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PROSPECTS FOR THERMONUCLEAR IGNITION IN A "COLLISIONAL" TOKAMAK

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ABSTRACT

We determine the parameters of a tokamak reactor plasma that attains ignition in the same regime of collisionality as present-day ohmic-heated tokamak plasmas, where the confinement scaling $n\tau \propto n^2$ is observed. The use of Nb_3Sn toroidal field coils and a plasma elongation $\gtrsim 1.5$ are necessary to attain the high plasma density ($n \sim 10^{15} cm^{-3}$) required for ignition in this collisional regime. Under these conditions, the fusion power density is of order 10 W/cm^3. This high value is probably necessary for an economic tokamak reactor.

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1. INTRODUCTION

The need to minimize the capital cost of tokamak reactors places a premium on high power density. The purpose of this paper is to discuss some of the features of high-density reactors which make use of both high magnetic field and elongated plasma cross section. In particular, we show that for certain high-power-density tokamak plasmas operating under ignition conditions, the density is sufficiently large that the plasma is in the same "collisional" regime as present-day tokamak plasmas. Assuming that degree of collisionality is the most important parameter for scaling tokamak performance, we can then predict with some confidence the confinement time of our reactor plasma, using empirical scaling laws that describe present-day tokamak plasmas.

The degree of collisionality of a plasma regime may be characterized by the parameter $C = \nu_{ei} A/\omega_{be}$, where ν_{ei} is the electron-ion collision frequency, ω_{be} is the electron bounce frequency, and $A = R/a$ is the plasma aspect ratio. The values of C for most present-day machines operated at high current are in the range 0.05 to 2. In this paper we define a "collisional" plasma as one characterized by $C \geq 0.1$. We then determine the machine parameters for collisional tokamak reactors operating with the $n\tau$ and temperature values required for ignition in D-T. (By "ignition", we mean that the plasma temperature is maintained by power deposition of alpha particles resulting from D-T fusion.) For collisional operation, the reactor temperature must be low, probably $T_e \approx T_i \approx 6$ keV. While the $n\tau$-values required for ignition are very large at low T_i, the $n\tau \propto n^2$ scaling that is observed in most present-day tokamaks [1,2] indicate that these high $n\tau$-values are attainable in the collisional plasma regimes described herein. The prospect of building a tokamak reactor that operates in the collisional mode is attractive, since scaling laws for collisionless regimes have not been experimentally established and may prove to be unfavorable for attainment of ignition in machines of practical size.

2. DENSITY DEPENDENCE OF COLLISIONALITY PARAMETER

The electron bounce frequency is given by [3]

$$\omega_{be} = \frac{v_{Te}}{qR_o}\left(\frac{2}{A}\right)^{1/2} \qquad (1)$$

where v_{Te} is the electron thermal velocity, R_o is the major radius of the torus, and q is the safety factor at the limiter. The collisionality parameter C is then

$$C = \frac{\nu_{ei}A}{\omega_{be}} \approx \frac{6 \times 10^{-19} q\, R_o^{5/2} Z_{eff}\, n}{T_e^{2} a_p^{3/2}} \qquad (2)$$

where a_p is the minor radius of the plasma (cm), n is the density (cm^{-3}), T_e is the electron temperature (keV), and Z_{eff} is the effective charge of the plasma. Values of C for Alcator, which has $Z_{eff} \sim 1$, are in the range 0.04 to 1.5 [2].

3. EQUILIBRIUM CONSTRAINT ON ELECTRON DENSITY

Figure 1 shows a schematic layout of the tokamak reactor. Fixed parameters are the thickness d_{tf} of the toroidal field (TF) coils (0.9 m), thickness d_b of the blanket/shield (1.3 m), and thickness d_s of the plasma scrape-off layer (0.2 m). The core radius R_c is in the range 1.5 -2 m. For the field at the inner TF coil bore, B_{to}, we use the maximum that is practically realizable with Nb_3Sn in toroidal geometry [4], viz. 160 kG. The magnetic field on axis is given by

$$B_t = \frac{B_{to}(R_c + d_{tf})}{R_c + d_{tf} + d_b + d_s + a_p} \qquad (3)$$

The highest density in a tokamak plasma that is allowed by MHD equilibrium constraints is [3]

$$n_{eq} = \frac{\alpha R_o}{a_p} \frac{B_p^2}{16\pi T_e} \qquad (4)$$

where $\alpha \leq 1$. Here we have assumed that $T_e = T_i$. The poloidal field B_p is related to B_t through the safety factor, q:

$$q = \frac{a_p}{R_o} \frac{B_t}{B_p} S \qquad (5)$$

The shape factor S = plasma circumference/$2\pi a$. Equations (3) to (5) can be combined to give

$$n_{eq} = 1.2 \times 10^{13} \frac{\alpha B_{to}^2 (R_c+d_{tf})^2}{T_e q^2 R_o^3} a_p S^2 \qquad (6)$$

where B_{to} is in kG, and T_e is in keV.

In the following we use $q = 2.5$ and $\alpha = 0.5$. (Present tokamak plasmas operate with $q \geq 3$ and $\alpha \leq 0.3$ [3].) Figure 2 shows the dependence of n_{eq} on S and T_e for $R_c = 1.5$ m and $a_p = 1.0$ m. The densities shown are a factor of 2-10 larger than those that have been achieved to date in tokamaks.

4. REGIMES OF COLLISIONAL OPERATION

The largest values of C are obtained from Eq. (2), using $n = n_{eq}$ from Eq. (6):

$$C = \frac{1.8 \times 10^{-20} \alpha B_{to}^{2} (R_c + d_{tf})^2 Z_{eff} S^2}{q T_e^{3} R_o^{1/2} a_p^{1/2}} \qquad (7)$$

The regimes of collisional operation are then defined by parameter values that give $C \geq 0.1$. Figure 3 shows the dependence of C upon S and T_e, for $a_p = 1.0$ m. For a circular cross-section plasma (S=1), the collisional regime is attained only for $T_e < 5$ keV. Since radiation losses preclude ignition at $T_e < 5$ keV [5], the possibility of a circular tokamak plasma operating at ignition in the collisional mode seems remote. A moderately deformed cross-section ($S \gtrsim 1.5$) insures collisional operation in the range 6-7 keV. If $Z_{eff} > 1$, the minimum temperature for ignition increases [6], but at the same time the parameter C increases (Eq. 7), so that collisional operating regimes are still available for $Z_{eff} < 3$.

5. REQUIREMENTS ON $n\tau$

Figure 4 shows the $n\tau$-value for ignition as a function of $T_e = T_i$. For moderate values of S, we have seen that collisional operation is obtained only at relatively low plasma temperatures, ~6 keV, where the $n\tau$ for ignition is extremely large. We now investigate whether the $n\tau$-values that should apply to high density operation are sufficient to attain ignition.

The scaling law for energy confinement time that has been derived from experimental studies on tokamaks such as ATC [1], ORMAK [1], and Alcator [2] is

$$\tau = K_m n q^{1/2} a_p^{\ m} \tag{8}$$

where K_m is a constant. Determination of the parameter m requires experiments on larger devices, but $m \simeq 2$ if the primary energy loss mechanism is diffusive and $m \simeq 1$ if the primary loss mechanism is convective. (There is also evidence of an increase in τ with T_e [1,2], but this favorable dependence is ignored here.) Combining (6) and (8), we have

$$(n\tau)_m = K_m \left[\frac{\alpha\ B_{to}^{\ 2}(R_c+d_{tf})^2}{16\pi T_e q^2 R_o^{\ 3}}\right]^2 S^4 q^{1/2} a_p^{\ m+2} \tag{9}$$

Figure 4 shows the dependence of $n\tau$ upon T_e and S for $m = 2$ and $a_p = 1.0$ m. The values of K_m were taken from Alcator results [2]: $K_{1.5} = 1.0\text{x}10^{-18}$ and $K_2 = 3.2\text{x}10^{-19}$, with a_p in cm. Evidently, the large value of $n\tau$ required for ignition at $T_e = T_i = 6$ keV is attainable at $S \approx 1.6$ for $m = 2$. In the case of a rectangular cross-section plasma, S = 1.5 and 2.0 correspond to relatively moderate elongations, viz. b/a = 1.36 and 2.1 , respectively.

6. REACTOR PARAMETERS

Table 1 lists illustrative machine and plasma parameters for collisional ignition reactors, for $\tau \sim a_p^{1.5}$ and $\tau \sim a_p^{2}$ scaling. For given values of T_e and S, the plasma radius is chosen so that $n\tau$ is the ignition value when $\beta_p \simeq \frac{1}{2} R_o/a_p$. (The reactors can be made somewhat smaller, and the collisionality increased, if equilibrium is maintained as β_p is increased toward the MHD-limiting value of R_o/a_p.) While the plasma current is very large, even for $\tau \sim a_p^{1.5}$ scaling the physical size of these reactors is much smaller than those of similar power output that have been proposed for operation at $n_e \lesssim 10^{14} cm^{-3}$[7]. As a result, the neutron wall loading is many times larger than is thought to be feasible with presently known structural alloys, but large power densities and wall loadings similar to those of Table 1 may well be essential for acceptable capital costs.

Let us briefly consider the problem of heating the plasma to ignition. If the plasma is to be heated in about one confinement time τ, then the required heating power is

$$P_{heat} \approx \frac{3nT_eV}{\tau} \propto n^2T_eV \qquad (10)$$

where V is the plasma volume, and $n\tau$=constant is the ignition value. Evidently, reactors of the same temperature and power output ($P_{out} \propto n^2 \langle\sigma v\rangle V$) require the same heating power. On the other hand, the heating energy input is

$$W_{heat} \approx 3nT_eV \propto 1/n \qquad (11)$$

for reactors of the same power output and temperature. Since the enormous power required for heating (by neutral beams or microwaves, for example) at the beginning of each burn cycle will probably have to come from an energy storage system, then additional substantial savings in capital cost are realized by operating at the highest possible density.

7. CONCLUSIONS

It appears possible to develop a tokamak reactor that can attain ignition conditions while operating in the same collisional regime as present-day tokamaks, where $n\tau \propto n^2$ scaling is observed. To insure adequate collisionality, a low plasma temperature ($T \sim 6$ keV), very high magnetic field, and non-circular plasma cross-section are required. The high values of density thus attainable also insure the large values of $n\tau$ required for ignition at low temperature. Even at 6 keV, the fusion power density is of order 10 W/cm^3, so that the reactor power output should be adequate for economic operation.

The feasibility of the collisional ignition reactor depends upon our assumption that the scaling law for confinement time is determined only by degree of collisionality, so that $n\tau \propto n^2$ scaling will hold in larger tokamaks with confinement times approaching 1 s. Another caveat is that the empirical scaling law has been obtained for ohmic-heated tokamaks only, while attaining ignition temperature is dependent in practice upon more powerful heating techniques such as neutral beam injection. Heating and confinement experiments on high-field tokamaks (Alcator, Frascati) and on noncircular tokamaks (Doublet III, PDX) will give invaluable information concerning the high-density approach to an ignition reactor.

ACKNOWLEDGMENT

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TABLE 1.

ILLUSTRATIVE PARAMETERS FOR COLLISIONAL TOKAMAK REACTORS

	Unit	A m=2.0	B m=1.5	C m=1.5
R_o	m	5.0	5.05	4.8
a_p	m	1.1	1.15	0.90
Aspect ratio		4.5	4.4	5.3
$S = \text{circum.}/2\pi a_p$		1.5	2.0	2.0
B_t on axis	kG	77	76	80
B_t at coil	kG	160	160	160
I_p	MA	8.4	15.8	10.8
q at limiter		2.5	2.5	2.5
$\bar{n}$	cm^{-3}	4.8×10^{14}	8.5×10^{14}	6.0×10^{14}
$\bar{T}_e = \bar{T}_i$	keV	6.0	6.0	8.0
β_p		2.25	2.2	2.7
Collisionality		0.10	0.17	0.10
$\bar{n}\tau$	$cm^{-3}s$	1.5×10^{15}	1.5×10^{15}	5×10^{14}
Fusion power density	W/cm^3	4.2	13.0	15.8
Plasma Volume	m^3	207	352	205
Neutron wall loading	MW/m^2	1.8	7.2	6.7
Total neutron power	MW	695	3660	2590
Total thermal power (22 MeV/neutron)	MW	1085	5710	4040

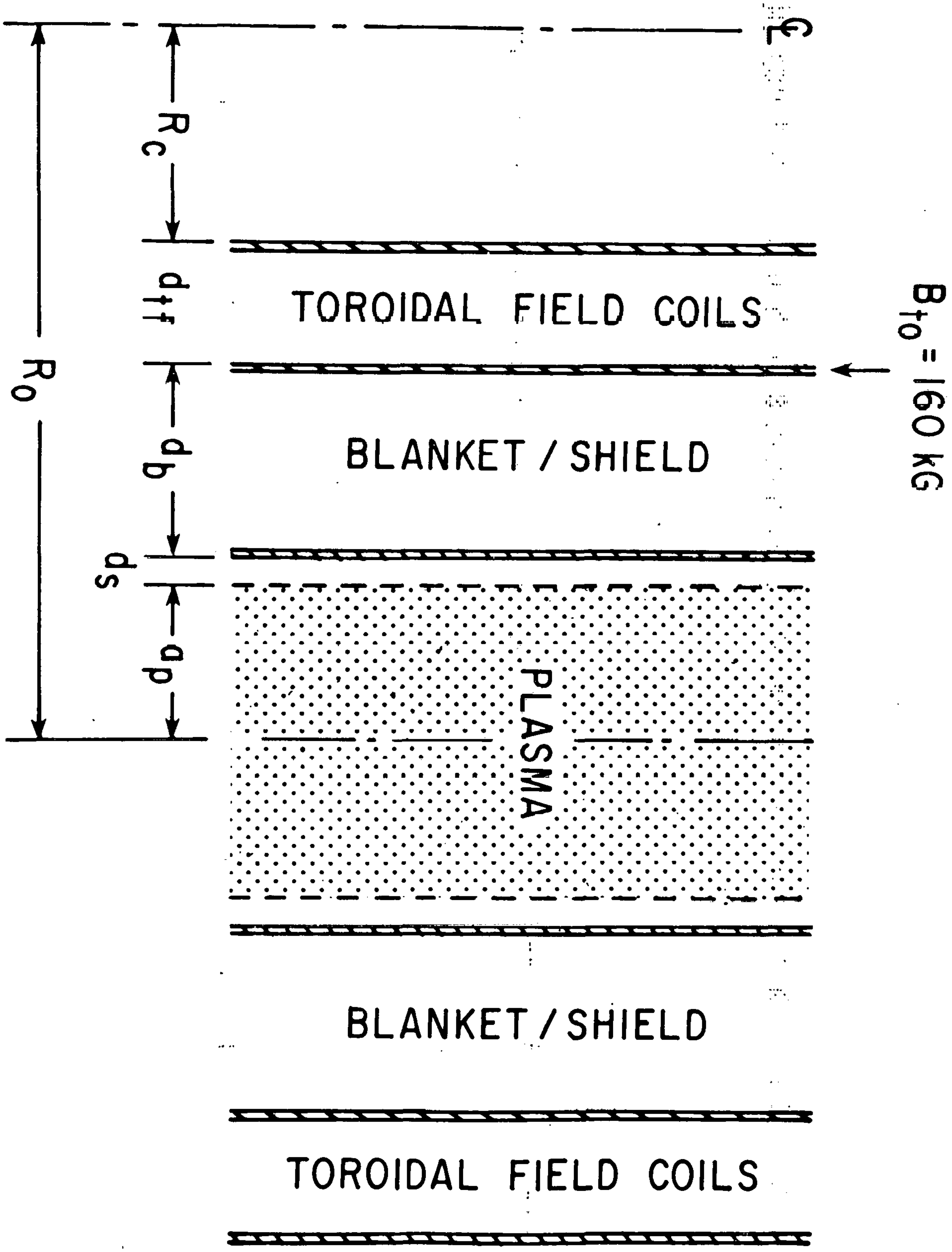

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Fig. 1. Schematic layout of the tokamak reactor.

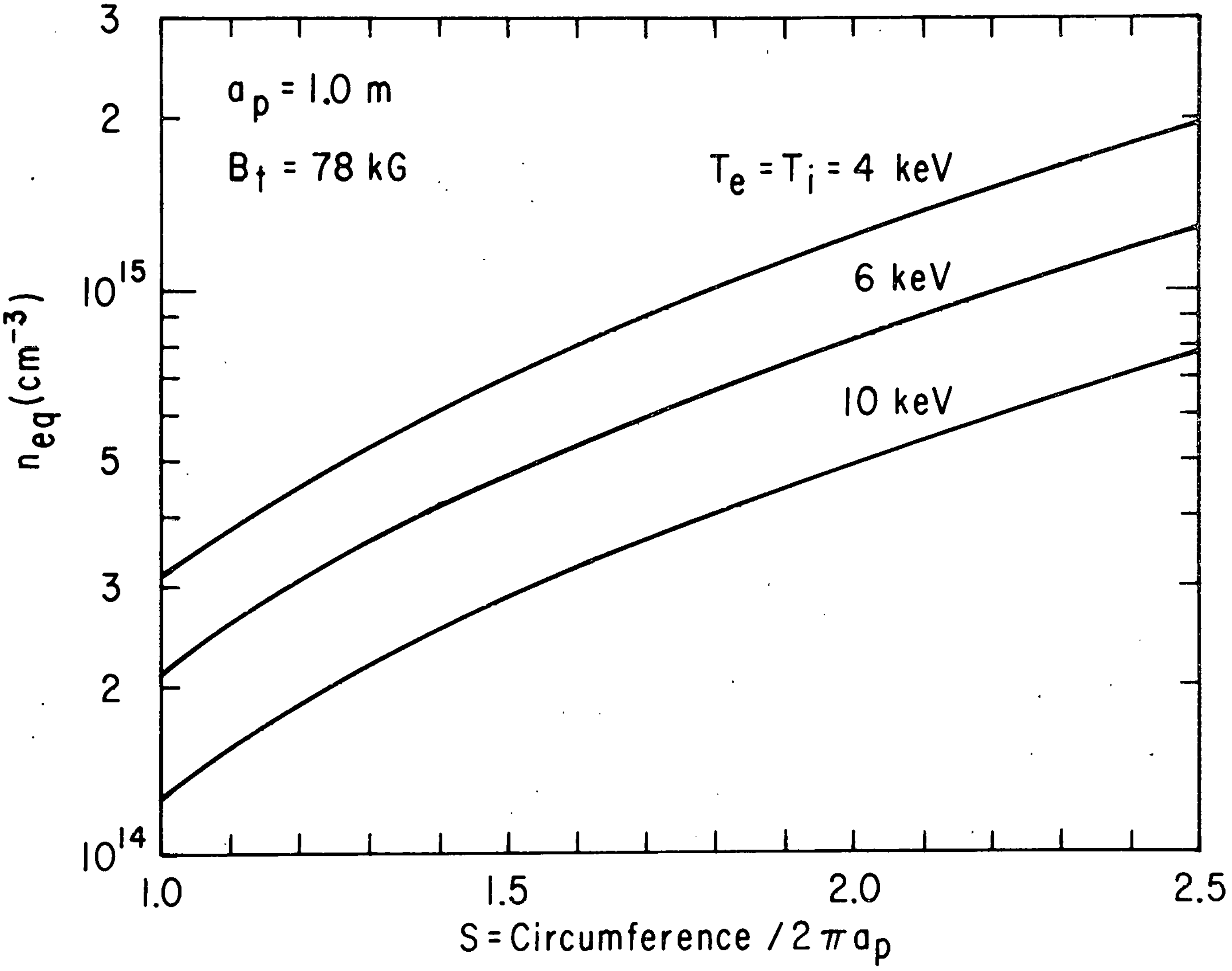

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Fig. 2. Plasma density for $\beta_p = \frac{1}{2} R_o/a_p$, as a function of plasma shape factor, S. R_c = 1.5 m .

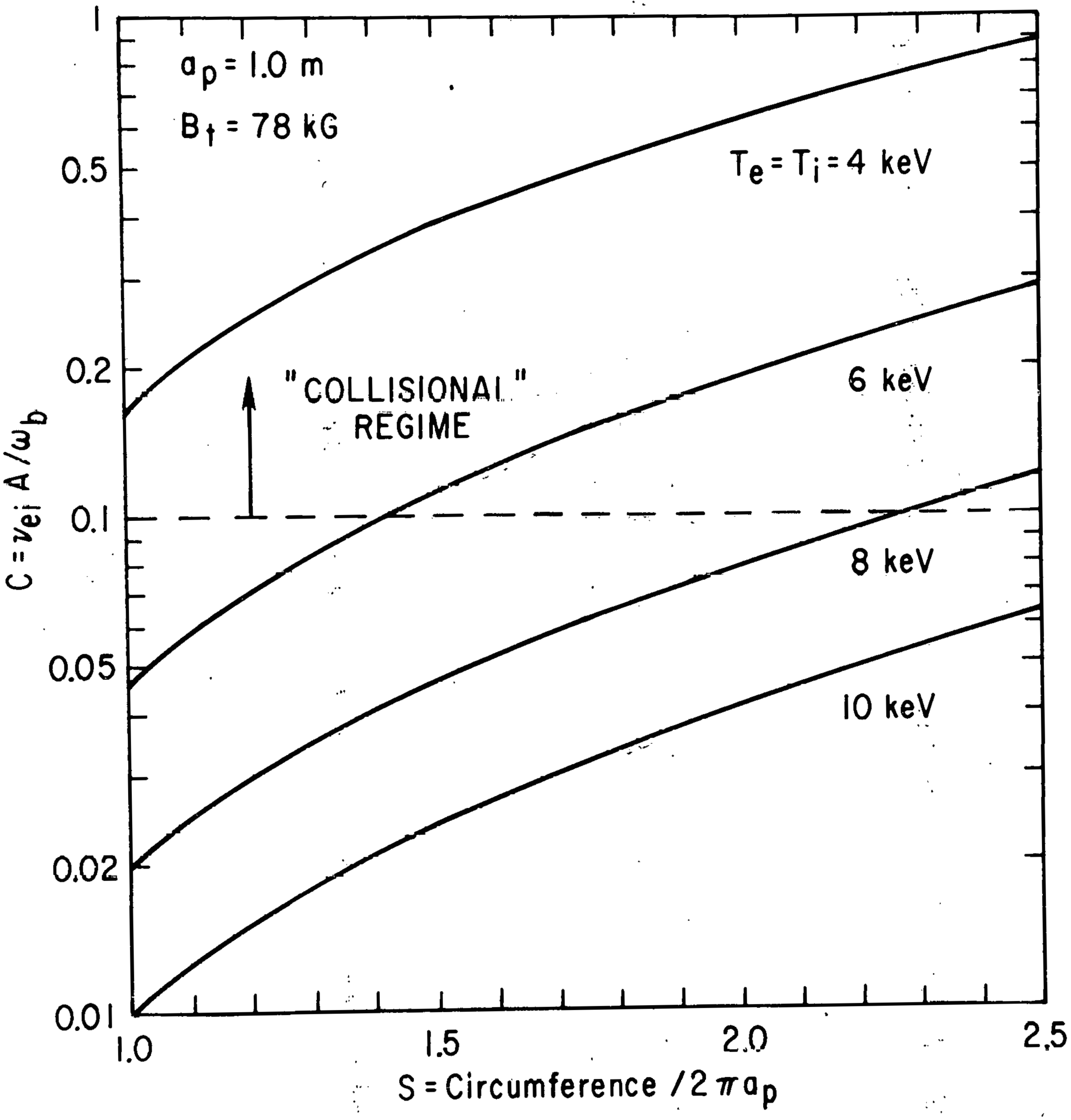

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Fig. 3. Collisionality parameter, C, for $\beta_p = \frac{1}{2} R_o/a_p$, as a function of plasma shape factor, S. $R_c = 1.5$ m^2.

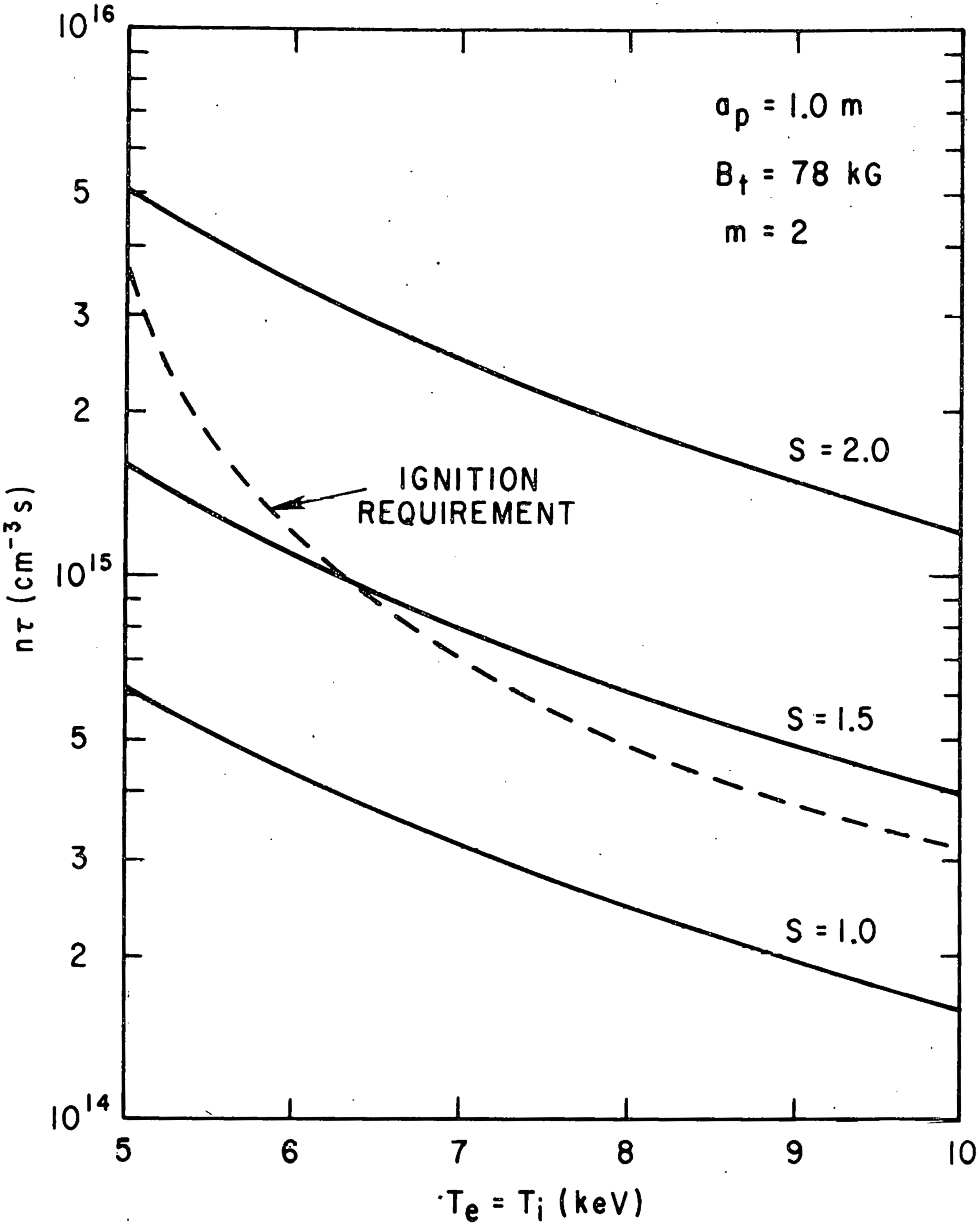

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Fig. 4. Temperature dependence of nτ at a_p = 1.0 m for various plasma shape factors, S. The scaling $n\tau = Kn^2a_p^2$ is used, with the constant K taken from Alcator results. The dashed line shows the minimum nτ for ignition. R_c = 1.5 m.