Experimental studies of electric currents in the divertor plasma of a heliotron/torsatron

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Abstract. In the $l=2/m=19$ Heliotron E helical device, with an NBI and NBI+ECH currentless plasma, measurements of poloidal distributions of electric current $I_p$ to grounded collector plates installed near the vacuum chamber wall were carried out in 4 poloidal cross-sections within 1/2 field period. This current was shown to form a complicated sign-varying structure. The distribution of current flowing along the diverted field lines was distinguished with a strong vertical asymmetry (up-down asymmetry). The main characteristics of the asymmetry were a multiple increase of $I_p/\rho_e$ in the lower part of the torus as compared with the current in the upper part, and the opposite direction of currents in divertor flows symmetrically disposed about the midplane.

Under NBI conditions and with the ECH imposed on the NBI, the average-density-normalized electric current in a divertor flow, $I_p/\rho_e$, was a rising function of the average-density-normalized total absorbed power, $P_{\text{abs}}/\rho_e$. Such a dependence is considered as a manifestation of a common for tokamaks and stellarators regularity, power degradation of confinement. Within the data accuracy, the $I_p/\rho_e - P_{\text{abs}}/\rho_e$ dependencies did not depend on the toroidal position of the heating source and the injection angle.

As the analysis has shown of the form of floating potential $V_f$ and current $I_p$ variations under the effect of an additional short NBI- or ECH pulse imposed on a long NBI, in general, these variations consisted of fast and slow components. The fast variations are treated as a consequence of a convection-like suprathermal ion and electron loss or a re-distribution of these particles in the confinement volume, while the slow variations were caused by diffusion-like processes connected with thermal particles.

Among possible reasons for the observed electric current generation in the divertor flows of Heliotron E and of the vertical asymmetry of these currents, discussed are (1) the thermoelectric effect resulting from the near-wall plasma temperature difference at the ends of divertor field lines in the lower and upper parts of the torus, and (2) SOL plasma potential variations under the effect of a redistribution or a loss of some groups of locally-trapped ions and electrons due to helical field ripple asymmetry in a heliotron.

1. Introduction

For the first time, non-ambipolar plasma flows (electric currents) parallel to the magnetic field in the SOL plasma of a closed magnetic trap drew attention in the single-null divertor experiment on
the JET tokamak [1]. When working with grounded target plates, the Langmuir probes recorded an electric current to these plates (units and tens mA/cm²). The value and direction of the current were affected by the state of the confined plasma and boundary conditions (L- or H-mode of confinement, heavy impurity content, ELM excitation, etc.). Parallel electric currents have been also observed and studied in diverted SOL plasmas of the DIII-D [2,3], JFT-2M [4], JT-60 [5] tokamaks.

A detailed explanation for the origin of the currents based on the thermoelectric effect was presented in [6], then improved and corrected in [7,8]. A simplest model of an isothermal collisional plasma was considered with an 1D transport along the magnetic field. If an open field line connects two grounded plates with different temperatures of the adjacent plasma, then the sheath potential drop at these plates is different, and therefore, an electric current along the field line arises, which tends to compensate the corresponding potential difference. In the model considered, the thermoelectric current flows from the hot side toward the cold one, provided the electron pressure gradient along the field line, \( \nabla P_e \), is zero. If \( \nabla P_e \neq 0 \), then the current can flow from the cold side to the hot one. Among other possible reasons giving rise to non-ambipolar flows in the SOL plasma of a tokamak, also mentioned are loop voltage, outward helicity transport, bootstrap effect (see [3] and the references therein).

For many reasons, studies of electric currents in SOL plasmas of closed magnetic traps are of significant interest. Such currents, when striking the chamber wall, give rise to an erosion (or modification) of the surface and leave footprints as characteristic stripes, which confirm the existence of divertor flows and their inhomogeneity [9,10]. If an antenna for RF heating of the plasma is intersected by the divertor flows, the electric currents result in an erosion of the antenna material and an additional plasma contamination, provided special measures have not been undertaken [11]. One of possible (if not most common) modes of divertor facility operation is that with the grounded target plates. Under these conditions, it is non-ambipolar particle flows along the divertor field lines, as an intrinsic element of the process of particle and heat loss, that cause a substantial (and besides, inhomogeneous) energy load on the target plates. The knowledge of factors giving rise to these flows, their magnitude and spatial distribution is necessary for a realistic design of the regime of divertor operation in a future fusion reactor on the basis of stellarator or tokamak.

Non-ambipolar flows of particles in the SOL and associated potentials are necessary to be taken into account, when such ideas are realized as an additional current generation by electron beam injection to support the discharge in a tokamak [12], plasma transport and stability control near the boundary [13], divertor flow redistribution by applying a differential electric bias to divertor plates or special electrodes [14].
In the Heliotron E device, the first evidence of parallel electric current generation in the SOL plasma (diverted plasma) was obtained in a currentless ECH plasma [15,16]. To study the diverted plasma, sets of collector plates (CPs) were installed near the vacuum chamber wall and used as electric probes. It was observed that the floating potential of isolated plates could take both positive and negative values, thus pointing to non-ambipolarity of plasma flows coming to the plates, when they were grounded. The present work, which was carried out with a currentless plasma supported and heated by NBI and ECH, can be considered as a continuation of our works [17-19]. In [17-19], when studying diverted plasma flows, the ion saturation current (ISC) to the CPs was taken as a measure of these flows, that is, the conditions were modelled, in particular, as if the diverted plasma came to the isolated target plates. In the present work, the diverted plasma flows were studied, which hit grounded CPs. Since the sets of CPs were mounted near the vacuum chamber wall, the obtained data allow to judge the properties of plasma flows hitting the wall. The purpose of the work was (1) to measure poloidal distributions of non-ambipolar divertor plasma flows in different poloidal cross-sections of the torus within one helical field period, (2) to find the link between electric currents in divertor flows and characteristics of divertor field lines, and (3) to find the effect of different methods and regimes of plasma heating on the value and direction of these currents. Proceeding from the data obtained, some possible mechanisms of electric current generation in the diverted plasma of a heliotron/torsatron are discussed.

The rest of the paper is formed as follows. In section 2 short data are presented of the Heliotron E device, its plasma heating sources, plasma parameters and sets of SPs, which were used to record electric currents to the wall. The results of measurements of poloidal distributions of the currents are presented in section 3. In section 4 the electric currents in the divertor flows are considered in function of plasma heating power. At last, the results of investigations are summarised and some possible mechanisms of current generation are discussed in section 5.

Some preliminary results of non-ambipolar divertor flow studies in the Heliotron E heliotron/torsatron are published in [20,21].

2. Experimental conditions

The Heliotron E device [22] is an $l=2/m=19$ heliotron/torsatron. The major radius of the torus $R_o = 2.2$ m, the average minor radius of the plasma is $\bar{a} \approx 0.2$ m. The inner radius of the rounded parts of the vacuum chamber is 0.41 m, so the "X-point" structure of the boundary magnetic field is well inside the vacuum chamber. In the studies presented, the toroidal magnetic field was produced by the helical coils only and fixed at $B_\varphi = 1.9$ T, the rotational transform at the boundary $t(\bar{a}) \approx 3$. A
magnetic configuration was used with about 2 cm inward shift of the magnetic axis from the minor axis of the torus (corresponds to the vertical field strength normalized by the toroidal field produced by the helical coils $\beta^* = -0.192$). Currentless plasmas were produced by the fundamental ECH (further on ECH-1, 53.2 GHz, irradiated power $\leq 0.4$ MW) or by the 2nd harmonic ECH (ECH-2, 106.4 GHz, $\approx 0.3$ MW). Then they were supported and heated by the NBI with the injection voltage of 23-24 kV, total injected power $P_{\text{inj}}$ up to 3 MW and the pulse length up to 160 ms. An ECH pulse ($\leq 40$ ms) was imposed on NBI plasmas in some cases. The disposition of the heating sources around the torus is shown in figure 1(a). The neutral beam injection lines BL-2, BL-3, BL-5 and their injection angles, ECH power inlets and the frequencies are indicated. The typical values of the central chord-averaged electron density were $n_e \approx (1.5-2.5) \times 10^{19}$ m$^{-3}$. The typical values of the electron and ion temperatures were $T_e(0) \approx 0.6 \div 1.5$ keV, $T_i(0) \approx 0.3 \div 0.6$ keV.

To study the divertor plasma, a set of 56 CPs was used, each plate being 5 cm long and 0.8 cm width [15]. All the plates were divided into 8 arrays with 6 or 7 operating plates in each array. The arrays were arranged poloidally on both sides of the rounded parts of the vacuum chamber (i.e., in the space between the helical coils) at the distance of 1.5 cm from the wall in 4 poloidal cross-sections with the interval of 1/8 field period. The positions of these cross-sections are indicated in figure 1(a), and the cross-sections of the vacuum chamber themselves with the CP arrays and CP numbers 1,2,...,8 in each array are shown schematically in figure 1(b). The position of each array was identified by the poloidal angle $\Theta$ of its center: $\Theta = 0^o, \Theta = 45^o, \Theta = 90^o, \Theta = 135^o, \Theta = 180^o, \Theta = 225^o, \Theta = 270^o, \Theta = 315^o$. The values of $\Theta$ also are indicated in figure 1(b). Thus, using all set of CPs, we were able to detect plasma flows approaching the wall in 8 sections within one field period. For some fixed regime of machine operation, the current $I_p$ ("plasma current") to the grounded plates of one array and the floating potential $V_f$ of the isolated plates of another array were recorded in one operating shot with shot-to-shot array changing. Thus, the whole set of $V_f$ and $I_p$ values for all the CP arrays was measured in 8 shots. In some measurement series with a fixed regime, the values of $V_f$, $I_p$ and ISC $I_s$ for all the CP arrays were measured in 16 operating shots. Having these data, the electron temperature and electron density could be estimated near the plates, supposing the "ideal" $V$-$I$-characteristics of the plates.

3. Poloidal distributions of non-ambipolar divertor flows

It has been already observed in previous experiments on Heliotron E under ECH conditions [15,16] that the potential $V_f$ of isolated CPs took positive or negative values depending on $\Theta$ and plate number. The same was also observed in the case of NBI or a combination of NBI and ECH
(NBI+ECH). In accord with \(VI\)-characteristic, the direction of current \(I_p\) is definitely related to the sign of \(V_f\). In figure 2 distributions of \(I_p\) in the plates are shown for all the CP arrays. The positions of plates are indicated by bold segments 1,2,...,7 on the horizontal axes (\(\theta\)-axes), in accord with figure 1(b), and corresponding currents are plotted as shaded rectangles (the height in mA). The measurements were carried out in relatively simple conditions, where plasma was supported and heated by NBI from a single beam line (BL-2) with a low injection power \(P_{\text{inj}} \approx 0.7\) MW and almost symmetric toroidal position of the inlet about the CP arrays. The values of \(I_p\) were taken at the density \(n_e \approx 2 \times 10^{19}\) m\(^{-3}\).

Also, in figure 2 calculated connection length \(L\) of open field lines is plotted as a function of angle \(\theta\) for all \(\Theta\), with the starting points of calculation lying on the lines of array disposition. The same magnetic configuration as for measurements (\(\beta^* = -0.192\)) was taken for the calculations, and the interval of calculation was \(\delta \theta = 0.5^\circ\) in the poloidal direction. The field line segments departing in the \(B_\phi\) direction (clockwise in figure 1(a)) and against it form the families \(A\) and \(B\), respectively. For each \(\Theta\) the longest field lines (\(L \geq 2\) m) are grouped with their starting points in two bundles, thus pointing the expected locations of two most intense flows of the diverted plasma in the given poloidal cross-section, \(A\) and \(B\) ("main divertor flows", MDFs), in the "ideal", i.e. non-perturbed, magnetic configuration of Heliotron E. For short, we shall denote these flows as \(A-0,\ B-0,\ A-45,\ B-45,\ A-90,\ B-90,\) and so on. A specific "helical" vertical symmetry ("up-down symmetry") is inherent to calculated distributions of divertor field line parameters. With this symmetry, in particular, the \(L\left(\theta\right)\) distributions for the pairs \(A-90/B-270,\ B-90/A-270,\ A-45/B-315,\ B-45/A-315,\ A-0/B-0,\ A-135/B-225,\ B-135/A-225,\ A-180/B-180\) in the upper/lower parts of the torus, have the same form within the accuracy of calculations. (For a better visualization of this symmetry in figure 2, the angle \(\theta\) for the \(\Theta = 45^\circ,\ 90^\circ,\) and \(135^\circ\) distributions in the top half of the torus is counted from right to left.)

As follows from figure 2, in contrast to the calculated connection length distributions, there is no vertical symmetry in the measured plasma current distributions in \(\Theta\) and \(\theta\). One of the manifestations of the asymmetry is a multiple increase of the absolute values of \(I_p\), when going from the top of the torus to the bottom, similar to what has been already observed with the ISC \(I_s\).[18,19]. In particular, \(|I_p|\) rises from 1.4 mA in the MDF \(A-90\) (plate 5) up to 225 mA in the symmetrically disposed MDF \(B-270\) (plate 5). Besides, a new element of asymmetry has occurred, specific just to non-ambipolar divertor flows. We can see in figure 2 that directions of \(I_p\) are mutually inverse in the pairs \(A-90/B-270,\ A-45/B-315,\ B-45/A-315,\ A-0/B-0\) on the upper, lower and outboard sides of the torus. The opposite directions of the plasma current correspond to opposite polarities of the potential \(V_f\) in the flows of each pair.
It is reasonable for a further analysis of the observed $I_p(\Theta,\theta)$ distributions to use calculated data on mutual poloidal location of the ends of the longest ($L \geq 2$ m) divertor field lines and CPs intercepting these field lines. In figure 3 the poloidal positions of such plates on the top, bottom and outboard sides of the torus are marked with bold arc segments on 8 circles, each of these circles corresponding to a certain considered MDF (plates P2, P3, P5 for $\Theta = 90^\circ/270^\circ$; P2 and P6 for $\Theta = 45^\circ/315^\circ$ and $\Theta = 0^\circ$; note that the signal from the plate P3 at $\Theta = 90^\circ$ could not be recorded, such plates are not shown in figures 1 and 2). Poloidal positions of the field line ends are marked by solid and open circles (remind that $\delta\theta = 0.5^\circ$). It follows from the form of $L(\theta)$ plots in figure 2 that in two cases (A-45/B-315 and A-0/B-0) the MDFs are formed by narrow ($\Delta\theta \sim 1^\circ$) bundles of comparatively long field lines. The number of field periods traversed by such field lines when going along the torus is $M \geq 10$, and the number of corresponding poloidal turns is $N > 2$. The poloidal positions of the ends of such divertor field lines are indicated by solid circles. In the cases considered, the plate receiving the main flow and the ends of corresponding field lines are distinctly separated poloidally and lie on different sides relative to the midplane. In other two cases ((A-90/B-270, and B-45/A-315), the MDFs are formed by broader bundles ($\Delta\theta \leq 7^\circ$, the angular size of CP) of shorter field lines than in the first two cases. For these field lines $M \leq 3$, $N < 1$. In figure 3 the positions of their ends are marked by open circles, and average values are indicated of the numbers of traversed periods $\overline{M}$ and poloidal turns $\overline{N}$. For each of the flows in the pairs A-90/B-270, and B-45/A-315 the region with maximum density of field line ends and the corresponding CP are located on different sides from the midplane. The poloidal separation between the plates and the regions with maximum density of ends is pronounced more distinctly for the pair A-90/B-270, where this separation is close to $90^\circ$. At last, in one more case (B-90/A-270), the MDFs are formed by broad bundles of comparatively short field lines ($\overline{M} = 2.7$, $\overline{N} = 0.69$, the locations of ends are marked by open circles) in combination with narrow bundles of the longest field lines ($M = 19.25$, $N = 4.1$, solid circles). The starting points of field line calculation for each of the flows B-90/A-270 cover two CPs (P2 and P3), and the ends are distributed in a wide region of poloidal angles, $\Delta\theta > 180^\circ$, both below and over the midplane.

Referring to the pair A-90/B-270 of symmetrically disposed MDFs, we also take into account that the field lines make less than one poloidal turn in these flows, and there is no heating inlets near their trajectories. So, we may not expect possible local perturbations of the SOL plasma along these field lines. Then it follows from opposite direction of plasma current in these flows that a charge separation occurred in the SOL plasma under figure 2 conditions, with electrons carried away predominantly from the top side of the layer and ions carried away from the bottom side. An additional confirmation of charge separation in the SOL follows from opposite direction of current.
\( I_p \) in the pairs of symmetrically disposed MDFs \( A-45/B-315 \) and \( A-0/B-0 \), where the starting points and ends are separated most distinctly on both sides from the midplane. However, in this case, the field lines, when going along the torus, make more than one poloidal turn and pass near the inlet of the injection line BL-2. Therefore, it is more complicated to make a definite conclusion about the direction of SOL plasma polarization, proceeding from the plasma current direction in the MDFs \( A-45/B-315 \) and \( A-0/B-0 \).

As to the plasma current distributions on the inboard side of the torus (\( \Theta = 135^\circ, 180^\circ, 225^\circ \)), it follows from the form of corresponding \( L(\theta) \) distributions in figure 2 that all the starting points of the longest field lines leaving the CPs in both \( A- \) and \( B- \) directions for such values of \( \Theta \) are located on a single plate (P4). This means that the divertor field lines cross the plate under a small angle \( \alpha \) (tangency in the limit \( \alpha = 0 \)).

The character of plasma current distributions shown in figure 2 did not change qualitatively, when another low-power injector BL-3 (\( P_{\text{inj}} \approx 0.5 \text{ MW} \)) was used with the \( 90^\circ \) injection angle and a non-symmetric position of the inlet about the CP arrays (5 field periods from the CP arrays on the side \( B \), see figure 1). The current \( I_p \) direction in all the MDFs stayed the same as in the BL-2 case.

4. The effect of plasma heating on non-ambipolar divertor flows

4.1. NBI heating. In figure 4 shown are \( I_p(\Theta,\theta) \) distributions measured at \( \bar{n}_e \approx 2 \times 10^{19} \text{ m}^{-3} \) under NBI conditions with the total injection power raised up to 2.1 MW (BL-2+BL-3+BL-5 (2 ion sources of 6)). The inlet of BL-5 was located at a distance of one field period from the \( \Theta = 0^\circ \) CP array, and the injection angles of the sources energized were \( 79^\circ \) and \( 90^\circ \). It follows from comparison of \( I_p(\Theta,\theta) \) distributions in figures 2 and 4 that the absolute values of \( I_p \) increased with the heating power in all the MDFs. In particular, the values of \( |I_p| \) in the pair \( A-90/B-270 \) became now 9.2 mA and 489 mA, respectively. Besides, \( I_p \) is reversed in this pair of MDFs and in the MDF \( B-45 \). A comparatively large positive current occurred to the plate 5 at \( \Theta = 135^\circ \), as if a broadening of the summed MDF (A+B)-135 appeared with the heating power increase.

In more detail, the effect of NBI heating on the value and direction of the current \( I_p \) in the MDFs can be elucidated after plotting the plasma current as a function of the power absorbed in the plasma. The initial data were obtained in measurement series differing with the values of \( \bar{n}_e \) and neutral beam power left in the plasma. Besides, a shot-to-shot \( \bar{n}_e \) spread was possible even in one measurement series with a fixed regime of plasma heating. Therefore, to compare heterogeneous data, the absorbed power \( P_{\text{abs}} \) and the measured plasma current were normalized by
In the first approximation, the NBI power absorbed in the plasma in Heliotron E can be estimated from the relation [19]

$$P_{\text{abs}}/P_{\text{inj}} = 1 - \exp(-0.266 \bar{n}_e)$$

(1)

where $\bar{n}_e$ is taken in $10^{19}$ m$^{-3}$. The $I_p/\bar{n}_e - P_{\text{abs}}/\bar{n}_e$ plots under NBI conditions for 5 pairs of symmetrically positioned MDFs on the top, outboard and bottom sides of the torus (open and solid circles for the flows leaving above and below the midplane, respectively) are shown in figures 5 (A-90/B-270), 6 (A-45/B-315), 7 (A-0/B-0) as well as in figures 8 (B-90/A-270, the current $I_p$ to the plate 2 was taken for both these flows), and 9 (B-45/A-315). Also, a similar dependence for the summed flow (A+B)-180 on the inboard side is shown in figure 10. In figures 5-10 the points obtained in two plasma heating regimes with the use of ECH are also plotted: NBI+ECH-1 (△,▲) and NBI+ECH-1+ECH-2 (⊙,◆). However, the interpolating straight lines ("trends") are drawn through the NBI-only points. The spread of experimental points could be caused at least by such factors as a non-precise shot-to-shot reproducibility of plasma parameters, non-accurate current measurements (especially, small $I_p$s specific for the top part of the torus), and approximate character of expression (1). The following can be concluded from the analysis of presented plots.

Under the NBI conditions, the most obvious trends in $I_p/\bar{n}_e$ versus $P_{\text{abs}}/\bar{n}_e$ behavior can be seen in the MDF pairs A-90/B-270 (figure 5), A-45/B-315 (figure 6) and A-0/B-0 (figure 7). As it has been already mentioned in section 3, for these pairs the field line ends and the CPs intercepting these field lines lie on different sides from the midplane.

The $I_p/\bar{n}_e - P_{\text{abs}}/\bar{n}_e$ plots shown in figure 5 confirm that with small values of $P_{\text{abs}}/\bar{n}_e$, the plasma current was negative in the flow A-90 and positive in B-270. With $P_{\text{abs}}/\bar{n}_e$ increasing, $I_p$ is reversed in both flows in the interval from 200 to 300 kW/10$^{19}$ m$^{-3}$.

Reversing of plasma current in the MDF B-270 depending on heating power and plasma density is clearly demonstrated within one operating shot in figures 11.1 and 11.2. In a more simple case (figure 11.1), at the initial phase of the discharge, up to the moment 300 ms, an ECH-2 pulse generated a low-density plasma ($\bar{n}_e \approx 0.7 \times 10^{19}$ m$^{-3}$). As follows from figure 11.1, $I_p$ was negative in the B-270 flow at this phase. The $I_p/\bar{n}_e - P_{\text{abs}}/\bar{n}_e$ dependence has not been specially studied under ECH-only conditions in this work. Nevertheless, in the case considered, $P_{\text{abs}}/\bar{n}_e = 400$ kW/10$^{19}$ m$^{-3}$ at the initial stage of discharge, and as follows from figure 5, the current $I_p$ was negative with such values of $P_{\text{abs}}/\bar{n}_e$ like NBI heating case. At the next phase of the discharge (300-408 ms), the plasma was heated by NBI from the injection line BL-2 ($P_{\text{inj}} = 0.7$ MW). With the density increasing gradually, the parameter $P_{\text{abs}}/\bar{n}_e$ changed from 167 to 144 kW/10$^{19}$ m$^{-3}$ on this stage of
discharge, and a positive current $I_p$ corresponded to all these values of $P_{abs}/\bar{n}_e$. At last, at a final stage of the discharge, $P_{inj}$ was raised up to 1.9 MW. In accord with the density variation on this stage of the discharge, the parameter $P_{abs}/\bar{n}_e$ changed in the interval (390-340) kW/10$^{19}$ m$^{-3}$ and gave rise to negative values of $I_p$. In a more complicated case in figure 11.2, the initial phase of the discharge followed a similar way as in figure 11.1, but at the moment 355 ms a 30 ms pulse of ECH-1+ECH-2 with the absorbed power up to 0.47 MW was imposed on the NBI. The ECH was accompanied by a density decrease due to the effect of "pump-out" [23], and the density rose again after ECH switched off. At the final stage of discharge, starting from 406 ms, the NBI power was raised up to 1.6 MW. In the course of all the active phase of the discharge, the plasma current changed its direction four times in line with the $P_{abs}/\bar{n}_e$ variations.

For the MDF pair $A$-45/$B$-315 (figure 6), the current $I_p$ was positive in the $A$-45 flow with all values of $P_{abs}/\bar{n}_e$. In the flow $B$-315 the negative $I_p$ region began from 100 kW/10$^{19}$ m$^{-3}$. In the $A$-0/$B$-0 pair (figure 7) the plasma current was negative in the $A$-0 flow and positive in $B$-0 within all the interval of $P_{abs}/\bar{n}_e$ values being realized. When extrapolating the $I_p/\bar{n}_e - P_{abs}/\bar{n}_e$ dependencies for $A$-0/$B$-0 toward small values of $P_{abs}/\bar{n}_e$, we may assume that the plasma currents would be reversed at $P_{abs}/\bar{n}_e \leq 100$ kW/10$^{19}$ m$^{-3}$.

Thus, the $I_p/\bar{n}_e - P_{abs}/\bar{n}_e$ plots shown in figures 5,6,7 confirm by their character that a vertical electric polarization of the SOL plasma arose during NBI. With this, we may suppose that the direction of polarization was different at low and high values of the normalized absorbed power, and the reverse of plasma current in some pairs of symmetrically positioned MDFs occurred at the higher value of the $P_{abs}/\bar{n}_e$ parameter, the farther away from the midplane these flows left the SOL.

The $I_p/\bar{n}_e - P_{abs}/\bar{n}_e$ dependence presented in figure 8 relates to the pair $B$-90/$A$-270, where, in accord with figure 3, the ends of field lines were distributed over an interval of poloidal angles both above and below the midplane. For the figure 9 case ($B$-45/$A$-315), the ends of field lines in each flow are also positioned on both sides from the midplane (see figure 3). With this, the regions of maximum end density are located near the midplane. We may expect that in the cases of figures 8,9 even with a certain vertical polarization of SOL plasma, the resulting direction of plasma current recorded by a CP would depend not only on the direction of polarization but also on the relation between the contributions to this current from two groups of field lines, one of these groups having the ends in the top side of the torus and the other group having the ends on the bottom side.

In figures 5-9 some NBI-only points are specially indicated, which were obtained with a separate use of the BL-2 and BL-3 beam lines differing by their injection angles and by toroidal position of their inlets (see figure 1(a)) as well as with the use of a combination of these two injection lines and with a combinations of BL-2 and BL-3 with BL-5, whose inlet was located most
close to the CP arrays. We may conclude that within the present data spread neither the toroidal position of an NBI inlet nor the injection angle had a governing effect on the value and sign of $I_p$. Perhaps, it was the density-normalized absorbed power that could be taken as the main parameter, which determined the sign and value of the density-normalized plasma current in the MDFs.

4.2. Plasma current response to a fast variation of NBI power. The $I_p/\bar{n}_e - P_{\text{abs}}/\bar{n}_e$ dependencies shown in figures 5-10 were measured not less than 30 ms after the NBI pulse was switched on, so the processes governing the formation of the plasma potential and of the corresponding plasma current presumably attained a (quasi)stationary level. However, an analysis of potential and current behavior under obviously non-stationary conditions would facilitate a better understanding of the nature of non-ambipolar divertor flows. With an additional shorter (50 ms) NBI pulse imposed on a long (160 ms) NBI pulse, variations of floating potential $V_f$ and current $I_p$ were always observed in the MDFs. With this, the final value and direction of the current always agreed with the plots shown in figures 5-10 within the general data spread. However, as follows from the form of temporal $V_f$ and $I_p$ variations, in general case these variations consisted of two components, a fast (the rise- and fall time $\sim$1 ms or smaller) and a slow ($\sim$10 ms or longer) ones. The fast component of potential and current variation manifested itself in the form of a more or less sharp bend of the signal at the moments of additional NBI switched on and off. Most obviously this effect was observed in the summed MDF (A+B)-180 on the outboard side of the torus (figure 12). The fast fall of $V_f$ and $I_p$ after NBI switched off is an indication that the process governing the observed fast rise of $V_f$ and $I_p$ lasted for all the time of additional NBI. Hence, such a process persisted during the (quasi)stationary phase of NBI too.

In figure 13.1 shown are potential $V_f$ variations under the effect of an additional NBI in the pairs of symmetrically positioned MDFs A-90/B-270, A-45/B-315 and A-0/B-0 with the starting points and ends of diverted field lines lying on different sides from the midplane. A more or less sharp bend of $V_f$ and $I_p$ time dependence with the additional NBI switched on and off was observed in all the selected MDFs. The fast and slow variations of the potential (and current) in each flow had the same direction.

4.3. Plasma current response to an ECH pulse imposed on NBI. Two varieties of the ECH used on Heliotron E provided different power deposition profiles in the plasma [23]. With the ECH-1, a considerable fraction of the microwave power irradiated in the form of a broad non-focused beam was deposited at the periphery of the confined plasma. With the ECH-2, a main part of the launched power (a well-focused Gaussian beam with the beam-waist size of $\sim$2 cm) was deposited in the central region ($r/a < 0.5$ cm). In both cases, an ECH pulse imposed on the NBI resulted in a variation of the plasma current, its direction and maximum value as functions of the
total absorbed power following the dependencies for NBI (figures 5-10), though with somewhat larger deviation in some MDFs from the reference straight line drawn through the NBI-only points (see figures 5-10).

The character of floating potential variations in the same MDFs as in figure 13.1 with an ECH-1 pulse imposed on the NBI (BL-3) can be seen in figure 13.2. Like the additional NBI case, with the ECH-1 (or ECH-1+ECH-2) imposed on the NBI, the potential (and plasma current) response generally also had fast and slow components. Proceeding from the form of signals in figure 13.2, it can be concluded that the slower variations of $V_f$ (and $I_p$, consequently) in the MDFs considered behaved themselves by their direction in a way similar to that in the case of additional NBI. As to the faster variations, these either were practically absent in the top part of the torus ($A$-90) or were directed toward potential decrease ($A$-45, $A$-0). In the bottom part ($B$-0, $B$-315, $B$-270), the fast variations everywhere were directed toward potential (and current) decrease.

With an ECH-2 pulse imposed on the NBI, only slow variations of plasma current and floating potential were observed in the MDFs. Therefore, with the difference between microwave power deposition profiles in the cases of ECH-1 and ECH-2 taken into account, it is natural to suppose that the fast $V_f$ and $I_p$ variations arising with an ECH imposed on the NBI were caused by processes developing at the plasma periphery.

5. Summary and discussion

In the Heliotron E heliotron/torsatron, with a currentless NBI and NBI+ECH plasma, spatial distributions were measured of non-ambipolar charge particle flows (plasma currents), which came to grounded collector plates installed near the vacuum chamber wall in 4 poloidal cross-sections of the torus with the interval of 1/8 helical field period. A strong vertical asymmetry of these distributions was observed, which was characterized by the following main features. (1) In the MDF pairs positioned symmetrically about the midplane, the absolute values of plasma current were different in the upper and lower parts of the torus, this difference attaining two orders of magnitude. (2) In the pairs of symmetrically positioned MDFs with the starting points and calculated end positions of diverted field lines lying on different sides from the midplane ($A$-90/$B$-270, $A$-45/$B$-315, $A$-0/$B$-0), the plasma currents had opposite direction. In each of the MDFs $A$-90/$B$-270 the plasma current was reversed with the parameter $P_{abs}/\bar{n}_e$ increase. It looks like an $I_p$ reverse could also occur in two other MDFs mentioned above, however, the corresponding $P_{abs}/\bar{n}_e$ values were reduced with approaching the midplane and could not be realized under conditions considered.
In all the MDFs the absolute value of average density-normalized plasma current was a rising function of the heating power per one particle in the confinement volume. (In those flows where \( I_p \) changed sign with \( P_{abs}/n_e \) increase, an obvious rise of \( |I_p|/n_e \) was observed after the sign had been changed.) Perhaps, this can be considered as a manifestation of a regularity common for tokamaks and stellarators, power degradation of confinement [24].

It follows from the form of floating potential and plasma current time response to an additional short IBN or ECH pulse imposed on a long NBI that this response had a fast component with a characteristic time of \( \sim 1 \) ms or less and a slow component (\( \sim 10 \) ms or longer). The processes giving rise to fast variations of \( V_f \) and \( I_p \) with an additional heating switched on and off existed during the stationary heating too.

We consider now some mechanisms, which might result in generation of electric currents in the divertor flows.

1. As it has been already mentioned in Introduction, one of such mechanisms having been studied theoretically and verified experimentally in single-null diverted tokamaks is based on the thermoelectric effect. Here, the electric current along the diverted field lines is caused by the difference in potential drops at the ends of field lines, and this difference, in turn, results from the plasma temperature difference at the ends. Under heliotron/torsatron conditions, a direct application of the simplest model considered in [6-8] is embarrassing. In the heliotron magnetic configuration, the field lines forming a main divertor flow and starting from a single CP generally can end on different regions of the vacuum chamber wall with different values of the temperature (and density) of the adjacent plasma (see, in particular, figure 3).

To find out a possibility of thermoelectric effect to contribute to the formation of observed non-ambipolar divertor flows in Heliotron E, we estimate the temperature \( T_e \) and density \( n_e \) at the plates in MDFs. To do this, we use the measurement data of the ISC \( I_s \), the current to a grounded CP, \( I_p \equiv I(0) \), and the floating potential \( V_f \), substituting these data into expressions for the \( VI \)-characteristic, \( I(V) = I_s \left[ 1 - \exp \left( \frac{V - V_f}{T_e} \right) \right] \), and ISC, \( I_s = \left( \frac{1}{2} \right) |V_f| \sqrt{2T_e/m_i} \), for a plain Langmuir probe. The results of estimations for the cases presented by figures 2 and 4 are brought together in Table 1.

The two values of \( T_e \) and \( n_e \) presented in Table 1 for each MDF were obtained by substitution of two values of \( V_f \) into the relation for \( I(0) \), one of them having been taken from the \( I_s \)- and the other from \( I_p \) measurement series. In particular, it follows from Table 1 that in each pair of symmetrically positioned MDFs the electron temperatures are distinctly different in the top and bottom, with the top temperature being lower than the bottom one, except the pair A-0/B-0, nearest to the midplane. These relations between the temperatures remain qualitatively the same, when
going from the lower (figure 2) to higher (figure 4) heating power. Such a temperature difference near the chamber wall could result in a certain thermoelectric current being amenable at least to a qualitative estimation in those pairs of symmetrically positioned MDFs, where starting points and ends of diverted field lines lie in different sides from the midplane. Among such MDFs, the direction of plasma current really agrees with thermoelectric effect in the pair \(A-45/B-315\) at both lower and higher heating power (the electron current comes to the plate with a higher temperature of the adjacent plasma). In the pair \(A-90/B-270\) the plasma current and the expected thermoelectric current were opposite at the lower heating power and had the same direction at the higher power. In the pair \(A-0/B-0\) at both lower and higher heating power, a negative current came to the plate 2 (\(A-0\)) with a higher temperature of the adjacent plasma, and a positive current came to the plate 6 (\(B-0\)) with a lower temperature, as if the relation between the temperatures at the field line ends and at the plate were qualitatively the same as between the temperatures at the plates 2 and 6.

The level of agreement between measured values of \(I_p\) and those expected from [7] can be estimated for the MDF pairs \(A-90/B-270\) and \(A-45/B-315\), if we suppose for each of these flows, proceeding from figure 3, that the electron temperature at the field line ends is close to that at the plate receiving the symmetrically positioned flow. With the difference in electron density values at symmetrically disposed CPs having been taken into account, equation (17) from [7] for the reduced parallel current between grounded plates A and B, \(\hat{I}_{\parallel} = I_{\parallel}/I_{sA}\), can be presented in the form

\[
\hat{I}_{\parallel} = -\gamma \left\{ k + 0.85 - \alpha \right\} (T_a/T_e - 1) \left[ \left( n_e/n_s \right) B \right] \hat{I} \left[ 1 + \hat{I} \right] \left\{ \left[ 1 - \hat{I} \right]/\left[ \left( n_e/n_s \right) \sqrt{T_a/T_e} \right] \right\} \right\}
\]

(2)
where the term with parallel electron pressure gradient is approximately expressed as [25] 
\[(1/T_A)[(T_B - T_A + 0.5(T_B + T_A)\ln(n_{eB}/n_{eA})]. \text{ Here } k = 3.89, \quad \alpha = 0.7, \quad \gamma = \sigma_1 l_1/e\lambda_1 l_1 e. \]

\[
\sigma_1 = \left(\frac{e^2}{2m_e} \frac{L_1}{\lambda_1} \int_{A}^{A} \left(\frac{dv_1}{n_e \tau_{ei}}\right)\right)^{-1}, \quad \lambda_1 = 0.7, \quad l_1 \text{ is the connection length.} \]

For typical conditions in Heliotron E, the coefficient \(\gamma\) is 10^3 in order of magnitude. At the same time, the maximum possible value of \(|\hat{I}|\) never exceeds several units. This means that the term in {} in equation (2) must be much less than unity in its absolute value. Taking this into account together with the crudeness of all approximations and suppositions accepted above, it is sufficient to put the term in {} to zero to estimate the value of \(\hat{I}\) with given \(T_B, T_A, n_{eB}, n_{eA}\). As a result of such operation, we get 0.95 for the ratio \(I_B/I_A\) in the MDF A-90 and -0.03 in B-270 under figure 4 conditions (experimentally found ratios are 0.44 and -0.34, respectively. For the pair A-45/B-315 we get, respectively, 1.0 (0.42)/-0.23 (-0.18) at the lower heating power (figure 2), and 1.0 (0.64)/-0.23 (-1.17) at the higher heating power (figure 4). Thus, in separate cases, at least the observed directions of the plasma current correspond to those expected from the theory of thermoelectric current even with the non-zero parallel electron pressure gradient taken into account. In whole, it follows from the analysis having been made that the observed values and directions of the plasma currents cannot be explained on the basis of thermoelectric effect only, and some other mechanisms of current generation should be involved.

As to the difference between the near-wall plasma temperatures in the lower and upper parts of the torus, it could be associated with one of presumed factors, governing the vertical asymmetry of divertor flows in Heliotron E. It has been established in [19], that the asymmetry remained even in the limit of low heating power. Therefore, it was supposed by analogy with a double-null divertor in a tokamak [26] that in these conditions the asymmetry resulted from distortions of the divertor magnetic structure due to gradual deformation and/or shift of the helical coils. If such effect really existed, then the observed multiple excess of the divertor flow magnitude in the lower part of the torus over that in the upper part could result from the "lower X-points" turning into the "inner X-points", by the terminology used in [26]. As a consequence, the temperature of the plasma outflowing onto corresponding divertor field lines was higher.

2. Under NBI and ECH conditions, electric currents of different magnitude and polarity flowing along the divertor field lines to the wall, temporal behavior of these currents, can also be connected with fast particle dynamics in the confinement volume. It is known [27] that the perpendicular transport of some groups of trapped ions and electrons has a convective character. A fast loss or redistribution of these particles can give rise to fast self-consistent variations of the
space potential in both confined and SOL plasmas and to electric currents arising along open field lines. It follows from estimations of plasma potential \( V_p \) near the CPs by using the values of \( V_f \) and \( T_e \) (see Table 1) that \( V_p \approx V_f + 2.5T_e/e \) was positive for all considered MDFs. This result agrees with the data on edge plasma potential obtained from Langmuir probe measurements [28]. A fast rise or fall of floating potential and of plasma current consistently with additional NBI or ECH imposed on an initial NBI could result from SOL plasma potential variations induced by fast, convection-like redistribution of suprathermal electrons and ions in the confinement volume. At the same time, slower \( V_f \) and \( I_p \) variations, probably, were induced by processes bearing a diffusion character, with thermal particles playing the main role (plasma heating, modifications of density and temperature profiles). Proceeding from the form of \( V_f \) and \( I_p \) variations arising with an additional heating switched on and off, we concluded that the fast processes existed during quasistationary (160 ms) NBI heating too.

A qualitative treatment of \( V_f \) and \( I_p \) variations based on fast particle dynamics can be suggested with the use of the MDF pair \( A-90/B-270 \) as a way of example. As it has been already mentioned, for these symmetrically positioned flows the starting points and ends of field lines are well poloidally separated and lie on different sides from the midplane, and the field lines make less than one poloidal turn (figure 3). Proceeding from the form of plasma current distribution for the flows \( A-90 \) and \( B-270 \) at a low heating power (figure 2, \( P_{abs}/n_e < \sim 200 \text{ kW}/10^{19} \text{ cm}^{-3} \)), we may suppose that an excess of electron concentration in the upper part and of ion concentration in the lower part occurred. Under the influence of additional NBI or ECH a fast transition arose to the state qualitatively characterized by plasma current distributions shown in figure 4 (\( P_{abs}/n_e > \sim 200 \text{ kW}/10^{19} \text{ cm}^{-3} \)). In this state an excess of ion concentration in the upper part of the torus and of electron concentration in the lower part occurred. In both cases, a strong vertical asymmetry was retained, with the absolute value of \( I_p \) in the lower part considerably exceeding that in the upper part. As it has been already mentioned above, we supposed [19] that the observed up-down asymmetry of the divertor flows in part resulted from distortions of the real magnetic structure of the divertor layer, and this part of asymmetry remained even in the limit of zero heating power. Besides, the asymmetry could be in part connected with dynamics of high energy particles occurring due to NBI and ECH. In the latter case, a vertical asymmetry of the helical magnetic field ripple wells of a heliotron could be an initial reason [29]. In particular, this asymmetry could be initiated by a vertical shift of the plasma column [29]. However, there has been no experimental evidence of any vertical shift of the plasma in Heliotron E. At the same time, a natural vertical asymmetry of the coordinates of helical ripple wells along field lines is inherent to some helical magnetic field configurations, including Heliotron E [30]. This kind of asymmetry results from the presence of
satellite harmonics in the Fourier series of the magnetic field. If these harmonics have such amplitudes that their effect on the magnetic configuration is not mutually compensated (the vertical modulation parameter $\sigma \neq 0$), then, as a final result, a mismatch of helical ripple well depths near the vertical axis in the upper and lower halves of the torus takes place. For the passing particles and passing helical bananas freely going around the torus along the major azimuth, this helical ripple well asymmetry is compensated by a strong poloidal rotation of particles and does not lead to a vertical asymmetry of their orbits. For the transient particles with the energies near the trapping/detrapping boundary and turning points (with their poloidal angle) located near the vertical axis (toroidal bananas and superbananas), especially for fast particles, the vertical asymmetry of helical ripple wells results in a vertical asymmetry of turning points ($\theta_{b+} \neq \theta_{b-}$) and in a vertical asymmetry of their orbits [31]. With this, the particle drift velocities near the upper and lower turning points are also different. For high energy particles this difference becomes so large that it gives rise to a net vertical drift of the entire banana, such that the drift of toroidal banana-ions is directed toward deeper helical ripple wells, while the superbanana-ions drift toward less deep ripple wells. The direction of drift of fast barely-trapped and weakly-passing electrons is opposite to that of ions.

An NBI usually results in occurrence of an ambipolar radial electric field $E_r$ in the confinement region with a negative potential ("ion root") $e\Phi / T \sim 1/2$ [32]. Therefore, in general case, charge particle motion is characterized by two parameters, the drift frequency $\Omega_d$, which is proportional to the gradient-$B$ drift frequency, $\Omega_{VB} = V_{VB} / r$, and the precession frequency of the electric drift, $\Omega_E = cE_r / (Br)$. With a low injection power, the electric field is too small to affect the orbits of fast particles emerging due to the injection, so $\Omega_{VB} \gg \Omega_E$ for both fast electrons and fast ions. As calculations have shown [31,33,34], with a perpendicular or oblique injection, the fast particles deeply trapped in the helical ripple of Heliotron E are well-confined ones. In this case, the main part of lost particles consists of barely-trapped and weakly-passing ones. At the periphery of the confinement region, most of the escaped particles are toroidal banana-ions [31]. Under Heliotron E conditions, owing to the vertical asymmetry of the helical ripple wells with $\sigma < 0$, the drift of these particles is vertical and directed to the lower part of the torus, just where a maximum magnitude of the divertor flow (ISC) [17-19] and a maximum positive plasma current (figure 2) were observed. The toroidal banana-electrons with transient orbits drift toward the upper half of the torus under the influence of the vertical asymmetry of helical ripple wells. This just could result in occurrence of a small negative current to the CPs in the upper part (figure 2).

As follows from figures 4 and 5, with an increase of NBI heating power, the plasma current was reversed in the MDFs $A$-90 and $B$-270, and to explain this effect, some other mechanisms of
particle loss should be involved. One of the factors affecting the loss is the ambipolar electric field, its role has been already analyzed recently in [34,35]. A heating power increase for the account of beam density increase leads to an increase of fast ion loss. As calculations show [35,36], the resulting ambipolar potential becomes more negative due to this loss and results in an improvement of thermal ion confinement because of delocalization of most ions from the helical ripple wells. An ambipolar potential such that $\Omega_E > \Omega B$ can lead to transition of some fraction of fast deeply trapped ions to superbananas and their vertical drift toward the upper part of the torus and escape. This potential still remains too weak to ensure a total confinement of fast toroidal bananas drifting vertically toward the lower torus side. The electron confinement is deteriorated due to the negative potential effect. Besides, as these particles tend to be more deeply trapped in the helical ripple wells under the potential effect, the fraction of fast superbanana-electrons increases. These electrons drift vertically upward and escape. Thus, at a certain value of the potential the convective flows of ions drifting vertically downward and of electrons drifting upward must coincide, and this will result in a full disappearance of the non-ambipolar divertor flows.

In the course of a further heating power increase accompanied by a negative potential rise, the electric drift frequency becomes comparable with the fast electron drift frequency, $\Omega_d + \Omega_E \approx 0$, and a so-called helical resonance occurs [35]. In these conditions, the most of fast ions are confined, and only a small fraction of them can be transformed into superbananas and lost. Among fast deeply-trapped electrons, a significant fraction of them can turn into superbananas, and the loss of this type of orbits becomes dominated. In Heliotron E, the drift of superbanana-ions is directed to the upper part of the torus, where a small positive plasma current was observed at a high heating power (figure 4). The superbanana-electrons, which form a most of lost particles in this case, drift mainly toward the lower part of the torus, this being in agreement with observations of a strong negative current to the lower CPs.

Thus, in non-fully drift optimized heliotron/torsatron magnetic configurations, the presence of the poloidal non-uniformity of the coordinates of the secondary magnetic wells (the helical ripple wells) results in a correspondent spatial non-uniformity of particle loss regions and, consequently, of divertor plasma flows. This can occur only in configurations, where a significant fraction of the first orbit loss contains barely-trapped/passing particles with a weak velocity of the poloidal rotation and a strong vertical drift velocity.

The second of two mechanisms having been considered, which give rise to non-ambipolar divertor flows, seems stronger than thermoelectric effect, and the influence of the former dominated even at low NBI and ECH heating power, where the observed directions of the plasma current in some MDFs did not agree with thermoelectric effect.
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References

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Figure captions

**Figure 1.** (a) Disposition of heating sources and collector plate arrays over the Heliotron E torus. (b) Disposition of collector plate arrays in the vacuum chamber of Heliotron E with indication of the angle $\theta$ and plate numbers for each array.

**Figure 2.** Distributions of plasma current $I_p$ in collector plates (shaded rectangles) under NBI conditions (BL-2, $P_{\text{inj}} \approx 0.7$ MW, $n_e \approx 2 \times 10^{19}$ m$^{-3}$, # 74264-74271). Calculated connection length $L$ as a function of poloidal angle $\theta$ (solid lines) for open field lines with starting points lying on the lines of collector plates alignment.

**Figure 3.** Calculated poloidal positions of starting points (collector plates P2, P3, P5, P6) and ends ($\bigcirc$, $\bigotimes$) of field lines forming the main divertor flows on to the upper lower and outboard sides of the torus. For these field lines the numbers of passed field periods, $M$ and $\overline{M}$, and of poloidal turns, $N$ and $\overline{N}$, are also indicated.

**Figure 4.** Distributions of plasma current $I_p$ in collector plates (shaded rectangles) under NBI conditions with the injection power raised up to 2.1 MW (BL-2+BL-3+BL-5, $n_e \approx 2 \times 10^{19}$ m$^{-3}$, # 74168-74175).

**Figure 5.** Density-normalized plasma current $I_p/n_e$ as a function of density-normalized absorbed NBI power $P_{\text{abs}}/n_e$ in symmetrically disposed main divertor flows A-90 ($\bigcirc$) and B-270 ($\bigbullet$). On these plots imposed are the points obtained with NBI+ECH-1 ($\triangle$, $\blacksquare$) and with NBI+ECH-1+ECH-2 ($\bigtriangleup$, $\clubsuit$).
Figure 6. The same as in figure 5 for the flows A-45 (○, △, ◇) and B-315 (●, ▲, ◆).

Figure 7. The same as in figure 5 for the flows A-0 (○, △, ◇) and B-0 (●, ▲, ◆).

Figure 8. The same as in figure 5 for the flows B-90 (○, △, ◇) and A-270 (●, ▲, ◆).

Figure 9. The same as in figure 5 for the flows B-45 (○, △, ◇) and A-315 (●, ▲, ◆).

Figure 10. The same as in figure 10 for the summed flow (A+B)-180.

Figure 11.1. Density $\bar{n}_e$ together with time sequence of initial ECH, long NBI and additional NBI pulses. Plasma current $I_p$ in the main divertor flow B-270 (# 74082).

Figure 11.2. The same as in figure 11.1 with an additional ECH pulse imposed on the long NBI (# 74097).

Figure 12. The same as in figure 11.1 for the summed main divertor flow (A+B)-180 (# 74268).

Figure 13.1. Floating potential $V_f$ response to an additional 50 ms NBI pulse imposed on the long (160 ms) NBI in the pairs of symmetrically disposed main divertor flows A-90/B-270, A-45/B-315, A-0/B-0. The additional NBI is switched on and off at 400 and 450 ms, respectively (# 74263-74271).

Figure 13.2. The same as in figure 13.1 with an ECH-1 pulse (340-370 ms) and an additional NBI pulse (392-440 ms) imposed on the long NBI. The additional NBI-induced variations of $V_f$ are similar to those shown in figure 13.1 till the moment of Li injection at 419 ms (# 73893-73902).
NBI BL-2 (62°)

NBI BL-3 (90°)

ECH (106 GHz)

ECH (53 GHz)

NBI BL-5 (90°, 79°)

(a)

COLLECTOR PLATE ARRAYS

$B_\phi$
Fig. 1
Fig. 2
Fig. 3
Fig. 4
Fig. 5
Fig. 6
Fig. 7
Fig. 9
Fig. 10
Fig. 11.1
Fig. 11.2
Fig. 12
Fig. 13.1
Fig. 13.2