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On interrelation between inward turbulent flux and lower order rational magnetic surfaces at plasma edge

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The interrelation between experimentally measured inward turbulent flux and lower order rational magnetic surfaces is demonstrated by the example of system with externally imposed magnetic surfaces – L-2M stellarator [Plasma Phys. Control. Fusion **50**, 045001 (2008)]. In this note we show that average turbulent flux change sign from outward to inward in the vicinity of lower order rational magnetic surface located at plasma edge. There exists an upper threshold in plasma density for inward flux observation.

Nowadays it is commonly accepted that transport at the plasma edge is dominated by turbulence. Similarities in the characteristics and structure of edge turbulence between different confinement devices (tokamaks, stellarators, reversed field pinches) were found (see, e.g., Refs [1, 2], the reviews). It occurs quite often that for interpretation of experimental data in different confinement systems one must invoke inward turbulent transport. The most frequently used method of plasma edge turbulence analysis is based on the use of Langmuir probes as a method with high time and spatial resolutions. In a broad variety of these experiments turbulent flux measurements were performed. Normally, the observed turbulent flux is directed outwards. The observations of inward turbulent flux are considerably more rare. Most often experimentally measured inward turbulent flux is associated with shear electric field suppression of turbulence [3 – 7], including externally imposed electric fields [3, 4, 7]. In the vicinity of low order magnetic islands in TJ-II Heliac turbulent flux reverses from radially outwards to radially inwards [5]. In [6] was advanced a hypothesis that turbulent flux may reverse in the vicinity of low order rational magnetic surface. It is important to consider this hypothesis in more detail (and to verify or reject it) since such an information can help in choosing reliable mathematical model for plasma edge turbulence.

The prime purpose of this note is to clarify some peculiarities of interrelation between inward turbulent flux and lower order rational magnetic surfaces in the absence of visible magnetic islands around them as well as without use of externally imposed electric field. For this purpose an attempt will be made to analyze inward turbulent fluxes in L-2M – high-shear stellarator with externally imposed magnetic surfaces [8]. Two rational magnetic surfaces where rotational transform μ is equal to 2/3 or 3/4 are located at the plasma edge and are observable with Langmuir probe technique. At plasma pressures relevant to for the experiment magnetic surfaces (with the exception of central region) are weakly disturbed by plasma pressure effects. Magnetic surfaces at the plasma edge coincide practically [8] with the vacuum magnetic surfaces that are measured periodically (since [9]). Inward turbulent flux is systematically observed within parameter region such that transport transitions to the regime with better confinement are possible [8]. During such transitions drastic changes in turbulence are observed in the region that is close to the plasma boundary. The region has definite sandwich structure being subdivided in three smaller zones with different plasma parameters dynamics. Thus we can compare inward flux behavior during different turbulent states.

L-2M is a medium size high shear classical stellarator with the multipolarity $l = 2$, the total number of magnetic field periods $N = 14$ and the major radius $R_0 = 100\,\text{cm}$. The vacuum magnetic surfaces have rotational transform $\mu = 0.18$ at the magnetic axis and $\mu = 0.78$ at the separatrix. It is convenient to characterize three-dimensional magnetic surfaces with the help of single-valued standardization. For this purpose we use average radius of magnetic surfaces a. At the magnetic axis $a \equiv 0$ and lineary grows to its maximum value at the separatrix $a = a_p = 11.5\,\text{cm}$. The vacuum magnetic field at the magnetic axis is $B_0 \sim 1.34\,\text{T}$. The plasmas in these experiments were produced and heated by means of central ECH with a maximum power of 250 kW. The experiments were performed at boronized wall conditions. The plasma pressure was sufficiently small $\bar{\beta} < 0.2\%$ ($\bar{\beta}$ is the volume averaged ratio of the plasma pressure to the pressure of magnetic field). The vacuum magnetic configuration has magnetic hill all over

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the plasma volume. However, plasma induced shifts of magnetic surfaces lead to creation of the magnetic well at $x < 0.6$, here $x = a/a_p$ [10]. For all the plasma pressures relevant to the experiment, plasma is stable with respect to ideal MHD modes. Resistive interchange modes that cannot be stabilized by shear are unstable at the plasma edge. Moreover, we can state that the relative gradients of plasma temperatures are significantly lower than that of density at the plasma edge and temperature gradient electrostatic instabilities are hardly probable. It is not to be supposed that resistive interchanges serve as the only source of plasma edge turbulence. We hypothesized in [8] that transport transitions can be triggered by non-MHD instabilities. Such instabilities can be found in the framework of two-fluid hydrodynamics [11] if coupling of drift modes with Alfven and acoustic waves [12] is taken into account.

For the purposes of this note we use movable triple Langmuir probe. Two tips of the probes aligned perpendicular to the magnetic surface and poloidally separated ($a\Delta\theta = 0.4$ cm) were used for measuring the value of floating potential V_f and its poloidal derivative. Here, θ is the poloidal angle. Another tip is biased at a fixed voltage in ion saturation current I_p regime. Each tip is cylindrical with length equal to 0.2 cm. The probe penetrates transversely into plasma from the bottom of system (structure of magnetic surfaces and position of probe are presented in detail on Fig.1, where magnetic surfaces at finite pressure are calculated with the procedure developed in [13]). In this position plasma induced changes of magnetic surfaces are minimal. Moving probe with distance 1.0 cm it covers 1.1 cm in average radius of magnetic surfaces. The sampling frequency of the probes was 1 MHz. It is necessary to mention that in order to guarantee correctness of Langmuir probe turbulent flux measurements we have limited their penetration depth inside separatrix by the value of 1.0 cm. In [3–7] transversive turbulent flux was investigated $\Gamma \sim n_{\sim}(\Delta\Phi_-/a\Delta\theta)_{\sim}/B_0$. Here, Φ is the plasma electric potential, n is the plasma density, wavy subscript denotes oscillations. So that this value will correspond to normal component of electric drift, one must suppose that disturbances are electrostatic and strongly elongated along magnetic field lines. In currentness equilibrium electromagnetic corrections to the formula is negligibly small (see, details and numbers in [8]). Therefore electromagnetic effects play role of additional degrees of freedom, making possible, e.g. resistive interchange instability. However, it is necessary to mention that Langmuir probes are measuring not n and Φ directly but floating potential $V_f = \Phi - AkT_e/e$ and ion saturation current $I_p \sim n\sqrt{T_i + T_e}$. Here, A is the constant ($A \sim 3$ in the case of hydrogen), k and e are the Boltzmann constant and module of electron charge, respectively. Here as in majority of investigations [3–7] temperature fluctuations are postulated to be negligible. In order to move the probe deeply in plasmas we have used similar discharges with not very high parameters, where $n_e \sim 1.7{\cdot}10^{13}\,\mathrm{cm}^{-3}$ and $W \sim 400$ J. Here n_e is the line averaged plasma density, W is the plasma energy. Fast transport event under these conditions usually occurs closer to the end of active heating phase. For all cases presented below the active heating phase begins at 48 ms and finishes at 60 ms. Let us present experimental results in the following order. Initially probe is located so that its taper crosses plasma boundary. In what follows probe is moved insight with spacing 0.2 cm (equal to probe taper length). Therefore, we define the penetration depth of probe with respect to its midpoint. In Fig.2 we present turbulent flux obtained in duplicate discharges and two different probe locations x. Thus we show that turbulent flux may change direction at probe positions separated by small distance in δx. Position of transport transition is marked with vertical line. Negative values correspond to the normal (outward) flux direction, positive values correspond to the inward flux. Since only the non vanishing part of turbulent flux is meaningful for transport studies the experimentally obtained turbulent flux was averaged with respect to time. We have used 1 ms window in the procedure of averaging and moved it over time scale. The results are also presented in Fig.2. It is pertinent to note that signal (depicted at Fig.2b) has time cell where negative values

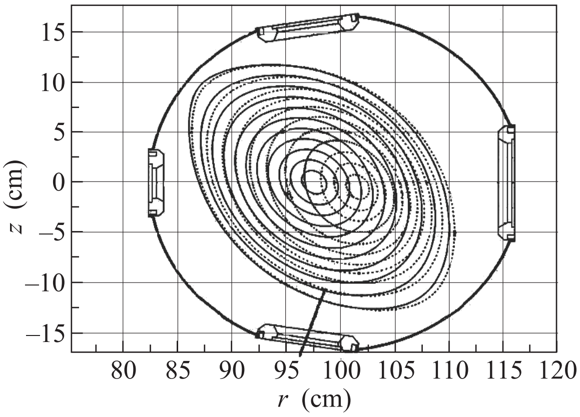

Fig.1. Plasma induced changes of magnetic configuration. Vacuum magnetic surfaces (solid lines) and surfaces (broken lines) that are shifted due to plasma induced magnetic fields. Zero net current case, $\bar{\beta} = 0.2\%$, $\beta(x) \sim (1 - x^2)^3$. Double line indicates vacuum chamber with branch tubes. Probe moving direction is depicted with bold line, r, z are cylindrical coordinates

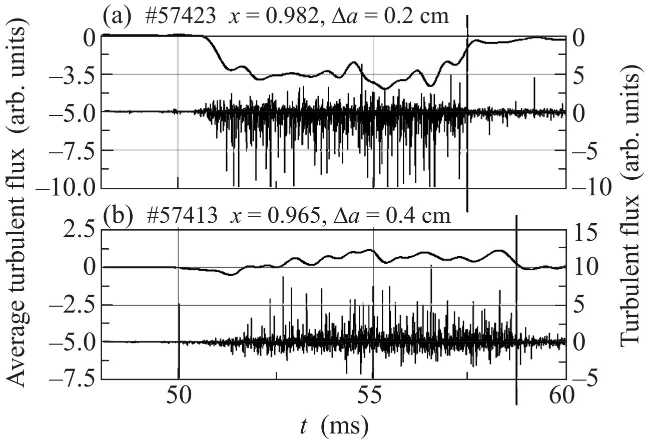

Fig.2. Turbulent flux and average turbulent flux versus time at different probe positions. Five-unit number is the order number of discharge in data base, Δa is the distance of probes midpoint from separatrix. Vertical line denotes the start of fast transport event determined from diamagnetic signal

of average turbulent flux can be found. The negative flux zone at the initial stage of discharge may probably be attributed to small density and temperature there.

We attempt to identify plasma parameters that govern the direction of turbulent flux. In Fig.3 profiles of floating potential and ion saturation current are presented. Curves are obtained by interpolation of data base where for each position of Langmuir probe five values of floating potential and ion saturation current in similar discharges were used. In Fig.3a floating potential is presented versus mean of probe position x. Upper curve presents the value of floating potential before the transition to the regime with better confinement, lower show floating potential profile after the fast (with duration less 0.2 ms) transition to the regime with better confinement. After the transition in all probe positions average turbulent flux drops significantly. Therefore we have indicated at Fig.3a also the sign of average flux. Mark "–" means that in this position probe average flux is directed outwards, while "+" indicates inward flux. Mark "$\approx$ 0" indicate zone of positive flux whose value is much smaller than those (in absolute value)observed in neighboring points. Shape of presented curves gives a possibility to estimate the role of electric field in the inward turbulent flux appearance. In the region of x space where inward turbulent flux is observed V_f graph (upper curve in Fig.2a) has local flattening (flex point). As the only method of plasma heating is ECH, electric field is positive (i.e. preventing electrons to escape); electron temperature is the monotonic function of magnetic surfaces average radius. This suggests that the electric field value decreases in this region. If accept current hypothesis [3 – 7] that second derivative of $T_e(x)$ is inessential then shear electric field is not the cause of inward flux observation. In Fig.3b ion saturation current profile is presented just before the transition and 1 ms after. Despite of strong decrease of turbulent flux in absolute value lead to small increase in I_p value. In all the cases ion saturation current is the monotonically decreasing function of average magnetic surface radius a. Such a behavior coupled with majorant etamation of island width basing on magnetic activty measurements [8] definitely points at lack of visible magnetic island. For the sake of definiteness we have also indicated in Fig.3 positions of magnetic surfaces with $\mu = 2/3$ and $\mu = 3/4$. It is necessary to search other possible reasons of turbulent flux inversion. We may conclude that it is impossible to explain sign change in the frame of linear stability theory. Within this approach odd and even modes (stable and unstable) are possible. However, the latter have larger gross rates [12] and it is unclear which mode will be dominant in strongly nonlinear regime. Note that the main reason for nonlinear stabilization is the magnetic field line bending and localization of the mode with larger gross rate may be less than that of smaller gross rate. However, this problem demands separate consideration. It is pertinent to note also that inward turbulent flux was indicated in particular space region. However, turbulent flux may possibly be non-uniform at the poloidal path on given magnetic surface and may close at different poloidal positions. Other possibilities can not be excluded and demand separate consideration.

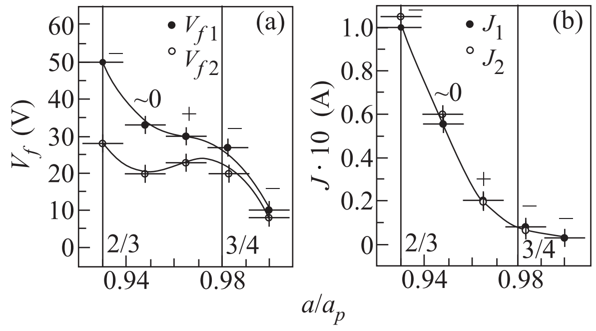

Fig.3. Average floating potential and ion saturation current versus radial coordinate. (a) Average floating potential versus radial coordinate. Upper and lower curves correspond to time before and 1 ms after the transition. Vertical lines mark positions of rational magnetic surfaces. (b) Average ion saturation current versus radial coordinate. Black line corresponds to time before transition. Big dots correspond to the time before transition and open circles 1 ms after the transition

An effort must be made to understand the role of different spectral components of V_f and I_p in average flux formation. As spectra of V_f and I_p decrease with respect to frequency, it is obvious that there is upper limit in frequency that can influence the value of average flux. It was found that contribution of higher harmonics decreases with probe immersion depth. In particular contribution of harmonics $f \leq 60$ kHz in average turbulent flux increases from $\sim 85\%$ for the case depicted on Fig.2a to $\sim 95\%$ for deepest probe position. Contribution of harmonics $f \leq 20$ kHz increases from $\sim 15\%$ to $\sim 60\%$ and for $f \leq 10$ kHz increases from $\sim 1\%$ to $\sim 40\%$, respectively. For cases depicted in Fig.2 the average turbulent flux value is governed mainly by frequency spacing of 20–50 kHz in floating potential and ion saturation current. It becomes clear why is the drop of average turbulent flux value so significant during the transition to the regime with improved confinement for probe locations close to the plasma boundary but just visible for deepest position. Floating potential and ion saturation current spectra change drastically in frequency spacing of 20–50 kHz during the transition [8]. The role played by lower frequency components increases with probe penetration into plasma. For the deepest probe position significant is the input of frequencies $f \leq 10$ kHz where dominates mode with $n = 1$. This possibly points to the fact that average turbulent flux is influenced not only by local disturbances but also by the modes localized deeper inside (mode $n = 1, m = 2$ is localized at $x = 0.8$). Here, n, m are toroidal and poloidal numbers respectively. We have performed subsidiary search of plasma parameters at which inward turbulent flux is observed. Similar to [6] we have found definite density threshold for inward turbulent flux existence. It was found that there exists an upper threshold in plasma density for inward flux observation. Inward flux was never observed at $n_e \geq 2.2 \cdot 10^{13}\,\text{cm}^{-3}$. However since now it is unclear how this threshold will survive at significantly larger heating power. It is necessary to mention that inward turbulent flux seems to have negligible effect on confinement (similar to [6]). As at given heating power plasma energy grows with density [8], plasmas with positive flux have visibly larger energy.

To summarize, we have shown that average turbulent flux change sign from outward to inward in the vicinity of lower order rational magnetic surface located at plasma edge in the absence of visible magnetic island around it. We hypothesize that shear electric field is not the cause of inward flux observation in our case. There exists an upper threshold in plasma density for inward flux observation. We have pointed that experimentally measured turbulent flux can be used (being intrinsically nonlinear in nature) as sensitive qualitative indicator of the change of state.

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1. C. Hidalgo, Plasma Phys. Control. Fusion A **37**, 53 (1995).
2. M. Endler, J. Nucl. Mater. **266–269**, 84 (1999).
3. J. Boedo, D. Gray, S. Jasmich et al., Nucl. Fusion **40**, 1397 (2000).
4. M. G. Shats, K. Toi, K. Ohkuni et al., Phys. Rev. Lett. **84**, 6042 (2000).
5. M. A. Pedrosa, C. Hidalgo, D. Lopez-Bruno et al., Plasma Phys. Control. Fusion **43**, 1573 (2001).
6. K. Toi, M. G. Shats, K. Okhyni et al., Plasma Phys. Control. Fusion A **44**, 237 (2002).
7. M. Ramisch, F. Greiner, K. Mahdizadeh et al., Plasma Phys. Control. Fusion **49**, 777 (2007).
8. S. V. Shchepetov, Yu. V. Kholnov, O. I. Fedyanin et al., Plasma Phys. Control. Fusion **50**, 045001 (2008).
9. D.K. Akulina, E.D. Andrykhina, M. S. Berejetskii et al., in: *Plasma Physics and Contr. Nucl. Fusion Res.* IAEA, Vienna, 1977.
10. L. M. Kovriznykh and S. V. Shchepetov, Sov. J. Plasma Phys **6**, 533 (1980).
11. S. I. Braginskii, in: Rev. Plasma Phys. **1**, Consultants Bureau, New York, 1977.
12. S. V. Shchepetov, A. B. Kuznetsov, and J. A. Jimenez, in: *Proc. of 30th EPS Conf. on Controlled Fusion and Plasma Physics* A **27**, European Physical Society, Geneva, 2003.
13. S. V. Shchepetov and A. B. Kuznetsov, Nuclear Fusion **36**, 1097 (1996).