Ultrafast wire loading with multi-megaampere current

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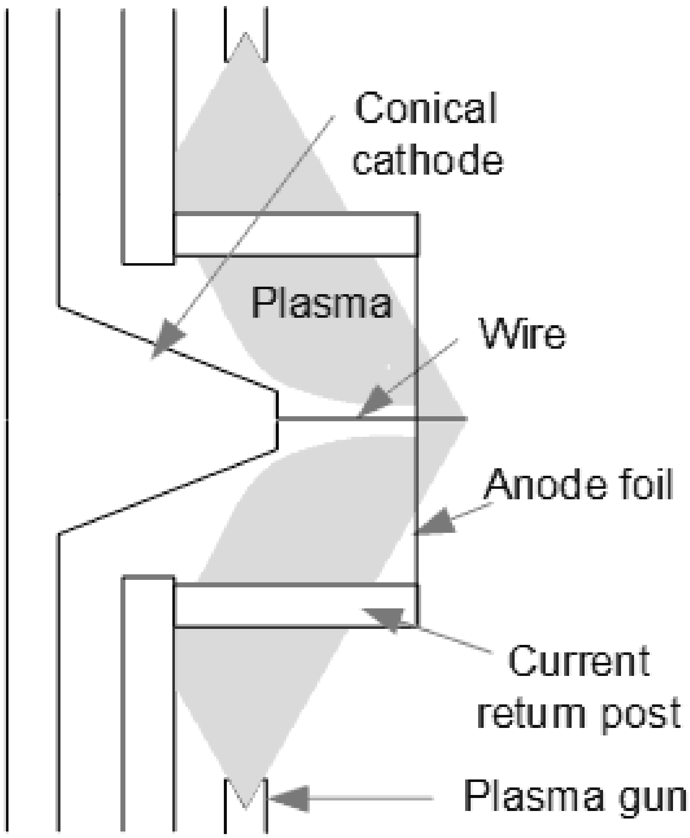
Explosion of fine single wires

In experiments of the early seventies of the last century, high-temperature dense plasma was created by the explosion of fine single wires driven by a terawatt-power pulse generator. However, when the generator pulse duration is several tens of nanoseconds, the high inductive impedance of the wire, the rapid expansion of the plasma from the wire surface (to a diameter of about 1 mm) and the destruction of the plasma column by sausage instability already at the front of the rising current create certain problems for the efficient transfer of the generator energy to the wire plasma.

Our previous studies have shown that the nanosecond switching of a megaampere current to a conductor (cylindrical rod) is accompanied by the explosion of a thin current skin layer with the formation of a layer of hot dense plasma. During the current rise, the plasma layer does not have time to expand significantly and its active impedance is comparable to or exceeds the generator impedance (0.65 Ω).

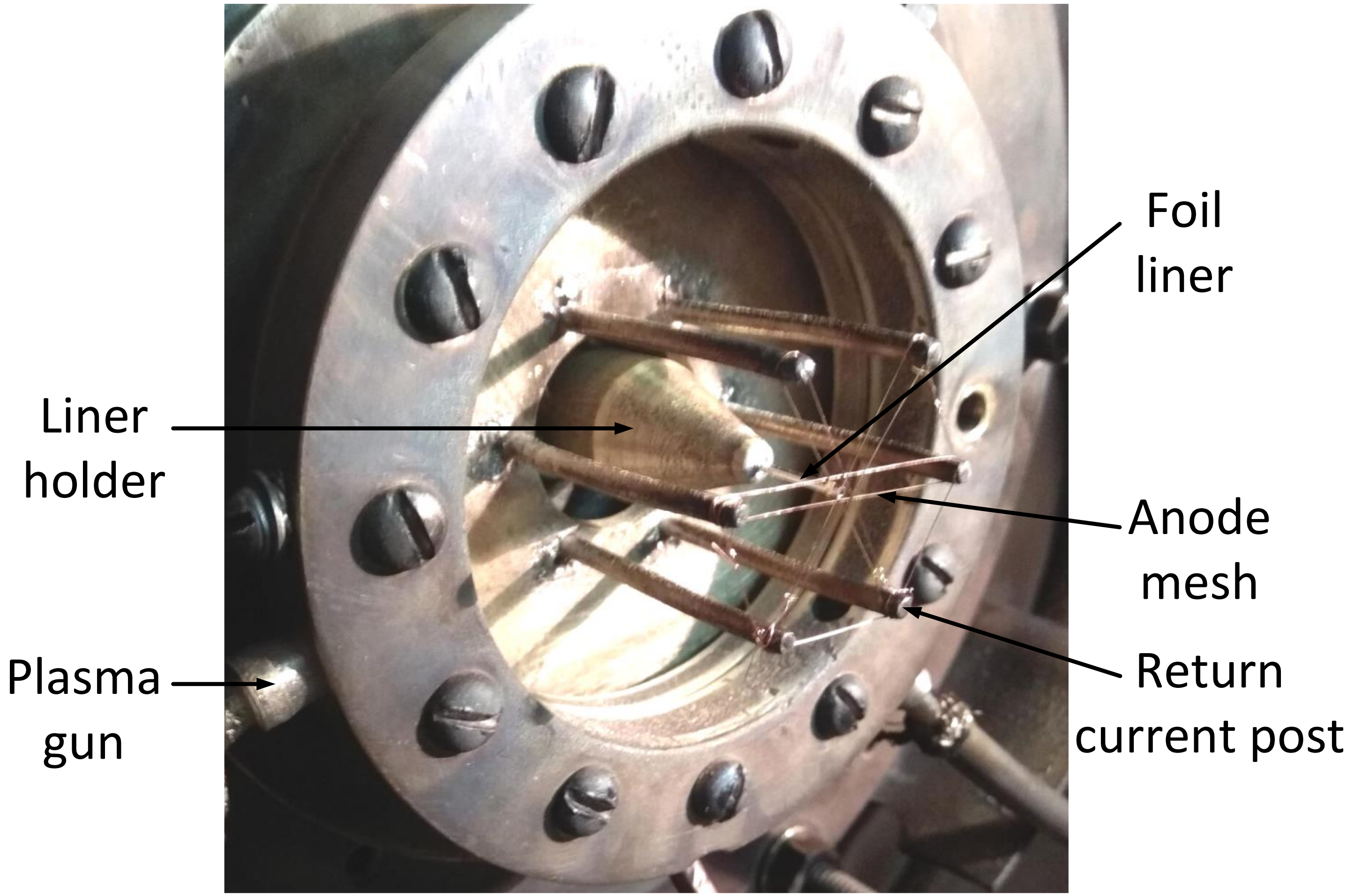
In this work, experiments were performed on the explosion of single wires with a current of about 2 MA, both with sharpening (current rise time 1-3 ns) and without sharpening (current rise time 80 ns) of the front of the current through the wire.

Experimental design



Plasma with density 10^{16}-10^{17} cm^{-3} is preliminarily injected in the area of the wire load using a set of radial plasma guns. The $\boldsymbol{J}\times\boldsymbol{B}$ force sweeps up the injected plasma along the surface of the electrodes and the current switches to the wire in a few nanoseconds.

Photograph of the load region



High current generator MIG

Components

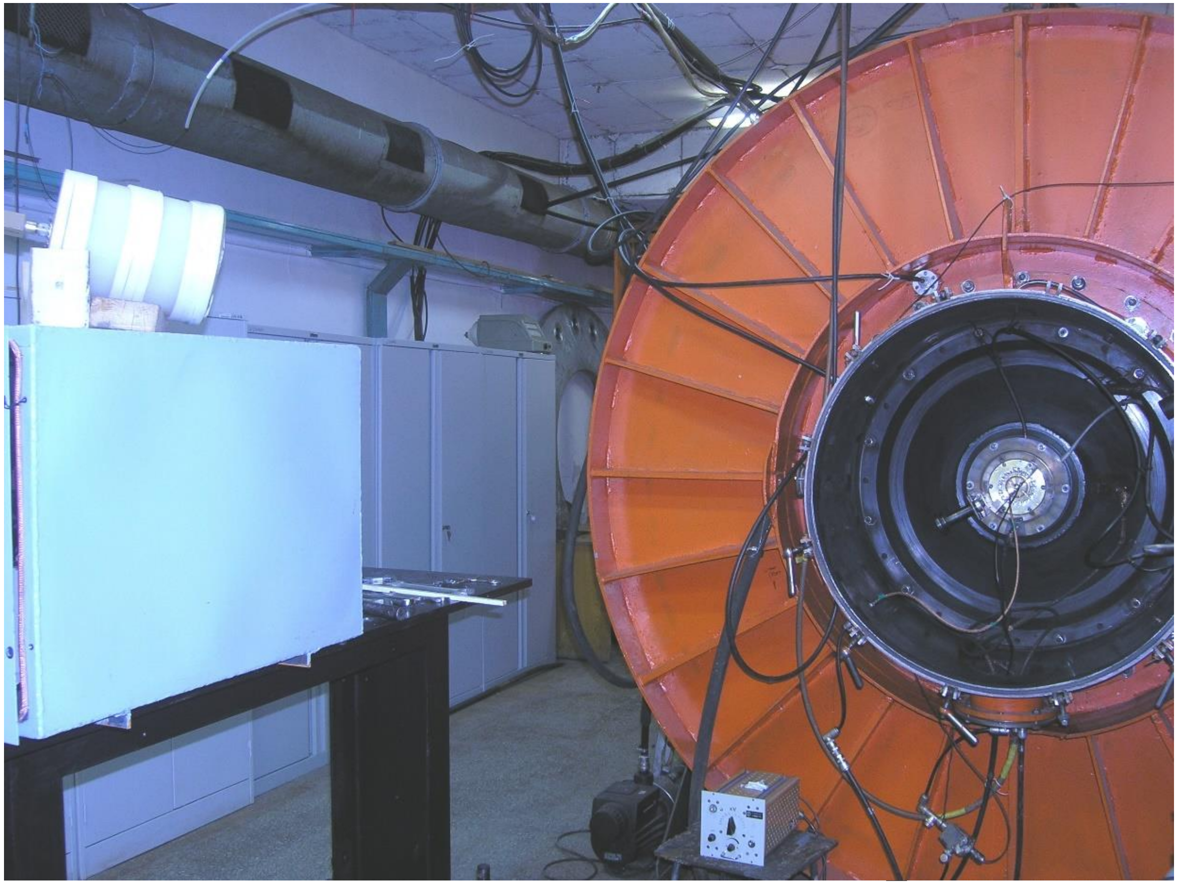
- Linear transformer driver
- Pulse forming line 1 (1.3 Ω)
- Pulse forming line 2 (0.65 Ω)
- Transfer line (0.65 Ω)
- Diode stack, MITL and load

Parameters

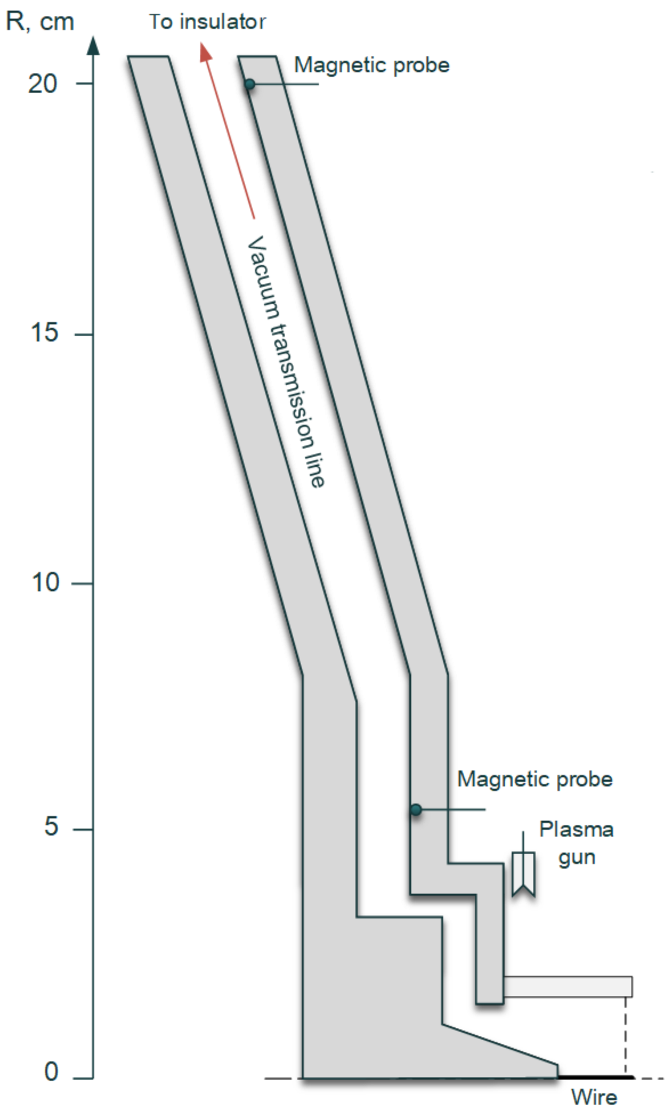
• Stored energy	300 kJ
• Peak current	2 MA
• Current risetime	80 ns
• Impedance	0.65 Ω

Diagnostics

- Rogowski coils
- Magnetic probes
- Voltage devider
- X-ray diodes
- Pinhole cameras

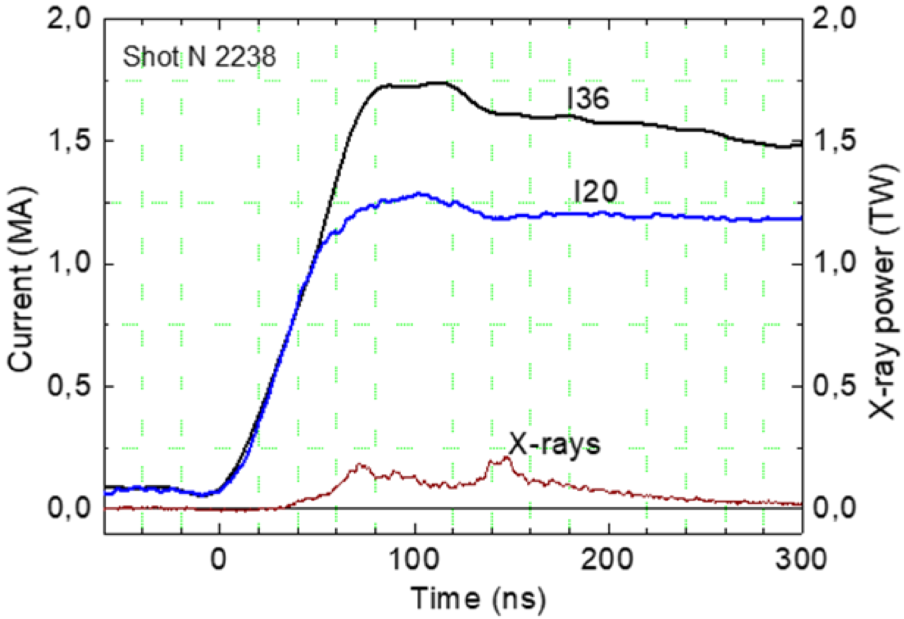


Schematic of the MITL and the load region

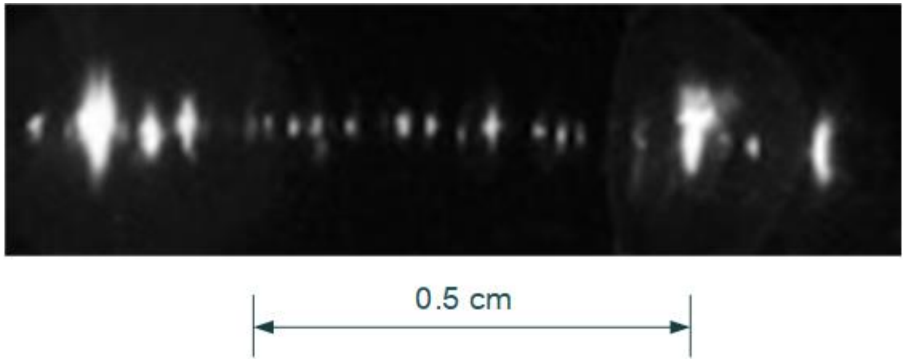


The inductance of the water-vacuum separation insulator stack and the MITL is 16 nH. The inductance of the plasma injection region for a 1-cm-long wire is about 17 nH. The current is measured by two magnetic probes located in the conical MITL (at radii of 5.3 cm and 20 cm) and a Rogowski coil located near the vacuum boundary of the insulator stack (at a radius of 36 cm). At the waterside surface of the insulator stack is a capacitive voltage divider. The soft X-ray power in the range of quantum energies of 60 - 900 eV is measured by a photoemission X-ray diode (XRD) with a carbon cathode and a filter made of a 0.33-µm- thick polystyrene film.

100-μm-diameter, 10-mm-length tungsten wire without plasma injection



Currents measured by monitors at radii of 36 cm (I36) and 20 cm (I20), as well as the power of X-ray radiation in the range of quantum energies of 60 - 900 eV.

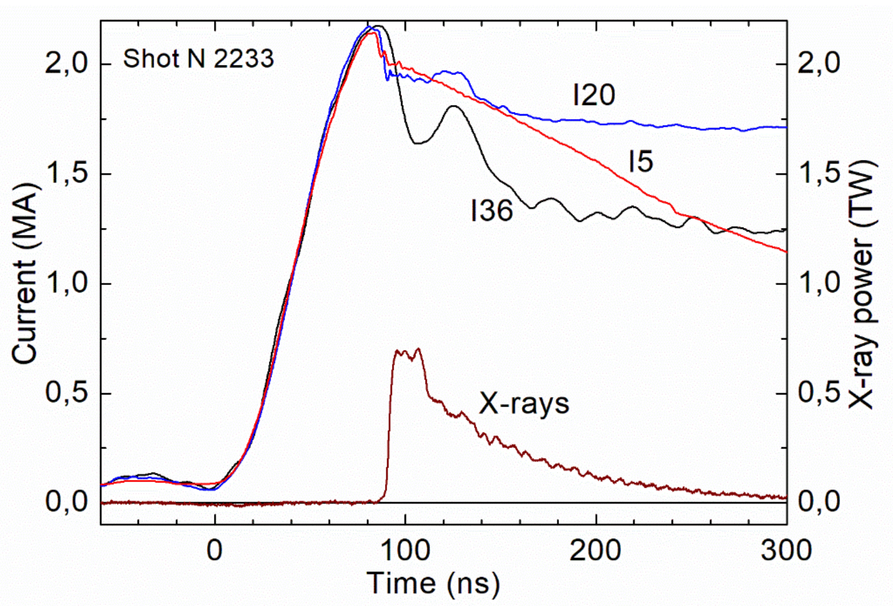


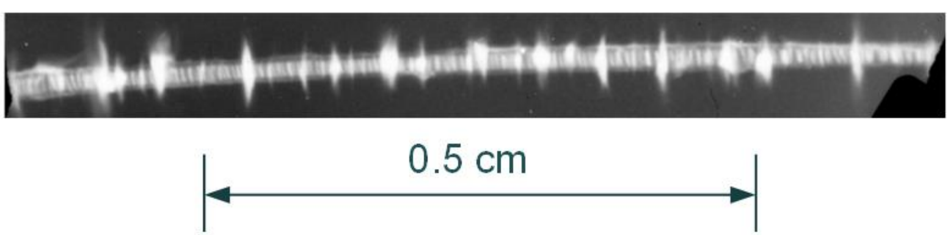
Up to 50 ns, the currents measured by the coil (I36) and probe (I20) coincide. By this time, the voltage near the insulator stack reaches a maximum value of about 0.9 MV, and the current is about 1.1 MA. The critical current estimate above which the electrons emitted from the cathode do not reach the anode for the disk radius of 33 cm and the electrode gap of 1 cm gives about 1 MA. That is, the conditions for“magnetization” of electrons in the region between the coil and the probe (I20) are close to critical and electron loss to the anode disk is possible. The soft X-rays starts at about 35 ns and, after the current rises to the maximum (at 70 ns), the radiation power is maintained at about 0.2 TW until the flashover of the insulator stack surface (at 140 ns). The long decaying X-ray tail is caused by the dissipation (in the pinched plasma) of magnetic energy captured in the region of the load.

The total soft X-ray yield per pulse ($h\nu$ <900 eV) was 25 $\pm$ 3 kJ.

On the X-ray image (pinhole camera, 1.8-μm thick aluminum filter), only a sequence of bright formations (the so-called "hot spots") is visible.

100-μm-diameter, 11-mm-length tungsten wire with plasma injection





The current measured by the three monitors are in good agreement until the current switches to the wire at about 85 ns. Since the generator was loaded with an inductance of about 16 nH (before the significant movement of the injected plasma began), the current rises to 2.15 MA (about 90 ns). By 45 ns, the voltage near the insulator stack reaches a maximum value of about 0.7 MV, and the current is about 1.1 MA. This ratio of current and voltage provides "magnetization" of electrons in the MITL and efficient transport of current to the load. In the process of sweeping up the plasma and switching the current to the wire, the current decreases to 1.9 MA. At this time, part of the magnetic energy is spent on plasma acceleration, and part dissipates in the wire surface layer, providing an increase in the soft X-ray power to 0.7 TW in 3 ns. The total radiation yield per pulse ($h\nu$ <900 eV) was 41 $\pm$ 4 kJ. The energy transferred to 140 ns (the current capture time) from the water dielectric line to the insulator stack, MITL and load region is about 60 kJ. A core with a diameter of 120-130 μm is visible on the x-ray image. The core is surrounded by an emitting plasma shell with a diameter of 220 -230 μm. The shell is formed because of the explosion of the current skin layer and the expansion of the plasma from the surface of the wire. The strata are apparently formed during the evolution (development of m = 0 instability) of the surface plasma.

Generation of megagauss magnetic fields

The magnetic field at the surface of the cylindrical rod is $B_\theta = \mu_0 I/(2\pi r_0)$. Assuming that the rise time of the current τ should be less than the time of disruption of the cylindrical structure of the rod, that is, less than Alfven transit time $\tau < r_0/V_A = r_0(\mu_0\rho)^{0.5}/B_\theta = 2\pi r_0^2 \rho^{0.5}/(I\ \mu_0^{0.5})$, we obtain that the permissible radius of the rod is proportional to $\tau^{0.5}$. Here ρ is the conductor mass density. Thus, reducing the current rise time by two orders of magnitude makes it possible to increase the maximum attainable magnetic field by one order of magnitude. In particular, at a current of 2 MA and a rise time of 1 ns, the radius of the copper conductor should be at least 60 μm, which corresponds to the maximum attainable magnetic field of about 67 MG.

Note that due to the fact that with an increase in the field on the surface of the conductor, the Alphen velocity also increases, the scaling of the magnetic field is $I^{1/2}$ ($B_\theta \propto I^{1/2}\tau^{-1/2}\rho^{1/4}$), and not proportional to I, as for the compression of the magnetic flux by a liner.

However, the “direct” approach is advantageous for limited (but rather high, up to ~ 15 MA) level of generator currents and, accordingly, the level of magnetic fields (150–180 MG).

Conclusion

The report presents experiments on the MIG generator with sharpening of the font of the current through the wire by initially filling the load region with plasma.

The experiments showed that, due to the preliminary injection of plasma into the region of the wire and the sharpening of the front of current through the wire, the generator energy can be effectively converted to the magnetic energy of the insulator and MITL area and then to the internal energy of the exploding wire plasma. The relatively low ratio of the voltage across the MITL disks to the current ensures the transport of current to the load without electron losses, and the high active impedance of the plasma layer on the wire surface ensures the Joule dissipation of the generator energy with its subsequent conversion to soft X-ray energy.

Possible applications

The ultrafast wire loading with multi-mega-ampere current makes it possible to

1. efficiently generate pulses of soft x-ray radiation of metal plasma,
2. generate 100 MGs magnetic fields using currently available high-current generators in a relatively simple load configuration.

1. S. A. Sorokin Explosion of the thick metallic surface during ultrafast rise of a multimegagauss magnetic field// Physics of Plasmas V.25, 082704 (2018).
2. S.A. Sorokin Fast implosion of foil liners//Physics of Plasmas V.26, 082706 (2019).

Acknowledgments

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