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Fine Structure of Divertor Flow Distributions in the l = 3 Uragan-3M Torsatron

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Abstract

An up-down asymmetry is inherent to the spatial distributions of divertor plasma flows in the l=3 Uragan-3M (U-3M) torsatron, similar to the l=2 Heliotron E heliotron. This asymmetry is attributed to convective losses of charged particles. Measurements of poloidal distributions of divertor flows carried out with sufficiently high resolution also reveal some other specific properties of these distributions, namely, (1) the existence of a pair of non-ambipolar flows of opposite sign corresponding to the basic ambipolar flow in a divertor leg; (2) a splitting of ambipolar flow; (3) the presence of a comparatively large non-ambipolar flow with an excess of electrons outflowing near the torus midplane; (4) a comparatively high ion saturation current and corresponding negative current to a grounded electric probe in the divertor private region. Physical mechanisms are discussed, which could result in the above mentioned structural features of divertor flows in U-3M.

Keywords:

heliotron, torsatron, helical divertor, up-down asymmetry, ambipolar flow, non-ambipolar flow, plasma drift

1. Introduction

Measurements of poloidal distributions of plasma flows in the natural helical divertors of the l=2 Heliotron E heliotron (H-E) [1-4] and the l=3 Uragan-3M (U-3M) torsatron [5] have revealed a strong up-down asymmetry of these distributions. The main characteristics of the asymmetry are (1) a many-fold difference in the ambipolar particle flow magnitude in the divertor legs symmetrically positioned in the top and bottom parts of the torus and (2) opposite polarity of corresponding non-ambipolar flows. In H-E, with low and medium levels of heating power (ECH, NBI, NBI+ECH), and in U-3M, with a fixed regime of RF plasma heating, a non-ambipolar flow with an excess of ions corresponded to the larger ambipolar divertor flow. Both these flows were directed with the ion toroidal $\boldsymbol{B} \times \nabla B$ drift. Basing on this, the observed asymmetry is related to direct (non-diffusive) charged particle losses from the confinement volume. Such a relation has been confirmed by results of numerical simulations of fast particle losses in U-3M [5] and H-E [6]. The simulations

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have really shown a strong up-down asymmetry of poloidal distributions of these losses with a predominant escape of fast ions in the ion toroidal $\boldsymbol{B} \times \nabla B$ drift direction.

In both devices the diverted plasmas were detected by arrays of plane electric probes, and the ion saturation current (ISC) I_s was taken as a measure of plasma flow magnitude. Such an estimation is valid, if the flow hits an isolated probe (or target plate). In this case, the flow is ambipolar and the total electric current to the probe is $I = I^+ + I^- = 0$, where $I^+ \equiv I_s$. However, if a plasma flow hits the chamber wall or a probe (target plate) short-circuited to the wall, then the flow can be essentially non-ambipolar. In this case, the probe current ("grounded probe current", GPS) I_g, its sign and value, can be taken as characteristics of flow non-ambipolarity. The spatial distributions of divertor flows in U-3M were measured with a higher resolution as compared with H-E. Owing to this, some new peculiar features of these distributions have been observed. These features indicate an obvious non-uniformity of plasma flow characteristics even within one divertor leg, some of these features being presumably related to plasma drift effects in the SOL and divertor region. The account of such a non-uniformity may appear necessary, when designing the divertor facility for a large device of heliotron/torsatron type.

2. Experimental Conditions

The U-3M device is an $l = 3/m = 9$ torsatron ($R_0 =$ 1 m, $\bar{a} \approx 0.12$ m, $B_\phi = 0.72$ T, $\iota(\bar{a}) \approx 0.4$). The whole magnetic system is enclosed into a large vacuum chamber, with the minor radius of the helical coil casings being 0.19 m, so an open helical divertor is realized in this device. Diverted plasma parameters are measured with B_ϕ directed both counterclockwise ("positive field", the ion toroidal $\boldsymbol{B} \times \nabla B$ drift is directed upward) and clockwise ("negative field"). A hydrogen plasma is RF produced and heated ($\omega = 0.8\omega_{ci}(0)$), with the irradiated RF power $P \approx 200$ kW in the 25 ms pulse as a standard operating regime. The electron density is $\bar{n}_e \approx 2 \times 10^{18}$ m^{-3}. The electron (ECE) and ion (CX analyzer) temperatures are $T_e \approx 0.3$ keV and $T_i \approx 0.1$ keV, respectively. Also, minor groups of suprathermal electrons (≥ 1 keV at the confined plasma periphery) and ions (0.2–0.3 and 0.6–0.8 keV) are detected.

To detect the diverted plasma, 78 plane 1.25×0.8 cm^2 electric probes are used. The probes are grouped in 6 arrays. The arrays are arranged poloidally in the

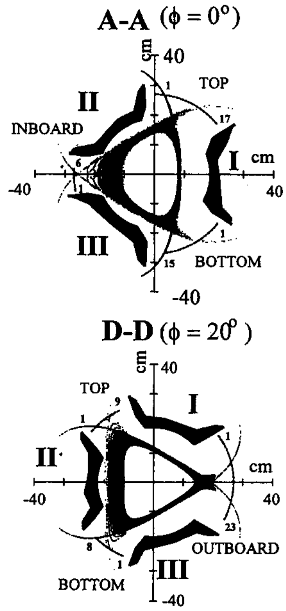

Fig. 1 Lay-out of electric probe arrays in the symmetric poloidal cross-sections of the U-3M torus A-A and D-D. Shown are the helical coils, I, II, III and Poincare plots of edge field lines. The probe numbers N in A-A: 1-17 (top), 1-15 (bottom, in D-D: 1-23 (outboard)

spacings between the helical coils beyond the X-point at the minor radius 0.27 m in two half period-separated "symmetric" poloidal cross-sections of the torus with different configuration of field lines in the divertor region: $\phi = 0°$ (cross-section A-A) and $\phi = 20°$ (cross-section D-D) as is shown in Fig. 1. From the viewpoint of the present work, an important feature of the cross-section D-D is the existence of the outboard spacing between the helical coils with two divertor legs symmetric about the midplane. As it will be shown below, however, the structural features of the plasma flows in these legs occur quite different. The spacing between adjacent probes (0.1 cm) is considerably less than the probe size in the poloidal direction (1.25 cm).

3. Peculiarities of Divertor Flow Structure

3.1 Cross-section A-A

For the standard regime of device operation, poloidal distributions of ambipolar divertor flows in the top and bottom spacings between the helical coils are presented in Fig. 2(a) as current I_s versus probe number N plots (positive magnetic field). Within the accuracy of probe array adjustment and the array resolution, the positions of I_s maxima ($N = 3$ and $N = 11$ at the top, $N =$ 7 and $N = 15$ at the bottom) correspond to the calculated positions of the divertor legs (cf. Fig. 1). The $I_s(N)$ distributions are distinguished by an up-down asymmetry [5], with the I_s maximum in the inner leg at the top being 2.4 times higher than that at the bottom. The direction of the larger divertor flux outflow (upward) corresponds to that of the toroidal ion $\boldsymbol{B} \times \nabla B$ drift. The largest absolute values of GPC in the corresponding $I_g(N)$ distributions (Fig. 2(b)) fall at the probes, recording the I_s maxima, and the GPC maxima have opposite polarity at the top and the bottom. With this, the maximum of GPC with an excess of ions ($I_g > 0$) corresponds to the higher ISC maximum (at the top), thus confirming the effect of the toroidal ion $\boldsymbol{B} \times \nabla B$ drift on the up-down divertor flow asymmetry.

Also, a more fine structure of the $I_g(N)$ distributions can be seen in Fig. 2(b), where a small I_g maximum of opposite polarity adjoins to each main maximum both at the top and bottom. At the top, these additional maxima of negative polarity are shifted poloidally clockwise relative to their main (positive) maxima, when being seen in the positive magnetic field direction. At the bottom, the additional maxima of $I_g > 0$ are shifted counterclockwise relative to the main (negative) maxima. The adjacent plasma currents of opposite sign exist with all levels of heating power.

With magnetic field reversal, together with reversal of the asymmetry of ambipolar divertor flows in their magnitude, a change of GPC sign occurs in corresponding non-ambipolar flows, including the sign of I_g in the adjoining flows. This means that the observed polarization of flows and occurrence of adjoining flows could be related to a charged particle drift across magnetic field.

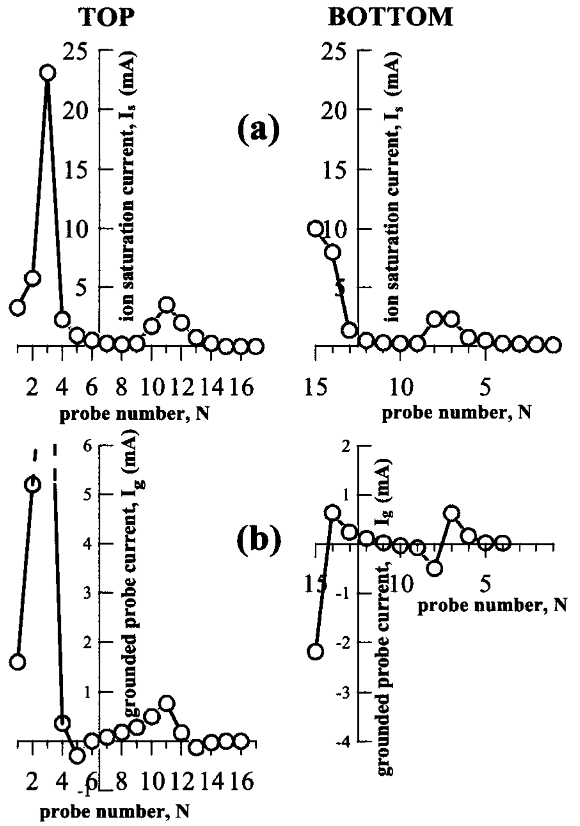

Fig. 2 (a) Ion saturation current I_s versus probe number N in the top and bottom spacings between the helical coils in the cross-section A-A;
(b) same as (a) for the grounded probe current I_g, $I_g(3)$ = 13.8 mA. The vertical axes correspond to the minor radii, passing through the X-points.

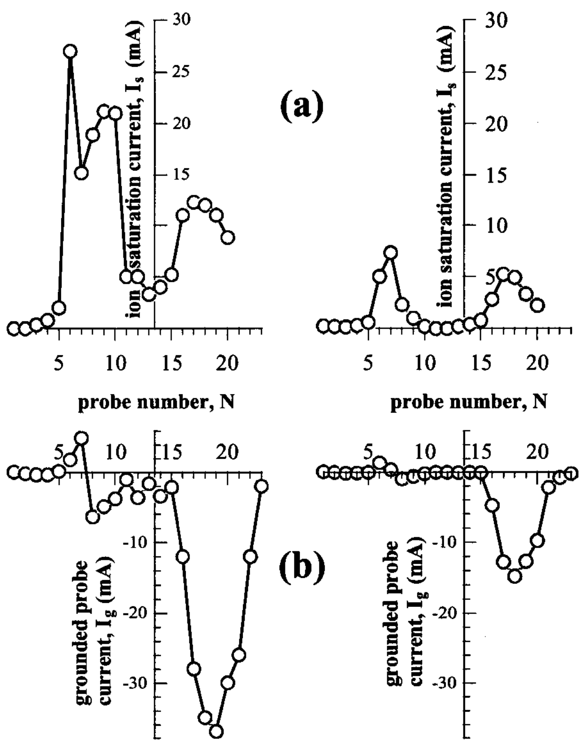

Fig. 3 (a) Ion saturation current I_s versus probe number N in the outboard spacing between the helical coils in the cross-section D-D with P ≈ 200 kW (on the left) and P ≈ 80 kW (on the right);
(b) same as (a) for the grounded probe current I_g. The vertical axis position corresponds to that of the torus midplane.

3.2 Cross-section D-D

The $I_s(N)$ distribution in the outboard spacing of the D-D cross-section is shown in Fig. 3(a) (positive magnetic field) for $P \approx 200$ kW (standard regime) and $P \approx 80$ kW. With the lower heating power, the positions of I_s maxima, N = 6 and N = 17, are close to the calculated positions of divertor legs (cf. Fig. 1). For this case, the degree of asymmetry of ambipolar particle flows, when estimated as the ratio α of maximum values of I_s, is comparatively low, $\alpha = 1.4$, with the larger particle flux outflowing over the torus midplane, that is, on the ion toroidal drift side. A pair of adjacent non-ambipolar fluxes corresponds to the larger ambipolar flux (Fig. 3(b), on the right) with an excess of ions in one flux (N = 6) and of electrons in the other flux (N = 8) and currents I_g comparable in their absolute values. To the ambipolar flux outflowing under the midplane a comparatively high maximum of negative current I_g corresponds (N = 18), while no adjoining maximum of the positive plasma current is observed.

At a higher heating power (Fig. 3(a), on the left, the standard regime), the difference between the maximum values of I_s in the divertor legs increases (α = 2.3), similar to what has been observed earlier in H-E [3]. Also, a qualitatively new element of asymmetry occurs, namely, splitting of the larger flow and appearance of two I_s maxima (N = 6 and N = 9) in the vicinity of the calculated divertor leg position. The same effect has been observed earlier in the Uragan-3 torsatron [9], the U-3M predecessor. A substantial current I_s in the private region (N = 11–15) is one more peculiarity of the $I_s(N)$ distribution occurring at the higher heating power. As follows from the comparison of the upper and lower plots in the left column of Fig. 3, to the splitted ambipolar plasma flow in the divertor leg over the midplane two adjacent maxima of GPC comparable in their absolute values correspond, with domination of ions in one maximum (N = 7) and of electrons in the other maximum (N = 8). Similar to the lower heating power case, the non-ambipolar plasma flux outflowing below the midplane is characterized by a large negative I_g maximum (N = 19) without any substantial adjoining flux with $I_g > 0$. In the private region (N = 11–15), the plasma current is negative. In the negative magnetic field, the splitted higher I_s maximum is observed in the divertor leg under the torus midplane. The structure of poloidal distributions of current I_g shown in Fig. 3(b) also reverses in the vicinity of divertor legs. However, the sign of I_g in the private region does not change. This might signify that a substantial current I_g in the private region is not connected directly with a plasma drift across magnetic field.

4. Summary and discussion

In addition to a distinctly pronounced up-down asymmetry of divertor flows in the value of I_s and the sign of I_g [5], some other structural features of the diverted plasma flows contributing to the up-down asymmetry have been revealed.

1. In the top and bottom spacings of the cross-section A-A, two adjacent plasma currents with opposite signs have been observed in each divertor leg. A polarization of diverted plasma flow due to the centrifugal drift of charged particles moving along the bended field lines beyond the X-point seems to be a plausible explanation for this effect. (A qualitative picture of such a drift could be presented more evidently, when going into the plane perpendicular to the helical direction with the magnetic field component in this plane $\boldsymbol{B} - (\boldsymbol{B}\boldsymbol{e}_h)\boldsymbol{e}_h$, $\boldsymbol{e}_h$ being the unit vector in the helical direction, similar to what has been done in the analysis of the LHD helical divertor, see ref. [8] and Fig. 1 therein). At present, the absence of more detailed data on parameters of diverted plasma does not allow us to make quantative estimations of the centrifugal drift effect on the space structure of plasma flow.

The splitting of the larger ambipolar flux in the cross-section D-D, with occurrence of the pair of oppositely directed I_g maxima can also supposedly result from a flux polarization due to the centrifugal drift of ions and electrons beyond the X-point.

With such an interpretation of the observed fine structure of plasma flows in the divertor region, this structure seems to arise independent of the up-down asymmetry of the divertor flows, though both these effects are caused by similar factors, i.e., particle drifts across magnetic field.

2. As it follows from the calculations of direct electron losses [5], in the positive magnetic field case, the maximum of the angular distribution of these losses falls at a narrow interval of θ adjacent to the midplane under it on the inner side of the torus (see Figs. 7 and 8 in ref. [5]). The velocity distribution of escaped electrons is also highly peaked. Most of them leave the confinement volume moving with the magnetic field (see Fig. 9 in ref. [5]). Crossing the LCFS on the inner torus side and possessing a large parallel velocity and, consequently, a large poloidal rotation velocity, the lost fast electrons in the process of their drift in the SOL can approach the X-

point on the outboard torus side and escape to the divertor region along the nearest divertor leg. Such an assumption is consistent with the observation of a large negative plasma current in the non-ambipolar plasma flux outflowing under the midplane (Fig. 3). (A similar behavior of fast electrons has been also observed experimentally in the edge plasma of a tokamak with the symmetric single-null divertor [10]).

3. The occurrence of a substantial (as compared with the A-A cross-section) current I_s and a corresponding negative current I_g in the divertor private region at a sufficiently high heating power means that a region of reduced potential arises beyond the X-point on the outboard torus side. Such a potential drop can be presumably caused by a fraction of lost fast electrons being trapped in the private region and bouncing between two divertor legs.

4. The measured poloidal distributions of diverted plasma flows in U-3M are distinguished with a width multiply (up to 30 times) exceeding that of corresponding calculated magnetic divertor channels. At least partially, such a broadening can be caused by the physical effects having been considered in the present work, such as plasma flow polarization, outflowing of fast particles along the divertor channels and accumulation of electrons in the private region of the divertor. The possibility of divertor flow broadening should be taken into account, when designing a closed helical divertor for a heliotron/torsatron device.

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