Spectral measurement of $|B|$ via Motional Stark Effect in the MST Reversed-Field Pinch

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ABSTRACT

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Using a 30 keV, 4 A diagnostic neutral H beam, we have made an initial measurement of the separation of the pi manifolds of the H-alpha Motional Stark Effect (MSE) spectrum in the MST Reversed-Field Pinch. The wavelength separation of approximately 0.2 nm is as expected for the B of about 0.5 T in the core of MST. The DINA beam is nearly monoenergetic and has low divergence, thus the Doppler-shifted Stark manifold is clearly separated from the background H-alpha, and beam-induced smearing of the Stark components is minimized. Since the magnitude of B in the core of MST provides an important constraint for equilibrium modeling, three refinements are planned to increase measurement accuracy. First, we will accurately model the expected H-alpha MSE spectrum for low magnetic fields, assuming statistical weighting of the Stark components. Second, using an existing fast spectrometer, we will attempt time-resolved simultaneous measurement of the smeared pi and sigma manifolds. Third, we will implement a new CCD spectrometer and viewing geometry to attempt direct time integrated measurement of the individual components of the Stark manifold.

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Introduction

We have made measurements of $|B|$ in the core of MST
- $|B|$ in the core of MST provides an important constraint for equilibrium modeling

This is a direct measurement of the Stark spectrum
- polarimetry for measuring field line pitch is not suitable for low-field devices
- measure the separation of the $\pi$ manifolds of the H$\alpha$ Motional Stark Effect (MSE) spectrum
The RFP is a toroidally axisymmetric current-carrying plasma with toroidal field $B_\phi \approx$ poloidal field $B_\theta$

- Self-generated currents drive plasma to relaxed state in which toroidal field is reversed at edge
DNB on MST - what it looks like
Beam is mono-energetic (almost)

Beam mass-energy spectrum

- Components with $E/2$ and $E/3$ present in hydrogen beams.
- Result of dissociation of energetic ($E$) molecular ions $H_2^+$ and $H_3^+$.

\[
\begin{align*}
H^+ & \xrightarrow{\text{Acc}} E & H^+ & \xrightarrow{\text{Diss}} H^+ \quad E/2 \\
H & \quad \quad \quad H & \quad \quad \quad H \quad \quad E/2
\end{align*}
\]

High density and high temperature plasma $\Rightarrow$ low concentration of $H_2^+$ and $H_3^+$
Beam is focused for higher intensity and to pass through small MST portholes.

Small port size requires beam to be focused.

Waveform and Radial Profile
Hydrogen Beam
4A/30 keV

Beam radius (cm)

MST plasma size

Entrance port

Beam current density (A/cm²)

Beam diameter 5.22 cm

Distance from MST axis (cm)

Beam Current (A)

Time (ms)

5.22 cm

Beam Radial Profile (at 160 cm)
Stark Effect
- Investigated by Stark in 1913
- Breaking of the degeneracy of the energy levels of a hydrogen-like atom via the application of an electric field
- Results in the splitting of a given line, e.g., Hα at 656.3 nm, into several lines whose wavelength separation is linearly proportional to the magnitude of the electric field

Motional Stark Effect
- An atom moving with a velocity \( \mathbf{v} \) in a magnetic field \( \mathbf{B} \) experiences an equivalent electric field \( \mathbf{v} \times \mathbf{B} \) in its frame of reference
- When a beam of neutral hydrogen atoms is directed into a magnetically confined plasma, the atoms are excited and the resulting line emission is split as if the atoms were in an electric field \( \mathbf{E} = \mathbf{v} \times \mathbf{B} \)
- If the velocity of beam atoms is known, the magnetic field in the plasma can be determined.
What is measured:
Linear Stark effect - splitting of hydrogen beam emission line \((H_{\alpha}, 656.3 \text{ nm})\) due to \(v \times B\) electric field.

Separation of Stark manifold components for 30 keV H beam vs. magnetic field.
Nine Stark components are fitted

\[ S = C \sum a_i \exp\left\{-(\lambda - \lambda_i)^2/2\Delta \lambda^2\right\} \]

a_i and \( \lambda_i \)- amplitudes and wavelengths of Stark split lines
\( \Delta \lambda \) – line smearing

Fitted parameters

Calculated values \( a_i \)

- \( \pi_4 \) 30.77%
- \( \pi_3 \) 42.13%
- \( \pi_2 \) 13.31%
- \( \sigma_1 \) 35.13%
- \( \sigma_0 \) 100%
- \( -\sigma_1 \) 35.22%
- \( -\pi_2 \) 13.25%
- \( -\pi_3 \) 44.81%
- \( -\pi_4 \) 30.42%

\( B_0 = 0.43 \) T
Line Smearing

Finite temperature effect

\[ \exp\left( -\frac{mv^2}{2T} \right) \Rightarrow \exp\left( -\frac{\lambda^2}{2\lambda_T^2} \right) \]

\[ \lambda_T[nm] = 3.26 \times 10^{-5} \lambda_0[nm] \sqrt{T[eV]} = 2.14 \times 10^{-2} \sqrt{T[eV]} \]

Non-mono-energetic beam

\[ T_{\parallel} = \frac{\Delta\varepsilon_{\parallel}^2}{2\varepsilon_0} = 0.17 \text{ eV} \]

\[ \Delta\lambda_{\parallel}[nm] = 8.1 \times 10^{-3} \cos(\theta) \]

\[ \Delta\varepsilon_{\parallel} = 100 \text{ eV} - \text{beam energy spread} \]

\[ \varepsilon_0 = 30 \text{ keV} - \text{beam energy} \]

\[ \theta = 22.5^\circ - \text{angle between the beam and the sight line} \]

Finite beam divergence \( T_{\perp} \)

\[ T_{\perp} \approx 30 \text{ eV} \text{ and } \Delta\lambda_{\perp}[nm] = 0.126 \times \sin(\theta) = 0.045nm \]

Finite light collection solid angle

\[ T_{\perp \text{coll}} = 2\varepsilon_0\alpha_{\text{coll}}^2 = 7.5 \text{ eV} \text{ and } \Delta\lambda_{\text{coll}}[nm] = 5.9 \times 10^{-2} \sin(\theta) = 0.022nm \]

\[ \alpha_{\text{coll}} = 0.01 \text{ rad (determined by the viewing optics)} \]

\[ \Delta\lambda_{\text{tot}} = \sqrt{\Delta\lambda_{\parallel}^2 + \Delta\lambda_{\perp}^2 + \Delta\lambda_{\text{coll}}^2} \approx 0.05nm \]
On axis measurement of $|B|$ provides a strong constraint for equilibrium modeling of $q$ and $J_{||}$ profiles

- important for differentiating standard (dotted lines) and improved confinement (solid lines) profiles
On-axis magnetic field has been measured via MSE for the first time in an RFP.

- Magnetic field as low as 0.16 T is measured.
- Improvements needed to increase accuracy and time resolution.
Summary

• Motional Stark Effect measurements of $|B|$ have been accomplished in a low-field (< 0.5 T) magnetically-confined plasma.

• Good measurement sensitivity differentiates between standard and improved confinement profiles in MST.

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Planned Refinements

- We will more accurately model the expected H-alpha MSE spectrum for low magnetic fields, checking the assumption of statistical weighting of the Stark components.

- We will implement a new CCD spectrometer and FLC shutter to attempt time resolved measurement of the Stark manifold.

- Using a fast spectrometer, we will attempt time-resolved simultaneous measurement of the smeared pi and sigma manifolds.