ENERGY CONFINEMENT IN THE TORSATRON URAGAN-3M DURING THE RF-HEATING MODE

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Energy confinement time of plasma in torsatron U-3M was measured both during quasi-stationary stady of RF-discharge and after RF-power cut-off. Power absorbed by plasma in the confinement region was estimated. A mechanism which explain the plasma density behavior in the confinement region is proposed.

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INTRODUCTION

The integral characteristic describing the energy confinement in toroidal helical traps is the plasma energy confinement time τ_E. Under the stationary conditions τ_E is determined by the expression: $\tau_E = \frac{3\Gamma}{2W}$, where $\Gamma = \int\left(n_e T_e + \sum_i n_i T_i\right)dV$ – is the plasma energy content, W-is the plasma-absorbed power, n_e - is the electron density, n_i - is the ion density, T_e and T_i - are the electron and ion temperature correspondingly. However, in some cases it is difficult to determine the value of the plasma-absorbed power. Such a situation is observed during the RF-plasma heating in the torsatron U-3M. It is caused by the RF-heating features in this facility [1].

Paper [2] presents the results of τ_E determination by the plasma energy content decrease after RF-power switching-off. But in this case the influence of the RF-heating on the energy confinement in this facility is not clear.

In paper [3] one offers the method for τ_E determining under the stationary conditions which is based on the fast and insignificant increase of the RF-power introduced into the plasma ($\delta W << W$). An advantage of this technique is that there in no need to carry out absolute measurements of plasma parameters for τ_E determination.

The goal of the present paper is to determine the plasma energy confinement time in the torsatron U-3M during the RF-heating. For this purpose we will use the results of [3], compare the results obtained with the data of stellarator scaling and explain the previous results obtained at the torsatrons U-3 and U-3M.

EXPERIMENTAL RESULTS AND THEIR DISCUSSION

Experiments were carried out at the torsatron U-3M using the RF-heating mode with a quasi-stationary behavior of discharge parameters [1]. The working gas was hydrogen. It was injected into the vacuum chamber continuously. The magnetic field value on the magnetic axis was B_o= 0.72 T. The average plasma density was determined by means of a 2 mm interferometer. Distributions of the electron temperature T_e over the plasma column cross-section was determined by the intensity of plasma cyclotron radiation.

To determine τ_E the method described in [3] was applied. According to this method, for the case of insignificant increase of the RF-power introduced into the plasma the plasma energy confinement time behavior is described by the expression: $\delta\Gamma(t) = \delta\Gamma_0(1 - e^{-t/\tau_E})$. (1)

From here it follows:

$$\tau_E = \frac{\delta\Gamma_0}{\left.\frac{\partial}{\partial t}\Gamma\right|_{t\to 0}}. \quad (2)$$

For the case of the RF-power switching-off, the plasma energy confinement time is determined by the relationship:

$$\tau_E = -\frac{\frac{3}{2}\Gamma_0}{\frac{3}{2}\left.\frac{\partial}{\partial t}\Gamma\right|_{t\to 0} - \varepsilon\frac{\partial n_e}{\partial t}V}, \quad (3)$$

where $\delta\Gamma_0$ - is the maximum gain of the plasma energy content, Γ_0 – is the plasma energy content in the time of RF-power change ($t \to 0$), ε - is the energy consumed by every act of working gas atom ionization. In expression (3) growth of plasma density and additional loss of plasma energy in the volume, due to ionization of working gas, is taken into account.

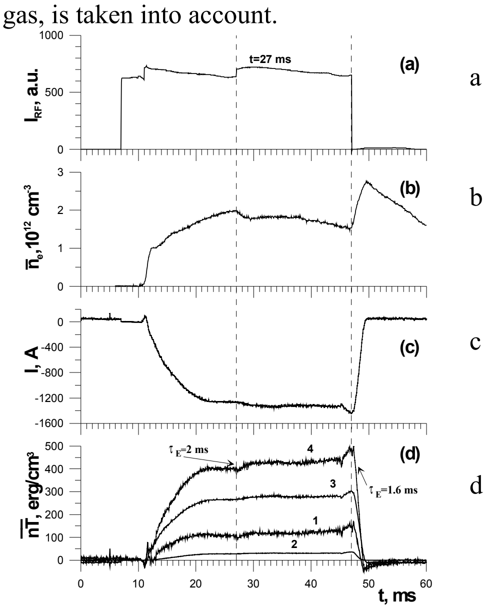

Fig.1. Time dependence: (a) – of the RF-antenna current I_{RF}, (b) – of the average plasma density $\bar{n}_e$, (c) – of the longitudinal plasma current I, (d) curve 1 – term (I),

curve 2 – term (II), curve 3(III), curve 4 - $\overline{nT}$, calculated basing on expression (4)

According to [4,5] the expression for plasma energy confinement is written in the following form:

$$\Gamma = \frac{B_0 R}{2}\Delta\Phi - \frac{2\pi I^2 R}{c} - \frac{2\pi B_0}{c}\int_0^a j_0 \frac{\partial}{\partial r}\left[r^2 \int_0^r \iota_{st} dx \right] dr . \quad (4)$$

(I) (II) (III)

Here R – is the major plasma radius, c – is the light velocity. Term (I) in expression (4) is related with the diamagnetic flux change $\Delta\Phi$, term (II) is the tokamak term related with the longitudinal current I in the plasma, term (III) is determined by the interaction between the longitudinal plasma current of a density j_0 and the helical magnetic field described by the rotational transformation angle ι_{st} ("stellarator effect").

Fig.1 shows the change in time of the RF-antenna current (Fig.1a), of the average density of plasma electrons $\overline{n}_e$ (Fig.1b), of the longitudinal plasma current I (Fig.1c) and of the value $\overline{nT} = \overline{n_e T_e} + \overline{n_i T_i}$ (Fig.1d) which was determined from expression (4). From Fig.1a it is seen that the sharp increase of the RF-antenna current and, respectively, of the antenna-irradiated RF-power (t=27 ms), causes the increase of the longitudinal plasma current I (Fig.1c), of the plasma energy content $\overline{nT}$ (Fig.1d, curve 4) and the decrease of the density $\overline{n}_e$ (Fig.1b). Curve 1 in Fig.1d describes the behavior of term (I) in expression (4), curve 2 – of term (II) and curve 3 – of term (III), respectively. From comparison of curves presented on fig.1d it's evidently, that a value of term (III), describing a "stellarator effect", is the most for determination of plasma energy content.

It should be noted that values $\overline{nT}$ on fig.1d, curve 4, are close to the values $\overline{nT}$, which were obtained on the basis of measuring of saddle coil [2]. The good coincidence of results of the diamagnetic measuring is also observed with $\overline{nT}$ value, which was calculated on the basis of average plasma density and average plasma electronic temperature. $\overline{T}_e$ was calculated from the profile of electronic temperature on the cross-section of plasma column. Distributing of electronic temperature T_e in radial direction on the cross-section of plasma column is showed on fig. 2.

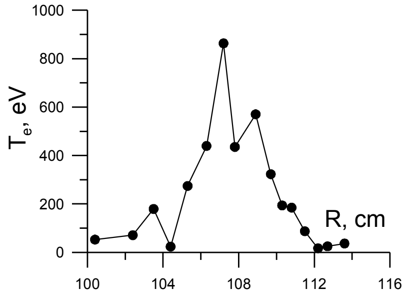

Fig. 2. Distribution of electrons temperature Te in radial direction

On the basis of expressions (2) and (3), the values of plasma energy confinement time were determine during the stationary stage of discharge in the moment of sharp insignificant increase of RF-power and after the shutdown of RF-power, accordingly. In the first case $\tau_E \cong 2$ ms and in the second case $\tau_E \cong 1.6$ ms. The difference in the values obtained arises due to the additional energy losses (not taken into account in (3)), as a result of the process of charge exchange on neutral atoms being enhanced by the plasma density increase after RF-power switching-off (Fig.1b).

The value of the energy confinement time τ_E in the torsatron U-3M was compared with the data of the stellarator scaling ISS95 [6]. The energy confinement time calculated from the stellarator scaling $\tau_E^{ISS95} = 2.5$ ms. This value is close to the experimental one of $\tau_E \cong 2$ ms. Similar values of the plasma energy confinement time at the quasi-stationary stage of the RF-discharge ($\tau_E \cong 2$ ms) and after RF-power switching-off ($\tau_E \cong 1.6$ ms) show that the RF-plasma heating mode does not deteriorate the energy confinement in the torsatron U-3M.

Determination of $\overline{nT}$ and τ_E allowed one to estimate the plasma-absorbed RF-power basing on the expression:

$$W = \frac{3\Gamma}{2\tau_E} = 9.45 \text{ kW}. \quad (5)$$

This value is in a good agreement with that of the plasma-radiated power $W_{rad} \approx 12$–14 kW, obtained on the base of bolometric measurements. As the experimental value of the antenna-radiated RF-power was approximately $W_a \approx 200$ kW, the value of the plasma-absorbed power does not exceed 5% of the radiated power.

The above-mentioned measurements evidence on the significant difference between the RF-antenna irradiated power (≈200 kW) and the plasma-absorbed power in the confinement region (≈ 10 kW). In other words, about 95% of the antenna-radiated RF-power is lost in the processes taking place outside the confinement volume. The current RF-antenna is designed for breakdown, formation and heating of the plasma in the confinement region and, apparently, it is capable to provide breakdown, formation and heating of the plasma also in the region of divertor field lines behind the helical coil poles. The available experimental data confirm this assumption.

For example, in paper [2] given are the microwave interferometer measurement data on the plasma density in the divertor region behind the helical coil poles. The data show that after RF- switching-off the divertor plasma density sharply decreases during the time of 100 µs, while the plasma density in the confinement volume increases (Fig.1b).

The probe measurements outside the confinement region demonstrate similar results (see, for example, Figs. 5 and 8 in [7]).

The probe measurements [7] of the plasma density and temperature outside the confinement volume in the RF-heating mode give the values of $\overline{n}_e \leq 10^{11}$ cm^{-3} and $T_e \approx 20$ eV, that permits to evaluate the hydrogen molecule mean free path $\lambda \approx 40$ cm [8]. The plasma having such parameters is able to screen the confinement region against the neutral gas molecule entering.

The evidence of the RF-plasma screening of the confinement region from the neutral molecule entering is confirmed by the plasma average density decrease in the discharge after additional energy switching (Fig.1).

As is seen from Fig.3, the plasma density in the confinement region decreases with the anode voltage increase on the oscillating tube of the RF-complex and, consequently, with the antenna-irradiated RF-power increase beginning from $U_a \geq 6$ kV. And, conversely, after RF-power switching-off the plasma density increases (Fig.1b). That evidences on the RF-plasma screening disappearance and on the additional working gas molecule entering into the confinement volume.

Paper [9] gives the estimated value of the average plasma density in the torsatron U-3M confinement volume equal to $Z \cong 2$. Just this low value of Z provides the existence of a "banana mode" in the part of the confinement region and bootstrapt current generation. The low value of Z can be explained by the RF-plasma screening of the plasma confinement region and by the divertor effective operation.

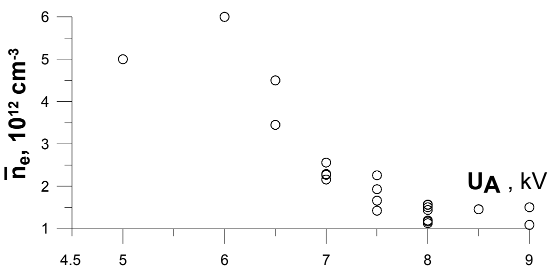

Fig.3. Maximum average plasma density in the discharge $\bar{n}_e$ versus the RF-generator anode voltage U_A

CONCLUSIONS

The energy confinement time has been found experimentally in the quasi-stationary stage of the RF-discharge and after switching-off of the RF-discharge in the torsatron U-3M. The results show that the RF-plasma heating mode does not deteriorate the energy confinement and the energy confinement time value $\tau_E \cong 2$ ms is slightly different from the data obtained for the stellarator scaling $\tau_R^{ISS95} \cong 2.5$ ms.

The plasma-absorbed power, evaluated in the confinement region, equals to $W \cong 10$ kW that is much lower than the antenna-radiated power $W_a \cong 200$ kW.

The work demonstrated that the plasma density behavior in the confinement region can be explained by the appearance in the plasma heating process of the RF-plasma confinement screening against working gas entering from the ballast vacuum volume.

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УДЕРЖАНИЕ ЭНЕРГИИ В ТОРСАТРОНЕ УРАГАН-3М В РЕЖИМЕ ВЧ-НАГРЕВА

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Экспериментально определено энергетическое время жизни плазмы во время квазистационарной стадии ВЧ-разряда и при выключении ВЧ-разряда в торсатроне У-3М. Оценена доля мощности, излучаемой ВЧ-антенной, которая поглощается плазмой в области ее удержания. Предложен возможный механизм, объясняющий поведение плотности плазмы в области удержания.

УТРИМАННЯ ЕНЕРГІЇ В ТОРСАТРОНІ УРАГАН-3М В РЕЖИМІ ВЧ-НАГРІВУ

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Експериментально визначено енергетичний час життя плазми під час квазістаціонарної стадії ВЧ-розряду і при вимкненні ВЧ-розряду в торсатроні У-3М. Оцінена частка потужності, що випромінюється ВЧ-антеною, яка поглинається плазмою в області її утримання. Запропоновано можливий механізм, що пояснює поведінку щільності плазми в області утримання.