SCALING WITH TOROIDAL CURRENT
OF IMPURITY TRANSPORT IN ATC

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ABSTRACT

We report on an experiment measuring the scaling with changing plasma conditions of a parameter characteristic of the transport of aluminum injected into the ATC tokamak. This parameter is the time after injection at which the photon signal from Al XI reaches its maximum. It is found that the data are in agreement with the predictions of a computer code which uses neoclassical theory in the Pfirsch-Schlüter regime. An approximate model describing impurity transport in ATC is also presented. This model is utilized to calculate the expected scaling with current of the aluminum transport assuming classical, neoclassical and pseudoclassical forms for the diffusion coefficient. The data are in agreement with both the neoclassical and pseudoclassical results from this model.

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1. INTRODUCTION

Employing laser-impelled impurity injection [1], in conjunction with VUV spectroscopy, we have previously measured and reported on the transport of aluminum ions in the ATC tokamak [2]. The results showed good agreement with the predictions of neoclassical theory in the Pfirsch-Schlüter regime. To pursue further the question of whether heavy impurity transport is indeed neoclassical, we have performed an experiment to measure the scaling with changing plasma conditions of a particular parameter characteristic of that transport.

As described elsewhere [1], the impurity injector provides a delta function-like source in time of neutral Al atoms at the edge of the plasma. The Al is quickly ionized and transported along the toroidal field lines; higher states of ionization appear successively as the ions are more slowly transported across the field into the hotter, denser region of the plasma. Using a grazing incidence VUV monochromator, we observe the line integral of photon signals in the midplane across the minor cross section. Typical signals for transitions of Al VII-Al XI are shown in Fig. 1. A parameter characteristic of the transport rate is the time (after injection) at which the signal from a given Al ionization state reaches its maximum. The peak time for the Al XI signal, t_{XI} , has been measured for Al injection into hydrogen discharges whose toroidal current I_p was varied from 40 to 80 kA. Al XI was chosen because it is the highest observable aluminum ionization state in the VUV, since the He-like Al XII and H-like Al XIII

both radiate only weakly. The Al XI appears after the greatest radial excursion from the edge of the plasma, peaking typically at $r=10$ cm [2], and is thus the most sensitive to changing transport rates. Radial profiles of impurities, in addition to being tedious and difficult to measure due to the need for Abel inversions, are relatively insensitive to the transport rates, the position of a particular ionization state depending mainly on the electron temperature profile. (Profile widths are useful for distinguishing spreading plus inward transport from the case of spreading transport alone). The variation of t_{XI} with plasma current, density, and temperature has been calculated using a computer code based on neoclassical theory. The results are in agreement with the experiment. A simplified model for predicting t_{XI} is developed to facilitate the computation and to elucidate the physical processes involved in the transport. This model allows convenient calculation of t_{XI} using various forms for the diffusion coefficient. We have performed such computations for classical, neoclassical and pseudoclassical coefficients, and find that both the neoclassical and the pseudoclassical scale in agreement with the data.

2. EXPERIMENTAL RESULTS AND COMPARISON WITH THEORY

Figure 2 shows the time dependence of electron density and current for the case of a 60 kA (peak current) ATC discharge. The density is measured by a 4 mm microwave interferometer system and the current by a Rogowski loop. The Al was injected at $t=25$ ms, just at the beginning of the flat top in the plasma current.

Figure 3 shows the data points for t_{XI} vs. current. The data are compared to the results of a computer code which integrates the coupled diffusion equations including ionization and recombination source terms:

$$\frac{\partial n_j}{\partial t} = - \frac{1}{r} \frac{\partial}{\partial r} (r \Gamma_j) + S_j \quad j = 1, \dots, 13, \quad (1)$$

where r is the minor radius and the S_j are the ionization [3] and recombination [4] source terms to the j^{th} ionization state. The flux of the j^{th} species is given by:

$$\Gamma_j = \sum_b \frac{\rho_b^2 z_b^2 v_{bj}}{z_j T_b} (1 + \alpha_b q^2) (T_b \frac{\partial n_b}{\partial r} - \frac{n_b}{n_j} \frac{z_b}{z_j} T_j \frac{\partial n_j}{\partial r}), \quad (2)$$

where the collision frequency has the form

$$v_{bj} = \frac{4 \sqrt{2\pi} n_j z_j^2 z_b^2 e^4 \ln \Lambda}{3 m_b^{1/2} T_b^{3/2}} \quad (3)$$

n_b , m_b , T_b , z_b , and ρ_b are the density, mass, temperature, charge, and gyro-radius of the b^{th} background species; n_j , T_j , and z_j are the density, temperature, and charge of the j^{th} state of Al; q is the safety factor and the α_b are constants of order unity.

Equation 2 is obtained by extending the theory of Rutherford [5] to the case of a (negligibly) small amount of Al diffusing in a background plasma containing more than one ion species. We have calculated that diffusion caused by collisions between different Al ionization states, as well as that caused by temperature gradient terms, is negligible. In the present calculation, the background plasma is assumed to be stationary in time and composed of hydrogen and oxygen, with the ratio of oxygen to electron

densities determined from an estimated $Z_{\text{eff}} = 5$ on axis. The electron density and oxygen density and temperature profiles are taken as parabolic, and the electron temperature profile is taken as the square of a parabola [6]. The charge profile of the oxygen is then approximated, utilizing experimental observations of OVI and OVII [7], by

$$\bar{Z}_O(r) = 4 + 4 (1 - r^2/a^2)^{1.84} \quad (4)$$

Charge neutrality then determines the proton density profile. In "standard" tokamak discharges, the term proportional to $\partial n_p / \partial r$ causes inward impurity transport, while the term proportional to $\partial n_j / \partial r$ causes spreading of the impurity profile.

Using X , the electron impact excitation coefficient given by [4]

$$X = \frac{1.6 \times 10^{-5} f_{pg}}{\Delta E T_e^{1/2}} \langle \bar{g} \rangle e^{-\Delta E/T_e} \quad (5)$$

where f_{pg} is the absorption oscillator strength for the transition from the state g to the state p , $\bar{g}$ is the Gaunt factor averaged for a Maxwellian electron distribution, ΔE is the transition energy in eV and T_e is the electron temperature in eV, the monochromator signal B_{XI} is given by

$$B_{XI} = \frac{1}{4\pi} \int_{-a}^a \frac{n_{XI} n_e X A(p, g)}{\sum_{q \leq p} A(p, q)} dr \quad (6)$$

where n_{XI} is the density of Al XI, and $A(p, q)$ is the spontaneous probability for transition between the states p and q (g is the ground state), and the integration is along the line of sight of the monochromator. Thus t_{XI} can be predicted.

When the plasma current is varied, while the toroidal field is held fixed, $T_e(r)$ and $n_e(r)$ also change. The variation of the average density was measured with the microwave system. However, as Thomson scattering scans were not available during the experiment, we are forced to assume some scaling for T_e with I_p . The results from a large number of Thomson scattering scans on ATC [6] indicate that $T_e \propto I_p^{1/2}$ and we have chosen to use this scaling. The implications of this assumption will be discussed in Sect. 4. We have also assumed that Z_{eff} and all profile shapes are independent of current. The results of the computer calculations are shown as the open circles in Fig. 3, and, within the experimental shot-to-shot deviation, are in excellent agreement with the data.

3. APPROXIMATE MODEL

To elucidate the competing effects which contribute to the variation of t_{XI} with current, as well as to facilitate comparison with other possible transport theories, we present an approximate model for calculating t_{XI} . Consider, as in Fig. 4, that the impurities are in a shell-like radial distribution, and the peak of the density moves inward at some velocity $v(r)$. As time proceeds, the Al ionizes to successively higher states. For an electron density n_e and ionization coefficient $S_{a \rightarrow b}$, the rate at which ionization from state a to state b takes place is $n_e S_{a \rightarrow b}$. Consider a particular ionization state and integrate $n_e S_{a \rightarrow b}$ over time as the ions diffuse inward. The peak time of the photon signal for state b should correspond to the limit of integration where the integral becomes equal to a constant of order unity. This integral condition for t_{XI} is expressed as

$$\int_0^{t_{XI}} n_e S_{X \rightarrow XI} dt' = C, \quad (7)$$

where $C \approx 1$ and is determined exactly from a comparison to the full code. The integrand depends upon the radial location r of the density peak of the diffusing species. Therefore, n_e and $S_{X \rightarrow XI}$ depend upon t through the equation of motion

$$\frac{dr}{dt} = v(r), \quad (8)$$

with the initial condition $r(t=0) = r_0$, r_0 being the injection deposition radius [1]. Taking the lower limit in Eq. 6 to be zero is an approximation. This approximation is valid because $S_{X \rightarrow XI}$ is negligibly small for the times when the peak of the Al distribution is at radii larger than $r(t_X)$.

To make this condition useful, we require a convenient expression for $v(r)$. Since the total Al flux is equal to the product of total Al density and $v(r)$, we write

$$v(r) = \left(\sum_j \Gamma_j \right) / \left(\sum_j n_j \right). \quad (9)$$

Specializing to neoclassical diffusion, we obtain from Eqs. 2, 3, and 9

$$v(r) = \frac{1}{N} \sum_j \sum_b \left\{ \frac{4\sqrt{2\pi}}{3} \frac{e^4 \ln \Lambda}{m_b^{1/2} T_b^{3/2}} \rho_b^2 z_b^3 (1 + \alpha_b q^2) \right. \\ \left. \times \left(n_j z_j \frac{\partial n_b}{\partial r} - n_b z_b \frac{\partial n_j}{\partial r} \right) \right\} \quad (10)$$

where $N \equiv \sum_j (n_j)$ is the total Al density and we have assumed that $T_j = T_b$ for all b and j . The first simplifying assumption we will

make is to eliminate the sum over b by considering only the oxygen terms (since their effect is greater than that of the protons), and we utilize the charge profile for 0 given by Eq. 4. Summing over j results in the factor $\bar{z}_{Al}$ given by

$$\bar{z}_{Al} = \frac{1}{N} \sum_j n_j z_j \quad (11)$$

multiplying the $\frac{\partial n_b}{\partial r}$ term. $\bar{z}_{Al}$ can be approximated by an analytical expression explicitly involving t which is unity at $t=0$ and gives $\bar{z}_{Al} = 11$ as $t \rightarrow \infty$, with a parameter t_{max} chosen to match the full code for the 60 kA case: $\bar{z}_{Al}(t=3.23) = 10$ (see Fig. 5(a).) This expression is

$$\bar{z}_{Al} = 1 + 10[1 - \exp(-t/t_{max})] \quad (12)$$

The sum over j for the $\frac{\partial n_j}{\partial r}$ term results in a logarithmic derivative of N which we approximate by

$$\frac{1}{N} \sum_j \frac{\partial n_j}{\partial r} = \frac{1}{N} \frac{\partial N}{\partial r} \approx \frac{1}{(a-r)} \quad (13)$$

where a is the plasma minor radius. The spreading term is included in $v(r)$ because spreading diffusion coupled with the asymmetric loss of particles at the edge of the plasma leads to a net inward movement of the peak of the total impurity density distribution.

Incorporating all of these approximations, we put Eq. 10 into a form which makes the terms with radial dependence explicit

$$v(r) = \frac{\gamma(1 + \alpha_o q^2)}{T_o^{1/2}} \left[\bar{z}_o \bar{z}_{Al} \frac{\partial n_o}{\partial r} + \frac{\bar{z}_o^2 n_o}{(a-r)} \right] \quad (14)$$

where the subscript o refers to oxygen. The constant γ includes all the factors in Eq. 10 not appearing explicitly in Eq. 14, plus a free multiplicative constant to be determined along with C of Eq. 6 by simultaneously matching, for the 60 kA case, the model t_{XI} and $r(t_{XI})$ with the full code peak time and the radius of maximum Al density at the time respectively. Figure 5(b) shows the comparison between $v(r)$ from the full code and the approximate model. It is found that the free parameter in γ equals 1.1, and $C = 2.14$. Having determined C and γ , they are then held fixed while I_p , T_e , and n_e are varied. Figure 6 shows the comparison of the results of the approximate theory with those of the full code for two ionization states. The prediction for t_X is made with the approximate theory by simply replacing $S_{X \rightarrow XI}$ with $S_{IX \rightarrow X}$ in Eq. 6.

The changes in T_e , n_e , and I_p (and therefore q), each affect t_{XI} in different ways. Since the neoclassical diffusion coefficient is proportional to $(1 + \alpha q^2)$, increasing the current decreases this factor and t_{XI} should get longer. However, increasing I_p increases T_e , and n_e , and thus the ionization rate at a given radius. This shortens the radial distance the peak must move to satisfy Eq. 6, and since this latter effect dominates, t_{XI} is shortened. Both the transport and the ionization are linear in n_e . If n_e were the only background plasma parameter changing, we would expect the product of n_e and t_{XI} to remain constant. T_b also appears in the transport coefficient:

$$v(r) \propto \frac{1}{T_b^{1/2}} \quad (15)$$

The scaling of Artsimovitch [8] predicts a relatively weak dependence of T_b on I_p : $T_b \propto (n_e I_p)^{1/3}$. The diffusion coefficient would then vary as $(n_e I_p)^{-1/6}$. We have not included any effects from changing T_b in these results.

Different transport theories can be compared with the neo-classical using Eqs. 6 and 7, with a different form for $v(r)$, and thus different dependences on plasma parameters. For the plasma conditions in this experiment, the effective collision frequency $\nu^* = \nu R_O q / (\epsilon^{3/2} v_T)$ [9] for aluminum-oxygen collisions at $r = 10$ cm is approximately equal to 230, so $\nu^* \epsilon^{3/2} = 20$, and we expect to be well into the Pfirsch-Schlüter regime. If the transport were caused by some kind of plasma turbulence (for example drift waves) one might expect the diffusion coefficient to have the pseudo-classical form [10]:

$$D_{pc} = \frac{\nu_c}{\omega_e} \left(\frac{c T_e}{e B} \right) \left(\frac{\tilde{n}}{n} \right)^2 \frac{k_\perp^2}{k_\parallel^2} \quad (13)$$

where ν_c is the electron-ion collision frequency, ω_e the electron gyrofrequency, $\tilde{n}/n$ the level of density fluctuations, $k_\perp$ the perpendicular wavevector of the fluctuations $\approx 1/\rho_i$ [10], and $k_\parallel$ is the parallel wavevector of the fluctuations $\approx 1/R_O q$ [11].

In Fig. 7 we show the results from Eqs. 6 and 7 for the two transport theories, classical and pseudo-classical and compare them with the neoclassical. We take the following forms for the respective diffusional velocities:

$$v_{\text{classical}} = \gamma_c \frac{n_b}{T_b^{1/2}} \left[\frac{1}{n_b} \bar{z}_b \bar{z}_j \frac{\partial n_b}{\partial r} + \frac{\bar{z}_b^2}{(a-r)} \right] \quad (14)$$

$$v_{\text{pseudo-classical}} = \frac{n_b \bar{z}_b^4 q^2 \left(\frac{\tilde{n}}{n}\right)^2}{T_e^{1/2} T_b} \left[\frac{1}{(a-r)} \right] \begin{matrix} \text{(spreading only,} \\ \text{no inward term)} \end{matrix} \quad (15)$$

The velocities are normalized, through the choice of γ_c for the classical and $\tilde{n}/n$ for the pseudoclassical, to make t_{XI} equal 3.23 ms, for the 60 kA discharge. Without this normalization, the classical transport is more than a factor of 10 too slow. The motivation for including the classical calculation is to show explicitly the effect of the q^2 term in the diffusional flux. For the pseudo-classical theory, it is assumed that $\tilde{n}/n$ is constant, independent of radius and plasma current. Since both the Pfirsch-Schlüter and pseudo-classical coefficients are approximately proportional to q^2 , it is not surprising that they scale almost identically in this model. The pseudo-classical transport requires $\tilde{n}/n$ of about 10^{-2} for the observed transport. This is to be compared with experimental observations of small scale electron density fluctuations in ATC which have been performed with microwave [11] and CO_2 laser [12] scattering. Estimates of $\tilde{n}/n$ from these two methods are $\geq 5 \times 10^{-3}$ and 1×10^{-2} respectively. On the basis of this scaling of t_{XI} with I_p , as well as the absolute magnitude of t_{XI} , it is not possible to distinguish between neoclassical and pseudo-classical transport. —

4. IMPLICATIONS OF UNKNOWN PROFILES

As previously mentioned, certain parameters of the plasma were not measured during the course of this experiment. The most

important of these are the electron temperature and density profiles (average electron density is known). Using the approximate model, we compare the predictions for t_{XI} with various assumptions for these profiles. Figure 8(a) shows the results for the three choices:

$$T_e \propto I_p^\epsilon (1 - r^2/a^2)^2 \quad \epsilon = .3, .5 \text{ and } .7,$$

where I_p is the plasma current, r the minor radius, and a the limiter radius. Figure 8(b) shows the comparisons for:

$$T_e \propto I_p^{1/2} (1 - r^2/a^2)^\eta \quad \eta = 1.5, 2 \text{ and } 3,$$

and finally Fig. 8(c) compares t_{XI} for the three cases:

$$n_e = n_{e0} (1 - r^2/a^2)^\xi \quad \xi = .5, 1 \text{ and } 1.5.$$

Once again all curves have been normalized to 3.23 msec for the 60 kA case. It is clear from these three graphs that even over the wide variation allowed for the parameters ϵ , η , and ξ , the agreement of the predictions with the experiment is still good.

5. CONCLUSIONS

We have performed an experiment to measure the scaling of the peak time of the Al XI photon signal with changing plasma conditions. The results are in agreement with the predictions of both neoclassical theory in the Pfirsch-Schlüter regime, and pseudo-classical transport with $\tilde{n}/n \approx 10^{-2}$.

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Fig. 1. Time evolutions of experimental line integral photon signals after aluminum injection for transitions of Al VII through Al XI.

Fig. 2. (a) Peak electron density (assuming a parabolic radial profile).

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Fig. 2. (b) Toroidal plasma current for the 60 kA peak current discharge.

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 Fig. 3. Comparison of the experimental data for t_{XI} vs. plasma current with the predictions of the neoclassical computer calculations.

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Fig. 4. Approximate model used to predict t_{xI} for various diffusion coefficients. $n_e S_{a \rightarrow b}$ is the electron impact ionization rate from state a to state b and $v(r) = \Gamma_D / N_{\text{impurity}}$:

Fig. 5. (a) Comparison of $\bar{Z}_{Al}$ from the full code with the formula used in the approximate model calculations.

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Fig. 5. (b) Comparison of the diffusional velocity as a function of radius from the full code with that of the approximate model (Eq. 14).

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Fig. 6. Comparison of the approximate model predictions for t_X and t_{XI} with those of the full code.

Fig. 7. Comparison with the experimental data of three different diffusion theory predictions using the approximate model.

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Fig. 8. (a) Comparisons of t_{xI} vs. I_p using the approximate model assuming $T_{e0} \propto I_p^{.3}$, $I_p^{.5}$ and $I_p^{.7}$.

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Fig. 8. (b) Comparison of t_{xI} vs. I_p using the approximate model assuming $T_e \propto (1-r^2/a^2)^{1.5}$, $(1-r^2/a^2)^2$, and $(1-r^2/a^2)^3$.

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Fig. 8. (c) Comparisons of t_{xI} vs. I_p using the approximate model assuming $n_e \propto (1-r^2/a^2)^{1/2}$, $(1-r^2/a^2)$, and $(1-r^2/a^2)^{1.5}$.

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