Measurement of Iron Transport in TFTR by Charge
Exchange Recombination Spectroscopy

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ABSTRACT

Transport of iron in TFTR discharges is studied by spatially-resolved charge exchange recombination spectroscopy in the visible region of the spectrum. Time evolutions of the densities of Fe^{24+} and Fe^{23+} ions following injection of iron are modeled by the neoclassical flux plus a moderately hollow diffusivity increasing linearly from $1.3 \text{ m}^2/\text{sec}$ on axis to $2.4 \text{ m}^2/\text{sec}$ at the plasma edge. For $r/a > 0.5$, the iron diffusivity is significantly smaller than the helium diffusivity measured in identical discharges, while it is larger in the region immediately surrounding the plasma axis.

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Comparison of transport of different particle species has the potential to provide constraints on theories of fluctuation-driven transport in tokamaks. In particular, comparison of diffusivities and convective velocities for different species of impurity ions is valuable due to the significantly different gyroradii of these particles. For such comparisons to be meaningful, the spatial profiles of the diffusivity and convective velocity must be measured for each species. In most previous studies of metallic impurity transport, including those on the Tokamak Fusion Test Reactor (TFTR),¹ a spatially constant diffusivity and parameterized convective velocity were inferred from time evolutions of chord-integrated line brightnesses following impurity injection; uncertainties in modeling such data do not permit the spatial dependencies of the transport parameters to be determined.¹ These spatial dependencies can be deduced from measurements of the time evolution of impurity density profiles following a perturbation. Charge-exchange recombination spectroscopy (CXRS) has been used to study low-Z impurity transport,^{2,3} and Knize, et al.⁴ have demonstrated that metallic impurity profiles can be measured via CXRS, but their limited data did not permit transport parameters to be determined.

This Letter presents the first application of CXRS to the measurement of metallic impurity transport in a tokamak: the spatial dependence of the diffusivity of iron is determined from relatively simple measurements in the visible region of the spectrum on TFTR. Transitions between Rydberg levels ($n=18-19$) of Fe^{+23} (5001 Å) and Fe^{+22} (5445 Å) were observed with a spatially-resolving spectrometer following injection of iron into the plasma. These lines are excited by charge exchange recombination of deuterium atoms in injected neutral beams with Fe^{+24} and Fe^{+23} ions, the most abundant iron ions in the core region of the discharge, and their intensities are proportional to the local densities of these ions. The diffusivity and

convective velocity were deduced by modeling the time evolutions of the lines with an impurity transport code. The data are well fit by the neoclassical flux plus a diffusivity which increases linearly from $1.3 \text{ m}^2/\text{sec}$ at the plasma axis to $2.4 \text{ m}^2/\text{sec}$ at the edge. The iron diffusivity is compared with the helium diffusivity measured by Synakowski, et al.⁵ in identical discharges.

The experiment was performed in deuterium plasmas with major and minor radii of $R=2.45 \text{ m}$ and $a=0.80 \text{ m}$. The plasma current, I_p , was 1.4 MA and the toroidal field was 4.0 T . Three co-tangential deuterium beams at an energy of 100 keV and 6.7 MW total power were injected for one second starting at 3.5 sec , well into the plasma current flat top. The line average density reached $2.5 \times 10^{19} \text{ m}^{-3}$ at 4.0 sec and remained constant until the end of beam injection at 4.5 sec . The central electron and ion temperatures during this period were 5 keV and 10 keV , respectively.

The lines were observed using the CHERS diagnostic, a visible and near-ultraviolet spectrometer with simultaneous spectral and spatial resolution. CHERS has eleven tangential views lying in the midplane of the torus which intersect the beams at equally spaced major radii from 2.34 m to 3.34 m . The spatial resolution in the radial direction for each channel is $0.03\text{-}0.05 \text{ m}$. The time resolution of the measurements, determined by the detector integration time, was 0.02 sec .

Iron was injected at 4.06 sec using the laser blowoff technique.⁶ Time evolutions of the intensities of the $\text{Fe}^{23+} 5001 \text{ \AA}$ line at the seven radii at which the data have a usable signal-to-noise ratio are shown in Fig. 1, with the pre-injection signal levels subtracted. Because the plasma was in steady state and the line excitation was therefore constant, these intensities are proportional to the local Fe^{24+} densities. The minor radii viewed by each spectrometer channel (corrected for the calculated Shafranov shift) are

indicated. The lines were weak; in order to improve statistics, data from six identical shots are averaged together. While sawteeth were present during beam injection and they were not in phase in all six shots, an average of three shots in which the sawteeth were in phase yields time evolutions with rise and decay times the same as those shown in Fig. 1. Thus, the sawtooth phase can be disregarded in averaging the data without affecting the deduced transport. The Fe^{24+} densities reach their maxima in approximately 0.05 sec after injection, and then return to the pre-injection values in 0.3 sec. The rise times do not vary by more than 0.02 sec from the edge to the center, implying that transport is rapid over the entire plasma radius.

The time evolutions of the Fe^{24+} density shown in Fig. 1 were modeled using the MIST⁷ impurity transport code. MIST solves the impurity continuity equations

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

where n_q is the impurity density in ionization state q , Γ_q is the impurity flux density, and I_q and R_q are ionization and recombination rates. S_q , the impurity source, and τ_q , the impurity confinement time in the scrapeoff region, as well as the electron impact ionization, dielectronic recombination, radiative recombination, and charge exchange recombination rates, are as described in Ref. 1, except that the ionization rates are adjusted to agree with the more accurate values of Pindzola, et al.⁸ Γ_q is assumed to be the sum of diffusive and convective terms:

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

where $D(r)$ is a diffusivity and $v_q(r)$ is a convective velocity. $D(r)$ is assumed

to be independent of impurity charge state.

Time evolutions of the Fe^{24+} density calculated by MIST are shown in Fig. 1. A transport model consisting of the neoclassical flux calculated in the Pfirsch-Schlüter regime⁹ plus a diffusivity which increases linearly from 1.3 m^2/sec on axis to 2.4 m^2/sec at the plasma edge was used. (The effects of plasma rotation were not included in the neoclassical calculation, but are expected to be small at $I_p=1.4$ MA for the measured toroidal rotation velocity of 250 km/sec.¹⁰) The measured and calculated values are normalized at the time of peak density. This transport model was chosen as being the simplest which produces good agreement with the data. The diffusivity is shown in Fig. 2, along with error bars indicating the range of values that reproduce the data acceptably. Neoclassical transport alone does not fit the data because the neoclassical diffusivity, which rises from 0.002 m^2/sec on axis to 0.04 m^2/sec at the plasma edge, is too small to predict the rise and decay times shown in Fig. 1. A spatially constant diffusivity does not fit the data as well as the one shown in Fig. 2. It is not possible to model the data with a diffusivity significantly more hollow than shown in Fig. 2 because such transport models predict a much longer time to peak density near the plasma axis than at the edge, which is inconsistent with the measurements in Fig. 1. (This continues to be true even if a convective velocity larger than that predicted by neoclassical theory is used.)

The measured time evolutions of the Fe^{23+} density from the Fe^{22+} 5445 Å line are very similar to those for Fe^{24+} and are in good agreement with code predictions. The time evolutions of the chord-integrated intensities of the Fe^{22+} 133 Å and Fe^{23+} 192 Å lines observed by a vacuum ultraviolet spectrograph also agree well with code predictions.

The neoclassical convective velocity for Fe^{24+} falls rapidly from an inwardly-directed value of 4 m/sec at the plasma edge to much smaller

values in the core region. Over most of the period shown in Fig. 1, the transport is diffusion dominated. As a result, this experiment does not provide a sensitive measurement of the convective velocity, and small values different from the neoclassical values have been found which reproduce the data well. However, it is possible to exclude much larger values of the convective velocity.

For the transport model to be valid, the observed profiles of the Fe^{24+} and Fe^{23+} densities must also agree with the code predictions. Profiles at a number of times following iron injection were obtained by modeling the line intensities as described by Fonck, et al.¹¹ The intensity of a charge exchange excited line is proportional to the sum over the full, half, and one-third energy components present in the beam of the product of the local beam particle density, the impurity density, and the cross section for populating the upper level of the observed transition. Absolute values of the cross sections are not required to measure the shapes of the profiles, but because the beam has three energy components, the energy dependence of the cross sections must be known.⁴ The energy dependence of the cross sections was taken from cross sections for capture into the $n=19$ levels of Fe^{+24} calculated by Olson¹² using the Classical Trajectory Monte Carlo method.¹³ This approximation is reliable at energies of 50 keV/amu and 25 keV/amu, the full and half energy components of the beam, but it is not applicable to the one-third energy component at 17 keV/amu. The cross section at this energy was obtained by extrapolation from higher energies. Uncertainty in this value does not greatly affect the deduced profiles because the one-third energy component contributes only 9% to the total line intensity at the plasma edge and 4% on axis. The beam particle densities at the energies of the three components were calculated using the mean free paths of Boley, et al.,¹⁴ which include the effects of collisional excitation of

the beam atoms. The deduced profiles of Fe^{24+} and Fe^{23+} ions at the time of peak density (0.05 sec in Fig. 1) are shown in Fig. 3. The error bars on the profiles are determined by the statistics of the data, uncertainty in the cross section at 17 keV/amu, and the uncertainty in the beam mean free paths, which is estimated to be 15%.¹⁴

Figure 3 also shows the predicted Fe^{24+} and Fe^{23+} profiles. The measured and calculated profiles are normalized at their peak values. The calculated Fe^{24+} profile is in good agreement with the measured one, while the calculated Fe^{23+} profile is not as hollow as the observed one. This is probably caused by inaccuracies in the dielectronic recombination rates in MiST¹ (which are similar to those given by the Burgess-Merts formula¹⁵) because transport models which predict this behavior, such as those with a very hollow diffusivity, do not reproduce the time evolutions of the lines. (An increase in the Fe^{23+} recombination rate combined with a decrease in the Fe^{24+} rate would produce a hollow Fe^{23+} profile and a slightly more peaked Fe^{24+} profile, in better agreement with the measured profiles.) Similarly good agreement between the measured and calculated Fe^{24+} profiles is found at other times following the iron injection and for the equilibrium profiles before injection. However, because of the uncertainties in the measured and calculated profiles, the profiles do not provide as strong a constraint on the transport model as the time evolutions of the lines. For this reason, the measured and calculated time evolutions in Fig. 1 are normalized at the peak values for each radius.

Figure 2 shows a comparison of the iron diffusivity with the helium diffusivity measured in identical discharges by Synakowski, et al.⁵ The helium diffusivity is very hollow, dropping from 10 m²/sec at the plasma edge to less than 0.1 m²/sec on axis. At radii greater than 0.4 m, the iron diffusivity is significantly smaller than the helium diffusivity measured in

identical discharges, while it is larger in the region immediately surrounding the plasma axis. The convective velocity for helium is also considerably larger at the plasma edge than that for iron. In the absence of measured spectra for fluctuations with radial wavenumbers in the $1-5 \text{ cm}^{-1}$ range, it is difficult to say whether these differences would be expected. Such spectra are expected to be available in future experiments.

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FIGURE CAPTIONS

1. Measured (dots) and calculated (solid lines) time evolutions of Fe^{24+} density (Fe^{23+} 5001 Å line intensity) at seven spatial locations. The values are normalized at the time of peak density.
2. Measured iron diffusivity (solid line), and, for comparison, the helium diffusivity (dashed line) measured in identical discharges by Synakowski, et al.⁵
3. Measured (dots) and calculated radial distributions of Fe^{24+} (solid line) and Fe^{23+} (dashed line) densities 0.05 sec after iron injection. The profiles are normalized at their peak values.

FIG. 1

FIG. 2

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FIG. 3

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