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Studies of specific action integral and electro-thermal instabilities in the sub-microsecond underwater electrical explosions of shaped foils

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ABSTRACT

We present the results of two studies: (1) on the specific action integral h and (2) on the electrothermal instability (ETI) during underwater electrical explosions of different material foils. Values of h were studied in experiments with the explosion of tapered (“butterfly”) foil geometries using current pulses with an amplitude of ~ 300 kA and ~ 400 ns rise time using the MAGEN [Kovalchuk *et al.*, Rev. Sci. Instrum. **80**, 083504 (2009)] generator at Technion. Shadow images of foils, together with strong shock waves generated in the surrounding water by their explosion and results of COMSOL [Asmedyanov *et al.*, J. Appl. Phys. **136**, 133303 (2024)] numerical simulations, were used to determine the values of h . These values were found to be significantly smaller than those stated in earlier research of wire explosions in vacuum. ETI was studied with butterfly and rectangular shaped foils explosion using pulsed driver generating current pulses with an amplitude of ~ 120 kA and ~ 450 ns rise time and multi-frame x-ray radiography at the European Synchrotron Radiation Facility. In the case of the butterfly, x-ray radiography showed the ETI instability initially appeared at the “waist,” where later explosion starts. In the case of the rectangular foil, it was found that the ETI perturbations have a minimum wavelength and a broad spectrum of larger wavelengths.

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I. INTRODUCTION

Underwater electrical wire explosion (UEWE) or underwater electrical explosion of foils (UEFE) can be used efficiently for studying the parameters of metals in the wide range of densities from solid to $1/100$ of solid density. Due to the high-voltage breakdown threshold and small compressibility of water, the formation of the plasma along the wire/foil surface, which can capture part of the discharge current, and fast wire/foil expansion typical to explosions in gas or vacuum^{1–6} are avoided. This allows high energy density deposition with pressures $>10^9$ Pa and temperature of several eV to be reached.^{7–9} Hence, this technique enables access to the “warm dense matter” regime—an area of great interest to high energy density physics,^{7,8,10–13} and the data can be considered a benchmark for comparison with the existing equations of state^{8,10,12,14–17} and conductivity models.^{11,14,18,19}

To achieve high energy density and energy density rate deposition, the explosion of a wire/foil should occur at a discharge current amplitude close to its maximal value and the discharge should be critically damped.^{20–22} The required cross section of the wire/foil, S , for this can be estimated using the tabulated values of specific action integral $h = \int_0^{\tau_{\text{exp}}} j^2 dt \approx S^{-2} \int_0^{\tau_{\text{exp}}} I^2 dt \approx \int_C \rho \sigma d\varepsilon$, where j is the current density, I is the total discharge current, and τ_{exp} is the time of the explosion, ρ and σ are the density and conductivity of the material, respectively, and ε is the internal energy. Here, it is assumed that an increase in the cross-sectional area of the conductor is not significant until the explosion. The integral for internal energy is calculated until explosion, i.e., along the phase trajectory C^{23} representing the changes in material states up to the critical point in the phase diagram where liquid, gas, two-phase regions, and plasma coincide. Simply put, τ_{exp} can also be considered

the time when the magnetic pressure of the current becomes significantly smaller than internal thermal pressure and fast material expansion starts, accompanied by a fast energy deposition and decrease in the current due to increase in material resistivity. The expansion of the material has typical velocities of $\sim 10^3$ m/s due to this rapid deposition of the energy [with the expansion also generating strong shockwave (SSW) in the water]. It is preferable that at τ_{exp} , the current reaches its almost maximal value so the maximum power can be deposited prior to the material expanding too much, lowering collisionality and massively increasing its conductivity.^{2,21,24}

In many earlier studies,^{1,9,23} the value of h was determined in experiments with wire explosions in vacuum, when part of the current could be captured by surface plasma, leading to an overestimate of its value. Additionally, as follows from the definition of the specific action integral, these earlier studies^{20,21} showed that the value of h depends on the current density and deposited energy density. Our recent experimental and numerical research,²⁰ where the values of h were studied using μs -timescale underwater electrical explosion of thin foils of “butterfly” shape (two isosceles trapezoids with a common “waist”), showed smaller values of h than those obtained for wire explosions in vacuum. The “butterfly” foil shape allows one to calculate values of h in one explosion for different current densities using Time of Flight (ToF) data of the SSW to determine onset times of the SSW at different heights of the foil and temporal current density dependence at the edge of the foil. The latter was obtained by numerical simulations (based on the Multiphysics software—COMSOL) coupled with experimental electrical circuit parameters. These results agree with our recent studies of wire explosions in water,²⁵ which also showed the values of h smaller than those obtained in vacuum explosions. The latter was explained by an overestimate of the h value in vacuum explosions because of a part of the discharge current shunting by the plasma formed along the surface of wires.

The same underwater electrical explosions allow us to study electrothermal instabilities^{4,25–29} (ETIs), which can be important for the understanding of exploding wire/foil resistance and for comparison with existing conductivity models that do not consider this instability. Much ETI research has been carried out in vacuum^{28,30} when $>10^4$ m/s wire expansion occurs, which leads to a fast decrease in density ρ and thermal conductivity. This could be a possible reason for an increase in the instantaneous buildup increment²⁵ $\gamma \propto \rho^{-1}$ of the ETI, which can be started at the liquid phase of the material. Recent research showed that underwater electrical wire explosions^{25,26} are also accompanied by ETI development with a typical wavelength of several tens of μm . However, probably due to the high density of the material and, consequently, high thermal conductivity, ETI was obtained only when the wire was in its vapor phase.²¹ Additionally, the results obtained with aluminum and silver wires explosions showed comparable ETI wavelengths, despite their different minimal instability wavelengths, which were predicted by the linear ETI development theory.⁴

In this article, we extend our research on both the values of h and the ETI instability obtained in experiments with sub- μs -timescale underwater electrical explosions of “butterfly” foils, while also comparing the ETI formation straight rectangular geometries. We utilize both aluminum (Al) and copper (Cu) foils. As in our previous studies,²⁰ h is calculated using the experimentally

determined onset times of the SSW, and the temporal dependence of the current density at the edge of the foil obtained by numerical simulations. Like for μs -timescale underwater wire explosions, the values of h are found smaller than those stated by earlier research when these values were determined for wire explosions in vacuum when part of the discharge current could be captured by surface plasma.²³ For ETI studies, x-ray radiographs of the exploding foils were used, similarly to those described for underwater wire explosion studies.²⁵ It was found that the ETI perturbations have a minimum wavelength and a broad spectrum of larger wavelengths.

II. EXPERIMENTAL SETUP AND DIAGNOSTICS

The experimental setup is shown in Fig. 1. The MAGEN generator³¹ used for studies of the specific action integral, delivering a current of up to 300 kA with a rise time of ~ 400 ns. The experimental setup was the same as that used in our recent research on the specific action integral for μs -timescale foil explosions.²⁰ We tested explosions of 30 mm long Cu ($10\mu\text{m}$ thick) and Al ($15\mu\text{m}$ thick) “butterfly” shaped foils with base and waist widths of 40 and 3 mm, respectively. Foils were stretched between the grounded cathode and high-voltage anode electrodes immersed in a de-ionized water filled experimental stainless-steel cylindrical chamber. The chamber has two opposite windows for optical observations. A continuous wave single-mode laser (≤ 1.5 W, $\lambda = 532$ nm) was used for backlighting the exploding foils and the shocks in the water. The shadow images of the exploding foils and SSWs generated in water were obtained by an XXRapidFrame camera (Stanford Computer Optics, frame duration of 10 ns) at different times relative to the beginning of the discharge current. These images allow us to determine the onset of the SSW for different cross-sectional areas of the foil using the linear extrapolation of the position of the shockwave vs time. We note that in experiments with μs -timescale explosions,²⁰ we obtained almost linear trajectories for the first 1.5 mm of the shock propagation; hence, we feel justified in considering an approximately constant shock velocity.

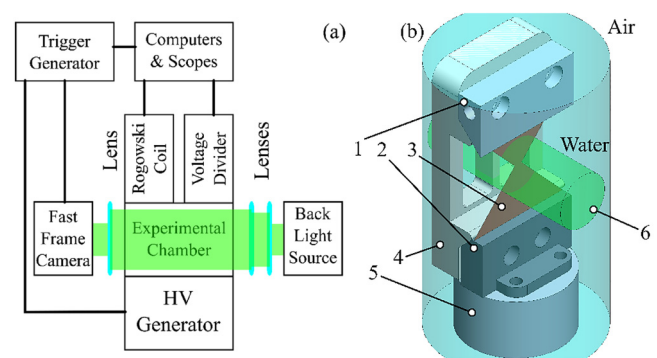


FIG. 1. Experimental setup: (a) block-diagram for both experimental setups. (b) Model of the load depicting grounded (1) and high-voltage (2) electrodes, foil (3), insulator (4), high-voltage electrode holder (5), and the continuous wavelength (CW) green laser for shadow imaging or x-ray beam for radiography (6).

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The development of ETI during the explosion of Cu and Al foils necessitated the use of x-ray radiography. Hence, these experiments were imaged using the micro-tomography beamline (ID19) of the European Synchrotron Radiation Facility (ESRF), described in detail in our previous UEWE studies.^{25,32,33} Due to its size and infrastructure requirements, the MAGEN generator could not be transported to ESRF, and we relied on a portable generator delivering ~ 120 kA with a similar rise time (450 ns) instead. In these experiments, the foils and the electrodes were placed in 50 mm diameter polymethyl methacrylate (PMMA) capsules filled with de-ionized water. After passing through the water, x rays propagated to a scintillator that was lens-coupled to a Shimadzu HPV-X2 high-speed framing camera. ESRF was used in a 16-bunch mode with undulators arranged to provide 20–50 keV burst of x rays, each 60 ps duration separated by 176 ns. Lensing to the camera was arranged to work either at $\times 1$ magnification, which results in a total image size of 8×12 mm² and an on-camera resolution of $32 \mu\text{m}$ per pixel or $\times 10$ magnification with 0.8×1.2 mm² recorded at the camera at a resolution of $3.2 \mu\text{m}$ per pixel. For the tenfold magnification, 16 Be Compound Refractive Lenses (CRLs) were inserted into the x-ray path upstream of the target. This configuration further collimated the x-ray beam and increased the intensity incident on the scintillator.

The waveforms of the discharge current (I) were measured using a calibrated self-integrated Rogowski coil (measurement error of $\sim 5\%$), and those of the voltage (V) were measured by a Tektronix P6015A high-voltage divider (measurement error of $\sim 3\%$). The inductive voltage LdI/dt was subtracted from the measured value of V to obtain the resistive voltage V_r , where L is the inductance of the foil determined in short circuit shots with non-exploding loads imitating the foil.

III. EXPERIMENT RESULTS

A. Specific action integral studies in sub- μs explosion of Al and Cu foils

Similarly to recent studies,^{20,24,34} as a control/comparison to later shots with a “butterfly” form foils, we carried out UEWE

experiments with a 30 mm long, 6 mm wide, and $35 \mu\text{m}$ thick rectangular Cu foil characterized by uniform current density along its length. This is wider than the waist of the butterfly foil experiments (6 vs 3 mm); hence, the current density is expected to be lower than at this point in the butterfly experiments. Figure 2(a) displays the waveforms of the discharge current, resistive voltage, and time-dependent resistance. The latter reaches $\sim 0.27 \Omega$ at the maximum of the resistive voltage, which indicates the formation of a high resistance plasma channel. Later in time, the resistance decreases because of foil expansion and the continuing ionization. The deposited energy density, necessary for the vaporization of copper foil³⁵ [see Fig. 2(b)], is reached at ~ 400 ns, when the current reaches its maximal amplitude of ~ 260 kA [see Fig. 2(a)]. This suggests that the explosion, when magnetic pressure becomes significantly smaller than the thermal pressure, accompanied by fast energy density deposition and foil expansion, occurs when the deposited energy becomes larger than the vaporization energy along the entire length of the foil.²³

Next, experiments with “butterfly” shaped foils were carried out. Parameters of this explosion for Cu foil are shown in Fig. 3. Like for the μs -timescale studies,²⁰ the maximal values of resistance and resistive voltage are smaller than those obtained for rectangular foil explosions [Fig. 2(a)]. Additionally, the sharp increase in resistance and voltage starts much earlier, $\tau \sim 120$ ns relative to the beginning of the current, even though the deposited energy density does not reach a value necessary for total foil vaporization. This earlier increase in voltage and resistance is related to the beginning of the explosion at the waist of the foil where the current density is maximum (and significantly higher than in the rectangular control experiment).

After reaching the value of $\sim 0.15 \Omega$, the resistance of the butterfly experiment remains almost constant for ~ 400 ns [see Fig. 3(a)]. In addition, resistive voltage after reaching its maximal amplitude of ~ 32 kV at $\tau \sim 400$ ns remains quasi-constant during almost ~ 350 ns. This is significantly different from the rectangular foil control experiments and is consistent with the foil explosion starting at different times at various positions along the length of

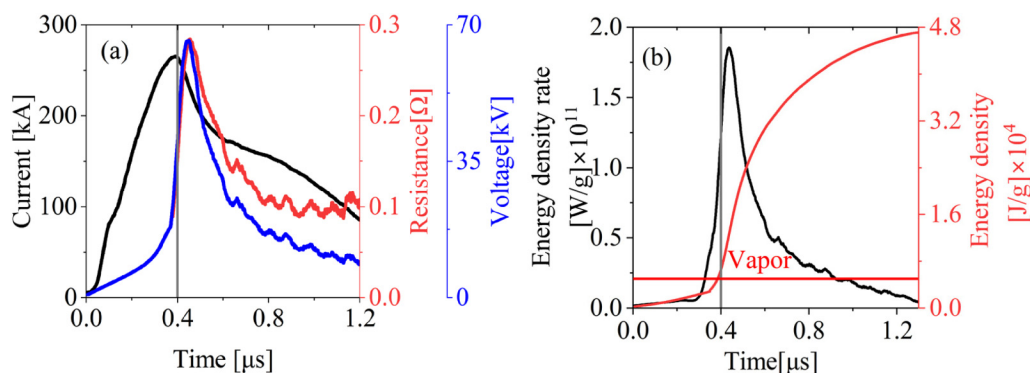


FIG. 2. Waveforms of (a) the discharge current (black), resistive voltage (blue), and resistance (red) and (b) the average deposited energy density rate (black) and the deposited energy density (red). The horizontal and vertical lines show the vaporization energy and time when this energy was deposited into the foil, respectively. The rectangular Cu foil dimensions (length $\times$ width $\times$ thickness): 30 mm $\times$ 6 mm $\times$ 35 μm .

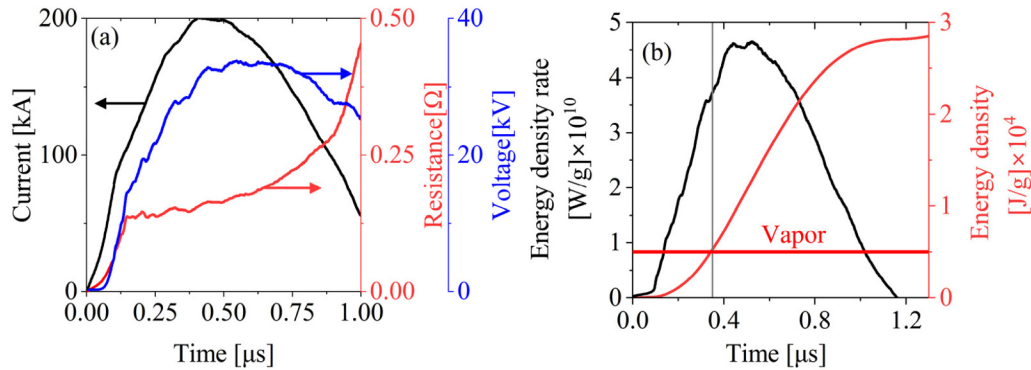


FIG. 3. As in Fig. 2 for a “butterfly” shaped 50 mm long, $10\text{ }\mu\text{m}$ thick Cu foil. The foil base and waist widths are $W_0 = 40\text{ mm}$ and $W = 3\text{ mm}$, respectively. (a) Waveforms of the discharge current (black), resistive voltage (blue), and resistance (red); (b) the average values of the deposited energy density rate and energy density for all exploded foils.

the foil, i.e., different cross sections, $S(z)$, of the foil. Similar waveforms of the discharge current, resistive voltage, and temporal behavior of the resistance were obtained for explosions of Al foils.

As discussed in the introduction, the foil explosion occurs when the magnetic pressure of the current becomes smaller than the internal thermal pressure and fast expansion of the foil begins, accompanied by the onset of the SSW generation in water. The latter defined as τ_{exp} was determined by using ToF measurements of SSW captured by a XXRapidFrame camera. First, the initial foil shadow image was captured and then overlaid with shadow images of the SSW with a time delay of 400 ns between frames, each of 10 ns duration. These overlaid shadow images, shown in Fig. 4 and obtained at different times with respect to the beginning of the discharge current, allow us to determine the SSW front XZ coordinate for various Z along the length of the foil. The SSW velocity in the X-direction determined from these ToF measurements was found to be $\sim 4.5 \times 10^3\text{ m/s}$ at the waist and decreased down to

$\sim 2.2 \times 10^3\text{ m/s}$ at the foil $Z \sim 4.4\text{ mm}$ with respect to the waist. The total velocity, which is perpendicular to the edge of the foil in the ZX plane, also decreases down to $2.83 \times 10^3\text{ m/s}$ at $Z \sim 4.4\text{ mm}$. This can be explained by the almost three times increase in the cross-sectional area of the foil at this height and almost tenfold decrease in the energy density deposition. Let us note here that TOF data showed that at each Z position, the shock velocity remains almost constant vs the distance from the foil. This allows the straightforward determination of the shock onset from the foil edge at each specific cross section of the foil.

Now, using the equivalent electrical circuit of the experiment and simulations based on 3D COMSOL Multiphysics software, which includes Maxwell’s equations, thermal diffusion, Ohm’s law, and the database for conductivity,^{36,37} the time-dependent current densities at the edge of the foil at its different cross sections were calculated. These were used to calculate the values of h at the explosion times, obtained by the TOF method for the onset of the SSW in

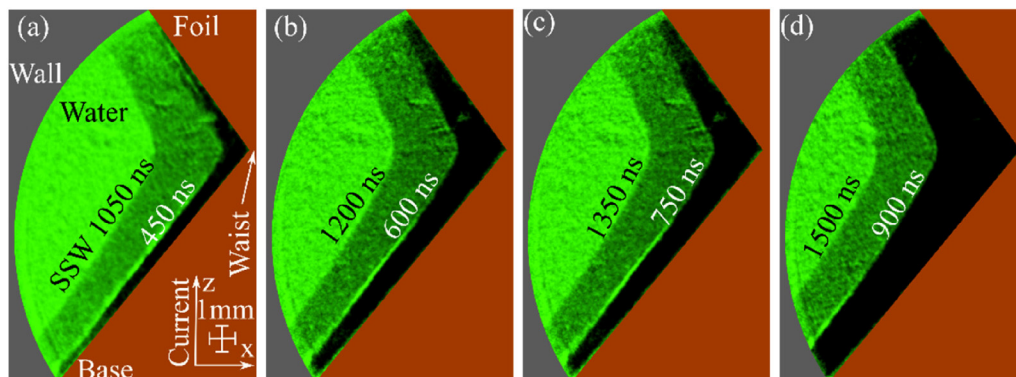


FIG. 4. Optical shadow images of the explosion of a $10\text{ }\mu\text{m}$ thick butterfly shaped Cu foil in water. (a)–(d) Three overlaid shadow images each of 10 ns frame duration and obtained time delays with respect to each other.

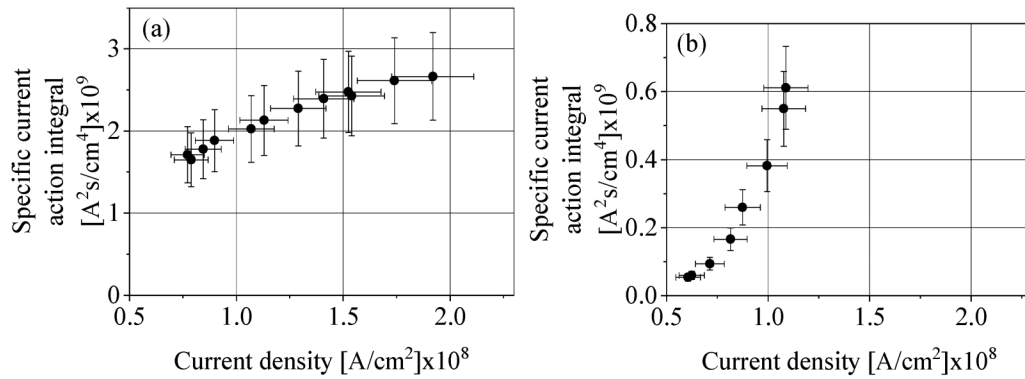


FIG. 5. The specific current action integral vs current density for Cu (a) and Al (b) “butterfly” shaped foils.

TABLE I. Specific current action integral, $h \left[\frac{A^2 s}{cm^4} \right] \times 10^9$, for current density $j = 10^8$ A/cm² obtained in underwater electrical explosions of foils (UEFE) having butterfly form and electrical explosion of wires in water (UEWE) and electrical explosion of wires in vacuum (VEWE) and specified timescales.

Present	Cu h value	Al h value
Sub- μ s UEFE	1.8 ± 0.5	0.4 ± 0.1
μ s UEFE ²⁰	1.5 ± 0.5	0.8 ± 0.2
Sub- μ s UEWE ²¹	1.7 ± 0.5	1.0 ± 0.3
Sub- μ s VEWE ⁴	4.1 ± 1	1.8 ± 0.4

the range 100–200 ns with respect to the beginning of the discharge current, at each specific cross section of the foil. In Fig. 5, we present the dependence of h on the current density for $Z = 0$ –4 mm for Cu and Al foils having the same shape. One can see that for these materials, the value of h increases with an increase in the current density. This result agrees with the tendency obtained in the earlier research for wire explosions in vacuum,¹⁹ and it relates to a larger mass of the conductor, which experiences the explosion. Here, the range of relative errors in the values of h and current density arises from uncertainties of 2.5% in the current measurements and 10% in the ToF measurements.

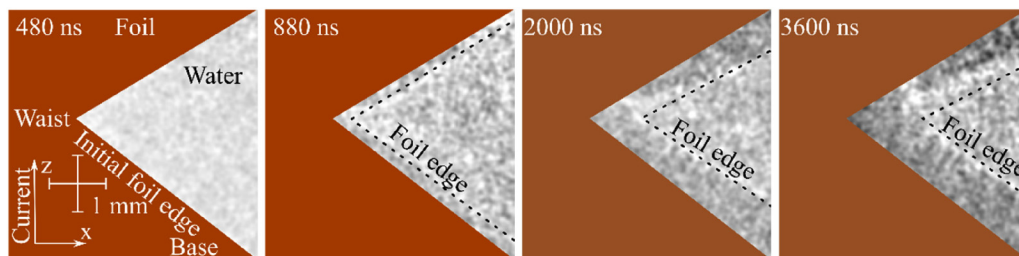


FIG. 6. X-ray shadow images of explosion of a 15 μ m thick Cu “butterfly” foil in water. The “copper” color area is the initial foil shadow.

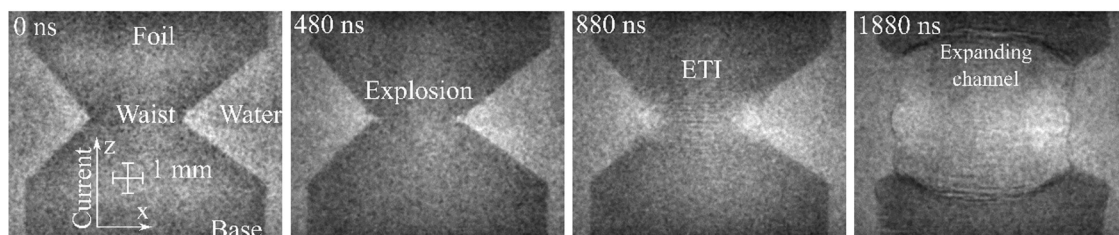


FIG. 7. X-ray shadow images of the “butterfly” shaped brass foil (30 mm $\times$ 8 mm $\times$ 50 μ m, and 3 mm waist) explosion in water.

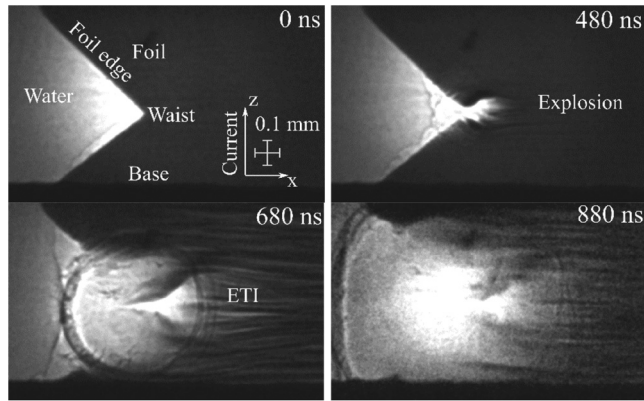


FIG. 8. X-ray shadow images of the “butterfly”-shaped brass foil ($30 \text{ mm} \times 8 \text{ mm} \times 50 \mu\text{m}$, and 3 mm waist) explosion in water. The frame size is $0.8 \times 1.2 \text{ mm}^2$.

In Table I, we present a comparison between the values of h obtained in the present study, in μs -timescale energy deposition during underwater explosions of “butterfly” shaped foils²⁰ and in earlier wire explosion studies.^{4,9,21,23} One can see that the values of h for underwater explosions of butterfly shaped Cu foils and wires are almost the same within the experimental error determined by the accuracy of the measurement of the current, voltage, and shock wave front (see Sec. II). However, the value of h for Al foils was smaller by a factor of almost 2 compared to when this value was studied for Al wire explosions.²¹ At present, we do not know the reason for this difference and can only suggest that the Al foil experiences faster expansion than the Al wire that could lead to smaller current density sufficient for explosion. Finally, one can see that the values of h obtained in underwater explosions are significantly smaller than those determined in the vacuum explosion of wires. As we have proposed in our earlier research,^{20,21} which can be related to a part of the current captured by corona plasma in the case of conductor’s explosion in vacuum.

B. X-ray studies of sub- μs explosion of Cu and brass “butterfly” shaped foils

In experiments at ESRF using x-ray radiography, we studied ETI instabilities that appear during the underwater electrical explosion of a “butterfly” shaped $15 \mu\text{m}$ thick Cu foil. However, because of insignificant contrast for Cu foil explosions due to the transparency of the foil for x rays (see Fig. 6), only rough estimate of the foil lateral expansion’s average velocity of $\sim 420 \text{ m/s}$ was possible.

To obtain better contrast and evolution of the “butterfly” shaped foil explosion, a $50 \mu\text{m}$ thick brass “butterfly” shaped foil was used instead. In Fig. 7, one can see that the explosion starts at the waist and propagates with velocity $\sim 1400 \text{ m/s}$ toward the base of the foil forming an expanding plasma channel having either cylindrical or elliptical form.

The details of the development of the brass foil’s waist explosion, obtained with a 1:10 magnification, are shown in Fig. 8. One can see that already at 480 ns , an explosion occurred at the waist. Additionally, zones of rarefaction can be observed in the water layer at the waist and within a few micrometers of the foil edge. The less dense region in the waist can be related to fast foil expansion due to explosion. Similarly, the less dense water layer can be related to vaporization due to high radiation and heat fluxes from the edge of the foil. In the next radiography image obtained at 680 ns , one can see the formation of ETI, seen as a series of horizontal layers in the brass material, and the SSW having circular form in the XZ plane. Assuming that the SSW was generated at $\sim 480 \text{ ns}$, its velocity was estimated as $\sim 3 \times 10^3 \text{ m/s}$, which is close to that obtained in experiments on a microsecond generator.²⁰

C. Electro-thermal instabilities in thick rectangular brass foils during underwater electrical explosions

Thin rectangular Al ($15 \mu\text{m}$ thick, 50 mm long, and 8 mm wide) and Cu ($10 \mu\text{m}$ thick, 50 mm long, and 8 mm wide) foil explosions did not show detectable changes in the density due to the limited contrast of the x-ray beam. Thus, experiments with thicker brass ($50 \mu\text{m} \times 30 \text{ mm} \times 8 \text{ mm}$) and Al ($40 \mu\text{m} \times 30 \text{ mm} \times 8 \text{ mm}$) foils were carried out. In these experiments, the energy deposition

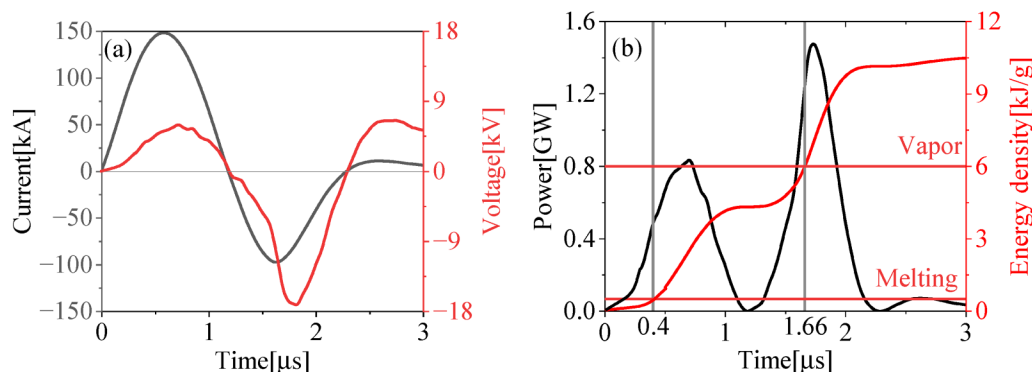


FIG. 9. Waveforms of the discharge current and resistive voltage (a); the deposited power P and energy density (b). The horizontal lines in (b) represent the energy density necessary for melting and evaporation of the brass. Brass foil: $30 \text{ mm} \times 8 \text{ mm} \times 50 \mu\text{m}$.

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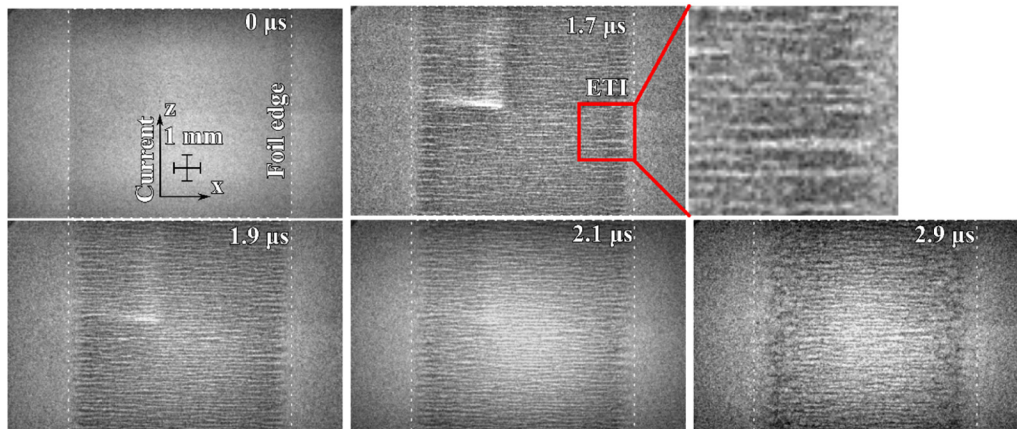


FIG. 10. X-ray images of the explosion of a brass foil ($30 \text{ mm} \times 8 \text{ mm} \times 50 \mu\text{m}$). The size of the frame is $8 \times 12 \text{ mm}$. In the experiments, we observed the instabilities from 1.4 to $3.5 \mu\text{s}$.

was far from optimized, and explosions of brass foils were characterized by an under damped discharge with oscillating waveforms of the current and resistive voltage [see Fig. 9(a)]. Similar waveforms were obtained for Al foils. In Fig. 9(b), one can see that the brass foil overcomes the energy density threshold for melting at $\sim 350 \text{ ns}$ and for vaporization at $\sim 1660 \text{ ns}$. However, x-ray images show that ETI instabilities appeared at the edge of foils at 1500 ns after the discharge current began and before the energy density reached the vaporization threshold. Later in time, this instability becomes visible along the entire width of the foil (see Fig. 10). Earlier appearance ETI at the edges can be related to the lateral skin effect,^{38,39} which dictates larger current densities at the edges and, consequently, earlier vaporization of the material. The same results were obtained in experiments with Al foil but with much weaker contrast. Let us note that similarly to ETI studies during underwater explosions of Al and Cu wires,²⁵ this instability was not seen after the foils

experienced the solid-liquid phase transition. This can be related to high thermal conductivity, which prevents ETI instability development in the liquid phase when the material density decreases slowly due to the transverse expansion of the foil.

X-ray images of the exploding brass and Al foils were analyzed using the Fast Fourier Transform (FFT) of density nonuniformities to obtain the spectrum of ETI wavelengths at different times of explosion. An example of x-ray shadow images of the brass foil and density profiles is shown in Fig. 11.

The linear model of ETI development is expressed by the following equations:

$$\lambda_{\min}(t, x) = \frac{2\pi}{j(t, x)} \sqrt{\kappa(t, x)\alpha(T)}, \quad (1)$$

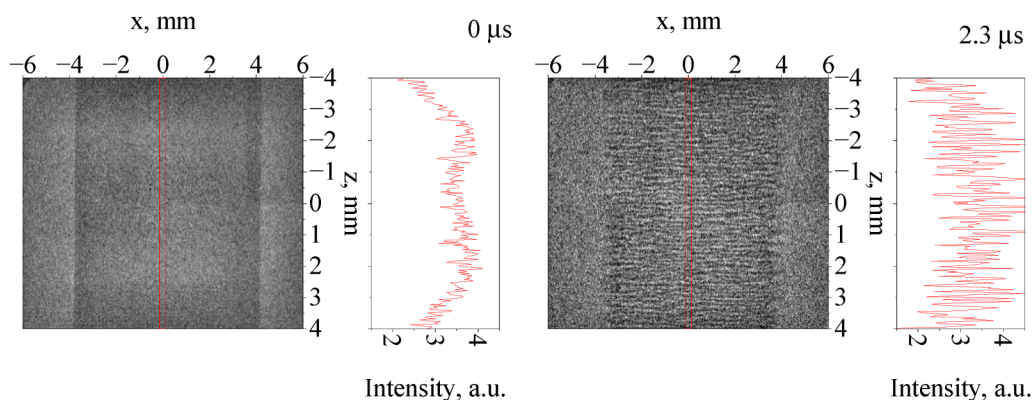


FIG. 11. X-ray radiographs of the brass foil ($30 \text{ mm} \times 8 \text{ mm} \times 50 \mu\text{m}$) and density profiles along the red line prior to the beginning of the discharge current and when ETI develops at $2.3 \mu\text{s}$.

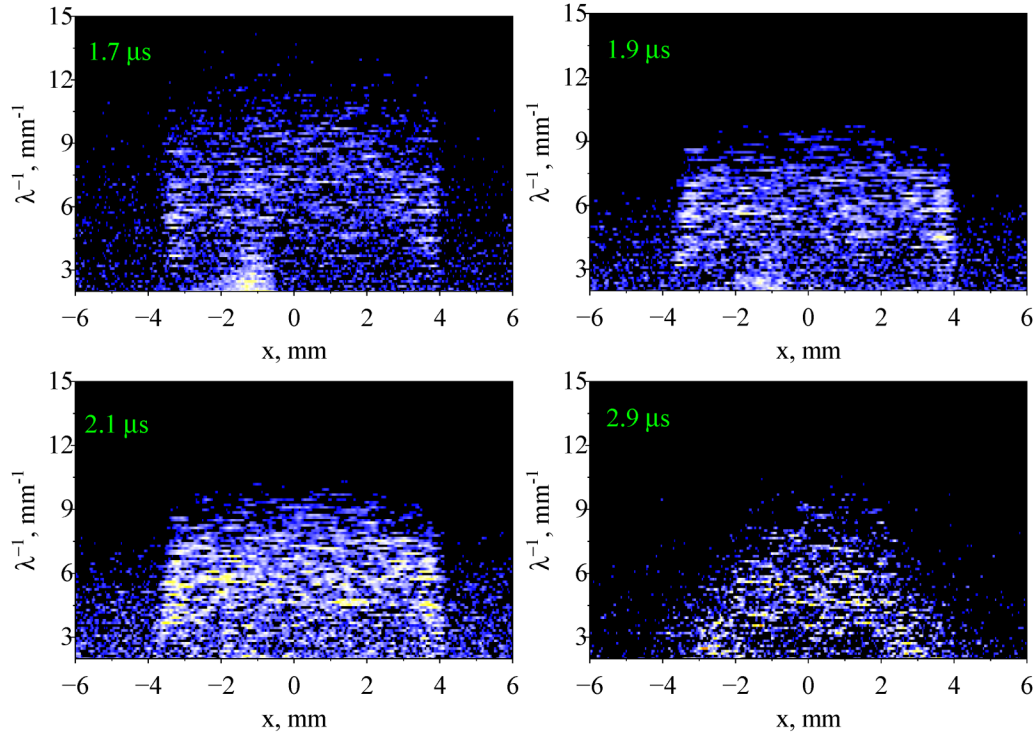


FIG. 12. Spectra of the inverse wavelength of ETI instability presented in Fig. 10. Here, the foil is between $-4 \text{ mm} \leq x \leq 4 \text{ mm}$.

$$\kappa(t, x) = \frac{\pi^2 k_B^2 T(t, x)}{3e^2 \delta(T)}, \quad (2)$$

$$\alpha(T) = \left(\frac{\partial \delta(T)}{\partial T} \right)^{-1}, \quad (3)$$

where x is the distance from the center of the foil, t is the time relative to the beginning of the discharge current, and κ is the thermal conductivity estimated by the Wiedemann–Franz law,⁴⁰ δ is the resistivity, k_B is the Boltzmann constant, and e is the charge of the electron. In Fig. 12, one can see the results of the FFT analysis of density nonuniformities. In the same figure, we present the dependence of the minimal wavelength of the ETI vs the position on the axis “ x .” The values of $\lambda_{\min}$ were calculated using the linear model²⁵ of ETI development [see Eqs. (1)–(3)] and the results of COMSOL simulations, i.e., the current density, j , the resistivity δ , and the temperature, T at times when the radiography images were obtained. Let us note that the linear model²⁶ considers only small thermal perturbations and it does not include hydrodynamic motion, which could not be the case when we have obtained ETI. In this approximation, one can see that each spectrum is characterized by a low boundary of the wavelength, which is almost coincide with the minimal wavelength predicted by the linear model and COMSOL simulations. Additionally, we analyzed the x-ray images

(see Figs. 10 and 11) with a standard Python FFT algorithm. The algorithm analyzed the images with Nyquist frequency 16.5 mm^{-1} , which was determined by the spatial resolution of the optical system used in this experiment (see Sec. II). The experimental results presented in Figs. 12 and 13 showed a broad spectrum of wavelengths above its minimal value. Additionally, one can see in Fig. 12 the temporal evolution of the wavelength spectra, which

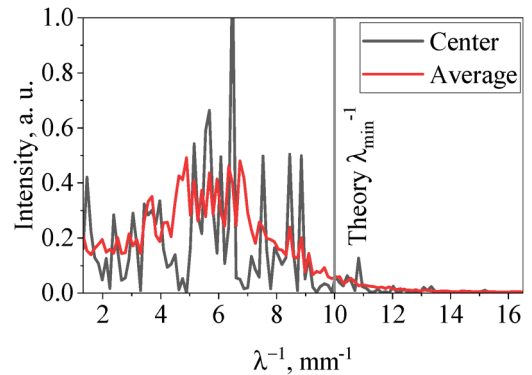


FIG. 13. Central and average spectrograms of the x-ray image in $2.1 \mu\text{s}$. See Figs. 10–12.

correlates with the discharge current shown in Fig. 9. Namely, the broadest spectrum is obtained at $1.7\ \mu\text{s}$, which corresponds to the maximal amplitude of the current. On the other hand, the termination of the current at $2.9\ \mu\text{s}$ is accompanied narrowing of the spectrum, which indicates the fast smearing of ETI instability. Similar results were obtained for Al foils.

Finally, we compare the minimal wavelength calculated using Eq. (1) and the experimentally obtained spectra at $2.1\ \mu\text{s}$ (see Fig. 13). One can see that the central ($x=0$) and average ($x \in [-4,4]$ mm) spectra have the visible threshold, which coincides with the calculated wavelength.

We did not estimate the density modulation using x-ray absorption because the exact composition of the brass is not known to us and because of the polychromatic spectrum (20–50 keV) of the x-ray beam.

IV. SUMMARY

The result of the sub- μs -timescale explosion experiments of this study, including the shadow imaging of “butterfly” shaped foils, determines the values of the specific current action integral for current densities 10^{10} – 10^{12} A/m² where the skin effect is more significant than in previous studies.²⁰ It has been reconfirmed that values of h are significantly smaller than those stated in earlier research of wire explosions in vacuum.⁴

X-ray images of “butterfly” shaped foils show that the explosion starts from the waist and is accompanied by foil expansion with a velocity smaller than the velocity of sound in water and that a cylindrical like discharge channel forms. Additionally, clear signatures of the ETI instability were obtained at the waist.

Experiments with x-ray imaging of sub- μs timescale rectangular foil explosions in water indicate that the ETI wavelength has a minimal value, which almost coincides with that predicted by the linear model. Above this minimal wavelength, a broad spectrum of wavelengths was obtained. This result indicates that ETI appears most probably as the result of randomly distributed micro-nonuniformities introduced in the foil material during its manufacturing.

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AUTHOR DECLARATIONS

Conflict of Interest

The authors have no conflicts to disclose.

Author Contributions

N. Asmedyanov: Conceptualization (equal); Data curation (equal); Formal analysis (equal); Funding acquisition (equal); Investigation (equal); Methodology (equal); Resources (equal); Software (equal); Visualization (equal); Writing – original draft (equal). **R. Grikshtas:** Data curation (equal); Formal analysis (equal); Funding acquisition (equal); Investigation (equal); Methodology (equal); Resources (equal); Writing – original draft (equal); Writing – review & editing (equal). **S. Pavlov:** Formal analysis (equal); Methodology (equal); Software (equal); Validation (equal). **G. Liziakin:** Formal analysis (equal); Investigation (equal); Software (equal); Validation (equal); Writing – review & editing (equal). **S. Efimov:** Data curation (equal); Formal analysis (equal); Funding acquisition (equal); Investigation (equal); Methodology (equal); Writing – review & editing (equal). **O. Belozerv:** Data curation (equal); Investigation (equal); Writing – review & editing (equal). **J. Strucka:** Conceptualization (equal); Data curation (equal); Formal analysis (equal); Funding acquisition (equal); Investigation (equal); Methodology (equal); Resources (equal); Software (equal); Writing – review & editing (equal). **Y. Yao:** Data curation (equal); Formal analysis (equal); Investigation (equal); Writing – review & editing (equal). **B. Lukic:** Data curation (equal); Formal analysis (equal); Project administration (equal); Software (equal); Writing – review & editing (equal). **A. Rack:** Data curation (equal); Funding acquisition (equal); Methodology (equal); Project administration (equal); Resources (equal); Software (equal); Writing – review & editing (equal). **S. N. Bland:** Conceptualization (equal); Data curation (equal); Formal analysis (equal); Funding acquisition (equal); Investigation (equal); Methodology (equal); Project administration (equal); Resources (equal); Supervision (equal); Validation (equal); Writing – review & editing (equal). **Ya. E. Krasik:** Conceptualization (equal); Data curation (equal); Formal analysis (equal); Investigation (equal); Methodology (equal); Project administration (equal); Resources (equal); Supervision (equal); Writing – original draft (equal); Writing – review & editing (equal).

DATA AVAILABILITY

The data that support the findings of this study are available within the article.

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