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Fast switching of megaampere current to the load

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Abstract. Previous experiments on the MIG generator (2 MA, 80 ns) showed that the generator current can be switched to a load in 1–3 ns in the process of sweeping (pushing away from the load) by the magnetic field of the plasma, previously injected in the area of the load and the conical load holder. Fast switching of the megaampere current to a foil liner or a solid metal rod is accompanied by an explosion of the liner (rod) surface and the formation of a thin layer of hot (>100 eV) dense plasma. In the course of these experiments, the question arose of whether the formation of a surface plasma is the result of implosion onto the load surface of a part of the injected plasma swept by the current. To clarify this issue, test shots were made in this work with different configurations of the load area and the composition of the injected plasma. The performed studies confirm that when plasma is injected into the load region with a conical holder, the plasma is pushed away from the load and the current is switched over to the surface of the load (liner or rod) in a few nanoseconds.
Keywords: fast current switching, liner implosion, soft X-rays.

1. Introduction

In experiments [1–3] on fast switching of the mega-ampere current to a foil liner or a solid metal rod 1–2 mm in diameter, the formation of a thin layer of hot (>100 eV) dense plasma was observed on the surface of the liner (rod). The current is switched to the load when the magnetic field sweeps the plasma that was previously injected into the load region (Fig.1a). The load (liner or rod) is mounted on a conical cathode (holder). At the junction of the load with the cathode, the diameter of the cathode is close to the diameter of the load. With such a configuration of the cathode, it is expected that the current sheath moving along the cathode and then the load surfaces pushes the plasma away from them (Fig.1b). Behind the moving current sheath, the current flows over the surface of the cathode and the load. The rise time of the current on the surface of the conductor is determined by the thickness and velocity of the moving current sheath (skin layer). Estimates show that with the time of plasma sweeping to the load of about 100 ns, the Spitzer conductivity of the skin layer plasma with a temperature of about 10 eV, and the velocity of its movement close to the local Alphen velocity, the current rise time (I = 2 MA) on the surface of a rod with a radius of 1 mm is 0.1–0.3 ns.

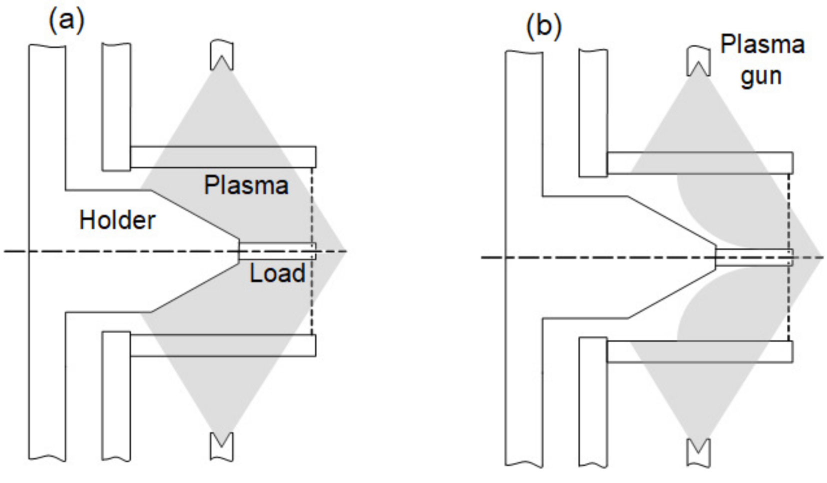

Fig.1. Schematic of the load area with a conical holder.

At a subnanosecond current rise time, a thin current skin layer on the conductor surface explodes, and its plasma is heated to a temperature of about or more than 100 eV. The process of switching the current to the load is accompanied by a powerful pulse of soft X-rays emitted from the surface of the load. In the course of these experiments, the question arose of whether the formation of surface plasma is the result of implosion onto the surface of the conductor of a part of the injected plasma swept by the current. To clarify this issue, several test shots were made with different injected plasma compositions and load region configurations. The experiments were performed on the MIG pulse generator [4] with a peak current of about 2 MA and a current rise time of about 80 ns.

2. Experiment

2.1. 1st test

In experiments [1], the soft X-ray (SXR) output from the surface of a tungsten rod 1.1 mm in diameter was about 35% of the magnetic energy accumulated in the load area and magneto-insulated transmission line (MITL) by the time the current was switched. That is, a high efficiency of the conversion of magnetic energy into thermal energy of the plasma and then into radiation energy is realized. A high efficiency of thermal energy conversion into radiation energy can be achieved for the plasma of elements with a high atomic number Z. The injected plasma is created by an electric discharge over the dielectric surface. In the first test, the Teflon dielectric was replaced with a polyethylene dielectric. The radiation output has not changed. That is, the emissivity of the observed surface plasma does not depend on the composition of the injected plasma.

2.2. 2nd test

In this test, a cathode configuration (Fig.2) was used close to the configuration used in the plasma focus [5, 6]. The load is mounted on a cylindrical cathode. In such a configuration, after the swept plasma reaches the cathode end face, plasma implosion to the load is possible (it takes place in the plasma focus, Fig.2b).

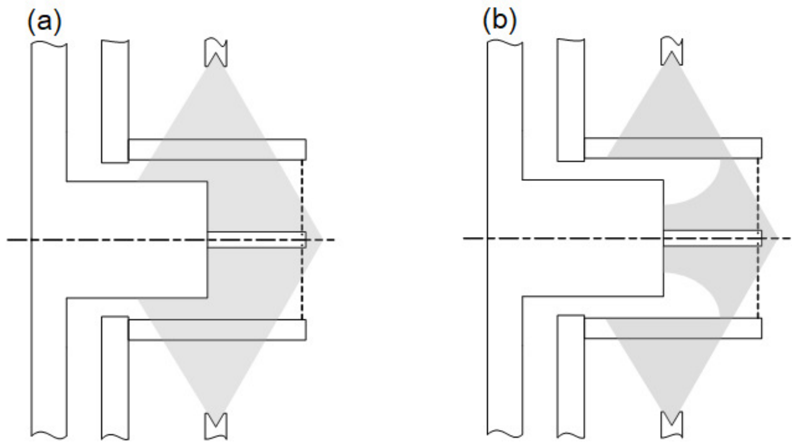

Fig.2. Schematic of the load area with a cylindrical holder.

Fig.3 shows the current and photoemission X-ray diode (XRD) signal for a shot on a liner with a diameter of 1 mm, made of aluminum foil with a thickness of 2.5 μm. Liner length is 4.5 mm. The cathode is conical. The XRD consists of an aluminum photocathode and a 10-μm thick polypropylene filter. Its spectral sensitivity is shown in Fig.4. The first X-ray peak at 80 ns is due to the explosion of the liner surface when the generator current switches to it. The emission from the surface of the liner in its initial position is clearly visible in the X-ray image (Fig.5). The image was obtained using a pinhole camera with an aluminum filter 2.5 μm thick ($h\nu$ > 700 eV). The second emission peak at 87 ns is due to the stagnation of the liner plasma on its axis. The subsequent peaks appear to be the result of the liner oscillating around the Bennett equilibrium position and the formation of constrictions (hot spots). The liner implosion process is essentially unstable. The X-ray image shows sections of pinched plasma with a diameter of about 50 μm and 5 hot spots.

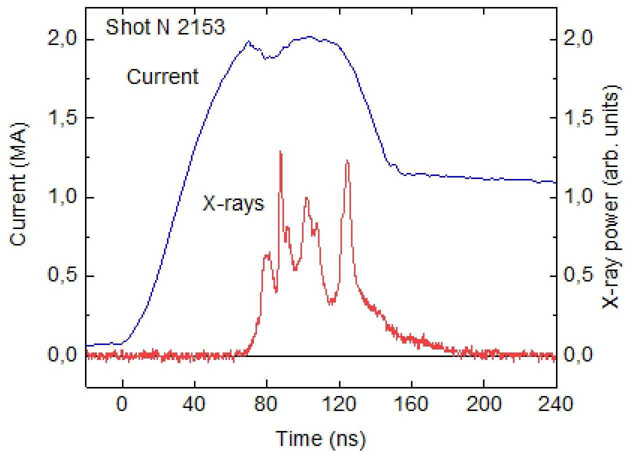

Fig.3. Current and signal of XRD with 10-μm thick polypropylene filter for imploding a 2.5-μm thick aluminum liner. Liner diameter is 1 mm. The load holder is conical.

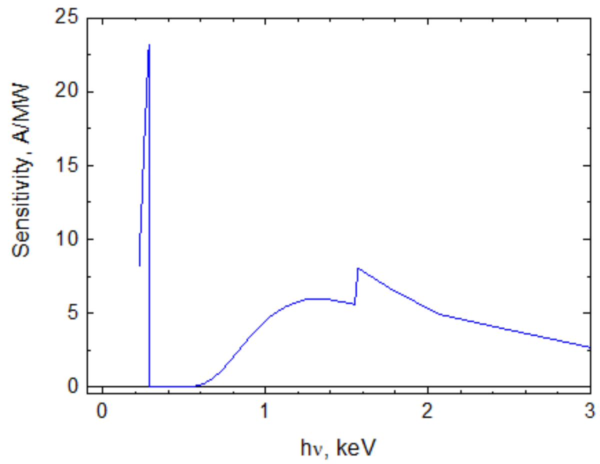

Fig.4. Spectral response of a XRD with an aluminum photocathode and 10-μm thick polypropylene filter.

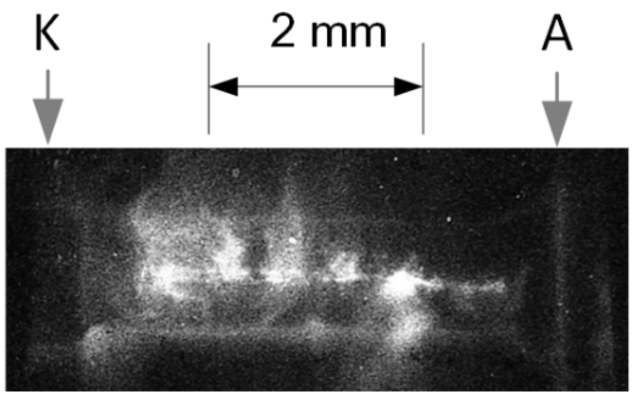

Fig.5. Time-integrated x-ray image (1.8-μm thick aluminum filter) for a shot with a 1.0-mm diameter liner. The liner consists of one turn of 2.5-μm thick aluminum foil. The load holder is conical.

Fig.6 shows the current and XRD signal for a shot also on a liner with a diameter of 1 mm, made of 2.5-μm aluminum foil. However, the cathode is cylindrical. The XRD signal is shown on the same scale as in Fig.3. The first X-ray pulse (at 100 ns) is much weaker in this shot. The second X-ray peak at about 110 ns apparently corresponds to the first liner stagnation. Its amplitude is 7 times lower than the amplitude of the corresponding peak in a shot with a cone cathode. The X-ray image (Fig.7) shows only a part of the liner in the initial position and the contact point of the liner with a set of radial wires 130 μm in diameter (anode), with the help of which the current through the liner is closed to the rods of the return conductor. X-rays emitted from this area does not enter the XRD. The stagnated liner is not visible in the image. The results of this shot can be explained by the implosion on the liner surface of a part of the injected plasma swept by the current. This plasma carries current even after its stagnation on the surface of the liner.

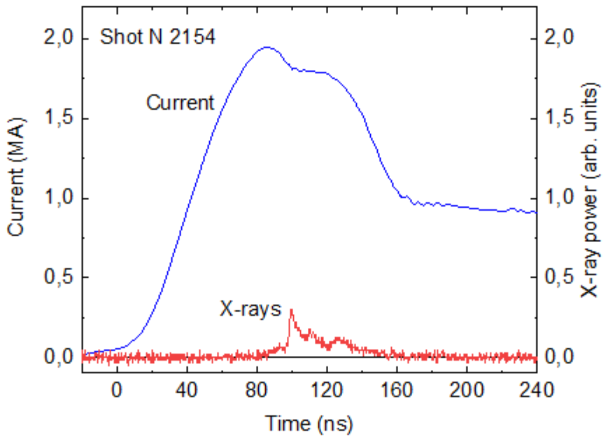

Fig.6. Current and signal of XRD with 10-µm thick polypropylene filter for imploding a 2.5-µm thick aluminum liner. Liner diameter is 1 mm. The load holder is cylindrical.

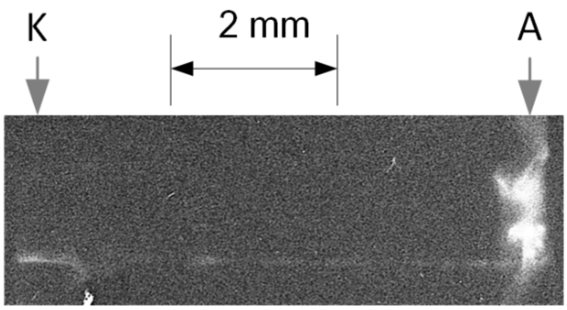

Fig.7. Time-integrated x-ray image (1.8-µm thick aluminum filter) for a shot with a 1.0-mm diameter liner. The liner consists of one turn of 2.5-µm thick aluminum foil. The load holder is cylindrical.

2.3. 3rd test

In this test, to eliminate the possibility of radial implosion of the injected plasma on the load, a screen was used (Fig.8). The presence of the screen eliminates the possibility of sweeping the injected plasma from the periphery to the axis. Below are the results of two shots with and without a screen. The load was a copper rod with a diameter of 1.4 mm.

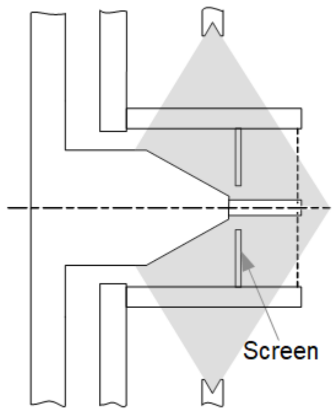

Fig.8. Schematic of the load area with a conical holder and a screen.

In a shot with a screen, after switching the current to a load of about 75 ns, a radiation pulse is formed (XRD with a 10-µm polypropylene filter) with a duration of 7 ns (Fig.9). The X-ray image (Fig.10, filter – aluminum 2.5 µm, cutoff – 700 eV) shows emission from the surface of the rod. A similar result was obtained in a shot without a screen (Fig.12). The more powerful and shorter (about 4 ns, FWHM) radiation pulse in this shot (Fig.11) can be qualitatively explained by the higher plasma velocity along the load surface. In this shot, the injected plasma density near the load was reduced by moving the plasma guns by 5 mm towards the cathode (to the left in the figure). The duration and power of the radiation pulse is largely determined by the time (velocity) of the current sheet movement along the load [1], since during this movement, sections of the load surface are sequentially loaded (and explode) with current. This test confirms that the anode configuration (presence or absence of a screen) does not affect the result and the formation of a short radiation pulse is due to the process of plasma displacement from the load surface.

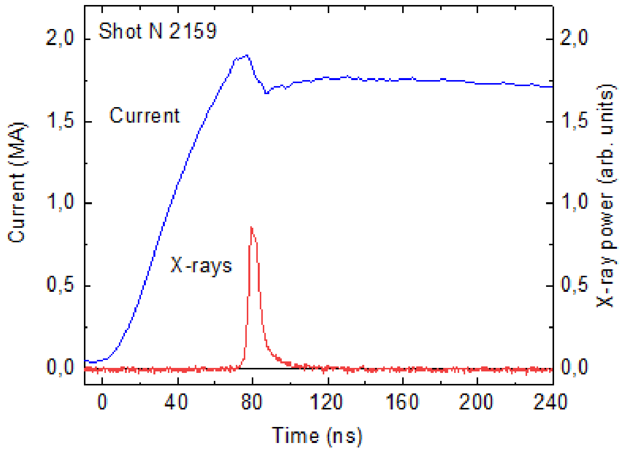

Fig.9. Current and signal of XRD with 10-μm thick polypropylene filter for a shot with a screen. The load was a copper rod with a diameter of 1.4 mm.

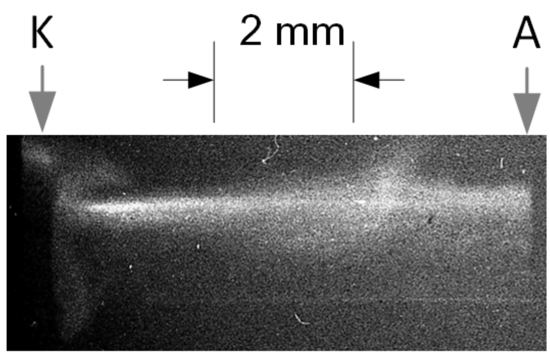

Fig.10. Time-integrated x-ray image (2.5-μm thick aluminum filter) for a shot with a screen. The load was a copper rod with a diameter of 1.4 mm.

Shots on the rod with filling of the load area with plasma demonstrate the possibility of generating high-power X-ray pulses with a duration of several nanoseconds. In the two shots presented above, the XRD received X-rays from a section of the rod 6 mm long. In this case, the pulse duration is determined mainly by the time of the current sheath movement along the specified section of the rod. In [1], the duration of an X-ray pulse received from a 2.5-mm long section of a rod was no more than 2.5 ns.

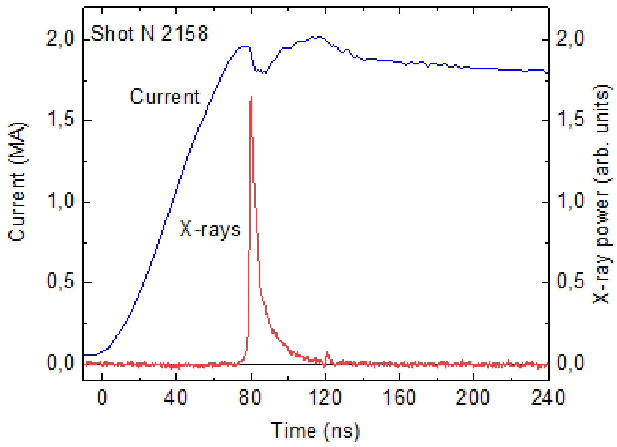

Fig.11. Current and signal of XRD with 10-μm thick polypropylene filter for a shot without a screen. The load was a copper rod with a diameter of 1.4 mm.

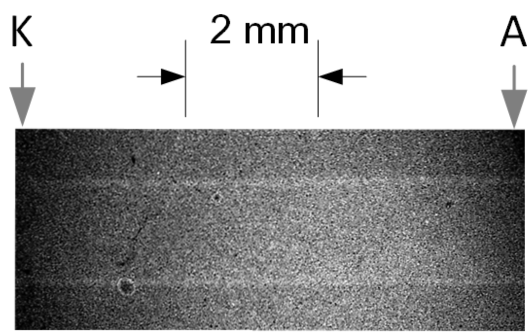

Fig.12. Time-integrated x-ray image (2.5-μm thick aluminum filter) for a shot without a screen. The load was a copper rod with a diameter of 1.4 mm.

The X-ray power and output per pulse in the spectral range 60–900 eV were measured by an XRD with a graphite cathode and a 0.3-μm thick polystyrene filter. Since such an XRD is sensitive to X-rays emitted from a relatively cold plasma expanding from the surface, the pulse width is about 20 ns. For the first 30 ns from the beginning of the pulse, the radiation yield in shots with and without a screen was 6 and 8 kJ, respectively.

3. Conclusion

In this paper, experiments were performed to refine the mechanism of nanosecond switching of the pulse generator current to a load (hollow cylindrical liner or rod) in a configuration with a conical load holder and pre-filling the load area with plasma. The test shots performed with a conical load holder, with a cylindrical load holder, with a conical holder and a screen confirm that with a conical load holder, in the process of pushing the injected plasma from the load by a magnetic field, the current switches to its surface. Estimates show that when the current sheath velocity is close to the local Alphen velocity, the current rise time (I = 2 MA) on the surface of a rod with a radius of 1 mm is 0.1–0.3 ns.

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