Delayed growth of large-scale instabilities on the surface of double-layer (Cu + Ti) conductors in strong magnetic fields

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Abstract. The delay time to the onset of large-scale instabilities on the surface of a double-layer conductor was investigated for copper conductors coated with titanium. The experiment was performed on the MIG terawatt high-current generator. The generation of plasma on the conductor surface and the onset and growth of large-scale instabilities were monitored by imaging the conductor in visible light and in the x-rays generated by an X-pinch. It has been demonstrated that for a copper plus titanium conductor exploded in a strong magnetic field, the deposited titanium layer provides a delayed growth of large-scale instabilities compared with their growth on the surface of the bare copper conductor.

1. Introduction

Investigations of the electrical explosion of conductors in strong fast-rising magnetic fields are related, in particular, to the problem of electromagnetic energy transport from multiterawatt generators (capable of producing currents of amplitude up to 30 MA and rise time less than 100 ns) [1, 2], which are intended for use in Z-pinch-based controlled thermonuclear systems [3]. With these currents, the electromagnetic energy density in the load region is so high that the conducting surfaces may explode, leading to plasma generation [4, 5] and, thus, lowering the efficiency the electromagnetic energy transport to the load. In this connection, the surface explosion of heavy metal liners, the plasma generation on their surfaces, and the onset and growth of instabilities are experimentally investigated on various terawatt pulse generators [6-8].

The flow of a megaampere current through a heavy metal liner is accompanied by a shock wave and a nonlinear magnetic diffusion wave propagating toward the interior of the conductor. Nonlinear magnetic diffusion may occur only in a strong magnetic field (several tens of teslas for most metals) [9, 10]. In the case of a pronounced skin effect, the conductor will explode if the magnetic field at its surface reaches [11]:

\[ B_s \approx \sqrt{2\mu_0 \Lambda_0} \]  

where \( \Lambda_0 \) is the sublimation energy of the conductor material. The critical values of \( B_s \) for metals lie in the range 270-350 T.
Previously, it was shown that the plasma generation on the surface of a conductor can be delayed by using a double-layer conductor with the outer layer having a lower conductivity than the base conductor. At magnetic fields of up to 300 T, the outer layer of thickness 20-80 µm sufficed to delay the generation of surface plasma by 200-500 ns from the onset of current flow, depending on the material of the base conductor [12, 13]. For Cu+Ti conductors, the delay in plasma generation was 200 ns longer than that for D16T+Ti conductors. A similar approach was used to suppress instabilities on the surface of a duralumin conductor. It was observed that the growth of large-scale instabilities on duralumin conductors coated with a titanium layer of thickness 20-70 µm occurred considerably slower compared with that on bare duralumin conductors [14]. The longer delay in plasma generation on Cu+Ti conductors suggests that the suppression of instabilities for conductors of this type would be more efficient.

The goal of the experiment presented below was to compare the behavior of the large-scale instabilities developing on the surface of a Cu+Ti conductor with that of the instabilities developing on a bare Cu conductor. In addition, the results of the experiment were compared with those obtained for double-layer and bare duralumin conductors.

2. Experimental procedure and results

The experiment was performed on the MIG high-current generator [15, 16] capable of producing currents of up to 2.5 MA rising within 100 ns. The diagnostic equipment of the MIG generator comprised voltage dividers, Rogowski coils, magnetic probes, vacuum x-ray diodes, an HSFC Pro four-frame optical camera capable of 3-ns frame exposure time, and a triggered generator loaded with an X-pinch. The MIG generator load was a cylindrical copper conductor of diameter 3 mm with a titanium layer of thickness 20-80 µm deposited on the conductor part adjacent to the cathode. The load is shown schematically in figure 1a. The deposition of titanium was carried out on the QUINTA facility [17, 18] intended for plasma-assisted coating deposition. The vacuum chamber of the experimental setup was evacuated with an oil-vapor pump to a pressure below 10⁻⁴ Torr.

The visible self-radiation of the surface of both double-layer and bare conductors (the onset of the radiation emission generally corresponds to the onset of the generation of plasma of temperature less than 1 eV) was recorded with the HSFC Pro camera. The structure of the surface plasma was examined using its shadow images obtained on x-ray illumination with \( h\nu > 0.8 \text{ keV} \). Images were recorded on MikratORTO film. Upstream of the film, a filter stacked of two 2-µm-thick kimfoil films, each having a deposited aluminum layer of thickness 0.2 µm, and 6-µm-thick polypropylene film were placed. The X-pinch-loaded triggered generator (capable of producing currents of up to 250 kA with rise times of 150-200 ns) was used to obtain shadow images was designed and built at the Institute of High Current Electronics SB RAS [19]. The switching system locked the X-pinch-produced probe x-ray pulse in synchronism with the MIG current pulse to within ±10 ns. The X-ray pulse duration, determined using an Al-cathode vacuum X-ray diode placed downstream of the filter, which transmitted X-rays with \( h\nu > 0.8 \text{ keV} \), was about 2 ns. The X-ray source was no more than 2 µm in size. The use of the triggered generator in the experiment had the feature that the energy transport from the generator to the displaceable case in which the X-pinch load was mounted occurred via a low-inductance flexible multi-cable line (see figure 1b). This provided a simple and fine adjustment of the X-ray system. The typical waveform of the MIG generator current is shown in figure 1c.

Figure 2 presents images of the surface of copper conductors of diameter 3 mm with a titanium layer of different thickness deposited on the cathode part of the conductor. The visible images were taken with the HSFC Pro camera at different times from the onset of the MIG generator current.

As can be seen from figure 2, on the image taken at about the 350th nanosecond, surface plasma instabilities are clearly visible on the bare conductor; their average wavelength is about 240 µm and amplitude ranges between 200 and 250 µm. However, only weak plasma instabilities of amplitude ~100 µm are seen on the conductor coated with a 20-µm-thick titanium layer. For the conductors coated with thicker titanium layers, the light emission from the surface was insignificant, making the
measurements incorrect. At later times (510-550 ns), the large-scale instabilities developing on the bare conductors increased to \( \sim 370 \mu m \), both in amplitude and in wavelength.

![Diagram](image1.png)

**Figure 1.** Schematic of the load unit (a), a photo showing the arrangement of the X-pinch unit in the MIG vacuum chamber (b), and the typical waveform of the MIG generator current (c).

![Images](image2.png)

**Figure 2.** Visible images of copper conductors of diameter 3 mm coated with a Ti layer of thickness 20 (a), 45 (b), and 80 (c) \( \mu m \) that were taken at different times from the onset of the MIG generator current.

For the conductor coated with a 20-\( \mu m \)-thick titanium layer, the instability amplitude increased insignificantly (to 130 \( \mu m \)). For the conductors with thicker titanium layers, the initial surface pattern remained unchanged. In this case, the peak magnetic field was comparable to the critical magnetic fields both for copper \( (B_s \approx 330 \ T) \) and for titanium \( (B_s \approx 310 \ T) \).

Figure 3 presents the average instability amplitudes \( \Delta A \) (a) and average increments in conductor diameter, \( \Delta w \) (b), estimated for different time intervals, in relation to the titanium layer thickness together with their values for bare conductors (zero-thickness titanium layer). The data were derived from optical images.

The instability amplitude \( A \) and the diameter increment \( \Delta w \) were estimated as:
\[ A(t) = \frac{D_{\text{max}}(t) - D_{\text{min}}(t)}{2}; \quad \Delta w(t) = \frac{D_{\text{min}}(t) - D_0}{2}, \]  

where \( D_{\text{max}}(t) \) and \( D_{\text{min}}(t) \) are the length-averaged maximum and minimum diameters of the conductor at time \( t \); \( D_0 \) is the initial diameter of the conductor.

\[ \text{(2)} \]

Figure 3. Instability amplitudes \( A \) (a) and diameter increments \( \Delta w \) (b) for a bare conductor (zero thickness of the Ti layer) and for double-layer copper conductors (20, 45, and 80 µm thickness of the Ti layer) for different time intervals.

As can be seen from figure 3, even a 20-µm-thick deposited layer sufficed to hamper the growth of instabilities within 550 ns, but it failed to efficiently inhibit the conductor expansion in this time interval. The expansion of the double-layer conductors with a Ti layer of thickness 45 and 80 µm and the instabilities of their surface plasmas could not be detected because of too weak light emission from their surfaces.

It should be noted that in some shots, the large-scale instabilities on the surfaces of bare copper conductors were less pronounced: their amplitudes and wavelengths were smaller than the respective average values (see figure 2c and figure 4a). They slowly increased with time, and the increment in conductor diameter corresponded to the average values. This observation can be accounted for, in particular, by the fact that our criterion for the plasma generation on metal surfaces in fast-rising magnetic fields of several hundreds of teslas [20] appeared to be inapplicable specifically to a bare copper conductor of external diameter 3 mm, as its brightness temperature was not above 2 eV. The visible light emission from the surface of such a conductor was detected within 90-110 ns from the onset of current flow; however, it was not always uniform and intense enough.

Data on the expansion of a double-layer conductor could be derived from the shadow images taken in the X-pinch-generated x-rays. Figure 4 presents a visible image (a) and an x-ray shadow image (b) of the load taken at the closest times in the same shot. As the HSFC Pro camera, the X-pinch unit, and the MIG generator load were lined up, the visible image (see figure 4a) shows the visible radiation emitted by the X-pinch. The X-pinch was out of focus; therefore its image is blurred. In the X-ray image, we see the surface plasma expanding both from the bare part of the conductor and from its part coated with a 50-µm-thick titanium layer.

The increment in diameter of the bare copper conductor derived from the visible image taken at the 590th nanosecond was ~850 µm, which is in reasonable agreement with the data above. The x-ray image bears witness of instabilities of amplitude 50-60 µm for the double-layer part of the load, whereas for the bare part, the instability amplitude was about 350 µm. At the 700th nanosecond, the diameter increment was 1150 µm for the bare conductor and 470 µm for the double-layer conductor (see figure 4b); that is, the double-layer conductor expanded almost two times slower. It should however be taken into account that the conductor diameter increments and, especially, the instability
amplitudes derived from x-ray images might be smaller than those obtained by processing visible images because the instability plasma “tongues” might be of low density and, hence, undetectable in X-ray images. This issue will be the subject of our further investigations.

Figure 4. Images of a copper conductor 3 mm in diameter partly coated with a 50-µm-thick titanium layer that were taken in the visible self-radiation (a) and in x-rays with $\hbar \nu > 0.8$ keV at different times from the onset of the MIG generator current.

Compare the experimental results discussed above with those obtained for similar bare and double-layer duralumin conductors [14]. For a bare copper conductor 3 mm in diameter, $\Delta w$ in the time interval from 510 to 550 ns is only 800 µm, which is smaller than that for a bare duralumin conductor in a close time interval (1300 µm and 545 to 590 ns, respectively) by a factor of 1.6. A layer of low-conductivity material deposited on a duralumin conductor hampers the conductor expansion; the thicker the deposited layer, the smaller the increment in conductor diameter. The data derived from shadow x-ray images indicate that the same took place for copper conductors. The instability amplitude for a bare duralumin conductor in the above time interval was 980 µm, whereas that for copper was, in average, 370 µm. It follows that the suppression of large-scale instabilities is more efficient for double-layer duralumin conductors. However, in view of their higher growth rates and higher conductor expansion rates compared with those for double-layer copper conductors, it is more reasonable to use copper conductors with similar lower-conductivity layers.

3. Conclusion
Thus, it has been found that a titanium layer of thickness 20-80 µm deposited on a copper conductor hinders the growth of large-scale instabilities on the surface compared with that of instabilities on a bare copper conductor. This was evidenced both by the visible images of the conductors taken in the self-radiation of their plasmas and by their shadow x-ray images. The use of copper conductors with a deposited layer of lower conductivity is more efficient compared with that of similar duralumin conductors with regard both to the delay in plasma generation on the surface and to the subsequent expansion of the plasma with accompanying growth of large-scale instabilities. The X-ray probing (with the radiation of an X-pinch) and the optical imaging performed with a four-frame camera gave substantially similar results. It is expected that the soft X-ray probing with the use of an X-pinch will make it possible to determine the material density distribution for an exploding conductor, and this will be the subject of our further investigations.

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