STUDY OF WAVE PROCESSES AT THE INITIAL STAGE OF RF-HEATING IN THE URAGAN-3M TORSATRON

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The study of wave processes occurring during the initial stage of RF plasma heating in the Uragan-3M torsatron was performed with using movable magnetic and electric probes. The heating was carried out by the frame antenna. The electric probe allowed to register changes of the plasma density profile, while the magnetic probes measured amplitude and phase shifts between all magnetic field components at different points over the plasma column cross-section. The frequency spectrum of magnetic field fluctuations contains the main frequency that coincides with the RF oscillator frequency and higher harmonics. The amplitude of the 2nd harmonic in this mode can be compared with the amplitude of the basic harmonic.

PACS: 52.55.Dy, 52.55.Hc

INTRODUCTION

RF heating is one of the main methods of plasma heating in toroidal magnetic traps due to resonance effects of absorption of electromagnetic radiation in a magnetized plasma. The ion cyclotron range of frequencies (ICRF) is one of the most important frequency ranges. Modern fusion facilities use these frequencies in the band from one to several tens of MHz. The ICRF includes at least two areas of resonance absorption, namely, ion cyclotron and Alfven resonances. The ITER tokamak which is under construction envisages the possibilities to facilitate the breakdown using RF techniques. The propagation of electromagnetic waves in a magnetized plasma within this frequency range has been studied theoretically in sufficient detail [1-4], and a large number of experiments on ICRF plasma heating has been conducted [5, 6].

In particular, experiments on ICRF wave generation and plasma heating are conducted for a long time on the Uragan-3M (U-3M) torsatron [7, 8]. With that, there are some problems for the U-3M. First of all, these are a little fraction of the RF power generated by the oscillator and absorbed in the plasma and difficulties arising with dense plasma heating ($> 5\times10^{18}$ m^{-3}) [9, 10].

The aim of this work was to study electromagnetic ICRF waves exited in the U-3M plasma at the initial stage of the RF discharge.

EXPERIMENTAL CONDITIONS AND RESULTS

In the U-3M torsatron [11] a hydrogen plasma is ICRF produced and heated [12]. The toroidal magnetic field in all the experiments was $B_0 = 0.72$ T. The behavior of excited electromagnetic waves was studied at the initial stage of the RF discharge.

The pre-ionization of the fueling gas was made by applying RF voltage to the so-called "three-half-turn antenna" (THTA) [10] (Fig. 1, indicated as A_2). As a result, a plasma was created with the line-averaged density (average density) of $<n_e> \approx 10^{16}$ m^{-3}. A further increase of plasma parameters was realized by energizing the so-called "frame antenna" (FA) [8] (indicated as A_1 in Fig. 1)). The RF power fed to the FA attained $W \approx 150$ kW. The plasma obtained in this discharge had the following parameters: the average density $<n_e> \geq 10^{18}$ m^{-3}, the electron and ion temperatures $T_e \approx T_i \leq (300\ldots400)$ eV. Plasma heating was performed at the frequency $\omega/2\pi \approx 8.8$ MHz, so the condition $\omega = 2\pi f = 0.8\,\omega_{ci}(0)$ [5], where ω_{ci} is the ion cyclotron frequency on the geometrical axis of the device.

The following discharge parameters were recorded: the high-frequency current in FA I_{RF}, the H_α radiation, the average density $<n_e>$ measured by the 2 mm interferometer, the current in plasma measured by the Rogowski loop I_{pl}, and the plasma energy content recorded by the diamagnetic loop. The local electron density n_e was estimated from Langmuir probe measurements. Magnetic fields of waves propagating in the plasma were measured using two three-component magnetic probes.

The design of the magnetic probes was as follows. Two magnetic probes MP-1 and MP-2 were fastened to a movable Langmuir probe (LP) one after the other sequentially in the direction of LP motion with the distance of 1.5 cm. Each MP could record 3 components of the magnetic field of plasma waves. The distance between the utmost MP and the LP was 5 cm. The MPs were provided into the electrostatic screen and placed in a quartz glass tube.

The magnetic probes allowed to record the B_R, B_Z, и B_φ components of the fluctuating magnetic field with the frequency of ≤ 100 MHz. The probe sensitivity was NS = 6×10^{-4} m$^2\times$turn in the $\vec{R}$ direction and NS = 3×10^{-4} m$^2\times$turn, in the Z and φ directions. Here N is the number of turns in the probe, S is the probe area.

Fig. 1 shows the scheme of probes layout relative to the RF antennas and magnetic surfaces in the poloidal cross-section where the probes are located. The dotted line shows the direction of probe movement. The probes are disposed at the toroidal distance of 2 helical magnetic field periods (9 periods in total) relative to the FA (antenna A_1).

Temporal behavior of main parameters of the discharge is given in Fig. 2 where probes are withdrawn from the confinement area. From Fig. 2 it is clear that within the 1st millisecond after RF voltage being applied to the antenna A_2 the current in the antenna starts to decrease and by the 2nd millisecond (vertical dotted line) it reaches its quasi-stationary value. H_α during the 1st millisecond reaches its maximum and the longitudinal current starts increasing steadily. The average plasma density reaches its quasi-stationary level in 1.5 ms. So, it could be assumed that the initial stage of the discharge ends by the 2nd ms. Hereinafter, the discharge was reduced up to 2 ms to be able to enter probes to the area of plasma confinement.

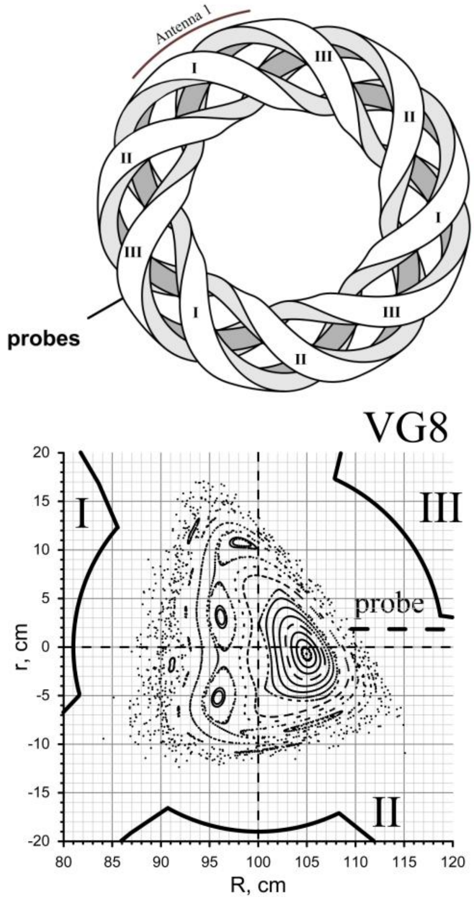

Fig. 1. Helical coils I, II, III of the U-3M torsatron. The poloidal cross-section of the torus showing positions of helical coils, magnetic probe and vacuum magnetic surfaces

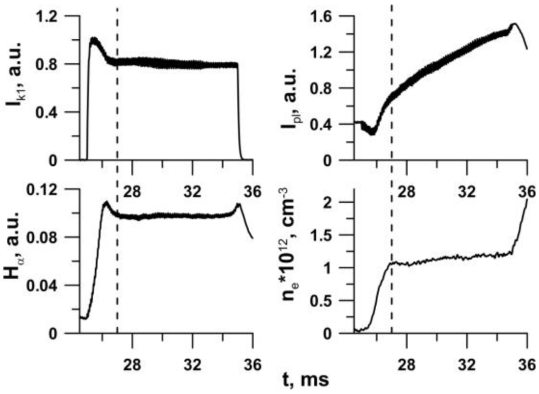

Fig. 2. Time behavior of main discharge parameters

Time dependence of the plasma density distribution on magnetic surfaces ‹r› (Fig. 3) was obtained basing on measurements of the LP saturation current. In this case, ‹r› is the average radius of the magnetic surface determined by the area of this surface $S = \pi \langle r \rangle^2$. The plasma density was calculated considering the electron temperature obtained from diamagnetic measurements assuming that the ion temperature was T_i=0 and the electron temperature distribution on magnetic surfaces coincides with the saturation current distribution. Also, it was assumed that the plasma density n_e and the electron temperature T_e are constant on the magnetic surface. It is seen that during the discharge there is a predominant density increase on the magnetic axis (‹r› = 0 cm). During measurements the magnetic probes were on the magnetic surface ‹r› = 2 cm (probe MP-1) and on ‹r› = 5 cm (MP-2).

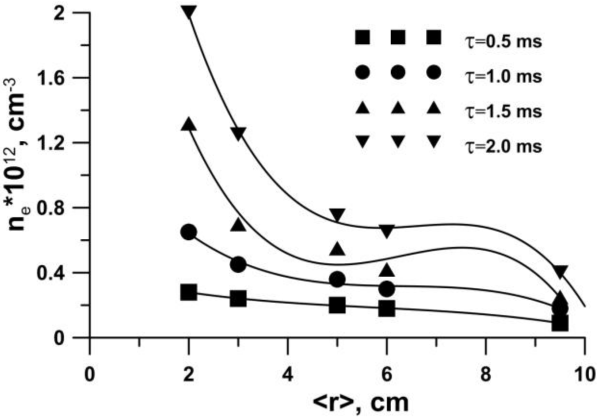

Fig. 3. Plasma density distribution on magnetic surfaces at different times

The signals from magnetic probes were recorded using 4-beam oscilloscopes that allowed to receive signals with the frequency up to 200 MHz (Fig. 4). It is seen that the signal form differs from sinusoid, i.e., the signal spectrum has also higher harmonics. A typical frequency spectrum of signals is given in Fig. 5.

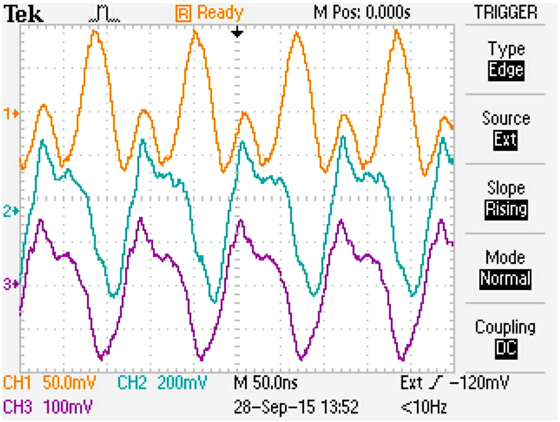

Fig. 4. Typical oscillations of the magnetic field components, registered by the magnetic probes: 1 – B_{tor}; 2 – B_R; 3 – B_{pol}

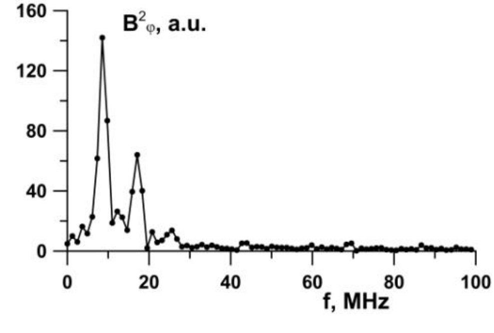

Fig. 5. The spectrum of the magnetic field fluctuations

Fig. 6 shows time dependence of the first harmonic amplitude of magnetic field fluctuations for different spatial components that were measured near the magnetic axis of the plasma configuration (‹r› = 2 cm, probe MP-1). It is seen that the B_R component is the highest in value and increases with the plasma density (Fig. 7); by the 2nd millisecond of the discharge B_R exceeds other components almost by the order of magnitude. The maximum amplitude of this harmonic attains $B_R \approx 0.6$ G.

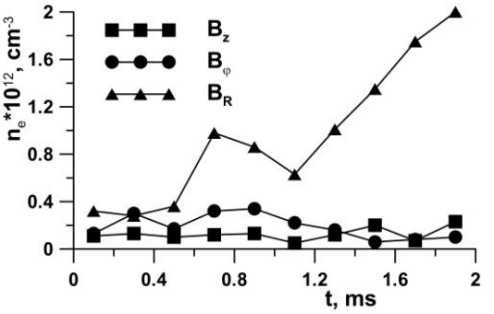

Fig. 6. Time behavior of the amplitude of the 1st harmonic oscillation (8.8 MHz) near the axis of the magnetic configuration (probe MP-1)

Fig. 7 shows time behaviors a) fluctuation amplitudes of the 1st harmonic of the B_R component that were measured by different probes (MP-1 and MP-2) in different spatial points of the plasma column; b) density trend in the area of magnetic probes location; c) phase difference between these fluctuations 1.5 cm separated in space.

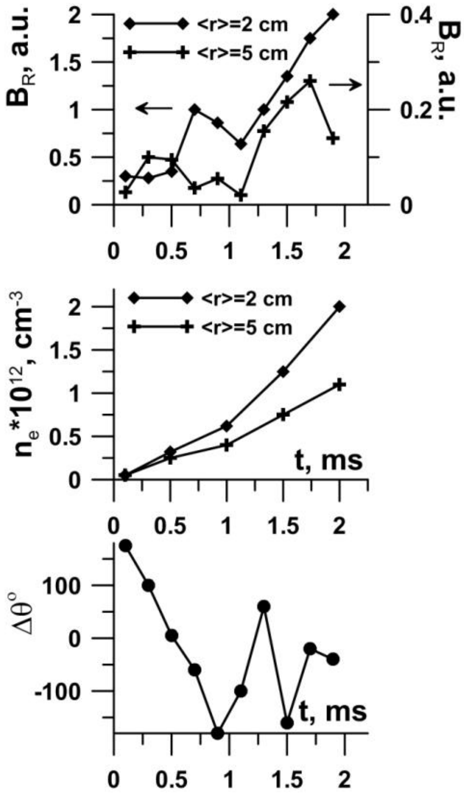

Fig. 7. Time variations of B_R components (1st harmonic) on the magnetic surfaces<r>=2 cm and <r>=5cm; the behavior of the local density n_e and the phase shift $\Delta\Theta$ between the oscillations on these surfaces

According to the plasma density distribution (Fig. 3) and the oscillation energy distribution (Fig. 7), the main power is introduced into the central region of the discharge.

CONCLUSIONS

1. Distributions of the plasma density and RF magnetic field fluctuations were obtained in the plasma confinement area at the initial stage of the FA driven discharge using electrostatic and magnetic probes.
2. The phase difference between the fluctuations was determined for different magnetic field components.
3. The density increase and the maximum level of the energy of the magnetic field fluctuation are in the area of magnetic axis of the plasma configuration. The main fluctuation energy is accumulated in the BR component.
4. At the initial stage of plasma accumulation the main power injected into the plasma volume using the frame antenna is concentrated near central areas of the plasma configuration.
5. Maximum fluctuation amplitude in the given discharge attains $B_R \approx 0.6$ G.
6. The frequency spectrum of the RF oscillation, besides the fundamental harmonic comprises the second and higher harmonics.

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Article received 19.01.2017

ИССЛЕДОВАНИЕ ПОВЕДЕНИЯ ЭЛЕКТРОМАГНИТНЫХ ВОЛН В НАЧАЛЬНОЙ СТАДИИ ВЧ-РАЗРЯДА В ОБЛАСТИ УДЕРЖАНИЯ ПЛАЗМЫ В ТОРСАТРОНЕ УРАГАН-3М

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С помощью подвижных магнитных и электрических зондов в торсатроне Ураган-3М были изучены волновые процессы, протекающие на начальной стадии ВЧ-нагрева. Нагрев плазмы проводился с помощью “рамочной” антенны. Электрический зонд позволял регистрировать изменение профиля плотности плазмы, а магнитные зонды измеряли амплитуду и сдвиг фаз между всеми компонентами поля в различных точках по сечению плазменного шнура. Частотный спектр регистрируемых колебаний магнитного поля содержит основную частоту, совпадающую с частотой ВЧ-генератора, и более высокие гармоники. Амплитуда второй гармоники в данном режиме может быть сравнима с амплитудой основной гармоники.

ДОСЛІДЖЕННЯ ПОВЕДІНКИ ЕЛЕКТРОМАГНІТНИХ ХВИЛЬ В ПОЧАТКОВІЙ СТАДІЇ ВЧ-РОЗРЯДУ В ОБЛАСТІ УТРИМАННЯ ПЛАЗМИ В ТОРСАТРОНІ УРАГАН-3М

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За допомогою рухливих магнітних і електричних зондів у торсатроні Ураган-3М були вивчені хвильові процеси, що протікають на початковій стадії ВЧ-нагріву. Нагрівання плазми проводилося за допомогою "рамкової" антени. Електричний зонд дозволяв реєструвати зміну профілю щільності плазми, а магнітні зонди вимірювали амплітуду і зрушення фаз між усіма компонентами поля в різних точках по перерізу плазмового шнура. Частотний спектр реєстрованих коливань магнітного поля містить основну частоту, яка збігається з частотою ВЧ-генератора, і більш високі гармоніки. Амплітуда другої гармоніки в даному режимі може бути порівнянна з амплітудою основної гармоніки.