Measurement of plasma density using nuclear techniques

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The magnitude of a fusion reaction rate in a plasma depends strongly on the relative energy of the reacting plasma ions and less strongly on the ion number density. The ratio of two reaction rates, however, is less dependent on the relative velocities while retaining the linear dependence on the relative densities of the plasma ion species. In this manner, the ratio of \( t(d,\alpha) \) to \( d(d,n) \) \( ^3\)He fusion reactions depends only on the ratio \( n_2/n_1 \), so that tritium levels in a deuterium plasma can be determined from the \( d-t/d-d \) reaction ratio \( n_2/n_1 \). Similarly, the density of \( ^3\)He can be determined in a deuterium plasma from the ratio of \( ^3\)He \( d,\alpha \) to \( d(d,n) \) \( ^3\)He fusion reactions. Such measurements of the \( ^3\)He density are of interest since they relate to the alpha ash removal problem expected on a tokamak reactor.

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I. INTRODUCTION

Determination of the particle transport, edge recycling, and convective heat flow of a plasma all require measurement of the plasma ion density. While the electron density is routinely measured in tokamaks with microwave interferometry and Thomson scattering, the densities of the ionic constituents of a plasma are not easily measured. Possible ion density measurement techniques include mass sensitive charge exchange,\(^1\) which can determine the relative hydrogen and deuterium concentrations, charge exchange enhanced atomic spectroscopy,\(^2\)-\(^4\) which has determined fully stripped oxygen and carbon concentrations, as well as ordinary atomic spectroscopy, which is useful for determining high Z impurity concentrations.

In this paper, nuclear techniques are reviewed which make use of the \( d(d,n) \) \( ^3\)He, \( ^3\)He \( d,\alpha \), and \( d(d,n) \) \( ^3\)He fusion reactions to measure the densities of deuterium, \( ^3\)He, and tritium. When these nuclear techniques are applicable they have the advantages of using naturally occurring emissions from the plasma and are, therefore, nonperturbative, of allowing good time resolution, and of preferentially detecting emissions from the plasma center. Initial applications of these nuclear techniques on the PLT and PDX tokamaks at Princeton include:

1. Determination of the deuterium density in discharges that follow a switch in the plasma working gas from deuterium to hydrogen. These measurements indicate the fraction of plasma ions contributed by recycled gas and the rate of removal of deuterium from the vacuum vessel.

2. Determination of the \( ^3\)He density following short gas puffs of neutral \( ^3\)He. These measurements indicate the \( ^3\)He particle transport coefficients from the rise in \( ^3\)He density following the puff, while the subsequent fall in density provides information on the \( ^3\)He edge recycling and pumping rates. The rate of removal of \( ^3\)He from the plasma relates to the alpha ash removal problem in a \( d-t \) reactor since \( ^3\)He and \( ^3\)He experience similar chemical interactions at the plasma-wall boundary.

3. Planned determination of the tritium density following laser blow-off injection\(^5\) of trace quantities of tritium. This experiment would be useful for determining tritium transport coefficients as well as for predicting the tritium inventory in \( d-t \) machines.

II. METHOD

The total fusion yield in a plasma is

\[
i_{12} = \int n_1 n_2 (\sigma v) d\mathbf{v},
\]

where \( i \) is the reaction rate, \( n_1 \) is one reactant ion density, \( n_2 \) is the other reactant ion density, \( \sigma \) is the fusion cross section, \( v_{12} \) is the relative velocity, the integral is over the plasma volume and the average, \( \langle \cdot \rangle \) is over the relative velocities between the 1 and 2 ions. The relative velocities of the reacting ion pairs are determined by the characteristics of the specific plasma and we note that there are two common situations: a) the plasma ions are Maxwellian so that the fusion reactions are thermonuclear and \( \langle \sigma v \rangle \) is a unique function of the plasma ion temperature, or b) the plasma ions include an energetic ion tail which produces the majority of the fusion reactions, the fusion reactions are no longer thermonuclear and \( \langle \sigma v \rangle \) is primarily determined by the characteristics of the energetic ion tail.

The use of Eq. (1) to yield either the particle 1 or 2 density from the measurement of the reaction rate \( i_{12} \), requires accurate knowledge of the relative velocities \( v_{12} \), since the fusion reaction cross section is strongly dependent on the relative velocity (Fig. 1). Small uncertainties in the relative velocity lead to large uncertainties in the inferred density. In fact, this was one major difficulty in early studies which determined deuterium densities in plasmas with low magnetic fields using the \( d(t,\alpha) \) fusion reaction rate caused by a diagnostic ion beam.\(^7\)-\(^8\)

An improvement occurs if the ratio of the rates of two reactions is measured. The ratio of the \( D-^3\He \) or \( d-t \) fusion rates to the \( d-d \) fusion rate can be less sensitive to the relative velocity of the reacting ion pairs than is the individual rate, while retaining the linear dependence on their densities. So far, it has turned out to be useful to create the fusion reactions with a deuterium neutral beam so that the fusion reac-
are beam target, and the importance of variations in relative velocity are further reduced since the behavior of the deuterium beam is common to all three reactions differing only in the cross-section weighting of the slowing down duration and the relative velocity. Specifically, this means that the beam species mix, neutral beam deposition, beam ion orbit losses on the first orbit, beam power, and beam slowing down rate do not enter into Eq. (3). This would not be true if the beam ions suffered large losses on time scales faster than the cross-section weighted slowing down time or if the slowing down were complex as is possible in tokamaks under some circumstances.

The reduction in sensitivity to the relative velocity is greatest for \( R_{d-\mu} \). Using the Gammow forms for the cross sections

\[
\langle \sigma \rangle_{d-d} = 2.35 \times 10^{-12} T^{-2/3} \exp(-19.421/T^{1/3}) \text{cm}^2/\text{s},
\]

\[
\langle \sigma \rangle_{d-\mu} = 3.49 \times 10^{14} T^{-2/3} \exp(-20.14/T^{1/3}) \text{cm}^2/\text{s},
\]

we find that

\[
R_{d-\mu} = (n_{d}/n_{d}) 67.3 \exp(0.72/T^{1/3}),
\]

where \( T \) is in units of keV. The ratio \( R_{d-\mu} \) is plotted in Fig. 1 of Ref. 11 for both beam-target (Fig. 2) and thermonuclear reactions.
cases and, as expected from the above, is very insensitive to $\sigma v$ even though each cross section individually is highly sensitive to the relative velocity. In this situation, the strong dependence of the cross section becomes a useful advantage of the technique since the fusion reactions tend to be localized in that part of the plasma containing the most energetic ions (e.g., the plasma center in tokamaks, Fig. 3) which is usually a region of considerable interest.

The ratio technique still retains a strong energy dependence in the determination of the $^3$He density, however, the ratio $R_{\alphaHe}$ (Fig. 2) is about 20 times less sensitive to energy in the range 30 to 100 keV than is the $d^{-1}$He cross section (Fig. 1).

III. EXAMPLES

A. Deuterium density measurement

The application of the ratio technique to the measurement of the deuterium density consists of the comparison of the $d(d,n)\alpha$ fusion reaction rates from two discharges in which the relative velocities of the reacting ion pairs are thought to be the same (for example, when the charge exchange ion temperature is measured to be the same). In one of the discharges, the deuteron density is assumed to be given by $n_d = n_0$, so that the microwave interferometer yields an approximation to the deuterium density. The deuterium density in the second discharge is then

$$n_d' = n_0 \frac{I_{dd}}{I_{dd}'}$$

or

$$n_d' = n_0 \left( \frac{I_{dd}}{I_{dd}'} \right)^{1/2}$$

depending on (a) if the reactions are of a beam-target nature caused by energetic ions from neutral beam heating or (b) if the reactions are of a thermonuclear nature as caused by the bulk plasma ions. Due to the $n_d = n_0$ assumption and the requirement that $\langle rv \rangle = \langle rv \rangle'$, applications of Eq. (4) tend to have large uncertainties and are, therefore, not too useful. One example in tokamak experiments is when the working gas in the device is changed from deuterium to hydrogen, then the shot-to-shot decrease in the neutron emission can be used to determine the deuteron concentration. In this situation, the 2.5-MeV neutron emission form $d(d,n)\alpha$He can be used to monitor the decrease in deuteron concentration in the plasma or, effectively, the replacement of deuterium with hydrogen in the vessel components. The progression of the deuterium density was measured on a series of PDX diverted discharges (Fig. 4) by the use of the steady-state thermonuclear neutron emission [Eq. 4(b)], by the use of the beam-target neutron emission [Eq. 4(a)] created by a 30-keV diagnostic neutral beam injected at 100 ms, and by the use of the $H_2$, HD, D$_2$ peaks in the residual gas analyzer several seconds after the discharge, which is the usual way that such measurements are made. By all three measurements, the deuteron density fell about a factor of 10 after about 30 discharges. The general agreement between the nuclear techniques and the residual gas analyzer indicates that the ratio of hydrogen isotopes in the plasma is similar to the ratio found in the walls and to the molecular concentrations observed several seconds after the discharge. Using the thermonuclear reactions of PLT neutral beam injection (beam-target fusion reactions).
clear ratio [Eq. 4(b)] means that one should monitor \( T_e \) on each discharge, but in reality such measurements were unavailable in this sequence. This means that 25% changes in \( T_e \) that are possible must be considered as an uncertainty in the \( n_p/n_e \) determination. For shot 2, one obtains \( n_p/n_e \sim 0.3 \) to 2 which is not too useful, but for shot 30 \( n_p/n_e \sim 0.05 \) to 0.2 has comparable accuracy to the RGA technique. Using the beam-target ratio [Eq. 4(a)] means that one should monitor \( T_e \) on each discharge to ensure a constant electron drag, but again such measurements were not available in this sequence. Reasonable expectations for the reproducibility of the plasma \( T_e \) and the beam voltage imply that 50% uncertainties in \( n_p/n_e \) are obtained. Again, this measurement ability is useful only when \( n_p/n_e \) is small.

Clearly, the \(^{3}\text{He} \) and tritium density measurements should attain higher reliability and accuracy since the ratios are measured on the same discharge.

### B. Helium density measurements

The application of Eq. (2) to the measurement of \(^{3}\text{He} \) densities\(^{15} \) consists of the comparison of the \( d-^{3}\text{He} \) reaction rate as measured by the 15-MeV proton emission\(^{16} \) and the \( d-d \) reaction rate as measured by the 2.5-MeV neutron emission. Since there is still a strong relative velocity dependence in the ratio of the cross sections [Fig. 2], \(^{3}\text{He} \) density measurements are made with beam-target fusion reactions induced by deuterium neutral beam injection so that the cross section is fixed by the beam voltage. In this case

\[
    n_{^{3}\text{He}} \sim n_d \frac{I_{d-^{3}\text{He}}}{I_{d-d}} \frac{\sigma_{d-^{3}\text{He}}}{\sigma_{d-d}} \frac{w_{\text{beam}}}{w_{\text{enu}}} \frac{\tau_{\text{enu}}}{\tau_{\text{thermal}}}. \tag{5}
\]

If we arrange for \( n_{^{3}\text{He}}/n_d \) small and for \( n_d/n_e \) to be a constant, then the central \(^{3}\text{He} \) density is

\[
    n_{^{3}\text{He}}(t) = C n_e(t) \frac{I_{d-^{3}\text{He}}}{I_{d-d}}(t) \frac{\sigma_{d-^{3}\text{He}}}{\sigma_{d-d}} \frac{w_{\text{beam}}}{w_{\text{enu}}} \frac{\tau_{\text{enu}}}{\tau_{\text{thermal}}}, \tag{6}
\]

evolution of the \(^{3}\text{He} \) density can be obtained without accurate determination of \( C \) so long as \( Z_m, w_{\text{enu}}, \) and \( T_e \) remain constant with time. Thus, one useful application of \(^{3}\text{He} \) density measurements is when small quantities of \(^{3}\text{He} \) are puffed into the edge of a tokamak. As a result of the \(^{3}\text{He} \) puff of Fig. 5 the \( d-^{3}\text{He} \) reaction rate increased by about a factor of 5 while the \( d-d \) reaction rate decreased by about 20% (due to increased electron drag on the energetic injected beam ions.)

The principle \(^{3}\text{He} \) gas puffing experiments performed to date are on PLT\(^{15} \) (132 cm major radius, 28 or 38 cm minor radius, 1 to 3.2 T toroidal magnetic field, 0.3 to 0.6 MA plasma current, 1 to 5.0 \times 10^{11} \) cm\(^{-3} \) line-averaged density, carbon limiters, titanium-gettered vacuum walls) during deuterium neutral beam heating (25 to 40 keV beam energy, less than 2 MW beam power, tangential injection.) In these experiments the neutral beam duration was 300 ms. After 100 ms of injection, when the beam-heated plasma was in steady state, \(^{3}\text{He} \) gas was puffed for 5 ms (the approximate gas valve exhaust time). The \(^{3}\text{He} \) thermalization time is \( \leq 0.5 \) ms so we expect the \(^{3}\text{He} \) to be in local thermal equilibrium with the plasma deuterons. The quantity of \(^{3}\text{He} \) puffed was increased by increasing the gas puff duration. A direct correlation was observed between the magnitude of the electron density rise associated with the \(^{3}\text{He} \) gas puff, the \(^{3}\text{He} \) density measured.

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![Fig. 5. Time evolution of the d-d reaction rate as measured by the 2.5-MeV neutron emission, the d-3He reaction rate as measured by the 15-MeV proton emission, and the electron density. The reactions are beam-target induced by a 35-kV deuterium neutral beam. The 10-ms He gas puff caused \( n_d \) to increase by 10%, the d-3He rate to increase by a factor of 5, and the d-d rate to decrease by 20%.
]
The line average $^3$He density rise (nuclear technique) vs the amount of $^3$He puffed into the PLT vessel. The $\Delta$ points are one-half the electron density rise resulting from the $^3$He puff. The $^3$He gas puff was accompanied by an increase in the $^3$He spectral line [Fig. 7(a)] which was excited within 5 cm of the limiter radius (Fig. 3). The central $^3$He density with and without the gas puff is shown for a high density [Fig. 7(b)] and a low density [Fig. 7(c)] case. In the high density case, the $^3$He 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 $^3$He 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 $^3$He density inside 20 cm is shown for reflecting wall [Fig. 7(d)] and absorbing wall [Fig. 7(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 rise in the central $^3$He density following a short (5 → 10 ms) $^3$He gas puff at the plasma edge [Fig. 7(a)] indicates that the transport time of $^3$He ions to the plasma center is $(20 \pm 10)$ ms, increasing modestly with density (Fig. 8) and toroidal magnetic field (Fig. 9). This time scale is comparable to previous spectroscopic measurements for the transit times of moderate and high $Z$ impurity ions in PLT. The inward transport time is consistent with a diffusion coefficient of $(4 \pm 2) \times 10^3$ cm$^2$/s or an inward directed velocity of $(2 \pm 1) \times 10^3$ cm/s, which are $\sim 10^2$ times larger than the corresponding neoclassical particle diffusion coefficient or Ware pinch velocity.

The exhaust time for $^3$He was long ($>10 \tau_k$), consistent with strong recycling and poor $^3$He pumping at the plasma edge. However, the pumping rate is about ten times faster than for neutral $^3$He to be removed by the PLT vacuum pumps. The helium exhaust process was stronger at low plasma density, which may have been caused by a change in the plasma edge conditions. The residual $^3$He density left from the previous discharge was approximately $1/2 → 1/5$ of the maximum $^3$He density in that discharge (Fig. 10), indicating that considerable $^3$He was retained in the vessel walls. Co + counter neutral beam injection caused higher residual $^3$He densities than either Co or counter injection alone (at 1/2 of the beam power).

C. Tritium density measurements

Density measurements by nuclear diagnostics is best utilized when determining small tritium concentrations in predominantly deuterium plasmas ($n_t/n_d \approx 10^{-4} → 10^{-1}$). The attractiveness of the tritium measurement is that since the triton and deuterium have the same Coulomb barrier, the ratio of the $d-t$/$d-d$ cross sections is about constant independent of relative velocity. Thus,

$$n_t \approx 10^{-2} n_d (I_d/I_t), \quad (7)$$

independent of the origin of the fusion reactions. Furthermore, since the $t(d,n)a$ cross section is large, it seems likely that sensitive tritium density measurements are possible. Experimentally, the difficulty is in selectively measuring 14-MeV neutron emission levels in the range $10^{-2} → 10$ times the 2.5-MeV neutron emission levels. Neutron spectrometers and threshold detectors are thought to be useful for such measurements. Experiments are planned on the PLT tokamak involving the laser blow-off injection of tritiated titanium in order to determine the inward tritium transport, the tritium exhaust, and the tritium removed by subsequent plasmas. Injection of $1 → 10$ mCi of tritium should be detectable.

![Fig. 9. $^3$He penetration and exhaust times vs toroidal magnetic field.](image)

![Fig. 10. Residual $^3$He plotted vs the level of $^3$He in the previous discharge.](image)
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