*34th EPS Conference on Plasma Phys. Warsaw, 2 - 6 July 2007 ECA Vol.**31F**, P-2.028 (2007)*

The Influence of Toroidal Field Ripple on H-mode Transitions on JET

Y Andrew[1], TM Biewer[2], K Crombe[3], C Giroud[1], NC Hawkes[1], D Keeling[1], A Korotkov[1], E de la Luna[4], V Naulin[5], V Parail[1], G Saibene[6], A Salmi[7], R Sartori[6], P de Vries[1] and JET-EFDA contributors[#]

[1]*Euratom/UKAEA Fusion Association, Culham Science Centre, Abingdon, OX14 3DB, UK*
[2]*Oak Ridge National Laboratory, Oak Ridge, TN 37831, USA*
[3]*Department of Applied Physics, Ghent University, Belgium*
[4]*Laboratorio Nacional de Fusión, Asociación EURATOM-CIEMAT, Madrid, Spain*
[5]*Risoe National Laboratory Technical University of Denmark, OPL-128, 4000 Roskilde, Denmark*
[6]*EFDA Close Support Unit, Garching, 2 Boltzmannstrasse, Garching (DE) Germany*
[7]*Association EURATOM-Tekes, VTT, P.O. Box 1000 FIN-02044 VTT, Finland*

** yasmin.andrew@jet.uk*

 # See appendix of M Watkins et al., Fusion Energy 2006 (Proc. 21st Int. Conf. Chengdu, 2006) IAEA Vienna

Introduction

The finite number of Toroidal Field (TF) coils on tokamaks results in toroidal variation of the magnetic field, TF ripple. The TF ripple is expected to be around $\delta = 0.5$ % at the outer separatrix on ITER and it is known that ripple ion losses can lead to significant counter toroidal rotation velocity, v_ϕ, at the plasma edge[1,2,3]. Any variation in v_ϕ or the poloidal rotation velocity, v_θ, can strongly influence the edge radial electric field, E_r, which in turn is thought to play a significant role in turbulence suppression. Therefore, it is important to understand how TF ripple affects the L-H, H-L and ELM phase transitions. JET has the unique capability to vary the TF ripple amplitude from a standard operating value of $\delta \sim 0.08$ % up to maximum of 3 % and it is therefore an ideal machine on which to perform this study. Results are presented from a recent experiment in which the TF ripple was systematically varied for shots with matched edge density. The effects of increased levels of TF ripple on both global and edge localised parameters over H-mode transitions are shown.

Experiment

A series of shots were run with I_p/B_t values of 2.0 MA/2.2 T and deuterium gas fuelling. The target edge electron density, $\bar{n}_e$, was controlled using active gas feedback (with a peak injection rate of 1.4 x10^{22} e^- s^{-1}) the effect of increased TF ripple to be measured at comparable densities. This method of density control also means that the level of gas puffing oscillates throughout the discharge, in order to maintain the target L-mode edge $\bar{n}_e$ and matched edge $\bar{n}_e$ values with and without TF ripple. The additional heating (Neutral Beam Injection, NBI) in all plasmas was slowly ramped up and down at 1 MW/s as shown by the example in figure 1. The heating power considered for this study is defined as:

$$P_{CORR} = P_{in} + P_{OH} - dW_{dia}/dt - P_{LOSS},$$

where P_{in} is the total NBI heating power, P_{OH} is the ohmic power, dW_{dia}/dt is the rate of change of stored diamagnetic energy and P_{LOSS} is the fast ion power loss due to TF ripple. P_{LOSS} has been calculated with the orbit-following Monte Carlo code ASCOT [4]. Two different amplitudes of TF ripple have been used, $\delta \sim 0.08$ % and 1 % at the outer separatrix, with a low triangularity magnetic configuration of 0.2 for all plasmas.

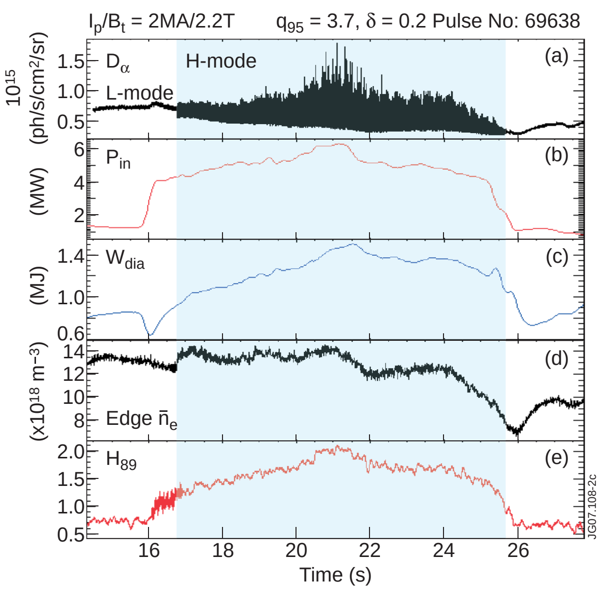

***Figure 1.** General plasma parameters for # 69638, part of the TF ripple scan.*

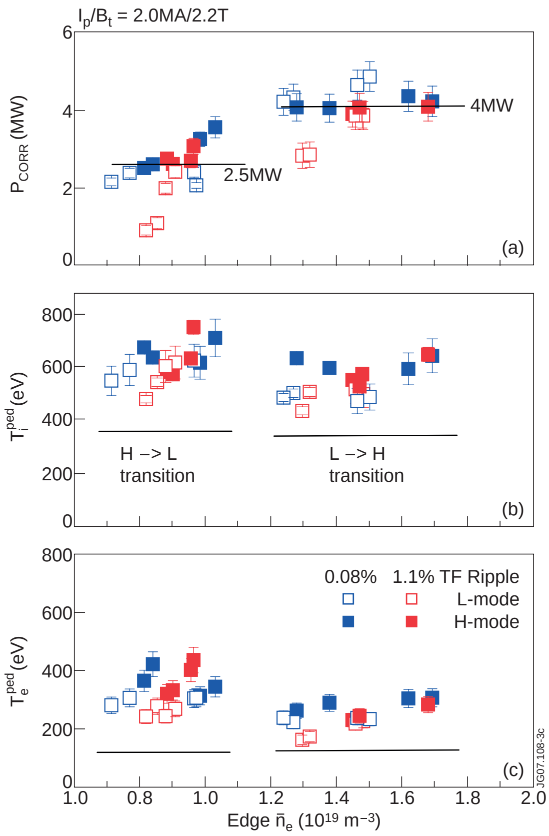

***Figure 2**(a) P_{CORR}, (b) T_i^{ped} and (c) T_e^{ped} , as a function of edge $\bar{n}_e$ for shots with (red) and without (blue) TF ripple across the L-H and H-L transitions*

L-H transition and H-L transitions

Values of P_{CORR}, T_i^{ped} and T_e^{ped} are plotted in figure 2 as a function of edge $\bar{n}_e$ for L-mode and H-mode time-slices preceding and following the L-H and H-L transitions. The data show the power threshold and pedestal temperatures for H-mode access and exit to be unaffected by the level of TF ripple. In addition, the hysteresis in the input power is also preserved with the increase in TF ripple level, with $P_{CORR}^{L-H} \approx 1.5 P_{CORR}^{H-L}$. The corresponding toroidal, v_ϕ, and poloidal, v_θ, rotation velocities, measured at both the location of T_i^{ped} (at ρ ~ 0.95) and further within the confined plasma at ρ = 0.85, are shown in figure 3(a) and (b) respectively. Plasmas with no TF ripple, δ = 0.08 %, are characterised by v_ϕ = -3 to -34 km s^{-1}, co-rotation across the edge region both before and following the L-H and H-L transitions. The plasmas with increased TF ripple, δ = 1 %, counter-rotate right across the edge region both before and after the L-H transition, with values ranging from v_ϕ = +6 to +19 km s^{-1}.

It is interesting to note that for the last 2 s of the power ramp-down as level of edge $\bar{n}_e$ falls (due to reduced gas puffing) v_ϕ decreases dramatically and changes direction from counter- to co-current for the shots with TF ripple. The edge v_ϕ then remains co-current for the shots with δ = 1% ripple for 1 s before and during the H-L transitions as shown by figure 3(a). This result demonstrates that low density, low power conditions exist under which the application of significant TF ripple does not provide sufficient counter-torque for edge plasma counter-rotation.

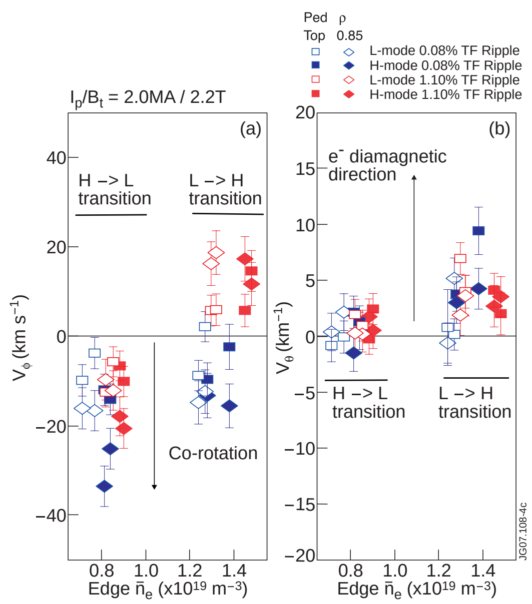

***Figure 3**(a) v_ϕ and (b) v_θ, plotted as a function of edge $\bar{n}_e$ for shots with (red) and without (blue) TF*

The edge v_θ is unaffected by the level of TF ripple at the L-H and H-L transitions with values ranging from v_θ = -2.5 to +9 km s^{-1} shown in figure 3(b). The E_r profile has been calculated using the force balance equation, from its measured components for a pair of matched discharges from this experiment with δ = 0.08 % and δ = 1% at the L-H transition. For this set of plasmas (#69638 and #69639) the change in direction of v_ϕ in the pedestal region does not cause a

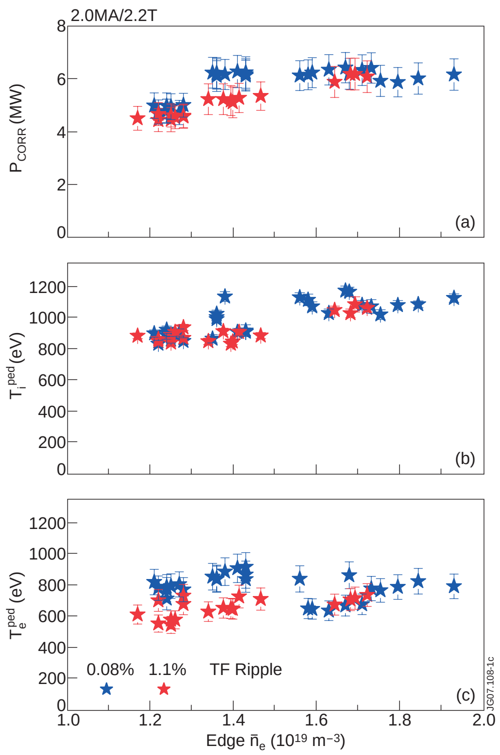

Figure 4*(a) P_{CORR}, (b) T_i^{ped} and (c) T_e^{ped} , as a function of edge $\bar{n}_e$ for shots with (red) and without (blue) TF Ripple across the ELMy H-mode*

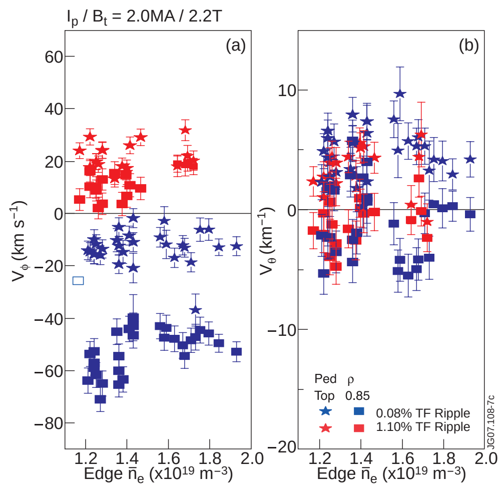

Figure 5*(a) v_ϕ and (b) v_θ plotted as a function of edge $\bar{n}_e$ for shots with (red) and without (blue) TF Ripple at the location of T_i^{ped} and at ρ = 0.85 for the ELMy H-mode phase.*

significant change in the pedestal E_r , -15 kV m^{-1}, without ripple, compared with -14 kV m^{-1} with ripple, at the location of the T_i^{ped} . Therefore, if the L-H transition if controlled through E_r, TF ripple should not have a large effect on H-mode access for these shots.

ELMy H-mode

Time slices are considered from the ELMy H-mode power ramp phase shown in figure 1, for all plasmas in this study. Values of P_{CORR}, T_i^{ped} and T_e^{ped} are plotted as a function of edge $\bar{n}_e$ in figure 4. The experiment reported in this paper has exploited JET's capability for density feedback control to vary the level of gas puffing in order to achieve comparable levels of edge $\bar{n}_e$ under conditions of varying TF ripple amplitude. In addition the levels of input power are relatively low, with a maximum total input power of 6.5 MW. For recent TF ripple studies on JET using steady state H-modes, no external gas fuelling and high input power (12.5 – 13 MW at 2.6 MA/2.2 T and 2.0 MA/1.7 T)see [2].

By matching P_{CORR} over the same range of edge $\bar{n}_e$ it is clear that T_i^{ped} is unaffected by the increase in ripple to $\delta \sim 1\%$. The values of T_e^{ped} are the same with and without TF ripple at the highest densities, but ~200 eV lower with $\delta \sim 1\%$ at the lower end of the $\bar{n}_e$ scan. The decrease in T_e^{ped} with increased ripple amplitude at the lowest values of edge $\bar{n}_e$ considered is not fully understood at present and required further analysis. Edge rotation velocities are shown in figure 5 with (a) v_ϕ and (b) v_θ once again measured at the location of the T_i^{ped} and also at ρ = 0.85 during the ELMy H-mode phase. While v_θ is unaffected by the level of ripple in these shots, v_ϕ is observed to rotate in the counter-current direction with $\delta \sim 1\%$. In addition the gradient in v_ϕ is shallower with the increased level of ripple, reduced by ~ 65 % for these shots.

The E_r and its component profiles, calculated from measured edge parameters are shown in figure 6 for the shots 69638 and 69639 during the ELMy H-mode phase. In the region of T_i^{ped} the E_r increases from -13 kV m-1 to -36 keV m^{-1}, with all three terms providing a significant contribution in the pedestal region.

The confinement factor, H_{89}, is 20 % lower for the ELMy H-mode time-points shown in figure 4, decreasing from 1.5 to 1.3 with increased levels of TF ripple, despite equivalent values of P_{CORR},

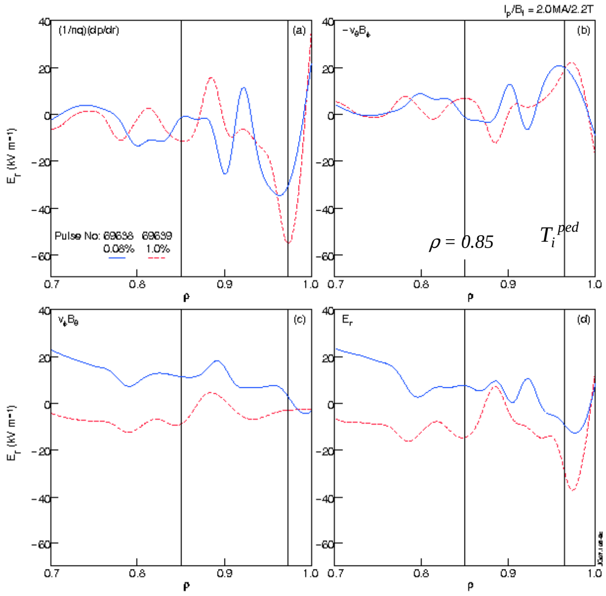

***Figure 6** Components of E_r across the edge plasma for two shots with (red line) and without (blue line) TF ripple during the ELMy H-mode phase. (a) Pressure gradient term, (b) v_θ term, (c) v_ϕ term and (d) total E_r.*

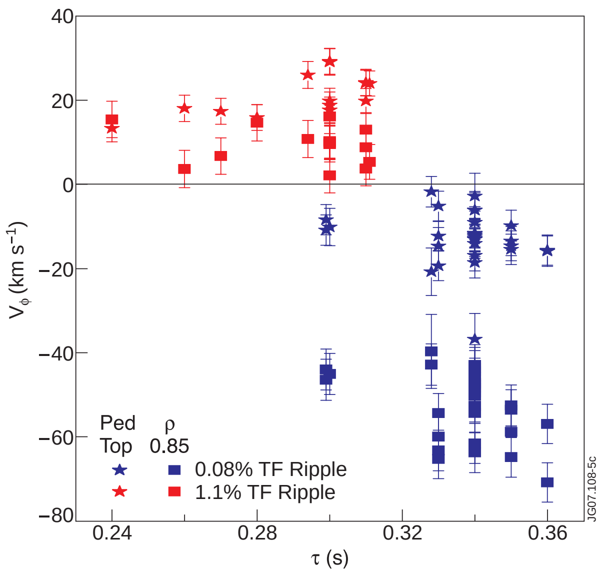

***Figure 7** v_ϕ plotted as a function of the global confinement time t the ELMy phase of the shots both with (red) and without (blue) TF ripple*

edge $\bar{n}_e$ and T^{ped}. The association of edge v_ϕ direction reversal and reduced energy confinement time, τ, is clearly shown in figure 7. The δ = 1 % data points range from, τ = 0.24 – 0.31 s while the non-ripple values ranging from, τ = 0.31 – 0.36, again for the matched P_{CORR} and edge $\bar{n}_e$ points shown in figure 5.

Summary

A series of shots have been run on JET to document the effect of TF ripple on the L-H, H-mode and H-L phases. An increased level of ripple was found to have no significant effect on the power required for H-mode access, T_i^{ped}, T_e^{ped} or on v_θ over a range of edge $\bar{n}_e$. The values of edge v_ϕ, measured at the locations of T_i^{ped} and ρ = 0.85, were measured to change direction from co- to counter-current rotation and to decrease in gradient on application of enhanced TF ripple. For the ELMy H-mode phase of the shots, time-slices with matched values of both P_{CORR} and edge $\bar{n}_e$ had very similar values of T_i^{ped} and v_θ. Further analysis is required to understand the observed lowering of T_e^{ped} by ~ 200 eV with increased ripple amplitude at the lower end of the $\bar{n}_e$ scan. Increased ripple amplitude during the higher power, ELMy phase results in even stronger reversal of the edge v_ϕ rotation from co- to counter-current direction. This change in edge rotation direction with ripple is also accompanied by a ~ 65 % decrease in v_ϕ gradient. Finally, a 20 % decrease in H_{89} and lowered energy confinement times are measured for the shots with enhanced TF ripple, despite closely matched values of P_{CORR}, edge $\bar{n}_e$ and T^{ped}. The braking and reversal of edge v_ϕ and its gradient appears to have a strong association with reduced confinement in the ELMy H-mode phase. Therefore, the level TF ripple on ITER should be minimised in order to reduce any detrimental effects of confinement.

Acknowledgement *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. This work was carried out within the framework of the European Fusion Development Agreement.*

References [1] H. Urano et al., Plasma Phys. Control. Fusion 48 (2006) A193-A199. [2] Saibene, G *et al.*, Proc. of the 34th EPS Conf. on Plasma Phys., Warsaw, Poland (2007). [3] de Vries, P *et al.*, Proc. of the 34th EPS Conf. on Plasma Phys., Warsaw, Poland (2007). [4] A. Salmi et al., Proc. of the 11th Intl. Workshop on Plasma Edge Theory in Fusion Devices, Takayama, Japan (2007).