Foil liner implosions with a nanosecond rise time of current through the liner

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Abstract. The paper presents the results of experiments on the implosion of cylindrical liners made of aluminum foil and mylar film with a deposited layer of aluminum. To reduce the rise time of current through a liner to several nanoseconds (1–3 ns), a low-density plasma was injected into the liner area. The experiments were carried out on the MIG generator at a current level through the liner of about 2 MA. A liner with a diameter of 1.8 mm, made of aluminum-deposited 2.5-μm thick mylar film, implodes in 11 ns and has a final velocity of $2 \times 10^7$ cm·s$^{-1}$. The radius of pinched plasma is about 80–100 μm, which corresponds to a 20-fold radial convergence of the liner.

1. Introduction
Columns of high-temperature dense plasma are formed by the implosion of cylindrical liners (Z-pinch configuration) by the current of high-power pulsed generators. The energy density in the pinched plasma is determined by both the generator energy and the final radial size of the column. It is well known that the process of liner implosion is susceptible to magnetic Rayleigh-Taylor instability [1], which limits the liner radial convergence $N$ (in practice, $N = 10–20$). For fast generators using water forming lines, the characteristic current rise time (this time is close to the liner implosion time) is about 100 ns. At this time of liner acceleration to a velocity of $> 10^7$ cm·s$^{-1}$, it is necessary to choose the initial liner diameter of about and more than 1 cm. As a result, the diameter of the pinched plasma is about and more than 1 mm. Reducing the rise time of the current through the liner allows to proportionally reducing the initial liner radius. In [2, 3], in order to increase the compactness of the column plasma, a double shell configuration with an initial magnetic field between the shells was proposed. In particular, an axial magnetic field had been introduced into the region between the shells before the current switching. Implosion of the outer shell can be optionally stabilized by a return current conductor in the form of a multi-way helix [4, 5]. In this configuration, the acceleration time of the inner plasma shell by a magnetic field compressed between the shells is several nanoseconds. The experiments were carried out on the SNOP-3 generator with a peak current of 1.1 MA. The limitation of the mass of the inner shell did not allow the use of metal foil for its preparation. Both gas shells were formed using Laval nozzles. As a result of a combination of a double shell liner structure, a helical return current conductor, and an axial magnetic field, a stable 100-fold radial convergence of the argon inner shell plasma (to a diameter of about 100 μm at an initial diameter of 10 mm) was obtained.
In [6], another method was used to sharpen the front of current through the liner. The initial load configuration also consists of two gas puff shells. However, the nozzle of the outer shell is inclined outward (from the axis) and forms a radially diverging gas jet. During implosion, the outer shell has both radial and axial velocity components, which leads to its “detachment” from the electrode and fast switching of the current to the inner shell in the process of sweeping the low-density plasma in the region between the shells. Experiments were carried out with a low-inductance capacitor bank at a current rise time of 1.2 µs. The initial radius of the neon inner shell was 9 mm. A compact pinch with a diameter of about 1 mm was obtained.

In [7], to reduce the rise time of current through a foil liner to several nanoseconds (1–3 ns), an external source plasma was injected into the liner area. Fast current switching to the liner is realized in the process of sweeping the injected plasma from the liner surface by the magnetic field. In the experiment, when the current through the liner was about 2 MA, it was found that the ultrafast increase of the magnetic field on the foil surface (about or more than 3 MG·ns\(^{-1}\)) is accompanied by the surface explosion with the formation of a high-temperature dense plasma layer and a powerful soft X-ray pulse (SXR) [7, 8]. The short rise time of the current through the liner allows you to select the liner initial radius of about and less than 1 mm. Available foil with a thickness of several micrometers can be used for the preparation of such liners (at a current of about 2 MA). Reducing the initial radius by 1–2 orders of magnitude potentially allows an increase in the energy density in a pinched plasma by 2–4 orders of magnitude (assuming the same liner radial convergence).

This paper presents the results of experiments on the implosion of liners made of aluminum foil and mylar film with a deposited layer of aluminum with a ultrafast increase of current through the liner.

2. Experimental results and discussion

The experiments were carried out on the MIG [9] generator at a current level through the liner of about 2 MA. A photograph of the load region is shown in figure 1. A cylindrical liner is put on the rod inserted into the conical holder. The return current conductor consists of 6 steel posts with a diameter of 4 mm. The winding of copper wires with a diameter of 130 microns ensures electrical contact of the liner with the return conductor.

![Figure 1. Photograph of the load region.](image)

Figure 2 shows the current and signal of a soft X-ray photoemission sensor (X-ray diode behind a 10-µm thick polypropylene filter) for a shot with an 8-µm thick aluminum foil liner. Liner diameter is 2 mm, and liner length is 10 mm. The current switches to the liner at about 60–65 ns. The subsequent SXR pulse (with a peak at 63 ns) is due to the explosion of the surface of the foil and adjacent electrodes. The second radiation pulse starts at 93 ns. At this time, on-axis liner stagnation begins. The X-ray pinhole-camera image (figure 3, the camera filter transmits quanta with an energy of more than
700 eV) shows the liner in the initial position and some parts of the pinched liner plasma (ring-shaped strata). A possible mechanism for the strata formation discussed in paper [7]. The liner implosion time $\tau$ (from the peak of the first pulse to the beginning of the second pulse) is about 30 ns, that is, much longer than the rise time of the current through the liner. The velocity of the liner at its 10-fold radial convergence can be estimated as $v = 2.5r_0/\tau$ ($r_0$ is the initial liner radius) and is about $10^7$ cm/s. The energy balance shows that during the thermalization of the kinetic energy of the liner with such a velocity, the temperature of a pinched plasma is about or less than 80 eV and the radiation from the main part of the plasma is cut off by the pinhole camera filter.

![Figure 2](image2.png)

**Figure 2.** Current and soft X-ray signal for a shot with an 8-µm thick aluminum foil liner. Liner diameter is 2 mm, and liner length is 10 mm.

![Figure 3](image3.png)

**Figure 3.** Time-integrated X-ray image (mylar 2.5 µm + aluminum 0.9 µm filter). An aluminum foil liner with a thickness of 8 µm and a diameter of 2 mm.

An aluminum foil liner with a thickness of 8 µm and a diameter of 2 mm is too heavy, which makes it impossible to fully take advantage of the fast rise of current through the liner. To reduce the implosion time of the liner and, accordingly, to increase the velocity of its implosion, liners were made of a 2.5-µm thick mylar film with a 0.33 µm thick deposited aluminum layer. Figure 4 shows the current and soft X-ray signal for a shot with a liner made of aluminum-coated mylar film. Liner diameter is 1.8 mm. A copper rod with a diameter of 1.8 mm is inserted into the conical holder. The rod leaves the holder at a length of 5.6 mm. The 8.5 mm liner is mounted on the rod at a length of 3.6 mm. That is, the length of the hollow liner is about 5 mm. A rather long (FWHM is about 9 ns) first pulse with two peaks apparently reflects the movement of the current plasma sheath in succession along the surfaces of 1) a conical holder, 2) a copper rod, 3) a mylar liner and 4) radial copper wires. Emission from these surfaces can be seen in the X-ray image (figure 5a). The assumption that the second peak corresponds to the explosion of the liner surface gives the estimates $\tau \sim 11$ ns, $v = 2.5r_0/\tau \sim 2 \times 10^7$ cm/s, for the implosion time and liner velocity. The duration of the second pulse (FWHM) is
5 ns. The third pulse (at about 106 ns) follows 15 ns after the second pulse and, apparently, is caused by the repeated liner implosion. Then the plasma column is in a state close to Bennett’s equilibrium. Subsequent pulses (at about 150 ns and 167 ns) are apparently due to the development of constrictions and the formation of hot spots. From the energy balance, it follows that during liner implosion at such a velocity, the temperature of a pinched plasma can reach ~ 400 eV. The emission spectrum of such a plasma contains quanta with energy > 700 eV, which penetrates the pinhole camera filter. However, as in figure 3, in the image (figure 5b) ring-shaped strata are visible, covering the invisible core. Apparently, this core consists of a plasma of the mylar film, which has a low emissivity. The core diameter is 80–100 μm, which corresponds to a 20-fold radial convergence of the liner. The image also shows several hot spots that are formed during and after the first plasma stagnation. An intensely emitting spot is present at the junction of the pinched plasma with the tip of the copper rod. Note that the liner of the mylar film is less stable than the liner of aluminum foil with a thickness of 8 μm, since it has a higher aspect ratio (the ratio of the liner radius to the liner thickness).

Figure 4. Current and soft X-ray signal for a shot with a liner made of aluminum-coated mylar film. Liner diameter is 1.8 mm. The length of the hollow liner is about 5 mm.

Figure 5. Time-integrated X-ray image (mylar 2.5 μm + aluminum 0.9 μm filter). A liner made of aluminum-coated 2.5-μm thick mylar film: a) full length of the load from the conical holder to the radial wires, b) hollow liner with a length of about 5 mm.

3. Conclusions
Experiments have shown that sharpening of the front of current through the liner to several nanoseconds can reduce the initial liner radius to 1 mm or less and, as a result, increase the density of matter and energy in a pinched plasma by two or more orders. In particular, the experiment recorded a 20-fold radial convergence of the liner with an initial diameter of 1.8 mm. Reducing the initial liner...
radius to 1 mm or less allows, at a current of about 2 MA and more, to use available several-
micrometers-thick foils and films for the manufacture of liners.

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