Helium Exhaust and Transport Studies with the ALT-II Pump Limiter in the TEXTOR Tokamak

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The first encouraging experiments demonstrating direct, explicit control of the He^{2+} density in a tokamak plasma have been performed in the TEXTOR tokamak with the Advanced Limiter Test-II pump limiter. Helium is injected in a short gas puff from the outside of the plasma, is observed to reach the plasma core, and then is readily removed from the plasma. An exhaust efficiency of ~8% is obtained. Active charge-exchange spectroscopy is used to study the exhaust and transport of He^{2+} within the plasma, and the density evolution is modeled with a diffusive-convective transport code.

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In future burning fusion devices, helium (He) ash must be continuously removed from the core to prevent dilution of the deuterium-tritium (D-T) fuel and concomitant quenching of the burn. Thus, He ash removal is fundamental to the operation of any fusion reactor, since the rate at which the α-particle by-products of the fusion reaction are purged from the core plasma will determine the pulse length available before the burn is quenched. For proposed steady-state tokamaks, such as the International Thermonuclear Experimental Reactor (ITER), continuous purging of the He ash is essential. Recent estimates[1] show that newly created He ions must be removed within 7 to 15 energy confinement times to maintain continuous reactor operation.

The recycling of injected He from the wall and the lack of direct diagnostic capability to measure He concentrations have complicated previous efforts to determine the He removal rate.[2-4] Estimating this rate requires knowledge of the recycling coefficient, which can only be determined indirectly and depends on the wall conditioning status and history of the device. The experiments reported here are the first in which direct, explicit removal of injected He has been demonstrated. This is made possible by the Advanced Limiter Test-II (ALT-II) system, a toroidal belt limiter[5-7] that uses turbomolecular pumps (TMPs). Most existing particle exhaust schemes use gettering materials or cryopumping systems, which do not pump He. We simulate the presence of recycled He ash in a tokamak by puffing concentrations of 3%–5% He (relative to n_e) into the TEXTOR plasma just before or during neutral-beam injection (NBI). The transport of the He into the plasma core and its subsequent pump-out phase using the ALT-II system are followed with spectroscopic techniques by observing the He in three locations: the plasma core, the plasma edge at the ALT-II limiter, and the ALT-II pumping duct. By combining the results from these measurements, the exhaust efficiency for the He found in the plasma core is obtained during ALT-II pumping.

In the plasma core, the He density is measured by charge-exchange excitation (CXE) spectroscopy, in combination with NBI. Measuring spatially and temporally resolved ion temperatures and absolute densities using CXE line intensities is a well-established technique on many tokamaks.[8-11] We use CXE spectroscopy to obtain the local He^{2+} density in the plasma core by observing the $He^{+}(4\rightarrow 3)$ transition at 4686 Å with an absolutely calibrated spectrometer that views the TEXTOR neutral heating beam vertically. In the intersecting viewing volume between the neutral beam and the spectrometer sightline, the charge-exchange reaction produces the 4686-Å He transitions, which are transmitted via conventional optics to a spectrometer equipped with an intensified optical multichannel analyzer (OMA). An integration time of 40 ms was used for the OMA to obtain each spectrum, and eighty spectra were accumulated per shot during NBI. From the calibrated photon flux measurements and the known neutral-beam characteristics, He^{2+} densities can be determined within ~30% after accounting for the spectrometer calibration, beam attenuation, and excitation rate uncertainties. A nonlinear least-squares fit to the data is used to obtain the ion temperature and absolute photon fluxes. The 4686-Å He^{2+} line shape is fitted with three Gaussian curves,[11] all coincident with the central wavelength. One Gaussian is required to fit the hot central plasma CXE feature

($T_i = 1.2$ keV); the other two represent cool-edge components (60–300 eV). The He^{2+} density is derived from the photon flux of the hot central CXE spectrum (see Ref. 11).

In the plasma edge, the He particle flux at the ALT-II limiter is measured with an absolutely calibrated photodiode and interference filter (4686 Å) combination that views a poloidal section of the limiter blade at one toroidal location. The He recycling is assumed to be toroidally symmetric, and the total He recycling flux at the ALT-II blade is estimated by multiplying the measured flux by the appropriate geometric factor. The neutral He properties in the ALT-II pumping duct are measured from the He (5875 Å) and the D_α (6563 Å) light emerging from a modified Penning gas discharge (see Refs. 12 and 13). This technique provides both D and He partial pressures inside the pumping duct, thus yielding the He concentration.

The TEXTOR plasma for these experiments had a major radius $R = 175$ cm, a plasma current $I_p = 340$ kA, and a toroidal magnetic field of 2.25 T. To provide active CXE measurements and additional plasma heating, a 1.6-MW (~55-keV) D^0 beam was injected between 0.8 and 2.3 s after discharge initiation, with a short (20-ms) He puff being injected at $t = 0.7$ s (shots 38 810–38 811) or $t = 1.0$ s (shots 41 059–41 066), causing a rise in the average electron density $\bar{n}_e$. Typically, the central electron temperature was $T_e \approx 1.5$ keV with some sawtooth activity.

The ALT-II limiter was the primary limiter and was positioned at a minor radius $r = 46$ cm. It consists of eight graphite blade segments that form an axisymmetric toroidal belt, located on the outboard side of the torus at 45° below the horizontal midplane. Each blade is equipped with a particle collection scoop, which is connected via vacuum ducting to a TMP. The total effective pumping speed for all eight limiter blades is $S_{\rm eff} = 5200$ L/s. Pumping of each limiter blade is activated independently via gate valves.

The temporal evolution of $\bar{n}_e$ and of the He^{2+} density near the plasma center ($r = 25$ cm) is shown in Figs. 1 and 2 for discharges with and without ALT-II pumping. Figure 1 is for typical low-density discharges, $\bar{n}_e \approx 2 \times 10^{13}$ cm^{-3}, in which the external D gas feed is the same. For the pumped discharge in Fig. 2, feedback control on the external D gas fueling was used to keep the electron density approximately constant, $\bar{n}_e \approx 3.2 \times 10^{13}$ cm^{-3} during the NBI phase. Figure 3 shows the He concentrations measured in the pumping duct using the modified Penning gauge technique with and without ALT-II pumping. In Figs. 1–3 the He density rises sharply just after the He gas puff, and the He appears in

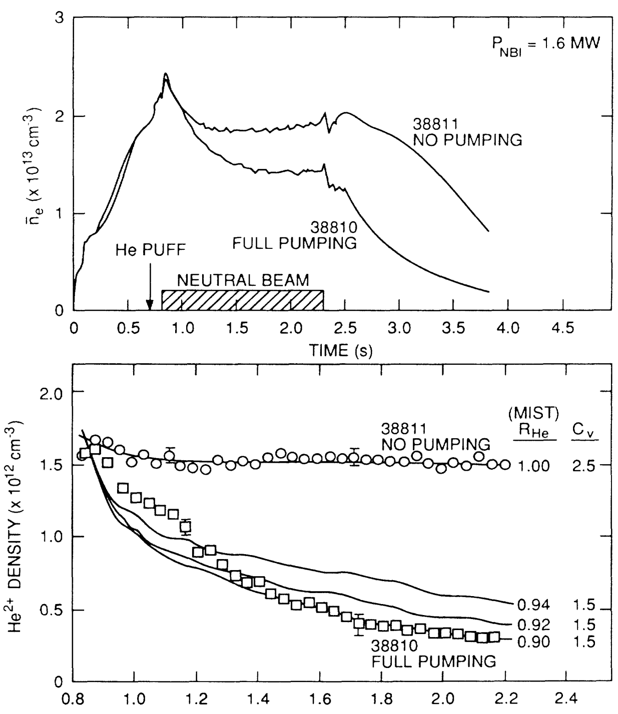

FIG. 1. Line-averaged electron density $\bar{n}_e$ and He^{2+} density measured with CXE spectroscopy vs time during low-density plasma discharges after a short He puff at 0.7 s with and without ALT-II pumping and 1.6-MW NBI. Points: He^{2+} density data; solid lines: MIST transport calculations.

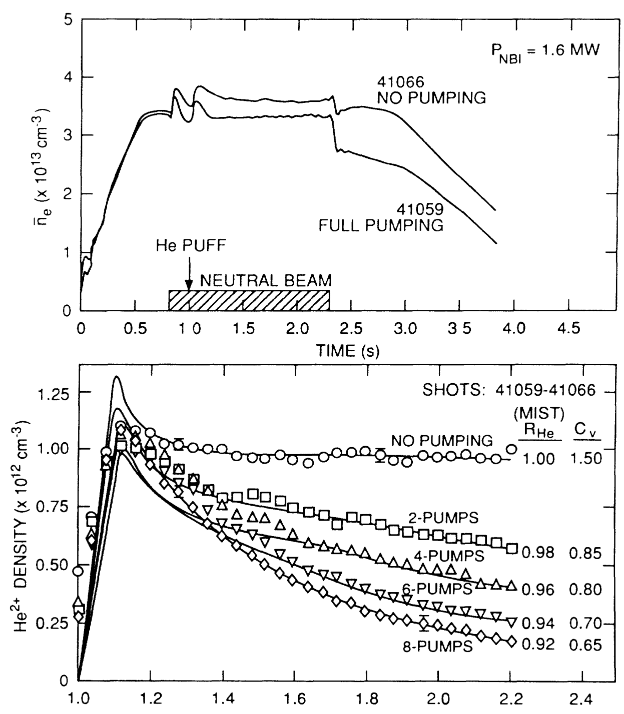

FIG. 2. Line-averaged electron density $\bar{n}_e$ and He^{2+} density measured with CXE spectroscopy vs time during higher-density plasma discharges after a short He puff at 1.0 s with and without ALT-II pumping and 1.6-MW NBI. Points: He^{2+} density data; solid lines: MIST transport calculations.

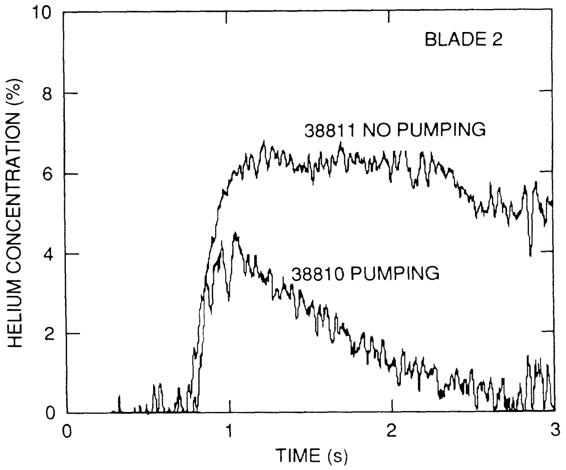

FIG. 3. Helium concentration in the ALT-II pumping duct of blade 2 vs time during plasma discharges with and without ALT-II pumping.

the plasma core within 100–200 ms. The He^{2+} density in the plasma core (~5% of $\bar{n}_e$ for shots 38810 and 38811 and ~3% of $\bar{n}_e$ for shots 41059–41066) agrees well with the observed rise in $\bar{n}_e$.

For the cases without pumping the He^{2+} density remains constant after the initial rise, indicating full recycling (recycling coefficient $R_{He} \approx 1.0$) of the He. The same effect occurs within the pumping duct, as shown in Fig. 3. With full ALT-II pumping (all eight pumps), the He^{2+} density drops rapidly and ~90% of the He found in the discharge at $r=25$ cm is exhausted within ≈ 1.0 s. For shots 38810 and 38811 (Fig. 1), the injected He gas puff corresponds to 0.28 Torr L, so the calculated He removal rate is about 0.28 Torr L/s. To further demonstrate the pump limiter's active control the He density within the plasma core, the number of actively pumped blades was reduced by increments of two from eight pumped blades (full pumping) to none (see Fig. 2). Clearly, the He recycling increases as pumping is reduced. Although the He is removed quite readily from the discharge, a shown in Figs. 1 and 2, the electron (and D) density is not changed so dramatically. This is easily understood since the tokamak walls and limiters contain a large inventory of D, which replenishes much of the D exhausted by the pump limiter.[6]

The total He exhaust efficiency is $\varepsilon = p_0 S_{eff}/\Gamma_0$, where p_0 is the He pressure measured in the pumping duct, $p_0 S_{eff}$ is the He removal rate, and Γ_0 is the He plasma efflux measured with the calibrated He monitor that views the ALT-II limiter. For the discharges of Fig. 1, $\Gamma_0 \sim 1.2\times 10^{20}$ atoms/s. The calibrated Penning gauge measured a He partial pressure $p_0 = 0.06$ mTorr for these discharges with $S_{eff} = 5200$ L/s; hence $\varepsilon \sim 8\%$. The D exhaust efficiency for these discharges was found to be 8%–10%. Since the pumping speeds for D_2 and He are the same for these TMPs, the exhaust efficiencies for the two gases should be approximately the same. The preferential He pumping suggested by several models,[14] based on the different atomic physics processes for D and He in the particle scoops, is not supported by these measurements.

Our measurements show that R_{He} is almost unity without pumping. With full pumping, the He recycling is modified by the exhaust efficiency, $R_{He} = 1 - \varepsilon = 0.92$. With this information and the measured decay time for the He^{2+} density (τ^*_{He}), we can estimate the He particle confinement time τ_{He} during full pumping, since $\tau^*_{He} = \tau_{He}/(1-R_{He})$. From Figs. 1 and 2, $\tau^*_{He} \approx 0.62$ s; this yields $\tau_{He} \approx 50$ ms, which is consistent with the measured Γ_0 and a total inventory $N_{He} \approx 6\times 10^{18}$ He atoms in the discharge. For these discharges, Langmuir probe and D_α measurements provided estimates of the deuterium particle confinement time of $\tau_p \approx 20$ ms, while diamagnetic measurements provided estimates of the energy confinement time of $\tau_E \approx 30$ ms. These measurements imply that $\tau_{He} \approx (1\text{–}3)\tau_p$, in agreement with recent measurements comparing pure He and D plasmas on the TEXT tokamak.[15]

To substantiate the He removal rate of 0.28 Torr L/s found during these experiments, a continuous He fueling experiment was performed. Helium was injected at a rate of 0.36 Torr L/s throughout a plasma discharge with full ALT-II pumping. The He^{2+} density remained constant, demonstrating the He was being added to the discharge at the same rate that it was being exhausted. This rate of 0.36 Torr L/s is in good agreement with that determined from the gas puffing experiments, 0.28 Torr L/s.

The data in Figs. 1 and 2 have been modeled with the MIST impurity transport code.[16] MIST uses as input the experimentally measured n_e (HCN interferometer) and T_e (electron cyclotron emission) profiles as functions of radius and time. These measurements are used to set the times and mixing radii (~15 cm) for the sawtooth events that occur during the discharges examined. The code computes the He^{2+} density profiles as a function of time and compares them with the measured He^{2+} density at $r=25$ cm. A spatially dependent anomalous diffusivity [from D_A(core) ~0.1 m^2/s to D_A(edge) = 1.0 m^2/s] is added to sawtooth mixing, a pinch velocity [$n_e v_p(r) = C_v D_A\, dn_e/dr$], and a global He recycling coefficient R_{He}, which is varied from 0.92 (full pumping) to ~1.0 (no pumping). The data are fitted by matching both the observed rise time and the longer pumping-induced decay of the He^{2+} in the plasma core as a function of R_{He}. Results are shown in Figs. 1 and 2.

For these calculations we use a model in which the diffusivity profile is held constant and the pinch coefficient is varied by changing C_v, assuming a steady increase in R_{He} from 0.92 to 1.0 as the number of pumps decreases. The low-density cases (shots 38810 and 38811, Fig. 1) require $C_v = 1.5\text{–}2.5$; $C_v = 0.65\text{–}1.5$ is satisfactory for the higher-density cases (Fig. 2). Alternatively, the value of C_v can be held fixed and the recycling coefficient varied; if C_v is fixed at 0.7 for the cases with pumping in Fig. 2, the effective recycling coefficient must increase by 2%–5%. The sensitivity to the assumed recycling coefficient is shown for shot 38810 in Fig. 1; $R_{\rm He}=0.9$ is a reasonably good fit for $C_v=1.5$, while $R_{\rm He}=0.92$ is a better fit for $C_v=1.25$.

The required transport coefficients are expected to vary since the background plasma and scrape-off layer parameters (density, temperature, and screening efficiency) vary as the recycling changes. The transport coefficients needed to match the He evolution, D_A(25 cm)$\sim 5\times 10^3$ cm^2/s and v_p(25 cm)$\sim$(3-6)$\times 10^2$ cm/s, are similar to those reported in earlier transport experiments.[2] As indicated by the discrepancy in the initial transient for the case without pumping in Fig. 2, cases with very high $R_{\rm He}$ ($\sim$0.995) will require closer examination, since it is possible that some He is retained in the walls.

The calculations show that the removal experiments can be fitted with a relatively constant plasma model, with external recycling as the major variable. However, such a fit to a single-point measurement does not allow the unique specification of the diffusivity, pinch, and recycling coefficients. The experimentally determined maximum He exhaust efficiency $\varepsilon\sim 8\%$ ($R_{\rm He}=0.92$) is consistent with these calculations. More detailed knowledge of the He radial profile as a function of time during the He influx and pump-out phase is needed to determine C_v and D_A uniquely. The effective He confinement time relative to the energy confinement time, $\tau^*_{\rm He}/\tau_E$, is an important figure of merit for extrapolation to reactor conditions. This ratio is estimated to be $10\le \tau^*_{\rm He}/\tau_E \le 30$ for the He database presently available from TEXTOR, and lies within the acceptable range for reactors.[1] Future experiments will investigate this ratio over a larger operational space and during high-confinement (H-mode) type discharges. Even though the present experiments use a pump limiter, which may not be the eventual choice for a fusion reactor, the fact that the core He can be removed with an edge particle exhaust system is encouraging.

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