

EFFECTS OF PLASMA HEATING ON THE MAGNITUDE AND DISTRIBUTION OF PLASMA FLOWS IN THE HELICAL DIVERTOR OF THE URAGAN-3M TORSATRON

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Recently, a strong up-down asymmetry in the poloidal distributions of diverted plasma flows has been observed in the $l = 3/m = 9$ Uragan-3M torsatron, in many features similar to what have been observed in the $l = 2$ Heliotron E heliotron/torsatron. With this asymmetry, the predominant outflow of the diverted plasma is directed with the ion toroidal drift. On this basis, the asymmetry can be related to the space non-uniformity of the charged particle loss. In the work reported, the magnitude of divertor flow in U-3M and the vertical asymmetry in its distribution are studied as functions of the heating parameter P/\bar{n}_e , P being the power absorbed in the plasma, and are juxtaposed with corresponding P -related changes in the density \bar{n}_e and fast ion content in the plasma. As P/\bar{n}_e increases, an increase of fast ion content and of particle loss, on the one hand, and an increase of divertor flow magnitude and of vertical asymmetry of the flow, on the other hand, are observed. A mutual accordance between these processes validates the hypothesis on a dominating role of fast particle loss in formation of vertical asymmetry of divertor flows in helical devices.

PACS: 52.55.Fa; 52.55.Rk

1. INTRODUCTION

Experimental studies of spatial distributions of plasma flows in the natural helical divertor of the $l = 2$ Heliotron E (H-E) heliotron/torsatron with NBI and ECH have shown [1,2] that a strong vertical asymmetry of these distributions is possible in helical devices. This conclusion has been confirmed by measurements of plasma flow distributions in the helical divertor of the $l = 3$ Uragan-3M (U-3M) torsatron with RF heated plasmas [3]. In many characteristics, the asymmetries in H-E and U-3M are similar, despite a substantial difference of these devices in magnetic configuration, plasma heating methods and plasma parameters, this being an indication of universality of this effect. Recently, some manifestations of vertical asymmetry in the distribution of diverted plasma parameters have been also revealed in the $l = 1$ Heliotron J device with a helical magnetic axis [4].

The existence of many-fold difference in the values of particle and energy fluxes to symmetrically positioned target plates can raise serious problems with the heat removal in future helical devices of ITER scale. Therefore, a search for the nature of divertor flow asymmetry should become an important issue of divertor research.

With magnetic field reversal in U-3M, the larger divertor flux is always observed on the ion toroidal drift side. On these grounds it is supposed [3] that a substantial contribution to the asymmetry is made by those fast ions, which are trapped into helical magnetic field ripple wells and, not "filling" the rotational transform, left the confinement volume due to the non-compensated toroidal drift [5]. Such a possibility has been confirmed by the results of calculations of angular distribution of particle direct loss in U-3M [3].

The objective of this work is to find out a possible link between plasma heating in U-3M and the magnitude of

divertor flow and the asymmetry of its distribution. In the studies reported, a qualitative correlation has been found between the heating power, the rate of particle loss and fast ion content, on the one hand, and the magnitude of divertor flow and degree of its vertical asymmetry, on the other hand.

2. EXPERIMENTAL CONDITIONS

In the $l = 3/m = 9$ U-3M torsatron ($R_0 = 1$ m, $\bar{a} \sim 0.1$ m, $\iota(\bar{a}) \approx 0.4$) an open helical divertor is realized. The magnetic field $B_0 = 0.7$ T is generated by the helical coils only. A hydrogen plasma is RF produced and heated ($\omega \leq \omega_{ci}$). The line-averaged electron density \bar{n}_e can attain $\sim 10^{19}$ m⁻³. The RF power P absorbed in the plasma attains 240 kW in the 50 ms pulse.

The diverted plasma is detected by 78 plane 1.25×0.8 cm² Langmuir probes. Six probe arrays are arranged poloidally in the spacings between the helical coils in two half-field-period separated symmetric poloidal cross-sections of the torus $\phi = 0^\circ$ (A-A) and $\phi = 20^\circ$ (D-D) as is shown in Fig. 1. The gap between the plates in an array (0.1 cm) is much less than the plate size in the poloidal direction (1.25 cm).

Two operating regimes are used specified by the pressure of hydrogen admitted continuously into the vacuum vessel. In the "lower pressure regime" (LPR, units 10^{-5} Torr), the plasma occurs at $P \approx 80$ kW. The level of quasi-steady state density \bar{n}_e is determined by the balance between ionization of the gas entering the confinement volume and plasma escape. At $P \approx 80$ kW \bar{n}_e takes $(2.5 \div 1.5) \times 10^{18}$ m⁻³. As P increases, \bar{n}_e gradually falls up to $(1.0 \div 0.7) \times 10^{18}$ m⁻³ at $P \approx 240$ kW (Fig. 2). The existence of a heating-related plasma loss is also evidenced by a short-time \bar{n}_e rise occurring after RF pulse switched off (Fig. 2, inset).

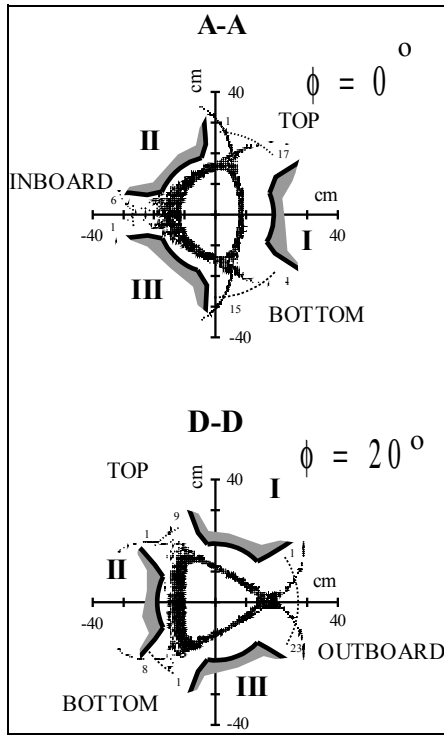


Fig. 1. Disposition of Langmuir probe arrays in the symmetric poloidal cross-sections A-A and D-D. Shown are the helical coils I, II, III and the calculated edge structure of the magnetic field. The probe numbering of interest in A-A: top spacing, 1-17; bottom spacing, 1-15. in D-D: top spacing, 1-9; bottom spacing, 1-8.

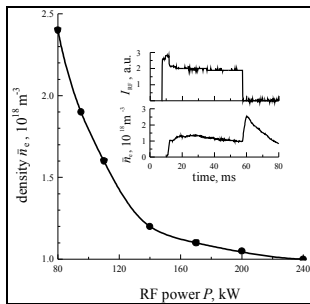


Fig. 2. Quasi-steady state line-averaged electron density \bar{n}_e as a function of absorbed RF power P at a fixed hydrogen pressure. In the inset, time traces of RF current in the antenna I_{RF} (envelope) and density \bar{n}_e .

In the “higher pressure regime” (HPR, units 10^{-4} Torr.), \bar{n}_e attains $(7 \div 10) \times 10^{18} \text{ m}^{-3}$. When studying the power dependence of divertor flow magnitude, both ion saturation current I_s and P are normalized by \bar{n}_e . In LPR, the range of P/\bar{n}_e values ($30 \div 320$) $\text{kW}/10^{18} \text{ m}^{-3}$ is covered. In HPR, P/\bar{n}_e can be reduced up to $\sim 10 \text{ kW}/10^{18} \text{ m}^{-3}$.

With $P \approx 240 \text{ kW}$ in LPR, the ECE-estimated electron temperature attains $T_e(0) \approx 300 \div 400 \text{ eV}$, while it does not exceed 20 eV in HPR.

The energy spectrum (ES) of plasma ions as measured by an CX neutral energy analyzer oriented normally to the torus midplane is distinguished by a slowly decaying high energy tail. For $P/\bar{n}_e = 300 \text{ kW}/10^{18} \text{ m}^{-3}$ a “perpendicular temperature” of $T_{i1} \sim 60 \text{ eV}$ can be assigned to the majority ($\sim 90\%$) of ions. Also, two minor groups of faster ions with “temperatures” $T_{i2} \approx 326 \text{ eV}$ and $T_{i3} \approx 900 \text{ eV}$

can be conventionally separated. The presence of the T_{i1} and T_{i2} groups is confirmed by the form of CV 227,1 nm profile. The high energy tail also remains for lower P/\bar{n}_e . However, as P increases, the relative content of low energy ions (T_{i1} group) does not change appreciably, while that of higher energy ions grows, with the growth rate increasing with energy (Fig. 3).

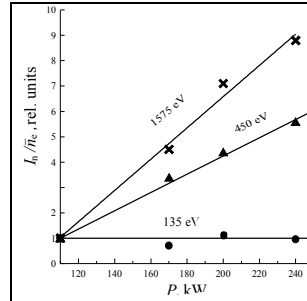


Fig. 3. Relative contents I_n/\bar{n}_e of ions with three fixed energies as functions of heating power P .

The heating related behavior of \bar{n}_e and ion energy can cause to a great extent the peculiarities, which are observed in the behavior of diverted plasma during the heating.

3. EFFECTS OF PLASMA HEATING ON DIVERTOR FLOWS

The effect of plasma heating on the magnitude and spatial distribution of diverted plasma flows in the symmetric cross-sections A-A and D-D is displayed most clearly in the flows, entering the top and bottom spacings between the helical coils. As an example, the poloidal distributions of these flows are shown in Fig. 4 (A-A) as

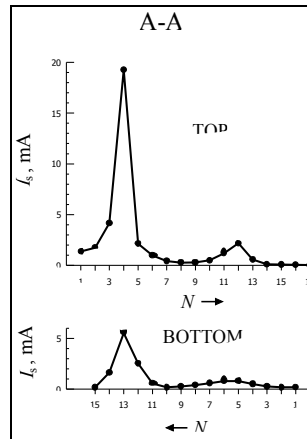


Fig. 4. Ion saturation current I_s vs probe number N in the top and bottom spacings between the helical coils in the poloidal cross-section A-A.

$I_s(N)$ plots taken in LPR with $P \approx 240 \text{ kW}$ and B_ϕ directed counterclockwise. The higher maxima at the top and bottom belong to the divertor legs located closer to the major axis. The I_s maxima in symmetric legs are several times different at the top and bottom, with the larger flow being directed upward, i.e., with the ion $\mathbf{B} \times \nabla B$ drift.

In Fig. 5 presented are I_s/\bar{n}_e (maximum values) vs P/\bar{n}_e plots for the top and bottom spacings in A-A. The data for both LPR (\circ) and HPR (\bullet) are used. The same plots for D-D have a similar form. In both cross-sections I_s/\bar{n}_e tends to grow with P/\bar{n}_e on the ion toroidal drift side. The maximum I_s/\bar{n}_e values are comparatively close at the top and bottom for the smallest P/\bar{n}_e values,

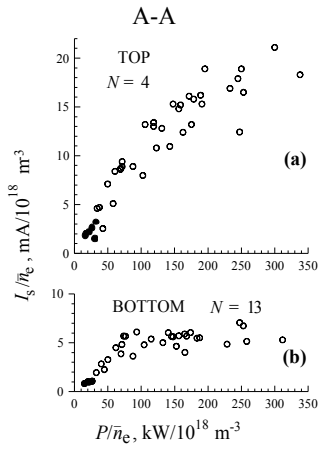


Fig. 5. Maximum values of \bar{n}_e - normalized ion saturation current I_s vs heating parameter P/\bar{n}_e in the top and bottom spacings between the helical coils in the poloidal cross-section A-A.

$10 - 20 \text{ kW}/10^{18} \text{ m}^{-3}$, their ratio α not exceeding ~ 2 . As P/\bar{n}_e increases, the flow grows more rapidly at the top, and α can attain ~ 10 for $P/\bar{n}_e \sim 300 \text{ kW}/10^{18} \text{ m}^{-3}$. The same holds for D-D. Thus, the degree of vertical asymmetry of divertor flows is a rising function of heating power (Fig. 6).

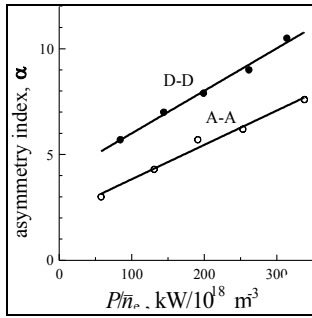


Fig. 6. The asymmetry index α as a function of heating parameter P/\bar{n}_e in the poloidal cross-sections A-A and D-D. The lower pressure regime.

4. SUMMARY AND DISCUSSION

In summary, the following processes are observed at the same time as the absorbed RF power increases.

In the confinement volume:

- charged particle loss increases; this is displayed in a reduction of quasi-steady state value of \bar{n}_e (Fig. 2);
- relative fast ion content increases, with the growth rate being a rising function of ion energy (Fig. 3).

In the divertor region:

- the total flow of diverted plasma increases (Fig. 5);
- a predominant rise of the diverted plasma flow in the ion toroidal drift direction, with the asymmetry index α rising with power (Fig. 6).

In view of ideas having been developed in [3], the following causality can be suggested for the processes observed. The heating power increase results in a rise of fast ion relative content (Fig. 3). Due to a poor confinement of these particles, particle loss increases and

the density \bar{n}_e decreases (Fig. 2), on the one hand, while the diverted plasma flow increases (Fig. 5), on the other hand. A dominating contribution to the particle loss is made by those fast banana ions, which become trapped into the helical ripple wells and leave the confinement volume due to the toroidal drift. Therefore, a dominating rise is undergone by plasma flows in the top spacings between the helical coils (Fig. 5). In turn, this results in a rise of vertical asymmetry of divertor flow (Fig. 6).

The range of P/\bar{n}_e values used in these studies allows to cover a wide range of characteristic collision frequencies, which govern the character of charged particle loss from the confinement volume (Fig. 7). In the higher density discharges (small P/\bar{n}_e , \bullet in Fig. 5) predominant orbit losses are limited by the plato (*pl*) or banana (*b*) diffusion and, therefore, the asymmetry of divertor flow is small. With P rise and \bar{n}_e decrease, the diffusion regime of ion-ion collisions shifts into the region of lower frequencies with higher transport coefficients. Since the diffusion in the velocity space is of stochastic character in its nature, it results in a uniform scattering of particles in the co-ordinate space. Therefore, the rise of diffusion (non-direct) ion loss can lead to only total value of the divertor flow increase without changing its asymmetry. In the lower density discharges (large P/\bar{n}_e , \circ in Fig. 5), the diffusion in the $1/\nu$ collisional regime typical for most of $>250 \text{ eV}$ ions, does not prevent the banana ions to be trapped into helical ripple wells. As a result, a considerable fraction of these particles enters the divertor region in the upper half of the torus, increasing the vertical asymmetry of the divertor flow.

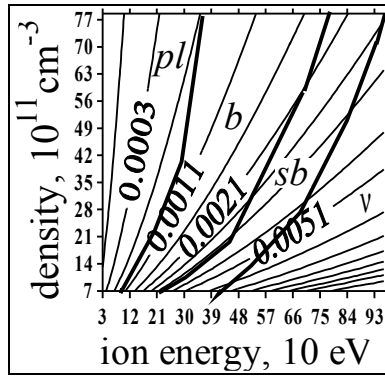


Fig. 7. Ion-ion collision time vs density and ion energy. The boundaries of corresponding diffusion regimes are indicated by bold lines.

This work was carried out in collaboration with NIFS (Toki, Japan) by the Program LIME

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