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FAST-ION DIFFUSION MEASUREMENTS FROM RADIAL TRITON BURN UP STUDIES

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A fast-ion diffusion coefficient of $0.1 \pm 0.1 \text{ m}^2\text{s}^{-1}$ has been deduced from the triton burnup neutron emission profile measured by a collimated array of helium-4 spectrometers. The experiment was performed with high-power deuterium discharges produced by Princeton University's Tokamak Fusion Test Reactor (TFTR). The fast ions monitored were the 1.0 MeV tritons produced from the $d(d,t)p$. These tritons "burn up" with deuterons and emit a 14 MeV neutron by the $d(t,\alpha)n$ reaction. The ratio of the measured to calculated DT yield is typically 70%. The measured DT profile width is comparable to that predicted by the TRANSP transport code during neutral beam heating and narrower after the beam heating ended.

1. INTRODUCTION

The transport of MeV ions is an important topic in the design of a reactor since a reactor will be heated by MeV alphas. The behavior of the MeV ions can be parameterized by their slowing-down time, τ_s , and their confinement time, τ_p (which if governed by diffusion is described by a diffusion coefficient

$$D \approx \frac{a^2}{4\tau_p}.$$

where a is the minor radius of the torus). For alpha heating to be effective and for the heat load on the first-wall materials from escaping alphas to be manageable, D has to be less than about $2 \text{ m}^2\text{s}^{-1}$ [1].

The $d(d,t)p$ reaction in deuterium plasmas provides a source of 1.0 MeV tritons in a deuterium discharge. The birth profile of these fast ions can be deduced by measurement of the 2.45 neutron profile from the $d(d,n)^3\text{He}$ reaction and calculation of the birth orbits. Some of the tritons will fuse with deuterons via the $d(t,\alpha)n$ reaction, and this paper reports measurements of the 14 MeV neutron emission profile on TFTR. The 14 MeV neutron emission was compared with TRANSP calculations to determine the possible effects of MeV-ion transport. Comparison of the measured to calculated DT yields indicates that during the beam heating the tritons may have $D = 0.1 \pm 0.1 \text{ m}^2/\text{sec}$, and that the profile width is comparable to the birth width. After the beam heating ends, the DT emission and width are less than calculated by TRANSP.

2. EXPERIMENTAL RESULTS

The 14 MeV neutron emission was measured by an array of helium-4 detectors [2,3]. This system is capable of measuring the 14 MeV neutron emission from TFTR at four major-radial locations. The detector was cross-calibrated to ZnS detectors [4] located in the same neutron flight paths. The cross-calibration occurred during the period from 400-700 ms after neutral-beam injection when the DT neutron production is dominant. The uncertainty in the absolute calibration of each channel is about 30%. The source strength measurement is computed largely on the basis of the two central detectors (that see the most flux) and the resultant uncertainty in determination of the total source strength is $\approx 20\%$. Count-rate statistics also are important. The DT flux has to be above 1×10^{15} neutrons $s^{-1} m^{-2}$ for the statistical noise to be the same order as the calibration uncertainty. The error in determining the full-width at half-maximum, Γ , is about 10 cm for shots above 1×10^{15} neutrons $s^{-1} m^{-2}$.

The best helium-4 detector data obtained on TFTR has been obtained by adding together ten similar shots with 1.4 MA, 5.2 Tesla, and 20 MW. One of the shots has been modeled by TRANSP. Figure 1 plots the average waveforms of the 10 shot overlaid on top of the same waveforms for the TRANSP shot. As a result, useful helium-4 data was obtained with 50 ms resolution (Fig. 2). The DT fluxes in each channel are within a factor-of-two of the TRANSP calculation from 3.0-3.5 s. From 3-4 s, the agreement between the measured and calculated fluxes on #5 and #6 is about 20%. The statistics on the outer two detectors are poorer (uncertainty $\approx 50\%$) but the measured DT flux agrees in magnitude with the TRANSP results. After 4s, the measured DT flux differs from the calculated flux and the triton population decreases at a faster rate than TRANSP calculated.

3. TRANSP CODE

The transport code TRANSP was developed at the Princeton Plasma Physics Laboratory to study the dynamic transport of plasma species [5–7]. TRANSP uses experimental data to deduce information that is not directly measured. For example, the deuteron density, n_D , is deduced from the electron density and depletion based on Z_{eff} (visible bremsstrahlung). In a similar way, the magnetic flux surface geometry is determined from the magnetics measurements, the current profile which is computed by solving the poloidal field diffusion equation, and the plasma pressure profile. Resistivity for the poloidal field diffusion equation is deduced from the measured electron temperature profile. Plasma pressure is deduced from electron density measurements, Z_{eff} measurements, and simulations for fast-ion species.

A key feature of TRANSP is its ability to simulate the observed DD neutron emission from models of the ion distribution functions as a function of time, velocity, and position. The code has recently been expanded to simulate the behavior of MeV ion fusion products. A Monte Carlo technique is used in the calculation of triton burnup. The triton source distribution is calculated from the sum of thermonuclear, beam-target, and beam-beam $d(d,t)p$ reaction rates in the models. The distribution of the birth tritons in velocity space is assumed isotropic to simplify the calculation. The confined fraction is computed by integration of fast triton orbits. The slowing-down and fusion of each sample triton is tracked. To perform this calculation, TRANSP uses the measured electron temperature, the modeled fast deuteron distribution function, modeled thermal ion species, and flat Z_{eff} profile. Charge exchange of tritons with neutral atoms in the plasma are calculated as are the effects of sawteeth on the fast ions.

The resultant DT neutron emissivity can then be mapped from magnetic flux surfaces

into the collimator geometry and chord-integrated to produce a DT radial profile flux as a function of time for comparison the helium-4 detector data.

Using the TRANSP calculated major radius of the peak DT emission (Fig. 3) and fitting the helium-4 data to a Gaussian allows determination of the total DT emission, S_{DT} , and the width, Γ_{DT} , of the emission profile with 50 ms time resolution (Figs. 3 and 4). The radial profiles can also be compared in 100 ms intervals (Fig. 5). There is good agreement (Fig. 2) prior to 4.2 s between the TRANSP calculations and the measured profile and magnitude of the 14 MeV neutron emission.

After 4.2 sec. the 14 MeV neutron emission is about three times less than calculated by TRANSP (Fig. 4). The ^4He total emission measurements are in agreement with the fission detectors after about 4.4 sec when the 2.5 MeV neutron emission became much smaller than the 14 MeV neutron emission. After 4.2 sec, the profile was about 10 cm narrower than that calculated by TRANSP (Figs. 3 and 5).

4. DISCUSSION

The data presented in Figs. 3 and 4 differ from TFTR activation measurements of triton burnup measurements [8] made in 1989. The activation data had less than the 1% burnup yield while some of the helium-4 data are above 1% (Fig. 6). The helium-4 detector data occurs at higher T_e (longer triton slowing down [9]) and is closer to the expected values than the activation results. Thus, the difference in these burnup measurements from the activation measurements could arise due to diagnostic differences or due to differences in the behavior of the different plasmas that was documented.

A measured-to-calculated burnup ratio of 0.7 corresponds to a τ_s/τ_p ratio of about 0.5

[10]. Hence, a 0.5 second slowing-down time and measured burnup of 70% of the classical burnup corresponds to a triton confinement time of 1 sec and fast ion diffusion coefficient of about $0.1 \text{ m}^2\text{s}^{-2}$. The uncertainty in the diffusion coefficient is also about $0.1 \text{ m}^2\text{s}^{-1}$, largely due to the uncertainties in the DT neutron yield measurement.

This paper represents the first spatially resolved measurements of triton burnup on TFTR. These measurements were developed at about the same time as were profile measurements on JET [11]. The reduction in burnup observed at beam turn off in TFTR was not observed on JET. Otherwise, the TFTR DT profile measurements are similar to the JET ones since the DT neutron profile was measured to be 4 cm wider (about a gyroradius) than the 2.5 MeV emission profile.

Possible explanations for the reduction in triton burnup at 4.2 sec include:

1. The DT emission from 3-4.2 sec is dominated by tritons with energies $> 0.5 \text{ MeV}$, while after 4.2 sec, the burnup is dominated by tritons near the peak of the DT fusion cross-section (0.1 - 0.2 MeV). Thus, it is possible that the lower energy tritons are being lost all the time.
2. The first sawtooth event occurred at about 4.2 sec. There were no sawtooth events during the beam heating. Thus, it is possible that some tritons are lost at the sawtooth. TRANSP can include spatial redistribution of the MeV ions at the sawtooth over the expected radial extent of the sawtooth. The TRANSP calculation which include triton redistribution at the sawtooth had better agreement with channel #5 but not #6 (Fig. 2) and did not significantly change the DT total yield (Fig. 4). Thus, it is possible that the sawtooth could influence the MeV ions more drastically than a limited spatial redistribution.

3. The narrowing of the neutron profile after 4.2 sec (Figs. 3 and 5) suggest that the MeV diffusion is larger or the Z_{eff} is larger in the larger minor radial locations.

5. SUMMARY

Measured triton burnup profiles from the helium-4 detector system were consistent with calculations from TRANSP during neutral beam heating. Analysis of the differences results in a diffusion coefficient estimate of $0.1 \pm 0.1 \text{ m}^2\text{s}^{-1}$. The profiles appear to be static during the neutral beam heating and narrow after the heating is turned off. In the decay phase, the DT neutron emission level is about two to five times below a calculation based upon only first orbit losses of the MeV tritons.

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TABLE 1. Integrated Neutron Yields

Shot	$\frac{Y_{DT,He4}}{Y_{DT,TRANSP}}$	$Y_{DT,He4}$	$Y_{DT,TRANSP}$	Y_{DD}
55806	0.75	3.03+14	4.0e+14	2.6770e+16
55804	0.84	3.4e+14	4.0e+14	2.6773e+16
55851	0.64	2.3e+14	3.7e+14	2.57293+16
55606	0.81	1.5e+14	1.9e+14	1.4869e+16
55607	0.79	1.5e+14	1.9e+14	1.4841e+16

Figures

Fig. 1. Average waveforms (solid line) for ten similar shots and the shot that had a TRANSP calculation (dashed curve). Each plasma had 5.2 T toroidal magnetic field, 1.4 MA plasma current, and 20 MW neutral beam heating.

Fig. 2. Comparison of the collimated DT fluxes Φ_{DT} , measured by helium-4 detectors (solid line) and calculated by two different TRANSP runs (dotted lines). The lower TRANSP curve incorporates energetic triton redistribution at a sawtooth at 4.2 s.

Fig. 3. Left: Calculation of Plasma Center from TRANSP for the magnetic axis (dashed line) and the center of the DT neutron emission (solid line). Right: Gaussian FWHM prediction by TRANSP (dashed line) and a Gaussian fit to the ^4He data (solid line)

Fig. 4. The DT source strength, S_{DT} , for the plasmas of Fig. 1. The solid line is the measurement of the total neutron emission from the fission detectors. The long dashed line is the ^4He detector measurement and the short dashed line is the TRANSP calculation. The lower TRANSP curve incorporates energetic triton redistribution at the sawtooth at 4.2 s.

Fig. 5. Profiles for the 10 shots. The y-axis is the DT emission per area from the volume above the detector, in neutrons $\text{s}^{-1}\text{m}^{-2}$. The x-axis is the major radius in cm. Dotted curve is fit of TRANSP data (open squares) to a Gaussian. The solid curve is the fit of the helium-4 data (solid diamonds) to a Gaussian using the TRANSP value of the DT neutron emission center. From 3.4-4.1 s (left), the TRANSP FWHM is 48 cm and helium-4 FWHM is 52 cm. From 4.3-5.0 s (right), the FWHM's are 40 cm from TRANSP and 30 cm from the ^4He data.

Fig. 6. The burnup (DT yield Y_{DT} divided by the 2.5 MeV neutron yield, Y_{DD}) as a function of electron temperature. The + points are activation results from 1989 [8]. The solid diamonds are the ^4He measurements. The open squares are TRANSP calculations and the solid line is $T_e^{1.1}$ [9].

Fig. 1

Fig. 2

Fig. 3

Fig. 4

Fig. 5

Fig. 6

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