DYNAMICS OF LONGITUDINAL PLASMA CURRENT DURING RF PLASMA HEATING IN TORSATRON U-3M

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When investigating plasma parameters in U-3M torsatron some magnetic diagnostics are used: diamagnetic loop, Rogovski coil, and saddle coil. Before the last experimental campaign the set of 15 magnetic probes (Mirnov coils) were installed additionally in one poloidal cross-section of the torus. Using magnetic diagnostics the toroidal plasma current and angular distributions of current-produced poloidal component of magnetic field were measured for two regimes of plasma production by RF power. In the paper the characteristics of the current are presented and discussed.

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INTRODUCTION

In the U-3M torsatron ($l = 3$, $N = 9$, $R = 100$ cm, $a \approx 10$ cm, $B_\phi \approx 0.7$ T, rotational transformation angle $\iota/2\pi \leq 0.4$) hydrogen plasma is created and heated by RF fields. The start of discharge for initial plasma production is provided by means of a RF-frame-antennas operating at frequency $\omega \approx 0.8\omega_{ci}$.

In the low-density plasma regimes ($n_e \leq 2\cdot10^{12}$ cm^{-3}) we observed toroidal plasma current within the range ≤ 2 kA [1]. The nature of the current can be directly related to a movement of the plasma particles in a complex geometry of the magnetic field of a stellarator type toroidal magnetic trap (bootstrap current) [2]. In the low field conditioning discharges ($B_0 \approx 0.025$ T, $\overline{n}_e \leq 2\cdot10^{12}$ cm^{-3}) no considerable toroidal plasma current was observed. In such discharges the distribution of the magnetic field typical for the field induced by the Pfirsch-Schluter currents was measured, and spatial distribution of their magnetic field is well fitted by theoretical predictions.

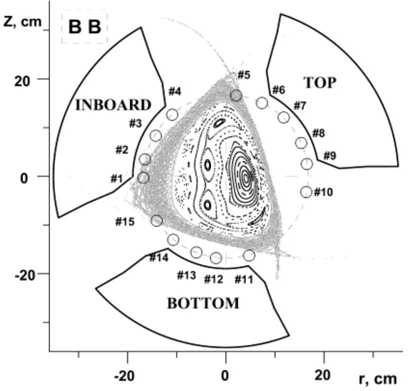

Fig. 1. The poloidal cross-section of the torus showing positions of helical coils, magnetic sensors and vacuum magnetic surfaces. The center of internal magnetic surfaces is shifted outward by 4.1 cm, whereas the external magnetic surfaces are shifted inward by 1 cm relative to geometric axis

The new diagnostics, 15 magnetic probes, were installed at radius b=16.8 cm from the torus axis, as shown in Fig. 1. The measurement were provided with the use of a set of integrators with constant of integration from 4700 up to 0.0051 μs and 16-channel analog-digital converter card with digitization speed up to 2.5 MHz. Thus, it is possible to measure the local values of poloidal component of the magnetic field generated by plasma currents at probe locations. By processing these data the information on the spatial distribution and dynamics of the currents in the plasma was obtained, what allows to obtain other information about the processes occurring in the confined plasma.

MAIN RESULTS

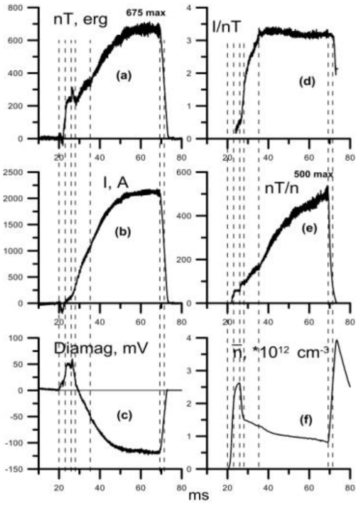

Fig. 2. The time behavior of plasma energy nT, toroidal plasma current I, signal from diamagnetic loop, the ratios of I/nT and nT/n, and average plasma density

Plasma energy content and plasma current were obtained by means of diamagnetic loop and Rogowski coil, correspondingly, the electron density averaged along central chord – by the use of interferometer with λ=2 mm. The dotted lines in Fig. 2 indicate the start and termination of RF heating 20…70 ms, as well as some other points in time, which we will pay attention below.

From Fig. 2,a it is clear that plasma energy content increases during the discharge duration and reaches the quasi-stationary value ≈ 670 erg by 15 ms before the end of RF pulse. Similarly behaves the measured toroidal plasma current (see Fig. 2,b). The average plasma density after 28 ms shows a constant reduction up to the end of RF pulse (see Fig. 2,f).

Fig. 2,d shows that constancy of *I/nT* value is observed during significant time of the discharge pulse denoting proportionality of plasma energy content and plasma current. Previously it was shown that in the mode with high magnetic field the toroidal current in plasma is a bootstrap current [2], hence it is directly proportional to the plasma pressure gradient. As seen, constancy of *I/nT* value is settled at the time when the energy content reaches the value 345 erg, and then is kept during the discharge up to 1.5 ms after RF power switched off, when the energy content value becomes less than 320 erg.

The ratio of *nT/n* could be considered as some function of electron and ion temperatures. It is clear (see Fig. 2,e) that main increase of this ratio occurred in the discharge stage where *I/nT*=const. It should be noted that increase of *nT/n* occurs during the whole stage of discharge [3]. At the final stage of discharge, 55…70 ms, where energy content reaches its saturation, the increase of temperature function is still continuing, although the average plasma density decreases (see Fig. 2,f).

Note, that in the U-3M for the considered mode, L-H transition does typically take place with increase of energy confinement time occurring [1], and this is clearly seen from the behavior of *nT* and *nT/n*. This point of time, 35 ms, marked with a dotted line, coincides with the start of time interval where *I/nT* constant ratio is maintained.

Fig. 3 presents, in polar coordinates, the magnetic field distribution of the plasma currents for 4 points in time. As seen, the poloidal distribution of the registered magnetic field has a pronounced triangular shape at quasi-stationary discharge stage. At the current rise stage, the distribution is closer to circle but shifted outward relatively to geometrical torus center. The vertexes of "triangle" are related to probes 2-3, 8, and 13. That is, as it is seen from Fig. 1, they are located just under the helical coils.

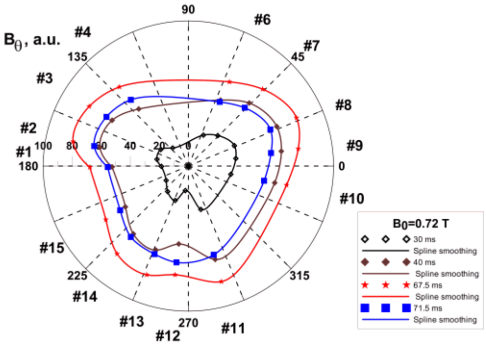

Fig. 3. Distribution in polar coordinates of magnetic field produced by toroidal current for 4 time moments

In Fig. 4 for three time intervals shown is the calculated shift in the horizontal direction of the centers of magnetic field distributions presented in Fig. 3. These calculations were carried out according to the formula: $\Delta=-b\cdot[U1-0.5(U9+U10)]/[U1+0.5(U9+U10)]$, where $U1$, $U9$ and $U10$ are signals from the sensors of corresponding numbers. Data are given for time starting from 30 ms because with lesser time the ratios of low signals lead to non-physical results. The value of Δ indicates the direction and value of the plasma current offset in horizontal direction.

As follows from Fig. 3 on the measuring surface the magnetic field has a pronounced third poloidal mode with ~0.13 amplitude relatively to zero poloidal mode.

Fig. 4,a shows that at initial discharge stage, 30 ms, the offset of magnetic distribution is positive, i.e., is directed outward and equals to 4 cm. Later in time, Δ decreases rapidly by 2.4 cm at 35 ms and by 0.6 cm at 52 ms. Afterward it stays almost unchanged up to the RF pulse end, when decreases again to negative -0.7 cm at 72 ms. At an initial discharge stage and after 2 ms later the RF power switching off Δ coincides with locations of centers of internal and external magnetic surfaces for vacuum magnetic configuration, i.e., +4 cm and -1 cm (see Fig. 1).

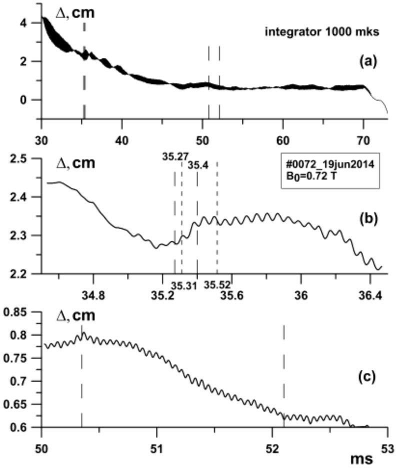

Fig. 4. Shift of the centers of magnetic field distributions

In general, a positive value Δ=4 cm at initial discharge stage denotes the peaked distribution of current density and concentration of its biggest part near the magnetic axis of the vacuum magnetic configuration. The negative Δ value denotes the strong flattening of the current profile and location of its main part inside external magnetic surfaces, the centre of which, in turn, is shifted inward.

Figs. 4,b,c show the dynamics of Δ near the time of transition into the mode of improved confinement – 35 ms. It is clear that the transition mode is followed by increase of Δ what means that the current is shifted to magnetic axis, i.e., to more picked profile of plasma current realized at the time of transition. After about 50 ms the plasma energy content strongly inhibits its rise. At this discharge stage there is a gradual decrease of Δ from 0.8 up to 0.6 cm, thus the distribution of plasma current is shifted to more peripheral surfaces.

The distribution of poloidal component of plasma current magnetic field was recorded also for the case of low magnetic field *B*=0.025 T during RF conditioning of vacuum chamber walls. The value of *nT* in this mode did not exceed 2.6 erg. The obtained distributions (Fig. 5) indicate on the presence of Pfirsch-Schluter currents in plasma in this operating mode with practical absence of longitudinal current.

The expression for the longitudinal current could be written as follows: $\vec{j}=\alpha\vec{B}$, where $\vec{j}$ – is current density, $\vec{B}$ – magnetic field induction, and α is some function of magnetic surfaces. In an *l*=3 torsatron the poloidal component of magnetic field should have 3rd poloidal mode.

Obviously, the ripple torsatrons field affects the measured spatial structure of the plasma current. We have calculated ripple of the vacuum magnetic field, ε_h, in the U-3M torsatron for the following radii: a=7.3 cm,

ε_h=0.125; a=9.0 cm, ε_h=0.151; a=9.9, cm ε_h=0.159; a=10.0 cm, ε_h=0.185. However, the measured ripple of the poloidal magnetic field components recalculated to the plasma boundary, a=10.0 cm, is 0.6, which is significantly greater than the calculated value 0.185. That is measured in the plasma toroidal current essentially depends on other parameters of the magnetic configuration.

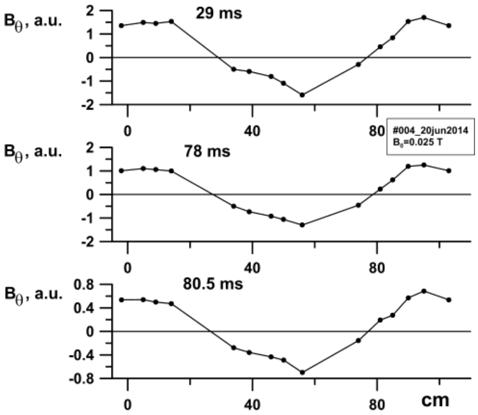

Fig. 5. Angular dependence of poloidal component of magnetic field for low magnetic field case (B=0.025 T)

CONCLUSIONS

1. Measurement of poloidal component of magnetic field were conducted using 15 magnetic sensors in one of the poloidal cross-sections of *l*=3 torsatron U-3M.
2. It is shown that the poloidal component of plasma current magnetic field is not constant on the measuring surface. At the quasi-stationary discharge stage and after switching off the RF power the poloidal distribution of the registered magnetic field has a pronounced triangular shape. At the stage of current rise the distribution is closer to circular with some shift outward relatively to geometrical torus center. The vertexes of triangle, as it is clear from Fig. 1, are located just under the helical coils.
3. For the conditioning operational mode (*B*=0.025 T) magnetic field distribution, measured by sensors, reflects the poloidal component of Pfirsch-Schluter currents; in the mode with *B*=0.72 T the distribution reflects the offset of plasma current and heterogeneity of distribution of this current both on magnetic surface and on plasma radius.
4. From the measurement of plasma current shift it could be concluded that at initial discharge stage the current is concentrated near the magnetic axis, and at quasi-stationary discharge stage the current is concentrated mainly near the edge surface, i.e., its distribution could be presented in the following way: $j = j_0(r/a)^k\left[1-(r/a)^d\right]$. Such current distribution corresponds to bootstrap current.
5. At the time of transition into the improved confinement the plasma current distribution becomes more picked and with that the current is shifted inward on 0.2 cm.
6. During the transition, the rapid increase of growth rate of plasma energy content is observed; the ratio of toroidal plasma current to plasma energy content becomes constant and is fixed at this level up to 1.5 ms after the end of RF pulse.

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ДИНАМИКА ПОВЕДЕНИЯ ОСНОВНЫХ ПАРАМЕТРОВ ПЛАЗМЫ ПРИ СПОНТАННОМ ПЕРЕХОДЕ В РЕЖИМ УЛУЧШЕННОГО УДЕРЖАНИЯ В ТОРСАТРОНЕ У-3М

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Среди методов диагностики параметров плазмы на У-3М используются некоторые магнитые: диамагнитная петля, пояс Роговского, седловидная катушка. Перед последней экспериментальной компанией 15 магнитных зондов (катушек Мирнова) были установлены дополнительно в одном из полоидальных сечений тора. Используя набор магнитной диагностики, тороидальный ток плазмы и угловое распределение полоидальной составляющей магнитного поля, создаваемого током, измерялись для двух различных режимов ВЧ-создания плазмы. Представлены и обсуждаются характеристики тока.

ДИНАМІКА ПОВЕДІНКИ ОСНОВНИХ ПАРАМЕТРІВ ПЛАЗМИ ПРИ СПОНТАННОМУ ПЕРЕХОДІ В РЕЖИМ ПОКРАЩЕНОГО УТРИМАННЯ В ТОРСАТРОНІ У-3М

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Серед методів діагностики параметрів плазми на У-3М використовуються деякі магнітні: діамагнітна петля, пояс Роговського, седловидна котушка. Перед останньою експериментальною компанією 15 магнітних зондів (котушок Мирнова) були встановлені додатково в одному з полоїдальних перетинів тора. Використовуючи набір магнітної діагностики, тороїдальний струм плазми і кутовий розподіл полоїдальної складової магнітного поля, створюваного струмом, вимірювалися під час ВЧ-розряду для двох різних режимів виробництва плазми. Представлені і обговорюються характеристики струму.