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Note: Zeeman splitting measurements in a high-temperature plasma

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The Zeeman effect has been used for measurement of magnetic fields in low-temperature plasma, but the diagnostic technique is difficult to implement in a high-temperature plasma. This paper describes new instrumentation and methodology for simultaneous measurement of the entire Doppler-broadened left and right circularly polarized Zeeman spectra in high-temperature plasmas. Measurements are made using spectra emitted parallel to the magnetic field by carbon impurities in high-temperature plasma. The Doppler-broadened width is much larger than the magnitude of the Zeeman splitting, thus simultaneous recording of the two circularly polarized Zeeman line profiles is key to accurate measurement of the magnetic field in the ZaP Z-pinch plasma device. Spectral data are collected along multiple chords on both sides of the symmetry axis of the plasma. This enables determination of the location of the current axis of the Z-pinch and of lower-bound estimates of the local magnetic field at specific radial locations in the plasma. © *2010 American Institute of Physics*. [doi:10.1063/1.3509400]

Measurements of the local magnetic field provide a more complete understanding of the equilibrium pressure profile in a Z-pinch plasma through radial force balance. Magnetic fields are often difficult to measure in high-temperature plasmas because the large energy densities typically prohibit the use of material probes. Other methods to measure the magnetic field in a plasma use the motional Stark effect, Zeeman effect, or Faraday rotation.[1–6] Most implementations of these techniques require neutral particle beams or sensitive interferometry/polarimetry. Typically, Zeeman splitting measurements of line radiation (bound–bound electron transitions) are limited to the relatively cold plasma edge. Doppler broadening is larger than the Zeeman splitting, or the neutral particle beam becomes fully ionized in the hotter region of the plasma.

There are a few examples of successful Zeeman splitting measurements in high-temperature plasmas. Most relevant to this paper are measurements of the magnitude of the magnetic field in plasma pinch devices.[4,5] In these two examples, measurements of Zeeman splitting were made with monochromators sampling narrow wavelength regions of line profiles using polarization as a discriminator. Although successful, the signal-to-noise ratio of these measurements was limited because only a small portion of the line profile was recorded. In addition, subtraction of background radiation is difficult with this technique. We have developed new instrumentation that overcomes these limitations and improves the accuracy of measurements of magnetic field in a high-temperature Z-pinch plasma. The full line profiles of the left and right circularly polarized components of Zeeman-split impurity emission are simultaneously recorded from multiple chords through the plasma. These data enable unambiguous determination of the current location of the Z-pinch and provide a lower-bound measurement of the local magnetic field at specific radii of the plasma column.

Impurity ions in a plasma emit line radiation at wavelengths given by the change of energy of the bound electrons as they fall to lower states. In a magnetic field the energy levels are split creating the Zeeman effect. The wavelength shift, $\Delta\lambda_z$, is given by

$$\Delta\lambda_z = \left(\frac{\mu_B}{hc}\right)(m_2 g_2 - m_1 g_1)\, B\lambda_o^2, \qquad (1)$$

where μ_B is the Bohr Magnetron, h is Planck's constant, c is the speed of light, m_i and g_i are the magnetic quantum number and the Landé factor associated with quantum state i, B is the magnetic field strength, and λ_o is the wavelength of the unshifted emission line.[3,7] The components of a transition for which $\Delta m = 0$ are called the π components; the σ components arise when $\Delta m = \pm 1$. The polarization of the components of a Zeeman spectrum depends on the viewing angle relative to the local magnetic field **B**. When emission is viewed parallel to **B**, only the σ components are observable and the light is circularly polarized, right handed when $\Delta m = +1$ and left handed when $\Delta m = -1$. Emission viewed perpendicular to **B** is linearly polarized, with the σ components polarized perpendicular to **B** and the π components polarized parallel to **B**. The light is elliptically polarized when viewed at intermediate angles with respect to **B**.

A line found to be useful for Zeeman splitting measurements in the ZaP Z-pinch plasma is the $^2S_{1/2}$–$^2P_{1/2}$ transition ($\lambda_o = 581.2$ nm) of the C IV doublet. When viewing emission from this transition parallel to **B**, only two σ components are recorded, a right circularly polarized $\sigma+$ line shifted lower from λ_o, and a left circularly polarized σ-line shifted higher from λ_o. This results in a relatively simple spectrum, although in a high-temperature plasma, the Doppler broadening of each of the σ components is much larger than the Zeeman shift. In a 100 eV plasma, for example, the full width half max Doppler broadening, λ_D, of the C IV line at 581.2 nm is 0.13 nm. This is an order of magnitude larger than the Zeeman splitting in a 1 T magnetic field, Fig. 1. However, Doppler broadening does not change the polarization of the

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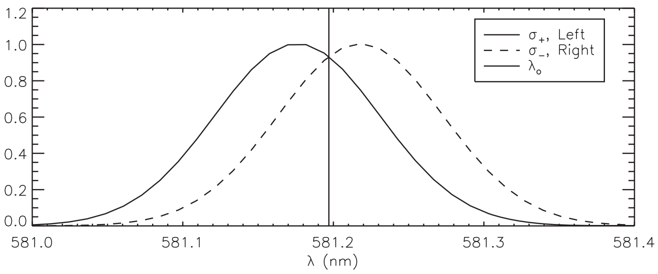

FIG. 1. The spectral intensity measured with a quarter wave plate and linear polarizer show the shift due to Zeeman splitting. The peak of the intensity shift between the right hand circularly polarized (dashed) and the left hand circularly polarized (solid) view is proportional to the magnetic field. The unshifted wavelength is shown for reference.

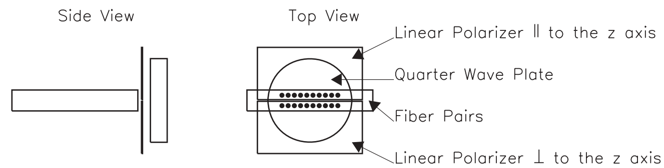

FIG. 3. Drawing of the configuration of the quarter wave plate, filter, and fiber bundles. Each of the fiber pairs views through a linear polarizer and then through the quarter wave plate.

light. Thus polarization discrimination allows the line profile of each of the σ components to be recorded independently. The wavelength separation of the centroid of each of these line profiles is equal to $2\Delta\lambda_z$.

Zeeman splitting measurements are made on Z-pinches formed in the ZaP experiment. The experimental apparatus is shown in Fig. 2.[8–11] Typically plasmas are formed with hydrogen, but methane mixtures can be used to provide carbon impurities. Z-pinches with only an azimuthal magnetic field are formed along the axis of the machine in the assembly region. The Z-pinch exhibits a quiescent period during which the plasma is in a largely stationary state near the axis of the machine. Measurements of the local magnetic field are needed to determine the equilibrium pressure profile and to compare the experimental results with the theoretical predictions.

Light is collected from the bottom port at the $z = 0$ plane with a telecentric telescope with ten pairs of fibers.[12] Each pair of fibers consists of two fibers that view the plasma at the same radial location but are displaced 6.2 mm in the axial direction, $z = \pm 3.1$ mm. The spacing between the pairs of fibers in the radial direction is 3.67 mm, perpendicular to the view shown in Fig. 2. The chief rays of all fibers are parallel to the telecentric telescope, so vertical displacements of the plasma do not affect the viewing geometry. The line radiation is not Doppler shifted because the view is perpendicular to the bulk plasma velocity. This arrangement allows for the collection of light parallel to, perpendicular to, and antiparallel to the magnetic field at the same time. A quarter wave plate and linear polarizer are placed in front of the fibers, shown in Fig. 3. The quarter wave plate is oriented with its axis 45° to the axis of the machine. The linear polarizers are oriented parallel to the axis of the machine for all the fibers at $z = 3.1$ mm, and perpendicular to the axis of the machine for the fibers located at $z = -3.1$ mm. With this arrangement, only left hand circularly polarized light is measured by the fibers at $z = 3.1$ mm and right hand circular polarized light is measured by the fibers located at $z = -3.1$ mm.

The spectral intensities are resolved with a 0.5 m imaging spectrometer, Acton Research SpectraPro 500i, with an intensified 512×512 CCD, PI-MAX (ICCD), at the exit slit/plane. The 20 fibers are arranged vertically at the entrance slit and imaged onto the ICCD. One image is taken per pulse with the ICCD gated at 0.1–1 μs. The dispersion is 0.0121 nm/pixel or approximately 0.6 T per pixel for the 581.2 nm line. Optical distortions caused by the spectrometer are corrected by processing the images. The wavelength curvature and tilt in the image are removed by mapping the image onto a space where each column of the image corresponds to a single wavelength.[13] Since the Doppler broadening is much greater than the Zeeman splitting, tens of pixels are used to find the centroid minimizing the effects of noise. This also enables calculation of the centroid to less than 0.25 pixels.

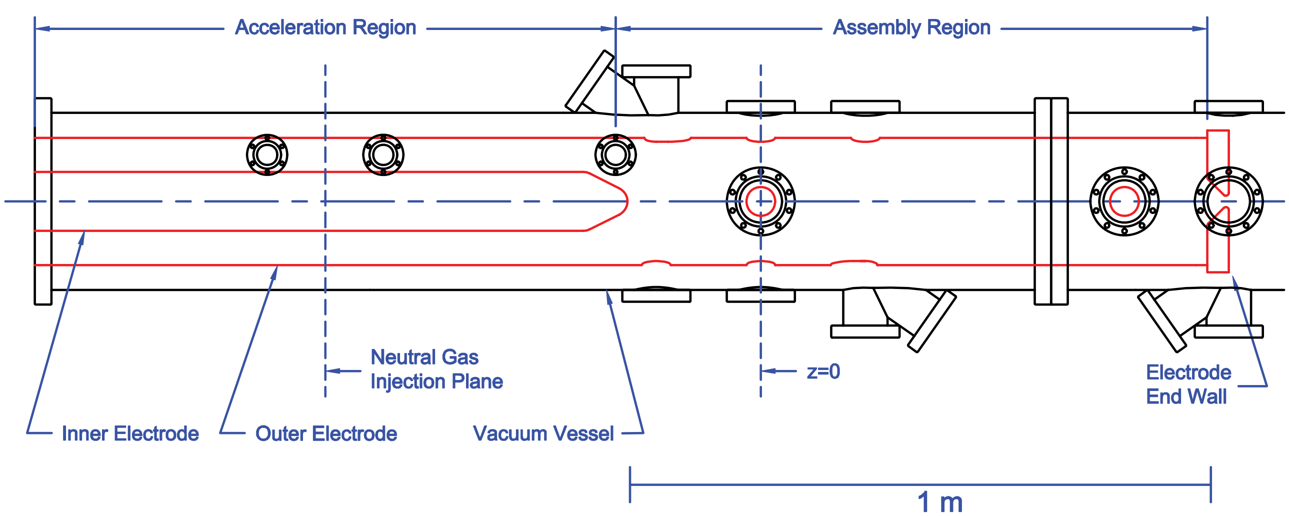

FIG. 2. (Color online) Drawing of the ZaP experimental apparatus is shown. The drawing identifies the key features — the acceleration region, assembly region, and the $z = 0$ plane. Zeeman splitting measurements are made through the bottom port at $z = 0$. A 1 m scale is included for reference.

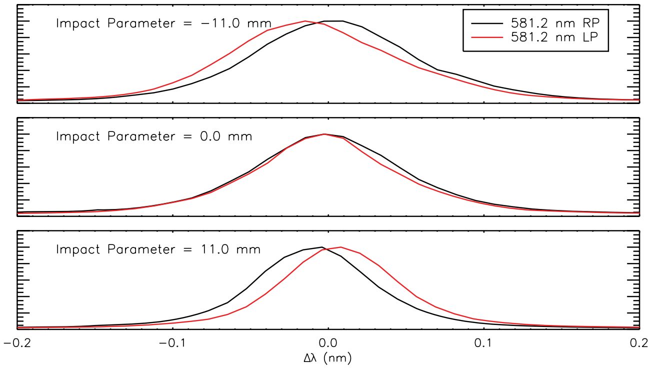

FIG. 4. (Color online) Normalized raw spectral data from three chords through the pinch plasma shows the shift of the right polarization (RP) and left polarization (LP) from the C IV doublet. The shift is plotted relative to the static wavelengths for each line of the doublet. The direction and magnitude of the shifts of the RP and LP are consistent with a Z-pinch magnetic field centered at the geometric center.

Measurements of the magnetic field magnitude are made during the quiescent period. During this time the Z-pinch is stationary near the axis of the machine. The brightness of the C IV doublet is increased by using methane as the working gas of the Z-pinch. The methane Z-pinches exhibit similar characteristics to the pure hydrogen Z-pinches. To prevent burn through to the C V lines, the charge voltage of the main banks is reduced from 9 to 7 kV. This generates Z-pinches with lower magnetic fields and lower temperatures, with similar stability characteristics as the hotter Z-pinches.

The spectral intensities of the C IV doublet at 581.2 nm are measured during a 0.5 μs window. Temporal evolution is determined by taking multiple pulses and adjusting the acquisition time of the ICCD. The spectral intensity functions for three pairs of fibers at different impact parameters are shown in Fig. 4. The unshifted wavelength for each line of the doublet has been subtracted from the x-axis. The splitting of the lines is due to the Zeeman effect. The center of the pinch corresponds to the chord location where no splitting is observed. The shift of the centroids reverses when the view changes from parallel to antiparallel. This corresponds to an azimuthal field from a current centered at the machine axis, impact parameter of 0.

The magnitude of the magnetic field is found for each chord assuming all of the collected line radiation is from the region where the magnetic field is parallel to the viewing chord. The spectral intensities for each chord are fit to

$$E(\lambda) = \frac{A}{\sqrt{2\pi}w} \sum_k I_k \exp\left[-\frac{(\lambda - \lambda_0 - \Delta\lambda_k)^2}{2w^2}\right], \quad (2)$$

where A is brightness of line radiation, $w = \Delta\lambda_D/(8\ln 2)$, and k is each Zeeman component. I_k, the relative intensity, and $\Delta\lambda_k$, the wavelength shift are calculated using Refs. 3 and 7. Fits to spectral intensities from the top and bottom plots shown in Fig. 4 give an azimuthal magnetic field of 0.4 T. This is consistent with the shift 0.007 nm away from the unsplit wavelength seen in those plots.

The measured spectral intensities are integrated along the line of sight. Emission from regions where the magnetic field is not parallel to the line of sight decreases the apparent magnitude of the observed split by contributing light from all of the Zeeman components. These contributions appear as unshifted emissions. The present method based on analyzing the polarization places a lower bound on the maximum magnetic field measured along each chord. While this improves the spatial localization of the magnetic field measurement along the viewing chord, a complete localization of the magnetic field requires spatially deconvolving the spectral intensities using a method similar to Ref. 14.

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