Diagnostics of Magnetic Field in High-Energy-Density Plasmas

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Outline of the talk

1. Introduction
2. “Quasi-isotropic” $B$-fields
3. Laser FxB
4. Z pinch diagnostics
5. Conclusions
Introduction: HED plasmas with magnetic fields

Z-pinches

MagLIF

Laser-matter interactions

Plasma switches, diodes
Magnetized Liner Inertial Fusion (MagLIF) concept (Sandia) aimed at reducing electron heat conduction losses.

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

Laser entrance hole
Azimuthal drive field
Liner (Al or Be)
Cold DT gas (fuel)
Axial magnetic field
Laser beam
Laser heated fuel
Liner beginning compression
Compressed axial field
Liner unstable but sufficiently intact
Compressed fuel reaches fusion temperatures
Yield_{DT}/Yield_{DD} can be used to infer magnetization at stagnation.

Low B

High aspect ratio cylinder

Tritons sample small $\rho_r$ when B-field is low so DT/DD is low.

High B

$\frac{R}{r_\alpha} \approx 4BR \ [MG \cdot cm]$

- $R \sim 0.005 \text{ cm}$
- $B > 5 \text{ kT}$
- $Z \sim 0.6 \text{ cm}$
- $\rho \sim 0.4 \text{ g/cm}^3$
- $\rho R \sim 0.002 \text{ g/cm}^2$
- $\rho Z \sim 0.2 \text{ g/cm}^2$

High B-field traps the 1-MeV tritons, increasing the effective $\rho_r$ so DT/DD increases.
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Among spectroscopic methods, usually employed are Zeeman/Paschen-Back effect or $B$-field-induced birefringence (Faraday rotation, Cotton-Mouton effect).

**Faraday effect**

\[ \beta = \nu \int_0^d \hat{B} ds \]

**Zeeman effect**

\[ \hat{V} = \mu_0 \hat{B}(\hat{L} + 2\hat{S}) \]

These diagnostic methods are based on detecting an anisotropy in either the dispersion properties of the medium (Faraday rotation) or in the emitted radiation (Zeeman effect).
**B-field measurements: traditional methods**

Consequently, these techniques **can not be used in situations** where the magnetic field has no constant **direction** during the time of observation in the space viewed.

Moreover, magnetic fields with amplitudes that vary in **time** or **space** pose additional problems in the applicability of these methods.
Fine-structure components split differently under $B$.

Stark and Doppler effects broaden the components equally.

Thus, a comparison of the line-shapes of these components reveals $B$.

$S_{1/2} - P_{1/2}$ is always wider than $S_{1/2} - P_{3/2}$!

Experiment: $B$-field penetration in plasma

- Lines are measured simultaneously.
- No need for polarization.

The line-shape simulation yields perfect fits to the experimental profiles.

Thus, the method allows for determining the $B$-field and plasma density in a single measurement.

$B = 0.9 \pm 0.2 \, \text{T}$    $N_e = (2 \pm 1) \times 10^{16} \, \text{cm}^{-3}$

$S_{1/2} - P_{1/2}$  $S_{1/2} - P_{3/2}$  $\text{Al III 4s} - 4p$
Scaling to higher fields and densities

B-field diagnostics with Stark-dominated line shapes

The transition from the “traditional” Zeeman spectroscopy to the multiplet-approach-based diagnostics is demonstrated for Al III 4s – 4p

\[ B = 8.5 \, T \pm 10\% \]

\[ n_e = 1 \times 10^{17} \, \text{cm}^{-3} \]

\(4\) mm from target
Zeeman pattern

Intensity (a.u)

\( B = 15 \, T \pm 20\% \)

\[ n_e = 1.2 \times 10^{18} \, \text{cm}^{-3} \]

\(1\) mm from target
Stark-dominated profile

\[ \text{Intensity (a.u)} \]

\( \lambda \, (\AA) \)

Scaling to higher fields and densities

Limitations: \[ \Delta E (\mu \cdot B) < \Delta E (L \cdot S) \] and \[ \Delta E (Stark) < \Delta E (L \cdot S) \]

Example of Al III 4s - 4p: \( B \leq 35 \, T \) and \( n_e \leq 3\times 10^{18} \, cm^{-3} \)

Finding transitions appropriate for the B-field diagnostics under a broad range of plasma and field parameters

Example: VUV lines for diagnosing high B-fields under relatively high temperatures and densities

<table>
<thead>
<tr>
<th>Ion</th>
<th>Transition</th>
<th>Ionization potential [eV]</th>
<th>Wavelength [Å]</th>
<th>Usefulness</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ti XII</td>
<td>5p – 6s</td>
<td>291</td>
<td>492.8</td>
<td>497</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>( B &lt; 500 , T, \ n_e &lt; 10^{21} , cm^{-3} )</td>
</tr>
</tbody>
</table>

Example: IR lines of space abundant element for the detection of relatively low magnetic fields*, typical to many astrophysical objects

<table>
<thead>
<tr>
<th>Ion</th>
<th>Transition</th>
<th>Ionization potential [eV]</th>
<th>Wavelength [Å]</th>
<th>Usefulness</th>
</tr>
</thead>
<tbody>
<tr>
<td>C IV</td>
<td>4s – 4p</td>
<td>65</td>
<td>14331</td>
<td>14358</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>0.15 &lt; B &lt; 5 , T</td>
</tr>
</tbody>
</table>

* Assuming spectral resolution of \( \lambda/\Delta \lambda \approx 50000 \), typical to the high-resolution near-IR spectrometers used for space observations (e.g., Phoenix, CRIRES, or the HRNIRS), we find that magnetic fields down to 0.15 T can be measured
Visible-UV lines of Li-like ions useful for the B-field measurements using the new approach

The maximum $n_e$ is calculated considering the restriction due the Stark broadening being comparable to the fine-structure splitting. The maximum $n_e$ due to the continuum level may impose another restriction (for the presented Li-like 3s - 3p vis.-uv transitions the limitation is $\sim 5 \times 10^{19}$ cm$^{-3}$).

<table>
<thead>
<tr>
<th>Ion</th>
<th>$E_i$ (eV)</th>
<th>$\lambda$ (Å)</th>
<th>Max. $B$ (T)</th>
<th>Max. $n_e$ (cm$^{-3}$) due to Stark</th>
</tr>
</thead>
<tbody>
<tr>
<td>C IV</td>
<td>65</td>
<td>5801</td>
<td>5811</td>
<td>14</td>
</tr>
<tr>
<td>O VI</td>
<td>138</td>
<td>3811</td>
<td>3834</td>
<td>50</td>
</tr>
<tr>
<td>Ne VIII</td>
<td>239</td>
<td>2820</td>
<td>2860</td>
<td>200</td>
</tr>
<tr>
<td>Mg X</td>
<td>368</td>
<td>2215</td>
<td>2281</td>
<td>500</td>
</tr>
<tr>
<td>Si XII</td>
<td>523</td>
<td>1803</td>
<td>1884</td>
<td>1000</td>
</tr>
<tr>
<td>Ar XVI</td>
<td>918</td>
<td>1282</td>
<td>1421</td>
<td>3500</td>
</tr>
</tbody>
</table>
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The problem of hydrogen atom in a harmonic electric field was first studied in 1933 by Blokhintsev.

In numerous researches, studying effects of the laser EM radiation on the atomic spectra, the electric field was considered, but never the magnetic one.

We have shown that the magnetic component may have profound effects. This happens due to unexpected interplay between the light-atom interaction and the spin-orbit ($LS$) coupling.

Selected as an *Editors’ Suggestion* and covered in *Physics*. 
Zeeman effect induced by intense laser light

\[ \Delta E_{ph} \ (eV) \]

Intense laser light properties:

- Laser intensity: \( I_{\text{laser}} = 10^{20} \ \text{W/cm}^2 \)
- Angular frequency: \( \omega = 2 \times 10^{15} \ \text{rad/s} \)
- Magnetic field strength: \( B \approx 100 \ \text{kT} \)
- Electric field strength: \( F \approx 30 \ \text{TV/m} \)

With proper LoS (or linear polarizer) \( \Rightarrow \) almost pure Zeeman effect!
Zeeman effect induced by intense laser light

The effect can be observed in many species, provided that:

- $V_{\text{MF}} \lesssim V_{\text{LS}} \lesssim V_{\text{EF}}$ and $\Gamma_{\text{rad}} \lesssim V_{\text{MF}}$ criteria are satisfied,
- the upper level is not field-ionized,
- $V_{\text{MF}}/\hbar\Omega \gtrsim 1$, and
- (for practical observability) $E_0/V_{\text{MF}} \lesssim$ the resolving power.
Zeeman effect induced by intense laser light

Kr XXXVI Ly-α

$$\omega_{\text{laser}} = 2 \times 10^{15} \text{ rad/s, observation } \parallel F$$

Can be used for laser power diagnostics.
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Z-pinch experiment

$I_{\text{max}} = 1 \text{ MA}$  \hspace{1cm}  $t_{1/4} = 500 \text{ ns}$

- Gas-puff load (Oxygen/Neon)
- Shell-on-jet configuration
- $\varnothing_{\text{out}} = 38 \text{ mm}$
- $A - K$ Gap $= 9 \text{ mm}$

Typical Current and XRD traces for $I_{\text{peak}} = 0.5 \text{ MA}$
Z-pinch experiment, $B$ field at implosion
Dense plasma—Impossible to observe Zeeman splitting

- Polarization spectroscopy* was used to discriminate between the $\pi$ and $\sigma$ components, providing the time-dependent magnetic field distribution.
- Penetration found to be due to diffusion and resistivity was found to be Spitzer.

Measurements were limited to $r \geq 9$ mm, and $t \leq -90$ ns.

Two sets of 50 fibers: Each set views the same spectra, but with a $\lambda/4$ plate, and a polarized beam splitter; thus, $\sigma^+$ and $\sigma^-$ are observed simultaneously, when viewing $\parallel B$.

Use of charge state layers: Here, example of Using O III and O VI lines (that are spectrally closed, but give the field in different radii).

Only viewing the outermost radius of each layer yields the local field strength.

- Rosenzweig et al, in preperation.
The chosen spectra are fit with Voigt profiles to obtain the splittings, which are subsequently compared with Zeeman calculations.

The relative shift ($2\Delta\lambda$) gives the magnetic field.
Z-pinch experiment, $B$ field at stagnation

$B(r)$ for $z = 5 \text{ mm}$

The $B$ field distribution is broad, and even at stagnation the field is nearly uniform up to a large radius.

Presently we are looking for 2D effects

Modeling:
A. Fruchtman
H. Strauss
J. Giuliani
A. Velikovich
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Measuring magnetic fields in high-energy-density plasmas is always a challenging task.

There is no “one-size-fits-all” method; consider different approaches—or develop a new one.

We have suggested and implemented several new approaches.

Magnetic fields in the range from a fraction of tesla to tens of teslas have been diagnosed in various HED plasmas.

Calculations suggest that the methods are scalable to many-kilotesla magnitudes.

Thank you for your attention!