1. INTRODUCTION

One of the most challenging problems in fusion research is that of producing hot dense plasmas in toroidal magnetic confinement systems by RF methods. These methods are based on the collisionless absorption of electromagnetic energy by plasma particles at different types of resonances. There are several frequency ranges in which the plasma can be efficiently heated. These are ECR, lower hybrid, and ICR frequency ranges. In the present paper, we consider the effects that occur during plasma production and heating by injecting RF power at the frequency of the Alfvén branch of the ion cyclotron resonance into the confinement region of the Uragan-3M (U-3M) torsatron—a toroidal stellarator-like device. This method of RF plasma heating in relatively small devices has some advantages. In particular, by injecting RF power into the confinement region at the ICR frequency, the plasma can be created and heated over a wide range of strengths of the confining magnetic field. It should be noted in this context that ECR plasma heating is used only in sufficiently strong magnetic fields and carrying out ECR heating experiments in which the magnetic field strength is to be varied is very problematic.

There are several factors that affect ICR heating efficiency. Thus, the heating is local because of the magnetic field nonuniformity, and the particle velocity distribution determines which of the plasma ions interact resonantly with the injected wave. One of the main factors that reduce the efficiency of both ICR and ECR heating is the radiative loss by impurities. Another factor to be noted is the generation of secondary fluctuations at the satellite harmonics of the pump frequency—a phenomenon that is usually observed when the RF power fed into the plasma is sufficiently high. In most cases, this effect raises the RF heating efficiency. The interaction of plasma particles with the pump wave field causes the electrons to oscillate relative to the ions. The growth of such oscillations can give rise to small-scale parametric instabilities, the fluctuations of the electric field of which scatter the ions and rapidly heat them.

In this paper, we present the results of a detailed study of fluctuations excited in the edge plasma of the U-3M torsatron during plasma creation and heating by an RF discharge in the ICR frequency range, accompanied by a transition to improved confinement. The main results are reported of diagnostic measurements of the spectral composition of oscillations, as well as of how the phase and amplitude relationships depend on time and on the RF power during its injection into the plasma. The measurements were carried out with electrostatic probes positioned at the edge of the plasma confinement region. The experimental results are interpreted using the kinetic theory of the electron–ion parametric instability of a plasma in the ion cyclotron frequency range and are compared with the results of numerical simulations.

2. EXPERIMENTAL DEVICE

The experiments were carried out in the U-3M device—a torsatron, stellarator-like toroidal magnetic confinement system without a longitudinal magnetic field winding [1]. In such a device, the confining magnetic configuration is created by a current flowing in a three-pole helical winding and in correcting magnetic field coils. Such a configuration produces a plasma confinement region in the form of a family of nested magnetic surfaces and also provides a spatial limiter, without violating the magnetic field topography within the plasma confinement volume. The entire magnetic system, including the mechanical support structure, is within a 70-m³-volume vacuum chamber.
The U-3M torsatron has the following parameters: the major radius of the helical winding is $R = 1$ m, the confining magnetic field is $B_0 \leq 1$ T, the minor radius of the helical winding is $r_0 = 0.27$ m, the mean plasma radius is $\bar{a} \leq 0.1$ m, the polarity of the helical winding is $l = 3$, the number of field periods is $m = 9$, the mean rotational transform at the last closed magnetic surface (separatrix) is $\kappa = 0.4$, and the rotational transform at the axis is $\kappa_0 = 0.18$. During the experiments, the residual gas pressure was maintained at a level of $p = (2–5) \times 10^{-7}$ Torr. The spatial magnetic field distribution in the device is described by the formula \[ B = B_0 \left(1 - \frac{r}{R} \cos \theta + \varepsilon \theta \cos(\theta - m\phi)\right). \] (1)

Here, $\varepsilon = \frac{m r^\frac{3}{4}}{(I - 1) R^\frac{1}{2}}$, $\phi$ and $\theta$ are the toroidal and poloidal angles, respectively; $r$ is the radial coordinate; and $R$ is the major radius of the helical winding.

The plasma in the device was created and heated by injecting RF power in the ICR frequency range ($\omega \leq \omega_{ci}$) into the confinement region. The power was supplied by two unshielded loop antennas of the same type, placed on the weaker magnetic field side. RF pulses were produced by two generators of the same type with an output power of up to 2 MW and a pulse duration of up to 100 ms, operating in the frequency range $f = 1–20$ MHz. In experiments, the mean plasma density amounted to a value of $n_e \approx 10^{12}$ cm$^{-3}$. During RF pulses of sufficiently high power, the discharge was observed to undergo a transition to an improved confinement mode with elevated plasma density and temperature. Measurements were carried out by the probes positioned in cross section DD just near the magnetic poles (see Fig. 1). The probes were held at a floating potential. The recorded signals either were sent to a spectral analyzer or were frequency pre-filtered and passed to an oscilloscope.

3. EXPERIMENTAL RESULTS

We measured the alternating component of the electrostatic potential in the edge plasma by a set of probes placed there. During the experiments, we observed the excitation of a fairly large number (up to ten) of harmonics of the pump frequency. Preliminary measurements showed that the frequency spectrum of the RF current supplied to the antenna contained only the first three harmonics. In addition, in the oscillation spectrum at the plasma edge, we observed the excitation of electrostatic fluctuations at frequencies close to the harmonics of the RF heating frequency. We found that the observed fluctuation spectrum depended strongly on the RF power supplied to the antenna and also on the confinement mode. It should be noted that the experiments were performed with only one generator of the RF heating system and the RF power was fed into the confinement region by only one antenna (RF antenna I in Fig. 1). The RF pump frequency was $f_0 = 8.8$ MHz.

3.1. Dependence on the RF Heating Power

Fluctuation spectra were measured at frequencies close to the first five harmonics of the RF pump frequency at different values of the power supplied to the RF heating antenna in experiments with the confining magnetic field $B_0 = 0.7$ T during the time interval $\tau = 32–42$ ms within the pulse duration $\tau_{RF} = 12–52$ ms. When the level of the input RF power was sufficiently...