Inverse polarity effect for electrical explosion of fine metal wires in vacuum

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It has been experimentally demonstrated that the geometry of a high-voltage electrode strongly affects the magnitude and structure of energy deposition into a thin metal wire before breakdown in vacuum. Additionally, two-dimensional electrostatic simulations provide evidence that the direction and magnitude of the radial electric field on a wire surface are dependent on the geometry of the electrodes. Increasing the size of the ground electrode leads to an increase in the radial electric field, but does not affect the direction of this field. However, modifications of the high-voltage electrode geometry alter the direction and magnitude of radial electric fields on the wire surface. Thus, the hot and homogeneous electrical explosion of a thin metal wire in vacuum can be realized with proper design of the wire's holding electrodes and independent from the polarity of the high-voltage electrode.

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I. INTRODUCTION

The effective magnetic compression and x-ray yield of a wire array strongly depends on the axial symmetry of the *Z*-pinch [1]. Increasing the number of wires, decreasing the interwire gap, and improving the symmetry of the *Z*-pinch results in generation of 2 MJ and 200 TW of x-ray pulse on the 20-MA *Z* machine at Sandia National Laboratories (SNL) [2]. The newest refurbished 26-MA *ZR* accelerator at SNL demonstrates 2 MJ and 330 TW in x-ray yield [3]. The main problems in the wire-array physics were discussed in detail by Haines in his last review [4].

Generation of a homogeneous wire-array *Z*-pinch depends on the symmetry of the electrical explosion of fine metal wires in vacuum. Initially, current flows through the wire and is Joule heated until it melts. When the wire temperature reaches ∼500 K, the hydrocarbon (HC) impurities begin intense vaporization from the wire surface and create low-density dielectric vapors surrounding the hot wire. Under certain conditions, these HC vapors can be ionized. The main reason for vapor ionization is electron avalanche caused by thermal electronic emission from the hot wire surface. At the melting point, thermal emission for refractory metals can reach abnormally high levels [5]. Electronic emission from the wire surface can be effectively regulated through controlling the external radial electric field [6]. As demonstrated in [6], a large difference in deposited energy and axial homogeneity was observed for exploding metal wires in vacuum with positive and negative polarity of the high-voltage electrode. This phenomenon is known as the "polarity effect" [6]. For positive polarity explosion, the radial electric field on a wire surface suppresses electronic emission due to an increase of the potential barrier for electrons on a metal-vacuum interface. For negative polarity explosion, the radial electric field on a wire surface increases electronic emission due to a decrease of the potential barrier for electrons on a metal-vacuum interface. The wire absorbs more Joule energy before breakdown for positive polarity electrical explosion than for a negative one. Termination of metal wire heating due to plasma generation can happen before melting, during melting, and after melting [7]. Faster current rate allows deposition of more energy into the wire core before breakdown [8,9].

The effect of radial electric fields on wire-array ablation dynamics was first reported in [10]. The MAGPIE 1-MA, 240-ns rise time accelerator at Imperial College was used to drive the extended 8-cm-long, 8-mm-diameter array consisting of 16 Al wires with negative polarity radial field at the top ground anode and positive polarity at the high-voltage cathode [10]. Explosion of this wire array demonstrated a remarkable difference in ablation rates for the negative and positive field parts of the wire array. The hot portion of the wire array (positive polarity) ablated faster while the cold portion (negative polarity) ablated slower. Similar experiments were done at 3-MA, 100-ns rise times with the ANGARA-5-1 accelerator. The effects of radial electric fields on a wire's ablation speed were demonstrated for short prepulse operation, and the absence of these effects were shown for operation with a long prepulse [11,12]. For long current prepulse and small current rate, dI/dt, per wire, the positive or negative polarity of the radial *E* field did not provide a visible effect on ablation because in both cases the breakdown happens before melting and the wires remained in solid state. Increasing of the current rate with a flashover switch resulted in an observation of the different ablation rates for positive and negative polarity portions of the wires. X-ray yields of wire arrays can be significantly improved by changing the wire state from solid to liquid during Joule heating time [13]. This can be achieved with shorter current prepulse, higher current rate per wire, and positive radial electric field on the wire surface [10–13]. In the first approach, the ablation rate depends on the wire's surface area and a hotter and faster expanding wire will vaporize faster than a colder and slower one.

All modern large-scale wire-array *Z*-pinch accelerators operate with negative polarity [1–3]. This is due to better dielectric properties of water transmission lines and the improved operation of vacuum convolutions during negative pulse [2]. As shown in [6], the negative polarity explosion of fine metal wires results in cold breakdown and axially inhomogeneous energy deposition. This effect will lead to small deposition in the central part of the wires and bigger deposition in the periphery. The initially cold and inhomogeneous explosion of fine wires will result in the nonsymmetrical ablation and magnetic compression of the final *Z* pinch [13]. It is important to find a simple way to induce hot and homogeneous explosion of fine metal wires in vacuum using a negative polarity current pulse.

In our paper, we will experimentally demonstrate that the geometry of the cathode and anode electrodes strongly affects the magnitude and axial symmetry of energy deposition into thin metal wires before breakdown in vacuum. Additionally, two-dimensional (2D) electrostatic simulations show that direction and magnitude of radial electric fields on a wire surface are dependent on electrode geometry. Increasing the size of the ground electrode leads to an increase in the radial electric field, but does not affect the direction of this field. Modification of the high-voltage electrode geometry can change the polarity and magnitude of the radial electric field. Thus, homogeneous and hot electrical explosion of a thin metal wire in vacuum can be realized with appropriate design of the wire's holding electrodes for both positive and negative current pulse.

II. EXPERIMENTAL SETUP

A high-voltage pulsed-power generator (FID, FPG-80-01NM, 5-ns rise time, 80 kV on 50-Ω load, 7 J, 40-ns pulse width, 1-ns jitter) was used for fast heating of fine metal wires in a vacuum chamber. The FID pulser was connected to the coaxial target unit with a high-voltage 50-Ω cable. Current and voltage were measured with a 1.2-GHz bandwidth, 0.05-Ω coaxial current viewing resistor CVR (T&M, 1M-T10) and a fast upstream V-dot probe (capacitive divider). The vacuum chamber and coaxial target unit are shown in Fig. 1. The pressure in the vacuum chamber was evacuated to 10^{-3} Torr to avoid surrounding air breakdown. All waveforms were captured by a Tektronix DPO3054 500-MHz four-channel digital oscilloscope. The metal wires were 13, 15, and 21 μm diameter, 1 cm in length, and were placed in the center of the coaxial target unit. Current rate through the short circuit is $dI/dt \sim 1$ kA/ns. Detailed information about these experimental setups can be found in [14].

The symmetry and value of deposited Joule energy into the wire's core was monitored with laser shadowgraphy. A short-pulse laser (TEMPEST 1-30, 100 mJ, 532 nm, 3-ns pulse, 1-ns jitter) was used for backlighting of exploding wires. A single lens after the imaging collimator created an image of the exploding wire in the charge-coupled device (CCD) camera (FLI ML8300, 8.3 megapixel, 16 bit). A fast silicone

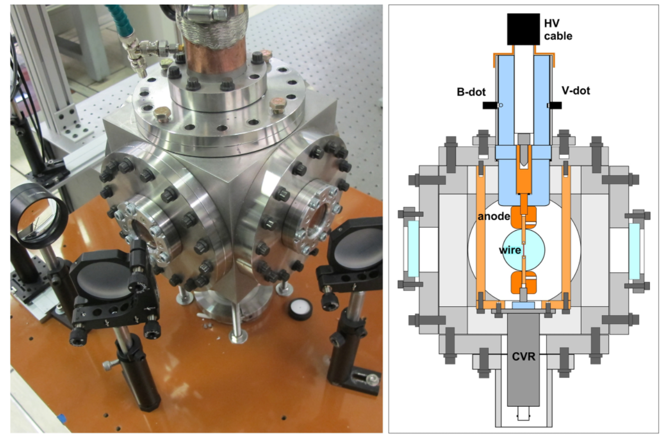

FIG. 1. Vacuum chamber with coaxial target unit.

PIN diode (DET10A, 350 MHz, 1-ns rise time) monitored laser-probing time.

III. EXPERIMENTAL RESULTS

To estimate the effect of electrode geometry on energy deposition and homogeneity, we conducted experiments with ten different metal wires: Ti/21-μm, W/13-μm, W/13-μm with 2 μm polyimide coating, Mo/13-μm, Pt/13-μm, Pd/13-μm, Al/15-μm, Au/13-μm, Cu/13-μm, and Ni/13-μm wires. Laser-probing time were counted from the onset of the current front. Figure 2 shows shadowgrams of exploding wires for standard electrode geometry (a), ground-cup enhanced geometry (b), and high-voltage cup enhanced geometry (c). The cup enhancer was manufactured from brass stock into a cylinder with a 20-mm internal diameter, 25.4-mm length, and 10-mm-wide cut for a probing laser. The 10-mm-long wires were connected to a small cylindrical brass electrode with a 3.2-mm diameter, 200-μm center hole, and 2-mm side hole.

The fast explosion under positive polarity and normal electrode geometry, represented in Fig. 2(a), demonstrates fast expanding wires. The explosion with ground-cup geometry of electrodes in Fig. 2(b) demonstrates increased expansion of the wires compared to normal electrode geometry. Finally, explosions with high-voltage cup geometry of electrodes on Fig. 2(c) demonstrates suppressed expansion in comparison with normal [Fig. (2a)] and ground-cup [Fig. (2b)] electrode geometry.

The differences in expansion velocities for the ten wire materials in three separate electrode geometries are presented in Table I. Electrode geometries were normal [Fig. (2a)], ground enhanced [GRN20+cup in Fig. 2(b)], and high-voltage (HV) enhanced [HV20+cup in Fig. (2c)]. All wire explosions with the HV20+cup [Fig. (2c)] geometry demonstrated the smallest expansion velocities at 0.5–3.7 km/s. The highest observed expansion velocities were with the GRN20+cup [Fig. (2b)] geometry at 2.2–10.3 km/s.

Similar differences in Ti wire expansion were observed for positive and negative polarity explosion in our first publication [6]. We call this phenomenon the "polarity effect" [6], and attribute it to the effect of radial electric fields on a wire surface which accelerate or suppress thermal electronic emission

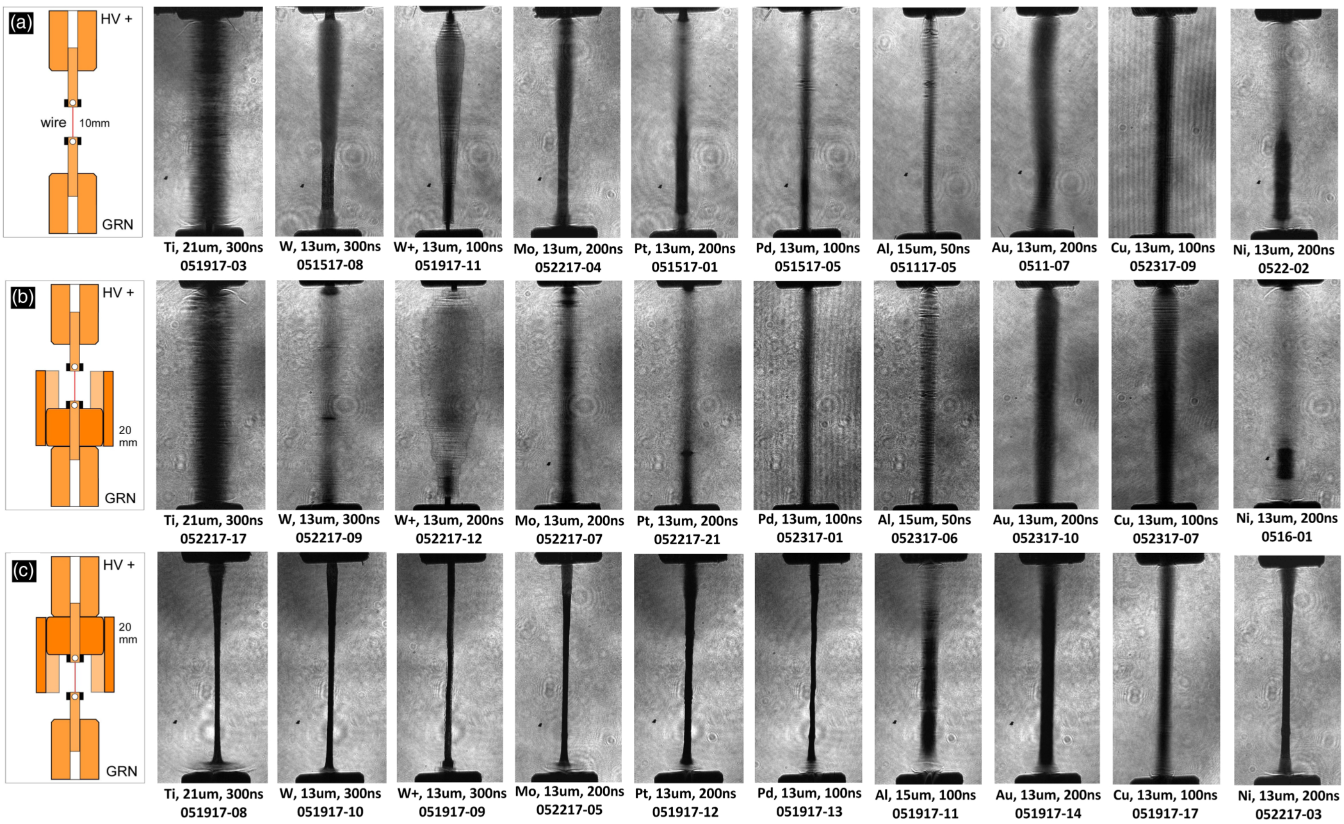

FIG. 2. Shadowgrams for Ti, W, W-polyimide coated, Mo, Pt, Pd, Al, Au, Cu, and Ni wires 1 cm long for normal (a), ground-cup enhanced (b), and high-voltage-cup enhanced (c) electrode geometry.

from the metal-vacuum interface. Thermally emitted electrons from a hot wire surface are responsible for triggering of the surrounding plasma shell and voltage collapse which prevents further heating of the wire core due to rejection of current from the wire core to the surrounding fast expanding corona.

Figure 3(a) shows current-voltage waveforms for exploding 13-μm W wire for normal electrodes. In this configuration, the maximum resistive voltage was ~57 kV and the deposited specific energy reached ~5.4 eV/atom. We calculated this energy up to the moment when voltage drops to half of the maximum magnitude. We assume that the rest of the Joule energy was deposited into the corona. This approach to calculation of the deposited specific energy was proven with magnetohydrodynamics (MHD) simulations of the wire explosion in [15].

Figure 3(b) shows an increase in the maximum resistive voltage up to ~72 kV for ground-cup geometry of electrodes. Deposited energy rises up to ~10 eV/atom. For high-voltage cup geometry of electrodes in Fig. 3(c) the exploding W wire demonstrates the lowest voltage maximum of ~27 kV and deposited energy ~2.8 eV/atom. According to thermodynamic (ThD) calculation of the voltage [15], breakdown starts before the melting when the temperature of the wire reaches only ~1500 K. Ground-cup electrodes demonstrate ~3.6 times larger specific energy deposition than for high-voltage cup electrodes with W wire loads. For all three shots, the reconstructed resistive voltage front coincides with ThD calculation [15] using current waveforms, W wire tabulated resistivity $\rho(T)$ [16], and heat capacity $C_P(T)$ [17] vs temperature data.

IV. ELECTROSTATIC 2D SIMULATION OF ELECTRIC FIELD

We conducted simulations using the ELECTRO 2D/RS electrostatic program (Integrated Engineering Software) for thin metal wire that was 12 μm in diameter and 1 cm in length with different axisymmetric geometry of electrodes. Figure 4 shows a distribution of the electric fields with voltage of +10 kV for normal geometry of electrodes [Fig. (4a)],

TABLE I. Expansion velocity for ten metal wires for three different geometries a, b, and c of electrodes.

Electrode and wire velocity (km/s)	Ti 21-μm	W 13-μm	W+ 13-μm	Mo 13-μm	Pt 13-μm	Pd 13-μm	Al 15-μm	Cu 13-μm	Au 13-μm	Ni 13-μm
Normal (a)	4.6	1.9	6.4	3.9	2.6	4.0	8.5	6.0	2.7	4.9
GRN20+cup (b)	4.7	2.2	7.0	4.2	3.1	5.2	10.3	6.7	3.0	5.3
HV20+cup (c)	0.9	0.5	0.5	0.8	1.1	1.3	3.7	2.9	1.5	0.9

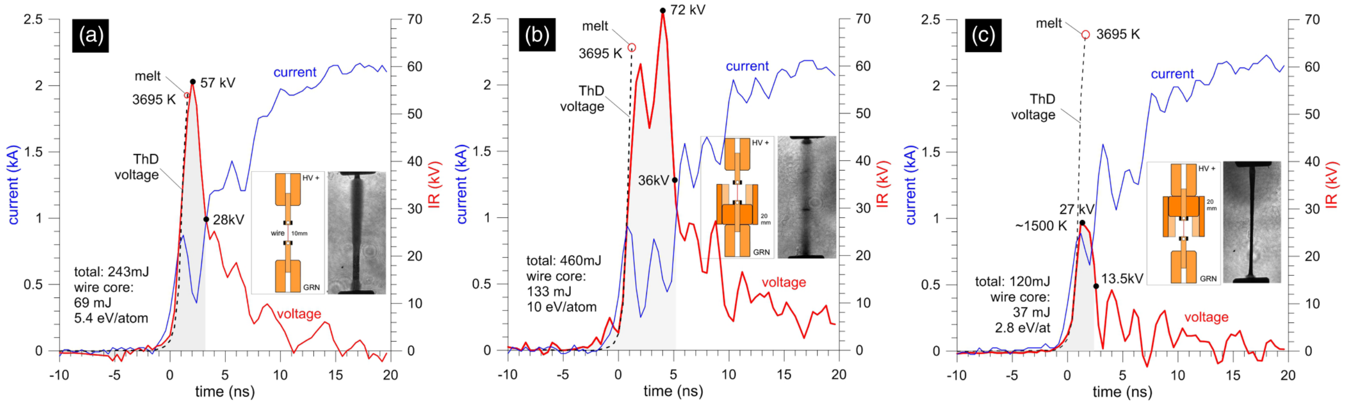

FIG. 3. Current-voltage waveforms for exploding W wire 13 μm in diameter and 1 cm long for normal (a), ground-cup enhanced (b), and high-voltage-cup enhanced (c) geometry of electrodes.

extended ground electrode with 10-mm-diameter cup [Fig. (4b)], and extended high-voltage electrode with 10-mm-diameter cup. The wire holder diameter is 4 mm.

We can see that the geometries in Figs. (4a) and (4b) demonstrate similar results and provide positive radial electric fields directed outside of the wire surface. The geometry in Fig. (4c) shows a change in the radial electric fields to a negative value and is directed inside of the wire surface. For (a) and (b) electrode geometries, the positive radial electric field increases the potential barrier on a wire surface for thermoelectronic emission. In this case thermal electronic emission and plasma generation will happen under higher temperatures. In (c), we observe that the electrode geometry induces a negative radial electric field which decreases the potential barrier on a wire surface for thermoelectronic emission. In this case the thermal electronic emission and plasma generation will happen under lower temperatures. This electrostatic simulation gives a clear explanation for the experimental difference in expansion and deposited energy on Figs. 2 and 3.

Figure 5 shows results of the 2D simulation with axial distribution of the radial electric field at a 1-μm distance from the wire surface that was 12 μm in diameter and 1 cm long. Voltage was set to +10 kV. We can see that enhancement of the ground electrode resulted in an increase of the positive radial electric field on the wire surface. The smallest ground cup, with a 10-mm internal diameter, provided the strongest increase of the radial electric field. Any modification of the ground side electrode results in a change of the radial electric field magnitude but not direction. Increase of the high-voltage electrode area with 20- or even 40-mm disks results in an inversion of the radial electric field

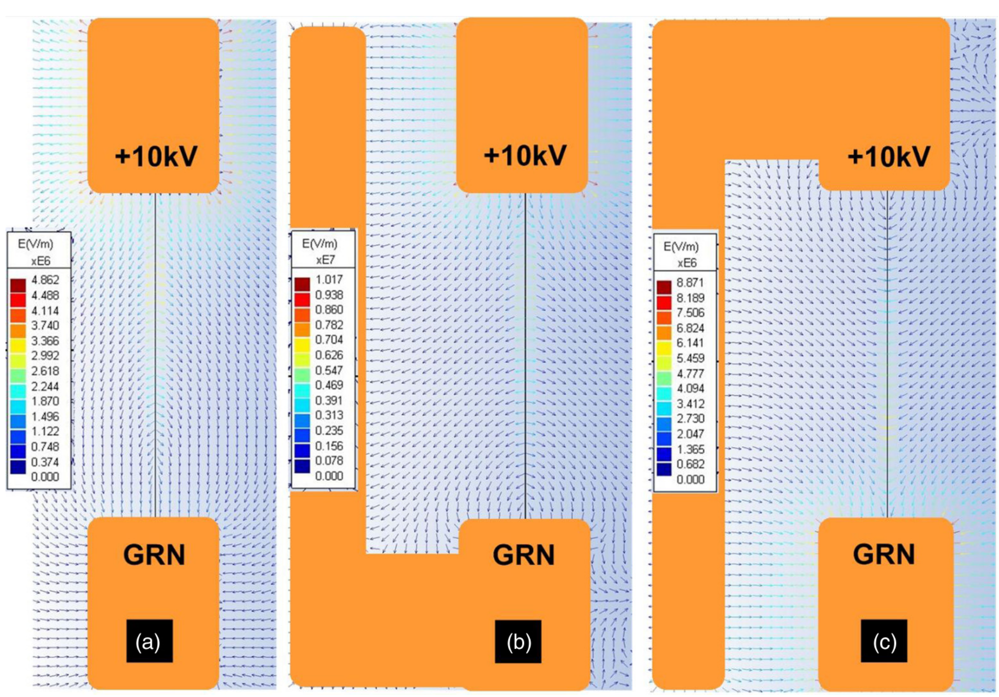

FIG. 4. Distribution of electric field for normal (a), ground side with cup ID = 10 mm (b), and high-voltage side with cup ID = 10 mm (c) geometry of electrodes. Wire diameter is 12 μm and length is 1 cm.

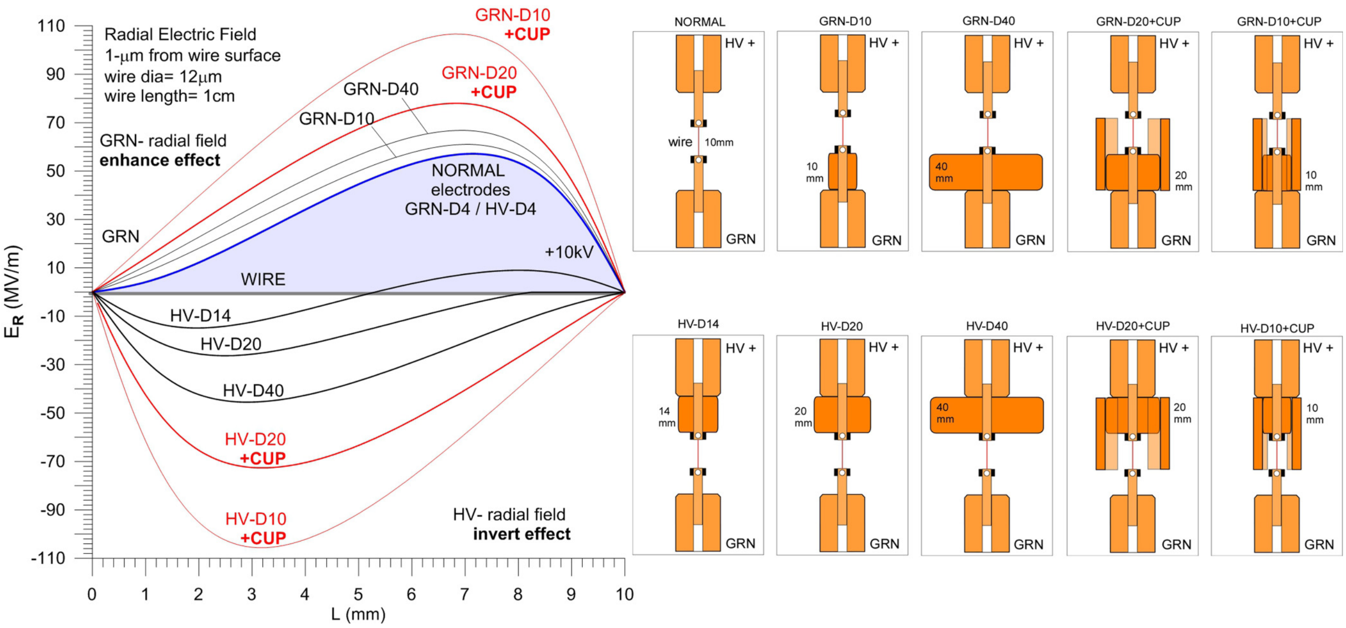

FIG. 5. Radial electric field profiles along the wire surface for ten different electrodes.

direction on the wire surface. The magnitude of the inverted radial field increases with application of the high-voltage cup and through a decrease of the cup's internal diameter.

Figure 6(a) demonstrates the effect of wire diameter (12 and 24 μm) on the magnitude of radial electric fields at 1 μm from the wire surface. We can see the radial field is inversely proportional to the wire diameter. This exact relation was analytically derived by Sasorov in [6]. The axial electric field remains almost constant and an order of magnitude smaller than the radial field. The value of this difference depends strictly on wire diameter. Figure 6(b) shows the profiles of the radial electric field at different distances from the surface of the 12-μm wire. The radial field drops almost exponentially with distance.

V. DISCUSSION

The first publication about the polarity effect for exploding wires in vacuum [6] assumes the polarity of a high-voltage electrode. When considering the normal geometry of electrodes and positive polarity of high-voltage electrode, the radial electric field on a wire surface is directed outside of the wire and helps to keep electrons inside the wire. For negative polarity of the high-voltage electrode, the radial

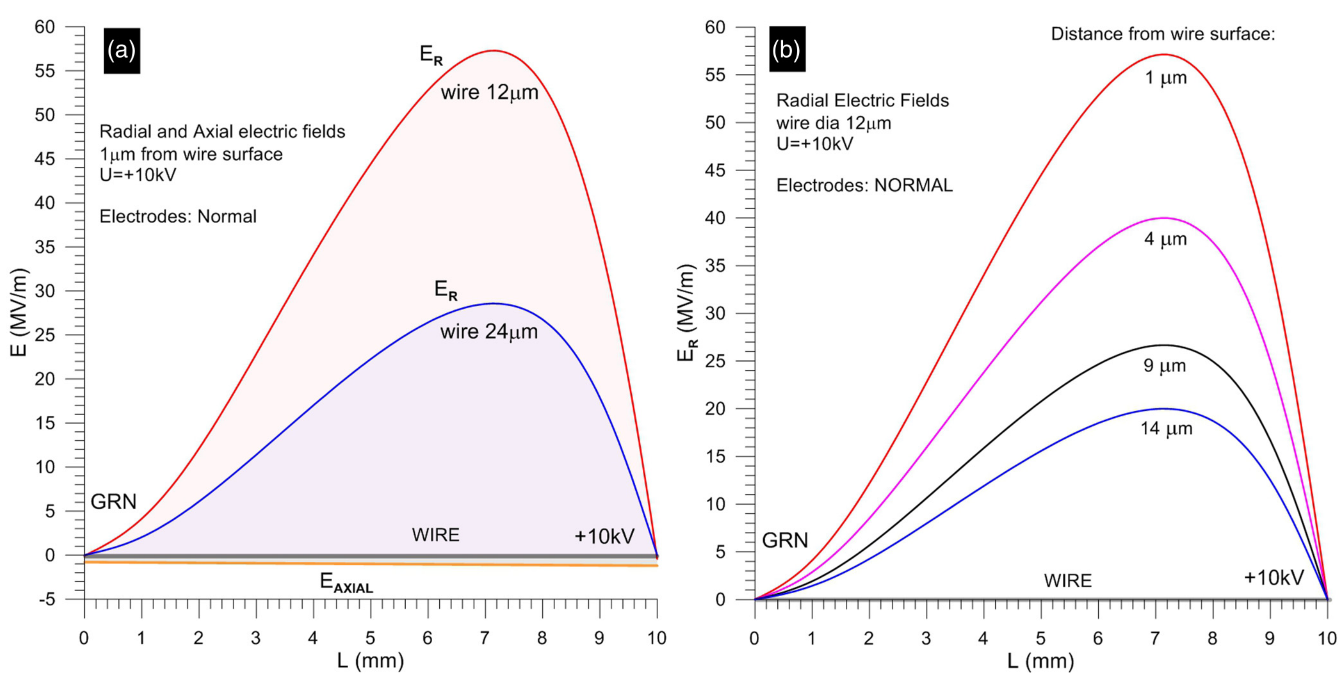

FIG. 6. Axial and radial electric field distributions for two wires with different diameters (a); radial electric field on different distances from wire surface (b).

electric field on a wire surface is directed inside of the wire and helps to expel electrons away. These emitted electrons can initiate avalanche ionization in surrounding low-density vapor. For explosion in a high-density surrounding medium (water, oil, air) the emitted electrons cannot initiate ionization and the polarity effect is absent [6]. Thermoemitted electrons between collisions must absorb enough energy for collisional ionization of the surrounding atoms. To realize this, we need high enough electric field and low enough density of the surrounding atoms.

In our case, we can change the direction of the radial electric field on a wire surface without changing the polarity of the high-voltage electrode. We can continue to call this phenomenon the polarity effect but assuming this applies to the polarity of radial electric fields on a wire surface. The positive radial electric field is directed outside of the metal surface and restricts electronic emission from the wire by increasing the potential barrier for electrons. Negative radial electric fields are directed into the wire surface and accelerate electronic emission from the wire by lowering the potential barrier for electrons. The hot and homogeneous electrical explosion of a thin metal wire in vacuum can be realized with proper design of the wire's holding electrodes for both positive and negative polarity of a high-voltage electrode.

VI. RADIAL FIELD INVERTER CAN IMPROVE WIRE-ARRAY Z-PINCH PERFORMANCE

All modern large-scale wire-array accelerators, such as the Saturn or *ZR* machine at Sandia National Laboratory, operate with negative polarity pulses. This is mainly due to a doubling of the dielectric breakdown voltage threshold for deionized water transmission lines with negative polarity power flow [2]. Finally, the negative pulse applied to the wire-array load results in "cold explosion" of the wires. In this case, the W wire-arrays can remain solid after voltage breakdown before melting [6]. If we use a radial field inverter for the wire array load, we could realize the "hot explosion" mode with significantly higher deposited energy and improved axial homogeneity of expansion for each individual wire. This can increase the ablation rate, mass, and cylindrical symmetry of axial pinch, resulting in greater x-ray yield.

Figure 7 shows a sketch of a standard wire-array holder with a ground reverse current cup (a) and a radial field inverter holder (b). Standard design of the wire-array holder keeps the reverse current cup in a ∼5-mm distance from the wires. This provides a significant increase in the magnitude of negative radial electric field on a wire surface and results in earlier plasma generation when the wire core is relatively cold. Application of an alternative radial field inverter design will improve the initial Joule heating of the wires due to positive radial electric fields and provides the hot explosion mode. Higher ablation rates and better axial symmetry are important factors for an increase of the final x-ray yield.

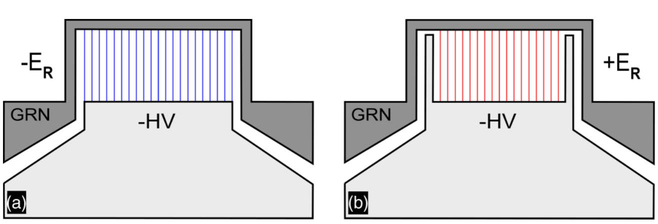

FIG. 7. Wire-array holders: standard (a) and alternative design with radial field inverter (b).

Impressive breakthroughs in magnetic compression and generation of the highest 2 MJ and 330 TW of x-ray power [3] were achieved through increasing the number of wires in the wire array, decreasing the gap between the wires, and making improvements of the axial and azimuthal symmetry of the *Z* pinch [1,2]. We believe that an improved design for a wire-array load with a radial field inverter can support the next step in significantly increasing x-ray power yield in large-scale accelerators.

The effects of positive radial electric field on expansion rate and homogeneity of a wire-array load for large-scale *Z*-pinch *ZR* accelerators will be higher than we observe in our experiments because of the smaller current rate per wire during the prepulse time ∼50–100 A/ns. Two wire-initiation factors are important for optimizing the x-ray emission from the wire-array load: a current rate per wire $dI/dt > 100$ A/ns (with flashover switch) and positive radial electric fields on a wire's surface (with radial field inverter).

The presented radial field inverter configuration is an idea demonstrating how to improve the homogeneity and ablation rate for a wire array. However, this requires a detailed three-dimensional electrostatic simulation of the radial field on the wire's surface in front of the solid wall and the diagnostic window. It is also necessary to optimize the load inductance, which is 7%–8% of the inductance of the vacuum part of the transmission line [2]. The difference in the initial radial field for the wire groups in front of the openings, and in front of the solid wall, is another source of azimuthal inhomogeneity of the axial *Z* pinch. This can be improved by keeping the wire groups only in front of solid walls. The final optimization of the target holder design can only be carried out experimentally.

VII. CONCLUSION

We presented experimental and computational investigations of fast electrical explosion of ten thin metal wires in vacuum using nine different geometries of electrodes. The value of the deposited Joule energy before breakdown and the axial symmetry of wire expansion strongly depend on the geometry and size of the wire's holding electrodes. Before breakdown, the value of the radial electric field on a thin wire surface reaches ∼500 MV/m. This field effectively regulates electronic emission from the wire surface by changing the potential barrier of the metal-vacuum interface. For positive polarity, the radial electric field suppresses electronic emission, while negative polarity accelerates electronic emission. The thermoemitted electrons from hot wire surfaces are responsible for initiating the surrounding vapor ionization. The proper design of electrodes and fast current rate allow for the realization of homogeneous and hot explosion of metal wires in vacuum for any polarity of high-voltage electrode. This is important for wire-array physics so as to maximize magnetic compression of the *Z*-pinch and generate the largest x-ray power due to the increase in the plasma ablation rate and improved symmetry of the axial plasma cylinder.

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