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Predictive Modelling of JET Optimised Shear Discharges

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ABSTRACT

Transport analysis of high performance JET plasmas with optimised magnetic shear (OMS) has revealed many interesting features which can not be explained by the existing JET empirical transport model [1]. TRANSP analysis shows that transport coefficients in OMS plasmas are often reduced in the plasma core [2] to the level of ion neoclassical transport. TRANSP analysis and predictive modelling with JETTO show that this region of improved confinement appears near the plasma centre and then expands outwards in a way which does not follow either the evolution of the region with the negative magnetic shear or the propagation of the region with a large shear in plasma rotation. The best agreement with experiment has been achieved by using a transport model which combines the effect of a long wavelength decoupling due to small magnetic shear with its suppression by strong rotational shear. Predictive modelling of some of the characteristic JET OMS plasmas gives quite good agreement between such a model and the experimental data.

I. INTRODUCTION.

The Optimised Magnetic Shear Scenario (OMS) has been extensively studied on JET [2-5] including operation with DT plasmas and it is considered to be a promising scenario for future JET operation. Figure 1 shows the characteristic time evolution of the main plasma parameters for one of the best OMS shot, #40847, in pure D. Figure 2 shows the time evolution of the measured profiles of ion and electron temperatures and density, and calculated q profiles for the same shot. It follows from Figures 1 and 2 that an internal transport barrier (ITB) emerges during the current ramp up phase after the beginning of the full scale heating by a combination of ICRH and NBI. The current ramp plays an important role not only because it helps to establish hollow or flat q profile in the inner half of the plasma volume, but also because it helps to keep plasma from making a transition to H-mode, presumably by triggering some edge MHD instabilities (such as an ideal external kink [6]). Figure 2 shows that once formed, an ITB usually expands outward with the characteristic velocity up to $v_r \leq 0.5$ m/sec. It is important to note that both the position of the ITB and its evolution in time do not correspond to the idea [7] that ITB appears in a plasma with the negative magnetic shear with its position is controlled solely by the region with zero magnetic shear. The q profiles as determined by

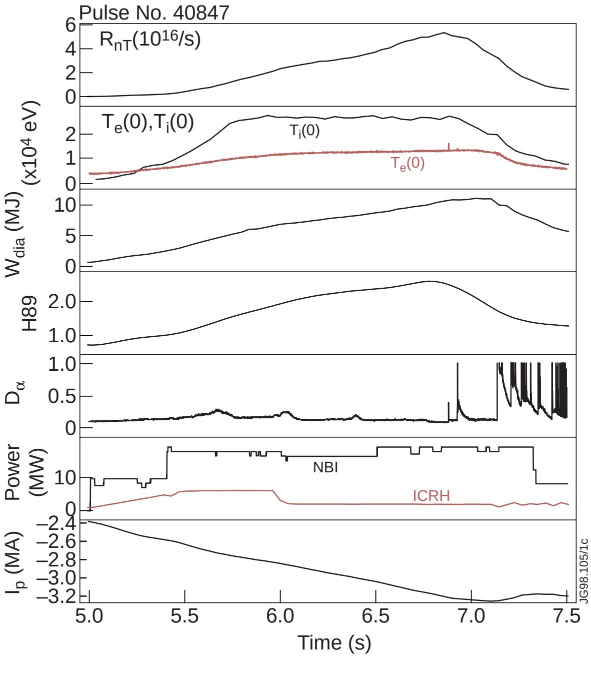

Fig.1. Time traces of the main plasma parameters for the OMS discharge #40847;

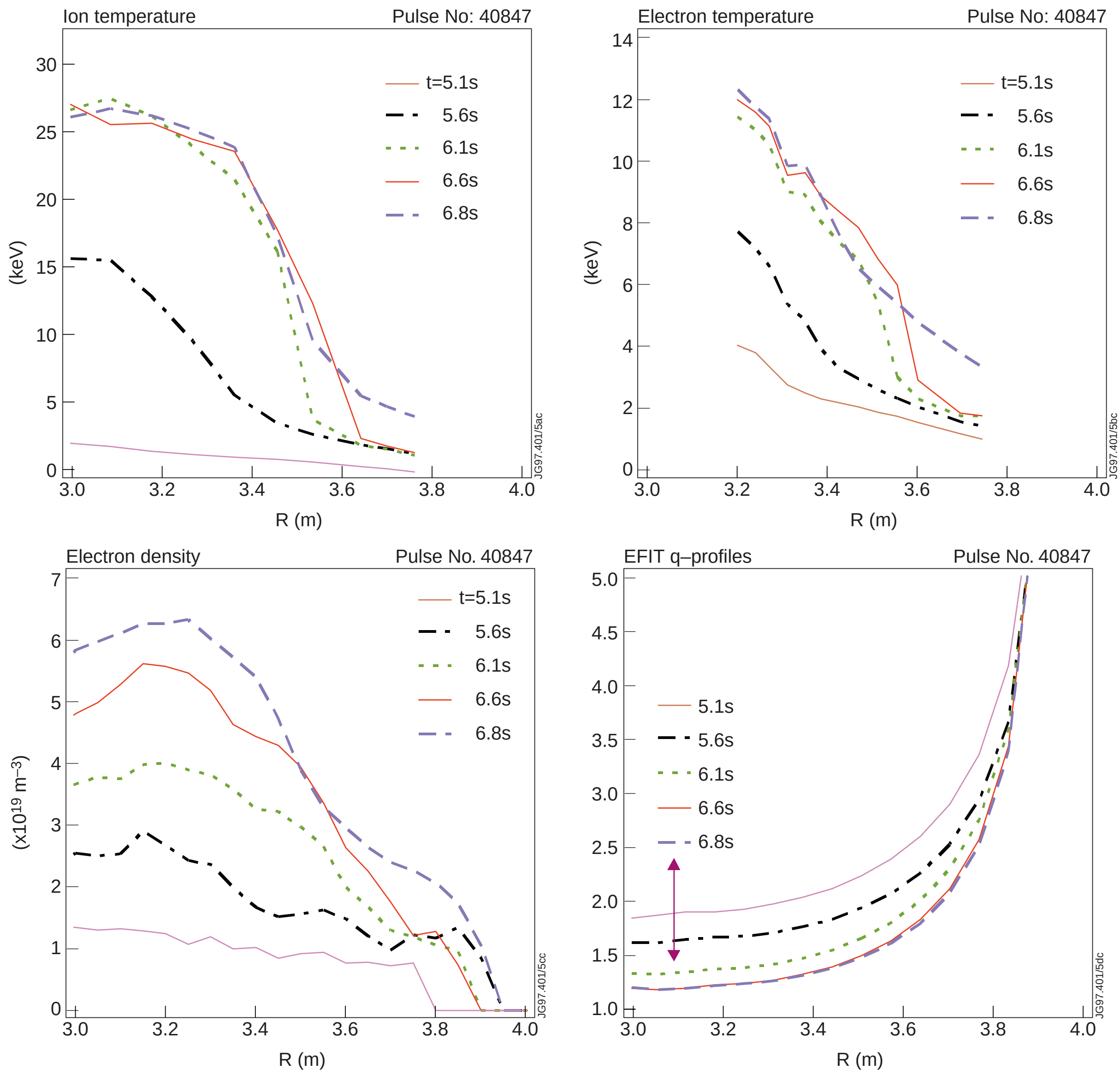

Fig.2. Time evolution of the main profiles for the discharge #40847: a- ion temperature, b- electron temperature, c - electron density and d - q profile;

magnetic reconstruction by EFIT, TRANSP analysis and predictive modelling are typically monotonic with a small shear near the plasma centre. At the same time the experiment indicates that the position of ITB is confined inside the q≈2 surface [4] which qualitatively coincides with a small magnetic shear region (s ≤ 1). After the formation of the ITB further evolution of the discharge is, on the one hand, controlled by the ideal core MHD stability [6] and, on the other hand, by the edge phenomena which include L-H transition (triggered sometimes by the core MHD) and by an onset of ELMs. Very often the transition to an ELM-free H-mode leads to a gradual erosion and sometimes to a complete disappearance of the ITB. In some cases this phenomenon could be explained by the appearance of the pressure driven ideal MHD turbulence. In other cases the explanation requires either a gradual or sudden change in anomalous transport coefficients. Finally experimental observation shows that formation of the ITB in discharges with strong ion heating leads to a much stronger reduction in the ion thermal transport than in its electron counterpart [4].

Several theoretical ideas have been proposed in order to explain the mechanism of the ITB formation and its further evolution. The first one, which is commonly used as an explanation for L-H transition, is the turbulence stabilisation by the shear in plasma rotation [7]. Another idea [8] suggests that the long wavelength turbulence can be decoupled and suppressed in the region with small or negative magnetic shear. Finally, these two mechanisms can actually work together [9].

The main goal of this article is to test these three mechanisms by comparison with JET data. The article is organised as follows. We discuss different transport models in section II. Section III discusses the result of predictive modelling of the characteristic JET OMS discharges with the different transport models, followed by Summary and conclusions.

II TRANSPORT MODELS.

In the following analysis we will use as a basic model an empirical transport model which has been developed on JET [1] and successfully tested on the range of the L-mode, ELMy and ELM-free H-mode shots from JET and ITER database. The distinctive feature of this model is that it consists of a combination of a Bohm and a gyroBohm type of anomalous transport combined with neoclassical ion transport. As has been discussed previously, a Bohm type of transport might result from the toroidal coupling of long wave length turbulence and therefore has a non local character; gyrobohm transport, on the other hand, could be produced by short wave length turbulence which is only weakly influenced by toroidicity. The resulting set of transport coefficients has the form:

$$\chi_e = \alpha_e^{gB}\chi_{gB} + \alpha_e^{B}\chi_B; \quad \chi_i = \alpha_i^{gB}\chi_{gB} + \alpha_i^{B}\chi_B + \chi_i^{neo};\ D = \alpha_D \frac{\chi_e\chi_i}{\chi_e + \chi_i}; \qquad (1)$$

where $\chi_{gB} = \sqrt{T_e}\left|\frac{\nabla T_e}{B^2}\right|; \quad \chi_B = \left|\frac{\nabla n T_e}{nB}\right| q^2 \left|\frac{\nabla T_e}{T_e}\right|_{r\approx a}, \quad \left|\frac{\nabla T_e}{T_e}\right|_{r\approx a} \equiv \int_{\rho\approx 0.8}^{\rho(tr.bar)} \left|\frac{\nabla T_e}{T_e}\right| d\rho$ and $\alpha_{e,i}^{B,gB}$ are numerical coefficients which have been tested against a broad range of JET discharges [1], fixed and kept constant since then.

The transport model assumes that the L-H transition leads to a formation of a transport barrier just inside the separatrix with the characteristic width $\Delta \propto \rho_{\theta i}^{beam}$ and fully suppressed ion anomalous transport within the transport barrier. This brings ion losses down to the level which corresponds to the ion neoclassical thermal conductivity: $\chi_i \approx \chi_i^{neo}$. It is also assumed, that residual magnetic flutter keeps the electron particle and energy transport on the same level ($\chi_e \approx D \approx \chi_i \approx \chi_i^{neocl}$) which ensures plasma ambipolarity. Recently this transport model was complemented by the boundary conditions which assume continuity of the heat and particle fluxes through the separatrix and are valid both for L and H-mode plasma [10]:

$$\chi_{e,i} n_{e,i} \nabla T_{e,i}\Big|_{\rho=1} = -V_{e,i} n_{e,i} T_{e,i}; \quad D\nabla n = -V_n n; \quad V_{e,i} = \sqrt{\frac{\chi_{e,i} v_{e,i}}{qR} \frac{\xi_{e,i}}{\xi_{e,i}+1}}; \quad \xi_{e,i} = \sqrt{\frac{\chi_{e,i} qR}{v_{e,i}\Delta^2}}$$

(2)

As was discussed in the Introduction, three basic theoretical ideas of core plasma turbulence stabilisation and ITB formation will be discussed in this paper. The first refers to stabilisation of the turbulence by shear in plasma rotation [7] which can be expressed by the dimensionless parameter [11]:

$$\Omega \equiv \frac{\omega_{E\times B}}{\gamma} \propto \frac{R\left|\frac{(RB_\theta)^2}{B}\frac{\partial}{\partial\psi}\left[\left(\frac{\nabla n_i T_i}{en_i} - v_\theta B + v_\varsigma B_\theta\right)\frac{1}{RB_\theta}\right]\right|}{v_{thi}} \quad (3)$$

where $\psi = \int_0^r RB_\theta dr'$ is a poloidal magnetic flux, $\gamma \propto \frac{v_{thi}}{R}$ is the characteristic growth rate of drift type plasma turbulence, v_θ and v_ς are poloidal and toroidal components of plasma rotation. We can expect that plasma turbulence (long wave length in particular) might be suppressed if the parameter Ω exceeds a certain value, say $\Omega \geq \delta = O(1)$.

The second mechanism under consideration is, strictly speaking, not a mechanism of plasma turbulence suppression but probably a tool to disconnect turbulent vortices initially linked together by toroidicity. Both theoretical analysis [8] and numerical simulation [9] show that global structures responsible for the Bohm type of anomalous transport, are effectively destroyed in a region with small magnetic shear $s \approx 0$. Short wave length turbulence, which produces gyroBohm transport, is not modified in such a region.

Finally the two mechanisms can work together, so that the turbulence might be suppressed in the region where $s - \xi\Omega \leq 0$ where ξ is a numerical parameter $\xi = O(1)$.

The modifications to a previously described transport model have been made in order to incorporate all three mechanisms of internal transport barrier formation in discharges with optimised magnetic shear. Since we assume that in the ITB only long wavelength turbulence is suppressed we multiply the Bohm coefficient in (1) by a step function, which depends on a combination of all three control parameters: s, Ω and δ:

$$\chi_B = \left|\frac{\nabla n T_e}{nB}\right| q^2 \left|\frac{\nabla T_e}{T_e}\right|_{r\approx a} \times \Theta(\alpha_1 + \alpha_2 s - \alpha_3\Omega); \; where \;\; \Theta(x) = \begin{cases} 1 \; if \, x \geq 0 \\ 0 \; if \, x < 0 \end{cases} \quad (3)$$

These serves to reduce the transport due to long wavelength turbulence. Numerical parameters α_1, α_2 and α_3 play a dual role in our modelling. First of all we use these coefficients as switches which allow us to test all three models of ITB formation separately. After selecting the most suitable mechanism or a combination of the mechanisms we adjust the coefficients in order to maximise the agreement with experimental data. We have also tested two different approaches to the physics of the ITB formation described by the formula (3). First, a local approximation, assumes that transport barrier emerges only within the region(s) where the argument of the step function $\Theta(\alpha_1 + \alpha_2 s - \alpha_3 \Omega)$ is less than zero. The second, global approach, supposes that Bohm transport is suppressed everywhere inside the region where $\alpha_1 + \alpha_2 s - \alpha_3 \Omega \le 0$. This model corresponds to the idea that the source of the global plasma turbulence is localised near the plasma edge and then spread over the whole plasma volume. Transport models (1-3) have been tested on selected JET plasmas which have ITB with both L and H-mode plasma edge.

III. RESULTS OF PREDICTIVE MODELLING OF JET OMS PLASMAS.

Four JETshots have been selected to test different ideas of the ITB formation (the main plasma parameters for these shots are listed in the Table).

Table

shot #	I_p **(MA)**	B_{tor} **(T)**	P_{max} **(MW)**	H_{89}
40847	3	3.45	24 (NBI+ICRF)	2.55
40542	3	3.45	23 (NBI+ICRF)	2.15
42746	3	3.45	24 (NBI+ICRF)	3
39275	2	3.45	2 (LHCD)	-

Three of them use the same heating scheme: a combination of full power NBI heating (which plays a role as a source of particles as well as a source of predominantly ion heating) and centrally peaked ICRF heating with varying power (the characteristic waveform of the heating power is shown in Figure 1). We start our analysis by the modelling of one of the best transient OMS discharges with B_T=3.45 T (shot #40847, Figures 1, 2). This discharge features a relatively long L-mode phase (about 1 sec.) with good ITB. This is followed by sudden transition to an ELM-free H-mode and further continuous degradation of the ITB. Finally the ELM-free period is interrupted by a series of very strong type I ELMs which destroy enhanced confinement both in the core and at the edge.

The next shot under consideration #40542 is an example of the quasi steady state OMS discharge with B_T=3.45 T in which ITB coexists with an edge transport barrier interrupted by grassy ELMs (Figure 3). In many respects this discharge is similar to pulse #40847 but with an early transition from L to ELMy H-mode edge without an ELM-free period. This appeared to prevent the erosion of the ITB.

As a further test we attempt to model one of the best DT plasmas, #42746 (illustrated in Figure 4).

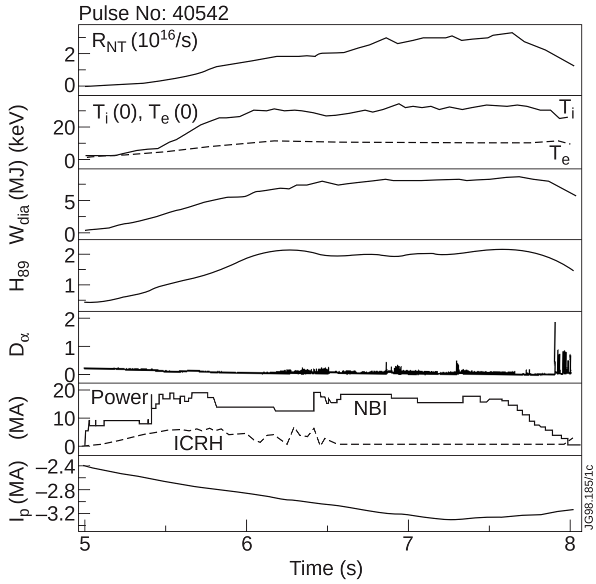

Fig.3. Time traces of the main plasma parameters for the quasi steady state OMS discharge #40542 with ELMy H-mode edge;

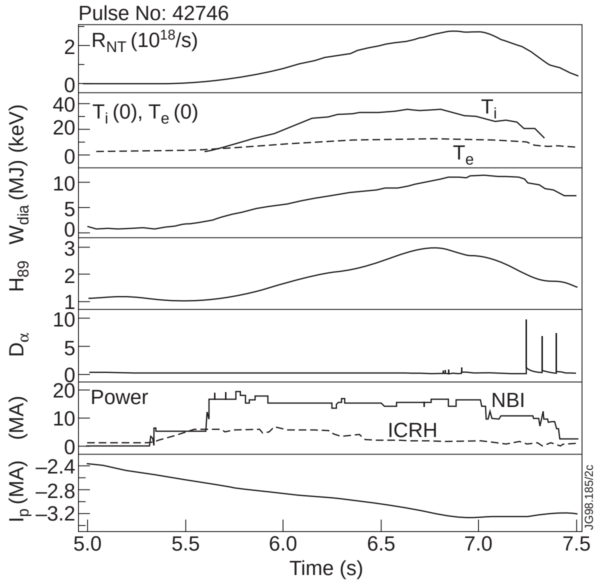

Fig.4. Time traces of the main plasma parameters for the DT shot #42746;

Finally, we have applied the numerical modelling to a very different JET plasma, #39275 with LH waves being the only method of plasma heating. This plasma shows (see Figure 5) that electron transport can be significantly reduced in the region of a negative magnetic shear even in the situation when there is no plasma rotation.

The following observations are important from the point of view of the model validation:

- plasmas with strong ion heating develop ITB's even if they do not have any region with negative magnetic shear (this conclusion is similar to previously discussed results from high β_{pol} discharges in JT-60U [12]) ;
- in such plasmas the width of the ITB initially rises in time and then come to a quasi steady state value within the time interval $\Delta t \le \tau_E$;
- as a rule, ion thermal conductivity experiences much stronger reduction within the ITB than its electron counterpart in discharges without negative magnetic shear;
- very often a transition of the discharge with an ITB into an ELM-free H-mode leads to a deterioration and further destruction of the ITB by the subsequent giant type I ELMs;
- discharges with negative magnetic shear develop a region with much reduced electron thermal conductivity even in case of a weak heating (there appears to be no power threshold in this case).

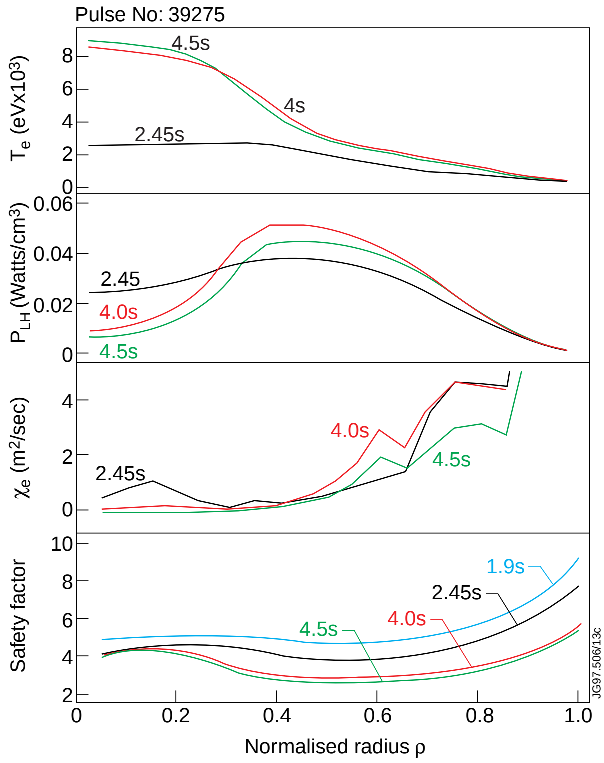

Fig.5. Evolution of the measured electron temperature profile and LH power deposition profile and calculated by TRANSP c_e *and q profiles for the LH heated discharge #39275;*

All these characteristics should be reproduced by the transport model which aims to fit the experiment.

We selected shot #40847 as a testbed for different transport models since it has all phases of ITB development - its formation, expansion, transition to an ELM-free H-mode, deterioration and disappearance of the ITB. Figures 6, 7 show the time evolution of the observed main plasma parameters and the results of the most successful model (a global ITB which is produced by a combination of a magnetic shear plus strong shear in plasma rotation with α_1=0.1, α_2=1, and α_3=1.2). One can see that the model reproduces all main features which have been enumerated above. Figure 8 compares the characteristic ion temperature profile for different transport models. The transport model which does not include shear in plasma rotation fails to produce any transport barrier.

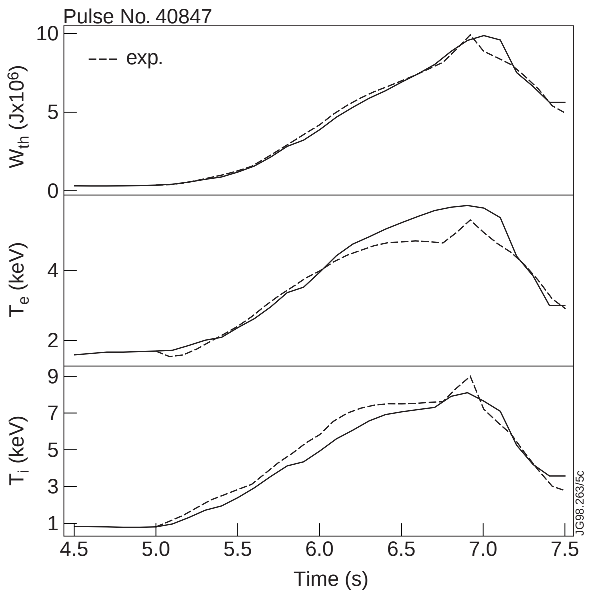

Fig.6. Time evolution of measured (solid lines) and simulated with the optimum model (dashed lines) plasma energy content and volume average ion and electron temperatures for shot #40847;

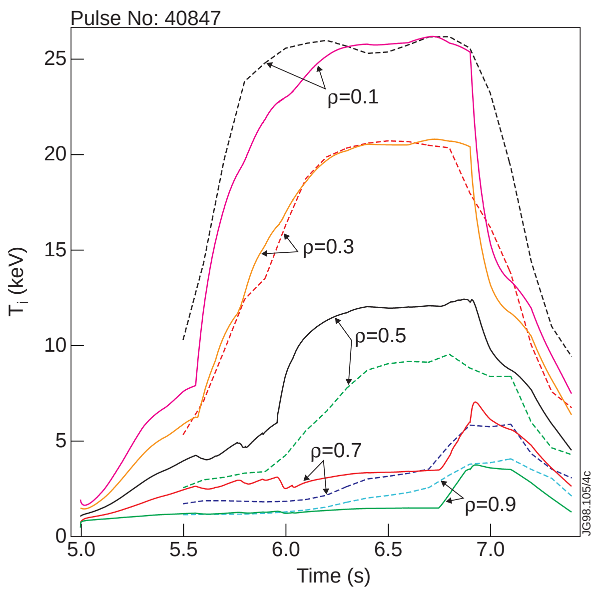

Fig.7. Time evolution of measured (dashed lines) and simulated with the optimum model (solid lines) ion temperature at different radii for the same shot;

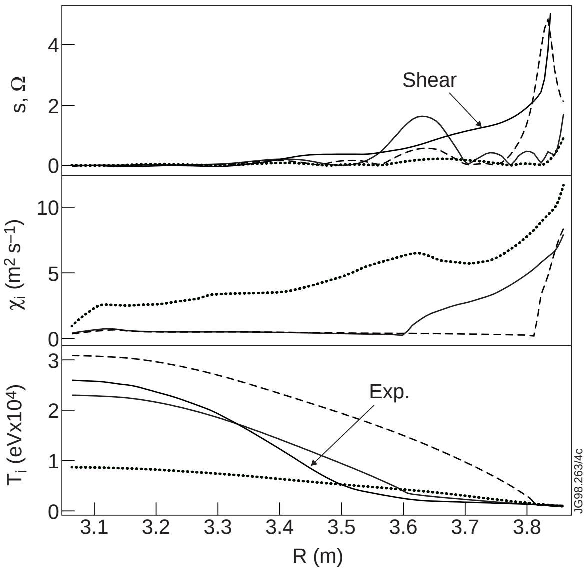

Fig.8. Simulated radial profiles of: a) magnetic shear and normalised rotational shear (solid line- optimum model, dashed line - rotational shear as a stabilising term only, dotted line- magnetic shear as a stabilising term only), b) ion thermal conductivity and c) ion temperature for shot #40847;

On the other hand, the model which relies only on the turbulence stabilisation by plasma rotation (without taking account of magnetic shear term) produces too wide a transport barrier. In the latter case we also fail to reproduce the experimentally observed gradual radial expansion of the transport barrier- the absence of the stabilising term with magnetic shear leads to a very rapid propagation of the transport barrier across the entire plasma volume. Therefore we can conclude that the model which takes into consideration both turbulence stabilisation by shear in plasma rotation and mode decoupling by small magnetic shear gives the best agreement with experiment.

It is interesting to note that the model which uses a combination of negative magnetic shear and shear in plasma rotation as a mechanism of the turbulence stabilisation, manages to reproduce not only a transition to an improved core confinement but also the erosion and disappearance of the ITB shortly after L-H transition (see Figure 7). It was not necessary to include the effect of additional MHD activity although MHD is thought to play a role in some discharges. The explanation of this phenomenon might come from the fact that L-H transition leads to a sharp rise of the edge pressure. The latter effectively reduces the shear in the core plasma rotation which in turn causes deterioration and further collapse of the ITB. In experiment this collapse coincides with the onset of the violent type I ELMs. At present it is difficult to say whether the degradation of the ITB leads to an increase of the heat flux near plasma edge and triggers giant ELM or the giant ELM comes first and destroy the ITG. One way or another, this violent termination of the high performance phase was successfully avoided in quasi steady state shot #40542 which will be discussed later.

The fact that the ITB reduces ion thermal conductivity much more than its electron counterpart at present can be explained in different ways. One possibility is that contribution of the Bohm type of transport to electron thermal conductivity is relatively weaker than in the ion transport (actually, we use exactly this model in our analysis and our results show that such a model works). However in the future this simplified, semi-empirical approach might be replaced by theory based models, which involve the possibility that electron transport is more influenced by the different (short wave length) part of the turbulent spectrum. This short wave length turbulence might require either a region with zero magnetic shear or stronger shear in plasma rotation for its stabilisation. Recent results from TFTR [13] show that this reasoning might provide a plausible explanation for deep narrow electron transport barrier which emerges near the minimum q in ERS discharges. More experimental information and theoretical work is required to distinguish between these models and we leave this topic for future analysis.

Another area which needs more experimental information in order to clarify the applicability of certain transport model is the question of whether the reduction of the transport coefficients inside (or within) an ITB is local or global. Figure 9 shows two ion temperature profiles for the shot #40847 for two different cases, simulated with the same optimum set of the constants α_1=0.1, α_2=1, and α_3=1.2 In one case it was assumed that the transport coefficients are reduced only within the region with $\alpha_1 + \alpha_2 s - \alpha_3 \Omega \leq 0$ (local barrier). In the other case (global barrier), it was assumed that the reduction in transport coefficients extends to the plasma centre. Clearly, the global model gives better agreement with JET observation. We therefore can conclude that in the case under consideration the formation of the ITB leads to a global reduction of transport coefficients everywhere inside the barrier (similar results have been reported from JT-60U [12] and D-IIID [14] in case of a weak central magnetic shear, high β_{pol} plasmas). However we are aware of some other experiments (JT-60U discharges with strong reversed magnetic shear [15] and TFTR ERS discharges [13]), where strong reduction of the transport coefficients has been proven to be localised within a narrow region which appears close to a zero magnetic shear. Much more experimental information and theoretical work supported by numerical simulation is needed before we can unambiguously determine the conditions for the reduction of transport to spread over a large plasma region, rather than being localised within a narrow region of either very strong shear in rotation of zero magnetic shear.

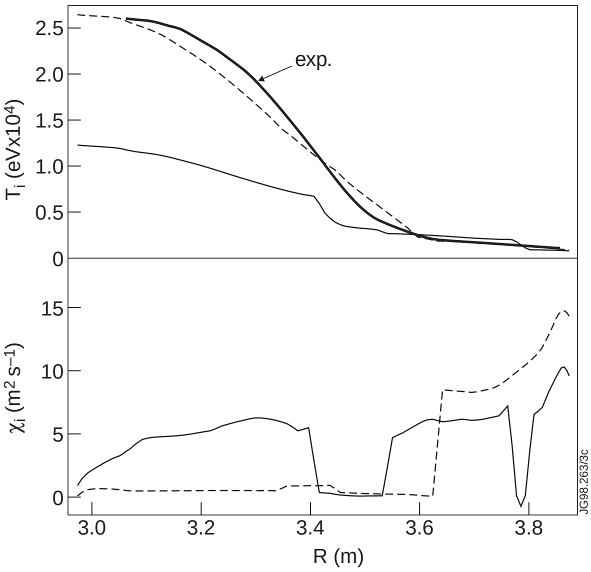

Fig.9. comparison of the: a) measured ion temperature profile and simulated with local transport barrier (solid line) and global transport barrier (dotted line) and b) simulated ion thermal conductivity (local barrier - solid line, global barrier - dotted line) for the shot #40847;

In all further modelling we used the same transport model with the optimum set of the constants α_1=0.1, α_2=1, and α_3=1.2 and an assumption that ITB has a global character.

Our next task was the modelling of the shot #40542 which has a long quasi steady state period of co existence of the ITB and an H-mode with grassy ELMs (see Figure 3). From the point of view of predictive modelling the long stable coexistence of two transport barriers is the most interesting feature of this discharge which ought to be reproduced by the transport model under consideration. The result of the modelling is shown in Figure 10. We can conclude that the model is able to reproduce this situation as well. The basic difference between quasi steady state shot #40542 and transient shot #40847 is that discharge #40452 managed to avoid a long ELM free period. As a result, its edge pressure was kept at a relatively low level which prevented shear of the core plasma rotation from gradual degradation and subsequent destruction of the ITB.

Discharge with sole LHCD heating #39275 is a challenge for those transport models which account for the shear in plasma rotation as the sole mechanism of the core turbulence stabilisation. Indeed, the result of predictive modelling shows that the main source of plasma turbulence stabilisation comes from the negative magnetic shear term, since pure electron heating in combination with a relatively low density does not produce significant plasma rotation. The optimum model under consideration reproduces the experimental results quite satisfactorily, as shown in Figure 11.

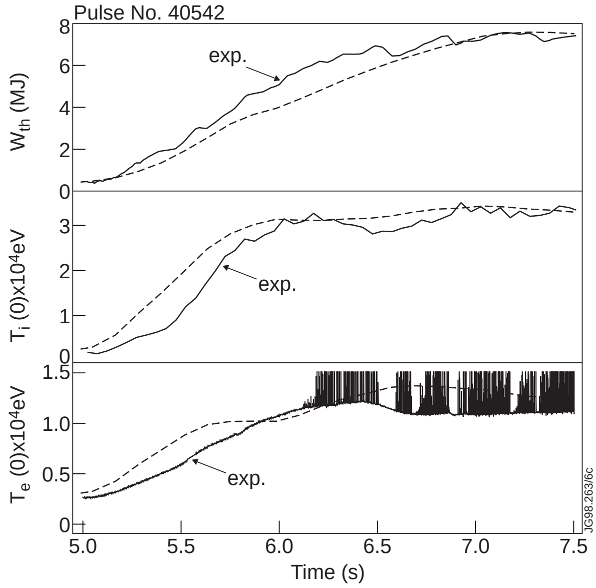

Fig.10. Time evolution of the measured (solid lines) and simulated with the optimum model (dashed lines) energy content and central ion and electron temperature for quasi steady state shot #40542;

Finally, we used the global transport model to simulate one of the best DT discharge #42746. Figure 12 shows some of the results illustrating quite a good agreement between modelling and experiment. This indicates as well the minor role of the isotope effect in the core confinement.

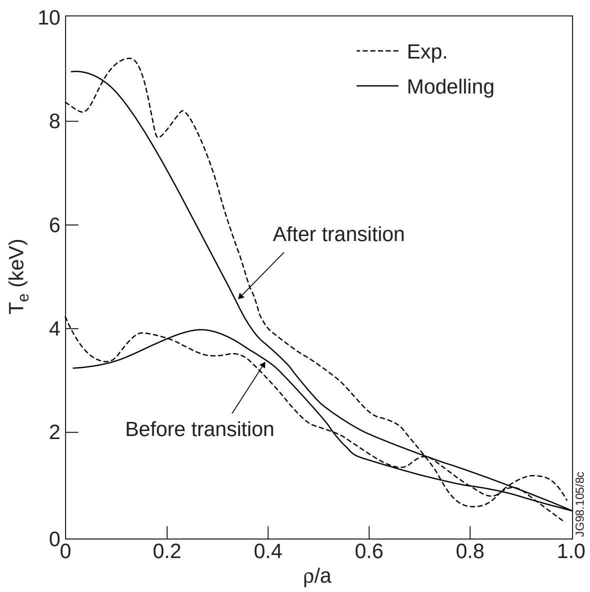

Fig.11. Comparison of the measured (dashed lines) electron temperature profiles and simulated with the optimum model (solid lines) for the discharge with a moderate LH heating #39275;

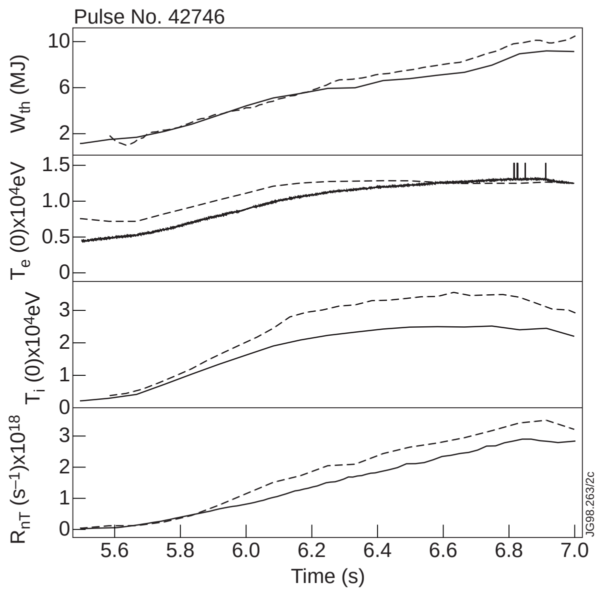

Fig.12. Time evolution of the main measured plasma parameters (solid lines) and simulated with the optimum model (dashed lines) for the DT OMS discharge #42746.

IV CONCLUSIONS.

Different theoretical ideas for the mechanism of ITB formation have been tested on a set of JET OMS discharges which includes a series of high performance shots with high power NBI and RF heating both in L, ELM-free and ELMy H-mode and a plasma with pure electron heating by LH waves. These include both the mechanism of turbulence stabilisation by shear in the plasma rotation and long wave length turbulence de-correlation by small or negative magnetic shear. Analysis show that neither of these mechanisms used individually can explain the whole entirety of experimental results. The best agreement with experiments has been achieved with a model which uses a combination of magnetic shear and shear in plasma rotation as a mechanism of long wave length turbulence suppression. It is worth mentioning here that this optimised transport model is very close to a theory based prediction: even normalisation numerical coefficients which are usually used in order to adjust the model with respect to a real experiment, are all close to one. More experimental information and numerical analysis is needed in order to clarify the details of the internal transport barrier formation such as its radial extent and the differences between electron and ion transport within the barrier.

REFERENCES

[1] M. Erba et al., Plasma Phys. Contr. Fusion **39** (1997) 261;

[2] G.A. Cottrell et al., Proceedings of the 24th EPS Conference on Controlled Fusion and Plasma Physics, Berchtesgaden, 1997, Vol. 21A, p. 81;

[3] C. Gormezano for the JET Team, in Proceedings of the 16n IAEA Fusion Power Conference , Montreal, Canada 1996, vol. I, page 487, Vienna 1997;

[4] F.X. Söldner for the JET Team, Plasma Phys. and Contr. Fusion **39** (1997) B353;

[5] A.C.C. Sips et al., in Proceedings of the 24th EPS Conference on Controlled Fusion and Plasma Physics, Berchtesgaden, 1997, Vol. 21A, p.97;

[6] G.T.A. Huysmans, et al., ibid. p. 21;

[7] K.C. Shaing, E.C. Crume, Jr., Phys. Rev. Lett., **63**, (1989) 2369; H. Biglari, P.H. Diamond and P.W. Terry, Phys. Fluids B**2**, (1990)1;

[8] F. Romanelli, F. Zonca, Phys. Fluids B**5**, (1993), 4081;

[9] Y. Kishimoto et al., in Proceedings of the 16n IAEA Fusion Power Conference , Montreal, Canada 1996, vol. II, page 581, Vienna 1997;

[10] V. Parail et al, IAEA Technical Committee on H-mode Physics, Kloster Seeon, Germany, 1997 (to be published in Plasma Phys. and Contr. Fusion, 1998.

[11] T.S. Hahm and K.H. Burrell Phys. Plasmas **2** (1995) 1648;

[12] Y. Kamada et al., in Proceedings of the 16n IAEA Fusion Power Conference , Montreal, Canada 1996, vol. I, page 247, Vienna 1997;

[13] F.M. Levinton et al., ibid. vol. I, p. 211;

[14] E.A. Lazarus, et al., ibid. vol. I, p. 199;

[15] T. Fujita, et al., ibid., vol. I, p.227.