Helium-3 Transport Experiments in the Scrape-Off Layer with the Alcator C-Mod Omegatron Ion Mass Spectrometer

R. Nachtrieb[a], B. LaBombard

MIT Plasma Science and Fusion Center, Cambridge MA, 02139-4213, USA

[a]*Lutron Electronics Co., Inc., Coopersburg, PA 18036 USA*

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Abstract

^{3}He gas was puffed from the wall into ohmic L-mode discharges of the Alcator C-Mod tokamak and the charged states were measured near the wall with the omegatron ion mass spectrometer. Analysis of the data shows that the concentrations of singly- and doubly-ionized helium near the wall are approximately equal. The electron temperature and density at the omegatron are too low to account for ionization of helium in the local flux tube, therefore the helium is ionized in a hotter region of the edge plasma and is transported to the omegatron. A simple one-dimensional radial transport model reproduces the observed values of charge state flux and density, but only if rapid cross-field transport is included, increasing with distance from the separatrix. A constant cross-field diffusion coefficient of order 2 m^2/s and an outward convection velocity profile increasing to of order 100 m/s in the far scrape-off layer is implied.

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I. INTRODUCTION

Experiments were performed on Alcator C-Mod to characterize the transport of helium ions in the scrape-off layer plasma. Helium gas with atomic number three was puffed from the wall into tokamak discharges, and the omegatron ion mass spectrometer[1,2] was used to record the absolute concentrations and fluxes of singly- and doubly-charged helium ions in the far scrape-off layer, near the wall.

Helium is a convenient impurity for transport experiments: it has only two charged states, it forms no molecules, and excited states can be neglected, so it is simple to model; it is a recycling impurity, so steady transport behavior is independent of the gas puff location; in deuterium majority plasmas we can safely neglect helium charge exchange; if we also neglect backscattering of helium ions as neutrals from wall surfaces then neutral helium atoms have the wall temperature; trace amounts of helium are benign for machine operation, so experiments can often proceed in "piggy-back" mode; finally, the charge to mass ratios are either unique ($M/Z = 3/2$) or uncommon ($M/Z = 3$), so the helium resonances can be identified unambiguously with the omegatron.

The ratios of doubly-charged to singly-charged helium ions flux and density measured by the omegatron provide information about impurity transport in the scrape-off layer. Qualitatively, if the impurity transport out of the hot plasma is rapid, there is insufficient time to form doubly-ionized helium, and the inward flux of neutral helium is balanced by an outward flux of singly-ionized helium. If instead the impurity transport out of the hot plasma is slow, then most of the singly ionized helium becomes doubly-ionized, and the inward flux of neutral helium is balanced by an outward flux of doubly-ionized helium.

It is found that the ratio of doubly-charged to singly-charged helium ion flux measured by the omegatron is near unity. The electron density and temperature near the omegatron are too low for the helium ions to have been produced locally, thus the helium must have been transported from a hotter region of the plasma. A simple one-dimensional diffusive model reproduces the observed values of density and flux, but only if the cross-field particle

transport is rapid and increases with distance from the separatrix.

Figure 1 shows a schematic of the two-dimensional cross section of the scrape-off layer. Helium, ionized near the separatrix, must transport across magnetic field lines through the scrape-off layer (SOL) to arrive at the Local SOL shared by the omegatron and the E-Port ICRF antenna. Using the notation as shown in Fig.1, the outline of this paper is as follows:

Singly- and doubly-ionized ^{3}He are collected in the omegatron RF cavity. The densities and parallel fluxes of singly- and doubly-ionized ^{3}He are inferred at the sheath edge of the entrance slit (Section II).

Helium ionization rates near the omegatron are compared with parallel transport times. It is shown that in order to explain the measured ratios of singly- and doubly-ionized ^{3}He fluxes, the helium ions must be formed outside the Local SOL and transported into it (Section III).

Cross-field transport of deuterium and helium in the Local SOL are considered in Section IV. Ionization can be neglected in the particle balance, thus the cross-field flux into the Local SOL is simply related to the parallel flux profile measured by Langmuir probes on the omegatron head. Assuming helium and deuterium ions are subject to the same cross-field transport mechanisms and knowing the presheath is highly collisional, the helium flux into the Local SOL can be simply scaled from the deuterium measurements.

A cross-field ^{3}He transport model is developed in Section V to relate the fluxes and densities of neutral, singly-ionized, and doubly ionized ^{3}He in the SOL. The background plasma electron temperature and density profiles in the SOL are obtained from scanning Langmuir probe measurements and are used to calculate helium ionization rates in the SOL. Since atomic helium enters the SOL plasma at the wall temperature, the profiles of neutral helium density and the singly-ionized helium source can be calculated directly.

Numerical solutions to the ^{3}He transport model using measured temperature and density profiles are presented in Section VI. Cross-field transport is adjusted (via $D_\perp$ and $V_\perp$) to yield measured values of density and perpendicular flux of helium ions arriving at the boundary between the SOL and Local SOL.

Finally, the results are discussed and compared with other estimates of cross-field transport in the SOL (Section VII).

II. EXPERIMENT

^{3}He gas was puffed into a typical Alcator C-Mod ohmic L-mode plasma (lower x-point diverted, with toroidal field $B = 5.4$T on axis, plasma current $I_p = 0.8$ MA, line-averaged electron density $n_e = 10^{20}$ m^{-3}). Both charged states of ^{3}He were observed unambiguously with the omegatron ion mass spectrometer, which resides approximately 45 degrees in poloidal angle above the outer midplane, and is positioned on flux surfaces approximately 40 mm from the separatrix (mapped to the midplane). Figure 2(a) shows the resultant ^{3}He impurity spectrum. The currents collected due to singly- and doubly-ionized ^{3}He are approximately equal.

The amplitude of the current collected by cyclotron resonance increases as the RF power applied to the omegatron is increased. The measured current, I_{RF}, obeys the relationship[1] $I_{RF} = I_{as}[1 - \exp(-P/c_1)]$, where I_{as} is the asymptotic helium current that would have been collected if (in principle) infinite RF power (P) had been applied to the omegatron, and c_1 is related to the helium ion temperature (kT) by

$$\frac{kT}{m} = c_1 \frac{2L^2 R}{B^2 D^4}.$$

Here, m is the helium ion mass, L is the RF cavity length, D is the spacing between the RF plates, $R = 50\,\Omega$ is the RF load, and B is the magnetic field strength. Measurements made with the retarding field energy analyzer on the omegatron indicate that the bulk deuterium ion temperature is typically ≈ 3 eV. Since the presheath in these discharges was highly collisional, both charge states of ^{3}He should also be at ≈ 3 eV. Spectra were taken for a number of RF powers and the asympototic currents, I_{as}, were computed with $T = 3$ eV. The results shown in Fig.2(b) show that $T \approx 3$ eV is a good assumption and that the collected current ratios are $I_{He}^{++}/I_{He}^{+} = 0.8 \pm 0.1$.

The parallel helium flux incident on the omegatron entrance slit is related to the asymptotic resonant current measured inside the omegatron by[1]

$$\frac{\Gamma_{\text{He},\parallel}^{++}}{\Gamma_{\text{He},\parallel}^{+}} = \frac{I_{\text{He}}^{++}}{I_{\text{He}}^{+}} \frac{1}{2g_{\text{trans}}}, \tag{1}$$

where $g_{\text{trans}} = \exp(-q\phi_0/kT)$ is the fraction of current that is sufficiently energetic to pass the maximum potential ϕ_0 in the RF cavity. Analysis of the transmission of bulk currents to the grids allows ϕ_0 to be inferred and gives $g_{\text{trans}} = 0.65 \pm 0.07$. In the case when the presheath is highly collisional, all ion species have the same fluid velocity at the sheath edge. Then by Eq.(1),

$$\frac{\Gamma_{\text{He},\parallel}^{++}}{\Gamma_{\text{He},\parallel}^{+}} = \frac{n_{\text{He}}^{++}}{n_{\text{He}}^{+}} \equiv \alpha = 0.6 \pm 0.1. \tag{2}$$

III. ^{3}HE$^+$ AND ^{3}HE^{++} IONIZATION IN LOCAL SOL

First we consider the possibility that all the helium ions detected by the omegatron are formed by ionization in the Local SOL connecting the face of the omegatron and the E-port ICRF antenna. Let $n_{\text{He}}^0, n_{\text{He}}^+, n_{\text{He}}^{++}$ represent the density of neutral, singly-ionized, and doubly-ionized helium, respectively. Consider the case when the charge states of helium are produced in the Local SOL by ionization in the plasma with electron density n_e and temperature T_e, and losses are due only to transport parallel to field lines. Neglecting volume recombination and considering ionization from the ground state only, the steady state continuity equations for n_{He}^+ and n_{He}^{++} are given by $n_{\text{He}}^+/\tau_\parallel = n_{\text{He}}^0 n_e \langle \sigma v \rangle_{\text{He}}^+ - n_{\text{He}}^+ n_e \langle \sigma v \rangle_{\text{He}}^{++}$, $n_{\text{He}}^{++}/\tau_\parallel = n_{\text{He}}^+ n_e \langle \sigma v \rangle_{\text{He}}^{++}$, where $\tau_\parallel = L_\parallel/\sqrt{kT_e/m_i}$ is the parallel transport time, $L_\parallel \approx 0.9\,\text{m}$ is half the connection length in the Local SOL, and $\langle \sigma v \rangle_{\text{He}}^+$ and $\langle \sigma v \rangle_{\text{He}}^{++}$ represent the ionization reaction rate parameters for electron impact on neutral helium and singly-charged helium, respectively.[3] Solving for the density ratios:

$$\frac{n_{\text{He}}^+}{n_{\text{He}}^0} = \frac{n_e \langle \sigma v \rangle_{\text{He}}^+}{(1/\tau_\parallel) + n_e \langle \sigma v \rangle_{\text{He}}^{++}}, \qquad \frac{n_{\text{He}}^{++}}{n_{\text{He}}^+} = \tau_\parallel n_e \langle \sigma v \rangle_{\text{He}}^{++}.$$

The electron density $n_e \approx 2 \times 10^{17}\,\mathrm{m}^{-3}$ and electron temperature $kT_e \approx 7\,\mathrm{eV}$ are available from Langmuir probes at the omegatron, giving $n_e \langle \sigma v \rangle_{\mathrm{He}}^+ \approx 43\,\mathrm{s}^{-1}$, $n_e \langle \sigma v \rangle_{\mathrm{He}}^{++} \approx 0.2\,\mathrm{s}^{-1}$, $\tau_\parallel = 67\,\mu\mathrm{s}$, $n_{\mathrm{He}}^+/n_{\mathrm{He}}^0 \approx 3 \times 10^{-3}$, and $n_{\mathrm{He}}^{++}/n_{\mathrm{He}}^+ \approx 10^{-5}$.

The results of this simple model contradict observation, which gives $n_{\mathrm{He}}^{++}/n_{\mathrm{He}}^+ \approx 0.6$. Also, the helium neutral pressure implied by the simple model is larger than expected, equal to the total neutral pressure observed in the upper chamber. We therefore conclude that the observed ^{3}He density and flux ratios at the omegatron principally arise from cross-field transport of ^{3}He into the Local SOL.

IV. CROSS-FIELD TRANSPORT IN LOCAL SOL

From Langmuir probe measurements of bulk plasma densities and fluxes along the face of the heat shield and from resonant helium current measurements with the ion mass spectrometer, helium ion densities and perpendicular fluxes at the boundary of the Local SOL can be obtained. We have no direct measurement of the helium transport in the Local SOL, but we postulate that the helium and the deuterium ions are subject to the same cross-field transport mechanisms. In addition, since the presheath is highly collisional, all ion species have the same fluid velocity at the sheath edge and the same parallel flow velocity everywhere in the Local SOL volume. Finally, since both helium and deuterium sources are negligible in the Local SOL, it is reasonable to assume that the concentrations and fluxes of ^{3}He relative to deuterium are constant, i.e. $n_{\mathrm{He}}^+/n_{\mathrm{D}}^+ = \Gamma_{\mathrm{He}}^+/\Gamma_{\mathrm{D}}^+ \equiv c_{\mathrm{He}}^+$ and $n_{\mathrm{He}}^{++}/n_{\mathrm{D}}^+ = \Gamma_{\mathrm{He}}^{++}/\Gamma_{\mathrm{D}}^+ \equiv c_{\mathrm{He}}^{++}$. Thus the ^{3}He fluxes into the Local SOL can be simply scaled from the deuterium fluxes. Note that from Section II, $c_{\mathrm{He}}^{++}/c_{\mathrm{He}}^+ = \alpha = 0.6 \pm 0.1$.

Define a coordinate x perpendicular to the magnetic field, where $x = x_0$ is near the separatrix and $x = x_1$ is at the boundary between the SOL and the Local SOL, near the edge of the omegatron probe (see Fig.1). It can be shown that to a good approximation the deuterium flux in the Local SOL is divergence free. Therefore,

$$-\Gamma_{\mathrm{D},\perp}^+(x_1)L_\parallel + \int_{x_1}^{\infty} \Gamma_{\mathrm{D},\parallel}^+(x)dx = 0, \tag{3}$$

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where $\Gamma_{D,\perp}^+$ is the average perpendicular flux of deuterium along the Local SOL boundary and $\Gamma_{D,\|}^+$ is the parallel flux of deuterium at the walls. It is found that $\Gamma_{D,\|}^+(x)$ decays exponentially with x with characteristic length $\lambda_\| = 8.3\,\mathrm{mm} \pm 1.2\,\mathrm{mm}$, from three Langmuir probes at locations x_1, $x_1 + 6.5\,\mathrm{mm}$, and $x_1 + 11\,\mathrm{mm}$. Therefore, the average perpendicular flux into the Local SOL is simply related to the measured parallel flux at x_1 by

$$\Gamma_{D,\perp}^+(x_1) = \Gamma_{D,\|}^+(x_1)\lambda_\|/L_\|. \tag{4}$$

For a plasma sound speed $c_s(x_1)$, the perpendicular deuterium flux is related to the deuterium density by

$$\Gamma_{D,\perp}^+(x_1) = n_D^+(x_1)\frac{c_s(x_1)}{2}\frac{\lambda_\|}{L_\|}, \tag{5}$$

and from the scaling argument above, we expect

$$\Gamma_{He,\perp}^j(x_1) = n_{He}^j(x_1)\frac{c_s(x_1)}{2}\frac{\lambda_\|}{L_\|}. \tag{6}$$

From Eq.(6) plus the measurement of Eq.(2), we can compute the cross-field $^3\mathrm{He}^+$ flux and $^3\mathrm{He}^+$ density at the edge of the SOL ($x = x_1$), normalized to the neutral helium flux and density, respectively, at that location. Conservation of mass flux requires $\Gamma_{He,\perp}^0 + \Gamma_{He,\perp}^+ + \Gamma_{He,\perp}^{++} = 0$ (dropping x_1 notation from now on). From Eq.(2), the normalized $^3\mathrm{He}^+$ flux is

$$\frac{\Gamma_{He,\perp}^+}{\Gamma_{He,\perp}^0} = \frac{1}{1+\alpha}. \tag{7}$$

Since neutral helium has the wall temperature, $\Gamma_{He,\perp}^0 = n_{He}^0 v_0$, with $v_0 = \sqrt{kT_{\mathrm{wall}}/(2\pi m_{He})}$. From Eq.(6) and Eq.(7),

$$\frac{n_{He}^+}{n_{He}^0} = \frac{1}{1+\alpha}\frac{L_\|}{\lambda_\|}\frac{2v_0}{c_s}. \tag{8}$$

For measured values of $\alpha = 0.6 \pm 0.1$, $\lambda_\| = 8.3 \pm 1.3\,\mathrm{mm}$, $L_\| \approx 0.9\,\mathrm{m}$, $kT_e = 7.4 \pm 1.9\,\mathrm{eV}$ and $v_0 \approx 350\,\mathrm{m/s}$, we have $\Gamma_{He,\perp}^+/\Gamma_{He,\perp}^0 = 0.62 \pm 0.05$ and $n_{He}^+/n_{He}^0 = 2.1 \pm 0.9$, which are used as boundary conditions for a cross-field transport model for helium ions in the SOL.

V. CROSS-FIELD ^{3}HE TRANSPORT MODEL

We consider the steady state continuity equations,

$$\frac{dg_0}{dx} = -y_0 A_0 + y_1 R_1, \tag{9}$$

$$\frac{dg_1}{dx} = y_0 A_0 - y_1 A_1 + y_2 R_2 - y_1 R_1, \tag{10}$$

$$\frac{dg_2}{dx} = +y_1 A_1 - y_2 R_2, \tag{11}$$

$$g_0 = -y_0, \tag{12}$$

$$g_j = \frac{-D_\perp(x)}{v_0}\frac{dy_j}{dx} + \frac{V_\perp(x)}{v_0}y_j(x), \quad j = 1, 2, \tag{13}$$

where for convenience we normalize all helium densities by the neutral helium density at the Local SOL boundary, $y_j(x) \equiv n_{\text{He}}^j(x)/n_{\text{He}}^0(x_1)$, and we normalize all fluxes by the neutral helium flux towards the plasma at the boundary, $g_j = \Gamma_{\text{He},\perp}^j/(n_{\text{He}}^0(x_1)v_0)$, $A_j = (n_e\langle\sigma v\rangle_{\text{He}}^j)/v_0$ represent the ionization coefficients, $R_j = n_e\langle\sigma v\rangle_{r,\text{He}}^j/v_0$ represent the recombination coefficients, $D_\perp(x)$ is the (anomalous) diffusion coefficient and $V_\perp(x)$ is the convection velocity with positive values corresponding to flow directed from the separatrix to the wall. It is assumed that the cross-field transport of singly- and doubly-ionized helium is described by a diffusive and convective process for which both ion species have the same diffusion coefficient and convection velocity. We neglect recombination by setting $R_j = 0$. This can be shown to be a very good approximation.[1]

Before solving the continuity equations, some general observations can be made. The continuity equation for the neutral helium has no volume source term, only a sink term. Therefore the flux of neutrals entering the plasma is monotonically attenuated. Since the sink term in the continuity equation depends on the neutral density itself, deep into the plasma the neutral density decreases exponentially. The flux of neutrals is always directed from the wall towards the separatrix. The continuity equation for the doubly ionized helium has no volume sink term, only a source term: the doubly ionized helium is lost only by recombination at the wall. Since the flux of doubly ionized helium vanishes deep in the plasma and increases further out, the flux of doubly-charged helium ions is positive (out of

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the plasma) everywhere. Note by summing up Equations (9)–(11) that the helium mass flux is constant in space. Deep into the plasma where the ionization rates are high we expect the fluxes of neutral and singly ionized helium to vanish. To maintain steady state, the flux of doubly ionized helium must also vanish deep in the plasma. Since the fluxes all vanish deep in the plasma and since the sum of the fluxes is constant, the sum of the fluxes is zero everywhere.

With the normalizations, $g_0(x) = -y_0(x)$ and $g_0(x) + g_1(x) + g_2(x) = 0$. The boundary conditions are $y_0(x_1) = 1$, $y_1(x_0) = 0$, $y_1(x_1) = n^+_{\text{He}}(x_1)/n^0_{\text{He}}(x_1) = 2.1 \pm 0.9$, and $g_1(x_1) = 0.62 \pm 0.05$. Note that we mathematically *overconstrain* the problem to supply boundary conditions for the singly-ionized helium density at the center and the edge *and* a boundary condition for the singly-ionized helium flux at the edge. We shall see that to find solutions which match all the boundary conditions we must restrict the possible spatial profiles of the diffusion coefficient and convection velocity.

A. SOL Background Profiles

Figure 3 shows profiles of electron temperature, electron density, ionization and radiative recombination rates across the scrape-off layer, mapped along magnetic flux surfaces to the midplane. The coordinate ρ corresponds to the distance of a flux surface from the separatrix measured at the midplane. The electron temperature and density are obtained from the A-port fast scanning Langmuir probe and the Langmuir probes on the omegatron heat shield.

Over most of the scrape-off layer plasma the electron temperature is high enough to neglect radiative recombination in the ion continuity equations. We neglect excitation-ionization compound reactions of the form $\text{He}^+(1s) \rightarrow \text{He}^{+*}(n \geq 2) \rightarrow \text{He}^{++}$. Since the ionization rates are much slower than the de-excitation rate (Einstein coefficient) of excited singly-ionized helium, $A \approx Z^4 6 \times 10^8\,\text{s}^{-1}$, we expect the density of excited helium to be negligible.

With the ionization rates, the normalized neutral helium density profile is found directly:

$y_0(x) = \exp\left[-\int_x^{x_1} A_0(x')dx'\right].$

VI. NUMERICAL SOLUTIONS

A numerical scheme was implemented to find solutions to Equations (9)–(11) consistent with the boundary conditions using the experimental density and temperature profile data. The adjustable parameters are the diffusion $D_\perp(x)$ and convection $V_\perp(x)$ profiles. Note that solutions need not exist for specified profile shapes of $D_\perp(x)$ and $V_\perp(x)$ which simultaneously match the flux and density conditions near the separatrix and at the edge.

Electron temperatures and densities are assumed to be constant on poloidal magnetic flux surfaces, which permits data obtained from the scanning Langmuir probe to be mapped to the omegatron probe. Helium ion flux near the omegatron balances the neutral helium flux, which ignores the magnetic field. Therefore the temperature and density gradients in physical space (not magnetic coordinates) near the omegatron are relevant. In the numeric calculation the physical coordinate is obtained by taking the distance between magnetic surfaces near the omegatron. The flux surfaces expand in the upper divertor near the omegatron, doubling the distance between flux surfaces compared to the midplane.

Figure 4 shows three representative cases of flat and ramped diffusion coefficient profiles, with zero or non-zero outward convection velocity. The cases were chosen to have the same helium ion densities at the edge, close to experimentally observed values (represented by the square symbols in Figs.5–6.) The first case (constant diffusion) yields ^{3}He fluxes at the boundary which *do not* match the observed values. Note that while the second and third cases (ramped diffusion coefficient with zero convection velocity, and flat diffusion coefficent with non-zero convection velocity, respectively) both match the flux and density at the boundary, their predictions for the doubly-ionized densities in the core are different by a factor of ten. Thus it might be possible to distinguish between the two cases if further data on core helium density is available.

For the experimental temperature and density profiles it is found that *no* constant profile

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of diffusion coefficient satisfies the (overdetermined) boundary conditions at the edge and separatrix, see Fig.5(a). The initial conditions of the singly-ionized density at $x = x_0$ are adjusted until the flux at the edge matches a specified ^{3}He$^+$ flux, $g_1(x_1) = 0.1$, 0.2, or 0.7. The ^{3}He density at the edge, $y_1(x_1)$, is obtained and plotted as a function of the (constant) amplitude of the diffusion coefficient profile. At very high values of diffusion coefficient the density of singly-ionized helium becomes small for all values of flux. The flux of ions leaving the plasma still balances the flux of neutrals entering the plasma, but most of the helium ions are doubly-charged. The high diffusion coefficient permits the singly-ionized helium ions to penetrate further into plasma regions of high ionization rate. At lower values of diffusion coefficient physical solutions do exist, but only for smaller flux, say $g_1(x_1) \approx 0.1$, when most of the flux of ions is from doubly-charged helium. If we artificially impose a higher value of singly-ionized helium flux at the edge ($g_1(x_1) \approx 0.7$) with lower values of diffusion coefficient, non-physical values of the density result, $y_1(x_1) < 0$. Note from Fig.5(a) that there is no value of the diffusion coefficient amplitude which gives results within the uncertainties of experimentally observed values of the ^{3}He$^+$ flux $g_1(x_1) \approx 0.7$ and (inferred) values of the ^{3}He$^+$ density $y_1(x_1) \approx 2$.

If instead the diffusion coefficient profile is allowed to increase with increasing x then solutions matching the overdetermined inner and outer boundary conditions *can* be obtained. Figure 6 shows the density $y_1(x_1)$ for cases with $g_1(x_1) = 0.7$ ($\approx$ measurement) and diffusion coefficient profiles that increase from $D_\perp(x) = 0.1 \, \text{m}^2/\text{s}$ at some location ("foot") to a higher value over $\Delta x = 15 \, \text{mm}$. The location of the "foot" and the maximum value of $D_\perp$ are varied. Note that the overdetermined boundary conditions do not uniquely determine the profile of diffusion coefficient. The results of Fig.6 can be interpreted as follows: in order for the observed flux of singly-ionized helium to reach the omegatron, a region of low transport is required at locations where the rate of ionization to doubly-charged helium is high. If instead a region of high transport exists at those locations, then singly ionized helium can diffuse there and be ionized, reducing the flux of singly-ionized helium observed at the omegatron.

It is also possible to match the observed values of density and flux at the boundary if

the transport is due to a mix of outward convection and diffusion. The key again is to provide a rapid outward transport mechanism for plasma in the far scrape-off layer. Here, the convection velocity profile is assumed to be constant over most of the region outside the separatrix; inside the separatrix the the convection velocity is assumed to be zero, and there is a continuous transition between the two regions. The diffusion coefficient profile is constant. Figure 5(b) shows the normalized values of singly-ionized helium density at the edge that result from different magnitudes of convection velocity and diffusion coefficient. Once again, note that the profiles are not unique.

VII. DISCUSSION AND CONCLUSIONS

The results obtained with the ^{3}He transport are consistent with the picture of rapid, radially outward transport in the far SOL proposed by Umansky[4] and directly measured recently on Alcator C-Mod.[5] The observed values of helium density and flux at the edge can be reproduced in the model only by including an effective diffusion coefficient that increases further from the separatrix. Evidence for rapid transport in the far SOL has been seen on other tokamaks as well, and may be related to the existence of large main-chamber recycling fluxes.[5]

Note that the Bohm diffusion coefficient for these SOL plasmas is of order $D_\perp^{\mathrm{Bohm}} = 0.06 T_e[\mathrm{eV}]/B[\mathrm{T}] \approx 0.1\,\mathrm{m^2/s}$. This value, which is often taken to be approximately the maximum value for transport due to microturbulence, is orders of magnitude smaller than the $D_\perp$ values obtained for the $V_\perp = 0$ case (see Fig.6). This suggests that the outward convection model, Fig.5(b), is more likely to simulate the actual transport mechanism. Note that convection velocities on the order of 100 m/s imply poloidal electric fields of $\approx 4\,\mathrm{V/cm}$, a reasonable value on open field lines that have 10 eV temperature variations in 1 cm (Fig.3).

Acknowledgements

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FIGURES

FIG. 1. Schematic of scrape-off layer geometry, showing directions parallel and perpendicular to the magnetic field, and orientation of omegatron probe face to separatrix and E-port ICRF limiter.

FIG. 2. (a) ^{3}He impurity spectrum. Resonant ion current (I_{RF}) is normalized to the total current in the RF cavity (I_{END}). (b) Asymptotic resonant current fractions due to singly- and doubly-ionized helium, assuming $T = 3\,\mathrm{eV}$ for helium ions.

FIG. 3. Profiles of electron temperature, electron density, and rates of ionization and radiative recombination in scrape-off layer. Asterisks represent data points, smooth line is spline interpolation.

FIG. 4. Comparison of calculated helium fluxes and densities in plasmas with constant and ramped diffusion and convection profiles. Solid, dotted, and dashed lines represents neutral, singly-ionized, and doubly-ionized helium, respectively. Arrow heads indicated experimental data which the model must match ($1 = {}^3\mathrm{He}^+, 2 = {}^3\mathrm{He}^{2+}$). The case of $D_\perp = \mathrm{const}$, $V_\perp = 0$ yields fluxes which do not match the observed values. Some form of ramped diffusion or outward convection profile is necessary to reproduce experimental observations of ionized helium density and flux at the omegatron.

FIG. 5. (a) Calculated ^{3}He$^+$ fluxes (g_1) and ^{3}He$^+$ densities (y_1) at the SOL boundary in plasmas with constant diffusion coefficient profiles. No constant diffusion coefficient profile reproduces both observed ^{3}He$^+$ flux, $g_1(x_1) \approx 0.7$ and observed ^{3}He$^+$ density, $y_1(x_1) \approx 2$. (b) Calculated density of singly-ionized helium at the omegatron for different outward convection velocities with as a function of the amplitude of the flat diffusion coefficient profile. All curves are computed for $g_1(x_1) = 0.7$, close to the measured value. Many flat profiles can reproduce the observed values of density and flux, but all of them require an outward convection velocity.

FIG. 6. Calculated density of singly-ionized helium at the omegatron for different ramped profiles of diffusion coefficient. All curves are computed for $g_1(x_1) = 0.7$, close to the measured value. Many different profiles can reproduce the observed values of density and flux, but all of them require an increase in diffusion coefficient across the scrape-off layer.
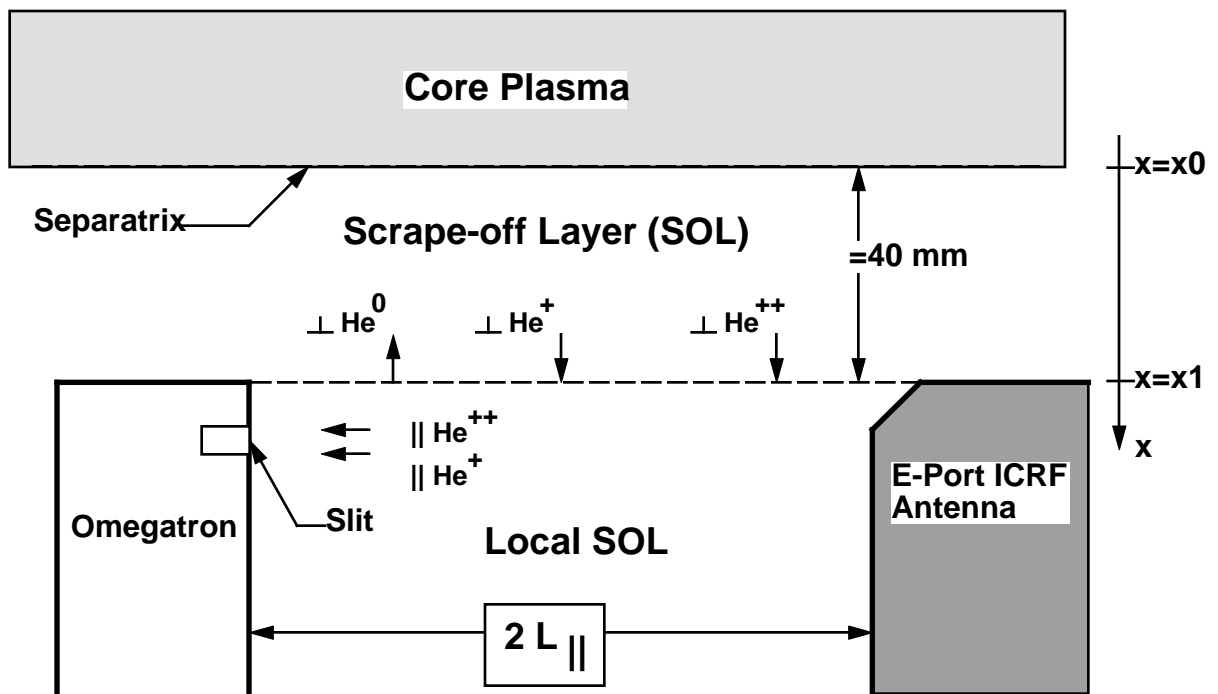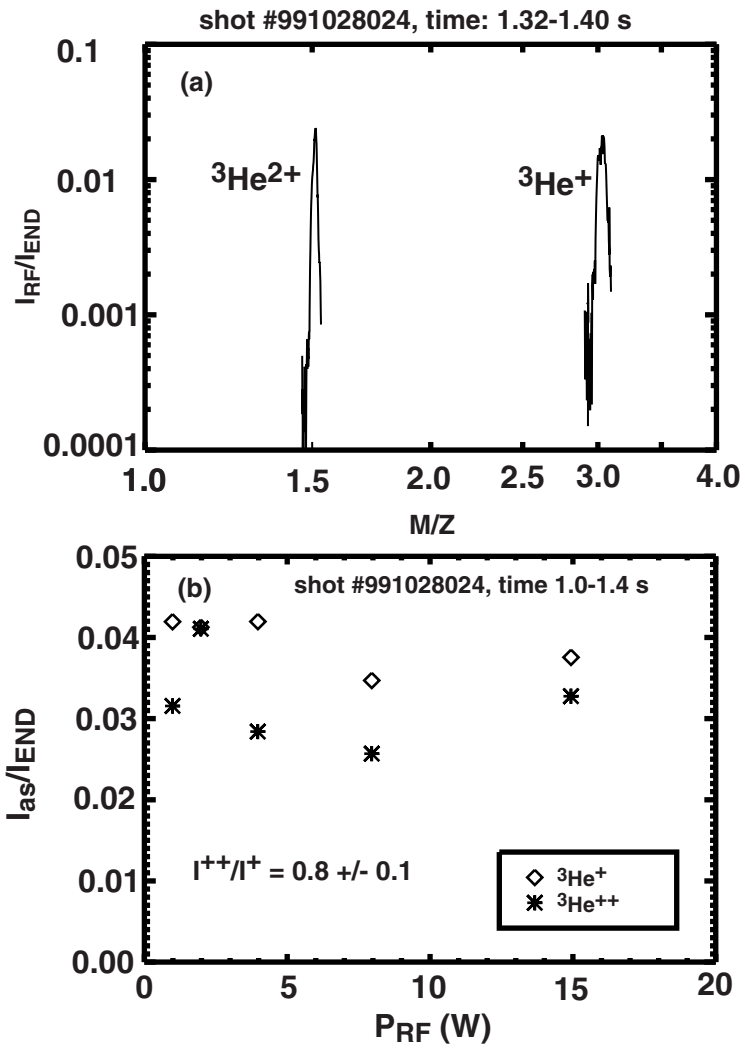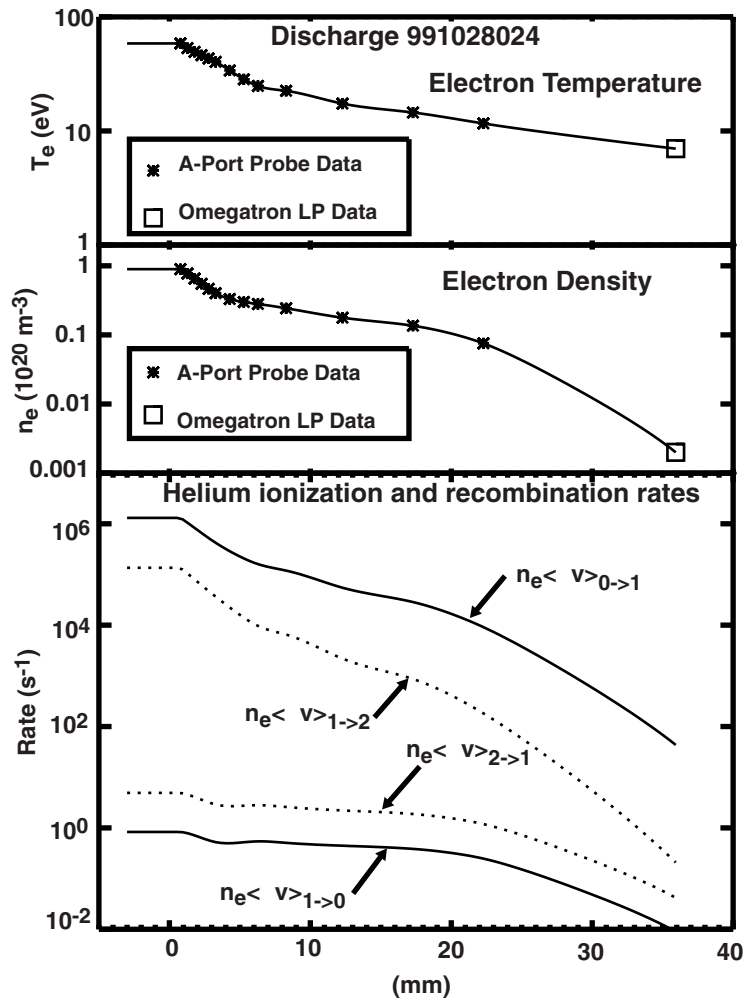
Figure 01

shot #991028024, time: 1.32-1.40 s

(a)

^{3}He^{2+}　　　^{3}He$^+$

I_{RF}/I_{END}

M/Z

(b)　　shot #991028024, time 1.0-1.4 s

I_{as}/I_{END}

$I^{++}/I^+ = 0.8 +/- 0.1$

◇ ^{3}He$^+$
✳ ^{3}He^{++}

P_{RF} (W)

Figure 02

Discharge 991028024

Electron Temperature

T_e (eV)

✳ A-Port Probe Data

☐ Omegatron LP Data

Electron Density

n_e (10^{20} m^{-3})

✳ A-Port Probe Data

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Helium ionization and recombination rates

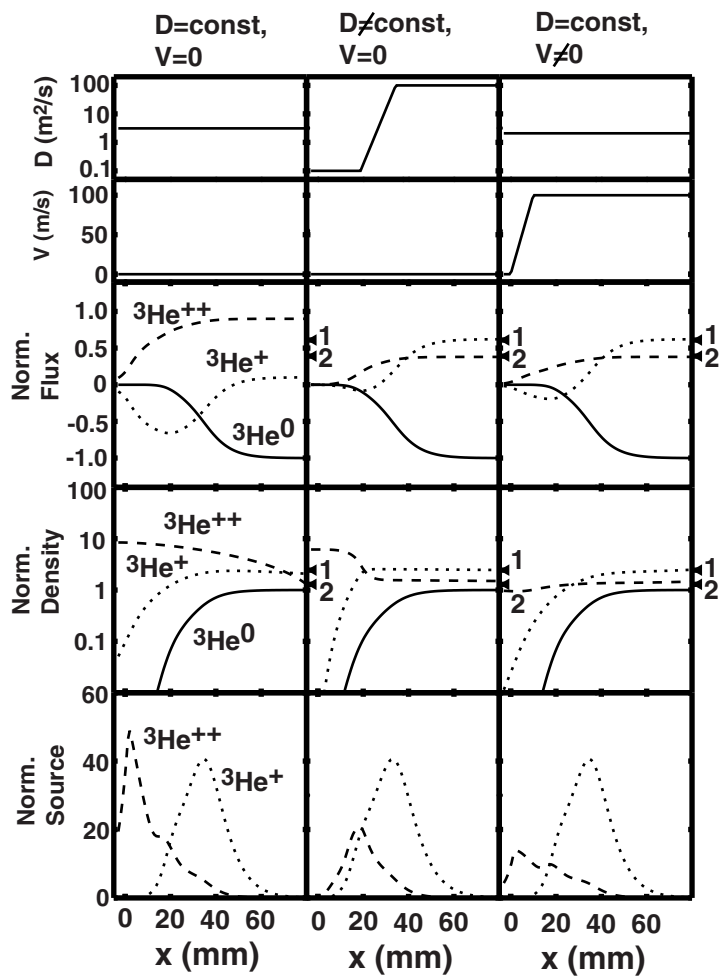Rate (s^{-1})

$n_e< v>_{0->1}$

$n_e< v>_{1->2}$

$n_e< v>_{2->1}$

$n_e< v>_{1->0}$

(mm)

Figure 03

Figure 04

Figure 05

Figure 06