Visible-light spectroscopy of pulsed-power plasmas (invited)

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We describe the investigations of the plasma behavior in three pulsed-power systems: a magnetically insulated ion diode, and plasma opening switch, and a gas-puffed Z pinch. Recently developed spectroscopic diagnostic techniques allow for measurements with relatively high spectral, temporal, and spatial resolutions. The particle velocity and density distributions within a few tens of microns from the dielectric-anode surface are observed using laser spectroscopy. Fluctuating electric fields in the plasma are inferred from anisotropic Stark broadening. For the plasma opening switch experiment, a novel gaseous plasma source was developed which is mounted inside the high-voltage inner conductor. The properties of this source, together with spectroscopic observations of the electron density and particle velocities of the injected plasma, are described. Emission line intensities during the switch operation are discussed. In the Z-pinch experiment, spectral emission-line profiles of various charge-state ions are studied during the implosion phase. Radial velocity distributions are observed from the line Doppler shifts and widths.

I. INTRODUCTION

The understanding of the complicated phenomena that take place in a high power device can be improved if high-resolution nonintrusive diagnostic methods are used to observe many physical quantities inside the device. We use observations of spectral line shapes to determine as a function of time in a single discharge, the magnetic field distribution from Zeeman splitting,[1] the ion velocity distribution from Doppler broadenings and shifts,[2] the electron heating from line-intensity ratios,[3] and the particle density distributions from laser absorption and laser-induced fluorescence.[4] For analyzing the line intensities for this nonequilibrium plasma we use our time-dependent collisional-radiative calculations.[5] The investigations reported here are done on plasmas in three pulsed-power devices: a magnetically insulated ion diode (MID), a plasma opening switch (POS), and a Z pinch. In Sec. II we summarize the main features of our diagnostic systems and recent results from the MID experiment are given in Sec. III. In Secs. IV and V, respectively, we describe the experimental systems for the plasma opening switch and the Z pinch, together with electrical measurements and preliminary spectroscopic observations.

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II. DIAGNOSTIC SYSTEMS

Figure 1 presents the various features of our diagnostic systems used for the various experiments, shown here in reference to the diode experiment. In brief, light is directed from the plasma onto 1-m or 1.3-m spectrographs. For each spectrograph, a profile of a spectral line is observed in a single discharge by optically dispersing the spectral line at the output of the spectrograph, projecting its image on a rectangular array of 12 fiber bundles, and measuring the light signal transmitted in each fiber by a photomultiplier tube and a digital oscilloscope. The temporal resolution in these systems is $\lesssim 5$ ns. Alternatively, the spectrograph exit window is streaked by a fast UV camera to allow for the observation of spectral profiles of a few lines in a single discharge with a nanosecond temporal resolution.

The spectrographs are equipped with 2400 grooves/mm gratings allowing for a spectral resolution down to 0.05 Å. The spatial resolution is determined by the input optics and it can be varied from tens of microns to a few millimeters. The fused-silica optics, the photomultiplier tubes, and the streak camera allow for sensitivity in the range 2000–7000 Å. Absolute calibration of the systems over the entire spectral range provides the absolute emission line intensities, thus allowing the absolute level populations in the plasma to be obtained.

For the diagnostics we also use a high-power pulsed (6 ns) dye laser pumped by a Q-switched Nd:YAG laser equipped with a unit that extends the wavelength range to 2160–9000 Å. Using this laser system, high-spatial-resolution measurements based on resonant laser absorp-

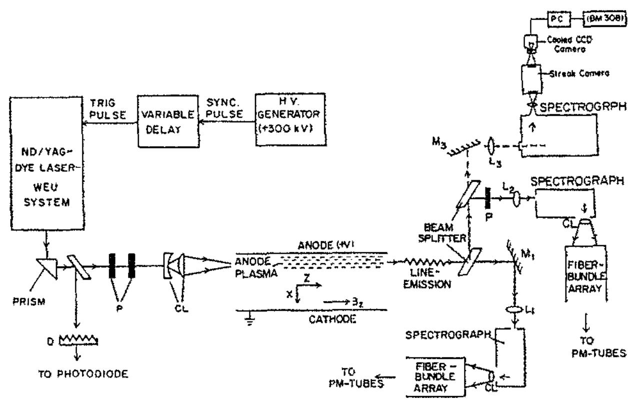

FIG. 1. The laser system and the diagnostic arrangement. WEU, D, Cl, and M denote a wave extending unit, a diffuser, a cylindrical lens, and a mirror, respectively. The laser light, synchronized with the diode voltage pulse, can be directed into the diode in the x and y directions. Laser light, induced fluorescence, and spontaneous emission can be collected in various directions by the two spectroscopic systems. The polarizers P are used for the polarization spectroscopy. For cylindrical plasmas the line emission is imaged on a cylindrical fiber array. For observing the spectral line profile as a function of time in a single discharge either a fiber-bundle-photomultiplier-tube-digitizer system or a fast streak camera system are used.

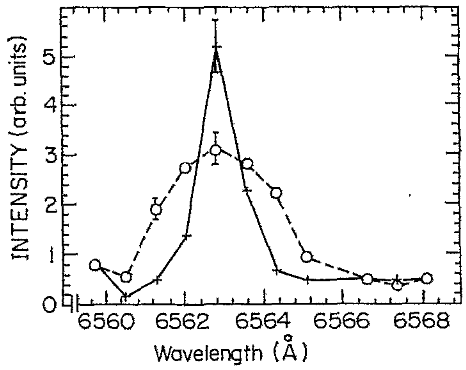

FIG. 2. Measured profiles of H_α observed using a line-of-sight parallel to the anode surface and perpendicular to the magnetic field applied parallel to the anode surface. The spectral resolution is 0.76 Å. The solid line is the profile obtained for a polarization parallel to the magnetic field and the dashed line for polarization perpendicular to the anode surface.

tion are obtained, as described in Sec. III.

Time-dependent collisional-radiative models of many atomic systems, such as carbon,[5] magnesium,[6] and silicon[6] have been constructed in order to interpret the absolute and relative spectral line intensities. These calculations are especially important for diagnosing short-lived pulsed-power plasmas whose level populations are far from being in a steady state.

III. HIGH-POWER DIODE EXPERIMENT

The behavior of the electrode plasmas in high power electron or ion diodes, transmission lines, and microwave sources significantly affect the device operation. Recently, we have investigated the anode plasma in the planar magnetically insulated diode.

The magnetic field penetration into the anode plasma was observed as a function of time throughout the 100-ns-long voltage pulse from line Zeeman splitting.[1] From the fast field penetration a plasma resistivity higher than the classical one was inferred. This led us to search for collective electric fields in the plasma that could be associated with the anomalous conductivity. The amplitude, direction, and frequency range of anisotropic fluctuating collective electric fields in the anode plasma were investigated by the use of polarization spectroscopy of the Stark broadened hydrogen lines.[7] The method utilizes the effect that when the emission line spectral profiles are affected by anisotropic fields the observed profiles are dependent on the polarization and of the line of sight, as was used for longer duration plasmas in a mirror machine.[8] In our experiments, the spectral profiles of H_α and H_β were measured for two lines-of-sight and for two different polarizations.[7] An example of such a measurement showing the different H_α widths observed for the two orthogonal polarizations is given in Fig. 2. The data are being analyzed using calculations of the Stark broadening for these lines under the combined influence of the collective fields and the isotropic particle fields in the plasma. Fluctuating electric fields with an amplitude of $\simeq 8$ kV/cm dropping to zero at the end of the pulse were inferred.[7] The fields point mainly perpendicular to the anode surface and to the applied magnetic field. Using the observed ion velocity distribution a lower bound of $\simeq 10^9\ s^{-1}$ for the field frequency was obtained.

In a previous study,[9] we have shown that the particle fluxes from the anode surface into the plasma are considerably affected by the plasma properties at the immediate vicinity of the anode surface. Here, we report on the use of laser absorption and laser-induced fluorescence to directly determine the particle ground-state densities and the particle velocities with a spatial resolution of $\simeq 30$ μm near the surface. Figure 3 gives a sample of our measurements and Fig. 4 shows the inferred ground state and excited-state densities. The densities of the Mg II ground and first-excited states and of the Li I ground state were observed to drop considerably within $\simeq 50$ μm from the anode surface.

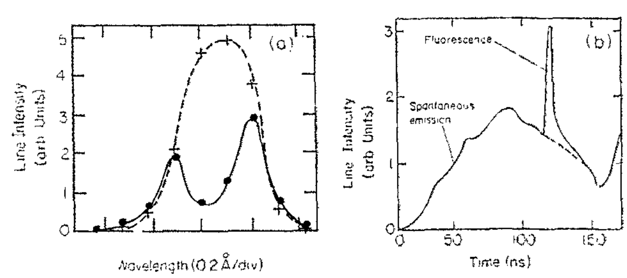

FIG. 3. (a) Typical spectral profile of the laser light transmitted through the anode plasma for the light wavelength $\lambda = 2795.53$ Å corresponding to the Mg II $3P_{3/2} \rightarrow 3S_{1/2}$ transition (solid curve). Also shown is the spectral profile with no plasma in the diode (dashed curve); (b) Spontaneous emission of the $3P_{3/2} \rightarrow 3S_{1/2}$ transition together with the fluorescence resulting from the same transition induced by the laser saturated excitation. Here, the observation distance from the anode surface was 0.1 mm.

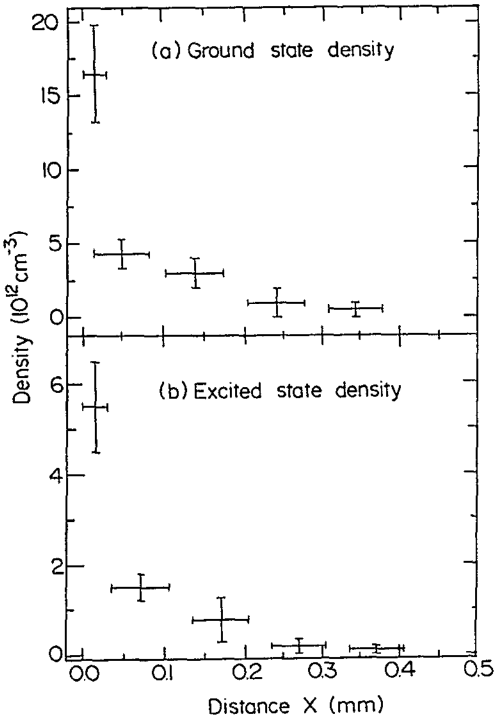

FIG. 4. (a) The Mg II ground state density as a function of the distance x from the anode surface obtained from the laser absorption at 2795.53 Å for $t=55$ ns after the start of the diode voltage pulse. The spatial resolution near the anode surface is $\simeq 30$ μm; (b) Similar to (a) for the density of the Mg II excited state, $3P_{3/2}$, obtained from the laser absorption at 2798 Å.

The Mg II Doppler broadened absorption profile showed that a significant fraction of the Mg II velocities seen in the anode plasma[2] is acquired by the ions within $\simeq 30$ μm from the anode surface. This is a complement to our previous data[9] which suggested that the ion kinetic energies in the plasma result from the presence of electric fields at the immediate vicinity of the anode surface.

The observed particle velocity and density distributions are being used to obtain estimates of the rate of particle ionizations near the surface and for the electron density and temperature within a few tens of μm near the anode surface. The inferred values are being compared to those estimated from the ratio between the ground and the first-excited level densities. This ratio can also give information on the material release from the surface into the adjacent plasma layer.

It has been suggested that the ionization of an expanding layer of neutral atoms near the anode surface makes a major contribution to the initial plasma formation.[10] Several theoretical models are currently being used to study the general problem of ion flow through an ionizing layer and the resulting plasma buildup and screening of the electric field. Our analysis indicates that the rate of electron leakage from the plasma to the anode has a major effect on the rate of electric field screening. Possible mechanisms for this electron flow include cross field drifts and losses parallel to the applied magnetic field.[11] For each mechanism there corresponds a range of possible electron flow rates.

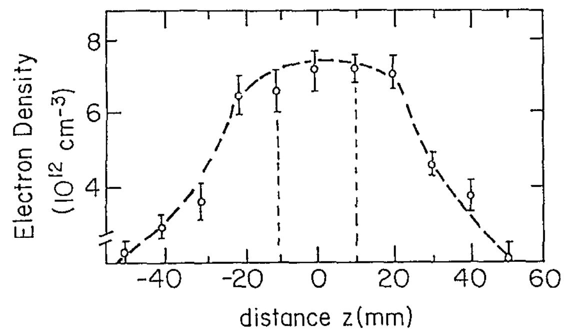

FIG. 5. The plasma density along the axis 3 μs after the gas discharge measured by biased collimated charge collectors placed at a radial distance of 20 mm from the capillaries. $Z=0$ is the axial center of the plasma source and the dashed lines indicate the capillary region of 20 mm length. The source gas is CH_4.

Therefore, comparison to time resolved measurements of the electric field in the diode gap will allow us to estimate the dominant mechanisms of electron flow from the anode plasma.

IV. THE PLASMA OPENING SWITCH EXPERIMENT

The POS concept is relevant to various pulsed-power applications. Although considerable progress in the use of plasma switches has been made in the recent years, experimental investigations are still highly required for the examination of the various underlying models. Knowledge of the distribution of the magnetic field, the electron density, and the particle flow in the switch plasma is of major importance. We intend to study these phenomena in our newly built experiment. We developed a novel gaseous plasma source that allows for satisfactory control of the plasma species and for seeding the plasma with various elements are required for the spectroscopic observations. The plasma source is based on forming gas discharges in many capillaries drilled in the wall of a hollow tube. The discharge current, of a density of a few kA/cm^2 in each capillary, produces highly ionized plasma that flows to the outside of the capillaries. Another feature of our experiment is that the plasma source is mounted inside the high-voltage cylindrical inner electrode, injecting the plasma radially outward into the spacing between the two electrodes.

The plasma source operation has been optimized and characterized by examining the effects of the source length, the number of capillaries, the hollow tube dimensions, and the various gases and pressures. The plasma electron density and temperature were measured simultaneously by three sets of double floating probes placed in various locations. In addition, two negatively biased collimated charge collectors were used to measure the time-dependent plasma ion density and uniformity along the axial, azimuthal, and radial dimensions. The axial density distribution, given in Fig. 5, shows that the plasma density is uniform over $\simeq 40$ mm and drops to zero at each side over $\simeq 20$ mm. The plasma source reproducibility, inferred from electric probes and light intensity signals, is $\pm 20\%$. The plasma electron density and temperature measured in the inter-

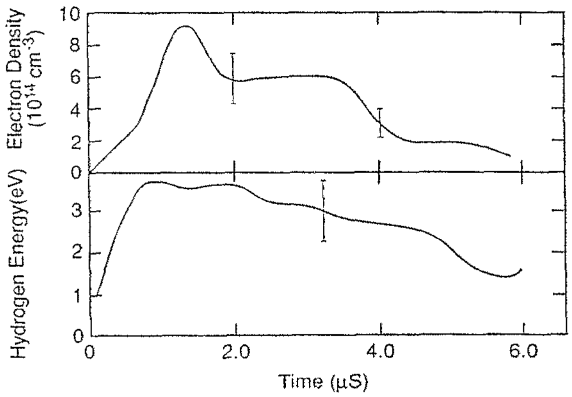

FIG. 6. Time-dependent electron density and hydrogen kinetic energy in the axial direction, obtained from H_α and H_β spectral profiles observed in this direction at 2 mm from the capillaries. The uncertainty in the measurements is ±20% as indicated.

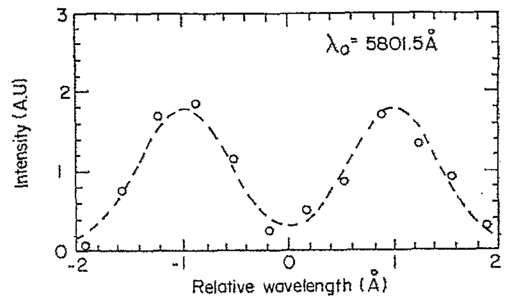

FIG. 7. Radial profile of the C IV 5801.5 Å line emission 90 ns prior to the pinch. The contribution from the continuum light has been subtracted from the profile. The wavelength separation between the two Doppler shifted distributions corresponds to a radial velocity $V_r \simeq 5\times 10^6$ cm/s.

electrode gap, using various gases and discharge currents, ranged between 10^{13}–10^{14} cm^{-3} and 10–20 eV, respectively. The plasma radial propagation velocity was found to be 2.0–5.0 cm/μs.

The plasma properties were also studied spectroscopically. Here, we report on measurements of the H_α and H_β line profiles from which the Doppler and Stark line broadening were unfolded self-consistently to yield the electron density and the axial hydrogen kinetic energy. These parameters are given as a function of time in Fig. 6.

The Marx water line generator (1.5 kJ, 600 kV, 1 Ω) can charge the inner electrode positively or negatively. In the positive mode it delivers a 90-ns-long current pulse with a peak value of 160 kA. Discharges were made for both Ar and CH_4 as source gases. In these experiments line intensities of various charge states were observed axially for four radial locations. The results show emission signals during the 100-ns-long current pulse and signals that rise 1–2 μs after the termination of the switch current. The carbon component of this late plasma is believed to originate from the inner and the outer electrodes since it appears similarly when both Ar or CH_4 are used in the plasma source. Based on the time delay of the late light signals with distance from the electrodes, a flow velocity of $\simeq 1$ cm/μs for the plasma injected from both the anode and the cathode surfaces is inferred. Knowledge of the density, composition, and velocity of the plasma injected from the electrodes is important for the development of long time Plasma Opening Switches.

V. THE *Z*-PINCH EXPERIMENT

The study of *Z*-pinch plasma is important for many present day applications such as in controlled fusion,[12] magnetic flux compressors, and particle beam sources as well as for sources of intense x-ray and vacuum ultraviolet (VUV) radiation used in material testing, lithography, and microscopy studies.[13] The dynamics of plasma pinches are very complicated involving processes such as plasma acceleration, heating, and magnetic field penetration. The main goal of this work is to study the implosion phase of the pinch which is important for understanding the dynamics of the pinching and its influence on the final state of the plasma and is also believed to contribute in general to the understanding of the flow of ionizing plasmas under strong magnetic fields.

A gas-puff *Z*-pinch experiment has been constructed which produces a 400 kA, 1 μs current pulse.[14] Gas, with pressure up to 6 atm is released into an annular nozzle, producing a well collimated gas shell extending between the anode and cathode. Voltage up to 35 kV is then switched across the electrodes initiating the breakdown. The pinch occurs approximately 600 ns after the beginning of the current rise.

Line emission from the *Z*-pinch plasma is observed for many transitions in singly, doubly, and triply charged ions throughout the UV-visible wavelength region during most of the discharge.[14] Using CO_2 as the injected gas, line emissions from oxygen and carbon ions are observed in the radial direction with spatial resolution of 500 μm. Emission from the central region of the plasma, a few millimeters away from each electrode, is mainly due to the dissociation and ionization of the injected CO_2 gas rather than from material injected from the graphite electrodes. This is supported by observations of carbon emission using Ar as the injected gas and will be presented in future publications.

Shown in Fig. 7 is a typical profile of the C IV 5802 Å line ($3P_{3/2}$–$3S_{1/2}$) 90 ns before the pinch time. Two Doppler shifted distributions are observed due to the emission from the far and near sides of the plasma shell. Measurements were also performed using polarizers oriented parallel and perpendicular to the magnetic field. No significant differences in the profiles were found, indicating that the contribution from Zeeman splitting was negligible at this time. This is also consistent with calculations of the magnetic field based on the measured current and radius determined from streak photography. Self-absorption effects were also estimated to be small, based on collisional-radiative calculations of the C IV level populations.[5]

The wavelength separation between the two distributions is used to determine the average radial velocity of the ions. The radial velocity of the C IV ions reach approximately 5 cm/μs. This value also corresponds well to estimates of the radial velocity determined from streak photography of the plasma diameter. Assuming an isotropic distribution the width of each lobe corresponds to a temperature of approximately 85 eV.

The O IV 3063.5 Å ($3S_{1/2}$–$3P_{3/2}$) was also observed to have a similar Doppler profile during the implosion phase. However, line emission from singly charged oxygen and carbon ions during the same period are best fit by a single Gaussian profile and have significantly smaller radial velocities. We are presently developing theoretical models to better understand this phenomena.

VI. SUMMARY

Recently developed spectroscopic diagnostic methods are being used to investigate the plasma behavior in an intense ion diode, a plasma opening switch, and a Z pinch. In the diode experiment, the magnetic field, turbulent electric fields in the plasma, and the particle density and velocity distributions at the immediate vicinity of the anode surface were observed using emission-line Zeeman splitting, polarization spectroscopy of Stark broadened lines, and Doppler effects in laser spectroscopy, respectively. In the plasma opening switch experiment, a gaseous plasma source was developed and characterized and time dependent line intensities of various charge states during the switch operation are studied. In the Z-pinch experiment, Doppler profiles are being used to study the particle velocity distributions of the imploding plasma shell. Differences in radial velocities and velocity distributions between various charge states and ions are being investigated.

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