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ABSTRACT.

The question whether density profiles in future burning plasmas such as in ITER will be flat or peaked has attracted considerable attention. The reason is that increased density peaking has consequences on the overall characteristics of the plasma. When pedestal density is fixed density peaking increases fusion power, energy confinement and bootstrap current. On the other hand peaking reduces the neoclassical tearing mode beta limit and may also lead to impurity accumulation. In a burning plasma only a turbulence-driven particle pinch can result in peaked density profiles because neo-classical pinch is too weak. The turbulence-driven particle pinch seems to be proven in L-mode plasmas [1] and it is supported by the theory of turbulence equipartition or thermodiffusion [2]. Its existence in ELMy H-modes is still, however, an open question [1, 3, 4]. Also from theory point of view the situation is not clear as the direction of the turbulence-driven particle flux may depend on other parameters such as T_e/T_i ratio [2]. This paper reports on a further investigation of the density profiles in stationary H-mode. The numerical studies of the subject and recent L-mode data are presented in the accompanying paper [5].

1. EXPERIMENTAL CONDITIONS.

So far density peaking studies were motivated mainly by an effort to increase the line averaged density $\bar{n}$ relative to Greenwald limit n_{Gr}. However, the ratio $\bar{n}/n_{Gr}$ is not an independent dimensionless number and it is correlated with other core dimensionless parameters. One of the strongest correlation is with the core collisionality. Figure 1 illustrates this by plotting the ELMy H-mode JET data in the International Confinement Database. It is seen that the plasmas with $\bar{n}/n_{Gr} \approx 1$ have the volume averaged collisionality more than an order of magnitude larger than the ITER value. Thus even a weak dependence of the core turbulence on collisionality would mean that the high density plasmas on JET do not represent the core transport expected for ITER conditions. The collisionality dependence of the core turbulence is not yet clear. A weak dependence of the core thermal diffusivity is measured in dimensionless scans ($\chi \propto \nu_*^{0.4}$) [6]. On the other hand an increase of trapped electron mode turbulence is predicted towards low collisionalities [7]. In order to map the dependence of density profiles on collisionality we have scanned ν_* from values corresponding to $\bar{n}/n_{Gr} \approx 1$ down to the values as close as possible to ITER. Simultaneously we restricted ourself to the ELMy H-mode with $q_{95} \approx 1$ and $T_e \approx T_i$. To minimise the beam fuelling we aimed to replace the beam heating by RF heating as much as possible. For this hydrogen minority heating were used at fundamental harmonics (plasma current $I_p = 2.8$MA, toroidal field $B_T = 2.7$T). The plasmas were sawtoothing with moderate 3/2-neoclassical tearing mode. Example of the density profile in such plasmas is shown in Figure 2. The full line represents the average of several LIDAR profiles over a period of ~1 s in order to reduce the noise level and to allow to calculate the density gradients. To avoid the effect of sawteeth and ELMs we concentrate on the “gradient zone” given by normalised poloidal (toroidal) flux coordinates $\psi_N = 0.35 - 0.8$ ($\rho = 0.3$-0.7) respectively.

2. RESULTS

Figure 3 shows the density peaking as a function of collisionality parameter for selected ELMy H-mode plasmas. At high ν_* moderately peaked profiles are obtained with balanced gas puffing and beam power (Pulse No: 52979 [3]) although flat profiles are observed at high densities as well. Systematic experiments were performed to produce ELMy plasmas with ITER-like collisionality and RF dominant heating to minimise the core fuelling. The results of these experiments are plasmas with ν_* down to 1.5× of the ITER value for the reference ELMy H-mode scenario. It is seen that at low ν_* only peaked density profiles are observed (Figures 2 and 3). The RF power, $P_{RF} \approx 6MW$, is larger than beam heating power $P_{NB} \approx 4MW$, although still somewhat lower than ideal. As a result these plasmas are in type-III ELMy regimes. This absence of type-I ELMy plasmas with RF heating at low collisionalities leaves still the room open for a possible correlation between the density peaking and the plasma edge. Note that in low density RF heated L-mode plasmas the densities are peaked and it is concluded that it is due to the anomalous pinch [1]. Clearly more experiments are required to extent the JET database in this important parameter range.

A q-scan (by changing I_p) has been performed with NBI heating at the higher end of collisionality range in Figure 3. The density profiles in this scan are shown in Figure 4. It is seen that profiles become more peaked with increasing q_{95}. There is a possibility that in our case flattening of density profile at higher I_p is correlated with higher core temperature. However, at least in L-mode plasmas, the correlation between the peaking factor for density and temperature is not observed so far in JET [5]. Therefore the correlation of density profiles with q-profiles may be pointing towards the curvature driven pinch as observed in L-mode plasmas on TCV [8] and JET [1].

3. TRANSPORT ANALYSIS.

Conventionally the particle velocity V is defined from the equation:

$$\frac{\Gamma_e}{n_e} = -D_e \frac{\nabla n_e}{n_e} + V \tag{1}$$

where Γ_e is the electron flux density through the particular magnetic flux surface, n_e is the electron density, ∇n_e is the electron density gradient and D_e is the electron diffusivity. Solution of equation (1) is ambiguous and it depends on knowledge of D_e. Here we use the assumption that the ratio of electron particle and heat diffusivities is $D_e/\chi_e = 1/3 - 1/2$. The quasi-linear theory and fluid simulations using the model described in [4] give the ratio $D_e/\chi_e \approx 1/2$ the value somewhat lower than obtained by random walk argument ($D_e/\chi_e \approx 2/3$). Note that in our case discussed below the electron and ion heat diffusivities at mid-radius $\chi_e \approx 0.5\ \chi_i \approx 1m^2/s$ are much larger than ion neoclassical value $\chi_{i\ NC} \approx 0.05m^2/s$ so that the ratio D_e/χ_e is determined by turbulence only. Under the assumption $D_e/\chi_e =$ const, the particle velocity V is the difference between two independent terms: Γ_e/n_e, and the term related to the electron heat flux, q_e: $D_e\ \nabla n_e/n_e \propto q_e/(n_e T_e) \times (\nabla n_e/n_e)/(\nabla T_e/T_e)$. The balance of these terms for Pulse No: 58894 is shown in Fig.5. In this plasma $T_e/T_i = 1$ and electron to ion energy flux ratio is 0.7 at mid-radius. Particle and heat fluxes are calculated by TRANSP code. The particle flux at ρ ~0.5 is sum of two approximately equal terms: the beam and wall neutrals. The beam term is known with a good accuracy as illustrated by good agreement between TRANSP and JETTO codes. The flux due to wall neutrals is calculated by TRANSP using the FRANTIC code [9, 10, 11] with boundary conditions set to match the gas valve rate and integrated wall D_α photon flux. The flux agrees within 10% by standalone FRANTIC calculations that include the edge density from Li-beam diagnostics. Large contribution of the wall neutrals in the balance (~10cm/s) remains the source of the large uncertainty in the present analysis. Nevertheless, it is seen that at ρ ~0.5 the particle and heat flux terms are about ten times larger than the Ware pinch velocity (2cm/s). Consequently the inferred value of particle velocity could reach ~20cm/s unless the ratio D_e/χ_e adjusts locally within 10% to the ratio of particle-to-energy fluxes (Fig.5).

CONCLUSION.

Moderately peaked density profiles are found under the conditions of ELMy H-mode, with ITER-like collisionality, significant RF heating, $T_e/T_i = 1$ and $q_{95} = 3$. Particle balance shows that inferred particle velocity might locally reach tens of cm/s. However, the uncertainty remains large and further work is needed to improve the prediction of density profile for ITER.

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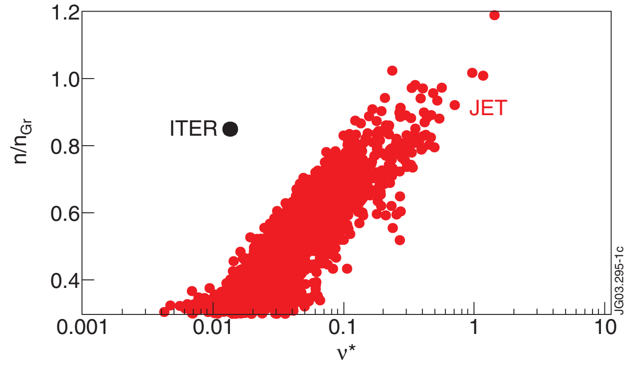

Figure 1: Correlation between density normalised to Greenwald density and volume averaged collisionality for JET data in the international ELMy H-mode confinement database DB3V8.

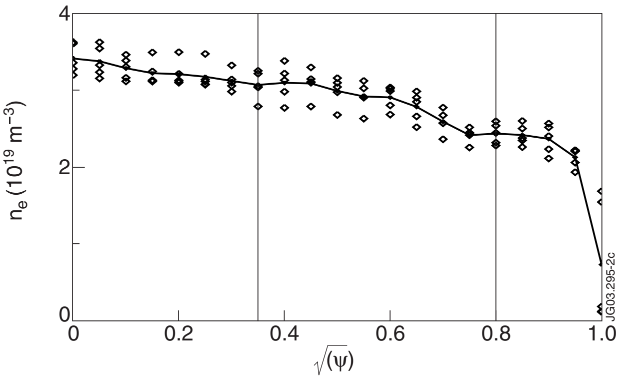

Figure 2: Density profile for Pulse No: 58894. The circles are the LIDAR data mapped to poloidal flux and solid line is the averaged profile over the t = 22.7-23.9s

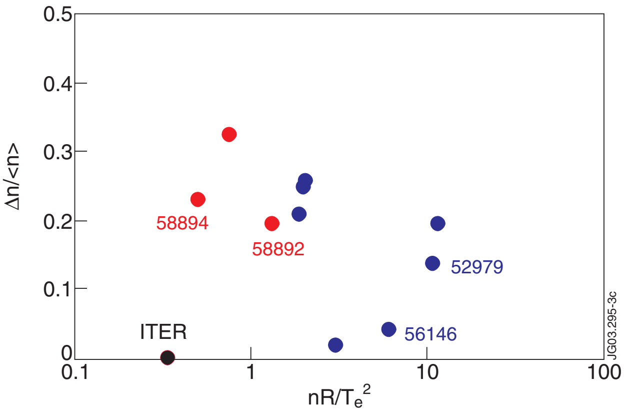

Figure 3: Density peaking $\Delta n/\langle n\rangle = -(n_{35} - n_{80})/[(n_{35} - n_{80})/2]n$ *as a function of collisionality parameter. Indices refer to flux label* $\sqrt{\psi}$*. Red symbols represents plasmas with* $P_{RF}>P_{NB}$.

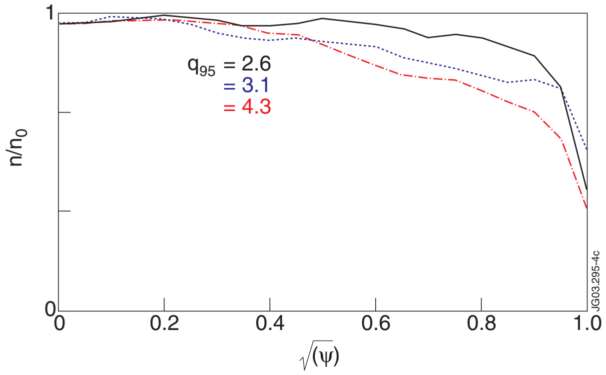

Figure 4: Density profiles normalised to the central value for different safety factors.

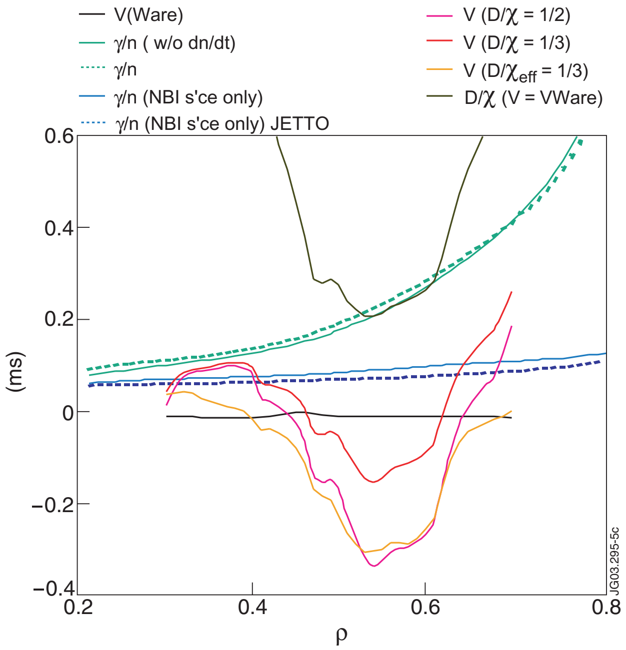

Figure 5. Calculated pinch velocities V from equation (1). Calculations by TRANSP for Pulse No: 58894 at t = 23s. Spatial derivatives are averaged over 22.5-23.5s. The terms due to NBI particle source are shown for comparison as calculated by TRANSP and JETTO as well as the ratio D_e/χ_e *needed for* $V = V(Ware)$ *.*