THE PROBLEM OF PLASMA DENSITY INCREASING IN THE U-3M TORSATRON AFTER RF HEATING TERMINATION

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In the U-3M torsatron a significant chord-averaged plasma density increase is observed after the RF-heating termination. The objective of this work is to find out possible mechanisms resulting in plasma density increasing.

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INTRODUCTION

One of most interesting effects that is observed during RF heating of a low density plasma in the U-3M torsatron is a chord-averaged plasma density increase after the heating termination [1]. There are three different versions explaining this effect. (1) The RF heating excites strong plasma instabilities causing a particle loss from the confinement volume. After heating termination the loss reduction results in the plasma density increase [2, 3]. (2) The RF heating gives rise to ionization of fuelling gas molecules outside the confinement volume resulting in a reduction of the flow of this gas inflowing into the confinement volume. After heating termination the RF screening vanishes and the fuelling gas is free to inflow from the region beyond the poles of the helical winding [4]. (3) A reduction of the toroidal plasma current with RF heating termination results in a toroidal electric field to occur. Under the action of this field, the inward drift of trapped particles and density rise come about [5].

OBTAINED RESULTS

The investigated discharge is characterized by the behavior of main plasma parameters shown in Fig. 1. It is seen that the mean plasma pressure $\overline{p}$ measured by the diamagnetic loop increases during the discharge, while the density decays slowly from $\overline{n}_e$ = 1.2×10^{12} cm^{-3} to $\overline{n}_e$ = 0.9×10^{12} cm^{-3} to the end of the discharge.

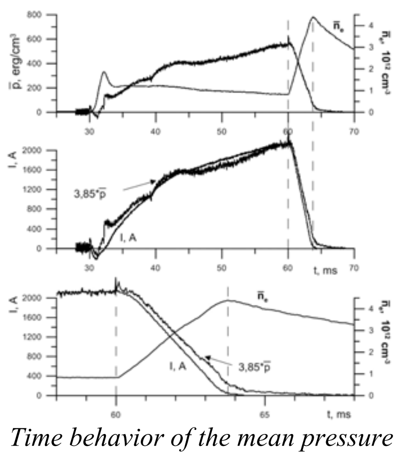

Fig. 1. Time behavior of the mean pressure $\overline{p}$, the line average plasma density $\overline{n}_e$, the value of the parallel current in the plasma I and the 3.85 $\overline{p}$ quantity in different time scales. Vertical dashed lines indicate moments of RF heating termination and the density maximum after RF heating off

After the heating switched off, the plasma pressure drops to the level of 0.1 of its maximum value practically for 4 ms, while the density increases to 4.3×10^{12} cm^{-3}. As it has been already mentioned in [1], current arises during the heating, attaining $I \approx 2$ kA. This current is proportional to the mean plasma pressure practically during all the pulse. After the heating switched off the density rise takes place during the current decay (see, also, [5]). Also, it should be noted that, as it has been mentioned in [5], the value of the density addition after RF heating off is proportional to the rate of current decay $\Delta I/\partial\Delta$.

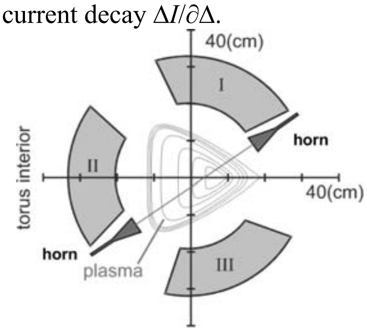

Fig. 2. Disposition of microwave horns for plasma probing with respect to helical winding probes and magnetic surfaces

To elucidate the mechanism of the density rise, it is extremely important to determine the density profile during the discharge. This can be made, under our conditions, by joint measurements of the line-averaged density, using a 2 mm interferometer, and plasma probing by microwave radiation at different frequencies near the electron plasma frequency. Fixing the moment of the probing radiation cut off at the given frequency, we can find the maximum density at this moment. Setting the density distribution in the form $n_e=n_0(1-r/a)^{\alpha}$, where r is the current radius, a is the size of the boundary surface, α can be determined, using the a value and interferometer data. The proposed method gives a true trend for the density profile variation during the discharge. The size of the boundary surface is determined using optical measurements of the CII and CIII impurity radiation near $\lambda \approx 4647 \pm 1$ Å. The ionization potential of these lines is less than 20 eV, so it is quite realistic to record the plasma boundary with the temperature < 5 eV.

The scheme of the microwave horns disposition is presented in Fig. 2. An example of time behavior of traversing of the meander-modulated microwave

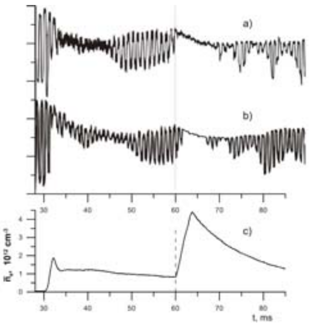

Fig. 3. Time behavior of microwave radiation passing through the plasma column at frequencies 15.33 GHz (a), 18.1 GHz (b) and line averaged density $\overline{n}_e$ (c). Vertical dashed line indicates the moment of RF heating off

radiation with two different frequencies is shown in Fig. 3. The chord distribution of the impurity line radiation from the plasma volume in the $\lambda \approx 4647$ Å is given in Fig. 4. The results of these data processing allow one to plot the variation of the density profile during the discharge (Fig. 5). It is seen in this figure that the density profile is sharp during all the active phase of the discharge. The boundary surface size amounts $a \approx 10.4$ cm. After RF heating termination the density profile becomes flat and the boundary surface size is reduced to $a \approx 8.5$ cm.

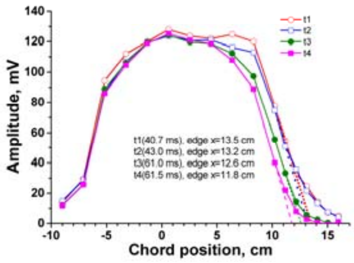

Fig. 4. Chord distributions of line intensity at different moments: 1, 40 ; 2, 43 ; 3, 61 ms (1 ms after RF heating off); 4, 61.5 ms (1.5 ms after RF heating off). The dashed and dotted lines are drawn to chord numbers corresponding to the plasma boundary

The reduction of the plasma column size and the density gradient increase at the boundary is the evidence that the radial velocity of the plasma motion inward exceeds the velocity of plasma loss.

For the case of molecular hydrogen inflowing from the vacuum volume beyond the helical winding poles the plasma particle balance can be presented as

$$\frac{a}{2}\frac{\partial \overline{n}_e^*}{\partial t} + \frac{\overline{n}_e^* a}{\tau_n} = 2AKn_0\upsilon_0 . \quad (1)$$

Here $\overline{n}_e^*$ is the cross-section-averaged plasma density, τ_n is the life-time of plasma particles, n_0 is the neutral hydrogen density in the vacuum volume, υ_0 is the thermal velocity of hydrogen molecules, K is the probability of the hydrogen molecule to fall into the confinement volume, and A is the penetrability of the helical winding poles. Taking K = 1/6, A = 0.3, $n_0 = 3\times$ cm^{-3} and $\upsilon_0 = 1.4\times10^5$ cm/s, we have after RF heating termination

$$\frac{a}{2}\frac{\partial \overline{n}_e}{\partial t} = 2AKn_0\upsilon_0 . \quad (2)$$

This result indicates that the plasma density rise after the heating termination is provided by the hydrogen influx from the vacuum volume, with the particle loss being absent. This confirms the conclusion made above from the data on the density profile. Note that the version on the turbulent transport coefficient changing after the heating termination contradicts Eq. (2). Since the reduction of the transport coefficient is accompanied by a rise of the density gradient, the value of τ_n practically does not change.

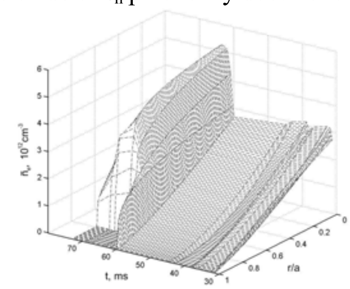

Fig. 5. Time behavior of plasma density profile

Now we try to find out the mechanism of the velocity of plasma motion to occur that exceeds the velocity of particle loss. After the heating termination a toroidal electric field arises connected with the current drop. The loop voltage of the torus is

$$u = -\frac{\partial}{\partial t}LI, \quad (3)$$

where L is the plasma inductance. The classical mechanism of the $E\times B$ drift gives a too small drift velocity which is considerably less than the loss velocity. Under conditions of rear collisions and the presence of trapped particles, the neoclassical theory predicts a higher velocity of the radial drift [6],

$$V_{dr} = -\frac{c}{B_\vartheta}\sqrt{\varepsilon}\,\frac{u}{2\pi R}, \quad (4)$$

where B_ϑ is the poloidal magnetic field, R is the major radius, ε is the magnetic field ripple. In U-3M the values of ε at the plasma boundary attain $\varepsilon_t \approx 0.1$ and $\varepsilon_h \approx 0.18$ for the toroidal and helical ripples, respectively [4].

In the discharge under study the drift velocity is directed inward with the current drop. Basing on experimental data obtained in a similar discharge, it is shown in [5] that the plasma is in the rear collision regime for both electron and ion components. This is confirmed by appearance of a parallel current in the RF heating. The neoclassical theory really predicts the occurrence of a parallel current in the regime of rear collisions (bootstrap-current) [6]. The simplest expression for such a current in toroidal traps of tokamak-type with round magnetic surfaces has the form

$$I_B \cong 2\pi\int_0^a \frac{c}{B_\vartheta}\sqrt{\frac{r}{R}}\frac{\partial p}{\partial r} r dr . \quad (5)$$

Following from Eq. (5), it is easy to show that the bootstrap current is proportional to the mean plasma pressure. Comparison with the data presented in Fig. 1 shows that the proportionality factor between I_B and $\overline{p}$ is ≈ 4 times smaller than that following from Eq. (5). Such a discrepancy is quite explainable in view of the real magnetic configuration of U-3M (triangle-like magnetic surfaces and a high level of magnetic field ripples) and of the parameters of different plasma components.

Thus, the existence of the parallel current proportional to the mean plasma pressure during the RF plasma heating confirms applicability of the neoclassical theory for description of the radial drift (see Eq. (4)).

Estimations show that the velocity of the plasma radial drift after heating termination can attain $V_{dr} \approx 1.5\times10^3$ cm/s. The velocity of the plasma particle loss is evaluated as $V_{dif} \approx a/\tau_n$. Under experimental conditions $V_{dif} \approx (1\div3)\times10^3$ cm/s. Probably, the particle loss does decrease a little after RF heating termination, to provide the condition $V_{dr} \geq V_{dif}$

It follows from Eq. 1 that if $\partial n_e/\partial t \to 0$, then the particle life time should be

$$\tau_n \cong \frac{\overline{n}_e a}{2AKn_0\upsilon_0} \leq 2\times10^{-3}\ \text{s}. \qquad (6)$$

Such a value of the particle life time in the confinement volume with RF heating is two times less than the energy life time $\tau_E \cong 4$ ms. In experiments on plasma confinement in toroidal traps $\tau_n > \tau_E$. Therefore, one can suppose that during the RF heating a fraction of the particle flow from the vacuum volume does not fall into the confinement region, and so, the effect of RF screening of the plasma from the neutral hydrogen entering the confinement region takes place.

CONCLUSIONS

With RF heating of low density plasma its density distribution has been obtained both in the active phase and after heating termination. To obtain the density distribution, the microwave probing of the plasma at different frequencies near the electron plasma frequency, results of line averaged plasma density measurements with using a 2mm interferometer and the chord distribution of impurity line intensity at $\lambda \approx 4647$ Å are used. It is seen from the data having been obtained that after the heating termination the plasma density profile significantly flattens, the density gradient strongly increases, and the size of the plasma along the minor radius considerably increases. The number of particles in the plasma volume undergoes almost fourfold increase after RF heating off.

The parallel plasma current observed in the experiment is proportional to the mean plasma pressure similar to the bootstrap current predicted by the neoclassical theory. The value of this current is almost 4 times less than that calculated for a tokamak-type toroidal trap with round magnetic surfaces. The observed difference is assumed to be connected with the presence of helical magnetic field ripples in a torsatron and non-round magnetic surfaces.

As it has been shown here, the reasons for the plasma density rise after RF heating termination could be

- an occurrence of the radial velocity of the plasma movement directed inward the confinement volume under the action of the parallel electric field caused by the current drop and proportional to $\partial I/\partial t$;
- a reduction of the plasma particle loss after RF heating termination;
- a rise of the neutral hydrogen flow into the confinement volume due to RF plasma screening cessation.

REFERENCES

1. V.L. Berezhnyj, V.S. Voitsenya, M.P. Vasil'ev, et al. // *Fizika plazmy.* 1990, v. 15, p. 523-536 (in Russia).
2. V.Ye. Bykov, V.V. Chechkin, I.P. Fomin et al. // *Plasma Phys. Control Fusion.* 1995, v. 37, p. 271.
3. N.T. Besedin, S.V. Kasilov, I.M. Pankratov et al. *Stellarators and other helical confinement systems.* Collection of papers presented at the IAEA TCM Garching, Germany, 10-14 may 1993, Vienna IAEA, 1993, p. 277.
4 V.K. Pashnev, P,Ya. Burchenko, A.V. Lozin et al. Energy confinement in the torsatron Uragan-3M during the RF-heating mode // *Problems of Atomic Science and Technology. Series "Plasma Physics" (14)*. 2008, №6, p. 28-30.
5 V.K. Pashnev, Ed.L. Sorokovoy. Appearance of neoclassical effects in plasma behavior in torsatron Uragan-3M // *Problems of Atomic Science and Technology. Series "Plasma Physics" (14)*. 2008, №6, p. 31-33.
6. A.A. Galeev and R.Z. Sagdeev. *Voprosy teorii plazmy (Problems of Plasma Theory)/ E*d by M.A. Leontovich. Moscow, Atomizdat, 1973, v. 7, p. 205 (in Russian).

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УВЕЛИЧЕНИЕ ПЛОТНОСТИ ПЛАЗМЫ В ТОРСАТРОНЕ У-3М ПОСЛЕ ВЫКЛЮЧЕНИЯ ВЧ-НАГРЕВА

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В торсатроне У-3М можно увидеть значительное увеличение средней плотности плазмы после прекращения ВЧ-нагрева. Целью данной работы является выяснение механизмов, приводящих к такому увеличению.

ЗБІЛЬШЕННЯ ЩІЛЬНОСТІ ПЛАЗМИ В ТОРСАТРОНІ У-3М ПІСЛЯ ВИМКНЕННЯ ВЧ-НАГРІВУ

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У торсатроні У-3М можна побачити значне збільшення середньої густини плазми після припинення ВЧ-нагрівання. Метою даної роботи є з'ясування механізмів, що призводять до такого збільшення.