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V V Parail, H Y Guo, J Lingertat.

JET Joint Undertaking, Abingdon, Oxfordshire, OX14 3EA,

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ABSTRACT.

The role of fast particles in the edge transport barrier formation is discussed. Analysis of recent experiments on JET which has been carried out in H, D, T and DT mixture with NBI and ICRH heating is presented which supports the idea that the width of the edge transport barrier is controlled by the banana width of the fast beam ions in case of NBI heating and by the banana width of the thermal ions in case of ICRH minority heating. A simple theoretical model which can account for this effect is analysed.

I. INTRODUCTION.

The role of the edge transport barrier in achieving high plasma performance has been recognised for years [1,2]. First of all, the transport barrier contributes directly to the energy content. In best hot-ion H-mode JET discharges the edge pedestal accounts for almost 30% of the entire stored energy [3]. On the other hand theoretical analysis shows that the edge pressure gradient is limited by ballooning and kink MHD instabilities [4], which cause saturation or even degradation of the edge pedestal [5]. Another sign of the importance of the edge transport barrier comes from the observation [6] that the core transport also depends on edge plasma parameters: the higher the temperature on the top of the barrier the better is the core confinement. Some theoretical and empirical transport models [7,8] use this link between core and edge in their predictions of the performance of future tokamak-reactors. All these facts lead to the conclusion that the edge transport barrier in general and processes which control its width in particular deserve careful investigation.

II. EXPERIMENTAL OBSERVATIONS.

In recent experiments on JET new data about the edge transport barrier in both Hot-Ion H-mode discharges with a long ELM-free period and in quasi steady state ELMy H-mode discharges were obtained. The experiments have been carried out in H, D, T and DT mixture with NBI or ICRF heating, or combined NBI+RF heating. Amongst other, these experiments lead us to the following conclusions:

- the pressure on the top of the barrier at the onset of type I ELMs is significantly (3-5 times) higher in discharges with NBI heating than in similar discharges with ICRF heating;
- in otherwise equivalent discharges with NBI heating the maximum plasma pressure on the top of the barrier (or the width of the edge transport barrier Δ_{bar}) increases with the main ion atomic number and with the plasma current in a way which is consistent with an assumption that Δ_{bar} scales proportionally to the ion poloidal Larmor radius.

The main purpose of this Letter is to show that both observations might be explained in a non controversial way if one assumes that the width of the edge transport barrier is controlled by the poloidal Larmor radius of the fast beam ions in case of NBI heating and by the poloidal Larmor radius of thermal ions in case of central ICRF minority heating.

To demonstrate how this approach is supported by experimental data we present here two examples of our study of the edge transport barrier. The first example relates to an ELMy H-mode plasma [9]. We use values of T_e, T_i and n_e measured inside the top of the barrier at the onset of the type I ELM. We next assume that at this time the edge pressure gradient corresponds to the ballooning stability limit, which in simple cylindrical approximation gives us an estimation of edge pressure on the top of the barrier:

$$R \cdot q^2 \cdot \frac{n_e T_e + n_i T_i}{\Delta_{bar}} \approx s \tag{1}$$

where Δ_{bar} is the width of the edge barrier and s the magnetic shear. We then make different assumptions about how Δ_{bar} scales with plasma parameters (like $\Delta_{bar} \propto \rho_{\theta i}^{th}$, $\rho_{\theta i}^{fast}$, $\sqrt{a \cdot \rho_{\theta i}^{th}}$ or Δ_{bar}= const, where poloidal Larmor radius of fast ions is defined by using the average energy of the beam ions). Finally we plot the experimental points on a $(n\text{-}T)_{edge}$ diagram and compare them with predictions from different models for Δ_{bar}. The result of such a comparison is shown in Figure 1 and allows us to conclude that the assumption that the transport barrier width scales with the poloidal Larmor radius of fast ion gives the best agreement with experiment. It should be noted however that the experimental error bar is so large that at present we can not exclude some other scalings like $\Delta_{bar} \propto \sqrt{\rho_{\theta i} \cdot a}$.

A similar comparison has been made for a series of Hot ion H-mode discharges with the same heating power but different isotope composition of both NBI and the main plasma [10]. Figure 2 shows that in this case the measured edge pressure also scales linearly with the poloidal

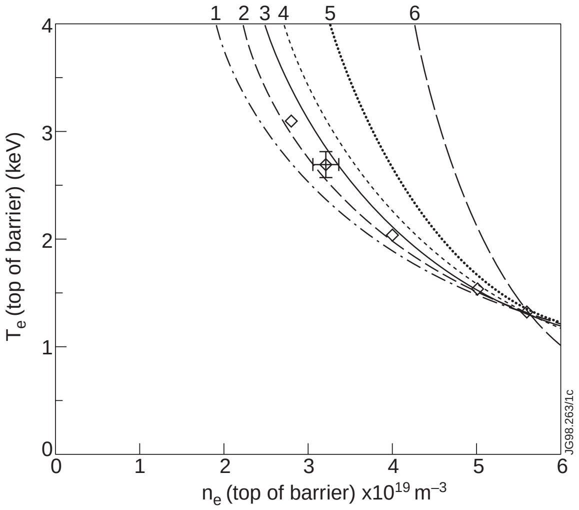

Figure 1. Comparison of the different models for the dependence of the transport barrier width Δ on the local plasma parameters (1- Δ= const; 2 - $\Delta \propto \rho_{\theta i}^{fast}$ *; 3 -* $\Delta \propto \sqrt{\rho_{\theta i}^{th} \cdot a}$ *; 4 -* $\Delta \propto \sqrt[3]{\rho_{\theta i}^{2} \cdot a}$ *; 5 -* $\Delta \propto \rho_{\theta i}^{th}$ *; 6 -* $\Delta \propto \lambda_{ion} \propto \frac{V_{neut}}{\langle \sigma v_e \rangle_{ion} \cdot n_e}$ *and diamonds - experimental data. All curves are normalised to* $n_e = 5.6 \cdot 10^{19}\, m^{-3}$.

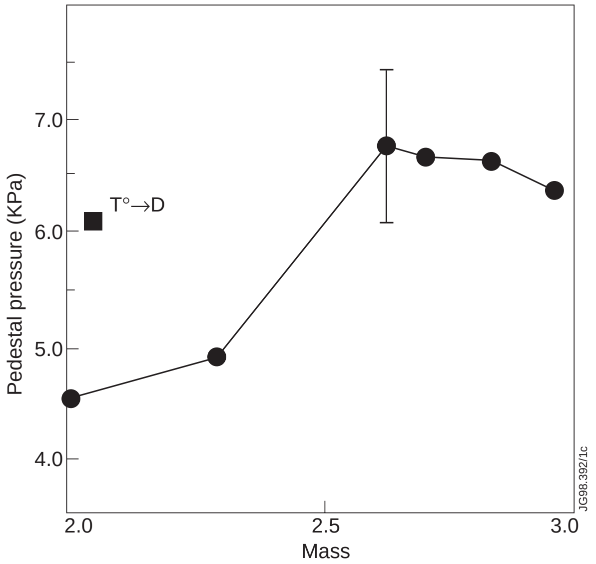

Figure 2. The dependence of the thermal plasma pressure on the top of the transport barrier at the end of the ELM-free period on the edge plasma composition for the hot-ion H-mode JET discharges in D, T and D-T mixture (circles- discharges with identical plasma and NBI composition, square- pure T beam into pure D plasma) .

ion Larmor radius. In most of selected discharges the isotope composition of the NBI was exactly the same as for the main plasma and therefore we can not separate the dependence of the transport barrier width on either fast or thermal ions. However, one discharge in this series had a pure deuterium plasma with a pure tritium NBI source (# 42656). This outstanding shot has an edge pressure which clearly put it together with other tritium rich discharges and allows us to conclude that in this case the edge transport barrier width is controlled by the fast ion Larmor radius.

III. ROLE OF FAST PARTICLES.

If indeed the width of the edge transport barrier is controlled by the fast ions Larmor radius in discharges with strong NBI heating then the question arises: how many fast particles should be present near the separatrix in order for them to control the transport barrier? To answer this question we assume that the main mechanism of the turbulence suppression which leads to the formation of the transport barrier is the shear in plasma rotation [11]. We will also assume that in case of the edge transport barrier the main source of such rotation comes from a non ambipolar ion losses [12]. To evaluate the characteristic width of the region with a strong rotation we suppose that the heating power significantly exceeds the L-H transition power threshold. That means the plasma turbulence is completely or almost completely suppressed within the transport barrier. Since in this case the only remaining transport near the separatrix is a collisional, neoclassical transport, we might expect that the characteristic width of the region with strong radial electric field is controlled by the perpendicular mean free pass length of escaping ions. If the edge plasma contains thermal ions only the ion banana width $\Delta_{bar} \approx \sqrt{\varepsilon} \cdot \rho_{\theta i}$ is the only parameter which determines the width of the transport barrier. Now let us assume that the edge plasma is composed of thermal ions and suprathermal beam ions with the characteristic energy $E_b >> T_i$ and beam density $n_b << n_e$. In this case we have two parameters which might control the width of the transport barrier: the banana width of thermal ions $\Delta_{th} \approx \sqrt{\varepsilon} \cdot \rho_{\theta i}$ and the banana width of suprathermal ions $\Delta_{sup.th} \approx \sqrt{\varepsilon} \cdot \rho_{\theta beam}$.

We can make a simple estimation of what kind of electric field we might expect from the escape of fast particles. To do this we will use a radial projection of the ion's momentum balance equation:

$$e(n_b + Z_i n_i)E_r = e n_i (v_{i\theta} B_\phi - v_{i\phi} B_\theta) - \nabla (n_i T_i + n_b E_b) \tag{2}$$

For a rough estimation of the electric field we can neglect both poloidal and toroidal plasma rotation in (2). If we also assume that the characteristic radial length of the fast particle inhomogenuity is of the order of their banana width we can obtain the following estimate for the fast particles contribution to the radial electric field E_r^{beam}:

$$E_r^{beam} \approx \frac{n_b E_b}{n_e \cdot \sqrt{\varepsilon} \cdot \rho_{\theta beam}} \tag{3}$$

This electric field becomes significant only if it can stabilise the plasma turbulence by itself. To do so, it should induce a shear in rotation $\omega_{E\times B}^{beam}$ stronger than the characteristic growthrate of the turbulence γ_{max}:

$$\omega_{E\times B}^{beam} \approx \nabla \frac{E_r^{beam}}{B} \approx \frac{n_b \cdot \omega_{\theta beam}}{n_e \cdot q} \geq \gamma_{max} \propto \frac{v_{Thi}}{q \cdot R}; \quad or \quad \frac{n_b}{n_e} \geq \frac{\rho_{\theta i}}{R} \tag{4}$$

Interestingly, inequality (4) depends on the number of fast particles, not on their energy. One should remember however that the width of the transport barrier does depend on the fast particles energy, if (4) is satisfied:

$$\Delta_{beam} \propto I_p^{-1} \cdot \sqrt{E_{beam} \cdot A_{beam}} \tag{5}$$

The conclusion which we can draw from (4) is that the number of fast particles which is necessary to produce a wide transport barrier is in excess of one percent of the plasma density. TRANSP analysis show that inequality (3) can be easily satisfied in the case of NBI heating since NBI always has a significant source of fast ions produced near the separatrix by charge exchange with thermal ions. The situation is notably different in the case of ICRF heating. Even if the minority heating scheme is used, the position of the cyclotron resonance is usually far from the separatrix and practically there are no fast particles near the plasma edge. Therefore we can conclude that the width of the transport barrier is controlled by thermal ions in case of ICRF heating and by fast ions in case of NBI heating. This can explain the experimentally observed strong difference between NBI and ICRH in type I ELM behaviour and in the edge pressure.

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