Multiphase Foamlike Structure of Exploding Wire Cores

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X-ray backlighter images (radiographs) of current-induced explosions of 7.5–25 μm diam metal wires show for the first time μm scale, time-resolved details of a persistent foamlike liquid-vapor structure of the expanded wire core. Experiments with refractory and highly resistive metals, with current rising to 2–5 kA per wire in 350 ns, show that a substantial portion of the wire material is not vaporized but remains in a condensed state. As the current damps out, the remaining liquid phase material coalesces into separate droplets.

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Recent experiments on the Z accelerator [1] have generated extremely high-power x-ray pulses from the implosion of multiwire array Z-pinch loads. In order to understand those experiments, several groups are attempting to develop the capability to model the whole process starting from the cold wire state [2–4]. Until now, however, there has been very little experimental information on the initial stages of wire explosion. The existence of long-lived dense cores within lower density coronal plasmas during nanosecond explosions of single wires or multiwire arrays is well established [5]. However, the physical state of the core material and the processes occurring there have been only a matter of conjecture. Using the technique of high resolution x-ray backlighting (radiography) [6], we have found complex small-scale (typical sizes of 2–30 μm) structure of the exploding wire cores of both single-wire and multiwire loads subjected to 2–5 kA per 7.5–25 μm diam wire for $\sim$1 μs. The radiographs show features implying that the core has become a foamlike, liquid-vapor mixture that is a result of explosive volume boiling. Most of the energy which drives these wire explosions is delivered during the initial 50 ns, when the current is only a few hundred amperes per wire. (The existence of a multiphase initial stage in current-driven wire explosions, but with a very different morphology, was described with photographs of microsecond discharges by Chace in 1959 [7].)

The persistence of liquid-phase material is demonstrated by the eventual formation of columns of droplets along the original wire position after the discharge current decays to zero in W, Mo, NiCr, and Ti wire explosions. By contrast, Al, Au, Cu, and Ag wires, all high conductivity, relatively low melting point materials, form fully vaporized, more uniform expanding columns of wire material, evidently because the energy deposited in them during the critical first 50 ns of the current pulse is sufficient to cause the multiphase condition to be short lived. Our results demonstrate that it is essential in modeling wire explosions to include a whole range of material properties, as well as the formation of plasma around the wire from desorbed gases and vaporized wire material. The current waveform applied to each of these wires is similar to that at the very beginning of the pulse on the Z accelerator.

The main diagnostic technique in the experiments reported here is pulsed point-projection radiography of the exploding wires. The x-ray sources are very short-time (<0.5 ns) x-ray bursts from collapsing 13–25 μm diam Mo-wire X pinches (Fig. 1), the characteristics of which are described in detail elsewhere [6]. In brief, Mo-wire X pinches are found experimentally to produce submicron, bright x-ray sources in the 2.5–10 keV x-ray energy range when the radiation is filtered by a 12.5 μm Ti foil; the spectrum consists of free-bound continuum and several L-shell lines. Radiographs are obtained of 1 to 4 wires exploded in parallel by a damped sinusoidal pulse of current which reaches a peak amplitude of up to 4.5 kA in about 350 ns (the auxiliary pulser in Fig. 1) and has an e-fold damping time of about 4 μs. The Mo-wire X pinches, usually two in parallel, separated by 2 cm, are driven using the 400–450 kA peak current XP pulser [8]. The setup gives radiographs at two times during each pulse, with the interval between the radiographs variable from near 0 to about 20 ns by changing the X-pinch wire size. A filtered film stack gives up to three radiographs of the wire(s) being tested for each X-pinch x-ray burst. The spatial resolution is 1–3 μm, depending upon the X-pinch quality and the

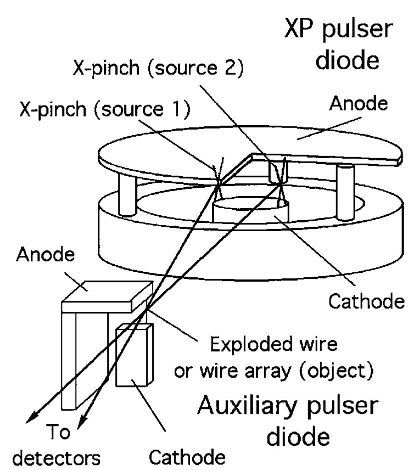

FIG. 1. Schematic view of the experimental setup showing the x-ray backlighter source positions relative to the exploding wire array being radiographed.

geometric factors. Experiments were carried out at a test chamber pressure of about 0.1 mTorr.

We have tested fine wires of many different materials (from Mg to Au) over a range of diameters from 7.5 to 50 μm. The results presented here emphasize W wires due to their relevance to the wire array Z-pinch experiments on the Z accelerator [1], but we also include results with materials demonstrating both very similar (Mo and NiCr) and very different (Al and Au) behavior. The Al results may be relevant to wire array experiments carried out on the Saturn accelerator [9]. In some experiments W wires were cleaned by preheating up to roughly 2000 K for several minutes, right up to the time of the current pulse, to eliminate adsorbed gases.

Representative examples of radiographs of exploding W wires are shown in Figs. 2 and 3. The relationship of the film exposure to W areal density has been determined by placing W layers of known thickness in front of the film stack [10]. The darkest parts of the radiographs are above our upper sensitivity limit of about 3×10^{-3} g/cm^2 (3 g/cm^3 for a 10 μm thick object). The lightest areas have areal density below 3×10^{-5} g/cm^2 (our lower limit of sensitivity). Although radiographs measure only areal density (g/cm^2) through the wire material, we believe that the structures observed are consistent only with a substantial portion of the wire material remaining in a condensed (liquid) state. However, this liquid has explosively boiled throughout its volume, producing a grossly cylindrically symmetric but inhomogeneous mixture of liquid and vapor over most of its length, as illustrated by Figs. 2b, 2c, and 3a–3c. The distinct but irregular outer boundary of the expanded wire cores (Figs. 2c and 3c) is likely due to surface tension, with vapor bubbles breaking the surface in many places. We will return to this hypothesis later. The factor of 10 expansion in radius of the core at the time of the radiograph of the preheated wire in Fig. 2 indicates that a significant fraction of its interior volume must be vapor contained within a liquid film "sponge." The thermal expansion of the vapor bubbles causes the observed expansion of the core as a whole, making it transparent to the radiation recorded by the film. The small-scale internal structure visible in Figs. 2 and 3 has typical sizes of 5 to 20 μm.

Figure 2 also compares radiographs of a preheated W wire and a wire which was not preheated, both initially 7.5 μm diameter. A significant expansion of both wire cores has occurred, but especially that of the preheated wire. We return to this difference shortly. The lack of, or reduced, expansion of the wire near the ends is observed in virtually all of our pulses, and is believed to be due to a plasma generated promptly at the contact point which enables the current to be shunted outside the wire very early in the pulse. [Thermal conductivity to the electrodes is unimportant since characteristic scale length (in μm) is about $(t/10\ \mathrm{ns})^{1/2}$.] Some wire explosions show one or more distinct steps in the expanded core diameter along the length of the wire, suggesting that plasma resulting from desorbed vapor breakdown along the wire is not always generated simultaneously over the full length of the wire.

Verification that a substantial fraction of the core material is continuously in a liquid state comes from the radiographs at times as late as 8 μs relative to the start of the current pulse, by which time the current is fully damped. Figures 3a and 3d show the radiographs from two separate tests of two parallel W wires of equal initial diameters at 2.6 and 8 μs after the current onset.

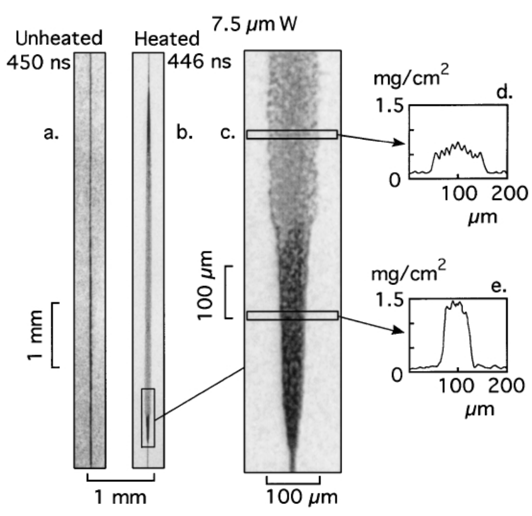

FIG. 2. Examples of radiographs from two separate tests of W wires with initial diameter 7.5 μm and length 1.04 cm at the indicated times from the discharge onset (a) without preheating, and (b) with preheating. An enlarged segment of the preheated wire (c), which appears like a liquid-vapor foam, and two tracings of the areal density in the indicated regions, (d) and (e), are also shown. The estimated absolute error in (d) and (e) is $\pm 25\%$.

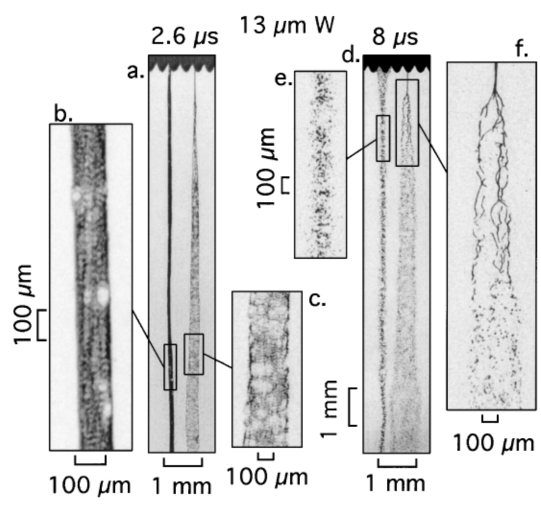

FIG. 3. Examples of radiographs during later stages of the current pulse for two-wire loads in two pulses, one radiographed at 2.6 μs (a)–(c) and the other at 8 μs (d)–(f). Enlarged segments of the left and right wire radiographs are shown in (b) and (c) for the 2.6 μs test and (e) and (f) for the 8 μs test. The 2.6 μs images show a foamlike structure with bursting vapor bubbles, while the 8 μs images show threadlike structures and separate droplets.

In both cases, the two parallel wires evidently carried different fractions of the current, possibly because of differences in the initial contacts at the wire ends. (A high conductivity plasma produced around either wire by breakdown of vapor effectively eliminates current flow in both wire cores.) In the test radiographed at 2.6 μs, the wire cores retain a pronounced foamlike structure with irregularly distributed holes that may correspond to single bubbles. The wires radiographed at 8 μs appear to show the collapse of bubble walls into threadlike structures and separate droplets a few μm in diameter.

The inhomogeneity of the observed effects along the wire length, as well as the asymmetry between the two wires, is probably due to corresponding nonuniformity of plasma formation along the wire during the initial energy input into the wire. These nonuniformities result in a variation in timing of the evolution of the foam into threads and droplets along the wires and from one wire to the other. Therefore, different stages of the relaxation process can be seen in one radiograph, as illustrated by Fig. 3.

Wire explosions using materials other than W have shown that the character of the wire explosion depends very strongly on the physical parameters of the material. The most significant parameters appear to be the electrical conductivity and the melting temperature of the wire material. For refractory wires with low initial or rapidly decreasing electric conductivity, the picture of the explosion looks quite similar to that of W, as shown for Mo and NiCr in Fig. 4. For materials with high conductivity (Al, Cu, Ag, Au), the foamlike structure is observed either near the electrodes, where the wire expansion is least, as previously discussed, or only briefly during the initial stage of the discharge, and is followed by complete vaporization, as illustrated in Fig. 5 for Al and Au.

Based upon many observations, W wire explosions with 2–5 kA peak current per wire may be described as follows. In the initial stage, Ohmic heating rapidly deposits energy into the wire, heating it to the melting temperature. After melting, the metal continues to carry current and increase in temperature, quickly exceeding the boiling temperature. The superheated liquid metal starts to boil throughout its volume, and the expanding bubbles of hot vapor overcome the surface tension of the liquid, producing the observed foamlike structure as bubbles enlarge and coalesce. However, before the visible expansion occurs, the voltage applied to the wire induces a breakdown in the vapor composed of desorbed gases and vaporized wire material from the wire surface. This gives rise to the formation of a highly conducting plasma around the wire core that shunts the current, causes a collapse of the applied voltage, and effectively terminates the energy input into the remaining liquid metal wire material. The finite time for the breakdown development depends on the applied voltage, circuit parameters, wire material properties, and the condition of the surface. Under the conditions of our experiments with W, Mo, and NiCr, the breakdown evidently fully develops before complete vaporization of the wire material. As the current pulse damps away, the foamlike structure, seen as late as several μs after the start of the current pulse, cools and the remaining liquid eventually forms separate droplets.

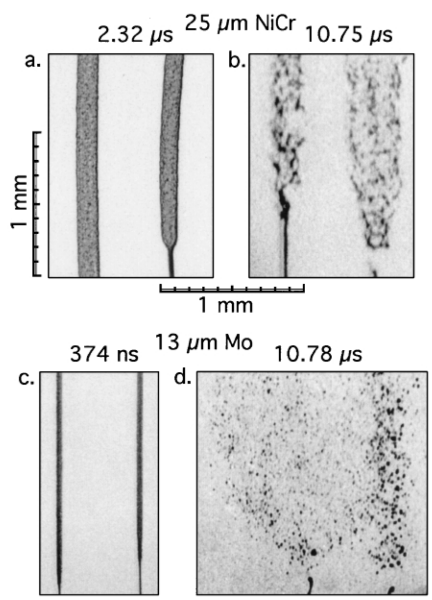

FIG. 4. Examples of radiographs of exploding wires of low conductivity refractory materials (two-wire loads): (a) NiCr wires at 2.32 μs, (b) NiCr wires at 10.75 μs, (c) Mo wires at 374 ns, and (d) Mo wires at 10.78 μs. The temporal development is similar to that seen with W wires.

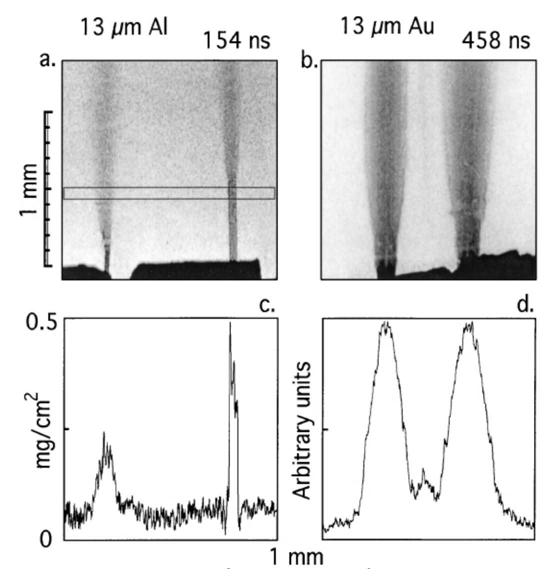

FIG. 5. Examples of radiographs of exploding wires of the highly conducting, low melting point materials tested as two-wire loads: (a) Al wires at 154 ns, and (b) Au wires at 458 ns. The dark cores are very homogeneous, suggesting that most of the wire core is in a vapor or plasma state. The gray background is the photographic film background and should be disregarded. Also shown are densitometer tracings of the Al and Au tests. The Al vertical scale (mg/cm^2) was calibrated with an estimated accuracy of $\pm 35\%$ with a step wedge but the Au scale is uncalibrated.

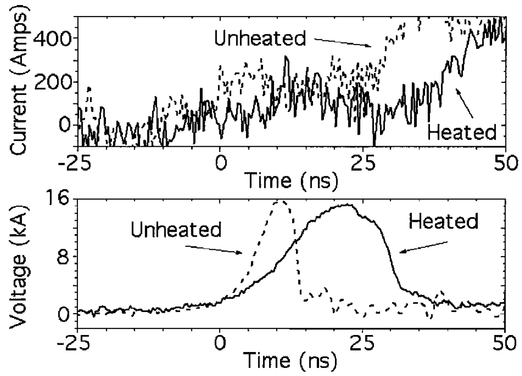

FIG. 6. Comparison of the voltage and current during the initial stage of the discharge for preheated and not preheated 7.5 μm diameter, 1.04 cm length W wires. The charging voltage of the 4.5 kA current pulser was 15 kV.

If the energy deposited in the wire in the initial stage of the discharge is sufficient for its complete vaporization, the foamlike structure survives only for a very short time as an intermediate stage in the formation of a vapor or plasma channel. Among the wires we have tested at low current, this condition appears to occur only for Al, Cu, Ag, and Au, as shown in Fig. 5 for Al and Au. We have also observed a foamlike structure in radiographs in previous experiments at 15–100 kA per wire 30–60 ns after the start of the current pulse [6] using a variety of wire materials and sizes from 13 to 40 μm. However, in those experiments, the much larger energy delivered to the wire-generated plasma by magnetically driven unstable implosion of the coronal plasma assured that the wires were completely vaporized by the end of the current pulse.

To determine the Ohmic heating rate of the wire(s) in the initial stage of wire explosion, we have measured the voltage and current applied to the wire using resistive voltage dividers and Rogowski coils. Examples of such measurements for a single wire without and with preheating are shown in Fig. 6. During the voltage spike the wire resistance dominates the circuit impedance, whereas before and after the spike the impedance is mainly due to inductance. Assuming the voltage collapse indicates the development of a coronal plasma around the wire, the fact that this occurs earlier for the wire that is the one not preheated is consistent with the idea that preheating delays vapor breakdown by eliminating easily desorbed gases. Notice that the currents during the voltage spikes are in the 100–200 A range.

Integrating the power deposited in the wire (from Ohmic heating) using the measured voltage and a model of the temperature-dependent resistance [11], a 7.5 μm W wire reaches the melting temperature ($\simeq$ 3400 K [12]) in about 10 ns. The latent heat of fusion $\sim$40 kJ/mol [13] implies that melting the entire wire should require an additional 2–4 ns which would be completed just before the voltage peak. The energy input during the rest of the voltage spike is sufficient to increase the temperature above the boiling point of W ($\simeq$ 5700 K). The liquid W becomes superheated up to about 6000 K for the wire without preheating and 9000 K for the preheated wire, and intense volume boiling will take place at some time after the voltage spike. However, not enough energy is deposited in either case ($\sim$10 mJ for the preheated wire) to completely vaporize the wire [14]. In the preheated case, with a vaporization enthalpy of $\sim$800 kJ/mol [13], the percentage of the wire material vaporized and forming vapor bubbles should be $\lesssim$10%. Given the liquid W surface tension of about 2000 ergs/cm^2 [12], about 3% is sufficient to provide an average vapor pressure (3–9 atm for the observed bubble diameters of 10–30 μm) to account for the observed expansion of the foamlike structure in Figs. 2 and 3. After coronal plasma formation and voltage collapse, the current through the remaining wire core should become too low to contribute significantly to the heat input and, via the magnetic pressure, to the force equilibrium within the wire core.

In wire arrays, the coronal plasma is swept away from the individual wires towards the current centroid of the array. Therefore some power may continue to be delivered to the wire core, leading to continuous evaporation from the surface and superheating of the volume.

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