Corona-Free Electrical Explosion of Polyimide-Coated Tungsten Wire in Vacuum

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We present experimental evidence of corona-free electrical explosion of dielectric-coated W wire in vacuum. A fast current rise of ~150 A/ns and a coating of 2 μm polyimide are both needed to achieve the corona-free regime of explosion. Breakdown is absent in corona-free explosion; the wire remains resistive, and this allows anomalously high energy deposition (~20 times atomization enthalpy). MHD simulations reproduce the main differences between corona and corona-free explosions. A corona-free explosion of a wire can be useful for the generation of a hot plasma column by direct energy deposition.

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The exploding-wire studies in the 1950s were motivated primarily by interest in inertial confinement fusion. The main idea was to create a hot, dense, and stable plasma column by passing high current through a metal wire in vacuum. That goal was never realized. The wire core temperature never exceeded a few electron volts due to early termination of energy deposition. Wire destruction by the development of liquid-phase MHD instabilities (for slow, microsecond explosions), or electrical breakdown (for fast, nanosecond explosions), always limited the energy that could be deposited to the wire core by direct Joule heating [1,2]. The exploding-wire plasma attains a high temperature ~100 eV only in the low-density corona, which contains a negligible fraction of the wire mass ~0.1% [3]. Electrical breakdown creates a "natural barrier" for Joule energy deposition [1] and transformation of the entire wire to a hot, dense plasma column.

Breakdown occurs due to ionization of the ambient metal or impurity vapor [2]. Electron emission from the hot metal surface [2,4], the development of an electron avalanche, and the generation of electron and ion beams along the wire [4] all contribute to the ionization of the vapor. After breakdown the current flowing through the wire switches to the fast-expanding plasma shell whose resistance is rapidly dropping. This current transfer results in the voltage and power collapse.

Wires have been rapidly (~100 ns) exploded in high-density, breakdown-impeding environments such as gas, water, or vacuum-pump oil [2] in order to suppress or delay the creation of the current-shunting corona. For wires rapidly exploded in vacuum a thin dielectric coating can give the same type of corona delay as the high-density environments, providing enhanced energy deposition of up to 3 times atomization enthalpy [5]. Raising the current rate results in increasing the energy deposition before breakdown [6]. However, the energy deposition in all of these explosions in vacuum eventually terminated due to electrical breakdown.

In his review [1] Bennett identified this energy deposition problem: "The voltage breakdown catastrophe presents an obstacle to indefinite increase of wire specific energy by means of larger energy storage." We have shown that this natural limit on Joule energy deposition to metal wire in vacuum is not insurmountable.

In this Letter we show that the faster (~10 ns) explosion in vacuum of 12 μm W wire with 2 μm polyimide coating occurs without formation of the shunting corona and results in anomalously high energy deposition. The Joule heating of the wire can surpass the atomization enthalpy $H_{\text{atom}} \sim 8.6$ eV/atom by a factor of 20. The polyimide coating and fast current rise are both important for the total suppression of the shunting corona.

A 100 kV Maxwell 40151-B (positive output) pulse generator with a 7 nF capacitor bank, a charging voltage of 60 kV, and stored energy of 12.6 J produces the electrical pulse that drives the wire explosions. A 12 μm diameter and 2 cm long W wire was placed across the cathode-anode gap of the coaxial target unit in the vacuum chamber at a pressure of $\sim 10^{-5}$ Torr. This experimental setup can operate in fast- and slow-pulse modes. For the fast mode the short-circuit current rate is ~150 A/ns. The slow-mode current rate is ~22 A/ns. The current through the wire was measured with a coaxial shunt resistor. The anode-to-ground voltage was measured with a capacitive divider. A *p-i-n* diode monitored light-emission from the exploding wire. Electrical waveforms were captured by a 1 GHz oscilloscope. A short-pulse laser (150 ps, 532 nm) was used for shadowgraphy. A detailed description of the experimental setup can be found in [6].

The shadowgram (taken at 1000 ns after voltage maximum) of the fast-exploding bare 12 μm diameter and 2 cm long W wire reveals in Fig. 1(a) a conical expansion with a velocity of ~0.1 km/s at the cathode end of the wire and 0.44 km/s at the anode end. The conical expansion indicates an energy deposition that monotonically increases toward the anode due to the polarity effect [4]. The axially

averaged specific energy deposited into the core up to the time when the wire resistance has dropped to half of its maximum is 3.3 eV/atom.

The corresponding time-integrated self-emission image in Fig. 1(a) shows a homogeneous and strongly radiating 1–2 mm wide cylinder. It has been shown in [7] that strong visible radiation from the underheated ($E < H_{atom}$) W wire core is due to the optical emission from hot, expanding liquid microdrops near boiling temperature.

The laser shadowgram of Fig. 1(b), obtained 523 ns after peak voltage, illustrates the slow explosion of the 12 μm W wire with a 2 μm polyimide coating. The shadowgram shows an increased energy deposition to the anode that is similar to the fast, bare-wire explosion of Fig. 1(a). The average deposited specific energy was ~9.2 eV/atom. The expansion velocity grows from 0.2 km/s at the cathode to ~1.2 km/s at the anode. Slow explosion of a bare 12 μm W wire typically results in the macrodisintegration of the wire with deposited energy $E \sim 1$–2 eV/atom [8]. The slow current pulse deposits more energy into the exploding coated wire than the slow or even the fast pulse can deposit into the exploding bare wire. Near the anode the wire becomes transparent to laser radiation. In the same region of the corresponding time-integrated self-emission image of Fig. 1(b), we observe a strong drop in time-integrated radiation. This feature indicates the vaporization of the part of the wire close to the anode. The unvaporized part of the wire expands slowly in the form of clusters and radiates strongly due to the firework effect [7]. The vaporized portion of the wire is in a gas-plasma state, and once breakdown terminates the heating, the wire core adiabatically cools by expansion. For the completely vaporized wire, the long-time-scale radiation (~10 μs) is absent [7].

Figure 1(c) exhibits the features of a fast explosion of a 12 μm W wire with a 2 μm polyimide coating. The probing time is 227 ns after the voltage maximum. The deposited energy reaches ~180 eV/atom, and the expansion velocity is ~2.5 km/s. The wire core expands almost homogeneously along its length. The time-integrated self-emission image demonstrates weak and narrow radiation similar to the radiation from the vaporized part of the slow-exploding coated wire in Fig. 1(b).

Figure 2(a) presents current, voltage, and white-light-emission waveforms for fast-exploding bare 12 μm diameter W wires. The voltage rises up to 60 kV during ~12 ns and collapses to almost zero during the next ~5 ns. While the voltage collapses, the current rises at a ~100 A/ns rate. A sharp and narrow peak of light-emission ~0.4 kW appears during the voltage collapse and is related to the ionization of the ambient vapor.

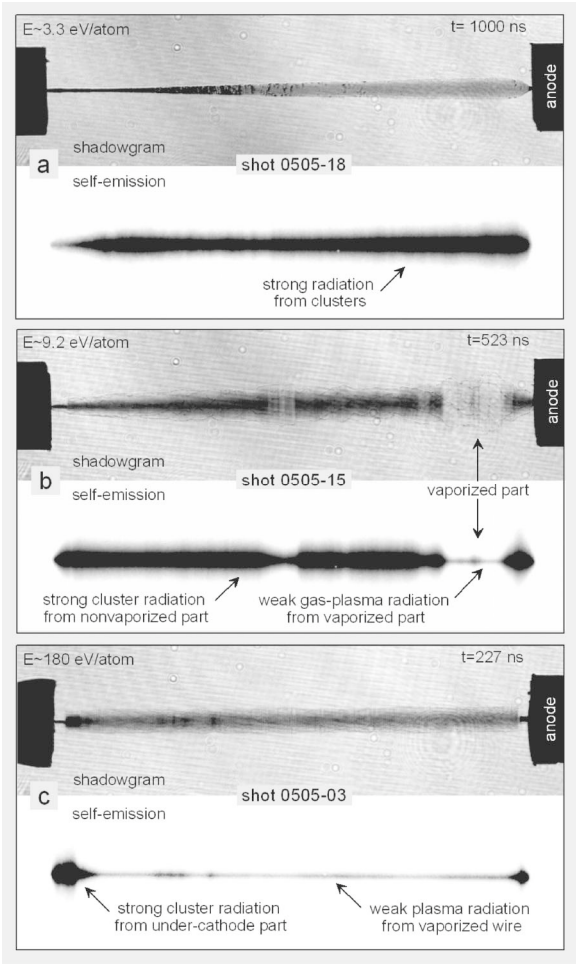

FIG. 1. Three complimentary sets of laser shadowgrams (top) and time-integrated self-emission images (bottom) of exploding 12 μm diameter and 2 cm long W wires with different values of deposited energy: (a) fast explosion of bare wire at 1000 ns; (b) slow explosion of coated wire at 523 ns; (c) fast explosion of coated wire at 227 ns.

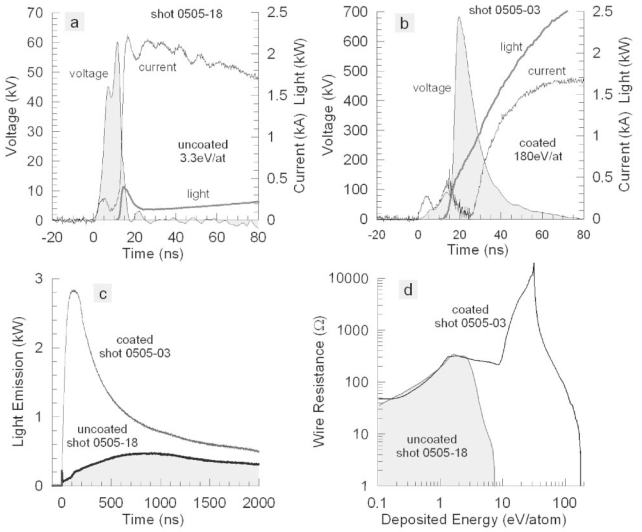

FIG. 2. Waveforms for current, voltage, and light emission for fast-exploding 12 μm W wires: (a) bare and (b) coated. (c) Dependence of long-time behavior of white-light emission for coated and bare wires. (d) Dependence of wire resistance on deposited energy for coated and bare wires.

Figure 2(b) presents the current, voltage, and light-emission waveforms of the fast-exploding 12 μm diameter W wire with a 2 μm polyimide coating. The voltage reaches a peak value of ~700 kV in 20 ns (more than 10 times the charging voltage) and then exponentially drops to zero during the next 50 ns. During this time the current rises at a rate 30–40 A/ns. This ~10 times more slowly rising current contrasts with the abrupt current rise produced in the explosion of the bare wire. The abrupt resistance drop in the bare-wire explosion, together with the evidence in Fig. 1(a) of a hot liquid core, constitutes the signature of a two-phase system: a slowly expanding cold core and a rapidly expanding hot corona. The gradual resistance drop in the coated-wire explosion, together with the evidence in Fig. 1(c) of a plasma core, forms the signature of a single-phase system. Also indicative of no corona formation, the coated-wire explosion exhibits no light-emission spike near peak voltage.

The coated-wire overvoltage coincides in time with a fast-oscillating (~1 ns period) dropping current. Observation of a similar overvoltage during the "current pause" for microsecond explosions is discussed in [1]. The total average deposited specific energy reaches $E \sim 180$ eV/atom, exceeding the atomization enthalpy of W by a factor of 20.

Figure 2(c) shows the long-time (after peak voltage) light-emission waveforms for the coated and bare-wire explosions of Figs. 2(a) and 2(b). The bare-wire explosion produces late-time radiation which increases in intensity up to ~0.5 kW during 800 ns and then decays with a 10 ms time scale. The exploding coated-wire produces radiation that peaks at ~2.8 kW in 100 ns and then drops quickly. This type of radiation waveform is typical for overheated ($E > H_{\text{atom}}$) metal in the gas-plasma state [7].

Figure 2(d) shows the behavior of the wire resistance against deposited energy. Both bare and coated wires display a similar behavior up to $E \sim 3$ eV/atom. The average deposited specific energy of 3.3 eV/atom corresponds to the liquid state of the wire core and tends to be the maximum energy deposited to bare wire before breakdown. After this point, the resistance of the exploding bare wire plummets due to its fast-expanding shunting corona. The expansion of the corona lowers its density and increases its cross section. Electrical resistance is proportional to the material resistivity divided by the conductive cross-sectional area. Since coronal plasma is in the Spitzer resistivity regime where the resistivity is insensitive to density, the increasing cross-sectional area of the conduction lowers the corona's resistance. As the resistance of the two-phase system (core and corona in parallel) falls, the core continues to Joule heat, until the corona resistance becomes essentially zero and current no longer flows through the core. At that point a total of ~7.5 eV/atom has been deposited, with no additional deposition possible.

In contrast with the bare wire above 3 eV/atom, the resistance of the coated wire rises starting at 9 eV/atom, reaching ~10 kΩ by $E \sim 30$ eV/atom. This escalating wire resistance coincides with the expansion of the totally vaporized metal core in the absence of a current-shunting corona. The core diameters inferred from the laser shadowgraphy suggest that the expanding vaporized core enters the metal-insulator transition for W where the density is between 0.5 and 10 g/cm^3 and the resistivity rises with decreasing density [9] from expansion. The total average energy deposited into the coated-wire core ultimately reaches ~180 eV/atom.

The features that distinguish coated from bare-wire explosion are reproduced by resistive MHD simulation. Previously the ALEGRA code was successfully applied to the simulation of exploding Al wires [3], and we employ the same basic Eulerian simulation setup here. The key to these simulations, as discussed in [3], is sufficient spatial resolution (radius only, unresolved axially) in conjunction with the use of accurate equation of state and electron transport tables. We use Los Alamos SESAME [10] equation of state tables 3540 for tungsten and 7550 for Mylar (to represent the polyimide coating) and accurate electron transport properties recently calculated by Desjarlais [9]. Elastic-plastic properties and a constant thermal conductivity of 0.12 W/m K for polyimide [11] were also included for the coated-wire simulation.

We chose the experimental current waveform from the coated-wire explosion of Fig. 2(b) to provide magnetic field boundary conditions for ALEGRA simulations of both coated and bare wires. Hence, we consider simulations that differ only by the wire surface conditions to clearly highlight the effect of the coating on the process of explosion.

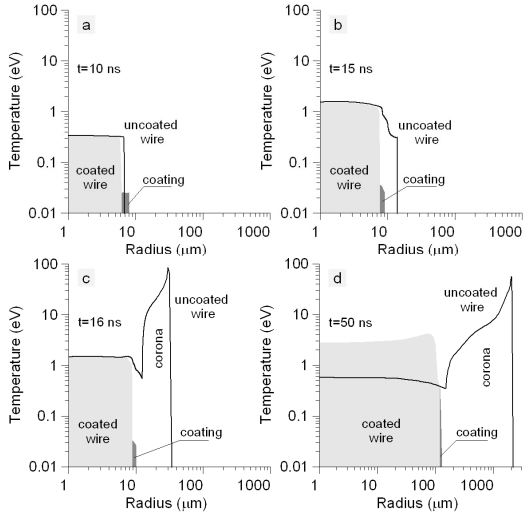

FIG. 3. Radial temperature profiles at different moments of time for explosion in vacuum of bare (line) and coated (shaded) 12 μm diameter W wires. The coating itself is indicated by darker shading.

Figure 3 presents the radial profiles of temperature for a coated and a bare wire at four different times. With the current of Fig. 2(b) both simulated wires heat in the same way until 15 ns. As Fig. 3(b) shows, the edge of the bare wire starts to vaporize at 15 ns. By $t = 16$ ns, we observe in Fig. 3(c) the generation of the hot corona with $T \sim 100$ eV and its fast expansion. After 16 ns the corona from the bare wire cools while expanding rapidly with velocities of 50–80 km/s. The simulation does not show the generation of corona for the coated wire. The coated wire thermally expands in a single phase during the first 16 ns with velocity ~ 0.5 km/s and no edge vaporization. The thermal properties of thin polyimide film allow the coating to remain significantly cooler than the wire, well into the period of explosion. This property of the coating prevents the vaporization of the liquid wire edge and the subsequent corona generation. The MHD simulation shows that by the time of Fig. 3(d) the coating is in the vaporized state along with the metal. After $t = 30$ ns the coated wire explodes, still in a single phase, with velocity ~ 3.6 km/s. The current continues to Joule heat the coated wire, while the current transfer to the corona terminates the heating of the bare-wire core.

The temperature of the bare-wire core increases to ~ 1.5 eV and subsequently drops owing to adiabatic expansion and to the end of Joule heating after the current transfers to the corona. The temperature of the coated wire rises to ~ 4 eV [Fig. 3(d)] and afterward drops due to expansion. This inevitable temperature drop occurs when cooling due to expansion overcomes Joule heating [3]. The Joule heating is lessened by the lowering of the resistance that results from increasing the cross section of the conductive core. This cooling can be inhibited by magnetic field pressure from high current.

The simulations supply details that correspond to the experimentally observed features of the dropping resistance above 3 eV/atom in the bare-wire explosion, and the increasing resistance above 9 eV/atom in the coated-wire explosion. The corona generated by the bare-wire explosion is well into the Spitzer regime (average charge state of 5–15, density $\sim 10^{-7}$–10^{-5} g/cm^3, and temperature $\sim$2–10 eV), so its expansion produces a dropping resistance. This rapidly transfers current from the more resistive core and stops further energy deposition. The current-carrying plasma in the coated-wire explosion (average charge state of 0.7–3, density ~ 0.1–6 g/cm^3, and temperature $\sim$1–4 eV) is much denser and somewhat cooler than the current-carrying plasma (corona) in the bare-wire explosion. This denser plasma enters the high-density side of the metal-insulator transition for W when the wire vaporizes and partially ionizes after absorbing H_{atom}, and moves to the low-density side of the metal-insulator transition once the energy deposition reaches about 12 eV/atom. During this period the resistivity grows enough with expansion so that the resistance rises even though the conductive cross section is increasing slightly. On the low-density side of the metal-insulator transition, as the vaporized core becomes more Spitzer-like with further energy deposition above 12 eV/atom, its resistance falls with expansion (nearly constant resistivity and growing conductive radius). While the resistance falls, the wire continues to absorb energy, and the total average energy deposited into the wire plasma reaches ~ 70 eV/atom.

A striking difference between the fast-exploding coated-wire data and simulation is the additional energy deposited in the experiment. The ideal, axially unresolved simulation predicts entering the Spitzer resistivity regime by 12 eV/atom, while the experiment exhibited increasing resistance with expansion until 30 eV/atom. This extended energy range increased the total energy deposition considerably beyond the 1D prediction.

Axially dependent expansion produces vorticity in the current [12]. This is a possible mechanism for the observed overvoltage. Our axially unresolved simulations cannot include this effect.

Our results demonstrate that the breakdown barrier for energy deposition into metal wire in a vacuum can be overcome. The wire remains resistive and can absorb extraordinarily high energy. This regime of wire explosion is useful for the generation of hot and dense plasma columns. Examples of possible applications are the high-current wire-array z pinches proposed to realize single-phase plasma-shell compression instead of typical two-phase compression that occurs with corona generation.

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