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MEASUREMENT OF ALPHA PARTICLES ON PLT

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MEASUREMENT OF ALPHA PARTICLES ON PLT

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ABSTRACT

The radial emission profile of the $d(^3\text{He},p)\alpha$ fusion reaction was measured on PLT by pitch angle resolution of the escaping 3.7-MeV alphas. The $d\text{-}^3\text{He}$ reactions were produced by ^3He minority ICRF and the emission was strongly peaked at the ICRF resonance layer.

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I. INTRODUCTION

Although ion cyclotron resonance heating has raised the central ion and electron temperatures on tokamaks,^{1,2} the influence of ICRF heating on the energy confinement remains uncertain.³ One difficulty in deducing the energy confinement is the fact that the RF energy deposition profile is not an experimentally measured quantity. Theoretical calculations are difficult since they require simultaneous three-dimensional modelling of RF wave propagation and damping, particle acceleration and trajectories, as well as possible particle minor radial transport which may be different inside and outside of the RF resonance layer.

In this paper, we report measurement of the radial emission profile of the $d(^3\text{He},p)\alpha$ fusion reaction by use of the escaping 3.7-MeV alphas. These $d-^3\text{He}$ reactions are created by the most energetic of the ^3He minority tail, which can reach energies of 200 keV in PLT.⁴⁻⁶ The principal result is that the $d-^3\text{He}$ reaction rate is peaked strongly at the RF resonance layer as if the reactions are caused primarily by banana trapped ^3He ions with banana tips in the resonance layer. Although we have measured the radial profile of the most energetic of the RF heated minority, it is still difficult to specify the radial RF power profile to the plasma since most of the power is coupled to the thermal ions by lower energy ^3He ions which do not cause the $d-^3\text{He}$ fusion reactions.

The $d-^3\text{He}$ fusion reaction is usually monitored on PLT by measurement of the 15-MeV proton.^{2,4,6} However, this proton has so much energy that its gyrodiameter is roughly the minor radius of PLT⁴ and spatial resolution is difficult. The measurements reported here are the first measurement of energetic alphas from a tokamak plasma. The eventual use of tritium in tokamaks will make measurements of the 3.5-MeV alpha from the $d(t,n)\alpha$ fusion

reaction important, since the confinement of that alpha is required for ignition to occur.

II. EXPERIMENT

The PLT plasma ($B_0 = 32.5$ kG, $I_0 = 575$ kA, $R = 132$ cm, $a = 40$ cm, $\bar{n}_e = 3 \times 10^{13} \text{ cm}^{-3}$, $T_e \approx 2\text{--}3$ keV, $T_i \approx 2\text{--}3$ keV) was heated by 2 MW of 30-MHz ICRF in the ^3He minority mode where the ^3He density was about 5–15% of the electron density. The $d(d,n)^3\text{He}$ fusion reaction rate was $2.8 - 4.3 \times 10^{11}$ per discharge as monitored by the 2.5-MeV neutron emission.

The escaping 3.7-MeV alphas were monitored by a CR-39 plastic nuclear track detector.⁷⁻⁹ The plastic was placed behind a pinhole (0.18-mm diameter) and a slit (0.22 mm width) (Fig. 1) and exposed to five PLT plasmas, each having 0.2 sec duration ICRF. The pinhole was placed directly below the plasma (in the direction of ion drifts) and was aligned parallel to the edge of the plasma (Fig.1). The plastic was then etched for 6 hours in a 6.25N NaOH solution at 70°C to reveal the tracks.

The probe assembly shown in Fig.1 is such that the vertical displacement of tracks corresponds to resolution of the gyroradius of the escaping particles. In principle, one could obtain some energy resolution of the escaping particles, and for the probe assembly shown in Fig. 1 the alpha energy resolution is about 3 MeV/mm. Vertical resolution also includes separation of the 15-MeV protons from the 3.7 MeV alphas. One-MeV tritons and 3-MeV protons created by the $d(d,p)t$ fusion reaction have orbits so similar to the 3.7-MeV alpha that they will not be separated; however, the density of tracks on the plastic was about seventy times as high as would be expected from 3-MeV proton or 1-MeV triton tracks as estimated from the 2.5-MeV neutron emission. For plasmas where measurement of the 15-MeV proton emission was

also available,⁶ the number of tracks was 70% of the expected number of alpha tracks as estimated from the 15-MeV proton emission (i.e., within the experimental uncertainty) and about ten times the $d(d,p)t$ rate as measured by the 2.5-MeV neutrons. Horizontal displacement of tracks on the plastic corresponds to resolution of the pitch angle (χ) of the escaping particles (Fig. 1). Pitch angle resolution of these particles corresponds to spatial resolution from the plasma (Fig. 2). Essentially, the escaping 3.7-MeV alphas which can strike the pinhole at a particular pitch angle must have come down through the plasma on a particular trajectory.¹⁰ This occurs because each alpha trajectory is a section of a very large banana orbit or circulating orbit which intersects the vessel wall, the particular orbit being determined by the magnetic moment and parallel velocity of the particle. The trajectories in Fig. 2 indicate the possible birth locations of alpha particles which can contribute to the alpha tracks. Each pitch angle corresponds to particles with a unique midplane crossing location of its guiding center (Fig. 3b).

The etched plastic was analyzed by counting the number of tracks in 222 micron wide vertical strips corresponding to single pitch angles, and then correcting for the geometry of the detector. Corrections included factors for the projected area of the pinhole and slit as seen from various pitch and gyroangles, and for the spreading of the tracks due to the inclination of particle trajectories to the plastic. The number of tracks was divided by the length of the alpha trajectory within 10 cm of the midplane to account for the difference in velocity space sampling by different orbits,¹¹ then by the product of the solid angle of acceptance of the hole-and-slit combination and the area of the pinhole to give the differential fluence of particles at the pinhole.

Expressing the corrected number of tracks seen at each pitch angle as a function of the guiding center location indicates a peak in the emission which is outshifted from the plasma center and is located at the ^3He cyclotron resonance layer. The width of the emission is approximately equal to the 3.7 MeV alpha gyrodiameter, which determines our spatial resolution for flat emission profiles. The vertical error bars in Fig. 3 are the counting statistics, while the horizontal error bars are the uncertainty in the orbit positions caused by lack of knowledge of the plasma current profile.¹⁰ The current profile is assumed to be

$$j = \left[1 - \left(\frac{r}{a} \right)^2 \right]^n$$

where n is taken as 3, 4, or 5. The uncertainty in n results in an uncertainty in the guiding center midplane crossing which is largest near the center of the vessel, but is always less than 2 cm, which is unimportant compared to the gyrodiameter of the alphas.

III. DISCUSSION

Pitch angle resolution of the escaping 3.7-MeV alphas has been used to identify the location of the $d(^3\text{He}, p)\alpha$ fusion reactions during ICRF resonant heating on PLT. This result is related to that of Chrien *et al.*⁴ who found that the $d\text{-}^3\text{He}$ rate was maximized when the ICRF resonance layer was near the plasma center. That work was accomplished by monitoring the 15-MeV proton emission level and shot-by-shot changing of the toroidal magnetic field to scan the ^3He minority resonance layer through the plasma. The work of Chrien *et al.*⁴ then tells more about the plasma conditions which maximize the energy

of the ^3He tail while the present work describes the spatial location of the most energetic of the ^3He ions.

The 15-MeV proton spectroscopic work of Heidbrink⁵ indicates that the energetic ^3He ions causing the $\text{d}-^3\text{He}$ fusion reactions have high perpendicular and low parallel velocities. Coupling that information to the present information on the spatial location of the $\text{d}-^3\text{He}$ rate implies that the energetic ^3He ions probably have 0.1-0.2 MeV of energy and are on banana orbits which have banana tips near the RF resonance layer (Fig. 4). Apparently (Fig. 3a), some of the ^3He ions ($\lesssim 10\%$) are on circulating orbits. As indicated recently by Hsu *et al.*,¹² this localization of the directly ICRF heated particles leads to poloidal asymmetries in quantities such as the plasma density and also in the ^3He tail heating of the background plasma (especially the electrons). Furthermore, this localization of the most energetic ^3He ions to the region of the resonance layer indicates that these particles have not undergone much transport during the time of their acceleration (~ 50 msec) as was also indicated by the time evolution of the $\text{d}-^3\text{He}$ rate.⁶

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FIGURE CAPTIONS

Fig. 1. Schematic of the detector showing the relative placement of the pinhole, slit, and CR-39 plastic, and how the parameters of the particle orbit affect the placement of the track.

Fig. 2. Extreme alpha orbits measured with this detector corresponding to pitch angles of $+0.50$ radians (inside) and -0.47 radians (outside) at the detector ($B_0 = 32.5$ kG, $I_0 = 575$ kA).

Fig. 3. (a) Number of alpha particles reaching the detector per μ sr acceptance angle per cm^2 pinhole area per cm alpha path length less than 10 cm from the midplane. The location of the resonance layer and the diameter of a 3.7-MeV alpha orbit are shown.

(b) Pitch angle at the detector as a function of the major radius of the guiding center midplane crossing for the plasma parameters mentioned in the text indicating the spatial resolution possible.

Fig. 4. 100-keV ^3He banana orbits with banana tips in the resonance layer.

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Fig. 1

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Fig. 2

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Fig. 3

Fig. 4

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