EUROPEAN FUSION DEVELOPMENT AGREEMENT
JET

EFDA–JET–PR(04)14

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** See annex of J. Paméla et al, "Overview of Recent JET Results and Future Perspectives", Fusion Energy 2000 (Proc. 18th Int. Conf. Sorento, 2000), IAEA, Vienna (2001).*

Preprint of Paper to be submitted for publication in
Plasma Physics and Controlled Fusion

ABSTRACT.
Low collisionality, low particle source, ELMy H-modes (type-III) with sawteeth are produced in JET in order to address the question of the density profile evolution in the reference $q_{95} = 3$ ITER scenario. By replacing a significant part of the neutral beam heating by RF power the particle flux at mid-radius has been reduced to $\Gamma/n_e = 0.17$m/s with up to one half being due to the wall neutrals. Density profiles are found modestly peaked in these conditions with a relative density difference of $\Delta n/\langle n\rangle = 0.23$ across the zone not affected by sawteeth and ELMs. In a region around mid-radius the effective particle diffusivity drops to $D_{e,eff} \approx 0.2\,\chi_e$ that could indicate an anomalous pinch. The data are in contrast with the present ITER model that has higher particle diffusivity ($D_{e,eff} \approx \chi_e$).

1. INTRODUCTION

The question whether density profiles in future burning plasmas such as in ITER will be flat or peaked has recently attracted considerable attention. The reason for this is that shape of the density profile has consequences on overall characteristics of the plasma. When the 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 the neo-classical pinch is too weak. The turbulence-driven particle pinch seems to be proven in L-mode plasmas [1, 8] 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 the 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]. Numerical studies on this subject and recent L-mode data are presented in [5].

So far density peaking studies were motivated mainly by an effort to increase the line average 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 correlations 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 $n/n_{Gr} \approx 1$ 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 may not represent the core transport expected for ITER. 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] with anomalous particle pinch as a consequence.

This paper reports on a new investigation of the density profiles in stationary H-modes under conditions similar to reference ITER scenario.

2. EXPERIMENTAL CONDITIONS

In order to map the dependence of density profiles on collisionality we have scanned collisionality 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 sawtoothing ELMy H-mode with safety edge factor $q_{95} \approx 3$ and electron and ion temperatures $T_e \approx T_i$. Figure 2 shows the density peaking as a function of collisionality parameter for selected ELMy H-mode plasmas. The density peaking is characterised by density difference $\Delta n/\langle n\rangle$ rather than a local density scale length. The reason is that it is impossible to characterise the density profile in the gradient zone by a single density scale length and typically the gradient increases with increasing radius. The difference $\Delta n/\langle n\rangle$ is taken across the zone that is not affected by sawteeth and ELMs. We bound this zone by normalised poloidal (toroidal) flux coordinates $\sqrt{\psi_N}$ = 0.35–0.8, (ρ = 0.3–0.7 respectively and it is marked in figure 3 by vertical lines. In order to reduce the noise level the LIDAR density profiles are averaged over a period of 1s.

It is seen from figure 2 that at high collisionality the density peaking data are scattered. On the one hand flat density profiles are observed as for example JET Pulse No: 56146 while with careful balance between gas puffing and beam heating power moderately peaked profiles are also achieved as illustrated by JET Pulse No: 52979 [3]. However as mentioned above it is difficult to extrapolate the particle transport characteristics from these high collisionality beam heated plasmas to ITER conditions. Figure 2 shows also the data from medium collisionality plasmas (JET Pulse No: 47743 and JET Pulse No: 47744) previously described in [18]. These type-III ELMy H-modes are part of the scan of increasing RF heating power while the total heating power was held constant. It is seen from figure 2 that the plasma with higher RF power has flatter density profile.

To access ITER-like collisionality systematic experiments were performed. To minimise the beam fuelling we aimed to replace the beam heating by RF heating as much as possible. For this hydrogen minority heating at fundamental harmonic ICRF (42MHz) was used (plasma current I_p = 2.8MA, toroidal field B_T = 2.7MA, minor radius $a = 0.95$m). The RF power, $P_{RF} \approx$ 6MW, is larger than beam heating power $P_{NB} \approx$ 3.5-4MW. At mid-radius the electron-to-ion heat flux ratio is ~0.7 as calculated by TRANSP. The ion and electron temperatures are almost equal for this plasmas with values $T_e \approx T_i \approx$ 4keV at ρ = 0.5. Figure 3 shows the density profile for such a plasma.

The effective charge is measured from carbon charge exchange and for the plasma in Fig.3 at mid-radius Z_{eff} (C)≈ 1.7 In these RF heated plasmas nickel is expected a dominant high-Z impurity. However, chord-averaged relative concentration of NiXXVI is found to be rather too low, $(1.5\div3)\times10^{-4}$, to contribute significantly to Z_{eff}. Thus the correction to collisionality in Fig.2 from the effective charge is not large and the plasma of JET Pulse No: 58894 represents the collisionality approximately ×2 higher than in the ITER nominal plasma.

The plasmas of JET Pulse No: 58894, and those in its neighbourhood are sawtoothing and typically m=3, n=2 neoclassical tearing modes are excited at the beginning of flat top of ICRH power. In order to minimise the possible effect of tearing mode on particle transport we have repeated the JET Pulse No: 58894 with modified RF heating with the aim to reduce the sawtooth amplitude

[16]. A slower ICRF power ramp and shifting the resonance from the magnetic axis to the inner q=1 surface for 50% of the heating power resulted in a reproducible suppression of the m=3, n=2 neoclassical tearing mode. The sawtooth period during the RF flat top phase, however, was not changed significantly and thus the question which of these two actions improved tearing mode stability remains open. The effect of suppression of neoclassical tearing mode on global density peaking parameter $\Delta n/\langle n \rangle$ is found to be small. This is seen from Fig. 2 where the data from shots without m=3, n=2 neoclassical tearing mode (JET Pulse No's: 61109, 61164) are a good reproduction of the plasma JET Pulse No: 58894 in which the mode was present.

Plasmas represented by the shot in Figure 3 are in type-III ELMy regimes. This is an unwanted consequence of the attempt to maximise the fraction of RF heating power which is only possible at low total power below transition to type-I ELMy regime. The relatively low level of RF power is also the reason that additional neutral beam heating is used to enter the H-mode regime but this power was deliberately kept low to minimise particle source. The absence of type-I ELMy plasmas with RF-only heating at low collisionalities leaves still the room open for a possible correlation between the density peaking and the plasma edge. Such correlation between ELM character and density peaking could be explained only if ELMs generate global transport events affecting the particle transport at mid-radius. Such an effect, however, was not reported for type-III ELMs and would invalidate the generally accepted concept of local transport. Another possible correlation could come from stiffness of temperature profiles. Lower pedestal temperature in type-III ELMy H-mode could mean higher level of turbulence in the confinement region than in type-I ELMy regime. This in turn could be enhancing the turbulence driven pinch in respect to its level in type-I regime. Note, however, such effect would require that anomalous diffusivity and pinch velocity have different dependence on turbulence amplitude.

In summary is it seen from Fig.2. that the group of plasmas described above has reached the collisionality (Z_{eff} corrected) approximately 2× of the value for the reference ITER ELMy H-mode scenario. At low collisionality only peaked density profiles are observed in contrast to high collisionality cases. The density peaking, however, is relatively modest. The question whether this is the evidence for anomalous particle pinch or it is the result of particle sources is addressed below.

3. PARTICLE FLUX

The existence of an inward particle pinch should be ideally demonstrated in a plasma with zero particle flux. Inward pinch is then manifested by a peaked density profile. As mentioned above such conditions are difficult to achieve and the particle flux is not negligible. The total flux is the sum of two terms: the contribution from neutral beam and contribution from neutrals penetrating from the wall. The contribution from neutrals produced by radiative recombination of the main ions is small in our case due to high temperature and low density. In principle there is also a contribution due to the temporal changes of electron density but in our stationary conditions this term is small. Figure 4 shows the electron flux density through the particular magnetic flux surface

Γ_e normalised to local electron density n_e. The figure shows the total flux and the flux due to the neutral beams. The difference between these two is the flux caused by wall neutrals.

The particle flux due to the neutral beams is calculated by TRANSP code using Monte-Carlo method and by JETTO code using Fokker-Planck equation. It seen from Fig.4 that the fluxes given by these two codes are in relatively good agreement and the out-flux at mid-radius is equivalent to Γ_{Beam}/n_e = 0.074m/s.

The second contribution to the outward particle flux is due to the neutrals penetrating into the core region. This inward particle flux of neutrals is calculated by 1.5-D FRANTIC, code [9, 10, 11] implemented into TRANSP. FRANTIC performs neutral gas transport calculation for tokamak core plasmas, taking into account charge exchange and impact ionization atomic reactions in a simplified nested cylindrical flux surface geometry. The boundary conditions are set to match the gas valve rate and the integrated D_α photon flux. For our conditions the calculated flux at mid-radius due to wall neutrals is equivalent to Γ_{Beam}/n_e = 0.093m/s i.e. approximately equal to the particle flux due to the neutral beam (Figure 4).

The fact that neutrals from the wall may play a role in the particle balance at mid- radius has been reported on TFTR [19], however, it is still somewhat surprising for large plasma as on JET. Therefore this result has been checked by standalone FRANTIC code. In addition to core LIDAR data we added also the edge density profile from Li-beam diagnostics. In these calculations the neutral atom density outside the plasma is adjusted to match the total measured D_α photon flux (2.6×10^{21} photons/s). To match this level of photon flux the neutral atom density outside the plasma is set to $n_0\,(r/a = 1.06) = 4.7 \times 10^{16}\,m^{-3}$. With this setting the standalone FRANTIC gives normalised flux velocity at mid-radius of Γ/n_e = 0.1m/s which agrees within 10% with calculations given by FRANTIC imbedded inside TRANSP.

To understand further how the rather small number of neutrals that are present in the core on the JET plasmas may generate significant particle flux we can calculate the influx of neutrals at the mid-radius. When the mean free path of charge exchange is shorter than the density and temperature gradients the kinetic theory for neutral flux gives [13]:

$$\Gamma_0 = n_0\,\lambda_{cx}\sqrt{\frac{T_0}{m_i}}\left(-\frac{\nabla n_0}{n_0} - 0.76 - \frac{\nabla T_0}{T_0}\right)$$

where $\lambda_{cx} = (2.93\sigma_{cx}\,n_i)^{-1}$, is the mean free path of charge exchange. At ρ = 0.5 the calculated neutral density is $n_0 = 2.0 \times 10^{13}\,m^{-3}$ with $n_0/\nabla n_0$ = 0.22m. The neutral temperature is close to ion temperature $T_0 \approx T_i$ =4keV with scale length $T_0/\nabla T_0 = -0.76$m. At this temperature and ion density $n_i = 3.0 \times 10^{19}\,m^{-3}$ the mean free path is λ_{cx} = 0.098m ($n_i = 3.0 \times 10^{19}\,m^{-3}$, $\sigma_{cx} = 1.1 \times 10^{-19}\,m^2$ [14]) giving the neutral influx of:

$$\Gamma_0 = -\,2.8 \times 10^{18}\,s^{-1}\,m^{-2}$$

This value has to be compared with the outflux of electrons calculated from the ionisation source from wall neutrals inside the volume ρ = 0.5:

$$\Gamma = r \int_0^{r/a} S\rho d\rho \Big|_{r/a = 0.5} = 3.0 \times 10^{18}\ s^{-1}\ m^{-2}$$

The good agreement between these two fluxes confirms the internal consistency of calculation of electron flux due to the wall neutrals.

The above results have been obtained for energy of edge neutrals E_0 = 5eV. To reveal sensitivity of the core neutral density to the choice of energy of edge neutrals we performed further sensitivity studies while other parameters were unchanged. For example for E_0 = 0.55eV the neutral density at mid-radius is found to be $n_0 = 0.8 \times 10^{13}\ m^{-3}$. Published spectroscopy data [11] suggests that the edge neutrals may be a 50%-50% mixture of particles with energies of E_0 = 0.55eV and E_0 = 5eV. For this mixture electron flux due to wall neutrals then would be Γ_{wall}/n_e = 0.07m/s and total flux would be 25% smaller than shown in Fig.4. Therefore we conclude that the uncertainty in energy of edge neutrals, though significant, has no large impact on calculated particle flux.

The largest uncertainty in calculation of neutral particle flux comes from the poloidal asymmetry of the D_α emission. In above calculations all emission (main chamber plus divertor) has been included in 1.5-D FRANTIC modelling. However, because of low level of gas puff most of this emission (~90%) originates in divertor region. However, due to the complex geometry of divertor such a choice clearly represents the upper limit for D_α emission. Somewhat indirect checks of how much of the divertor emission has to be included can be made by calculating the effective electron diffusivity just inside the separatrix. If all D_α emission from divertor is included than the average effective diffusivity (assuming no pinch) between separatrix and top of the pedestal (r/a = 0.95÷1) is found to be $D_{e,\ eff} \approx 0.8m^2/s$. If all divertor region is excluded, D_{eff} would be reduced tenfold. Such a value seems to be very low for region dominated by ELMs. This could be and indication that most of the divertor D_α emission has to be taken into account when calculating the neutral source in the core.

The uncertainty of how much of divertor neutrals contribute to the particle source in the plasma can be answered only by detailed 2D modelling of neutral distribution. In this contexts we refer to the recent very detailed study in [17] using EDGE2D code to analyse the ELMy H-mode plasmas with NBI heating and plasma densities somewhat higher that our case from fig.4. In this study the neutral density in the core is found to be lower than in our case and consequently the particle flux is given only by neutrals beams. When FRANTIC and EDGE2D codes are ran for the case in [17] so that they match the D_α emission in the main chamber (excluding divertor region) the calculated neutral densites agree within 30%. Therefore, as expected, the problem is reduced to modelling of neutrals in a region around the X-point. 1.5D-modelling inevitably underestimates the flux expansion in the divertor area that can result in overestimation of the neutral flux from the divertor. From the other side the lower penetration of neutrals from divertor to the core calculated by EDGE2D may be a consequence of low ion temperature at separatrix around the X-point in EDGE2D. As a consequence of such a temperature drop is a extremely large electron density gradient across separatix around the X-point indicating very low turbulence in this region. It is therefore possible that neutrals influx from divertor is linked to the level of the plasma particle transport around X-point. It is, however, outside the scope of this paper quantify such relationship.

Up to this point we conclude that in JET ELMy H-mode plasma designed to match the ITER collisionality the minimum particle flux achievable is still relatively large. The upper the upper limit for electron flux at mid-radius is Γ/n_e = 0.17m/s. This value is almost an order of magnitude larger than the expected in ITER and much larger that Ware pinch velocity V_W = 0.02m/s (see Fig. 4). Aproximatelly one half of this flux is to the wall neutrals if all divertor flux is included. The large uncertainty in what fraction of this flux has to be included for calculation of neutrals in the core imposes the accuracy of determination of the anomalous pinch. If divertor region is excluded the electron flux at mid radius reduced by factor of two and as shown below the evidence for anomalous particle pinch will be stronger. It has to be noticed that significant flux due the wall neutrals is a property of low collisionality (lower density) plasmas and as such is not typical for JET and unlikely for ITER. This case has been chosen deliberately to create the collisionality conditions as close as possible to ITER nominal plasma. This complication again underlines the importance of case-by-case analysis of particle sources before statements about character of particle transport are made.

4. PINCH VELOCITY

Conventionally the particle velocity V is defined from the equation:

$$\frac{\Gamma}{n_e} = -D_e \frac{\nabla n_e}{n_e} + V$$

where, ∇n_e is the electron density gradient and D_e is the electron diffusivity. It should be noted that such a linear dependence already assumes that the turbulence driving the particle flux does not depend on the density gradient itself. In the practically important case with $\Gamma > 0$ the solution of equation (1) is ambiguous and the inferred value of pinch velocity depends on the assumption on D_e. In the case when transport is dominated by turbulence basic theoretical considerations predict that the particle diffusivity is linked to heat diffusivity. For the case in Fig.4 the condition for turbulence driven transport is well satisfied because electron and ion heat diffusivities at mid-radius are $\chi_e \approx 0.5\, \chi_i \approx 1m^2/s$ while ion neoclassical heat diffusivity is $\chi_{i\,NC} \approx 0.05m^2/s$. The quantitative relationship between particle and heat diffusivities are not well known. For electrostatic turbulence the random walk argument provides the ratio D_e/χ_e = 2/3. In order to quantify this ratio more accurately non-linear simulations using the model described in [2] were performed. These calculations provide the ratio $D_e/\chi_e \approx$ 0.3-0.4 and this value is rather constant across the gradient zone. Simulations were done with deliberately large central particle source so that the correction to particle flux from pinch is small and $D_e \approx -\Gamma/\nabla n_e$.

Figure 5 shows the ratio of particle to heat diffusivities D_e/χ_e if no anomalous pinch is assumed ($D_{eff} = D_e$ ($V = V_{Ware}$). It is seen that the ratio has a minimum of $D_{eff}/\chi_e = 0.15-0.2$ in the region between $\rho \approx 0.5-0.7$. Note that without contribution of wall neutrals this minimum would be even lower ($D_{eff}/\chi_e = 0.1$). The region of low diffusivity coincides with zone of steeper density gradient where time-averaged density scale-length drops to $L_n \approx 1$m. The zone of low D_{eff}/χ_e extends deeper into the centre for plasma without m=3/n=2 neoclassical tearing mode (JET Pulse No: 61109) in comparison with plasma with such a mode (JET Pulse No: 58894). This may be an effect of mode on anomalous transport although this has not been studied in detail. This important aspect of particle transport deserves further attention.

The minimum of D_{eff}/χ_e is lower than the value predicted by available theories. However, whether this discrepancy means an existence of anomalous pinch is impossible to answer because the particle flux in our case is still not zero. We can only speculate that if the dependence of particle flux on density gradient is linear (eq 1) with the diffusivities ratio, say $D_{eff}/\chi_e = 0.3$, than the inferred pinch velocity will be $V \approx -(0.1\text{-}0.2)$m/s or $V/D_e \approx 0.4^{-1}$ at $\rho \approx 0.6$. Note, that it is the regime with very low particle flux we need to extrapolate because in the ITER reference scenario the normalised flux, Γ/n_e, is smaller than in our JET case.

Finally, it has to be noticed that the data presented in this paper are in contrast with the present model for particle transport used for ITER. This difference is independent of interpretation (with or without anomalous pinch). In this model the anomalous pinch is set to zero and the ratio of particle and heat diffusivities is assumed $D_e/\chi_e = 1$ [15]. On one hand such models could underestimate fusion performance as they lead to flat density profiles. On the other hand, however, in this model the helium particle diffusivity is chosen in the form of $D_{He} = D_e$ what could lead to overestimation the helium exhaust capability of the plasma. This discrepancy between model and data clearly justify further studies aimed to improve our particle transport model under ITER relevant conditions.

CONCLUSION

Dedicated experiments have been performed in JET to produce ELMy H-mode plasmas with ITER-like collisionality, significant RF heating, $T_e/T_i \approx$ and $q_{95} = 3$. Modestly peaked density profiles are found under these conditions. Particle balance shows that the outward flux at mid-radius is still significant in these plasmas and thus uncertainty in determination of anomalous pinch velocity remains large. It is found that at low collisionality the ratio of particle-to-thermal diffusivities drops at mid-radius to values as low as $D_{e,\,eff}/\chi_e \sim 0.2$ if no anomalous pinch is assumed. If particle flux due to wall neutrals is negligible this value are even lower. Low values of particle diffusiovitis can be interpreted as an indication for an anomalous pinch if particle flux depends linearly on density gradient. Independent of interpretation these data are in contrast with standard model for particle transport used for ITER. Clearly further work is needed to expand the database, in particular towards high RF power and relevant collisionality, in order to improve the prediction of the density profiles for future burning plasma experiments.

ACKNOWLEDGEMENT

This work has been conducted under the European Fusion Development Agreement and was funded partly by the United Kingdom Engineering and Physical Sciences Research Council and by EURATOM. R. B. was supported by US DOE contract DE-AC02-76CH)3073. O. S. and H. W. were also supported by Swiss National Science Foundation.

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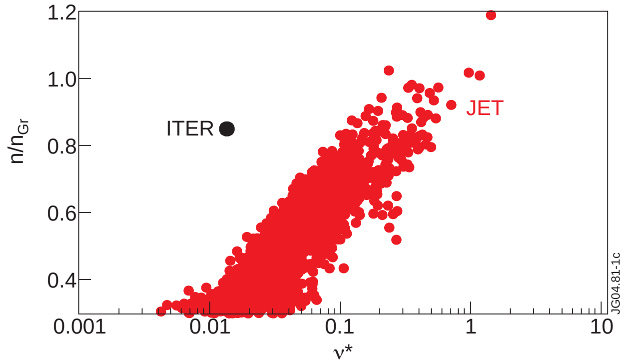

Figure 1: Correlation between density normalised to Greenwald density and volume averaged collisionality for JET data in the international ELMy H-mode confinement database DB3V8.

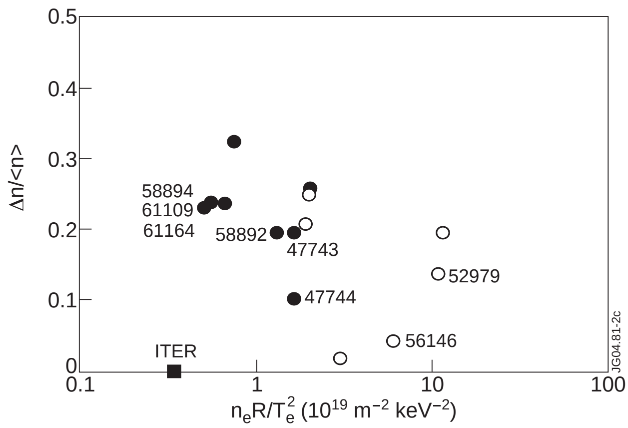

Figure 2: Density peaking $\Delta n/n\,\langle n\rangle = -(n_{35} - n_{80})/[n_{35} + n_{80})/2]$ as a function of collisionality parameter evaluated at mid-radius. Indices refer to % of flux label $\sqrt{\psi}$. Full symbols represents plasmas with $P_{RF} > P_{NB}$ while open symbols represent plasmas with NBI heating alone. All data are ELMing-sawtoothing with q_{95}=3. JET Pulse No: 47743 and JET Pulse No: 47744 are type-III ELMy H-modes with and P_{RF} = 7.8, 10MW resp. and q_{95}=4.1, $P_{RF} + P_{NB}$; 11MW [18].

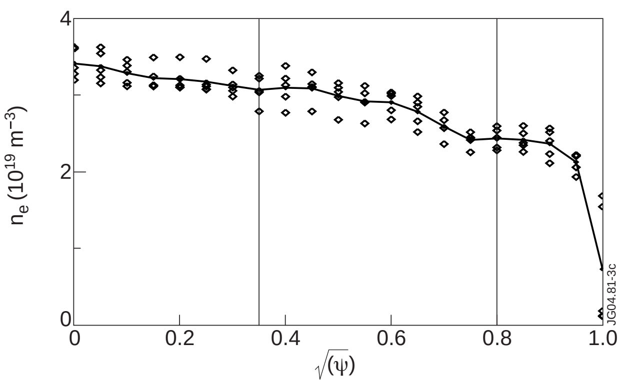

Figure 3: Density profile for Pulse No: 58894. The diamonds are the LIDAR data mapped to poloidal flux at multiple time points between. Solid line is the averaged profile.

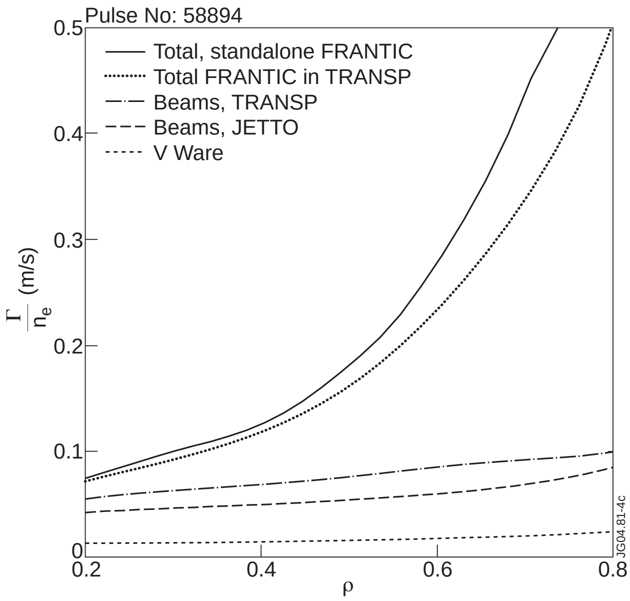

Figure 4: Calculated normalised particle fluxes for JET Pulse No: 8894 at 22.5-23.5s. Ware pinch velocity ($-V_W$) is shown for comparison.

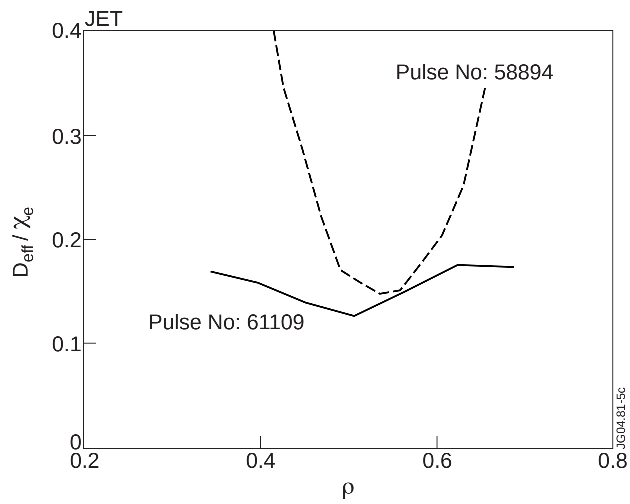

Figure 5: The ratio of effective particle and electron heat diffusivities as calculated by TRANSP. The values are averaged over 22.5 -23.5s.