EVOLUTION OF THERMAL ION TRANSPORT BARRIERS IN REVERSED SHEAR / OPTIMISED SHEAR PLASMAS

VOITSEKHOVITCH I.[1], GARBET X.[2], MOREAU D.[2], BUDNY R. V.[3], BUSH C.E.[2,4], GOHIL P.[5], KINSEY J.[5], LITAUDON X.[2, 6], TAYLOR T.S.[5]

[1]LPIIM, Equipe Turbulence Plasma, CNRS/Université de Provence, Marseille, France
(Permanent address: RRC “Kurchatov Institute”, Moscow, Russia)
[2]DRFC, CEA-Cadarache, 13108, St. Paul lez Durance Cedex, France
[3]Princeton Plasma Physics Laboratory, Princeton, New Jersey, USA
[4]Permanent address : ORNL, Oak Ridge, Tenessee, USA
[5]General Atomics, San Diego, California, USA
[6]Presently at JET Joint Undertaking, Abingdon, U.K.

Abstract

The effects of the magnetic and ExB rotation shears on the thermal ion transport in advanced tokamak scenarios are analyzed through the predictive modelling of the evolution of internal transport barriers. Such a modelling is performed with an experimentally validated L-mode thermal diffusivity completed with a semi-empirical shear correction which is based on simple theoretical arguments from turbulence studies. A multi-machine test of the model on relevant discharges from the ITER Data Base (TFTR, DIII-D and JET) is presented.

1. INTRODUCTION

High performance plasmas have been recently obtained in a number of tokamaks through the occurrence of internal transport barriers (ITB). Examples of such regimes are the reversed shear (RS) and enhanced reversed shear (ERS) plasmas of TFTR [1], the weak negative shear (WNS) and negative central shear (NCS) discharges of DIII-D [2] and the optimised shear (OS) scenarios of JET [3]. The creation and evolution of the ITB's are governed by shear effects which reduce the plasma turbulence by decreasing the linear growth rates of drift-like instabilities and the toroidal couplings between the unstable modes, and also through the non-linear decorrelation of the turbulent eddies. In this work the effects of the magnetic shear and of the ExB rotation shear on the formation and evolution of thermal ion ITB's are studied through 1-D time-dependent transport simulations of the above-mentioned discharges. Our modelling is based on a semi-empirical, shear-dependent, ion heat transport model which is consistent with theoretical arguments following from turbulence studies.

2. SHEAR EFFECTS ON THE THERMAL ION DIFFUSIVITY

Shear effects on the thermal ion diffusivity, χ_i, are deduced from the analysis of the evolution of the ITB's. These effects are quantified from the comparison of the experimental χ_i-value with an L-mode Bohm-like reference model [4] which has been validated on a large variety of L-mode plasmas. We will speak here of ITB's in a broad sense, whenever the temperature gradient increases *relative to the reference model prediction* in an internal plasma region where the confinement is locally improved with respect to L-mode confinement. Thus, a magnetic shear correction to the thermal diffusivity has been deduced from the comparison of the experimental χ_i-value with the reference, shear-independent, L-mode transport model in the regimes where the role of the ExB shear is negligible. Then, the ExB rotation shear correction has been obtained from the analysis of the regimes with high toroidal and diamagnetic rotation, where the magnetic shear effects alone cannot reduce the anomalous transport sufficiently. The application of this procedure to the RS/ERS scenario of TFTR led to a simple shear correction which describes the observed ITB evolution in plasmas with non-monotonic q-profiles [5]. Here we present a further development of this model which allows an extrapolation to regimes with monotonic q-profiles where the improvement in the thermal confinement is mostly provided by the ExB rotation shear.

Our model for the thermal ion diffusivity is written as $\chi_i = \chi_{i,Bohm} F_{shear} + \chi_{i,neo}$, where $\chi_{i,Bohm} = 6.6\ \ 10^{-4} \left(cT_e / eB\right)\left(a\ \ p / p\right) q^2$ (all notations from [4]) and the shear correction factor, $F_{shear} = C_{TB}\left[1 + \exp\left\{\left(s_{cr}\left|1 - f(s_E)\right| - s_m q / \left(1 + 5 s_m / q^2\right)\right) / 0.1q\right\}\right]^{-1}$, describes the decrease of the anomalous transport due to shear effects. Here s_m and s_E are the magnetic and ExB rotation shears, $C_{TB} = \left(1 + 1.5\left(|q_a - q_0| / q_0\right)^2 H(x_{TB} - x)\right)^{-1}$ quantifies the improvement, q_a and q_0 are the edge and central safety factors, x is the dimensionless radius and x_{TB} is the ITB location (the radius at which F_{shear} reaches 0.5), H is the step function, and s_{cr}=0.05. The dependence of χ_i on s_E is described by $f(s_E) = C_V c^2 a \left(C_1 \quad V_{tor} + C_2 \quad V_{dia}\right) / V_{Ti}{}^3$ where $C_V = 2.1*10^{-28} n_i a^2 R\kappa$ is a volume factor, n_i is the ion density, a (R) is the minor (major) radius, κ is the elongation, V_{tor} is the measured toroidal velocity of the carbon impurities, and V_{dia} is the diamagnetic velocity of main ions. Other notations are standard and are given in [5] as well as the justification of our approach in the estimation of the ExB shear. C_1 and C_2 are empirical coefficients adjusted from the simulations : $C_1=4.6*10^3$, $C_2<5*10^2$. An upper limit only for the coefficient C_2 is proposed because, in all the simulations described below, the dominant effect was due to the toroidal rotation term. The physics relevant to the phenomenology of this model has been discussed briefly in Ref. [5]. Our heuristic magnetic shear correction is based on the toroidal mode decoupling mechanism which entails a reduction of the large-scale Bohm-like transport in the region with low magnetic shear [6]. The stabilising role of the ExB rotation shear on the turbulence was shown both in linear and non-linear theoretical approaches (see the review in [7]). In the linear theory, the ExB rotation shear affects the growth rate of the modes, suppressing the turbulence when the shearing rate is larger than the growth rate of the most unstable mode [8]. In addition, numerical computations show that the correlation length of the non-linearly coupled modes decreases in the sheared flow. In our model, the effect of the ExB rotation shear is to modify the "critical" magnetic shear below which mode decoupling starts to occur. If a strong ExB shear appears inside the RS region with some residual anomalous transport, our model yields a further reduction of this transport resulting in a stronger ITB inside the RS region. This differs from the shear correction proposed in [9], where the ITB cannot be located inside the radius with shear reversal. Our model can indeed provide a reduction of the transport in plasmas with standard monotonic q-profiles when the ExB rotation shear is sufficiently large. The q^2 factor in $\chi_{i,\ Bohm}$ can be attributed to the influence of the edge turbulence on core transport through mode coupling. Since the ITB should decouple the global modes in the core from the edge turbulence, the parametric dependence in C_{TB} has been chosen to weaken this q^2 effect inside the ITB.

A reduction of the χ_i-value below the conventional neoclassical transport is also required to reproduce the core temperature evolution during the high power and "postlude" phases in TFTR. A correction to the neoclassical diffusivity has been obtained from the analysis of the trajectory of barely trapped particles in the region of steep gradients: $\chi_{i,neo} = \chi_{ban} / \left(1 - 0.5 s_m + yH(y)a / V_0\right)^2 + \chi_{PS}$ with $y = 2\pi| \quad V_{tor}| - 4.1| \quad V_{Ti}|$ and $V_0 = 1.7*10^{-4} \omega_i a\varepsilon \ / q$. However, this correction is approximate and it can only be considered as a first step to estimate the relevant neoclassical processes.

3. MODELLING OF THE ION TRANSPORT BARRIERS IN ADVANCED SCENARIOS

The evolution of the ion ITB's in the high performance discharges selected from the ITER Data Base is simulated using the experimental particle density, current density, electron temperature and toroidal rotation profiles. The results are briefly summarized as follows : **(a)** in a RS configuration, the effect of the magnetic shear alone can provide an improved thermal ion confinement at low heating power, as was already invoked for thermal electron confinement in plasmas where electron heating is dominant [10, 11]. The example of such a behaviour is the prelude phase of the ERS scenario on TFTR (Fig. 1) where the RS configuration is obtained by moderate NBI heating during the current ramp-up [1] and where the stabilizing effect of the ExB rotation shear as estimated with our model is negligible ($f(s_E)<<1$). **(b)** The transition to the high power heating phase and the “postlude” phase in TFTR shows a strong increase of the ion temperature in the core, which cannot be reproduced with our magnetic shear correction (Fig.1a, dotted line). The temperature rise correlates with the increase of the shear in the toroidal and diamagnetic rotation. An ITB, where confinement is improved *with respect to the model with magnetic shear correction,* appears in the plasma core and moves outside (the evolution of the ITB location in this scenario is shown in Ref. [5]). The scan in the toroidal rotation performed in the “postlude” phase illustrates the correlation between the ITB evolution and the ExB rotation shear : the improved core confinement is maintained with a fixed location of the ITB after the power decrease, as long as sufficient ExB shear stabilization is maintained. Thus, balanced NBI maintains a high toroidal rotation shear and an improved confinement whereas, in the case of co-injection, the toroidal rotation profile broadens slowly and its gradient decreases, leading to a back transition to poor confinement. The ITB in the last case moves slowly outwards as well as the toroidal rotation shear. The second improvement phase (at t ≈ 2.6 s) is accompanied by the increase of the toroidal rotation shear and the shift of the ITB outside the radius with shear reversal. **(c)** A strong effect of the ExB shear on the turbulent thermal ion transport is found also in the WNS/NCS discharges of DIII-D [2] (Fig. 2). Magnetic shear alone is not sufficient to reproduce the ion temperature evolution (Fig. 2, dotted line). The ITB appears *inside the radius with shear reversal* and moves outwards. This extension of the ITB observed in the NCS configuration correlates with the evolution of the toroidal rotation shear. Other examples of such a correlation in DIII-D are VH mode transitions and magnetic braking experiments where the drag in the toroidal rotation leads to the loss of the improved confinement [12]. **(d)** In the regimes above, the ExB and magnetic shear effects add up in the RS region of the plasma and it is difficult to identify their respective roles. The decoupling of these effects is clearly illustrated when the ITB and shear reversal occur at different plasma radii while the ITB moves outside along the monotonic q-profile. The more illustrative example of the ExB rotation shear stabilisation is the OS plasmas of JET where the magnetic shear is not strongly reversed or is even positive [3]. In these regimes the ITB appears in the plasma core and moves outwards (Fig. 4) resulting in a large global improvement. The comparison of the confinement inside the ITB for three tokamaks shows that it could scale as the volume of the machine and this is included in the coefficient C_V. Interestingly, the core confinement is also well reproduced with our shear-dependent model when an ITB with a large ExB shear is combined with an H-mode. However, in this case, our model is not relevant to the edge transport barriers since important edge processes are not included in the model (fast ion losses, poloidal asymmetry with the Stringer spin-up).

4. CONCLUSIONS

Shear effects on the ion heat transport in high performance plasmas have been studied, and a shear correction to the L-mode thermal ion diffusivity has been proposed. This correction includes: (a) the stabilizing effect of the toroidal and diamagnetic rotation (compare to [9]); (b) the threshold character of the ExB rotation shear stabilization which indicates that the origin of the shear effects on the transport lies in the shear dependence of the instability growth rate. Our modelling illustrates: (a) the importance of both magnetic shear and ExB rotation shear suppression of anomalous transport; (b) the possibility to sustain ITB's by the ExB rotation shear alone in plasmas with monotonic q-profiles; (c) the favourable effect of the combination of magnetic and ExB rotation shears on the reduction of the ion diffusivity below the conventional neoclassical predictions. This work is an attempt towards a multi-machine test of our model, which includes a scan in plasma parameters and allows a comparison of the advantages of the shear effects on different tokamaks. A desirable extension of these experiments would be to operate tokamaks with a broad RS region, over durations of the order of (or larger than) the resistive diffusion time, but this would require an accurate real-time control of the current profile. A possible scheme for operating tokamaks in steady state in a high confinement regime governed by the magnetic shear is indicated in [13]. Additionnal control of the plasma rotation profile would also allow to take advantage of the ExB rotation shear effects illustrated in this paper.

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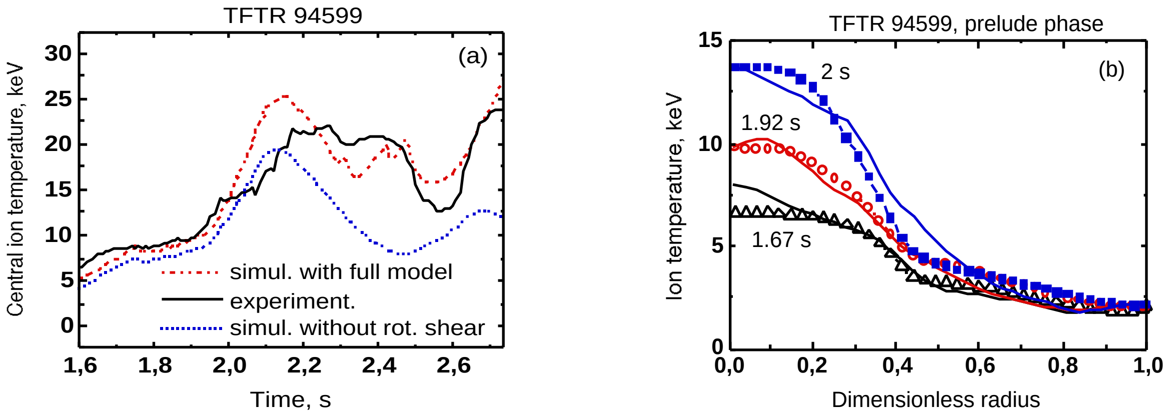
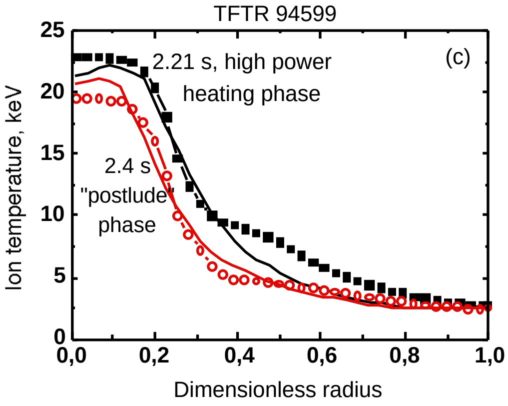




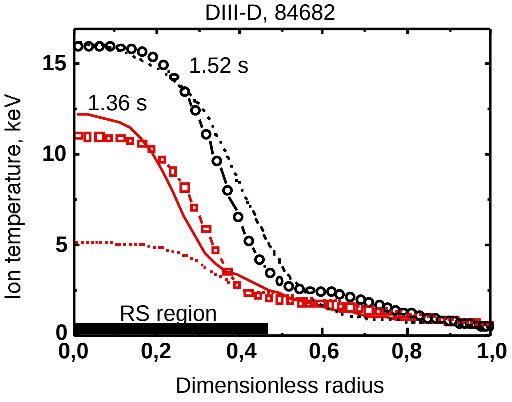
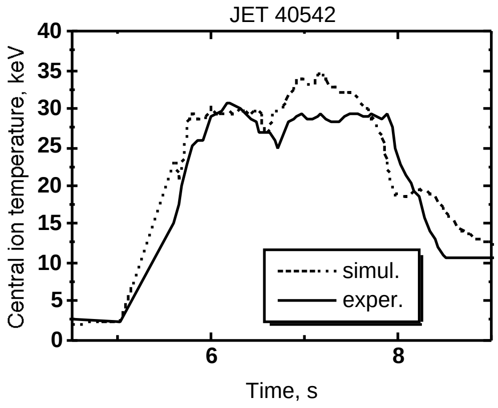


FIG. 1. ERS scenario of TFTR : time evolution of central temperature (a) and evolution of temperature profiles (b, c). The results of simulations are shown here and on other figures by curves with symbols.

FIG.2. Temperature profile evolution with a power rise in a DIII-D NCS plasma. Dotted line shows the calculated temperature profile without ExB rotation shear at 1.36 s.



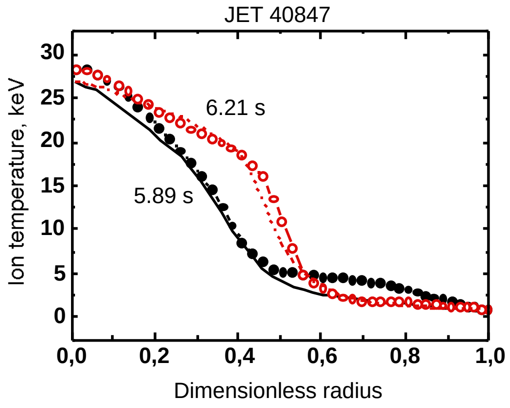


FIG. 3. Evolution of the central temperature in a JET OS plasma combined with an ELMy H-mode.

FIG. 4. Dynamics of the ITB in an OS JET plasma.