

Local Transport in JET ELMy H-Mode Discharges with H, D, DT, and T Isotopes*

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Introduction – Several paradigms are being used to analyze the transport in Tokamak plasmas. Dimensionless scaling arguments [1] have been used to derive constraints on the energy confinement times and transport coefficients. These arguments imply that the thermal energy confinement time τ_{th} can be expressed in terms of dimensionless parameters in the form:

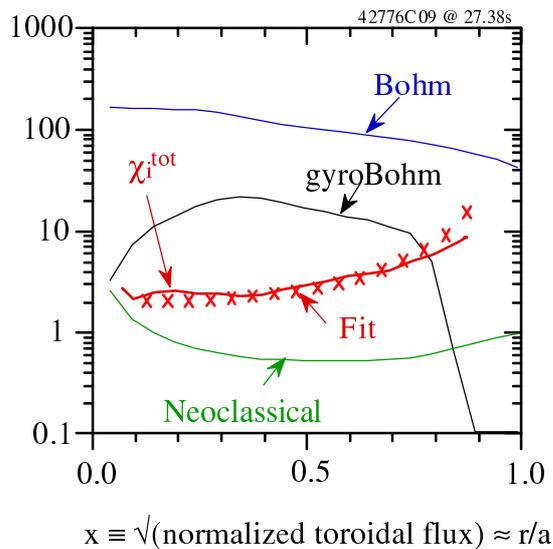
$$\omega \tau_{th} \propto \langle \rho_* \rangle^a \langle \beta \rangle^b \langle v_* \rangle^c \langle A \rangle^d \quad (1)$$

Here $\omega = eB / (m_H A)$ is the ion gyrofrequency, ρ_* is the ion-gyroradius (v_{th} / ω) normalized by the plasma minor radius, v_* is the normalized collisionality ($\propto n_i / T_i^2$), β is the normalized thermal pressure ($\propto n T / B^2$), A is the isotopic mass of the thermal hydrogenic species, and $\langle \dots \rangle$ indicates volume-averages. This approach has had success in fitting the thermal energy confinement times of a large set of ELM-free and ELMy H-mode discharges from a variety of Tokamaks [2]. The exponent of ρ_* from the fits is between -2 and -3 , the values expected from Bohm and gyro-Bohm scaling respectively.

An alternative approach is to attempt to derive transport coefficients from theory [3]. Early theory suggested that the profiles of local transport coefficient such as χ_i should be proportional to either the Bohm or gyro-Bohm expression, defined here as: $\chi_{Bohm} \equiv T_e / (16 B)$ and $\chi_{gBohm} \equiv T_i \rho_* / B$, where here and below ρ_* is normalized by the ion temperature scale length, $L_{Ti} \equiv - T_i / \nabla(T_i)$. Recent physics-based models indicate that χ_i is governed by marginal stability, with critical temperature gradients playing a pivotal role.

We show that although the transport coefficients measured in JET ELMy H-mode pulses do not have the shapes given by the Bohm or gyro-Bohm dependencies, they can be fitted over much of the plasma radius using local dimensionless parameters in analogy with Eq. (1). Preliminary results for the scaling of the transport coefficients at the half-radius were reported in a previous paper [4]. This paper extends that study in several ways: **1)** a larger number of discharges are studied, **2)** transport over a wide range of radii are included, **3)** an additional dimensionless parameter, M , the Mach number of the hydrogenic toroidal rotation speed (computed from the measured carbon rotation) is used, and **4)** an analysis of marginal stability with critical gradients, including the effects of shear in the $E \times B$ flow is included.

Data and Analysis - Experiments were performed in JET to study the scaling of



Fi. 1 Comparison of the measured χ_i^{tot} profile [m^2/s] (for an ELMy H-mode discharge with $B = 1 T$ and T-NBI) and the predictions of simple models and the Fit (\cdot) in Eq. (2)

confinement with dimensionless parameters in ELMy H-mode discharges. The TRANSP plasma analysis code was used to analyze more than 60 of these discharges. A profile database was constructed from the TRANSP output at a representative time during a quiescent phase of the auxiliary heating. The pulses in the database have B / I_p held constant, between 1 and 4 [T/MA], and $T_e \approx T_i$, and $q_{95} \approx 3.8-4.1$. The neutral beam injected (NBI) power ranged from 4 to 21 MW. Some of the pulses had ICRH, but we restricted the dataset to those with ICRH power less than 20% of the neutral beam power. The profiles of the atomic mass A ranged from approximately 1 to 3. Values of the Troyon-normalized thermal β_n ranged from 0.5 to 2.7, and the central values of the Mach number M ranged from 0.05 to 0.8. An example of the thermal ion energy

transport coefficient for one of the JET discharges is shown in Fig. 1. The coefficient χ_i^{tot} is defined to include both the convective and conductive transport. The convection is calculated to be relatively small, so $\chi_i^{tot} \approx \chi_i$. For comparison, the profiles of χ_{Bohm} , χ_{gBohm} , and χ_{neocl} (neo-classical transport) are also given. As can be seen, these simple theory profiles are very different from the measured profile.

Regression Analysis – Although the simple theory profiles are dissimilar to the measured ion transport, the transport at a fixed radius might still scale, say as gyro-Bohm in ρ_* . This could be tested by comparing pulses where only ρ_* varied, say by varying A or B. Unfortunately the plasma profiles could not be held constant. For instance the electron density n_e tended to increase with both A and B. Even if pairs of discharges where only one dimensionless parameter varied cannot be found, dimensionless scaling implies that a unique function of dimensionless parameters governs the transport. We assume this function has the form of a product of powers (as in Eq.1). We studied the scaling of the dimensionless ratios of transport coefficients normalized by ωL_{Ti}^2 , and restricted the fit range of the toroidal flux index: $0.3 < x < 0.7$, excluding the central region, where sawtooth effects cause periodic changes in plasma parameters, and the edge region, where ELMs cause periodic changes.

The results for the normalized χ_i^{tot} are not fitted accurately over an extended range of x using only the local values of the four parameters in the right-hand-side of Eq. (1). However if we also include the Mach number M we do find an approximate fit for the results:

$$\chi_i^{\text{tot}} / (\omega L_{Ti}^2) \propto \rho_*^a \beta^b v_*^c A^d M^e \quad (2)$$

with the values of the powers and their errors given in Table I. Also the fits for the transport of the total thermal energy χ_{eff} and of the momentum χ_{phi} (using the same fit range and normalization) are given in the Table.

Table I – Fit powers and errors from regression

	a	b	c	d	e
$\chi_i^{\text{tot}} / (\omega L_{Ti}^2)$	2.5 ± 0.07	-1.11 ± 0.07	0.33 ± 0.04	-0.62 ± 0.07	-1.13 ± 0.14
$\chi_{\text{eff}} / (\omega L_{Ti}^2)$	2.8 ± 0.06	-0.98 ± 0.06	0.31 ± 0.04	-0.61 ± 0.07	-0.82 ± 0.13
$\chi_{\text{phi}} / (\omega L_{Ti}^2)$	2.6 ± 0.08	-0.47 ± 0.08	0.01 ± 0.05	-0.31 ± 0.09	-1.29 ± 0.17

The measured values of χ_i^{tot} are compared with the fit in Fig. 2. The fit profile for the pulse in Fig. 1 is shown in that Figure as \cdot 's.

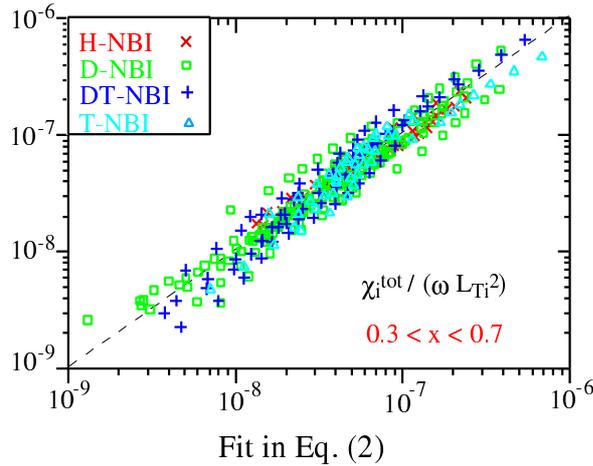


Fig. 2 Comparison of the measured and fit (Eq.2) values for $\chi_i^{\text{tot}} / (\omega L_{Ti}^2)$

Generally the fit is in approximate agreement with measurements even outside the range $0.3 < x < 0.7$ where the fit was derived.

There is covariance among the parameters used in the fit. Besides the increase of n_e with A and B, the peaking factor, $n_e(0) / \langle n_e \rangle$, decreases systematically as A increases from 1 to 3. To increase the confidence in the fit, we checked that the ratio of the left and right sides of Eq. (2) does not vary systematically with radius or parameters such as A, B, M, the peaking factor, or ELM frequency. To further increase the confidence, we studied fits with one of the five parameters held approximately constant. The fits in the remaining parameters had powers similar to those given above.

Marginal Stability Analysis – An example of the alternative paradigm of marginal stability driven by critical ∇T_i is the IFS-PPPL model for L_{crit} [5]:

$$\chi_i^{\text{IFS-PPPL}} \propto \chi_{g\text{Bohm}} (1 - L_{Ti} / L_{\text{crit}}) \quad (3-a)$$

$$\chi_i^{\text{tot}} = \chi_i^{\text{IFS-PPPL}} (1 - 0.5 \omega_{\text{ExB}} / \gamma_{\text{lin}}) \quad (3-b)$$

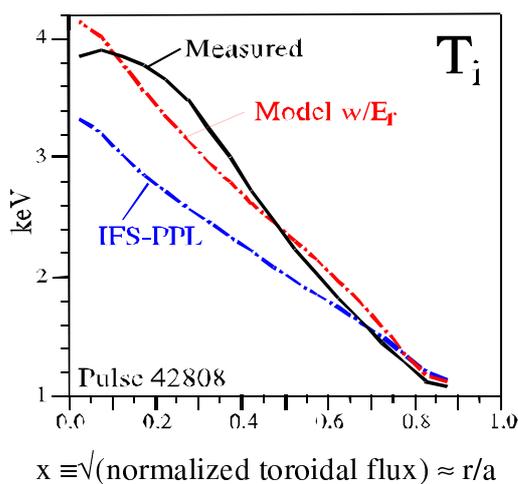


Fig.3 Comparison of IFS-PPPL simulations of the ion temperature (for an ELMy H-mode with B=2T and Tritium-NBI)

Discussion – Both the dimensionless scaling and marginal stability approaches give approximate agreement with measurements of JET ELMy pulses. The fit in Eq.(2) gives a power-law scaling for χ_i^{tot} over a wide range of radii. The ρ_* exponent-a in Table I is between the Bohm and gyro-Bohm values of 2 and 3. For the fits, v_* is normalized by L_{T_i} . If instead the parallel connection length ($R q$) is used, the fits are similar except the value for the exponent-a is lowered toward the Bohm value 2. The explicit scaling in A and B implied by the explicit A dependence and the implicit dependencies in ω and ρ_* in Eq. (2) is:

$$\chi_i^{\text{tot}} \propto A^{-0.37} B^{0.72}. \quad (4)$$

It must be remembered that there are correlated changes in several important parameters that enter into this overall apparent scaling.

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References

- [1] J.W. Connor, “Tokamak Confinement Scaling Laws”, UKAEA FUS 384 (1998).
- [2] J.G. Cordey, *et al.*, Plasma Phys. & Cont. Fusion **38**, 115 (EPS, 1997).
- [3] J.W. Connor, Plas. Phys. and Controlled Fusion **37**, A119-A133 (1995).
- [4] R. Budny, B. Balet, D. Bartlett, *et al.*, 1998 EPS, Praha.
- [5] M. Kotschenreuther, W. Dorland, M.A. Beer, *et al.*, Phys of Plasmas, **2**, 2381 (1995).
- [6] D. Ernst, *et al.*, Phys. Rev. Lett **81**, 2454 (1998); & submitted to Physics of Plasmas.