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POTENTIALITY OF THE PROTON-BORON FUEL FOR CONTROLLED THERMONUCLEAR FUSION

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ABSTRACT

The reaction $p + {}^{11}B \rightarrow 3\alpha + 8.7$ MeV is evaluated as a potential fuel for a controlled thermonuclear fusion reactor.

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1. INTRODUCTION

Several nuclear reactions other than D-T have been investigated already to a large extent for producing fusion power with the hope that working temperatures in the 100 keV range will be attainable. The resulting "advanced" fuel cycles are the D-D or "catalyzed" D-D cycle and the D-^{6}Li cycle which have the common characteristic that they release a large amount of high energy neutrons, although less than the classical D-T cycle. However there are several reasons for which "neutron-free" fusion reactions would be very attractive provided that their cross section and energy release are large enough. Among the disadvantages of the previous fuels are:

- The necessity of having a thick and sophisticated blanket around the plasma. This blanket increases very much the size of the reactor and has a bad economic repercussion on fusion power generation.

- The radiation damage and the radioactivity induced by these intense neutron fluxes in the blanket which tend to reduce the advantage of fusion power over fission power as far as cleanliness, is concerned.

On the other hand, charged-particle fusion reactions are interesting for the following reasons:

- All the energy released in such a reaction is given to the unburned plasma thus contributing to the self-sustainment of the burning.

- Charged-particle reactions are very well suited to direct energy conversion, a scheme which might reach 60-70% efficiency, whereas the energy carried by escaping neutrons must be recovered through a Carnot cycle with at most 40% efficiency.

Among the few "neutron-free" fuel cycles that are possible, the proton-boron cycle, based on the reaction $p + {}^{11}B \rightarrow 3\alpha + 8.7$ MeV, has been pointed out only recently as being of interest for fusion. The work that is reported here evaluates its potentiality and makes more precise evaluations of characteristics that have previously led to many unfounded speculations.

2. MAIN CHARACTERISTICS OF ^{11}B AS A THERMONUCLEAR FUEL

One of these characteristics has been presented in the introduction, namely the absence of large neutron fluxes and the associated advantages for the reactor design. Other features of the hydrogen-boron fuel can be listed as follows:

- The p-^{11}B reactivity, as calculated from this work (Section III), is comparable with that of the best thermonuclear fuels at high temperatures [2].

- The bremsstrahlung losses will be large because of the high charge of boron and the relative concentration of boron will have to be rather low.

- The most troublesome side reaction is $^{11}B(p,\gamma)^{12}C$ yielding very high energy gamma rays (97% at 12 MeV and 3% at 16 MeV). However the branching ratios for these reactions are very low, respectively 5×10^{-5} and 2×10^{-6} for the range of temperatures in which we are interested, so that materials like water or simple metals can be used to provide an adequate biological shielding.

- Although there would be no large neutron fluxes, some neutrons would be generated by $^{11}B(p,n)^{11}C$ which has a branching ratio of 1.5×10^{-5} and $^{11}B(\alpha,n)^{14}N$ which has a very low cross section and involves the fusion-boron alpha particles present in very low concentration. On the other hand, these neutrons are soft, their energy being mainly below 3 MeV.

- The separation of ^{11}B from ^{10}B in an economical way is already well developed.

- Finally, natural boron is composed 80% of boron-11 and is very abundant. Moreover, it is cheaply available.

In conclusion, p-^{11}B looks, at first sight, like a very good competitor in the choice of the thermonuclear fuel cycle for a future energetic economy based on fusion power. However, it is still to be proved that a reactor burning such a fuel can be ignited and produce net power.

3. REACTION RATE

3.1 CROSS SECTION DATA FOR $^{11}B(p,2\alpha)\alpha$

The experimental data for the p-^{11}B reaction being still very crude, two estimates of the cross section as a function of the proton energy have been made in this work, an optimistic one and a pessimistic one. The cross section shows several resonances corresponding to the energy levels of the compound nucleus ^{12}C. This compound nucleus decays to 3α mostly via α + ^{8}Be, ^{8}Be decaying immediately to 2α in comparison with other time scales.

At low energies the cross section is given by the Gamow extrapolation [3]:

$$\sigma(E_p) = \frac{1.09 \times 10^5}{E_p} \exp\left(-\frac{157}{\sqrt{E_p}}\right) \text{ barns}$$

where E_p is the proton energy in the laboratory frame in keV. This approximation is used up to $E_p = 140$ keV. Above this energy the cross section is obtained from the resonance data (cf. Table I). In the vicinity of the peaks a good approximation of the Breit-Wigner formula is given by a Lorentz line shape function:

$$\sigma(E) = \frac{\sigma_R \Gamma^2}{4\,(E - E_R)^2 + \Gamma^2}$$

in which σ_R and E_R are the cross section and energy at the resonance, and Γ the total width of the excited state $^{12}C^*$. Seven resonances have been taken into account; their characteristics are listed in Table I according to references [3], [4], [5], [6], [7], and [8]. The resultant cross section is plotted in Fig. 1 where the curve has been drawn between the peaks by following as closely as possible the available experimental data.

3.2 CALCULATION OF THE REACTION RATE

The number of fusion reactions taking place in the plasma per unit time, per unit volume is given by the classical expression:

$$\frac{dN}{dt} = n_p\, n_B \, \langle \sigma v \rangle$$

Table I: Characteristics of the Main $^{11}B(p,\alpha)^{8}Be$ Resonances

Peak number	E_p (MeV)	$\Gamma_{c.m.}$ (keV)	σ_R (mb)	References
1	0.163	6.4 - 6.7	10.2 - 41.7	Fowler, Anderson
2	0.675	295 - 300	600 - 840	Fowler, Segel
3	1.39	1150 - 1160	156 - 183	Ajzenberg-Selove, Fowler
4	1.98	92 - 110	30 - 34*	Ajzenberg-Selove, Segel, Symons
5	2.62	310 - 320	200 - 347	Ajzenberg-Selove, Segel, Symons
6	3.75	1100	220 - 348	Ajzenberg-Selove, Segel, Symons
7	4.93	180	130 - 210	Ajzenberg-Selove, Symons

*In Figure 1, the resonant cross section is 113 - 132 mb because of the strong influence of the third peak which must be added to the 30 - 34 mb of the fourth resonance.

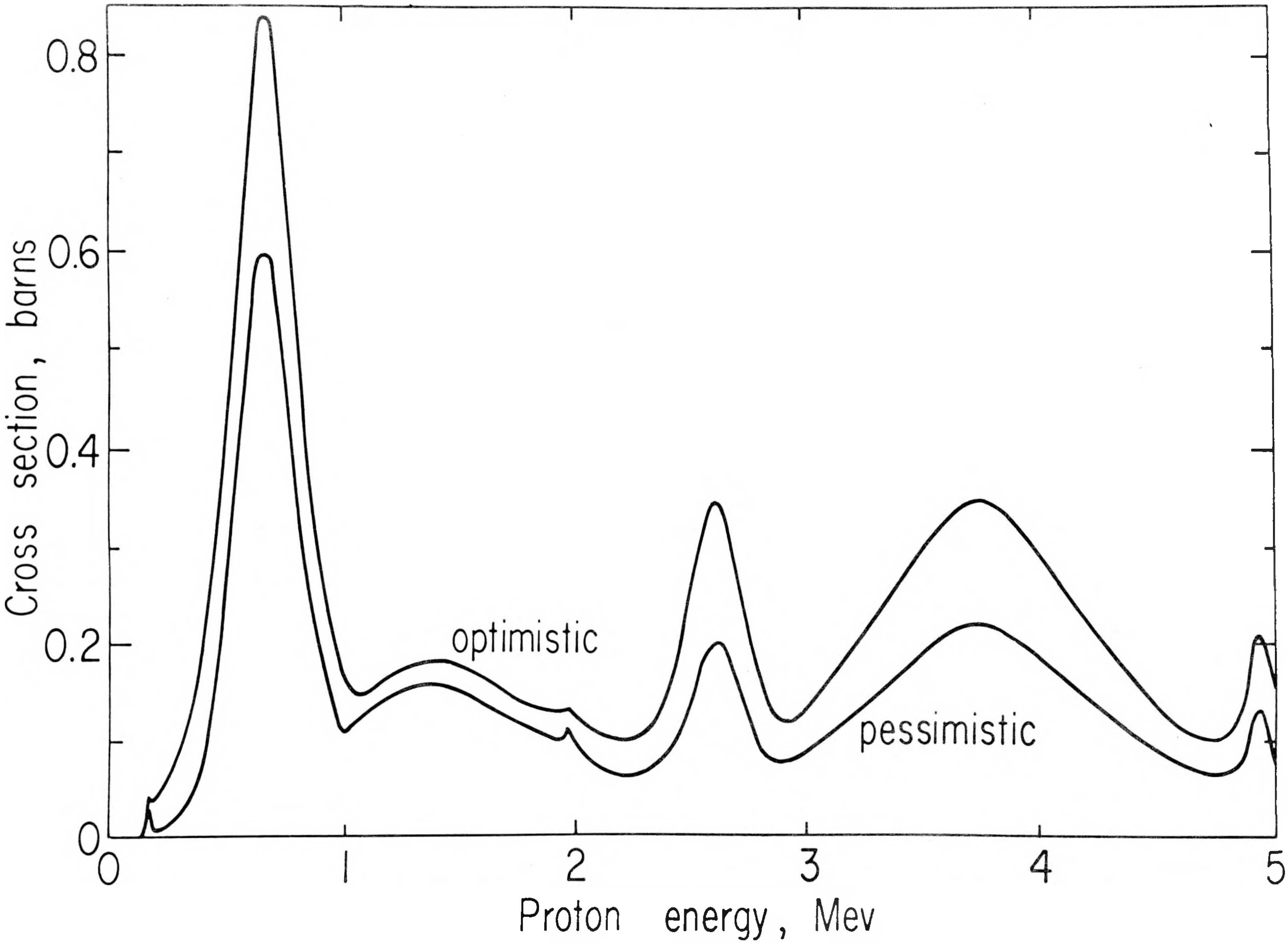

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FIG. 1. $^{11}B(p,2\alpha)\alpha$ cross section versus proton energy.

where n_p is the proton density, n_B the boron density and $<\sigma v>$ the reaction rate parameter obtained from:

$$<\sigma v> = \frac{8\pi}{m_p^2}\left[\frac{M}{2\pi kT_i}\right]^{3/2}\int_0^\infty e^{-\frac{ME_p}{m_p kT_i}}\ \sigma(E_p)\ E_p\ dE_p$$

where we assume a Maxwellian ion distribution at temperature T_i. E_p is the proton energy in the laboratory frame, m_p the proton mass and M the reduced mass of the proton-boron-11 system. The reactivity, $<\sigma v>Q$, where Q = 8.7 MeV, is plotted in Fig. 2 versus ion temperature both for the optimistic and pessimistic cross section data.

A rough criterion based on an energy balance as well as economical and technological considerations has been published for selecting thermonuclear reactions of potential interest [9]. When applied to the $p-{}^{11}B$ reaction this criterion becomes:

$$<\sigma v> \gtrsim 1.1 \times 10^{-16}\ cm^3/sec$$

or

$$\sigma \gtrsim 77 \text{ mbarns for } T_i \approx 1 \text{ MeV} \quad .$$

These numbers are obtained with $n_p = 3n_B$, i.e. $\overline{Z^2} = 7$, which gives the maximum product $n_p n_B$ for a given total pressure. Both of these inequalities are satisfied which justifies the

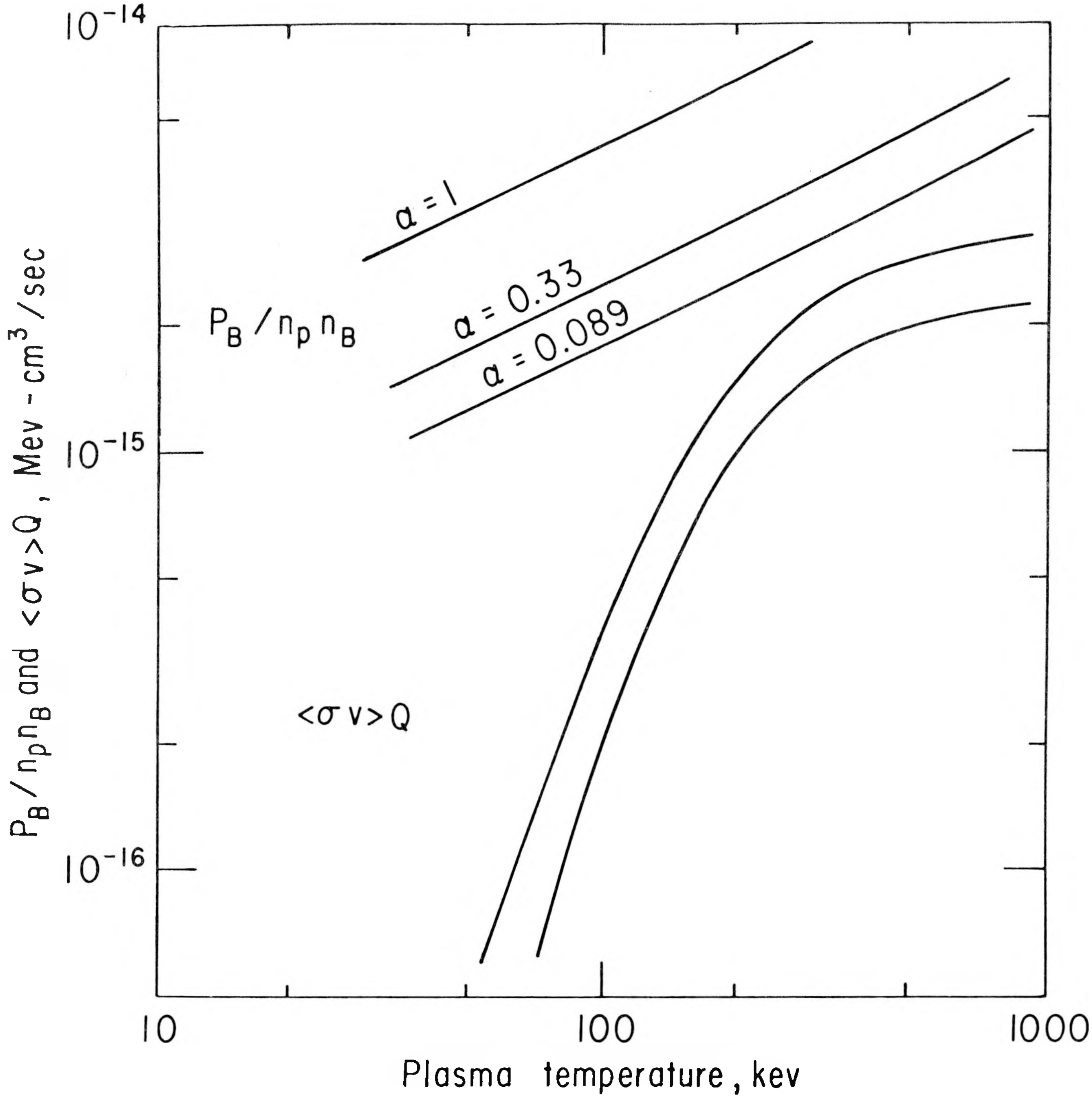

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FIG. 2. p-^{11}B reactivity and normalized bremsstrahlung versus temperature ($T_e = T_i$).

more profound investigation that is done in the rest of this work.

4. RADIATION ENERGY LOSSES

4.1 BREMSSTRAHLUNG RADIATION. OPTIMUM CONCENTRATION RATIO

The rate at which bremsstrahlung radiation is emitted per unit volume of a high temperature plasma is given by [10]:

$$P_B = 0.535 \times 10^{-23} \, n_e \, T_e^{1/2} \sum_i n_i \, Z_i^2 \ \text{ergs/cm}^3\text{-sec} \qquad (1)$$

where T_e is the electron temperature in keV, n_e the electron density in cm^{-3}, n_i and Z_i the ion density and charge number for each ion species. If we call α the boron to proton concentration ratio ($\alpha = n_B/n_p$) equation (1) becomes:

$$P_B = 0.334 \times 10^{-17} \, n_e^2 \, T_e^{1/2} \left(\frac{1 + 25\,\alpha}{1 + 5\,\alpha} \right) \ \text{MeV/cm}^3\text{-sec} \qquad (2)$$

whereas the fusion energy released per unit time, per unit volume is:

$$P_F = \frac{\alpha}{(1 + 5\alpha)^2} \, n_e^2 \, \langle\sigma v\rangle \, Q \quad . \qquad (3)$$

The ratio P_F/P_B is maximum for $\alpha_o = 0.089$ ($\overline{Z^2} \approx 3$) which gives, therefore, the optimum composition of the fuel as far as ignition is concerned. We see from Fig. 2 that even at this optimum composition the fuel does not ignite if the ion and electron temperatures are the same. However this is not realistic since the hot alpha-particles do not share their energy equally between the plasma ions and electrons and the radiation processes affect essentially the electrons whose temperature is then expected to drop below the ion temperature.

4.2 SYNCHROTRON RADIATION

When the electron temperature of a magnetically confined plasma reaches the 100 keV range this radiation process becomes quite severe. The model which is used in this work to evaluate the magnitude of this particular radiation loss has been described previously [11,12] and assumes black-body radiation up to a critical frequency ν_{max} at which:

$$\frac{\alpha r}{1 - R} = 1$$

where r is the plasma radius, α the absorption coefficient of the plasma and R the reflectivity of the walls. Above this critical frequency emission is neglected. Following reference [11] we use the vacuum magnetic field to compute ν_{max}, even with $\beta = 1$ [13]. The electron density is taken to be 10^{15} cm^{-3} which gives magnetic fields of the order of 100 kilogauss. In Fig. 3 the total radiation losses are plotted versus electron temperature (the ion temperature is not taken to be larger in order to minimize the magnetic field) for different plasma radii.

As an example, another calculation has been done assuming that the ion temperature can be twice that of the electron and that the radiated energy is recovered (efficiency η_{th}) and fed back to the plasma electrons by microwave heating for example (efficiency η_{μ}) so that the final loss is reduced by a factor $(1 - \eta_{th}\ \eta_{\mu})$. With $\eta_{th} = 0.4$ and $\eta_{\mu} = 0.9$ it is shown in Fig. 4 that there would be an ignition temperature at the price of all the previous optimistic assumptions provided that the plasma radius exceeds 5 meters. However, it will be shown that the plasma would not sustain such a difference between the ion and electron temperatures because the ion-electron energy transfer would be too fast.

5. ESTIMATION OF THE ELECTRON TEMPERATURE

5.1 PARTITION OF FUSION ENERGY BETWEEN ELECTRONS AND IONS

Sivukhin's slowing down model [14] is adopted in this work to calculate the energy loss rate of the fast

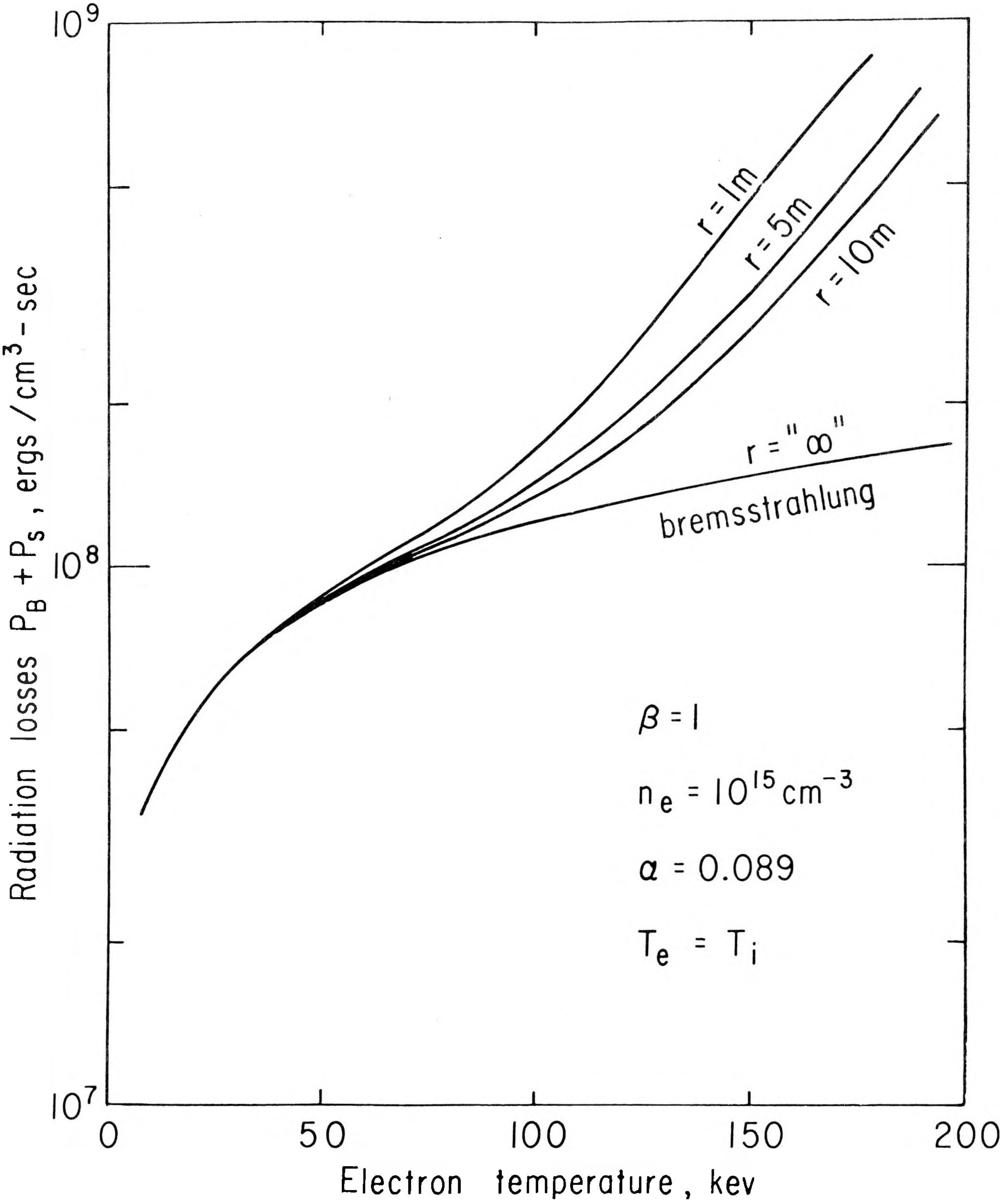

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FIG. 3. Total radiation losses in the most optimistic case for various plasma radii r.

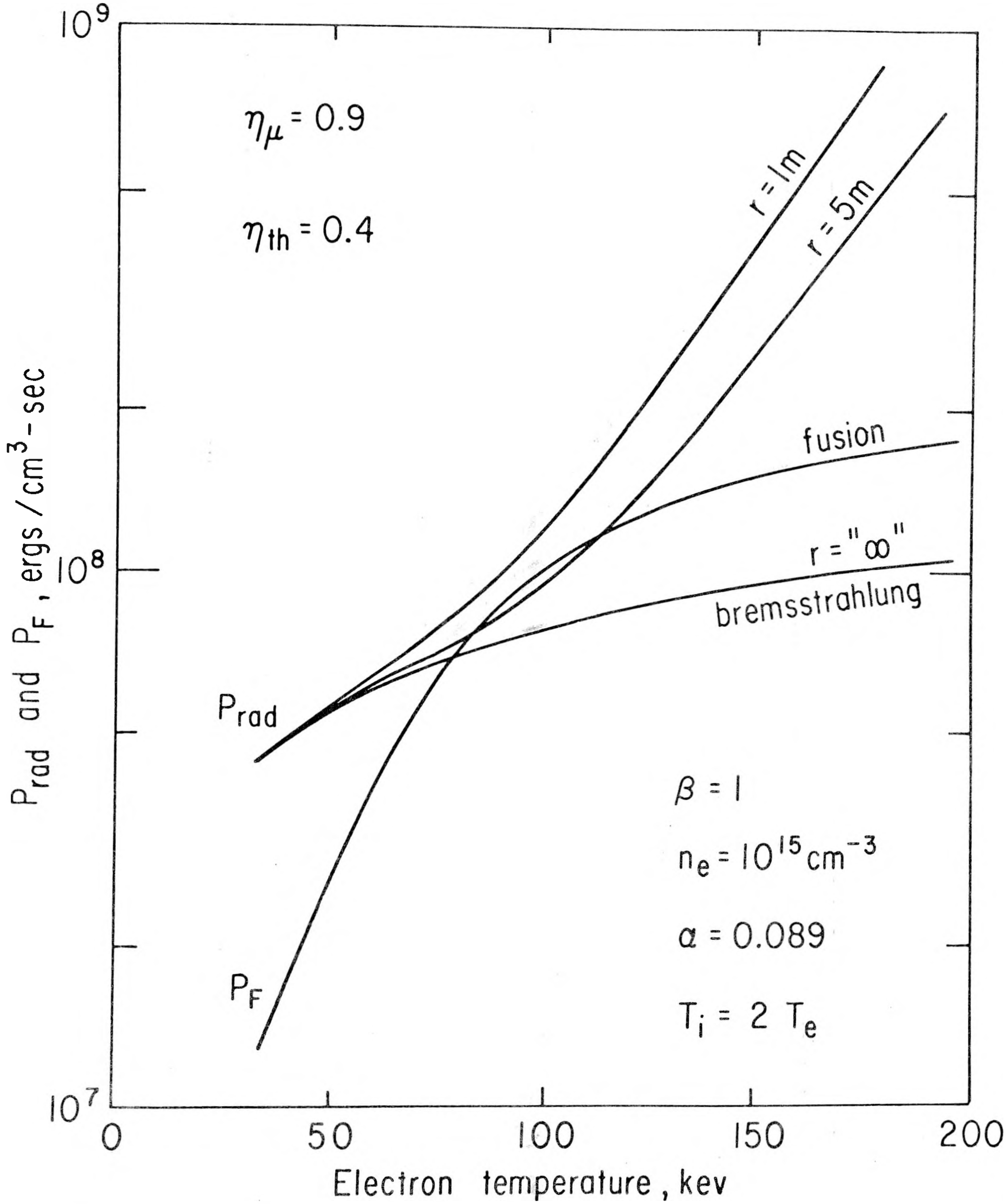

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FIG. 4. Total radiation losses after feedback. $(P_B + P_S)(1 - \eta_{th}\eta_\mu)$ and fusion energy release $(T_i = 2T_e)$. r is the plasma radius.

alpha-particle by Coulomb collisions respectively with electrons and with the different ion components. The fraction f_i of fusion energy which is given to the unburned ions is found to be very close to unity [1] when the ratio T_e/T_i lies between 0.5 and 1. We will be a little optimistic by assuming that it is indeed unity so that a breakeven situation would be obtained if the fusion energy release, ion-electron energy transfer and electron radiation can occur at the same rate.

5.2 ENERGY TRANSFER FROM THE IONS TO THE ELECTRONS

The rate at which energy is transferred between two species having Maxwellian velocity distributions at different temperatures T_e and T_i is given by:

$$\frac{dT_i}{dt} = - \frac{(T_i - T_e)}{\tau_{eq}}$$

where τ_{eq} is given in reference [15]. We must consider separately protons and boron nuclei so that the rate of energy transfer from the ions to the electrons becomes:

$$\frac{dW_i}{dt} = - \frac{3}{2} \left[\frac{n_p}{\tau_p} + \frac{n_B}{\tau_B} \right] (kT_i - kT_e) \quad . \qquad (4)$$

By equating (3) and (4) we find the relationship between the ion and electron temperatures in an ignited plasma. For a given ion temperature, this relationship gives the lowest possible electron temperature, T_e^{min}, since for $T_e < T_e^{min}$ the ions would transfer to the electrons more energy than they receive from the fusion born α-particles. On the other hand, equating (3) with the total radiation losses yields another relationship which gives an upper bound to the electron temperature: T_e^{max}. These two extreme electron temperatures will be determined graphically and plotted versus ion temperature in the next sections for both magnetic confinement and laser fusion.

6. p-^{11}B FUSION IN MAGNETIC CONFINEMENT DEVICES

6.1 MAXWELLIAN ION DISTRIBUTION

Figure 5 shows the curves defined above in the case of magnetic confinement ($n_e = 10^{15}$ cm^{-3}, $\ln\Lambda \approx 20$); $\alpha = 0.089$ is conserved because it is close to the optimum. Part of the radiation is supposed to be fed back into the plasma as explained in section (IV,2). An ignition domain exists in the (T_e, T_i) plane only if $T_e^{min} < T_e < T_e^{max}$ for a given T_i. We see that synchrotron radiation prevents the plasma from reaching ignition conditions, even with a plasma radius of about 10 meters.

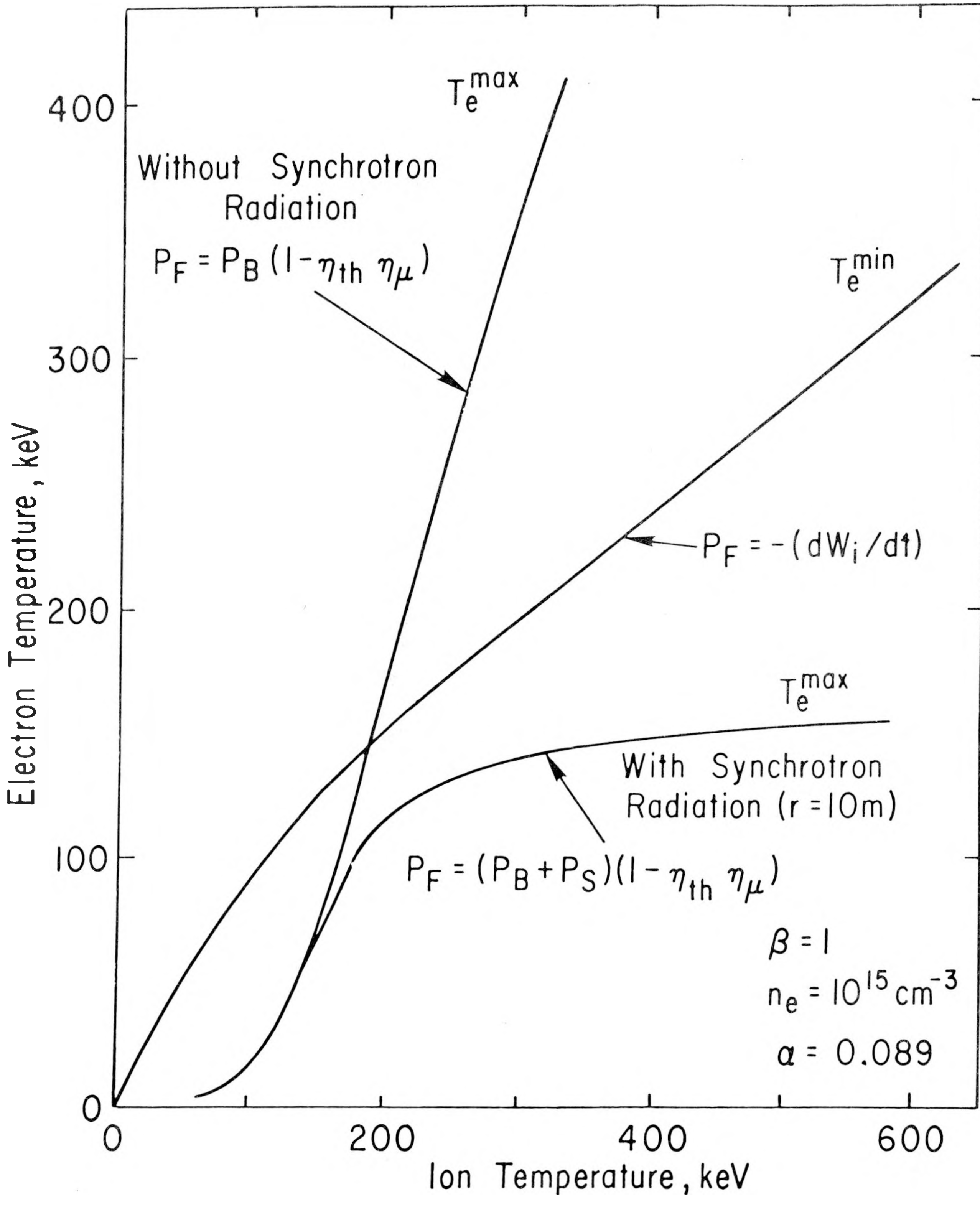

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FIG. 5. Electron temperature corresponding to ion equilibrium (T_c^{min}) or to fusion - radiation balance (T_e^{max}).

6.2 BEAM-DRIVEN FUSION

We consider now the "two-component" approach [16], i.e., the injection of an energetic neutral hydrogen beam into a "cold" Maxwellian boron plasma. If on the average a proton injected with an initial energy E_o produces F times this energy in fusion reactions before slowing down, the criterion for net power generation is:

$$(1 + F)\, E_o\, \eta_{dc} \geq \frac{E_o}{\eta_I}$$

where η_{dc} and η_I are the efficiencies for plasma energy conversion and beam injection. Radiation losses are neglected. For $\eta_{dc} = 0.7$ and $\eta_I = 0.9$ this criterion becomes:

$$F \geq 0.59$$

which is far from being reached as shown in Fig. 6. Even with $\eta_{dc} = 0.8$, F should be larger than 0.39.

7. LASER IGNITED p-^{11}B FUSION

In the laser ignition approach, ultrahigh densities of the order of 10^{27} cm^{-3} might be achieved as a result of very

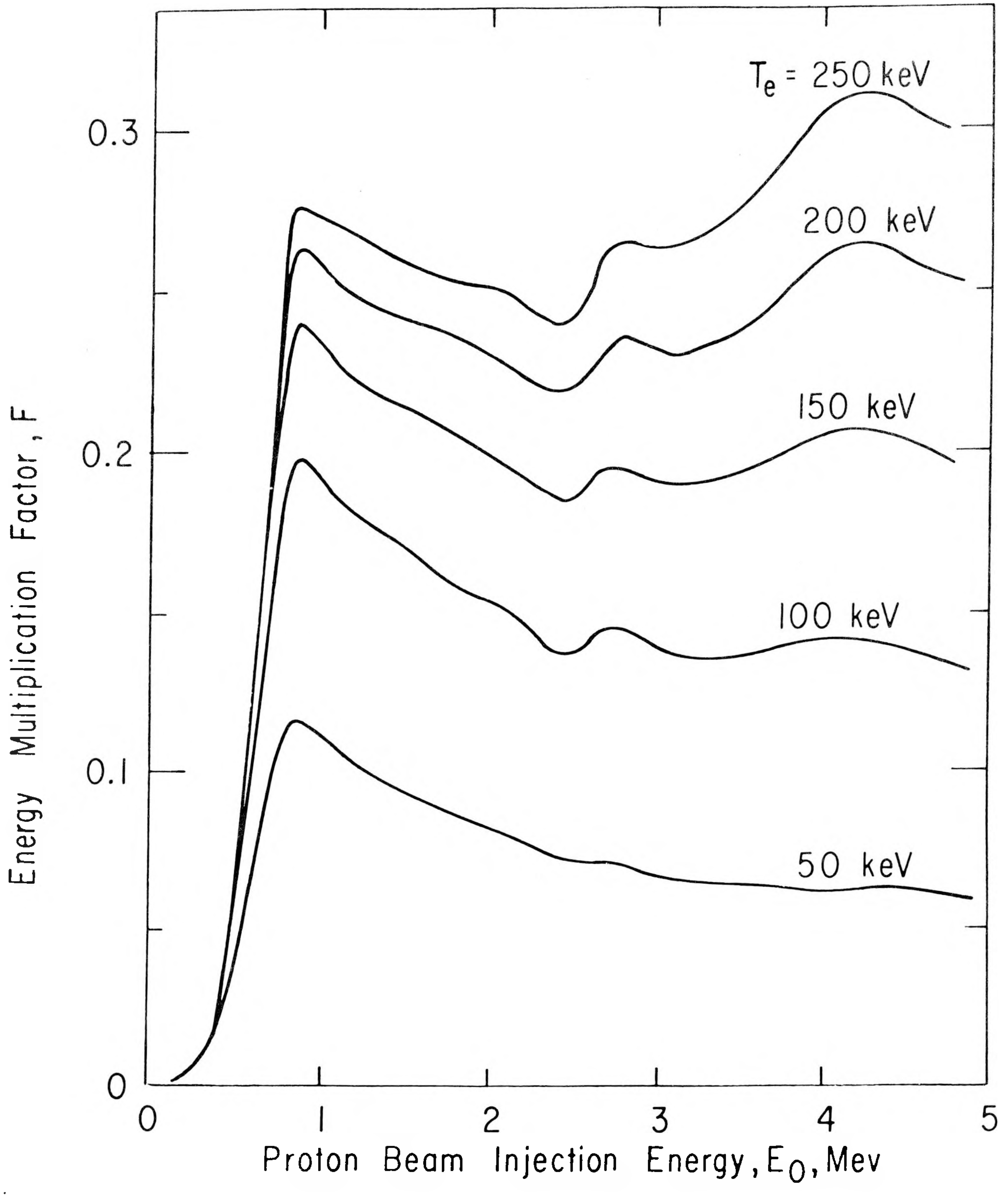

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FIG. 6. Energy multiplication factor versus injection energy for various electron temperatures.

strong converging compression waves. The Coulomb logarithm then decreases to an average value of 5 instead of 20 thus permitting a larger difference between the ion and electron temperatures. The synchrotron radiation losses are assumed to be negligible (although strong magnetic fields might be self-generated in the pellet giving rise to large synchrotron losses) and bremsstrahlung energy is not fed back in this case. Figure 7 shows that an ignition point can be obtained at the following temperatures:

$$T_e = 140 \text{ keV}$$

$$T_i = 280 \text{ keV}$$

with $f_i \approx 0.7$ which is consistent with $T_e/T_i \approx 0.5$ in this range of temperature and $\alpha = 0.089$ which is still close to the optimum.

During the thermonuclear burning these temperatures will rise up to the second intersection of the T_e^{min} and T_e^{max} curves so that the plasma energy which is recovered in each cycle corresponds to $T_e \approx 300$ keV and $T_i \approx 1000$ keV. This plasma energy is assumed to be recovered with efficiency $\eta_{dc} = 0.6$ by direct conversion and the radiated energy with efficiency $\eta_{th} = 0.4$ through a Carnot cycle. If the laser-plasma coupling could be achieved with efficiency $\eta_\ell = 0.2$, a positive energy balance would be obtained provided that:

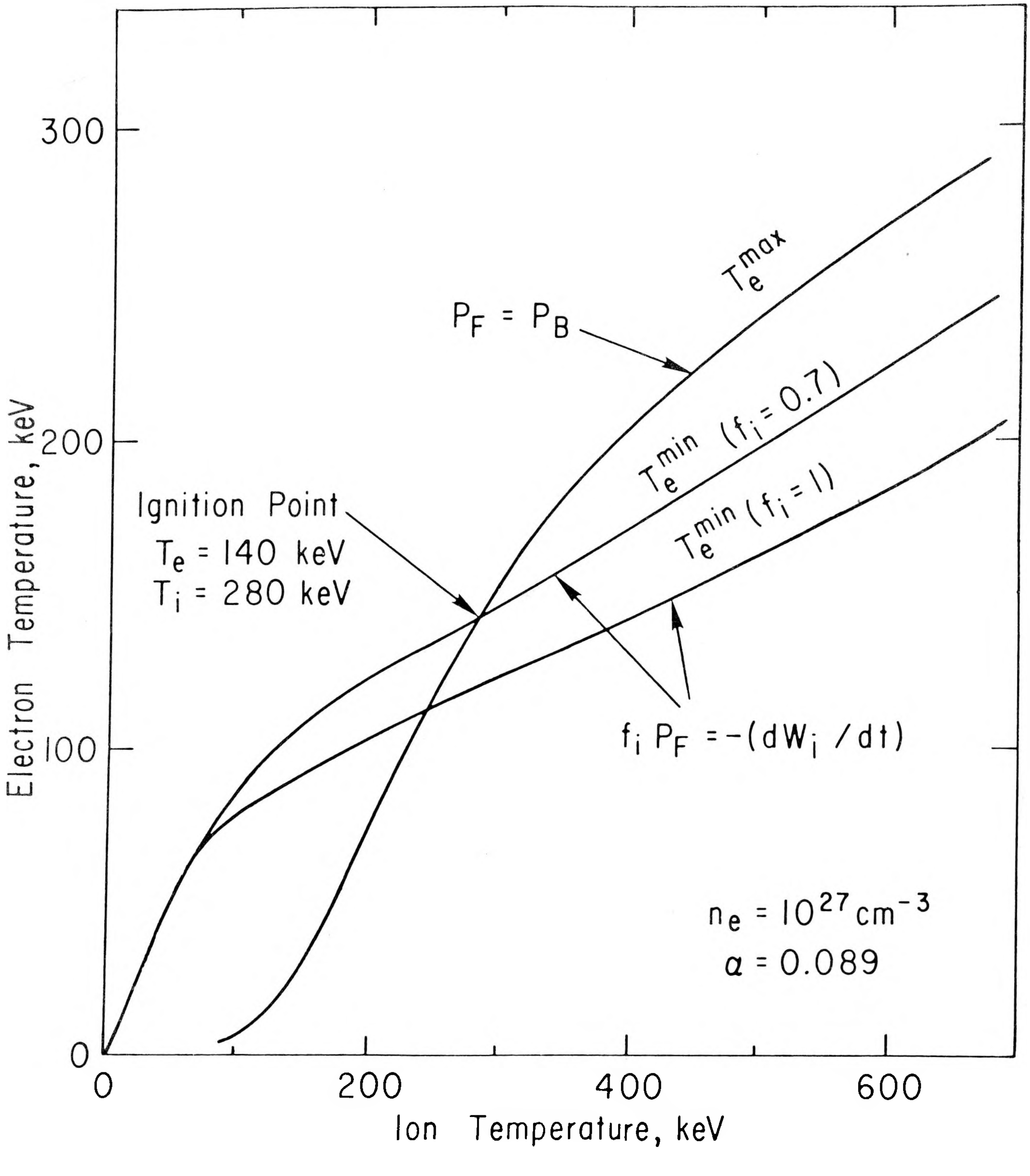

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FIG. 7. Electron temperature corresponding to ion equilibrium (T_e^{min}) or to fusion-bremsstrahlung balance (T_e^{max}) for laser fusion.

$$n_e \tau \geq 1.6 \times 10^{16} \text{ sec-cm}^{-3}$$

where τ is the confinement time. For $n_e = 10^{27}$ cm^{-3}, τ must be larger than 1.6×10^{-2} nanoseconds implying the radius of the pellet to be larger than 1.6×10^{-3} cm (the speed of sound is roughly 10^8 cm/sec). As a consequence a laser energy of about 7×10^6 Joules would be required to reach ignition. If n_e could reach 10^{28} cm^{-3} this laser energy would be only 70 kJ.

The possibility of a chain reaction, where the energetic α-particles scatter protons into the high 675 keV resonance so that they react before thermalizing, has been investigated. The resulting multiplication factor is found to be merely a few percent so that these considerations can only provide a justification for using the optimistic cross section data.

8. CONCLUSION

A quantitative study of the different energy losses and energy transfer mechanisms which would accompany the fusion of the proton-boron fuel has been done in this work. It shows that such a fuel might be of potential interest only in the limit where synchrotron radiation can be neglected. In particular it has been proved in a quite definite way that this "exotic" fuel cannot generate net power in a magnetic confinement device.

In the laser ignition approach the requirements do not seem too high if the recently observed high magnetic fields generated in laser heated pellets are not prohibitive. Yet temperatures in the 100-300 keV range might prove very difficult to reach and tremendous laser energy outputs would be necessary as well as a very efficient laser-plasma energy coupling in order to produce net power from proton-boron fusion.

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REFERENCES

[1] MOREAU, D. C., Potentiality of the Proton-Boron Fuel for Controlled Thermonuclear Fusion, thesis 1277-T, Department of Aerospace and Mechanical Sciences, Princeton University (1976).

[2] GREENE, S. L., JR., Maxwell Averaged Cross Sections for Some Thermonuclear Reactions on Light Isotopes, Lawrence Livermore Laboratory Report UCRL-70522 (1967).

[3] FOWLER, W.A., CAUGHLAN, G., ZIMMERMAN, B., Thermonuclear Reaction Rates, Ann. Rev. Astron. and Astrophys., 5, 525 (1967).

[4] AJZENBERG-SELOVE, F., LAURITSEN, T., Energy Levels of Light Nuclei, Nucl. Phys., A 114, 1 (1968).

[5] ANDERSON, B.D., DWARAKANATH, M.R., SCHWEITZER, J.S., NERO, A. V., A New Determination of the Partial Widths of the 16.11 MeV States in ^{12}C, Nucl. Phys., A 223, 286 (1974).

[6] BECKMAN, O., HUSS, T., ZUPANČIČ, Č., Excitation Curves for Alpha-particles from B Bombarded with Protons, Phys. Rev., 91, 606 (1953).

[7] SEGEL, R. E., HANNA, S. S., ALLAS, R. G., States in ^{12}C between 16.4 and 19.6 MeV, Phys. Rev., 139, B 818 (1965).

[8] SYMONS, G. D., TREACY, P. B., The $^{11}B(p,\alpha)^{8}Be$ Reaction and ^{12}C States between 15 and 20 MeV, Nucl. Phys., 46, 93 (1963).

[9] CROCKER, V.S., BLOW, S., WATSON, C. J. H., Nuclear Cross-Section Requirements for Fusion Reactors, Proceedings of Second International Conference on Nuclear Data for Reactors, (International Atomic Energy Agency, Vienna 1970), Vol. I., pp. 67-91.

[10] GREENE, J., Bremsstrahlung from a Maxwellian Gas, Astrophys. J., 130, 693 (1959).

[11] TRUBNIKOV, B. A., KUDRYAVTSEV, V. S., Plasma Radiation in a Magnetic Field, Proceedings of the Second International Conference on Peaceful Uses of Atomic Energy (United Nations, Geneva, 1958), Vol. 31, pp. 93-98.

[12] MILLS, R. G., Synchrotron Radiation from Fusion Reactors, Princeton Plasma Physics Laboratory Report MATT-658 (1969).

[13] DRUMMOND, W. E., ROSENBLUTH, M. N., Cyclotron Radiation from a Hot Plasma, Phys. Fluids, 3, 45 (1960).

[14] SIVUHIN, D. V., Coulomb Collisions in a Fully Ionized Plasma, Reviews of Plasma Physics, M. A. Leontovich, ed. (Consultants Bureau, New York, 1966) Vol. 4., pp. 93-239.

[15] SPITZER, L., Physics of Fully Ionized Gases (Interscience Publishers, Inc., New York, 1966).

[16] DAWSON, J. M., FURTH, H. P., TENNEY, F. H., Production of Thermonuclear Power by Non-Maxwellian Ions in a Closed Magnetic Field Configuration, Phys. Rev. Letters, 26. 1156 (1971).