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Numerical Modelling of Ripple Induced Transport

T. Johnson[1], V. Hynönen[2], V. Parail[3], I. Jenkins[3], T. Kiviniemi[2],
T. Kurki-Suonio[2], J. Lönnroth[2], A. Salmi[2], and JET EFDA contributors*

[1]*Fusion Plasma Physics, Association EURATOM-VR, School of Electrical Engineering, KTH, Stockholm;* [2]*Association EURATOM-Tekes, Helsinki University of Technology, P.O. Box 4100, FI-02015 TKK, Finland;* [3]*EURATOM/UKAEA Fusion Association, Culham Science Centre, Abingdon, OXON OX14 3DB, United Kingdom.*

Abstract

The ASCOT code has been used to analyse transport and calculate the thermal conductivity in plasmas with toroidal field ripple. The scaling of the thermal conductivity with dimensionless plasma parameters is similar to transport in the ripple plateau regime [1]. The ripple in machines with toroidal field coils similar to those in JET and JT-60U are quite different; while the maximum ripple is larger with 16 JET coils, the ripple at the X-point is larger with the JT-60U coils. The results are that the heat conductivity is similar in the two plasmas, while the particle losses are higher with the JT-60U coils.

Introduction

A finite number of toroidal field (TF) coils generates magnetic fields with a toroidally periodic ripple. Recent experiments on JET and JT-60U have generated renewed interest in the transport induced by ripple [2]. In JET it was shown that enhancing the TF ripple in an L-mode plasma can trigger an early L-H transition, while at too high ripple the plasma returned to L-mode [3]. In dimensionless identity pedestal experiments at JET and JT-60U a differences in the pedestal performance and ELM frequency was observed [4]. The difference may be explained by the larger ripple in JT-60U. Theoretically TF ripple activates two transport mechanisms [1]. Firstly, the turning points of a trapped particles are displaced by the ripple. When successive displacements are not correlated this transport is known as “ripple plateau”. Secondly, ripple can generate magnetic wells in between the TF coils. If a particle is trapped in such a well it will experience an uncompensated vertical drift. Both processes are mainly affecting the plasma edge, as the ripple amplitude decreases exponentially with the distance to the TF coils. Thus, when operating in H-mode with suppressed anomalous transport in the plasma edge, then ripple could provide significant transport which could affect the plasma performance [2].

The numerical model

Numerical simulations of ripple transport have been performed with the guiding centre following Monte Carlo code ASCOT [5, 6]. In the simulations a set of test particles with a

*appendix of J.Pamela et al., Fusion Energy 2004 (Proc. 20th Int. Conf.,Vilamoura, 2004), IAEA, Vienna (2004).

Maxwellian velocity distribution has been initialised on a single flux surface. As time evolves the variance $V(t,v)$ of the radial distribution of test particles with velocity v has been evaluated. As the radial transport is approximately diffusive the variance grows at a constant rate, and the thermal conductivity can be calculated as

$$\chi = \int d^3v\, \frac{1}{2}\dot{V} \left(\frac{mv^2}{2T} - \frac{5}{2} \right)^2 f_M(v) \tag{1}$$

where T is the temperature and f_M is the Maxwellian distribution function.

For this work plasma parameters from the JET pulse #60856, from the dimensionless identity pedestal experiments at JET and JT-60U [4], has been used. The main plasma parameters near the plasma edge are $n_e = 10^{19}$ m^{-3}, $Z_{eff} = 2$, $T_i = 1$ keV, $B_0 = 2.9$ T and $I_p = 1.2$ MA. Since the TF ripple was very weak in this pulse, the currents in the TF coils have artificially been altered in the simulations to generate an $N = 16$ ripple. Three different configurations have been used; operation with 16 TF coils, with 32 TF coils and with the ratio $1/2$ between the currents in neighbouring coils, here called “1/2 ripple”. The maximum ripple amplitudes $\delta \equiv \tilde{B}/B$ in the three configuration are 3.85 % with 16 coils, 0.12 % with 32 coils and 1.28 % with “1/2 ripple”. The transport with 32 coils has been shown to agree with axisymmetrix neo-classical theory, i.e. the ripple transport is negligible compared to the neo-classical transport. This configuration will therefore be used as a reference for the ripple enhancement in the other configurations. In addition to these three cases, the JET ripple-map $\delta(R,Z)$ was replaced by one calculated from a coil system similar to that in JT-60U[1]. This ripple-map has a maximum ripple 1.3 % in the outboard midplane.

Results

Fig. 1 shows the radial profiles for the ion transport in the four configurations. Using the 32 coil configuration as a reference representing the neo-classical transport, it is clear that for the “1/2 ripple” case the ripple transport is relatively weak, while for both the 16 coils and with JT-60U coils the ripple contribution is comparable in magnitude to the neo-classical transport.

Analytical models of the transport of heat by thermal particles are in general restricted by expansions in “small parameters”, e.g. $NB\delta/B_\theta \ll 1$ [1], that for JET parameters tend to be small only when the effects of ripple are negligible. The same theory predicts that the thermal conductivity is proportional to $(NB\delta/B_\theta)^\sigma$, where $\sigma \geq 2$ for all transport regimes. This would imply that the transport would be very localised to the plasma edge, where the ripple decreases exponentially with the distance to the TF coils. In contrast to these predictions the ASCOT results in Fig. 1 show that the thermal conductivity is roughly independent of the radial location for $0.9 < \rho < 0.98$.

[1]This ripple-map corresponds to the ripple in JT-60U without the ferritic inserts [8].

The scaling of the thermal conductivity with the dimensionless plasma parameters $\nu^* \propto 1/(n_e Z_{eff})$, $\rho^* \propto 1/B_0$ and q is shown in Fig. 2. In this figure the thermal conductivity is normalised to that obtained with 32 coils, i.e. to the neo-classical level. The three figures suggests that the ripple induced thermal conductivity scales similarly to the neo-classical conductivity, with respect to ρ^* and q, but not with respect to ν^*. This scaling is what one expects from ripple plateau transport [1], while it strongly disagrees with the scaling for transport due to trapping in ripple wells. However, the ripple plateau transport also suggests that the thermal conductivity is proportional to δ^2, i.e. the conductivity should vary by a factor ~ 2 for $0.9 < \rho < 0.98$, which is not in agreement with the radial profiles in Fig. 1.

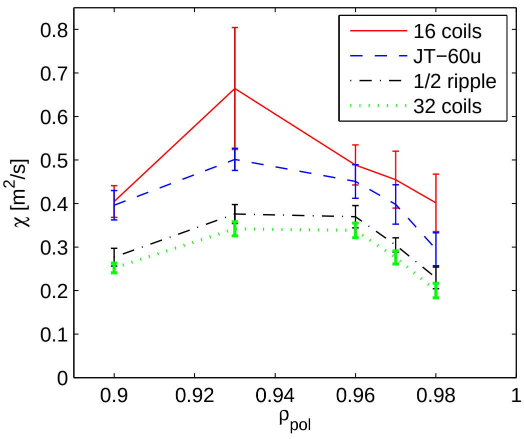

Figure 1: Radial profile of the transport with different levels of ripple.

Fig. 2 shows that the transport with JT-60U ripple map is similar to that with 16 coils in JET, despite the maximum ripple being 3 times higher in the JET configuration. A likely explanation for this difference was proposed in [2], in which it was suggested that ripple near the X-point, which is negligible in JET but not in JT-60U, may cause transport. Although the ripple at the JT-60U X-point is smaller than at the outboard midplane, the guiding centre drift near the X-point is almost perpendicular to the flux surface, allowing higher transport at lower ripple amplitude.

Another significant difference between the transport with the JET and the JT-60U ripple-maps is found in the losses of test particles to plasma facing components. In Fig. 3 the particle losses in the JT-60U configuration is shown to be larger than in JET with 16 coils, in particular at lower collisionality. These particle losses are not driven by a diffusive process

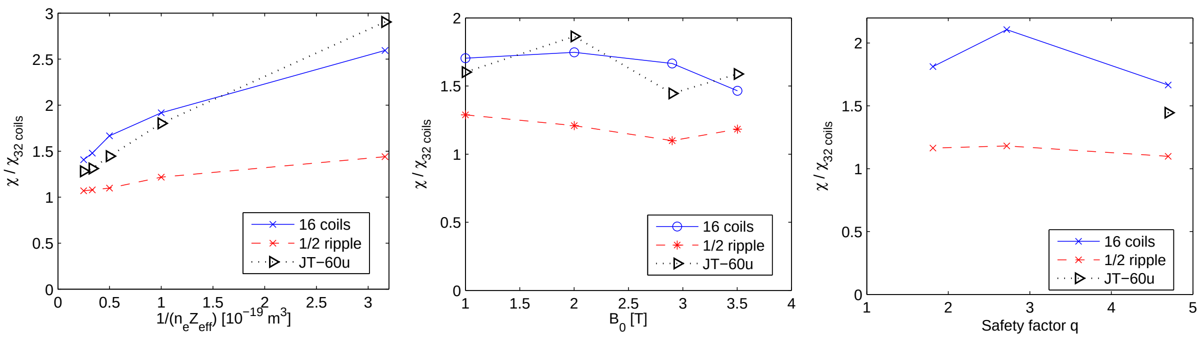

Figure 2: The ratio of collisional heat conductivity with and without ripple, **a)** versus $1/(n_e Z_{eff})$, with $B_0 = 2.9$ T and $q = 4.7$, **b)** versus B_0, with $1/(n_e Z_{eff}) = 5 \times 10^{-20}$ and $q = 4.7$, and **c)** versus q, with $1/(n_e Z_{eff}) = 5 \times 10^{-20}$ and $B_0 = 2.9$ T.

since the diffusion coefficients $\int d^3v\, f_M(v)\dot{V}(v,t)/2$ are similar for the two cases. The detailed nature of the losses is still to be examined, but it has been shown that the lost particles go to the divertor plates, and not to the outboard vessel wall. In fact the losses to the outboard wall are significantly larger in JET with 16 coils. Thus this result is consistent with enhanced transport near the X-point in the JT-60U configuration.

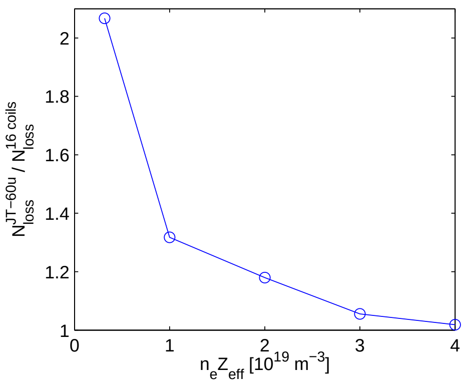

Figure 3: The ratio of particle losses in the JT-60U and JET 16 coil configurations.

Conclusions

The ASCOT code has been used to study the transport in plasmas with toroidal field ripple. It has been shown that when JET is operating with 16 toroidal field coils the thermal conductivity in the plasma edge region is of the same magnitude as the neo-classical transport. The scaling of the ripple transport with the dimensionless parameters ρ^*, ν^* and q is similar to that obtained from analytical theory of ripple-plateau transport, while it strongly disagrees with the scaling for transport due to trapping in ripple wells. However, the ripple-plateau theory also predicts that the transport coefficients should vary exponentially in the edge region, which does not agree with the flat profiles obtained from the simulations. When changing the ripple-map from the JET configuration with 16 coils to a coil system like that in JT-60U, the maximum ripple is reduced by a factor 3 and the ripple at the X-point is increased to a non-negligible level. The result is that the thermal conductivity is unchanged, while the particle losses are increased through a non-diffusive proccess. These difference may be caused by diffusive and non-diffusive ripple transport near X-point in the JT-60U configuration.

Transport coefficients calculated with ASCOT have been used in fluid plasma transport modelling with the JETTO code. The results of this work can be found in [2, 7].

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