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**Neutron Time Behavior for Deuterium
Neutral Beam Injection into a Hydrogen
Plasma in ORMAK**

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NEUTRON TIME BEHAVIOR FOR DEUTERIUM NEUTRAL BEAM
INJECTION INTO A HYDROGEN PLASMA IN ORMAK*

ABSTRACT

Neutrons were produced by D-D interactions when a 28-keV deuterium beam was coinjected into a hydrogen plasma in the Oak Ridge Tokamak (ORMAK). Fokker-Planck calculations, which correctly predict the time behavior of the neutron rate after beam turnon, show that the majority of the neutrons are from injected particles interacting with previously injected deuterons that have scattered to pitch angles of $\sim 60-90^\circ$ while slowing down.

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1. INTRODUCTION

A deuterium beam injected into a hydrogen plasma gives rise to neutrons as a result of nuclear reactions with deuterium already in the plasma. The possible sources of deuterium in the plasma are (1) gas streaming from the injectors, (2) deuterium accumulated on the liner which comes off from particle bombardment earlier in the discharge, (3) injected beam particles which are scattered while slowing down [1], and (4) injected beam particles which have slowed down and are in thermal equilibrium with the plasma.

Early in 1975, measurements were made of the time evolution of neutrons produced by D-D interactions when a 28-keV deuterium beam was injected into a hydrogen plasma in the Oak Ridge Tokamak (ORMAK). The time dependence of the neutron production is compared with the results of Fokker-Planck slowing-down calculations. The comparison shows that the largest source of neutrons is due to the interaction of injected particles with deuterons that have scattered through large angles while slowing down. Comparison of absolute neutron yields with theory was not possible because the neutron detection system was not calibrated at the time of the experiment.

2. THEORY

The initial time behavior of the neutron production rate due to beam-beam and beam-plasma D-D fusion reactions has been estimated at the plasma center by solving a time-dependent Fokker-Planck equation which describes the evolution of the fast ion distribution function in velocity space. Slowing down and pitch angle scattering of the ions in velocity space are included, as are the secondary effects of the toroidal electric field and energy diffusion. Loss region effects due to trapped fast ions hitting the wall are included in an approximate manner; otherwise, radial transport of fast ions during slowing down is not considered. A full discussion of the treatment of the Fokker-Planck equation has been given by Rome et al. [2]; the computer code used has been described extensively by Fowler et al. [3].

2.1 REACTION RATES

The general form for the reaction rate between two ion populations described by velocity distribution $f_1(\vec{v}_1)$ and $f_2(\vec{v}_2)$ is

$$R = \gamma \iint \tilde{v}_\sigma(v) f_1(\vec{v}_1) f_2(\vec{v}_2) d^3v_1 d^3v_2 \quad (1)$$

where $v = |\vec{v}_1 - \vec{v}_2|$ and $\gamma = 1/2$ if $f_1 = f_2$, $\gamma = 1$ if $f_1 \neq f_2$. Two cases are considered here: (1) a fast ion population interacting with a slow thermal plasma (beam-plasma interactions) and (2) a fast ion population interacting with itself (beam-beam interactions).

For beam-plasma interactions, $f_1(\vec{v}_1) = f_b(\vec{v}_1)$, where f_b is the slowing-down beam distribution function, and $f_2(\vec{v}_2) = f_2(\vec{v}_2)$, where

$f_i(\vec{v}_2)$ is the thermal Maxwellian at temperature T_i . Because most interactions occur when the beam particles are near the injection energy (E_b) and $E_b \gg KT_i$, we let $v = |\vec{v}_1|$ in Eq. (1) and obtain

$$R_{BP} = n_i \int v \sigma_{DD}(v) f_b(\vec{v}) d^3v \quad (2)$$

which is, in general, a simple threefold integral over the fast ion distribution function. Because $f_b(\vec{v})$ is symmetric about the magnetic field, this reduces to

$$R_{BP} = 2\pi n_i \int_0^\infty dv v^3 \sigma_{DD}(v) \int_0^\pi d\theta \sin \theta f_b(v, \theta) \quad (3)$$

where θ is the pitch angle.

For beam-beam interactions, $f_1(\vec{v}) = f_2(\vec{v}) = f_b(\vec{v})$, and Eq. (1) is, in general, a sixfold integral over the fast ion distribution function. The symmetry about the magnetic field reduces this to a fivefold integral, which is

$$\begin{aligned} R_{BB} = 2\pi \int_0^\infty dv_1 v_1^2 \int_0^\infty dv_2 v_2^2 \int_0^\pi d\theta_1 \sin \theta_1 \int_0^\pi d\theta_2 \sin \theta_2 \\ \times f_b(v_1, \theta_1) f_b(v_2, \theta_2) \int_0^\pi d\phi v \sigma_{DD}(v) \end{aligned} \quad (4)$$

where $\phi = \phi_1 - \phi_2$ is the difference in azimuthal angle of the velocity vectors $\vec{v}_1$ and $\vec{v}_2$ and

$$v = [v_1^2 + v_2^2 - 2v_1v_2(\cos \theta_1 \cos \theta_2 + \cos \phi \sin \theta_1 \sin \theta_2)]^{1/2} \quad (5)$$

The fivefold integral that yields the beam-beam reaction rate was evaluated using a straightforward Monte Carlo method [4]. The cross section for the reaction $D(D,n) \text{He}^3$ used in the numerical calculations was the fit of Duane [5] and for the energy range below 100 keV is

$$\sigma_{DD}(\text{barns}) = \frac{8.81 \times 10^{-2}}{y \exp(1/\sqrt{y})} \quad y = E(\text{MeV})/2.292 \quad (6)$$

The deuterium plasma density of slowedown deuterium is estimated from a simple point model,

$$\frac{\partial n_D}{\partial t} = S_B(t) - \frac{n_D}{\tau_p} \quad (7)$$

where n_D is the deuterium density and τ_p is the particle confinement time. The source $S_B(t)$ is determined from the Fokker-Planck solution and is the rate at which fast ions cross the low velocity boundary (at $E = 2KT_i$) of the fast ion distribution into the thermal distribution. Thus,

$$n_D(t) = \exp(-t/\tau_p) \int_0^t S_B(t') \exp(t'/\tau_p) dt' \quad (8)$$

and the asymptotic (in time) value of $\dot{n}_D$ is $\dot{n}_D = \tau_p^0 S_B^0$ where, in steady state, S_B^0 is the rate of fast ion injection less the fast ions lost to

charge exchange and the loss region during slowing down. To lowest order and with no charge exchange,

$$n_D(t) = \begin{cases} 0 & t < \tau_f \\ \tau_p \dot{n}_f \{1 - \exp [-(t - \tau_f)/\tau_p]\} & t \geq \tau_f \end{cases} \quad (9)$$

where $\dot{n}_f$ is the fast ion birthrate and τ_f is the time for a fast ion to thermalize. Thus, no beam-plasma interactions should be observed until a time τ_f after beam turnon.

2.2 ORIGIN OF BEAM-BEAM NEUTRONS

Most of the beam-beam neutrons result from the motion of the fast deuterium perpendicular to the magnetic field. The steady-state fast ion distribution function (solution of the Fokker-Planck equation) is shown in Fig. 1 as a contour plot in $v_{\parallel}$, $v_{\perp}$ space. The entire function is a figure of revolution about the $v_{\parallel}$ axis. Because of the steep increase of the D-D fusion cross section with energy, beam-beam neutrons arise from interactions between particles with large separations in $v_{\parallel}$, $v_{\perp}$ space, i.e., particles with large center-of-mass energy. There are two groups of such particles: previously injected ions which have scattered in pitch angle until they are counterstreaming (large $v_{\parallel}$ separation) and ions which have pitch angle scattered to large pitch angles (large $v_{\perp}$ separation).

Ions which scatter through large pitch angles to become counterstreaming must pass through the trapped particle region in velocity space. Due to the large radial excursion of trapped fast ion orbits, most of these particles are lost to the wall before being pitch angle

scattered to large counterstreaming velocities. The fast ion distribution function (Fig. 1) is depleted for pitch angles greater than 90° due to the loss region, and very few of the fusion neutrons in this experiment are due to counterstreaming ions.

The importance of perpendicular motion for producing neutrons is demonstrated by calculation of the neutron rate as a function of pitch angle. In Eq. (5), the upper limit for the pitch angles θ_1 and θ_2 is set equal to θ_u , and the reaction rate as a function of θ_u is shown in Fig. 2. About 90% of the neutrons come from the range $50^\circ \leq \theta_u \leq 100^\circ$. Most of the neutrons are due to ions in this pitch angle range interacting with ions which have just been injected, and this interaction is primarily due to perpendicular motion.

3. EXPERIMENT

The experiment was performed first with one and then with two injectors with an equivalent current of about 4 A of deuterium each. In order to obtain discharges with the same electron density and electron temperature in the discharges with one injector, the amount of gas streaming from the unused injector was the same as for the discharges with two injectors. The experimental results are taken from 14 discharges with two injectors and 8 with one injector. The average parameters of these discharges are given in Table I. The comparison of line averaged electron densities for two plasma discharges out of this series, given in Fig. 3, shows that the electron densities for one- and two-injector cases were very similar.

The neutrons from this experiment were monitored with three moderated ^3He proportional counters placed around the machine and far enough away so that dead time effects were less than 10% for the highest count rates. The counters were approximately 120° apart to average out the attenuation of various machine parts. The data obtained in these measurements are shown in Fig. 4. The following observations can be made:

(1) With two coinjected beams (7.8 A total), the equilibrium production rate is 3.5 times the rate with one coinjected beam (4.0 A). Because the beam current is producing its own target, the neutron production should be proportional to I^2 ; in these experiments it scaled within 10% of this. This indicates that the neutrons result from the interaction of instantaneous injected beams with previously injected beam particles.

(2) The counting rate was independent of shot number. This indicates that deuterium deposition on or reflux from the liner was not changing from shot to shot.

(3) The saturation rate (count rate after 35 msec) increases slowly with time. This may be due to the beam interacting with a previously injected beam which is in thermal equilibrium with the plasma (this would indicate short particle confinement time) or to deuterium from the liner which has accumulated on previous plasma discharges.

(4) There is a delay of ~ 5 msec between the beam turnon, defined as the time when the current in the injector power supply reaches 80%, and the appearance of neutrons. In this experiment, the beam current achieved 80% of its steady-state value at 10 msec with a rise time of ~ 5 msec, while the neutron production rate did not appear until 15 msec after plasma initiation. (Because parallel charge-exchange analysis was not available to ascertain exactly when the injected beam particles entered the plasma, the uncertainty in this time could be as much as ~ 3 msec.) The delay in the rise of the neutron production corresponds approximately to the time necessary for a deuterium beam particle to pitch angle scatter approximately perpendicular to the magnetic field.

4. COMPARISON OF THEORY WITH EXPERIMENT

The time dependence of the neutron production rate for the case of two injectors was calculated using the fast ion velocity distribution obtained from the Fokker-Planck slowing-down theory, as described in Section 2. The plasma parameters used as input were obtained from measurements by other diagnostics of ORMAK during these experiments (Table I). The calculations considered three mechanisms for neutron production in the experiment: (1) beam-beam neutrons, (2) beam-plasma neutrons due to plasma deuterons present before injection, and (3) beam-plasma neutrons due to slowed down injected deuterium.

The calculated initial turnon transient of the neutron rate from each of the mechanisms is shown in Fig. 5. The calculated and experimental values have been normalized to a reaction rate value of 2.4×10^6 neutrons/cm³/sec at the equilibrium level, and the time scale for the calculation has been shifted by the ~ 3 msec associated with the uncertainty in beam turnon.

The deuterium for case (2) is assumed to be present in the ratio $n_D/n_e = 0.05$. For case (3), the neutron rate is shown for deuterium confinement times [defined in Eq. (7)] of 10 msec and 200 msec. The experimental transient is reproduced best by the calculated beam-beam neutrons. The calculated beam-plasma neutron transient due to deuterium in the plasma before injection is faster than the observed transient (steeper slope and opposite initial curvature), and the calculated buildup of deuterium in the background due to the beam is slower than that actually observed.

5. CONCLUSIONS

The agreement of the measured time dependence with that calculated assuming only beam-beam interactions indicates that in the experiment almost all the neutrons are produced from beam interaction with previously injected beam particles which have not slowed down in energy. Furthermore, the calculations show that most of the neutron production is from beam interaction with previously injected beam particles which have scattered to pitch angles of $60-90^\circ$ while slowing down. Saturation levels varying as beam current squared indicate that the beam is producing its own target. The delay of 5 msec in the rise of the neutron production rate and the shape of initial rise of the neutron level indicate that the neutron production from beam interaction with thermal deuterium already in the plasma is small.

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TABLE I. PLASMA CHARACTERISTICS

I_p	110 kA
V	3 V
B_T	18 kG
$n_e(0)$	3×10^{13}
$T_e(0)$	950 eV
$T_i(0)$	260 eV
Z_{eff}	~ 5
Injection	2 coinjectors

FIGURE CAPTIONS

- FIG. 1. Steady-state fast ion distribution.
- FIG. 2. Reaction rate as a function of pitch angle.
- FIG. 3. Typical electron density as a function of time for discharges with one and two injectors.
- FIG. 4. Neutron counts vs time for deuterium coinjected into a hydrogen plasma in ORMAK.
- FIG. 5. Comparison of calculated and measured neutron count rates as a function of time.

Fig. 1

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Fig. 2

Fig. 3

Fig. 4

Fig. 5

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