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 He^{++} TRANSPORT IN THE PDX TOKAMAK

By

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He⁺⁺ TRANSPORT IN THE PDX TOKAMAK

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ABSTRACT

A powerful new approach to the study of particle transport and helium ash confinement in high-temperature fusion plasmas is demonstrated by charge-exchange recombination spectroscopy of He⁺⁺ in ohmically heated PDX discharges. Time and space resolved measurements of He⁺⁺ density following a short puff of helium gas into the plasma edge are fitted using a diffusive/convective transport model with coefficients $D = (2.1 \pm 0.9) \times 10^4 \text{ cm}^2 \text{ s}^{-1}$ and $v(r)/D = (0.8 \pm 0.3) \partial(\ln n_e)/\partial r$.

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Detailed measurement of ${}^4\text{He}^{++}$ particle transport in tokamaks is of considerable interest both for the study of fundamental particle confinement physics as well as for the evaluation of techniques proposed to control the buildup of thermalized helium ash produced by the $\text{T(d,n)}{}^4\text{He}$ reaction in fusion reactors.¹ Helium and other very low-Z impurities are attractive for particle transport studies because they are fully stripped throughout most of the discharge, and hence detailed knowledge of rates for atomic processes such as ionization and recombination is not necessary in order to arrive at accurate measurements of transport coefficients for these ions.² Usually, studies of particle transport in tokamaks have concentrated on heavier impurities which still have electrons and can radiate even in a hot plasma core.³⁻⁶ Such studies are limited in accuracy by uncertainties in electron temperature and density profiles and imprecise knowledge of atomic rates for high-Z ions.⁷

In the new generation of tokamak experiments (such as TFTR and JET), significant alpha particle densities are expected during D-T operation ($n_\alpha \approx 10^{12} \text{ cm}^{-3}$ at $Q = 1$ in TFTR). Both fast (14 MeV) and thermalized alphas will be present, but no technique has yet been demonstrated which will allow radially resolved measurements of these fusion products although some have been theoretically discussed.⁸ Earlier studies of helium pumping or transport relied either on an indirect inference of central helium density via changes in the electron density⁹ or on the detection of ${}^3\text{He}$ through nuclear processes.¹⁰ Since ash control devices, such as divertors and pumped limiters, are necessarily located at the edge of a hot plasma, only direct knowledge of the confinement and transport of the He^{++} throughout the plasma allows a reasonable modeling of the effects of manipulation of the plasma edge on the central He^{++} concentration.

In this paper, we present the first example of detailed transport

coefficient determination for a low-Z impurity by following fully-ionized helium through a tokamak plasma after a puff of He was introduced at the plasma edge. The measurements were made in the PDX tokamak using the active spectroscopic technique of charge-exchange recombination spectroscopy (CXRS), wherein a highly collimated (FWHM ~ 3 cm) low power (8 kW) diagnostic neutral deuterium beam is injected across the line-of-sight of a spectrometer.¹¹ In the intersection volume of the neutral beam and the spectrometer sightline, charge-exchange reactions between the fast D^0 and thermal He^{++} produce He^+ in excited states which decay via photon emission. The $He^+ \Delta n=2-1$ transition at 304 Å is detected for these measurements since the beam energy of 15 keV/amu is too low to significantly populate levels with $n > 2$. CXRS has been used previously to measure fully-stripped intrinsic low-Z impurities (C^{6+} , O^{8+}) in the T-10,¹² ISX-B,¹³ and PDX tokamaks,¹¹ and it has recently matured to the level where ion velocity distributions are also measured.¹⁴⁻¹⁷

For these experiments, the PDX tokamak was run with graphite rail limiters giving a minor radius of $a=40$ cm. The ohmically heated H^+ discharges had major radius $R_{pl} = 150$ cm, $I_{pl} = 270$ kA, $B_T = 13$ kG, and $Z_{eff} = 2.4$. The total discharge pulse length was 900 ms, and a short puff of helium was injected into the plasma at $t = 365$ ms, causing a rise in $\bar{n}_e$ of $\sim 8\%$. Plasma electron density and temperature profiles at $t = 550$ ms are shown in Fig. 1. No discernible MHD activity was present during the experiment.

The time evolution of the near central ($r = 7$ cm) He^{++} density and central chord He^+ 304 Å intensity following the gas pulse are shown in Fig. 2. A sharp rise in $n_{He^{++}}$ is seen after the puff, followed by a slow decay which results from the equilibrating He^{++} radial distribution. This density of He^{++} ($\sim 5\%$ of n_e) is consistent with the observed rise in $\bar{n}_e$. The constant He^+ edge radiation at late times indicates full recycling of helium at the

plasma periphery.

Figure 3 shows the radial profile of He^{++} measured at $t = 550$ ns, the same time for which plasma profiles are given in Fig. 1. The He^{++} profile was found to be symmetric about the plasma major radius R_{pl} to within our measurement error, and the data points in Fig. 3 are weighted averages of values from both $R > R_{pl}$ and $R < R_{pl}$. The absolute scale on this plot is accurate to $\sim 30\%$ when spectrometer calibration, beam attenuation, and excitation rate uncertainties are taken into account. The uncertainty in the relative profile shape is much smaller, being determined mainly by the signal-to-noise ratio attained in a given shot. The data in Fig. 3 also include a correction for light emitted by electron excitation of He^+ ions which are created along the beam path and drift along the magnetic field lines into the spectrometer line-of-sight.¹⁷ This effect accounts for $\sim 30\%$ of the observed signal in these measurements, but has only a minor influence on the derived He^{++} radial profile shape.

Cross-field transport coefficients for He^{++} are obtained by modeling the data in Figs. 2 and 3 with solutions of the one-dimensional continuity equations for the helium ions:

$$\frac{\partial}{\partial t} n_q + \frac{1}{r} \frac{\partial}{\partial r} (r \Gamma_q) = -(I_q + R_q) n_q + I_{q-1} n_{q-1} + R_{q+1} n_{q+1} - \frac{n_q}{\tau_q} \quad (1)$$

Here, q is the ion charge, n_q is the density of charge state q , Γ_q is the radial flux for charge state q , R_q is the total recombination rate, I_q is the total ionization rate, and τ_q^{-1} denotes an effective loss rate for particles outside the limiter radius (i.e., $\tau_q^{-1} = 0$ for $r < a$). All of the terms in Eq.

(1) are functions of r , and the coupled equations are solved numerically using the PPPL MIST impurity transport code.¹⁸

In addition to adding a particle loss rate for $r > a$, a neutral helium influx at $r = a$ is specified which accurately reproduces the He^+ (304 Å) time evolution in Fig. 2(b). The three-dimensional neutral particle deposition calculation used assumes monoenergetic 0.1 eV helium neutrals, consistent with the low reflection coefficients for He on C.¹⁹ Our modeling results are only weakly sensitive to large variations in the neutral energy, the influx radius, and the assumed $T_e(a)$ and $n_e(a)$. A multiplicative scale factor was applied to the helium source rate in order to match the observed central He^{++} absolute density. Depending on the transport coefficients used, this factor ranged from 1.5 to 3.2. This is consistent with toroidal asymmetries of H_α emission in PDZ discharges.

The particular virtue in using He^{++} for these measurements lies in the fact that the right side of Eq. (1) is essentially zero for this ion over most of the plasma cross section. The time and space variations of $n_{\text{He}^{++}}$ in the core plasma ($r < a$) are thus predominately determined by the transport processes of interest instead of atomic processes.

Even a cursory estimate of the values of $\Gamma_{\text{He}^{++}}$ needed to reproduce our measurements shows that the required flux is one to two orders of magnitude larger than that expected from neoclassical transport theory, and we thus employ a general diffusive/convective model for the flux to obtain empirical transport coefficients via

$$\Gamma_q(r,t) = -D(r) \frac{\partial}{\partial r} n_q(r,t) + v(r)n_q(r,t) , \quad (2)$$

where the diffusion coefficient $D(r)$ and convective velocity $v(r)$ are both assumed to be independent of time and charge state. This model has been used in transport studies of low and high-Z impurities^{3,6,11,18} and for studies of the plasma density buildup in tokamaks.²⁰

In transport equilibrium, the total ionic flux, $\Sigma \Gamma_q$, is zero in the central, source/sink free region of the plasma. Also $n_{\text{He}^{++}}(r) \gg n_{\text{He}^+}(r)$ in the $r < 35$ cm region observed, which in principle allows us to use the late-time radial profile in Fig. 3 to directly relate the convective and diffusive transport in this region via $v(r)/D(r) = (\partial(\ln n_{\text{He}^{++}})/\partial r)$. The measured profile is not, however, complete or accurate enough to evaluate $v(r)/D(r)$ smoothly over the entire plasma radius, so instead we fit the data using a model function. Noting that the $n_{\text{He}^{++}}(r)$ profile is similar to that of $n_e(r)$, we choose the parameterization

$$\frac{v(r)}{D(r)} = c_v \frac{\partial(\ln n_e)}{\partial r}, \quad (3)$$

which yields $n_{\text{He}^{++}}(r) \propto (n_e(r))^{c_v}$ in equilibrium. Choosing c_v to give the best fit to the radial profile, $D(r)$ can then be derived from knowledge of the time evolution $n_{\text{He}^{++}}(t)$ at several radii. Since $n_{\text{He}^{++}}(t)$ was measured only at $r = 7$ cm in these initial experiments, we parameterize the diffusive transport using a radially constant diffusion coefficient, $D(r) = D$.

Fitting the data of Figs. 2 and 3 with time-evolving solutions to Eq. (1) reveals the calculated radial profiles to be indeed indistinguishably close to equilibrium at $t = 550$ ms. Figure 3 shows three such profiles in comparison with the data. The calculated profiles are all normalized to agree with the weighted average of the two innermost data points. The adopted value of $c_v = 0.8 \pm 0.3$ describes a helium radial profile which is similar to $n_e(r)$, but

slightly less peaked. This result is independent of the assumed value of D , and only weakly sensitive to the helium source parameters. The need for a convective term in addition to diffusion in impurity flow models is thus unambiguously demonstrated.

Taking $c_v = 0.8$ and modeling the time evolution of the near-central He^{++} in Fig. 2 provides the diffusion coefficient, D . The value of D thus derived is somewhat sensitive to the assumed value of τ_1 , the effective edge plasma confinement time due to parallel flow to the limiter. In our model, we take $\tau_1^{-1} = c_s v_s / \pi q(a) R_{pl}$ where v_s is the plasma sound speed in the scrapeoff, c_s is an adjustable Mach number for parallel flow, and $q(a)$ is the discharge safety factor. In general, if c_s is reduced, a correspondingly higher D is derived from the data. For example, taking $c_s = 1.0$, we arrive at $D = 1.8 (\pm 0.6) \times 10^4 \text{ cm}^2/\text{s}$, while $c_s = 0.1$ yields $D = 2.4 (\pm 0.6) \times 10^4 \text{ cm}^2/\text{s}$. Representative calculations using $c_s = 1.0$ are shown in Fig. 2 to indicate the sensitivity of the model to variations in D . Taking $0 \leq c_s \leq 1$ together with $c_v = 0.8 \pm 0.3$ yields $D = (2.1 \pm 0.9) \times 10^4 \text{ cm}^2 \text{ s}^{-1}$. This error range could be substantially reduced by obtaining $n_{\text{He}^{++}}(t)$ time evolution data at several radial points. Such data would also allow the radial dependence of D to be determined. The transport coefficients derived from this experiment are consistent with the less exact values derived from earlier studies of C^{6+} and O^{8+} radial profiles¹¹ and scandium injection experiments²¹ on PDX, and with the values derived from plasma density buildup experiments in ohmically heated PLT discharges.²⁰

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FIGURE CAPTIONS

- FIG. 1. Electron density and temperature profiles obtained from Thomson scattering at $t = 550$ ms. Experimental uncertainty is 5-10%.
- FIG. 2. Change in $n_{He^{++}}(r = 7\text{cm})$ and central chord He^+ 304 Å radiation after a short helium puff. The solid line is the estimated best fit to the data using the diffusive/convective model discussed in the text, and the dashed curves show the sensitivity of the model to variation of the diffusion coefficient. The peaking factor $c_v = 0.8$ and $c_g = 1.0$ for these curves.
- FIG. 3. Radial profile of He^{++} at $t = 550$ ms. The solid line is the estimated best fit to the data using the diffusive/convective transport model, while the dashed curves show the sensitivity to variation of the peaking parameter c_v .

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FIG. 1

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FIG. 2

FIG. 3

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