Holographic interferometry of a high-energy-density exploding lithium wire plasma

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Single-wavelength holographic interferometry was applied to the study of an exploding lithium wire plasma. The wire was 1 mil in diameter, extruded in vacuum. A holographic-quality ruby-laser probe produced a 16-ns FWHM pulse at $\lambda = 694.3$ nm with 45 mJ in the TEM_{00} mode. A temperature-controlled resonant reflector restricted laser operation to essentially a single-longitudinal mode. Linear charge density measured from Abel inverted interferograms implied that a significant amount of neutral or un-ionized lithium was present in a cold core. Peak electron density reached 1.4×10^{19} e^-/cm^3 and $2 < T_e < 10$ eV, but significant neutral contribution prevented accurate electron density determination near the core. Three characteristic periods of plasma development were identified and compared to time-resolved streak photographs of the luminous plasma front and optical spectra. Of special interest, a period of localized neutral "cloud" formation was observed with densities reaching 8×10^{17} cm^{-3}, forming after self-pinching and before peak discharge current.

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I. INTRODUCTION

Exploding wires have been studied for years as x-ray-sources, detonation fuses, shock sources,[1,2] and as sources of high-density plasma for laser-plasma coupling experiments.[3] Theoretical modeling of the plasma spectroscopic, electronic, and MHD characteristics requires detailed knowledge of the radial electron density profile across the plasma column. With such knowledge one can ray trace through the known profile and predict absorption along the path.[4] Spectral emissivity can then be estimated, electronic characteristics can be explained, and MHD models can be verified.

The steep density gradients ($> 10^{20}$ cm^{-4}) and high peak electron densities (10^{18}–10^{19} cm^{-3}) of the exploding wire plasmas restrict the techniques of density-profile measurement to optical interferometry. Since exploding wire plasmas of high energy density are infamously irreproducible, an entire profile measurement must be made in one shot. By choosing a laser of sufficiently small pulse width, but sufficiently large energy, one can freeze plasma motion and illuminate the entire plasma in one arm of an interferometer. Optical interferometry of the Jamin or Mach-Zehnder type requires high-optical-quality windows, lenses, and reflecting surfaces. Double-exposure holographic interferometry does not have such limitations, and was utilized in this investigation of exploding lithium wires.

Holographic interferometry has been successfully utilized elsewhere to provide high temporal and spatial resolution of fully ionized high-density plasmas.[5-7] Exploding wire plasmas, however, are rarely fully ionized and present a formidable challenge to quantitative electron density measurement. Two-wavelength interferometry is specifically equipped to solve this problem by eliminating the neutral contribution to refractivity.[8] Much two-wavelength work appears in the literature,[6,9,10] but little of it is applied to partially ionized plasmas. In one particular case, two-wavelength holographic interferometry was applied to exploding wire plasmas with rather uncertain results.[11]

Single-wavelength holographic interferometry still holds the possibility of obtaining qualitative information regarding temporal plasma development and hydrodynamic stability. It also permits estimation of the level of ionization, which may be compared to computed estimates based on a matrix of equilibrium rate equations. Neutrals in a partially ionized plasma contribute both to refractivity and to absorption. They not only increase the ambiguity of interferometric measurements, but they may destroy fringe contrast by decreasing the transmitted beam intensity in the interferometer object arm.

The primary experiments performed to date in holographic interferometry of exploding wire plasmas have been those of Seftor.[11,12] In his publications Seftor commented that improved laser spatial behavior would significantly improve the quality of his holograms.

In the work described in this paper, a KORAD ruby laser has been modified to produce a uniform TEM_{00} output mode of 45-mJ energy and 16-ns FWHM pulse width. This holographic-quality laser has been utilized to generate holographic interferograms of a 1-mil (25 μm diameter) exploding lithium wire plasma. The study has revealed much in terms of wire-plasma dynamics and effective charge state.

II. EXPERIMENTAL CONFIGURATION

Holographic interferograms were produced with a double-exposure image-plane technique. Referring to Fig. 1, a ruby laser operating at 694.3 nm generated a 2.0-mm-diam

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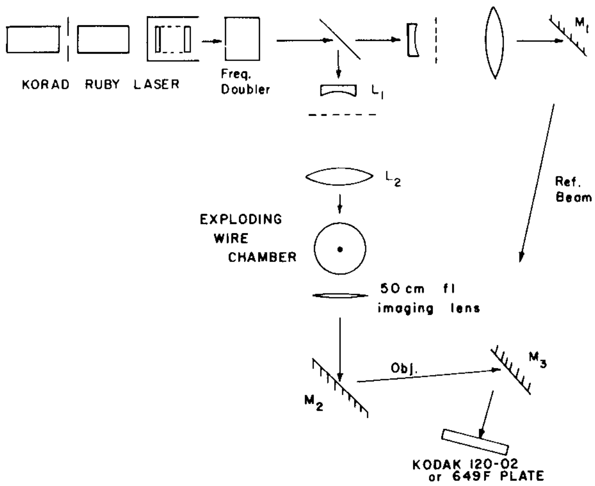

FIG. 1. Schematic of holographic interferometer; L_1 = − 1-cm fl, L_2 = 35-cm fl.

TEM_{00} beam, which was expanded via lenses L_1 and L_2 to 7 cm in diameter. The reference beam was collimated and directed via beam-steering mirrors (not shown in Fig. 1) to the holographic plate. KODAK 120-02 plates were used throughout. The object beam was collimated and directed through the vacuum chamber containing the 5.0-cm-long 1-mil-diam lithium wire. The exploding wire plasma was imaged 1 : 1 onto the holographic plate in order to capture refracted rays. A 50-cm–focal-length 6.3-cm-diam lens was used for imaging. This permitted the observaton of electron density gradients reaching 7×10^{20} cm^{-4} over the entire plasma radius during a pinch. Between the two laser exposures, one of the reference beam-steering mirrors was rotated. This changed the incident reference beam angle by ~ 1.7 mrad and placed moiré fringes on the interferogram spaced 4–5 lines/mm. Neutral-density filters in the interferometer arms adjusted exposing intensity to achieve a final exposed density of ~ 1.0. The laser- and beam-expanding optics were floated on inner tubes to maintain the laser mirror alignment, but all other components were hard mounted.

Large holographic diffraction efficiency was obtained by ensuring a single- or adjacent-longitudinal-mode laser operation and TEM_{00} transverse-mode operation. Spatial coherence was further maintained by selecting better quality vacuum chamber windows (i.e., windows of high optical finish as observed by the eye) and by avoiding inhomogeneous regions of optical filters. An intracavity aperture restricted oscillation of the lowest-order transverse mode. Longitudinal-mode control was obtained by replacing the normal output sapphire etalon with a BK-7 four-surface resonant reflector. The reflector was placed within a temperature-controlled oven steady to ± 0.01 °C. The measured interferometer coherence length was 0.8 m, implying a lasing bandwidth of 0.0025 Å (when frequency sweep during the pulse is taken into account).[13] This corresponds to one axial mode oscillating strongly and one adjacent axial mode oscillating weakly in the 75-cm laser cavity.

The exploding wire plasma was initiated by discharging a 13.7-μF 40-nH capacitor charged to + 15 kV through a 1-mil-diam lithium wire. The wire was extruded through a diamond die in a vacuum of 5×10^{-6} Torr, ensuring no oxygen or hand oil contamination (see Fig. 2). Peak current reached 100 kA with a quarter ringing period of 3.25 μs. (The electrical charging and triggering circuit has been presented elsewhere.[3]) A streak camera viewed the plasma at 90° to the interferometer object arm, monitoring the plasma luminous front with an S-20 response photocathode. Streak photographs were compared with observations of di/dt through the plasma, as observed on a Rogowski coil (where i = current and t = time).

III. PLASMA CHARACTERIZATION

Earlier spectroscopic studies of this exploding lithium wire plasma had placed electron densities in the range of (2–6)$\times 10^{18}$ cm^{-3} (via Stark broadening) and electron temperatures in the range of 2–10 eV (via line-to-line and line-to-continuum ratios).[3,14] The only prior study of the electron density profile was qualitative and indicated the presence of a cold slightly ionized neutral core.[3] Together with streak photographs, spectroscopic, and di/dt data, a picture has been formed of a dense partially ionized cold plasma whose radius would pinch down at unpredictable times before peak current was attained. During a pinch caused by self-generated B fields, the electron density and the temperature rose and anomalous dips in di/dt resulted from changes in the plasma inductance. Spectra and streak photographs only viewed a small linear segment of the exploding wire, and one could not confidently extrapolate these findings to the entire plasma length. Holographic interferometry promised to fill this gap and to provide electron-density-profile information and MHD stability information over the entire wire length.

Reconstructed interferograms revealed significant temporal and spatial details of our exploding-wire dynamics. The sausage or $m = 0$ instability was seen to occur, although early plasma-column disassembly did not usually result. Significant variations in plasma-column diameter were observed over short distances, indicating nonuniform lithium extrustion. Peak electron density, however, remained fairly uniform along the plasma-column axis in spite of local radial

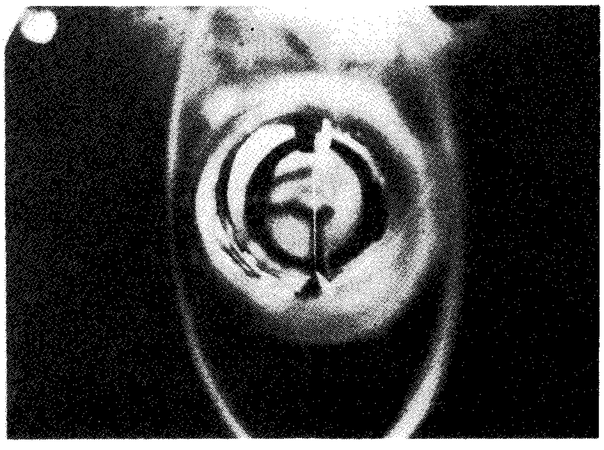

FIG. 2. 5-cm-long 25-μm extruded lithium wire is seen held between electrodes within the vacuum chamber.

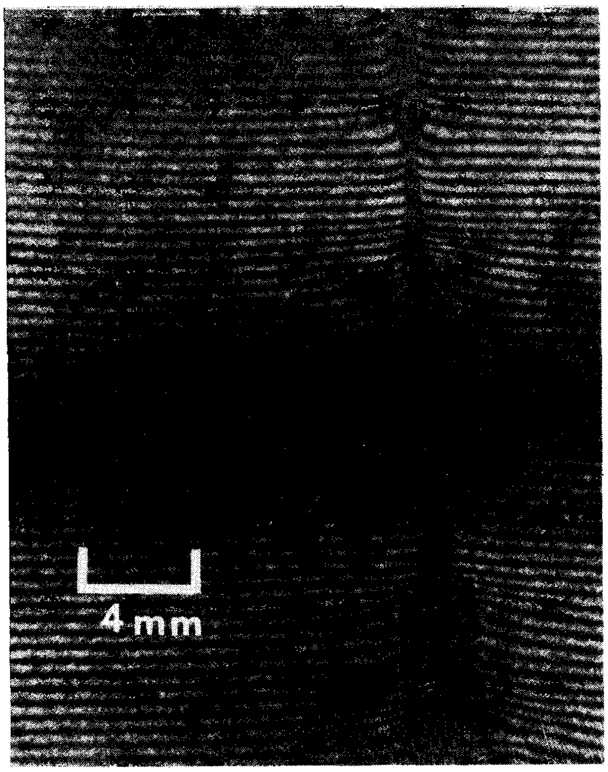

FIG. 3. Interferogram of exploding lithium wire plasma at $t_0 + 1.0\,\mu$s.

variations. For ease of discussion the axis of symmetry of the plasma column will be termed the z axis.

Three principle periods of exploding wire plasma development were studied interferometrically. These periods follow the initiation of current flow through the lithium wire at time $= t_0$.

(a) Most profound self-pinching occurred between $t_0 + 1.0$ and $t_0 + 1.8\,\mu$s. Such rapid reductions in plasma radius were easily observed in streak photographs and often corresponded to dips in di/dt. An interferogram taken during a pinch at $t_0 + 1.0\,\mu$s is shown in Fig. 3. The 2.4-mm-diam turbulent region at the base of the plasma shows the influence of the lower electrode on plasma formation. Clearly holographic interferometry identifies scientifically usable regions of the wire plasma. While pinching does appear to occur over the entire length, absolute plasma radii vary along the z axis. This implies a nonuniformly extruded wire in spite of the hard diamond die.

Electron density is indicated by the rate of fringe shift as the fringe enters the plasma. This rate varies significantly along the z axis and indicated the presence of an $m = 0$ instability. A close inspection of the interferogram of Fig. 3 reveals the lack of fringe penetration through the core of the plasma. Density profiles were measured at two z positions along the plasma. One profile was measured at the very narrow region near the top of the interferogram, where a fringe completely penetrates the plasma. A second profile was measured 0.75 cm below this. The fringe shifts were Abel inverted and are plotted in Fig. 4. The profile indicated by the circles was measured in a region where fringes did not penetrate the core. The significant variation in radial profile at different points along the z axis has been interpreted as being caused by the nonuniform wire extrusion.

The extent of ionization may now be directly calculated. The linear atom density (No./cm) is known from the initial lithium wire diameter. The linear electron density may be calculated from Fig. 4 by integrating under the curve over the differential area element $2\pi r\,dr$, where r is the plasma radius. The integration reveals an effective charge $Z_{\rm eff}$ of 0.55. Computations based on Saha equilibrium and on equilibrium rate equations both predict $Z_{\rm eff} = 1.0$ for electron temperatures above 1.5 eV. The low apparent effective charge results from the contribution of neutrals to the index of refraction, resulting in a reduced phase shift through the medium.

The interferometrically measured phase shift of a straight-line ray through the circular cross-section plasma may be expressed as

$$\Phi = \int_0^L \left(\frac{2\pi}{\lambda}\right)[\eta(r) - 1]\,dl, \tag{1}$$

where Φ is the phase shift, L is the straight-line path through the plasma, λ is the laser-probe wavelength, $\eta(r)$ is the index of refraction as a function of radius, and dl is the differential physical path length. $\eta(r)$ for neutrals varies only weakly

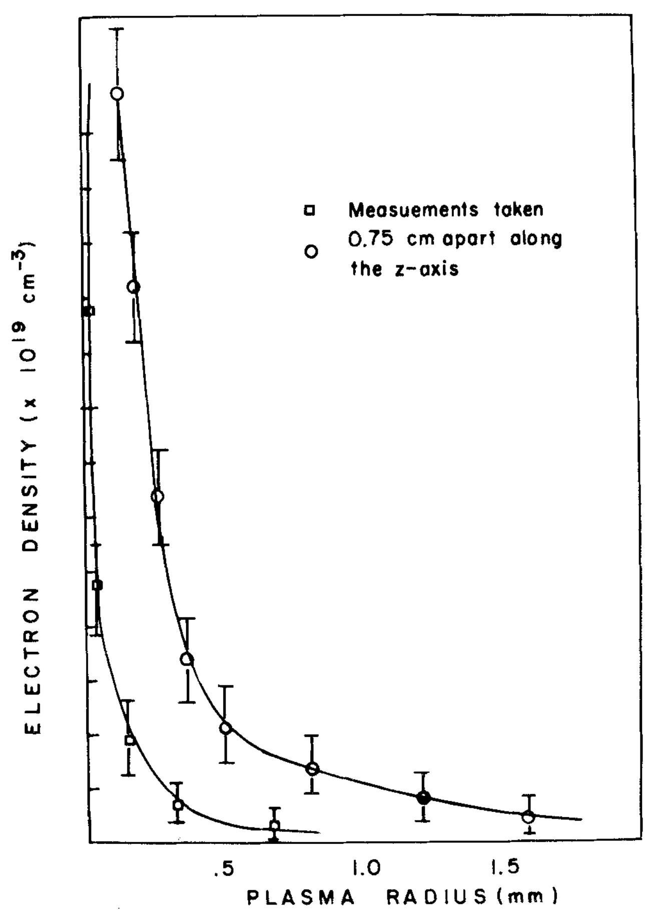

FIG. 4. Abel inverted electron density profiles measured at two points along the z axis in Fig. 3, separated by 0.75 cm (see text). Curve errors are $\pm$ 10% resulting from image-plane uncertainty.

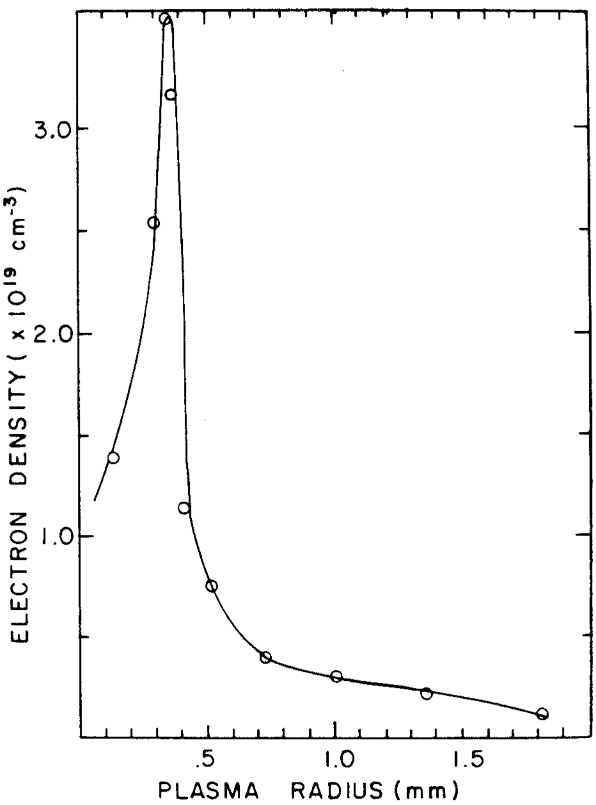

FIG. 5. MHD code computed density profile during a pinch.

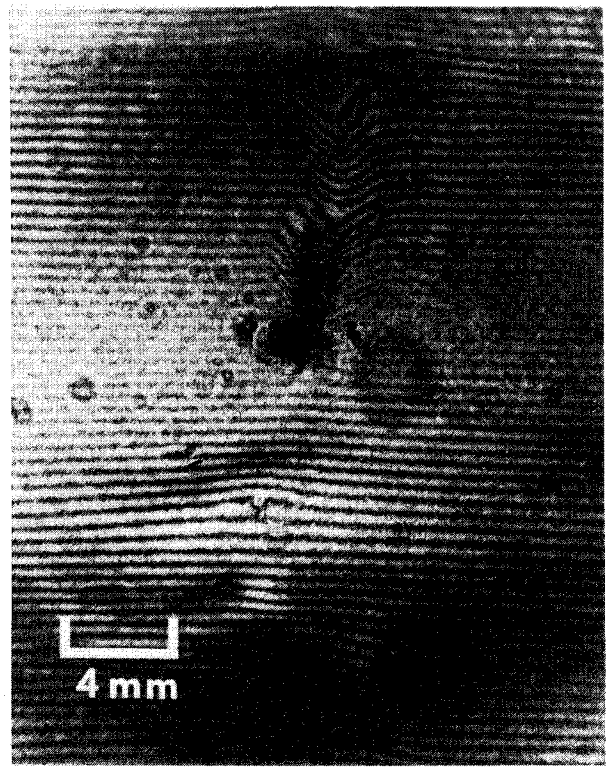

FIG. 6. Interferogram of exploding lithium wire plasma at $t_0 + 2.1\ \mu s$.

with λ and the phase shift Φ essentially varies as λ^{-1} and is positive in sign. The electron index of refraction is always less than unity and varies with λ^2. Thus, the electron contribution to Φ varies as λ and is negative in sign. A neutral density of 2×10^{18} Li atoms/cm^3 would contribute equally to refractivity (but in the opposite direction) as would an electron density of $1.5 \times 10^{19}\ e^-/\text{cm}^3$ at $\lambda = 694.3$ nm. Small neutral concentrations can seriously reduce measured fringe shifts. This, in turn, reduces the calculated electron density profile, if only electrons are assumed to contribute.

The presence of neutrals could be expected to have caused the loss of fringes in the core region, $r < 0.013$ cm. Photoionization losses in this cool lithium plasma could account for 30% absorption across a 0.2-cm path.[15] This loss could reduce fringe visibility and along with small-scale turbulence eliminate observed fringes in the core.

A one-dimensional single fluid two-temperature MHD code with equilibrium rate equations was run to predict wire-plasma dynamics. It showed a very peaked structure in the electron density profile away fromt he z axis during a pinch (see Fig. 5). The drastically reduced interior electron density may be alternatively interpreted as a region of a low level of ionization.

The picture of the pinched exploding wire plasma consisting of a warm exterior and a cool poorly ionized interior appears confirmed.[3] Electron temperature inferred from the Bennett relation yields 27 eV for $Z_{\text{eff}} = 0.55$ and 19 eV for $Z_{\text{eff}} = 1.0$, respectively. Since spectra confirm lower temperatures, a higher Z_{eff} is supported. A refraction code was run to ensure that lost fringes could not be due to steep gradients. All angles of refraction should have been caught by the imaging lens.

(b) The second time period of interest occurred between $t_0 + 1.8$ and $t_0 + 2.1\ \mu s$. During this time, current was still

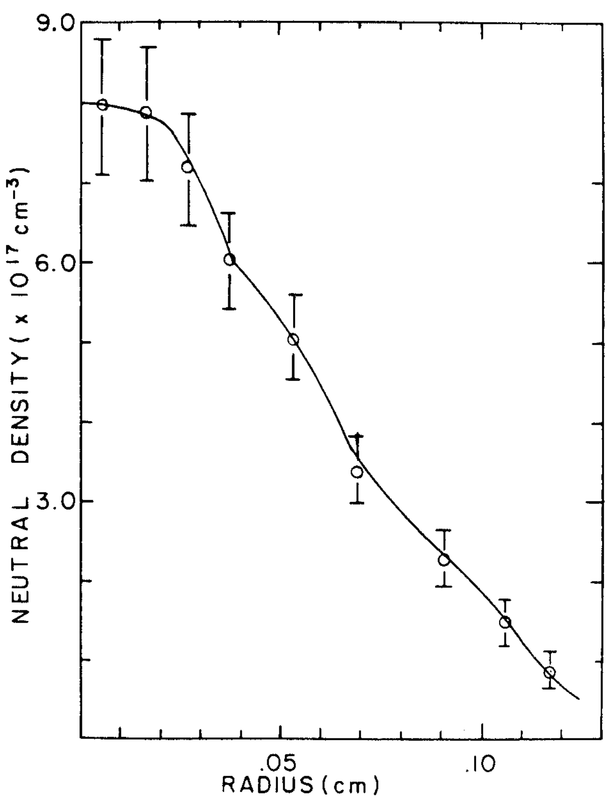

FIG. 7. Abel inversion of neutral cloud observed on interferogram of Fig. 6.

rising through the electrical circuit and had reached ~80 kA. Streak photographs revealed a wide diffuse illuminated region with no further pinching taking place. Figure 6 is a reconstructed interferogram taken during this period. It reveals the surprising presence of a cloud of neutrals, condensed within a background of a broad low-density plasma. Such clouds were consistently observed at these times as evidenced by fringes which were shifted downward, opposite to fringes shifted by electrons.

An Abel inversion through the center of the neutrals produced the profile seen in Fig. 7. The index of refraction for LiI was computed via the Lorentz-Lorenz formula.[16] The microscopic polarizability at 694.3 nm was calculated from the LiI transitions and oscillator strengths found in the NSRDS-NBS 4 tables.[17,18] Surprisingly low densities are seen in the cloud, considering the amount of fringe shift measured. A calculation of linear density in this cloud shows that only 5% of the original linear density is present. That is, 94% of the original lithium is outside the condensed region.

The presence of the neutral clouds has two possible explanations. Adiabatic cooling of the plasma may occur as it rapidly expands following a pinch. A simpler explanation, however, is that the core was never ionized and Joule heating occurred primarily on the wire surface. This latter explanation is supported both by (1) classical electromagnetism, which would imply an exponential current penetration of the wire, due to the fast-rising external-circuit turn-on, and (2) MHD computations of the current density as a function of the plasma radius, showing a decrease with decreasing radius.

(c) The final interesting stage of exploding wire plasma development occurred between $t_0 + 2.4$ and $t_0 + 2.6\,\mu$s. Interferograms taken in this period finally show the broad diffuse plasma that one would expect, *sans* neutrals; current has reached 93.5 kA, near its peak value. The plasma appears as a hoop expanding outward at a radius of 0.5 cm. The simultaneous observation of a strong 610.4-nm neutral lithium line implies a low level of ionization with the current being shunted along the outermost regions of the plasma.

IV. CONCLUSIONS

Single-wavelength holographic interferometry of a 1-mil exploding lithium wire plasma was able to provide valuable information on plasma dynamics and ionization state not available with streak photography. However, it was limited in quantitative data extraction because of the unique mix of neutrals and electrons. Neurtral refractivity and absorption prevented complete interferometric analysis of the partially ionized lithium plasma.

Confirmation was gained of several previously unclear phenomena. It was learned that a pinch as observed in a streak camera corresponded to a reduction in radius along the entire z axis of the wire, not just the portion observed in the streak camera. Pinches did in fact, correspond to dips in di/dt. In spite of the hard diamond die, pinching was nonuniform, implying a nonuniform extrusion.

Electron densities exceeded 1×10^{19} cm^{-3} in the pinch with gradients of $\sim6\times10^{20}$ cm^{-4}. More accurate measurements were precluded by the presence of neutrals.

Shortly following the pinches, localized clouds of neutrals have been observed in the midst of a low-density plasma. Neutral densities reached 8×10^{17} cm^{-3} and existed at a time when the current was 80 kA. No similar reports have been made in the literature of exploding wires.

Comparison to exploding wire work at other laboratories was not possible because of widely varying experimental conditions. The closest work was that of Seftor who has performed holographic interferometry of exploding wires at 694.3 nm, and at 694.3 and 347.2 nm.[11,12] His energy density was lower with a peak current of 14 kA and a charging voltage of 15 kV, and his circuit was approximately three times faster than ours. His two-wavelength interferometry on 5-mil exploding aluminum wire plasmas was unclear because his interferograms showed a greater sensitivity at 347.2 nm than at 694.3 nm (unless the spatial scale differed between his interferometric reconstructions). This implied that he was viewing neutrals rather than electrons since electron refractivity decreases as wavelength decreases as discussed earlier in this paper.

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