On the in-out asymmetry of divertor plasma flows in heliotron/torsatron devices

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Abstract

Understanding of the reason for the divertor flow asymmetry in heliotron/torsatron type fusion devices is important for safety of the in-vessel components, such as divertor plates subject to direct impact of the plasma or the electrical probes and thermocouples for measurements of the particle and energy fluxes to the divertor plates. In previous works, the divertor flow distributions in a heliotron type fusion device, Heliotron E, was studied mainly with focusing on asymmetry in vertical direction. In this paper we analyze the in-out asymmetry of divertor flows and discuss the effects on this asymmetry of the magnetic axis position (the horizontal shift due to variation of the vertical magnetic field or plasma pressure), power of neutral beams, and plasma parameters.

1. Introduction

In heliotron/torsatron type devices there is a possibility for the natural divertor configuration to exist. Such possibility can be realized if the outermost magnetic surface is deeply inscribed into the vacuum chamber with X-points located far from the wall with enough place for forming the “divertor legs”. The devices with intrinsic divertor structure are: Uragan-3M [1], Heliotron E (H-E) [2], and Large Helical Device (LHD) [3]. In contrast to tokamaks, the helical divertor possesses a strong inhomogeneity of divertor flows as was shown by detailed calculations of magnetic field lines (e.g., [4-6]) and by measuring the plasma flows along the diverted field lines [5-9]. The rate of inhomogeneity depends on the experimental conditions: position of magnetic axis, method of plasma production, direction of magnetic field, etc.

In the past, the analysis of divertor flow distributions in H-E was with emphasis on their asymmetry in vertical directions, i.e., comparing the flows registered by the collector arrays at the upper and lower parts of the vacuum chamber in the toroidal position where the longer axis of the elliptical plasma cross section is directed vertically. The in-out asymmetry was only briefly mentioned in the review [10], although it was observed for divertor flows registered by collector arrays displayed at the inner and outer parts of the vacuum chamber where the longer axis of the elliptical cross section lies horizontally. In this paper we focus on the in-out asymmetry of divertor flows and discuss the effect of the magnetic axis position (the horizontal shift due to varying the vertical magnetic field or plasma pressure), the power of neutral beams, and the plasma parameters. We also discuss the effect of magnetic axis shift on the poloidal distribution of divertor plasma flows along different probe arrays.

2. Experimental conditions

H-E [2] (Fig.1a) was an l=2 heliotron type device with m = 19 periods of the helical magnetic field, major radius \( R_0 = 2.2 \) m and the averaged radius of the outermost magnetic surface of nearly elliptical shape \( \tilde{a} \approx 0.2 \) m. The inner radius of the rounded parts of the vacuum chamber, \( a_{ch} = 41 \) cm, significantly exceeded the major elliptic semi-axis of the plasma (\( \approx 30 \) cm), thus guaranteeing formation of the divertor flows between the X-points and the chamber wall. In the standard operation regimes the magnetic field was -1.9 T (the clockwise direction).

Plasma was produced by electron cyclotron heating at the fundamental (ECH-1) and/or at the second harmonic (ECH-2) of the electron cyclotron frequency, and injection of beams of hydrogen atoms (NBI) with the energy \( \sim 23 \) keV. The full injected (port-through) power was limited by 0.7 MW and 3.2 MW for ECH and NBI, respectively. The scheme of disposition of
plasma heating sources is shown in Fig.1a. Plasma parameters for main regimes were: \( n_e = (1.5-3) \times 10^{19} \) m\(^{-3}\), \( T_e(0) \approx 0.6-1.5 \) keV, \( T_i(0) \approx 0.3-0.6 \) keV.

To study the divertor plasma flow (DPF) distribution, 56 collector plates (CP) were used combined into 8 arrays with 7 plates numbered \( N = 1,2,…,7 \) in each array \([5,9]\). The arrays were arranged poloidally on both sides of the vacuum chamber at the distance 1.5 cm from the wall in four poloidal cross-sections with the interval \( 1/8 \) of the helical magnetic field toroidal period. The plate length in the poloidal direction was 5 cm, the width 0.8 cm and the gap between plates \( \sim 0.6 \) cm. The locations of the cross sections with arrays and disposition of CPs in each array are indicated in Fig.1. The central CPs of arrays were located at the poloidal angles \( \Theta = 0^\circ, 45^\circ, 90^\circ, 135^\circ, 180^\circ, 225^\circ, 270^\circ \) and \( 315^\circ \), with \( \Theta \) counted counterclockwise. With negative potential \(-120 \) V to the collectors, the ion saturation current (ISC) was measured and used as a measure of the magnitude of the divertor flow to the collector.

The results in \([5,9]\) demonstrated the maximum separation between the divertor legs for the \( \Theta = 0^\circ \) array. Contrary to this, for \( \Theta = 180^\circ \) the plasma flows in both divertor legs hit the \( N = 3,4,5 \) CPs, the central part of this array. Owing to their angular positions, the \( \Theta = 0^\circ \) and \( \Theta = 180^\circ \) arrays can be used for estimation of in-out asymmetry at different stages of discharge. Because the \( N = 3 \) circuit for the \( \Theta = 180^\circ \) array was broken, a sufficiently correct comparison of in-out plasma flows can be made by comparison of ISC to the CP #2 at \( \Theta = 0^\circ \) and CP #5 at \( \Theta = 180^\circ \) arrays, which is denoted below as \( i_{2}/i_{5} \) and \( i_{2}/(i_{5}+i_{4}/2) \), correspondingly. In addition, in connection with the large portion of the divertor flux crossing the CP #5 reached also the CP #4, as the in-out asymmetry factor the ratio \( i_{2}/(i_{5}+i_{4}/2) \) may be accepted. Below both these ratios will be presented in the same graphs.

3. Results
3.1. Effect of magnetic axis shift on the in-out asymmetry
In Fig. 2 the time variation of the in-out asymmetry ratios \( i_{2}/i_{5} \) and \( i_{2}/(i_{5}+i_{4}/2) \) are shown for three positions of the magnetic axis: without shift of magnetic axis (\( \Delta R = 0 \)), with medium shift \( \Delta R = -2 \) cm, and with maximal shift \( \Delta R = -4 \) cm. In the first case there was no similarity of the experimental conditions for plasma pulses when divertor fluxes to the inner (\( \Theta = 180^\circ \)) and to the outer (\( \Theta = 0^\circ \)) collector arrays were measured, therefore only data for the first part of the
pulse (280-350 ms) are presented as distinct from the data for other cases in this figure and further in the text (280-450 ms). Nevertheless, the strong dependence of both ratios on the shift of the magnetic axis can be seen. In Fig. 3 both values characterizing the asymmetry taken from Fig. 2 are presented upon the shift of magnetic axis. We can see that the difference in $is_2/is_5$ and $is_2/(is_5+is_4/2)$ ratios for extreme positions of magnetic axis, $\Delta R=0$ and $\Delta R=-4$ cm, exceeds 6.

Fig. 2. Time dependence of ratio of DPF at $\Theta=0^\circ$ (is2) to DPFs at $\Theta=180^\circ$ (is5 and is5+is4/2) measured for different magnetic axis positions: a) $\Delta R=0$, b) $\Delta R=-2$ cm, c) $\Delta R=-4$ cm.

Fig. 3. Characteristics of in-out asymmetry depending on magnetic axis shift.

Fig. 4. Effect of NBI power on characteristics of in-out asymmetry. The rhombuses show results obtained from data published in [2] (Fig. 15).

With fixed magnetic axis position both ratios, $is_2/is_5$ and $is_2/(is_5+is_4/2)$, show the tendency to decrease when total NBI power was increased, as Fig. 4 demonstrates. Additionally at this graph are shown the results of comparison of the ratio $Q_{out}/Q_{in}$ of the heat fluxes registered by the outer and inner thermocouple arrays as was found from the data published in [2]. Let us note quite good qualitative agreement in dependences on NBI power of the data obtained by measuring the particle and heat fluxes. At the same time, there was not found a correlation between characteristics of in-out asymmetry and plasma parameters near the plasma center, $n_e(0)$ and $T_e(0)$.

The in-out asymmetry of DPF distribution can be characterized also in a global sense, as the ratio $\Gamma_{OUT}/\Gamma_{IN}$ of the fluxes registered by all outer collector arrays, $\Gamma_{OUT} = \Gamma(45^\circ) + \Gamma(315^\circ) +$
Γ(0°), to fluxes registered by all inner collector arrays, Γ_{IN} = Γ(180°) + Γ(135°) + Γ(225°). The result for two extreme positions of magnetic axis is presented in Fig. 5. As could be expected, the difference of global IN-OUT asymmetries (∆Γ_{OUT}/Γ_{IN} ≈ 2.5) is much below the asymmetry registered for local divertor flows (∆(is2/is5) ≈ 7 at Fig. 3).

3.2. Effect of magnetic axis shift on DF distributions inside different arrays

According to calculations [6], in LHD a small relative shift of magnetic axis (~4% of the major radius) results in a strong modification of the divertor flow distribution along both divertor legs. Similarities between Heliotron E and LHD fusion devices make a ground for the qualitative comparison of experimental results obtained at Heliotron E with calculation results for LHD on the divertor field lines tracing [6]. However, comparing positions of collector arrays in Heliotron E (Fig.1) with results of calculations for LHD (Fig. 1 in [6]) it is seen that for comparison with these results the data not from all probe arrays of Heliotron E are suitable, namely those from arrays located at Θ = 180° and Θ = 0°. Besides, because of broken collectors #3 inside arrays located at Θ = 90° and Θ = 225°, the data from these arrays also have to be excluded from further analysis.

Figure 6 shows the ISC values registered for magnetic configurations with shifted and nonshifted magnetic axis by every CP in arrays placed at: Θ = 45°, Θ = 135°, Θ = 315°, and Θ = 270°. Taking into account the position of every CP shown in Fig. 1 we can conclude that for the first three of these arrays there is a perfect qualitative agreement with data of Fig. 6, but there is no similar correspondence for the array placed below vertically (Θ = 270°).

When shifting magnetic axis inward, the outer divertor ‘legs’ (at Θ = 0°) do widen and some part of the divertor flow registered by CP #6 (Θ = 0°) without shift becomes to be registered by the CP #7 located farther from the central plane, as can be seen in Fig. 7.

Correspondingly, an inverse behavior was observed for collector array disposed at 180°: with shift ΔR = -4 cm there was no any divertor flow registered by CP #6 (Θ = 180°) in...
comparison to the case without shift when this collector has registered a quite big portion of that
divertor flow measured by this probe array ($\Theta = 180^\circ$), Fig. 8.

4. Discussion
The results presented above demonstrate that for heliotron/torsatron magnetic configuration
even relatively small shift of the magnetic axis (2.2% of the major radius) results in a significant
change of the in-out asymmetry (by factor of 6-7). In some other experiments at this device the
difference between extreme positions of magnetic axis was noticeably greater but DPF
distributions were not measured. Namely, when searching for the conditions that would provide
the optimal plasma confinement and higher efficiency of electron cyclotron resonance heating,
the magnetic axis position was shifted from $\Delta R=-6.5$ cm by $\Delta R=+4$ cm relative to the position
of the geometrical axis $\Delta R=0$ cm [11]. In other experiments, on investigation of the possibility
to suppress the Pfirsh-Schluter currents by changing the characteristics of the magnetic
configuration, the magnetic axis was positioned between $\Delta R=6$ cm and $\Delta R=+1$ cm [12], and
later up to $\Delta R=8$ cm [13]. If one approximates the data of Fig. 3 to these extreme points, the
difference in the factor characterizing the in-out asymmetry would be significantly higher than
shown in Fig.3.

It should be noted that the time variations of in-out asymmetry seen in Fig. 2, Fig. 7, and
Fig. 8 could only in minor degree be caused by the shift of magnetic configuration due to
variation of the plasma pressure (Shafranov shift). This follows from the results of the direct
measurements of this shift depending on the characteristics of plasma and on parameters of
magnetic configuration [12,13]. The maximal shift reached at the maximum NBI power was
only ~0.3 cm, what is equivalent to a small change of in-out asymmetry factor, $\Delta (is2/is5) \leq 0.5$.
Besides, the time dependence of plasma pressure was found to be quite smooth at both stages:
the rise up to the time 75-95 ms after discharge start and the decay afterward [12]. Thus, all
sharp variations of is2/is5 ratio should be attributed to peculiarities of particle diffusion during
variation of experimental conditions, like changing the plasma heating method (1st or 2nd
harmonic of ECH, NBI, or their combination) and the port-through power. The detailed
description of effects of experimental conditions on distribution of the divertor flows in
Heliotron E was done in [10].

The operation of LHD in regimes with magnetic axis shifted inward is due to much better
plasma confinement in comparison to the case without axis shift [14,15]. For this device the
optimal magnetic configuration was obtained with the magnetic field axis shifted inward by 30
cm from the standard position of the geometrical axis (3.9 m), i.e., the relative shift here, 7.5%
[6] or 10.3% [16], much exceeded similar values for Heliotron E (~2%) and CHS (4.8% relatively
to the magnetic axis position in a standard configuration) [17]. (Note, that for the first
time the effect of shift of magnetic axis on the plasma confinement was studied in experiments
at the Uragan-3 torsatron, where the optimum was found with the relative shift ~4.5% [18].)

Thus, the optimization of confinement properties of heliotron/torsatron magnetic
configuration can be reached by the inward shift of magnetic axis from the position of
geometrical axis by several percent of the major radius. Such shift causes the redistribution of
divertor flows along the divertor legs. As follows from results of calculations [6] the important
consequence of the redistribution is an increase of inhomogeneity of flows in such a way that
the heat fluxes to some divertor plates can exceed the permissible level, if the optimal
configuration would be determined in the course of device operation.

Note the effect of widening of the divertor flux to those divertor plates (or collectors), which
are opposite to the direction of shift of magnetic axis (Figs. 7 and 8), and correspondingly, the
contraction of flux to those plates that are located in the direction of magnetic axis shift. This is
additional reason of increase of difference between density of particle (and energy) fluxes to inner and outer divertor plates (or collectors).

The lack of agreement of DPF distributions measured for the $\Theta = 270^\circ$ array, Fig. 6d, with results of calculations for LHD, [6], can be a serious indication on existence of some other reasons strongly influencing the plasma flows onto the arrays located vertically, like e.g., the $\nabla B$ drift of locally trapped particles [8,19].

5. Conclusion
1. The in-out asymmetry strongly depends on the shift of magnetic axis;
2. In the case of Heliotron E, the in-out asymmetry depends on the total NBI power but no correlation was found with $T_e(0)$ and $n_e(0)$;
3. Very good qualitative agreement was found of DPF distributions measured inside three collector arrays in Heliotron E with calculations made for LHD.
4. Care has to be taken when looking for the optimization of plasma confinement by shifting the magnetic axis inward what inevitably leads to strong change of divertor flows distribution.

References