Development of a spectroscopic technique for simultaneous magnetic field, electron density, and temperature measurements in ICF-relevant plasmas

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(Presented XXXXX; received XXXXX; accepted XXXXX; published online XXXXX)
(Dates appearing here are provided by the Editorial Office)

Spectroscopic techniques in the visible range are often used in plasma experiments to measure B-field induced Zeeman splitting, electron densities via Stark broadening and temperatures from Doppler broadening. However, when electron densities and temperatures are sufficiently high, the broadening of the Stark and Doppler components can dominate the emission spectra and obscure the Zeeman component. In this research, we are developing a time-resolved multi-axial technique for measuring the Zeeman, Stark, and Doppler broadened line emission of dense magnetized plasmas for Z-pinch and Dense Plasma Focus (DPF) accelerators. The line emission is used to calculate the electron densities, temperatures, and B-fields. In parallel, we are developing a line-shape modeling code that incorporates the broadening effects due to Stark, Doppler, and Zeeman effects for dense magnetized plasma. This manuscript presents the details of the experimental setup and line shape code, along with the results obtained from an Al III doublet at the University of Nevada, Reno (UNR) Nevada Terawatt Facility. Future tests are planned to further evaluate the technique and modeling on other material wire array, gas puff, and DPF platforms.

I. INTRODUCTION

Visible spectroscopic techniques are often used in plasma experiments to measure B-field induced Zeeman splitting, electron densities via Stark broadening and temperatures from Doppler broadening. Pulsed power research Z-pinch machines, like Sandia's Z machine, National Security Technologies (NSTec) DPF and the University of Nevada, Reno (UNR) Zebra produce dense magnetized plasmas using a Marx bank to drive current through a load or gas. These machines can have current rise times on the order of 100's of nanoseconds with target performance that are magnetically driven and dependent on the current which travels along the outer sheath of the plasma column formation. This current induces a B-field that compresses the plasma, increasing plasma electron density and temperature. Spectroscopy provides a noninvasive way to make these measurements.

Using a time-resolved spectroscopic technique, we can measure the spectral line emission from the plasma sheath. However, when plasma temperatures and densities are high, Stark and Doppler broadening can dominate line profiles, making it difficult to measure the Zeeman component. Two techniques can allow a measurement of both the Stark and Doppler components and the Zeeman component. The first method has been outlined elsewhere[1] and has been experimentally verified[2] at the Z machine in Sandia. In the second approach, the fine structure components of a given multiplet or doublet are split differently due to the B-field.

In the linear regime, the splitting is determined by the change in energy as defined by $\Delta E = g_{LSJ}\mu_B MB$. Where g_{LSJ} is Landé g factor, μ_B is the Bohr Magneton, M is the projection of the total angular momentum J on to the given state in the direction for B. L and S represent the total spin of the orbital momentum of the radiator, where the change in energy defines the broadening of the Zeeman splitting. Since the doublet components have similar Stark and Doppler broadening in the same plasma, the difference in the line broadening of the two doublets depends solely on the B-field, along with the L and S components of the Landé g factor[3,4]. By modeling the transition of the Al III doublet, 4p $^2P_{3/2}$ to 4s $^2S_{1/2}$ and 4p $^2P_{1/2}$ to 4s $^2S_{1/2}$ we can then plot collected data against the model and measure the magnetic fields. The splitting due to weak and strong fields as well as the transitions is illustrated in FIG.1.

In Experiments conducted at the University of Nevada

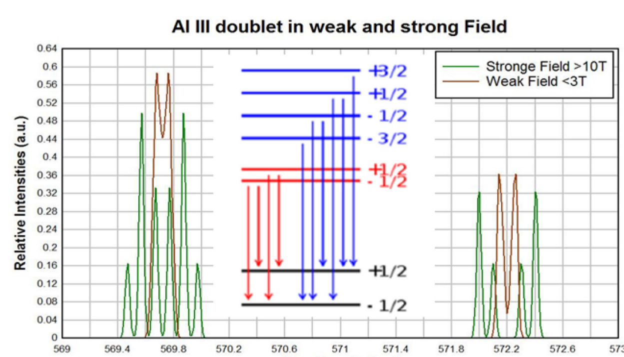

FIG. 1. 4p $^2P_{3/2}$ to 4s $^2S_{1/2}$ and 4p $^2P_{1/2}$ to 4s $^2S_{1/2}$ transition

(Reno) at the Nevada Terawatt Facility (NTF) using the 1 MA Z-pinch (Zebra). The research explored the response of Al III doublet, 4p $^2P_{3/2}$ to 4s $^2S_{1/2}$ and 4p $^2P_{1/2}$ to 4s $^2S_{1/2}$ transitions. Optical light emitted from the pinch is fiber coupled to high-resolution spectrometers. The dual spectrometers are coupled to two high-speed visible streak cameras to capture time-resolved emission spectra from the experiment. The data reflects emission spectra from 100 ns before the current peak to 100 ns after the current peak, where the current peak is approximately the time at which the pinch occurs. The Al III doublet is used to measure Zeeman, Stark, and Doppler broadened emission. The line emission is then used to calculate the temperature, electron density and B-fields. The measured quantities are used as initial parameters for the line shape code to simulate emission spectra and compare to experimental results.

II. EXPERIMENTAL METHOD

A. Characterization

For these experiments a time- resolved spectrometer system was used. The system consisted of an Acton SpectraPro, SP-2750 spectrometer that was coupled to an NSTec L-CA_24 medium speed streak camera with a SI-1000 CCD imager. The linear dispersion of the spectrometer's three gratings, 150 lines/mm (l/mm), 1800 l/mm and 240 l/mm, were characterized with an Oriel Instruments' 6035 Hg(Ar) lamp. The light was fiber coupled to the spectrometer and focused onto the slit of the streak camera. For the 150 l/mm grating multiple spectral lines are incident on the slit. These lines correspond to a pixel, and we can determine the linear dispersion of the wavelengths per pixel. To characterize linear dispersion for the 1800 l/mm and 2400 l/mm grating we used three spectral lines from Hg, the 546.1 nm line, the 577 nm line, and the 579 nm line. In this method, the spectrometer center wavelength was initially set to 546.1 nm. We proceeded to shift the center wavelength across the slit down until the line walked off the slit and image window. Taking the difference of the high and low wavelength divided by the total number of pixels gave us a value of the linear dispersion. We then used the 577 nm and 579 nm spectral lines to validate the linear dispersion found with calculated by this method.

B. Experiment

The experiment was conducted at the Zebra facility, and consisted of two optical probe systems to collect light in the different regions of the plasma. The probes were aligned to two different areas, at 90° from each other and radially from the pinch. FIG. 2 illustrates the experimental setup. Probes 1 and 2 used an F220SMA-532 fiber collimator to collect light emitted from the plasma in the Zebra chamber. The probes allowed for light collection from a circular area with an approximate diameter of 1 cm.

Light was delivered from the pinch to an optical streaked spectrometer with a series of fibers, these consisted of: a F220SMA-532 fiber collimator that was connected to a vacuum fiber used to pass through a vacuum port feedthrough on the Zebra chamber wall. An external optical fiber was then connected to the feedthrough and coupled to an Acton SpectraPro SP-2750 spectrometer. The output of the spectrometer was aligned to the slit of an NSTec L-CA-24 streak camera that used a microchannel plate intensifier and SI-1000 CCD.

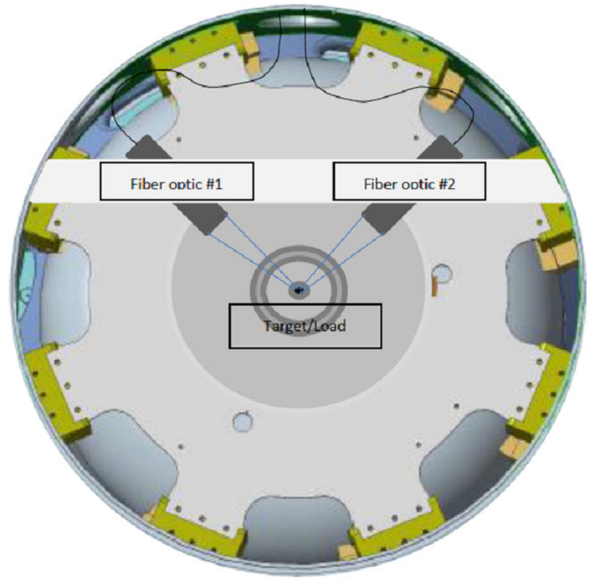

FIG. 2. Experimental setup. Diagram of the Zebra chamber and fiber optic probe configuration.

The wire array loads used for this experiment were Aluminum (Alloy XX) wires. The wire configuration consisted of x-pinch, cone, inverse cone, and cylindrical wire arrays. FIG. 3 is a picture of an inverse conical wire array and the optical probe in the chamber and as seen in FIG. 2.

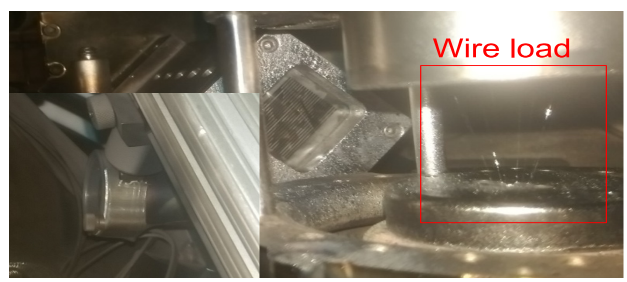

FIG. 3. Left optical probe to the right inverse cone array

The streak camera sweep duration was set to 480 ns and the spectrometer was set to a center wavelength of 570 nm. Data was collected 250 ns before the peak current. An initial survey of visible spectra was done using the 150 l/mm grating. When the Aluminum III doublet was identified, higher resolution gratings, 1800 l/mm and 240 l/mm, were used.

III. RESULTS AND ANALYSIS

Data was taken over two weeks at a rate of several shots a day. Streaked data was then processed by applying the characterization data and used to map the wavelength (nm) across the pixels. A lineout was taken at 100 ns before the current peak, averaged over 20 ns, and taken every 20 ns throughout the entire sweep record. A typical Al III doublet emission lasts approximately 60-70 ns. FIG. 4 presents an example of a typical image and line out from a conical wire array load.

The collected data is further compared to a line emission model using PrismSpec. The model allows us to vary the electron density and temperature parameters to fit the streak data. Once an approximate fit is achieved the output line width, from PrismSpec is used as an input parameter in a Zeeman splitting code. The code models the line emission of the different transitions caused by the B-field. This process is iterated until an approximate fit, including broadening from Zeeman, Stark, and Doppler is achieved. This model is then used to infer the electron density, temperature, and magnetic fields.

In FIG. 4, shot 4369, the temperature and electron density were modeled at 10 eV and 1e16 cm^{-2}. The B-field at 120 ns before the current peak is found to be 2.3 Tesla, 1 Tesla at 140 ns before current peak and 0.5 Tesla 160 ns before the current peak. A plot of the B-field as a function of time is shown in FIG. 5. This is compared to the theoretical B-fields, using the current measure from the B-Dot system in the Zebra chamber.

Using the model for a cylindrical geometry, the B-field between the two conductors is given by

$$B=\mu I/2\pi r \qquad (1)$$

Where there is current passing axially through the conducting cylinder, μ is the permeability of the material between the conductors and r is the radius of the conductor[4]

$$B[T] = 200*I[MA]/r[mm] \qquad (2)$$

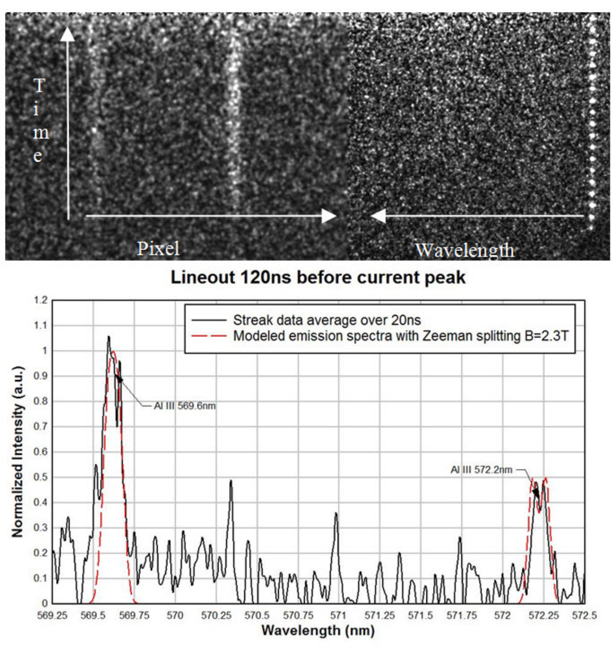

FIG. 4. Streaked spectra image and line out, averaged over 20ns, of an Al III doublet 120 ns before the current peak.

Typical fields are plotted in FIG. 5 for a cylindrical load.

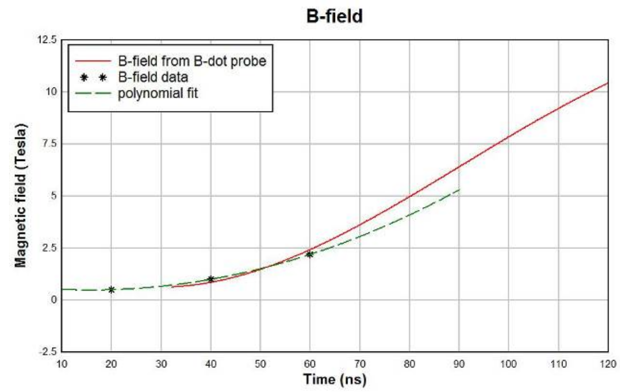

FIG. 5. B-field as a function of time from spectroscopy and B-dot data.

Spectroscopic measurements of Aluminum wire arrays have been made using the Al III doublet, 4p $^2P_{3/2}$ to 4s $^2S_{1/2}$ and 4p $^2P_{1/2}$ to 4s $^2S_{1/2}$ transitions. Using PrismSpec in conjunction with a modeling that has been developed at UNR for Zeeman Splitting, we have measured temperature, electron densities and B-fields. Measurements at higher temperatures, >15 eV, and electron densities >1e17 will require additional modeling and the use of other material or dopants.

V. ACKNOWLEDGMENTS

The authors would like to thank the support staff and graduate research assistants at the University of Nevada, Reno Nevada Terawatt Facility. This work was done by National Security Technologies, LLC, under Contract No. DE-AC52-06NA25946 with the U.S. Department of Energy and supported by the Site-Directed Research and Development Program. DOE/NV/25946--2875.

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