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The Use Of A Hot Sheath Tormac for Advanced Fuels

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July 1977

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THE USE OF A HOT SHEATH TORMAC FOR ADVANCED FUELS

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Abstract

The use of hot electrons in a Tormac sheath is predicted to improve stability and increase $n\tau$ by an order of magnitude. An effective $n\tau$ for energy containment is derived and system parameters for several advanced fuels are shown. In none of the advanced fuels cases considered is a reactor with fields greater than 10 Wb/m^2 or major plasma radius of more than 3 m required for ignition. Minimum systems have power outputs of under 100 MW thermal. System parameters for a hot sheath Tormac have a wide latitude. Sizes, magnetic fields, and operating temperatures can be chosen to optimize engineering and economic considerations.

The use of a D-T fuel for a fusion reactor has the advantage of needing the lowest temperature and lowest $n\tau$ of any fuel so far considered. On the other hand, fuel such as D-D, D^3-He, and $P^{11}B$ offer advantages over D-T either in reduced radiation, less waste heat, or simpler handling. The problem is to find a reactor system that can meet the more stringent requirements of an advanced fuel system by sustaining the higher temperatures and longer containment times. In this paper the operation of a hot sheath Tormac is discussed as an answer to this problem.

Tormac [1] (toroidal magnetic cusp) is a cusp magnetic field configuration that has an absolute minimum-B geometry. The advantage of absolute minimum-B is that it is MHD stable at high β. The importance of this to advanced fuel systems is that the magnetic field within the plasma can be reduced to very small intensities so as to miminize synchrotron radiation. In Tormac the local β can be made as high as 4 without degrading the containment time. Higher β values are possible with only a small cost in containment time.

In Tormac a high β plasma is held in the surface by a cusp magnetic field. A four-pole line cusp is illustrated in Fig. 1 with a pressure profile shown in Fig. 2. The absolute minimum-B geometry implies (Jukes theorem) [2] that the plasma pressure is held on open field lines. If we define the sheath as the surface region over which the pressure change occurs, then this region must contain open magnetic field lines.

A crucial feature of Tormac is the containment of particles on open field lines. In the sheath region, particles are trapped between collisions by a canonical invariant [3], and an adiabatic invariant [4]. These invariants combine to give mirror-like trapping in the sheath. The only way a particle can escape from Tormac is along an open field line so that the loss rate is determined in the sheath. In the ideal case, the sheath loss is due only to interparticle collisions. These collisions scatter particles into the loss cone. Since the probability of loss is then about equal to the probability of cross field diffusion, the sheath thickness is about an ion gyroradius, r_i. The containment time for such a system is then given by

$$n\tau = 0.1\ R_p/r_i\ \tau_{ii} \tag{1}$$

where τ_{ii} is the ion collision time and R_p is the plasma characteristic minor radius. The factor 0.1 includes geometric factors and implies a cusp mirror ratio of about 1.5. For most reactor designs R_p/r_i is the order of 100.

If collisions are classical, τ_{ii} is large enough for most reactors. On the other hand, microturbulence in the sheath could lead to an effective τ_{ii} much lower than classical. Recent 2XII results [5] have indicated a degradation of τ_{ii} by about five; however, in Tormac magnetic field shear is thought to reduce this factor [6].

A second effect that could increase the particle loss rate from the sheath is the drift of particles from the main plasma into the sheath region. This drift can be prevented by including a twist in the magnetic field lines inside the region of open field lines. This rotational transform can be accomplished by including in the plasma a toroidal current and resulting poloidally closed magnetic field component.

The question of how small the internal magnetic field can be in Tormac is tied to the drift problem. Fortunately, it is only the particles whose velocities are most closely aligned with the magnetic field that are lost from the sheath [4]. In the boundary between the sheath and the internal region there are the particles whose "banana" orbits are virtually the same size as the particle orbit in the toroidal magnetic field. Thus, when the gyroradius in the internal toroidal field is larger than the sheath thickness, the containment time for the device is degraded. For a sheath thickness of $2r_i$, this occurs when $\beta > 4$.

The implementation of the internal magnetic field can best be discussed in terms of a specific example. In the current Tormac experiments the toroidal bicusp [7] shown in Fig. 3 is used. In this shape the radius of curvature of the magnetic field lines in the surface of the plasma is negative as required for an absolute minimum-B geometry. This is accomplished by having the magnetic field lines at small radius dominated by the toroidal component of field and the intensity of the field lines at the outer toroidal radius dominated by the poloidal component of field.

Limiting the number of cusps to two, as shown in the bicusp, has several advantages over shapes with a larger number of cusps. Experimentally, fewer cusps reduces the complexity of the device and makes it easier to produce the required magnetic field shaping without bringing the coils too close to the plasma. Theoretically, the bicusp reduces the particle loss cone [3] and optimizes the volume to surface ratio.

A possible poloidal configuration for a bicusp is given in Fig. 4. There is indicated in Fig. 4 a poloidal reversal in the sheath. It should be remembered in considering this diagram that the toroidal magnetic field is present everywhere. What appears as a region field reversal is only a region of mild field shear. Thus while the field reversal region appears as a critical region in this drawing, theory indicates a positive stability of this region. In particular, if the radius of curvature of the field line is negative over the pressure surface the flow of material in this region goes at the diffusion rate [8].

The closed poloidal magnetic field line in this figure exhibits bad curvature in the cusp region. Stability in this region depends on an average minimum-B, averaging the short cross over distance in the cusps with the good curvature over the rest of the device [9]. Fortunately the bad curvature region is small, and the curvature, dominated by the toroidal magnetic field, is large.

To estimate the stability of this region of unfavorable curvature in the cusp, one can use the relationship $\beta \ell^2 < R_\ell S$ [10], where $\beta = 8\pi\, n k\, t/B^2$ where ℓ is the connection length; R_ℓ is the radius of curvature of the magnetic field line; and S is the pressure gradient length. Assume about half the plasma pressure is supported on closed magnetic field lines. In the cusp region the closed poloidal magnetic field line extends about $R_p/2$ from the plasma. If this field supports one half the plasma pressure, $S \sim R_p$ estimating the strength of the toroidal and poloidal component strength the connection length from one side of the cusp to the other is about $R_p/2$. The curvature is then about $R_p\, A/2$ where A is the aspect ratio. Using the above values, stability requires $\beta < 2A$. For $A = 3$ this restricts $\beta < 6$.

The use of closed poloidal magnetic field lines to support part of the plasma pressure in the bicusp is a way to limit particle drifts and to improve the $n\tau$. However, the use of such a field opens another possibility.

As mentioned above a most serious question about Tormac is the sheath stability against microturbulence. In particular, the drift cyclotron loss cone modes with frequencies between ω_i and $(\omega_i \omega_e)^{\frac{1}{2}}$ are predicted to be mildly unstable. In the 2XII experiment these instabilities were saturated at low levels with cold ions. Part of the problem is that because of the negative potential found in mirror contained plasmas, all low energy ions are promptly lost from the plasma.

One method of curing this problem is to heat the electrons so that their loss rate matches or is less than that of the ions. Without an internally closed poloidal magnetic field to control electron thermal conductivity this would be impossible. This internal reverse field Tormac makes it possible to hold hot electrons in the sheath.

The ability to maintain a stable, hot, nonisotropic electron density in the presence of cooler ions has been experimentally demonstrated [11] and a method of producing such plasmas is currently under development [12]. Hot electrons have previously been proposed as a method of improving electron thermal conductivity along magnetic field lines and the tolerance of the sheaths to a neutral gas background [13]. These are not seen as severe problems in a conventional Tormac. However, hot electrons do have a dramatic effect on the classically predicted sheath containment time.

To calculate the time constant for a hot electron sheath, consider the case of a D-D plasma with a temperature of T_i.

The electrons in the sheath are maintained (say by microwaves) at 24 T_i so that the sheath time, $\tau_s = \tau_{ii} = \tau_e$. The sheath pressure is $n_e \ (T_i + T_e) = 25 \ n_e \ T_e$. One representative solution to the magnetic profile in the sheath is given by

$$B = B_c \tanh^2 (x_\perp / \lambda), \tag{2}$$

where B_c is the cusp field intensity just outside the plasma surface. So that for equilibrium

$$N_e \ (T_e + T_i) \sim (B_c^{\ 2} - B^2)/8\pi. \tag{3}$$

This implies that in the region where $T_e = 24 \ T_i$ the density n_e is 1/12.5 the value it would have if $T_e = T_i$. Correspondingly, the sheath time constant τ_s is 12.5 times as large as it would be for a cold sheath Tormac.

If a fraction α of the plasma pressure is supported on open field lines, then the particle loss rate is further reduced by

$$\gamma = \int_\alpha^\infty n_e^{\ 2} \, dx_\perp \Big/ \int_0^\infty n_e^{\ 2} \, dx_\perp \tag{4}$$

where n_e is determined from Eq. (3) (using the value of T_e on the open field lines). Taking $1/\gamma = 4$ the sheath loss time is a factor of

60 longer than the normal case. Thus from Eq. (1)

$$(n\tau)_p = 5\ n\tau_{ii}\ R_p/r_i$$

$$(n\tau)_p = 3.6 \times 10^{13}\ R_p\ (\mathrm{m})\ B\ T\ \mathrm{keV\ sec/cm^3}. \qquad (5)$$

Figure 5 shows diagrammatically the pressure and density profiles for a hot sheath.

$(n\tau)_s$ as calculated is misleading in the sense that the energy balance mearly equates the energy loss rate to the plasma energy density. However, as idealized most of the energy loss is carried by the hot electron which must be pumped up from an external source. Thus, the ion loss rate and the flow out of energy produced in the plasma is very small. If in practice, the ion loss rate is too small, the spatial distribution of hot electrons can easily be modified to open up a region where ions can escape more rapidly. The increased ion loss rate would also carry with it internally generated plasma energy, and prevent a temperature build up.

Equation (5) neglects synchrotron radiation. For a hot sheath Tormac, synchrotron radiation gives

$$(n\tau)_s = 7.1 \times 10^{20}\ R_p(\mathrm{m})\ T_i^{-5/2}\ (\mathrm{keV})\ \mathrm{sec/cm^3} \qquad (6)$$

Equation (6) assumes the synchrotron radiation is 0.1 times the single particle loss rate.

The combined $n\tau\ T_i$ due to the sum of both particle losses and synchrotron radiation is shown in Fig. 6.

Curves are drawn for $R_pB = 1$ and $R_pB = 10$. Also plotted are the ignition curves for various reactions. Thus the curve intersections represent operating parameters for ignition reactor. These curves neglect bremsstrahlung radiation.

The net power P produced in charged particles for systems is given by

$$P = \frac{2\ \pi^3\ A\ R^3_p\ B^4}{2\ n\ T_i\ \tau} \tag{7}$$

Typically for D-T, $R_pB = 1$, $A = 3$, the total thermal output including neutrons is about 70 MW thermal. For $p{-}^{11}B$, $R_pB = 5$ only about 2 MW is produced. Other reactions give intermediate power output. It must be pointed out that the long time constants and low reaction rates predicted for these minimum systems require vacuum pressures surrounding the plasma that may be difficult to realize in practice.

The use of heated electrons both stabilizes the sheath and improves the $n\tau$ by about an order of magnitude. Thus, the hot sheath Tormac can support almost any of the known reactions at ignition with a very modest size system.

In conclusion, it might be stated that system parameters for a hot sheath Tormac have a wide latitude. Sizes magnetic fields, and operating temperatures can be chosen to optimize engineering and economic considerations.

ACKNOWLEDGMENTS

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REFERENCES

[1] COMBES, L. S., GALLAGHER, C. C., LEVINE, M. A., Phys. Fluids 5 (1962) 1070.

[2] JUKES, J. P., Rep. Prog. Phys. 31 (1968) 305.

[3] LEVINE, M. A., BOOZER, A. H., KALMAN, G., BAKSHI, P., Phys. Rev. Lett. 28 (1972) 1321.

[4] BOOZER, A. H., LEVINE, M. A., Phys. Rev. Lett. 31 (1973) 1287.

[5] COENSGEN, F. H., CUMMINGS, W. F., LOGAN, B. G., MOLVIK, A. W., NEXSEN, W. E. SIMONEN, T. C., STALLARD, B. W., TURNER, W. C., Phys. Rev. Lett. 35 (1975) 1501.

[6] GLADD, N. T., DAVIDSON, R. C., GOREN, Y., LIU, C. S., Phys. Fluids (to be published).

[7] LEVINE, M. A., Bull. Am. Phys. Soc. 17 (1972) 1040.

[8] FURTH, H. P., KILLEEN, J., ROSENBLUTH, M. N., Phys. Fluids 6 (1963) 459.

[9] FURTH, H. P., in "Advances in Plasma Physics" (SIMON, A. and THOMPSON, W. B., Eds.) Wiley Interscience (1968), Vol. 1, p. 67.

[10] JOHNSON, J. (private communication).

[11] SIEBERMAN, M. A., LICHTENBERG, A. J., TEKESHITA, T., Plasma Phys. (GB) 13 (1971) 141.

REFERENCES

[12] DANDL, R. A., et al., in *Plasma Physics and Controlled* Nuclear Fusion Research (Proc. 5th Int. Conf. Tokyo 1974) 2, IAEA, Vienna (1975) 141.

[13] FURTH, H. P., Comments Plasma Phys. Controlled Fusion 2, 119, (1976).

[14] McNALLY, Jr., J. R., IEEE Int. Conf. Plasma Science, Troy, N. Y. (1977).

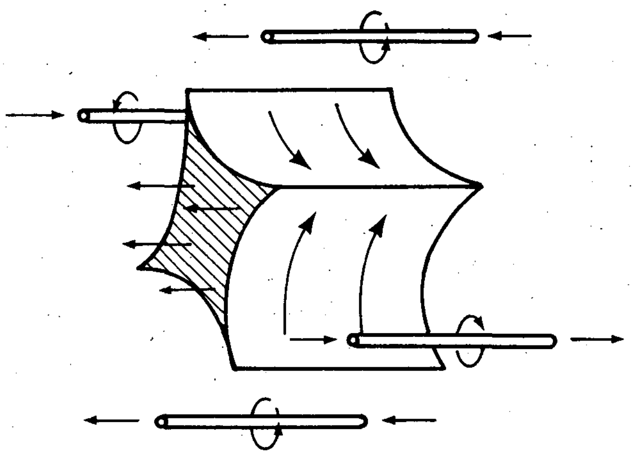

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Fig. 1. Tormac

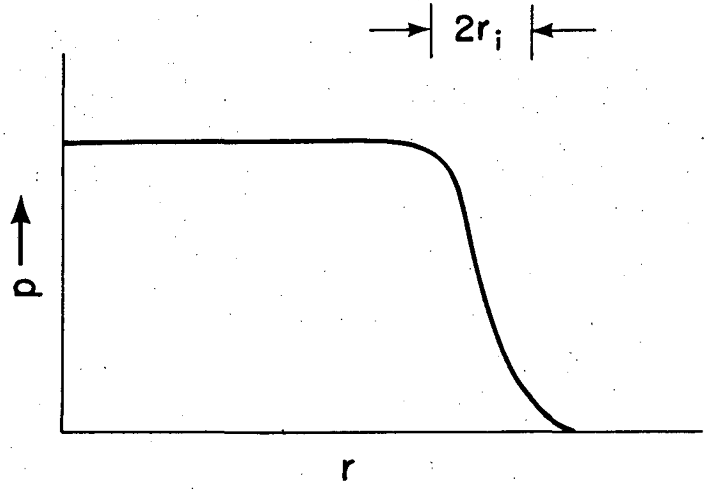

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Fig. 2. Pressure vs radius.

REFERENCES

[12] DANDL, R. A., et al., in Plasma Physics and Controlled Nuclear Fusion Research (Proc. 5th Int. Conf. Tokyo 1974) 2, IAEA, Vienna (1975) 141.

[13] FURTH, H. P., Comments Plasma Phys. Controlled Fusion 2, 119, (1976).

[14] McNALLY, Jr., J. R., IEEE Int. Conf. Plasma Science, Troy, N. Y. (1977).

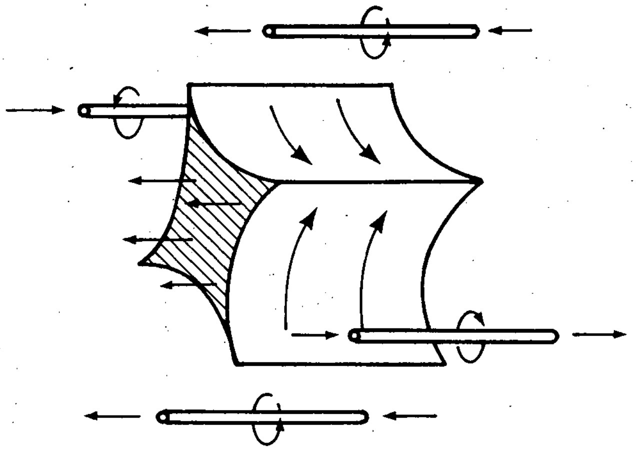

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Fig. 1. Tormac

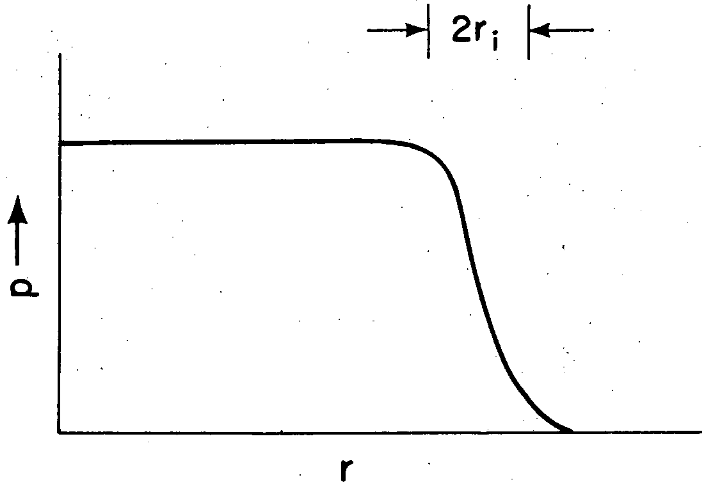

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Fig. 2. Pressure vs radius.

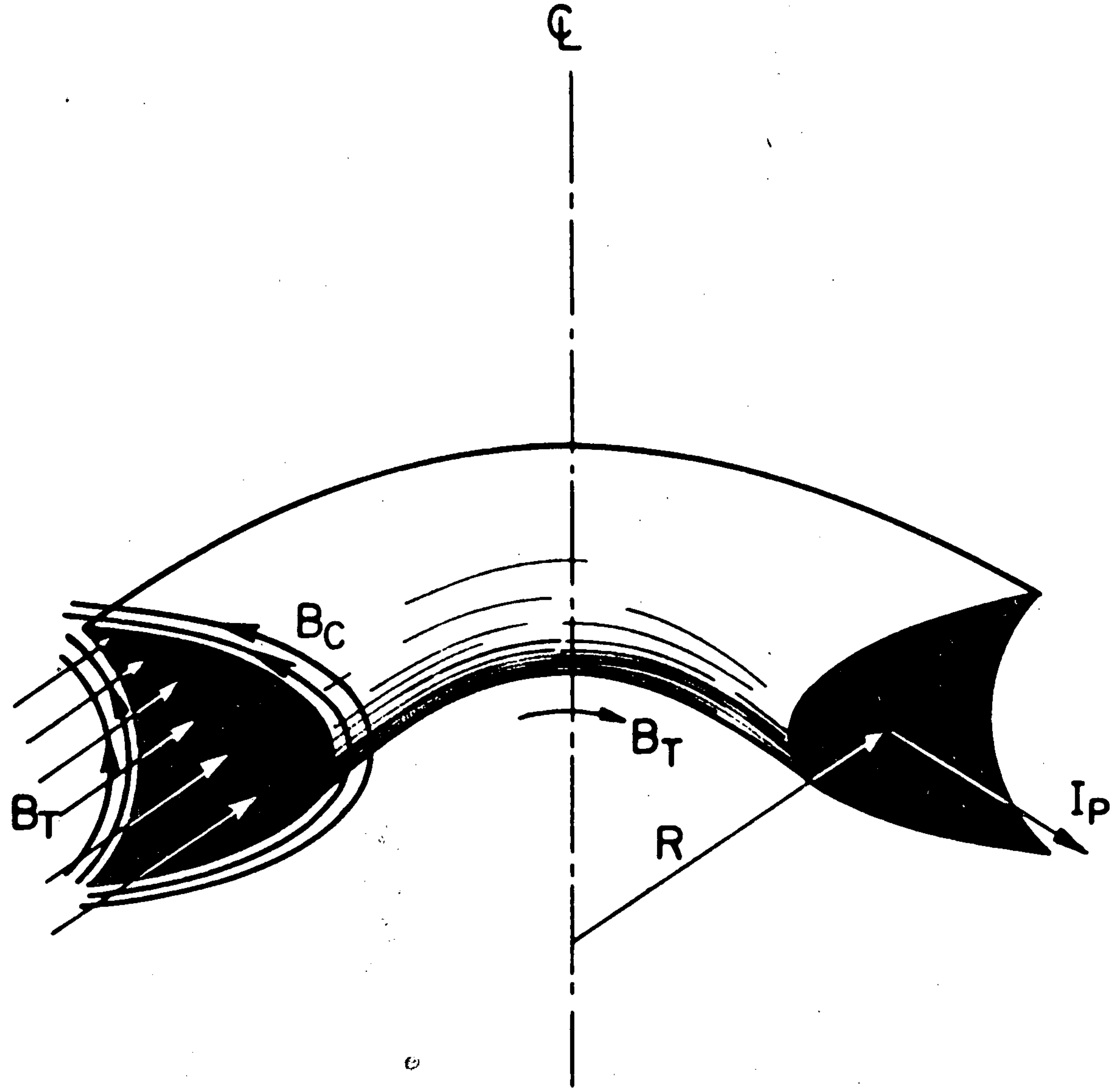

Fig. 3. Toroidal bicusp

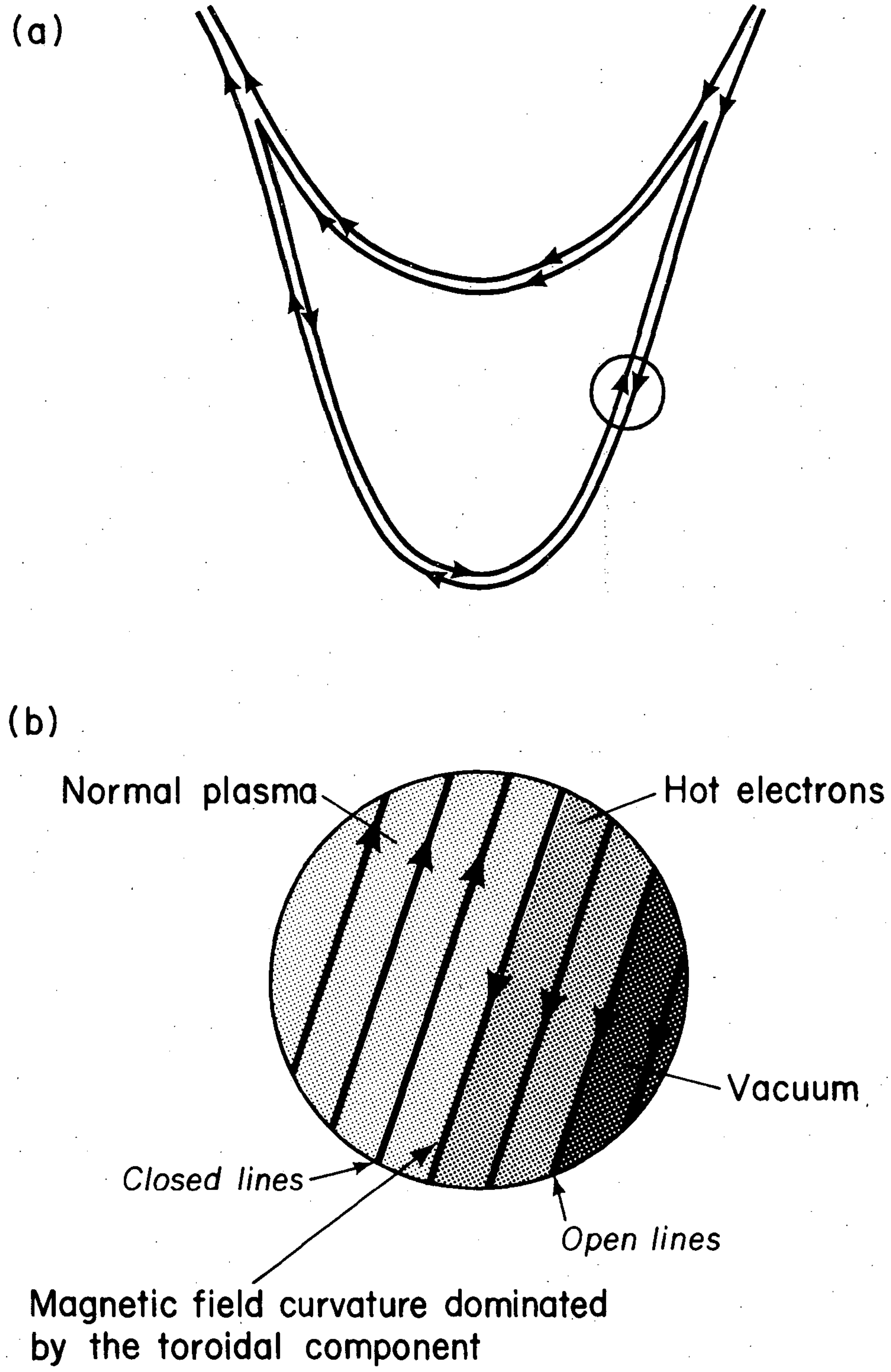

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Fig. 4. Cross sections of bicusp with internally closed poloidal field.

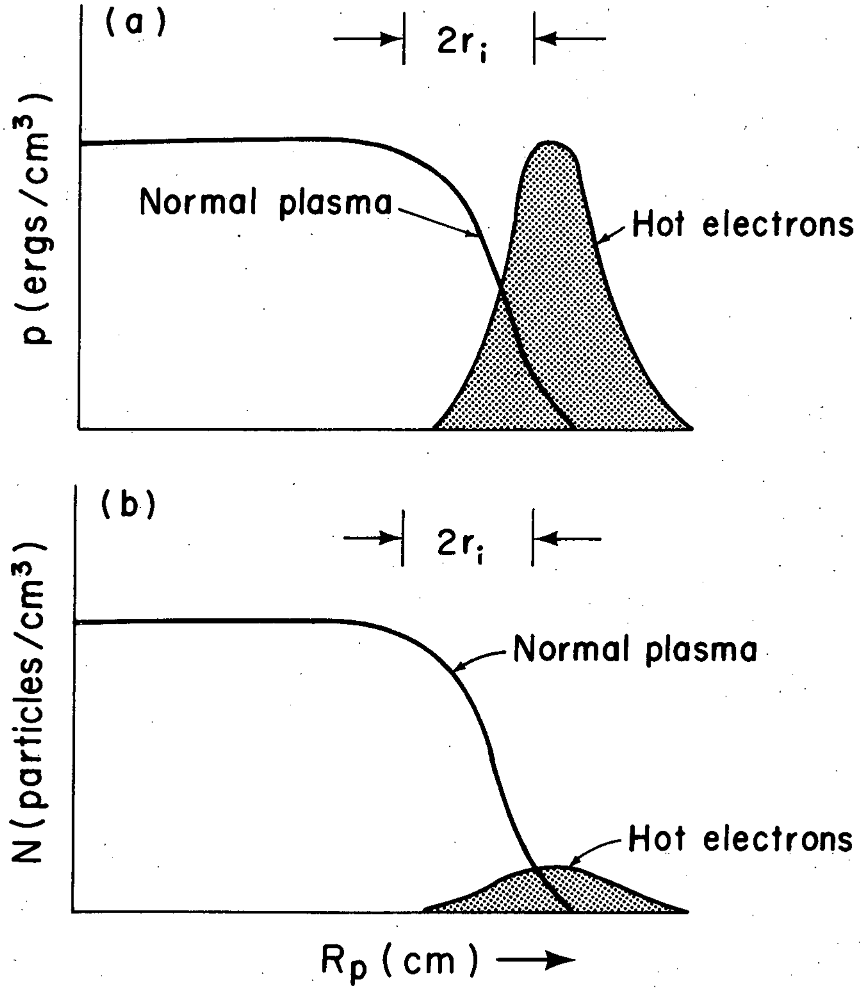

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Fig. 5. (a) Pressure vs radius for a Tormac bicusp with a hot electron sheath.

(b) Density vs radius for a Tormac bicusp with a hot electron sheath.

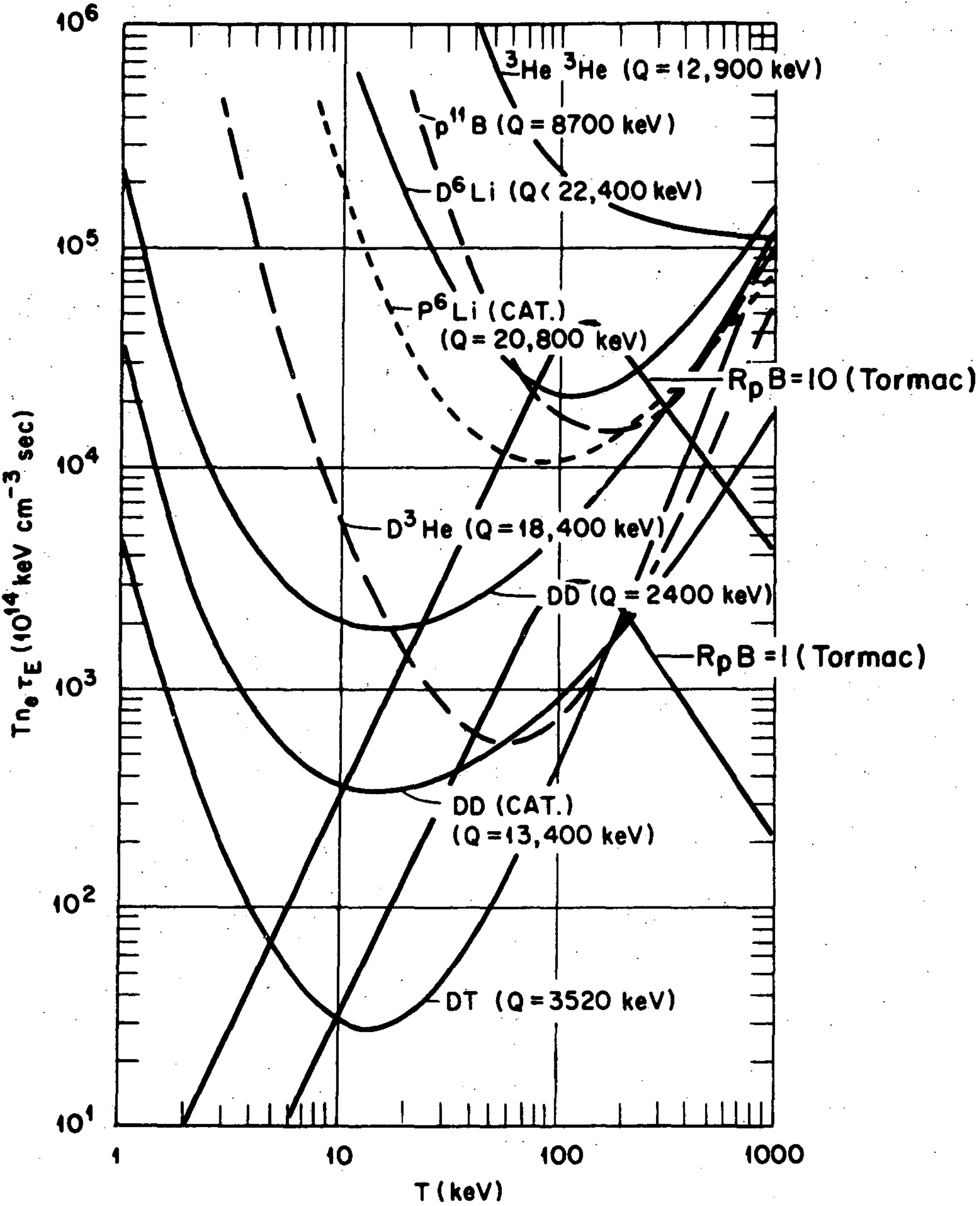

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Fig. 6. Tormac energy loss parameter ($T\ n_e\ \tau_E$) for R_p(m) B(Tesla) = 1 and R_pB = 10 plotted on top of ignition curves as given by J. R. McNally, Jr. [14]. These curves do not include bremsstrahlung losses.

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