Global and Local Energy Confinement Properties of Simple Transport Coefficients of the Bohm Type

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GLOBAL AND LOCAL ENERGY CONFINEMENT PROPERTIES OF SIMPLE TRANSPORT COEFFICIENTS OF THE BOHM TYPE

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1. Introduction

Dimensional analysis requires that the coefficients of thermal and particle diffusion in plasmas have to be written as the product of a combination of local plasma variables which produce the correct dimensions $[l^2t^{-1}]$ and a function of local dimensionless plasma quantities. For example in the case of a thermal diffusion coefficient χ one has $\chi = \chi_o F(x_1,x_2,x_3...)$ where χ_o is some basic diffusion coefficient (classical, neoclassical, Bohm...) that can be chosen in an essentially arbitrary way, and $x_1,x_2,x_3...$, are local dimensionless parameters. The so called Kadomtsev constraint, that is verified in JET and other devices, implies that dimensionless parameters related to atomic physics can be excluded.

A transport coefficient is called of the Bohm type if $\chi_o = \chi_B \propto T/B$ and F does not depend on ρ^*, a Larmor radius normalized to a typical length, for example the plasma minor radius. In the following we choose $T = T_e$, the electron temperature and $B = B_t$ the toroidal magnetic field. A coefficient with $\chi_o = \chi_B$ but with F depending linearly on ρ^* is called of the gyro-Bohm type.

We will show that simple functions F leading to local coefficients of thermal conductivity of the Bohm kind can be constructed that are consistent with results found so far from local and global energy confinement analysis of the so called L-mode regime in the JET tokamak.

Most of what follows applies to both the electron and ion energy loss channel if they are equally important in determining the energy confinement properties. Alternatively it could be applied to the loss channel that determines confinement. The results of numerical simulations reported here have been obtained assuming $\chi_e = \chi_i$, an assumption known to be valid within the experimental error bars in the experiments considered.

2. Simple empirical energy transport coefficients

Recent results of local transport analysis in large tokamaks indicate that local energy transport coefficients seem to be of the Bohm type. Taking this result into account we write $\chi = \chi_B F$ and try to determine a function F, independent of ρ^*, which enables us to simulate the temperature profiles observed in experiments. This means that χ must imply a global energy confinement scaling showing power degradation and improvement with plasma current in agreement with the results of global energy transport analysis; it should also be 'bowl shaped', i.e. naturally increasing towards the plasma boundary. Finally it should provide the required degree of 'resilience' of the temperature profiles in L-mode discharges. As a guide for the empirical determination of F, we also take into account the following results of local transport analysis:

a) The dependence of F on the normalized collision frequency ν^* and on the atomic mass A is very weak [1,2]; thus a function F that does not depend on ν^* and A is compatible with experimental observations.

b) χ should depend on the current density distribution, consistently with the results of current ramp experiments (see e.g. [3]).

Simple expressions of F having the required properties are:

$$F = \alpha\, q^2/|L_T^*| \qquad \text{or} \qquad F = \alpha\, q^2/|L_p^*| \,, \tag{1}$$

where α is a numerical constant to be determined by simulations of experimental results. Here q is the local safety factor, $(L_T^*)^{-1} = a^* \frac{\nabla T_e}{T_e}$ and $(L_{p^*})^{-1} = a^* \frac{\nabla p_e}{p_e}$; p is the plasma pressure and a^* is a normalization length. This length should represent the scale length of the turbulence causing the anomalous transport. For long wavelength turbulence consistent with Bohm-like transport, a^* will be of the order of the plasma minor radius a.

From our numerical simulations using the $1\,^1/_2$-D predictive transport code JETTO we find that a^* must be a rather weak function of the local normalised minor radius. Tests carried out so far show that both $a^* = a$ and $a^* = q/\nabla q$ lead to acceptable results which are almost undistinguishable as long as normal, non inverted q profiles are considered.

Simulations of time-dependent discharges slightly favour $\chi = \alpha \frac{T_e}{B_t} \frac{q^2}{|L_p^*|}$ and $a^* = a$, with $\alpha = 3.3.10^{-4}$ (SI units with T_e in eV). The results in the next section refer to this choice. We also assumed $\chi_e = \chi_i = \chi$ and neoclassical resistivity.

3. Results and concluding remarks

One can find analytically, and numerical simulations confirm the result, that in steady state and in the absence of sawteeth the thermal energy confinement time τ_E^{th} given by both expressions in (1) scales with good approximation as

$$\tau_E^{th} \propto R^{3/2}\, I\, P^{-1/2}\, n^{1/2}\, B_t^{-1/2} \,. \tag{2}$$

The dependence on the major radius R, the plasma current I and the input power P reproduce well-known results of global confinement analysis. The power degradation comes through the ∇T_e dependence of χ, that also provides the degree of resilience of T_e profiles observed in experiments. The dependence of τ_E on the plasma density is consistent with observations when the non thermal energy contribution is subtracted from the energy content [4].

The $B_t^{-1/2}$ dependence implied by our models is different from empirical scaling laws that show $\tau_E^{th} \propto B_t^{\alpha}$ with $\alpha \approx 0\text{-}0.2$. This may indicate that the proposed local energy transport model requires additional dependences of the function F on parameters like β, ν^*. However in practice the correlation between experimental variables (in particular n and B_t), and the effect of sawtooth activity, introduce a degree of uncertainty in the determination of the exponent of B_t) to be expected for sawtoothless discharges. Similarly at high current (for a given B_t) sawtooth activity tends to saturate the predicted improvement of τ_E^{th} with current, as observed in JET high current experiments ($I_p \approx$ 6-7 MA) [5].

The thermal diffusion coefficients proposed imply, via their dependence on q, the dependence of the thermal energy content on l_i that is observed experimentally in JET [3]. Fig.1 illustrates this by comparing the measured and computed evolution of W_{th}^e, the electron energy content, for typical current ramp up and ramp down discharges in JET.

The observed shape of the electron temperature profile is also reproduced well by our simulations. As an illustration of this Fig. 2 shows computed and experimental profiles at the beginning (t = 8 sec) and the end (t = 10 sec) of the current ramp up case of Figure 1. Similarly T_e profiles are compared in Figs 3 and 4. Fig. 3 refers to two discharges at 3 MA with on axis and off axis ion cyclotron heating ($P_{rf} \approx$ 10 MW) [6]. Fig.4 refers to discharges at 2 MA and 4 MA for the ρ^* scaling experiment in JET [7].

Our results indicate that the simple expressions of χ proposed here can be used for reasonable simulations and predictions of L-mode discharges. They may represent a first step towards the development of a more complete and general transport model of the Bohm type.

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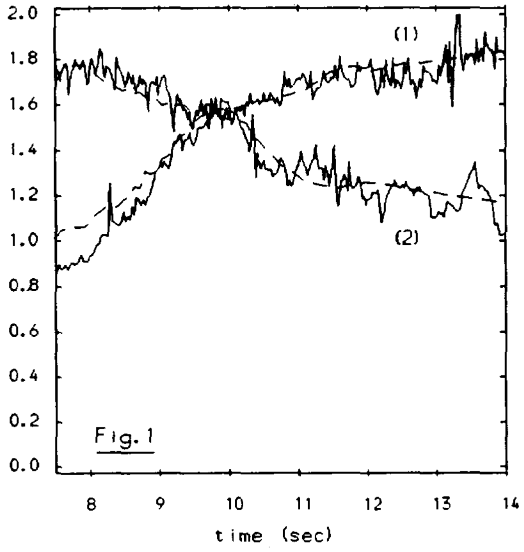

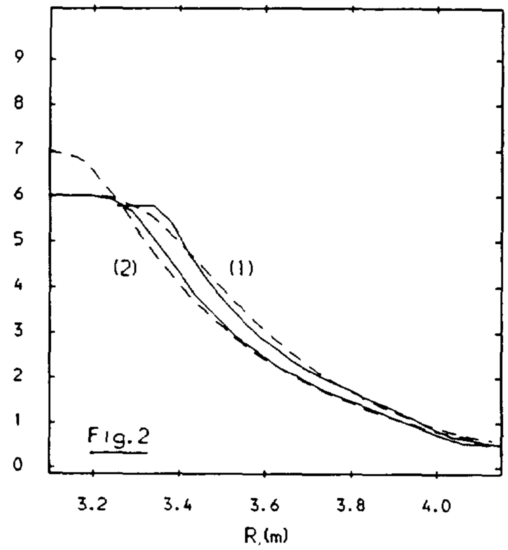

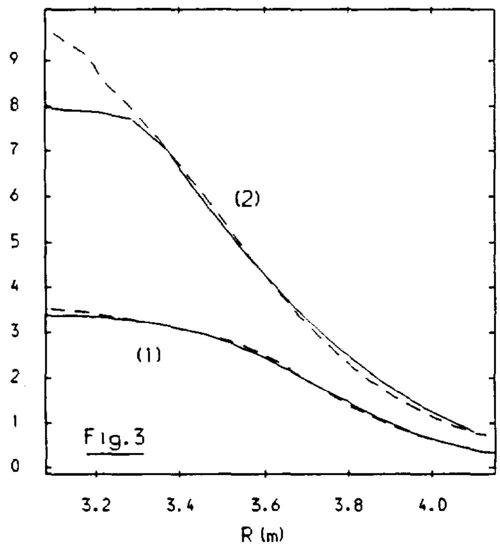

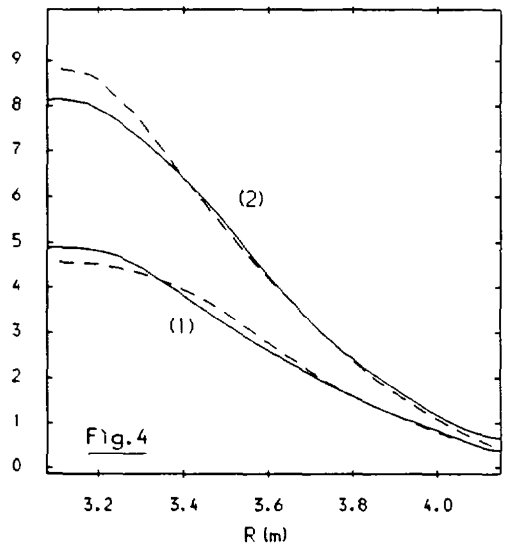

Fig. 1 Time evolution of the thermal electron energy content (MJ) during ramp up (1, I:1.5 MA → 3 MA as t : 8 sec → 10 sec) and ramp down (2, I:3 MA → 1.5 MA as t : 8 sec → 10 sec). Experimental (–) and computed (---) values are compared.

Fig. 2 Experimental (–) and computed (---) profiles of T_e (keV) at t = 8 (1) and t = 10 (2) during the current ramp up experiment.

Fig. 3 Experimental (–) and computed (---) profiles of T_e (keV) reached in steady state in off axis (1) and on axis (2) heating experiments.

Fig. 4 Experimental (–) and computed (---) T_e profiles reached in steady state during the $\rho*$ scaling experiments at 2 MA (1) and 4 MA (2).