ROLE OF TURBULENCE AND ELECTRIC FIELDS IN THE ESTABLISHMENT OF IMPROVED CONFINEMENT IN TOKAMAK PLASMAS

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An extensive (INTAS) research programme started in 2002 to investigate the correlations between on the one hand the occurrence of transport barriers and improved confinement in the medium-size tokamaks TEXTOR and T-10 and on the smaller tokamaks FT-2, TUMAN-3M and CASTOR, and on the other hand electric fields, modified magnetic shear and electrostatic and magnetic turbulence using advanced diagnostics with high spatial and temporal resolution and of various active means to externally control plasma transport . This has been done in a strongly coordinated way and exploiting the complementarity of TEXTOR and T-10 and the backup potential of the three other tokamaks, which together have all the relevant experimental tools and theoretical expertise.

PACS: 52.55.Fa, 52.30.-q, 52.35Ra, 52.55.-s

1. INTRODUCTION

About a decade ago local zones (called internal transport barriers, ITBs) with reduced transport were discovered in tokamaks. These ITBs can act on the electron and/or ion fluid.The understanding and reduction of turbulent transport in magnetic confinement devices is not only an academic task, but also a matter of practical interest, since high confinement is chosen as the regime for ITER and possible future reactors because it reduces size and cost.

Generally speaking, turbulence comes in two classes: electrostatic and magnetic turbulence. Over the last decade, step by step new regimes of plasma operation have been identified, whereby turbulence can be externally controlled, which led to better and better confinement.The physical picture that is generally given is that by spinning up the plasma, it is possible to create flow velocity shear large enough to tear turbulent eddies apart before they can grow, thus reducing electrostatic turbulence. This turbulence stabilization concept has the universality, needed to explain *ion transport* barriers at different radii seen in limiter-and divertor tokamaks, stellarators, reversed field pinches, mirror machines and linear devices with a variety of discharge- and heating conditions and edge biasing schemes. The *electron heat conduction*, however, which normally is one to two orders above the collisional lower limit, remained strongly anomalous also in the regime with suppressed electrostatic turbulence. In that case it became the dominant heat loss channel. From this, it is conjectured that magnetic turbulence drives the anomalous electron heat conduction..

Although turbulence measurements have been performed on many magnetic confinement devices during the last decades, the additional insight gained from these experiments is relatively limited. This can be attributed to a number of reasons: Firstly, only a very coarse spatial resolution was achieved in many measurements of electric fields and turbulence. Secondly, simultaneous measurements of different fluctuating quantities (temperature, density, electric potential and magnetic field) at the same location, needed for a quantitative estimation of the energy and particle transport due to turbulence were only performed in a very limited number of cases. Thirdly, theoretical models were often only predicting the global level of turbulence as well as the scaling of this level with varying plasma parameters.

The investigation of the correlations between on the one hand the occurrence of transport barriers and improved confinement in magnetically confined plasmas, and on the other hand electric fields, modified magnetic shear and electrostatic and magnetic turbulent fluctuations necessitates the use of various active means to externally control plasma transport. It also requires to characterize fluctuations of various important plasma parameters inside and outside transport barriers and pedestal regions with high spatial and temporal resolution using advanced diagnostics, and to elucidate the role of turbulence driving and damping mechanisms, including the role of the plasma edge properties. The experimental findings have to be compared with advanced theoretical models and numerical simulations.

The Consortium of the INTAS project 2001-2056 disposes of 5 tokamaks (the medium-size and similar tokamaks TEXTOR and T-10, and the smaller-scale tokamaks FT-2, TUMAN-3M and CASTOR), equipped with advanced diagnostics with high spatial and temporal resolution. Research activities are strongly coordinated and exploit the complementarity of TEXTOR (mainly ion heating, Dynamic Ergodic Divertor) and T-10 (electron heating, Heavy Ion Beam Probe, HIBP) as well as the backup potential of the three other tokamaks, which together have all the relevant experimental tools and theoretical expertise. A substantial effort was made for the improvement and development of diagnostics which were necessary for the successful execution of the project: HIBP[1],correlation reflectometry (CR) [2,3], Doppler reflectometry [4], correlative enhanced scattering [5], fluctuation reflectometry theory [6,7], advanced Gundestrup probe [8].

The most important results obtained in the investigations of the physical mechanisms underlying different types of transport barriers are presented in Section 2. The results of studies on turbulence characteristics are discussed in Section 3.

2. TRANSPORT BARRIERS: PHYSICAL MECHAMISMS

2.1. ELECTRON INTERNAL TRANSPORT BARRIERS

Recent research in the T-10 and TEXTOR devices has concentrated on understanding the physical mechanisms that are responsible for the generation of electron internal transport barriers (e-ITBs) and also on finding out in which way they are related to the concept of profile consistency, in which the plasma pressure and temperature profiles have a tendency to organize themselves [9] into an ‘universal’ profile shape, in agreement with the plasma minimum free energy principle. If ∇p exceeds a certain critical value, instabilities connected with the pressure gradient will counteract the formation of an even steeper gradient. The radial distribution of transport coefficients is determined by the necessity to maintain the self-consistent pressure profile under different external impacts.

Previous work [10] has shown that e-ITBs are formed when dq/dr is low in the vicinity of rational magnetic surface with low m and n values. The investigation of effects bound with ITB formation was continued in T-10 experiments in 2005. For this purpose experiments with a rapid plasma current ramp up were performed. In this case, due to $(\beta_p + l_i/2) \sim 1/I_p^2$ a rapid change of the magnetic surface densities in the central part of plasma takes place, while current penetration in this region occurs only after t>50ms. So confinement changes observed in the plasma core are the result of a magnetic surface density change only. The results are under analysis [11].

Experiments with Internal Transport Barrier (ITB) formation and the maintenance of self-consistent plasma profiles under the action of Electron Cyclotron Resonance Heating and Current Drive ECRH/ECCD were performed at T-10. The results are still being analyzed. A joint analysis of T-10 and TEXTOR experimental results enabled to analyze effects bound with plasma self-organization. It was shown that the plasma pressure profiles obtained in different operational regimes and even in various tokamaks may be represented by a single typical curve, called the self-consistent pressure or canonical profile, also often referred to as profile resilience or profile stiffness.

The investigation of self-consistent profile effects was carried out under different experimental conditions, such as regimes with plasma density near the Greenwald limit and regimes with deuterium pellet injection. It can be concluded that the effect takes place in a wide region of plasma density up to that, which leads to disruption. The conditions described by this self-consistent profile are realized in a very short time, less than the experimental time resolution $\Delta t \geq 2\ldots4$ ms. During ECRH it is realized by a plasma density redistribution: n_e decreases in the plasma heating zone. This implies that the famous “density pump out” is the result of plasma self-consistent organization. Experimentally this means that, when one tries to distort the self-consistent pressure profile, the heat (cold) pulse spreads much more quickly than can be expected from transport coefficients, calculated from a radial power balance. However, in ITB regions ∇p can largely exceed that from the self-consistent pressure profile.

The work at TEXTOR has made it also possible to give an answer to a long-standing question why the electron temperature profiles during off-axis Electron Cyclotron Resonance Heating (ECRH) in the late Rijnhuizen Tokamak Project are hollow. These experiments have been repeated in TEXTOR with a much more advanced set of diagnostics and the conclusion is that during the first 100 ms of off-axis ECRH application, the ohmic input power in the plasma core drops below the power lost by the electrons to the ions via collisions.

Rational surfaces thus play a key role in the establishment of e-ITBs, as has been observed in stellarators, too. However, this does not exclude a possible supporting role of ExB shear in ITB formation near rational surfaces. Recent work on DIII-D and gyrokinetic simulations [12] hint at possible synergy between ExB shear and effects of rational surfaces. Large profile corrugations in electron temperature gradients at lowest-order singular surfaces lead to the buildup of a huge zonal flow ExB shear layer which provides a trigger for the low power ITB observed in DIII-D.

2.2. TRANSPORT BARRIERS INDUCED BY DED IN TEXTOR

The influence of a magnetic perturbation field, generated by the Dynamic Ergodic Divertor (DED), on the turbulence and transport properties is studied and compared to plasmas without such a field perturbation. The external magnetic field breaks up the magnetic field lines structure and causes an ergodization of the plasma edge [13]. The strength and radial range of the perturbation field can be widely varied. Together with tangential neutral beam injection in co–and counter–current directions, the turbulent transport has been investigated.

One main effect of the DED is the modification of the radial electric field. The ergodization of the magnetic field lines leads to an increased electron loss rate which charges the plasma edge more positively. The application of the DED increases the rotation in the scrape-off-layer, where the original rotation is in the ion diamagnetic drift direction. Since the rotation at radii smaller than the limiter radius is in the electron diamagnetic drift direction, the DED slows down the rotation. The inversion point of the radial electric field (as well as the poloidal rotation velocity) is shifted further inside. This effect does not depend on the DED configuration (m/n= 3/1 or 12/4), but on the field strength of the perturbation field. Note that this conclusion concerns only DC DED operation; the AC DED scenarios are the subject of future work.

The data obtained in a single discharge with by the fast scanning Gundestrup probe (Fig. 1) clearly demonstrate the effects of DED on the plasma edge parameters.

The combination of counter-current neutral beam injection and the DED can lead to the formation of a transport barrier at the plasma edge [14]. The turbulence rotation is decreased at the barrier, which again demonstrates the braking effect of the DED. The acceleration of rotation by counter neutral beam injection and braking by the DED yields an increase in the velocity shear at r/a = 0.9. At the barrier, the level of density fluctuations is constant, the turbulence decorrelation time is increased and the turbulence wavelength is decreased. The evaluation of turbulent diffusion using a random walk model yields the reduction of transport by about 50 % within the barrier.

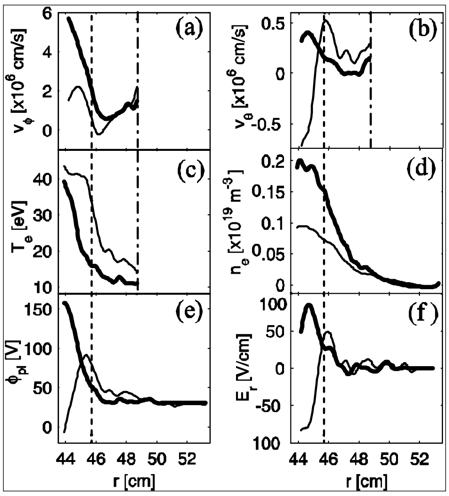

Fig. 1. Radial profiles (#99777) of the (a) toroidal flow v_{ϕ} *, (b) poloidal flow* v_{θ} *, (c) electron temperature* T_e *, (d) electron density* n_e *, (e) floating potential* ϕ_f *and, (f) radial electric field* E_r *before (thin line) and during (thick line) DED in TEXTOR. The vertical dashed line marks the position of the Last Closed Flux Surface(LCFS). The dashed-dotted line indicates the end of the reliability of the Gundestrup probe data*

2.3.TRANSPORT BARRIERS DURING OH DISCHARGES IN TUMAN-3M

The influence of low frequency magnetohydrodynamic (MHD) activity bursts during ohmic H-mode in the TUMAN-3M tokamak [4] has been studied focusing on the measurements of plasma fluctuation poloidal velocity performed by microwave Doppler reflectometry. During the MHD burst a transient deterioration of improved confinement was observed. As shown in Fig. 2 the plasma fluctuation poloidal rotation observed before the MHD burst in the vicinity of the edge transport barrier was in the direction of plasma drift in the negative radial electric field. During the MHD activity the measured poloidal velocity was drastically decreased and even changed its sign. Radial profiles of the poloidal velocity measured in a series of reproducible tokamak shots exhibited the plasma fluctuation rotation in the ion diamagnetic drift direction at the location of the peripheral transport barrier.

The positive E_r perturbation at the plasma edge obviously leads to a transient deterioration of the H-mode transport barrier. On the other hand, the inward propagation of the positive electric field increases the shear of plasma rotation deeper in the core. Such a displacement of the shear pattern to the core region might cause a transport barrier shift towards the inner region of the plasma column.

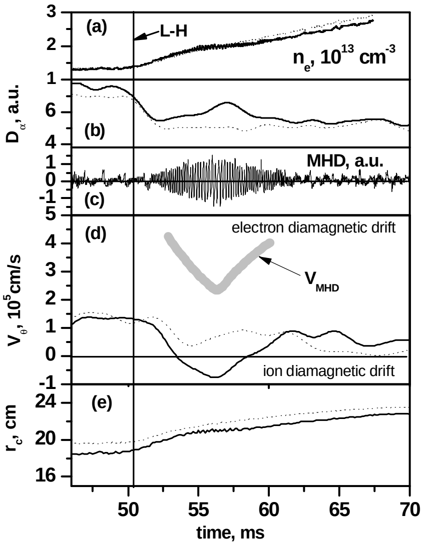

Fig 2. Time evolution of the signals measured in a shot virtually without MHD activity (dotted line) and in a shot with a sharp MHD in TUMAN-3M:
a) line averaged plasma density measured along central chor; b) Dα emission intensity; c) magnetic probe signal with MHD burst; d) magnetic island poloidal velocity derived from magnetic probe signal evolution (thick grey curve) and the Doppler velocities; e) cut-off radii (dotted line, microwave frequency 23.5 GHz and solid line, microwave frequency 24.68 GHz)

3.TURBULENCE CHARACTERISTICS

3 .1. GEODESIC ACOUSTIC MODES (GAM)

Geodesic Acoustic Modes (GAM) were investigated on the *T-10 tokamak* using the HIBP, correlation reflectometry (CR) and multipin Langmuir probe diagnostics [1]. GAM are torsional plasma oscillations with poloidal wavenumber *m*=0, a high frequency branch of Zonal Flows (ZF). Regimes with ohmic heating and with on- and off-axis ECRH were studied. It was shown that GAM are mainly potential oscillations, but GAM are pronounced enough in the density fluctuation to be detected by CR, making the latter to an effective tool for further study of ZF/GAM.

Typically, the power spectrum (Fig.3) of the HIBP potential oscillations exhibits a dominating solitary quasi-monochromatic peak. The frequency of GAM changes in the region of observation and decreases towards the plasma edge. After ECRH switch-on, the frequency increases, correlating with growth of the electron temperature T_e. The GAM frequency (see Fig.4) depends on the local T_e as: $f_{GAM}{\sim}c_s/R{\sim}T_e^{1/2}$ which is consistent with a theoretical scaling for GAM, where c_s is the sound speed within a factor of unity.

Along with the above mentioned features, predicted for ZF/GAM, some additional characteristics were found on T-10:

- GAM tend to be more excited near low-*q* magnetic surfaces.
- Along with being mainly electrostatic, GAM also have some magnetic component.
- GAM amplitude has an intermittent character.
- GAM exhibit a density limit.

Characteristics of GAM observed with O-mode CR in OH discharges in the plasma edge of *TEXTOR tokamak* are similar to those on T-10. The frequency of the observed mode obeys the theoretically predict ed GAM scaling with local temperature and ion mass. The poloidal distribution of the amplitude of the GAM-induced density fluctuations was studied. On the basis of measurements at several poloidal positions a good qualitative agreement with theoretically predicted sinθ (or m = 1) distribution was found.

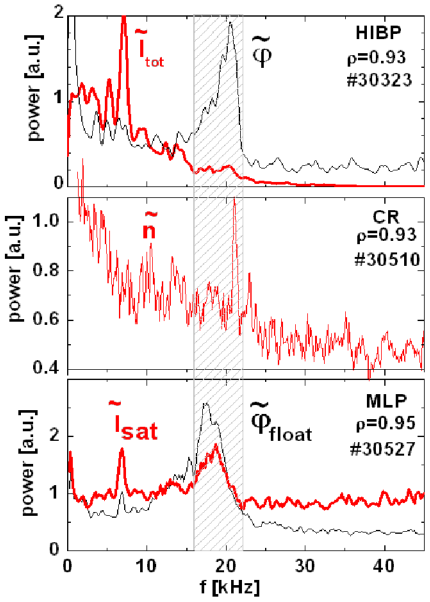

Fig. 3.Top: Power spectrum of potential oscillations and total beam current (proportional to the plasma density) measured by HIBP in T-10; Middle:Spectrum of plasma density oscillations measured by the reflectometer;Bottom:Spectra of floating potential and ion saturation current oscillations measured by the Langmuir probe. Parameters of similar shots: B_T *= 2.42 T, Ip = 290 kA, q(a) = 2.5,* n_e *= 4 × 1019 m*$^{-3}$

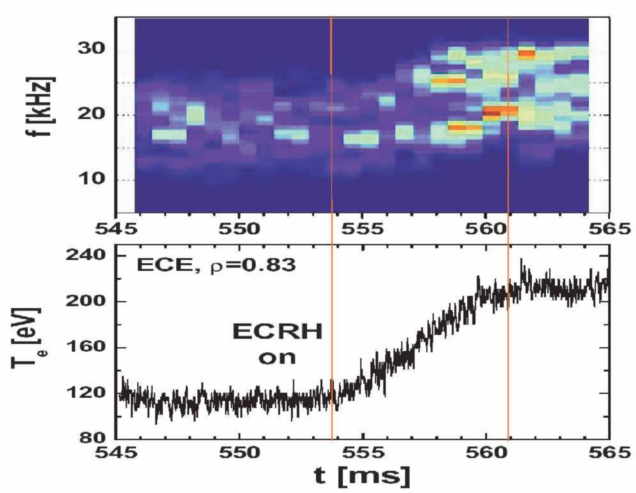

Fig. 4. Evolution of spectrum measured at ρ =0.83 during ECRH switch-on in T-10. The frequency of peak increases together with growth of electron temperature

The phase coherence over about 90° confirms the long-scale nature of the observed density oscillations which is also consistent with the predicted m = 1 structure. The level of the oscillations of turbulence rotation related with the GAM is found to be in the range 5-10% of the ambient turbulence rotation, which result in an increase of shearing rate by a factor of approximately 5. The resulting shearing rate is comparable with the decorrelation rate of ambient turbulence. It is shown that the fluctuations in the ambient plasma turbulence level are strongly correlated with those of the oscillations of turbulence rotation due to the GAM.

Doppler reflectometry has recently been employed to detect GAM as oscillations of poloidal velocity in the ASDEX Upgrade tokamak [15]. A similar diagnostic has been used to reveal GAM oscillations in the *TUMAN-3M tokamak* during transition to ohmic H-mode triggered by impulse gas puffing [16]. The oscillations of poloidal velocity in the GAM frequency region were evaluated via the averaging of the Doppler frequency shift spectra.

To study an influence of the GAM oscillations on the RMS level of plasma scattering fluctuations cross-correlation spectral analysis has been employed. Quasi-coherent oscillations of the poloidal velocity in the GAM frequency region between 20 and 40 kHz were observed. The oscillations were detected for cut-off locations near the edge transport barrier occurring during the H-mode. There is no quasi-coherent oscillation of the poloidal velocity if the cut-off is located in the SOL. The discovered correlation between the plasma fluctuation level and the poloidal velocity oscillation indicates an impact of the GAM oscillations on the plasma turbulence.

3.2. CORE TURBULENCE IN T-10

Turbulence characteristics were investigated in detail in OH and ECRH discharges in T-10 using correlation reflectometry, HIBP and Langmuir probe arrays [2]. The OH and ECRH discharges show a distinct transition from the core turbulence, having a complex spectral structure, to the unstructured one at the plasma boundary.

The core turbulence includes the “Broad Band” (BB), “Quasi-Coherent” (QC) features, arising due to the excitation of rational surfaces with high poloidal m-numbers, “Low Frequency” (LF) near zero frequency, and the GAM oscillations at 20…30 kHz. All experimentally measured properties of LF and HF QC are in a good agreement with the behaviour of the linear increments of Ion Temperature Gradient/Dissipative Trapped Electron Mode (ITG/DTEM) instabilities. Significant local decrease of the turbulence amplitude and coherency was observed at the edge velocity shear layer and in the core near q =1 radius at 5…15 ms after ECRH switch-off.

Reflectometry at half minor radius shows that long wavelength turbulence is replaced by shorter wavelength turbulence when the density increases up to half of the Greenwald density. The shorter wavelength turbulence is dominant at higher densities. This observation offers the possibility to explain the confinement rise at low and its saturation at higher densities. The second factor, which may influence the confinement, is the strong decrease of the Te/Ti ratio with the density increase which could also lead to the confinement rise.

3.3. TURBULENCE CHARACTERISTICS IN FT-2

The new highly localized correlative enhanced scattering diagnostics is capable of determinating the small scale turbulence wave number spectra developed at the FT-2 tokamak and provided already the following results [5]:

- Two modes are found in the UHR BS spectra under conditions when the threshold for the Electron Temperature Gradient (ETG) mode instability [17] is exceeded. The ETG mode is a possible candidate to explain anomalous electron energy transport.

- The first mode has a frequency less than 1 MHz and radial wave number 25 $\text{cm}^{-1}<q<150\text{cm}^{-1}$, and is localized at the plasma edge and associated with the ITG mode. Its wave number spectrum is quickly decaying in a way similar to that observed on Tore Supra.
- The second mode has a frequency higher than 2 MHz and radial wave number $q>150\text{cm}^{-1}$, and is associated with the ETG mode. Its phase velocity is twice as high and its amplitude is growing towards the centre. In the region of observations its level is comparable to that of the ITG mode, but is however much smaller than that of the latter mode at the edge.
- The possibility of the poloidal rotation profile determination with the UHR BS technique is demonstrated.

4. CONCLUSION AND OUTLOOK

The strong innovation potential of this INTAS project lies in the field of tokamak physics and tools to control plasma turbulence and electric fields, as well as in the field of advanced plasma diagnostics. This project led to an improved understanding of the relation between the global confinement properties of tokamak plasmas and the physics of the electrostatic and magnetic turbulence.

The main goal of the coherent approach was to identify the major physical laws and instabilities ruling the transport in tokamak plasmas in order to incorporate them into theoretical turbulence models as well as in analytical transport models. This is of crucial importance, because the ITER project relies mostly on scaling laws. A thorough understanding can pave new ways towards advanced scenarios and their external control, and hence lead to an optimized construction of next generation tokamaks. Any new ideas on external control of transport barriers by means of magnetic and electrostatic perturbation on the plasma edge can be easily tested since the tokamaks in the project can be relatively easily modified according to new ideas.

A new INTAS project has started in October 2006 with the same partners plus four other institutions. This will in addition provide advanced theoretical models and numerical simulations, access to the long pulse tokamak Tore Supra, and the availability of advanced magnetic sensors to study magnetic turbulence inside the plasma.

ACKNOWLEDGEMENT

The authors are grateful to INTAS (International Association for the promotion of co-operation with scientists from the New Independent States of the former Soviet Union) which supported the research activities in the framework of project INTAS 2001-2056.

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ВЛИЯНИЕ ТУРБУЛЕНТНОСТИ И ЕЛЕКТРИЧЕСКИХ ПОЛЕЙ НА УСТАНОВЛЕНИЕ УЛУЧШЕННОГО УДЕРЖАНИЯ ПЛАЗМЫ В ТОКАМАКАХ

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В 2002 г. по проекту INTAS были начаты обширные исследования корреляции между появлением транспортных барьеров и улучшенного удержания в токамаках средних (TEXTOR, Т-10) и меньших (ФТ-2, ТУМАН-3М и CASTOR) размеров, с одной стороны, и электрическими полями, модифицированным магнитным широм и электростатической и магнитной турбулентностью, с другой стороны, при использовании передовых методов диагностики с высоким пространственным и временным разрешением и различных активных средств внешнего управления переносом в плазме. Всё это проводилось при наличии строгой координации и использовании взаимной дополняемости TEXTOR и Т-10 и поддерживающих возможностей трёх других токамаков, которые в совокупности обеспечили все надлежащие экспериментальные средства и теоретическую проверку.

ВПЛИВ ТУРБУЛЕНТНОСТІ ТА ЕЛЕКТРИЧНИХ ПОЛІВ НА УСТАНОВЛЕННЯ ПОЛІПШЕНОГО УТРИМАННЯ ПЛАЗМИ В ТОКАМАКАХ

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