1. INTRODUCTION

In the $\ell = 3$ Uragan-3M torsatron, hydrogen plasma is produced and heated by RF fields in the Alfvén range of frequencies ($\omega \approx \omega_{ci}$). To this end, a frame antenna with a broad spectrum of generated parallel wavenumbers is used. The RF discharge evolution is studied experimentally at different values of the RF power fed to the antenna (the anode voltage of the oscillator and the antenna current) and the initial pressure of the fueling gas. It is shown that, depending on the antenna current and hydrogen pressure, the discharge can operate in two regimes differing in the plasma density, temperature, and particle loss. The change in the discharge regime with increasing anode voltage is step-like in character. The particular values of the anode voltage and pressure at which the change occurs are affected by RF preionization or breakdown stabilization by a microwave discharge. The obtained results will be used in future experiments to choose the optimal regimes of the frame-antenna-produced RF discharge as a target for the production and heating of a denser plasma by another, shorter wavelength three-half-turn antenna.

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**Abstract**—In the $\ell = 3$ Uragan-3M torsatron, hydrogen plasma is produced and heated by RF fields in the Alfvén range of frequencies ($\omega \approx \omega_{ci}$) [1]. In the experiments described below, a frame-type antenna with a broad spectrum of parallel (with respect to the magnetic field) wavenumbers is used to introduce RF power into the plasma. Enclosing the entire magnetic system into a large vacuum chamber and plasma production and heating techniques with a continuous supply of the fueling gas result in some specific features of discharge development and changes in the plasma parameters during the RF pulse and after its termination, depending on the RF power, hydrogen pressure, and the presence of RF preionization or breakdown stabilization by a microwave discharge.

Earlier, with an RF power fed to the antenna of $P \leq 150$ kW, plasma with a line-averaged electron density of $n_e \approx 2 \times 10^{12}$ cm$^{-3}$; an electron radiation temperature in the central region of $T_e^{rad}(0) \approx 500$–800 eV; and two groups of ions with different temperatures, the higher temperature being $\sim 300$–600 eV (see, e.g., [2]), was produced. In U-3M, plasma with such parameters is weakly collisional, and its investigation is of special interest from the standpoint of modeling physical processes in large fusion devices. In particular, in this regime, the effect of the vertical asymmetry (up–down asymmetry) of the divertor plasma flow was observed and studied, and it was shown that such asymmetry results from direct (collisionless) charged particle loss [3]. With a sufficiently high power $P$, a transition into the H-like confinement mode was observed [2, 4]. As a result of the transition, the energy confinement time $\tau_E$ increased nearly twofold [5]. It was shown that the transition was bifurcational in character and was triggered by a single short-time pulse of enhanced fast-ion loss.

On the other hand, the plasma produced by the frame antenna in U-3M is used as a target for the production and heating of a denser plasma (up to $10^{13}$ cm$^{-3}$) in the $\omega \approx \omega_{ci}$ frequency range by another, shorter wavelength antenna with azimuthal currents (a so-called three-half-turn antenna [6, 7]). Note that the production of the initial plasma by electromagnetic fields in a wide range of frequencies is used (or planned to be used) in a number of closed magnetic confinement systems (see, e.g., [8]). Advantages of the method employed in U-3M are a relatively simple design of the frame antenna, its compactness,
The next stage of studies planned for the nearest future will be the choice of optimal regimes of the discharge for its picking up by the three-half-turn antenna to produce plasma with higher parameters.

Earlier, the initial phase of discharge evolution in which the near field of the frame antenna having no electrostatic shield produces breakdown of the neutral gas and its ionization and rises the plasma density to several units of $10^{11}$ cm$^{-3}$, at which excitation of Alfvén waves becomes possible, was thoroughly examined both experimentally and theoretically in [10–12].

2. EXPERIMENTAL CONDITIONS

The U-3M device (Fig. 1) is an $\ell = 3$ torsatron with nine periods ($m = 9$) of the helical magnetic field. The major radius of the torus is $R_0 = 100$ cm, the average plasma radius is $\bar{r} \approx 12$ cm, and the rotational transform at the plasma boundary is $(a)/2\pi \approx 0.3$. The toroidal component of the magnetic field, $B_\phi \leq 1$ T, is produced by the helical coils only. The experiments were carried out in a magnetic configuration with the axis shifted by $\pm 5$ cm outward relative to the minor axis of the torus. The entire magnetic system, including the helical and vertical field coils, is enclosed into a 5-m-diameter 3.6-m-high vacuum chamber, the free volume of which ($\approx 70$ m$^3$) is nearly 200 times as large as the confinement volume. The inner and outer radii of the vacuum casings of the helical coils are 19 and 34 cm, respectively, and the width of the free space between the casings ranges from 13 to 27 cm. Under such conditions, a natural open helical divertor is realized.

The fueling gas (hydrogen) is continuously admitted into the vacuum chamber at a pressure of $p \sim 10^{-5}$ Torr. Direct measurements show that, during the operating shot, the pressure decreases by about 20%. Taking this into account, the pressure $p$ will further be referred to as the "initial pressure" (i.e., that measured before the start of the operating shot).

Plasma with an average density of several units of $10^{12}$ cm$^{-3}$ is produced by RF fields and heated in the regime of multimode Alfvén resonance ($\omega \approx \omega_\phi$) [1], when the resonance conditions (local Alfvén resonance conditions) for the antenna-excited oscillations with the parallel wavelength $\lambda_\parallel$ and wavenumber $k_\parallel = 2\pi/\lambda_\parallel$, are satisfied in the confinement volume. Here, $N_\parallel = k_\parallel a_c/\omega_\phi$, $\varepsilon_1 \approx \omega^2_p/(\omega^2 - \omega^2)$ is the component of the dielectric permittivity tensor, and $\omega_p$ is the ion plasma frequency. The RF power is injected into the plasma by an unshielded frame antenna [1] (Fig. 2). The parallel conductors of the antenna frame are twisted along the plasma-facing surfaces of the helical winding casings, whereas the perpendicular conductors are twisted.