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Ion heat transport in JET and ASDEX Upgrade tokamak plasmas

R. C. Wolf[1], Y. Baranov[2], M. de Baar[3], C. Challis[2], W. Dorland[4], X. Garbet[5], C. Giroud[2], N. C. Hawkes[2], E. Joffrin[5], D. Mazon[5], A. G. Peeters[1], K.-D. Zastrow[2], and contributors to the EFDA-JET workprogramme

[1] *Max-Planck-Institut für Plasmaphysik, EURATOM-Assoziation, D-85748 Garching, Germany*
[2] *UKAEA/EURATOM Fusion Association, Culham Science Centre, Abingdon, OX14 3DB, UK*
[3] *FOM Instituut voor Plasmafysica 'Rijnhuizen', Associatie EURATOM-FOM, Trilateral Euregio Cluster, 3430 BE Nieuwegein, The Netherlands*
[4] *Imperial College of Science, Technology and Medicine, London SW7 2BW, UK*
[5] *Association EURATOM-CEA sur la fusion, CEA Cadarache, F-13108 S[t] Paul lez Durance, France*

Introduction

In regions of tokamak plasmas, which are dominated by anomalous transport, the normalised temperature gradient, R/L_T (R: major radius, L_T: gradient length), changes little over a wide range of plasma parameters. This so-called profile stiffness is observed for both the electron [1] and the ion heat transport [2,3]. Internal transport barriers (ITBs) can be characterised by an increase of R/L_T above the critical value determined by the turbulent transport processes [2].

L- and H-mode plasmas

Transport theory predicts a dependence of the critical temperature gradient, $R/L_T\big|_{crit}$, on plasma quantities, such as T_e/T_i, pressure gradient, rotation velocities and magnetic shear [4]. Accordingly, some change of the gradient length is expected even for stiff temperature profiles, if only the parameter range is large enough.

The R/L_{Ti} value for JET L- and H-mode plasmas is derived from

$$T_i(\rho_1) = T_i(\rho_2)\cdot e^{\varepsilon\Delta\rho\frac{R}{L_{Ti}}+c_1\left(\frac{T_i}{T_e}-1\right)+c_2\frac{\omega_{E\times B}}{\gamma_{ITG}}},$$

where $T_i(\rho_1)$ and $T_i(\rho_2)$ are the ion temperatures at $\rho_1 = 0.2$ and $\rho_2 = 0.6$ (or 0.8) respectively, $\varepsilon = a/R$ is the inverse aspect ratio, $\omega_{E\times B}$ the $E\times B$ shearing rate and γ_{ITG} the maximum linear ion temperature gradient (ITG) mode growth rate (c_1 and c_2 are fit coefficients).

In the subsequent analysis $\omega_{E\times B}$ is assumed to be determined by the toroidal rotational shear $\partial v_\phi/\partial r$ only and γ_{ITG} is approximated by $\gamma_{ITG} = v_{i,th}/\sqrt{RL_{Ti}}$, where $v_{i,th}$ is the ion thermal velocity.

The R/L_{Ti} values for 20 JET discharges, inferred from a fit to $T_i(\rho_1) = f(T_i(\rho_2))$ without considering changes of T_e/T_i or $\partial v_\phi/\partial r$, are shown in Fig. 1. The underlying T_i data include the L-mode phase at the beginning of the auxiliary heating phase with neutral beam injection (NBI) and reach to the maximum T_i achieved in the respective discharge. Fig. 2 compares $T_i(\rho_1) = f(T_i(\rho_2))$ for all the 20 discharges with and without considering the effect of T_e/T_i or $\partial v_\phi/\partial r$ on the central ion temperature. As already hinted in Fig. 1, the trend towards higher R/L_{Ti} for increasing T_i suggests a dependence on T_e/T_i or $\partial v_\phi/\partial r$. Without this correction the fit to the data yields $R/L_{Ti} = 6.83$, but does not describe the data at high T_i very well. With correction, in contrast, the fit improves, representing R/L_{Ti} by $5.34 + 0.1/(\varepsilon \cdot \Delta\rho)(T_i/T_e - 1) + 2/(\varepsilon \cdot \Delta\rho)\omega_{E\times B}/\gamma_{ITG}$. It is worth noting that the effect of T_e/T_i and $\partial v_\phi/\partial r$ cannot be easily distinguished, as in plasmas dominated by unidirectional NBI heating, like in JET, raising T_i above T_e also means increasing the toroidal rotation.

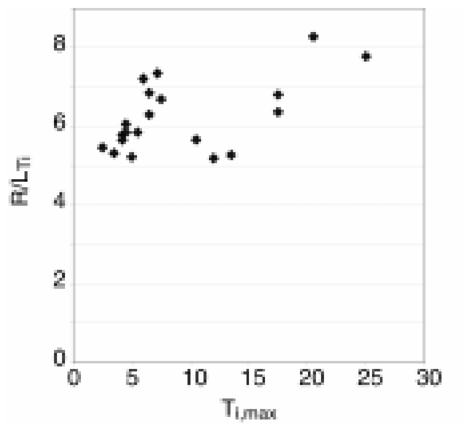

Fig. 1: R/L_{Ti} versus maximum T_i for 20 JET discharges. For each discharge R/L_{Ti} has been determined form the T_i data ranging from L-mode to the maximum temperature during H-mode.

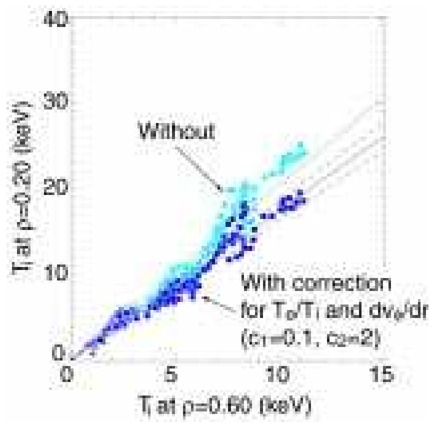

Fig. 2: $T_i(\rho_1)$ as a function of $T_i(\rho_2)$ for all the 20 discharges also underlying Fig. 1. Correcting for effects of T_e/T_i and $\partial v_\phi/\partial r$ on R/L_{Ti} achieves a better fit at high T_i.

Since there are indications that also density gradients may raise R/L_{Ti}, for the selection of the data in Fig. 2, large R/L_n have been excluded. In particular in ELM free H-mode plasmas [5], which reach central ion temperatures in excess of 20keV, deviations towards higher R/L_{Ti} are observed during the build-up of the plasma pressure, which can be explained to some extent by stronger density gradients.

In ASDEX Upgrade L- and H-mode discharges, reaching central ion temperatures up to 10keV, the R/L_{Ti} lies in the range of 5 to 5.5 [6], which corresponds to the JET values in that temperature range (see Fig. 1).

Characterisation of internal transport barriers

Here, the JET ITB scenarios are classified into three types: (a) the optimised shear (OS) regime, corresponding to target *q*-profiles with low but positive magnetic shear [7], (b) the reversed shear (RS) regime with a region of negative magnetic shear in the plasma centre [8] and (c) the pellet enhanced performance (PEP) mode, where the central shear reversal is produced by the combination of pellet injection and strong central heating [9]. In Fig. 3 $T_i(\rho_1) = f(T_i(\rho_2))$ is shown for the three ITB scenarios together with the L- and H-mode reference, corresponding to $R/L_{Ti} = 5.34$. At low heating power and low T_i, before the formation of the ITB or after its collapse, R/L_{Ti} agrees with the reference value of the stiff profiles. When an ITB is formed, this value is exceeded considerably, reaching R/L_{Ti} up to 18. It is also evident that in this picture, where an ITB is characterised by an increase of R/L_{Ti} above a critical value, the PEP mode qualifies as an ITB also for ions. In the ITB plasmas the increase of the pedestal temperature, due to the transition of the plasma edge from L- to H-mode or type-III to type-I ELM confinement, is, for the cases investigated, never accompanied by a rise of the central ion temperature. This is most visible in the OS cases, where the increase of $T_i(\rho_2 = 0.6)$ results in a reduction of R/L_{Ti} to almost the level of the stiff temperature profiles.

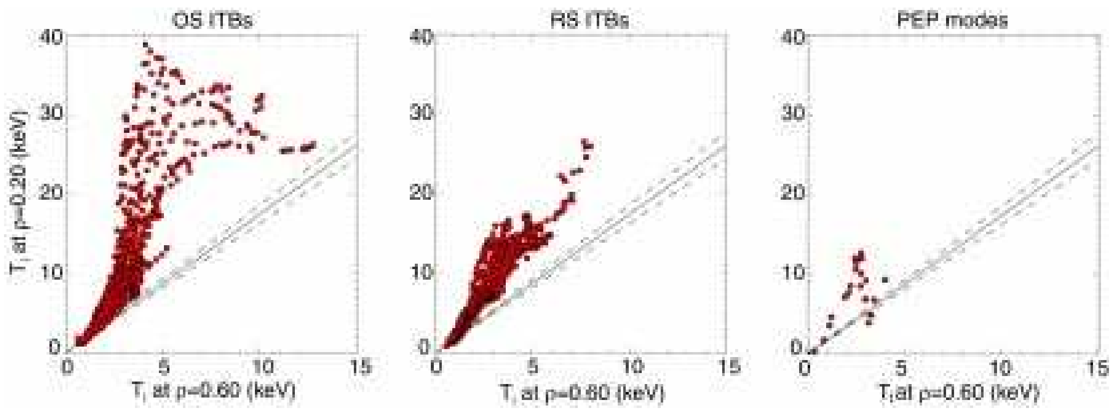

Fig. 3: $T_i(\rho_1) = f(T_i(\rho_2))$ *for three types of ITB discharges, OS (23 discharge)s, RS ITBs (17 discharges) and PEP modes (3 discharges). The straight line corresponds to the fit of the L- and H-mode reference cases shown in Fig. 2 (*$R/L_{Ti} = 5.34$*).*

Effect of magnetic shear

The main candidates for causing a reduction of transport by ITG or trapped electron modes in ITB plasmas are magnetic and $E \times B$ shear, but also the effects of T_e / T_i, Shafranov shift and density gradients on turbulence.

While in some cases with monotonic *q*-profiles the temperature profiles evolve like stiff profiles before making the confinement transition, the plasmas with reversed magnetic shear immediately depart from the stiff temperature profiles once auxiliary heating power is applied in both JET and ASDEX Upgrade. This different behaviour is exemplified in Fig. 4. Although the magnetic shear is positive in pulse 51860 and negative in 53537 at the ITB location, the actual values are very close to zero in both cases (+0.01 and -0.05, respectively), which makes it difficult to attribute the difference to the magnetic shear. A comparison with turbulence simulations using the gyro-fluid code TRB [10] shows that the initial difference between the two discharges could be attributed to the effect of a magnetic shear reduction, if in the positive shear case (51860) the experimental magnetic shear at the ITB was larger. On the other hand, calculations of the critical R / L_{Ti} by the gyro-kinetic turbulence code GS2 [11] only can reproduce the effect, if in the negative shear case (53537) the experimental magnetic shear was lower by about a factor of 10.

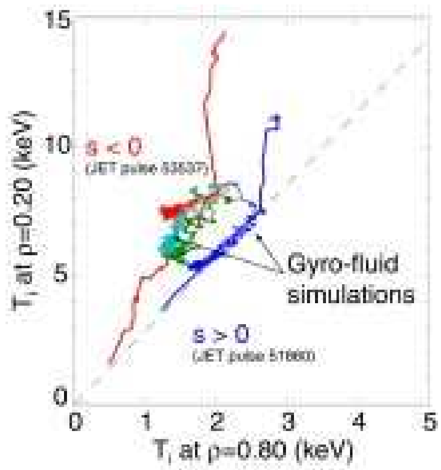

Fig. 4: Comparison of JET OS (s>0) and RS (s<0) discharges. Only in the first the initial temperature evolution follows that of stiff profiles. In the second an immediate reduction of R / L_{Ti} is seen. Also shown are gyro-fluid simulations, which in principle could produce such an effect. The blue line corresponds to L-mode confinement (which uses a higher than experimental value), while the red, cyan and green lines represent ITB cases with different toroidal momentum transfer.

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