Fast Transport Transitions in High Shear L-2M Stellarator: Role of Moderate-Order Rational Magnetic Surfaces

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Abstract. Fast transport transitions in high shear L-2M stellarator under zero net current mode of operation are analyzed. In much detail we discuss fast transport transitions to the regime with improved confinement. Each transition is easily identified by a sudden fast (< 200 µs) small drop of total plasma energy fixed by diamagnetic measurements. After that plasma energy regains its value and slowly monotonically increases up to the end of the active heating phase (just as the line average plasma density n_e). In the bulk of plasma parameters evolve slowly. Drastic changes are observed in the region that is close to the plasma boundary where two moderate order rational magnetic surfaces are located with the rotational transform μ taking the values 2/3 and 3/4. The region has definite sandwich structure being subdivided by above-named moderate order rational magnetic surfaces in three smaller zones with different plasma parameters dynamics. For reference we use conventional transport transition having no sandwich structure that happens at the initial stage of the discharge. The availability of several different transport states gave a chance to draw definite conclusion on the properties of plasma edge turbulence. It is demonstrated here that experimentally measured turbulent flux cannot serve as effective tool of plasma transport analysis but can be used (being intrinsically nonlinear in nature) as sensitive qualitative indicator of the change of state. It is shown that contribution of non-Markov processes in plasma edge turbulence is significant. Role of electromagnetic effects in plasma edge turbulence is examined. Different hypotheses on the nature of the phenomena are discussed.

1. Introduction

The aim of this paper is to present peculiarities of fast transport events in high shear L-2M stellarator and to discuss the role that is played in these transitions by moderate-order rational magnetic surfaces. Plasma edge turbulence will be analyzed also with the emphasis to investigating the electromagnetic and memory effects.

Nowadays transitions to the regimes with better confinement (H-modes) are at the centre of attention (see, e.g., Refs [1, 2], the reviews). It is well known that low- and medium-order rational magnetic surfaces may play a key role in plasma confinement and transport transitions (see, e.g., [3-5]). Here, we discuss fast transport transitions (with duration < 200 µs) to the regime with better confinement in L-2M stellarator and their interconnection with moderate-order rational magnetic surfaces at the plasma edge. The characteristic feature of the experiment is that plasma pressure is small enough (β < 0.2%, where β is the volume averaged ratio of the plasma pressure to the pressure of magnetic field). Therefore, with the exception of central region magnetic surfaces are weakly disturbed by plasma pressure effects and the only source for plasma instabilities [6] is the thermal energy of electrons and ions. At that moderate-order rational magnetic surfaces at the plasma edge coincide practically with the vacuum magnetic surfaces that were measured experimentally (for the first time in [7]). In order to have deeper insight in the problem we consider additional transport transition that usually happens at the initial stage of the discharge. This transition is simpler than mentioned above and has different plasma dynamics at the plasma edge. At higher densities transitions to stationary state may be as fast as the transition to the regime with better confinement. Such discharges can not be successfully simulated with traditional approach using neoclassic transport coefficients in the bulk of plasmas and model local (i.e. dependent on plasma parameters but not on their gradients) representation for anomalous transport coefficients at the plasma edge [8]. Not raising the question whether transport coefficients are intrinsically non-local we shall search properties of plasma edge turbulence and estimate role of non-Markov processes. Nowadays it is commonly accepted that transport at the edge is dominated by plasma turbulence. Similarity in characteristics and structure of edge turbulence between different confinement devices was found (see, e.g., [9,10], and references therein). Most frequently used method of edge turbulence analysis is based on the use of Langmuir and magnetic probes. Here, we shall examine properties of experimentally measured turbulent flux and clarify role of electromagnetic effects in plasma edge turbulence.

2. Experimental device

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 $R = 100$ cm. So called "standard" (most frequently used) configuration has the rotational transform μ ($a = 0$) = 0.18 at the vacuum magnetic axis and μ ($a = a_p$) = 0.78 at the vacuum separatrix with the average radius $a_p = 11.5$ cm. Here a is the average radius of magnetic surface. The vacuum magnetic field at the magnetic axis is $B_0 \approx 1.34$ T. Plasmas in these experiments were produced and heated by means of ECH with a maximum power of 300 kW. The experiments were performed at boronized wall conditions. The plasma pressure was sufficiently small $\beta \leq 0.2\%$. Small positive (i.e. increasing vacuum rotational transform) plasma currents with total current $I_p < 1$ kA (bootstrap current) cannot visibly change shear, modify equilibrium and be a driving force for instability. The vacuum magnetic configuration has magnetic hill all over the plasma volume. However, plasma induced shifts of magnetic surfaces lead to creation of the magnetic well at $x < 0.6$. 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. In low-β case they can lead only to the enhancement of transport.

3. Fast transport transitions to the regime with improved confinement

In subsequent two sections two different transport phenomena will be discussed. Among other diagnostics they are well defined by diamagnetic measurements. Therefore at Fig.1 are depicted thermal plasma energy W extracted from diamagnetic measurements and its time derivative dW/dt versus time for typical discharge. Also necessary characteristic times are introduced. Those are: characteristic time of dW/dt twofold decrease Δt_{drop}, blue broken line marks the beginning of the transport transition t_{spike}, red broken line marks the end of active heating phase t_{off}. We start with the description of the fast transport transition to the regime

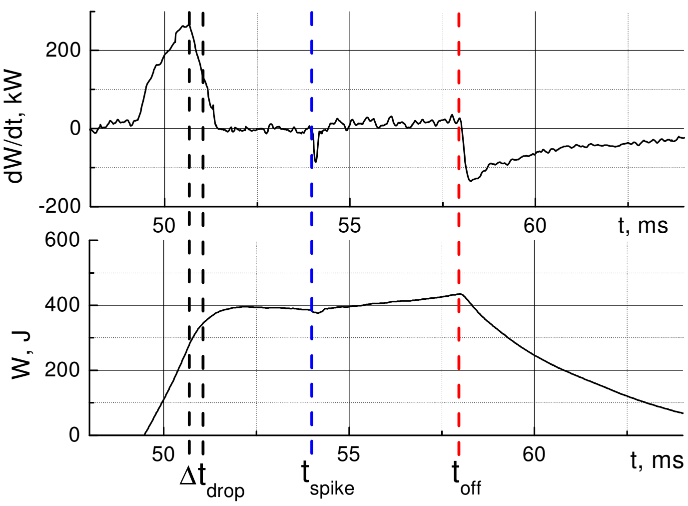

Fig.1. Plasma energy and its derivative

with improved confinement [6] that is easily identified by a sudden fast (< 200 μs) small drop of total plasma energy fixed by diamagnetic measurements. After that plasma energy regains its value and then slowly monotonically increases up to the end of the active heating phase (just as the line average plasma density n_e). However, increase of total energy is small ~ 5-10% (in rare cases 15%). In the bulk of plasmas after the transition plasma parameters evolve slowly. Drastic changes can be observed in the region that is close to the plasma boundary, where two moderate order rational magnetic surfaces are located with the rotational transform μ taking the values 2/3 and 3/4. Relative values of plasma parameters fluctuations and their spectrum widths decrease significantly in this region. The region has definite sandwich structure. It is shown that plasma energy fast loss occurs in the closest to the plasma boundary smaller zone and plasma parameters do not restore their previous values there up to the end of discharge. In the rest of region drastic changes are observed in floating potential value. In the vicinity of magnetic surface with μ = 2/3 (and deeper inside) floating potential abruptly drops with the beginning of transition and does not restore its value even after the end of active heating phase. In the zone between positions of rational magnetic surfaces with μ equal to 2/3 and 3/4, respectively, floating potential abruptly drops with the beginning of transition and restores to the value smaller than the initial one after the small delay with respect to the end of active heating phase. On the whole transport event demonstrates features typical of bifurcations with the exception of small zone between positions of rational magnetic surfaces with μ equal to 2/3 and 3/4, where plasma behavior is more complicated. For reference we have presented in Fig.2 profiles of rotational transform at vacuum magnetic surfaces (solid line) and surfaces (broken line) that are shifted due to plasma induced magnetic fields. Zero net current case was considered, β = 0.2%, plasma pressure was taken to be rather peaked p ~ $(1-x^2)^3$, $x = a/a_p$. The plasma pressure profile is slightly more peaked than that of experiment, the β value is the largest possible in the frame of experiments presented. Necessary conditions for the phenomenon appearance are presented in Fig.3. Part of L-2M database discharges in co-ordinates n_e, W and P (heating power) is presented. Dark red circles (black one for projections) denote discharges without transport event and pink circles (open circles for projections) with. Discharges with transport event have as a whole higher energy. Here the values of plasma energy at the end of active heating phase are presented. At given value of average density transport events appear only at higher heating powers. However, heating power necessary for transport event grows with density but weaker than power per particle law. Definite lower density threshold is seen in plasma line averaged density n_e ~ 1×10^{13} cm^{-3} for existence of transport event. The discharges with densities below the lower threshold show no fast transport events. No definite higher density threshold is seen. Maximum density here is that attained for ECH plasmas in L-2M. At higher densities there is a lack of microwave absorption due to refraction. Data from this region are fragmentary. Thus it

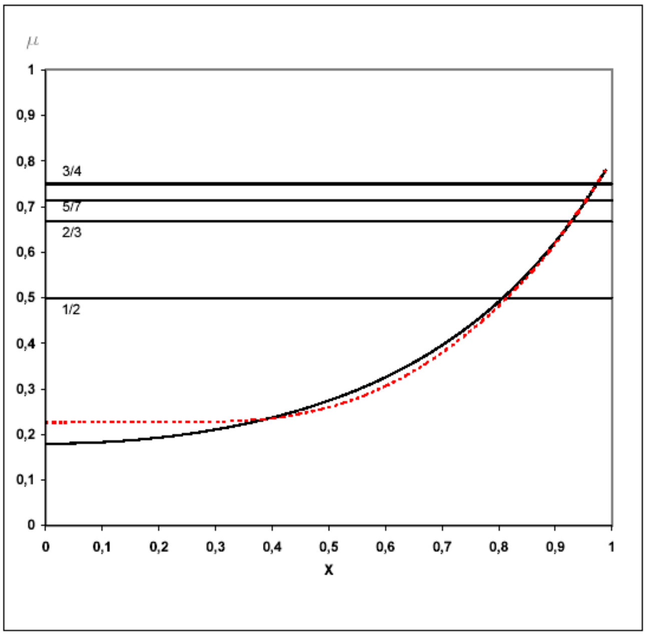

Fig.2. Rotational transform profiles

is not possible to determine safely if there is an upper density limit for transport event. The beginning of transport event shifts towards the beginning of the discharge with the increase of heating power at given density. For example, in the range of n_e ~ (1-1.5)×10^{13} cm $^{-3}$, we obtain using method of least squares that the averaged shift of the beginning of the event ~ 3 ms for changing P from 180 to 250 kW.

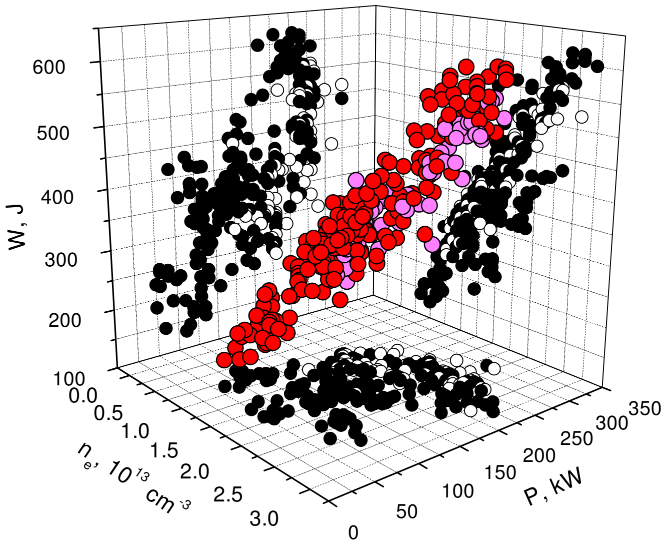

Fig.3. Database with indication of transport transition to regime with improved confinement

The observed transport event bears some similarities with H-modes observed at different devices. In the vicinity of low order rational 2/3 (and deeper inside) average floating potential behavior is qualitatively the same that was observed in CHS experiments [4] where Langmuir probe was located close but inside of separatrix. In the zone between positions of rational magnetic surfaces with μ equal to 2/3 and 3/4, respectively, floating potential behavior is similar to that was observed in W7-AS experiments [11]. We hypothesized that such a behavior is characteristic for the vicinity of low or moderate rational magnetic surfaces. On rational magnetic surfaces magnetic field lines close on themselves after n toroidal (m poloidal) turns having shortest connection lengths ~ $2\pi Rn$ (where R is the major radius). In order to have positive feedback along these shortest ways instabilities are necessary. Traditional magnetohydrodynamic (MHD) instabilities cannot be considered as the trigger for transport transition. Calculations show that at the values of β typical of experiment, plasmas are more than order of magnitude below Mercier threshold that guarantee also the stability of ideal MHD modes in the vicinity of sandwich structure. Resistive interchange modes that are typical for stellarator plasma edge cannot be considered as the candidate for trigger as they have no threshold in plasma parameters. We suppose that coupling of drift modes to Alfven and acoustic waves in the presence of stationary electric field may be responsible for triggering transport event. Recently [12] we have already used this approach (neglecting electric field) for explanation of electromagnetic modes in completely MHD stable TJ-II (Spain).

4. One more fast transport transition

In this section we consider additional transport transition that usually happens at the initial stage of the discharge. This transition is not so interesting as mentioned above and has no sandwich structure. It occurs that the transition to stationary phase of plasma energy (from the beginning of the discharge) depending on the value of heating power and plasma density may be fast or slow. Our prime interest here is with the fast transport transitions having the characteristic times of the same order as of the transition to the regime with improved confinement. In order not to complicate the issue let us divide all the discharges into two groups on the basis of characteristic time $\Delta\, t_{drop}$ and use the same co-ordinate system as in

Fig.3. At Fig.4 discharges with $\Delta\ t_{drop} > 300$ μs are depicted in dark green (black circles for projections) and with $\Delta\ t_{drop} < 300$ μs in light green (open circles for projections). Comparing Figs.3,4 one can see that fast transition to stationary state and fast transition to the regime with improved confinement can adjoin in one discharge but only at higher densities and higher heating powers. From Fig.4 we observe that there is no definite power per particle condition for the fastness of the transition to stationary state. It is pertinent to note that during the transition the majority of plasma parameters evolve slowly. However, two processes are as fast as the change of *dW/dt.* At the plasma edge fluctuations (measured by Langmuir probes) abruptly grow and in the spectrum of Mirnov oscillations grow high frequencies (> 20 kHz). This observation arise question whether high frequency components of magnetic oscillations can play leading role in plasma transport. We can give definite negative answer to this question. At the amplitudes of magnetic signals estimated island widths are small and cannot overlap. Thus high frequency electromagnetic oscillations can only be the characteristic of plasma edge turbulence. Two particular properties of plasma edge turbulence will be discussed in following sections.

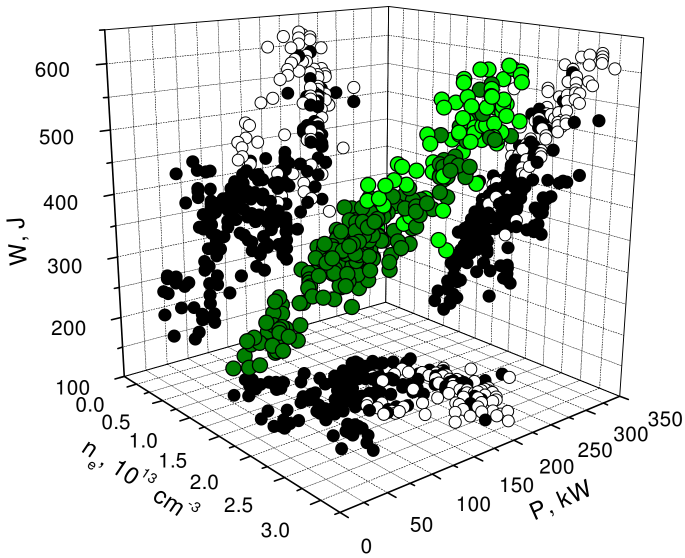

Fig.4. Database with indication of fast transitions to stationary state

5. On memory effects in plasma edge turbulence

Let us discuss one of the properties of the time series that are formed by the experimental signals. Here we shall use data from Langmuir probes inside plasmas. Construction of probe and principles of measurement are just the same as in [6]. It is necessary to mention that signals from magnetic probes definitely contain quasiharmonic oscillations [6]. That is not surprising as in vacuum region magnetic field is governed by linear differential equation. In order to move the probe deeply in plasmas we have used discharges with not very high parameters, where $n_e \approx 1.5\times10^{13}$ cm $^{-3}$ and $W \approx 400$ J. For the sake of definiteness we use experimentally measured floating potential V_f . Here and below in Figs x denotes position of probe, five-unit number is the number of discharge in database. As an example let us choose time interval 2 ms at the stationary phase of discharge and consider in detail properties of time series formed by $V_f\,(t)$ signal with temporal quantization $\Delta t = 1$ μs. From the signal another one can be formed, namely $\Delta V_f = V_f\,(t + \Delta t) - V_f\,(t)$. At Fig.5 (a) autocorrelation functions versus time displacement are presented and it can be seen that correlation time for the increment of function is the order of magnitude lower than that for the function. Such a behavior is typical (not only, however) for nearly-Markov processes. Remind that in some special cases increments instead of functions are used in order to increase the role of high frequency processes and to get rid from elements of memory (see, e.g. [14]). However, it is improvident to conclude on memory effects comparing autocorrelation functions of the signal and its increment only. To get insight into the problem let us use the procedure that consists in expanding the signal in Fourier spectrum and cutting the spectrum in parts with

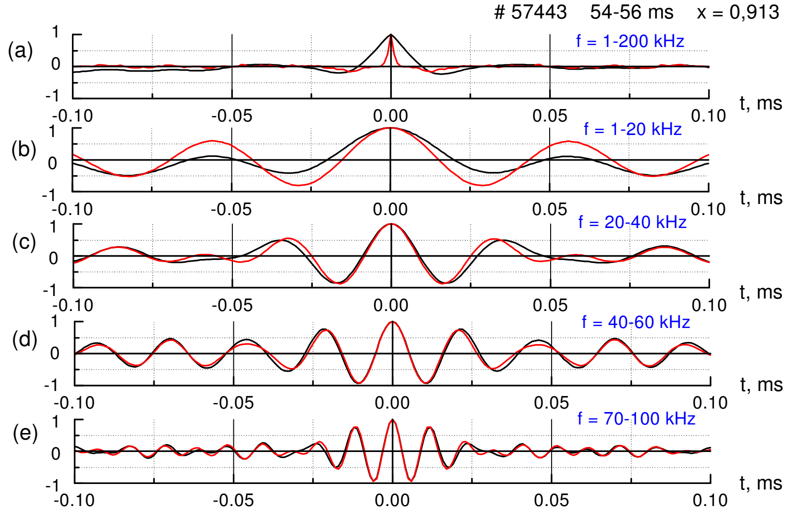

Fig.5. Autocorrelation functions of $V_f(t)$ (black) and its increment $\Delta V_f(t) = V_f(t+\Delta t)) - V_f(t)$ (red) (a) and the same for different spectrum intervals (b - e)

the help of filters. After this for parts of spectrum signals autocorrelation functions are calculated. The results of analysis are presented at Fig.5 (b-d). It can be seen that autocorrelation times for the parts of spectra are significantly larger than those of V_f and ΔV_f. For parts of spectra autocorrelation functions differ little that indicate existence of long-living structures in plasma. We have not depicted in Fig.5 high-frequency components (> 100 kHz) as spectra are rather narrow [6] and as we see below their contribution to experimentally measured turbulent flux is negligible.

6. Is it possible to use experimentally measured turbulent flux for quantitative transport analysis?

Nowadays it is commonly accepted that transport at the edge is dominated by plasma turbulence. Similarities in the characteristics and structure of edge turbulence between different confinement devices were found (see, e.g., Ref [7], the review). The most frequently used method of edge turbulence analysis is based on the use of Langmuir probes. In many cases so-called turbulent flux is used for transport analysis. Let us remind briefly the physical foundation for this approach. At the first stage, common part of charged particles drift is used, namely electric drift. In so doing this part cause local flux of particles $n\boldsymbol{v} = nc[\boldsymbol{E}\times\boldsymbol{B}]/B^2$. Here n, v, c, E, B are density, velocity, velocity of light, electric and magnetic field respectively. Bold type denotes vectors. At small plasma pressures ($\beta << 1$) B^2 can be replaced by its vacuum value. In order to replace $\boldsymbol{B}$ by its vacuum value one is led to use electrostatic paradigm that cannot be justified experimentally [6]. With this (assuming in addition large wave lengths in longitudinal direction) quantity $\Gamma = n_{\sim}c(\Delta\Phi/\Delta\theta)_{\sim} /B$ in a leading order is the normal component of turbulent particle flux caused by electric drift. Here, Φ is the plasma electric potential, wavy subscript denotes oscillations, θ is the poloidal angle on the magnetic surface. 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 $I_p \sim n\,(T_i + T_e)^{1/2}$. Here, A is the constant ($A \sim 3$ in the case of hydrogen), k and e are the Boltzmann constant and electric charge, respectively. Therefore, in majority of investigations temperature fluctuations are postulated to be negligible. Taking into account electron temperature fluctuations [15] leads to visible change of turbulent flux and its statistical properties. Therefore, there are many physical limitations on turbulent flux measurement accuracy. It seems reasonable to estimate availability of turbulent flux measurements for transport analysis experimentally. For this purpose we select typical discharge from L-2M database that has transport transition to the regime with better confinement. Results are depicted at Fig.6. Probe for measurement of turbulent flux is

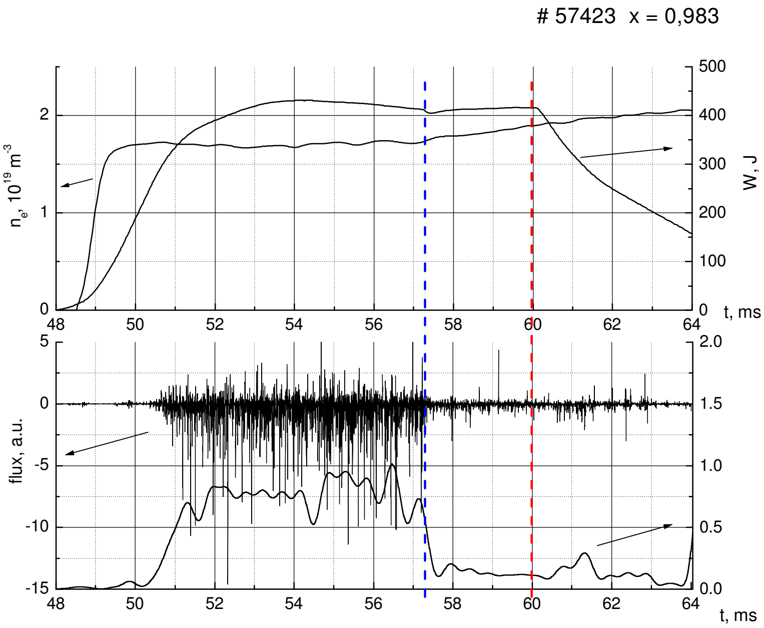

Fig.6. Plasma energy, average density, turbulent flux and module of its averaged value versus time

presented in detail in [6]. Fig.6 presents from top to bottom plasma energy measured with the help of diamagnetic loop, turbulent flux versus time and averaged turbulent flux module. Negative flux is directed outwards. Experimentally obtained turbulent flux was averaged with respect to time over 1 ms window that was moving with time. Comparing of average turbulent flux curve to plasma energy immediately leads to contradiction. If suppose that strong increase in average flux value is responsible for saturation of energy it is unclear why strong decrease does not lead to corresponding renewal of growth and vice versa. It is important to mention that impact of high frequencies in average flux (> 50 kHz in I_p and V_f) is negligible. Let us present another illustration of turbulent flux behavior. At Fig.7 we present turbulent flux obtained in different discharges and different probe locations *x*. As it can be seen turbulent flux definitely reverses (negative values mean outwards). Previously such a behavior was found inside large externally imposed magnetic island [16]. There are strong grounds for believing in absence of large magnetic island with μ = 2/3. Vacuum magnetic surfaces do not contain such an island, island width that can be produced by plasma induced fields was estimated in [6] on the base of magnetic measurements of oscillating fields and is small (~ 0.1 cm). Attractive hypothesis that at the edge of plasma is located double layer with outward/inward flux whose confining properties are strongly dependent on fluctuation level breaks if consider experimental observations of plasma behavior very close to separatrix after the transition to the regime with better confinement.

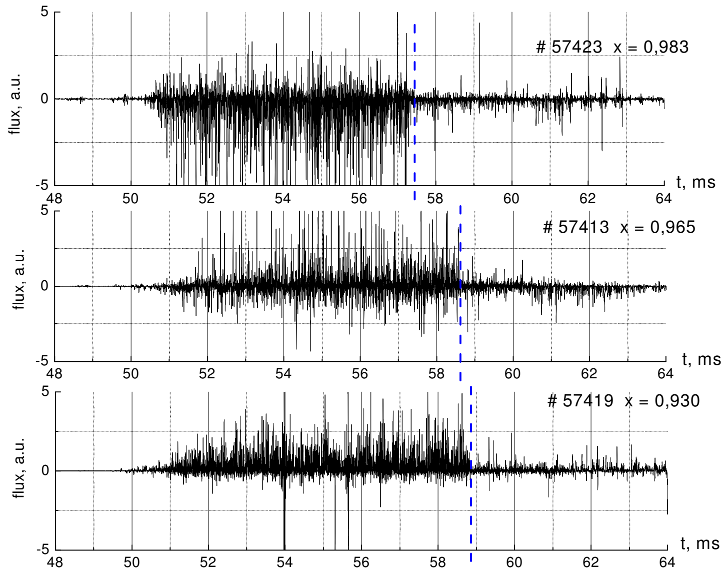

Fig.7. Turbulent flux at different positions of probe

7. Conclusions

Fast transport transitions in high shear L-2M stellarator are analyzed. In much detail we discuss fast transport transitions to the regime with improved confinement. Transitions are indicated only at sufficiently high plasma densities, and for the given value of average density they appear only at higher heating powers. Each transition is easily identified by a sudden fast (< 200 μs) small drop of total plasma energy fixed by diamagnetic measurements. After that plasma energy regains its value and then slowly monotonically increases up to the end of the active heating phase (just as the line average plasma density n_e). Drastic changes are observed in the region that is close to the plasma boundary where two moderate order rational magnetic surfaces are located with the rotational transform μ taking the values 2/3 and 3/4. Relative values of plasma parameters fluctuations and their spectrum widths decrease significantly in this region. The region has definite sandwich structure being subdivided by above-named moderate order rational magnetic surfaces in three smaller zones with different plasma parameters dynamics. Transition is triggered by local disturbances of plasma parameters that are caused by instabilities in the vicinity of magnetic surfaces where μ is equal to 2/3 or 3/4. For reference we use conventional transport transition having no sandwich structure that happens at the initial stage of the discharge. The availability of several different transport states gave a chance to draw definite conclusion on the properties of plasma edge turbulence. It is shown that experimentally measured turbulent flux cannot serve as effective tool of plasma transport analysis but can be used (being intrinsically nonlinear in nature) as sensitive qualitative indicator of the change of state. It is shown that contribution of non-Markov processes in plasma edge turbulence is significant.

Acknowledgements

We would like to thank all the fruitful discussions held with the members of the L-2M team. The work was supported in part by the RF Presidential Program for Support of Leading Scientific Schools (grant no.NSh-452.2008.2) and Grant of Russian Foundation of Basic Research 08-02-13602.

[1] WAGNER, F., Plasma Phys. Control. Fusion **49** (2007) B1.
[2] FUJISAWA, A., Plasma Phys. Control. Fusion **45** (2003) R1.
[3] HIRSCH, M., et al., Plasma Phys. Control. Fusion **40** (1998) A361.
[4] TOI, K., et al., Nucl. Fusion **44** (2004) 217.
[5] WATANABE, K., et al., Plasma Phys. Control. Fusion **48** (2006) A201.
[6] SHCHEPETOV, S.V., et al., Plasma Phys. Control. Fusion **50** (2008) 045001.
[7] AKULINA, D.K., et al., Plasma Physics and Contr. Nucl. Fusion Res. IAEA, Vienna, **2** (1977) 115.
[8] GREBENSHCHIKOV, S.E., Plasma Physics Reports **22** (1996) 551.
[9] HIDALGO, C., 1995 Plasma Phys. Control. Fusion **37** (1995) A53.
[10] ENDLER, M., 1999 J. Nucl. Mater. **266-269** (1999) 84.
[11] WAGNER, F., et al., Phys. Plasmas **12** (2005) 072509.
[12] JIMENEZ, J.A., Plasma Phys. Control. Fusion **48** (2006) 515.
[13] FRISCH, U., Turbulence. Legacy of A.N.Kolmogorov, University Press, Cambridge, (1995).
[15] SCHRITTWIESER, R., et al., Plasma Phys. Control. Fusion **50** (2008) 055004.
[16] PEDROSA, M.A., et al., Plasma Phys. Control. Fusion **43** (2001) 1573.