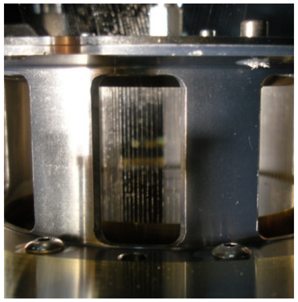
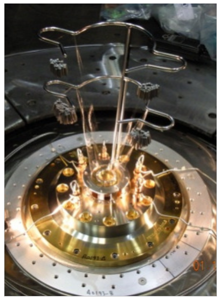
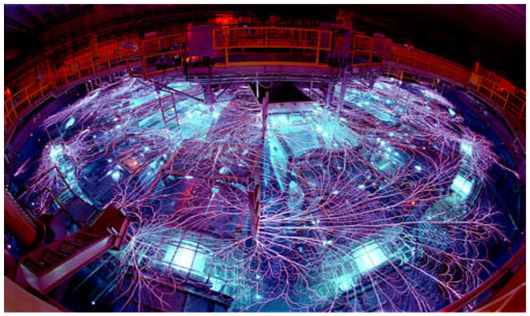
SAND2013-9396C







Spectroscopic magnetic field measurements of the drive current on the Z machine

S.B. Hansen, M.R. Gomez, D.J. Ampleford, T.J. Awe, D.E. Bliss, A.L. Carlson, M.E. Cuneo, C.A. Jennings, A.J. Harvey-Thompson, B. Jones, P.F. Knapp, D.C. Lamppa, R.D. McBride, K. Peterson, D. Sinars, J. Bailey, G. Rochau, and S.A. Slutz

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D. Schroen and K. Tomlinson

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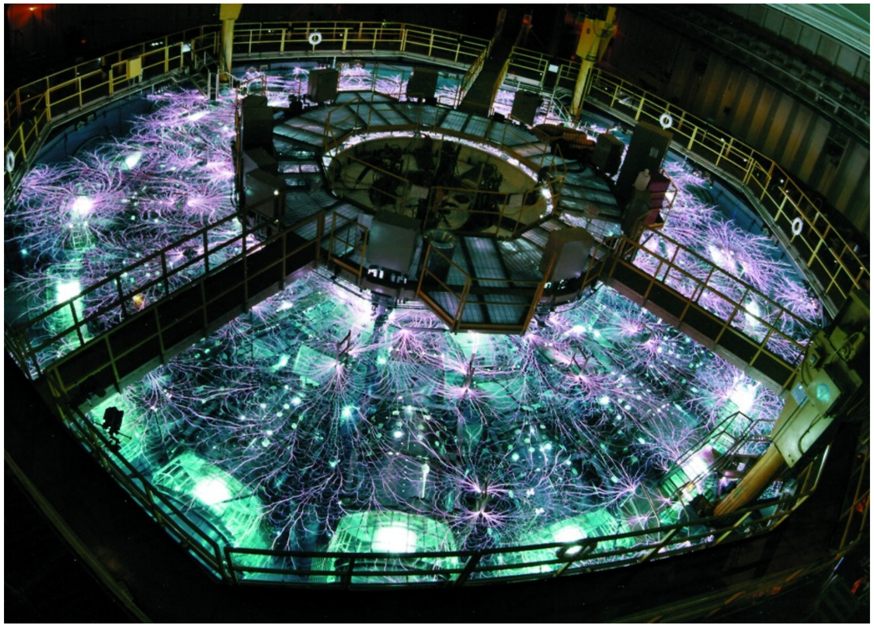
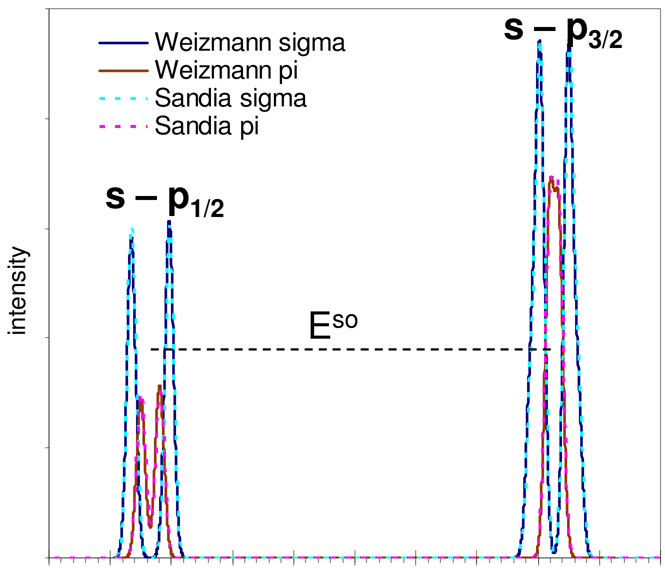
Understanding current delivery is a critical part of predicting and optimizing target performance on Z

- The Z machine compresses 10 MJ of stored electrical energy in time and space, delivering ~100 kJ into cm-scale targets over ~100 ns
  - This energy is used for radiation, materials, and ICF studies
  - Measurements of the ~20 MA drive current at the target are challenging but critical for validating simulations and understanding current loss
- We can measure or infer current using:
  - B-dots
    - Fail for r << 10 cm
  - VISAR
    - At target; complex interpretation
  - Faraday Rotation
    - At target; limited to early times
  - Zeeman splitting
    - At target; I ~ B ~ $\Delta\lambda$



Zeeman splitting has been used to characterize B fields in laboratory and astrophysical plasmas

When the effect of the external field is small relative to the internal spin-orbit splitting, differential splitting of s-p doublets can be used to determine |B|.

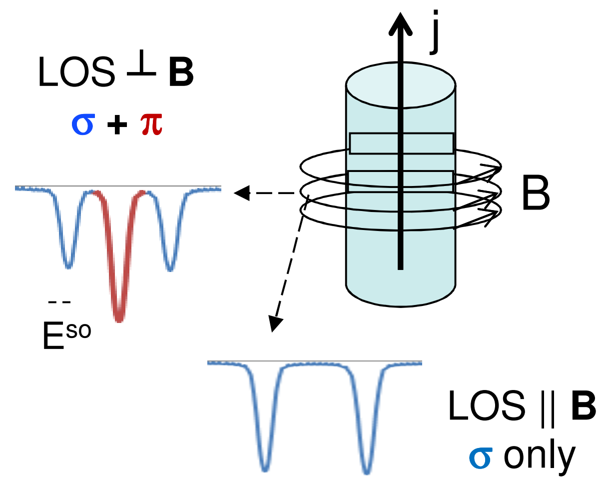


Comparisons courtesy E. Stambulchik

Few-T fields have been measured from 160 kA Z-pinch at Weizmann Inst.

Stambulchik, Tsigutken, and Maron
PRL **98**, 225001 (2007)

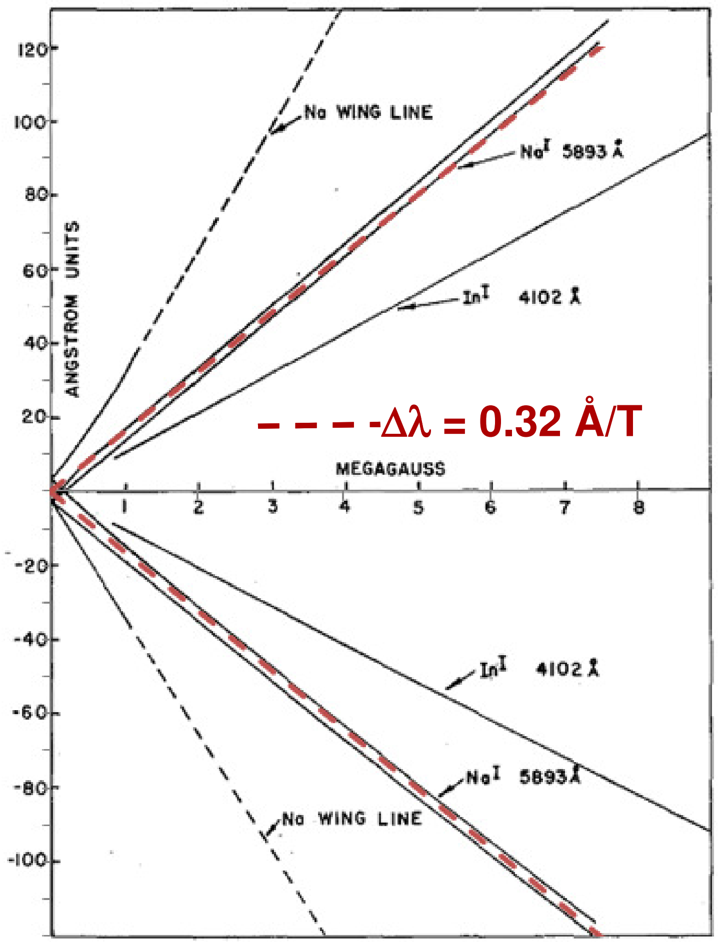
In strong external fields, s-p transitions form normal Zeeman triplets whose components reveal **B**

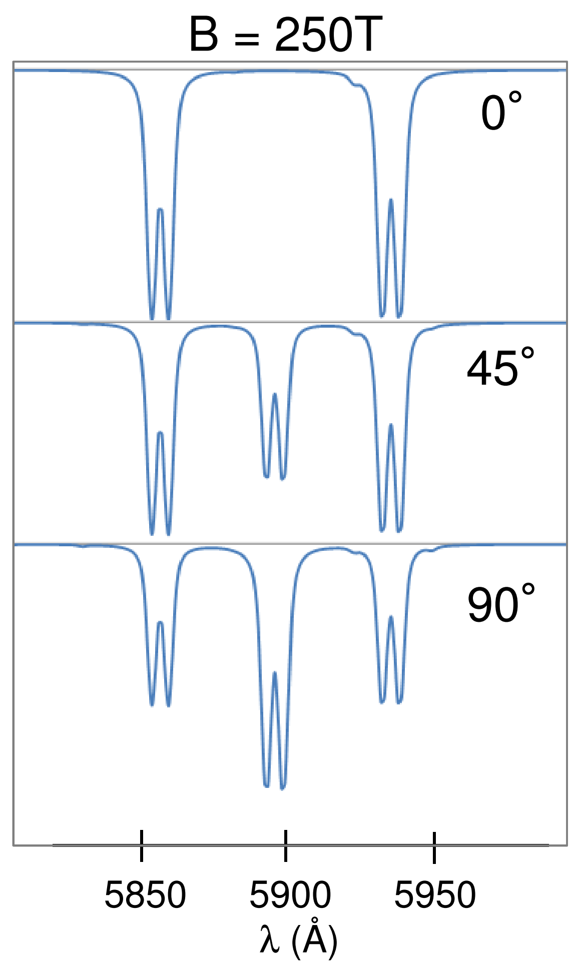


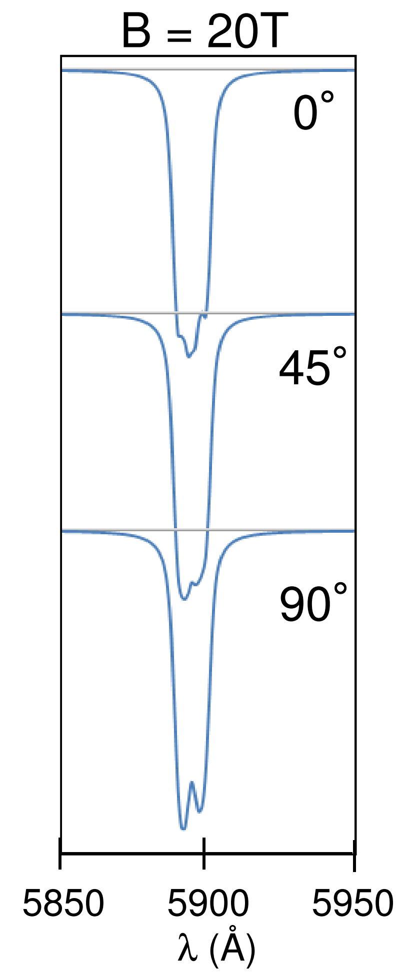
Few-100T fields have been measured in explosive flux-compression experiments and around magnetic white dwarfs

Garn, Cairn, Thomson, Fowler, RSI **37,** 762 (1966)
Reid, Liebert, and Smith, *Ap.J.* **550**, L61 (2001)

In the strong-field (Paschen-Back) limit, σ splitting is directly proportional to |B| and π intensity indicates $\hat{B}$



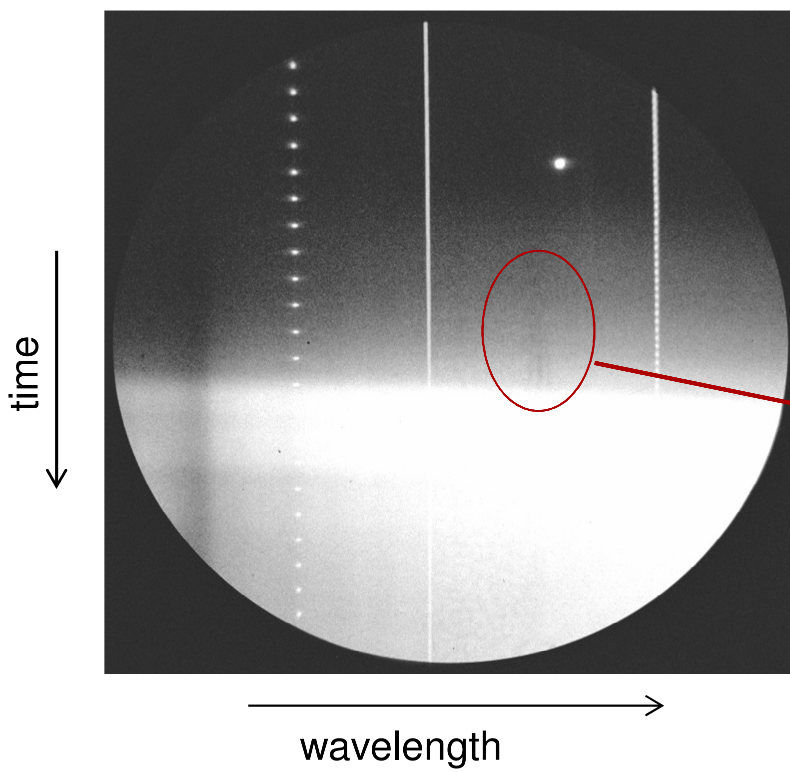


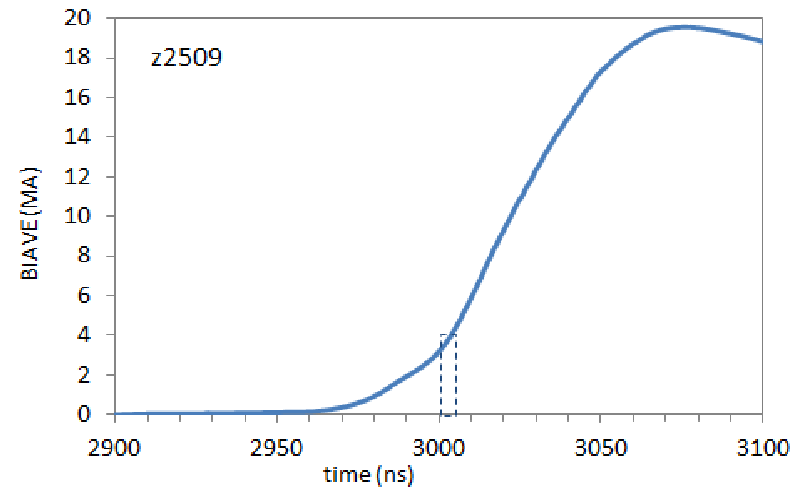


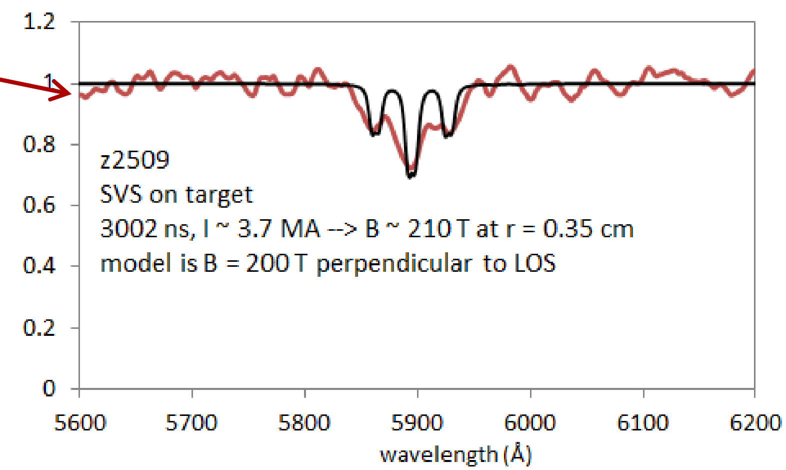
Bethe and Salpeter, *Quantum Mechanics of One and Two Electron Atoms*, 1957

The relative strength of σ and π components indicates field direction

In May 2013, measured absorption lines from Z appeared to form a Zeeman triplet

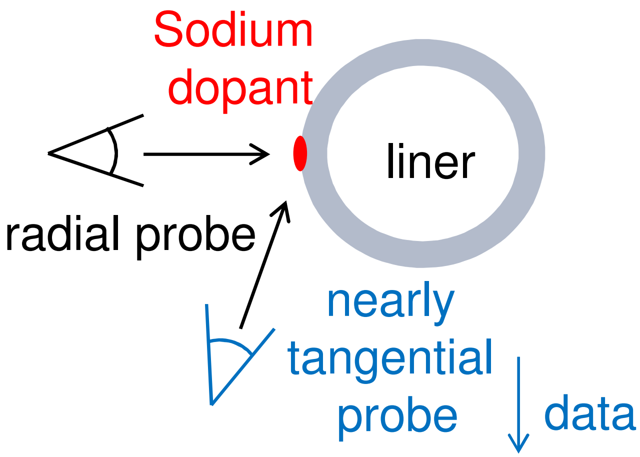


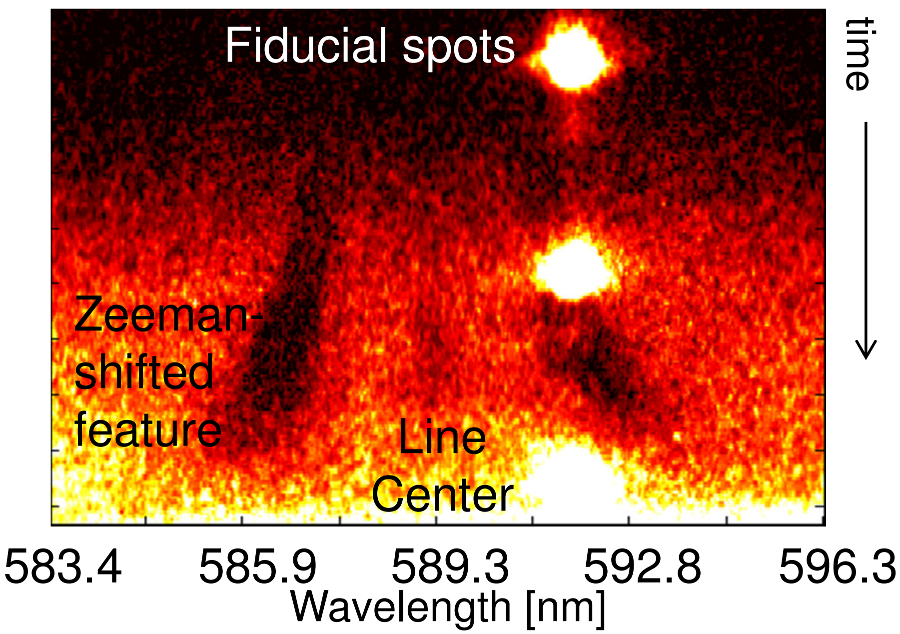


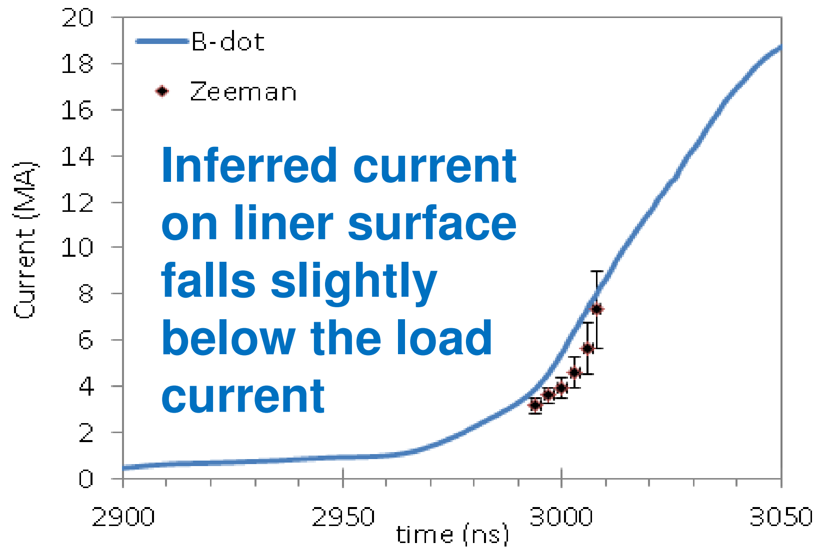


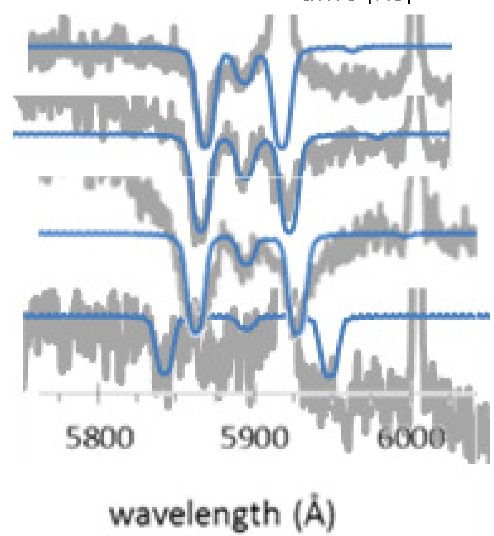
The absorption feature captured on the Streaked Visible Spectrometer (M. Gomez) was tentatively identified as the 3s – 3p transition in Na I. Although the origin of the sodium on the target was unknown, the splitting was consistent with estimated B ~200 T.

Placing droplets of salt water on various targets confirmed the line identification and provided **B** diagnostic





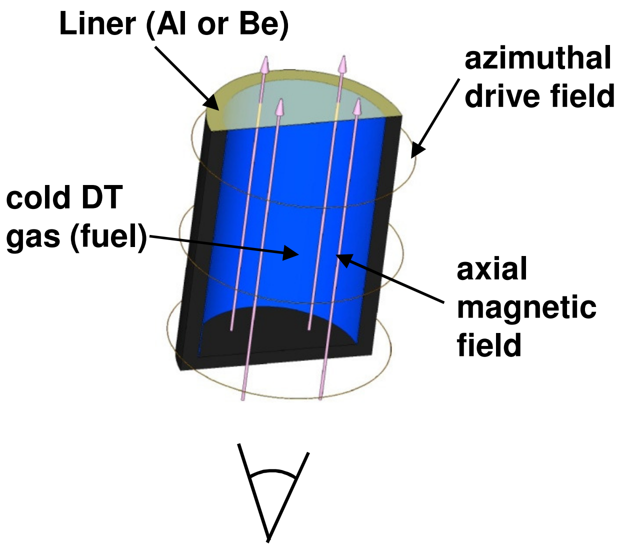




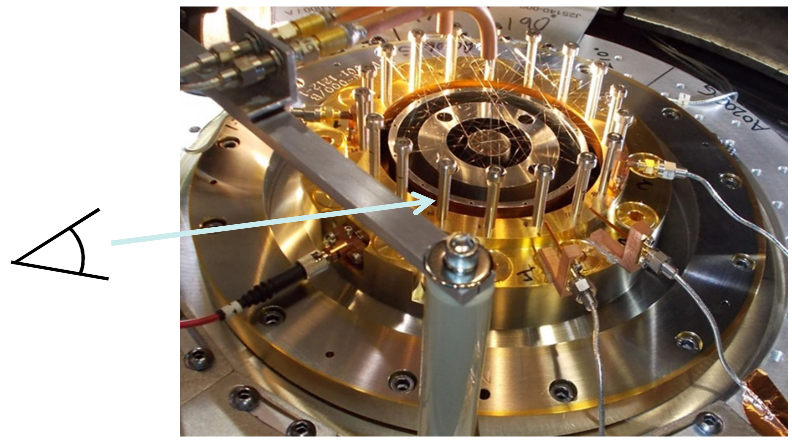
Fits indicate
B = 150 - 350 T
25° to SVS LOS
~10 ng/cm²

We will continue to refine the measurements and analysis for a variety of loads

SVS on an axial LOS could measure flux compression of the seeded axial field in MagLIF* targets



Measurable fields may be present around current return posts on gas puff loads, where losses are thought to be significant



The absorption diagnostic requires both a reasonably bright backlighting source and ~10 ng/cm^2 neutral sodium for good S/N; but the brightness of the target and hardware can vary significantly over the current pulse, and very bright environments will ionize Na.

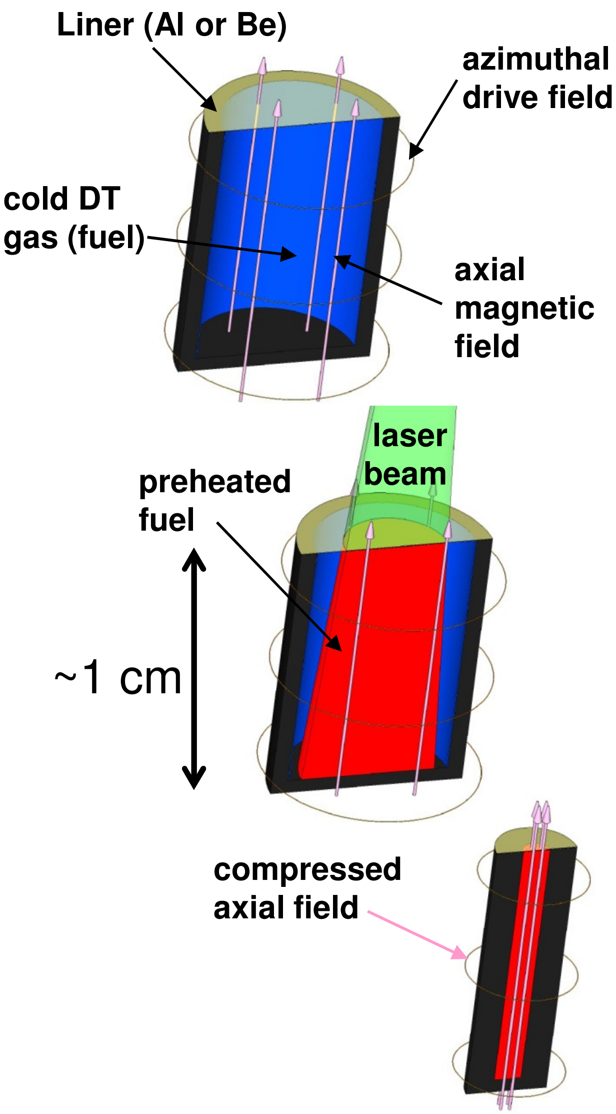
*See talks by M. Gomez (BO7/6), T. Awe (CI2/2), and R. McBride (BO7/8)

Summary

- Current loss is a critical issue for modeling and optimizing target performance on Z, but measuring the current at the load is challenging
- SVS measurements of Zeeman splitting in optical absorption features from Na I can provide continuous measurements of both the magnitude and direction of B fields, and thus current
- To obtain measurements over longer durations, we will need to understand how the droplets vaporize and ionize and explore options for positioning dopants and the SVS
- We are also exploring additional dopants* to increase the effective range of the measurement
  - Ba II 6s-6p lines at 4554 and 4934 Å
  - In I 5p-6s lines at 4102 and 4511 Å

*NIST ASD

The Magnetized Liner Inertial Fusion (MagLIF)* concept



- An initial 30 T axial magnetic field inhibits thermal conduction losses, enhances alpha particle energy deposition, and may help stabilize implosion at late times.
- During implosion, the fuel is heated using the Z-Beamlet laser (about 6 kJ). This reduces the convergence ratio needed to obtain ignition temperatures to about 25 on Z and 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
- Gain = 1 may be possible on Z using DT (fusion yield = energy into fusion fuel)

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

Weizmann method:
take advantage of differential splitting

Since Lyα2 (or any $np_{1/2} - ns_{1/2}$ line) is broadened more than Lyα1 (or any $np_{3/2} - ns_{1/2}$ line) but has identical Stark, temperature, motional, and opacity broadening, the difference between the two widths isolates the effect of B field.

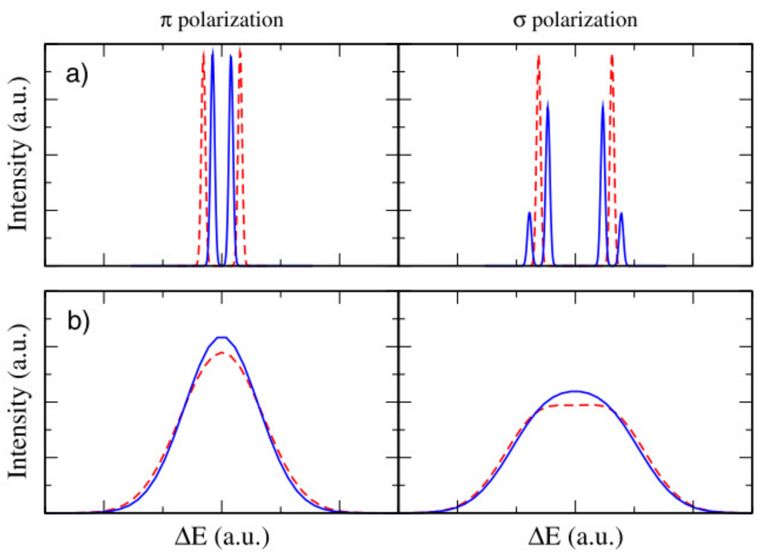


FIG. 1 (color online). Zeeman splitting of the $^2S_{1/2}$-$^2P_{3/2}$ (solid curves) and the $^2S_{1/2}$-$^2P_{1/2}$ (dashed curves) components of a ^2S-^2P transition, convolved with a small (a) and a dominant (b) Doppler effect (that is assumed to be the same for the two components). Profiles of the σ and π polarizations are given separately. For the comparison, the intensity of the $^2S_{1/2}$-$^2P_{1/2}$ component is scaled up by 2 times, to match the intensity of the $^2S_{1/2}$-$^2P_{3/2}$ component.

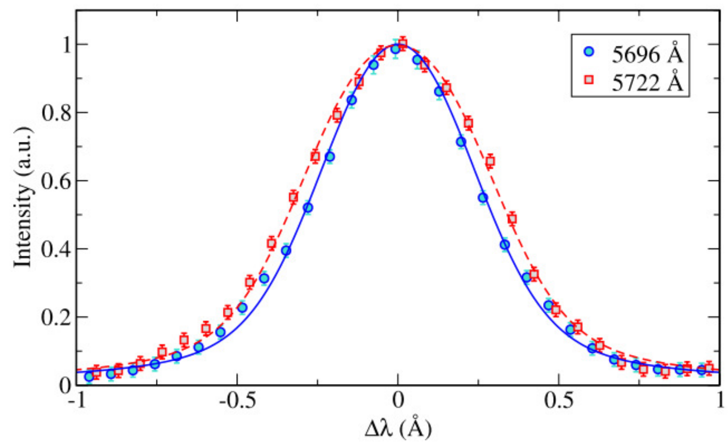
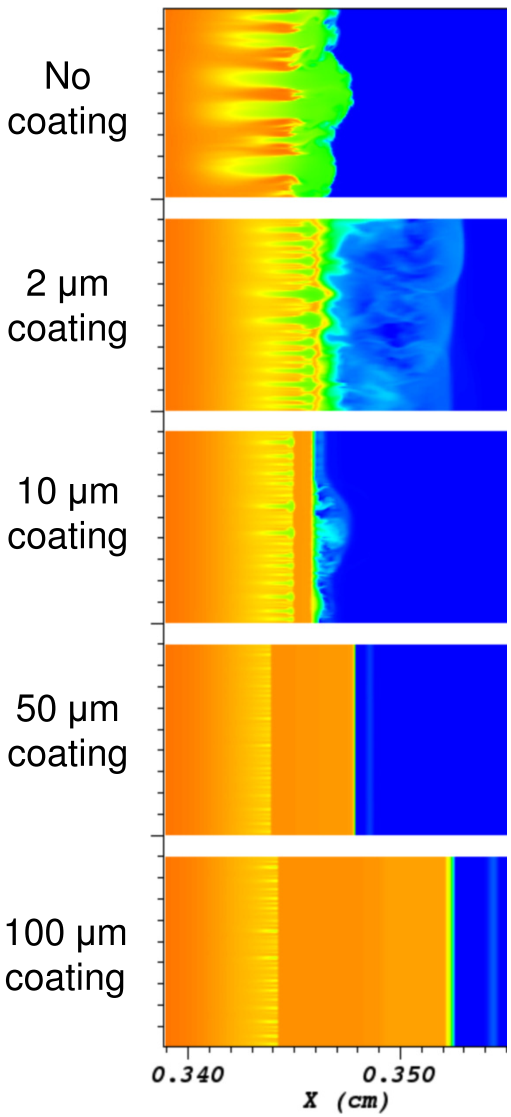
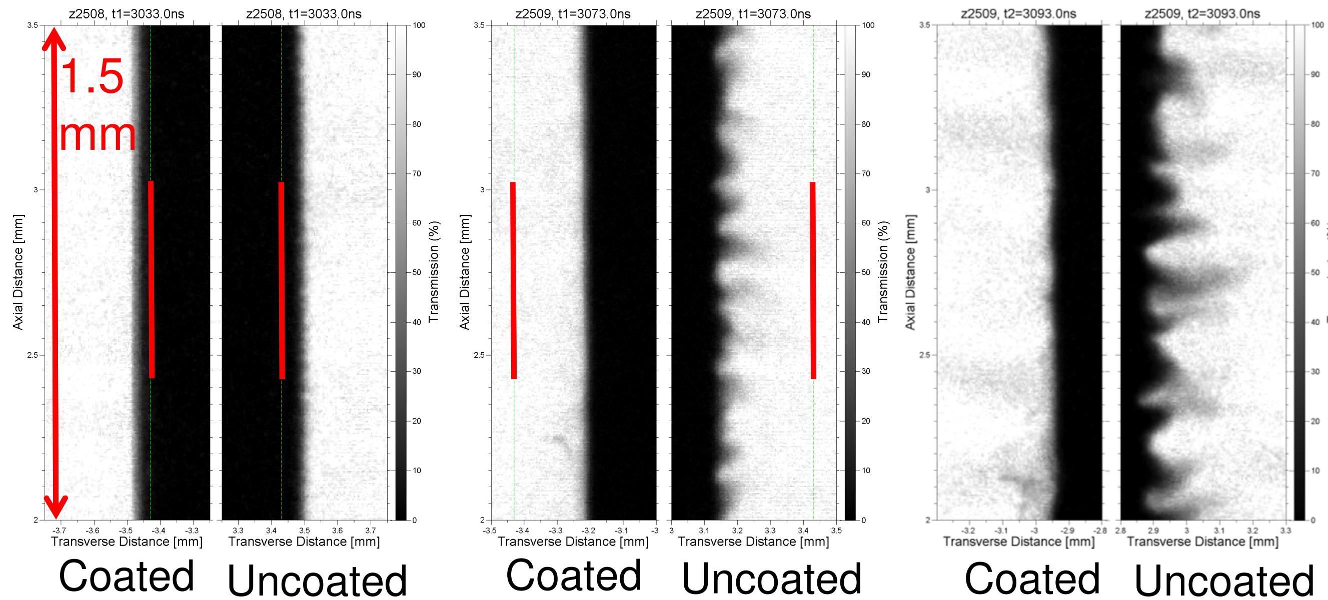


FIG. 5 (color online). The AlIII 4p-4s (5696 & 5722 Å) doublet. The line shapes of the two components are peak-normalized and shifted to a common spectral center. The smooth lines represent best-fit calculations for $B = 0.9$ T, $N_e = 2 \times 10^{16}$ cm^{-3}, and $T_e = 10$ eV.

Stambulchik, Tsigutken, and Maron, *Phys. Rev. Lett.* **98**, 225001 (2007).

The electro-thermal instability (ETI) is one possible mechanism for seeding MRT growth – and it can be mitigated by an outer coating

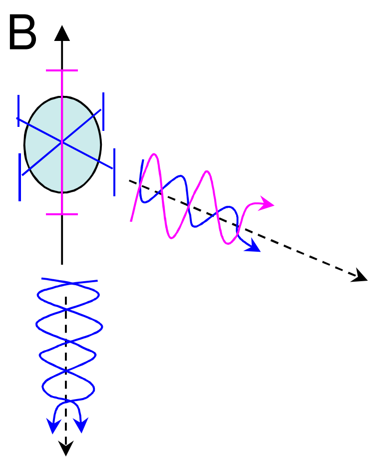




- ETI: regions with higher T have higher resitivity and are heated further; pressure variations eventually redistribute mass
- A plastic coating carries very little current and is theoretically ETI stable, with resistivity that decreases with temperature
- A thin coating significantly reduces the mass redistribution and provides a more stable implosion

In the high-field environment of Z (B > 1 kT at r = 1 cm), Zeeman splitting can reveal the magnitude and direction of B

External magnetic fields change the electronic structure of atoms, with greatest distortion normal to **B**.



Line shifts due to Zeeman splitting are larger for Δm = +/-1 (σ) than for Δm = 0 (π).

Thus the relative strengths of σ and π change along different lines of sight: