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Spectroscopic Investigations of the Energy Flow in a Nonequilibrium Imploding Plasma

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Abstract

The history of the ionization dynamics and energy deposition processes during the implosion phase of a 0.6 μs, 220-kA gas-puff *Z*-pinch plasma are studied by means of high-resolution spectroscopic measurements of the intensities and spectral profiles of optically-thin ionic emission lines in the UV-visible spectral region. The gas source used is CO_2, and singly- to five-times-ionized oxygen ions were observed as a function of time during the implosion, between ~ 180 to ~ 50 ns before maximal compression.

The radial-distribution history of the magnetic field has been determined by the observation of the contribution of the Zeeman effect to the spectral line profiles of various charge-state ions. The dominance of the line profiles by the Stark and Doppler broadening effects required high-accuracy profile measurements and the use of polarization spectroscopy. These measurements showed that the plasma conducts the entire circuit discharge current during the implosion. Comparison of the data to the solution of the magnetic diffusion equation allowed for the determination of the electrical conductivity of the plasma, which was found to be in agreement with the Spitzer value.

The electron and ion densities in the plasma are obtained using three independent methods, namely measurements of the continuum radiation, measurements of the particle ionization times, and a self-consistent procedure for analyzing measurements of absolute line intensities in a multi-component plasma, which also yields the histories of the electron temperature and charge-state composition. Based on the densities obtained, it was found that between 140 to 50 ns prior to maximal compression, a period during which the front of the ionized shell propagates radially inward from r = 12 mm to $r \approx 4$ mm, the total mass of the imploding plasma increases by ~ 15%. Since this is in agreement with the amount of gas known to be present between these two radial positions, it shows that no mass is lost from the imploding shell at this time and location intervals.

Time dependent measurements of spectral-line widths for the various charge states were carried out in order to independently determine the electron density based on the Stark effect on the line profiles. The data were analyzed using two independent treatments for Stark broadening calculations. For the lines of the high charge states, the spectral widths observed were found to be higher by a factor ~ 3 than the Stark-broadening calculations, expected for the density values determined using the other three methods described above. Several possible mechanisms that may contribute to the line broadening are discussed, and it is suggested that a small-scale turbulent ion motion within the imploding plasma is a likely scenario for explaining the large line widths observed. Such a study, which represents an experimental investigation of a hydrodynamic turbulence in a dense plasma, to the best of our knowledge is made here for the first time.

The radial-distribution history of the electron temperature is determined from the comparison of ionic level-population ratios, obtained from line-intensity measurements, to the results of time-dependent collisional-radiative calculations. With the aid of these calculations, the measurements were so designed to allow for the minimization of the effects of the plasma flow and the continuous ionizations on the determination of the electron temperature. Using the distributions obtained of the temperature, the electron density, the current density, and the independently measured ion radial velocities [M.E.

Foord *et al*, Phys. Rev. Lett. **72**, 3827 (1994)], each term in the 1-D hydromagnetic equations has been separately obtained experimentally. This allowed for studying the history of the magnetic-field energy coupling to the plasma by comparing the experimentally-determined energy deposition and dissipation rates in the plasma (within a 1-D approximation). It is found that at this phase of the implosion, ~ 65% of the energy deposited in the plasma is converted into kinetic energy, and the rest is dissipated in the forms of heat, ionization, and radiation. In addition, these data yield the particle momentum gain due to the contributions of each of the magnetic-field and the thermal pressure gradients. Also for this plasma, an ionization wave is seen to propagate radially inward faster than the particles. The energy sources that support this ionization front propagation in the plasma were determined.

Such detailed experimental investigations of imploding plasmas as reported here can be used for examining hydrodynamic codes for the simulations of dense plasmas.