INFLUENCE OF PLASMA WITH FINITE PRESSURE ON MAGNETIC CONFIGURATION OF TORSATRON U-3M

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Series of experiments on generation of mode with high β (up to about 1.3%) in torsatron U-3M were performed using nitrogen as working gas. The dependence of average β from input power was obtained. The average plasma radii in modes with various β were determined. The estimation of rotational transformation angle was done in view of presence of the plasma in device.

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INTRODUCTION

Equilibrium of plasma in toroidal helical magnetic traps, such as tokamaks or stellartors (torsatrons), is supported by flows of plasma currents. The expressions for these currents can be written as [1]:

$$\vec{j} = P'(\rho)\frac{\lfloor B\nabla\rho\rfloor}{B^2} + \alpha(\rho)\frac{B}{B^2}P'(\rho), \quad (1)$$

where j – density of plasma current, P – gas-kinetic plasma pressure on magnetic surfaces ρ, $P'(\rho)$ – derivative of P with respect to instant radius, B – magnetic field induction, $\alpha(\rho)$ – coefficient, which was obtained from solution of the expression $div\vec{j} = 0$:

$$\vec{B}\nabla\frac{\alpha}{B^2} = -\left[\vec{B}\nabla\rho\right]\nabla\frac{1}{B^2}. \quad (2)$$

The first term in expression (1) describes the current, that flows across magnetic field lines (diamagnetic current). The second term of (1) corresponds to the dipole component of de-polarization current (Pfirsch-Schlueter current). The simple form of expression for de-polarization current can be written as follows [2,3]:

$$j_{p.s.} = -\frac{2c}{B\iota}P'(\rho)\cos\vartheta, \quad (3)$$

where ι – rotational transformation angle and ϑ – poloidal angle. The current described by (3) flows along the magnetic field lines and creates the additional magnetic field, that perturbs the initial magnetic configuration. To the first approximation, the influence of the disturbing magnetic field on a magnetic configuration is similar to the influence of equivalent transverse uniform magnetic field with value of

$$B_\perp/B \cong \bar{\beta}/2\iota. \quad (4)$$

Here $\beta = 8\pi P/B^2$. If we take into account the real distribution of gas-kinetic plasma pressure on magnetic surfaces, the difference between the disturbing magnetic field and the transverse uniform magnetic field is distinctly increased. In stellarators (torsatrons), the helical harmonics of de-polarization current appear and influence the variation of the rotational transformation angle.

It is well known, that the transverse magnetic field of stellarators shifts the internal magnetic surfaces of the magnetic configuration, disrupts the near-separatrix magnetic surfaces and modifies the profile of the rotational transformation angle.

The purpose of our experimental study was to obtain the maximal value of β in torsatron U-3M, as well as to measure the small radius of the plasma and to determine variation of the rotational transformation angle with increasing β.

EXPERIMENTAL RESULTS AND DISCUSSION

The experiments in torsatron U-3M were performed in RF-heating mode [4]. In a typical operation mode of RF-heating the hydrogen plasma was heated by Alfven wave at the frequency ratio $\omega/\omega_i \approx 0.8$ (ω_i – ion cyclotron frequency). In this mode $\bar{\beta} \approx 0.03\%$ was achieved at magnetic field induction on axis of $B_0 \approx 0.72$ T [5], where overline means averaging over cross-section of the plasma column. To obtain the large values of $\bar{\beta}$, we chose the RF-heating in which the plasma was heated by fast magneto-sonic (FMS) wave using nitrogen as working gas, at small magnetic field induction of $B_0 \approx 0.04$ T and at anode voltages of lamps of two RF-generators U(G1) = 5…7.5 kV and U(G2) = 5…6.5 kV.

The value of β was determined based on measurements of magnetic diagnostics sensors (diamagnetic loop and saddle coil) [6]. The variation of the toroidal magnetic flux measured by the diamagnetic loop in a "current less" plasma can be expressed:

$$\Delta\Phi = -\frac{8\pi^2}{B_0}\int_0^a P\rho\, d\rho = \frac{4\pi^2 a^2}{B_0}\bar{P}. \quad (5)$$

The variation of the poloidal magnetic flux measured by the saddle coil, looks like

$$\Delta\Psi = -A\frac{4\pi}{B_0}\int_0^a \frac{P'(\rho)}{\iota}\rho^2 d\rho, \quad (6)$$

where A – coefficient, which is connected with geometrical size of the test coil.

From (5) one can see, that value of average gas-kinetic plasma pressure $\bar{P}$ can be easily determined with accuracy of the size of plasma column. The correlation between variation of the poloidal magnetic flux measured by the saddle coil and plasma pressure is more complicated. However, in case of homogeneous distribution of the rotational transformation angle over the cross-section of the plasma column and when we set a distribution of the plasma pressure in the form of $P = P_0\left[1-\left(\frac{\rho}{a}\right)^m\right]$, the expression, which describes the variation of the poloidal magnetic flux, can be written as

$$\Delta\Psi = -A\frac{4\pi}{B_0\iota}\bar{P}a^2. \quad (7)$$

It is obvious, that in case of homogeneous or weakly unhomogeneous distribution of the rotational transformation angle ι over the cross-section of the plasma column, the simultaneous measurements of diamagnetic loop and saddle coil allow us to determine the value of ι.

The radiance of neutral atoms of nitrogen is sensitive to the profile of electron temperature and to the plasma density on the boundary of the plasma column. Therefore, the cross-section size of the plasma column was estimated from the profile of the chord distribution of spectral line radiance of neutral nitrogen NI ($\lambda = 4109$Å), which was scanned over the vertical plane. To achieve the sufficient accuracy of measurements, the plasma radiation was obtained from plasma volume with vertical size of less then 1 mm.

Figure 1 shows the time dependence of the average chord density of electrons and the variation of the poloidal magnetic flux $\Delta\psi$ measured by the saddle coil in the causes, when one (G1, t≥7 ms) or two (G1+G2, t ≥ 24 ms) RF-generators were switched on. It can be seen, when the second RF-generator (G2, t ≥ 24 ms) was switched on, that plasma density and energy content of plasma, which is interconnected with flux variation $\Delta\psi$, were raised. The fronts of these signals are strongly overextended because we used additional HF-filtrations to reduce the high frequency inducings.

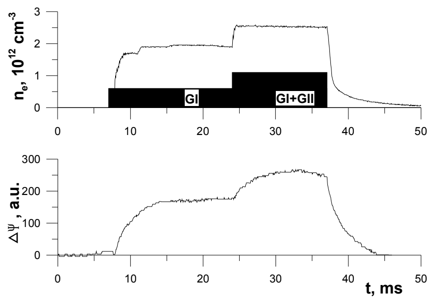

Fig.1. Time dependence of average chord density of electrons and variation of poloidal magnetic flux $\Delta\psi$ measured by saddle coil

Reliable diamagnetic measurements were obtained only during the operation of RF-generator G1 (t=7…24ms), because when RF-generator G2 was switched on, the level of high frequency inducings were increased strongly and, as a result the operation of electron integrators, was distorted. On the basis of simultaneously measurements by diamagnetic loop and saddle coil at maximal RF-power of generator G1 and under the assumption of uniform distribution of ι over the cross-section of the plasma column, the value of $\iota \approx 0.4$ was obtained.

As it is clear from expressions (5) and (7), $\bar{\beta}$ can be determined on the basis of magnetic measurements, if we know the average radius a of the plasma column. To determine a, at first, the chord distribution of spectral line radiance of neutral nitrogen NI ($\lambda = 4109$Å) was obtained using optical measurements (see Fig. 2). Then, we determined a from comparison of chord distribution of spectral line radiance of neutral nitrogen and location of calculated magnetic surfaces. Thus, during the operation of RF-generator G1, the average radius of the plasma column was equal to $a = 9$ cm. When generators G1 and G2 were switched on simultaneously, $a = 8$ cm.

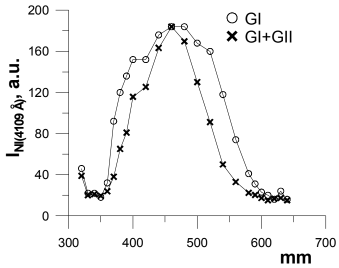

Fig.2. The chord distribution of spectral line radiance of neutral nitrogen NI ($\lambda = 4109$Å) over the vertical plane of the plasma column

During the operation of RF-generator G1 at minimal RF power, $\bar{\beta} \approx 0.45\%$ was obtained from diamagnetic measurements (in this case $a = 9$ cm). If we assume, that profile of ι is uniform and $\iota \approx 0.4$, then the value of equivalent transverse magnetic field, which is connected with the presence of plasma with $\bar{\beta} \approx 0.45\%$, will be equal to $B_\perp/B \cong \bar{\beta}/2\iota \approx 0.56\%$. In the described experiments at $\bar{\beta} = 0$ the value of the transverse magnetic field was equal to $B_\perp/B = 1.25\%$. Therefore, the total equivalent transverse magnetic field at the presence of plasma will be equal to $B_\perp/B = 1.25 + 0.56 = 1.81\%$. The previous results of investigations of magnetic configuration of U-3M [7] confirm our assumptions. As it can be seen from these results (see Fig. 3), at $B_\perp/B \approx 1.81\%$ the distribution of rotational transformation angle ι is approximately uniform over cross-section of the plasma column and ι equals to about 0.4. When we used this profile of ι in calculations of plasma pressure $\bar{P}$ on the basis of independent measurements of diamagnetic loop and saddle coil, the obtained values of $\bar{P}$ were close to each other. This confirms validity of choice of uniform profile of $\iota = 0.4$.

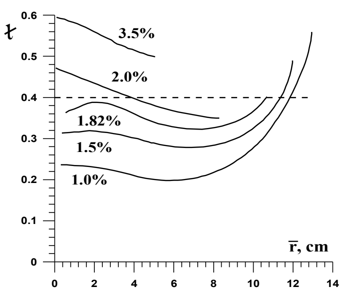

Fig.3. The calculated radial profiles of the rotational transformation angle ι at various $B_\perp/B$: 1%, 1.5%, 1.82% [7], 2.0%, 3.5% [8]

Fig. 4 shows the dependences of the average radius a of the last magnetic surface on the value of $B_\perp/B$, which were obtained during investigations of magnetic configuration of U-3M (dotted line) and from numeric calculations (solid line). It can be seen, that $a = 9$ cm obtained from optical measurements at $\bar{\beta} \approx 0.45$ is some less, than one at $B_\perp/B$ =1.81 % in both causes in Fig. 4.

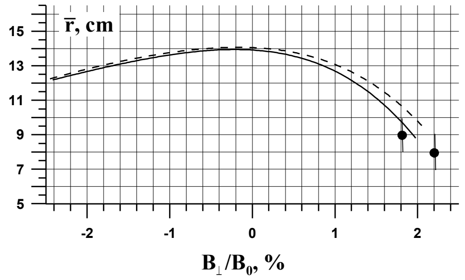

Fig.4. The calculated (solid line) [7] and measured (dotted line) average radius a of the last magnetic surface as a function of $B_{\perp}/B$

It can be seen from Fig. 3 that the rotational transformation angle of $\iota \approx 0.60$ is maximal near magnetic axis at $B_{\perp}/B \cong 3.5\%$ and than ι weakly drops towards the edge of the confinement region. It is obvious, that the value of ι must be approximately in the range of $0.4<\iota<0.6$ at values of transverse magnetic field of $1.81 < B_{\perp}/B < 3.5\%$, which corresponds to our experimental conditions. If we assume that uniform profile of ι, the maximal value of $\bar{\beta}$ of about $\bar{\beta}_{max}$ ~ 1.3% at $<\iota> = 0.5$ ($1.11 < \bar{\beta}_{max} < 1.625\%$ at $0.4<\iota<0.6$) can be obtained from (6) when a = 8 cm (generators G1 and G2 were switched on simultaneously). In this case the value of total equivalent transverse magnetic field will lie in the range of $2.175 < B_{\perp}/B < 3.28\%$. According to tendency of calculated curve in Fig. 4 (solid line) $a < 6.5$ cm at $2.175 < B_{\perp}/B < 3.28\%$. But the optical measurements give a = 8 cm. Therefore, these results allow us to conclude that disruption of magnetic configuration of U-3M at maximal values of $\bar{\beta}$, which have been achieved in our experiments, occurs slowly than it results from calculated curve in Fig. 4. In [7] the results of measurements of magnetic configuration of U-3M also give values of a, which are higher, than the calculated curve. They are close to values of a obtained from optical measurements at maximal value of $\bar{\beta}$.

The dependences of $\bar{\beta}$ on input power W are shown in Fig. 5. In this figure we assumed that input power W is proportional to square of anode voltage of generator lamp. It can be seen that dependences of $\bar{\beta}$ are linear in all range of input power W. This indicates that in our experiments the limited value of $\bar{\beta}$ is not achieved.

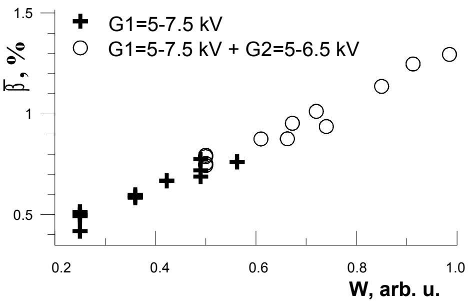

Fig.5. The dependence of $\bar{\beta}$ on input power W

CONCLUSIONS

In this study, we have investigated the influence of plasma on magnetic configuration of torsatron U-3M. During the experiments the maximal value of $\bar{\beta}$ of about $\bar{\beta}_{max}$ ~ 1.3% was obtained using nitrogen as working gas and at magnetic field induction on axis of $B_0 \approx 0.04$ T. It is shown, that the limited value of $\bar{\beta}$ was not achieved. With $\bar{\beta}$ increasing from 0 up to maximal value, which have been achieved in experiments, the average radius a of the plasma column was decreased from a = 12 cm up to a = 8 cm, respectively. The presence of plasma in the device changes the rotational transformation angle analogously to the action of uniform transverse magnetic field created by compensating coils.

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ИЗУЧЕНИЕ ВОЗДЕЙСТВИЯ ПЛАЗМЫ КОНЕЧНОГО ДАВЛЕНИЯ НА МАГНИТНУЮ КОНФИГУРАЦИЮ ТОРСАТРОНА У-3М

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На торсатроне У-3М проведена серия экспериментов по созданию режима с высоким β (до 1.3%) с использованием азота в качестве рабочего газа. Получена зависимость среднего β от вводимой мощности. Был определён средний радиус плазмы в режимах с различным β. Оценка угла врщательного преобразования была сделана с учетом наличия плазмы в установке.

ВИВЧЕННЯ ДІЇ ПЛАЗМИ КІНЦЕВОГО ТИСКУ НА МАГНІТНУ КОНФІГУРАЦІЮ ТОРСАТРОНА У-3М

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На торсатроні У-3М проведено серію експериментів по створенню режиму з високим β (до 1.3%) з використанням азоту в якості робочого газу. Отримано залежність середнього β від потужності, що вводиться. Було визначено середній радіус плазми в режимах з різним β. Оцінка кута обертального перетворення була зроблена з урахуванням наявності плазми в установці.