Observation of a Stable Dense Core within an Unstable Coronal Plasma in Wire-Initiated Dense Z-Pinch Experiments

D. H. Kalantar and D. A. Hammer

Laboratory of Plasma Studies, 369 Upson Hall, Cornell University, Ithaca, New York 14853

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Dense Z-pinch plasmas initiated from a single 25–100 μm diam aluminum wire using a 100–350 kA, 100 ns current pulse have been studied with ≤ 1 ns time resolution. Rapid unstable expansion of a coronal plasma formed around the wire was observed with a subnanosecond pulsed nitrogen laser, while a dense core, which expanded more slowly and stably, was observed with 1–2 ns x-ray backlighting pulses. The core contained most of the initial wire mass, but there appeared to be little or no current flowing in it.

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A dense Z-pinch plasma may be generated from one or more fine wires by connecting them between the output electrodes of a high current pulsed power generator (pulser). The beginning of the power pulse explodes the wire(s), generating expanding plasma(s) which may be subsequently imploded ("pinched") to small radius and high density by the magnetic forces arising from the current flowing in the plasmas themselves. Initial configurations as simple as a single conducting wire [1,2] or nonconducting fiber [3–5], or having several wires in parallel [6–8], have been tested for applications requiring intense soft x-ray sources [2,6–10] and for controlled fusion research [3–5].

In several studies of dense Z pinches initiated from fine wires, shadows have been observed in x-ray pinhole pictures [11] which suggest that some fraction of the wire material was not involved in the pinch dynamics as inferred from, for example, visible light streak or framing photography. Furthermore, in order to match the results of frozen deuterium fiber pinch experiments with 2D magnetohydrodynamics computer simulations, Sheehey *et al.* [5] had to assume that the fiber gradually vaporized over several ns. However, prior to the experiments reported here, no direct measurements of the dynamics of the residual wire or fiber material have been obtained.

In this Letter, we are concerned with single wire Z pinches. We show unequivocally that aluminum (Al) wire-initiated dense Z-pinch plasmas produced by a 100 ns, 145 kA peak current pulse consisted of two components, a relatively low density, unstable corona, surrounding a high density, apparently stable core which contained at least 50% of the initial wire mass. The coronal plasma expanded radially at a rate of 1–4 cm/μs, depending upon wire size, and an axisymmetric instability (the well known "sausage" instability of a Z pinch [12]) developed. When the coronal plasma reimploded to small radius in its self-magnetic field, the core plasma still existed as a separate plasma component. The dominant instability wavelength of the coronal plasma was approximately equal to the plasma radius, increasing as the plasma expanded. Instability growth at early time occurred as predicted by a straightforward magnetohydrodynamic (MHD) model [12,13], while the apparent stability of the core plasma is also consistent with that model only if little current flows in the core.

The results presented here demonstrate that interpretation and modeling of wire-initiated dense Z-pinch experiments require consideration of two distinct plasma components, the relatively low density corona and the much higher density core, and their interaction. Furthermore, recent observations [14] of seemingly stable Z pinches based upon time integrated soft x-ray pinhole photographs can also be explained if the on-axis wire in those experiments, like the core plasma here, carries little or no current and is not actively involved in the Z-pinch implosion caused by the self-magnetic field.

Single wire Z-pinch experiments were carried out using 25, 37, 50, 75, and 100 μm diam Al wires, and 100–350 kA peak current, 100 ns [full width at half maximum (FWHM)] pulses. Details of the pulser are presented elsewhere [15]. The configuration is shown in Fig. 1. In addition to the Z-pinch wire, this figure shows two wires used to generate an X pinch in parallel with the Z pinch for x-ray backlighting. When the x-ray backlighting technique is used, the 345 kA (typical) pulser current divides inductively so that about 145 kA flows in the Z

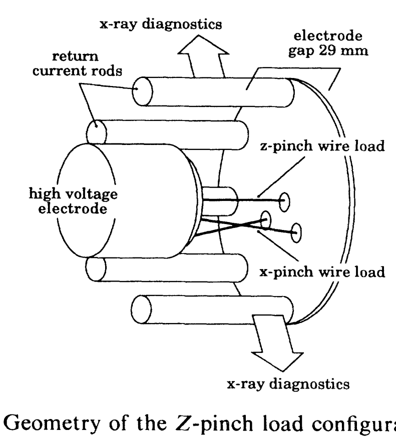

FIG. 1. Geometry of the Z-pinch load configuration showing a single wire Z pinch placed on axis between the pulser output electrodes, and a two-wire X pinch placed in parallel for x-ray backlighting of the Z pinch.

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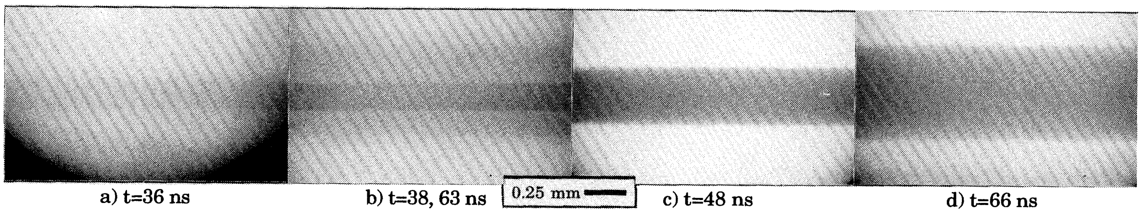

FIG. 2. Sequence of x-ray backlit images of 100 μm diam Al-wire Z-pinch plasmas taken at different times during the current pulse. The length of the scale bar is 0.25 mm for all images.

pinch and about 200 kA in the X pinch [16]. Therefore, results presented here are predominantly for 145 kA Z pinches.

In addition to the x-ray backlighting diagnostic, the Z-pinch plasmas were monitored using filtered x-ray pinhole cameras, a set of 2–4 filtered photoconducting diodes (PCDs) [17], and a pulsed nitrogen laser [18] for schlieren imaging. As the x-ray backlighting technique used here is a novel feature of these experiments, we describe it first and then proceed to present results from all of the diagnostics.

X-ray backlit images of the Z pinch were obtained with an Al, copper (Cu), titanium (Ti), or tungsten (W) wire X pinch in parallel with the Z pinch between the output electrodes of the pulser, as illustrated in Fig. 1. The X pinch has been shown to produce intense soft x-ray radiation from a submillimeter region at the wire cross point under the conditions used in this experiment [10]. Included in this emission is 3–7 keV radiation from bright spots that are ≤ 10 μm in size [16]. These few keV, very small radiation sources were used to obtain a shadow image of the Z pinch on Kodak Exploration GWL graphic arts film [19] filtered with 15 μm Ti, which transmits soft x rays in the 4–5 keV energy range [20].

Backlit images at different times were obtained by using 12–50 μm diam wires of various materials in the backlighter X pinch on successive pulses since for a fixed current pulse the time of the first burst of x-ray emission varies with the wire material and diameter [16]. The PCDs showed one to several bursts of x rays produced by each X pinch, resulting in as many as three resolvable x-ray images of the dense core plasma at different times as it expanded. (If a backlighter X pinch produced more than three x-ray bursts, image overlap made it difficult to identify individual images.) The PCD with a filter identical to that used to obtain the film image (15 μm Ti) recorded the 1–2 ns (FWHM) pulses of 4–5 keV radiation used for x-ray backlighting, thereby giving the timing of the images on a given pulse.

Figure 2 shows a sequence of x-ray backlit images of 100 μm Al wire Z pinches. The timing of the peaks of the backlighter x-ray pulses relative to the current pulse is shown in Fig. 3. The timing error is ± 1 ns. The two earliest image times come from the initial x-ray pulse from 25 μm diam Al-wire X pinches. The 48 ns image was made with a 25 μm Cu wire X pinch. The latest image time was obtained using the heaviest wire X pinch, 25 μm W, that would produce an intense x-ray flash with only 200 kA peak current. These images show the dense core plasma expands uniformly at a rate of 0.8 ± 0.2 cm/μs. This corresponds to an energy of about 10 eV for Al neutrals or ions.

Absorption of the 4–5 keV backlighter x rays by the dense Z-pinch core plasmas was determined using the calibration for the Kodak GWL film [19] and published material attenuation coefficients [20]. Assuming the core consists of neutral or low ionization states of Al, the amount of material remaining in the core was determined to be 50%–100%. The uncertainty is large because most of the film exposure is due to a general background of harder (>4 keV) x rays produced throughout the experimental pulse.

The 337 nm nitrogen laser beam was 1 cm in diameter and consisted of a ≤ 1 ns (FWHM) pulse containing about 0.3 mJ [16]. The laser was used to obtain schlieren images of the Z-pinch plasma, i.e., images showing where the line integrated density gradient in the plasma is sufficiently large that light rays are refracted out of the optical system. The limiting value was in excess of 10^{20}/cm^3 in these experiments. Images were recorded using 400 speed Kodak TMAX black and white film. A single laser image was obtained for each Z-pinch pulse, and sequences of images at different times in the current wave form were obtained by varying the timing of the laser with respect to the current pulse over a series of pulses.

Figure 4 shows a sequence of schlieren images from the same series of 100 μm Al-wire Z-pinch pulses used to ob-

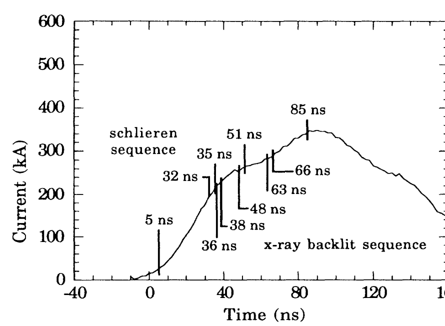

FIG. 3. Relative timing of the x-ray backlit and schlieren images shown in Figs. 2 and 4.

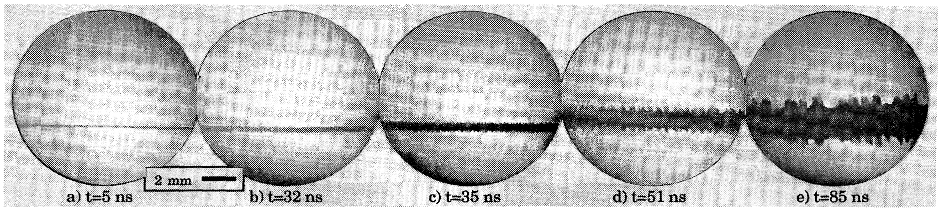

FIG. 4. Sequence of laser schlieren images of 100 μm diam Al-wire Z-pinch plasmas taken at different times during the current pulse. The length of the scale bar is 2 mm for all images.

tain the x-ray backlit images shown in Fig. 2. Notice that the length of the scale bar for the schlieren images is 2 mm, in contrast to the 0.25 mm long scale bar in Fig. 2. Timing of the laser relative to the start of the current pulse for each of the images in Fig. 4 is shown in Fig. 3. The development of an azimuthally symmetric instability commonly seen in Z-pinch plasmas and known as the sausage instability [12] is clear. Notice that the instability amplitude and the dominant wavelength increase together as the instability develops, indicating its nonlinear nature.

Figure 5 shows a comparison of the expansion rate of the coronal plasma and the dense core plasma for the 100 μm wire-initiated pinches. The outer edge of the coronal plasma imaged by the laser expands at a speed of 2.4 ± 0.2 cm/μs beginning at 21 ± 3 ns, versus 0.8 ± 0.2 cm/μs for the core, which apparently starts to expand at the same moment (see Fig. 5). The growth rate of the amplitude of the sausage instability can also be obtained from the sequence of images in Fig. 4 at about 1.8 cm/μs.

The diameter of the backlit images at a time of 65 ns is about 700 μm. This is consistent with time integrated pinhole images obtained on Kodak GWL film with a thin (6 μm) aluminized Mylar filter, which show a hollow emission pattern having approximately the same average diameter. This suggests that the intense extreme ultraviolet radiation imaged through the aluminized Mylar filter was generated by the coronal plasma when it imploded and stagnated on the core plasma late in the current pulse.

For 25 μm wire pinches, x-ray backlit images show axial nonuniformity of the dense core plasma early in the pulse, as shown in Fig. 6. Notice that the wavelength is long compared to the core plasma radius and appears to correspond to the coronal plasma instability wavelength in the schlieren image, also shown in Fig. 6, that was taken close to the time the x-ray image was recorded. The core distortion at the time of these images is consistent with the fact that coronal plasma implosion and intense ultraviolet and extreme ultraviolet emission were observed with the 25 μm Al-wire Z pinches early in the pulse at 145 kA peak current [16].

The sausage instability in the coronal plasma grew to a large amplitude nonlinear level on a time scale of only 10–20 ns with all wires tested at 145–330 kA peak current. Using a simple MHD model [12,13] in the form presented and solved numerically by Pereira, Rostoker, and Pearlman [13], the linear growth rate γ for azimuthally symmetric surface oscillations in a Z pinch with radius r and the current flowing on the surface is given by

$$\gamma \simeq \left(\frac{\mu_0}{4\pi} \frac{I^2}{\pi r^2 r_0^2 \rho \delta} \right)^{1/2} \Gamma \quad \text{(MKS units)}, \qquad (1)$$

where ρ and r_0 are the initial mass density and radius of the wire material, respectively, the factor Γ (of order 1) is plotted as a function of instability wavelength in Fig. 1(a) in Ref. [13], and δ is the fraction of the initial wire mass contained in the corona. Since the large plasma density gradients made a direct measurement of the coronal plasma density by laser interferometry impossible, we must obtain an estimate for δ from other experimental information. The upper limit estimate, 0.5, is obtained from the lower limit estimate of the initial wire material in the core measured from x-ray attenuation, as discussed above. Second, with an approximate resolution limit of 0.1 optical density on the film (due to high background),

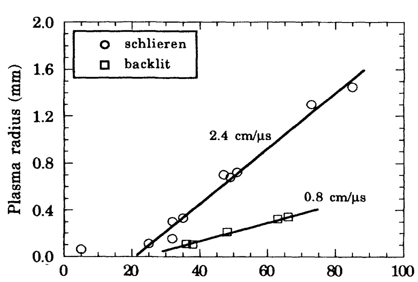

FIG. 5. Coronal plasma and dense core radii as a function of time for 100 μm diam Al-wire Z pinches.

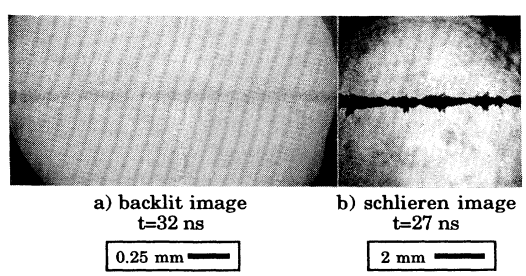

FIG. 6. Schlieren and x-ray backlit images of a 25 μm diam Al-wire Z pinch. The backlighter was a 25 μm Al-wire X pinch.

the fact that the coronal plasma does not cast a shadow in early time backlighter images implies $\delta < 0.3$. Finally, the current at which self-pinching of the coronal plasma occurs yields an estimate [16] of $\delta \lesssim 0.1$ for the 100 μm diam Al-wire Z pinches through the Bennett pinch relation [21]. Taking $\delta = 0.1$ for a 50 μm initial radius Al wire, together with 75 kA, $r = 200$ μm, and a wavelength equal to the plasma radius ($\Gamma \approx 2.5$), which are about right for the second and third schlieren images in Fig. 4, we find an e-fold growth time ($1/\gamma$) of about 5 ns.

Support for the current flow being predominantly at the surface of the corona is provided by the sharp coronal plasma boundary observed in schlieren images. In fact, the plasma radius was the same in separate schlieren images that were made simultaneously using up to four different refraction-angle-limiting apertures that varied by a factor of 2.7. Furthermore, the calculations of Pereira, Rostoker, and Pearlman [13] indicate that sausage instability growth rates decrease negligibly if the current is carried in a boundary layer of about 10% of the radius, but would drop by a factor of about 2 if the current were carried in the outer half of the plasma, and by a factor of 10 if the current were uniformly distributed in the plasma. These reductions are inconsistent with the observed rapid growth of the sausage mode on the corona surface. In addition, with $\delta = 0.5-1$ and a radius of 100 μm appropriate for the core plasma at $t = 30-40$ ns, there should be evidence for sausage instability on the core plasmas in Fig. 2 if they were carrying more than a very small fraction of the current in the pinch.

In summary, we have found that exploding wire-initiated dense Z-pinch plasmas driven by ~ 100 ns current pulses consist of a relatively low density corona containing $\sim 10\%$ or less of the initial wire material and a high density core. The stability properties of these plasmas are consistent with MHD calculations if the pinch current flows predominantly on the surface of the coronal plasma. The core plasma still exists as a separate component when the corona plasma pinches down to a small radius in its self-magnetic field. The observations and insight provided by these experiments should be very helpful to the development of analytical and computational models intended to predict and understand the behavior of wire-initiated dense Z-pinch plasmas.

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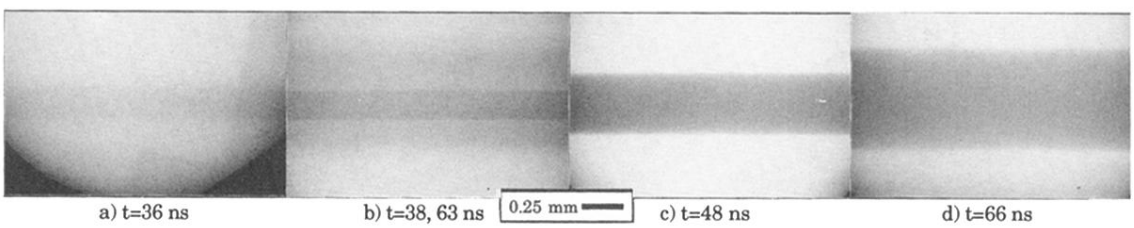

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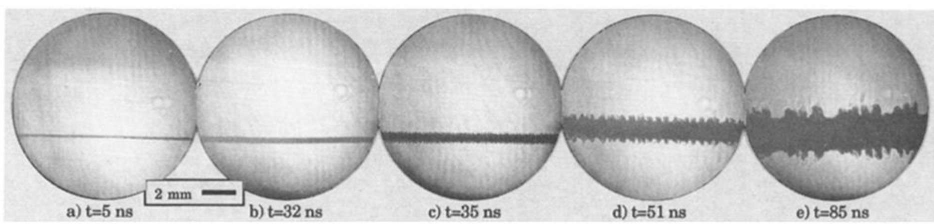

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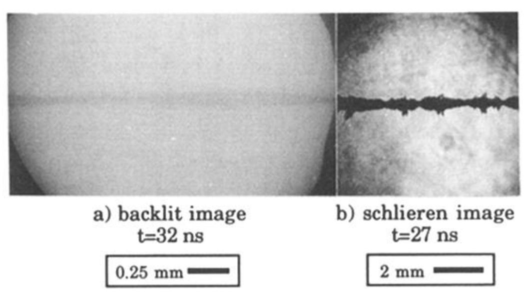

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