THERMAL ION DIFFUSION AND EVOLUTION OF THE INTERNAL TRANSPORT BARRIER IN REVERSED SHEAR PLASMAS

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1. Introduction

High performance phases of tokamak operation are characterized by transport barriers (TB) which result from the reduction of anomalous transport due to shear effects. In this work the effects of the magnetic and electric shear on the formation and evolution of thermal ion internal TB are studied through predictive simulations of thermal ion balance in different magnetic configurations. As an example, we analyze TFTR discharges with reversed shear (RS) and enhanced reversed shear (ERS) configurations taken from the ITER data base [1], and JET discharges in the optimized magnetic shear (OS) configuration [2]. As a result, a shear correction to the anomalous L-mode thermal ion diffusivity based on simple theoretical arguments is proposed.

2. Experimental scenarios of the high performance discharges

Experimental scenarios with various combinations of magnetic and rotation shear have been selected to analyze the thermal transport. Thus, the discharges of TFTR include: a) a prelude phase with moderate neutral beam (NBI) power heating (7 MW) where the RS magnetic configuration has been accompanied by a low toroidal and diamagnetic rotation shear; b) a high power heating phase (28 MW) with an enhanced reversed shear (ERS) configuration; c) a "postlude" phase (14 MW) with a scan in the co-injected NB power and therefore, in the toroidal rotation; d) a second transition to the improved confinement in RS plasmas correlated with the large increase of the shear of toroidal rotation. This second improvement has been observed after the loss of the improved confinement with the co-rotated NBI in the "postlude" phase.

These discharges are described and analyzed in Ref. [1]. In what follows, we propose a simple empirical model for the ion diffusivity, which allows a consistent reproduction of the dynamics of thermal ion transport in such a scenario. This model is then applied to the OS plasmas of JET [2] where the improved plasma confinement has been obtained in another magnetic configuration (with a nearly zero or slightly positive magnetic shear), and it can be attributed mainly to the effect of the rotation shear.

3. Model for the thermal ion diffusivity with shear corrections

A model for the thermal diffusivity in a plasma with low magnetic and high electric shear is deduced from the analysis of the TB evolution in the TFTR scenario mentioned above. As a first step, we must define a "transport barrier" and also specify the procedure for determining its location. In our study the following definition of the location of the "transport barrier" is used: "A thermal transport barrier *regarding to a reference confinement regime* is determined at a radial location where the experimental thermal diffusivity decreases below the predictive value which characterizes the transport in this reference regime." Applying this definition, the shear effects are studied in two steps. We start with the L-mode Bohm-like reference model for ion diffusivity, $\chi_{i,L}$, [3] and find the magnetic shear correction by analyzing the RS configuration with a low rotation shear (prelude phase). Then, the L-mode thermal diffusivity with magnetic shear correction is used as a reference model to specify the effect of rotation shear during the high power heating and "postlude" phases. The boundaries of the plasma regions which are described respectively by various reference models resulting from this procedure, are shown in Fig. 1 as a function of time. The experimental thermal diffusivity is well described with the Bohm-like prediction [3] in the outer part of the plasma and it drops below this value inside mid-radius, reaching the neoclassical value [4] in the central region. The inner boundary of the L-mode transport is well correlated with the position of the minimum in the q-profile, r_{min}, during the prelude, high power and "postlude" phases. The reduction of the L-mode transport inside r_{min} is produced by the magnetic shear, s_m, and the electric shear, s_E. The shear correction, $F_{shear}(s_m,s_E)$, is included in the model for χ_i in the following way,

$$\chi_i = \chi_{i,L} F_{shear}(s_m,s_E) + \chi_{i,neo} \qquad (1)$$

(here $\chi_{i,L} = \chi_{Bohm} a(\nabla p/p) q^2$ with all notations from Ref. [3]) and is described below.

a) Magnetic shear effect on the thermal ion transport. Assuming the toroidal mode decoupling as the mechanism which reduces the large-scale Bohm-like transport [5] an heuristic magnetic shear correction can be written as

$$F_{shear}(s_m,s_E=0) = 1/\{1 + \exp[(s_{cr} - s_m q)/s_d]\} \qquad (2)$$

where s_d=0.1q and the "critical shear", s_{cr}, is rather small. In the following simulations we use s_{cr}=0.05 whereas an uncertainty within a factor 2 is possible due to the large error bars in the estimation of the magnetic shear. The term (s_{cr} - s_mq) provides the reduction of the $\chi_{i,L}$-value when the distance between rational surfaces ($1/s_m q$) becomes larger than the normalized width of the most unstable mode which determines the “critical shear”, s_{cr}. At high magnetic shear the modes are toroidally coupled, and $F_{shear}(s_m, s_E=0)=1$. A similar magnetic shear correction for the thermal electron transport has been obtained from the analysis of the electron confinement in the RS configurations on Tore Supra [6].

The simulations of the ion temperature evolution with the magnetic shear correction given above shows a good agreement with experiments in the prelude phase (Fig.2). However, the ion temperature is underestimated at high power and during the "postlude" phases where the rotation shear strongly increases. This gives an indication of the stabilizing effect of rotation shear. Taking now the L-mode transport model with magnetic shear correction as a reference model, the location of the TB is plotted in Fig.1 and separates the region where the stabilization effect is due to the magnetic shear (R1) from the region where it is mainly due to the rotation shear (R2).

b) Effect of the rotation shear on the thermal ion diffusivity. The stabilizing role of the rotation shear on the turbulence was shown both in linear and non-linear theoretical approaches. In the linear theory, the rotation shear affects the growth rate of the modes providing the turbulence suppression when the shearing rate $\partial(E_r/RB_{pol})/\partial R$ is larger then the growth rate of the most unstable mode [7]. In the case of non-linear coupling of the modes the rotation shear acts through the correlation length, which decreases in the sheared flow. The effect of the electric shear, $\nabla(E_r/B_{pol})$, is included in the shear correction as follows:

$$F_{shear}(s_m,s_E) = 1/\{1 + \exp[(s_{cr}\,|1 - f(\nabla E_r/B_{pol})| - s_m q)/s_d]\} \qquad (3)$$

where the radial electric field E_r should be generally determined from the radial momentum balance. As a first step to test this simple empirical approach, the electric shear is estimated with the experimental data only as $f(\nabla(E_r/B_{pol})) = (C_1\nabla V_{tor} + C_2\nabla V_{dia})(a/c)$, where V_{tor} is the measured toroidal rotation, c is the speed of light, a is the minor radius, $V_{dia} = c\nabla p_i/(eZ_i n_i B_{pol})$ and C_1 and C_2 are empirical coefficients, C_1=4.6 10^3 and C_2=510. Such an approach is rough enough since the contribution from the neoclassical poloidal rotation to the radial momentum balance and the difference between the toroidal rotation of the main ions and the measured impurity rotation are partially assumed in the adjusted coefficients. In this approach we rely on the experimental data only attempting to avoid the uncertainty in the estimations of other terms in the radial momentum balance following from the code assumptions. The anomalous poloidal rotation resulting from other effects (Reynolds stress tensor, losses of the edge banana ions, etc.) is important for the L-H transition and makes our model irrelevant for describing the H-mode transport barriers.

It should be mentioned that a reduction of χ_i below the conventional neoclassical transport [4] is required in addition to the decrease of the anomalous transport to reproduce the core temperature evolution during the high power and "postlude" phases (region NC2 in Fig.1). A correction of the neoclassical diffusivity has been obtained from the analysis of the trajectory of barely trapped particles in the gradient region which results in the squeezing of the banana orbit width due to the negative magnetic shear and to the high ∇V_{tor} value, so that $\chi_{i,neo} = \chi_{ban} F_{neo} + \chi_{PS}$, with $F_{neo} = \chi_{ban}/(1 - 0.5 s_m + yH(y) a/V_0)^2$, $y = |\nabla V_{tor}| - 4.1|\nabla V_{Ti}|$, $V_0=1.7*10^{-4}\omega_i \varepsilon a/q$ (here V_{Ti} is the ion thermal velocity and ω_i is the ion gyro-frequency, H(y) is a step function, $\varepsilon = r/R$). This correction can be considered as a first step to identify the relevant neoclassical effects. More accurate estimations of the neoclassical transport in the core are required.

The modelling of TFTR discharge with shear corrections is shown in Fig.2. Our model allows to reproduce the ion temperature evolution including the transition to the second improved confinement phase. The effect of the magnetic shear as quantified by the model, provides the dominant reduction of the anomalous transport in TFTR RS plasmas, whereas the effect of the rotation shear is not quantitatively large, but is important to understand the extension of the TB outside. The strongest effect in the core is the reduction of the neoclassical transport. In contrast, the rotation shear is the main stabilizing term in the OS plasmas of JET where magnetic shear is not strongly reversed (the simulations of the typical discharge is shown in Fig. 3). The causal role of the rotation shear is illustrated also by the decoupling of the TB location and the position of r_{min} observed at JET [2] and also during the second improvement phase in the TFTR discharge (Fig.1a). The different efficiency of transport reduction by the rotation shear in RS and OS plasmas could result from the different state of the turbulence. The toroidal modes are decoupled in RS plasmas, and if the local modes do not produce an important contribution to the quasilinear heat flux, their further stabilization by rotation shear does not affect much the transport. In contrast, the stabilization of the coupled toroidal modes in OS plasmas by the rotation shear reduces strongly the large-scale L-mode transport.

It should be mentioned that in contrast to Ref. [8], the proposed shear correction includes both the heat and momentum bifurcation in explicit form. The stabilizing effect of the shear of toroidal rotation is important and provides a better simulations of the ion temperature dynamics. The correlation between the TB evolution and the toroidal rotation is illustrated by the comparison of Fig.1a and 1b. The TB location does not change in the "postlude" phase with balanced NBI (Fig.1b) until the peaked profile of toroidal rotation with a large shear is maintained. In contrast, the TB moves outside with the co-rotated NBI (Fig.1a) where the profile of toroidal rotation broadens with the simultaneous decrease of its shear in the region of dominant anomalous transport before the degradation of confinement.

4. Conclusions

The shear effects on the ion heat transport in various magnetic configurations have been studied, and a shear correction for the L-mode thermal ion diffusivity has been proposed. The characteristics of the model are: (a) combination of the momentum and heat bifurcation; (b) threshold character of the 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 analysis of the high performance phases in TFTR and JET discharges illustrates: (a) the importance of both magnetic shear and rotation shear suppression of anomalous transport; (b) the control of the TB evolution by rotation shear when the magnetic shear is inefficient; (c) the favourable effect of the combination of magnetic and rotation shear on the reduction of the ion diffusivity below the conventional neoclassical level. The importance of the momentum bifurcation displayed through the stabilizing effect of the toroidal rotation shear puts forward the problem of control of the rotation in future advanced scenarios.

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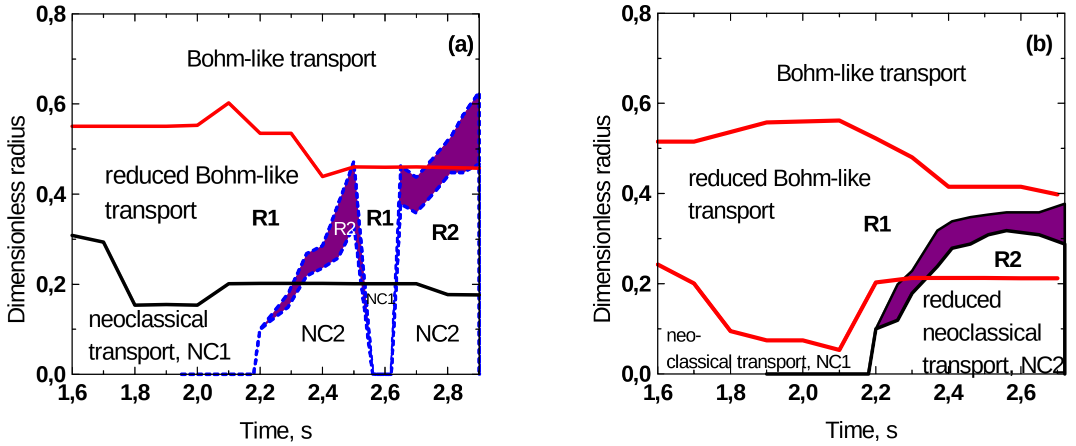

Fig. 1. Evolution of the regions with different kinds of transport during RS->ERS->RS phases in TFTR: Bohm-like transport, reduced Bohm-like transport due to magnetic shear effect (R1), reduced Bohm-like transport due to rotation shear effect (R2), conventional neoclassical transport (NC1), reduced neoclassical transport (NC2). Reference model to define the TB is the Bohm-like model with magnetic shear correction. The shaded region indicates the 10% deviation from the reference model. Shot 94599 with co-injected NBI in postlude phase (a) and shot 94603 with balanced injection in postlude phase (b).

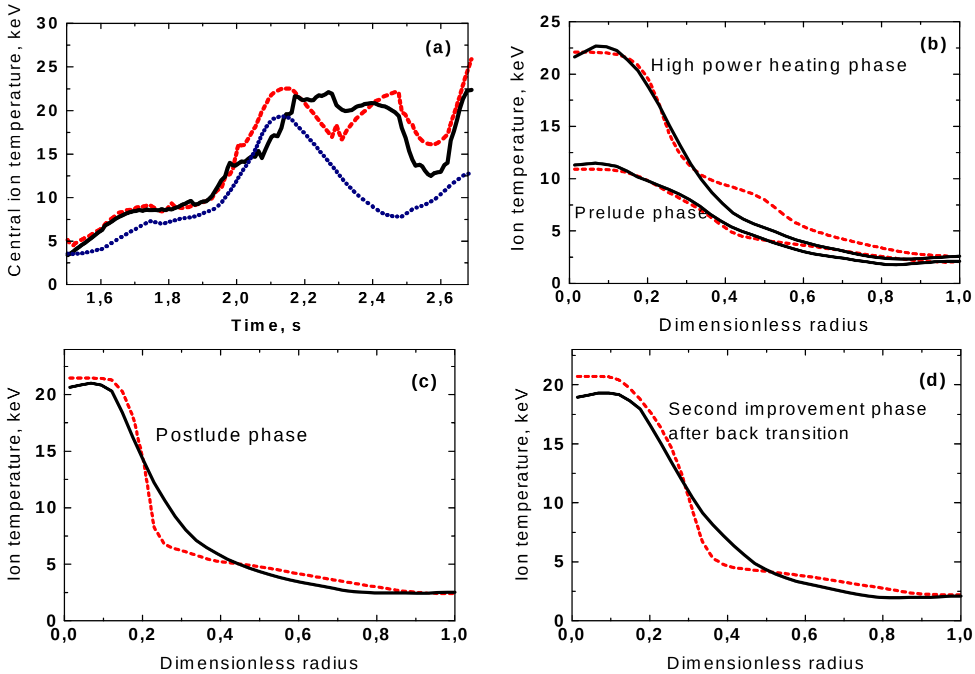

Fig. 2. Central temperature evolution (a) and temperature profiles at different phases for shot 94599 of TFTR. Solid line corresponds to the experimental temperature and dashed line indicates the calculated one with shear correction. Dotted line in (a) shows the calculated temperature with magnetic shear correction only.

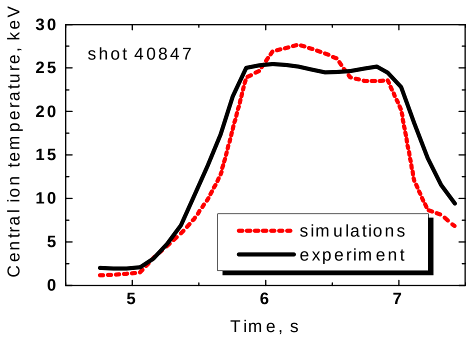

Fig. 3. Modelling of central temperature evolution in OS scenario of JET.