EXPERIMENTAL INTERTWINEMENT OF RADIAL ELECTRIC FIELDS, FLUCTUATIONS AND TRANSPORT WITH DENSITY IN TJ-II PLASMAS

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Traditionally, three transport regions have been considered in the TJ-II stellarator: the plasma core, where heat deposition physics seems to dominate transport and therefore the radial electric field; a confinement or bulk plasma region where collisional and, very likely, turbulent fluxes cooperate interlinked by radial electric fields and plasma rotation; and a third region near the edge where plasma-wall interaction and magnetic topology add new phenomena. This latter region, however, may still preserve the transport properties of the bulk region. We present our latest experimental results on edge fluctuations based on probe data and fast camera image analysis, as well as HIBP plasma potential and heat diffusion profiles in the bulk plasma, all of them tuned under a same experimental knob: the plasma density, which is indication of a close intertwinement of transport, turbulence and electric fields in stellarator plasmas.

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1. INTRODUCTION

Already in 1990, with a first generation of medium-sized stellarators operative, low collisionality plasmas obtained with Electron Cyclotron Heating (ECH) showed that the plasma core region could be reasonably well described by collisional transport, but most of the bulk plasma presented an anomalously high electron heat transport [1,2]. The present gyro-Bohm stellarator scaling of the energy confinement time [3] is compatible with diffusive processes based on microscopic transport. In addition, global scalings with heating power, as it happens with tokamaks, support the notion of transport dominated by mechanisms fed non-linearly on thermodynamic gradients, of which turbulent transport is a paradigm. Since sheared ExB flows (DC or fluctuating) are expected to affect turbulent transport, it is worth looking for any systematic relationship between flows, turbulence and transport.

In TJ-II experiments up to date, plasma potential and heat transport vary with density in a systematic manner. Here we summarize the experimental relationships found between poloidal flows, plasma potential, fluctuations and heat transport as one experimental controller, the plasma line density (<n_e>), is varied.

2. EXPERIMENTAL RESULTS

The Heavy Ion Beam Probe (HIBP) diagnostic installed in the TJ-II is able to resolve a flattening of the plasma potential profile, φ(ρ), in the presence of a low order rational value of the rotational transform. This situation of close to null or small E_r = -∇φ(ρ) in an extended radial region can be found also without the presence of major magnetic resonances. A transition of φ(ρ) evolving from positive to negative as the density is increased is known in stellarator devices (see e.g. [4]). In the case of the TJ-II, it has been seen on a shot to shot basis (stationary plasmas) and dynamically. In Fig. 1 we see φ(ρ) varying as the density grows during an ECH+NBI discharge. Near the edge (positive ρ), the slope of the plasma potential profile reverses sign when the average density reaches some $0.8\cdot10^{19}$ m^{-3}. There is little change in φ(ρ) for line average densities above some $2\cdot10^{19}$ m^{-3}. The *smooth* change from everywhere positive to everywhere negative plasma potential is known to be a systematic feature not dependent on configuration as far as it has been checked.

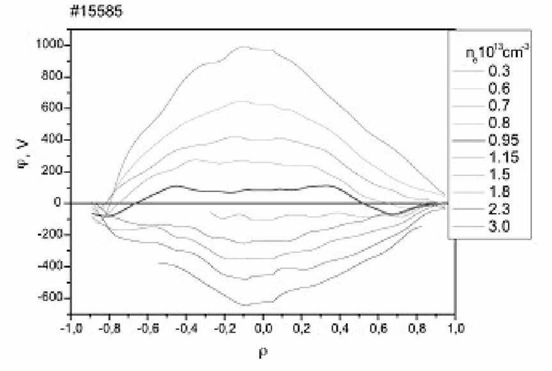

Fig.1. HIBP profiles decaying during the growth of the plasma density in a discharge with ECH+NBI heating. When <ne>≈$1.4\cdot10^{19}$ m^{-3} the plasma is sustained by NBI alone

The higher densities of Fig. 1 are obtained in the pure NBI phase of the discharge (densities above ECH cutoff, <n_e> ≥$\cdot1.2\cdot10^{19}$ m^{-3}), when the density profiles change from hollow to peaked. More HIBP data for different density scans show that the region -∇φ(ρ) ≈ 0 moves inwards in a rather smooth way as the density increases. The shear layer caused by the corresponding structure of the ExB drift moves inwards and seems to widen. Here we define shear layer as the radial region where E_r reverses sign, although in most of the experimental data shown in this work, it extends (within resolution) to a considerable part of the plasma.

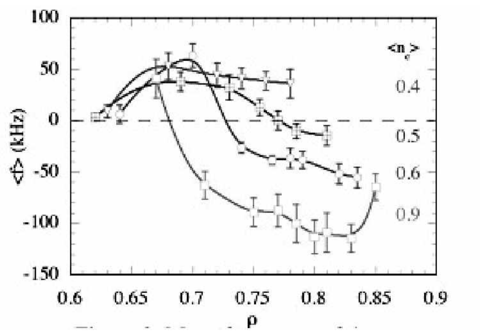

Fig. 2. Mean frequency of the reflectometer spectra vs. cut-off radius in discharges with increasing densities

Normally, the regions of flat φ are bounded by regions with high poloidal velocity. Therefore, it makes sense speaking of boundary shear layers not only in the plasma edge but also in the confinement zone. The existence of a shear layer in the bulk plasma of the TJ-II has been confirmed by means of microwave reflectometry [5] (MWR). In Fig. 2 we plot the mean frequency of the spectra obtained in four ECH discharges with different line averaged densities. The diagnostic can give with good spatial accuracy the radial position of the inner shear layer, here detected as the location where the mean frequency changes sign as a consequence of the reversal in the rotation of the detected fluctuations. Since the diamagnetic drift here is quite smaller than the ExB drift, the data from the reflectometer should be compatible with the electric fields deduced from HIBP data. Aside from the spatial uncertainty of the HIBP, the qualitative result is confirmed: a shear layer moves towards the center as the plasma density increases. For densities above the ECH regime, the radial electric field is negative and monotonous in essentially all of the plasma and a shear layer can only exist in the plasma edge.

HIBP data show that the regions of approximately null E_r and their corresponding inner shear layer can be followed in every radial region of the plasma as density is augmented. A link between flows and transport is a natural expectation already from the basic formulation of transport in a cylindrical column. However, despite notable difficulties in quantifying fluctuation levels, MWR in the TJ-II indicates that there is significant turbulence in the entire radial range of Fig. 2. Therefore, it is natural to suspect that the link between electric fields or plasma flows and turbulence responds to the same mechanisms than further out in radius, where electric probes can be used.

The edge region can be explored with detail by means of different kinds of electric probe. TJ-II plasmas (as well as other confinement machines) are characterized by flat φ profiles from the plasma border out. Thus, the plasma edge can develop naturally a shear layer as soon as there is a change of plasma potential near (inside) the edge.

We recall from experiments in the Advanced Toroidal Facility [6] that a change in poloidal rotation as seen in the phase velocity of fluctuations at the plasma periphery ($\rho \sim 0.9$) correlates with the onset of a shear layer with altered fluctuation levels. More recent data from the TJ-II evidence a threshold line density, near $0.6\cdot10^{19}$ m^{-3} in typical ECH plasmas in standard configuration, that marks the start of a systematic link between density fluctuation levels, plasma potential and poloidal rotation [7]. Fig. 3 shows (left panels) the profiles of probe ion saturation current, proportional to plasma density in the corresponding experimental conditions, for different values of $\langle n_e \rangle$ obtained in different discharges. At low line densities the gradient in the ion saturation current remains roughly the same. After reaching $\langle n_e \rangle \approx 0.6\cdot10^{19}$ m^{-3}, a larger gradient develops and, at the same time, the floating potential measured by the same probe drops to negative values (bottom panel). As a consequence, an edge shear layer develops.

It is interesting to follow the formation of the edge shear layer on the evolution of time-traces in a fixed radial position: Also in Fig. 3 (right panels) we plot with dots the *rms* value of the fluctuating ExB radial velocity estimated from the tip separation on the probe, as a function of $\langle n_e \rangle$ for a large set of discharges. The bottom panel shows the corresponding values of the phase velocity of the fluctuations. The relationship between fluctuations, poloidal phase velocity and density is robust: when $\langle n_e \rangle$ is changed in *one* discharge by modulation of the gas puffing waveform, we obtain the data shown with thin lines in the right panels of Fig. 3. At the threshold density we see a change in the phase velocity that correlates with increasing fluctuations. However, once the new (negative) value of such velocity reaches its maximum magnitude, the fluctuations stop growing and tend to diminish instead. Here we assume that the line density can be associated in this region to the local density scale length, which is really considered as a more relevant parameter. The threshold $\langle n_e \rangle$ is marked in the right panels of Fig. 3 with vertical bands.

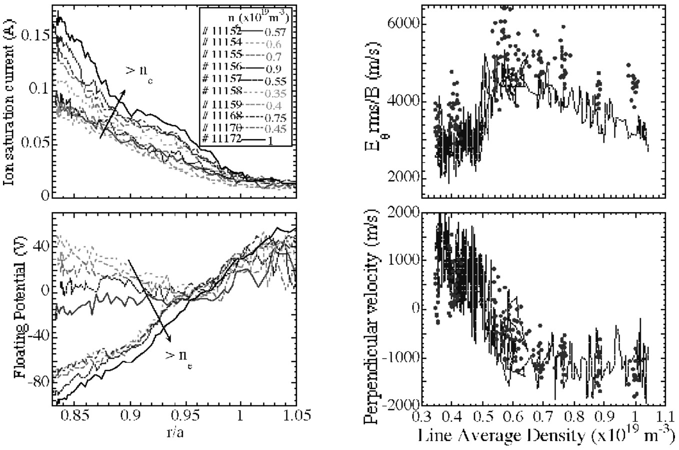

Fig. 3. Left: edge profiles of ion saturation current (top) and floating potential (bottom). Right: rms value of the fluctuating poloidal electric field (top) and phase velocity of the fluctuations (bottom) for a set of stationary discharges (dots) and for a single discharge with evolving density (lines). Probe radial position: $\rho \approx 0.9$

The results of Fig. 3 suggest that when there is enough available free energy the plasma-flow system self-regulates: near (below) the threshold density, the level of fluctuations and the magnitude of flow rotation increase in parallel until the shear flow is established at the edge; then the fluctuations decrease while edge gradients and plasma density increase. The critical nature of this phenomenon is suggested by observations at the density threshold, when fast transients (tens of μs) can be obtained in the phase velocity measured with the probes [8], as shown in Fig. 4. There we see a case in which the threshold is reached from below: the time-trace of the floating potential in $\rho \approx 0.9$ stays positive on average but it explores intermittently the negative values.

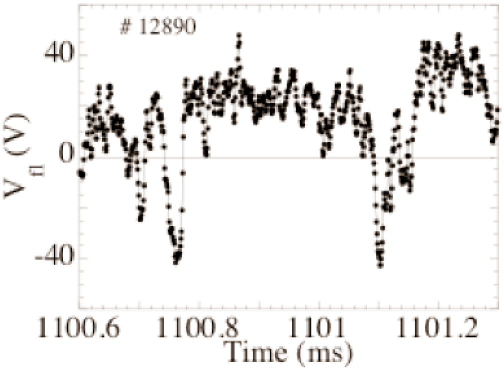

Fig.4. Detail of the transients observed when sheared flows are being developed at the critical density

The data shown above are obtained from fluctuating electric signals in the plasma edge region. The phase velocity of the fluctuations is intuitively associated to the movement of elongated turbulent structures convected by the mean poloidal flow. Recent results, coming both from the NSTX spheromak and the TJ-II Heliac indicate similar behaviour of turbulent structures, which we shall refer to as "blobs", in the plasma edge region [9]. The data have been obtained with recordings of fast cameras that are able to resolve typical time-scales of electrostatic turbulence. After processing, it has been found convenient to define such geometrical parameters as scale size, orientation and aspect ratio of the blobs. All three parameters get affected during the L-H transition in the NSTX: the net orientation and aspect ratio of the blobs population increase in H mode with respect to the L mode, while the overall population decreases. Interestingly, the same qualitative results, albeit less pronounced, are seen in the TJ-II but taking as "transition" process the formation of a shear layer commented above. Therefore, these recordings confirm what has been said on the existence of a shear layer that develops after the threshold density is reached, and add the information that there are statistically significant morphological changes in the visualized structures.

A detailed quantification of the above and some other aspects of the images recorded by the high speed cameras still require further study. What can be cast out of any doubt in the TJ-II is that the blobs reverse rotation at the density threshold. Let us recall that, below such density, E_r as obtained from the HIBP diagnostic is everywhere positive. Above the density threshold an edge shear layer shows up and the inner one moves inwards as the density keeps on rising (Fig. 1). The bi-dimensional structures detected by the cameras reverse their poloidal movement at that density, in close agreement with the behaviour of the phase velocities obtained with electric probes: Fig. 5 shows six consecutive frames of a recording where such reversal of the detected poloidal rotation occurs. Following the frames from top to bottom and from left to right, we see (marked with small squares) one of these blobs moving counterclockwise (left) and then clockwise (right) at the density threshold. The fast transients (~10 μs) detected by the Langmuir probes (like those shown in Fig. 4) share the density threshold with the reversal found with high speed imaging.

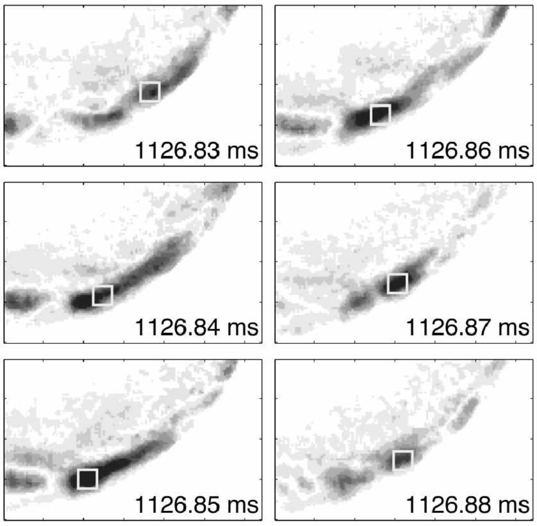

Fig.5. Evolution of the poloidal movement of blobs when the threshold density is reached in a discharge with density ramp-up

3. DISCUSSION AND CONCLUSIONS

For low densities or typical ECH plasmas of the TJ-II, the region of normalized radii $\rho < 0.3$ is dominated by the electron dynamics, e. g. ECH-driven pump-out. Recalling Fig. 1, we see that the core values of φ in that case are what one would expect from a simple radial momentum balance with frozen ions and electrostatically "stopped" electrons: the $\nabla(n_e T_e)/(e n_e)$ contribution yields a core E_r like the one found in the experiments. These values of E_r are expected also from neoclassical calculations for the TJ-II [9]. Fig. 6 shows φ obtained after integrating the quantity $E_{dia} = -\nabla(n_e T_e)/(e n_e)$ (with $\varphi = 0$ at the edge), which can be compared with HIBP data in Fig. 1. Since the core density gradient is very small in ECH plasmas, $\varphi \approx T_e/e$. The close relationship found between central electron temperature and plasma potential in low density plasmas is compatible with the results from ECH modulation experiments, where the modulation of ECRH power causes a small (~10%) change in beam ion current (say plasma density), but a much more marked change (~50%) in φ in most of the core region, $\rho < 0.6$ [11]. Furthermore, the time-scales associated with the fast transients of φ in these modulation experiments, are compatible with time-scales of the electric field dynamics according to the equations for radial and poloidal electron momentum balance,

$$\dot{\Gamma}_r = -\frac{en}{m} E + \frac{e}{m} \Gamma_\theta B - \frac{1}{m} \nabla p$$

$$\dot{\Gamma}_\theta = -\frac{e}{m} B \Gamma_r - \nu_\theta \Gamma_\theta$$

and Poisson's $\dot{E} = (e/\varepsilon)\Gamma_r$. Here we simply consider that an initial (and local) condition of non-equilibrium electron radial flow Γ_r must alter the radial electric field and, consequently, the balances. The plasma response should come through E_r-dependent transport coefficients. These equations yield a characteristic time-scale of order $1/\nu_\theta$, much faster than typical transport time scales but slower than plasma oscillations.

In addition, let us remember that plasma rotation measurements taken since the earliest TJ-II campaigns (ECH plasmas) [12] indicated positive E_r near the core, with a strong increase in E_r in cases of high $T_e(0)$. The electric field here is obtained under the assumption that all the plasma rotation is due to the ExB drift, a fair assumption for the ions. Lower temperature (higher density) plasmas in the same campaigns yield smaller E_r that decrease more gently as T_e decreases. Further studies showed a *qualitative* behaviour of the estimated plasma rotation in fair agreement with neoclassical calculations of the radial electric field [13].

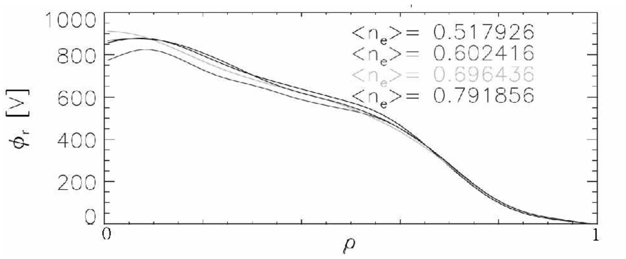

Fig. 6. The electrostatic potential obtained integrating the diamagnetic contribution to E_r for TJ-II ECH plasmas looks alike for different densities. There is agreement with HIBP measurements only for the lowest densities

In the bulk plasma region of ECH discharges, heat diffusion has been quantified from T_e measurements and an estimate of the heat deposition zone [13]. Fig. 7 is a surface plot of $\chi(\rho)$ as a function of $<n_e>$. The values have been obtained from a large set of ECH discharges of the TJ-II with stationary conditions and using a typical diffusive description of transport. The heat source is assumed to be Gaussian-shaped and centered, and experimental profiles of density and temperature are obtained from Thomson Scattering data. Discharges have been grouped and averaged by small density ranges. It was checked that including total radiation does not alter significantly the results. The data in Fig. 7 are presented only for the region $0.2 \leq \rho \leq 0.8$ because outside this range the statistical errors are too large. A fit of the data for the variation of local $\chi(\rho)$ with line-density only yields significant dependencies in the density gradient region, $0.5 \leq \rho \leq 0.8$, where we can appreciate that the thermal diffusivity decreases as the line-density increases.

Generally speaking, the calculations of collisional diffusivities and E_r in the density gradient region of ECH plasmas of the TJ-II are reliable within the hypothesis of the calculations [10]. Qualitatively, the electric field should be found in the so called ion root in this radial region with larger magnitude the larger the density. Except for the very low densities of Fig. 1, this is the case according to the experiments. χ is expected to decrease with $<n_e>$ in this region because of the smaller ambipolar particle fluxes that correspond to the ion root. On the other hand, the thermal diffusion expected from these calculations appears to be too small with respect to the experimental values of Fig. 7, something in agreement to well established results from several other machines (CHS, L-2, W7-AS...). Therefore, the TJ-II seems to be no exception to the importance of, presumably, turbulent ambipolar fluxes.

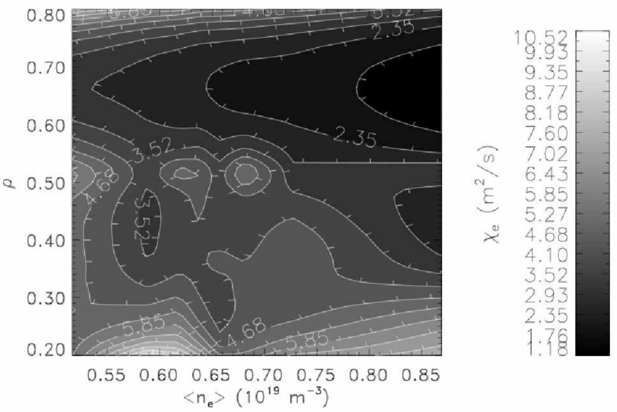

Fig. 7. Density scan of χ profiles in TJ-II ECRH plasmas. The contours indicate iso-diffusivities with values according to the vertical palette

Turning to HIBP data, we can roughly relate the inner shear layer or, perhaps, the extension of the flatter φ region with the extension of the furrow in $\chi(\rho)$ of Fig. 7. From MWR we know that there is turbulence in this region, but it is unknown to what extent turbulent transport can explain the changes in diffusion there. What can be said in view of Figs. 7 and 2 is that the shear layer is compatible with better heat confinement, at least in the density gradient region of TJ-II ECH discharges ($<n_e> \leq 10^{19}$ m^{-3}). Let us also recall that improved confinement achieved in the TJ-II with polarized limiters affects density but not electron temperature [14], which is the behaviour found in the density scan: what Fig. 7 shows is consequence of the density profiles developing larger gradients ($\rho \geq 0.5$) and also larger absolute values while the electron temperatures stay roughly the same, i. e., the thermal transport must be decreasing as represented by the interpretative thermal diffusivity of Fig. 7. According to this, the heat diffusion also follows closely any changes in E_r with a reasonable chance that not only the establishment of an ion root, but also a flow regulated turbulence, is tailoring the transport. An important question for which we still do not have data is whether the flatter φ regions can be related with null or small E_r or, rather, with fluctuating fields of null time-average (for the time resolution of the diagnostics) but able to moderate transport, as is expected from zonal flow dynamics.

Although the bulk region is further in than the zone explored with fast cameras and electric probes, we may assume that the relation between flows and turbulence remains the same in the entire density gradient region, which really extends up to the very edge (see e. g. Fig. 3). We have seen that there is a spontaneous generation of shear flow right at the edge, which in turn moderates turbulence levels and, assuming steady sources, particle (and heat) transport. General considerations about the effect of shear flows on turbulence levels and transport [15] lead to the notion that turbulence and macroscopic flows must be considered together, especially when the physical conditions are close to developing structural changes in the turbulence levels, as is the case in the vicinity (in parameter space) of L-H transitions [16]. The results found in the edge of the TJ-II seem to confirm this notion. Furthermore, the similarity between results in the TJ-II (where no L-H transition has been achieved) and measurements in other machines in conditions of actual L-H transition, suggests that the underlying physics is the same. There are, however, two important aspects to consider in a general description such transitions [17]. First, a threshold in some relevant parameter must mark the beginning of the transition mechanism. Once reached the threshold value, the system heads rapidly to the new confinement regime. And, second, after the transition the threshold condition (which in many theories is a critical gradient) for the back transition changes implying hysteresis in the system. With this in mind, the fact that there is no such hysteresis (neither L-H transition) in the TJ-II, but the link between shear flow and turbulence can be observed as in other machines that do undergo L-H transition, may be an indication that the plasma conditions in the TJ-II (perhaps the strong plasma-wall interaction) can make apparent the seeding mechanism for the transition but there is not enough power to force the, so to speak, hard transition. By seeding mechanism we mean a trigger for the amplification of shear-flow due to Reynolds stress momentum redistribution. Further shearing should make the Reynolds stress drive for poloidal momentum decrease due to decreasing turbulence levels and perhaps turbulent anisotropy. A hard transition can be maintained by steep gradients that allow for ExB shear flows through the diamagnetic contribution to the radial electric field. In this frame, TJ-II experiments are exploring the pre-transition dynamics. Further studies and experiments are aimed at clarifying these aspects, extending them if possible to the bulk plasma region.

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ЭКСПЕРИМЕНТАЛЬНОЕ ИССЛЕДОВАНИЕ ВЗАИМОСВЯЗИ РАДИАЛЬНЫХ ЭЛЕКТРИЧЕСКИХ ПОЛЕЙ, ФЛУКТУАЦИЙ И ПЕРЕНОСА С ПЛОТНОСТЬЮ В СТЕЛЛАРАТОРЕ TJ-II

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Обычно в стеллараторе TJ-II рассматривается перенос в трех областях: в горячей зоне, где перенос и, следовательно, радиальное электрическое поле определяются, по-видимому, механизмом вклада мощности нагрева; в зоне удержания или основной зоне плазмы, где столкновительные и турбулентные потоки связаны с радиальным электрическим полем и вращением плазмы; и в третьей периферической области, где взаимодействие плазмы со стенкой и магнитная топология добавляют новые явления в физику переноса. Однако эта последняя область еще может сохранять транспортные свойства основной области. В работе представлены последние экспериментальные данные по исследованию флуктуаций на периферии с помощью зондов и быстрой видеокамеры, а также измерения потенциала плазмы путем зондирования пучком тяжелых ионов (HIBP), и профили коэффициента теплопроводности в основной зоне. Все эти данные регулируются одним и тем же экспериментальным параметром – плотностью плазмы. Этот факт указывает на тесную взаимосвязь переноса, турбулентности и электрических полей в плазме стелларатора.

ЕКСПЕРИМЕНТАЛЬНІ ДОСЛІДЖЕННЯ ВЗАЄМОЗВ'ЯЗКУ РАДІАЛЬНИХ ЕЛЕКТРИЧНИХ ПОЛІВ, ФЛУКТУАЦІЙ І ПЕРЕНОСУ ПЛАЗМИ У СТЕЛАРАТОРІ TJ-II

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Звичайно в стелараторі TJ-II розглядається перенос у трьох областях: у гарячій зоні, де перенос і, отже, радіальне електричне поле визначаються, очевидно, механізмом внеску потужності нагріву; в зоні утримання або основній зоні плазми, де зіткненні і турбулентні потоки пов'язані з радіальним електричним полем і обертанням плазми; і в третій, периферійній області, де взаємодія плазми зі стінкою і магнітна топологія додають нові явища у фізику переносу. Проте ця остання область ще може зберігати транспортні властивості основної області. Представлено останні експериментальні дані по дослідженню флуктуацій на периферії за допомогою зондів і швидкої відеокамери, а також вимірювання потенціалу плазми шляхом зондування пучком важких іонів (HIBP), і профілі коефіцієнта теплопровідності в основній зоні. Усі ці дані регулюються тим самим експериментальним параметром – густиною плазми. Цей факт указує на тісний взаємозв'язок переносу, турбулентності й електричних полів у плазмі стеларатора.