MEASUREMENTS OF RADIAL PROFILES OF He^{2+} TRANSPORT COEFFICIENTS ON TFTR

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Abstract: Measurements of the spatial structure of the transport coefficients of He^{2+} on the Tokamak Fusion Test Reactor is reported. He^{2+} profiles were measured using charge exchange spectroscopy after a helium puff into co-rotating L-mode plasmas. Modelling shows that the He^{2+} diffusivity is about $10 \text{ m}^2/\text{s}$ near the plasma edge and drops to below $1 \text{ m}^2/\text{s}$ inside of the $q=1$ surface. The convective velocity ranges from 1-3 m/s near $q=1$ to 20-40 m/s near the edge. The helium diffusivity is on the order of the ion momentum and thermal diffusivity and is greater than the electron thermal diffusivity.

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The behavior of helium ash in a tokamak plasma will be of tremendous importance to the cost and operation of future fusion devices.¹ Also, characterization of the transport of ionic plasma species will serve as powerful leverage when comparing experiment to various transport theories. In this light, an understanding of helium transport is highly desirable. Previous measurements of helium transport have been spatially averaged.^{2,3} In this report we describe the first measurements of the spatial structure of transport coefficients of He^{2+} in a tokamak plasma. Charge exchange recombination spectroscopy (CHERS)⁴ has been used to measure the time evolutions of the density of $\text{He}^{2+}(r)$ following a helium puff on the Tokamak Fusion Test Reactor (TFTR). The temporal behavior of the He^{2+} density at several spatial points has been modelled with the impurity transport code MIST,⁵ allowing the spatial structure of transport coefficients to be deduced.

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The transport coefficients have indeed been found to have large spatial variations, increasing by a factor of several between the sawtooth inversion radius and the plasma edge. Diffusivities and convective velocities in this region are at least an order of magnitude above those predicted by neoclassical theory. Inside the inversion radius, transport rates are reduced, but are still larger than neoclassical values except possibly near the magnetic axis.

The plasmas for this experiment had a major radius of 2.45 m, a minor radius of 0.80 m, a plasma current of 1.4 MA, a toroidal field of 4 T, and a discharge duration of 6 seconds. These deuterium plasmas were heated with 7 MW of co-directed tangential deuterium neutral beam injection from 3.5 to 4.5 seconds. The average electron density during the density flattop was $2.5 \times 10^{19} \text{ m}^{-3}$. The electron density peaking parameter, the ratio of the central density to the average density $n_e(0)/\langle n_e \rangle$, was 1.6, typical of most low-density L-mode discharges on TFTR, while the energy confinement time τ_E was modestly higher than the L-mode value ($\tau_E = 1.3\tau_{EL\text{mode}}$). The central ion temperature was 9-10 keV during the beam flattop, and the central electron temperature was ~ 5 keV. The central toroidal velocity was ~ 250 km/s, and the central Z_{eff} was 4.0. These discharges possessed sawteeth with ~ 150 -200 ms duration and had an inversion radius at $r/a = 0.35$, where r is the plasma minor radius and a is the limiter radius. A 16 ms helium puff was introduced at 4.2 s, well into the equilibrium phase of the neutral beam pulse. The line-averaged density of the plasma increased by 2-3% as a result of the puff; the perturbation in electron temperature was somewhat less.

The CHERS spectrometer was used to view a coinjecting heating beam. The neutral beam-CHERS sightline intersection radii are separated by ~ 0.1 m. The He^{2+} density evolution after the puff was measured by following the time behavior of the 4686 Å line ($n=4-3$) of He^{1+} , induced by charge exchange recombination with beam neutrals. Time resolution for these measurements was 10 ms, and the data from fourteen discharges was averaged together without regard to sawtooth phase. Interpretation of measured line brightnesses can be complicated by the presence of He^{1+} ions (ion plume) produced by charge exchange and subsequently excited by electron impact.³ For tangential views through the center of the plasma, the plume brightnesses can rival the prompt charge exchange signal and must, therefore, be taken into

account. He^{2+} profiles were deduced using a self-consistent treatment in which trial He^{2+} profile shapes were iterated until agreement between predicted and observed line brightnesses was achieved. Beam attenuation was calculated using the mean free path treatment of Boley *et al.*,⁶ and reaction rate coefficients for inducing the $n=4-3$ transition were taken from measurements by Ciric *et al.*⁷ The reaction rate coefficient for exciting this transition by charge exchange from the $n=2$ level of beam neutrals,⁸ important for the one-third (E/3) energy component of the beam, has been calculated using the Classical Trajectory Monte Carlo (CTMC) code of Olson.⁹ Where the E/3 component is not significantly attenuated, this increases the total line emission reaction rate by at most 15%. This effect has been included in these measurements. With central ion temperatures of ~ 10 keV, charge exchange from thermal halos is negligible.¹⁰

The time evolution of the densities was modelled by solving the one-dimensional continuity equations for the helium ions:

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

where 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 recombination rate, I_q is the ionization rate, $\tau_{//}$ is an effective loss rate for particles outside the limiter radius, and S_q is a volume source for $q=+1$ ions due to edge neutral influx. It is assumed that the helium flux can be expressed as

$$\Gamma_q(r,t) = -D_{\text{He}}(r) \partial/\partial r(n_q(r,t)) + V_{\text{He}}(r)n_q(r,t) \quad (2)$$

where D_{He} is the helium diffusivity and V_{He} is the convective velocity. Transport of He^{1+} and He^{2+} are assumed to be the same. The neutral helium source has been programmed into MIST by assuming that the energy of recycled neutral helium is 0.1 eV, typical of the temperature of a carbon tile on the bumper limiter. The use of energies lower than this do not affect the transport conclusions presented here; energies on the order of an eV or more are unphysical and give time histories of edge densities that cannot be

modelled with any values of D_{He} and V_{He} . The time behavior of the He^{2+} source was deduced from measurements of the 304 Å He^{1+} line ($n=2-1$) by a vacuum ultraviolet spectrometer viewing along a radial chord at the inner wall limiter, the location of most of the recycling. Use of this measurement of the source eliminates the need for any assumptions regarding helium recycling efficiency.

In the modelling, D_{He} and V_{He} are constrained to reproduce the He^{2+} profile observed long after the puff (> 250 ms). Under this constraint, it is found that no spatially constant D_{He} will reproduce the data satisfactorily. The range of D_{He} and V_{He} that best fit the data is shown in Fig. 1. Here, D_{He} was allowed to vary linearly between the radii at which helium densities were measured. Errors in the inferred transport coefficients were established by including estimates of the uncertainty of the best fits as well as propagating a $\pm 20\%$ uncertainty in the beam stopping cross sections through the profile shape calculations. Less satisfactory fits were obtained near the plasma axis, possibly because sawtooth effects were not completely averaged out in this ensemble of data. Still, examination of predicted profile shapes indicates that the best-fit D_{He} increases rapidly with minor radius inside the $q=1$ surface. Of note is that the good-fit $D_{\text{He}}(r)$ varies by over an order of magnitude across the plasma, with the extreme values found near the plasma boundary and inside the inversion radius. Fig. 2 shows the measured local He^{2+} density at (a) $r = 0.65$ m and (b) $r = 0.39$ m. Error bars represent estimates of the statistical uncertainty in the measured signal brightnesses. Also shown in this figure are MIST modelling results using $D_{\text{He}}(r)$ and $V_{\text{He}}(r)$ of Fig. 1 and results from varying this form of $D_{\text{He}}(r)$ by $\pm 30\%$ (again with $D_{\text{He}}/V_{\text{He}}$ chosen to reproduce the long-time He^{2+} profile). Even modest variations in the assumed diffusivity predict transport times that are outside of the statistical errors.

Measured and modelled profiles after the puff are shown in Figure 3. Figure 3a shows the profiles inferred from CHERS measurements. Note the short time scales (~ 50 ms) required for the profile at $r/a > 0.5$ to reach its final scale length. However, the time scale required to reach the final scale length for $r/a < 0.5$ is typically ~ 100 ms, indicative of slower transport there. Figure 3b shows the modelled profile shapes from MIST using the transport

coefficients of Fig. 1. Good reproduction of the measured profiles is achieved. However, the profiles obtained using the constant D_{He} required to match the data near the plasma edge do not reproduce the measured time evolutions (Fig. 3c); transport is predicted to be much too rapid in the interior. A more modest value of constant D_{He} , typical of the value near $r/a = 0.5$ from Fig. 1, also fails to reproduce the profile evolutions observed (Fig. 3d).

Thermal transport coefficients have been calculated using the 1-D steady-state transport code SNAP. Figure 4 shows D_{He} , the ion thermal diffusivity χ_i , the ion momentum diffusivity χ_ϕ , and the electron thermal diffusivity χ_e . Error estimates of χ_i , χ_ϕ , and χ_e were obtained by performing 100 transport analyses using the measured profiles (n_e as measured by a 10 channel infrared interferometer, T_e as measured by electron cyclotron emission, and T_i and V_ϕ as measured by CHERS) and other input data simultaneously varied within their ranges of uncertainty by Monte Carlo sampling a Gaussian distribution for both statistical and systematic errors.¹¹ Profiles were obtained near the top of a sawtooth cycle. Interestingly, it is found that $D_{He}(r) \sim \chi_i(r) \sim \chi_\phi(r) > \chi_e(r)$ over much of the plasma cross section (Fig. 4). If electrostatic turbulence is the dominant transport mechanism, this is not completely unexpected. If helium can be regarded as a trace impurity, its transport is not tied to the constraints of ambipolarity. The helium ions can then be expected to transport at a rate comparable to the ion thermal energy, consistent with $D_{He}(r) \sim \chi_i(r)$. Also, this work is being carried out in conjunction with iron transport measurements using CHERS.¹² Indications are that the helium-like iron diffusion coefficient is comparatively flat, and the convective velocity is consistent with neoclassical theory, in sharp contrast with the results presented here for He^{2+} . Further examination of the details of the predicted ratios of the helium, iron, and heat fluxes may yield useful constraints on the scale size of turbulence. Results from such a comparison will be described in a more comprehensive publication.

In this context, it has been pointed out that dependencies of the transport coefficients on plasma parameters can cause the perturbative phase

of the transport to deviate significantly from that in steady state if the transport coefficients are functions of bulk plasma quantities such as n_e , ∇n_e , T_e , ∇T_e , etc.¹³ Such dependencies are predicted by drift-wave theories.¹⁴ In the case of electron transport experiments with gas puffing, this is especially important because the fractional change in n_e and ∇n_e as a result of the perturbation may be the same order as the fractional change in the transport coefficients themselves. However, the problem is of greatly reduced order for impurity transport experiments involving gas puffing or impurity injection. If the fluctuations assumed to be driving impurity transport are not changed significantly by the introduction of the impurity itself, then the fractional change in n_{He} and ∇n_{He} can easily be an order of magnitude larger than the fractional change in the transport coefficients (again determined by bulk plasma parameters). In this experiment, the fraction of ions n_i/n_e is less than 2% for helium, far below that of the thermal deuterons (~30%), slowing-down beam ions (~15%), and carbon (~8%), making it unlikely that a large change in helium transport coefficients results from the introduction of helium itself. Of course, this issue deserves examination by introducing various size gas puffs and will be the subject of future experiments.

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Figure Captions

Fig. 1 - Diffusivity and convective velocity of He^{2+} as functions of radius. Error bars indicate estimated range of acceptable transport coefficients, including statistical errors and those due to uncertainties in He^{2+} profile shape.

Fig. 2 - Measured He^{2+} density and MIST modelling results for the transport coefficients in Fig. 1 (hollow D_{He}) $\pm 30\%$ variations in the diffusivity (with $D_{\text{He}}/V_{\text{He}}$ constrained as discussed in the text).

Fig. 3 - Helium profiles for various times after the puff. (a). Measured (b). Simulated with MIST with D_{He} and V_{He} from Fig. 1. (c). From MIST, with $D_{\text{He}} = 10 \text{ m}^2/\text{s}$. (d). From MIST, with $D_{\text{He}} = 4 \text{ m}^2/\text{s}$. In (b), (c) and (d), $D_{\text{He}}/V_{\text{He}}$ is constrained to reproduce the long-time ($> 120 \text{ ms}$) scale length. Closed circles: $t=0.005 \text{ s}$ after puff, open circles: $t=0.035 \text{ s}$, closed triangles: $t=0.065 \text{ s}$, open triangles: $t=0.095 \text{ s}$, closed squares: $t=0.125 \text{ s}$.

Fig. 4 - Helium diffusivity $D_{\text{He}}(r)$, electron thermal diffusivity χ_e , ion thermal diffusivity χ_i , and momentum diffusivity χ_ϕ as calculated with SNAP.

FIG. 1

FIG. 2 (a & b)

FIG. 3 (a-d)

FIG. 4