DIVERTOR FLOW AND PARTICLE LOSS BEHAVIORS IN SPONTANEOUS CHANGE OF CONFINEMENT STATE IN THE URAGAN-3M TORSATRON

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Under conditions of spontaneous change of plasma confinement state having been observed recently in the U-3M torsatron with a natural helical divertor, it is shown that at the initial phase of this change all the components of the diverted plasma flow (DPF) decrease, while thermal (TI) and suprathermal (STI) ion content in the bulk plasma increases and the TI+STI fraction in the DPF is reduced on the ion $\boldsymbol{B}\times\nabla B$ drift side, thus indicating an improvement of ion confinement. The initial phase is ended by a DPF rise on the ion $\boldsymbol{B}\times\nabla B$ drift side, a TI+STI content decay in the bulk plasma and a rise of TI+STI outflow into the DPF, these being indications of an ion confinement deterioration. However, a simultaneous DPF reduction on the electron $\boldsymbol{B}\times\nabla B$ drift side and a rise of electron density and ECE indicate an improvement of electron confinement.

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1. INTRODUCTION

In the l = 3 Uragan-3M (U-3M) torsatron with a natural helical divertor and a plasma produced and heated by RF fields, spontaneous changes of electron temperature and density, stored energy and other plasma parameters occur, provided the heating power is high enough [1,2]. Similar to tokamaks with an auxiliary heating and some stellarator-type devices with NBI and ECH [3], these effects are associated with transition to an improved confinement state (hereafter, "transition"). In U-3M the transition has been shown to occur due to formation of an internal transport barrier near the τ =1/4 rational magnetic surface [2]. With this, a layer with signs of an edge transport barrier has also been shown to form near the plasma boundary [4].

It is natural to expect that the change of confinement mode should affect diverted plasma characteristics. The diverted plasma flow (DPF) in U-3M is distinct by a vertical asymmetry of its distribution [5,6], where a predominant part of the ambipolar plasma flow outflows on the ion toroidal $\boldsymbol{B}\times\nabla B$ drift side and ions predominate in the corresponding non-ambipolar flow. These effects have been related to the asymmetry of angular distribution of direct (non-diffusive) ion loss with the main contribution from suprathermal ions (STI) [5].

The main objective of this work is to find out the effect of the change of confinement state in U-3M on the DPF magnitude and the ion loss. The data having been obtained allow one to estimate, at least qualitatively, the ion loss contribution to the DPF magnitude and find out the dynamics of ion confinement during the transition.

2. EXPERIMENTAL CONDITIONS

In the U-3M torsatron (l = 3, m = 9, R_o = 1m, $\bar{a} \approx$ 0.1m, $\iota(\bar{a})/2\pi \approx 0.3$) the whole magnetic system is enclosed into a large 5 m diameter vacuum chamber, so that an open natural helical divertor is realized in this device. The toroidal magnetic field, B_ϕ = 0.7 T, is produced by the helical coils only, the ion toroidal drift $\boldsymbol{B}\times\nabla B$ is directed upward. A "currentless" plasma is produced and heated by RF fields ($\omega \approx \omega_{ci}$). The RF power deposited in the plasma is ~200 kW in the 30-50ms pulse. The working gas (hydrogen) is admitted continuously into the vacuum chamber at the pressure of ~10^{-5} Torr.

The electron temperature in the bulk plasma estimated by intensity of 2nd harmonic ECE attains $T_e(0)$ ~ 500 eV. The perpendicular ion energy distribution as determined by a CX neutral mass-energy analyzer consists of two temperature groups, T_{i1} ~ 50 eV and T_{i2} ~ 250-400 eV. As previously [5,6], to detect the DPF (by the ion saturation current, I_s, and/or by the current to a grounded probe, I_p), arrays of 1.25×0.8 cm^2 plane Langmuir probes ("divertor probe", DP) are used. The probes are arranged poloidally in the spacings between the helical coils beyond the X-point (r = 27 cm) in two symmetric poloidal cross-sections of the U-3M torus, $\phi = 0^0$ (cross-section A-A, Fig. 1(a)) and $\phi = 20^0$ (D-D, Fig. 1(b)). The gap between adjacent probes is 1 mm. The character of the energy distribution of charge particles escaping to the divertor region can be determined with the help of an array of 13 three-electrode retarding potential analyzers ("divertor electrostatic analyzer", DEA). The array is mounted beyond the X-point in the top spacing of an A-A cross-section nearest to that, where the DPs are installed (Fig.1(a)).

3. POLOIDAL CROSS-SECTION A-A

A predominant fraction of the DPF in the cross-section A-A (Fig. 1(a)) outflows to the top spacing (i.e., with the ion $\boldsymbol{B}\times\nabla B$ drift), along the divertor channel passing closer to the major torus axis ("inner leg", the I_s maximum falls at the DP N = 4). In Fig. 2 the time evolution is shown of the line-averaged electron density, $\bar{n}_e$, (a) and some other diverted and bulk plasma parameters of interest.

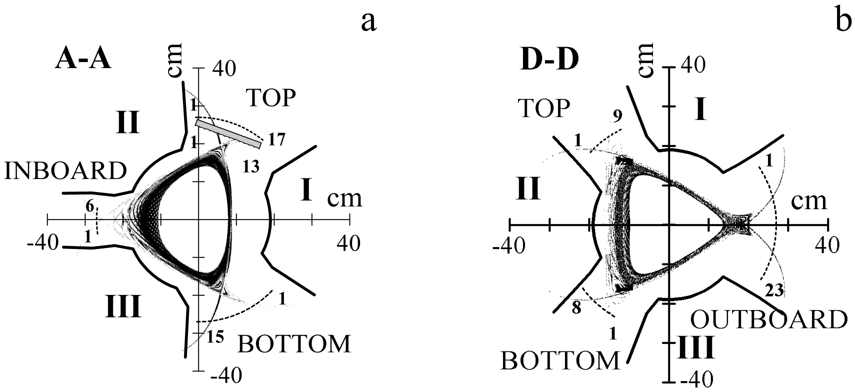

Fig. 1. Disposition of divertor probe arrays and retarding potential analyzers in the poloidal cross-sections A-A (a) and D-D (b), showing the helical coils I, II, III and the edge structure of magnetic field lines. The probes and analyzers in the top spacing of A-A are numbered as N = 1-17 and 1-13, respectively; the probe numberings in the top and outboard spacings of D-D are N = 1-9 and N = 1-23, respectively

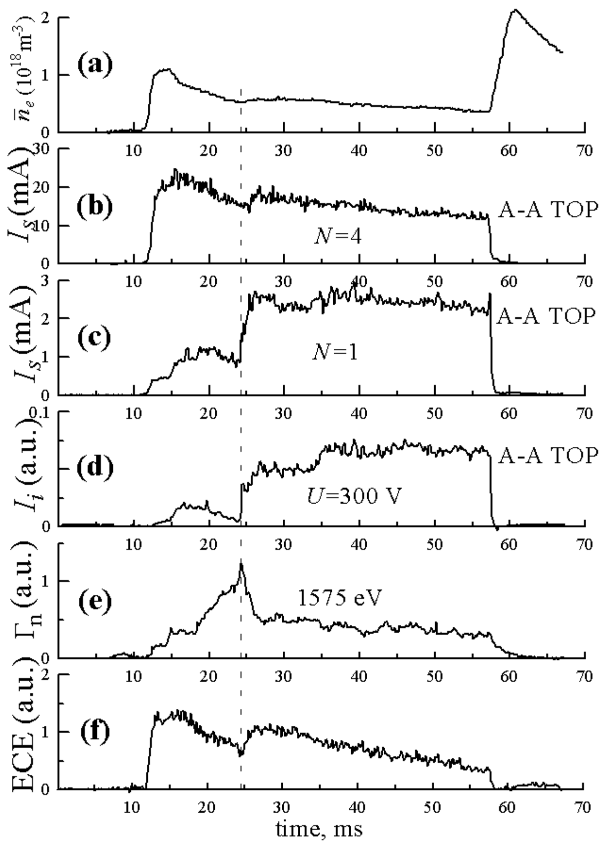

Fig. 2. Time evolution of (a) line-averaged electron density, $\bar{n}_e$, (b) ion saturation current I_s to DP N = 4 in the top spacing, (c) same to DP N = 1, (d) ion current to the analyzer No. 5 at the retarding voltage U = 300 V, (e) CX neutral flux, Γ_n, with the energy 1575 eV, (f) 2nd harmonic ECE. Starting density $\bar{n}_{e1}$ ≈ 0.6×10^{18} m^{-3}. The vertical dashed line indicates the end of the initial phase

In the shot presented the transition starts at t ≈ 21 ms, when the decaying density attains $\bar{n}_{e1}$ ≈ 0.6×10^{18} m^{-3} ("starting density") and then retains around this level for approximately 10 ms. At the beginning of this time interval ("initial phase of transition") a reduction to some minimum value is observed of the DPF (as current I_s to the DP $N = 4$, Fig. 2(b); the current I_s to DP $N = 1$ is also shown in Fig. 2(c)) and the integral ion current I_i to a DEA at the retarding voltage U = 300 V, i.e., including thermal ions (TI, group T_{i2}) and STI (Fig. 2(d)). At the same time, the flux of CX neutrals with the selected energy 1575 eV, Γ_n, increases (Fig. 2(e)), thus indicating a rise of STI content in the confinement volume. Qualitatively similar to Fig. 2(b), the maximum values of other DPF components in all the spacings of the A-A and D-D cross-sections change at the initial phase. The time behavior of Γ_n is kept qualitatively the same in the ~300-2000 eV energy interval that includes both TI (group T_{i2}) and STI. Accordingly, the ion temperature T_{i2} increases from 250 eV to ~400 eV at the initial phase (Fig. 3). At the same time, the CX neutral flux with the selected energy < 300 eV and the temperature T_{i1} ≈ 50 eV do not change substantially during the transition.

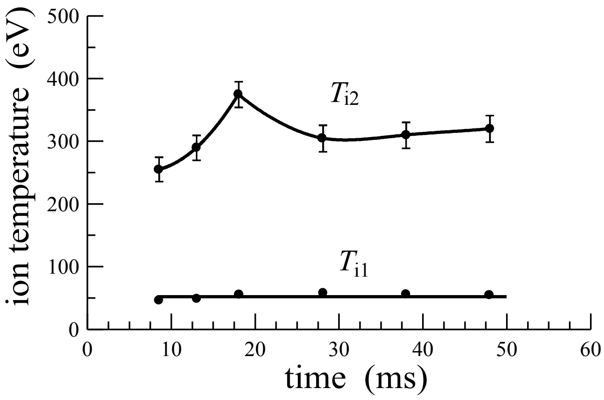

Fig. 3. Time evolution of ion temperatures T_{i1} and T_{i2}. In the case in point, the I_s minimum to the DP N = 4 occurs at t ≈ 19 ms

It follows from $I_i(U)/I_i(0)$ plots (Fig. 4) that the energy distributions of the DPF ions do not differ strongly before the transition (◇) and at the initial phase (□). With this, only ~ 10% of the outflowing ions have the energy > 400eV comparable with the average energy of the group T_{i2} ions.

Thus, the DPF decrease on the ion $\boldsymbol{B}\times\nabla B$ drift side combined with the current I_i decrease in the divertor region and the increase of the TI (group T_{i2}) and STI content and of the ion temperature T_{i2} at the initial phase confirm an improvement of plasma confinement at least for the account of ions (including STI) at this phase of transition.

The time behavior of I_s, Γ_n and I_i at the initial phase, its duration being not more than several ms, is essentially non-stationary. The I_s decay is replaced by its rise, beginning with $t \approx 25$ ms (Fig. 2(b)). With the I_s rise, a step-like I_i rise (Fig. 2(d)) and a Γ_n decay (Fig. 2(e)) correlate, thus indicating a rise of both TI and STI loss from the confinement volume. Also, the temperature T_{i2} decreases (Fig. 3).

It follows from Fig. 4 that the fraction of > 400 eV ions in the PDF attains ~ 40% at the end of the initial phase (✕). Thus, the decrease of TI and STI content in the confinement volume at the end of initial phase is consistent with the rise of more energetic fraction in the DPF. This means that the increase of DPF at the end of initial phase at least partially is caused by a rise of TI and STI loss.

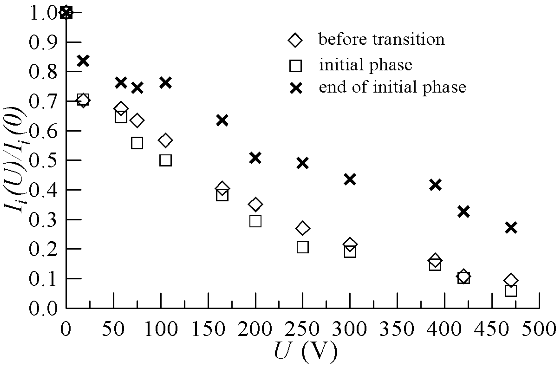

Fig. 4. $I_i(0)$-normalized ion current I_i to the collector of the analyzer No. 5 as a function of retarding voltage U: ◇, before the initial phase (t = 21 ms); □, in the minimum of I_s at the initial phase (t = 25 ms); ✕, after the end of initial phase (t = 26 ms). $\bar{n}_{e1} \approx 0.6\times10^{18}$ m^{-3}

An attention should be paid to the similarity in the signal form between the current I_s to the DP $N = 1$ in the top spacing A-A (Fig. 2(c)) and the current I_i in Fig. 2(d). This may indicate that the flows of escaping TI and STI cross the boundary of the confinement region in the process of their $\mathbf{B}\times\nabla B$ drift, not following the corresponding divertor magnetic channel.

The data similar to those shown in Figs 1,2 but taken at a higher starting density, $\bar{n}_{e1} \approx 1.3\times10^{18}$ m^{-3}, are presented in Figs 5,6, respectively. Here, in contrast to the lower $\bar{n}_{e1}$ case, the ion current to the DEA collector, I_i, undergoes a step-like fall at the end of the initial phase (Fig. 5(d)), and the ion energy distribution in Fig. 7 (✕) stays nearly the same as before the transition (◇) and at the initial phase (□). With this, the fraction of the > 400 eV ions amounts only ~ 10% like before the transition and at the initial phase in the lower density case (cf. Fig. 4). The absence of consistency during the transition between the time behaviors of the flux Γ_n with the selected particle energy < 300 eV and the temperature T_{i1}, on the one hand (unaffectedness of Γ_n and T_{i1}), and the current I_i of ions with a relatively low energy (< 400 eV) in the PDF, on the other hand (a step-like fall at the end of the initial phase) makes one to suppose that such ions occur in the DPF mainly outside the confinement region rather than diffuse from it.

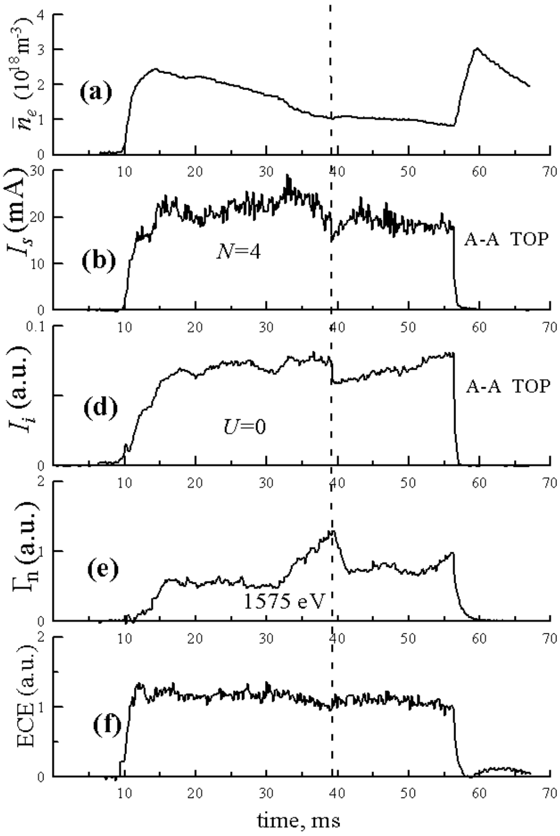

Fig. 5. Same as in Fig. 2 at the starting density $\bar{n}_{e1} \approx 1.3 \times10^{18}$ m^{-3}. The Fig. 2(c) analogue is omitted

Thus, comparing Figs 5,6 with Figs 2,3, respectively, we may suppose that the confinement improves around the cross-section A-A as the density increases. At the same time, it follows from Fig. 5(e) that the TI and STI content in the confinement volume decreases similar to the lower $\bar{n}_{e1}$ case (cf. Fig. 2(e)). Hence, we have to suppose that the main TI and STI loss with a subsequent outflow of these particles to the divertor region happens in the sections of the helical magnetic field period adjacent to the poloidal cross-section D-D. Since there are no DEAs in the cross-section D-D, this supposition can be verified only indirectly, e.g., by comparing the forms of I_s signals in D-D with those in A-A for the lower density case, where an energetic ion outflow to the divertor has been observed (Fig. 4).

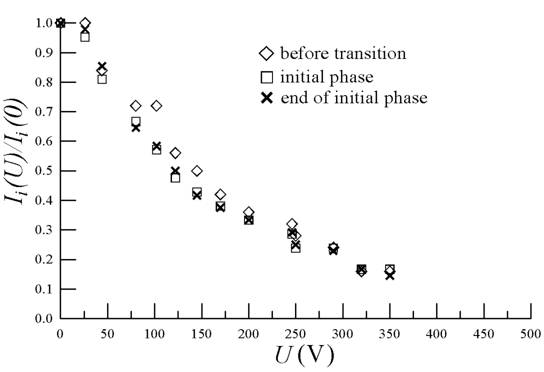

Fig. 6. Same as in Fig. 4 for $\bar{n}_{e1} \approx 1.3\times10^{18}$ m^{-3}

4. POLOIDAL CROSS-SECTION D-D

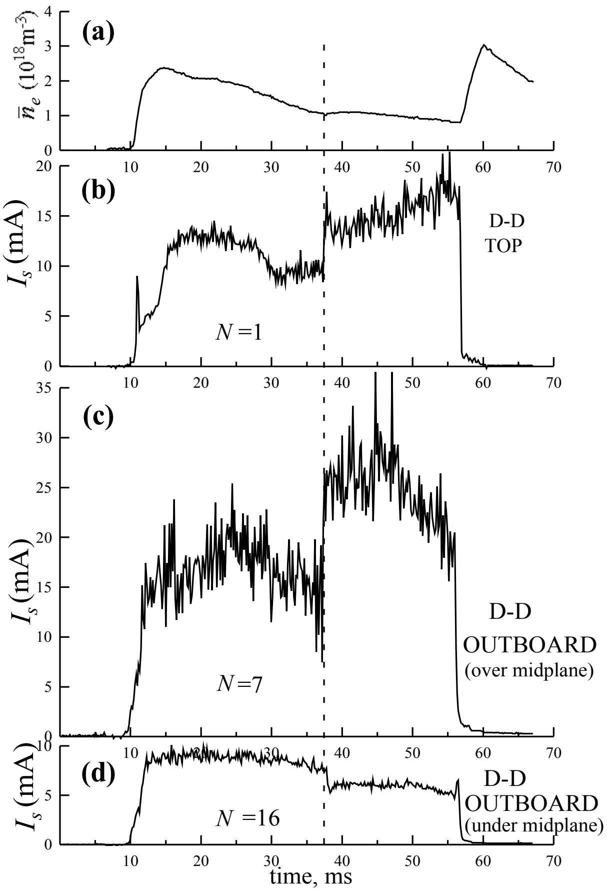

Fig. 7. Time behavior of (a) line-averaged electron density, $\bar{n}_e$, (b) ion saturation current I_s to DP N = 1 in the top spacing, (c) same to DP N = 7 in the outboard spacing, (d) same to DP N = 16 in the outboard spacing.The vertical dashed line indicates the end of initial phase. $\bar{n}_{e1}$ ≈ 1.3×10^{18} m^{-3}

Top spacing. Due to peculiarity of the edge magnetic structure, only a single, inner magnetic channel is distinctly formed beyond the X-point (Fig. 1(b)). A predominant fraction of the DPF is concentrated in the top spacing (I_s maximum at the DP N = 1,2). The signal of I_s to the DP N = 1 at $\bar{n}_{e1}$ ≈ 1.3×10^{18} m^{-3} (Fig. 7(b)) is similar by its form to the signal I_s to the DP N = 1 and to the TI and STI current I_i to the DEA collector in the top spacing of A-A at $\bar{n}_{e1}$ ≈ 0.6×10^{18} m^{-3} (Figs 2(c) and 2(d), respectively). On the basis of such a similarity, we may hypothesize that the step-like DPF rise at the end of the initial phase seen in Fig. 7(b) results from a TI and STI loss rise around the cross-section D-D.

Outboard spacing. Two symmetric magnetic channels emerge from the X-point to this spacing (Fig. 1(b)). In the $\bar{n}_{e1}$ ≈ 1.3×10^{18} m^{-3} case, similar to the top spacing of D-D, the time evolution of the current I_s maximum over the midplane (DP N = 7) at the initial phase is ended by a step-like I_s increase (Fig. 7(c)), thus pointing to a possible TI and STI loss rise.

It is known [7] that the non-ambipolar DPF under the midplane (N = 16-21) is characterized by a large and broad peak of negative current I_p [7], its absolute value exceeding the currents I_s and I_p in other divertor legs of both A-A and D-D cross-sections. This indicates a major fraction of lost electrons to fall into the divertor region just on the outboard torus side near the midplane. In contrast to the DPF in the top spacing (Fig. 7(b)) and in the outboard spacing over the midplane (Fig. 7(c)), the flow under the midplane undergoes a step-like *drop* in both I_s (Fig. 7(d) and I_p at the end of initial phase. Accounting for the mentioned above, this indicates a possible electron loss decrease and, consequently, an improvement of electron confinement. In particular, such a conclusion is consistent with an $\bar{n}_e$ and ECE rise at the end of the initial phase (Figs 2(a), 5(a), 7(a) and 2(f), 5(f), respectively).

5. SUMMARY

1. According to the measurements having been carried out in two symmetric poloidal cross-sections of the U-3M torus, A-A and D-D, with a spontaneous change of the confinement mode, a short-time decrease of all the DPF components occurs, thus indicating a reduction of particle loss at this phase ("initial phase of transition").

2. At the initial phase the TI (group T_{i2}) and STI content increases in the confinement volume, while at $\bar{n}_{e1}$ < 10^{18} m^{-3} the fraction of such ions decreases in the PDF on the ion toroidal $\boldsymbol{B}\times\nabla B$ drift side. This is an evidence of an ion confinement improvement at this phase. The low energy ions (group T_{i1}) do not respond to the change of the confinement mode.

3. The rise of all the DPF components at the end of the initial phase evidences a plasma loss increase. This increase correlates with a decay of TI (group T_{i2}) and STI content in the confinement volume. With this, an abrupt increase of the fraction of such ions in the PDF on the ion toroidal $\boldsymbol{B}\times\nabla B$ drift side is observed in A-A at $\bar{n}_{e1}$ < 10^{18} m^{-3}. For the case considered this means that the plasma loss rise at the end of the initial phase at least partially results from a deterioration of the TI and STI confinement.

4. In the higher starting density case, $\bar{n}_{e1}$ > 10^{18} m^{-3}, a rise of the energetic ion fraction in the PDF is not observed in A-A at the end of the initial phase. However, comparing the PDF time behavior in D-D on the ion $\boldsymbol{B}\times\nabla B$ drift side with that in A-A at $\bar{n}_{e1}$ < 10^{18} m^{-3}, we may suppose that the observed decrease of the TI and STI content at the end of the initial phase results from an escape of these ions in the vicinity of the D-D cross-section.

5. In the outboard spacing of the D-D cross-section on the electron $\boldsymbol{B}\times\nabla B$ drift side, where a considerable part of lost electrons supposedly outflows, a step-like drop of DPF is observed at the end of the initial phase. Combined with an observation of an $\bar{n}_e$ and ECE increase, we may suppose an improvement of electron confinement at the end of initial phase of transition.

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ПОВЕДЕНИЕ ДИВЕРТОРНОГО ПОТОКА И ПОТЕРЬ ЧАСТИЦ ПРИ СПОНТАННОМ ИЗМЕНЕНИИ СОСТОЯНИЯ УДЕРЖАНИЯ ПЛАЗМЫ В ТОРСАТРОНЕ «УРАГАН-3М»

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В условиях обнаруженного ранее спонтанного изменения режима удержания в торсатроне У-3М с естественным винтовым дивертором показано, что на начальной стадии этого изменения уменьшаются все составляющие плазменного диверторного потока (ПДП) и растёт содержание тепловых (ТИ) и сверхтепловых (СТИ) ионов в основной плазме, свидетельствуя об улучшении их удержания. Начальная стадия завершается возрастанием ПДП на стороне ионного дрейфа $\boldsymbol{B}\times\nabla B$, уменьшением содержания ТИ и СТИ в основной плазме и повышенным их уходом в ПДП, что говорит об ухудшении удержания ионов. Однако, при этом уменьшается ПДП на стороне электронного дрейфа $\boldsymbol{B}\times\nabla B$ и растут плотность электронов и электронное циклотронное излучение, что указывает на улучшение удержания электронов.

ПОВЕДІНКА ДИВЕРТОРНОГО ПОТОКУ ТА ВТРАТ ЧАСТИНОК ПРИ СПОНТАННІЙ ЗМІНІ СТАНУ УТРИМАННЯ ПЛАЗМИ В ТОРСАТРОНІ "УРАГАН-3М"

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В умовах виявленої раніше спонтанної зміни режиму утримання в торсатроні У-3М з природним гвинтовим дивертором показано, що на початковій стадії цієї зміни зменшуються всі складові плазмового диверторного потоку (ПДП), в той час, як зростає кількість теплових (ТІ) та надтеплових (НТІ) іонів в основній плазмі, засвідчуючи про покращення їх утримання. Початкова стадія завершується зростанням ПДП на боці іонного дрейфу $\boldsymbol{B}\times\nabla B$, зменшенням кількості ТІ та НТІ в основній плазмі та підвищеним виходом їх до ПДП, що є ознакою погіршення утримання іонів. Але одночасне зменшення ПДП на боці електронного дрейфу $\boldsymbol{B}\times\nabla B$ і зростання електронної густини та електронного циклотронного випромінювання вказують на покращення утримання електронів.