Relaxation oscillations of a high-β plasma produced by an rf method in the Uragan-3 torsatron

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Quasisteady discharges have been produced in the Uragan-3 torsatron. A plasma pressure, at which relaxation oscillations occur in the parameters because of a disruption of the plasma equilibrium, has been achieved.

1. The outlook for the development of a steady-state fusion reactor from the stellarator concept depends to a large extent on the highest attainable value of the parameter $\beta = [8\pi n(T_e + T_i)/B^2]$. The theory predicts that the value of this parameter will be limited in stellarators by effects related to the equilibrium and stability of a high-β plasma.[1] It is thus important to carry out experiments on the behavior of a high-β plasma in a stellarator.

In the present letter we report the observation of relaxation oscillations in the parameters of a plasma produced by an rf method[2] in the Uragan-3 torsatron. These oscillations are observed at values of the parameter β near the limiting value from the standpoint of a plasma equilibrium.

2. The magnetic configuration of the Uragan-3 torsatron, with a diverter, is produced by an $l = 3$, $m = 9$ helical winding around a toroidal magnetic surface with a major radius $R = 100$ cm and a minor radius $a_b = 27$ cm and also by two circular coils ($R = 150$ cm $\Delta Z_{\text{coil}} = \pm 50$ cm), which cancel the vertical component of the field of the helical winding.[3] The entire magnet system is housed in a vacuum chamber with the volume of 70 m^3.

The parameters of the magnetic configuration can be varied by varying the cancelling vertical field.[3] In most of the experiments described here, the rotational transform in the region with closed surfaces, with an average radius $\bar{a} = 8.5$ cm, ranged from $\iota(0) = 0.18$ to $\iota(a) = 0.4$.

The plasma is produced by the absorption of rf power at frequencies corresponding to the excitation of an Alfvén wave ($\omega \simeq 0.8 \cdot \omega_{H_i}$). We use unshielded helical loop antennas made of stainless steel or the same antennas but coated with titanium nitride, positioned at a toroidal surface with a radius $r_a = 10$–12 cm and excited at the frequency 5.3 MHz by a two-step pulse. The length of the first step ($\Delta t = 2$–3 ms) is chosen long enough to cause the breakdown of the hydrogen or deuterium which is continuously being admitted into the vacuum chamber ($p = 1.3 \times 10^{-5}$ torr) and to produce a foreplasma with an electron density $\bar{n}_e = 5 \times 10^{11}$ cm^{-3}. The length of the second step, in which the voltage on the rf antenna is doubled, can reach 50 ms. The

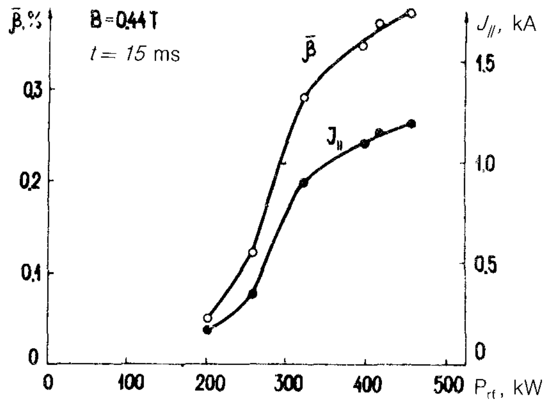

FIG. 1. The quantity $\bar{\beta}$, measured by a saddle-shaped magnetic winding, and the longitudinal plasma current $J_{\|}$ versus the rf power at the antenna.

experiments are preceded by a prolonged cleaning of the surfaces of the antenna and of the magnet system by rf discharges at a low magnetic induction.^{2}

3. In the experiments with the uncoated antenna ($r_a = 10$ cm), in work with deuterium ($B_0 = 0.9$ T), we observe a progressive degradation of first the electron

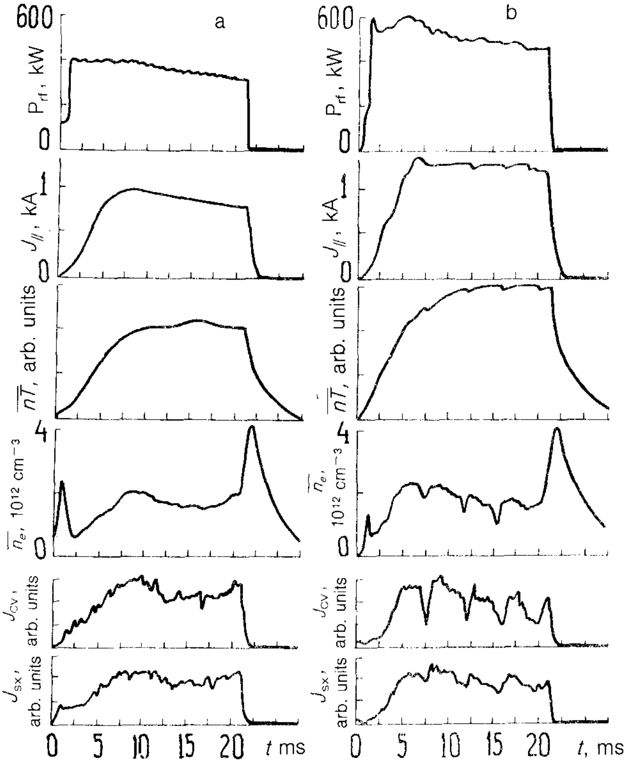

FIG. 2. Time evolution of the rf power at the antenna, P_{rf}, of the longitudinal plasma current $J_{\|}$, of the plasma energy and $\overline{nT}$, of the average plasma density $\bar{n}_e$, of the emission intensity (J_{CV}) in the CV line at $\lambda = 2271$ Å, and of the soft x-ray emission (J_{sx}) for various values of the rf power launched into the plasma.

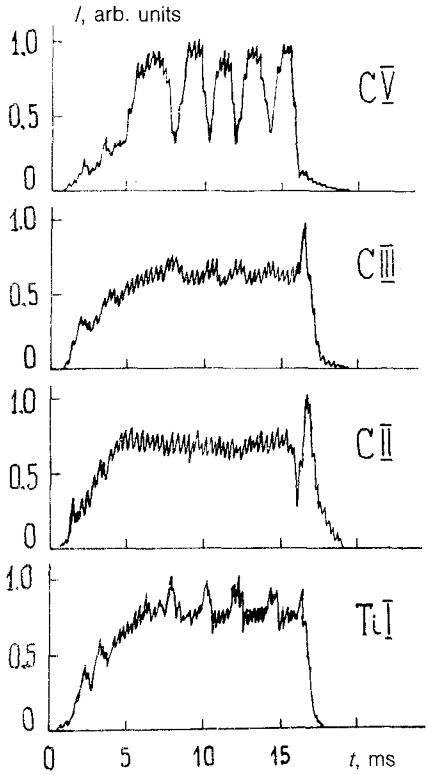

FIG. 3. Time evolution of the intensity of the emission in impurity lines.

temperature and then the ion temperature after a rapid heating of the plasma, in 2 ms [$n_e \leqslant 1 \times 10^{13}$ cm^{-3}, $T_i(0) \leqslant 300$ eV, $T_e(0) \leqslant 230$ eV].

Discharges up to 50 ms long could be achieved, without degradation of the plasma parameters, by coating the antenna with titanium nitride ($r_a = 12$ cm). Measurements of the flux of metallic impurities from the antenna, carried out in a hydrogen plasma at an absorbed power of 200 kW, showed that the impurity (Ti) flux from the coated antenna is 60–70 times lower than that in the experiments with the stainless-steel antenna.

When the input power is raised in quasisteady discharges, we observe an increase in the plasma energy, measured by a saddle-shaped magnetic winding,[2] and also in the longitudinal current (Fig. 1). A distinctive feature of the discharges is the presence of significant fluctuations of the signals from the diagnostic pickups over the frequency range 1–30 kHz (Fig. 2a).

As the rf power is raised further, at $\beta = [8\pi n(T_e + T_i)/B^2] \simeq 0.3\%$, the discharge goes into a new regime (Fig. 2b), characterized by sawtooth-shaped relaxation oscillations in the measured plasma parameters. For most of the measured parameters, the oscillations are of the nature of surges; the effect is seen most sharply in the emission in the CV and OV lines, which are localized at the center of the plasma column. Evidence for the propagation of a perturbation wave from the central zone to the periphery comes from spikes in the emission intensity in TiI lines near the surface of the antenna (Fig. 3) and the line H_β in the diverter streams.

The pattern of relaxation oscillations changes upon a variation of the parameters of the magnetic configuration, achieved by changing the strength of the vertical magnetic field $B_\perp$. For example, the discharge becomes stabler upon the decrease in $B_\perp$, which is accompanied by an inward displacement of the axis of the vacuum magnetic configuration and by an increase in the shear. In this manner, at $B_\perp/B = 0.36\%$ we achieved stable discharges with values $\bar{\beta} \simeq 0.6\%$, only twice as low as the value $\beta_c = \iota\!\!\!-^2(a)a/R$—at which effects of the deviation from plasma equilibrium should be very apparent.

Relaxational oscillations have been observed in the Heliotron-E torsatron during plasma heating by neutral injection. In that case, the oscillations resulted from an MHD instability of the plasma driven by a pressure gradient. In the Uragan-3, in addition to the pressure gradient, the quasisteady longitudinal current may serve as a driving force for the tearing-mode instability. Under the conditions of the experiments described here, the magnetic configuration of the Uragan-3 contains closely spaced magnetic surfaces with $\iota\!\!\!- = 1/5$, 1/4, 1/3, and 1/2. During the onset of the MHD instability, islands may form near these surfaces, followed by a destruction of the magnetic configuration and a sharp increase in the loss of particles and heat.

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