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PLASMA PHYSICS
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CENTRAL HELIUM DENSITY MEASUREMENTS IN PLT

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ABSTRACT

The central helium density in PLT has been deduced from measurements of the ratio of $d\text{-}^3\text{He}$ to $d\text{-}d$ fusion reactions during deuterium neutral beam injection. The inward transport time for ^3He puffed at the edge plasma was 10 ± 30 msec. The decay time of the central ^3He density increased with electron density, varying from 0.2 sec to greater than 1.0 sec over the density range of $(1\text{-}5) \times 10^{13} \text{ cm}^{-3}$.

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In this paper, we describe measurements of the central ^3He density in the Princeton Large Torus (PLT) tokamak. The central ^3He density was deduced from the ratio of the measured $^3\text{He}(d,p)\alpha$ and $d(d,n)^3\text{He}$ fusion reaction rates during deuterium neutral beam injection into PLT plasmas.¹ The rise in the central ^3He density following a short ^3He gas puff at the plasma edge has been used to determine the transport time of ^3He ions to the plasma center and thus provides information on the ^3He particle transport coefficients. The subsequent fall of the central ^3He density has been used to determine the exhaust time of ^3He from the plasma and thus provides information on the ^3He edge recycling and pumping. The transport and exhaust of ^3He (and other low Z ions) cannot be examined with atomic spectroscopy as the helium becomes fully stripped in the plasma edge² so that poloidal and toroidal asymmetries due to limiters and gas inlets complicate the measurements.

The central ^3He density measurements showed an inward transport time of (20 ± 10) msec, increasing modestly with electron density. This time scale is comparable to previous spectroscopic measurements for the transit times of moderate and high Z impurity ions in PLT.³ The inward transport time is consistent with a diffusion coefficient of $(4 \pm 2) \times 10^3 \text{ cm}^2/\text{sec}$ or an inward directed velocity of $(2 \pm 1) \times 10^3 \text{ cm/sec}$. These empirical transport coefficients are $\sim 10^{-10^2}$ times larger than the corresponding Neoclassical particle diffusion coefficient or Ware pinch velocity.

The ^3He exhaust time was 0.3 to 1.0 sec, increasing with density in the range of $\bar{n}_e = 1.5 \times 10^{13} \text{ cm}^{-3}$. This exhaust time is $\sim 10\times$ typical electron energy confinement time scales for PLT but is $\sim 10^{-1}$ of the exponential pumping time of neutral ^3He puffed into the PLT vacuum vessel. This extra pumping may be due to energetic ^3He particles becoming embedded in the vessel components. The ^3He exhaust properties are of interest since ^3He and ^4He

experience the same chemical interactions at the plasma wall boundary so that the ^3He exhaust properties provide insight into potential ash removal problems in d-t fusion reactors.⁴ Clearly, further experimental work, using the ^3He density measurement techniques reported here, would be useful to test helium pumping schemes such as divertors or pumped limiters.

Experiment:

Assessment of the central ^3He density was based on the ratio of the $^3\text{He}(d,p)^4\text{He}$ to $d(d,n)^3\text{He}$ reaction rates during deuterium neutral beam injection into a deuterium plasma containing a small fraction of ^3He . The reactions took place between the circulating deuterium beam ions and the thermal d^+ or $^3\text{He}^{++}$ target ions. The reaction rates for "beam-target" reactions are approximately given by⁵:

$$R = n_T (\xi_1 \dot{N}_B) (\xi_2 \tau_B) \langle \sigma v \rangle \Big|_{W_B + \xi_3} \quad (1)$$

where n_T is the number density of target ions, $\dot{N}_B$ is the injection rate of the beam ions with energy W_B , τ_B is the slowing down time for the beam ions, and the reactivity, $\langle \sigma v \rangle$, is evaluated at the cross section-weighted average velocity. The constants ξ_i are: ξ_1 , the fraction of beam ions that are ionized and trapped in the central plasma region; ξ_2 , the fraction of the beam slowing down duration, τ_B , required for the fusion reactivity of the injected ions to decrease by a factor of $1/e$; and ξ_3 , the average energy of the target ions with which the beam interacts. The ratio of the $d\text{-}^3\text{He}$ and $d\text{-}d$ reaction rates is then given by

$$\frac{R_{d-^3\text{He}}}{R_{d-d}} = \frac{n_{^3\text{He}}}{n_d} \frac{3}{7} \frac{\sigma(d-^3\text{He})v}{\sigma(d-d)v} \left| \begin{array}{l} W_B + 7 T_i \\ W_B + 3 T_i \end{array} \right. \quad (2)$$

If we arrange for the fraction $n_{^3\text{He}}/n_d$ to be small and for n_d/n_e to be constant, then an absolute measurement of the central ^3He density is obtained by

$$n_{^3\text{He}}(t) = C_1 n_e(t) R_{d-^3\text{He}}(t)/R_{d-d}(t), \quad (3)$$

where C_1 is determined by the impurity depletion of the deuterium ions, Z_{eff} , the beam injection energy W_B , and the target ion temperature, T_i . The relative time evolution of the ^3He density can be obtained without accurate determination of C_1 if T_i , W_B , and Z_{eff} remain constant with time. The d-d and d- ^3He reaction rates were measured by detecting the 2.45 MeV neutrons with an array of $^3\text{F}_3$ counters⁵ and by detecting the 14.7 MeV protons with a silicon surface barrier detector,¹ respectively.

The radial profiles of the 2.5 MeV neutron emission and the 14.7 MeV proton emission have been calculated using a bounce averaged Fokker-Planck code.⁵ The neutron and proton emission profiles are strongly peaked inside 20 cm minor radius (Fig. 1) due to the centrally peaked neutral beam deposition profile.⁵

In this experiment, PLT (132 cm major radius, 28 or 38 cm minor radius, 2.0+3.2 Tesla toroidal magnetic field, 0.3+0.6 MA plasma current, $1.5 \times 10^{13} \text{ cm}^{-3}$ line-averaged electron density, carbon limiters) was heated by one or two deuterium neutral beams (25-40 keV beam energy, ≤ 1.2 MW beam power) injected parallel (Co) and anti-parallel (Counter) to the plasma current. The neutral beam duration was 300 msec. The ^3He gas puff occurred after 100 msec of injection to allow for beam-heated plasma to equilibrate and lasted for about 5 msec. The quantity of ^3He added to the deuterium discharge was raised by increasing the gas puff duration. A direct correlation was observed between the magnitude of the electron density rise associated with the ^3He gas puff, the central ^3He density, and the amount of ^3He puffed into the vacuum vessel (Fig. 2). The main uncertainty in using Eq. (2) to determine the ^3He density was the absolute calibration of the 14.7 MeV proton detector. In this paper, we have normalized the emission rate to account for one-half of the associated electron density rise during a major ^3He gas puff (Fig. 2). We note from Fig. 2 that this normalization is consistent with the amount of ^3He gas put into the PLT vacuum vessel as determined by the measured pressure rise for the range of ^3He gas levels used. The Co plus Counter injection caused higher central ^3He density for the same quantity of ^3He puffed into the PLT vessel. Possible explanations for this effect might be that a) the desorption of ^3He from the vessel increased with beam power and, therefore, was greater with two beams than with one, or b) the inward particle transport was inhibited by toroidal rotation and, therefore, was greater when the beam injection was balanced.

While the absolute ^3He concentration was determined to about a factor-of-two accuracy, the determination of the time evolution of the relative ^3He concentration was limited only by counting statistics. The relevant time

scales which competed with the ^3He transit time scales were the transit times of the 2.5 MeV neutrons and 14.7 MeV protons to the detector (10^{-6} sec), the thermalization time of the cold ^3He gas (10^{-4} sec), and the duration of the ^3He gas pulse (5×10^{-3} sec). These time scales were all shorter than the measured influx or exhaust transit times or the time bins for the proton and neutron counts (10 msec). The ^3He gas puff occurred at 450 msec and was accompanied by the ^3He II spectral line [Fig. 3(a)] which was excited within 5 cm of the limiter radius (Fig. 1). The central ^3He density with and without the gas puff is shown for a high density [Fig. 3(b)] and a low density [Fig. 3(c)] case. In the high density case, the ^3He density rose rapidly following the gas puff and continued to rise for the duration of the neutral beam injection. In the low density case, the ^3He density showed a similar initial rise which peaked and then decreased steadily. These two cases are to be compared to the solutions of a cylindrical diffusion equation with constant diffusion coefficient and a delta-function initial density at a radius of 35 cm. The time evolution of the average ^3He density inside 20 cm is shown for reflecting wall [Fig. 3(d)] and absorbing wall [Fig. 3(e)] boundary conditions. The initial density rise in this model is similar for the two boundary conditions, but the long time behavior differs markedly as particles are taken out of the system by the absorbing wall.

The ^3He density time evolution for a variety of discharge conditions can be analyzed in terms of an inward transit time increasing as $n \propto \exp(t/\tau_R)$ and an outward exhaust time decreasing as $n \propto \exp(-t/\tau_F)$. The rise is expected to be due to transport of ^3He to the plasma center while the fall is expected to be determined by edge recycling and exhaust properties. In this experiment we found that $\tau_R \ll \tau_F$ and $\tau_F \gtrsim$ (neutral beam duration). The fall time tended to increase with electron density while the rise time showed only a small change

with density (Fig. 4). The rise and fall times were approximately independent of the direction of the beam injection, the plasma current, or the toroidal magnetic field. The inward transit time was about the same for $a = 28$ cm and $a = 38$ cm plasma minor radius (Fig. 4), suggesting that the inward transport was not a purely diffusive process.

The exhaust time for ^3He was long ($\geq 10 \tau_E$), consistent with strong recycling and poor ^3He pumping at the plasma edge. The helium exhaust process was stronger at low plasma density, which may have been caused by a change in the plasma edge conditions such as the edge temperature. The residual ^3He density left from the previous discharge was approximately $1/2 + 1/5$ of the maximum ^3He density in that discharge (Fig. 5), indicating that considerable ^3He was retained in the vessel walls. Again Co + Counter neutral beam injection caused higher residual ^3He densities than either Co or Counter injection alone (at $1/2$ of the beam power).

This paper has reported the first experimental measurements of central helium density, transport, and recycling in a tokamak plasma. These results can be improved by raising the level of the reaction rates (e.g., by raising the beam voltage) so that better counting statistics could be obtained. Nuclear methods of central density measurement are also readily applicable to studies of trace tritium concentrations in a deuterium plasma⁵ using either beam-target or thermonuclear fusion reactions where the ratio of 14 MeV and 2.5 MeV neutron emissions will be measured.

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Fig. 1 Radial profiles of $\text{d-}^3\text{He}$ and d-d reaction rates (volume averaged) and the $^3\text{He II}$ spectral line intensity.

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Fig. 1 The ³He line averaged density rise for Counter x, Co, Co + Counter (•) neutral beam injection plotted as a function of the amount of ³He gas puffed into the PLT vessel. The Δ points are one-half the $\bar{n}_e$ rise resulting from the ³He gas puff.

Fig. 3 a) Time evolution of the $^3\text{He II}$ spectral line, and time evolution of the central (inside 20 cm) ^3He density for: b) high density Co + Counter injection $\bar{n}_e = 4.2 \times 10^{13} \text{ cm}^{-3}$. Dotted line shows residual ^3He density without ^3He gas puffing. c) Co injection $\bar{n}_e = 1.2 \times 10^{13}$, with residual ^3He density. d) A calculated case of four edge recycling and a diffusive gas penetration. e) A calculated case of no edge recycling and a diffusive gas penetration.

Fig. 4 Exponential ^3He penetration (τ_p) and exhaust (τ_F) times as a function of the average line density.

Fig. 5 The residual ^3He density prior to the ^3He gas puff plotted vs the maximum ^3He density during the previous PIT discharge.