TRANSPORT IN JET HIGH PERFORMANCE PLASMAS.

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Abstract

Two type of high performance scenarios have been produced in JET during DTE1 campaign. One of them is the well known and extensively used in the past ELM-free hot ion H-mode scenario which has two distinct regions- plasma core and the edge transport barrier. The results obtained during DTE-1 campaign with D, DT and pure T plasmas confirms our previous conclusion that the core transport scales as a gyroBohm in the inner half of plasma volume, recovers its Bohm nature closer to the separatrix and behaves as ion neoclassical in the transport barrier. Measurements on the top of the barrier suggest that the width of the barrier is dependent upon isotope and moreover suggest that fast ions play a key role. The other high performance scenario is a relatively recently developed Optimised Shear Scenario with small or slightly negative magnetic shear in plasma core. Different mechanisms of Internal Transport Barrier (ITB) formation have been tested by predictive modelling and the results are compared with experimentally observed phenomena. The experimentally observed non-penetration of the heavy impurities through the strong ITB which contradicts to a prediction of the conventional neo-classical theory is discussed.

1. TRANSPORT IN THE ELM-FREE HOT ION H-MODE JET PLASMAS.

Two distinct regions with basically different transport properties have been identified in ELM-free Hot ion H-mode plasma [1,2]. First region is the plasma core which includes the whole plasma volume inside the barrier. Its still anomalous transport balances the heating power and is responsible for the peakedness of the core plasma pressure. Second region with a significantly reduced or even completely suppressed anomalous transport occupies a narrow layer near the separatrix and plays a dual role. First it controls the energy losses through the separatrix so that the lower is transport within the barrier the higher is plasma pressure on the top of the barrier $p_{ToB} \approx \left(n_i T_i + n_e T_e\right)_{ToB}$ provided the heating power and the width of the barrier Δ_{bar} are kept constant. Second, transport barrier controls edge ballooning (and partly kink) stability which depends on the edge pressure gradient. If we will use natural assumption that $\left(\partial p / \partial r\right)_{ToB} \approx -p_{ToB} / \Delta_{bar}$ we can conclude that edge barrier could be characterised by its width Δ_{bar} and by transport within the barrier χ_{bar}^{eff}. We therefore will concentrate on study of three main "transport characteristics" of the ELM-free Hot ion H-mode: its effective thermal conductivity in the core and within the edge barrier and the width of the barrier. DTE-1 campaign provided us with a valuable information about possible isotope effect in local transport. It is worth mentioning here the result of earlier study [3] which indicates that isotopic effect in global confinement is very weak.

DTE-1 campaign gave us the possibility to study the ρ_i^* dependence of the core transport in D, T and D-T mixture while keeping all other plasma parameters the same. The result of the comparative TRANSP analysis of Hot ion H-mode in D, T and DT mixture is shown on Fig. 1 and confirms previous indication that the core transport scales as a gyroBohm in the inner half of plasma volume (with $\chi_{eff} \propto \sqrt{M_i}$) and recovers its Bohm nature closer to the separatrix even in ELM-free H-mode.

[1] see Appendix to IAEA-CN-69/OV1/2, The JET Team (presented by M.L. Watkins)

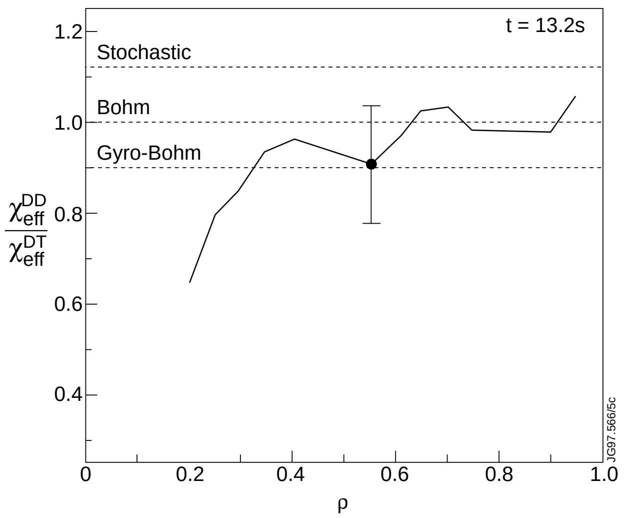

Fig.1. $\chi_{eff}^{DD}/\chi_{eff}^{DT}$ *versus normalised radius* ρ *for the hot ion H-mode pulses.*

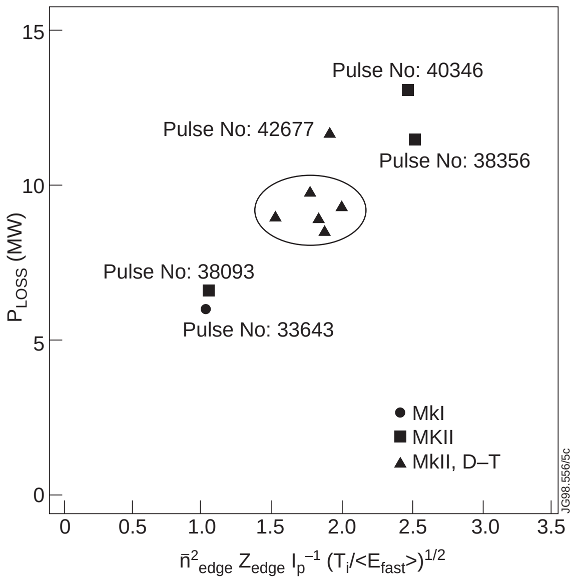

Fig.2. Power losses as a function of the edge parameters for the hot ion H-modes from MkI and MkII assuming the barrier width scales as a fast ion Larmor radius.

As it was shown earlier, the main improvement in energy and particle confinement in ELM-free Hot ion H-mode comes from the edge transport barrier, where transport was considered to be reduced to the level of the ion neo-classical thermal conductivity [2]. A detailed analysis of experimental data from the DTE1 and previous campaign shows that indeed the energy losses through the separatrix scales as $Q \propto (n\chi_i^{neo}T)_{ToB}/\Delta_{bar} \propto (n^2 Z_{eff})_{ToB} I_p^{-1}$ which indicates also that the width of the transport barrier scales as an ion poloidal Larmor radius (either thermal or fast NBI ions, see Fig. 2). The power loss through the separatrix P_{LOCC}^{CC} was determined by subtracting the radiation inside the separatrix P_{RAD}^{BULK} and the change in the content of thermal energy dW_{th}/dt from the total heating power P_{ABS}^{th} absorbed by the thermal plasma, including Ohmic heating and the total plasma heating by the NBI and alphas (taking account of orbit losses, beam shine through and charge exchange losses). The results of predictive transport modelling with transport code JETTO confirm that not only the dependence of the power losses through the separatrix scales as predicted by neoclassical theory, its calculated value agree with experimental losses as well.

We also carried out a detailed study of the edge transport barrier width in the ELM-free hot ion H-mode in pure D, in a DT mixture and in pure T plasma. Direct method of the transport barrier width determination relies upon simultaneous detailed measurement of electron density, electron and ion temperature and Z_{eff} profiles with adequate spatial resolution. This was proven to be very difficult on JET although some data exist [4] and indicate that the barrier width is of the order of fast ion banana width. To make analysis regular, we adopt a simplified method [5] which is based on assumption that the onset of type I ELMs is controlled by a ballooning stability limit. Combined with the supposition of constant pressure gradient within the barrier $\nabla p \approx -p_{ToB}/\Delta_{bar}$ this approach allows us to find the width of the transport barrier by measuring plasma parameters on the top of barrier at the onset of a type I ELMs and substituting them into ballooning stability criteria: $R \cdot q^2\, p_{ToB}/B_\phi^2 \approx \Delta_{bar} \cdot \varphi(s)$, where $\varphi(s)$ depends on magnetic shear and other details of magnetic configuration within the barrier.

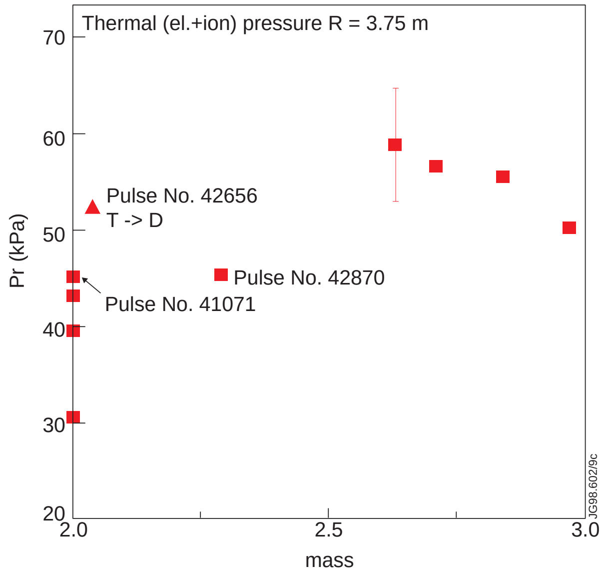

Fig.3. Pedestal pressure at the onset of type I ELMs vs. edge isotopic composition for a series of 3.8MA/ 3.4T hot ion H-mode with ~10MW of NBI power

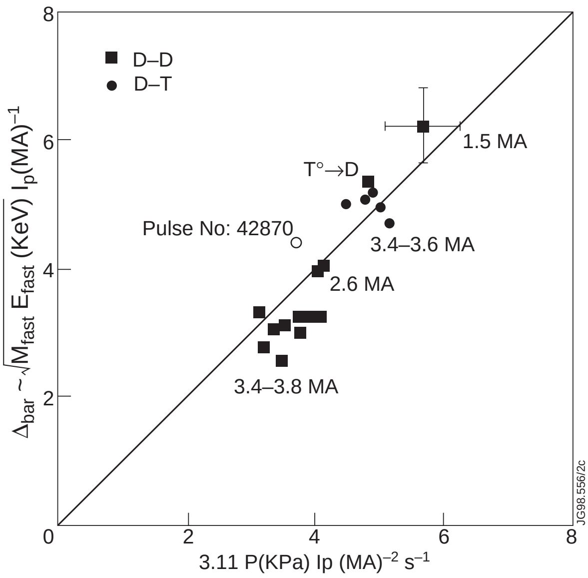

Fig.4. Scaling of the edge transport barrier width with the Larmor radius of the fast particles for D-D and D-T hot ion H-mode.

To investigate the isotopic dependence of the edge transport barrier width, we have chosen a series of discharges during the alpha particle heating experiments [3]. These discharges were performed at 3.8MA/ 3.4T with constant NBI heating power (10MW) and little variation in the particle source. The tritium concentration in the plasma was varied from 0 to 100% by simultaneous control of the fuelling from neutral gas and that from the neutral beam injection system. Figure 3 shows the pedestal pressure at the onset of the giant ELM (which terminates the high performance phase), as a function of the edge isotopic composition. The pedestal pressure appears to be significantly higher in tritium rich discharges.

It is to be mentioned that in Fig.3 only a few deuterium reference discharges for the alpha particle heating experiments are shown, but a survey of the entire 10 MW hot ion H-mode data base shows that no other pure deuterium discharges reach the pedestal pressure obtained in #41071.

As we discussed earlier, it is unclear whether the higher pedestal pressure in D-T is due to fast or thermal ions since the isotopic composition of the NBI source is the same as that in the background plasma. This uncertainty has been clarified by the result from the discharge #42656 with a pure D background plasma and pure tritium NBI beam source, as indicated in Fig. 3. This particular shot has an edge pressure significantly higher than the pure deuterium discharges but comparable to that of tritium rich discharges. This strongly suggests that the edge transport barrier width is determined by the fast particles. It should be noted that the discharge #42870, which has lower tritium concentration and, in particular, lower tritium beam composition, has much lower pedestal pressure compared to the tritium rich pulses. This result goes in line with the idea [6] that the concentration of fast particles should exceed certain level (about 1% of the thermal ions density) before they start play a decisive role in determination of the radial electric field which in turn controls the transport barrier width.

To find if transport barrier width depends on other plasma parameters (on plasma current, in particular) we analyse a set of hot ion H-mode discharges with a range of power and current. The result of this analysis is shown in Fig. 4 which plots the experimentally measured edge plasma pressure, normalised in accordance with ballooning stability criterion versus poloidal Larmor radius of fast particles for a range of Hot ion H-mode discharges with plasma current varying from I_p=1.5-3.8 MA. It appears that there is a rather good correlation between the pedestal pressure and the fast ions poloidal Larmor radius. However the experimental uncertainties in the measurements of edge plasma parameters are rather large (see Fig.3,4). This does not allow us to make an unambiguous statement whether the transport barrier width is indeed controlled by the fast ions. There are however many other, indirect evidences which confirm our conclusion about the role of fast ions. This includes difference between ELMs in NBI and

ICRF heated plasma, increase in ELM frequency in a plasma with strong gas puffing and eventual transition to a type III ELMs. All these facts could be explained in a self consistent way by using the idea of the fast particles role in the formation of the edge transport barrier.

II. TRANSPORT PROPERTIES OF THE OPTIMISED MAGNETIC SHEAR SCENARIO

The ELM-free Hot ion H-mode scenario delivered a world record in fusion power [7] and has proven itself as being one of the best scenario to achieve transiently the highest performance. As it was discussed above the main drive for high performance in this scenario comes from the edge transport barrier within which transport is reduced to the neoclassical level. Unfortunately at the same time strong dissimilarity between core and edge transport does not allow to reach high pressure gradient in the plasma core before plasma become ballooning unstable near the separatrix. The Optimised Magnetic Shear scenario (OMS) potentially is able to reduce core/edge contrast by providing an additional transport barrier in the plasma core. This scenario has been extensively studied prior and during the DTE-I campaign.. Fig. 5 shows the time evolution of the measured profiles of ion and electron temperatures for the recent shot #45. One can see 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 support the idea [8] that ITB appears in a plasma with the negative magnetic shear and that its position is controlled solely by the region with zero magnetic shear. The q profiles reconstruction by EFIT, TRANSP analysis and predictive modelling usually give a monotone q-profile 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 [9] which qualitatively coincides with a small magnetic shear region. After the formation of the ITB further evolution of the discharge is, on the one hand, controlled by the ideal core MHD stability [10] and, on the other hand, by the edge phenomena which include L-H transition (triggered sometimes by the core MHD) followed by either ELM-free period or by type I ELMs. Very often the transition to an ELM-free

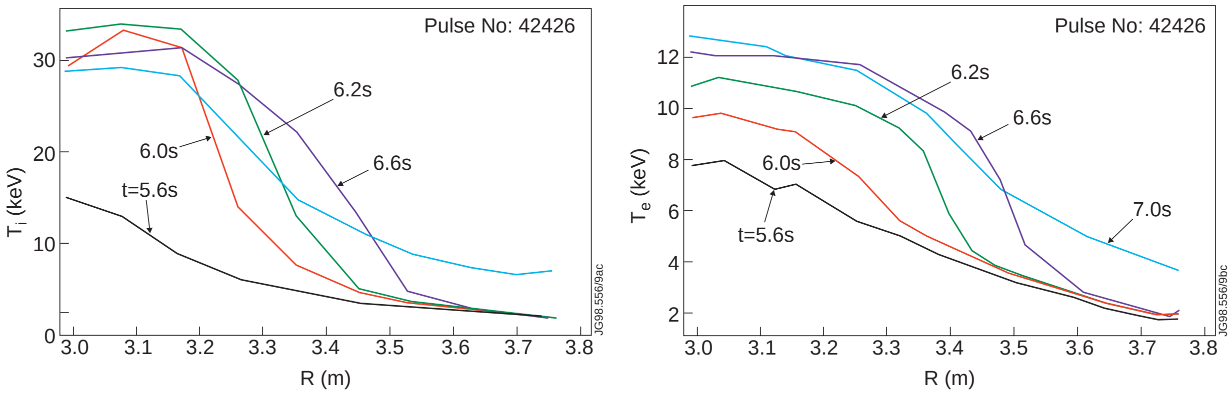

Fig.5. Time evolution of the ion (a) and electron (b) temperature profiles for the pulse No. 42426.

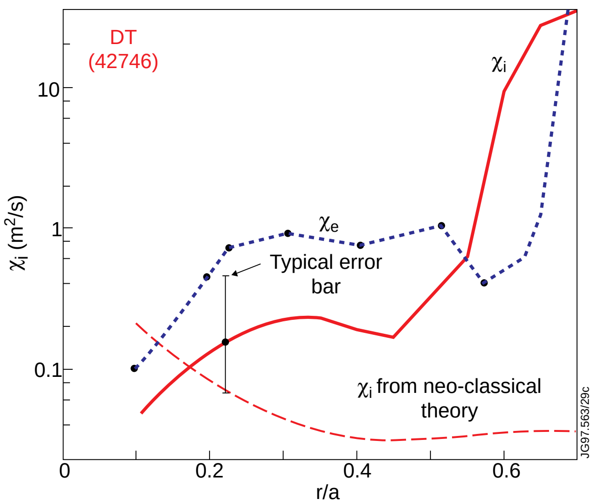

Fig.6. Radial profiles of χ_I, χ_e and χ_{neo} for OMS pulse No. 40847

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 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 stronger reduction in the ion thermal transport than in its electron counterpart [9]. Experimental observations suggest also that while a region with reduced ion transport inside the ITB usually occupies the whole area inside the barrier, the reduction in electron transport is sometimes localised in a narrow region close to a footpoint of the barrier (see Fig.6). This indicates that electron and ion transport might be controlled by the different type of plasma turbulence.

III. TRANSPORT MODELS AND PREDICTIVE MODELLING OF THE OMS SCENARIO

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 [11]. 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 [12]. We tested all these ideas in a range of JET OMS discharges by using predictive transport code JETTO.

As a basic model we use an empirical transport model which has been developed at JET 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 it 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.

Three basic theoretical ideas of core plasma turbulence stabilisation and ITB formation have been tested. The first refers to stabilisation of the turbulence by shear in plasma rotation [11] which can be expressed by the dimensionless parameter:

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

where $\psi = \int_0^r RB_\theta dr^{\copyright}$ 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 and numerical simulation show [12] 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.

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 by a step function, which depends on a combination of all three control parameters: s, Ω and δ:

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

The 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 optimise the agreement with experimental data.

We have also tested two different approaches to the physics of the ITB formation described by the formula (2). 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 $\alpha_1 + \alpha_2 s - \alpha_3 \Omega \leq 0$.

The main results of the modelling are shown on Figs.7,8. Figure 7 shows the time evolution of the measured T_i at different radii 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 the main experimentally observed phenomena. 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. 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 conclude that the model which takes into consideration both turbulence stabilisation by shear in plasma rotation and mode decoupling by small or negative 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 Fig.7). It was not necessary to include the effect of additional MHD

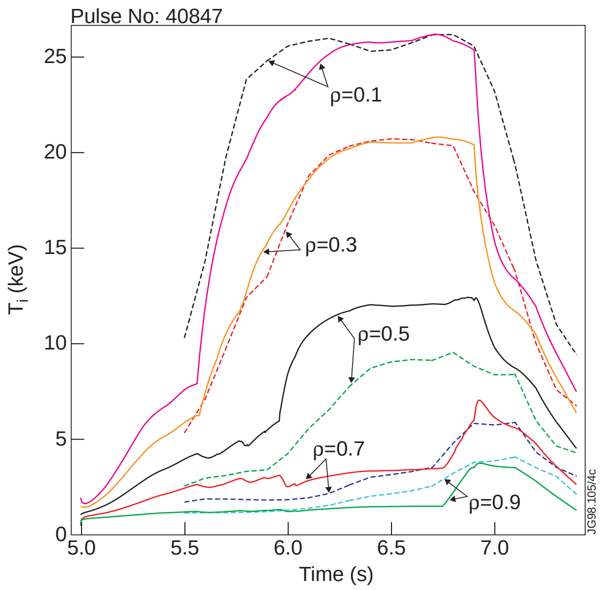

Fig.7. Time evolution of measured ion temperature (solid lines) and simulated with the optimum model (dashed lines) at different radii for pulse No. 40847.

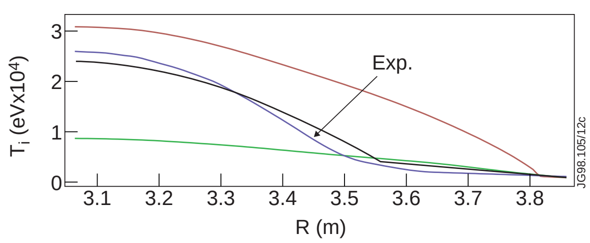

Fig.8. Radial profiles of ion temperaturesimulated with the different transport models (solid line- optimum model, dashed line - rotational shear as a stabilising term only, dotted line- magnetic shear as a stabilising term only), pulse No. 40847.

activity although MHD is thought to play a role in some discharges. The explanation of this phenomenon comes 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 ITB. One way or another, this violent termination of the high performance phase was successfully avoided in quasi steady state OMS discharges with small type III ELMs [13].

The fact that the ITB reduces the 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, our model includes this effect and the results agree with experimental observations. However in future this simplified, semi-empirical approach should be replaced by theory based models, which involve the possibility that electron transport is more influenced by 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. Results from TFTR [14] 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.

IV. TRANSPORT OF HEAVY IMPURITIES IN JET HIGH PERFORMANCE PLASMAS.

A study of the dynamics of the heavy impurities accumulation in the plasma core after laser blow off have been done in both Hot ion H-mode and OMS discharges. It was found that heavy impurities (like Ni) are effectively screened near plasma edge in the Hot ion H-mode plasma. Two mechanisms might contribute to this kind of behaviour. The first one relates to the neo-classical thermal force, the other one uses experimentally observed non monotone radial distribution of the main ions in the Hot ion H-mode and the fact that in neo-classical theory impurity accumulate near the maximum density.

The dynamics of the blown off heavy impurities in discharges with OMS do not always follow the conventional neo-classical theory prediction. Figure 9 show the characteristic radial distribution of background subtracted SXR emission some 200 msec after laser blow off for two OMS pulses. One can see the clear signature of the neo-classical impurity gathering near plasma centre for the pulse No.38441 with a weak ITB. However, the second pulse No. 40572, which has an ITB with much better quality, does not show any sign of impurity penetration through the ITB. This fact can be possibly attributed to the strong poloidal plasma rotation. For heavy impurity poloidal Mach number might exceed critical level of $M_\theta>1$. The resulting centrifugal force exceeds its pressure gradient and effectively presses heavy impurity out of the central region. It is interesting to note, that light carbon impurity, for which centrifugal force is significantly smaller, does concentrate in the central part of plasma column.

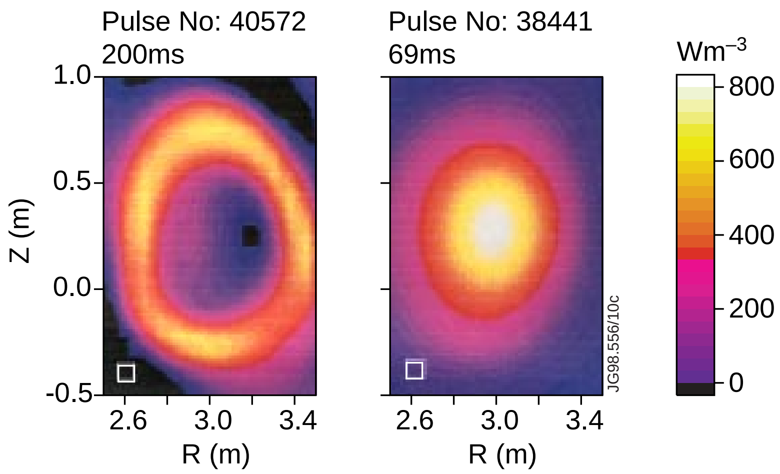

Fig.9. Radial distribution of metal impurity in OMS discharge with strong internal transport barrier (#40572) and in plasma with weak barrier (#38441).

V. SUMMARY.

Two type of the high performance scenarios have been produced in JET during DTE1 campaign- ELM-free Hot ion H-mode and Optimised Magnetic Shear scenario. The transport analysis of the D, T and D-T plasmas can be summarised as following.

The core transport in hot ion H-mode has a gyroBohm character in the inner part of the plasma volume and recovers a Bohm character closer to the edge. On the other hand, power losses through the separatrix are controlled by the transport within the edge barrier which is shown to be reduced to the level of ion neoclassical heat conductivity. Another parameter which controls the plasma performance is the width of the edge transport barrier. The recent proposal about possible role of fast ions in the establishment of the edge transport barrier has been studied. The analysis confirms that the best agreement with experiment is achieved with an assumption that edge transport barrier width corresponds to a banana width for fast beam ions.

Different ideas about possible mechanism of internal transport barrier formation have been tested on a series of JET OMS discharges. It comes out that a model combining turbulence suppression by strong rotational shear with vortices separation by small magnetic shear gives the best agreement with experiment. More experimental information and analysis is needed in order to clarify the experimentally observed difference between ion and electron transport modifications inside the barrier.

Transport of trace impurities in high performance plasma has been studied. In hot ion H-mode plasma heavy impurities evolve in accordance with neo-classical theory. However, OMS plasmas with strong barrier show no sign of heavy impurity penetration through the barrier and therefore defy conventional neoclassical behaviour.

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