Gyroradius Scaling of Helium Transport

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(Received 23 December 1996)

The scaling of the transport rate of helium ash with normalized gyroradius has been measured for the first time, utilizing ELMing H-mode plasmas on the DIII-D tokamak. The helium diffusivity is found to scale in a gyro-Bohm-like manner, similar to the thermal diffusivity. Even though the extrapolation in normalized gyroradius from DIII-D to a reactor-grade device is large, sensitivity studies indicate that helium ash dilution in such a device will be primarily dependent on the helium exhaust efficiency at the plasma edge and not on the core transport rates. [S0031-9007(97)03580-1]

PACS numbers: 52.25.Fi, 52.55.Fa

At present, the most promising path for power production based on magnetic fusion energy is based on the deuterium-tritium (D-T) fuel cycle. The viability of such an approach relies upon the sustainment of high D-T fuel densities at thermonuclear temperatures (~20 keV). In this regard, reducing the rate at which thermal energy is lost from the fusion plasma is essential to the success of such an approach. Of equal importance is the efficient removal of the helium "ash" that is produced by the D-T reactions themselves, since any dilution of the fuel caused by this ash will reduce the fusion power produced at a given plasma density. One long-standing objection to confinement regimes with improved transport properties has been the possibility that the particle transport rates would be insufficient to obtain adequate exhaust of the helium ash. Recent experimental studies on several present-day tokamaks operating in high confinement regimes have demonstrated that sufficient levels of helium exhaust can be obtained in these regimes [1–3]. One concern, though, is how (or even if) these favorable results scale to larger, ignition-sized devices. In this regard, the nondimensional scaling studies reported here indicate that the core transport rate of helium in ELMing H-mode plasmas increases approximately linearly with the normalized gyroradius (i.e., the ratio of the ion gyroradius to the plasma size), which is similar to the scaling for thermal transport rates. These results suggest core transport rates of helium in a reactor based on ELMing H-mode plasmas will be sufficient such that the helium dilution will be primarily determined by the helium exhaust efficiency at the plasma edge.

Since the helium ash is generated in the plasma core and can be removed only through pumping systems located at the plasma edge, the helium exhaust problem is truly global in nature. Hence, in order to narrow the uncertainties in the extrapolation from present-day devices to a reactor, the physical processes (or their scaling) which control the flow of helium from the plasma core to the exhaust plenum must be characterized. This involves not only characterizing the transport of helium within the core plasma, but also understanding helium transport in the edge and divertor plasmas and the effect of incomplete helium exhaust (i.e., recycling of helium). In terms of core transport of helium, one would like to understand the underlying physical processes which govern transport such that this extrapolation could be done with a high degree of certainty. The anomalously high particle and energy transport rates in fusion plasmas have long been the subject of vigorous investigations; however, the exact form of the processes determining plasma transport has not been determined. Recent studies have focused on the scaling of anomalous energy transport with normalized gyroradius (defined as $\rho_* = r_L/a$, where r_L is the Larmor radius and a is the plasma size) [4–7]. The value of this approach with respect to the prediction of future machine performance is that present-day devices can operate at ignition-relevant values of the standard dimensionless parameters with the exception of ρ_* [8]. In this regard, the results reported in this Letter are the first to assess the ρ_* scaling of helium transport in any confinement regime.

The nondimensional scaling approach commonly used in the study of energy transport is based on scale invariance and assumes that the diffusivity can be expressed in a dimensionally correct form:

$$\chi = \chi_B \rho_*^{\alpha_\rho} F(\beta, \nu_*, q_\Psi, \lambda_n, \lambda_T, R/a, \kappa, \delta, \ldots), \quad (1)$$

where $\chi_B = cT_e/eB, \beta \sim nT/B^2, \nu_* \sim q_\psi n/T^2, \lambda_{n,T} = -(a^2 - r^2)/2rL_{n,T}$, and κ and δ are the plasma elongation and triangularity, respectively. Here, q_ψ is the plasma safety factor, n is the plasma density, T is the electron or ion temperature, B is the magnetic field strength, and L is the density or temperature scale length. In general, this approach can also be adopted for helium transport by simply replacing χ with D_{He} in Eq. (1). Using this approach, the comparison of diffusivities for dimensionally similar discharges of the same size but with different magnetic field allows the determination of the exponent α_ρ since the unspecified function F remains constant. In order to keep F constant, the appropriate plasma parameters must be scaled as $n \propto B^{4/3}$, $T \propto B^{2/3}$, and $I \propto B$ while keeping the magnetic geometry fixed. The scaling of diffusivity using this approach then takes the form

$$D \propto B^{-(1+2\alpha_\rho)/3}. \tag{2}$$

The value of the exponent α_ρ can be interpreted as indicating the characteristic scale length of the plasma turbulence responsible for anomalous transport: (a) $\alpha_\rho = 1$ would imply $\Delta x \sim r_L$, which is called gyro-Bohm-like, (b) $\alpha_\rho = 0$ would imply $\Delta x \sim a$, which is called Bohm-like, and (c) $\alpha_\rho = -1$ would imply $\Delta x \gg a$, which could arise from magnetic stochastic processes [6].

These experiments were performed on the DIII-D tokamak. To provide a basis for extrapolation of the results discussed here to a presently envisioned reactor-grade plasma, both the plasma configuration and the dimensionless parameters (except ρ_*) were chosen to approximately match those expected for the International Thermonuclear Experimental Reactor (ITER). The plasma configuration was lower single-null divertor with major radius $R = 1.67$ m, minor radius $a = 0.56$ m, $\kappa = 1.65$, and $\delta = 0.2$ with dimensionless parameters $\beta^{\text{th}} = 1.5\%$, $\nu_{*_{i,\min}} = 0.03$, and $q_{95} = 3.5$. All of these experiments were conducted in the H-mode confinement regime with edge localized modes (ELMs). In order to maintain constant β and ν_* while varying ρ_*, independent control of the plasma density and temperature is required. In this regard, density control is accomplished in DIII-D by deuterium gas puffing or deuterium neutral beam injection (NBI) and simultaneous plasma exhaust via a cryopump located in the divertor region while the plasma temperature is separately controlled by choice of the injection energy of the deuterium neutral beams. To obtain a variation in ρ_* of 1.6 while the other dimensionless parameters were held nearly constant, measurements were made in two cases: (1) toroidal magnetic field $B_T = 2.1$ T, plasma current $I_p = 1.14$ MA, line-averaged-density $n_e = 6.26 \times 10^{19}\ \text{m}^{-3}$, input power $P_{\text{input}} = 5.9$ MW, and (2) $B_T = 1.05$ T, $I_p = 0.57$ MA, $n_e = 2.74 \times 10^{19}\ \text{m}^{-3}$, $P_{\text{input}} = 1.2$ MW. The resulting dimensionless parameters are shown in Fig. 1. Although not shown, the profiles of magnetic shear, q_ψ, and α_{T_i} are also well matched as is the normalized power deposition profile.

In these experiments, the helium transport properties are inferred from analysis of the evolution of the helium density profile subsequent to a helium gas puff (~3% of the electron density) during an otherwise steady-state portion of the discharge. The helium density profile shape is inferred from the intensity of the $n = 3$–4, 4686 Å He^+ line excited by charge exchange with energetic deuterium neutrals injected by the neutral beams and measured by a high resolution charge-exchange recombination (CER) spectroscopy system [9]. Since the plasma electron temperature is above 100 eV over the entire plasma, the He^{+2} density profile represents the total helium density in these discharges. The local helium transport coefficients are determined by linear regression analysis of the inferred helium particle flux $\mathbf{\Gamma}_{\text{He}}$ and the measured helium density gradient, assuming the helium flux takes on the general form: $\mathbf{\Gamma}_{\text{He}} = -D_{\text{He}} \nabla n_{\text{He}} + \mathbf{V}_{\text{He}} n_{\text{He}}$, where $\mathbf{\Gamma}_{\text{He}}$ is determined from the helium continuity equation $dn_{\text{He}}/dt = -\nabla \cdot \mathbf{\Gamma}_{\text{He}}$. Here, n_{He} is the helium density, D_{He} is the helium diffusivity, and $\mathbf{V}_{\text{He}}$ is the convection velocity for helium. In computing the uncertainties in the integrals that are required for the determination of $\mathbf{\Gamma}_{\text{He}}$, the statistical error is propagated assuming that the errors are uncorrelated. Finally, both the errors in the normalized density gradient $(\nabla n_{\text{He}}/n_{\text{He}})$ and the normalized flux $(\mathbf{\Gamma}_{\text{He}}/n_{\text{He}})$ are included in the linear regression analysis to determine D_{He} and $\mathbf{V}_{\text{He}}$ and their uncertainties. Note that because the perturbation induced by the helium puff propagates too rapidly to a normalized radius of $r/a = 0.6$ to be followed accurately by the CER system, determination of the transport coefficients are possible only inside this radius.

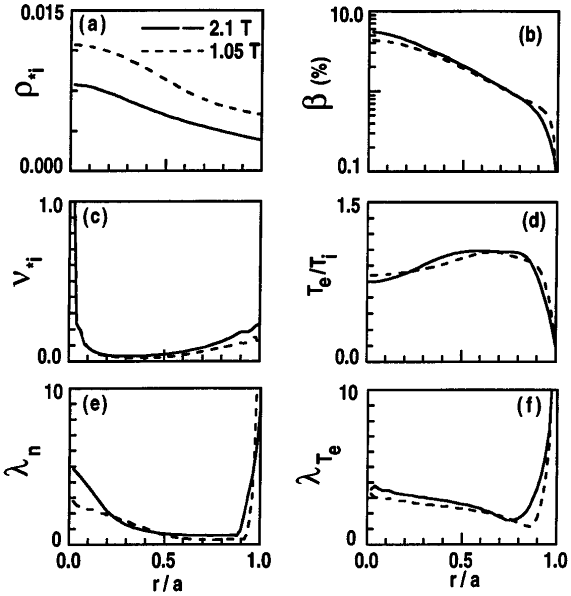

FIG. 1. Nondimensional parameters for a pair of dimensionally similar ELMing H-mode plasmas.

In order that a comparison could be made between helium diffusivity and thermal diffusivity, a local power balance analysis was also performed for these discharges. The radial power flow is assumed to be composed of a conductive and convective component $\nabla \cdot (\mathbf{q} + 5/2\mathbf{\Gamma} T) = Q$, where $\mathbf{q}$ is the heat flux, $\mathbf{\Gamma}$ is the particle flux, and Q represents the net heat sources and sinks. The radial heat flux is assumed to be purely diffusive in this analysis (i.e., $\mathbf{q} = -n\chi\nabla T$). Thermal transport calculations are performed by the ONETWO transport code [10], which takes as input the experimentally measured profiles of electron and ion temperature, electron density, effective ion charge Z_{eff}, and radiated power, as well as the magnetic geometry and plasma current profile. The ion and electron thermal diffusivities, as well as the single-fluid diffusivity $\chi_{\text{eff}} = -(q_e + q_i)/(n_e dT_e/dr + n_i dT_i/dr)$, are then determined using the computed power balance and the measured plasma profiles. Here q_e and

q_i represent the radial heat flow in the electron and ion channels, respectively.

In both discharges, the inferred helium and thermal diffusivities have nearly the same magnitude and radial dependence (see Fig. 2). This is consistent with previous results from DIII-D [11] and TFTR [12] that have shown $\chi_{\mathrm{eff}}/D_{\mathrm{He}} \sim 1$ in most confinement regimes studied to date, and is suggestive of an integral link between helium and energy transport in these regimes. Both the helium and thermal diffusivities in each case are significantly above (>10) transport levels expected from neoclassical theory, suggesting that both particle and energy transport are dominated by anomalous processes in these plasmas. Upon comparing D_{He} between the $B_T = 2.1$ T and $B_T = 1.05$ T case, one finds that D_{He} scales in an approximately gyro-Bohm-like manner over most of the analysis region (see Fig. 3). This is determined from the ratio of D_{He} for the two cases, shown in Fig. 3, in conjunction with Eq. (2). Although there is significant radial variation in the ρ_* scaling for D_{He} in Fig. 3, gyro-Bohm scaling does reflect the average scaling inside $r/a = 0.5$. This result is consistent with drift-wave turbulence theories which predict turbulence-driven transport to have a radial scale length of the Larmor radius (i.e., gyro-Bohm scaling). The D_{He} scaling is seen to be approximately the same as χ_{eff}, suggesting that the scaling of $\chi_{\mathrm{eff}}/D_{\mathrm{He}}$ is independent of ρ_*, and further strengthening the argument that energy and particle transport are integrally linked in these plasmas. The end result of this analysis is that $\alpha_\rho^{D_{\mathrm{He}}} = 0.89 \pm 0.24$ and $\alpha_\rho^{\chi_{\mathrm{eff}}} = 1.24 \pm 0.3$. In both discharges, the convective velocity $\mathbf{V}_{\mathrm{He}}$, shown in Fig. 4, is directed inward (i.e., an inward pinch). Analysis shows that $\mathbf{V}_{\mathrm{He}}$ increases with decreasing ρ_* with a scaling of the form $|\mathbf{V}_{\mathrm{He}}| \propto \rho_*^{-2.1}$. Although this suggests peaking of the helium density profile as ρ_* decreases (i.e., $|\mathbf{V}_{\mathrm{He}}|/D_{\mathrm{He}} \propto \rho_*^{-1.2}$), a similar trend is observed for the electron density profile with the concentration profile being roughly the same in the two discharges.

The degree to which helium transport rates in the core plasma affect D-T fuel dilution in an ignited plasma is dependent on the ratio of the helium diffusivity to the thermal diffusivity $D_{\mathrm{He}}/\chi_{\mathrm{eff}}$ [13]. This results from the fact that in a fusion plasma heated entirely by the thermalization of the fusion-generated alpha particles, the source of both energy and helium ash is the alpha particle generation rate S_α. This assumption allows a coupling of the energy transport equation ($\nabla \cdot \mathbf{q} = S_\alpha E_\alpha$) and the helium continuity equation ($\nabla \cdot \mathbf{\Gamma}_{\mathrm{He}} = S_\alpha$). Assuming the energy flux to be purely conductive ($\mathbf{q} = -n\chi\nabla T$) and the helium particle flux to be made up of both a diffusive and convective part ($\mathbf{\Gamma}_{\mathrm{He}} = -D_{\mathrm{He}}\nabla n_{\mathrm{He}} + \mathbf{V}_{\mathrm{He}} n_{\mathrm{He}}$), one obtains a steady-state solution of the form (in cylindrical coordinates)

$$\frac{dn_{\mathrm{He}}}{dr} = n_{\mathrm{He}}\frac{V_{\mathrm{He}}}{D_{He}} + n\frac{\chi_{\mathrm{eff}}}{E_\alpha D_{\mathrm{He}}}\frac{dT}{dr}, \tag{3}$$

where $\mathbf{V}_{\mathrm{He}}$ here represents the helium convective velocity in the radial direction. χ_{eff} is the single-fluid thermal diffusivity, $E_\alpha = 3.5$ MeV is the alpha particle energy, and n and T are the plasma density and temperature, respectively. Note that this equation is valid only in the region in which the local source rate due to ionization of recycling helium neutrals from the edge plasma is small compared to the local fusion-generated source rate. The first term on the right-hand side (RHS) of Eq. (3) represents the "natural" helium density gradient that would be obtained in the absence of any source. In this case, the helium density profile takes the form $n_{\mathrm{He}}(\rho) = n_{\mathrm{He}}(\rho_S)\exp(-\int_\rho^{\rho_S} V_{\mathrm{He}}/D_{\mathrm{He}}\, d\rho')$, where ρ_S is the plasma radius at the edge of the alpha particle source region. In terms of the effect on plasma performance, the helium density profile must be compared to the electron density profile to determine the degree of dilution. In this regard, there is an accompanying equation for the electron density that has the same form as Eq. (3) (i.e., $dn_e/dr = n_e V_e/D_e + S_e$ where S_e is the electron source). Experimental results from several tokamaks have shown that the shapes of the helium and electron density profile in many different regimes are nearly identical [11,12], suggesting that $V_e/D_e \approx V_{\mathrm{He}}/D_{\mathrm{He}}$ in these regimes. Since electrostatic fluctuations are believed to be the main cause of anomalous transport in tokamaks, this result is not entirely surprising since in such a case, all particles regardless of charge or mass should have the same transport properties. Assuming that $V_e/D_e \approx V_{\mathrm{He}}/D_{\mathrm{He}}$, the

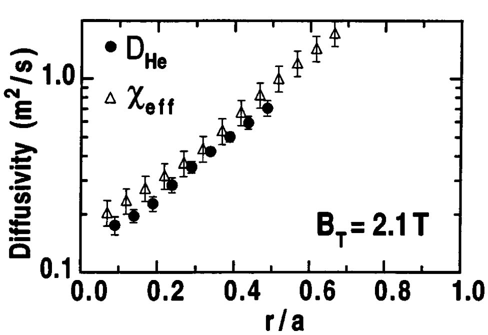

FIG. 2. Helium diffusivity D_{He} and thermal diffusivity χ_{eff} for a $B_T = 2.1$ T ELMing H-mode discharge.

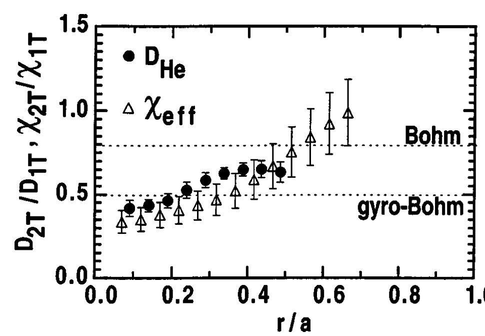

FIG. 3. Ratio of the helium and single-fluid diffusivities for the $B_T = 2.1$ T and $B_T = 1.05$ T discharges.

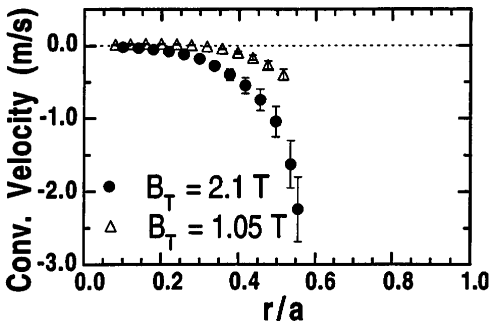

FIG. 4. Convective velocity V_{He} in the $B_T = 2.1$ T and $B_T = 1.05$ T discharges.

degree of helium dilution becomes dependent on two parameters: (1) the helium concentration at the edge of the source region, $f_{\mathrm{He}}(\rho_S) = n_{\mathrm{He}}(\rho_S)/n_e(\rho_S)$; and (2) the magnitude of the second term on the RHS of Eq. (3). The parameter $f_{\mathrm{He}}(\rho_S)$ is dominated by helium recycling in the edge plasma and is therefore dependent on the details of helium transport in the plasma edge, scrape-off layer (SOL), and divertor plasma, as well as the exhaust efficiency of the pumping system. Since the processes involved in determining $f_{\mathrm{He}}(\rho_S)$ are localized near the plasma edge, some degree of control for this value might be possible. However, the magnitude of the second term on the RHS of Eq. (3) is completely determined by the transport properties of the core plasma. Since independent control of this parameter is limited, it is essential to assess the magnitude of this term and its effect in any design concept.

Since the extrapolation in ρ_* from the present experiments to an ignition-sized plasma such as ITER is large ($\sim$10) compared to the variation of ρ_* in the experiment ($\sim$1.6), it is important to assess the impact of the uncertainties in the analysis on the projection. This has been done by solving Eq. (3) and the accompanying equation for the electron density profile with the following assumptions: $f_{\mathrm{He}}(\rho_S) = 0.1$; $S_e = 0$; $V_e/D_e \approx V_{\mathrm{He}}/D_{\mathrm{He}}$; and the temperature profile is linear with a central value of 30 keV and an edge value of 0.5 keV. Note that the final assumption is nonphysical because of required symmetry at the magnetic axis; however, such a choice maximizes the contribution of the source-dependent term in Eq. (3). Also, the assumption that $S_e = 0$ is intended to maximize the contribution of the source-dependent term since S_e will only tend to decrease the helium concentration. The extrapolation of $\chi_{\mathrm{eff}}/D_{\mathrm{He}}$ is based on Eq. (1) and the values of $\alpha_\rho^{D_{\mathrm{He}}}$ and $\alpha_\rho^{\chi_{\mathrm{eff}}}$ deduced from the present analysis. Such an extrapolation projects a radially averaged $\langle \chi_{\mathrm{eff}}/D_{\mathrm{He}} \rangle \approx 0.70$ for ITER and a central helium concentration of 10.5%. In such a case, the helium concentration is primarily determined by $f_{\mathrm{He}}(\rho_S)$. If the most unfavorable scaling that is justifiable from the present analysis is taken for $\chi_{\mathrm{eff}}/D_{\mathrm{He}}$ (i.e., assuming $\alpha_\rho^{D_{\mathrm{He}}} = 1.13$ and $\alpha_\rho^{\chi_{\mathrm{eff}}} = 0.94$), one finds $\langle \chi_{\mathrm{eff}}/D_{\mathrm{He}} \rangle \approx 1.67$ and a central helium concentration of 11%. Again, the helium concentration is found to be primarily determined by $f_{\mathrm{He}}(\rho_S)$. Hence, with a high degree of certainty, these results indicate that the degree of helium dilution in an ITER-like device based on ELMing H-mode confinement will be predominantly determined by the helium concentration at the edge of the alpha source region, provided $V_e/D_e \approx V_{\mathrm{He}}/D_{\mathrm{He}}$. It should be pointed out that extrapolations based on these results are valid only for future devices based on ELMing H-mode confinement which lie on a ρ_* scaling path to ITER. For devices which are on another ρ_* scaling path or based on a different enhanced confinement regimes (e.g., VH-mode or negative central shear regimes), similar ρ_* scaling experiments as well as detailed documentation of $V_{\mathrm{He}}/D_{\mathrm{He}}$ versus V_e/D_e are required to assess the effect of helium dilution in these regimes.

In conclusion, ρ_* scaling experiments in the ELMing H-mode confinement regime on DIII-D have shown that D_{He} scales in a gyro-Bohm-like manner, similar to the observed scaling for thermal diffusivity. Given this information and the fact that the observed value of $\chi_{\mathrm{eff}}/D_{\mathrm{He}} \sim 1$ in the present experiment, these results suggest that $\chi_{\mathrm{eff}}/D_{\mathrm{He}}$ will be $\sim$1 in any device lying along the ρ_* scaling path examined in this study, including ITER. Furthermore, calculations show that the estimated helium dilution in ITER will be primarily determined by the recycling-dominated solution even when using the most pessimistic scaling for the core transport rates supported by the present data set, confirming that helium recycling will dominate the helium concentration.

This work is supported by the U.S. Department of Energy under Contracts No. DE-AC03-93ER5114 and No. DE-AC05-96OR22464. We would like to thank the DIII-D operations and physics staff for their support in carrying out these experiments and R. Groebner for continuing upkeep of the CERFIT spectral analysis code.

[1] M. R. Wade *et al.*, Phys. Rev. Lett. **74**, 2702 (1995).
[2] H. S. Bosch *et al.* (to be published).
[3] A. Sakasai *et al.*, in *Proceedings of the Sixteenth IAEA Fusion Energy Conference, Montreal, Canada, 1996* (IAEA, Vienna, 1996), Vol. F1-CN-64/AP-2-1.
[4] R. E. Waltz, J. C. DeBoo, and T. H. Osborne, Nucl. Fusion **32**, 1051 (1992).
[5] F. W. Perkins *et al.*, Phys. Fluids B **5**, 477 (1993).
[6] J. P. Christiansen *et al.*, Nucl. Fusion **33**, 863 (1993).
[7] C. C. Petty *et al.*, Phys. Rev. Lett. **74**, 1763 (1995).
[8] R. E. Waltz, J. C. DeBoo, and M. N. Rosenbluth, Phys. Rev. Lett. **65**, 2390 (1990).
[9] P. Gohil *et al.*, in *Proceedings of the 14th Symposium on Fusion Engineering, San Diego, 1992* (IEEE, New York, 1992), Vol. 2, p. 1199.
[10] W. Pfeiffer *et al.*, Nucl. Fusion **25**, 655 (1985).
[11] M. R. Wade *et al.*, Phys. Plasmas **2**, 2357 (1995).
[12] E. J. Synakowski *et al.*, Phys. Fluids B **5**, 2215 (1993).
[13] D. Reiter, G. H. Wolf, and H. Kever, Nucl. Fusion **30**, 2141 (1990).