Title

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Permalink

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Journal

Nuclear Fusion, 28(10)

ISSN

0029-5515

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Publication Date

1988-10-01

DOI

10.1088/0029-5515/28/10/018

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(Manuscript received 14 March 1988
Final manuscript received 17 May 1988)

COMPARISON OF EXPERIMENTAL AND THEORETICAL FAST ION SLOWING-DOWN TIMES IN DIII-D

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ABSTRACT. Short deuterium beam pulses are injected into the D III-D tokamak to study the variation of beam slowing-down time with temperature and density. The slowing-down time is inferred from the rate of decay of the $d(d,n)^3He$ neutron emission. To within ~30%, the results are consistent with Sivukhin's classical theory. The short beam pulses are also useful for measurements of the central deuterium density.

Analysis of tokamak plasmas routinely assumes classical Coulomb coupling between different plasma species. For example, the conclusion that ion thermal conduction is anomalous in beam heated tokamaks [1] hinges on the assumption that the beam power is deposited in the ion channel classically. Only a few experiments have tested the assumption of classical coupling between species. Beam ion spectra measured by charge exchange agreed with spectra computed from classical theory [2, 3], although discrepancies of a factor of two were observed in the fits. A higher impurity temperature than hydrogen temperature in low density, beam heated PLT plasmas was explained by using classical coupling arguments [4]. Measurements of the time evolution of the 15 MeV proton emission indicated that 0.8 MeV ^3He ions [5] and fast wave heated ^3He minority ions [6] slowed down at roughly the expected rate. On T-10, the time evolution and magnitude of the drop in ion temperature during electron cyclotron heating was consistent with the expected reduction in power flow from the electrons [7]. Although each of these experiments was consistent with classical theory, their accuracy was such that deviations as large as 50%, or more, from theory may have escaped detection.

Perhaps the best quantitative check of beam energy loss is from studies of the rate of decay of the neutron emission following deuterium beam injection [8, 9]. This emission comes from the $d(d,n)\,^3He$ reaction between the fast ions and the plasma deuterons. Since the neutron measurement is volume averaged, ±10% uncertainties in the profiles of electron temperature and density have a relatively small effect on the expected rate of decay; hence, the interpretation of the measurements is straightforward. The major weakness of the previous studies [8, 9] is that the decay in neutron emission was measured immediately after beam injection, when the classical slowing-down time τ_s [10] was rapidly changing due to changes in T_e and n_e. In a preliminary study, Kim et al. attempted to improve the accuracy of the neutron technique by injecting short beam pulses into the D-III tokamak [11].

In our experiment, we have studied the deceleration of beam ions by measuring the decay in neutron

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emission following the injection of ~2 ms pulses of deuterium beams into steady state deuterium plasmas in the D III-D tokamak. The total energy injected during the beam pulse was only ~3% of the plasma stored energy, and, hence, density and temperature of the discharge were not perturbed (T_e changed by <5%), and the slowing-down time could be studied under constant conditions. In previous work [8, 9], the velocity distribution before deceleration was the steady state fast ion distribution established during beam injection. Our experiment was characterized by the important simplification that the beam pulse length was much shorter than the slowing-down time. Thus, the fast ion velocity distribution at the end of the beam pulse essentially consisted of ions with a discrete spectrum of velocities corresponding to the original spectrum of fast neutrals at E_b, $E_b/2$, and $E_b/3$ injected by the beam. Since the cross-section for the $d(d,n)^3He$ reaction is a steeply increasing function of energy [12], the contribution of half and one-third energy ions to the neutron emission rates was relatively small; so the slowing-down of an essentially monoenergetic population of fast ions could be observed, giving a more precise comparison with theory. The previous studies [8, 9] found that the decay of the neutron emission is consistent with classical predictions to within a factor of two. We find that the decay in emission agrees with classical theory to within 30%.

A deuterium probe beam was injected into steady state divertor plasmas with T_e = 0.6-2.2 keV and $\bar{n}_e = (1\text{-}12) \times 10^{13}\ \mathrm{cm}^{-3}$. The central ($r/a \approx 0.3$) electron temperature was measured by absolutely calibrated Thomson scattering [13] and electron cyclotron emission [14] diagnostics with an accuracy of ~20%. Within experimental uncertainties, no systematic discrepancies between the two temperature diagnostics were observed. The line averaged electron density was measured by a CO_2 interferometer. The profiles of electron density and temperature were measured by Thomson scattering. Many of the plasmas were heated by hydrogen beams ($P_b \lesssim 10$ MW), and the highest densities were obtained in H-mode [15] plasmas. With the exception of the lowest temperature plasmas, the discharges had sawteeth. Most of the data were obtained at $B_t = 2.1$ T and the plasma current varied from $I_p = 0.5$ to 2.0 MA. Impurity levels were generally modest ($Z_{eff} \lesssim 2$). The typical hydrogen concentration ($n_h/n_d \cong 30\%$) was estimated from the ratio of H_α to D_α emission.

The probe beam injected 1.7 MW of 74 keV deuterium neutrals at either an angle of 47° with respect to the plasma current at the magnetic axis or at 63° (Fig. 2 of Ref. [16]). The beam current rose in ~0.1 ms and fell in 0.01 ms. Typically, the probe beam injected 33% full-energy neutrals (power fraction), 35% half-energy neutrals, and 32% one-third-energy neutrals (as determined by in situ Doppler shift spectroscopy). The time evolution of the neutron emission was measured by using uncollimated plastic and ZnS (^{6}Li) scintillators with a temporal resolution of < 0.1 ms [8, 17].

The effect of a short neutral beam pulse on the neutron emission is shown in Fig. 1. The neutron rate I_n rises linearly until the end of the beam pulse, and then decays approximately exponentially for several e-foldings with a time constant τ_n. The neutron emission associated with the probe beam is due to beam-plasma interactions. Since the beam velocity ($v_b \cong 2.7 \times 10^8\ \mathrm{cm\cdot s^{-1}}$) is large compared to the ion thermal velocity ($v_{th} \cong 4 \times 10^7\ \mathrm{cm\cdot s^{-1}}$) and plasma rotation ($v_{rot} \lesssim 5 \times 10^6\ \mathrm{cm\cdot s^{-1}}$), the fusion reactivity essentially depends on the velocity of the beam ions alone. As the beam ions slow down, the fusion reactivity decreases and the neutron emission falls. For the high density H-mode plasmas, thermonuclear reactions were comparable in magnitude to the beam-target reactions. (In low density plasmas, the beam-target emission was one to two orders of magnitude larger than the thermonuclear emission.) Nevertheless, except in a few cases where a sawtooth caused a large reduction in thermonuclear emission during the decay of the beam-target emission, accurate measurements of τ_n were still possible. In these high density discharges, τ_n (~4 ms) was much shorter than the sawtooth period (~15 ms).

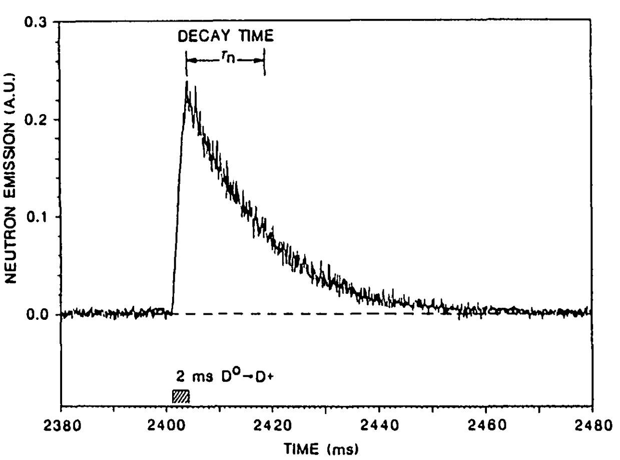

FIG. 1. Response of neutron emission to a 2 ms pulse of deuterium neutral beams injected into a deuterium plasma with central $T_e \approx 0.8$ keV and $\bar{n}_e = 1.2 \times 10^{13}\ \mathrm{cm}^{-3}$. The emission decays approximately exponentially with the time constant τ_n.

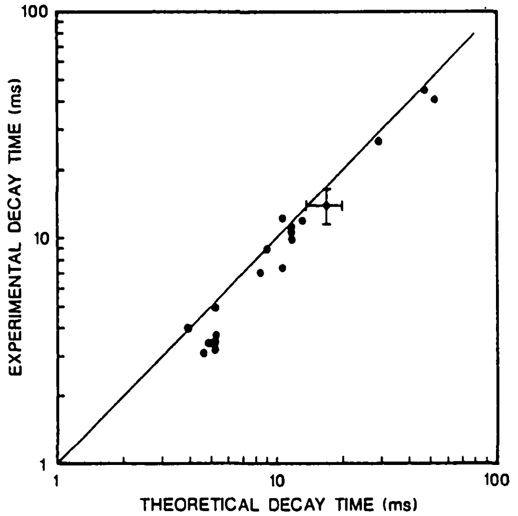

FIG. 2. Experimentally measured decay time τ_n versus prediction of classical theory. The theory is uncertain to 30%, because of uncertainties in hydrogen concentration, beam deposition and electron density and temperature. The experiment is accurate to 10% except for $\tau_n < 6$ ms, where the errors are larger. The datum with the error bar is the average of several nominally identical discharges. The line indicates agreement of experiment and theory.

The observed decay times agree with classical theory (Fig. 2). To obtain the theoretical prediction, the neutron emission produced by decelerating, monoenergetic beam ions was calculated numerically. The code employed analytic fits to the measured temperature and density profiles and an analytic fit to the fusion cross-section of the form [12]

$$\sigma = \frac{A_2/[(A_4 - A_3E)^2 + 1]}{E[\exp(A_1/\sqrt{E}) - 1]}$$

Deceleration of the beam ions was computed by using Sivukhin's formula for $\langle dW/dt \rangle$ [18] including three ion species (hydrogen, deuterium, carbon). Inclusion of hydrogen ($n_h/n_d = 30\%$) decreases τ_n by approximately 10%, which improves the agreement with experiment. Stix's asymptotic expansion of Sivukhin's formula [19] yields similar results for τ_n. The expression given by Strachan et al. [8]

$$\tau_n \approx \frac{\tau_{se}}{3} \ln \left(\frac{E_b^{1.5} + E_{crit}^{1.5}}{E_n^{1.5} + E_{crit}^{1.5}} \right) \qquad (1)$$

also gives similar results for $E_{crit} = 24T_e$. (In Eq. (1), τ_{se} is the slowing-down time on electrons and E_n is the energy at which the fusion reactivity has fallen to e^{-1} of its value at E_b.) The ~27% contribution of half-energy ions to the neutron emission was included in the calculation. Since a 36 keV ion decelerates ~2.4 times faster than a 72 keV ion, inclusion of half-energy ions reduces τ_n by approximately 16%. The code neglects energy diffusion (test particle approximation). To estimate the accuracy of this approximation, we use the Green's function solution for the beam distribution function given by Goldston [3] and approximate the fusion cross-section by the Gamow form [$\sigma \propto \exp(-A/v)$]. We find that energy diffusion increases the neutron emission by a factor

$$\frac{I_n^{\text{diffusion}}}{I_n^{\text{monoenergetic}}} \sim \exp(-2A^2\gamma t/v^4) \qquad (2)$$

where v is the mean velocity of the beam ions at time t and γ is the energy diffusion term given in Ref. [3]. Evaluating Eq. 2 at $t = \tau_n$, we find that the test particle approximation results in a ~10% underestimate of τ_n. A sensitivity analysis indicates that uncertainty in the beam deposition profile (which was not measured in these plasmas) and other profile uncertainties yield ~15% uncertainty in the theoretical prediction. The weak dependence of τ_n on profile effects is confirmed by the observation that a moderate amplitude ($\Delta T_e/T_e \approx 10\%$) sawtooth caused an imperceptible (<5%) change in the decay of I_n in plasmas where the thermonuclear emission was negligible. Uncertainty in the electron temperature measurement accounts for the largest uncertainty (~ 20%) in the prediction. Uncertainty in the hydrogen concentration contributes an additional 10% uncertainty in the theory. Except at the shortest decay times where the beam pulse duration is no longer short compared to τ_n, the experimental measurements of τ_n are accurate to better than 10%. For variations in τ_n of over a decade, the data are consistent with theory. Averaged over the data, the ratio of measured decay time to computed decay time is $\tau_n^{\text{experiment}}/\tau_n^{\text{theory}} = 0.85 \pm 0.15$. Although electron drag dominates in all cases ($E_b > E_{crit}$), both ion and electron drag must be included in the theoretical prediction to obtain an excellent fit to the data.

The dependence of τ_n on the injection angle was studied by injecting pulses from two beam sources with different orientations into the same plasma 200 ms apart. On a subsequent discharge, the timing of the pulses was reversed. It was found that for

$\bar{n}_e = 1.2 \times 10^{13}$ cm^{-3} and $\bar{n}_e = (2\text{–}3) \times 10^{13}$ cm^{-3} (interferometer data were unavailable for the second discharge), the time evolution of the emission is virtually identical for the two orientations. Calculations of the source rate of full-energy ions with the ONETWO code [20] predict that, at $\bar{n}_e = 1.2 \times 10^{13}$ cm^{-3}, the deposition profiles for both beam orientations should peak very strongly near the magnetic axis (FWHM ≈ 0.15 r/a). If the calculated profiles are used, the predicted difference in τ_n for the two orientations is 5%, in good agreement with experiment.

Pulsed deuterium injection is also useful for measuring the central deuterium density. The beam-plasma reaction rate is given by

$$I_n = \int n_b n_d \langle \sigma v \rangle \, d\vec{r} \qquad (3)$$

where n_b and n_d are the beam and deuterium densities, respectively, and $\langle \sigma v \rangle$ is the fusion reactivity averaged over the distribution functions. Immediately after the beam pulse, the beam ions have scarcely decelerated so that

$$\Delta I_n \approx \sigma v \int n_b n_d \, d\vec{r} \qquad (4)$$

The reactivity σv is evaluated at $v = v_{inj} + c_1 v_{th} - c_2 v_{rot}$, where c_1 and c_2 are constants of O(1). Since the injection velocity of full-energy ions v_{inj} is known accurately and is much larger than v_{th} and v_{rot}, σv can be evaluated accurately. The number of full-energy beam ions N_b is known accurately from calibration of the beam power. Defining a central deuterium density $\hat{n}_d$ as the average value of n_d at the radius of the beam ions, $\hat{n}_d \equiv \int n_b n_d \, d\vec{r} / \int n_b \, d\vec{r}$, Eq. (4) yields

$$\hat{n}_d \approx \frac{\Delta I_n}{N_b \sigma v} \qquad (5)$$

Equation (5) implies that the accuracy of the deuterium density measurement is limited principally by the accuracy of the absolute calibration of the neutron emission. In our experiments, the absolute calibration of I_n is only known to within a factor of two; hence, determination of the absolute magnitude of $\hat{n}_d$ is poor. Nevertheless, determination of relative changes in $\hat{n}_d$ can easily be made with an accuracy of 10%. To date, we have performed two initial studies to test the validity of this technique. In one study, we switched working gases from deuterium to hydrogen in ohmically heated plasmas. After ~8 hydrogen discharges, the measured deuterium concentration $\hat{n}_d/\bar{n}_e$ fell to 57 ± 11% of its previous level, consistent with spectroscopic measurements of the H_α and D_α emissions. In a second experiment, the dependence of $\hat{n}_d/\bar{n}_e$ on the plasma current I_p in $H^0 \rightarrow D^+$, H-mode plasmas was studied. The inferred deuterium density $\hat{n}_d$ scaled linearly with electron density for $\bar{n}_e = (3\text{–}12) \times 10^{13}$ cm^{-3}. In these plasmas, Z_{eff} was sufficiently low ($Z_{eff} < 2$, with carbon and nickel being the dominant impurities [21]) that fuelling by hydrogen gas from the beamlines was primarily responsible for dilution of n_d/n_e and so a linear dependence of $\hat{n}_d$ on $\bar{n}_e$ is not unexpected. In the light of the uncertainty in the neutron calibration, the absolute magnitude of $\hat{n}_d$ (4×10^{13} cm^{-3} for $\bar{n}_e = 9.0 \times 10^{13}$ cm^{-3}) was also reasonable.

In conclusion, the use of short deuterium beam pulses has permitted accurate measurements of beam slowing-down time in Ohmic and beam heated D III-D plasmas. Accurate relative measurements of the central deuterium density have also been made. The slowing-down time agrees with classical theory to within 30%.

ACKNOWLEDGEMENTS

The authors thank John Evans of Lawrence Livermore National Laboratory for constructing the neutron detector, R.J. Goldston of Princeton Plasma Physics Laboratory for a helpful suggestion, and the D III-D operations and physics groups for their support. The measurements of electron temperature and density were made by T. Carlstrom, J.C. DeBoo, P. Gohil, C.L. Hsieh, John Lohr, R. Snider and R.E. Stockdale and the absolute magnitude of the neutron emission was measured by T. Osborne.

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(Manuscript received 28 March 1988
Final manuscript received 11 July 1988)

ALTERATION OF THE DIVERTOR STRUCTURE IN A STELLARATOR THROUGH EXTERNALLY APPLIED MAGNETIC FIELDS

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ABSTRACT. The magnetic divertor structure in a modular stellarator has been predicted to change with the addition of an external vertical magnetic field. The diverted flux is expected to emerge predominantly on the inside of the torus when a vertical magnetic field which shifts the magnetic surfaces towards the inside is applied, and vice versa. The prediction has been verified using probe arrays located in the divertor regions. In addition to the redistribution of diverted particle flux, the distance a field line travels from the separatrix until it reaches the wall has been predicted to increase for each of the magnetically altered cases. The formation of magnetic island chains beyond the separatrix has been found to be responsible for the increase.

1. INTRODUCTION

Magnetic divertors have been employed in many devices to control impurity reflux and improve plasma parameters [1–4]. Unfortunately, the diverted plasma flows may intersect such necessary obstructions as diagnostics and antennas before reaching an area where it is feasible to collect the diverted plasma, which results in enhanced impurity generation close to the central plasma. This can present a significant problem in stellarators where a naturally occurring divertor structure often distributes particle fluxes over a large portion of the device [5]. The work reported here shows that in a stellarator geometry the addition of a small vertical magnetic field can dramatically alter the locations of plasma flow out of the coil volume. This letter discusses the predicted changes in the divertor structure which occur as a result of the application of various external magnetic fields to the Interchangeable Module Stellarator (IMS) [6], and experimental evidence confirming the alterations to the divertor structure.