APPEARANCE OF NEOCLASSICAL EFFECTS IN PLASMA BEHAVIOR IN TORSATRON URAGAN-3M

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At present paper the existence of longitudinal current in plasma and time dependence of plasma density in experiments on torsatron U-3M are explained from the point of neoclassical theory. The time evolution of longitudinal current in plasma is explained by excitation of bootstrap current within internal areas of the plasma column and by appearance of reverse-current in the external areas of plasma. The observed rise of plasma density after RF-power cut-off is explained by influence of anomalous pinch-effect. This effect is caused by the electric field, appearing due to decrease of longitudinal current in plasma after the RF-power cut-off.

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INTRODUCTION

Neoclassical theory of plasma transport in toroidal magnetic traps based on record of particle traffic in toroidal magnetic configuration binds parameters of trap and macroscopic parameters of plasma with transport factors of heat and particles. Effect of this theory is prediction of longitudinal current generation by plasma (bootstrap-current) [1,2] and abnormal pinch effect occurrence [1,3]. Notwithstanding the fact that there is a difference between transport factors in predictions of theory and experiment reaching order of two, bootstrap-current and abnormal pinch effect observed in experiments are described quite precisely by the theory. This fact points out that the processes which provide real transport of particles and heat in experiments do not influence the distortion of distribution function caused by plasma particles movement.

Direct attempts to measure bootstrap-current have been carried out only on stellarators (see example [4]). It is explained by the fact that in stellarators in order to create magnetic configuration there is no necessity in flow of big longitudinal current on the background of which it should be registered. Nevertheless, in stellarators at bootstrap-current registration one should be certain that this current is not created by RF or HF-wave fields that provide plasma heating. Abnormal pinch effect can be observed in toroidal traps only at existence of longitudinal electric current. This effect is usually used to explain the losses of plasma particles observed in experiments on tokamaks.

Explanation of plasma behavior (existence of longitudinal current and temporal density behavior) from the point of view of neoclassical theory – existence of bootstrap-current and abnormal pinch effect – is given in this work. Besides, in this work, great attention is given to explain the longitudinal current behavior on the initial, dynamic stage of the charge.

RESULTS OF THE EXPERIMENT AND THEIR DISCUSSION

Experiments have been carried out on torsatron U-3M [5] in the mode of RF-heating at magnetic field $B \approx 7.2$ kG. Hydrogen was used as working gas. Temporal behavior of longitudinal plasma current I and other parameters of the discharge are given in the Fig. 1.

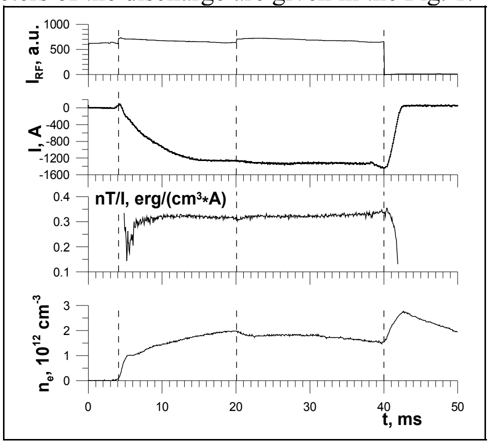

Fig. 1. Temporal behavior of the discharge parameters: I_{RF} – current in antenna of RF-heating; I –longitudinal plasma current; nT/I –energy-content plasma, measured by diamagnetic loop, ratio to longitudinal current and n_e – average plasma density

As it is clear from the Fig. 1, the longitudinal plasma current appears just after working gas breakdown and after ~ 10 ms goes to the stationary level. Value of energy-content plasma ratio to longitudinal current nT/I is almost constant along the whole length of RF pulse.

From neoclassical theory, expression for density of bootstrap-current excited on stationary stage looks as follows:

$$j_B \cong \frac{c}{B\iota}\left(\frac{R}{r}\right)^{1/2}\frac{\partial}{\partial r}nT(r) \propto nT . \qquad (1)$$

Dynamics of behavior of such current in discharge is described by expression:

$$L\frac{\partial I}{\partial t} + R^* I = R^* \alpha n T(t) . \qquad (2)$$

Here L is inductance of plasma column, R* - its resistance and α - operator that describes neoclassical electromotive force. As it is seen from expression (2), nT/I ratio can be constant only on condition when L = 0. Evidently, total inductance of plasma column in not equal to 0, therefore, we will consider that neoclassical electromotive force appears only in limited area along cross-section of plasma column in order to describe plasma current behavior. Thus, at bootstrap-current excitation in the rest part of plasma column the current of opposite sign can flow. If bootstrap-current flows in internal areas of plasma column and the current of opposite sign excites in external, then, we suppose that $nT(t)=nT_0[1-\exp(-t/\iota^*)]$, where $\iota^*=L/R^*$, solution to electro technical equation (2) looks in the following way:

$$I = I_0[1-\exp(-t/\iota^*)] \quad (3)$$

and nT/I ratio = constant on initial dynamic stage of the charge.

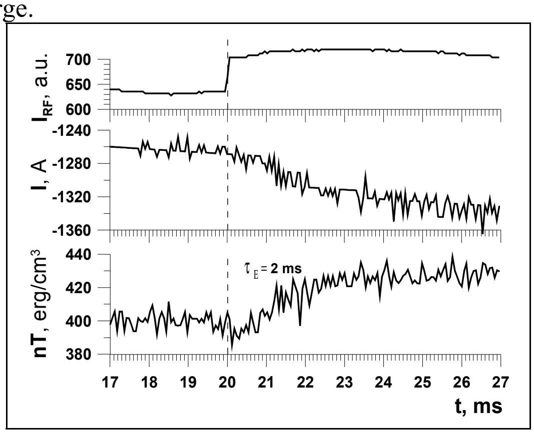

Fig. 2 Temporal behavior of I_{RF} at activation of additional power on quasi-stationary stage of the discharge, longitudinal plasma current I and energy-content plasma density nT

Addition of RF-power done on quasi-stationary stage of the discharge, as it is seen from the Fig. 2, variously influences on a temporal behavior of *nT* and *I*. It means that on quasi-stationary stage the profile T_e and n_e differs from initial stage. Reverse current, in this case, is not excited, that is confirmed by fulfilling the condition $\left.\frac{\partial I}{\partial t}\right|_{t\to 0} \cong 0$. Solution of the equation (2) allows, in this case, to determine ohmic resistance of plasma column [6]

$$R^* \cong \frac{L\left.\frac{\partial^2 I}{\partial t^2}\right|_{t\to 0}\tau_E}{I_0}. \quad (4)$$

Z ≅ 2 – average charge value in the discharge has been determined knowing the T_e(r) profile distribution [7] and conductivity.

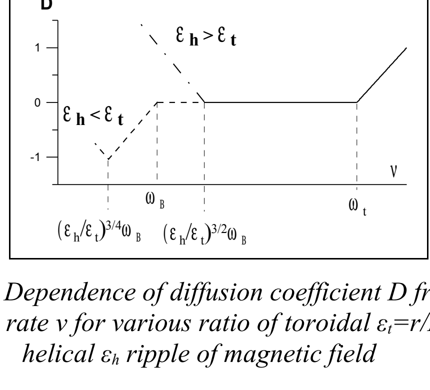

Fig.3. Dependence of diffusion coefficient D from collision rate ν for various ratio of toroidal $\varepsilon_t=r/R$ and helical ε_h ripple of magnetic field

According to neoclassical theory, the dependence of diffusion coefficient D from collision rate ν is given in the Fig. 3. Boundary value of collision rates $\nu=\omega_B= V_T\frac{\iota}{R}\left(\frac{r}{R}\right)^{3/2}$ - boundary rate of "banana" area and $\nu=\omega_t=$ [illegible] - boundary rate in the mode of "plateau", where V_T – thermal velocity of plasma particles, *t* – angle of rotational transformation and R – major plasma radius.

Fig. 4 shows spatial distribution of values of U-3M magnetic field ripple due to helical harmonics ε_h and toroidicity ε_t. It is clear that $\varepsilon_t > \varepsilon_h$ is in the bigger part of plasma column.

Fig. 5, based on the well-known distribution T_e(r) [7], n(r) [8] and assuming that Z = 2 along the whole cross-section of the pinch, distribution of collision ratio ν_e is given, and boundaries of banana ω_B and super-banana areas $\omega_B(\varepsilon_h/\varepsilon_t)^{3/4}$ for electrons. It is clear that electronic component of plasma in the range of 0.18<r/a<0.68 lies in banana area by parameters. Accuracy of determination of plasma parameters, and Z value mainly, does not allow to state the possibility of plasma existence in super-banana area. At the same time, the presence of bootstrap-current itself indicates occurrence of considerable part of plasma in banana area. Bootstrap-current can flow in the range of 0.18<r/a<0.68 that is pointed by vertical dotted line in Figs. 4 and 5. The obtained data allows to calculate the value of bootstrap-current that makes $I_B \approx 2$ kA. The calculated value of bootstrap-current differs not very much from the measured in the experiment I ≈ 1.6 kA.

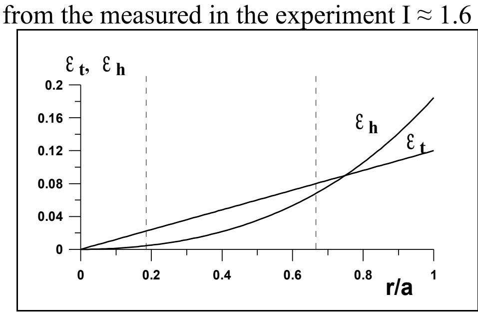

Fig. 4. Distribution of toroidal ε_t and helical ε_h of magnetic field ripples along the cross-section of plasma column in torsatron U-3M

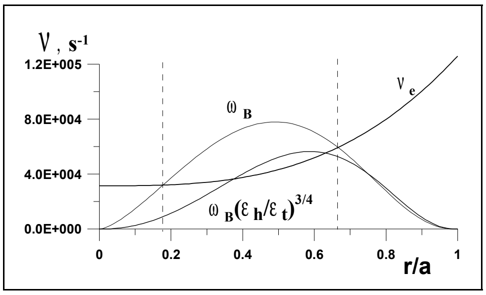

Fig. 5. Distribution of collision rate of ν_e electrons, boundary particles of banana area ω_B and super-banana area $\omega_B(\varepsilon_h/\varepsilon_t)^{3/4}$ along the cross-section of plasma column

If to pay attention to temporal behavior of density in the discussed discharge (see Fig. 1) it is clear that after switching off of RF-pulse the density increases. This problem has caused surprise to researchers since 1985. The assumption, confirmed by many experimental facts, that RF-field shields inflow of working gas into confinement area causing ionization of working gas outside the confinement volume in the area of divertor magnetic field lines, was stated in this work [7]. Apparently, that after RF-pulse is switched off the additional flow of neutral hydrogen gets to confinement area and, being ionized there, leads to increase of density. Nevertheless, it is not the only one explanation of phenomenon. If to examine carefully the process after RF-pulse was switched off you can see that increase of density starts with decrease of current and finishes in the moment of its conversion into zero. It is clearly seen in the Fig. 6.

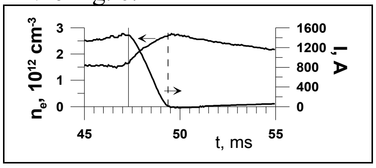

Fig. 6. Temporal behavior of average plasma density n_e and to longitudinal current I when RF-power is switched off

Evidently, that electrical field will appear after RF-field is switched off due to current decay

$$E = \frac{1}{2\pi R} L \frac{\partial I}{\partial t} \approx 4*10^{-3}\ \text{V/cm} \qquad (5)$$

Under influence of this field for plasma which is in “banana” area on collision rate (according to fig. 5 this area 0.18<r/a<0.68) the abnormal pinch effect [1] should appear and it will lead to drift of plasma inward with velocity

$$v_{dr} = c \frac{E}{\iota \frac{r}{R} B} \approx 10^3\ \text{cm/s} \qquad (6)$$

Value of drift velocity is comparable to diffusion flow which should lead to increase of density in the moment of current decay. Fig. 7 shows dependence of maximal increase value of plasma density Δn_e after RF-power is switched off and normed on density value before switching off of RF-power depending upon velocity of current decay $\partial I / \partial t$ for various meanings of power supplied to RF-antenna (W ≈ 70–150 kW) and working gas pressures ($0,6*10^{-5}$–$1*10^{-5}$ torr).

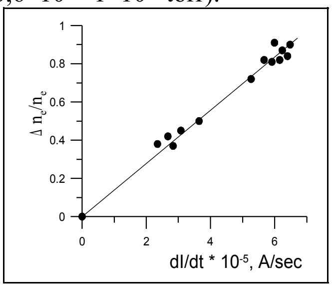

Fig. 7. Dependence of density increase value $\Delta n_e/n_e$ from velocity of longitudinal current $\partial I / \partial t$ after RF-power is switched off

It is clear that increase of density linearly depends on decay velocity of longitudinal current, i.e., from the value of appearing electric field that determines velocity of abnormal plasma pinching.

CONCLUSIONS

The work presents experimental data related to longitudinal current excitation in RF-heating mode of plasma in U-3M. The available experimental data allows to consider the observed current to be a bootstrap-current. Calculations based on available data of plasma parameters showed that banana area, where bootstrap-current can be excited, is near the column axis. Calculations of bootstrap-current value are close to experimentally measured meanings of current.

It is shown that temporal current behavior on the stage of increase is similar to *nT* behavior which is explained by excitation of bootstrap-current in internal areas of plasma column and presence of reverse current in external areas of plasma.

Increase of density when RF-heating is switched off can be explained by appearance of abnormal pinch-effect due to electric field that emerges at plasma current decay.

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ПРОЯВЛЕНИЕ НЕОКЛАССИЧЕСКИХ ЭФФЕКТОВ В ПОВЕДЕНИИ ПЛАЗМЫ В ТОРСАТРОНЕ У-3М

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Приведены экспериментальные данные, связанные с возбуждением продольного тока в режиме ВЧ-нагрева плазмы в торсатроне У-3М. На основании экспериментальных данных сделан вывод, что наблюдаемый продольный ток является бутстрэп-током. На основании расчетов показано, что банановая область, где может возбуждаться бутстрэп-ток, находится вблизи оси шнура, а расчетные величины бутстрэп-тока близки к экспериментально измеренным значениям. Объяснено временное поведение тока на стадии нарастания, а также возрастание плотности плазмы после выключения ВЧ-нагрева.

ПРОЯВЛЕННЯ НЕОКЛАСИЧНИХ ЕФЕКТІВ В ПОВЕДІНЦІ ПЛАЗМИ В ТОРСАТРОНІ У-3М

В.К. Пашнєв, Е.Л. Сороковий

Наведено експериментальні дані, які пов'язані із збудженням подовжнього струму в режимі ВЧ-нагріву плазми в торсатроні У-3М. На підставі експериментальних даних зроблено висновок, що спостережуваний подовжній струм є бутстреп-струмом. На підставі розрахунків показано, що бананова область, де може збуджуватися бутстреп-струм, знаходиться поблизу вісі шнура, а розрахункові величини бутстреп-струму близькі до експериментально виміряних значень. Пояснена тимчасова поведінка струму на стадії наростання, а також зростання щільності плазми після вимкнення ВЧ-нагріву.