ROLE OF TURBULENCE AND ELECTRIC FIELDS IN THE FORMATION OF TRANSPORT BARRIERS AND THE ESTABLISHMENT OF IMPROVED CONFINEMENT IN TOKAMAK PLASMAS THROUGH INTER-MACHINE COMPARISON

G. Van Oost[1], V. Bulanin[2], A.J.H. Donné[3], E. Gusakov[4], A. Krämer-Flecken[5], L. Krupnik[6], J. Heikkinen[7], A. Melnikov[8], K. Razumova[8], V. Rozhansky[2], J. Stöcke[9], M. Tendler[10], M. Van Schoor[11], V. Vershkov[8], J. Zajac[9], A. Altukov[4], V. Andreev[8], L. Askinazi[4], I. Bondarenko[6], A. Dnestrovskij[8], L. Eliseev[8], L. Esipov[4], S. Grashin[8], A. Gurchenko[4], G.M.D. Hogeweij[3], M. Kantor[4], E. Kaveeva[2], T. Kiviniemi[7], S. Khrebtov[6], D. Kouprienko[4], T. Kurki-Suonio[7], S. Lashkul[4], S. Lebedev[4], S. Leerink[7], S. Lysenko[8], F. Ogando[7], S. Perfilov[8], A. Petrov[2], A. Popov[4], D. Shelukhin[8], R. Shurygin[8], S. Soldatov[1,5], A. Stepanov[4], Y. Xu[11]

[1]Department of Applied Physics, Ghent University, Ghent, Belgium;
[2]St-Petersburg State Polytechnical University, St-Petersburg, Russia;
[3]FOM-Institute for Plasma Physics Rijnhuizen, Association EURATOM-FOM,
Nieuwegein, The Netherlands;
[4]Ioffe Institute, St-Petersburg, Russia;
[5]Institute for Energy Research-Plasma Physics, Forschungszentrum Jülich GmbH,
EURATOM Association, Jülich, Germany;
[6]Institute of Plasma Physics, NSC "Kharkov Institute of Physics and Technology", Kharkov, Ukraine;
[7]Euratom-Tekes Association, VTT, Finland;
[8]RRC Kurchatov Institute, Moscow, Russia;
[9]Institute Plasma Physics, Association EURATOM/IPP.CR, Prague, Czech Republic;
[10]Alfvén Laboratory, Royal Institute of Technology, Stockholm, Sweden;
[11]Laboratory for Plasma Physics, ERM/KMS, Association EURATOM-Belgian State,Brussels, Belgium

Over the past decade new regimes of tokamak operation have been identified, whereby electrostatic and magnetic turbulence responsible for anomalous transport, can be externally suppressed, leading to improved confinement. Although turbulence measurements have been performed on many confinement devices, the insight gained from these experiments is relatively limited. To make further progress in the understanding of plasma turbulence in relation to improved confinement and transport barriers, an extensive experimental and theoretical research programme should be undertaken. The present INTAS project investigates the correlations between on the one hand the occurrence of transport barriers and improved confinement in the tokamaks TEXTOR & T-10 and Tore Supra as well as on the smaller-scale 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. This is done in a strongly coordinated way and exploiting the complementarity of TEXTOR and T-10 and the backup potential of the other tokamaks, which together have all the relevant experimental tools and theoretical expertise. Advanced theoretical models and numerical simulations are used to check the experimental results.

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

1. INTRODUCTION

Local zones (called edge transport barriers ETBs, respectively internal transport barriers ITBs) with reduced transport are intensively studied in tokamaks. 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.

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 05-100008-8046 with 14 partner institutions disposes of 6 tokamaks (the medium-size and similar tokamaks TEXTOR in Jülich and T-10 in Moscow, the long pulse large French tokamak Tore Supra in Cadarache, as well as the smaller-scale tokamaks FT-2, TUMAN-3M in St. Petersburg and CASTOR in Prague), equipped with advanced diagnostics with high spatial and temporal resolution. Research activities which are a continuation and extension of a previous INTAS project [1] are strongly coordinated and exploit the complementarity of TEXTOR (mainly ion heating, Dynamic Ergodic Divertor, DED) and T-10 (electron heating, Heavy Ion Beam Probe, HIBP) as well as the backup potential of the other tokamaks which dispose of turbulence diagnostics and/or means of active control of plasma transport which are complementary to those of T-10 and TEXTOR, and which provide important backup information that is very difficult to obtain on larger tokamaks. Furthermore, strong theoretical and modelling support is provided.

The most important results obtained in the investigations of the physical mechanisms underlying different types of transport barriers are presented in Section 2. In Section 3 the modeling of plasma dynamics in ohmically heated FT-2 discharges with the global full f gyrokinetic particle-in-cell code ELMFIRE is outlined.

2. TRANSPORT BARRIERS: PHYSICAL MECHANISMS

2.1. ELECTRON INTERNAL TRANSPORT BARRIERS AND SELF-ORGANIZATION

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 [2] 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.

From previous experiments on T-10 [3] we know that ITBs form near the rational surfaces with low numbers m and n, and that the fluctuation spectrum in this region does not exhibit the usual peaks and its broadband component has lower amplitude and shorter correlation lengths. We tried to investigate the specific effects in these ITB regions with the help of HIBP diagnostic. We still did not see any effects on plasma potential and its fluctuation in the region where we suppose the ITB to occur. However, the accuracy of determination of the ITB position at the deepest position available for the plasma potential analysis was not good enough. Therefore, further experiments with deeper HIBP penetration into the plasma core are needed. The multichannel Thomson scattering diagnostic shows that the structure of the rational surface (with low n,m) is very complicated, especially when the ITB is formed there. Local regions with enhanced Te are registered. For the investigation of this phenomenon we need more than one laser pulse per discharge, what we have on TEXTOR and hope to have on T-10 in the future. To-day results show that the effect may be asymmetric in poloidal direction. Further progress in these investigations may be important to understand the ITB formation physics.

The tokamak plasma self-organization is a fundamental turbulent plasma phenomenon, which leads to the formation of self-consistent pressure profile. This phenomenon was investigated in T-10 tokamak by means of different experiments[4, 5]. It was shown that normalized pressure profile $p_N(r)=p(r,t)/p(0,t)$, is independent on plasma densities in wide range of its values. Also it was shown that $p_N(r)$ is independent on the auxiliary ECR heating power and its deposition profile. Experiments show that the $p_N(r)$ depends only on the value of q at the plasma edge, and only weakly on the average plasma density, and on the deposited power and its radial distribution. The shape of $p_N(r)$ depends on the total plasma current, but not on j(r) [5]. Special experiments, in particular with rapid current ramp-up show that the $p_N(r)$ conservation is established during a time $t_c<0.1\tau_E$, with τ_E the energy confinement time. As a result of these experimental investigations it can be concluded that the self-consistent pressure profile $p_N(r)$ in tokamaks is linked to the equilibrium of a turbulent plasma. Strongly turbulent plasma can regulate its pressure profile due to its possibility to change in a wide range transport coefficients changing the level of instabilities and their coherency. However, $p_N(r)$ exists everywhere, except in the regions where ITBs occur. In these regions fluctuation coherency decreases, and more steep pressure gradient are allowed. Tokamaks with elongated plasma cross section were compared tokamaks with circular cross section like T-10 using the model developed by Yu.N. Dnestrovskij. [6] The results appears to be in a good accordance.

2.2. TRANSPORT BARRIERS INDUCED BY AN ERGODIC DIVERTOR 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 [7]. The strength and radial range of the perturbation field can be widely varied.

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 [1].

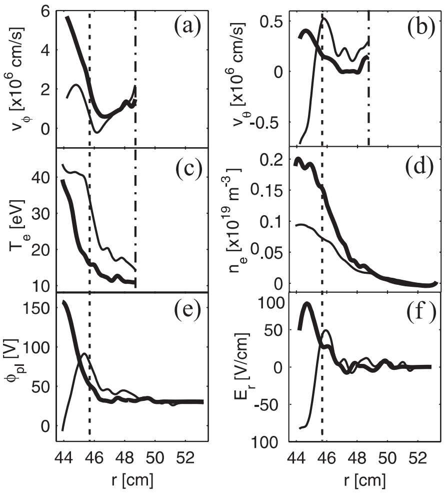

Fig. 1. Radial profiles (#99777) of the (a) toroidal flow v_ϕ*, (b) poloidal flow* v_θ*, (c) electron temperature* T_e*, (d) electron density* n_e*, (e) floating potential* ϕ_f *and, (f) radial electric field* E_r *before (thin line) and during (thick line) DED in TEXTOR. The vertical dashed line marks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

The influence of the DED on edge turbulence and turbulence-induced transport has been investigated in TEXTOR by Langmuir probes under three different static DED configurations [8]. Common features are observed. With DED, the edge equilibrium profiles are altered and the resultant positive E_r is in agreement with modelling. In the ergodic zone, the potential fluctuations are strongly reduced and the local turbulent flux changes direction from radially outwards to inwards. In the same zone, the turbulence properties are profoundly modified by energy redistribution in frequency spectra, suppression of large-scale structures and reduction of the radial and poloidal correlation lengths for all frequencies. Meanwhile, the fluctuation poloidal phase velocity changes sign from the electron to ion diamagnetic drift, consistent with the change of the $E_r \times B$ flow, whereas the slight radially outward propagation of fluctuations is hindered by the DED. In the laminar region, the turbulence correlation is found to react to the observed reduced flow shear.

The radial profiles of electrostatic Reynolds stress and fluctuation-driven particle flux have been measured in the plasma boundary using a multi-array of fast reciprocating Langmuir probes during the static 6/2 and 3/1 mode DED operation on TEXTOR [9]. In the ohmic discharge phase before DED, a large radial gradient of Reynolds stress is observed around the flow shear region, suggesting the importance of turbulence-driven flows in the plasma edge. With DED, it is shown that the magnetic ergodization may suppress the Reynolds stress at the plasma boundary and thus rearrange the profile of poloidal momentum.

2.3. IMPACT OF MHD ACTIVITY ON EDGE TRANSPORT BARRIERS IN TUMAN-3M AND FT-2

The influence of low frequency magnetohydrodynamic (MHD) activity bursts during ohmic H-mode in the TUMAN-3M tokamak [10] 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.

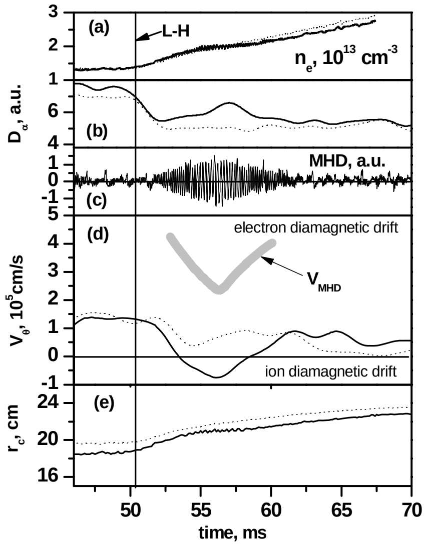

Fig 2. Time evolution of the signals measured in a shot virtually without MHD activity (dotted line) and in a shot with a sharp MHD in TUMAN-3M:
a) line averaged plasma density measured along central chord; b) Dα emission intensity; c) magnetic probe signal with MHD burst; d) magnetic island poloidal 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)

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.

According to the HIBP diagnostic the potential in the central region of TUMAN-3M also changed sign and became positive during MHD events while normally it is negative. There exists experimental evidence that MHD activity is associated with the growth of a magnetic island at a flux surface in the core a few centimeters inside the LCFS, as well as the growth of smaller islands at q=4 and q=2 surfaces, and formation of a stochastic layer in the LCFS vicinity.

A model for the origin of the positive radial electric field during the rise of the MHD activity is put forward, based on the assumption of the existence of a strong radial flux of electrons associated with the formation of an ergodic layer. The radial electron flux requires the same radial flux of ions to provide quasi-neutrality. To create the positive radial ion current the radial electric field should become more positive. This situation is similar to edge biasing experiments and a corresponding theory has been already developed before. A similar model has been used recently to explain the observed dependence of the radial electric field on the level of ergodization during experiments with DED on TEXTOR. In the extreme case, when the electron conductivity associated with the stochastic layer dominates over the ion conductivity which occurs in the TUMAN-3M experiments, the radial electric field should become positive inside the stochastic layer. The radial ion current generates toroidal rotation in the co-current direction by the toroidal jxB torque, so the ergodic layer becomes the source of the toroidal momentum. The co-current toroidal rotation should be transported outside the ergodic layer to the core by the turbulent viscosity thus creating the co-current toroidal rotation in the center of a tokamak. The co-current toroidal rotation makes the radial electric field more positive also outside the ergodic layer and for sufficiently large toroidal rotation the radial electric field becomes positive also in the central regions in accordance with the observations.

The influence of the MHD activity on edge transport barrier has also been studied on the FT-2 tokamak with enhanced power level of Lower Hybrid Heating ($P_{\mathrm{LHH}} \approx 2P_{\mathrm{OH}} = 180$ kW). Two types of discharge with strong and weak MHD activity near rational surface $q = 4$ have been observed in the post-heating stage. The different MHD behavior is accompanied by a different character of the plasma density increase during the RF pulse and different displacement of the plasma column along the major radius. In the presence of MHD activity burst, there appears a strong perturbation of the velocity derived from Doppler frequency shift. A sharp decrease in the velocity of rotation in the electron diamagnetic drift direction occurred, and moreover, a reversal of velocity took place in case of strong MHD activity. The original mechanism of such velocity evolution may be fast plasma displacement along the major radius or/and the MHD development itself. In any case the most plausible reason for the occurrence of rotation in the ion diamagnetic drift direction is a dramatic change in the electron–ion balance. It could be caused by the parallel escape of the fast electrons to the limiter due to magnetic flux surface distortion or displacement. The hard X-ray burst might be an indication of this fast electron loss. The effect is similar to the impact of an ergodic divertor on plasma rotation.

Close connection between the rotation of the scattering fluctuations and their level has been observed in the experiments. Approximately over the whole frequency range (up to 1MHz) fluctuation suppression is observed slightly before the velocity inversion occurred due to the cut-off movement through last closed flux surface. It can be assumed that the fluctuation suppression is due to strong shear of plasma rotation.

The actual derived velocity with respect to the laboratory frame is the sum of the fluctuation phase velocity and the plasma rotation velocity. Therefore, it is useful to compare the Doppler reflectometry data with those of another measurement. In the FT-2 tokamak experiment the plasma poloidal velocity was measured also using Doppler spectroscopy of impurity ion lines and the velocity was determined from the ion radial force balance. The radial profiles of the poloidal plasma velocity are compared with the profiles of the velocity derived from the Doppler reflectometry measurements [1]. The profiles were close to each other at the end of the Lower Hybrid Heating pulse and in the post -heating stage. However, the differences between the profiles are bigger than the diagnostic uncertainty for the ohmic heating stage and for the beginning of the RF pulse, requiring further analysis.

3. GYROKINETIC FULL F PARTICLE SIMULATION OF FT-2

Plasma dynamics in ohmically heated FT-2 discharges were modelled with the global full f gyrokinetic particle-in-cell code ELMFIRE [11,12]. With this code, one has been able for the first time to model a tokamak discharge with turbulence and neoclassical dynamics present at the same time. The code can follow the plasma density, temperature, and various moments of the distribution function of ions (including oxygen impurity ions) and electrons together with the electrostatic potential in a dense spatio-temporal grid in toroidal configuration. The code can extract the heat and particle losses as well as specify the power deposition. It can Fourier analyse the mode spectrum in turbulence and isolate the effect of the slowly varying neoclassical fields and transport. The code outputs the particle and heat diffusivities as well as the Reynolds stress.

ELMFIRE was further developed and applied in the study of dynamics of the radial electric field in the FT-2 tokamak. The diagnostics of the ELMFIRE code variables and their correlation analysis were used together with the frequency shift in the Doppler reflectometric signal at the outer plasma regions of the FT-2 tokamak plasma in ohmic plasma heating conditions.

The neoclassical radial electric field and the concomitant ExB poloidal flow were evaluated. In the plasma code, the field was found to agree with the neoclassical estimate but at the outer edge, the field was somewhat clamped, probably due to the Reynolds stress effects arising from the turbulence. At the outer edge, the correlation analysis of the turbulence was used together with a synthetic Doppler reflectometry model to extract the modelled spectrum of the frequency of the reflected signal. The shift in the spectrum was interpreted as to arise from the plasma ExB flow and from the phase velocity (in electron diamagnetic direction) of the major drift modes responsible for the microwave reflection in the reflectometry. Agreement of the reflectometry frequency shift between the experiment and ELMFIRE prediction for ohmic FT-2 plasma discharge was found. Moreover, the estimated phase velocity of the modes from ELMFIRE was found to agree with the corresponding flux-tube gyrokinetic code GS2 (in ballooning eigenmode approximation) result for the same wave vector of fluctuations under same plasma conditions. Agreement between the ELMFIRE calculated radial electric field and an analytical neoclassical estimate was found in ohmic core plasmas.

4. CONCLUSIONS AND OUTLOOK

The experimental and theoretical investigation of the correlations between on the one hand the occurrence of transport barriers and improved confinement, and on the other hand electric fields, modified magnetic shear and electrostatic and magnetic turbulence in tokamaks 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. The strong innovation potential of this INTAS project using six tokamaks in the EU (TEXTOR , Tore Supra, COMPASS) and in Russia (T-10, FT-2 TUMAN-3M), 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 with high spatial and temporal resolution. This running project has already made a substantial contribution to an improved understanding of the relation between the global confinement properties of tokamak plasmas and the physics of the electrostatic and magnetic turbulence.

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 1000081-8046.

REFERENCES

1. G.Van Oost et al // *Plasma Phys. Control. Fusion.* 2007, v. 49, p. A29.
2. M. Tendler, G. Van Oost and J. Stöckel // *Comments on Modern Physics.* 2002, v. 2, N 6, p. C 203.
3. K.A. Razumova et al // *Nucl. Fusion.* 2004, v. 44, p. 1067.
4. K.A. Razumova et al // *Plasma Phys. Control. Fusion.* 2006, v. 48, p. 1373.
5. K.A. Razumova et al // *Plasma Phys. Control. Fusion* 2008, v. 50, p. 105004.
6. Yu.N. Dnestrovskij et al // *Nucl.Fusion.* 2006, v. 46, p. 953.
7. K.H. Finken et al // *Fusion Eng.Des.* 1997, v. 37, p. 335.
8. Y.Xu et al // *Nucl.Fusion.* 2007, v. 47, p. 1696.
9. Y.Xu et al// *J.Nucl.Mater.* 2007, v. 718-722, p. 363.
10. V.V. Bulanin et al // *Plasma Phys. Control. Fusion.* 2006, v. 48, p. A101.
11. T. Kurki-Suonio, J.A. Heikkinen, S. Lashkul // *Phys. Plasmas.* 2007, v. 14, p. 072510.
12. S.J. Janhunen et al // *Nucl.Fusion.* 2007, v. 47, p. 875.

Article received 12.12.08

РОЛЬ ТУРБУЛЕНТНОСТИ И ЭЛЕКТРИЧЕСКОГО ПОЛЯ В ФОРМИРОВАНИИ ТРАНСПОРТНЫХ БАРЬЕРОВ И УСТАНОВЛЕНИИ УЛУЧШЕННОГО УДЕРЖАНИЯ В ПЛАЗМЕ ТОКАМАКОВ: СРАВНЕНИЕ ДАННЫХ ОТ РАЗНЫХ УСТАНОВОК

G. Van Oost, В. Буланин, A.J.H. Donné, Е. Гусаков, A. Krämer-Flecken, Л. Крупник, J. Heikkinen, А. Мельников, К. Разумова, В. Рожанский, J. Stöckel, M. Tendler, M. Van Schoor, В. Вершков, J. Zajac, А. Алтуков, В. Андреев, Л. Аскинази, И. Бондаренко, А. Днестровский, Л. Елисеев, Л. Есипов, С. Грашин, А. Гурченко, G.M.D. Hogeweij, М. Кантор, Е. Кавеева, T. Kiviniemi, С. Хребтов, Д. Куприенко, T. Kurki-Suonio, С. Лашкул, С. Лебедев, S. Leerink, С. Лысенко, F. Ogando, С. Перфилов, А. Петров, А. Попов, Д. Шелухин, Р. Шурыгин, С. Солдатов, А. Степанов, Y. Xu

В последние десять лет были получены новые режимы работы токамаков, в которых электростатическая и магнитная турбулентность, ответственная за аномальный перенос, могла подавляться путём внешнего воздействия, и тем самым достигалось улучшенное удержание. Несмотря на то, что исследования турбулентности проводились на многих установках, понимание этих процессов остаётся весьма ограниченным. Для достижения дальнейшего прогресса в понимании плазменной турбулентности с точки зрения улучшенного удержания и транспортных барьеров необходимы интенсивные экспериментальные и теоретические исследования. Проект INTAS направлен на выяснение корреляции между возникновением транспортных барьеров и улучшенного удержания в токамаках TEXTOR, Т-10 и Tore Supra, а также в токамаках малых размеров ФТ-2, ТУМАН-3М и CASTOR, с одной стороны, и электрическими полями, модифицированным магнитным широм и электростатической и магнитной турбулентностью, с другой стороны, с использованием передовых диагностических средств с высоким пространственным и временным разрешением. Исследования проводятся с высокой степенью координации работ и использованием взаимодополняемости установок TEXTOR и Т-10, и возможностей других токамаков, что в совокупности обеспечит необходимую экспериментальную и теоретическую проверку. Для проверки экспериментальных результатов будут использованы новые теоретические модели и численное моделирование.

РОЛЬ ТУРБУЛЕНТНОСТІ Й ЕЛЕКТРИЧНОГО ПОЛЯ У ФОРМУВАННІ ТРАНСПОРТНИХ БАР'ЄРІВ І ВСТАНОВЛЕННІ ПОЛІПШЕНОГО УТРИМАННЯ В ПЛАЗМІ ТОКАМАКІВ: ПОРІВНЯННЯ ДАНИХ ВІД РІЗНИХ УСТАНОВОК

G. Van Oost, В. Буланін, A.J.H. Donné, Є. Гусаков, A. Krämer-Flecken, Л. Крупнік, J. Heikkinen, О. Мельников, К. Разумова, В. Рожанський, J. Stöckel, M. Tendler, M. Van Schoor, В. Вершков, J. Zajac, А. Алтуков, В. Андреєв, Л. Аскиназі, І. Бондаренко, А. Днестровський, Л. Елісеєв, Л. Єсипов, С. Грашин, А. Гурченко, G.M.D. Hogeweij, М. Кантор, Є. Кавеєва, T. Kiviniemi, С. Хребтов, Д. Купрієнко, T. Kurki-Suonio, С. Лашкул, С. Лебедєв, S. Leerink, С. Лисенко, F. Ogando, С. Перфілов, А. Петров, А. Попов, Д. Шелухін, Р. Шуригін, С. Солдатов, А. Степанов, Y. Xu

За останні десять років було отримано нові режими роботи токамаків, у яких електростатична і магнітна турбулентність, відповідальна за аномальний перенос, могла заглушатися шляхом зовнішнього впливу, і тим самим досягалося поліпшене утримання. Незважаючи на те, що дослідження турбулентності проводилися на багатьох установках, розуміння цих процесів залишається досить обмеженим. Для досягнення подальшого прогресу в розумінні плазмової турбулентності з погляду поліпшеного утримання і транспортних бар'єрів необхідні інтенсивні експериментальні і теоретичні дослідження. Проект INTAS спрямовано на з'ясування кореляції між виникненням транспортних бар'єрів і поліпшеного утримання в токамаках TEXTOR, Т-10 і Tore Supra, а також у токамаках малих розмірів ФТ-2, ТУМАН-3М и CASTOR, з одного боку, і електричними полями, модифікованим магнітним широм і електростатичною і магнітною турбулентністю, з іншого боку, з використанням передових діагностичних засобів з високим просторовим і тимчасовим розділенням. Дослідження проводяться з високим ступенем координації робіт і використанням взаємодоповнюваності установок TEXTOR і Т-10, і можливостей інших токамаків, що в сукупності забезпечить необхідну експериментальну і теоретичну перевірку. Для перевірки експериментальних результатів буде використано нові теоретичні моделі і чисельне моделювання.