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CONFINEMENT OF FUSION PRODUCED MeV IONS IN THE DIII-D TOKAMAK

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ABSTRACT. The behaviour of tritons and ³He ions produced in deuterium-deuterium fusion reactions is studied using the d(t, n) α and d(³He, p) α fusion reactions. Fusion produced MeV ions exhibit classical behaviour in high field (B_T ≥ 1.0 T) discharges, including the new class of 'very high' confinement plasmas. However, anomalous behaviour is observed in discharges with strong sawtooth, fishbone or toroidicity induced Alfvén eigenmode (TAE) activity. For the high field discharges without strong MHD activity, the data imply an effective diffusion coefficient smaller than ~ 0.1 m²/s, but in the presence of strong MHD activity the effective diffusion of the MeV ions exceeds 1 m²/s.

1. INTRODUCTION

It is widely accepted that ignition serves as a demonstration of the scientific feasibility of fusion power. Therefore, a major goal in fusion research is to understand the conditions necessary to sustain ignition. Ignition can be sustained if the fusion power produced within the plasma provides enough plasma heating to balance the power losses so that no additional external heating is required. The necessary plasma heating can be provided by energetic particles produced from the fusion reaction. In the case of deuterium-tritium fuel, the D-T fusion reaction produces 3.5 MeV α -particles that, if confined long enough to transfer most of their energy to the bulk plasma, may provide the power needed to sustain ignition. With fusion research rapidly entering the phase of burning plasma physics, understanding the confinement of the alphas in reactor-like conditions is essential. Because of the additional precautions required for handling tritium, the DIII-D tokamak does not operate with tritium as a main component of the plasma; therefore, a direct confinement study of fusion products from D-T reactions is difficult. However, examination of the behaviour of ³He ions and tritons from the D-D reactions can assess some aspects of alpha physics. Although the density of the D-D fusion products (typically $\leq 10^7$ cm⁻³) is far too small to drive collective instabilities, the orbits and thermalization rates of the D-D reaction products closely resemble those of alphas, so the tritons and ³He ions are useful test particles to study the effect of plasma instabilities on alpha confinement. While slowing down, these D-D reaction products may produce 14 MeV neutrons and 15 MeV protons through secondary D-T

and D^{-3} He fusion reactions. Measurements of these secondary reaction products (often dubbed 'burnup' measurements in the literature) are used to study the confinement and slowing down of the tritons and ³He ions.

Triton burnup has been studied on TFTR [1, 2], JET [3-7], PLT [8, 9], ASDEX [10] and FT [11]. Burnup of ³He ions has been studied on TFTR [2, 12] and PDX [9, 13]. In most of these previous studies, the behaviour of these MeV ions was consistent with classical predictions. Anomalous ³He ion loss was observed during strong fishbone activity in PDX [13]. Anomalous triton burnup was observed during large sawteeth on PLT [9] and when the triton slowing down time was long in JET [6, 7] and in TFTR [2]. The confinement of MeV ions was also assessed through direct measurements of escaping fusion products [14–17].

This paper reports the first simultaneous measurements of triton and ³He burnup. In addition to serving as a check on the validity of the measurements, simultaneous measurements are useful in assessing the mechanism(s) responsible for anomalous burnup. The flexibility of the DIII-D tokamak permits burnup measurements for a variety of interesting and previously unexplored conditions, including H-mode discharges [18], VH-mode discharges [19], discharges with very high toroidal beta $(\beta_T \ge 10\%)$ [20], discharges with toroidicity induced Alfvén eigenmode (TAE) activity [21] and discharges with sawtooth [22] or fishbone [23] activity. The results indicate that, for most discharges, fusion produced MeV ions exhibit classical behaviour, but, in discharges with strong MHD activity, anomalous triton and ³He ion losses occur.

2. EXPERIMENTAL TECHNIQUE

2.1. Burnup method

The D-D fusion reaction produces approximately the same number of 1.0 MeV tritons, 0.8 MeV ³He ions and 2.45 MeV neutrons. While slowing down, some MeV ions will react with the deuterium plasma to produce 14 MeV neutrons from the $d(t, n)\alpha$ reaction and 15 MeV protons from the $d({}^{3}\text{He}, p)\alpha$ reaction. The fraction of ³He ions or tritons that undergoes secondary fusion reactions depends on the ion confinement, the ion slowing down time, the deuterium density n_d , and the magnitude and shape of the reaction cross-section. In DIII-D, MeV ions slow down mainly as a result of Coulomb collisions with electrons, resulting in a classical burnup fraction that scales as $n_d T_e^{3/2}/n_e$, where T_e and n_e are the electron temperature and density, respectively. Classicaly, the confinement of the MeV ions is determined primarily by the poloidal gyroradius of the fusion products on their initial orbit; neoclassical diffusion is sufficiently small that few MeV ions that are initially confined escape during thermalization. Ions with too large a poloidal gyroradius collide with the vacuum vessel and are lost from the plasma. The probability of a nuclear reaction in the vessel wall is negligible compared to the probability of a reaction in the plasma, so measurements of 14 MeV neutrons and 15 MeV protons provide a good indication of the triton and ³He confinement. In a typical DIII-D H-mode discharge $(I_p = 1.5 \text{ MA}, T_e(0) = 3.5 \text{ keV}, n_e(0) = 7 \times 10^{13} \text{ cm}^{-3}),$ the calculated prompt losses are about 20% for 1.0 MeV tritons and about 5% for 0.8 MeV ³He ions. Taking into account the classical confinement and the classical slowing down time, approximately 1.0% of tritons burn up in subsequent D-T reactions and approximately 5×10^{-4} of ³He ions burn up.

2.2. Measurements

In DIII-D, silicon surface barrier diodes (SSBD) are used to measure 15 MeV protons from the ³He ion burnup. The 15 MeV proton detector [24] consists of a rectangular SSBD placed at the end of a probe inside the vacuum vessel (Fig. 1). The heat sensitive diode can be retracted behind the vessel wall when the vessel is baked to $\sim 300^{\circ}$ C. Under normal operating conditions, the DIII-D magnetic field configuration is such that the fast ion ∇ B drift is downward towards the bottom of the vessel. The largest uncertainty in the ³He ion burnup measurements is the absolute calibration of the 15 MeV proton detector. The efficiency of the probe is calculated



FIG. 1. Poloidal projection of the DIII-D vessel with typical orbits for charged fusion products. Also shown is the 14.7 MeV proton detector at its poloidal position. $B_T = 2.0 T$ and $I_p = 1.6 MA$.

using an orbit code that uses calculated magnetic fields from the equilibrium code EFIT [25]. The uncertainty in the efficiency of the probe is approximately 60%, with the dominant uncertainties being the location of orbit obstacles and modelling of the source profile. The uncertainty is determined by varying the detector and aperture geometry as well as the source profile in the calculation of the efficiency. Because of its vulnerable position, the 15 MeV proton detector is often subjected to high thermal flux from the plasma. Silicon diodes can malfunction in environments that exceed 25°C [26]. Occasionally, the detector would fail following plasma disruptions or after a series of plasmas with high power, long pulse neutral beam injection.

Silicon diodes are also used to measure the 14 MeV neutron flux. Upon entering the silicon diode, neutrons with sufficient energy undergo reactions that produce alphas and protons with energies between 9 MeV and 12 MeV, which in turn are detected by the SSBD [27]. The reaction threshold is sufficiently high (~7 MeV) to discriminate against MeV neutron from D-D reactions but not against high energy gammas ($E_{\gamma} \leq 6$ MeV [28]).

In order to minimize pulse pile-up from high energy gammas, we use fast preamplifiers with wide bandwidth $(\leq 100 \text{ MHz})$. The background gammas are filtered using pulse height discriminators. The discriminators are set at different energy levels ranging from 2.5 MeV to 20 MeV. For the 14 MeV neutron measurement, we count pulses that exceed 7.5 MeV. Data for the 15 MeV proton measurement are discriminated at 12.5 MeV. An ²⁴¹Am source is used to give the energy calibration for the discriminators. The electronics for the 14 MeV neutron detector are similar to those of the 15 MeV proton probe [24]. The diode measurements of D-T neutrons are calibrated using 14 MeV neutron fluence measurements from copper foil activation [28]. Copper samples located at the plasma midplane just outside the vacuum vessel are activated during plasma discharges and are analysed immediately after the shot. The accuracy of the absolute calibration is estimated to be 45%, with the largest uncertainty due to uncertainty in the relationship between the measured fluence and the total emission. After calibration, the fluence obtained by integrating the silicon diode signal agrees with the fluence measured with copper foils for all conditions investigated (including classical and anomalous burnup conditions). Both the 15 MeV proton data and the 14 MeV neutron data are processed through a series of counters, with the data collected in 10 ms time bins. In general, counting statistics are good enough to give us the full 10 ms time resolution for both the 14 MeV neutron and the 15 MeV proton measurements. The fractional standard deviations are typically 1% and 10% for the 15 MeV proton and the 14 MeV neutron measurements, respectively. However, in a few discharges with anomalous burnup, several time bins were combined to gain better counting statistics for the 14 MeV neutron measurement.

The creation rate of tritons and ³He ions is obtained from measurements of the 2.45 MeV neutron emission. The time evolution of the 2.45 MeV neutron emission is measured by scintillators [29] that are cross-calibrated to a set of ³He and BF₃ neutron counters. The counters are absolutely calibrated to $\sim 15\%$ [30].

2.3. Modelling

Two codes developed at Princeton [9, 31, 32] are used to predict the expected burnup: the steady state code MIS that calculates the burnup ratio and the time evolving code TIMEEV that predicts the 14 MeV neutron and the 15 MeV proton signals. Both codes assume that the MeV ions experience a Coulomb drag at their birth position (modified in situ approximation). The codes neglect the effect of pitch angle scattering,

CONFINEMENT OF FUSION PRODUCED MeV IONS IN DIII-D

Doppler broadening and charge exchange losses. They also assume that the background deuterium plasma is cold and that the energy diffusion is negligible. The effect of these assumptions on the burnup ratio is <5% for T_i < 10 keV [32]. The validity of the MIS code for low temperature plasmas was recently confirmed [32].

The steady state code MIS solves the equation

$$B = \frac{\int r S(r)C(r)P(r)dr}{\int S(r)dr}$$
(1)

where B is the ratio of secondary to primary reactions (the burnup fraction), S(r) is the fusion product birth distribution, C(r) is the MeV ion confined fraction and $P(r) = \int_0^\infty n_d \sigma(v) v dt$ is the reaction probability. This code is used for rough comparisons of the measured fluence with theory.

For a more careful comparison of theory and experiment, the time evolution of the plasma parameters is incorporated into the calculation (TIMEEV). The electron temperature is measured by Thomson scattering [33], the electron density is measured by Thomson scattering and by interferometry [34], and the MeV ion birth rate is obtained from measurements of the 2.45 MeV neutron emission and the plasma impurity level (Z_{eff}) from the visible bremsstrahlung emission [35]. The electron temperature and density profiles are fitted analytically to the Thomson scattering data. The code also assumes that both the plasma current profile and the MeV ion birth distribution are parabolic to some power. The current profile is estimated from the electron temperature profile, and the MeV ion birth profile is estimated from calculations of beam deposition. Comparison of the current profile obtained from an equilibrium fit using magnetics data and kinetic profiles with the current profile obtained from the electron temperature profile alone indicates good agreement for the discharges presented here (within 20%). In the code, the Z_{eff} profile is assumed to be flat.

The largest uncertainties in the theoretical prediction are those from the modelling of the current profile and the MeV ion birth profile. Additional uncertainties arise from systematic errors in the calibration of the measurements of the electron temperature, the electron density, the D-D neutron emission and Z_{eff} . The uncertainties of the absolute calibration for both n_e and T_e are approximately $\pm 10\%$ for these discharges [33, 34]. For most discharges studied here, $Z_{eff} \leq 2$, with carbon as the dominant impurity. The uncertainty in the Z_{eff} measurement is about $\pm 15\%$ [35]. The central electron tem-



FIG. 2. Ratio of the burnup with diffusion to the burnup without diffusion versus the parameter $\alpha = \tau_s/3\tau_c$ for various values of the electron temerature (Eq. (11) of Ref. [36]). The effective diffusion coefficient D^{*} is related to the fast ion confinement time by $D^* = a^2/5.88\tau_c$. In our evaluation of the slowing down time τ_s we use $\tau_s = 6.3 \times 10^8 A_b T_e^{3/2} [eV]/Z^2 n_e \ln \Lambda_e$, rather than the erroneous value given in Eq. (13) of Ref. [36].

perature and density are often not measured in DIII-D. This contributes an additional 30% uncertainty in the calculation of the burnup fraction. We estimate that the uncertainty in the prediction of the absolute burnup fraction is approximately 60% for both triton and ³He ion burnup.

In general, the burnup may deviate from the classical prediction because of anomalies in slowing down time, in prompt losses or in confinement [9]. If we assume that reductions in burnup are due to a degradation in confinement (rather than anomalously rapid slowing), the measured burnup can be related to a volume averaged, effective diffusion coefficient D^* for the MeV ions, as shown by Anderson et al. [36]. Using their formalism, the ratio of the measured burnup to the expected burnup is plotted in Fig. 2 as a function of

 $\alpha = \tau_s/3\tau_c$, where τ_s is the slowing down time on electrons and τ_c is the effective confinement time of the MeV ions. These curves are used in Section 4 to relate the measured burnup to the effective diffusion coefficient.

3. RESULTS

The burnup database consists of measurements taken during the 1990-1991 run period of the DIII-D tokamak. All data reported here were compiled during deuterium neutral beam injection in deuterium plasmas ($D^0 \rightarrow D^+$). The database is limited to discharges that are on the DIII-D good shot list and that have a comprehensive set of diagnostic measurements. Whenever possible, simultaneous burnup measurements of both MeV ions were made.



FIG. 3. Time evolution of n_e , T_e , Z_{eff} , the plasma stored energy W_{plasma} and the divertor D_{α} radiation for a 2.0 T, 1.6 MA, doublenull divertor discharge. The L-H transition occurs at 3100 ms. The plasma begins to exhibit edge localized modes (ELMs) at 3250 ms after peaking at a stored energy of 1.7 MJ.



FIG. 4. Thomson scattering profiles of electron temperature (a) and electron density (b) at the peak of the D-D neutron emission for the discharge shown in Fig. 3. In the code TIMEEV, both the electron temperature and the electron density profiles are time dependent functions.

3.1. Classical burnup

The time evolution of the fusion product burnup is consistent with classical predictions in low beta discharges. To facilitate comparison of the time evolution of the signal with theory, all data analysed with TIMEEV are normalized to the theoretical prediction. For all 'classical' data, the correction factor is $\leq 20\%$ for triton burnup and $\leq 35\%$ for ³He ion burnup, consistent with estimates of the accuracy of the absolute calibrations. In the case of discharges with strong MHD activity, the normalization process involves scaling the experimental data to the theoretical prediction during the quiescent phase of the discharge. Classical behaviour in a representative H-mode plasma is documented in Figs 3–5. The plasma parameters are plotted in Fig. 3 and the electron temperature and density profiles are shown in Fig. 4. The

CONFINEMENT OF FUSION PRODUCED MeV IONS IN DIII-D

plasma starts out in L-mode as deuterium beams are introduced. During the L-mode phase, the plasma has some sawteeth that cause drops $(\Delta I_n/I_n)$ of up to 15% in the D-D neutron emission. At 3100 ms, the plasma enters the H-mode phase, as indicated by the drop in the D_{α} signal. The stored energy reaches its maximum value of 1.7 MJ at 3250 ms. Both MeV ions exhibit classical behaviour in this discharge (Fig. 5). Recall that the birth rate of the tritons and the ³He ions is characterized by the D-D neutron (2.45 MeV) emission (Fig. 5(a)). The MeV ions are more likely to undergo a secondary reaction when they have reached the peak of the D-T (~185 keV) or D-³He (~650 keV) reactivity than at their birth energies. This results in a delay in the D-T and D-³He fusion reaction rates with respect to the 2.45 MeV neutron emission (Fig. 5). The observed delay agrees well with the prediction based on classical Coulomb scattering (Fig. 5). For this discharge, the peak-to-peak delay is about 200 ms for triton burnup



FIG. 5. (a) Time evolution of the measured D-D (2.45 MeV) neutron emission and the measured D-T (14 MeV) neutron emission, as well as the calculated D-T neutron emission using TIMEEV for the high field discharge shown in Fig. 3. (b) Time evolution of the measured and calculated D^{-3} He proton emission for the same discharge.



FIG. 6. Time evolution of n_e , T_e , Z_{eff} , W_{plasma} and divertor D_{α} radiation for a VH-mode discharge. The plasma enters the VH-mode at 3270 ms and evolves into the H-mode at 3620 ms with ELMs. $I_p = 1.6$ MA and $B_T = 2.1$ T.

and about 30 ms for ³He ion burnup. The triton burnup for this discharge is $\sim 1.1 \times 10^{-2}$; the ³He ion burnup is $\sim 4.5 \times 10^{-4}$.

Recently, after boronization, a new regime of 'very high' confinement (dubbed VH-mode) was obtained in the DIII-D tokamak [19]. This regime is characterized by values of the energy confinement time that are nearly a factor of two higher than that of the normal H-mode. Fusion product burnup in VH-mode discharges is consistent with classical theory. One of the best documented cases of the VH-mode is shown in Fig. 6. The VH-mode transition occurs at 3267 ms, after additional beam power is added at 3000 ms. During the 'very high' confinement phase the central ion temperature is higher than that of normal H-mode discharges with the same plasma conditions ($T_i(0) \leq 14$ keV). The central electron density is approximately 1×10^{14} cm⁻³ and the central electron temperature is about 5.7 keV. The time evolution of the 14 MeV neutron emission and the 15 MeV proton emission is shown in Fig. 7. Triton burnup for this plasma is approximately 1.2% and ³He ion burnup is about 5.1×10^{-4} . In order to model the VH-mode discharge, it is necessary to include the effect of an evolving MeV ion source profile as well as the time evolution of the electron temperature and density profiles. In the calculation shown in Fig. 7, the 'peakedness' of the source profile increases by a factor of two at the L-mode to VH-mode transition. (The source profile is more peaked in the VH-mode than in the H-mode because, in contrast to normal DIII-D conditions where beam-plasma reactions predominate, in the VH-mode thermonuclear reactions constitute a significant fraction (roughly 50%) of the neutron emission.) When the time evolution of the plasma profiles is properly included, the predicted time evolution of the signal agrees well with the data (Fig. 7).



FIG. 7. (a) Time evolution of the measured D-T (14 MeV) neutron emission and the D-T neutron emission predicted by TIMEEV for the VH-mode discharge shown in Fig. 6. (b) Time evolution of the measured $D^{-3}He$ (15 MeV) proton emission, the $D^{-3}He$ proton emission predicted by TIMEEV and the measured D-D (2.45 MeV) neutron emission. During the VH-mode phase, the thermonuclear reaction rate is comparable to the beam-plasma rate, and the MeV ion birth distribution is more peaked than in the normal H-mode.



FIG. 8. Triton burnup data versus plasma current. The burnup fraction is taken to be the ratio of the 14 MeV neutron fluence to the 2.45 MeV neutron fluence. All of the discharges represented in this figure have no fishbone nor TAE activity. The curve indicates the theoretical dependence of the confined fraction upon the plasma current (normalized to the data at $I_p = 1.6 \text{ MA}$). During this current scan, T_e varied from 1.3 to 3.8 keV, n_e varied from 1.1 × 10¹³ to 9.6 × 10¹³ cm⁻³, and Z_{eff} varied from 1 to 2. The error bar shown is representative of the absolute uncertainty in the triton burnup fraction.

Burnup of MeV ions is a time evolving process, and a good comparison between theory and experiment cannot be made without incorporating the time evolution of the plasma parameters in the modelling. However, for the purpose of showing systematic dependences as observed in the burnup database, it is convenient to use the *steady state* burnup code MIS (even though the steady state code can only provide a rough comparison between theory and experiment). The trends observed in the database are consistent with classical expectations for high field discharges.

An important parameter in the burnup of fusion products is the plasma current I_p . Together with the MeV ion birth distribution, the magnitude and radial profile of the plasma current determine the confined fraction C of the tritons and ³He ions. The shift of the MeV ion drift orbits scales as I_p^{-1} [37]; therefore, at higher plasma current, the particles are better confined. In Fig. 8, the triton burnup fraction and the confined fraction are plotted against the plasma current. Between 0.4 MA and 1.6 MA, the burnup fraction increases rapidly owing to the reduction in prompt losses to <10% of the total population. Above 1.6 MA, the data increase more gradually, since most of the tritons are already well confined. Figure 8 shows that the measured triton

CONFINEMENT OF FUSION PRODUCED MeV IONS IN DIII-D

burnup fraction, within experimental errors, exhibits a classical dependence over the full range of plasma currents used on DIII-D.

Another important burnup parameter is the electron temperature. For energetic MeV ions, electron drag dominates ion drag; thus, the MeV ion slowing down time scales as $T_e^{3/2}$. In Fig. 9, the triton and ³He burnup fractions are plotted against the electron temperature. Again, these plots show that for most DIII-D discharges the triton and ³He ion burnup fractions are consistent with the classical electron temperature scaling of $T_e^{3/2}$.

As expected theoretically, the triton and ³He burnup fractions show no systematic dependence upon \overline{n}_e or injected beam power. Also, because of the relatively low level of impurity in DIII-D discharges ($Z_{eff} \leq 2.0$), no systematic dependence upon Z_{eff} is observed.



FIG. 9. Triton and ³He ion burnup data versus electron temperature for high field discharges ($B_T \ge 1.0$ T) in DIII-D. The burnup fraction is denoted by the ratio of the 14 MeV neutron (or 15 MeV proton) fluence to the 2.45 MeV neutron fluence. The theory band is calculated by the steady state MIS code for plasma currents from 0.4 MA to 3.0 MA and densities of (1.1–9.6) × 10¹³ cm⁻³. The burnup fraction scales as $T_e^{3/2}$, as predicted. The error bar represents the uncertainty in the absolute calibration of the detectors.



FIG. 10. (a) ³He ion burnup data versus toroidal beta inferred from the equilibrium [25]. (b) Triton burnup data versus toroidal beta. The open circles represent data for high field discharges and the solid circles data for discharges with TAE or fishbone activity. The data are limited to plasma currents of >0.8 MA to minimize the effect of prompt losses. It is important to recognize that any correlation between high β_T and MHD activity is a byproduct of the burnup database; therefore, these plots are not representative of all DIII-D discharges.

3.2. Anomalous burnup

The burnup data in Section 3.1 apply to discharges at relatively high field ($B_T \ge 1.0$ T) and plasma current ($I_p \ge 0.8$ MA). These discharges have sawtooth MHD activity but no fishbone or TAE activity. In this section, we discuss burnup data that depart from the classical predictions. In DIII-D, we observe anomalous burnup in plasma discharges with strong MHD activity. Since most high beta discharges ($\beta_T \ge 6\%$) are plagued with MHD activity, there is a correlation between anomalously low fusion product burnup and high toroidal beta. In Fig. 10, the triton and ³He burnup fractions, calculated from the 14 MeV neutron and 15 MeV proton fluences, are plotted against the toroidal beta. Data represented by open circles are for discharges with little or no MHD activity. Data represented by solid circles are for discharges with fishbone or TAE activity. The burnup fractions in discharges without strong MHD are consistent with classical predictions, but the discharges with fishbones and TAE modes all have anomalously low burnup fraction values, with the triton burnup exhibiting a greater reduction than the ³He burnup. In our dataset, all high beta discharges exhibit either fishbone activity, or TAE activity, or both. From the time evolution of the signals (see below), it appears that anomalous behaviour is caused by the MHD activity and is not a direct byproduct of the large values of beta.

In DIII-D, TAE modes can be excited by intense populations of super-Alfvénic beam ions [21]. Plasma



FIG. 11. Time evolution of the triton and ³He ion creation rate I_n , n_e , T_e , Z_{eff} and the Mirnov \dot{B}_{θ} signal for a DIII-D discharge with TAE and fishbone activity. $B_T = 0.81$ T, $I_p = 0.9$ MA, $\bar{n}_e = 5.0 \times 10^{13}$ cm⁻³, $V_{\parallel 0}/V_A \approx 1.0$, $\langle \beta_b \rangle \approx 2.6\%$, $\bar{B}_{\theta}/B_0 \sim O(10^{-3})$.



FIG. 12. (a) Time evolution of the measured D-T reaction rate and the rate predicted by TIMEEV for the discharge shown in Fig. 11. (b) Time evolution of the predicted and the measured $D^{-3}He$ reaction rates in the same discharge. Also shown are the theoretical predictions for the D-T reaction rate and the $D^{-3}He$ reaction rate calculated assuming flat birth profiles (dotted lines).

parameters for a discharge with both TAE and fishbone instabilities are shown in Fig. 11 and the corresponding burnup signals in Fig. 12. In this discharge the measured 14 MeV neutron emission and the 15 MeV proton emission fluctuate erratically and their fluences are significantly lower than those predicted theoretically. Since fishbones and TAE modes cause anomalous beam-ion transport [21, 23], the birth profile for the MeV ions may be flatter than that expected from classical predictions. (The profile of the 2.45 MeV neutron emission is not measured in DIII-D). The theoretical prediction under the assumption that the birth profile is completely flattened by the MHD activity (which probably overcompensates for this effect) is included in Fig. 12. While it is apparent that flattening of the birth profile may account for

CONFINEMENT OF FUSION PRODUCED MeV IONS IN DIII-D

some of the reduction in the D-T and D-³He signals, some of the reduction must be due to anomalous MeV ion behaviour. For this discharge, the triton burnup is approximately an order of magnitude lower than the classically predicted value of 3×10^{-3} , and the ³He burnup is about three times lower than the predicted value of 1.7×10^{-4} . In discharges with stronger TAE activity, even greater reductions in burnup are observed.

In the discharge illustrated in Figs 11 and 12, the TAE and fishbone bursts appear in periods that are much shorter than the particle slowing down time; thus we cannot determine whether the burnup reduction is caused by TAE activity or by fishbone activity. In the discharge shown in Fig. 13, the fishbone bursts, as indicated by the low frequency Mirnov activity, are clearly separated from the TAE events, which are characterized by high frequency Mirnov activity. Both



FIG. 13. (a) Time evolution of the measured and predicted triton burnup rates for a discharge with TAE and fishbone activities that are clearly separated in time. (b) Mirnov \dot{B}_{θ} signal showing the time separation of the fishbone activity and the TAE activity. $\tilde{B}_{\theta}/B_0 \sim O(10^{-3})$.



FIG. 14. Time evolution of the ³He birth rate (represented by the 2.45 MeV neutron emission), n_e , T_e , Z_{eff} , and the toroidal beta determined from the equilibrium for a high beta discharge ($\beta_T = 11.1\%$) with $B_T = 0.8$ T, $I_p = 1.3$ MA, a = 57 cm, normalized current $I_n \equiv I_p/aB_T = 2.8$, elongation $\kappa = 2.2$, triangularity $\delta = 0.85$ and internal inductance $\ell_i = 0.84$.

the triton burnup and the ³He burnup are suppressed in both phases of the discharge. Therefore, it appears that both fishbone activity and TAE activity have unfavourable effects on MeV ion confinement.

One of the greatest assets of DIII-D is the ability to shape the plasma. Recently, record beta values $(\beta \ge 10\%)$ were obtained by constructing elongated plasmas with high triangularity [20]. Plasma parameters for a discharge with a toroidal beta of 11.1% are shown in Fig. 14. This high beta discharge suffers moderate MeV ion loss, since there is MHD activity throughout the discharge. Figure 15 shows that the 15 MeV ion emission is reduced as the MHD activity develops. The discharge disrupts at 1.5 s, which results in low triton burnup because the tritons do not have enough time to slow down through the peak of the D-T crosssection before the discharge terminates. Therefore, low counting statistics prevent any useful triton burnup data in this discharge. The fact that the reduction in ³He ion burnup in this high β_T discharge is not as large as that in the other discharges supports the premise that MHD activity (rather than high beta itself) is responsible for the anomalous burnup.

As noted previously (Fig. 5), modulations in the 15 MeV proton signal are correlated with the sawtooth instability. During the L-mode phase of the discharge shown in Fig. 3, there are a series of sawteeth that cause rapid drops in 2.45 MeV neutron emission. Since the neutron emission is dominated by beam-plasma reactions (beam-plasma reactions constitute about 70% of the total neutron emission) and the deuterium density profile is very flat for these conditions, the sudden drops indicate ejection of beam ions from the plasma core at the sawtooth event [38]. These sawteeth also have an adverse effect on ³He ion confinement (Fig. 5). In



FIG. 15. (a) Time evolution of the predicted and measured $D^{-3}He$ reaction rates for the high beta discharge shown in Fig.14. (b) Mirnov \dot{B}_{θ} signal. The ³He ions suffer anomalous losses when the MHD activity begins (as indicated by the \dot{B}_{θ} time trace). $\tilde{B}_{\theta}/B_{0} \sim O(10^{-3})$.



FIG. 16. Detail of the D^{-3} He reaction rate shown in Fig. 5. The selected region displays the L-mode phase of the discharge where sawtooth MHD activity caused anomalous ³He ion loss.



FIG. 17. (a) Time evolution of the predicted and measured D-T reaction rates for a plasma with sawtooth MHD activity. (b) Time evolution of the predicted and measured $D^{-3}He$ reaction rates for the same discharge. The D-T and $D^{-3}He$ birth rate (as indicated by the D-D reaction rate) is also shown in (a). $B_T = 2.02 T$, $I_p = 1.63 MA$, $\bar{n}_e = 4.2 \times 10^{13} \text{ cm}^{-3}$ and $T_e = 3.4 \text{ keV}$.



FIG. 18. Detail of the ³He ion burnup from Fig. 17(b) showing the effect of sawtooth MHD activity on ³He ion confinement.

Fig. 16, the portion of the discharge with large sawteeth is expanded for greater clarity. The theory line in the figure is calculated by TIMEEV, with effects of the drop in the D-D reaction rate (as indicated by the drop in the D-D neutron emission) included in the calculation. The drops in 15 MeV proton emission at each sawtooth are too large and too rapid to be explained by modulation of the source rate. Unfortunately, there are no soft X-ray (SXR) data for this discharge to help us understand the event. However, we do have SXR data for the discharge shown in Fig. 17, which is similar to the discharge shown in Figs 3-5. The sawtooth period is about 180 ms, with the inversion radius located at $\rho \simeq 0.3$ (ρ is the radial co-ordinate normalized to the volume of the flux surface). At each sawtooth crash, there is a $\sim 15\%$ drop in the D-D neutron (2.45 MeV) emission, indicating that fast ions are being ejected or redistributed away from the centre of the plasma. In this discharge, we see a reduction in burnup for both the tritons and the ³He ions. Similar to the discharge in Fig. 5, there is a one-to-one correlation between the drop in 15 MeV proton emission and sawtooth crashes (see Fig. 18). A 15-20% reduction in 15 MeV proton emission occurs at each sawtooth crash, which is roughly equal to the reduction in 2.45 MeV neutron emission. Any sudden reduction in triton burnup at the sawtooth crash is obscured by poor counting statistics, but it is apparent that the triton burnup is also suppressed during this phase of the discharge (Fig. 17).

4. DISCUSSION

Our results indicate that in the absence of strong MHD activity ($B_T \ge 1.0 \text{ T}$, $I_p \ge 0.8 \text{ MA}$), DIII-D

DUONG and HEIDBRINK

discharges exhibit classical burnup behaviour. The good agreement of the measured burnup fraction, current dependence (Fig. 8), temperature dependence (Fig. 9) and time evolution (Figs 5, 7) with classical predictions implies that most fusion produced MeV ions in these discharge are confined long enough to slow down through the peak of their reaction crosssection and that the MeV ions slow down mainly owing to electron drag. To within the $\sim 20\%$ accuracy of the theoretical predictions, the delay between the rise in the 2.45 MeV neutron emission and the 15 MeV proton and 14 MeV neutron signals is consistent with classical Coulomb drag. From the absolute calibration of the 14 MeV neutron fluence using copper foils, we estimate an upper bound on the effective triton diffusion coefficient of $D^* \leq 0.15 \pm 0.07 \text{ m}^2/\text{s}$. This value is of the same order of magnitude as those from JET [6, 36] and TFTR [2, 17].

These low values of diffusion in high field discharges are consistent with theoretical expectations. Because of their large orbits and high speeds, MeV ions do not interact effectively with small scale-length turbulence (radial decorrelation lengths of ≤ 1 cm), so fast ions are predicted to diffuse much more slowly than thermal particles [39]. Transport due to toroidal field ripple is also expected to have little effect. Calculation of the field ripple for DIII-D shows that the magnitude of the ripple is $\delta \ll 1.0\%$ everywhere inside the vacuum vessel (Fig. 19) [40]. Trapping in secondary ripple wells [41] is only expected near the outer edge of the chamber (Fig. 19), and the stochastic ripple region [42] is also calculated to occupy a small volume in the plasma (Fig. 19). For most MeV banana orbits, the turning point is near the magnetic axis ($\leq a/2$), so very few MeV ions escape via these mechanisms in DIII-D.

In high field discharges with large sawtooth activity, measurable reductions in burnup are observed (Figs 5, 17). The 2.45 MeV neutron emission produced by the \sim 75 kV beam ions is also affected. These observations suggest that some fast ions are lost to the edge of the plasma at the sawtooth event. Several alternative explanations for the observations can be excluded. In principle, a reduction in burnup can be caused by flattening of the electron temperature profile, but this reduction occurs on a slowing-down time-scale, which is about 50 ms for the ³He burnup in these conditions. The observed reduction occurs in < 10 ms. Another possibility is that the reduction is due to flattening of the fast ion and thermal deuterium profiles within the sawtooth mixing radius [43, 44]. However, the estimated reduction in burnup due to this mechanism [43] is only $\leq 5\%$ for our flat H-mode density profiles, so this



FIG. 19. Poloidal projection of DIII-D and calculated TF ripple stochastic region for a plasma with $B_T = 0.8$ T and $I_p = 0.7$ MA. The stochastic region satisfies the condition $\delta > \delta_S \equiv (\epsilon/N\pi q)^{3/2} \times (1/2\rho q^{1})$ [42]. The figure neglects the small stochastic region near the centre of the plasma. The TF ripple contour amplitudes are: $A = 2.5 \times 10^{-6}$, $B = 2.2 \times 10^{-4}$, $C = 3.1 \times 10^{-3}$.

mechanism cannot account for the observations either. Another possibility is that ³He ions are redistributed into the loss cone [45]. However, for the data presented here, the sawtooth inversion radius is about 20 cm from the magnetic axis. Since the plasma current is relatively high (1.6 MA), the ³He ions are well confined throughout the entire sawtooth mixing volume. To explain the observed reduction in burnup through transport into the loss cone, the ³He ions must move to $r \ge 40$ cm. A final excluded possibility is that changes in proton detection efficiency account for the reduction [43, 46]. Thus, we conclude that some of the ³He ions must move from the plasma core to the low density edge of the plasma. Similar arguments apply to the reduction in 2.45 MeV neutron emission.

The losses of beam ions, ³He ions and tritons seem to be similar at these sawtooth events. The 2.45 MeV emission drops by ~15%, suggesting [38] that approximately 15% of the 75 keV deuterons are lost. The 15 MeV proton emission drops by ~20%, but ~5% of the reduction may be due to other effects, so we estimate that 10-15% of the ³He ions are also lost. Any sudden reduction in 14 MeV neutron emission is obscured by poor counting statistics, but the data are not inconsistent with a drop of comparable

CONFINEMENT OF FUSION PRODUCED MeV IONS IN DIII-D

magnitude. The average value of the 14 MeV neutron emission is approximately 20% less than that from classical predictions during the strong sawteeth, while the average value of the 15 MeV proton emission is reduced by about 10%. The effective diffusion coefficient associated with the sawteeth is $D^* \approx 0.07 \text{ m}^2/\text{s}$ for tritons and $D^* \approx 0.3 \text{ m}^2/\text{s}$ for ³He ions.

Both fishbones and TAE modes cause large reductions in fusion product burnup. Large losses of beam ions are also associated with these instabilities [21, 23], but the mechanism responsible for the losses may be different for the beam ions. Since the beam ions travel at the same velocity as the instability, the beam ions may be lost via mode-particle pumping [47]. However, the velocity of the fusion products is two to three times larger than that of the beam ions, so their orbits do not resonate with the mode. In PDX, large reductions in ³He burnup during the fishbone instability were observed [13]. In their interpretation of the PDX results, Heidbrink et al. speculated that the helical distortion of the flux surfaces associated with the fishbone instability pushed the marginally confined ³He ions into the loss cone [13]. This model cannot explain the DIII-D observations, however. In the PDX experiment, the plasma current was only 0.4 MA, but in DIII-D the current is 0.9 MA and the ³He ions in the centre of the discharge are well confined. A more likely mechanism for the reduction in burnup is that the orbits of the MeV ions become stochastic in the helical fields created by the instabilities [48]. This mechanism requires helical fields of the order of $\tilde{B}_{\theta}/B_0 \sim 10^{-3},$ which is comparable to the values observed in the experiment.

The effective diffusion coefficient associated with TAE and fishbone activity is large. If we assume that the birth profile of the MeV ions is flat, the effective diffusion coefficient is $D^* \approx 1 \text{ m}^2/\text{s}$ for the tritons and $D^* \approx 2 \text{ m}^2/\text{s}$ for the ³He ions in the discharge shown in Fig. 12. Since the assumption of a flat birth profile underestimates the burnup reduction, these values constitute a lower bound on the effective diffusion. For comparison, application of the same formalism to the 2.45 MeV neutron data (Fig. 12) implies that the effective diffusion coefficient of beam ions in this discharge is $D^* \approx 3 \text{ m}^2/\text{s}$.

5. CONCLUSION

The absolute magnitude of the fusion product burnup is consistent with classical theory in high field discharges, within experimental error ($\sim 45\%$ for the triton and ~ 60% for the ³He ion) and uncertainties in the theoretical prediction (~ 60%). The slowing-down time is consistent with predictions based upon Coulomb drag to within ~ 20%. The parametric dependence of the burnup on plasma current, electron temperature and electron density is also consistent with theoretical expectations. The upper bound for triton diffusion in these discharges is of the order of 0.1 m²/s.

Anomalies are observed during MHD activity, however. Large sawteeth can cause measurable reductions in burnup, although the net transport associated with the sawtooth instability is relatively modest (~0.1 m²/s). Fishbones and TAE modes can effectively destroy the confinement of MeV ions (equivalent diffusion coefficients of ≥ 1.0 m²/s). The most promising model for explaining these observations is that the large helical perturbations associated with the instabilities cause the MeV ion orbits to become stochastic [48].

In future work, we plan to model the fields associated with TAE modes and to compute the MeV ion orbits in this field geometry. Further study of the effect of the sawtooth instability on MeV ion confinement is also desirable. Our results suggest that the single-particle confinement of alphas in a reactor will be adequate for ignition *if* large-amplitude MHD instabilities can be avoided.

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