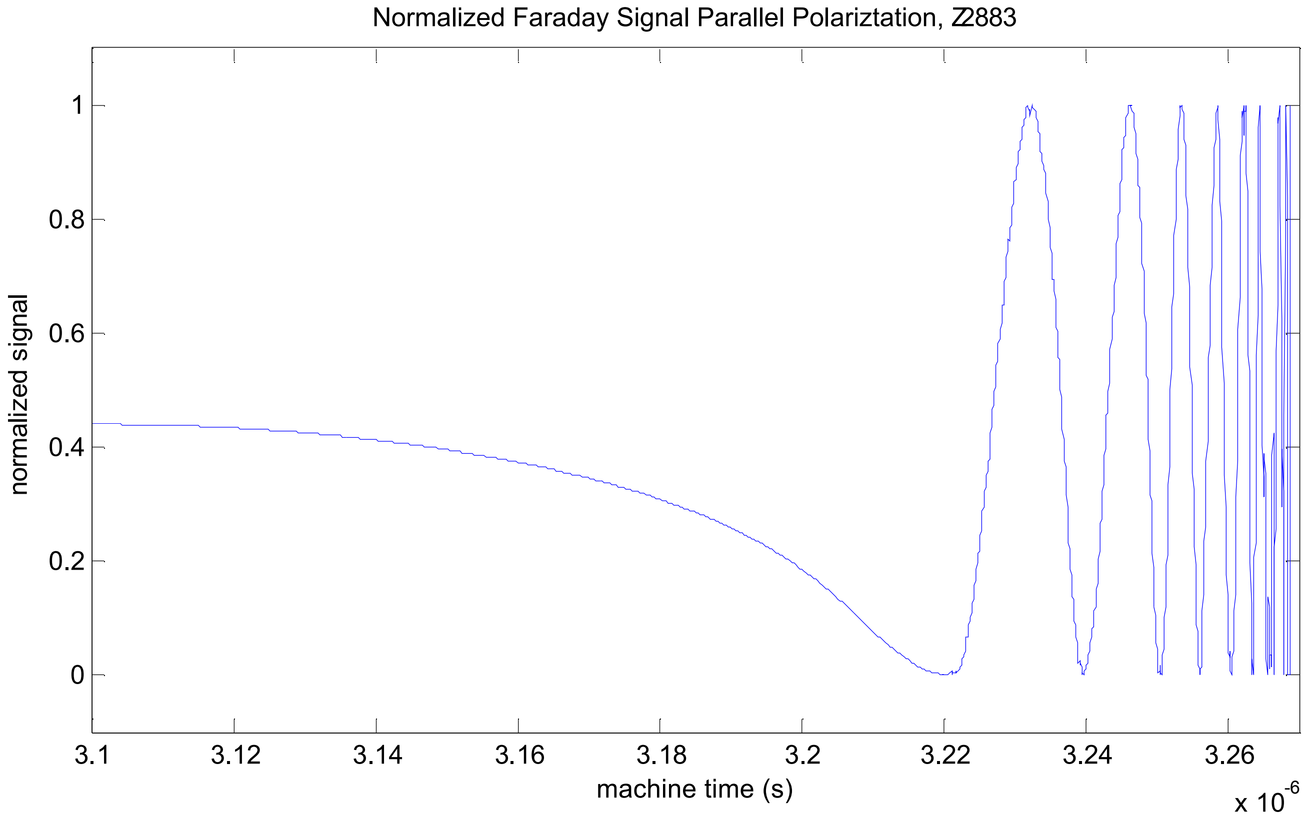
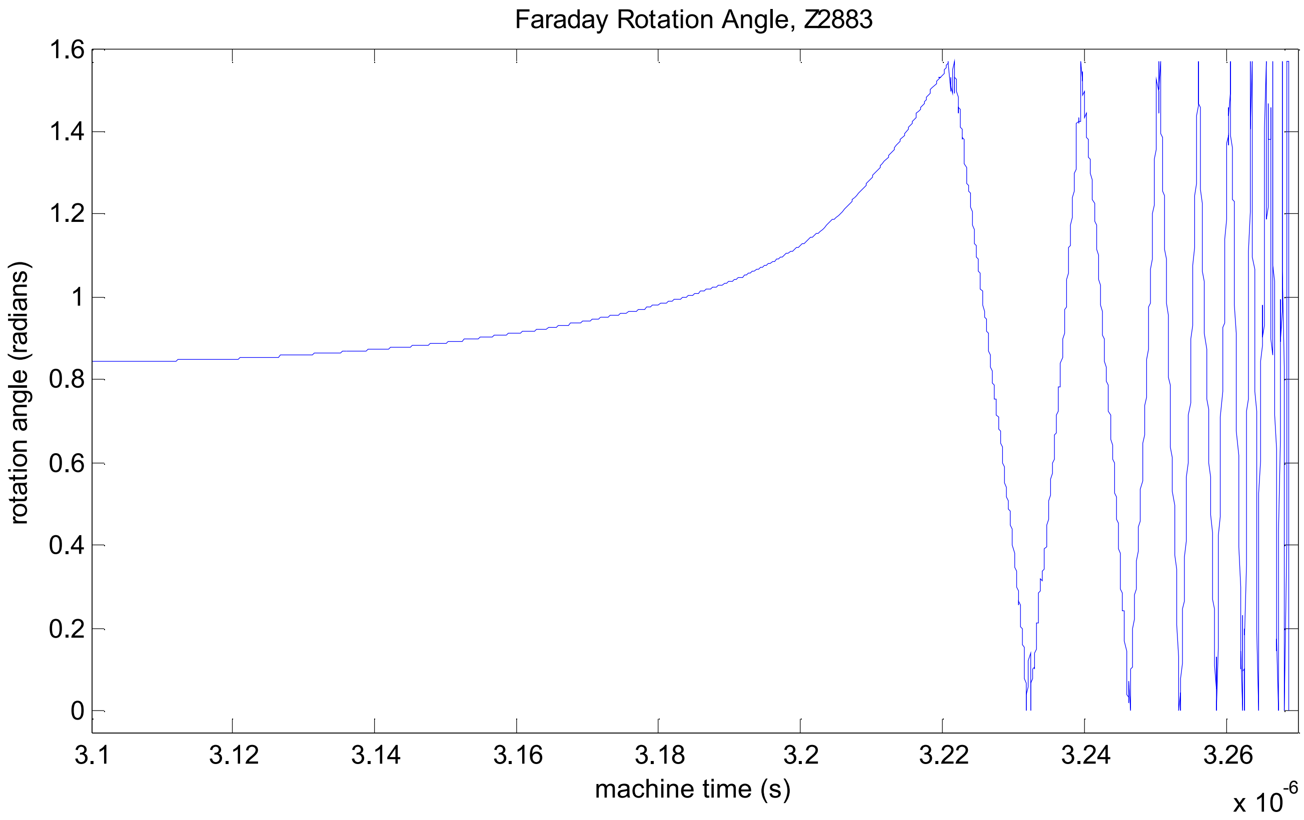


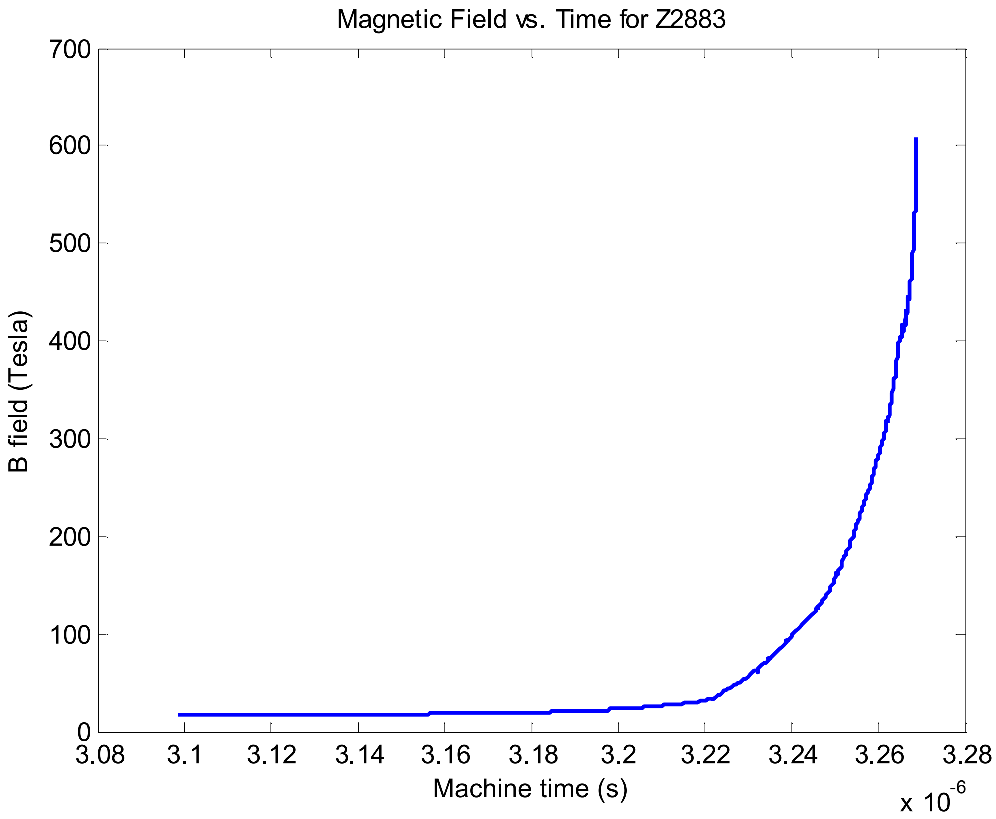
Normalized Faraday signal, V_f after shifting and scaling



Reduced rotation angle: $\varphi = \cos^{-1}\left(\sqrt{V_f}\right)$, $0 > \phi > \pi/2$



The unfolded rotation angle multiplied by the probe calibration factor (20.3 T/radian) gives time dependent magnetic field



Comparison of Z2883 Faraday Rotation measurements to SAMM-1D code shows good overall agreement but contains extra features

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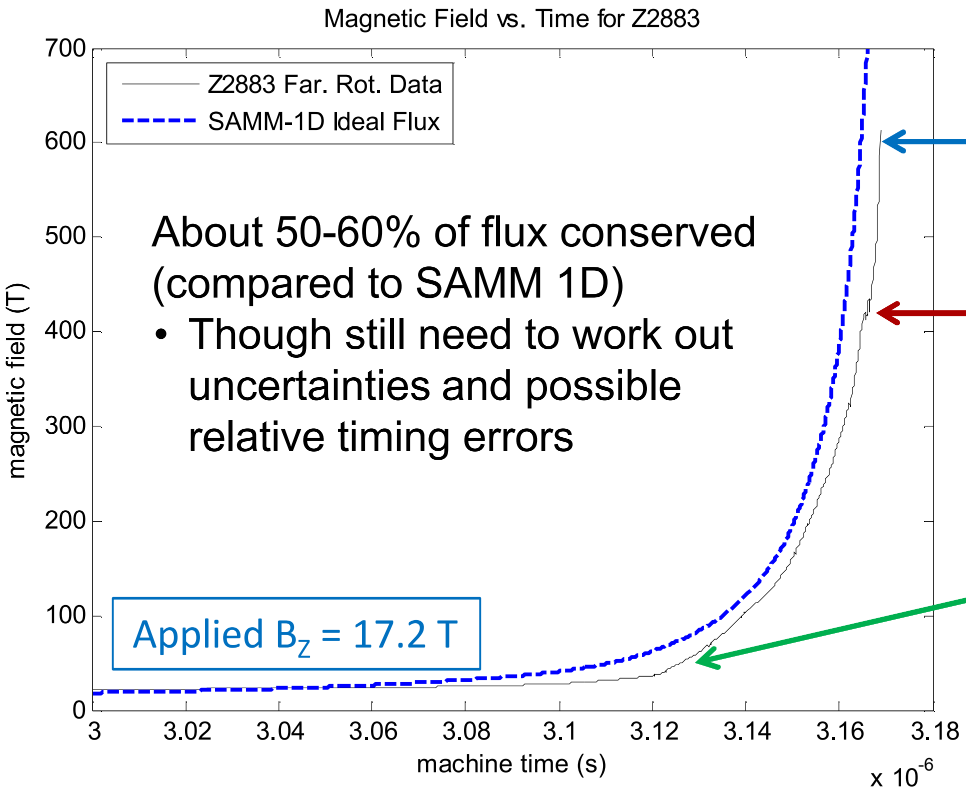

At probe failure:

B_{Zmax} = 600 T

B-dot = $2x10^{11}$ T·s^{-1}

B·r = 0.18 ±0.03 T·m

Late time deviation possibly due to noise or generation of a surface plasma on the silica tube, shielding magnetic flux penetration.

Early time deviation possibly due to influence of mechanical strain on the PM fiber-probe region. (Funky wiggles)

After compression, the conserved flux is 80-90% of predictions by ALEGRA simulations and 40% of SAMM/ideal simulations

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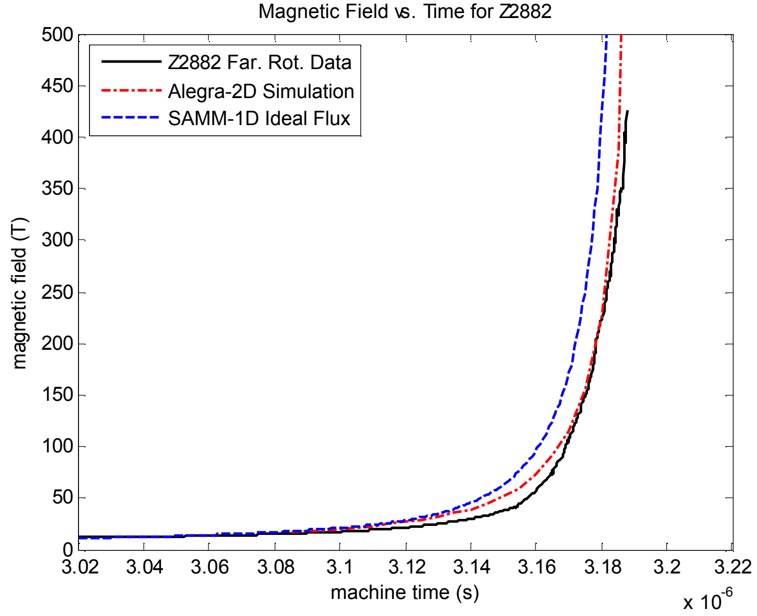
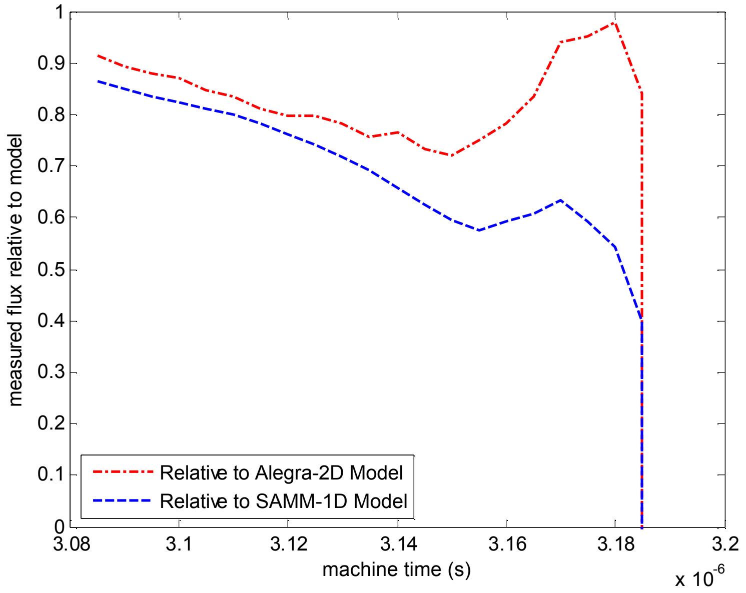
Z Shot 2882:
Applied B_Z = 9.9 T
Maximum B_Z = 425 T





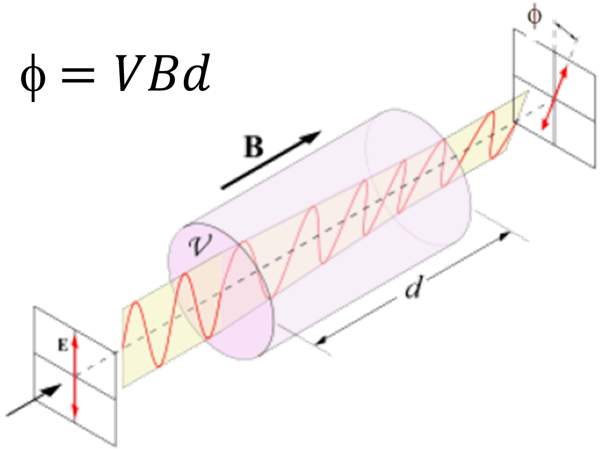
"The secret is comprised in three words — Work, finish, publish."

-Michael Faraday

- Fiber-based Faraday rotation works in the harsh environment on Z and liner design is important!
- For Al liners with a 200-ns implosion time, ~50% of the original flux is retained, but with caveats …
- Measured a maximum B_Z = 600 Tesla
- Maximum measured B-dot = $2x10^{11}$ T/s
- Measured B·r = 0.18 $\pm$0.03 T·m at probe failure
- Projected B·r at MagLIF stagnation radius will be higher and could be sufficient to magnetize alphas; B·r = 0.5 T·m is not unreasonable

We used a Tb-doped fiber as the magneto-sensitive element of the probe

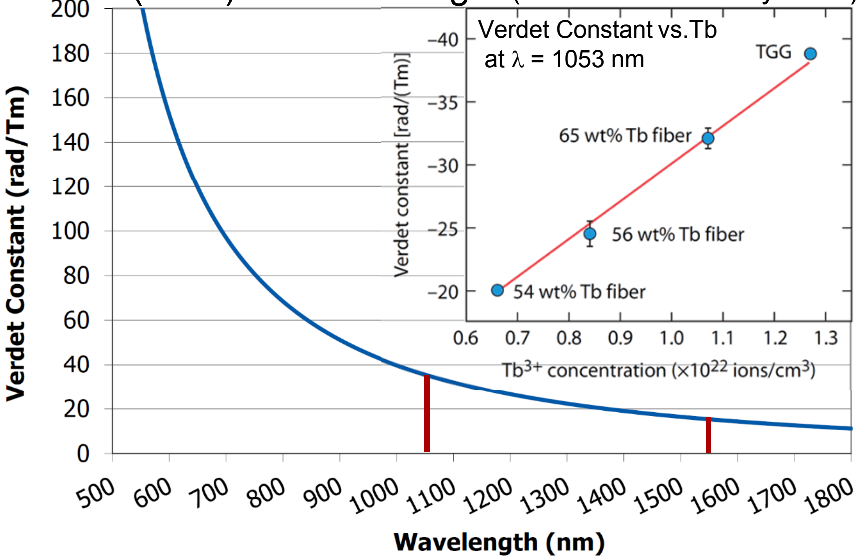
$$\phi = VBd$$



V is the Verdet constant

$$V = \frac{\phi}{Bd} = -\frac{1}{2}\frac{e}{m}\frac{\lambda}{c}\frac{dn}{d\lambda}$$

Verdet Constant of Terbium Gallium Garnet (TGG) vs. Wavelength (Barnes and Petway 1992)



The Verdet Constant of our 65 wt% Tb fiber at λ = 1550 nm is -8.2 rad/T/m.

All probes calibrated at the Sandia magnet lab with 3, 10, and 15 Tesla B fields.

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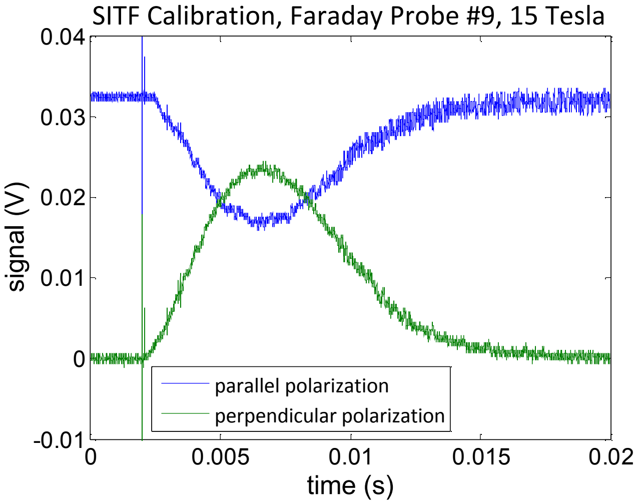
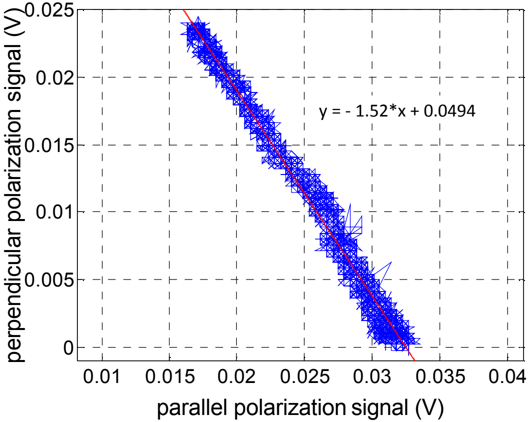


$$\varphi = \cos^{-1}\left(\sqrt{\frac{V_{min}}{V_o}}\right)$$

$$\varphi = 0.75 \text{ radian}$$

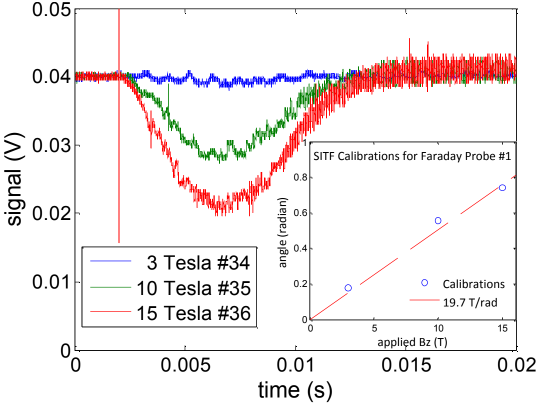
$$\text{Cal} = 20 \text{ T}\cdot\text{radian}^{-1}$$

$$\mathcal{V} = \text{-}8.3 \text{ radian}\cdot\text{T}^{-1}\cdot\text{m}^{-1}$$



Parallel and perpendicular polarization channels scale linearly against each other.

Light intensity rotated out of the parallel polarization channel should end up in the perpendicular channel.



Rotation angle scales linearly with B-field.

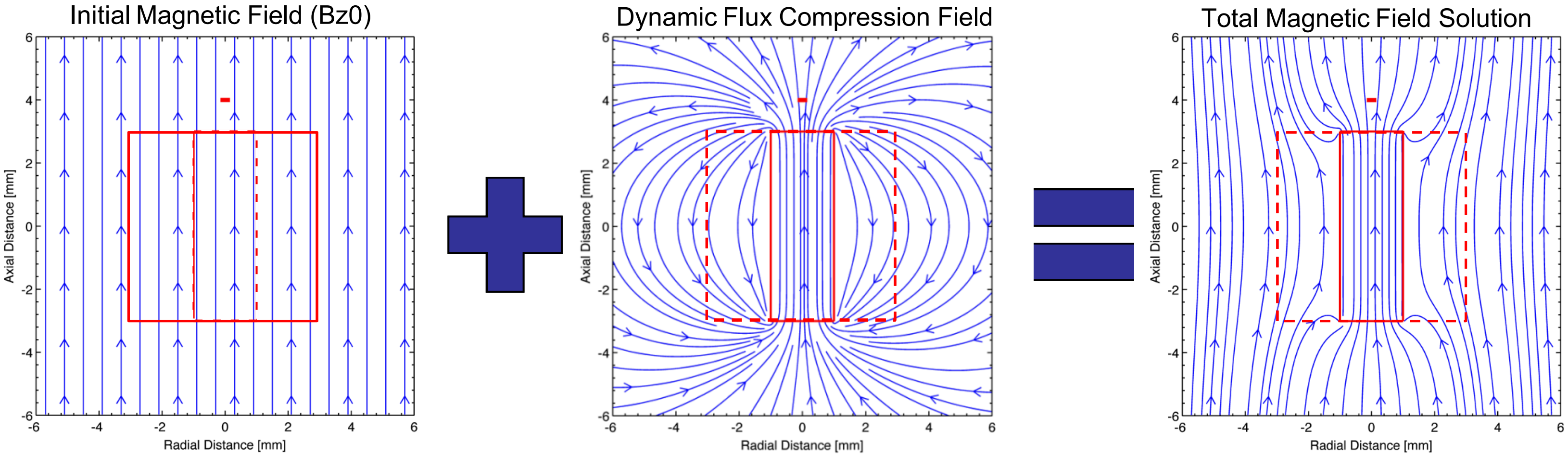
Overall Calibration of all probes: 20 ±1 T/radian

Conceptually, magnet flux compression is the superposition of an initial, uniform magnetic field and a dynamic solenoidal field due to J_θ on the liner's inner surface.

Initial magnetic field set by current applied to external coils, ABZ.

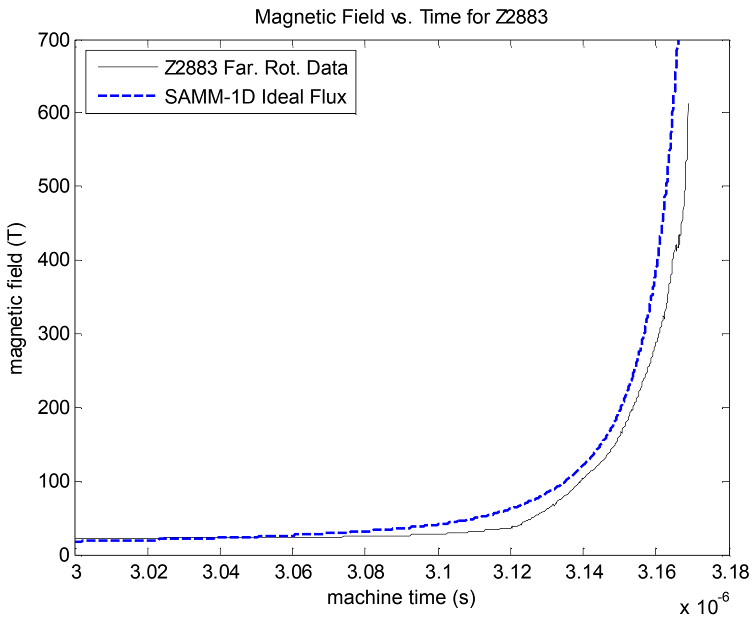
B-dot probes detect the dynamic field.

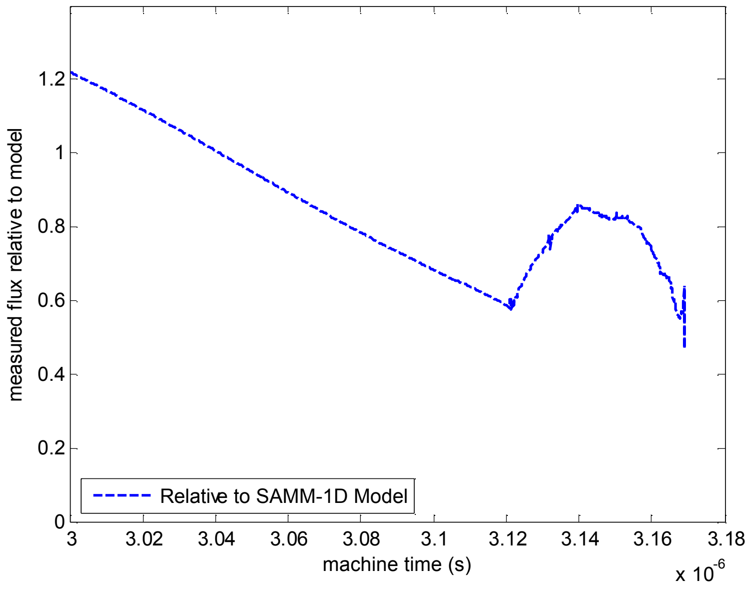
Faraday rotation and Zeeman spectroscopy measure the total field



Ideal Flux Compression: $B_Z(t) = B_Z(0) \times \left({}^{r(0)}\!/_{r(t)} \right)^2 = ABZ \times \mathrm{CR}^2$

About 50-60% of the flux is conserved compared to the SAMM-1D ideal flux compression





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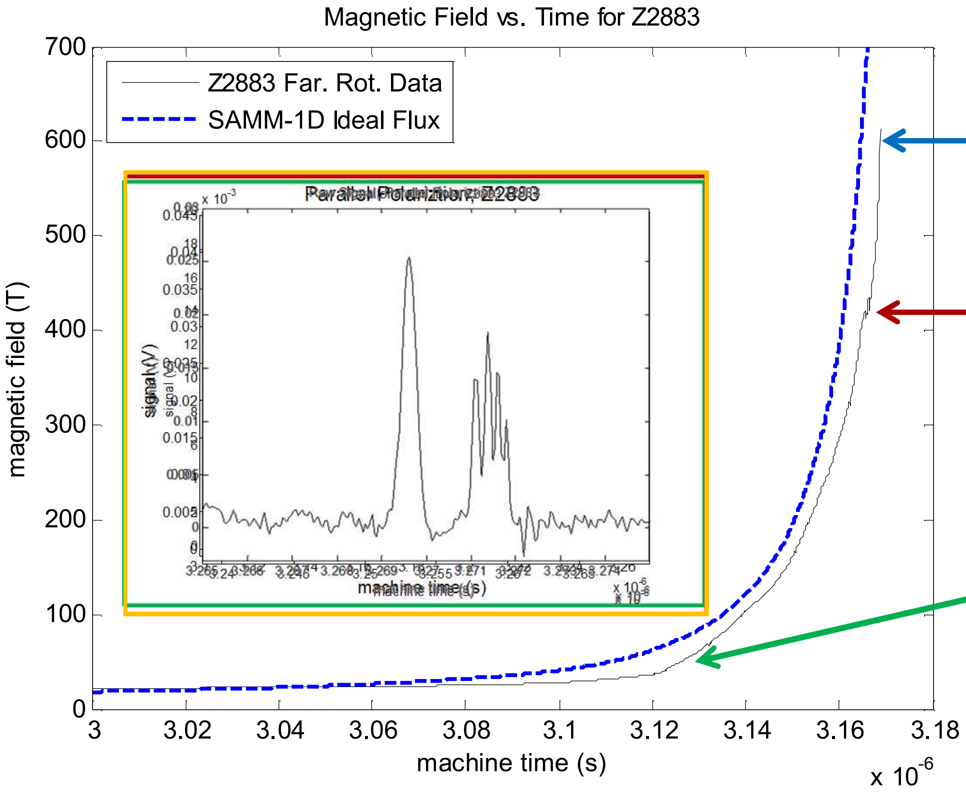

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