IMPURITY TRANSPORT STUDIES ON THE FTU TOKAMAK

D. PACELLA , **F. ROMANELLI**, B. GREGORY [1] , M. LEIGHEB,
G. MAZZITELLI, L. GABELLIERI, R. DE ANGELIS, M. FINKENTHAL[2],
M. MAY[2], K. B. FOURNIER [3], W. H. GOLDSTEIN[3]

Associazione EURATOM-ENEA sulla Fusione, CR Frascati, 00044 Frascati, Rome, Italy

Abstract

In this work, the radial profile of the diffusion coefficient D and the convective velocity V in the plasma core ($0 < r/a < 0.7$) are obtained directly by the measurement of the absolute fluxes of a few molybdenum charge states (intrinsic impurity). The fluxes are derived from the measured ion density profiles and application of the continuity equation in stationary conditions. The peak values of these coefficients in the intermediate region of the plasma are $D \approx 10$ m^2/s and $V \approx 100$ m/s. A model for the anomalous transport induced by electrostatic turbulence is developed. With a typical fluctuation spectrum ($\omega = 10^5$-2×10^5 Hz), calculations can reproduce very well the experimental results. To investigate the impurity behavior in a non-stationary phase, Kr gas was injected into the plasma. It is found that the total flux of Kr gas flowing into the core is also driven by diffusion but the magnitude is much lower than the single ion fluxes derived for Mo ions. The effect of the turbulence on the single ion is very strong but it is reduced when averaged over many charge states.

1. MEASUREMENT OF THE ABSOLUTE FLUXES

The *L*-shell emission spectra of Mo^{29+} - Mo^{33+} in the range 4-5.5 Å were obtained with a rotating crystal spectrometer. Using a detailed collisional-radiative model developed at LLNL that incorporates *ab initio* atomic calculations [1], we identify a reliable line transition from each ion in each discharge and measure its brightness as a function of the impact parameter. From these measurements, it is possible, using the calculated atomic data, to get the radial density profile $N_Z(r)$ for the three ions (Z=32, 31 and 30). Then, the flux Γ_{31+} can be derived from the continuity equation [2], in steady state, from the knowledge of the source terms (eq. 1)

$$\Gamma_z = \frac{1}{r}\int_0^r r' N_e (N_{i-1}S_{i-1} + N_{i+1}\alpha_{i+1} - N_i\alpha_i - N_iS_i)dr' \tag{1}$$

$$\Gamma_z = -D\frac{dN_z}{dr} + VN_z \tag{2}$$

where α and S are the total recombination and ionization rates.

The resulting flux, Γ_{31+} of Mo^{31+} in the range $0 < r$ (cm) < 20 (minor radius a = 30 cm) is shown in Fig. 1, together with Γ_{32+} of Mo^{32+} obtained using the continuity equation and profiles of Mo^{33+}, Mo^{32+} and Mo^{31+}. It is possible to show, as will be done in section II, that for low impurity concentration, i.e. in the limit in which impurities do not alter the background turbulence (e.g. by destabilizing impurity-driven modes) and are simply passively advected by it, turbulent impurity flux can be written, in a general form, as in eq. 2. Writing this equation for Γ_{31+} and Γ_{32+} and assuming that the coefficients D and V are the same for the Mo^{32+} and Mo^{31+}, we can solve the system of two equations for the unknown functions V(r) and D(r). The results are shown in Fig. 3 for D(r) and in

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[1] Institut National de la Recerche Scientifique (INRS), Montreal, Canada

[2] The Johns Hopkins University, Baltimore, MD 21218

[3] Lawrence Livermore National Laboratories, Livermore, CA 94550

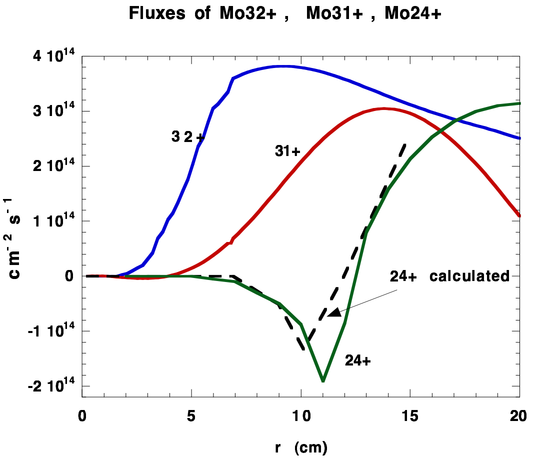

FIG. 1 Fluxes of Mo^{32+}, $^{31+}$ (continuous). Mo^{24+} is normalized to the same density of Mo^{31+}. Calculated flux Mo^{24+} (dotted)

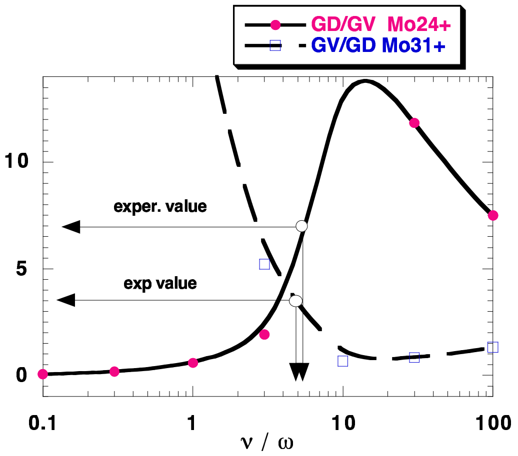

FIG. 2 Theoretical curves Γ_D / Γ_V for Mo^{24+} at r=10 cm, Γ_V / Γ_D for Mo^{31+} at r = 15 cm and the respective experimental values

fig. 4 for V(r) (dotted lines). The uncertainty grows at high radii. Note first that the convective flux is outward (V positive). A second result for these centrally peaked ions is that in the intermediate region where the anomalous transport is strong, the values of D and V are much larger (up to an order of magnitude) than the phenomenological values commonly used in the impurity transport code to simulate averaged quantities (brightness of line transitions along central lines of sight, Z_{eff}, radiated power, soft x-ray tomography, etc.).

The same method has been applied to find the flux profile of Mo^{24+}. The peaks of the emission profiles of Mo^{25+}, Mo^{24+} and Mo^{23+} occur in the intermediate region of the plasma. The profiles are acquired with a grazing incidence time resolving spectrometer (GRITS) developed at the Johns Hopkins University (JHU) and now installed at FTU. Radial scans of the emission profiles of these ions allow the reconstruction of the ion radial density profiles. Hence we obtained the flux, Γ_{24+}, (Fig. 1). It also must be emphasized that while the radial profile of Mo^{31+} is approximately monotonic, the Mo^{24+} density profile has a off axis bell-shape. The total flux of Mo^{24+}, Γ_{24+}, changes sign depending on the derivative of the ion density, meaning that the transport is dominated by the diffusion term. We used the coefficients D and V, derived for the ions 32+, 31+ , to calculate the fluxΓ_{24+} (dotted line in fig. 1) and compare it with the measured one (continuos line fig.1). The agreement is excellent, both in shape than in absolute value. This relevant experimental result, showing that the D, V do not depend significantly on the different charge states, is predicted by the model , as discussed in the next section. From all these measurements it is therefore possible, for an ion at fixed radial position, to assess the ratio between the convective and diffusive terms. It results Γ_V / $|\Gamma_D|$ ≈ 3.5 at r = 15 cm for Mo^{31+} and $|\Gamma_D|$ / Γ_V ~ 7 at 10 cm for Mo^{24+}. These experimental values will be then compared with the theoretical ones.

2. A MODEL FOR THE ANOMALOUS TRANSPORT

The model we have developed calculates the effect of an electrostatic fluctuating field, with real frequency ω and wavevector k, on the impurity via the fluctuating ExB velocity in the radial direction. Writing the Drift Kinetic Equation, linearized in the distribution function, and solving it, we obtain the non adiabatic part of the perturbed distribution function [3]. Integrating the expression for the flux over time scale ω^{-1} and then over τ_g, the time scale of the growth rate of the turbulent field, we obtain

$$< \Gamma > = - D_B < |\frac{e\delta\phi}{T}|^2 > \mathrm{Im}\, k_y \int d^3 v \left[\frac{\omega - \omega_n^* - \omega_T^*(E/T-3/2)}{\omega + i\nu - \omega_t(v_{//}/v_{th}) - \omega_d} \right] Z f_M$$

where D_B is the Bohm diffusion coefficient, $\omega^*_n = k_y cT/(ZeB)\, d\ln(n_Z)/dr$ and $\omega^*_T = k_y cT/(ZeB) d\ln T/dr$ are the diamagnetic frequencies, $\omega_d = -2k_y cT/(ZeBR)(v^2_{||}+v_\perp^2/2)$ is the magnetic drift frequency, $\omega_t \approx v_{th}/qR$ is the transit frequency, v_{th} is the thermal velocity, ν is the impurity collision frequency and n_z is the impurity density.

For a FTU plasma with Mo as the dominant impurity and with the local plasma parameters taken in the region around half radius (in order to compare the results with the experiments), the frequency ordering (calculated in s^{-1}) turns out to be $\nu > \omega^*_n > \omega^*_T > \omega_d \approx \omega_t$. Neglecting ω_d and ω_t, taking into account the dependence of ν on energy E and estimating the ratio of the mean energy associated with the electrostatic turbulence to the thermal content, $<|e\delta\phi/T|^2>$ with a mixing length model based on the result of Ref. [4] , we obtain the diffusive and convective fluxes $\Gamma_D + \Gamma_V$ (eqs. 3) ($\chi = E/T$)

$$< \Gamma_D > = - \alpha \left(\frac{\nu}{\omega}\right)^2 \frac{\omega_n^*}{\nu} \int_0^\infty \frac{\chi^2 e^{-\chi}}{\chi^3 + (\frac{\nu}{\omega})^2} d\chi$$

$$< \Gamma_V > = - \alpha \left[\left(\frac{\nu}{\omega}\right)^2 \frac{\omega_T^*}{\omega} \int_0^\infty \frac{\chi^2 e^{-\chi}(\chi - 1.5)}{\chi^3 + (\frac{\nu}{\omega})^2} d\chi - \frac{\nu}{\omega} \int_0^\infty \frac{\chi^2 e^{-\chi}}{\chi^3 + (\frac{\nu}{\omega})^2} d\chi \right]$$

where $\alpha = D_B (a/L_T)^2 (1/s) \exp(-c/s) (2/\sqrt{\pi})\, n_z$, s is the magnetic shear, $c \approx 2$ is a constant and L_T is the thermal gradient length. Solving the two integrals numerically for different values of ν/ω and calculating ω^*_T and ω^*_n for a given Mo ion at a fixed radial position, we find that the two fluxes Γ_D, Γ_V are functions only of the parameter ν/ω.

3. COMPARISON BETWEEN MODEL AND EXPERIMENT

The theoretical curves $\Gamma_V / |\Gamma_D|$ for Mo^{31+} at r=15 cm and $|\Gamma_D| / \Gamma_V$ for Mo^{24+} at r=10 cm, obtained from the model above discussed and shown in fig 2 , exhibit a strong dependence on ν / ω. Imposing now on these theoretical curves the experimental values $\Gamma_V / |\Gamma_D| \approx 3.5$ for Mo^{31+}, and $|\Gamma_D| / \Gamma_V \approx 7$ for Mo^{24+}, we obtain approximately the same value $\nu / \omega \approx 5$. This is very satisfactory result, because the different behavior of the two ions (Mo^{31+} and Mo^{24+}) is well predicted by the theory. Since $\nu = 1\times10^6\ s^{-1}$ for Mo^{31+} and $\nu = 5\times10^5\ s^{-1}$ for Mo^{24+}, at the respective radii, we obtain that the range for ω is 100 – 200 kHz. We can conclude that electrostatic turbulence, in the frequency range roughly $10^5 < \omega$ (Hz) $< 2\times10^5$ explains the experimental observations. This range for ω is in agreement with the FTU fluctuation spectra. Once fixed ω (2×10^5 Hz), we derived from the equations (3) the theoretical curves D, V, shown in continuos lines respectively in fig. 3 and fig.4, as function of the radius. The agreement is excellent all over the range. Finally we obtain, from the model, that the D (V) for Mo^{31+} and Mo^{24+}, at fixed position, is the same (by a few percent) in agreement with experimental results.

4. INJECTION OF KRYPTON

This impurity was injected during the discharge plateau. Bremsstrahlung emission profiles, measured with a 12 channel detector array, before and after the injection, have been used to find the radial density profile of the gas at different times [5]. This profile is found to be flat in the centre

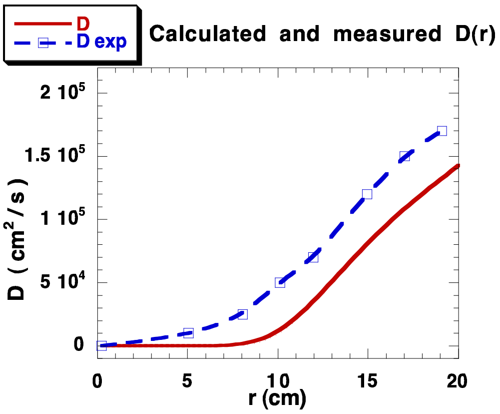

FIG. 3 Diffusion coefficient: measured (dotted) and calculated (continuos)

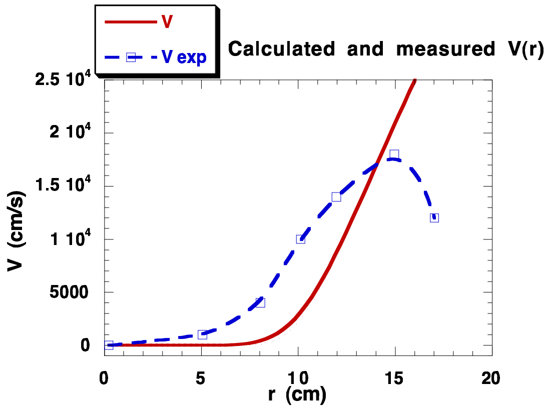

FIG. 4 Convective coefficient: measured (dotted) and calculated (continuos)

(0–10 cm) because of the sawtooth activity, but with a positive gradient in the intermediate region (10–20 cm). The proportionality, experimentally found, between the total flux of the inflowing gas and its radial density gradient shows that the total transport of the gas (i.e. regardless of each ion's behavior) is driven by diffusion, similar to the result obtained for the intermediate charge states of Mo. However, the difference in the two cases is that the absolute values for the Kr flux are an order of magnitude smaller than Γ_{24+} and Γ_{31+}. This is due to the fact that when diffusion is the dominant process, the fluxes of the single ions change sign and, when summed over, can compensate each other, yielding a total flux much less intense than the individual ones.

5. CONCLUSION

The “microscopic” effect of the transport on single ions (of Mo) is found to be very strong, higher than expected, in the intermediate radial region and, for non central ions, dominated by the diffusion. This is well explained by the radial drift induced by a turbulent electrostatic field, in the FTU limit of high impurity collisionality. The “macroscopic” transport effect, i.e. summed over all the charge states of an impurity, is still dominated by the diffusion, but of much smaller absolute magnitude.

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