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** See the appendix of JET EFDA contributors (prepared by J. Paméla and E.R Solano),*
**See appendix of the paper by J.Pamela "Overview of recent JET results",*
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INTRODUCTION

Predictive modelling of a series of JET plasmas with both edge (ETB) and core (ITB) transport barriers has been done using the transport code JETTO with empirical or theory based transport models. Three specific experimental situations, which present a significant challenge to modern transport models, have been selected and analysed. The first one, recently found on JET, is optimised shear plasma with double ITBs [1]. The second experiment deals with stationary ELM-free H-modes, reported by many tokamaks, including JET [2,3]. Finally, we look at recent attempts to reach type-I ELMy H-mode above Greenwald density limit without degradation in plasma performance [4].

1. OPTIMISED SHEAR JET PLASMAS WITH DOUBLE ITBS

An existence of optimised shear plasmas with double-ITBs is a relatively new feature of JET plasma [1], which usually occurs in discharges with negative magnetic shear (see Fig. 1). There are some noticeable differences in the behaviour of these barriers. The inner barrier is “frozen” into the region with the negative magnetic shear and evolves slowly together with the current profile evolution. The outer barrier can expand or shrink depending on the heating power and plasma rotation, with the characteristic time scale of the order of the energy confinement time. It is important to notice that inner ITB are found as well in discharges with pure electron heating, where there should be no significant plasma rotation. The difference between inner and outer ITB behaviour indicates that they might be controlled by different mechanisms. One of these is the universally accepted mechanism of long wavelength turbulence stabilisation by strong shear in plasma rotation [5]. Our past experience shows [6] that better agreement with experiment can be reached if we use a strong shearing rate in combination with small/negative magnetic shear as a stabilising mechanism. Small magnetic shear however can reduce the level of even short wavelength plasma turbulence by itself due to depletion of eddies’ density in the region of small magnetic shear. To reflect these theoretical ideas we use the heuristical JETTO Bohm/gyroBohm transport model [6] and multiply the Bohm transport coefficient by a step-function: $\chi_B^{new} = \chi_B^{old} \times \theta\,(0.1 + s - \omega_{E\times B}/\gamma)$. We also assume that the short wavelength part of the turbulence is depleted in the region of small magnetic shear: $\chi_{gyro}^{new} = \chi_{gyro}^{old} \times \frac{|s|}{1 + |s|}$.. We first apply our transport model to JET Pulse No: 53510 with pure electron heating (3 MW of LHCD). Figure 2 shows the measured and simulated central electron temperature and allows us to conclude that the selected transport model reproduces the experimental trend reasonably well. Note that in this discharge the position of the ITB should coincide with zero magnetic shear, since there is no strong plasma rotation. Then we modelled Pulse No: 53521 which, on the top of LHCD, had strong NBI and ICRF heating. To highlight the role of plasma rotation, we compare two runs-one with strong plasma rotation and one with half of the rotation. The main result of the modelling is shown in Fig. 3 and we conclude that strong plasma rotation can split ITB into two ITBs, one of which is still positioned near zero magnetic shear, the other, outer one moves outward by the strong rotational shearing rate.

2. QUASI STATIONARY ELM-FREE H-MODE PLASMA

Many tokamaks (Alcator C-Mod, DIII-D, ASDEX-Upgrade and JET) have reported recently that under certain condition it is possible to get stationary H-mode plasma with either very benign (so-called type-II) ELMs or ELM-free H-mode. In all cases one or another MHD instability has been reported to exist near the separatrix. However the MHD localisation is, as a rule, very narrow (much narrower that the edge barrier width) and should not significantly influence transport within the ETB. As a result, the question arises under what conditions ELM-free H-mode plasma can become stationary without triggering a big ELM. To address this question, we first try to make a simple analytical estimation of the maximum heat flux, which can be transported through the ETB. If we assume that anomalous transport is completely suppressed within the ETB then the outgoing heat flux is controlled by the ion neo-classical thermal diffusivity. This leads to the following estimate for the heat flux: $q \propto {}^{-2}\pi R r n_{bar} \chi^{i}_{neo} {}^{¥} \nabla T |_{bar} \propto \frac{R a n^{2}_{bar} Z_{ef}\, \hat{}\overline{T_{bar}}}{\Delta {}^{¥} B_{\phi}^{2}}$, where D is the barrier width, all plasma parameters with subscript “bar” refer to value on the top of the ETB. If we assume that the maximum pressure gradient is limited by ballooning stability $R \frac{nTq^{2}}{\Delta {}^{¥} B_{\phi}^{2}} \dagger \alpha_{crit}$, we can conclude that the plasma will remain ELM-free if the heat flux through the ETB does not exceed its maximum value: $q_{max} \propto \frac{n_{bar} Z_{eff}}{\hat{}\overline{T}_{bar}} {}^{¥} \alpha_{crit}$. We therefore can conclude that it is beneficial to bring the plasma edge into the second ballooning stability region. To test this idea we selected two JET shots, one with low and one with high triangularity and ran JETTO in a predictive way with Bohm/gyroBohm transport model. Unlike many other simulations, JETTO explicitly includes the edge transport barrier in the simulation domain. To do it, we assume a certain ETB width and suggest that the transport within an ETB between ELMs be controlled by ion neoclassical thermal conductivity. As a result of the low transport within the barrier, the edge pressure gradients builds up. The code checks ballooning stability and it increases temporarily the transport within ETB as soon as the pressure gradient exceeds a critical value. After that the cycle repeats until the next ELM. Figure 4 and 5 show the ballooning stability diagram for low and high triangularity shots from [2] at the onset of ballooning instability. It is worth noting that JETTO has a fixed boundary equilibrium solver, which self-consistently takes into account steep edge pressure gradient and corresponding edge bootstrap current. Analysis shows that both features are extremely important for a self-consistent evaluation of the ballooning stability.

Comparison of the two stability diagrams allows us to conclude that high triangularity plasma is favourable for reaching the second stability region. To complete our analysis we perform predictive modelling of the same discharge but with two different assumptions about its ballooning stability. Namely we assume that plasma is in the first stability region in first case and that the critical pressure gradient is two times higher in the second case. The result of this simulation is shown in Fig. 6. One can see that indeed high-density plasmas can reach an ELM-free steady state condition with realistically improved edge ballooning stability.

3. HIGH DENSITY ELMY H-MODE PLASMA

It has been found recently, that by careful tailoring of gas puffing and beam fuelling it is possible to bring ELMy H-mode above Greenwald limit without degrading performance [4]. It was shown, in particular, that density profiles remain peaked even if the density is so high that NBI particle source becomes hollow. Our task therefore was to evaluate whether modern transport models can reproduce an observed behaviour, or whether we need to introduce some additional inward particle pinch. We used two transport models for this test. One is the JET Bohm/gyroBohm model, complemented by Ware pinch. The other was the Weiland model with self-consistent anomalous pinch in it. This work is still in progress, however we can tentatively conclude that Weiland model reproduces experimental density evolution quite well (provided that all related processes such as sawteeth reconnections are taken into account). The Ware pinch alone tends to underestimate the central density.

CONCLUSIONS

The predictive transport modelling of a series of JET plasmas has been done with transport code JETTO. This modelling revealed some important features of the transport model, which can reproduce a wide range of experimentally observed phenomena.

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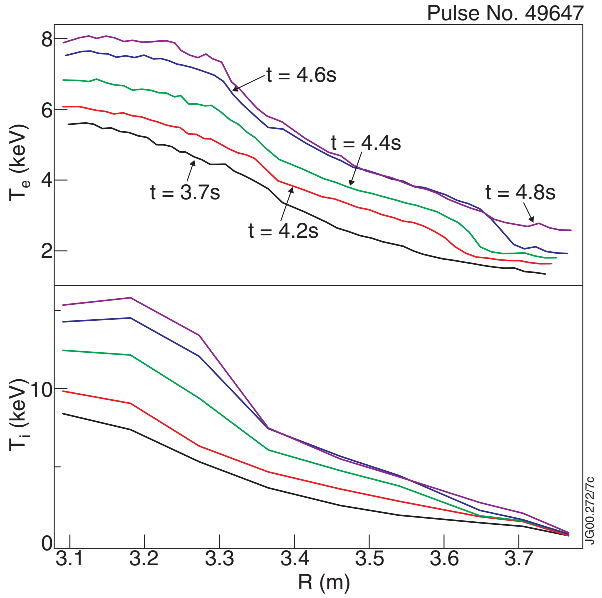

Figure 1: Electron and ion temperature profiles showing formation and evolution of double-ITB in JET.

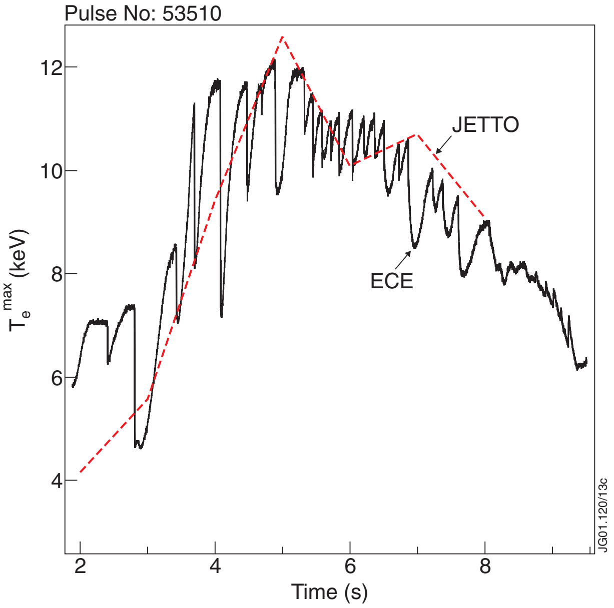

Figure 2: Time evolution of central electron temperature for Pulse No: 53510.

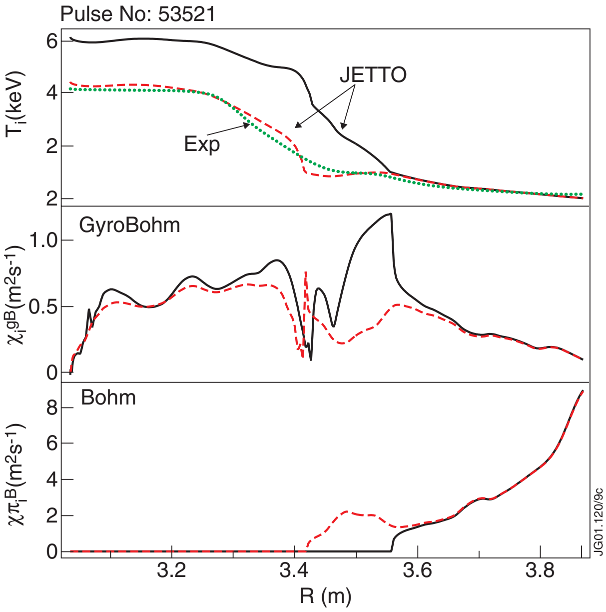

Figure 3: Ion temperature profile, gyroBohm and Bohm contribution to ion transport for strong (solid) and weak (dashed) plasma rotation.

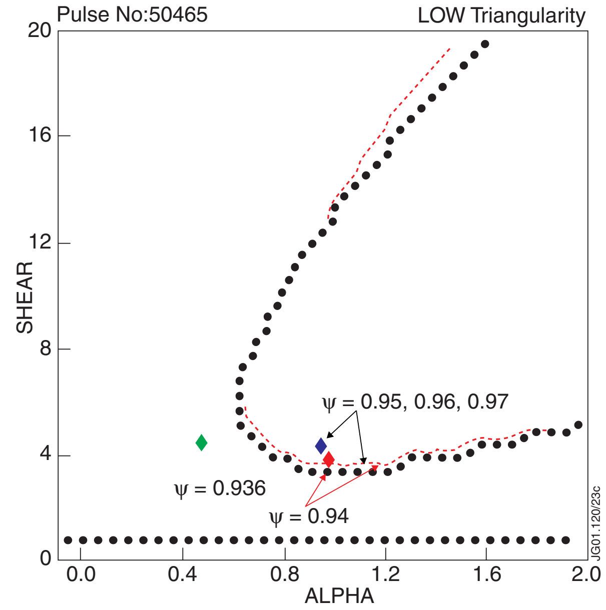

Figure 4: Ballooning stability diagram for low triangularity plasma.

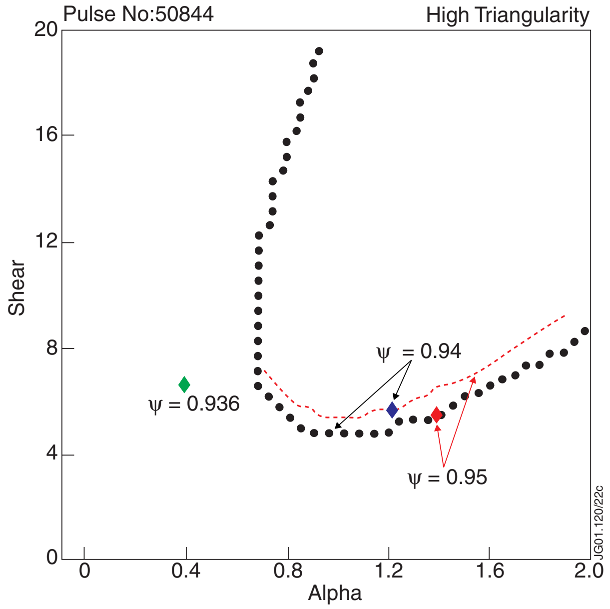

Figure 5: Ballooning stability diagram for high triangularity JET plasma.

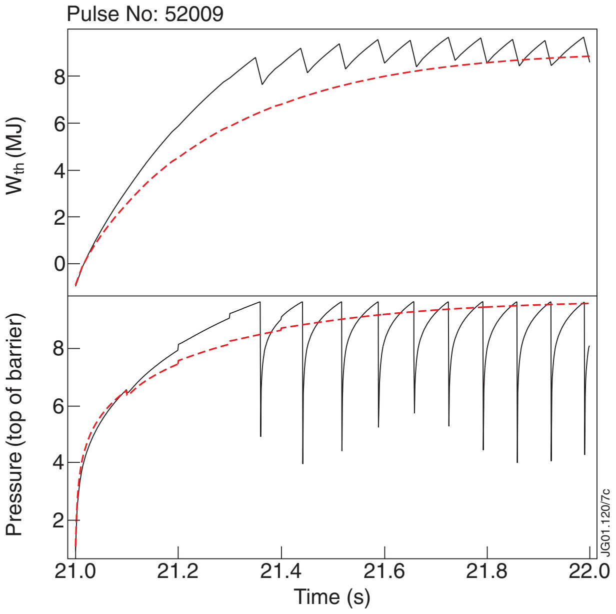

Figure 6: Time evolution of the energy content and edge pressure for low (solid) and high (dashed) triangularity JET plasmas.

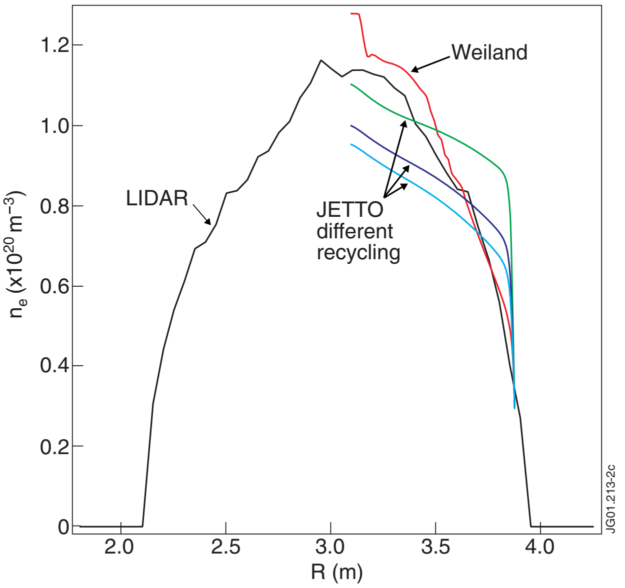

Figure 7: Experimental density profile at the end of density build-up and density simulated with Bohm/gyroBohm and Weiland models.