Physics of Plasmas LETTER scitation.org/journal/php

X-ray radiography of the overheating instability in underwater electrical explosions of wires

Cite as: Phys. Plasmas **26**, 050703 (2019); doi: 10.1063/1.5089813
Submitted: 23 January 2019 · Accepted: 28 April 2019 ·
Published Online: 8 May 2019

D. Yanuka,[1] A. Rososhek,[2] S. Theocharous,[1] S. N. Bland,[1] Ya. E. Krasik,[2] M. P. Olbinado,[3] A. Rack,[3] and E. V. Oreshkin[4]

AFFILIATIONS

[1]Plasma Physics Group, Imperial College London, London SW7 2BW, United Kingdom
[2]Physics Department, Technion-Israel Institute of Technology, Haifa 32000, Israel
[3]European Synchrotron Radiation Facility, CS40220, 38043 Grenoble Cedex 9, France
[4]Lebedev Physical Institute, RAS, 119991 Moscow, Russia

ABSTRACT

We present the measurements of the development of striation like instabilities during the electrical driven explosions of wires in a water bath. In vacuum based wire explosion experiments, such instabilities have long been known. However, in spite of intense research into the explosion of wires in liquids, the development of these instabilities has either not been observed or has been assumed to play a minor role in the parameters of the exploding wire due to the tamping of the wire's explosion. Using synchrotron based multiframe radiography, we have seen the development of platelike density structures along an exploding copper wire. Our measurements were compared to a 2D magnetohydrodynamics simulation, showing similar striation formation. These observed instabilities could affect the measurements of the conductivity of the wire material in the gas-plasma state—an important parameter in the warm dense matter community. The striations could also act as a seed for other instabilities later in time if the wire is in a dense flow of material or experiences a shock from an adjacent wire—as it would do in experiments with arrays of wires.

The pulsed power driven explosion of metallic wires provides a simple method for accessing high energy density physics conditions. This method is used in several areas of basic research, including equation of state studies, and is the foundation of wire array z-pinch experiments, dedicated to producing intense X-ray sources and making measurements of dynamic plasma flows.[1–4] Most wire explosion experiments take place in vacuum; however, recently the explosion of wires in water (and other insulating media) has been under intense scrutiny due to the significantly higher level of energy density deposition into the wires that can be achieved. This is a result of surface breakdown processes that dominate wire explosions in vacuum, being suppressed, and water's low compressibility also tamps the expansion of the wire when it reaches the gas-plasma state. The latter enables resistive heating to continue efficiently, while the expansion of the wire also drives a strong shock wave through the water, which itself can be used to access high pressure conditions.[5–8]

Monitoring of the current through and voltage across exploding wires has long been used as a basis for resistivity measurements in warm dense matter conditions. However, understanding how the wire expands is crucial to the interpretation of this research. In experiments with the wires in vacuum,[9–13] air,[14–18] or pressurized SF_6 gas,[19] on both the nanosecond (ns) and microsecond (μs) timescales, the wires develop a core–corona structure, with a relatively dense gas-plasma "core" ablating into warmer, lower density "corona" plasma. The wire cores often display a highly heterogeneous, striated pattern which has been explained as a result of the overheating (a.k.a. electrothermal) instability. This instability assumes that wires initially have a random arrangement of microscopic regions of higher resistance along their length and radius (consistent with the wires' internal structure of grain structures and boundaries, dislocations, and impurities in the manufacturing process). In an experiment, a higher resistance region of a wire will initially heat faster, and so this region tends to increase in resistance, shunting current into the radially adjacent material. The adjacent material then also heats faster and increases in resistance, and the process continues until an entire radial layer of the wire has been overheated. Simultaneously, the overheated layer expands compressing material in the axially adjacent layer, thus reducing the resistance in these regions, and helping to prevent overheating. The end result is a series of alternating layers of relatively hot, low density, high resistivity plasma with cold, high density, low resistivity plasma.

In experiments with water, the development of similar instabilities has been questioned and is often "overlooked." On the tens of μs-timescale experiments dating back to the 1960s[15,16] show the evidence of striations in optical emission, but there was no probing of the inner structure of the wire. It was often argued that these striations were the result of magnetohydrodynamic (MHD) m = 0 instability and that at much faster time scales there would be a much more uniform expansion. This was supported by recent X-ray diode-based radiography experiments[20] which seemed to show a relatively uniform expansion of a wire in water driven by currents on the hundreds of ns-timescale, suggesting that any measurements of conductivity of the wire material could rely on uniform wire expansion. However, the X-ray diode and point projection imaging system used was of limited spatial resolution ($\sim$70 μm) and extended over 20 ns in duration. This may have meant that any instability growth remained hidden or obscured, particularly as the diode could only sample 1 time per experiment.

In this paper, we report that the expansion of an exploding Cu wire in water during a μs-timescale electrical explosion can be very far from uniform, resulting in a highly heterogeneous state. Many early conductivity models and tables were constructed from similar experiments and assumed a uniform expansion of the wire material. These results help highlight the issues with such data. More modern conductivity models[21] recognize the difficulties associated with the phase changes from liquid–gas–plasma, but there is a shortage of high quality experimental measurements that can be compared to theory—as such these results can then help constrain the models.

Our research utilized the European Synchrotron Radiation Facility (ESRF) to explore the explosion of copper and tungsten wires, with each experiment producing a sequence of 128 radiographs of $\sim$10 μm spatial and 100 ps temporal resolution spaced 704 ns apart. Our images were enhanced using propagation-based phase contrast to emphasize any small or sharp differences in the density of the exploding material. Utilizing this system, striations were seen throughout the whole volume of copper wire explosions although there were not observable in experiments with tungsten wires. Comparison of our results with detailed 2D MHD simulations shows a similar striation formation.

The experiments were carried out in the ID19 beamline at ESRF which is located at a distance of 150 m from the undulators, providing partial spatial coherence. The X-ray beam energy spectrum was polychromatic ranging from $\sim$20 keV to $\sim$50 keV with a mean energy of $\sim$30 keV. A photon flux of 3.7×10^7 photons/mm^2 was recorded before the experimental chamber containing the wire. After the chamber, the beam propagated 5 m to provide phase enhancement, before hitting a LYSO:Ce scintillator imaged to a Shimadzu HPV-X2 camera.

The pulsed power generator used to explode the wire consisted of 4 parallel low-inductance High-Voltage (HV) Maxwell capacitors of 220 nF each, charged to 32 kV, and triggered by a spark gas switch. Experiments with both Cu and W wires were performed—in each case the wires were 45 mm long and 200 μm in diameter, chosen to critically damp current and maximize energy transfer to the wires. The wires were suspended in an 8 mm inner diameter 1.5 mm thick acrylic tube filled with deionised water. The discharge current was measured by a current-viewing-resistor, and the voltage was measured using a Tektronix HV voltage divider. The timing of the X-rays relative to the pulsed power was adjusted and optimized in short circuit experiments using a fast photodiode. A detailed description of the experimental setup of ID19 is available in Refs. 22 and 23 and a detailed diagram of the experimental setup is described in Ref. 24.

The current and resistive voltage waveforms are presented in Fig. 1. Copper displays typical current and voltage characteristics associated with a critically damped discharge—with voltage rapidly rising as the wire expands and undergoes phase changes, before falling as conductivity starts to increase and more material in the wire is ionized. In tungsten, the voltage remains relatively high over a longer period—this is associated with the gas-plasma state maintaining a much lower conductivity for the duration of the current pulse.

Radiography images of the Cu wire are presented in Fig. 2. The times shown are with respect to the beginning of the current. One can see striations in Fig. 2(c), which is the first image (0.869 μs) containing clear striations. In the previous image recorded at 0.682 μs [Fig. 2(b)], striations were still not resolvable; however, the beginning of a striated structure can be observed at 0.684 μs in a low-magnification image presented in Ref. 24. It is reasonable to assume that this process starts

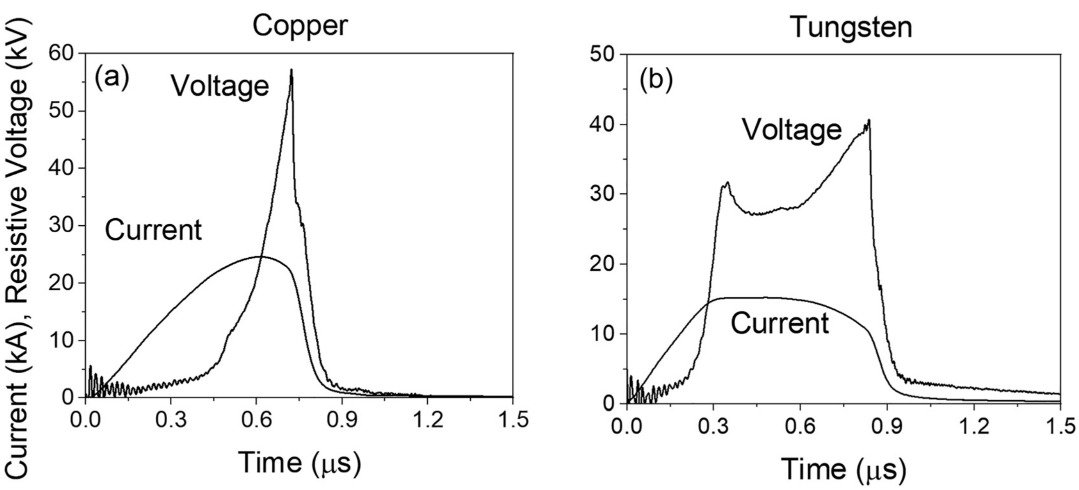

FIG. 1. Current and resistive voltage for (a) copper and (b) tungsten wire explosions.

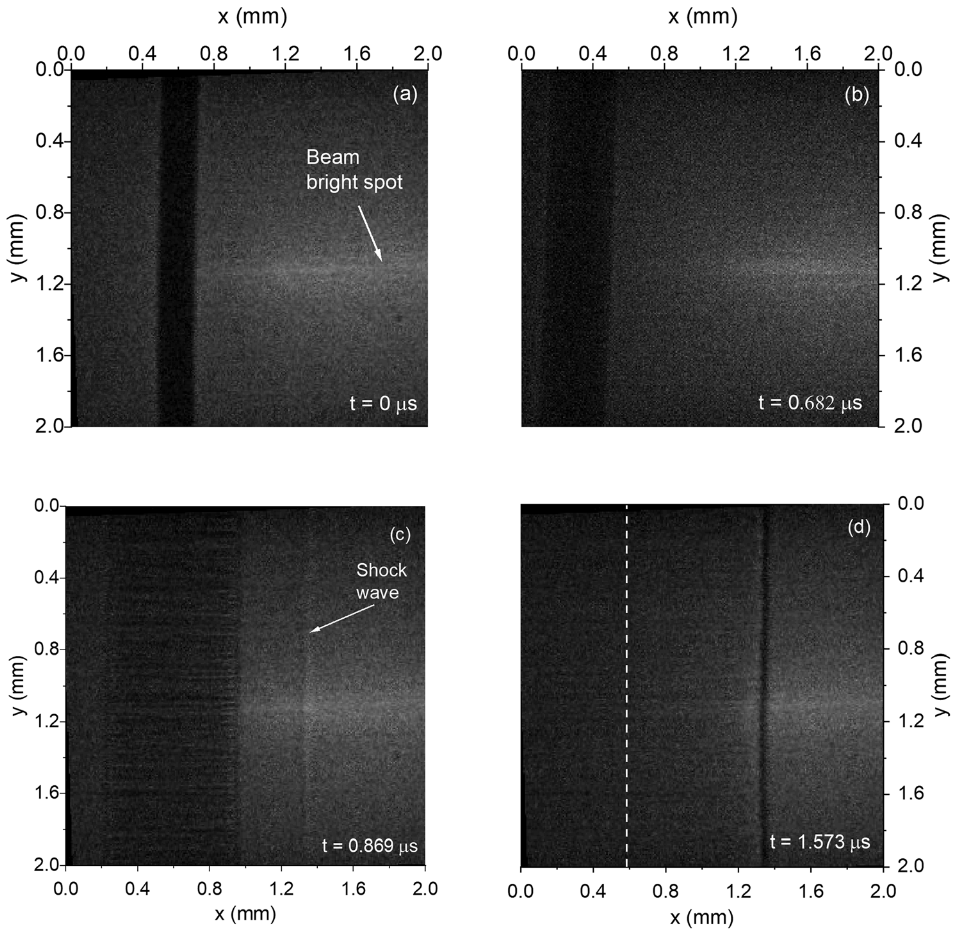

FIG. 2. X-ray radiography images of a Cu wire (a) before and (b)–(d) after explosion. (b) is taken from a different explosion than (a), (c), and (d), with similar current and voltage waveforms. The bright spot in the middle of the images is an optical effect caused by the lenses used to collimate the x-ray beam. The dashed line in (d) indicates the center of the wire.

to happen as the wire is vaporized, and fast expansion of the wire material begins. At 0.682 μs, the wire has only just vaporized, and any instability could be too small to view or obscured by the still high-density wire material.

The wavelength of these striations seen at 0.869 μs is $\sim$40 μm. At this point in time, current has already fallen to only $\sim$2 kA. Over subsequent frames, the striations slowly fade [as seen in Fig. 2(d)], until the shock wave generated by the expanding wire in the water reaches the inner surface of the plastic tube at $\sim$3 μs, distorting the image. With almost no current flowing through the copper wire after $\sim$0.9 μs, the decay of the striations in the radiographs is likely due to diffusion of the different density plasma regions into one another.

Due to high levels of noise, it is only possible to roughly estimate the densities of the striation layers. The x-ray attenuation through a material with density ρ is $I = I_0 \exp[-(\mu/\rho)\rho L]$, where I_0 is the original intensity, (μ/ρ) is the mass attenuation coefficient, and L is the width of the material. The value of (μ/ρ) was evaluated using the first frame of the shot, before the beginning in the expansion of the wire, where the density is known to be 8.96 g/cm^3 for copper. Using this coefficient and the attenuation formula, the densities of the striations were evaluated at 0.869 μs to be $\sim$0.3 g/cm^3 and $\sim$2 g/cm^3 for the low- and high-density layers, respectively.

While striations were obvious in experiments with Cu wire, with W wires no striations are visible at any probing time. We are examining if this is due to the striations forming on too small a length scale or being too obscured by the higher density of tungsten resulting in smaller increment of this instability development. Another reason could be related to the suggestion in Ref. 25, where it is shown that the energy sufficient for material sublimation should be deposited into exploding wire in order to obtain striations. However, in our experiments, the energy deposition in the copper wire was $\sim$260 J which significantly exceeds the required sublimation energy of $\sim$68 J. In the case of the tungsten wire explosion, the deposited energy of $\sim$380 J also exceeded the required sublimation energy of $\sim$125 J.[26] However, the rate of the energy deposition processes in these wires was very different with a faster deposition of the energy in copper wires, compared to tungsten.

In vacuum experiments, several explanations have been suggested for the presence of striations. For example, Gus'kov *et al.* suggest that the Rayleigh-Taylor instability caused the striations they obtained.[9] This instability is realized when a lower density fluid is supporting a higher density fluid against a given force.[27] In these experiments, wire explosions were carried out in vacuum, where a dense wire core was surrounded by a smaller density plasma layer carrying a significant part of the discharge current and compressing the core.

This instability is not likely to cause the striations in our experiments as the water surrounding the wires is preventing the formation of low-density plasma at the surface of the wire.

Another explanation of the striations is the MHD $m = 0$ instability.[28] This instability is realized when the azimuthal magnetic field resulting from the current in the wire tends to increase radial nonuniformities along itself.[29] The time of explosion in our experiment is $\tau_{\mathrm{exp}} \sim 0.6\,\mu$s, and the duration of the wire being in liquid and vapor phases can be estimated as $\tau_{\mathrm{lv}} \leq 0.4\,\mu$s. On the other hand, the time-scale of the significant development of MHD instabilities can be roughly estimated as $\tau_{\mathrm{inst}} \approx r_0/c_{\mathrm{A}}$,[30] where r_0 is the wire radius, and $c_{\mathrm{A}} = B/\sqrt{4\pi\rho}$ is the Alfvén velocity in Gaussian units,[31] where B is the magnetic field and ρ is the wire density. Assuming an average current amplitude of $\sim$23 kA, this estimate leads to $\tau_{\mathrm{inst}} \sim 0.8\,\mu$s which is significantly larger than τ_{lv}. Thus, we conclude that the MHD instability is not likely the cause of the striations obtained in our experiment.

The third and most common explanation of the obtained striations is the overheating instability, a.k.a. electrothermal instability[30,32] suggested by several wire explosion experiments in vacuum and air.[11–14,33] In Ref. 30, a characteristic scale for this instability was found using small perturbation theory neglecting wire radial expansion: $\lambda = 2\pi\sqrt{\kappa(\partial T/\partial\delta)}/J$, where J is the current density, κ is the thermal conductivity, δ is the specific resistance, and T is the temperature. Here, we will use these estimates considering the range of wire radii to be 0.1–0.35 mm to account for the wires' expansion from $t = 0$ until the peak of the current ($\sim$30 kA), and the maximal increment of this instability and the range of this characteristic scale was found to be 2×10^6 s^{-1} and 50–200 μm, respectively. The lower limit of this range is similar to the wavelength obtained in the experiment.

To explore the possibility of the overheating instability in further detail, we performed an MHD simulation using the JULIA code.[33] The simulations were coupled with semi-empirical equations of state[34] for copper which account for effects of the high-temperature melting and vaporization. The electrical conductivity and coefficient of thermal conductivity were obtained using a conductivity table for copper[35] calculated following a model described in Ref. 36. The water was taken into account at the boundary of the wire as a mobile wall. The radial propagation velocity of that wall was modeled according to the experimentally measured expansion velocity of the exploding wire, and the axial velocity at the boundary was taken to be zero. Also, the azimuthal magnetic field at the boundary was calculated as follows: $B_\phi = \mu_0 I(t)/(2\pi R_{\mathrm{max}})$.

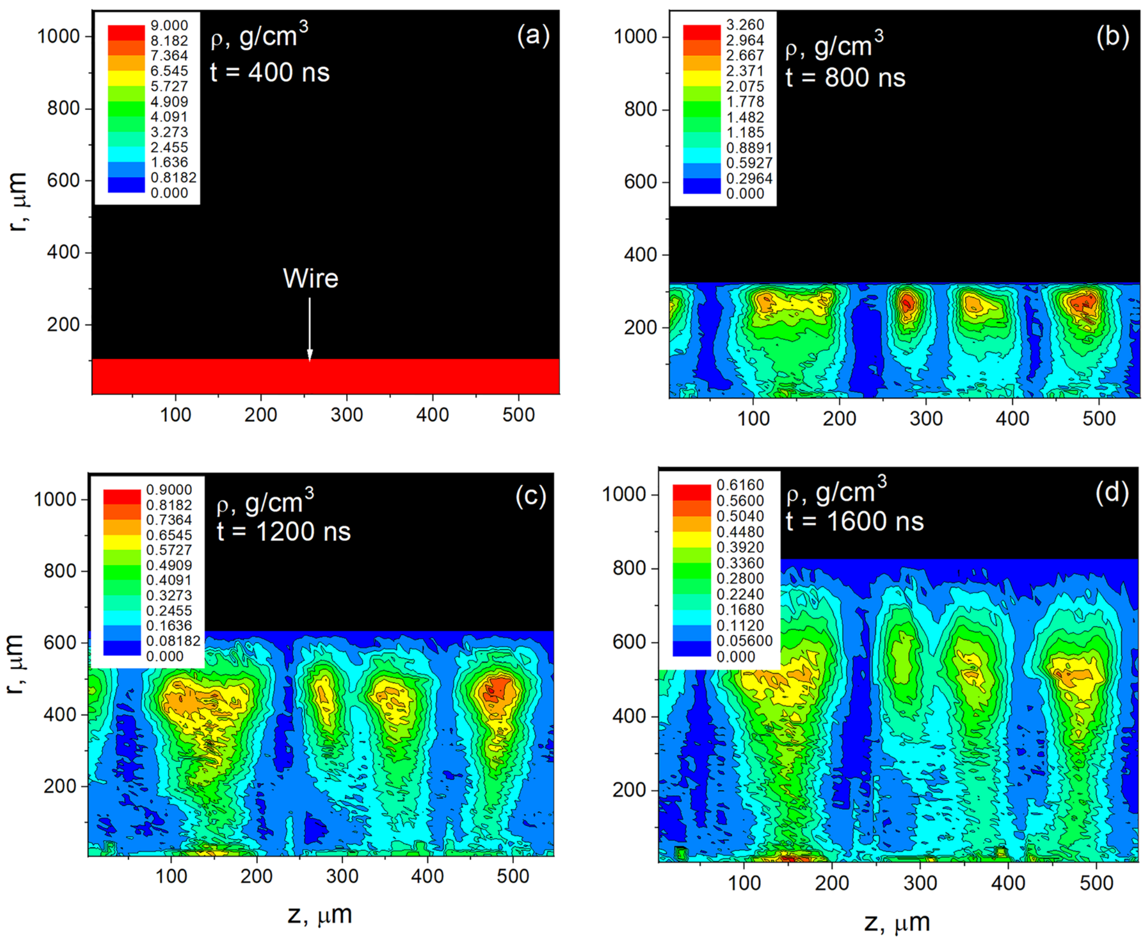

FIG. 3. MHD simulation results for density of the exploded wire. Times are with respect to the beginning of the rise of the current.

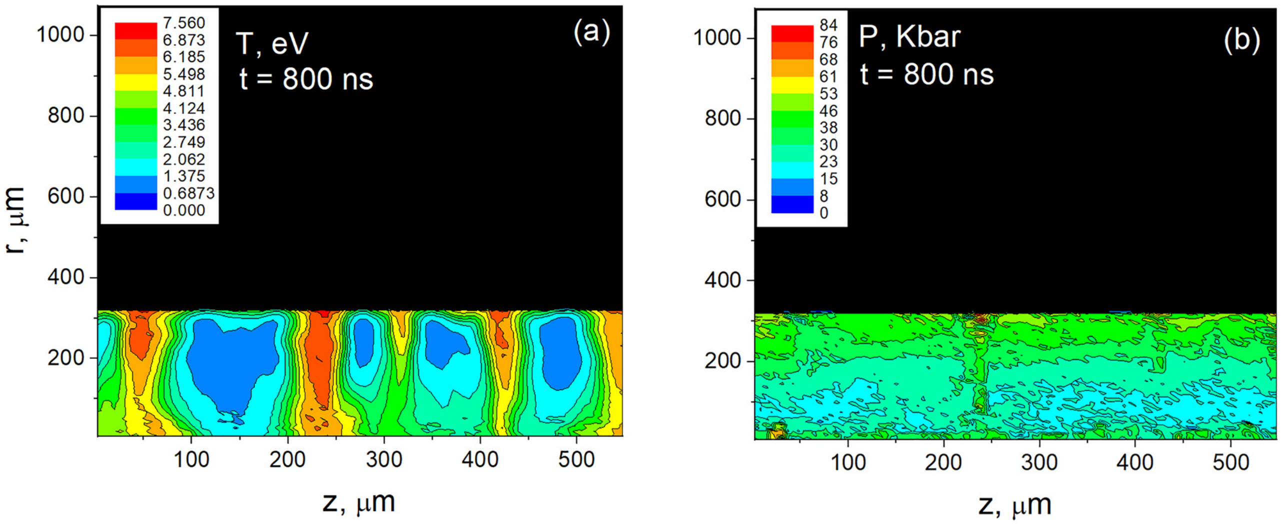

FIG. 4. MHD simulation results for (a) temperature and (b) pressure of the exploded wire at $t = 800$ ns.

To reduce simulation runtime, only the segment shown in Figs. 3 and 4 was simulated.

We note that at the low temperatures and high densities expected in the experiments, estimates of radiative heat transfer processes suggest these were orders of magnitude smaller than hydrodynamic processes; hence, they could be effectively ignored in calculations. The current and voltage waveforms obtained in the simulation were compared to the waveforms measured in the experiment resulting in satisfactory agreement. As a seed for the striations, the density in each cell was reduced by a random value of up to 1% of the normal density. This represents an estimate of local changes in density within a wire given its internal structure.[37]

The simulation results for the density distribution of the wire are shown in Figs. 3(a)–3(d) at different times, and for pressure and temperature distributions in Fig. 4 at $t = 800$ ns which is close to the time of Fig. 2(c) where the striations are best visible. The number of cells along z is 100 and the size is 5.5 μm, and the number of cells along r is 90. The grid for r was uneven; at the initial position of the wire, the grid size for r was equal to the size of the grid for z. Then, as the cold metal was moving away from the initial distribution, the grid size in r increased in a geometric progression, but the cell length in r was no more than the size of the cell length in z multiplied by two. Let us note here that the cell sizes are an order of magnitude smaller than the striations wavelength. At the time the striations become evident, the temperature approaches ~1 eV and ~5 eV in high- and low-density regions, respectively. Thus, one can consider that the substance of the wire is in plasma state both in the low- and high-density regions of the wire. At ~800 ns, the wavelength of the striations has saturated at 70–130 μm. The discrepancy in this result compared to the experiment could be related to uncertainty in the electrical conductivity model[7] as changes in thermal conductivity did not result in better agreement with the experimental data.

Let us note that while the results of these simulations could be interpreted as the MHD m = 0 instability, this is highly unlikely due to the higher thermal pressure compared to the magnetic pressure, which is responsible for the development of the m = 0 instability.

In conclusion, we present direct evidence of striation development in pulse power driven underwater wire explosions. The striations appear over the entire radius of the expanding wire material and are evident from just after the end of the current pulse, then decay in time. In copper, the striations are spaced ~40 μm apart; however, in tungsten the striations are not visible, at least within the capabilities of our diagnostics. MHD simulations of the experiment are able to produce similarly configured striations due to the overheating (electrothermal) instability and suggest, as expected, that the striations begin to develop after the wire starts to vaporize and rapid expansion of the wire material begins.

The results of our research suggest that previous experiments which utilized pulsed power driven underwater wire explosions to determine the conductivity of dense gases and plasmas could contain uncertainties. Most of these studies assumed a uniform model for wire expansion, and the presence of striations could skew the calculated values. Many conductivity tables used in high energy density physics and warm dense matter simulations are based on such data. In the future, with the upgrade of synchrotrons and other light sources, we hope to perform these experiments with higher resolutions, obtaining better density measurements of the striations. We will also attempt to measure the different temperatures of the striations through absorption spectrometry. Together such data would give an excellent reference to compare conductivity models to.

This research was funded by EPSRC, First Light Fusion Ltd, the Institute of Shock Physics, the ESRF user program, U.S. Department of Energy under Cooperative Agreement Nos. DE-NA0003764 and DE-SC0018088, and Sandia National Laboratories.

The authors would also like to thank Harald Reichert of ESRF, Paul Berkvens and the safety team at ESRF, W. G. Proud and D. Chapman of Imperial College, D. Eakins of Oxford University and F. Zucchini and C. Chauvin of CEA Gramat for their support in planning these experiments, and S. Gleizer, S. Efimov, and E. Flyat from Technion for technical assistance.

REFERENCES

[1] E. A. Martin, "Experimental investigation of a high-energy density, high-pressure arc plasma," J. Appl. Phys. **31**, 255 (1960).

[2] W. M. Lee and R. D. Ford, "Pressure measurements correlated with electrical explosion of metals in water," J. Appl. Phys. **64**, 3851 (1988).

[3] T. W. L. Sanford, R. B. Spielman, G. O. Allshouse, G. A. Chandler, D. L. Fehl, W. A. Stygar, K. W. Struve, C. Deeney, T. J. Nash, J. F. Seamen, R. C. Mock, T. L. Gilliland, J. S. McGurn, and D. O. Jobe, "Wire number doubling in high-wire-number regime increases Z-accelerator X-ray power," IEEE Trans. Plasma Sci. **26**, 1086 (1998).

[4] A. W. DeSilva and J. D. Katsouros, "Electrical conductivity of dense copper and aluminum plasmas," Phys. Rev. E **57**, 5945 (1998).

[5] A. Grinenko, V. T. Gurovich, Y. E. Krasik, A. Sayapin, and S. Efimov, "Analysis of shock wave measurements in water by a piezoelectric pressure probe," Rev. Sci. Instrum. **75**, 240 (2004).

[6] A. Grinenko, S. Efimov, A. Fedotov, Y. E. Krasik, and I. Schnitzer, "Addressing the problem of plasma shell formation around an exploding wire in water," Phys. Plasmas **13**, 052703 (2006).

[7] D. Sheftman and Y. E. Krasik, "Evaluation of electrical conductivity and equations of state of non-ideal plasma through microsecond timescale underwater electrical wire explosion," Phys. Plasmas **18**, 092704 (2011).

[8] B. Liu, D. Wang, and Y. Guo, "Influence of water conductivity on shock waves generated by underwater electrical wire explosion," Phys. Lett. A **382**, 49 (2018).

[9] S. Y. Gus'kov, G. V. Ivanenko, A. R. Mingaleev, S. A. Pikuz, T. A. Shelkovenko, and D. A. Hammer, "Temporal evolution of the hydrodynamic instability of the boundary between the dense core and the plasma corona during nanosecond explosion of wires," JEPT Lett. **67**, 559 (1998).

[10] D. B. Sinars, T. A. Shelkovenko, S. A. Pikuz, M. Hu, V. M. Romanova, K. M. Chandler, J. B. Greenly, D. A. Hammer, and B. R. Kusse, "The effect of insulating coatings on exploding wire plasma formation," Phys. Plasmas **7**, 429 (2000).

[11] D. B. Sinars, T. A. Shelkovenko, S. A. Pikuz, J. B. Greenly, and D. A. Hammer, "Exploding aluminum wire expansion rate with 1–4.5 kA per wire," Phys. Plasmas **7**, 1555 (2000).

[12] D. B. Sinars, M. Hu, K. M. Chandler, T. A. Shelkovenko, S. A. Pikuz, J. B. Greenly, D. A. Hammer, and B. R. Kusse, "Experiments measuring the initial energy deposition, expansion rates and morphology of exploding wires with about 1 kA/wire," Phys. Plasmas **8**, 216 (2001).

[13] A. G. Rousskikh, V. I. Oreshkin, S. A. Chaikovsky, N. A. Labetskaya, A. V. Shishlov, I. I. Beilis, and R. B. Baksht, "Study of the strata formation during the explosion of a wire in vacuum," Phys. Plasmas **15**, 102706 (2008).

[14] W. G. Chace, "Liquid behavior of exploding wires," Phys. Fluids **2**, 230 (1959).

[15] H. D. Edelson and T. Korneff, "A comparative study of exploding wires in air and water," J. Appl. Phys. **37**, 2166 (1966).

[16] H. Goronkin, "Striations in fast wire explosions," J. Appl. Phys. **39**, 5345 (1968).

[17] R. B. Baksht, S. I. Tkachenko, V. M. Romanova, A. R. Mingaleev, V. I. Oreshkin, A. E. Ter-Oganes'yan, T. A. Khattatov, T. A. Shelkovenko, and S. A. Pikuz, "Stratification dynamics and the development of electrothermal instability at the wire explosion," Tech. Phys. **58**, 1129 (2013).

[18] Y. Me-Bar and R. Harel, "Electrical explosion of segmented wires," J. Appl. Phys. **79**, 1864 (1996).

[19] J. Stephens, A. Neuber, and M. Kristiansen, "Experimental and theoretical evaluation of surface coated exploding wires," Phys. Plasmas **19**, 032702 (2012).

[20] M. Nitishinskiy, D. Yanuka, A. Virozub, and Y. E. Krasik, "Radial density distribution of a warm dense plasma formed by underwater electrical explosion of a copper wire," Phys. Plasmas **24**, 122703 (2017).

[21] M. P. Desjarlais, "Practical improvements to the Lee-More conductivity near the metal-insulator transition," Contrib. Plasma Phys. **41**, 267 (2001).

[22] M. P. Olbinado, X. Just, J. Gelet, P. Lhuissier, M. Scheel, P. Vagovic, T. Sato, R. Graceffa, J. Schulz, A. Mancuso, J. Morse, and A. Rack, "MHz frame rate hard X-ray phase-contrast imaging using synchrotron radiation," Opt. Express **25**, 13857 (2017).

[23] M. P. Olbinado, V. Cantelli, O. Mathon, S. Pascarelli, J. Grenzer, A. Pelka, M. Roedel, I. Prencipe, A. L. Garcia, U. Helbig, D. Kraus, U. Schramm, T. Cowan, M. Scheel, P. Pradel, T. De Resseguier, and A. Rack, "Ultra high-speed x-ray imaging of laser-driven shock compression using synchrotron light," J. Phys. D: Appl. Phys. **51**, 055601 (2018).

[24] D. Yanuka, A. Rososhek, S. Theocharous, S. N. Bland, Y. E. Krasik, M. P. Olbinado, and A. Rack, "Multi frame synchrotron radiography of pulsed power driven underwater single wire explosions," J. Appl. Phys. **124**, 153301 (2018).

[25] V. I. Oreshkin, K. V. Khishchenko, P. R. Levashov, A. G. Rousskikh, and S. A. Chaikovskii, "Strata formation at fast electrical explosion of cylindrical conductors," High Temperature **50**, 584 (2012).

[26] C. J. Smithells, *Metals Reference Book* (Butterworths, London/Boston, 1976).

[27] R. P. Drake, *High-Energy-Density Physics* (Springer, Berlin/Heidelberg, 2006).

[28] K. B. Abramova, N. A. Zlatin, and B. P. Peregud, "Magnetohydrodynamic instability of liquid and solid conductors. Destruction of conductors by an electric current," Sov. Phys. JETP **42**, 1019 (1975).

[29] J. Freidberg, *Plasma Physics and Fusion Energy* (Cambridge University Press, Cambridge, 2007).

[30] V. I. Oreshkin, "Thermal instability during an electrical wire explosion," Phys. Plasmas **15**, 092103 (2008).

[31] L. D. Landau and E. M. Lifshits, *Electrodynamics of Continuous Media* (Nauka, Moscow, 1982).

[32] A. A. Valuev, I. Ia. Dikhter, and V. A. Zeigarnik, "Striations arising in the explosion of cesium wires at supercritical pressures," Zh. Tekh. Fiz. **48**, 2088 (1978).

[33] V. I. Oreshkin, R. B. Baksht, N. A. Ratakhin, A. V. Shishlov, K. V. Khishchenko, P. R. Levashov, and I. I. Beilis, "Wire explosion in vacuum: Simulation of a striation appearance," Phys. Plasmas **11**, 4771 (2004).

[34] V. E. Fortov, K. V. Khishchenko, P. R. Levashov, and I. V. Lomonosov, "Wide-range multi-phase equations of state for metals," Nucl. Instrum. Methods Phys. Res., A **415**, 604 (1998).

[35] V. I. Oreshkin, R. B. Baksht, A. Y. Labetsky, A. G. Rousskikh, A. V. Shishlov, P. R. Levashov, K. V. Khishchenko, and I. V. Glazyrin, "Study of metal conductivity near the critical point using a microwire electrical explosion in water," Tech. Phys. **49**, 843 (2004).

[36] Yu. D. Bakulin, V. F. Kuropatenko, and A. V. Luchinskii, Zh. Tekh. Fiz. **20**, 1963 (1976).

[37] B. Landolt-Bornstein, *Technology Classification, Value and Behavior of Metallic Materials (Technik, Teil, Stoffwerte und Verhalten Von Metallischen Werkstoffen)* (Springer-Verlag, 1964).