MAY 1977

PPPL-1300

REDUCTION IN FUSION-NEUTRON
PRODUCTION IN
NONAXISYMMETRIC TOKAMAK DEVICES

BY

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Printed in the United States of America.

Available from
National Technical Information Service
U. S. Department of Commerce
5285 Port Royal Road
Springfield, Virginia 22151
Price: Printed Copy \$ * ; Microfiche \$3.00

<u>*Pages</u>	<u>NTIS Selling Price</u>
1-50	\$ 4.00
51-150	5.45
151-325	7.60
326-500	10.60
501-1000	13.60

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REDUCTION IN FUSION-NEUTRON PRODUCTION
IN NONAXISYMMETRIC TOKAMAK DEVICES

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ABSTRACT

In tokamak plasmas subjected to substantial toroidal-field ripple, sufficiently energetic members of the bulk-ion population can diffuse rapidly away from the hot central region by the superbanana process. The result is a truncation of the ion velocity distribution, causing a marked reduction in the fusion reactivity. This tail-depletion effect may account in part for the anomalously low central ion temperature deduced from the neutron flux emitted from dense deuterium plasmas in the Alcator device, and also may have relevance to similar observations in the beam-heated TFR plasma.

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1. INTRODUCTION

In a plasma with relatively small ion temperature, thermonuclear reactions involve mainly ions with energies far out on the tail of the ion energy distribution, $f_i(E)$. Hence a preferential loss process for very energetic ions results in a reduction in the neutron-deduced temperature. In Sections 2 and 3 of this paper we show that a significant energy-dependent loss rate is established by the large toroidal-field ripple in certain tokamak devices. Energetic ions trapped in local magnetic wells near the magnetic axis diffuse vertically at a rate sufficiently fast so that the tail of $f_i(E)$ cannot be kept filled by collisions among the bulk ions. This tail depletion leads to a significant decrease in fusion reactivity in the hot central region.

The tail-depletion process has implications for neutron and alpha-particle production in all compact tokamak devices, for which the toroidal-field ripple tends to be substantial (unless a large blanket is placed between the vacuum vessel and the toroidal-field coils). The effect becomes more serious with increasing ion temperature, inasmuch as a larger fraction of the bulk-ion population is subject to this "superbanana" diffusion.

This process may explain, at least in part, the anomalously low T_i deduced from neutron flux measurements in Alcator, the compact high-field tokamak at M.I.T. [1]. The Alcator device has a ripple of several percent in the central plasma

region. In the high-density operating regime of Alcator, the central deuterium ion temperature, T_{ic} , as deduced from neutron flux measurements, is only 0.55 to 0.70 times the central electron temperature T_{ec} , although one expects that $T_{ic} \geq 0.85 T_{ec}$, from the condition that the Ohmic power density must exceed the rate of energy transfer from electrons to ions [2]. The corresponding shortfall in neutron flux is a factor of 3 to 6. On the other hand, the value of T_{ic} deduced from charge-exchange measurements, taking into account neutral attenuation by the dense plasma, is in reasonable agreement with the calculated value [2]. The application of the tail-depletion process to Alcator is discussed in Section 4.

The same process may account in part for certain observations in the neutral-beam-heated TFR device at Fontenay-aux-Poses. Here the neutron-deduced T_i of a bulk deuterium plasma failed to increase by more than 100 eV during injection of several hundred kilowatts of hydrogen beam power, even though the T_i deduced from charge-exchange neutral measurements increased by several hundred electron-volts [3]. This discrepancy was attributed entirely to displacement of plasma deuterons by hydrogen flowing from the beam injectors, but quantitative agreement with this hypothesis is difficult to show. In TFR, the field ripple is smaller than in Alcator,

but still significant. As shown in Section 5, part of the neutron deficit can be explained by tail depletion set up by superbanana diffusion.

It should be noted that in tokamaks having negligible ripple, there has been generally good agreement between the charge-exchange and neutron determinations of T_i , with or without the use of intense beam heating [5,6].

2. DEPENDENCE OF FUSION REACTIVITY ON CUT-OFF ENERGY

In calculating the fusion reactivity $\langle \sigma v \rangle$ of a reacting plasma with Maxwellian ion velocity distributions, the usual procedure is to transform into center-of-mass coordinates [4], so that only a one-dimensional integral need be solved. In the present case we wish to terminate the integration at a certain velocity in the laboratory frame, so that the usual transformation cannot be made. Consider a deuterium plasma in which the ions form an isotropic Maxwellian velocity distribution $f_i(v)$ up to a velocity v_m , but with $f_i(v) = 0$ for $v > v_m$. Then

$$\begin{aligned} \langle \sigma v \rangle_m &= 8\pi^2 \int_0^{v_m} \int_0^{v_m} \int_0^\pi f_i(v_1) f_i(v_2) |\vec{v}| \sigma(|\vec{v}|) \\ &\quad \times v_1^2 dv_1 v_2^2 dv_2 d\theta \end{aligned} \quad (1)$$

where

$$|\vec{v}| = (v_1^2 + v_2^2 - 2v_1v_2 \cos\theta)^{1/2}$$

and

$$f_i(v_j) = \left(\frac{M_D}{2\pi T_i} \right)^{3/2} \exp \left(- \frac{M_D v_j^2}{2T_i} \right) \quad (2)$$

This triple integral has been evaluated by a 32-point Gaussian quadrature technique. Figure 1 shows $\langle \sigma v \rangle_m$ normalized to the value of $\langle \sigma v \rangle_\infty$ at $v_m = \infty$, for various T_i and cut-off energies $E_m = \frac{1}{2} M_D v_m^2$. Figure 2 shows the corresponding variation in T_n , the ion temperature deduced from the measured neutron flux. Evidently, enormous reductions in the rate of neutron production are reflected by small (but alarming) reductions in the apparent T_i .

3. CLASSICAL DIFFUSION PROCESSES

Experiments in the plasma regimes of interest here indicate that the bulk ions exhibit approximately neoclassical transport [2,3,5] (although electron transport is anomalously large). Furthermore, fast beam-injected ions in TFR [3], ORMAK [5], ATC [6] and other devices also appear to be confined classically. Therefore, we assume that the transport of energetic members of the bulk-ion distribution is also determined only by classical processes.

3.1 RIPPLE DIFFUSION MECHANISMS

Our inquiry concerns whether a large fraction of the energetic ions in an energy range near E_m can diffuse out of the hot central region in a time smaller than that required to replenish the tail near E_m . This "filling" time, τ_m , has nearly the same value as the 90° scattering time for an ion of energy E_m in a hydrogenically pure plasma of density n_e [7]:

$$\tau_m = 3.4 \times 10^{11} \frac{A^{1/2} E_m^{3/2}}{\ln \Lambda n_e} \quad (3)$$

where E_m is in keV, n_e is in cm^{-3} , and A is the atomic mass of the ions. When impurity ions are present, τ_m is altered only slightly from the value given by Eq. (3) (although τ_{90} , the 90° scattering time, is reduced by the factor Z_{eff}). Collisions with electrons are effective in filling the tail only for $\tau_{ci} < \tau_m(E_m)$, or $E_m \geq 20 T_i$ for deuterons.

Because τ_m varies as $E^{3/2}$, one expects a diffusion process to cause a truncation of $f_i(E)$ at large energy only if the diffusion coefficient does not decrease with E , or at least decreases only weakly with E . Of the three standard transport regimes resulting from Coulomb scattering ('banana', plateau, and Pfirsch-Schluter), only the plateau regime has a diffusion coefficient that increases with energy [8]:

$$D_{pl} \approx \frac{v \rho^2 q}{\pi R_0} \propto E^{3/2} \quad (4)$$

Here v is the ion velocity, ρ is the ion gyroradius, R_0 is the plasma major radius, and q is the inverse rotational transform. When E is sufficiently large so that the ion collision frequency is less than the bounce frequency in a

banana orbit, the diffusion coefficient has the banana-regime value [8]:

$$D_b = v_c \rho^2 q^2 \epsilon^{-3/2} \propto E^{-1/2} \quad (5)$$

where $v_c = \tau_{90}^{-1}$ and $\epsilon = a_p/R_0$ is the inverse plasma aspect ratio. Plateau diffusion occurs in too low an energy range to contribute to tail depletion, while the energy dependence of banana diffusion is too weak to have a substantial effect.

There are two ripple-induced diffusion processes that are extremely sensitive to ion energy:

(i) Superbanana diffusion applies to ions that are trapped in local magnetic wells and drift vertically with the VB-drift velocity [9]. The fraction of ions trapped in the ripple is $f_\delta \approx \delta^{1/2}$,

$$\text{where} \quad \delta = 2 \left(\frac{B_{\max} - B_{\min}}{B_{\max} + B_{\min}} \right) \quad (6)$$

While trapped, these ions drift a radial distance $d = \delta v_d \sin\theta / v_c$, where $v_d = v\rho/2R$ is the ΔB -drift velocity. The mean time between trapping is $t_\delta \approx \delta / (f_\delta v_c)$. Hence the diffusion coefficient is $D_{sb} = \langle d^2 \rangle / t_\delta$, or

$$D_{sb} = \delta^{3/2} \left(\frac{v\rho}{2R} \right)^2 \frac{1}{v_c} \propto \frac{E^{7/2}}{n_e B^2} \quad (7)$$

(ii) Banana-drift diffusion arises because in the presence of local magnetic wells, banana-trapped ions experience random radial displacements of the tips of their bananas. Successive banana orbits are unclosed, leading to a stochastic wandering of these orbits [10,11]. The correct form of the diffusion coefficient for this process is somewhat controversial at present [12]. Because of the relatively small number of particles banana-trapped near the plasma center (the region of interest here), banana-drift diffusion plays a minor role in the fast-ion loss process in this region, and can often be neglected. Its inclusion would slightly enhance the tail-depletion process to be discussed in later sections.

Table I shows parameters for the relevant plasma regimes in Alcator and TFR. In Alcator, the ripple periodicity in the toroidal direction (ϕ) is $N = 4$, but δ is a sinusoidal function of ϕ only near the magnetic axis. Figure 3 shows ion diffusion coefficients for Alcator central parameters, calculated with a Monte Carlo code that follows the guiding-center trajectories of large numbers of energetic ions [10,13]. For each point shown, 100 ions starting at $r_0 = 0.5$ cm with random $v_{||}/v$ and θ were followed for 1 ms for the $\delta = 0$ cases, and for 0.2 ms for the $\delta = 0.04$ cases.

(For times longer than 0.2 ms, a significant number of ions begin to reach the limiter in the $\delta = 0.04$ cases. However, D_{sb} cannot be calculated accurately for ions with $\tau_m > 0.2$ ms—that is, for $E > 6$ keV at $n_e = 10^{15} \text{ cm}^{-3}$.) The Monte Carlo calculations are in reasonable agreement with the simple analytic expressions for diffusion. Evidently, superbanana diffusion becomes the dominant transport process for $E > 3.5$ keV, when $n_e = 10^{15} \text{ cm}^{-3}$. Because $D_{sb}/D_{pl} \propto E^2/n_e$ and $D_{sb}/D_b \propto E^4/n_e^2$, superbanana diffusion is expected to be dominant at even lower energies, when n_e is decreased.

3.2 RANGE OF VALIDITY OF SUPERBANANA DIFFUSION

The diffusion coefficient D_{sb} applies only if (i) v_c^{-1} exceeds the ion bounce time in a superbanana orbit, and if (ii) the step size $\delta v_d v_c^{-1}$ is less than r_1 , the maximum radius of interest. Hence the allowed range of v_c is

$$\frac{\delta}{2} \frac{\rho}{r_1} \frac{v}{R_0} \lesssim v_c \lesssim \left(\frac{\delta}{2} \right)^{3/2} N \frac{v}{R_0} \quad (8)$$

In the presence of rotational transform, the actual ripple on a given field line is reduced significantly from the "vacuum" ripple, because of the smoothing effect of the $1/R$ dependence of the toroidal field [9]. However, in the region near the magnetic axis, which is our principal concern, this reduction in δ can be neglected.

3.3 TRUNCATION OF THE VELOCITY DISTRIBUTION

Ions must have a minimum energy E_m in order to diffuse a radial distance Δr from a position r_0 near the center of the plasma in a time smaller than $\tau_m(E_m)$ — the time to replace these ions by Coulomb collisions. This condition is

$$\left[(D_b + D_{sb} + D_{bd}) \gamma \tau_m \right]^{1/2} \geq \Delta r \quad (9)$$

where $\gamma < 1$. Equation (9) holds if the step-length $d \lesssim \Delta r$. The distance $r_1 = r_0 + \Delta r$ is sufficiently large so that the fusion reactivity of a Maxwellian ion distribution at $T_i(r_1)$ is a small fraction of that at T_{ic} . For example, when $T_i(r_1) = 0.75 T_{ic}$ (see Fig. 4a), the fusion reactivity is reduced by a factor of 6 when T_{ic} is of the order of 1000 eV. Ions that drift to $r > r_1$ then thermalize with an ion population which is sufficiently cold so that fusion reactions here can be neglected. (Note that $r_1 \gg r_0$.)

Equation (9) can be solved to find E_m . We then truncate the ion energy distribution at $E = E_m$, so that the fusion reactivity can be determined from Fig. (1). This procedure is justified by the following analysis.

The Fokker-Planck equation for ions, neglecting interaction with electrons, and (as an approximation) taking the velocity distribution as isotropic, is [14]

$$0 = \frac{\partial f}{\partial v} = \frac{\alpha}{v^2} \frac{\partial f}{\partial v} + \frac{\alpha}{v^2} \frac{\partial}{\partial v} \left[\frac{T_i}{mv} \frac{\partial f}{\partial v} \right] - \frac{f}{\tau_r(v)} \quad (10)$$

where $\alpha = v^3/\tau_m$ is a constant, and $\tau_r(v)$ is the confinement time of ions of velocity v in the region of interest (i.e., $r < r_1$). For ions for which $d < r_1$, one has $\tau_{r1} = r_1^2/D_{sb}$, if superbanana diffusion is dominant. For ions for which $d \geq r_1$, τ_{r2} is essentially the mean time between trapping, or $\tau_{r2} \approx \sqrt{\delta}\tau_{90}$, where $\tau_{90} = \tau_m/Z_{eff}$ is the 90° scattering time. In the following, we use $\tau_r = \tau_{r1} + \tau_{r2} = bv^{-7} + cv^3$. Then the loss time is overestimated by a factor of 2 at $v = v_0$, the velocity where $\tau_{r1} = \tau_{r2}$; but for most velocities, the overestimate is small, being only 11% at $v = 0.8 v_0$, and 15% at $v = 1.2 v_0$.

To solve Eq. (10) we write $f_i(v) = \exp(-\phi_0 - \phi_1 - \dots)$, where ϕ_0 is of order (-1) and ϕ_1 is zero-order in the quantity $(2T_i/mv^2)$. Then ϕ_0 gives the Maxwellian solution for no losses: $\phi_0 = mv^2/2T_i$. It is readily shown that

$$\phi_1 = \int \frac{v^2}{\alpha\tau_r(v)} dv = \frac{Z_{eff}}{10\sqrt{\delta}} \ln \left[1 + \left(\frac{v}{v_0} \right)^{10} \right] \quad (11)$$

Hence

$$f_i(v) = \left[1 + \left(\frac{v}{v_0} \right)^{10} \right]^{-\frac{Z_{eff}}{10\sqrt{\delta}}} \exp \left(-\frac{1}{2} \frac{mv^2}{T_i} \right) \quad (12)$$

When $Z_{eff} \sim 1$ and $\delta \sim 0.01$, $f_i(v)$ drops below the Maxwellian value by a factor of 2 at $v = v_0$, and decreases extraordinarily

rapidly at $v > v_0$, as shown in Fig. 4(b). Furthermore, from the definition of v_0 one has $v_0 = v_m (Z_{\text{eff}} \gamma / \delta^{0.5})^{1/10} \approx v_m$, where v_m is the solution to Eq. (9). Hence the rapid fall-off of $f_i(v)$ at $v \approx v_m$ justifies the truncation of the ion energy distribution at $E = E_m$, in order to calculate the fusion reactivity of the ion population in the region $r < r_1$. (While v_m is slightly less than v_0 , our definition of τ_r used to derive Eq. (12) in fact implies that v_0 is a slight overestimate of the actual 'cut-off' velocity.)

Thus in calculating the fusion-neutron production rate, we assume that at $r \leq r_1$, $f_i(v)$ is a truncated Maxwellian at temperature T_{ic} ; the truncation velocity is v_m . For $r > r_1$, T_i/T_{ic} is sufficiently small so that neutron production in this region can be neglected. (A similar procedure is often used in experimental analysis. For example, in the PLT device with $a_p = 40$ cm, the neutron-deduced temperature T_n agrees with the value of T_{ic} deduced from charge-exchange measurements, when $T_n = T_{ic}$ at $r \leq 11$ cm, and $T_n = 0$ at $r > 11$ cm [15].)

4. EFFECT OF SUPERBANANA DIFFUSION IN ALCATOR

The measured electron temperature profile in the high-density Alcator regime is [2]

$$T_e(r) = T_{ec} \exp(-r^2/25) . \quad (13)$$

Because of the short equilibration time between electrons and ions when $n_e \geq 3 \times 10^{14} \text{ cm}^{-3}$, the ion temperature profile is also expected to be described approximately by Eq. (13). We define r_1 by $T_i(r_1) \approx 0.75 T_{ic}$, or $r_1 = 2.7 \text{ cm}$. The density range for which the simple treatment of superbanana diffusion is valid is found from Eq. (8), with $Z_{\text{eff}} = 1.0$:

$$6.0 \times 10^{12} E^{5/2} \leq n_e \leq 1.6 \times 10^{14} E^2 \quad (14)$$

where E is in keV and n_e is in cm^{-3} . For example, when $n_e = 5 \times 10^{14} \text{ cm}^{-3}$, E must lie between 1.8 and 5.9 keV. For values of E outside this range, D_b will be reduced.

Equation (9) gives the energy at which the ion distribution at $r < r_1$ is truncated. In Alcator, $D_{sb} \gg D_{bd}$. When $D_{sb} \gg D_b$, $E_m \geq 3.8 \gamma^{-1/5} [\Delta r (B_t/8) (n_e/10^{15})]^{2/5}$, where B is in Teslas. Actually, banana diffusion serves to reduce E_m by 5 to 10%. Table II shows E_m calculated from Eq. (9), retaining both D_{sb} and D_b , and taking $r_0 = 0.5 \text{ cm}$, $\Delta r = 2.2 \text{ cm}$, and $\gamma = 2/3$. These values of E_m all lie inside the range of validity specified by Eq. (14).

In Alcator, one expects that $T_{ic} \geq 0.85 T_{ec}$ for $n_{ec} \geq 5 \times 10^{14} \text{ cm}^{-3}$, from the condition that the Ohmic power density must exceed the rate of energy transfer from electrons to ions [2]. However, the measured T_n is significantly lower, corresponding to a neutron "shortfall" of at least a factor of 3 [2]. As indicated in Table II, substantial reductions in neutron flux are expected as a result of the tail-depletion processes discussed herein, but

the predicted T_n at the highest density may still be somewhat larger than measured. Whilst the predicted neutron deficit is of the same magnitude as observed, very close agreement is not expected in view of the approximate nature of our calculation. Finally, another effect that would further reduce the neutron flux by about 30% is that banana-trapped deuterons ($\sim 20\%$ of the population at $r \sim 1$ cm) have orbits that extend well outside the hot, dense central region.

(It should be noted that very large T_i (≥ 1 keV) have been measured from the neutron flux in Alcator when $n_e \lesssim 10^{13} \text{ cm}^{-3}$ [16]. In this density range, superbanana diffusion does not apply [cf Eq.(14)]; only those ions produced directly in the loss cone escape. At any rate, losses from the energetic tail would be replaced rapidly by the lower-hybrid instabilities which are thought to be responsible for the large T_i in this regime [16].)

5. EFFECT OF SUPERBANANA DIFFUSION IN TFR

As mentioned in Sect. 1, the temperature of a deuterium plasma in the TFR device, as inferred by the measured neutron flux, failed to increase by more than about 100 eV (for example from 900 to 1000 eV) when sufficient hydrogen beam power was injected so that T_i increased by at least several hundred electronvolts, according to charge-exchange neutral measurements [3]. The relevant parameters of TFR are given in Table I. The charge-exchange measurements show that $T_i \approx 0.7 T_{ic}$ when $r_1 = 10$ cm [3]; at this radius, the fusion reactivity is reduced by a factor of 6 compared with its value at T_{ic} , when $T_{ic} \sim 1500$ eV.

In TFR the ripple well-depth actually varies strongly around the magnetic surface. For example, at $r = 5$ cm, δ decreases from 0.5% at $\theta = 0^\circ$ to 0.3% at $\theta = 90^\circ$ and to 0.1% at $\theta = 180^\circ$ [17]. But δ also increases rapidly with r , and the plasma shifts outward during heating. Here we take $\delta = 0.005$ throughout the region of interest ($r \leq 10$ cm). Then from Eq. (9), keeping only the ripple-diffusion terms, we find that $E_m \geq 2.9 (Z_{\text{eff}}/\gamma)^{1/5} [\Delta r n_e / 10^{14}]^{2/5}$ keV. (The banana-drift diffusion has been estimated from Refs [11,12]. Its omission would increase E_m by 6%.) For the conditions giving highest T_i [3], namely $n_{ec} \approx 5 \times 10^{13} \text{ cm}^{-3}$ and $Z_{\text{eff}} \approx 4$, one has $E_m \geq 7.3$ keV when $r_o = 1$ cm, $\Delta r = 9$ cm, and $\gamma = 2/3$. If $T_{ic} = 1.6$ keV, then Fig. 1 shows that the expected neutron flux is reduced by a factor of 2.7. An additional factor of three reduction in flux can be accounted for by displacement of 40 to 45% of the deuterium by hydrogen flowing from the beam lines [3]. (The expected shortfall in neutron flux increases with T_{ic} , reaching 77% when $T_{ic} = 2.0$ keV. In the Ohmic-heated regime, $T_{ic} < 1$ keV in deuterium, so that the shortfall in neutron flux would be at most 25%.)

Superbanana diffusion of the tail of the bulk-ion population has been observed in the TFR plasma [18]. In the presence of intense beam injection, the bulk-ion tail can be enhanced by collisions of the bulk ions with the injected energetic ions, but this effect should be small for hydrogen injection into deuterium plasmas. At any rate, it is difficult in experiment to distinguish the bulk-ion tail from decelerated energetic ions, unless a mass-discriminating charge-exchange analyzer is used.

6. OTHER IMPLICATIONS OF TAIL DEPLETION

Diagnostics. Although the fusion reactivity can be reduced drastically by tail depletion, the total energy in the ion distribution may be essentially unchanged. In the Alcator example of Table II, for $E_m = 4.0$ keV only 2% of the total ion energy is lost when $T_{ic} = 800$ eV. In the TFR example of Sect. 5, where $E_m = 7.3$ keV, only 3% of the total ion energy is lost when $T_{ic} = 1.6$ keV. Hence, whilst the neutron ion temperature, and possibly the charge-exchange temperature, are reduced significantly, a diagnostic such as far-infrared Thomson scattering that is sensitive to the mean ion energy will give a good estimate of T_i .

Heating to Ignition. Tokamak plasmas that are to demonstrate thermonuclear ignition must satisfy, for example, $T_i = 7$ keV when $n_e \tau_E = 8 \times 10^{14} \text{ cm}^{-3} \text{ s}$. When alpha-particle heating is important during heating to ignition, it is obviously essential to minimize toroidal-field ripple in the hot central region, both to retain the highly reactive tail of the bulk-ion population, and to retain all the fusion alpha particles in this region. If a tokamak device is equipped with access ports (for example, for pumping, or for applying nonOhmic heating), then negligible ripple can be maintained at the center of the plasma only if the coil bore is significantly larger than the plasma diameter. Thus it would seem difficult to demonstrate alpha-particle heating to ignition temperature in very compact tokamaks with close-fitting toroidal-field coils, inasmuch as such construction inevitably leads to appreciable ripple throughout the plasma.

On the other hand, if ignition temperature is to be obtained primarily by an externally applied heating method, then a reduction in alpha-particle production and confinement in the hot central region can be tolerated during the heating phase. Thus in the ripple-assisted beam-injection technique [10], where toroidal-field ripple is applied by special coils, alpha particles can play a minor or even insignificant role in heating to ignition. (Actually, in the scheme of Ref. [10], the bulk-ion tail can be lost only through the banana-drift process.) Once ignition temperature is reached, the ripple field is deactivated, so that the plasma temperature can then be sustained by fusion alpha particles.

ACKNOWLEDGMENT

The authors thank Dr. P. Moriette for information concerning ion temperature measurements in the TFR device. This work was supported by United States Energy Research and Development Contract E(11-1)-3073.

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TABLE I. PARAMETERS FOR ALCATOR AND TFR

	ALCATOR	TFR
B_t (T)	8.0	5.0
R_o (cm)	54	98
a_p (cm)	9.5	20
No. ripple periods, N	4	24
Ripple well depth, δ	≈ 0.04	≈ 0.005 near $r = 5$ cm
n_{ec} (cm^{-3})	$2 \times 10^{14} - 10^{15}$	$5 \times 10^{13} - 10^{14}$
T_{ic} (eV)*	600-900	$\geq 1500^{**}$
Z_{eff}	≈ 1.0	3-5

* Deduced from charge-exchange measurements (with corrections for plasma opacity).

** With neutral-beam heating (≥ 400 kW)

TABLE II. PREDICTED ION TEMPERATURES FROM NEUTRON FLUX
IN ALCATOR FOR $B_t = 8.0$ T

n_{ec} (cm^{-3})	E_m^{**} (keV)	$T_{ic}^* = 700$ eV		$T_{ic} = 800$ eV		$T_{ic} = 900$ eV	
		$\frac{\langle \sigma v \rangle_m}{\langle \sigma v \rangle_\infty}$	$T_n^\dagger$	$\frac{\langle \sigma v \rangle_m}{\langle \sigma v \rangle_\infty}$	T_n	$\frac{\langle \sigma v \rangle_m}{\langle \sigma v \rangle_\infty}$	T_n
			(eV)		(eV)		(eV)
3×10^{14}	3.3	0.23	580	0.16	610	0.10	635
5×10^{14}	4.0	0.40	620	0.29	670	0.21	715
1×10^{15}	5.3	0.74	665	0.62	730	0.53	810

* T_{ic} is actual ion temperature at $r = 0$

** E_m is 'cut-off energy' for $r < 2.7$ cm.

† Neutron flux is calculated using $T_i = T_n$ at $r \leq 2.7$ cm.
and $T_i = 0$ at $r > 2.7$ cm.

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Fig. 1. Reduction in fusion reactivity for a truncated Maxwellian distribution of deuterons at temperature T_i . E_m is the truncation energy.

Fig. 2. Equivalent ion temperature T_n corresponding to neutron flux from a truncated Maxwellian distribution of deuterons at temperature T_i . E_m is the truncation energy.

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Fig. 3. Coulombic diffusion coefficients near the center of the Alcator plasma, assuming uniform ripple (Coulomb drag is ignored). The points shown are the results of a Monte Carlo guiding-center calculation; the bars represent standard deviations. δ is the peak-to-peak toroidal-field ripple. The theoretical lines are calculated with $q = 1.0$, $\epsilon = 0.05$.

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 Fig. 4. (a) Ion temperature profile. The "neutron-producing temperature" profile can be approximated by the dashed line. (b) Ion velocity distribution at $r < r_1$ when $Z_{eff} = 1.0$, ripple depth $\delta = 0.01$, $v_0 = 6.4 \times 10^7$ cm/s ($E = 4$ keV).