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MAXIMUM NEUTRON WALL LOADINGS IN BEAM-DRIVEN TOKAMAK REACTORS

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ABSTRACT

If a beam-driven D-T tokamak reactor is operated at the maximum density allowed both by pressure limitation and by adequate neutral-beam penetration, the 14-MeV neutron wall loading increases approximately linearly with magnetic field or vertical elongation of the plasma. With elongation = 3 , B_{tmax} = 15 T , W_{beam} = 200 keV , Q ~ 1.0 , maximum wall loading is about 5 MW/m^2 .

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INTRODUCTION

Certain potential applications for the 14-MeV neutrons from a D-T fusion plasma require extremely high uncollided neutron flux, despite the accelerated damage rate to the reactor first wall. In fact, one of the main objectives of a fusion engineering test reactor is the investigation of neutron radiation damage to wall materials.(1) In recently proposed schemes for the burning of long-lived actinide wastes,(2) the largest possible wall loading is required to accomplish sufficiently rapid actinide depletion. For this application, it would be quite acceptable to replace the vacuum wall after 300 days, for example. Finally, the breeding of ^{233}U or ^{239}Pu in a fertile blanket surrounding the fusion plasma(3) may turn out to be most economic when the fissile production rate (proportional to the 14-MeV flux) is as large as possible in a given-size device — provided that the down-time for replacing the wall can be made sufficiently short.

For a magnetically confined fusion plasma with a limited total pressure, the largest fusion power density, P_f , and therefore the largest neutron wall loading, ϕ_w , can be obtained in target-plasma operation.(4) In this paper, we are concerned with tokamak plasmas driven by injected neutral beams.(4,5) For a reactor-sized plasma ($B_t a \gtrsim 3$ T-m), the neutral-beam energy, W_o , will be determined in practice by efficiency of production. The desired bulk-plasma temperature, $T_e = T_i$, is determined by the acceptable fusion power multiplication, Q . (Q increases with T_e.(5)) Given T_e and W_o , the attainable values of ϕ_w are determined in part by the magnetic field allowed by technological limitations, and the plasma height-to-width ratio, κ, for which a stable equilibrium is possible. The purpose of this paper is to show how maximum ϕ_w varies with magnetic field and κ, when the constraints on neutral-beam penetration and the total plasma pressure are taken into account.

CALCULATIONAL MODEL

Figure 1 shows a schematic layout of our tokamak reactor. On the inner portion of the torus near the midplane, only a shield (with coolant) is provided, in order to eliminate the problem of accessibility to an inner blanket region. The loss of neutrons that impinge on this region is compensated by the increased B_t at the plasma. Fixed parameters are the thicknesses of the TF (toroidal field) coils (0.6 m), the inner shield (1.0 m), and the plasma scrape-off channel ($\Delta = 0.25$ m). For plasma currents of interest here, viz. $I_p < 5$ MA , a core radius of 1.2 m is adequate. If B_M is the field at the inner TF windings, the field on the magnetic axis is

$$B_t = B_M \frac{1.8}{3.05 + a} \qquad (1)$$

In the following analysis, we fix W_o , T_e , and n_h/n_e , where n_e and n_h are the densities of electrons and energetic ions, respectively. Then Q = constant and

$P_f = n_e^2 P_o$, where $P_o = <\sigma v> E_{fusion}$ is now constant. In this paper, we consider plasmas of rectangular cross section, with half-width a and half-height b, so that $\kappa = b/a$. The average neutron wall loading is then

$$\phi_w = 0.8\ P_f \frac{ab}{a + b + 2\Delta} \propto \frac{n_e^2 a\kappa}{1 + \kappa + 2\Delta/a} \quad (2)$$

The neutral-beam penetration condition may be taken as(6) $\lambda_t/a \gtrsim 0.5$, where λ_t is the mean-free-path for beam trapping.(7) Since $\lambda_t = L(W_o, T_e)/n_e$, the maximum allowed density is given by

$$n_e a = 2L(W_o, T_e) \quad (3)$$

This density must not exceed the maximum value allowed by MHD equilibrium:

$$n_{eM} = \frac{p_{max}}{T_e\left(2 - \frac{n_h}{n_e}\right) + \overline{W}\ \frac{2}{3}\ \frac{n_h}{n_e}} \quad (4)$$

where $\overline{W}$ is the average hot-ion density(4), and the maximum plasma pressure (keV/cm^3) is

$$p_{max} = 2.49\times 10^{15}\left(\frac{B_t S}{qA}\right)^2 \beta_{pmax} \quad (5)$$

Here, $S = 2(1 + \kappa)/\pi$, q is the safety factor at the limiter, $A = 1 + 3.05/a$, and β_p is the poloidal beta. We take $q = 2.5$ and $\beta_p = 2/3\ A$, so that even when all fusion alphas are confined, β_p will be less than the MHD-limiting value of $\beta_p = A$.(8) (Confinement of fusion alphas is not necessary in heavily beam-driven reactors.(4)) Note that variations in B_M and κ are reflected in n_{eM} .

From Eqs. (2) and (3), we have $\phi_w \propto n_e$. To increase ϕ_w by increasing n_e , one must decrease a to satisfy Eq. (3). The minimum allowed a occurs when $n_e = n_{eM}$ given by Eq. (4). Thus maximum ϕ_w is attained when

$$\frac{2L(W_o, T_e)}{a} = n_{eM} = C \frac{a(1+\kappa)^2 B_M{}^2}{(R_1 + a)^3} \tag{6}$$

where $R_1 = 3.05$ m , and C is a constant. Eq. (6) is a cubic equation in a , whose solution then gives n_e from Eq. (3) and ϕ_w from Eq. (2).

QUALITATIVE RESULTS

From Equations (1) to (6), we can immediately deduce some qualitative dependences on κ and B_M , when $A \gg 1$ (i.e., $R_1 \gg a$).

(1) Wall Loading. From Eq. (6), we have

$$a^2 \propto \frac{(R_1 + a)^3}{B_M{}^2} \frac{1}{(1+\kappa)^2} \tag{7}$$

With $n_e a$ = constant and $R_1 \gg a$, Eq. (2) becomes

$$\phi_w \propto \frac{1}{a} \frac{\kappa}{1 + \kappa + 2\Delta/a} \propto \frac{B_M\,\kappa}{1 + \frac{2\Delta/a}{1+\kappa}} \tag{8}$$

Thus ϕ_w is proportional to B_M , and also to κ , if $1 + \kappa \gg 2\Delta/a$. (This linear dependence, which is a consequence of Eq. (3), differs strikingly from that of an ignited thermonuclear reactor, where $\phi_w \propto B_M^4(1 + \kappa)^3$, since the plasma radius need not be reduced with increasing n_e.)

(2) Beam Power. $P_{beam} = P_f \times$ (plasma volume)/Q

$$= n_e^2 P_o 8\pi(R_1 + a)a^2\kappa/Q \qquad (9)$$

For $R_1 >> a$ and $n_e a$ = constant, P_{beam} is proportional to κ, and independent of magnetic field.

(3) Plasma Current. For constant q, we have

$$I_p = \frac{C_1 a^2 B_M(1 + \kappa)^2}{(R_1 + a)^2} \qquad (10)$$

where C_1 is a constant. Using Eq. (7) with $R_1 >> a$, we have $I_p \propto 1/B_M$. To this approximation I_p is independent of κ.

QUANTITATIVE RESULTS

Equation (6) can be solved exactly for a, as a function of κ and B_M. The qualitative dependences on κ and B_M given above do not require knowledge of W_o, T_e, and n_h/n_e. These quantities must now be specified, in order to determine L and C in Eq. (6). Once a is determined, P_{beam}, I_p, and relative ϕ_w can be obtained from Eqs. (9), (10), and (2), respectively. The absolute value of ϕ_w (and Q) depends on the relative proportion of D and T in the bulk plasma and in the energetic ion distribution. (In practice, the plasma composition is determined by the methods employed for fueling and for particle exhaust.(4))

The maximum κ at which plasma stability at low q is still possible is $\kappa \simeq 3$, for rectangular cross sections.(9) With NbTi TF windings, B_M up to 9.5 T is feasible, while Nb_3Sn windings would permit B_M up to 16 T, provided that the magnet strain is tolerable. In this section, we use $T_e = 6$ keV, $W_o = 200$ keV, $n_h/n_e = 0.15$, since these values are typical of most beam-driven tokamak designs intended for operation at $Q \sim 1$.(1,2,4) Figure 2(a) shows the dependence of plasma radius on κ and B_M, calculated from Eq. (6) when $Z_{eff} = 1$. Figure 2(b) shows relative values of ϕ_w. Provided that $a \ll R_1$ $(A \gg 1)$, ϕ_w increases nearly linearly with κ and B_M, as expected. Absolute values of ϕ_w are given for the practical case of D^o injection into a background plasma maintained at 78% tritium, 22% deuterium, so that $Q = 1.0$. (The tritium is fueled by pellet injection.) Evidently, wall loadings as large as 5 MW/m^2 are attainable, provided that both large B_M and κ are utilized.

Figure 3 shows P_{beam} and I_p for the same W_o, T_e, n_h/n_e. As expected, P_{beam} is nearly proportional to κ, but only weakly sensitive to B_M, for $B_M \gtrsim 9T$. In this range, I_p is rather insensitive to κ, but nearly inversely proportional to B_M. Thus the qualitative dependences derived previously are valuable guides to reactor design, provided that $R_1 \gg a$. When this approximation is valid, the <u>relative</u> ϕ_w curves of Fig. 2(b) are reasonably "universal," that is, independent of W_o, T_e, n_h/n_e. Furthermore, we obtain similar results for other plasma shapes, such as elliptical.

If the plasma contains an impurity-ion population, then $L(W_o,T_e)$ is nearly inversely proportional to Z_{eff}, the effective ionic charge.(10) For the same κ and B_M, the plasma radius must be reduced, unless W_o can be increased. The variation of reactor characteristics with κ and B_M will be similar to those shown in the figures, but with different numerical values. If beam injection at oblique angles with respect to the plasma current can be employed, then the present numerical results would actually apply for $Z_{eff} \lesssim 2$.

For some applications, such as a materials test reactor that requires large wall loading with minimum power consumption, the most important criterion may be maximization of ϕ_w/P_{beam}. From Eqs. (8) and (9), we see that this quantity is proportional to B_M and nearly independent of κ. Therefore, the most appropriate operating point is $\kappa = 1$ and $B_M = 16$ T, requiring 300 MW of injected power and delivering 1.65 MW/m^2, for the plasma parameters used above.

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REFERENCES

1. R.W. CONN, D.L. JASSBY, "A Tokamak Engineering Test Reactor," Princeton Plasma Physics Lab. Report MATT-1155 (1975).
2. R.P. ROSE, et al., "Fusion-Driven Actinide Burner Design Study," Westinghouse Electric Corp. Reports WFPS-TME-003, 024 (1975).
3. L.M. LIDSKY, Nucl. Fusion 15 (1975) 151; S.L. BOGART, ed., Proc. DCTR Fusion-Fission Energy Systems Review Meeting, U.S.E.R.D.A. Report ERDA-4 (1975).
4. D.L. JASSBY, Nucl. Fusion 14 (1975) 453.
5. H.L. BERK, et al., in Plasma Physics and Controlled Nuclear Fusion Research (Proc. Fifth Int. Conf., Tokyo, 1974), paper CN-33/G2-3 (to be published).
6. J.A. ROME, J.D. CALLEN, J.F. CLARKE, Nucl. Fusion 14 (1974) 141.
7. A.C. RIVIERE, Nucl. Fusion 11 (1971) 363.
8. V.S. MUKHOVATOV, V.D. SHAFRANOV, Nucl. Fusion 11 (1971) 605.
9. M. OKABAYASHI, G.V. SHEFFIELD, Nucl. Fusion 14 (1974) 263.
10. J. P. GIRARD, et al., in Plasma Physics and Controlled Nuclear Fusion Research (Proc. Fifth Int. Conf., Tokyo, 1974), paper CN-33/A17-2 (to be published); J. SHEFFIELD, Proc. Seventh European Conf. on Controlled Fusion and Plasma Physics I (Lausanne, 1975) 21.

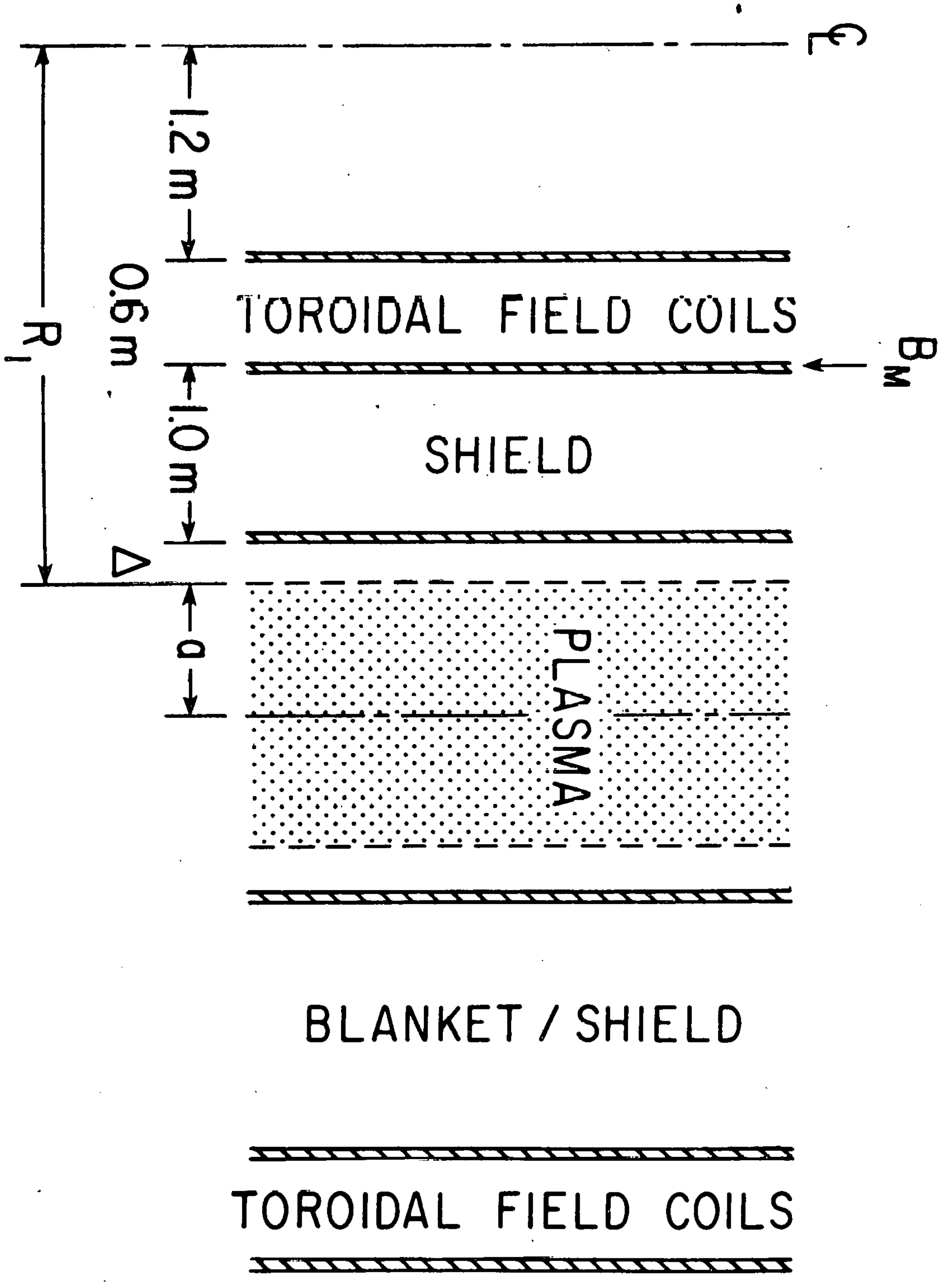

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Fig. 1. Schematic layout of the tokamak reactor in the midplane.

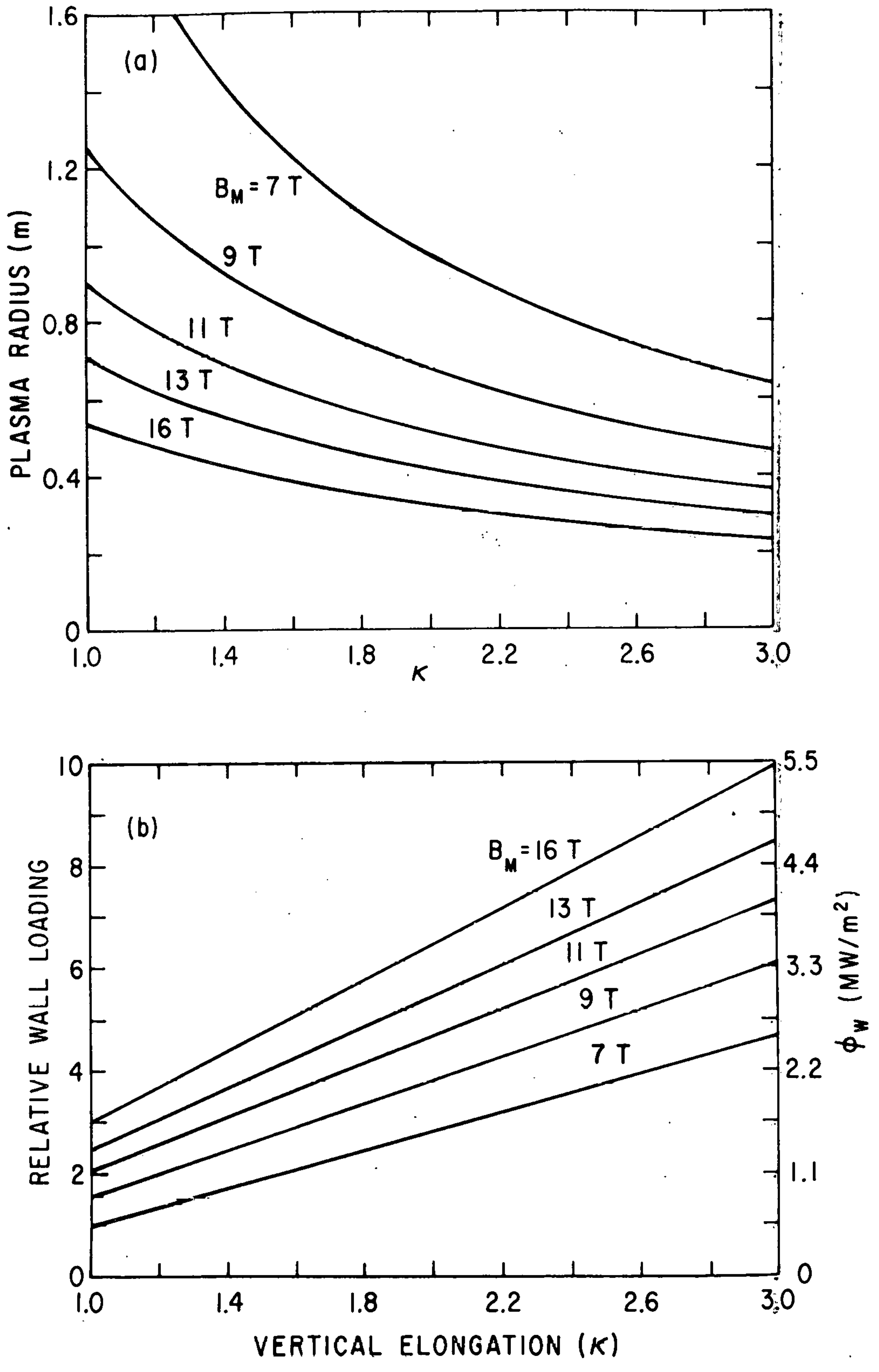

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Fig. 2. (a) Plasma radius when the density is limited both by the neutral-beam penetration requirement and by the allowed plasma pressure (β_p = 2/3 A). W_o = 200 keV (D^o), T_e = 6 keV, n_h/n_e = 0.15, q = 2.5. B_M = magnetic field at the TF coils. (b) Neutron wall loading (uncollided 14-MeV) with plasma conditions as in (a). The right-hand scale is for Q = 1.0. (Target plasma 78%T, 22%D.)

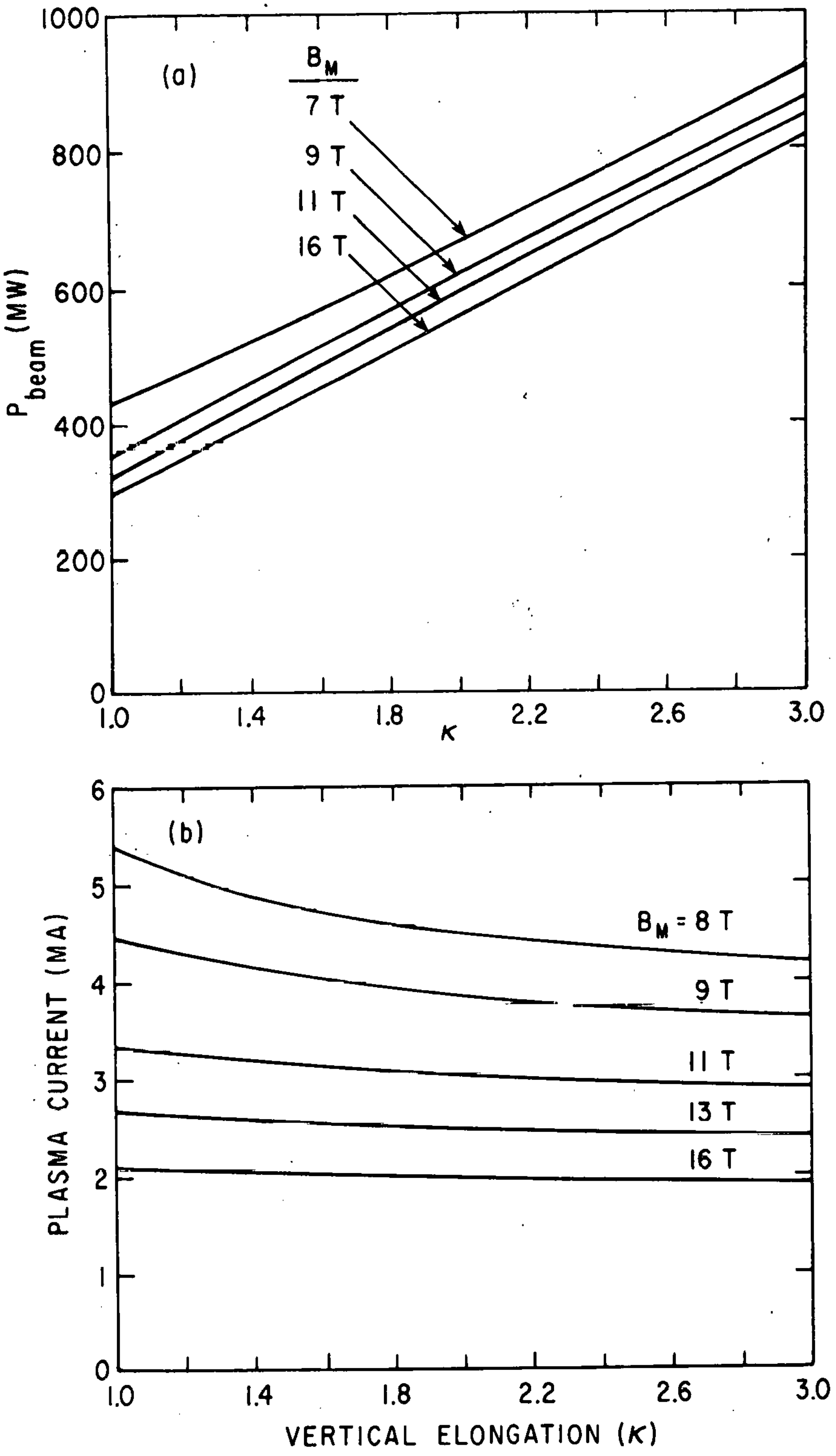

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Fig. 3. (a) Injected beam power and (b) plasma current for conditions of Fig. 2.