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Leakage of current from MITL with ceramic coating cathode

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Abstract. At the Angara-5-1 installation the experiments were carried out to study the processes occurring during the passage of current in a vacuum transporting line in which the cathode was protected by a ceramic coating. The linear current density was about 1–2 MA/cm; the time of the current rise to the maximum was ~100 ns. It is shown that in the case of coating the MITL cathode with ceramics, not all the current entering the MITL reaches its end.
Keywords: MITL, plasma, pinch.

1. Introduction

At installations for the study of high-current Z-pinches, energy is transferred to the load via vacuum magnetically insulated transporting lines (MITL). The linear density of the current flowing through the electrode can reach 10 MA/cm. The effect of pulsed super-strong currents and soft X-ray radiation (SXR) on current-carrying electrodes leads to the formation of plasma flows propagating at different speeds [1]. The formation of a plasma layer can lead to ion and electron current leakage across the interelectrode gap. Thus, the question arises of preventing current leakage across the interelectrode gap.

A detailed study of the processes occurring when a current with a high linear density flows through stainless steel electrodes has been studied in various papers [2–7]. Of particular interest is the study of gap bridging by rare plasma [8–10]. In [11], the explosion of the surface of current-carrying electrodes was investigated. In [8–11], the behavior of electrodes made of heavy metals was studied. It was also noted in [4] that it is possible to work with a heterophase system by covering the electrode with a thin dielectric layer.

In [4], in addition to studies of current conductors made of various materials, the results of experiments with a ceramic tube placed on the cathode are presented.

Plasma formation was experimentally investigated in [6] when the cathode of MITL was coated by lead foil or ceramics. This experiment was carried out with a linear current density of up to 4 MA/cm and in the absence of SXR on the surface of a current-carrying electrode. It was shown that the coating of the electrode with ceramics delays the expansion of dense plasma near the electrode during the first 200 ns after the start of the current. Plasma appears on the metal surface, but the ceramic coating slows its spread from the electrode surface. This inspired some optimism about the possibility of protecting MITL from current leaks when covering the electrodes with ceramics.

The experimental conditions in [6] were such that the ceramic-coated electrode was not a MITL electrode and the electric field normal to the electrode surface was practically absent. Another thing is when the electrode is the cathode of MITL. In this case, at least for the time of current rising, the electric field normal to the surface of the electrode has a significant value. The intensity of plasma formation in this case may be more, which may lead to an increase in current leakage in the MITL.

The results of current transfer studies in a MITL in which the cathode was covered by a ceramic protective tube were presented in [10]. It was shown that the protection of the cathode by ceramics was not successful. We decided to conduct additional studies of the protective properties of ceramics, since in [10] the MITL used was a cylindrical cathode surrounded by three cylindrical anodes standing separately at a great distance, which differs significantly from classical MITLs in which the cathode is located coaxially inside a cylindrical anode.

The purpose of the work was to study the processes occurring at current flowing in the MITL, in which the cathode is located coaxially inside a cylindrical anode. To study the protective properties of ceramics in some shots, the cathode was coated with ceramics.

It is shown, as in [10], that in the case of coating the MITL cathode with ceramics, not all the current entered the MITL reaches its end.

2. Experimental setup

The experiments were carried out on an eight-module installation of the Angara-5-1 [12]. The amplitude of the generator current was 3 MA; the time of the current rise to the maximum was ~100 ns.

2.1. The design of a short-circuited vacuum line

Instead of a wire assembly mounted on the axis of the installation to form a Z pinch, a short-circuited vacuum line (SCVL) was installed.

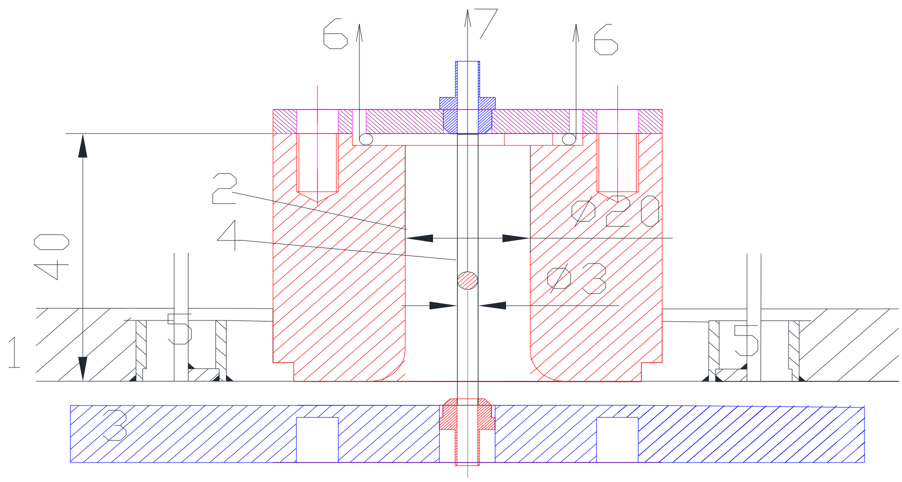

Fig.1. Layout of the electrodes and the short–circuited vacuum line : *1* – is the anode of the installation; *2* – is the anode of the SCVL; *3* – is the cathode of the installation; *4* – is the cathode of the SCVL (hollow stainless steel tube with a diameter of 3 mm and a wall thickness of 220 microns); *5* – are the current sensors at the entrance to the SCVL; *6* – are the current sensors at the end of the SCVL; *7* – is electric field strength sensor on the upper part of the inner surface of the SCVL cathode. In a number of experiments, a hollow ceramic tube with an outer diameter of 5 mm and a wall thickness of 1 mm was put on the SCVL cathode (not shown in the figure).

The location of the electrodes and the SCVL is shown in Fig.1. The SCVL is connected to the anode and cathode of the Angara-5-1 installation. The cathode of the SCVL is a hollow stainless-steel tube with a diameter of 3 mm and a wall thickness of 220 microns. The time of current skinning in a linear approximation (at small current amplitudes) is 16 ns, which is significantly less than the rise time of the current pulse.

The SCVL anode is made of stainless steel, its height is 40 mm, the inner diameter is 20 mm. The inductance of such a SCVL is equal to 10 nHn. The internal resistance of the generator of the Angara-5-1 installation is 0.25 Ohms; and the time of filling the gap between the anode of the SCVL (2) and the cathode of the SCVL (4) with a magnetic field is 40 ns, which is less than the duration of the current front by more than 2 times.

In a number of experiments, a ceramic tube with an inner diameter of 3 mm and an outer diameter of 5 mm was put on the SCVL cathode (not shown in Fig.1). The ceramic coating was made of mullite silica with a content of aluminum oxide Al_2O_3 more than 50% and iron oxide Fe_2O_3 less than 0.7%, and SiO2 less than 50%.

2.2. Diagnostic methods

An insulated conductor was located inside the cathode tube, which had contact with its inner surface in the middle of its length. This conductor was used to measure the electric field strength on the upper half of the inner surface of the tube.

The current flowing into the SCVL was determined by averaging the integrated signals from B-dot sensors *5*, located at a distance of 55 mm from the axis.

The current at the end of the SCVL was determined by averaging the integrated signals from B-dot sensors *6*, located at a distance of 15 mm from the axis.

The registration of the intrinsic radiation of the electrode surface in the optical range was carried out by the SFER-2 camera [13] in the streak camera mode. The temporal resolution of the camera is 0.3 ns; the spatial resolution of the object is about 100 microns. The slit was oriented along axis of the cathode.

3. Experimental results

3.1. Results obtained in a shot with a tube without ceramic coating

Fig.2 shows the current at the beginning of the SCVL (*Jin*), determined by the data from the sensors *5*, and the current at the end of the SCVL (*Jout*), determined by the data from sensors *6*. This figure shows that at a time of 950 ns, the currents registered at the beginning of the SCVL and at the end of the SCVL are practically the same. Therefore, it can be concluded that all the current received by the SCVL passes through it practically without loss. The difference between the *Jout* and *Jin* currents in a time of 820–930 ns is explained by the process of establishing magnetic self-isolation.

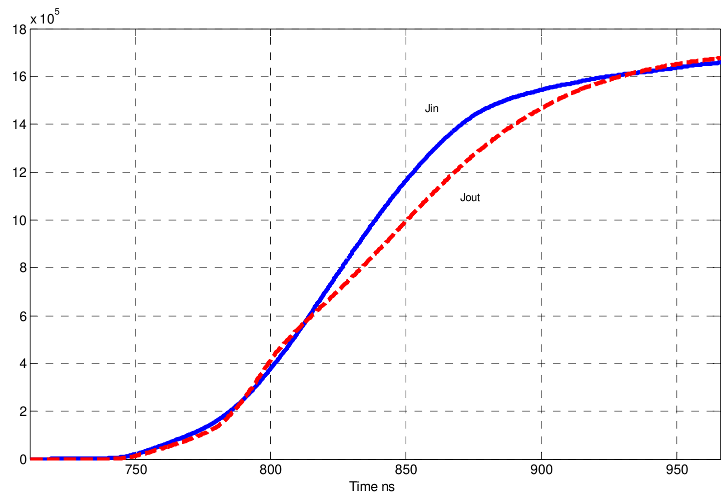

Fig.2. The currents [A] at the beginning of the SCVL (*Jin*) and at the end of the SCVL (*Jout*).

Fig.3 shows a time-synchronized streak image of the glow of the axial section of the visible part of the tube between the anode *1* and the cathode *3* and the voltage on the upper half of the inner surface of the tube *7*. It can be seen that the voltage drops at time 860 ns corresponds to the appearance of a glow on the tube surface.

In the voltage profile shown in Fig.3, a peculiarity is clearly visible: a noticeable decrease in growth over the interval of 820–830 ns. There is also a similar feature on the voltage profile obtained by numerical simulation the processes occurring in a thick-walled tube when a current with a high linear density is passed through it [14]. As a result of the simulation, it is obtained that by this moment the substance of the tube from the outer boundary and a little more than to the middle of its thickness is already in a liquid state; the remaining part near the inner boundary has not yet had time to melt completely and is in a two-phase solid-liquid state. Thus, the experimentally registered feature on the voltage profile corresponds to the same feature on the calculated voltage profile and is due to the melting of the tube substance located on its inner boundary.

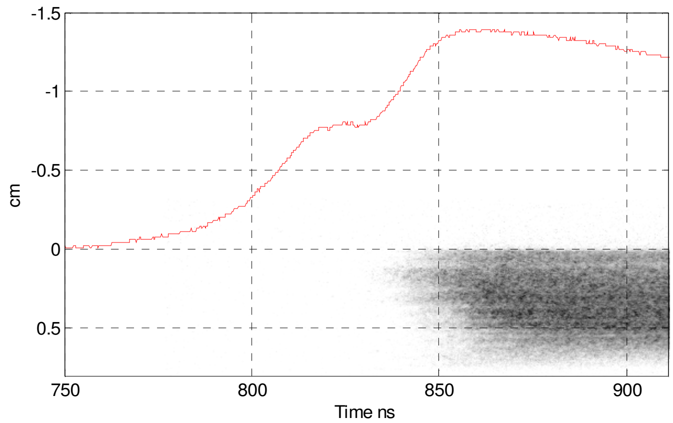

Fig.3. Streak image of the intrinsic glow (negative) of the axial section of the tube visible between the anode *1* and the cathode *3*, and the time dependence of the voltage on the upper half of the inner surface of tube. The vertical scale for voltage is 10 kV/cell.

3.2. Data obtained in a shot with a ceramic-coated tube

Fig.4 shows streak image of the glow of the axial section of the visible part of the tube between the anode *1* and the cathode *3* and the time dependence of the currents at the entrance to the SCVL (upper curve) and at the end of the SCVL (lower curve). The data is synchronized in time.

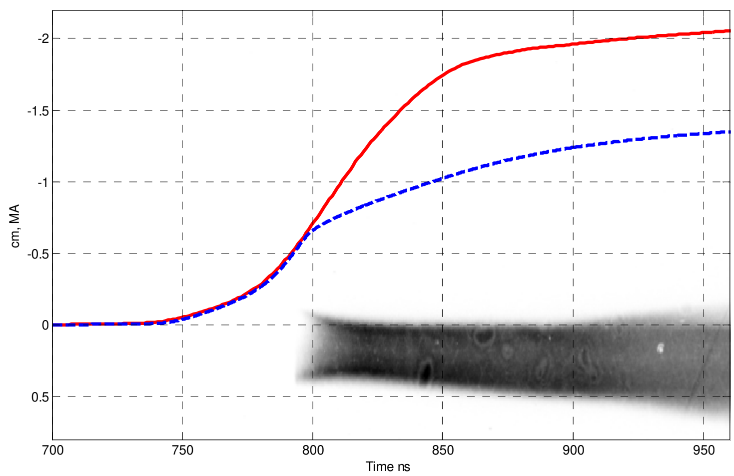

Fig.4. Streak image of the intrinsic glow (negative) of the axial section of the tube visible between the anode *1* and the cathode *3*, and the time dependence of the currents at the entrance to the SCVL (upper curve) and at the end of the SCVL (lower curve).

As can be seen in Fig.4, the current at the beginning of the SCVL and the current at the end of SCVL coincide with each other until the time of 800 ns, after which the current value at the end of the SCVL becomes significantly less than the current value at the beginning of the SCVL. The own glow of the axial section of the tube appears on the same time. The current amplitude at the beginning of the current's divergence (at 800 ns) is 700 kA, and by the time of 960 ns, the currents difference is 650 kA (~30% of the total current). This result shows that in the case of MITL, in which the cathode is covered with ceramics, there is a significant loss of current.

Thus, based on the totality of the information provided (electrical signals, streak images of the tube section's own glow), it can be concluded that in the case when the MITL cathode was coated with ceramics, plasma formation occurs on its outer surface earlier than on the surface of the cathode without ceramics. Which once again, in agreement with [10], confirms the futility of ceramic coating of MITL cathodes.

Thus, our optimism about the possibility of protecting MITL from current leakage when covering the electrodes with ceramics was not justified.

4. Conclusion

At the Angara-5-1 installation, experiments were carried out to study the processes occurring when the current flow in the MITL, in which the cathode was coated with ceramics. The linear current density was 1–2 MA/cm. The time of the current rise to the maximum is ~100 ns.

It is shown that in the case of coating the MITL cathode with ceramics, not all the current entering the MITL reaches its end.

The experimentally registered particularity on the voltage profile (decrease in the rise rate) corresponds to the same feature on the calculated voltage profile [14] and is due to the melting of substance on the inner surface of the tube.

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5. References

[1] Aleksandrov V.V., Grabovsky E.V., Laukhin Ya.N., Mitrofanov K.N., Oleinik G.M., Predkova E.I., Reshetnyak O.B., Tkachenko S.I. Frolov I.N., *Plasma Phys. Rep.*, **48**, 101, 2022; doi: 10.1134/S1063780X22020015

[2] Cuneo M.E., *IEEE Trans. Dielectr. Electr. Insul.*, **6**, 469, 1999; doi: 10.1109/94.788747

[3] Welch D.R., Bennett N., Genoni T.C., Rose D.V., Thoma C., Miller C., Stygar W.A., *Phys. Rev. Accel. Beams*, **22**, 070401, 2019; doi: 10.1103/PhysRevAccelBeams.22.070401

[4] Grabovski E.V., Levashov P.R., Oleinik G.M., Olson C.L., Sasorov P.V., Smirnov V.P., Tkachenko S.I., Khishchenko K.V., *Plasma Phys. Rep.*, **32**, 718, 2006; doi: 10.1134/S1063780X06090029

[5] Tkachenko S.I., Grabovskii E.V., Kalinin Yu.G., Oleinik G.M., Aleksandrov V.V., Khishchenko K.V., Levashov P.R., Ol'khovskaya O.G., *Izv. Vyssh. Uchebn. Zaved., Fiz.*, **57**(12–2), 279, 2014.

[6] Aleksandrov V.V., Branitskii A.V., Frolov I.N., Grabovskii E.V., Gribov A.N., Gritsuk A.N., Korolev V.D., Laukhin Ya.N., Mitrofanov K.N., Oleinik G.M., Predkova E.I., Samokhin A.A., Shishlov A.O., Smirnov V.P., *Plasma Phys. Rep.*, **46**, 604, 2020; doi: 10.1134/S1063780X2006001X

[7] Aleksandrov V.V., Branitskii A.V., Grabovskii E.V., Oleinik G.M., Predkova E.I., Samokhin A.A., Tkachenko S.I., Frolov I.N., Khishchenko K.V., Shishlov A.O., *Plasma Phys. Rep.*, **47**, 355, 2021; doi: 10.1134/S1063780X21040024

[8] Bakshaev Yu.L., Bartov A.V., Blinov P.I., Chernenko A.S., Dan'ko S.A., Kalinin Yu.G., Kingsep A.S., Korolev V.D., Mizhiritskii V.I., Smirnov V.P., Shashkov A.Yu., Sasorov P.V. Tkachenko S.I., *Plasma Phys. Rep.*, **33**, 259, 2007; doi: 10.1134/S1063780X07040010
[9] Anan'ev S.S., Bakshaev Yu.L., Bartov A.V., Blinov P.I., Dan'ko S.A., Zhuzhunashvili A.I., Kazakov E.D., Kalinin Yu.G., Kingsep A.S., Korolev V.D., Mizhiritskii V.I., Smirnov V.P., Ustroev G.I., Chernenko A.S., Shashkov A.Yu., Tkachenko S.I., *Vopr. At. Nauki Tekh., Ser.: Termoyad. Sint.*, **4**, 3, 2008.
[10] Anan'ev S.S., Bakshaev Yu.L., Bartov A.V., Blinov P.I., Dan'ko S.A., Zhuzhunashvili A.I., Kazakov E.D., Kalinin Yu.G., Kingsep A.S., Korolev V.D., Mizhiritskii V.I., Smirnov V.P., Tkachenko S.I., Chernenko A.S., *Plasma Phys. Rep.*, **34**, 574, 2008; doi: 10.1134/S1063780X08070064
[11] Chaikovsky S.A., Oreshkin V.I., Datsko I.M., Labetskaya N.A., Ratakhin N.A., *Phys. Plasma*, **21**, 042706, 2014; doi: 10.1063/1.4871719
[12] Al'bikov Z.A., Velikhov E.P., Veretennikov A.I., Gluhih V.A., Grabovskij E.V., Grjaznov G.M., Gusev O.A., Zhemchuzhnikov G.N., Zajcev V.I., Zolotovskij O.A., Istomin Yu.A., Kozlov O.V., Krasheninnikov I.S., Kurochkin S.S., Latmanizova G.M., Matveev V.V., Mineev G.V., Mihajlov V.N., Nedoseev S.L., Olejnik G.M., Pevchev V.P., Perlin A.S., Pecherskij O.P., Pis'mennyj V.D., Rudakov L.I., Smirnov V.P., Carfin V.Ya., Jampol'skij I.R., *Soviet Atomic Energy*, **68**, 26, January 1990.
[13] Borisov V.V., Veretennikov A.I., Vikharev V.D., Zaitsev V.I., Zotov V.P., Leont'evskii A.E., Mikhailov V.N., Slavnov Yu.K., Smirnov V.P., Usov Yu.B., Khromochkin E.D., Tsarfin V.Ya., *Prib. Tekh. Eksp.*, **1**, 215, 1989.
[14] Tkachenko S.I., Aleksandrov V.V., Frolov I.N., Grabovskii E.V., Laukhin Ya.N., Oleinik G.M. *Proc. of 8th Int. Cong. on Energy Fluxes and Radiation Effects, 2–8 October, Tomsk,* 2022; doi: 10.56761/EFRE2022.S2-O-048501