# Magnetoelectric Confinement and Stabilization of Z Pinch in a Soft–x-Ray $Ar^{+8}$ Laser

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Magnetoelectric confinement and stabilization of the plasma column in a soft-x-ray $Ar^{+8}$ laser, which is excited by a capillary Z pinch, via the combined magnetic and electric fields of the gliding surface discharge is experimentally demonstrated. Unlike soft-x-ray lasers excited by the conventional capillary Z pinches, the magnetoelectric confinement and stabilization of plasma do provide the laser operation without using any external preionization circuit.

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*Introduction.*—The importance of transverse electric fields in reduction of instabilities of a hot and dense plasma and improvement of its magnetic confinement has been recognized in early theoretical studies devoted to controlled thermonuclear fusion [1–3]. Since then, many theoretical and experimental studies of fusion plasma [4–10] have justified that applying an external transverse (radial) electric field allows us to control the magnetic confinement and stability of the plasma column. In x-ray lasers excited by Z pinches, only one physical method provides stability of a hot and dense laser plasma, namely, a preionization of the gas column by an electrical current of an external preionization circuit [11–24]. It is very important to find any alternative method providing a solution of the problem. Magnetoelectric confinement and stabilization of a hot and dense laser plasma by the combined magnetic and electric fields have been suggested for x-ray lasers in theoretical study [25]. An experimental realization of this idea in x-ray lasers was a challenge up to now. The present study experimentally demonstrates operation of a soft-x-ray $Ar^{+8}$ laser excited by a capillary Z pinch with the magnetoelectric confinement and stabilization of the hot and dense plasma column via the combined magnetic and electric fields generated in a so-called creeping (gliding) discharge [26–30] on the capillary internal surface. The confinement and stabilization technique modifies the conventional capillary pinch. It provides a laser that operates without a preionization circuit, simplifying how such lasers operate. The method could find implementation in many other research fields, where the plasma stabilization plays a key role.

*Physical processes in laser plasma.*—Let us briefly describe the physical processes and discharge parameters of the conventional capillary Z pinch which are most critical for operation of the $Ar^{+8}$ laser [11–24]. The soft-x-ray laser on the 46.9 nm line of the $2p^53p(J=0)$-$2p^53s(J=1)$ transition of neonlike argon, which is currently considered as one of the most practical soft-x-ray lasers, is produced in hot ($T_e \sim 100$ eV) and dense ($N_e \sim 10^{18}$ cm$^{-3}$) plasma of a capillary Z pinch. The hot and highly ionized plasma column with a diameter of $\sim 500$ $\mu$m and length up to $\sim 0.5$ m is produced by a high-current ($I > 10$ kA) electric pulse with short ($\sim 100$ ns) half-period flowing axially through an $Al_2O_3$-ceramic capillary channel with diameter of $\sim 3$ mm initially filled with low pressure ($\sim 0.5$ mbar) argon gas. The electron temperature ($T_e$) and density ($N_e$) are increased through fast radial compression (Z pinch) of the plasma column by means of the magnetic field created by the current itself. For preionization of the Ar gas, a current pulse with amplitude of 15–30 A and duration 3–6 $\mu$s is switched before the main high-current pulse. This does assure the uniform initial conditions providing uniform confinement and compression of the plasma column. Deviations in the discharge conditions, for instance, switching off the preionization circuit or small modification of the preionization current parameters, result in plasma instabilities that extinguish lasing entirely [12,17,20,21]. It is generally accepted that the intensive and homogeny preionization of argon by the preionization current pulse is the most critical physical process providing the uniform initial (preionization) conditions for the stable and uniform Z pinch, which warrants x-ray lasing [11–23]. A recent experiment [24], however, has shown that x-ray lasing in $Ar^{+8}$ plasma of the capillary Z pinch occurs when the direction of the preionization current pulse is the opposite of the main current pulse direction. Lasing is not observed when the direction of the currents is the same. According to Ref. [24], the role of the preionization current pulse is not just the formation of partially ionized gas, but it is to form a stabilizing magnetic field in the case of oppositely directed current pulses.

The mechanism of magnetoelectric confinement and stabilization of a capillary Z pinch in the $Ar^{+8}$ laser by using the combined magnetic and electric fields of the gliding discharge on the capillary channel surface rather than switching a preionization current from an external preionization circuit has been described in Ref. [25]. The gliding discharge was incorporated into the Z-pinch model using the basic concepts [29,30] of the gliding discharge

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theory. The gliding discharge is formed by the displacement current $I_d \sim d(C_d U)/dt$, which is determined by the applied voltage $U_a$ and the distributed capacitance $C_d$ between plasma and triggering electrode covering the opposite site of the dielectric (Fig. 1). At the first stage of the pinch formation, the displacement current $I_d$ charging the capacitance $C_d$ of the dielectric is locally self-terminated by the value of $C_d$. The electric field $\mathbf{E} = E_r\mathbf{e}_r + E_z\mathbf{e}_z$ is determined mainly by the radial component $E_r$. The field $E_r$, whose maximum value is limited by the breakdown of the dielectric, is a few orders of magnitude ($\sim L/h$) higher than that of a conventional longitudinal discharge. Here, $L$ and $h$ are the length and thickness of the capillary wall. The electron $N_e$ and ion $N_i$ densities are small, while the density of the displacement current is relatively high. The high ionization rate of the gas by the field $E_r$ under the self-terminating charging of local capacitance results in an homogeneous discharge in the first stage. The growth of local current density, which may result in growth of the plasma instability, is self-terminated by the value of local charging capacitance charged by the field $E_r$. In other words, the relatively small local capacitance limits the maximum displacement current. The second stage of the pinch formation is a high-current breakdown ($I > 1$ kA) and heating of the preionized gas near the surface of the dielectric. During this period the whole gas volume is ionized uniformly by the radiation from the cylindrical plasma sheet. Note that a $Z$-pinch plasma x-ray source using the surface gliding discharge in a gas for the gas preionization was suggested also in Ref. [31]. The particle collisions thermalize the gas to the kinetic temperature of few tens eV. The charge density increases almost to the threshold value providing the plasma quasineutrality. At such conditions the radial field $E_r$ cannot accelerate electrons as in the first stage.

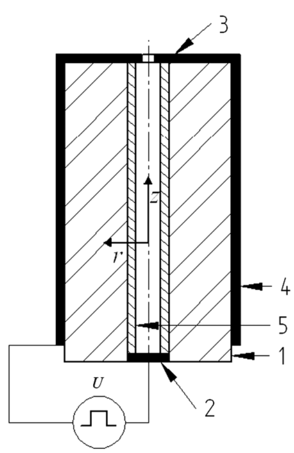


FIG. 1. Scheme of a capillary $Z$ pinch stabilized by the radial electric field of a creeping (gliding) surface discharge: 1, capillary dielectric wall; 2, anode; 3, cathode; 4, triggering electrode; and 5, an annular plasma shell of the gliding surface discharge polarized by the radial electric field.

Nevertheless, the role of this field remains very important. The field $E_r$ displaces negative and positive charges in opposite directions polarizing the plasma sheet. That leads to a decrease of the compression action of the magnetic force $\sim \mathbf{j}_z \times \mathbf{B}_\varphi$ on the value $\sim N_e^{\mathrm{dis}} e(dE_r/dr)\delta r$, where $N_e^{\mathrm{dis}}$ denotes the number of the displaced electrons, $\delta r$ is the displacement, and $e$ is the electron charge. A dramatic decrease of the compression causes a natural stabilizing effect on the onset of plasma instabilities. In this case, the electrons and ions are confined by the radial electrostatic force due to the charge separation. Under a strong radial electric field $E_r$, whose maximum value is limited by the breakdown of the capillary wall, the field $E_r$ of the gliding surface discharge could provide instability-free compression and heating of the plasma in the subsequent (ordinary) stage of the capillary $Z$ pinch. Note that the above-described physical mechanisms have been incorporated into the MHD model by using the semiphenomenological method, because the mechanisms cannot be described in the frame of MHD approximation, which requires plasma quasineutrality. Nevertheless, a steady-state equilibrium of the two-species, collisionless plasmas have also been found by varying the total energy subject to Maxwell's equations, momentum moment equations, and adiabatic equations of state, without imposing a quasineutrality condition [32]. The study [32] has showed that electrons can be confined by magnetic forces, and ions by internal, electrostatic forces due to charge separation. References [25,32] indicate that the role of the radial electric field of the surface gliding discharge in the operation of the $Ar^{+8}$ laser could be attributed simultaneously to formation of the uniform initial conditions by the surface discharge preionization and the magnetoelectric stabilization of the $Z$ pinch.

*Experiments and discussion.*—In our experiments we have used the laser device described in Ref. [23]. The laser active medium is generated by discharging a 6 nF water dielectric capacitor, which is initially charged to high voltage by a six-stage Marx generator ($U_M \sim 200$ kV), through a low inductance circuit that contains a water spark gap and a capillary channel. The energy stored by the capacitor is $\sim$0.1 kJ. The lasing is obtained in the capillary of the internal diameter 3.1 mm and length of 0.45 m filled with continuously flowing argon gas at the pressure 0.2–0.8 mbar by using a low-inductance coaxial discharge configuration. The total capillary wall was composed from the materials $Al_2O_3$ (2 mm), epoxy (8 mm), and plastic zx100 (15 mm). That corresponds to the radial distance $h \sim 25$ mm between the surface of the discharge channel and the triggering electrode (Fig. 1). The excitation current pulse monitored by a Rogowskys coil has the peak value of 17–22 kA and a half-cycle duration of $\sim$175 ns. While using the external preionization circuit, the main discharge pulse is preceded by a 3–4 $\mu$s long current pulse with amplitude

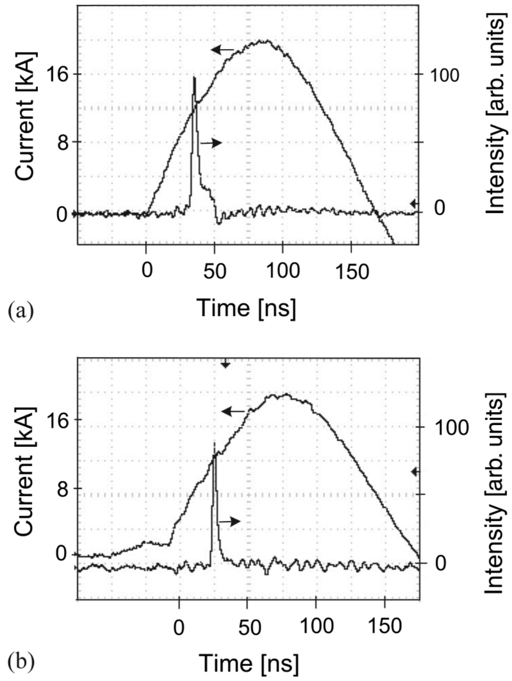


FIG. 2. The typical laser operation with the preionization circuit (a) and without (b).

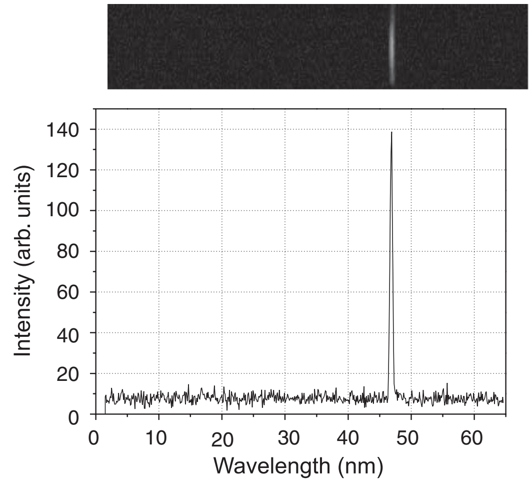


FIG. 3. The typical one-shot time integrated spectra corresponding to the laser pulses of Fig. 2.

of ~20 A, which preionizes the gas, ensuring the uniform initial conditions. The one-shot spectrum was recorded using a JobinYvon spectrometer coupled to a microchannel plate charge-coupled device detection system or directly to the phosphor film. The time characteristics of the laser pulse were measured by an x-ray diode (XRD). The laser output energy was measured by a commercially available XRD (SXUV 100Al). The far-field intensity distributions of the laser pulses were recorded by an imaging detector consisting of a phosphor film coupled to a CCD camera. For the signal analysis a 100 MHz digital oscilloscope (TDS1012) was used.

Figure 2(a) demonstrates the lasing in the laser configuration using the external preionization circuit. The model described above matches the laser operation without using the external preionization circuit, as shown in Fig. 2(b). In such a case, the magnetoelectric confinement and stabilization of the capillary $Z$ pinch is performed by the gliding surface discharge driven by the main excitation circuit on the internal surface of the capillary. Although the figures are almost indistinguishable, we note some modification of the current and delay of the laser pulse in Fig. 3(b) in comparison to Fig. 3(a), which should be attributed to the modification of the conventional capillary pinch by the action of the radial electric field. The deconvoluted duration of the laser pulse recorded by the 100 MHz oscilloscope is ~1.8 ns. As an example, Fig. 3 shows the typical one-shot spectra corresponding to the laser pulses of Fig. 2. Note that the 46.9 nm laser line completely dominates the spectra. Figure 4 shows the photographs of the laser beams of energy ~10 $\mu$J recorded at the distance 1.8 m from the capillary by using different experimental conditions. Beams of the laser that uses the external preionization are shown in Figs. 4(a)–4(c). For comparison, the laser operation without using the external preionization is demonstrated in Figs. 4(d)–4(f). The angle divergence of the beams shown in Figs. 4(c) and 4(f) is ~1 mrad. Analysis of Figs. 2–4 shows that the output characteristics of the laser using the magnetoelectric confinement for stabilization of plasma by the gliding discharge are very similar to the laser excited by the conventional capillary $Z$ pinch with an external preionization circuit. The small differences are related to shot-to-shot variations. The magnetoelectric technique modifies the conventional capillary pinch. It provides a laser that operates without a preionization circuit, simplifying how such lasers operate.

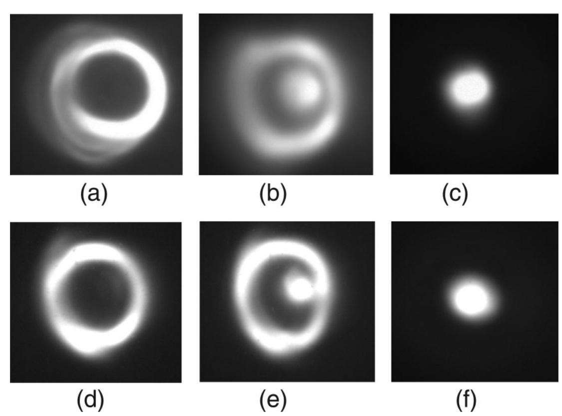


FIG. 4. Photographs of the laser beams for the voltage $U_M \sim 200$ kV, current $I \sim 20$ kA, and the argon initial pressures: (a), (d) −0.35 mbar, (b), (e) −0.3 mbar, and (c), (f) −0.25 mbar. The beams of the laser that uses the external preionization circuit (a)–(c). The laser beams without using the external preionization circuit (d)–(f).

In conclusion, the magnetic confinement of plasma and reduction of plasma instabilities has been demonstrated in a capillary $Z$ pinch of length up to ~0.5 m and diameter down to ~500 $\mu$m. The operation of a soft-x-ray $Ar^{+8}$ laser was achieved by magnetoelectric confinement and stabilization of the plasma column by the combined magnetic and electric fields of a gliding surface discharge without using a preionization circuit. That is a fundamental improvement in such laser systems. The method could be important not only for plasma physics related to controlled thermonuclear fusion and x-ray lasers. The results could inspirit researchers for investigation and implementation of the method in many other research fields, where the stabilization of a hot and dense plasma plays a key role, for instance, in the extreme UV and soft-x-ray sources for photolithography, high-harmonics generators, and particle accelerators. In addition to the gliding surface discharge, one may use more sophisticated discharge configurations incorporating the radial electric field.

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