THERMONUCLEAR NEUTRON PRODUCTION
IN ALCATOR DEUTERIUM PLASMAS

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ABSTRACT

Rates of thermonuclear neutron emission of up to $7 \times 10^{10}$ neutrons/sec have been observed in Alcator deuterium plasmas. It is found that contributions to the total neutron emission due to nonthermonuclear processes are not significant in the very high density ($n_e > 10^{14}$ cm$^{-3}$) regimes normally encountered in Alcator operation. For deuterium plasmas we present ion temperature by neutron emission over the range in plasma parameters: $1.0 \times 10^{14}$ cm$^{-3} \leq \bar{n}_e \leq 5.5 \times 10^{14}$ cm$^{-3}$, $110$ kA $\leq I_p \leq 220$ kA, $40$ kG $\leq B_t \leq 75$ kG, where $\bar{n}_e$ is the line averaged electron density, $I_p$ is the plasma current, and $B_t$ is the toroidal magnetic field. At the highest densities ($\bar{n}_e > 4 \times 10^{14}$ cm$^{-3}$) the ion temperature scaling results are found to be consistent with neoclassical predictions for a regime whose dominant role in confinement is attributed to ion thermal conduction.
1. INTRODUCTION

Neutron measurements in tokamaks can provide direct verification for the existence of plasmas having thermonuclear parameters. In addition, neutron measurements can enable the determination of ion temperatures, a feature of particular importance at high plasma densities where the measurement of ion temperature by the energy analysis of charge-exchanged neutrals has limitations.

Historically, however, these measurements have been viewed with skepticism mainly in that: 1) the neutron emission is strongly influenced by the tail of the ion energy distribution; 2) the neutron emission may be due to nonthermonuclear processes; and 3) there could be large error in the measured neutron rates due to difficulties in the calibration of the detectors.

In this paper, measurements of neutron emission from plasmas produced in the Alcator device are presented. The methods of calibration of the neutron counting and energy diagnostics used in the experiments are described. Evidence which indicates that the neutron emission from Alcator has thermonuclear origins is discussed. Finally, ion temperature scaling results in the high density regime of Alcator are given.

2. EXPERIMENTAL DESCRIPTION

The Alcator device provides a high field, high current-density, high plasma density, \( Z_{\text{eff}} = 1 \) tokamak plasma [1]. Toroidal magnetic
fields up to 85 kG, plasma current densities up to 3 kA/cm$^2$, and peak electron densities up to $1.5 \times 10^{15}$ cm$^{-3}$ have been achieved.

Shown in Fig. 1 is a cutaway of Alcator. The system is completely surrounded by a liquid nitrogen cryostat. The Bitter magnet winding, which provides the high magnetic field capability almost completely surrounds the toroidal vacuum vessel, thus restricting diagnostic access to the plasma volume. It will be shown below that this dense machine structure not only attenuates the neutron flux reaching the detectors, but also changes the neutron energy distribution. The effect on the neutron energy distribution, however, does not cause difficulty with the neutron emission measurements since standard BF$_3$ long counters are used, i.e., the measured neutron rates are relatively insensitive to the neutron energy[2]. The upper long counter shown in Fig. 1 is placed symmetrically above the torus and is used primarily for the ion temperature determinations. The lower long counters are placed on the equatorial plane of the torus, one next to the molybdenum limiter and one located 180° away in the toroidal direction. These two detectors are used for the neutron flux isotropy measurements. Behind the diagnostic port which is located 180° away from the limiter is a proton-recoil fast neutron spectrometer which is used for the neutron energy measurements. The spectrometer system consists of an NE-213 scintillator, phototube and electronics.

3. LONG COUNTER CALIBRATIONS

Absolute calibration of the upper long counter was accomplished by insertion of either a Cf$^{252}$ or PuBe neutron source into the vacuum vessel. The intensities of the two sources were known to within a few
percent. These two sources were chosen in order to eliminate errors in the calibration due to any energy dependence of neutron scattering in the machine structure. The energy spectrum of the two sources as compared to the very narrow 2.45 meV spectrum expected from D-D fusion neutrons is shown in Fig. 2. The calibrations using the two sources were performed and agreement between them was found to be within 12%. Thus significant error in the calibration due to the nonideal energy distributions of the neutron sources was eliminated. From these measurements it was also found that the neutron flux emanating from within the torus was attenuated by about a factor of 2/3. This result was in reasonable agreement with the expected attenuation due to the one or two mean free paths of copper in the Bitter magnet winding.

4. METHOD OF ION TEMPERATURE DETERMINATION

Using the result that \( n_i = n_e \) (since \( Z_{\text{eff}} = 1 \)) and under the assumption that the profiles of ion temperature were identical to the corresponding measured profiles of electron temperature, a rate of thermonuclear neutron emission was calculated with the central ion temperature as a free parameter. Then by comparing the calculated neutron emission with that experimentally observed, the central ion temperature was deduced. This calculation assumes that the measured neutron emission was thermonuclear in origin, an assumption that is justified in the following.

5. RESULTS

5.1. Potential nonthermonuclear contributions to the total neutron emission

It has been reported elsewhere that photonuclear neutron production can contribute heavily to the total neutron emission [3-5]. In those devices
photonuclear rates, up to $10^{13}$ n/sec, have been observed which can exceed the expected thermonuclear rates for ohmically heated discharges. These photonuclear neutrons can be produced if a significant amount of high energy electrons collide with the plasma limiter (usually tungsten or molybdenum). Generally, characteristics which indicate the presence of photonuclear neutrons are: 1. The neutron production is independent of filling gas; 2. a strong correlation exists between the neutron and hard x-ray emissions; 3. the neutron flux is anisotropic, i.e., the emission is localized at the plasma limiter [3-5].

Evidence which indicates that the neutron emission does not have photonuclear origins in the high density regimes normally encountered in Alcator operations are as follows:

1. Comparison of neutron emission in deuterium and hydrogen discharges. Shown in Fig. 3 are two typical Alcator discharges (i.e., $I_p = 150$ kA, $n_e = 3 \times 10^{14}$ cm$^{-3}$, $B_t = 60$ kG). The upper photograph shows the time behavior of the loop voltage, plasma current, line averaged electron density and neutron emission for the deuterium discharge. A neutron rate of about $10^9$ n/sec is observed at the density maximum during the shot. In contrast to this behavior is the neutron emission for the hydrogen discharge shown in the bottom trace of the lower photograph. Only a few neutron events are registered by the detector at the very end of the discharge. Their presence is attributed to some recycled deuterium still present in the system from previous deuterium discharges.

2. Time behavior of neutron emission and hard x-ray emission. In Fig. 4 we show another high density deuterium discharge. As can
be seen in this photograph there is no correlation between the forward hard x-ray emission and the neutron emission, thus adding further evidence for the lack of photonuclear neutron production.

3. Neutron flux isotropy. As shown in Fig. 1, two long counters were placed on the equatorial plane of the torus in order to check if the neutron flux was localized at the plasma limiter. Shown in Fig. 5 are some of the characteristics of another high density deuterium discharge. In the lower photograph we see the outputs of the two long counters, on an expanded time scale, at the density maximum during the discharge. To within statistical accuracy the rates measured from the detectors are equal, thus indicating the isotropic nature of the neutron emission.

5.2. Energy measurements

Since neutrons produced by D-D fusion reactions should have a narrow energy bandwidth (less than 100 keV spread for $T_1 = 1$ keV) centered about 2.45 meV, a fast neutron spectrometer having a modest energy resolution of about 20% could provide useful information regarding neutron origins. The choice of spectrometer was dictated not only by its energy resolution but also by its efficiency for neutron detection, due to the modest rates of neutron emission normally encountered (the maximum rates observed to date are in the range $10^{10} - 10^{11}$ n/sec). In addition, since the efficiency for detection of hard x-rays is usually quite high for these detectors a means of x-ray discrimination was also a necessary consideration.

As mentioned in Section 2, proton-recoil fast neutron spectrometer which consisted of an NE-213 scintillator, photomultiplier
tube (RCA 8575) and associated electronics was used for these measurements. This system was chosen since it satisfied the above requirements for energy resolution, neutron efficiency and neutron-hard x-ray discrimination capabilities.

1) Spectrometer calibration. In order to calibrate the system, spectra were obtained from the 2.45 meV (14 meV) neutrons produced from deuterons accelerated onto a deuterium (tritium) target. To improve the calibration a section of Bitter magnet was placed around the accelerator target thus somewhat simulating the Alcator environment. Additional calibration information was provided by obtaining spectra from a Na$^{22}$ gamma source. The neutron pulse height data were unfolded using the NUTSPEC computer code.

2) Spectrometer results. Shown in Fig. 6a is the unfolded accelerator D-D fusion neutron calibration spectrum. A reduction of the neutron energies by approximately 250 keV resulted due to the presence of the Bitter winding. In Fig. 6b, spectra obtained during actual Alcator deuterium operation are shown. Comparisons of the tokamak neutron energy spectrum with the calibration spectrum suggest the presence of the 2.45 meV neutron component. The count rates obtained thus far are insufficient for a more quantitative check.

5.3. Temperature correlations
As a check on the validity of the assumption that the neutrons measured were of thermonuclear origin, a comparison was made between the neutron ion temperature and charge-exchange ion temperature in the density range $1.0 \times 10^{14}$ cm$^{-3} \leq n_e \leq 3 \times 10^{14}$ cm$^{-3}$ [7]. Also since good equilibration between electrons and ions was expected for $n_e \geq 3 \times 10^{14}$ cm$^{-3}$ a comparison between the neutron ion temperature
and Thomson scattering electron temperature was made. The experimental results shown in Fig. 7 indicate that good agreement was found between the neutron ion temperature and charge-exchange ion temperature at intermediate densities. Also, at high densities, good agreement was found between the neutron ion temperature and the electron temperature from Thomson scattering.

5.4. Ion temperature scalings in the high density regime

Previously, ion temperature scalings have been performed in the Alcator low density regime (i.e., for $n_e < 10^{14}$ cm$^{-3}$)[8]. It was reported that the ion temperature increased linearly with increasing density (for fixed toroidal magnetic field and plasma current) over the density range $2 - 9 \times 10^{13}$ cm$^{-3}$. It was also reported that the plasma current and toroidal magnetic field had only a weak effect on the ion temperature in this low density regime. The above mentioned increase in ion temperature with increasing density is consistent with that expected due to the increase in electron-ion coupling. As an extension of the above results, ion temperature scalings are presented below for the Alcator high density regime (i.e., for $n_e > 10^{14}$ cm$^{-3}$).

1) Density effect on the central ion temperature. Referring to Fig. 8 we see the effect on the central ion temperature due to increasing plasma density for fixed toroidal magnetic field and plasma current. Two sets of data are shown, the lower data for currents of about 110 kA and the upper data for currents of about 160 kA. Both sets of data show that the ion temperature decreases with increasing plasma density. We also note from the data in Fig. 7 that the central electron temperature also decreases with increasing plasma density.
2) Plasma current effect on the central ion temperature.
Again referring to the two sets of data in Fig. 8, it can be seen that for fixed toroidal magnetic field and plasma density the ion temperature increases with increasing plasma current.

3) Toroidal magnetic field effect on the central ion temperature. Figure 9 shows the central ion temperature plotted as a function of density for four different levels of toroidal magnetic field. It can be seen from this data that for fixed plasma current and density that the central ion temperature increases with increasing toroidal magnetic field.

The above ion temperature scaling results are consistent with an energy balance view over the density range $1 - 6 \times 10^{14}$ cm$^{-3}$ as can be seen by employing arguments similar to that used in Ref. [1]. Specifically, we have for the electron and ion energy balance,

$$\frac{dW_e}{dt} + \frac{W_e}{\tau_e} = P_{OH} - \frac{W_e - W_i}{\tau_{ei}}$$  \hspace{1cm} (1)$$
and

$$\frac{dW_i}{dt} + \frac{W_i}{\tau_i} = \frac{W_e - W_i}{\tau_{ei}}$$  \hspace{1cm} (2)$$

where $W_e$ and $W_i$ are the average electron and ion thermal energy contents, $\tau_e$ and $\tau_i$ are the effective electron and ion energy containment times, $P_{OH}$ is the ohmic heating power, and $\tau_{ei}$ is the electron-ion energy relaxation time. Then letting $\tau^* = W_e/P_{OH}$ it is easy to show that

$$W_i \geq W_e \left(1 - \frac{\tau_{ei}}{\tau^*}\right)$$  \hspace{1cm} (3)$$
or since \( n_e = n_i \)

\[
T_i > T_e \left( 1 - \frac{T_{ei}}{T_i} \right) \tag{4}
\]

By solving Eq. (4) for \( n_e = 10^{14} \) cm\(^{-3} \) and for \( n_e = 5 \times 10^{14} \) cm\(^{-3} \) one finds respectively that \( T_i > 0.6 T_e \) and \( T_i > 0.9 T_e \) which is consistent with the findings i.e., for the data in Fig. 7.

For the highest density plasmas, i.e., for \( n_e \geq 4 \times 10^{14} \) cm\(^{-3} \), the total heat flux appears to be in agreement with the neo-classical ion conduction flux and thus the dominant role in confinement is attributed to ion conduction [9]. Thus, one can then obtain a qualitative idea as to the expected behavior of the central temperature by equating the ohmic power \( \eta J^2 \) to the ion heat loss \( \dot{Q}_i \) where \( \eta \) is the classical resistivity, \( J \) is the current density, and \( \dot{Q}_i \sim \kappa \nabla T_i \) [10] where \( \kappa \) is the ion thermal conductivity, and \( T_i \) is the ion temperature. For the plateau and Pfirsch-Schluter regimes, the ion thermal conductivities are respectively given as

\[
\kappa_{\text{plateau}} \sim \frac{\nu v_T}{R} \rho^2 q \sim \frac{n T_i^{3/2}}{R B^2} \tag{5}
\]

and

\[
\kappa_{\text{PfS}} \sim n \nu p^2 q^2 \sim \frac{n q^2}{T_i^{1/2} B^2} \tag{6}
\]

where \( n \) is the plasma density, \( v_T \) is the ion thermal velocity, \( \rho \) is the ion Larmor radius, \( q \) is the safety factor, \( \nu \) is the ion-ion collision frequency, and \( B \) is the toroidal magnetic field.

Equations (5) and (6) are of the form given in Ref. [11]. Thus the ion heat loss \( \dot{Q}_i \) for the two regimes can be written as
\[ Q_{i}(\text{plateau}) \sim \frac{nq}{B^2a} T_i^{5/2} \]  

and

\[ Q_{i}(\text{P.S.}) \sim \frac{2q^2}{B^2a} T_i^{1/2} \]  

Then by using $\eta \sim T_e^{-3/2}$ and $T_e \approx T_i \equiv T$ and equating the ohmic power to the ion heat loss we find (for simplification we suppress the geometrical dependencies which we assume constant)

\[ T \sim \frac{(BJ)^{1/2}}{(nq)^{1/4}} \]  

plateau regime

and

\[ T \sim \frac{(BJ)^{1}}{(nq)^{1}} \]  

Pfirsch-Schluter

Now since the diffusion coefficient for the plateau regime is only ideally independent of density \cite{12} and since the highest density operation lies in the transition region for the two regimes, it is expected that the actual scaling law would have a behavior lying somewhere between that found for the two cases, i.e., it is expected that the temperature scaling law be of the form

\[ T \sim \frac{(BJ)^{a}}{(nq)^{\beta}} \]  

where

\[ \frac{1}{2} \leq a \leq 1 \]

and

\[ \frac{1}{4} \leq \beta \leq 1 \]

The experimental evidence presented above is consistent with Eq. (11) as the data accumulated to date suggest that $a$ and $\beta$ are within the above limits. A more detailed discussion of these results will be presented in a forthcoming publication.

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REFERENCES


FIGURE CAPTIONS

1. Cutaway view of the Alcator device and relative positions of the neutron counting and energy diagnostics.

2. Neutron energy spectra of $^{252}$Cf and PuBe neutron sources as compared to the expected spectrum of D-D thermonuclear fusion neutrons.

3. a) A typical Alcator high density deuterium discharge. The neutron rate is approximately $10^9$ neutrons/sec at the density maximum. 
   b) A typical Alcator high density hydrogen discharge. No neutron events are registered at the density maximum. Each discontinuity in the density trace is the result of the interferometer phase shift reaching $2\pi$ which causes a reset in the phase measuring electronics. Therefore discontinuities should be ignored.

4. Time behavior of the neutron and hard x-ray emissions.

5. a) A typical high density Alcator deuterium discharge. 
   b) Outputs of the two isotropy long counters on an expanded time scale (2 msec/div) at the density maximum during the discharge.

6. a) D-D fusion neutron calibration energy spectrum. b) Alcator neutron energy spectrum.

7. Comparison of the neutron ion temperatures with charge exchange ion temperatures at intermediate densities and with Thomson scattering electron temperatures at higher densities.

8. Central ion temperature vs average plasma density with fixed toroidal magnetic field.

9. Central ion temperature vs average plasma density with fixed plasma current.
Figure 2
(a) Deuterium

Deuterium

\[ V_L \]
\[ I_p \]
\[ \bar{n}_e \]

Neutrons

2V/div
46 KA/div
1 \times 10^{14} \text{ cm}^{-3}/\text{fringe}
20 ms/div

(b) Hydrogen

Hydrogen

\[ V_L \]
\[ I_p \]
\[ \bar{n}_e \]
in/out
\[ Hx_\perp \]

Neutrons

2V/div
46 KA/div
10^{14} \text{ cm}^{-3}/\text{fringe}
2V/div
5V/div
20 ms/div

Figure 3
Deuterium

\[ V_L \]

\[ I_p \]

\[ \overline{n}_e \]

Neutrons

Hard X-Ray Emission

\{ Forward, Perpendicular \}

2 V/div

46 KA/div

\(10^{14} \text{ cm}^{-3}/\text{fringe}\)

20 ms/div

Figure 4
Figure 5

(a) Neutrons

(b) Long Counter
Position

- $V_L$
- $I_p$
- $\bar{n}_e$

$2V/\text{div}$
$46\text{ KA/\text{div}}$
$10^{14}\text{ cm}^{-3}/\text{fringe}$
$20\text{ ms/\text{div}}$

- $180^\circ$ from Limiter
- Limiter

$2\text{ ms/\text{div}}$
Figure 6
Deuterium
Ip = 134 KA
Bφ = 60 K Gauss

Figure 7

Temperature (keV)

\( \bar{n}_e \times 10^{14} \text{ cm}^{-3} \)
Bφ = 6T

× 148 KA < I < 175 KA
○ 111 KA < I < 129 KA

Figure 8
III KA < I < 129KA

* 75 K Gauss
□ 70 K Gauss
▲ 60 K Gauss
○ 40 K Gauss

Electron Density \( \bar{n} \left( 10^{14} \text{ cm}^{-3} \right) \)

Average Electron Density

Figure 9