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Homogeneous electrical explosion of tungsten wire in vacuum

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Experimental results on joule energy deposition at initiation of a fast electrical explosion of 16μm tungsten wire in vacuum at current densities of more than 10^8 A/cm^2 are reported. We find that explosion with a fast current rise-time ($\sim$ 170 A/ns into a short) results in homogeneous and enhanced deposition of electrical energy into the tungsten before surface flashover. The maximum tungsten wire resistivity reaches the value of up to $\sim 185\mu\Omega$ cm before surface flashover that significantly exceeds the melting boundary and corresponds to temperature of $\sim$ 1 eV. The highest values for light radiation and expansion velocity of wire $\sim$ 1 km/s have been observed for the fast explosion. For the explosion mode with a slower current rise-time ($\sim$ 20 A/ns into a short)), we observe the existence of an "energy deposition barrier" for tungsten wire. At slow explosion mode the current is reconnected to the surface shunting discharge before melting. The maximum tungsten wire resistivity in this case reaches the value of $\sim 120\,\mu\Omega$·cm which is less than indicative of melting. Also the energy deposition along the wire is strongly inhomogeneous and wire is disintegrated into parts. We attribute the early reconnection of the current to the surface discharge for the slow explosion to high electronic emission from the wire surface, which starts before melting.

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A better understanding of the initial stage in the electrical explosion of refractory metal wires is extremely important for modern z-pinch physics. The impressive result [1, 2] achieved on Z-facility at Sandia National Laboratories, of 1.8 MJ of X-rays radiated in 5 ns FWHM, crucially depends on mitigating the Rayleigh-Taylor ainstability, which degrades plasma compression. The initial perturbations for this instability arise in the plasma shell formed from the exploded wire array. Increased peak X-ray power correlates with decreased wire gap, presumably because this leads to the formation of a smoother plasma shell. Similarly, the dynamics of single-wire z-pinches depends on how energy is initially absorbed by the load.

It is assumed [3] that surface impurities, such as absorbed gases and hydrocarbons, play an important role in energy deposition processes. It is supposed that heated fast-vaporizing impurities create a gas shell around the wire and after field flashover, the current is switched from the wire to the ionized gas shell. The effectiveness of joule energy deposition decreases after flashover. The main strategy to avoid the influence of the early surface flashover is preliminary heating of the wire in vacuum for surface degasation. Preheating the wire has been shown [4] to increase the mass and uniformity of the plasma surrounding the cold core. Nevertheless, the maximum wire resistivity in experiments [4] did not reach the level of tungsten melting and the deposited energy was less than the energy needed for vaporization. The other approaches to increase energy deposition before surface flashover were: dielectric coating of the wire [5], explosion of the wire in oil [6], in deionized water [7], and in gas [8]. It has been shown that electrical explosion of tungsten wire in a dense medium and with a coating results in enhanced energy deposition before surface flashover.

We have found a new approach to significantly enhance the efficiency and homogeneity of the electrical explosion of pure tungsten wire in vacuum. In our experiments, for the first time, we find a connection between the rate of energy deposition and the absolute value and homogeneity of deposited energy into the tungsten wire before surface flashover. For energy a deposition rate of $\sim$ 0.1 (eV/atom)/ns we observe an "energy deposition barrier", when surface flashover reconnects current from the wire to the surface before melting. In this case the wire becomes mainly disintegrated into parts. Parts of the wire that absorbed some energy are expanding with a velocity $\sim$ 0.1 – 0.2 km/s. For a faster energy deposition rate, $\sim$ 0.7 (eV/atom)/ns we observe a qualitative and

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quantitative breakthrough in the energy deposition processes. Tungsten wire was exploded homogeneously and the deposited energy was $\sim$ 3 times higher. In this case we observe strong light emission synchronized with surface flashover and the wire expansion velocity reaches the value ~ 1 km/s.

A 120 kV Maxwell 40151-B pulse generator with stored energy of 12.6 J (7 nF, 60 kV) provides the current and voltage used to drive the wire explosions. A 50-Ω, 9-m coaxial transmission line delivers the positive-voltage pulse from the generator to the wire. The setup produces a fast pulse with a ~ 170 A/ns current rise into a short circuit (voltage rate $\sim$ 11 kV/ns in an open circuit), or, with an inductor inserted before the generator output, a slower pulse with a ~ 22 A/ns current rise into a short circuit (voltage rate ~ 1 kV/ns into an open circuit). The slower rise is characteristic of the prepulse through individual wires on the Z-facility at Sandia National Laboratories. The electrical pulse is applied to a single tungsten wire 2 cm in length and 16 μm in diameter. The wire forms the central conductor of a coaxial line evacuated to a pressure of $\sim 10^{-5}$ torr to prevent early gas breakdown.

The current flowing through the wire is measured with a 2 GHz bandwidth shunt resistor, and the voltage drop across the wire is measured with a resistive high-voltage probe (100 kV, 1.5 ns rise time). From current and voltage data, the resistive component of the voltage, the load resistance and the joule heating of the wire can be determined throughout the wire explosion. The evolution of space integrated light intensity emitted from the exploding wire is monitored by a PIN diode with a rise time of less than 1ns. The light is focused by a $f/0.7$ lens with a focal length of 50.3 mm. Streak camera shadowgrams of the wire during the explosion are obtained using a high-power diode pulsed laser back lighter (905 nm, 10 W, 200 ns). From these streaked images, the plasma expansion velocity and the starting time of the explosion are determined. Time-integrated visible-light CCD images of wire explosions give information on the 2-dimensional structure of the energy deposition. We also analyze the time-integrated emission spectra using a visible imaging spectrometer.

Typical time-integrated images of exploding 16-μm in diameter and 2-cm long W wire are shown in Fig.1. There are big differences in the energy deposition structure between the explosions driven by fast and slow pulses. The fast pulse produces a homogeneous "cylindrical" (a) or a "conical" (b) structure. The "conical" explosion (b) is wider at the anode and narrower at the cathode side. The slow pulse results in many peripheral vacuum arcs between the wire and the ground cylinder 2.8 cm away. Part of the wire is left unvaporized (d) after the slow pulse shot (c). For the cylindrical (a) and the conical (b) explosion modes, the region surrounding the wire is glowing brightly. For the slow pulse case (c), the light emission is over an order of magnitude less, and comes mostly from the peripheral vacuum arcs.

The velocity of expansion is dramatically greater for the fast pulse explosion than for the slow pulse case (Fig.2, data from the shots shown in Fig.1). The velocity of expansion in the middle of the 16-μm in diameter W wire is 0.83 km/s for the fast cylindrical explosion mode (Figs.2a and 1a), 0.59 km/s for the fast conical explosion mode (Figs.2b and 1b), and 0.15 km/s for the slow-pulse explosion (Figs.2c and 1c). In slow-pulse explosion, the wire expands only in the region where the peripheral vacuum arcs are absent. The wire remains unvaporized in the arcing region. The wire starts to expand after the voltage reaches the maximum value, i.e., after surface flashover. The expansion proceeds at a constant speed, indicating minimal heating of the wire after flashover.

Optical spectra for the fast and slow explosion of 16-μm W wire contain a high level of continuum radiation combined with spectral lines of W and some light species.

Temporal evolution of voltage (1), current (2), deposited joule energy (3) and light emission (4) for fast cylindrical (a) and slow (b) explosion modes of 16-μm W wire is presented in Fig.3a,b. For both types of explosions we can see the same feature: after reaching the maximum value, the voltage drops fast and then becomes inductive. The rate of specific energy deposition for the fast explosion is 7 times higher then for slow one (~ 0.7 (eV/atom)/ns for fast explosion and ~ 0.1 (eV/atom)/ns for slow explosion). The maximum electrical power for the fast explosion reaches the value of ~ 61 MW, and ~ 5.5 MW for slow one. The extremely fast rising (~ 2 ns initial spike) light intensity for the fast cylindrical explosion coincides in time with the rapid decrease in voltage and rapid increase in current, i.e., with surface flashover. Fast explosions yield the most powerful light emission. The first radiation peak is 4–5 times weaker for wires driven by the slow explosion.

There is a large in the long-time behavior of light emission for fast and slow explosion modes. The fast explosion mode gives a strong (3–4 times) increase in the light after the first peak during $\sim$ 500 ns and a slow drop during $\sim 5 - 10\,\mu$s. For slow explosion mode light intensity is only dropping after the first peak. Interestingly, the long–scale temporal shape of radiation for fast exploding mode is typical only for W. Other substances give significantly different temporal shapes

Fig.1. Time-integrated CCD images of a 16-μm in diameter and 2-cm long tungsten wire explosion: (a) fast "cylindrical" explosion (shot 0626-08); (b) – fast "conical" explosion (shot 0626-11); (c) slow explosion with peripheral vacuum arcs (shot 0801-06); (d) the cathode-anode gap after a slow explosion with unvaporized wire (black arrow). The white arrows show the cross-section imaged to the streak camera to investigate the velocity of the wire expansion (Fig. 2). Positions of the anode (A) and cathode (C) are marked on image (d)

for the radiation, indicating quite different conditions of the wire core and coronal plasma. For the fast cylindrical mode of explosion, the temporal shape of the radiation depends very strongly and distinctly on the wire material, but not much on the wire diameter.

The dependence of load resistivity *(1)*, current density *(2)*, electrical power *(3)* and magnetic field pressure *(4)* on deposited joule energy for fast cylindrical (c), and slow (d) explosion modes is presented in Fig.3c,d. During the voltage increase we can attribute recovered value of resistivity to the property of the wire. When the voltage starts to drop, the current splits between wire and surface flashover and we cannot attribute the recovered value of the resistivity to the only wire or flashover property. The resistivity curves *(1)* in Fig.3 c and d for fast and slow exploding wires coincide for low value of energy deposition. The only difference is the point at which surface flashover occurs ($\sim$ 3 eV/atom for the fast cylindrical mode, and $\sim$ 1.5 eV/atom for the slow explosion mode). For fast explosions the wire resistivity *(1)* reaches $\sim$ 185 $\mu\Omega$·cm, far above the melting boundary [9], corresponding to the saturation plateau in [10]. In contrast, the resistivity with the slow–rising pulse *(3)* only reaches $\sim$ 120 $\mu\Omega$·cm, which is below the melting boundary [9]. The maximum current densities before flashover (Fig.3c, d) are substantial $\sim$ 250 MA/cm^2 for fast pulses, and $\sim$ 130 MA/cm^2 in the slow case. The maximum magnetic field at the wire surface before flashover is $\sim$ 131 kG and $\sim$ 67 kG, for the fast- and slow pulses, respectively. The maximum of the average pressure inside the wire is approximately equal to the magnetic field pressure on the wire surface and corresponds to $\sim$ 135 MPa for the fast explosion and $\sim$ 36 MPa for the slow explosion modes. The magnetic field pressure in the fast explosion mode is 40% of the critical pressure for W (p_{cr} = 337 MPa, [11]) and can suppress boiling at liquid – gas phase transition. In this case we can assume a homogeneous expansion of the W wire.

The results of our experiments suggest the following scenario for the initial stages of the electrical explosion of tungsten wire. For the slow explosion mode, current flows through the wire and increases the temperature for the first $\sim$ 45 ns. Before melting the surface flashover starts. Current switching from the wire to surface flashover during a few nanoseconds and practically stops the heating the substance. In this case wire become mainly disintegrated on a macro–parts.

Fig.2. Radius vs. time ($R-T$) streaked laser shadowgrams of the expansion in the middle plane of the 16-μm diameter W wire. $R-T$ images (a), (b), (c) correspond to time-integrated images (a), (b), (c) in the cross-sections marked by white arrows in Fig.1

Now is about flashover reasons. The tungsten is well known as a strong electronic emitter. It has been found in [6] that in rapid electrical heating of fine W wire in a vacuum there is "anomalous electronic emission" phenomenon when thermo emission of electrons exceeds the normal value by $\sim$ 100 times before melting. Emitted electrons may be a "trigger" for the ionization of surrounding the wire vapors and creation of a low resistance plasma shell [12]. Ionization of the vapor shell can be due to direct electron-atom collision or/and photo ionization from X-ray and UV radiation due to collision of emitted electrons with high–density wire surface. The strong electronic emission from the W wire creates an "energy deposition barrier" for effective heating of the substance up to vaporization.

We can support this flashover scenario, because in the slow pulse case effective wire resistivity stops to growth at level of W wire melting. Furthermore, we observe a set of peripheral vacuum arcs (Fig.1c), which can be initiated by electronic emission from the wire during the negative period of the electrical pulse comes ($\sim$ 400 ns after explosion initiation). The high level of continuum radiation in the optical spectra for the fast and slow explosion modes may support the electronic emission hypothesis because it is well known that the interaction of electrons with the wire generates bremsstrahlung radiation. There is another argument for the electronic emission hypothesis. Experiments with W wire coated by vacuum pump oil demonstrate significantly higher values of deposited energy and expansion velocity than with uncoated wire. In this case oil can "deactivate" emitted electrons because high density at the metal-oil interface. We will describe in detail these experiments in future publications.

We found one of the first descriptions of "wire disintegration regime" in [13] and in recent investigations using high-resolution X-ray back lighting [14]. It has been found that in slow explosion mode ($\sim 10-20\,\mathrm{A/ns}$) W wire is disintegrated into longitudinal and radial parts, separated into drops [15, 16], destroyed into microscopic sol with sizes in order of magnitude for electron free pass in a metal $\sim 10\,\mathrm{nm}$ [17].

Energy deposition into the W wire is significantly improved in the fast implosion regime. In this case surface flashover starts far after melting. The W wire resistivity reaches a maximum value of $\sim 185\,\mu\Omega\cdot\mathrm{cm}$ which is beyond the melting level for W [9] and corresponds to the saturation plateau under normal density in [10]. For this value of wire resistivity (under normal density) the temperature before the surface flashover is supposed to be $\sim 1\,\mathrm{eV}$ [10]. For the fast explosion mode, the wire is heated at a larger value of current density and magnetic field then for the slow mode. In this case that larger magnetic insulation of the wire may result in the surface flashover occurring at a temperature that is much larger than the melting temperature. The first narrow peak in light emission, which coincides with time of flashover, can be attributed to the radiation of the exited atoms and recombination of the ions due to ionization of vapor shell surrounding the wire. Analysis of the role of electronic emission in the explosion of the refractory metals wire at current densities $\sim 10^6-10^7\,\mathrm{A/cm^2}$ can be found in [18].

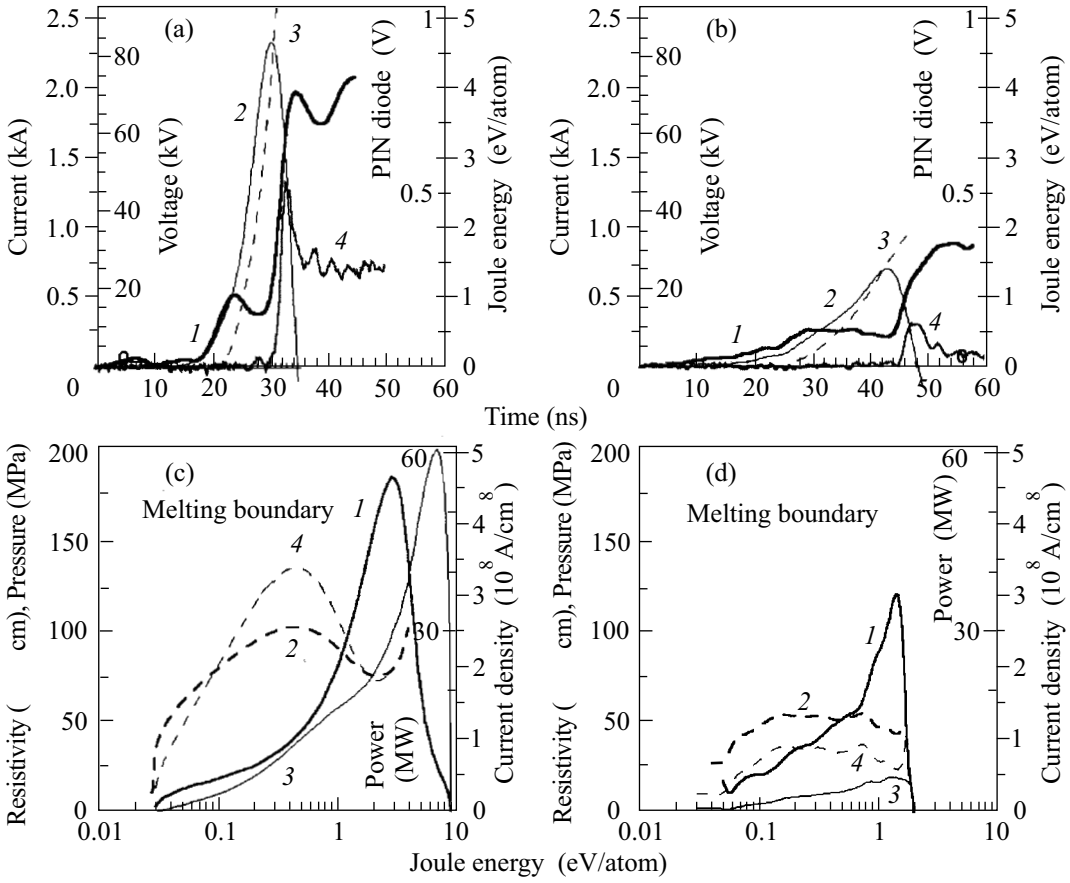

Fig.3. Temporal evolution of the current *(1)*, voltage *(2)*, deposited joule energy *(3)* and emission light intensity *(4)* for fast (a) and slow (b) explosions of 16 μm W wires. Dependence of wire resistivity *(1)*, current density *(2)*, electrical power *(3)*, and magnetic field pressure *(4)* on the deposited joule energy for fast (c) and slow (d) explosions. Magnetic field induction following by current density *(2)* on (c) and (d) with maximum value 131 kG and 67 kG respectively

There is no essential difference between the fast cylindrical (Fig.1a) and the fast conical (Fig.1b) explosion modes. For the fast conical explosion mode, electron emission may start the flashover at smaller values of absorbed energy and the maximum resistivity doesn't reach resistivity plateau [10] but is pass through the melting level. For the fast cylindrical explosion mode, flashover starts at higher absorbed energy (close to the vaporization energy) and the maximum resistivity reaches the plateau [10]. The conical deposition energy has been observed for many substances with large vaporization energy: W, Mo, Pt, Ti, Ni, Fe, and has never been observed for low vaporization energy substances: Au, Cu, Al and Ag. We will discuss this effect in latter publications.

In our experiments the energy necessary to start wire melting is 1.5 eV/atom that is $\sim$ 1.8 times as large as the tabulated value. This agrees with the observation of increased specific heat capacity before melting discussed in [18]. The high magnetic pressure may also play a role in increasing the energy deposition.

Finally we want to summarize the major results of this work. It has been shown that the quality of the electrical explosion of tungsten wire is critically dependent on the rate of energy deposition. The processes vary from electrical disintegrating of the wire into macro-parts (under slow-pulse mode $\sim$ 20 A/ns) to the homogeneous explosion with a large value of deposited energy (under fast- pulse mode $\sim$ 170 A/ns). The main barrier for enhanced energy deposition in the slow explosion mode is initiation of high thermo electronic emission before wire melting. Current becomes reconnected to the surface flashover and heating of the wire has stopped. This "energy deposition barrier" can be avoided by increasing the wire heating rate. In this case heating occurs under higher current density and larger magnetic field may restrict the electronic emission before melting. In the

fast explosion mode, the wire resistivity reaches the value of $\sim$ 185 $\mu\Omega$·cm that is a plateau for normal density of tungsten [10]. In this case the temperature of the wire before expansion reaches the values of $\sim$ 1 eV, and the energy deposition is homogeneous along the axis and expansion velocity reaches the maximum value of $\sim$ 1 km/s.

The effect of significant enhancement of energy deposition before surface flashover with increasing energy deposition rate has been observed for all available pure metal wires (Mo, Pt, Ti, Ni, Fe, Ag, Cu, Al, Ag) and we will discuss the results in future publications.

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