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Effects of trapped particles on distribution of divertor flow in Heliotron-E

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Abstract

The big asymmetry of divertor flows to symmetrically located collectors was observed when divertor plasma flow distributions (DPFD) were measured in Heliotron-E device. Several possible reasons of DPF asymmetry were discussed in previous publications but no one was singled out. In the present work, to clear up the plasma heating effects on DPFD asymmetry, the difference of the DPFDs at plasma heating phase and at an 'afterglow' phase of plasma discharge is analyzed for different experimental conditions. During the afterglow phase the plasma is in the regime of Pfirsch–Schlüter diffusion when effects connected with locally trapped particles would be negligible. Besides, the inhomogeneity connected with the locality of plasma heating would disappear and all plasma parameters should be constant along the torus. Therefore, the asymmetry of DPFD observed at this phase of discharge was taken as a base for evaluation of the effects stipulated by the trapped particles.

Keywords: Heliotron-E; Divertor plasma flow; Trapped particles; Divertor flow asymmetry

1. Introduction

The present paper is a continuation of previous publications [1–3] devoted to the investigation of behavior of divertor plasma flows in Heliotron-E fusion device.

The first data relating the correlation between the ion saturation current (ISC) values and the locations of divertor plasma collectors in Heliotron-E were presented in [1] for the no-current plasma produced in conditions of electron cyclotron resonance. The detail analysis of behavior of DPFD in this device for the magnetic configuration with fixed magnetic field direction and strength and magnetic axis shifted inward ($\Delta R = -2$ cm) was provided in [2,3] depending on the experimental conditions when plasma was produced and heated by ECH and neutral beam injection (NBI). It follows from the analysis that the main divertor flows cross the chamber walls in the same locations where the longest field lines. However, the measured spatial DPFD are characterized by strong vertical asymmetry (up–down asymmetry) and in much lower degree by an in–out asymmetry. The main feature of up–down asymmetry is a great difference (in the limit of tens) of ambipolar plasma flows moving along the longest open field lines to the collectors disposed, according to calculations,

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symmetrically to the torus central plane in the upper and lower parts of torus.

It was found in [2,3] when investigating the DPF dependence on the plasma density normalized NBI heating power that divertor flows grow with power increase and that the asymmetry degree rises also, on the one hand, but at the zero limit of the NBI heating power some 'initial' up–down asymmetry still exists, on the other hand.

As distinct from [2,3], the present paper accents on the comparison of the DPFD measured: (i) for two opposite directions of confining magnetic field, and (ii) at the active stages of discharge, when different methods of plasma heating were used (ECH, NBI, NBI + ECH), with the DPFD measured at the afterglow stage of discharge, after all sources of plasma heating were switched off.

2. Experiment

For investigation of the DPFD, eight arrays of plane collectors, 5×0.8 cm^2 each, were used disposed in four poloidal cross-sections at the distance ~1.5 cm from the wall. All collector plates in arrays were located near the rounded parts of the Heliotron-E chamber and distributed along the toroidal direction with an interval of 1/8 of a magnetic field period [1–3]. The collectors were biased to −120 V to obtain the ISC. The ISC value was used as a measure of divertor flow to the given collector. In every array consisted of seven collectors the central ones were poloidally positioned at $\Theta = 0°$, 45°, 90°, 135°, 180°, 225°, 270°, and 315° (as indicated in insert of Fig. 2 for $\Theta = 0°$ and 180°). There were only two collector arrays disposed in the same vertical plane symmetrically to the central plane of torus ($\Theta = 90°$ and 270°). Besides, in the $\Theta = 0°$ and 180°arrays the central plane intersected the middle collectors in such a way that three upper collectors (1, 2, 3) and three lower ones (correspondingly, 7, 6, 5) were also located symmetrically each other.

It is known from [2–4] that maximum separation of both branches of divertor flow occurs at $\Theta = 0°$ collector position whereas at the $\Theta = 180°$ position both main divertor flows come upon central collectors 3, 4, 5. The connection of one of this collector (#3) with circuit of measurement was broken and therefore the more or less correct comparison of flows to symmetrically disposed collectors could be provided only for arrays $\Theta = 90°$ and 270° and for collectors #2 and #6 of the $\Theta = 0°$ array. The latter collectors did register the main parts of the divertor flow in all regimes of device operation without toroidal magnetic field added [5]. The positions of $\Theta = 0°$ and 180° arrays allow to study the dynamic of in–out asymmetry during different stages of discharge pulse.

3. Time behavior of divertor flows

Fig. 1 shows the time behavior of the ISCs to symmetrically disposed collectors (#2 and #6) of the $\Theta = 0°$ array during a discharge with the 'history' indicated in the field of figure. At the initial ECH phase the current collected by the lower collector (is6) was about twice as large as that collected by the upper collector (is2). The is6/is2 ratio was reversed just after the NBI phase start. The additional ECH pulse being imposed on NBI, resulted in a sharp current jump to the lower (#6) collector and in a monotonic current rise to the upper (#2) collector. After finishing the additional ECH pulse, the behavior of both currents is essentially different, and just near the end of the active phase of discharge ($t = 405$ ms) the is2/is6 ratio reached ~2 and continued to stay at about this level throughout the afterglow phase of discharge.

The time dependences of ratio of the ISCs registered by the same collectors (i.e., the is2/is6 ratio) are shown in Fig. 2 for four discharge pulses with different conditions. In the pulse #63756 plasma was produced and maintained till $t = 325$ ms in a counterclockwise magnetic field $B = +1.26$ T by the ECH at $f = 35$ GHz. During pulse #73447 plasma was produced and maintained until 307 ms in a clockwise magnetic field $B = -1.9$ T by the ECH at $f = 53$ GHz. In the pulse #73494 plasma

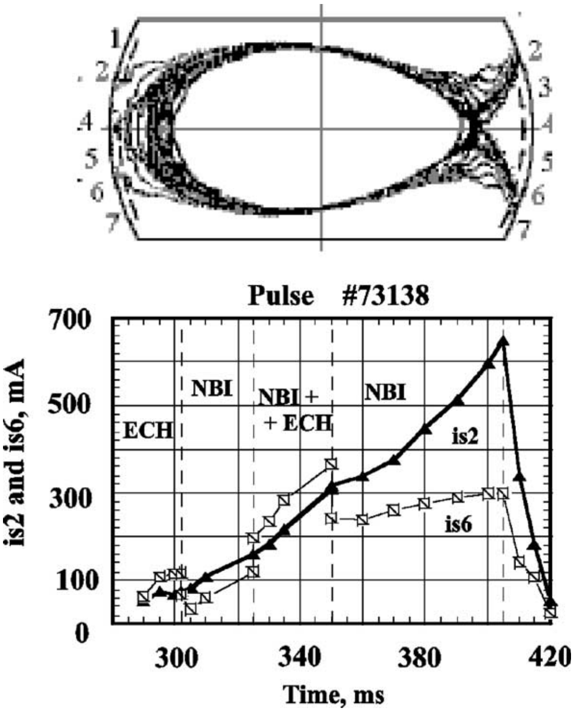

Fig. 1. Time behavior of DPFs to collectors #2 and #6 disposed in the $\Theta = 0°$ collector array symmetrically relatively to the central plane as shown in the inset above the graph (figures in inset indicate the collector positions).

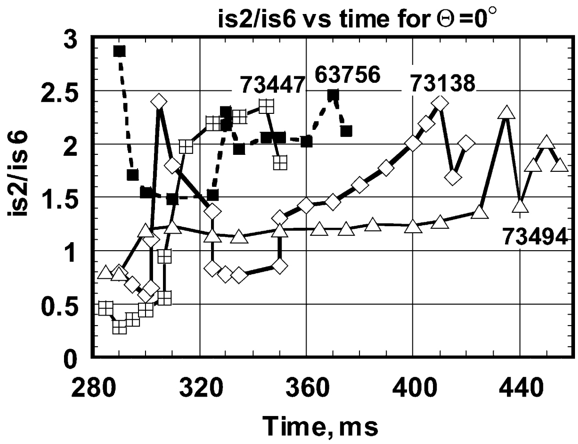

Fig. 2. Time behavior of ratio of DPF to symmetrically disposed collectors #2 and #6 of the collector array located at $\Theta = 0°$ for four different pulses (details are in the text).

was started by the ECH at $f = 53$ GHz in magnetic field $B = -1.9$ T and at the time interval 300–435 ms it was maintained by NBI (the energy of atoms 23 keV, the total feedthrough power 2.2 MW). During the pulse #73138 the beginning of the discharge was similar to the latter pulse but NBI feedthrough power was 1.8 MW and at the time interval 305–405 ms on the NBI plasma the additional ECH was imposed at the resonance frequency for this magnetic field strength (53 GHz).

Evidently that at active state of every pulse an approximate equality of ISCs to symmetrically disposed collectors #2 and #6 exists only during very short time periods consisting in total small fraction of the discharge.

Note that in spite of big differences of is2/is6 ratio at the active phases of these particular discharges, at the afterglow plasma stage the differences diminish significantly and in average the is2/is6 ≈ 2 for both directions of magnetic field. Approximately similar is2/is6 ratio was settled at the afterglow stage for the ECH discharges in magnetic field $B = -1.9$ T. Thus, even at the full absence of any reasons for asymmetry of plasma flows to symmetrically located collectors #2 and #6 in the $\Theta = 0°$ array, the ISCs registered differ in about factor 2. This value of ratio of both divertor flow branches in the $\Theta = 0°$ region can be taken as a ground when evaluating the effects stipulated by locally trapped particles in the plasma confinement volume on the is2/is6 ratio.

At the afterglow stage the difference practically disappeared also between main divertor flows measured by collectors #2 and #5 of the $\Theta = 270°$ array for opposite directions of magnetic field: is2/is5 $= 0.7$ for the discharge with $B = +1/26$ T and is2/is5 $= (0.7–0.8)$ for discharge with $B = -1.9$ T. At the same time, during active stages of discharges the is2/is5 ratio difference amounts to 5–7, i.e., is2/is5 ≈ 1.5 and is2/is5 $\approx 0.2–0.4$, correspondingly.

Similarly, in Fig. 3 the time behaviors are compared of ratio of the full divertor flows registered by vertically disposed collector arrays, namely, the $\Gamma(90°)/\Gamma(270°)$ ratio, measured for two discharges characterized by different experimental conditions. In the case of Fig. 3(a) plasma was produced and maintained (during 275–330 ms) by the gyrotron at frequency 35 GHz only (the resonant frequency for ECH in $B = +1.26$ T). In the case of Fig. 3(b) with opposite magnetic field direction ($B = -1.9$ T) plasma was initiated by operation of gyrotron at frequency 53 GHz and maintained by NBI (the feedthrough power 1.7 MW) at the time interval 290–390 ms. During time period 325–355 ms the additional ECH pulse was imposed on the NBI plasma. Note that the measuring circuit of the collector #3 of the $\Theta = 90°$ array was broken and therefore the $\Gamma(90°)/\Gamma(270°)$ ratio was systematically underestimated in all cases.

As seen from data of Fig. 3, the big difference of DPF distribution in vertical direction, i.e., the up–down asymmetry, is remaining at the afterglow stage of discharges. The indices of the asymmetry differ within the

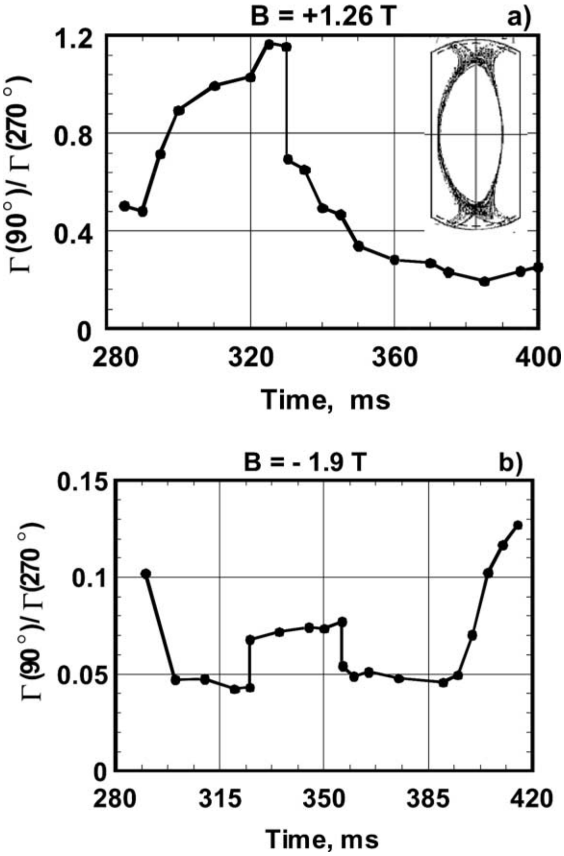

Fig. 3. Time dependences of the $\Gamma(90°)/\Gamma(270°)$ ratio for two discharges with opposite directions of confining magnetic field. The inset shows the field line mapping near the edge of the confinement volume in this cross section.

limit of factor two: 0.2–0.25 and ~0.13 for $B = +1.26$ and -1.9 T, correspondingly. However, this difference looks insufficient comparing to that observed at the active stages of discharges: up to 20–25 times in Fig. 3.

4. Discussion and conclusion

The results of previous section are evidence of significant difference in the values of divertor flows registered by symmetrically disposed collectors even at the afterglow stage of discharge. In contrast to active stages of discharge, such difference cannot be connected with existence of locally trapped particles or/and the discrete locations of plasma heating sources. In fact, the afterglow plasma with electron temperature $\leqslant 10$ eV is in the Pfirsh–Schluter regime of diffusion when one can neglect the effects relating to the trapped particles. Besides, the plasma parameters along the toroidal direction have to be equalized after switching off all heating power sources. The possible reason of retaining the plasma flow asymmetrical at this stage of discharge may be the lack of real symmetry in the system of measuring the divertor flows, e.g., due to not fully symmetrical locations of collectors. Furthermore, because of regular boronization procedure, all inner surfaces of vacuum chamber were coated with the dielectric film. The thickness of boron film is known to depend on the location of the given part of surface relatively to the inlet of the gas mixture and electrodes that initiates the discharge during a boronization procedure [6]. One more reason discussed in [2,3], is the lack of vertical symmetry of magnetic configuration due to disturbing magnetic fields. However, it seems that the coincidence of asymmetry indices for the afterglow plasma at opposite directions of magnetic field for three examined locations of collectors is evident indication that just the first of two mentioned reasons are the main one if not the only.

Accepting the asymmetry indices observed at the afterglow stage as the 'reference point' let us analyze the time behavior of divertor flows at the active stages of discharge.

As seen in Fig. 3(b), the ratio of divertor flows registered by the upper ($\Gamma(90°)$) and lower ($\Gamma(270°)$) collector arrays at the active stages, is much below the ratio measured for the afterglow plasma. The minimal $\Gamma(90°)/\Gamma(270°)$ values are realized at those time intervals when plasma is maintained by NBI, i.e., when the ions with high transversal energy must exist in the confined plasma. These ions being locally trapped have to drift downward with magnetic field clockwise directed ($B = -1.9$ T). The superposition of ECH on such a plasma (NBI + ECH stage) results in a noticeable rise of ISC values registered by whole collector set of the upper array ($\Theta = 90°$). But this direction corresponds to the direction of drift of the locally trapped electrons, i.e., there is no qualitative correlation between observed changes of divertor flow ratio, $\Gamma(90°)/\Gamma(270°)$, and expected effects stipulated by existence of trapped particles. As follows from Fig. 3(a), the increase of the divertor flow to the upper collector array (compare to the afterglow stage) takes place also for the ECH stage of a discharge with opposite magnetic field direction ($B = +1.26$ T), when trapped electrons generated due to ECH had to drift downwards.

The data of Fig. 3 indicate that the part of a vertical asymmetry index, $\Gamma(90°)/\Gamma(270°)$, which is introduced by trapped particles drifting vertically across the magnetic field, is not defined by their direct arrival to the collector plates, at least to those ones that register the main divertor flows. This remark can be supported by simple quantitative estimations. Indeed, the typical scale of the mean density of current to collectors characterizes by values from tens to hundred mA/cm^2 (the latter meaning relates to the collector #5 of the $\Theta = 270°$ array) and this corresponds to particle flux $>10^{17}$ cm^{-2} s^{-1}. Such a transverse to magnetic field flux of particles of the same charge sign with drift velocity 10^4–10^5 cm/s would create a space charge of enormous high amplitude. However, in reality in all experimental conditions the maximal values of collector floating potentials did not exceed 30 V [7]. Therefore, the large-scale time variations of ISC to collectors registering the main divertor flows and stipulated by dynamics of trapped particles should be attributed to variations of plasma flows along the open magnetic field lines and not due to direct arrival of the lost trapped particles. In other words, the important is not only the concrete position of a given collector but the location of the trajectory of the field line crossing this collector relatively to the regions where locally trapped particles are drifting out of the last outermost magnetic surface.

Based on what was mentioned above the following can be concluded about:

1. The asymmetry of divertor flows to symmetrically disposed collectors was observed at the afterglow plasma and was partly the result of asymmetry of the scheme of measuring the divertor plasma flows by means of collector array system in use.
2. The main reason of changing the asymmetry index at the active discharge stages in comparison to that for the afterglow plasma stage is the existence of trapped particles; the effects stipulated by locally trapped particles are becoming apparent differently for hot-ion (NBI stages) and hot-electron (ECH stages) plasmas.
3. These effects only in a minor degree are results of direct arrival to collectors of the locally trapped particles drifting out of the last outermost magnetic surface. The effects of trapped particles on divertor flow distribution do probably realize through the influence on the distribution of quasi-stationary electric

fields in the boundary range of the confinement plasma volume and on the plasma flows moving along the open magnetic field lines.

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