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* *See Appendix 1*

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ABSTRACT.

Recently JET has been operated with beryllium limiters. This permits a much wider range of operating densities $<n_e>$ for a given plasma current I_P than was possible with carbon limiters. The edge value of the cross-field diffusion coefficient $D_\perp^{SOL}$ been deduced from Langmuir probe measurements of the density scrape-off thickness in the SOL, λ_n. It is thus possible to establish whether $D_\perp$ depends on plasma parameters, independent of any dependence on I_P, q or B. It was found that the experimental results for 3MA, 2.3T ohmically heated discharges are in fairly close agreement with the Bohm value, i.e., linearly dependent on edge temperature. The edge temperatures and densities are closely coupled, however, and the data can also be reasonably fitted by $D_\perp^{SOL} \propto n^{-1/2}_{edge}$.

Introduction

The design for the next generation of tokamaks, including ITER, requires information on the cross-field transport coefficients in the Scrape-Off Layer, SOL. In particular it is critical to know how the particle diffusion coefficient, $D_\perp^{SOL}$, and the heat diffusivity, $\chi_\perp^{SOL}$, vary with operating parameters since the operating conditions of plasma current, edge temperature, etc., may be significantly different than for existing tokamaks.

Unfortunately, there are very little data on $\chi_\perp^{SOL}$. Even for $D_\perp^{SOL}$, which can be inferred from SOL density scrape-off lengths λ_n, there is little scaling information. In a recent JET edge study,[1] where carbon limiters were employed, it was found that for ohmic heating, and for plasma currents $I_p = 1 - 5$ MA, $D_\perp^{SOL} \approx 1/\bar{n}_e$ [m^2/s], with $\bar{n}_e$ the line-averaged density of the whole plasma in [10^{19} m^{-3}]. Operated with carbon limiters, however, JET[2] could only span a small range of $\bar{n}_e$ for each value of I_p, with higher $\bar{n}_e$ corresponding to higher I_p. Thus, because $\bar{n}_e$ and I_p were effectively coupled, it was not possible to distinguish an inverse dependence of $D_\perp^{SOL}$ on $\bar{n}_e$ or I_p. Further, since it was found[2] that T_e^{SOL} decreased with increasing $\bar{n}_e$, for given I_p, the $D_\perp^{SOL}$ results could also be reasonably well approximated by the Bohm diffusion coefficient, $D_\perp^{Bohm} = 0.06\ T_e^{SOL}/B$ [m^2/s] with T_e^{SOL} in [eV], magnetic field B in [T].[3] On JET, as for other tokamaks, it is often observed that the density radial variation in the SOL follows an exponential decay with remarkable fidelity - sometimes extending over two orders of magnitude in density. From the simple model of $\lambda_n \approx (D_\perp L/c_s)^{1/2}$

where c_s is the (local) acoustic speed, this could be taken to imply that $D_\perp$ has a dependence on the (local) temperature.

During the latter part of 1989, JET was operated with beryllium limiters which made it possible to increase the operating range of $\bar{n}_e$ by about an order of magnitude, compared with the carbon limiter case, at fixed I_p. This removed the implicit dependence of n_e on I_p and made it possible to examine the dependence of $D_\perp$ on the local plasma parameters n_e and T_e which remain coupled to a certrain degree.

Modelling

The limiters consist of two complete toroidal belts located at poloidal angle $\theta = \theta_L \simeq \pm 50°$, i.e., above and below the outside mid-plane. The SOL is thus divided poloidally in two: the small-R SOL extending from the top-side of the top limiter around to the bottom of the bottom limiter, and the large-R SOL between the two belts. The edge Langmuir probes provide information on λ_n, the particle scrape-off length, in the small-R plasma. Attention here is focussed on analysing the relation between this λ_n and $D_\perp^{SOL}$. The total particle flux to the limiters (top-side of top limiter plus bottom-side of bottom limiter) is

$$\phi_\parallel = 4\pi R_L\, n\, c_s\, \lambda(\theta_L, \theta_L) \sin \psi_L \tag{1}$$

where $R_L = R(\theta_L)$, major radius of the limiter,

n = plasma density on the Last Closed Flux Surface, LCFS, assumed not to vary poloidally,

$c_s = (k(T_e + T_i)/m_i)^{1/2}$, the sound speed on the LCFS, assumed not to vary poloidally,

ϕ_L = pitch angle of $\vec{B}$ at the limiter.

Here $\lambda(\alpha, \beta)$ indicates the density scrape-off length at poloidal angle $\theta = \beta$ for the case of limiters located at $\theta = \pm\alpha$. Because the poloidal cross-section of JET is non-circular $\lambda(\theta_L, \theta)$ varies due to magnetic compression:

$$\frac{\lambda(\theta_L, \theta)}{\lambda(\theta_L, 0)} = \frac{\Delta r(\theta)}{\Delta r(0)} \tag{2}$$

where $\Delta r(\theta)/\Delta r(0)$ is provided by a magnetic equilibrium code as a function of time during each discharge, and $\Delta r(\theta)$ is the radial separation of poloidal flux surfaces.

One also has that:

$$\frac{\sin \phi_0}{\sin \phi_L} \approx \frac{B_\theta(0)}{B_\phi(0)} \frac{B_\phi(\theta_L)}{B_\theta(\theta_L)} \tag{3}$$

and[1]

$$\frac{\Delta r(0)}{\Delta r(\theta_L)} = \frac{R(\theta_L)\ B_\theta(\theta_L)}{R(0)\ B_\theta(0)} \tag{4}$$

The particle source of the SOL is assumed to be cross-field diffusion from the core plasma at $\phi_\perp$ [particles/s]. Ionization within the SOL can generally be neglected as a significant particle source for JET ohmic discharges.[4] Thus

$$\phi_{\perp} = 2 \int_{\theta_L}^{\pi} 2\pi\, R(\theta)\, D_{\perp}^{SOL} \frac{n}{\lambda(\theta_L, \theta)}\, r(\theta)\, d\theta \tag{5}$$

$$= 4\pi^2\, r(0)\, D_{\perp}^{SOL} n\, R(0)\, f(\theta_L)/\lambda(\theta_L, 0) \tag{6}$$

where $f(\theta_L)$ is a magnetic shape factor given by

$$f(\theta_L) \equiv \frac{1}{\pi} \int_{\theta_L}^{\pi} \frac{R(\theta)}{R(0)} \frac{\Delta r(0)}{\Delta r(\theta)} \frac{r(\theta)}{r(0)}\, d\theta \tag{7}$$

and is obtained from the magnetic equilibrium code. Strictly, $f(\theta)$ should be calculated for each discharge and at the time of interest; the f-values, however, are approximately constant for a given plasma elongation and thus need only be calculated once for most purposes. One thus has that

$$\frac{\lambda^2(\theta_L, 0)}{\lambda^2(0, 0)} = \frac{f(\theta_L)}{f(0)} \frac{R(0)}{R(\theta_L)} \tag{8}$$

where

$$\lambda^2(0, 0) \equiv \frac{D_{\perp}^{SOL}\, \pi\, r(0)\, f(0)}{c_s \sin \phi_o} \tag{9}$$

Finally, one obtains the desired relation between $D_{\perp}^{SOL}$ and the density scrape-off lengths at the limiters:

$$D_{\perp}^{SOL} = \frac{\lambda^2(\theta_L, \theta_L)\, c_s \sin \phi_o}{\pi\, r(0)\, f(\theta_L)} \left[\frac{R(\theta_L)}{R(0)}\right]^3 \left[\frac{B_\theta(\theta_L)}{B_\theta(0)}\right]^2 \tag{10}$$

It should be noted that in a tokamak with toroidally symmetrical limiters, quantities such as $D_{\perp}^{SOL}$ are effectively averaged poloidally due to the rapid transport along flux tubes. Thus, for example, any local dependence of $D_{\perp}^{SOL}$ on the magnitude of the total magnetic field, which varies along the flux tube, could not be extracted from measurements of λ. That is, the $D_{\perp}^{SOL}$ in Eq. (5) may, in fact, be $D_{\perp}^{SOL}(\theta)$, while the $D_{\perp}^{SOL}$ in Eq. (6) is a weighted, poloidally-averaged value.

Experimental Results

Langmuir probe measurements of $\lambda(\theta_L, \theta_L)$, hereafter simply designated as λ_n, have been obtained[4] for ohmic heating conditions with $I_p = 3$ MA, $B_{\phi m} = 2.3T$ (the value of B_{ϕ} on the major magnetic axis $R_m = 3.1m$) for values of the volume averaged density $\langle n_e \rangle$ from $0.43 - 4.4 \times 10^{19}$ m^{-3}, operating with Be limiters. Two types of Langmuir probes were employed: a fast reciprocating probe was inserted near the top of the torus providing complete radial profiles in ~0.1 sec; fixed Langmuir probes installed in the limiters provided two-point measurements of λ_n. For these conditions: $\theta_L = 50°$, $\phi_o = 12°$, $R(0) = 4.1m$, $R(\theta_L) = 3.9m$, $f(0) = 0.5$, $(\theta_L) = 0.3$, $B_{\theta}(\theta_L) = 0.38T$, $B_{\theta}(0) = 0.51T$, $r(0) = 1.12m$, thus:

$$D_{\perp} = 0.095 \, c_s \, \lambda_n^2 \tag{11}$$

Results are given in Figs. 1 and 2. Error bars are estimated to be a factor of order 2. The Langmuir probe measures only T_e^{SOL} directly and often, in tokamak edge studies, there is no separate information on T_i^{SOL}.

The typical assumption is then to set $T_i^{SOL} = T_e^{SOL}$. In Fig. 1 this assumption has been made. Also shown is the $D_\perp^{Bohm}$ value based on T_e(LCFS). As can be seen, the scatter is significant, but $D_\perp^{Bohm}$ is a reasonable approximation to the experimental values.

For these JET discharges there are, however, several measurements indicating that T_i^{SOL} is substantially larger than T_e^{SOL} at low $\langle n_e \rangle$. This evidence includes: limiter calorimetry,[5] preliminary BeIV Doppler temperatures[6] and measurements of the radial electric field inside the LCFS.[6] Employing these higher values of T_i^{SOL} in the calculation of the sound speed c_s, changes the inferred values of $D_\perp^{SOL}$ somewhat, Fig. 2. Now the Bohm diffusion coefficient (based on T_e) fits somewhat better. Since the edge density and temperature are coupled, however, the data can also be fit with a dependence on n_{LCFS}. Results are shown in Figs. 3 and 4 with the same assumptions as in Figs. 1 and 2. Lastly, since n_{LCFS} and $\langle n_e \rangle$ are also coupled, the data could also be taken to indicate a dependence of $D_\perp^{SOL}$ on $\langle n_e \rangle$.

Discussion and Conclusions

Operation of JET with Be limiters permits a wide range of $\langle n_e \rangle$ for a plasma current I_p. This has made it possible to establish that $D_\perp^{SOL}$ has a significant dependence on plasma parameters - edge density, edge temperature or $\langle n_e \rangle$ - independently of any dependence on I_p, q or B.

The design of future tokamaks, such as ITER, calls for relatively high values of density compared with the range studied here. (Plasma temperatures in the divertor, on the other hand, may not be significantly different than those studied here.) It is desirable that $D_\perp^{SOL}$ and $\chi_\perp^{SOL}$ be as large as possible in order to avoid overheating of edge structures. For such applications it is clearly important to know whether a $(T_{edge})^{+1}$, $(n_{edge})^{-1/2}$ or $\langle n_e \rangle^{-1}$ scaling for $D_\perp^{SOL}$ holds. In principle, the distinction could be made from the data since T_e tends to be approximately constant with changing $\langle n_e \rangle$ for $\langle n_e \rangle \lesssim 2\times10^{19}$ m^{-3}. Unfortunately, as can be seen from the figures, the data scatter is too great to permit a meaningful distinction to be made at this time. It will be the object of continuing studies to obtain more data bearing on this question.

Acknowledgements

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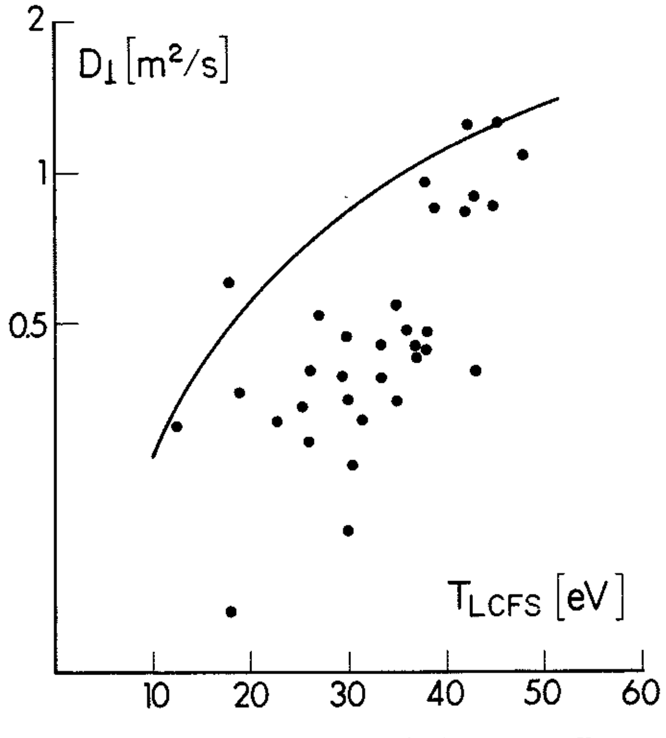

Fig.1 Experimental values of $D_\perp$ in the scrape-off layer from Langmuir-probe measurements of the plasma density scrape-off length, as a function of the electron temperature at the Last Closed Flux Surface, LCFS. Data analysis assumed $T_e = T_i$. Solid curve is the Bohm diffusion value.

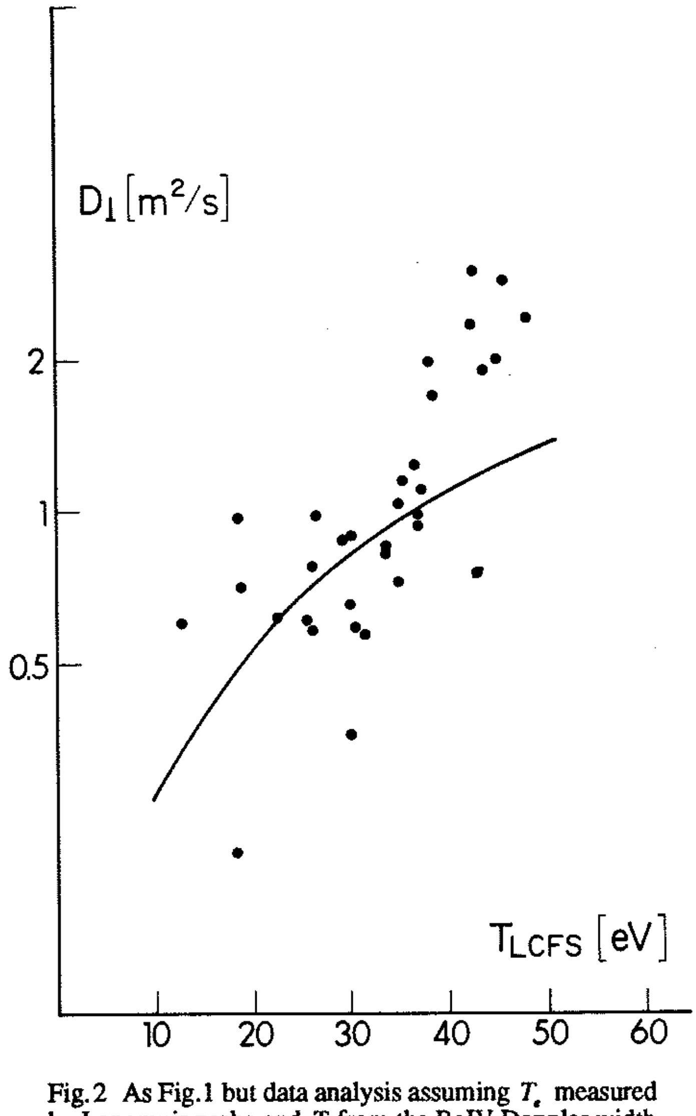

Fig.2 As Fig.1 but data analysis assuming T_e measured by Langmuir probe and T_i from the BeIV Doppler width.

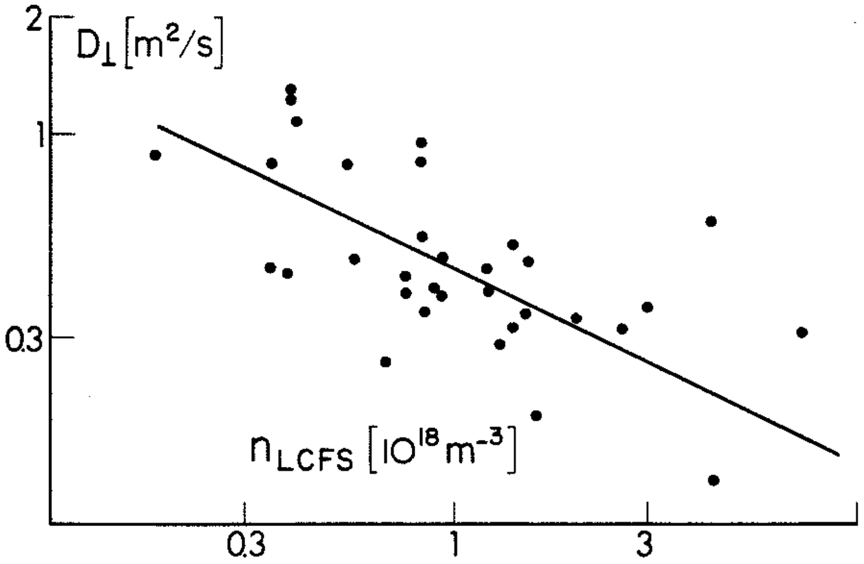

Fig. 3 As Fig. 1 but plotted vs. the plasma density at the LCFS. Solid line to guide the eye only.

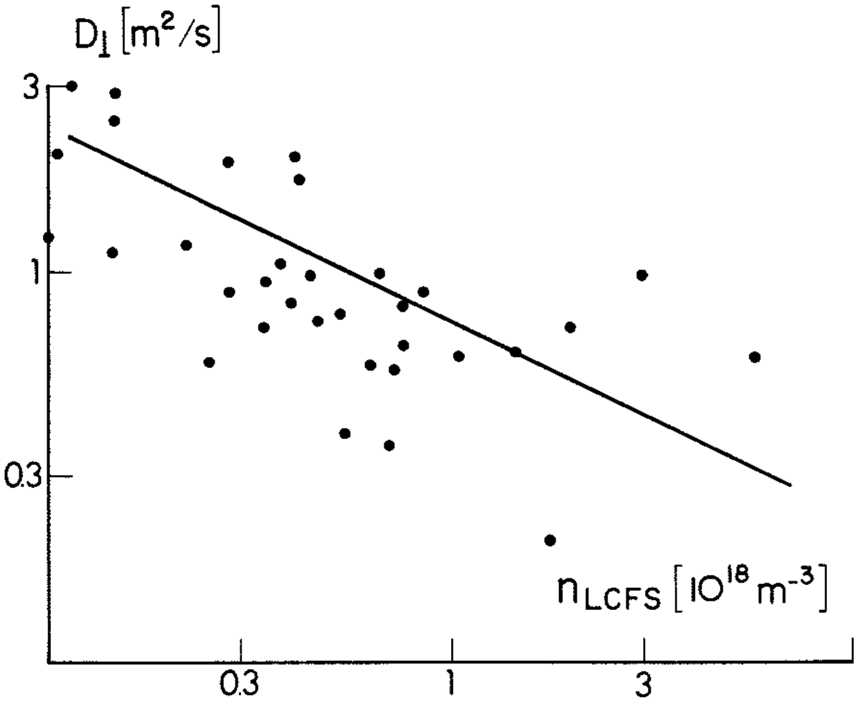

Fig. 4 As Fig. 2 but plotted vs. the plasma density at the LCFS.

APPENDIX 1.

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