Effect of Ripple-Induced Ion Thermal Transport on H-mode Performance

V. Parail[1], T. Johnson[2], T. Kiviniemi[3], J. Lonnroth[3], D.F. Howell[1], A. Loarte[4], G. Saibene[4], P. de Vries[1], T. Hatae[5], Y. Kamada[5], S. Konovalov [5], N. Oyama[5], K. Shinohara[5], K. Tobita[5], H. Urano[5] and JET EFDA contributors[a].

[1] *EURATOM/UKAEA Fusion Association, Culham Science Centre, Abingdon, Oxon OX14 3DB, UK;*
[2] *Association EURATOM-VR, Alfven Laboratory, Royal Institute of Technology, 10044 Stockholm, Sweden;*
[3] *Association EURATOM-Tekes, Helsinki University of Technology, P.O. Box 2200, 02015 HUT, Finland;*
[4] *EFDA Close Support Unit, c/o Max Planck Institut fur Plasmaphysik, Boltzmannstrasse 2, 85748 Garching, Germany;* [5] *Naka Fusion Research Establishment, JAERI, 801-1, Mukoyama, Naka-city, Ibaraki, 301-0193, Japan.*

Introduction

The effects of ripple-induced losses on the performance of ELMy H-mode plasmas have been found in a number of experiments [1,2]. A noticeable difference in plasma performance, plasma rotation, ELM frequency and amplitude between JET (with ripple amplitude δ~0.1%) and JT-60U (with δ~1%) was found in otherwise identical discharges [1]. JT-60U plasma generally has somewhat lower edge pressure with more frequent and smaller ELMs. It was previously shown in JET experiments with enhanced ripple [2] that a gradual increase in the ripple amplitude first leads to a modest improvement in plasma confinement, which is followed by the degradation of edge pedestal and further transition to the L-mode regime, if δ increases above a certain critical level. Marginally better confinement has been recently reported by the DIII-D Team [3] in experiments where edge transport was enhanced by an externally applied magnetic perturbation. The relative high impact of ripple or stochastisity induced transport on H-mode plasma is attributed to its reliance on the edge transport barrier as the main cause of improved confinement. Since transport in a narrow layer at the edge of H-mode plasma is suppressed to a very low, neo-classical level, the effects of any additional edge transport can be very discernible. This paper presents the results of the comprehensive numerical modelling of the ripple losses of thermal ions in JET and JT-60U magnetic configuration as well as dynamics of ELMy H-mode JET plasma relevant to a JET/JT-60U similarity experiment [1].

Ripple losses of thermal ions

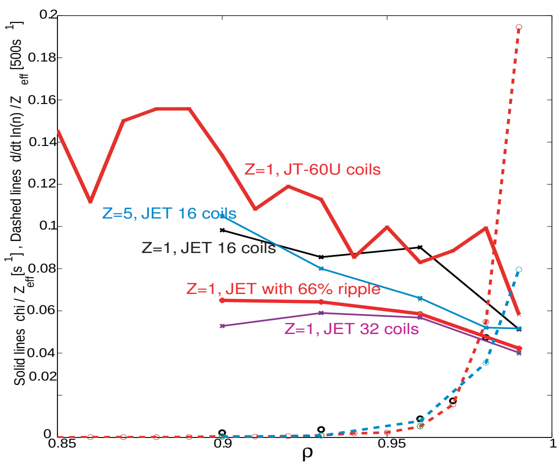

Figure 1. Collisional transport of thermal ions in the JET shot #60856 for a series of JET and JT-60U magnetic coils configurations computed by ASCOT: solid lines- thermal diffusivities, dashed lines- convective losses due to particle escape. Note the same colour code is used for solid and dashed lines.

The orbit following Monte Carlo code ASCOT was used to study the effect of toroidal ripple on the transport of thermal ions in JET and JT-60U magnetic configurations. Since JET has 32 toroidal field coils with a unique capability to change the ripple amplitude by varying the current in every second coil from zero to maximum, we studied the dependence of ripple induced transport on ripple amplitude as well as on plasma collisionality [4]. Two different techniques were used. The first, traditional method follows the drift orbits of test ions with a Maxwellian distribution, seeded in the whole plasma volume in accordance with selected plasma parameters. This method allows the

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

evaluation of the total level of particle, heat and momentum losses across the separatrix as well as poloidal and toroidal distribution of these losses. The main result of this study is presented in [4]. The second method uses ion seeding on one specific magnetic surface and allows the propagation of the heat and particle pulse across the magnetic field in the presence of toroidal ripple to be studied. Local heat and particle transport coefficients are deduced from such simulations and technique). Figure 1 shows a characteristic result of this study, where ion thermal transport coefficients are plotted as a function of a normalised toroidal flux. The same background density, temperature and current profiles were used in the simulation but three different levels of magnetic ripple were assumed for JET TF coils geometry and one for JT-60U TF coils geometry. First of all one can conclude that by increasing the ripple amplitude the ion heat transport can significantly exceed the level of neo-classical transport. It is also seen that the same level of magnetic ripple at the midplane increases transport much less for the JET magnetic configurations than for the JT-60U-like case. This difference comes from the fact that JT-60U uses circular coils, which produce much stronger ripple near the x-point than the D-shaped JET coils (see Figure 2, which shows a contour plot of magnetic well for two system of TF coils). ASCOT simulations also reveal that, depending on plasma collisionality, thermal ions can have both diffusive and convective losses. Diffusive losses are mainly associated with the ripple-banana and stochastic banana diffusion [5], which give practically uniform toroidal distribution of lost particles and exhibit a wide region of enhanced transport, extending deep inside plasma core. On the other hand convective losses are mainly attributed to a direct escape of toroidally trapped particles due to a vertical drift. They are mainly present in low collisionality plasmas and are more visible in the JT-60U configuration because of the stronger ripple near the x-point, where the trajectory of an ion escaping due to vertical drift is much shorter than the trajectory of an ion escaping from the outer midplane. These losses might play an important role explaining the difference between JET and JT-60U results.

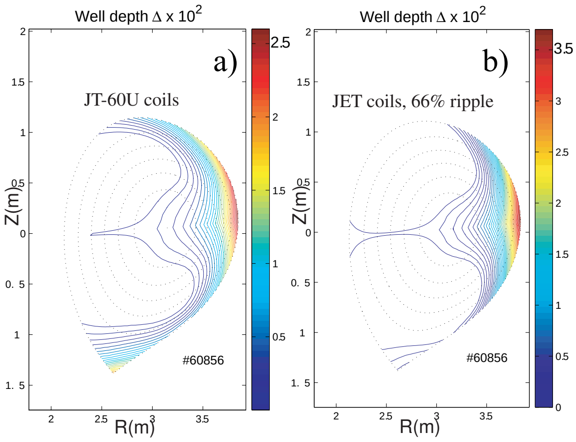

Figure 2. Map of magnetic ripple well for: a) JT-60U coils configuration; b) JET configuration with 66% of maximum ripple (which gives JET ripple equal to JT-60U ripple at the outer midplane).

Predictive transport modelling.

The results of ASCOT simulation have been used as an input into the predictive transport code JETTO, to simulate the dynamics of the ELMy H-mode JET plasmas in the presence of finite ripple losses. Bohm/gyroBohm model for anomalous transport was used together with the neo-classical transport, which plays a dominant role within the edge transport barrier (ETB). A previously discussed model for ELMs was used [6], which triggers ELM if the edge pressure gradient exceeds the critical level needed to destabilise ballooning or peeling modes. A simple analytical approximation for ripple-induced diffusive transport [5] was used, and its amplitude was adjusted using results of ASCOT simulations. Ripple amplitude scans show that this additional transport can have an impact on the severity of ELMs and overall plasma confinement. We first assume that ripple-induced transport is very edge-localised, so that an increase of ion transport above neo-classical level is confined well within the ETB, close to the separatrix (see Figure 3). This additional transport, in spite of being quite small with respect to anomalous transport inside ETB, leads to a significant increase in

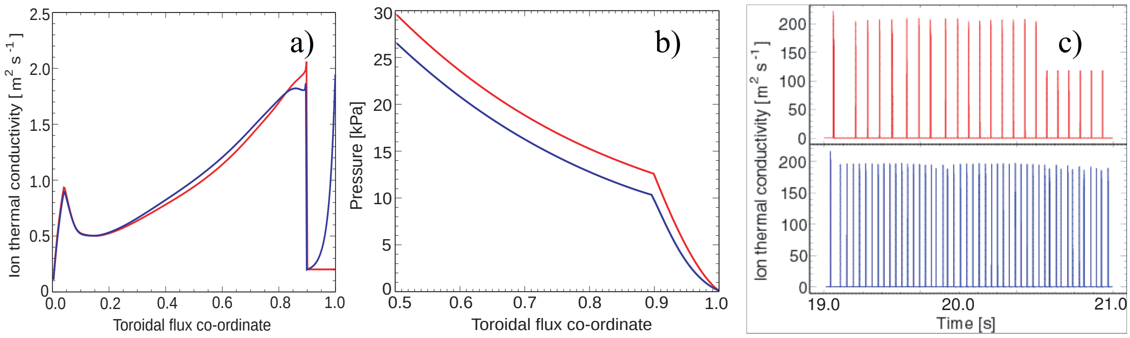

Figure 3. Narrow ripple: a) Ion thermal conductivity with (blue) and without ripple (red); b) Edge plasma pressure just before ELM and c) ELM frequency in case of ripple on (blue) and ripple off (red).

ELM frequency, whereby the energy and particle losses per ELM decrease. This is accompanied by a visible reduction in energy content. This mechanism may prove to be an important tool for ELM mitigation and may provide an explanation to the difference between JET and JT-60U observed in similarity experiment. It is important to note though that, according to our ASCOT code results, the radial extent of the diffusive ripple-induced transport region is wider than the ETB width. However, we should also take into account convective ripple losses due to direct escape of locally trapped ions and those are very edge-localised. To take these convective losses into account we introduce a very simple ad hoc model for convective ion losses in τ-approximation: $\frac{\partial n T_i}{\partial t} = P + divq - \frac{nT_i}{\tau_{ripple}}$, where $q = -\chi_i n_i \nabla T_i$ being the diffusive heat flux and τ_{ripple} being the characteristic edge confinement time, which decreases rapidly towards the separatrix due to convective ripple losses, see Figure 4). The result of predictive transport modelling (shown on Figure 4) shows that convective transport might be a very effective tool to deplete the edge pedestal. Although convective transport does not eliminate ELMs, it reduces ELM amplitude and increases ELM frequency. This trend is accompanied by a noticeable degradation of plasma confinement, which initially comes from the flattening of the ion temperature near the separatrix due to highly localised ripple losses. Since maximum pressure gradient is still limited by ballooning stability it effectively reduces pressure on the top of ETB. This reduction spreads all over the plasma core due to the stiffness of anomalous transport.

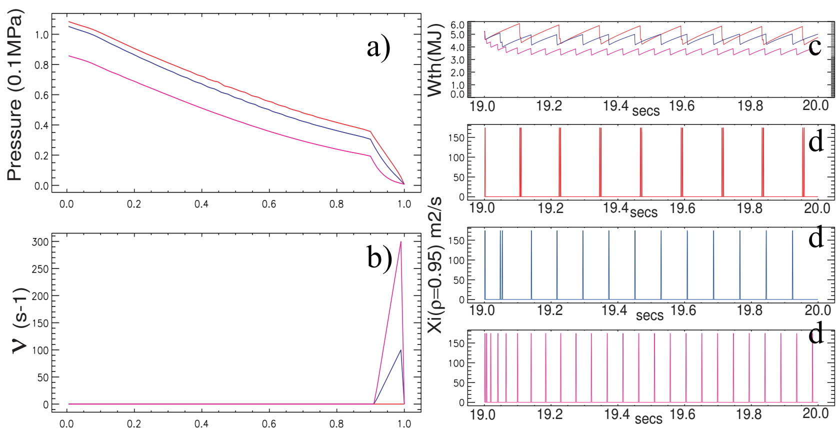

Figure 4. Predictive modelling of JET plasma with edge-localised convective ripple losses. a) plasma pressure just before ELM for three different level of convective losses (red-without losses, blue- with moderate edge losses and pink-maximum losses). b) amplitude of convective losses; c) energy content and ELM frequency for three level of convective losses, d) ELM frequency.

An interesting result was obtained when we assume wide diffusive ripple losses in transport equation (in accordance with ASCOT prediction). It comes out that wider ripple localisation leads, quite unexpectedly, to a reduced ELM frequency and somewhat improved overall confinement (see Figure 5). The explanation to this effect comes from the recognition that

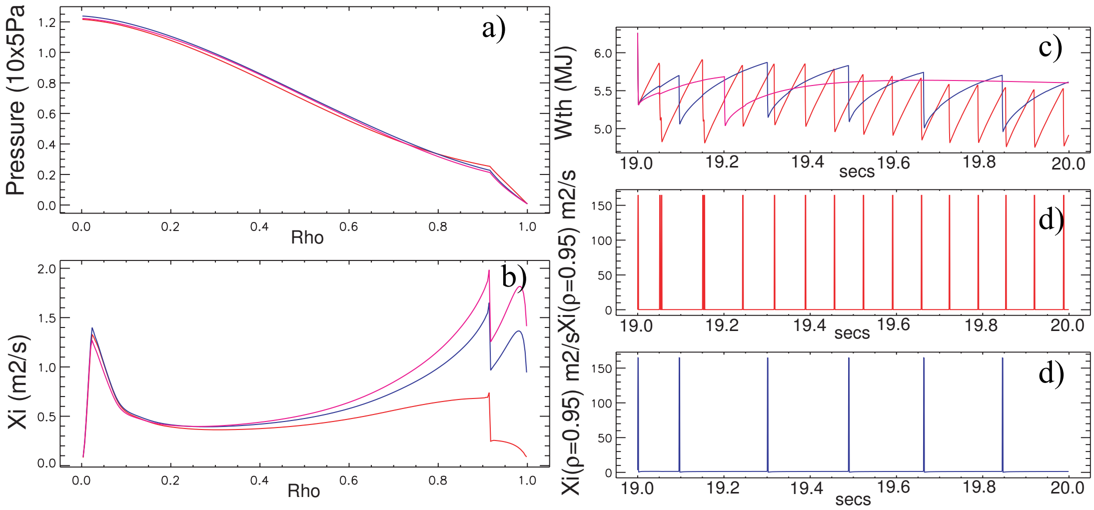

Figure 5. Predictive transport modelling of JET plasma with the different level of wide ripple: red- without ripple, blue- medium ripple, pink – maximum ripple. A) plasma pressure just before ELM; b) ion thermal conductivity before ELM; c) time evolution of the energy content; d) ELM frequency

energy confinement in ELMy H-mode depends on two ingredients. The first one is transport between ELMs and the other is transport during ELMs. By increasing transport between ELMs in a controlled way we can completely eliminate ELMs while keeping the plasma pressure at the top of ETB very close to its maximum level permitted by the MHD stability. This increases the time average top-of-barrier ion temperature, which translates into better confinement due to profile stiffness. This result is in line with earlier experimental observations from JET [2] and recent results from DIII-D [3].

Discussion.

The result presented in this paper show that magnetic ripple does not necessarily lead to a deterioration of plasma confinement. If carefully adjusted, magnetic ripple can be used as a constructive, practical tool for ELM mitigation right up to complete suppression of ELMs. Further experiments are needed, of course, to prove if this tool can be effectively used in practice. One potential problem with using ripple for ELM mitigation comes from the fact that ripple-induced transport mainly increases ion losses leaving electrons unaffected. It might lead to a well-known experimental situation of a quasi-stationary ELM-free H-mode, which has a serious problem with an impurity accumulation due to extremely low level of particle (or electron) transport within the ETB. In principle combining enhanced ripple-induced ion transport with an enhanced electron transport due to stochastic magnetic diffusion [3] could circumvent this problem.

This work was funded jointly by the United Kingdom Engineering and Physical Sciences Research Council and by the European Communities under the contract of Association between EURATOM and UKAEA. The views and opinions expressed herein do not necessarily reflect those of the European Commission. The work was also partly done under the IEA agreement on Large Tokamak Facilities.

References

*[1] G. Saibene et al., Plasma Phys. Control. Fusion **46** A195 (2004);*
[2] B. Tubbing, Proc. 22 EPS Conf. on Contr. Fus. Plasma Phys. Vol. 19C, p. IV-001 (1995);
[3] T.E. Evans et al., Proc. 20th IAEA Fusion Energy Conference (2004);
[4] T. Kiviniemi et al., this Conference
[5] P.N. Yushmanov, Review of Plasma Physics, v. 16, New York, Consultants Bureau (1991).
*[6] J. Lonnroth et al., PPCF **47** 767 (2004)*