

# Factors affecting energy deposition and expansion in single wire low current experiments

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Single wire experiments were performed on a low current pulse generator at Cornell University. A 220 nF capacitor charged to 15–25 kV was used to drive single wire experiments. The capacitor and wire holder were connected in series through an external variable inductor to control the current rise rate. This external series inductance was adjustable from 0.2 to 2  $\mu\text{H}$ . When coupled with the range of charging voltages this results in current rise rates from 5 to 50 A/ns. The current heated the wire through liquid and vapor phases until plasma formed around the wire. Energy deposition and expansion rates were measured as functions of the current rise rate. These results indicated better energy deposition and higher expansion rates with faster current rise rates. Effects of the wire-electrode connection method and wire polarity were also studied. © 2004 American Institute of Physics. [DOI: 10.1063/1.1771660]

## I. INTRODUCTION

Single and double wire array experiments on the Z accelerator at Sandia National Laboratory have demonstrated impressive results.<sup>1,2</sup> In the double pinch experiments the Z accelerator feeds current through two, cylindrical, wire array z pinches. These arrays are stacked vertically, are driven in series, and produce two primary hohlraums. A secondary cylindrical hohlraum surface is positioned between the anode of the lower array and the cathode of the upper. The individual wires of the two arrays are actually continuous and pass over the outside of the secondary hohlraum surface.<sup>3</sup> This structure is positioned vertically in the Z accelerator with current flowing up from the bottom, through the lower wire array, around the secondary hohlraum, and then through the upper wire array. The current returns to the Z accelerator by way of a return cylinder that is positioned outside of and concentric with the arrays. In some cases there is an observed asymmetry in x-ray yield between the upper and lower arrays. This has been attributed to current loss between the upper and lower pinches.<sup>3,4</sup>

Single array experiments have also been performed on the Z accelerator. Some of these experiments have also shown an apparent asymmetry in the radiated x-ray power emitted from the bottom and top of a single array z pinch.<sup>5</sup> In another set of single array experiments the wire-electrode connections were varied by utilizing different wire holders. The “flop-over” design yielded a factor of  $1.6 \pm 0.2$  more radial x-ray power than the “hang-down” design in certain experiments.<sup>6</sup>

Varying the number of wires while keeping the mass fixed has also been shown to alter the x-ray output of a z pinch.<sup>7</sup>

The current pulse on Z has two distinct parts, a 50 ns prepulse with a  $dI/dt$  per wire of 30–40 A/ns and a main power pulse with a  $dI/dt$  per wire of 750–1000 A/ns/wire. The previously mentioned effects motivated a set of experiments to identify factors that affect the prepulse dynamics of

wire arrays. Understanding how the wire array behaves during the prepulse may lead to a better understanding of the implosion during the main power pulse.

The geometry of the wire holders induces axially varying radial electric fields. In the double pinch experiments, there is a large variation in the radial electric field between the upper and lower arrays. In a single array the radial electric field is essentially zero at the top near the anode while it is a maximum at the bottom of the bottom array, near its cathode. Our experiments had a similarly varying radial electric field and looked for asymmetries in core expansion due to this. In addition, the importance of the direction of the radial electric field was studied.

Increasing the number of wires in the array has three main effects: (1) it makes the wire array more like a cylindrical shell by decreasing the inter wire gap, (2) it decreases the inductance of the array, and (3) decreases the current rise rate per wire. These observations motivated our experiments that studied the effects of different current rise rates during the heating phase of single wires.

The experiments that we report here were done with single wires driven by a current pulse that simulated the Z prepulse. During this time, wires in our experiments went through several phases that can be identified from voltage and current measurements (Fig. 1). Initially, both the current and voltage increased in time. As the wire heated ohmically its resistance also increased. The voltage continued to climb until it peaked. After this point in time the voltage collapsed in a matter of nanoseconds while the current continued to increase. This collapse of the voltage has been attributed to a plasma column forming around the wire that conducted the bulk of the current.<sup>8,9</sup> The energy graph in Fig. 1 was derived from the current and voltage graphs. In the rest of the paper “peak voltage” refers to the highest voltage before voltage collapses. “Energy deposited” is the energy deposited prior to voltage collapse. The time of the voltage collapse is defined to be the difference in time between the onset of the

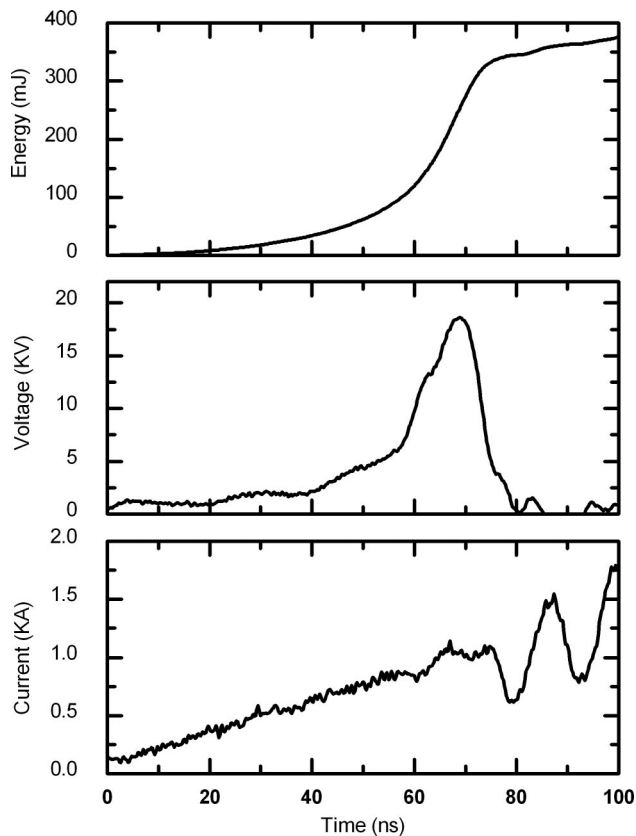


FIG. 1. Typical traces for a single 3 cm long, 25  $\mu\text{m}$  diameter copper wire.

current and the voltage peak. Resistive heating occurred in the wire during this time.

The wire electrode connection can be especially important during the prepulse. This paper presents data that show that better electrical connections during the prepulse resulted

in greater and more uniform expansion of the wire core along with enhanced energy deposition. Thus altering the connection can alter the state of the wire array material at the beginning of the main current pulse.

Our experiments have looked at the behavior of single wires driven by a simulated prepulse. Particular attention was paid to different radial electric fields controlled by geometry and wire polarity with respect to ground, soldered and mechanical wire electrode connections, and controlled current rise times that varied from 5 to 50 A/ns.

## II. EXPERIMENTAL SETUP

Cornell's low current pulser 2 (LCP2) consists of a single 220 nF capacitor with a gas switch trigger. The capacitor was charged to a voltage that could be varied from 15 to 25 kV with either positive or negative polarity with respect to ground. The capacitor was discharged through an external inductor, into a vacuum chamber, through the fine wire, and then to ground. The external inductance could be varied from 0.2 to 2  $\mu\text{H}$  and was used to alter the current rise rate. By varying the charging voltage and the external inductance, the current rise rate ranged from 5 to 50 A/ns. This resulted in approximately the same current pulse range as is present in single array experiments on the Z accelerator during its current prepulse. Single wires in our experiments were held in the vacuum chamber ( $<10^{-4}$  torr) with a geometry that was approximately cylindrical [Fig. 2(a)]. Everything in Fig. 2(a) is cylindrically symmetric except the current return posts. These four stainless steel posts connected the copper cathode (a circular plate) with the copper upper ground plate. The anode was a copper rod separated from the upper ground plate by epoxy insulation. The wire was strung by first taping it to the anode. It was then threaded through a hole cut at  $45^\circ$  to the bottom surface of the anode. The wire was then

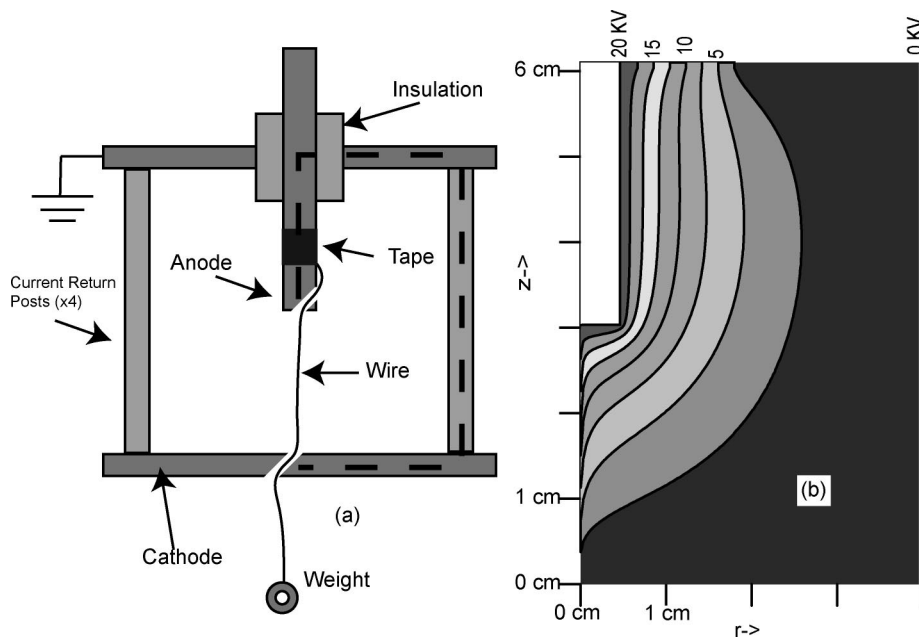


FIG. 2. (a) is the wire holder in the positive polarity configuration. For the negative polarity the wire holder is physically the same, but the roles of the cathode and anode are reversed. The calculated potential inside the dotted line is plotted in (b) where  $z=0$  is the cathode and  $r=0$  is the wire.

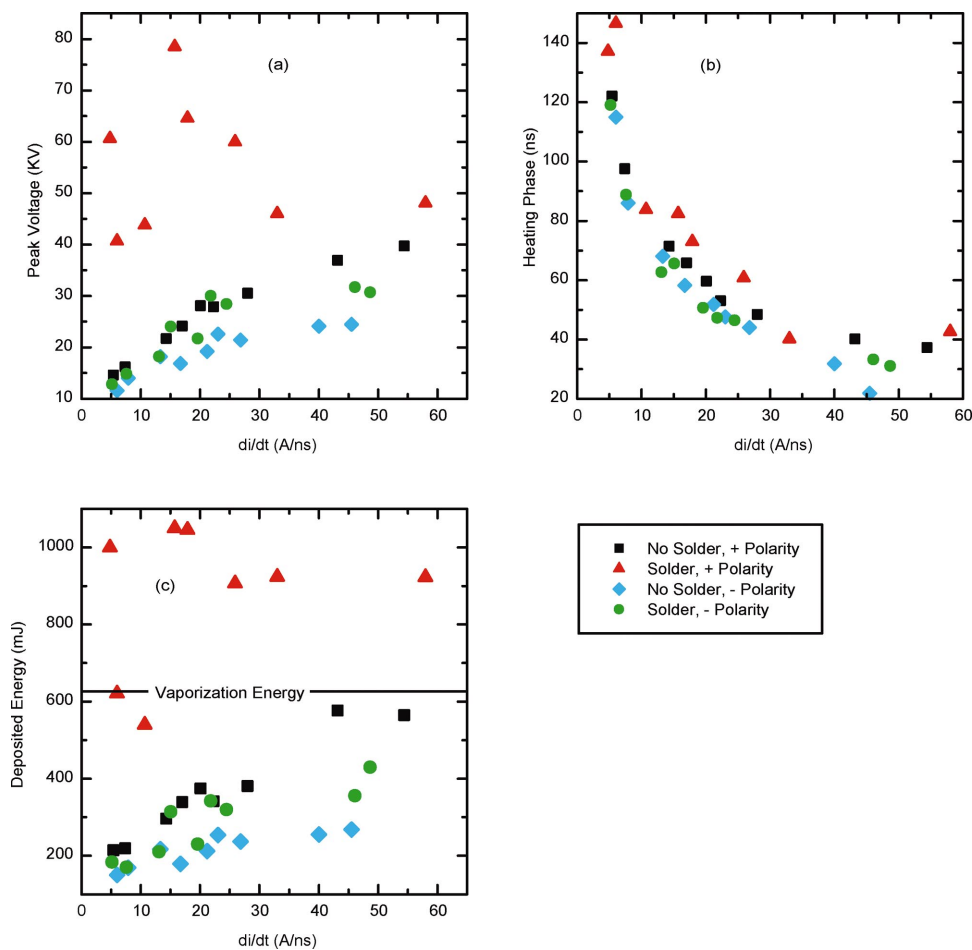


FIG. 3. (Color) Various electrical parameters of a 3 cm long, 25  $\mu\text{m}$  diameter copper wire. (a) is the peak voltage before breakdown vs current rise rate, (b) is the time between the start of the current and peak voltage, and (c) is the energy deposited in the wire.

threaded through a similar hole in the cathode. A weight was attached to provide tension. The mass of the weight varied from 3 g for relatively strong wires such as tungsten to 1 g for weak wires such as aluminum. This wire holder was used in most experiments.

To vary the connection method, the wire was strung as previously described. For some measurements the wires were soldered to the electrodes using an acid core solder. After cooling back down to room temperature, these wires and electrodes were carefully rinsed with acetone to remove any residual soldering flux. This soldering method was used with 3 cm long, 25  $\mu\text{m}$  diameter copper wire and 1 cm long, 25  $\mu\text{m}$  diameter tungsten. In most cases, the wire was soldered at both the anode and cathode. In other cases, it was only soldered at either the cathode or anode.

Laser shadowgrams were used to determine the radius of the core. The diameter of the core was easily determined by the sharp edge in the shadowgrams where the laser could not penetrate. The exposure time of the image was 4 ns, set by the length of the Nd:YAG laser pulse. The laser was setup to measure the diameter of the core once per shot. Several shots were needed to determine the expansion rate.

### III. RESULTS AND DISCUSSION

Figure 3 illustrates how the peak voltage, heating phase time, and energy deposition change as functions of current rise rate for the different connection methods using 3 cm

long, 25  $\mu\text{m}$  diameter copper wire. Figure 3(a) shows that for all the cases where the wire was not soldered to the electrodes or was in a negative polarity situation, the peak voltage increased with  $dI/dt$ . For the case of soldered positive polarity, the peak voltage was independent of  $dI/dt$  and also much higher than the 15–25 kV charging voltage of the capacitor. The external inductance in the circuit drove the wire to a voltage higher than the capacitor. At the time when wire resistance is changing the fastest (the time immediately before the voltage collapse), the series inductor had substantial current. As the voltage along the wire rose above the charging voltage, the energy stored in the inductor continued to drive current through the exploding wire until the stored energy was dissipated. Thus if the resistance of the wire changed fast enough, the voltage along the wire could have been driven arbitrarily high.

The time between the onset of the current and when the voltage collapse constituted the heating phase. Figure 3(b) shows that this time decreased with the increased current rise rate. Because the pulser deposited energy quicker with a faster  $dI/dt$ , the heating period was shorter. A careful inspection of Fig. 3(b) shows that the soldered positive polarity data has a  $\sim 10\%$ – $20\%$  longer heating period for a given  $dI/dt$ , compared to the other cases. It was during this time that the voltage was highest along the wire and there was ample current. Thus, much more energy was deposited in the soldered positive polarity wire as seen in Fig. 3(c). It can

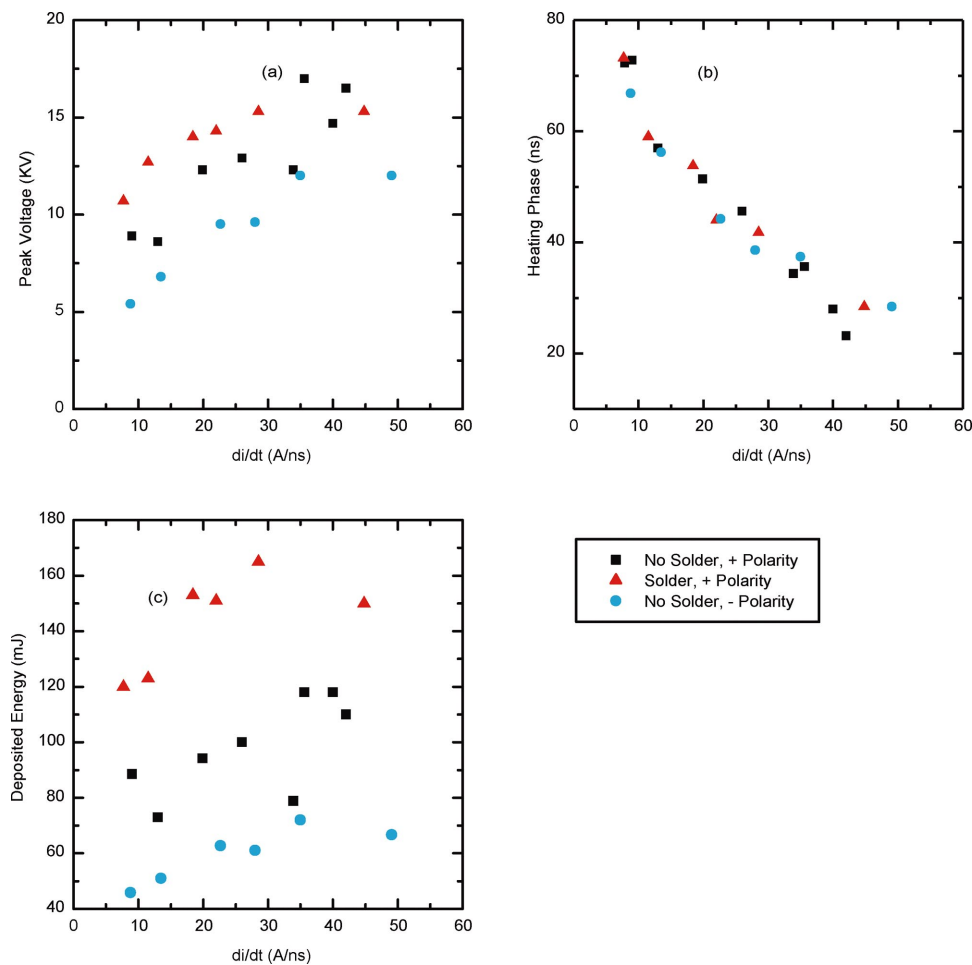


FIG. 4. (Color) Various electrical parameters of a 1 cm long, 25  $\mu\text{m}$  diameter tungsten wire. Note that in all three cases, the deposited energy increases with larger  $di/dt$ .

also be seen that the energy deposited in the unsoldered positive case was dependent upon current rise rates, whereas it was independent for the soldered positive case. In the soldered positive polarity case, the energy deposition averaged to be  $880 \pm 70$  mJ. In all other cases, the energy deposition was a function of current rise rate. The “vaporization energy” line shown in Fig. 3(c) is an estimate of the energy required to heat, melt, and vaporize the entire wire starting from room temperature. In the positive soldered case the deposited energy was almost always above this value. For the other cases shown in Fig. 3(c) (positive unsoldered, negative unsoldered, and negative soldered), the energy deposition is approximately a linear function of  $di/dt$ .

It was expected that because the energy deposition was greatest in the soldered positive case, the core expansion rate would be also. Experiments conducted at a rise rate of 14 A/ns showed that the core expansion rates were  $5.5 \pm 0.6 \mu\text{m/ns}$  for soldered positive polarity and  $2.5 \pm 0.6 \mu\text{m/ns}$  for not soldered positive polarity. Measurements of the negative polarity cases indicated an expansion rate of less than  $0.5 \mu\text{m/ns}$ . These observations are an independent confirmation of the energy deposition measurements.

The same set of experiments was carried out with tungsten wires. However, lead solder does not adhere to tungsten wires as it does to copper. Thus the connections could not be expected to be as good with tungsten as they were with cop-

per. Still, it is reasonable to assume that the connections should have been improved because the contact area was increased and the gap between the wire and electrode was filled with solder. Figure 4 shows the electrical characteristics of the tungsten wire. Note that in all the cases deposited energy increases with increasing  $di/dt$ . These experiments were completed with Cornell’s low current pulser 3 (LCP3).<sup>10</sup>

Figure 5 shows a similar set of graphs for 1 cm long, 25  $\mu\text{m}$  diameter aluminum with the addition of the core expansion rate as a function of  $di/dt$ . The deposited energy and expansion rate both peaked at around  $\sim 40$  A/ns and slightly decreased with increasing  $di/dt$  above that point. Shadowgrams were taken for various times from the start of the current to 200 ns after the voltage collapsed. In none of the cases was the core of the wire seen to expand before the voltage collapsed.

Sources of stray electrons may explain the observed dependence on polarity and connection method. Figure 2(b) shows the results of an electrostatic calculation for the electric potential in the wire holder region assuming cylindrical symmetry. This was used to predict axial variations of the radial electric field produced by the wire holder. For this figure the anode was defined to be +20 kV, the cathode and return conductors were at ground, and the voltage along the wire was taken to be linear. When the wire was not soldered, there was a poor connection between the wire and the electrodes. It is reasonable to speculate that the poor connection

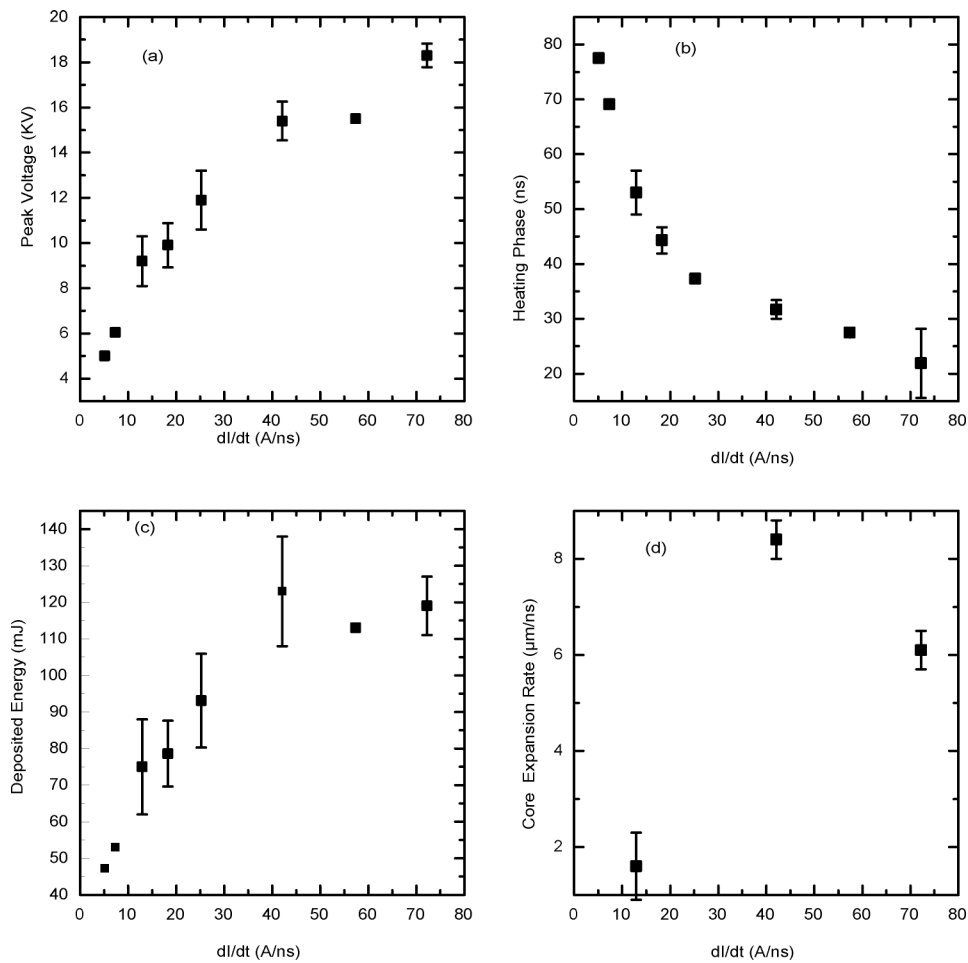


FIG. 5. Various electrical parameters of a 1 cm long, 25  $\mu\text{m}$  diameter aluminum wire. Part (d) is the core expansion rate measured by taking laser shadowgrams over several shots.

heated up very rapidly and started to emit electrons. Because electrons were generated near the cathode, they were accelerated along the wire to the anode, ionized any gas around the wire, and formed plasma. The relatively high conductivity of the plasma shunted current away from the wire causing the voltage to collapse and an end to the resistive heating phase of the explosion. Soldering the wire to the cathode reduced this source of electrons. Thus the wire heated longer became more resistive, and greater energy was deposited in the wire material.

In the case of the negative polarity, there existed another source of electrons besides the poor wire-electrode connection. Figure 2(b) still describes the situation with the exception that the upper electrode is now the cathode and the lower electrode is the anode. Note that there is a rapidly changing potential near the cathode signifying a strong electric field. This electric field along with field enhancement from the edges of the cathode could have caused the electrode itself to eject electrons. If this happened, soldering the wire to the cathode would not completely eliminate the generation of electrons at the cathode. It can be seen in Fig. 3(c) that there is only marginal benefit from soldering in the negative polarity case. In the negative polarity other papers have suggested that the wire itself emits electrons.

Sarkisov *et al.* also investigated how the radial electric field polarity affects the energy deposition<sup>11</sup> and their experiments are comparable to ours. Their wire holder has a similar

geometry but their current rise rate was faster ( $\sim 150$  A/ns). They report that switching from negative polarity to positive polarity increased energy deposition by  $\sim 30\%$  for 1 cm long, 20  $\mu\text{m}$  diameter copper wire and  $\sim 60\%$  for 1 cm long, 20  $\mu\text{m}$  tungsten wire. In comparison, Fig. 3 shows that the energy deposition in our not soldered copper experiments was increased 40% to 100% depending on  $dl/dt$ . Figure 4 shows an increase of 50% to 70% for tungsten wire. Sarkisov *et al.* attributed the difference to field emission of electrons by the wire in the negative polarity. This source is absent in the positive polarity so voltage breakdown is delayed and more energy is deposited. It is a similar argument to what we have proposed. However, we include the wire-electrode connection as an additional source of electrons.

The laser shadowgrams of Fig. 6 may also support the conclusion that the plasma starts near the electrodes. The copper wire was soldered in Fig. 6(a) and strung normally without solder in Fig. 6(b). A copper wire strung normally explodes nonuniformly. The expansion is significantly less toward the cathode. Assuming that the plasma is generated at the electrodes and that for a time it does not extend over the entire length of the wire but only surrounds a section near an electrode, the current will be shunted from the wire to the plasma only along that particular section of the wire. Those

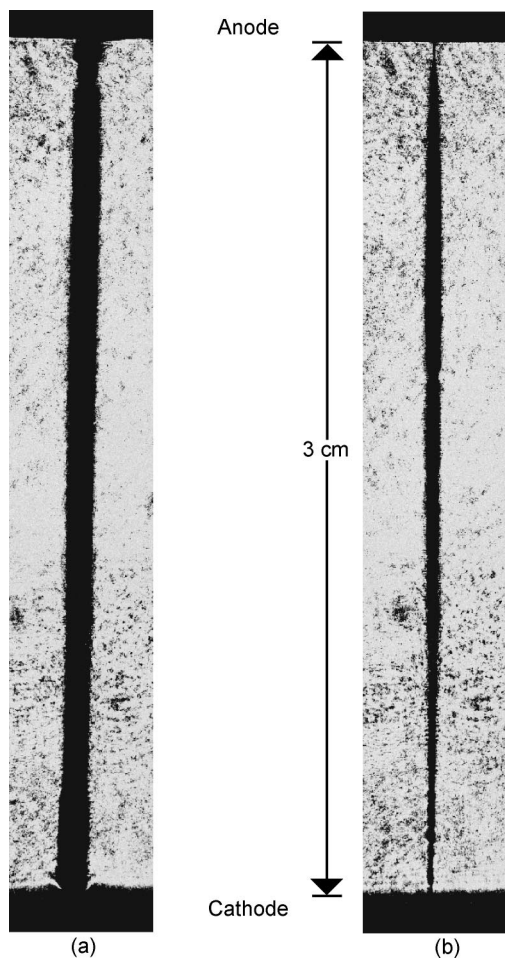


FIG. 6. A laser shadowgram of a 3 cm long, 25  $\mu\text{m}$  diameter copper wire shot in a positive polarity configuration on LCP3. In (a), the wire was soldered to the electrodes. In (b), the wire was strung normally. Note that in (b), the wire has expanded more at the anode. (a) and (b) were taken at 235 and 245 ns after the start of current, respectively. In the soldered case, the maximum width of the core was 980  $\mu\text{m}$  while the normal case was only 550  $\mu\text{m}$ .

sections of the wire will not have as much energy deposited locally and will expand at a lesser rate than other sections of the wire where the current shunting occurs later. We hypothesize that the least wire expansion identifies where the plasma originated. In the unsoldered experiments it appears that the plasma originated near the cathode and anode, but the plasma at the anode was more localized at the electrode. The plasma that formed at the cathode propagated quickly up the wire. The section of the wire that showed the greatest expansion was that section which was plasma free for the longest time. When the wire was soldered [Fig. 6(a)], the wire exploded much more uniformly with more anode/cathode symmetry. These images were typical of several shots.

This explanation can be tested by several different experiments. We looked at two. We constructed a wire holder that was more axially symmetric to try to minimize the polarity effect. The electrodes of a wire holder were constructed of two parallel plates to test this hypothesis. The plates were square with 7.5 cm sides and separated by 3 cm.

In these experiments the effects of changing the charging polarity were absent. Furthermore, the experiments also showed that it was necessary to have the copper wires soldered to both the anode and cathode. Soldering to either electrode alone did improve energy deposition to some extent but soldering both drastically increased the energy deposition.

Another obvious test was to string the wire and then coat the wire-electrode connection with epoxy. This did not increase the energy deposition because the epoxy partially insulated the wire from the cathode creating an electron emitting, poor connection.

The cathode-wire connection is more significant than the anode-wire connection. Experiments performed on 3 cm long, 25  $\mu\text{m}$  diameter copper wire in the positive polarity at a current rise rate of 14 A/ns yielded the following results. With mechanical connections of the wire to both electrodes the energy deposition was  $310 \pm 20$  mJ. Soldering only the anode connection increased the energy to  $378 \pm 30$  mJ. Soldering just the cathode connection resulted in  $454 \pm 54$  mJ. Of course, the greatest effect occurred when both connections were soldered and resulted in the deposited energy increasing to  $720 \pm 110$  mJ. This demonstrates that the cathode-wire connection is more important than the anode-wire connection. However, good contact at both ends resulted in the largest energy deposition before voltage collapse.

A consequential question is whether these externally produced electrons ignite plasma composed of background gas or wire material. A cursory answer was found using a time integrated, visible light, Acton 300i spectrometer. The wire was first mounted in the chamber. The chamber was pumped to  $<10^{-4}$  torr, flooded with argon to atmospheric pressure, and pumped back down again. When the wire was pulsed, no argon lines were seen in the visible light spectrum. Thus the plasma that formed consisted of either metal or contaminants from the wire.

#### IV. CONCLUSIONS

Polarity of the wire with respect to the return conductors naturally affected the radial electric field in the vicinity of the wire. In cylindrical geometry with negative polarity, the radial electric field is stronger near the cathode than at the anode. Consequently, electrons are more easily emitted from the cathode with negative polarity. This is consistent with the observation that voltage collapse appeared to occur earlier with negative polarity.

The sets of experiments reported here demonstrate that unless careful consideration is given to the wire electrode connection, the resistive heating phase will terminate prematurely due to stray electrons and plasma formation around the wire. Stringing tungsten wires and then melting solder into

the wire electrode connection was able to improve the connection and thus increased both energy deposition and expansion rates. A further approach may be to coat the wires with a material that can be soldered.

As expected, increased  $dI/dt$  resulted in a shorter heating phase. However, in all the cases with stray electrons, more energy was deposited with larger  $dI/dt$ . With a higher  $dI/dt$ , the wire heated more before the stray electrons were able to form plasma. Removing these electrons allowed the deposited energy to be independent of  $dI/dt$  for the case of copper. These results suggest the possibility that a large  $dI/dt$  may be able to compensate for poor wire-electrode connections. Poor wire-electrode connections may be indicated by the dependence of deposited energy on the current rise rate.

#### ACKNOWLEDGMENT

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