Delay in plasma generation on the surface of copper and duralumin conductors coated with dielectrics

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Abstract. The skin explosion was investigated for homogeneous and double-layer cylindrical copper and duralumin conductors coated with zirconium dioxide. The MIG generator used in the experiment produced a current of amplitude up to 2.5 MA and rise time 100 ns. To detect the plasma generated on the surface of a conductor due to its electrical explosion, the light emitted by the plasma was imaged using a four-frame optical camera with a frame exposure time of 3 ns. In addition, vacuum x–ray diodes were used to detect the instant at which the temperature of the surface plasma, assumed to be a blackbody, became greater than 1 eV. The internal structure and density of the surface plasma were examined based on its transmission images. The images were taken by exposing the plasma to the x-radiation with $h\nu > 1$ keV generated by an X-pinch for 2–3 ns. The QUINTA facility was used to carry out plasma-assisted deposition of multilayer coatings composed of alternating 0.8-$\mu$m-thick zirconium dioxide layers and (more durable) 0.2-$\mu$m-thick zirconium layers. The total number of layers in a coating could be up to sixteen. At magnetic fields lower than 300 T, the onset of plasma generation on the dielectric-coated load part occurred with a delay of up to 70 ns relative to that on a bare copper or duralumin conductor. Increasing the field to 350–400 T decreased the delay in plasma generation to about 30 ns.

1. Introduction
The interest in studies of the electrical explosion of conductors in the skin-effect mode and of the formation of plasma on the conductor surface is associated with various applications. Thus, for the level of currents characteristic of multimegaampere generators [1–4], the magnetic energy density in the load region is so high that it may initiate surface explosions of the transmission line electrodes. The plasma generated due to the explosions may lead to a breakdown of the electrode gap, reducing the efficiency of the electromagnetic energy transport to the load. As previously observed in experiments with copper and duralumin conductors coated with titanium [5, 6], for magnetic fields of up to 400 T at the conductor surface and titanium layer thicknesses of more than 20 $\mu$m, the surface plasma was generated with a significant delay. This was accounted for by the lower conductivity of the outer layer compared with that of the base conductor. For the outer layer, other materials with more than 15 times lower conductivity and with sublimation energy comparable to that of the electrode material can be used [7]. The conductivity of dielectric coatings is much lower than that of any metallic coating; therefore, it was expected that large delays in the surface plasma formation would be attained with coatings of smaller thickness. For magnetically accelerated liners coated with a dielectric layer of thickness 70 $\mu$m, enhanced implosion stability was demonstrated [8]. This paper present an experimental study of the skin
explosion of homogeneous and double-layer cylindrical copper and duralumin conductors coated with zirconium dioxide (ZrO₂).

2. Experimental arrangement

The MIG generator used in the experiment is capable of producing currents of amplitude up to 2.5 MA and rise time 100 ns [9]. The diagnostic equipment of the MIG includes Rogowski coils, magnetic probes, voltage dividers, and vacuum x-ray diodes (XRDs). The plasma generation onset time and the plasma expansion velocity were determined from visible-light images obtained using an HSFC Pro four-frame optical camera with a frame exposure time of 3 ns.

The generator load was a cylindrical copper or duralumin conductor of diameter 2 or 3 mm whose near-cathode part was coated, using vacuum deposition technology, with a ZrO₂ layer of thickness ~15 µm. The plasma-assisted coating deposition was carried out on the QUINTA facility [10]. Figure 1 presents a photo of the load unit of the MIG generator. The load consisted of two parts: a cylinder with a low-conductivity layer deposited on the segment from the cathode flange to about the middle of the load (double-layer conductor) and a solid cylinder extending from the middle of the load to the sliding contact of the anode flange (homogeneous copper or duralumin conductor). This allowed simultaneous measurements of the surface plasma generation on double-layer and homogeneous conductors and compare the data obtained. Unfortunately, the dielectric coatings deposited on the metal surfaces of large curvature (cylinder diameters of 2 and 3 mm) cracked due to internal stresses developed in them. Crack-free zirconium dioxide films of thicknesses no greater than 7.5 µm could be produced. The layered coatings of ZrO₂ and Zr turned out to be more durable. The alternating metal and oxide layers were deposited, respectively, in argon environment and in a 20% argon 80% oxygen mixture at a working gas pressure of 0.5 Pa. Ten metal layers and ten oxide layers were deposited with the layer thickness ratio equal to 2/8. The coating thickness was up to 18 µm. The number of layers and the thickness ratio were varied in different batches of specimens. For reasons of technological complexity, we deposited no more than sixteen layers. The loads were fabricated on a lathe providing a 6.3 surface finish as cylinders with a part gradually increasing in diameter toward the cathode. The surface roughness was ±10 µm. The cylinders were not subjected to additional surface treatment. The experiment was carried out using a vacuum chamber evacuated with an oil vapor pump to a pressure below 10⁻⁴ Torr.

Figure 1. Photo of the MIG generator load. 1 – X-pinch chamber; 2 – XRD; 3 – load unit of MIG generator; 4 – diaphragms with a 150-µm-thick beryllium filter; 5 – MIG vacuum chamber; 6 – low-inductance flexible multicable line; 7 – X-pinch generator.
The internal structure of the surface plasma was examined using an X-pinch-loaded lock-in generator [11] developed at the Institute of High Current Electronics (Tomsk). The generator provided an X-pinch current of amplitude up to 250 kA and rise time 150–200 ns, ensuring the formation of an x-ray ($h\nu > 0.8$ keV) pulse of duration (FWHM) no more than 2 ns. The X-pinch current was measured with a Rogowski coil placed in the immediate vicinity of the load. The waveform of the X-pinch x-radiation was recorded using an Al-cathode XRD placed downstream of a filter that provided detection of x-rays in the range $h\nu > 0.8$ keV. The size of the x-ray source was evaluated using a camera obscura.

The switching system locked the probe x-ray pulse in synchronism with the MIG current pulse to within ±10 ns. The small size of the x-ray source (no more than 2 µm) made it possible to take space-resolved x-ray shadow pictures of the exploded conductor. A feature of the generator is the use of a low-inductance flexible multiwire line to transfer energy from the generator to the displaceable case in which the X-pinch load was mounted. This provided a simple and fine adjustment of the x-ray system and made it possible to place the X-pinch load near the test plasma object immediately in the vacuum chamber of the MIG load unit. In this case, the X-pinch driver could be located at any convenient site near the chamber.

Besides taking shadow images of a test object, it was possible to perform absolute measurements of the mass density distribution for the expanding surface plasma by using step attenuators made of the material of the test conductor [12]. In our experiment, two shadow images, one of the exploded conductor and the other of the step attenuator made of the same material, were recorded on the same film. The optical density of a film, $D$, is known to be proportional to the intensity $I$ of the radiation having passed through a test material layer of thickness $h$. Therefore, at the points where the images of the plasma and of a step of the attenuator were identical in density, the plasma and the attenuator step would have the same mass per unit length along the line of sight.

Figure 2 shows the arrangement of the x-ray imaging of an exploded conductor. The X-pinch load was composed of four crossed tungsten or molybdenum wires of diameter 12 or 24 µm, respectively. The magnification ratio of the system was 3.5. Images were recorded on Mikrat-ORTO and RF-3 films disposed one after another, making possible to obtain shadow images in two spectral ranges. Upstream of the films, to protect them from the visible radiation emitted by the X-pinch and the test plasma object, a filter was placed. The filter was stacked of a 2-µm-thick kimfoil film with a 0.2-µm deposited aluminum layer and a 6-µm-thick polypropylene film with a 0.4-µm deposited aluminum layer. The step attenuator was prepared by magnetron deposition of copper or duralumin on the top part of the polypropylene filter. The photo camera was protected from the conductor explosion products with diaphragms and a 150-µm-thick beryllium filter. The overall filter transmitted more than 20% of the probe radiation with photon energies over 2.5 keV (see figure 2b).

Figure 2. Arrangement of the x-ray shadow imaging of an exploded conductor (a) and the transmission curve of the used filter stack (b).

3. Experimental results
Figure 3 presents optical images of the homogeneous and double-layer parts of a copper conductor of external diameter 3 mm coated with a zirconium dioxide layer of thickness 5 µm. The images were taken
with an HSFC Pro camera at different times from the onset of current flow. The dielectric layer was deposited on the cathode side of the conductor, as shown in figure 2.

![Figure 2. Diagram showing deposition of dielectric layer on the cathode side of a conductor.](image)

**Figure 2.** Diagram showing deposition of dielectric layer on the cathode side of a conductor.

As can be seen from figure 3, the light emission from a homogeneous copper conductor of diameter 3 mm was usually detected within 90–100 ns from the onset of current flow through the conductor, and the double-layer part of the load started weakly glowing at the 135th nanosecond.

![Figure 3. Images of a copper conductor with a 5-µm ZrO₂ layer deposited on the cathode side.](image)

**Figure 3.** Images of a copper conductor of diameter 3 mm with a 5-µm ZrO₂ layer deposited on the cathode side. The images were taken in the visible self-radiation of the conductor at different times from the onset of the generator current.

The curves that represent the delay in the onset of plasma generation relative to the onset of current flow through a copper and a duralumin conductor versus the thickness of the titanium coating on the double-layer part for the magnetic field at the surface less than 300 T and ranging between 350 and 400 T are given in [7]. For the copper conductor coated with a titanium layer of thickness 20–80 μm, they show that at magnetic fields lower than 300 T, plasma generation on its surface started 200–400 ns later than that on the surface of the homogeneous conductor. Decreasing the titanium layer thickness sharply decreased the onset time of light emission from the load double-layer part to 10–15 ns at the deposited layer thickness equal to 10 μm. Therefore, the 40-ns delay in plasma generation on the deposited layer of thickness as small as 5 μm inspired optimism. However, as mentioned above, deposition of crack-free zirconium dioxide layers of thickness more than 7.5 μm failed. Figure 4 presents visible-light images of the bare and the coated part of a duralumin conductor of outer diameter 3 mm taken with an HSFC Pro camera at different times relative to the onset of current flow through the conductor. The coating of overall thickness 14.5 μm consisted of fourteen zirconium layers alternating with fourteen zirconium dioxide layers. The metal-to-oxide thickness ratio was, as mentioned, 2/8. In the shots with loads of this type, the light emission from the part with the multilayer coating was observed after the 150th nanosecond, and that from the bare part of a duralumin conductor of outer diameter 3 mm was generally detected at the 70–75th nanosecond relative to the onset of current flow. Thus, at a magnetic field less than 300 T, the plasma generation on duralumin conductors with a multilayer coating of thickness less than 18 μm was delayed by a little greater than 70 ns relative to that on a bare duralumin conductor.

![Figure 4. Visible-light images of a duralumin conductor with a coating.](image)

**Figure 4.** Visible-light images of a duralumin conductor 3 mm in diameter with a coating of overall thickness 14.5 μm consisting of fourteen zirconium layers alternating with fourteen zirconium dioxide layers deposited on the cathode side of the conductor, taken at different times relative to the onset of the generator current.
At the same time, as shown previously for similar duralumin conductors coated with a titanium layer of comparable thickness [7], the delay in the onset of plasma generation was longer than 100 ns. It seems that the metal layers incorporated in a dielectric coating cause a redistribution of the current density in the conductor, increasing it in the coating.

When the magnetic field was increased to 350–400 T (for conductors of initial diameter 2 mm with a 14-μm-thick multilayer coating), the delay in plasma generation decreased to about 30 ns.

Figure 5 presents visible-light images of the homogeneous and double-layer parts of a duralumin conductor of outer diameter 3 mm (a) and x-ray shadow images of the same conductor (b). The images were taken at different times relative to the onset of the generator current during the exposure of the conductor to the x-radiation emitted by the X-pinch and passed through the filter the transmission curve of which is given in figure 2b. A coating of overall thickness 18 μm consisted of ten zirconium layers alternating with ten zirconium dioxide layers was deposited on the double-layer part of the conductor. The metal-to-oxide thickness ratio was, as in previous shots, 2/8. The images show a weak light emission from the (unexpanded) double-layer part of the conductor starting from the 125th nanosecond relative to the onset of current flow through the conductor, whereas by that time, the homogeneous part had increased in diameter to 3.2 mm. The delayed expansion of the plasma column compared with that of the homogeneous part was observed until the 500th nanosecond. The shadow images, taken with a probe radiation of $h\nu > 2.5$ keV, also indicate that the diameter of the double-layer part remained unchanged until the 180th nanosecond and increased to more than 7 mm by the 950th nanosecond. By that time, when the plasma column had increases in radius to 3.5 mm, its mass per unit length along the line of sight, judging by the transmission of 10-μm Al foil, was over linear mass of this foil.

Thus, in the experiment performed to study the skin explosion of homogeneous and double-layer cylindrical copper and duralumin conductors coated with a zirconium dioxide layer of thickness up to
15 μm, the onset of plasma generation on the dielectric-coated load part at magnetic fields lower than 300 T occurred with a delay of up to 70 ns relative to that on a bare copper or duralumin conductor. Increasing the field to 350–400 T decreased the delay in plasma generation to about 30 ns.

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References
[1] Azizov E, Alikhanov S, Velikhov E, Galanin M, Glukhikh V, Grabovsky E, Gribov A, Dolgachev G, Jitlukhin A and Kalinin J 2004 Plasma Devices and Operations 12 123
[2] Stygar W, Cuneo M, Headley D, Ives H, Leeper R, Mazarakis M, Olson C, Porter J, Wagoner T and Woodworth J 2007 Phys. Rev. STAB. 10 030401
[3] Kim A, Mazarakis M, Sinebryukhov V, Kovalchuk B, Visir V, Volkov S, Bayol F, Bastrikov A, Durakov V and Frolov S 2009 Phys. Rev. STAB. 12 050402
[4] Stygar W, Awe T, Bailey J, Bennett N, Breden E, Campbell E, Clark R, Cooper R, Cuneo M and Ennis J 2015 Phys. Rev. STAB. 18 110401
[5] Datsko I, Labetskaya N, Chaikovsky S and Shugurov V 2016 Tech. Phys. The Rus. J. of Appl. Phys. 61 855
[6] Datsko I, Labetskaya N, Chaikovsky S, Rybka D and Van’kevich V 2018 J. Phys.: Conf. Series. 1115 022008
[7] Datsko I, Labetskaya N, Rybka D, Chaikovsky S, Shugurov V and Vankevich V 2018 J. Phys.: Conf. Series. 946 012136
[8] Awe T, Peterson K, Yu E, McBride R, Sinars D, Gomez M, Jennings C, Martin M, Rosenthal S, Schroen D, Sefkow A, Slutz S, Tomlinson K and Vesey R 2016 Phys. Rev. Lett. 116 065001
[9] Luchinsky A, Ratakin N, Feduschak V and Shepelev A 1997 Russ. Phys. J. 40 1178
[10] Krysina O, Koval N, Lopatin I, Shugurov V and Kovalsky S 2016 J. Phys.: Conf. Series 669 012032
[11] Artyomov A, Zhigalin A, Lavrinovich I, Oreshkin V, Ratakin N, Rousskikh A, Fedyunin A, Chaikovsky S, Erfot A, Mitrofanov K, Grabovski E, Alexandrov V and Smirnov V 2014 Instrum. and Experiment. Tech. 57 461
[12] Sinars D, Shelkovenko T, Pikuz S et al 2000 Physics of Plasmas 7 1555