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ON THE CONDITIONS OF EXISTENCE OF COLD-BLANKET SYSTEMS

Bo Lehnert

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Department of Plasma Physics and Fusion Research
Royal Institute of Technology
S-100 44 Stockholm 70, Sweden

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Royal Institute of Technology, S-10044 Stockholm 70, Sweden

ABSTRACT

An extended analysis of the partially ionized boundary layer of a magnetized plasma has been performed, leading to the following results:

(i) In a first approximation the ion density at the inner "edge" of the layer becomes related to the wall-near neutral gas density, in a way being independent of the spatial distribution of the ionization rate.

(ii) The particle and momentum balance equations, and the associated impermeability condition of the plasma with respect to neutral gas penetration, are not sufficient to specify a cold-blanket state, but have to be combined with considerations of the heat balance. This leads to lower and upper power input limits, thus defining conditions for the existence of a cold-blanket state. At decreasing beta values, or increasing radiation losses, there are situations where such a state cannot exist at all.

(iii) It should become possible to fulfill the cold-blanket conditions in full-scale reactors as well as in certain model experiments. Probably these conditions can also be satisfied in large tokamaks like JET, and by fast gas injection in devices such as Alcator, but not in medium-size tokamaks being operated at moderately high ion densities.

(iv) A strong "boundary layer stabilization" mechanism due to the joint viscosity-resistivity-pressure effects is available under cold-blanket conditions.

1. Introduction

In quasi-steady magnetic confinement systems for hot plasmas, the cold-blanket concept is expected to introduce a number of features being both important and favourable with respect to the development of full-scale fusion reactors. Thus, wall protection from hot ion and neutral particle bombardment and plasma screening from wall-released impurities should become possible in cold-blanket systems, which are likely to offer methods of refuelling, ash and impurity removal, as well as alternative methods of plasma stabilization. All these features are mainly dependent on the existence of a sufficiently dense and cold partially ionized boundary layer, separating the fully ionized hot plasma core from surrounding vessel walls.

Full-scale fusion reactors are in many cases likely to satisfy the conditions for fully developed cold-blanket systems [1-7], i.e. where the hot plasma is separated from the surrounding wall surfaces by a boundary layer having only a few electron volts temperature. In the case of experiments being conducted or planned for the nearest future, however, the situation becomes less clear. Thus, present day tokamaks and other low-beta systems are mostly operated within parameter regimes which do not appear to allow for cold-blanket studies [2,3,5-7], whereas such studies have already been carried out in certain small-scale experiments at beta values in the range 0.1 to 0.3 [7-9].

Consequently, there is need for a theory by which the conditions of existence of fully developed cold-blanket systems can be formulated. Attempts in this direction have earlier been made in some investigations on the heat balance of the partially ionized boundary layer [1,4,7,10-12]. In the present paper the earlier theory will be extended by an analysis of the limiting conditions of this heat balance, and be illustrated by applications to tokamaks and confinement schemes with a main poloidal magnetic field.

2. Physical Description of Adopted Model

The present treatment is restricted to plasma bodies having much larger dimensions than the thickness x_b of the partially ionized boundary layer. The latter can then be treated in terms of a simplified plane model [1,4,7], as illustrated by Fig.1 where a cylindrical plasma column is confined in a strong axial magnetic field $\underline{B}$. In this steady-state model the outermost part of the plasma is defined by a wall or limiter edge at $r = a$ of a cylindrical frame $r \varphi z$. There is neutral gas present in the plasma boundary layer, in the form of slow neutral particles of density n_{ns} in the immediate neighbourhood of $r = a$, and of fast neutrals of density n_{nf} within the main part of this layer. Thus the plasma density drops from the value $n_b = n(r_b)$ at the inner "edge" $r = r_b$ of the layer to a value $n(a) << n_b$ at the outer wall or limiter edge, whereas the density of fast neutrals drops from the value n_{na} near the outer edge to a value $n_{nf}(r_b) << n_{na}$ at the inner edge. In the following descriptions of cold-blanket systems it is convenient to divide the boundary layer into an outer "diffusion region" defined by $r_d < r < a$, and an inner "ionization region" defined by $r_b < r < r_d$.

In the diffusion region the neutral density n_{nf} is too high for a large ionization rate ξ to be permitted by the available power input into the layer. In other words, this region is defined by an ionization rate ξ being much smaller than both its "saturation" (maximum) value ξ_{max} 10^{-14} m^3/s and the ion-neutral collision rate ξ_{in}. Thus, the plasma temperature T has to be much smaller than 10^5 K in the diffusion region. Here the plasma-neutral balance is governed mainly by an outward diffusion of plasma across the magnetic field, being balanced by an inward diffusion of neutral gas through the plasma. The thickness of this region is $x_d = a-r_d$.

In the ionization region the neutral density is low enough for an ionization rate of the order of ξ_{max} to be permitted by the available power input. Here the "residual" part of the incoming neutral gas flux becomes converted into the plasma, in a combined ionization--diffusion process having the e-folding penetration length $L_{nf}(T_b, n_b)$ corresponding to the temperature $T(r_b) = T_b$ and density n_b. Thus, the ionization region has a thickness of the order of $L_{nf}(T_b, n_b)$. In this connection it should be observed that L_{nf} decreases steeply with increasing T in the range $10^2 < T < 3\times10^4$ K, and then stays nearly constant in the range $3\times10^4 < T \lesssim 10^7$ K. Thus, $T = T_b \approx 10^5$ K becomes a rather good approximation of the temperature which defines the ionization region and the inner "edge" of the partially ionized boundary layer [1,4,7].

Inside the radius $r = r_b$ there is a fully ionized plasma, the temperature of which has a maximum at $r = 0$. In the case of a reactor system the temperature becomes high enough for the thermonuclear reaction rate to exceed the bremsstrahlung loss within an inner region defined by $r < r_t$.

Consequently, we denote a "well-defined" or "fully developed" cold-blanket as a system in which there exists a low-temperature diffusion region having a width at least exceeding $L_{nf}(T_b, n_b)$.

The present analysis will be concentrated on the balance of the boundary layer, In particular, we shall investigate under what conditions the heat input into the layer becomes too small or too large to be balanced by the heat losses under steady conditions. Thus, in the former case one should expect the layer to increase in thickness and replace the fully ionized plasma body by a partially ionized region of low temperature. In the case of a too large power input, a decrease in the thickness x_b will on the other hand steepen the spatial gradients in the boundary region, thereby enhancing the losses from heat conduction and particle diffusion as well as the associated ionization and heating work to be performed on the incoming neutral gas. In this way an increasing power input into the boundary layer through the surface at $r = r_b = a-x_b$ can be balanced by a decrease in x_b, but only up to a limit defined by [4,7]

$$x_{bmin} \simeq r_d - r_b \simeq L_{nf}(T_b, n_b) \qquad (1)$$

When passing this limit the cold diffusion region is "swallowed up" by the hotter ionization region, and there is no longer a well-defined cold-blanket. In other words, one should then expect a rather hot plasma to extend all the way out to the immediate neighbourhood of the limiter or wall surface when this upper power input limit is exceeded. Even in such a situation there exists, of course, a narrow partially ionized boundary layer within which fast neutral particles penetrate a distance of the order of $L_{nf}(T_b)$ into the plasma, but such a layer does not have the characteristic features of a cold-blanket.

3. Assumptions and Basic Equations

The analysis of a steady-state boundary layer is based on the following assumptions (see also Refs. [1,4,5,7]):

(i) All effective mean free paths and Larmor radii are small compared to the macroscopic length scales.

(ii) The beta value is restricted to situations where the magnetic field $\underline{B}$ can be approximated by its vacuum value in all expressions for the transport coefficients.

(iii) The diffusion velocities are small enough for the corresponding inertia forces to be neglected.

(iv) The difference between the ion and electron temperatures T_i and T_e is neglected, and we define $T = T_i \approx T_e$ as the plasma temperature.

(vi) The classical resistivity η_c is mainly due to electron-ion collisions.

(vii) The Nernst effect from electron-ion and ion-ion collisions and their influence on the plasma pressure gradient are neglected as compared to that arising from the ionization process. This is usually a valid approximation, even at the small ionization rates prevailing within essential parts of the diffusion region (compare Ref. [13]). Further, in the case of neoclassical and anomalous diffusion the Nernst effect can readily be neglected throughout the plasma body, but in the case of classical diffusion the corresponding approximation applies only to the partially ionized boundary layer. It implies that the temperature gradient becomes small compared to the plasma density gradient within the layer.

(viii) The cooling effect of the expansion work of the plasma becomes nearly compensated by the Joule heating from the electric current which balances the plasma pressure [14].

(ix) In the boundary layer there are on the other hand no externally imposed or induced electric currents which produce ohmic heating. Such currents can readily be taken into account in a refined version of the present theory.

(x) Frictional heating due to the slow mutual fluid motions of plasma and neutral gas is neglected.

(xi) Bremsstrahlung and cyclotron radiation from the hot plasma core are not absorbed to any noticeable extent by the boundary layer. This assumption is supported by an earlier analysis due to Verboom and Rem [15]. The general problems of the radiation balance need further examination, also including the role of line radiation, but these questions are out of the scope of the present paper.

(xii) Enhanced heat transport by the effects of a turbulent plasma blanket [10] is excluded from the present discussion.

With the present starting points the basic equations of the particle and momentum balance of the plasma and the neutral gas become, in SI-units,

$$\mathrm{div}(n\underline{v}) = nn_n(\xi-\rho) = -\mathrm{div}(n_n\underline{v}_n) \tag{2}$$

$$0 = \underline{j} \times \underline{B} - \underline{\nabla}p - mnn_n(\zeta_{in}+\zeta)(\underline{v}-\underline{v}_n) \tag{3}$$

$$\eta\underline{j} = \underline{E} + \underline{v} \times \underline{B} - (1/en)\underline{j} \times \underline{B} + (1/2en)\underline{\nabla}p \tag{4}$$

$$0 = - \underline{\nabla} p_n + mnn_n(\xi_{in} + \xi)(\underline{v} - \underline{v}_n) \tag{5}$$

and the heat balance equation of the compound plasma-neutral gas fluid can be approximated by [1,4]

$$\frac{3}{2}\,\mathrm{div}(p\underline{v} + p_n\underline{v}_n) \simeq - nn_n W\xi - \frac{3}{2}\,nn_n k f_{exc}\xi_{en} T +$$

$$+ \mathrm{div}(\lambda_\perp^* \underline{\nabla} T) - k_{br} n^2 Z^2 \sqrt{T} - k_{cr} n B^2 T \tag{6}$$

In these equations n, $p = 2nkT$, $\underline{v}$ are the density, pressure, and fluid velocity of the plasma, n_n, $p_n = n_n kT$, $\underline{v}_n$ represent corresponding quantities of the neutral gas, $\underline{j}$ is the current density, $\underline{E}$ the electric field, $m = m_i + m_e$, $W = e\phi_i$ with ϕ_i as the ionization potential, and η is the effective resistivity which has the classical value $\eta_c = 129(\ell n\Lambda)Z/T^{3/2}$ at the ratio Λ between the Debye distance and the impact parameter. Further, $\xi(T)$ represents the ionization rate being mainly due to electron-neutral collisions, ρ the volume recombination rate which usually is a function of both temperature and density, $\xi_{in}(T) = \langle\sigma_{in}w_{in}\rangle$ and $\xi_{en}(T) = \langle\sigma_{en}w_{en}\rangle$ are the ion-neutral and electron-neutral collision rates which include elastic, charge-exchange and inelastic impacts as defined by the corresponding effective cross sections and velocities σ_{in}, σ_{en}, and w_{in}, w_{en}, whereas f_{exc} stands for the fraction of heat lost by an electron in a collision leading to excitation radiation, and $k_{br} \simeq 1,7 \times 10^{-40}$ and $k_{cr} \simeq 5.3 \times 10^{-24}$ represent bremsstrahlung and cyclotron radiation without reabsorption. Finally, $\lambda_{\perp}^{*} = \lambda_{\perp} + \lambda_{n}^{*}$ is a "compound heat conductivity",in this simplified analysis represented by the contribution $\lambda_{\perp} = 5nk^2T\nu_{ii}gm_i/4e^2B^2 = k_2n^2A^{1/2}(\ell n\Lambda)/B^2T^{1/2}$ due to ion-ion collisions at the frequency ν_{ii} where $k_2 = 1.5 \times 10^{-42}$ and $g \simeq 1$ for $eB/m_i \gtrsim \nu_{ii}$, as well as by the contribution $\lambda_{n}^{*} \simeq 75n_nk^2T/16\sqrt{2}m_n\nu_n^{*}$ due to neutral particle collisions where $\nu_n^{*} = n_n\langle\sigma_{nn}w_n\rangle + n\langle\sigma_{in}w_{in}\rangle$ is the corresponding frequency due to neutral-neutral and neutral-ion impacts. The detailed and more rigorous analytical form of the factor g contains contributions from the collision and gyro frequencies of both ions and electrons, as given by Braginskii [16], Verboom [17] and others.

4. Particle and Momentum Balance of the Boundary Layer

We first consider the particle and momentum balance of the boundary layer in terms of an earlier simplified model in which the plasma and neutral gas temperatures are approximated by a constant meanvalue T_m [1,4]. Introducing the particle fluxes $\Gamma = -nv_x$ and $\Gamma_n = n_n v_{nx}$ in the present plane model, eqs. (2)-(5) yield (compare Refs. [1,4])

$$- \frac{d\Gamma}{dx} = nn_n(\xi-\rho) = - \frac{d\Gamma_n}{dx} \tag{7}$$

$$2kT_m \frac{dn}{dx} = (B^2/\eta n)\Gamma + m(\xi + \xi_{in})(n_n\Gamma + n\Gamma_n) \tag{8}$$

$$kT_m \frac{dn_n}{dx} = -m(\xi + \xi_{in})(n_n\Gamma + n\Gamma_n) \tag{9}$$

Integration of eq. (7) results in $\Gamma(x) = \Gamma_n(x)$. In the plane model of Fig.1 and with assumption (vii) of Section 3, the constant of integration vanishes because both n_n and v_x should approach zero at large distances x from the limiter edge in this case. The outflux of plasma and the influx of recombined back-scattered neutral gas have their maximum values $\Gamma(0) = \Gamma_n(0) \equiv \Gamma_a$ at $x = 0$. These values should be equal in a steady state where the loss of plasma is compensated by an equally large influx of neutral gas which is being ionized.

Introducing the characteristic parameters

$$n_B = k_B B = c_a k_{Bc} B \; ; \qquad k_{Bc} = 1/\left[\eta_c m(\xi_{in} + \xi)\right]^{1/2} \tag{10}$$

$$N = n/n_B \qquad N_n = n_n/n_B \tag{11}$$

$$G = \Gamma/\Gamma_a = \Gamma_n/\Gamma_a \tag{12}$$

$$s = \left[m(\xi_{in} + \xi)\Gamma_a/2kT_m\right]x \tag{13}$$

$$H = 2kT_m(\xi - \rho)B^2/\eta\left[m\Gamma_a(\xi_{in} + \xi)\right]^2 \tag{14}$$

where c_a is a coefficient representing non-classical or neo-classical diffusion, eqs. (7) - (9) now reduce to

$$\frac{dG}{ds} = -HNN_n \tag{15}$$

$$\frac{dN}{ds} = G\left(\frac{1}{N} + N + N_n\right) \tag{16}$$

$$\frac{dN_n}{ds} = -\, 2G(N + N_n) \tag{17}$$

Division of eq. (17) by eq. (16) yields an expression for dN_n/dN which is identical with that obtained from earlier deductions [1,4] and which can be integrated to yield a solution in terms of cylindrical Bessel functions [4,18]. In this context the asymptotic cases of large and small values of $N(x_b)$ are of main interest. We finally observe that k_{Bc} in eq. (10) is a slow function of η_c, ξ_{in}, ξ, and should therefore not depend critically on the assumed meanvalue T_m of the temperature being adopted in the models to be described later in this context.

4.1. Asymptotic Density and Particle Flux Relations

With respect to the coordinate x in Fig.1 we assume, under quite general conditions, that the normalized density N_n of fast neutrals has its maximum value $N_{na} \equiv N_n(x = 0)$ close to the limiter edge, and that the same density vanishes far inside the plasma. Further, the normalized plasma density should approach the value $N_b \equiv N(x_b)$ in the region where N_n becomes negligible, whereas its value $N(0)$ close to the limiter should be small as compared to N_b. With these boundary conditions the asymptotic solutions obtained from dN_n/dN lead to the two cases

$$\left.\begin{array}{llll} N_n \simeq 2(N_b^3 - N^3)/3 \ ; & N_{na} \simeq 2N_b^3/3 & \text{for } N_b \ll 1 & \text{(I)} \\ N_n \simeq 2(N_b - N) \ ; & N_{na} \simeq 2N_b & \text{for } N_b \gg 1 & \text{(II)} \end{array}\right\} \qquad (18)$$

Further, when the normalized ionization rate $H \neq 0$ but G vanishes far inside the plasma, the solution obtained from dN/dG becomes

$$G = H\sqrt{2}(N_b^3 - N^3)/3 \; ; \quad G_a \equiv G(x=0) = H\sqrt{2}N_b^3/3 \qquad \text{(I)}$$

$$G^2/2H = 3N_b^2 - 2N_bN - N^2 - 4N_b^2 \ln\left[2 - (N/N_b)\right] \; ; \qquad (19)$$

$$G_a = \left[2(3 - 4\ln 2)H\right]^{1/2} N_b \qquad \text{(II)}$$

in cases (I) and (II).

In fact, the transition from case (I) to case (II) occurs within a rather narrow region around $N_b = 1$, as demonstrated by Fig.2. In case (I) the plasma pressure gradient is mainly being balanced by diffusion due to Coulomb collisions, whereas the same gradient is mainly balanced by plasma-neutral gas friction in case (II).

Concerning the results of eqs. (1)-(19), the following points should be observed:

(i) The solution (18) applies to situations with variable as well as with constant G. The ionization and recombination rates in eq.(15) only affect the scales and forms of the distributions $n(x)$ and $n_n(x)$, but not the asymptotic values $n_b \equiv n_B N_b$ and $n_{na} \equiv n_B N_{na}$ at the inner and outer "edges" of the partially ionized boundary layer. Further, the thickness x_b of this layer becomes determined first when the results (10)-(19) are combined with the heat balance conditions described in Section 5.

(ii) When restricting the analysis to a region far inside a hot plasma where $N_n \ll N \simeq$ const., eqs. (15) and (17) combine to a solution of $n_n(x)$ which decreases exponentially with increasing x, by the e-folding penetration length [1,4,7]

$$L_{nf} \simeq [kT/m\xi(\xi_{in} + \xi)n^2]^{1/2} \equiv 1/\sigma_{cf}n \tag{20}$$

where $1/\sigma_{cf} \simeq 5 \times 10^{18}$ m^{-2} with hydrogen in the temperature range $10^5 < T < 10^7$ K. For the plasma column of Fig.1 the critical density with respect to neutral gas penetration thus becomes $n_{cf} = 1/\sigma_{cf}a$. Here $1/\sigma_{cf}$ can be considered as a kind of "impermeability limit" for the product $\bar{n}a$ and the average plasma density $\bar{n}$ in the region $0 < r < r_b$. We further observe that L_{nf} is a slow function of temperature in the range above $T = 10^5$ K. Therefore the walls should also be protected by the cold-blanket from interaction with the energetic neutrals which exist within the fully ionized plasma core.

(iii) When applying the present result to a fully developed cold-blanket system with a broad diffusion region as outlined in Fig.1, we should put T_m at a corresponding low level for which $\xi \ll \xi_{max}$ and ξ_{in} in eqs. (10)-(14). The values N_b and N_{na} then refer to the edges of the diffusion region. With $L_{nf}(T_b, n_b) \ll x_b$ we further have $n(r_b) \simeq n(r_d)$ in Fig.1, and the values N_b and N_{na} can then as well be considered to apply to the entire boundary layer [1]. Here again we observe that $k_{Bc} \propto \sqrt{T}$ of eq. (10) is a relatively slow function of temperature which does not depend critically on the choice of T_m. Thus, for such a system $k_{Bc} \simeq 3 \times 10^{21}$ A$^{-1/4}$ m^{-3} tesla^{-1}.

(iv) If the obtained results are instead applied to a system where x_b tends to become smaller than L_{nf}, the hot plasma should extend almost out to the edge $x = 0$, and T_m becomes high enough for a strong ionization rate to prevail within nearly the whole partially ionized layer. Then, N_b and N_{na} represent normalized densities at the edges of this type of layer, with ξ retained in eqs. (10)-(14) and being close to its "saturation value" $\xi_{max} \approx 10^{-14}\ m^3/s$.

(v) Volume recombination can often be neglected as compared to the wall recombination of plasma particles which escape to the limiter or vessel surfaces, because the latter act as efficient sinks for plasmas [19].

(vi) In tokamak and similar systems with a main toroidal field $\underline{B}_t$ and a comparatively weak poloidal field $\underline{B}_p$, Pfirsch-Schlüter diffusion could in some cases take place in the boundary layer. Then, $c_a = 1/(1 + q^2)^{1/2}$ in eq. (10) where $q = aB_t/RB_p$ with a and R standing for the minor and major radii of the configuration.

4.2. Density Relations in some Special Confinement Systems

The density relations (18) are now considered in connection with some special confinement systems. For this purpose the profiles of density and temperature within the region $0 < r < r_b$ are approximated in a first approach by

$$nT^{-\alpha} = n_o T_o^{-\alpha} = n_b T_b^{-\alpha} = \text{const.} \qquad (21)$$

where subscript ($_o$) refers to $r = 0$. We further introduce the beta value

$$\beta = 4\mu_o n_o kT_o/B^2 = 4\mu_o kT_o^{1+\alpha} n_b/B^2 T_b^{\alpha} = (4\mu_o kT_o^{1+\alpha} k_B/T_b^{\alpha})(N_b/B) \qquad (22)$$

The elementary analytical form of eq. (21) has been chosen only for the purpose of illustrating the present principles by some simple numerical examples.

4.2.1. Toroidal Field Systems

For toroidal field systems, such as tokamaks with Pfirsch-Schlüter diffusion in the boundary layer, eqs. (18) can be written in the form

$$\left.\begin{aligned} n_{na} &= 2(1 + q^2) n_b^3/3k_{Bc}^2 B^2 \qquad &(I) \\ n_{na} &= 2n_b \qquad &(II) \end{aligned}\right\} \qquad (23)$$

As a numerical illustration we put $A = 1$, $q = 3$, $T_b = 10^5$ K, $T_o = 10^7$ K, $\alpha = 1/4$, $n_b/n_o \simeq 0.3$, and $n_b \simeq 4.5 \times 10^{20}\ \beta B^2$. The result becomes as shown by Fig.3. Here neutral boundary layer densities n_{na} of the order of n_b become available only at very strong magnetic fields and beta values approaching 10%. Such high beta values are not available in present-day tokamaks.

If the collisions are too frequent even for Pfirsch-Schlüter diffusion to take place, the contribution from q in eq. (23) should be dropped and the corresponding value of n_{na} be reduced.

4.2.2. Poloidal Field Systems

For poloidal field systems, such as internal ring configurations and rotating plasma devices, an example is chosen with classical diffusion in the boundary layer of a cold-blanket model experiment. Eqs.(18) then reduce to expressions (23) with $q = 0$. As a numerical illustration of this case we put $A = 1$, $T_b = 10^5$ K, $T_o = 3 \times 10^5$K, $\alpha = 1/4$, $n_b/n_o \simeq 0.3$, and $n_b \simeq 3.7 \times 10^{22}\ \beta B^2$. The result becomes as shown by Fig.4. Here neutral boundary layer densities n_{na} of the order of n_b are easily available, especially as cold-blanket systems of this type can provide stable plasma confinement even at effective beta values up to some 30% [20].

5. Heat Balance of the Boundary Layer

Concerning the heat balance of a fully developed cold-blanket boundary layer, we follow the earlier analysis [1,4] and integrate eq. (6) over the interval $0 < x < x_b$. In combination with eq. (2) the result becomes

$$\Delta Q_b = Q_b - (C_\xi + C_s)/x_b - (C_\eta + C_R)x_b \tag{24}$$

where Q_b is the heat per unit area and time flowing into the layer at $x = x_b$ from the fully ionized region, C_ξ represents the plasma particle loss due to diffusion across the layer which is compensated by a corresponding ionization and heating work on the incoming neutral gas, C_s stands for the heat shunted away across the layer by the compound heat conductivity defined in Section 3, C_η represents the excitation radiation loss, and C_R the bremsstrahlung and cyclotron radiation losses. With subscripts $(_b)$ and $(_m)$ referring to $x = x_b$ and to meanvalues in the layer, these coefficients become

$$C_\xi = 4s_b(W + 3kT_b)kT_m/m\xi_{inm} \equiv c_\xi s_b \tag{25}$$

with $s_b = N_b^2/2$ and $\ell n2$ in cases (I) and (II) of Section 4.1,

$$C_s = c_{sn}N_{na}/(N_{na} + N_b) + c_{si}k_B^2N_b^2 \tag{26}$$

with

$$c_{sn} \approx 75(kT_m)^{3/2}(\pi/m)^{1/2}/64\sigma_{nnm} \tag{27}$$

$$c_{si} \approx 5k^2T_m^2 g\nu_{iim}m_i/4e^2n_b \tag{28}$$

$$C_\eta = c_\eta k_B^2 B^2 N_b N_{na} \tag{29}$$

with

$$c_\eta \approx \int_0^{x_b} \tfrac{3}{2}(nn_n/n_b n_{na})kf_{exc}\xi_{en}T dx/x_b \tag{30}$$

and

$$C_R = c_{br}k_B^2 B^2 N_b^2 + c_{cr}k_B B^3 N_b \tag{31}$$

with

$$c_{br} \approx \int_0^{x_b} k_{br}Z^2(n/n_b)^2\sqrt{T}\, dx/x_b \tag{32}$$

$$c_{cr} = \int_{o}^{x_b} k_{cr}(n/n_b)Tdx/x_b \tag{33}$$

5.1. Conditions for a Stable Heat Balance

The equilibrium state of the heat balance is given by $\Delta Q_b = 0$. When $\Delta Q_b > 0$ there is a heating power excess which tends to increase the ionization degree and shrink the layer thickness x_b, whereas $\Delta Q_b < 0$ leads to a heating power deficit which tends to decrease the ionization degree and expand the layer thickness x_b.

At fixed values of Q_b and of the C-coefficients of eq. (24), the equilibrium leads to the two solutions

$$x_b = (x_{b1}, x_{b2}) =$$

$$= \frac{Q_b}{2(C_\eta + C_R)} \{ 1(\mp) \left[1 - 4(C_s + C_\xi)(C_\eta + C_R)/Q_b^2\right]^{1/2} \} \tag{34}$$

of the layer thickness. Only the solution x_{b1} given by the minus sign corresponds to a stable heat balance. This can be seen from the rewritten form

$$\Delta Q_b = - \left[(C_\eta + C_R)/x_b\right](x_b - x_{b1})(x_b - x_{b2}) \tag{35}$$

of eq. (24), the right-hand member of which becomes negative in the intervals $0 < x_b < x_{b1}$ and $x_{b2} < x$, but positive in the interval $x_{b1} < x < x_{b2}$. Only equilibria with $x = x_{b1}$ will be considered henceforth.

At fixed values of the C-coefficients representing the various loss mechanisms being involved, a stable equilibrium with $x = x_{b1}$ will thus exist, but only within a certain range of the power input Q_b. There are two limits determining this range, as described in the following subsections (see also Refs. [1,4,7]).

5.1.1. The Lower Power Input Limit

When

$$Q_b < Q_{bmin} \; ; \qquad Q_{bmin} = 2\left[(C_s + C_\xi)(C_\eta + C_R)\right]^{1/2} \tag{36}$$

the losses cannot be balanced by the power input and the partially ionized layer is spread out, thus tending to cover the entire plasma body. The limit Q_{bmin} corresponds to a maximum possible layer thickness

$$x_{bmax} = x_b(Q_b = Q_{bmin}) = \left[(C_s + C_\xi)/(C_\eta + C_R)\right]^{1/2} \tag{37}$$

5.1.2. The Upper Power Input Limit

When Q_b increases in the range $Q_b > Q_{bmin}$, there is a corresponding decrease of x_b in the equilibrium state $\Delta Q_b = 0$. At a sufficiently large power input, x_b thus approaches the limit defined by eq. (1) where the diffusion region of Fig.1 becomes replaced by the ionization region. No well-defined cold-blanket exists in this case where the power input becomes too large to be balanced by the losses within a cold partially ionized boundary layer. The limit of eq. (1) is thus defined by eq. (24) with $\Delta Q_b = 0$, i.e.

$$Q_b > Q_{bmax} \; ; \qquad Q_{bmax} = Q_b(x_b = x_{bmin}) \tag{38}$$

where $T_b = 10^5$ K and

$$x_{bmin} = x_{blmin} = L_{nf}(T_b, n_b) = 1/n_b \sigma_{cf}(T_b) \tag{39}$$

5.1.3. <u>The Width of the Cold-Blanket Domain in Parameter Space</u>

The limits of the power input Q_b and of the layer thickness x_b have maximum and minimum values according to eqs. (36)-(39), being related through the expressions

$$F \equiv Q_{bmax}/Q_{bmin} = (f/2) + (1/2f) \tag{40}$$

and

$$f \equiv x_{bmax}/x_{bmin} = \left[(C_s+C_\xi)/(C_\eta+C_R)\right]^{1/2} n_b \sigma_{cf}(T_b) = \tag{41}$$

$$= \begin{cases} \sigma_{cf}(\frac{1}{2}c_\xi + \frac{2}{3}c_{sn} + c_{si}k_B^2)^{1/2}/\left[\frac{2}{3}c_\xi + (c_{br}/N_b^2) + (c_{cr}B/k_B N_b^3)\right]^{1/2} & \text{(I)} \\ \sigma_{cf}(c_\xi \ln 2 + \frac{2}{3}c_{sn} + c_{si}k_B^2 N_b^2)^{1/2}/\left[2c_\eta + c_{br} + (c_{cr}B/k_B N_b)\right]^{1/2} & \text{(II)} \end{cases}$$

where $F \gg 1$ when $f \gg 1$. For the cold-blanket state to exist within a wide domain of parameter space, it is therefore necessary, that $f >> 1$ and $F >> 1$. Then $x_{bmin} \approx (C_s + C_\xi)/Q_{bmax}$. In this connection the following general properties should be noticed:

(i) A cold-blanket can only exist inside the domain of parameter space being defined by the limits Q_{bmax}, Q_{bmin}, x_{bmax}, and x_{bmin}.

(ii) As seen from eqs. (41) and (22) the ratio f and the corresponding width of the cold-blanket domain becomes reduced at decreasing values of N_b and β, as well as when the radiation losses are enhanced by impurities. When f and F approach unity, this domain shrinks to zero and the cold-blanket state ceases to exist.

(iii) Even the largest available power input Q_{bmax} from an impermeable hot plasma core may in some situations become too small for x_{bmin} to reach the value $L_{nf}(T_b, n_b)$. Then the diffusion region will have no upper power limitation within the impermeable ion density range.

5.2. The Forms of the External Power Input

From the obtained results is seen that the heat balance and the layer thickness x_b are critically dependent on the power input Q_b. However, in some systems like tokamaks, Q_b has a rather uncertain and not well understood behaviour. From experimental observations of the energy containment time τ_E, the plasma density n, and of the temperature T, the power input can be defined by the semiempirical expression

$$Q_b = 3f_p f_b k n_o T_o a/2\tau_E \tag{42}$$

Here $f_p = \overline{nT}/n_o T_o$ with a bar indicating a mean-value taken over the plasma body which is approximated by a cylindrical column of radius a, and f_b is a correction factor depending on the relative magnitudes of the heat losses due to diffusion, heat conduction and radiation, as well as on the way in which the corresponding heat flow becomes transferred from the plasma core to the partially ionized boundary layer. With a density-temperature relation of the form (21), expression (42) can further be rewritten as

$$Q_b = 3f_p f_b kT_o^{1+\alpha} an_b / 2\tau_E T_b^{\alpha} \tag{43}$$

When studying the heat balance of Section 5.1 there are three alternative ways in which the power input can be treated:

(i) The quantity Q_b can be considered as a given independent variable.

(ii) To determine Q_b it is possible to use classical or neoclassical theory for the heat transport near the edge $x = x_b$ of the plasma core. In this case eq. (21) has to be combined with expressions obtained from the heat and particle transport terms $\mathrm{div}(\lambda_{\perp}^{*}\nabla T + 3p\underline{v}/2)$ of eq. (6), from which

$$Q_b = C_b N_b^2 / a \tag{44}$$

with

$$C_b \simeq c_{ab} k_2 \sqrt{A}(\ln\Lambda) k_B^2 (T_t^{\alpha+\frac{1}{2}} - T_b^{\alpha+\frac{1}{2}}) / (\alpha + \tfrac{1}{2}) T_b^{2\alpha} \ln(r_b/r_t) \tag{45}$$

Here $c_{ab} \geq 1$ is a coefficient due to anomalous or neoclassical heat losses from conduction and particle diffusion in the fully ionized region, and $T_t = T(r=r_t)$ in Fig.1. This approach corresponds to $\tau_E \propto B^2a^2 \sqrt{T_o}/n_o c_{ab}$.

(iii) Certain tokamak experiments indicate that the energy containment time obeys the relation [21,22]

$$\tau_E = c_E q^{1/2} f_n n_o \tag{46}$$

in the range $10^{19} < \bar{n} < 4.5 \times 10^{20}$ m^{-3}, where $f_n = \bar{n}/n_o$, $c_E \simeq 1.7 \times 10^{-23}$ $m^3 \cdot s$, and it is assumed that $T_i \simeq T_e$. Here c_E is found to be independent of the toroidal field within the range $4 < B_t < 7.5$ tesla, and c_E also seems to vary little with T_o and $\bar{T}$. Combination of eqs. (46) and (42) yields

$$Q_b = 3f_p f_b k T_o a/2f_n c_E q^{1/2} \tag{47}$$

Thus, for a given radius a and varying parameters T_o and q the treatment of this situation becomes equivalent to that of alternative (i) where Q_b is considered as an independent variable.

5.3. Special Evaluations of the Lower and Upper Power Input Limits

In Section 5.1 the general conditions for the existence of a well-defined cold-blanket system have been described. Among these the lower power input limit (36) has earlier been treated in detail [4,7] and can be obtained from combination of eqs. (36) and (42)-(45) which result in

$$Q_b = C_b N_b^2/a > Q_{bmin} = 2\left[(C_s + C_\xi)(C_\eta + C_R)\right]^{1/2} \qquad (48)$$

Here the two first members can be used as alternative expressions for the power input. In the special case where $N_b << 1$ and $C_\eta >> C_R$ the second and last members of expression (48) yield the condition

$$n_b a < (n_b a)_{lower} = \left[3C_b^2/8c_\eta(\tfrac{2}{3} c_{sn} + c_{si}k_B^2)\right]^{1/2} \qquad (49)$$

The upper power input limit of eq. (38) has only been briefly discussed in earlier papers [4,7]. It is obtained from a corresponding combination of eqs. (38) and (42)-(45). In situations where $Q_{bmin} << Q_{bmax}$ according to eq. (40), expression (41) yields the condition

$$Q_b = C_b N_b^2/a < Q_{bmax} \simeq (C_s + C_\xi)k_B B N_b \sigma_{cf}(T_b) \qquad (50)$$

In this connection the case $N_b << 1$ will be of particular interest. Expression (50) for the upper power input limit then reduces to

$$n_b a > (n_b a)_{upper} = (n_b a)_{cf} C_b / (\frac{2}{3} c_{sn} + k_B^2 c_{si}) \quad (51)$$

where $(n_b a)_{cf} \equiv 1/\sigma_{cf}$ can be considered as an impermeability "limit" defined by $L_{nf}(T_b, n_b) = a$ in eq. (20). It should be observed that expression (51) has been deduced from an impermeable plasma model.It becomes an acceptable first approximation when the average density $\bar{n}$ of the fully ionized plasma body is of the order of or exceeds n_b, and when $(n_b a)_{upper} > (n_b a)_{cf}$.

5.4. Numerical Examples

As numerical illustrations parameter values are now chosen which correspond to the examples of Sections 4.2.1 and 4.2.2 and Figs. 3 and 4. We also adopt the values $c_\xi \simeq 4 \times 10^5$ W/m, $c_{sn} \simeq 4 \times 10^5$ W/m, $c_{si} \simeq 6 \times 10^{-40}$ W $\cdot$ m^5 $\cdot$ tesla^2, $c_\eta \simeq 3 \times 10^{-35}$ W $\cdot$ m^3, $c_{br} \simeq 10^{-38}$ W $\cdot$ m^3, and $c_{cr} \simeq 10^{-19}$ W $\cdot$ tesla^{-2}. In the parameter range of B, q, n_b being of experimental interest in this connection, we further have $10^{-2} \lesssim N_b \lesssim 10$ which leads to $Q_{bmin} << Q_{bmax}$ when the corresponding expressions of eqs. (25)-(33) and (18) are inserted into eq. (40). The power input limits are finally determined from these data by means of conditions (48) and (49).

5.4.1. Power Input Limits of Toroidal Field Systems

With the data of Sections 4.2.1 and 5.2 we have $C_b \simeq 3 \times 10^6$ W/m, and a power input in the range $10^4 \lesssim Q_b \lesssim 10^6$ W/m^2. The lower power input limit then corresponds to

$$Q_b \simeq 3 \times 10^{-36} n_b^2/aB^2 \geqslant$$

$$\geqslant \begin{cases} 4\times10^{-28}\left[2\times10^{-58}(n_b^6/B^4) + 10^{-19}(n_b^4/B^2) + n_b^3\right]^{1/2} & \text{(I)} \\ 10^{-14} n_b & \text{(II)} \end{cases} \qquad (52)$$

and the upper power input limit to

$$Q_b \simeq 3\times10^{-36} n_b^2/aB^2 \leqslant \begin{cases} 10^{-55} n_b^3/B^2 & \text{(I)} \\ 10^{-13} n_b & \text{(II)} \end{cases} \qquad (53)$$

for cases (I) and (II) defined by $N_b << 1$ and $N_b >> 1$ in Section 4.1 and Fig.2.

In particular, when $\beta = 3 \times 10^{-2}$, only case (I) applies to the density range $10^{19} \leqslant n_b \leqslant 10^{22}$ m^{-3}. The lower and upper power input limits then define the regions of existence of a cold-blanket system as shown by Fig.5 with Q_b as an independent variable, and by Fig.6 for a neoclassical type of power input as defined by eq. (44).In the latter figure the cold-blanket domain has an upper power limit given by $(n_b a)_{upper} \simeq 3 \times 10^{19}\ m^{-2}$ and being independent of B and β within the present parameter ranges. The domain is situated well above the line $n_b a = 1/\sigma_{cf} \simeq 5 \times 10^{18}\ m^{-2}$ representing the impermeability "limit" $L_{nf}(T_b, n_b) = a$.

5.4.2. Power Input Limits of Poloidal Field Systems

With the data of Sections 4.2.2 and 5.2 as well as with $C_b \simeq 5 \times 10^5$ W/m, the lower and upper power input limits lead to expressions being analogous to eqs. (52) and (53). We further consider the special case $\beta = 0.1$ and retain the same parameter ranges as in Section 5.4.1. The lower and upper power input limits then become as shown by Fig.7 with Q_b as an independent variable, and by Fig.8 for a classical type of power input as defined by eq. (44). The results are analogous to those of Figs. 5 and 6.

5.4.3. Conditions for a Vanishing Cold-Blanket Domain

With the data given at the beginning of this section, eq. (41) yields $f >> 1$ for $N_b > 10^{-2}$, thus corresponding to a wide cold-blanket domain. However, in the case where the range of $N_b \propto B\beta$ is extended to lower N_b and β, or when radiation losses from impurities are introduced, the cold-blanket domain will in some cases cease to exist. An illustration is given by Fig.9 for B=3 tesla and the data specified in Sections 4.2.1 and 5.4.1. In this particular example there is no cold-blanket at all when $N_b < 2\times10^{-3}$ and $\beta < 4.5\times10^{-3}$.

There is some modification of the results of Figs. 5, 6, and 9 if Pfirsch-Schlüter diffusion has to be replaced by ordinary classical diffusion in the highly collisional regime.

6. On the Possibilities of Reaching the Cold-Blanket Regime

The results of Sections 4.2.1, 4.2.2, 5.4.1, 5.4.2, and Figs. 3-8 should only be taken as crude illustrations of the equilibrium particle, momentum, and heat balance, because there are uncertainties in the adopted coefficients, parameters, and transport laws which lead to corresponding uncertainties in the positions of the obtained limits in parameter space. Nevertheless some general cold-blanket features can be traced from these results:

(i) In toroidal field systems, such as tokamaks and stellarators, there are strong magnetic vacuum fields and low beta values. This often leads to low values of N_b and $N_{na} << N_b$, being far inside the Coulomb diffusion dominated range (I) of Fig.2. It also results in comparatively low densities n_b, n_{na} at which there are difficulties in keeping the system below the upper power input limit of Figs. 5-8. To reach the cold-blanket domain it is convenient to use the fast-valve technique of gas puffing [21-24]. On the other hand, at the desired high temperatures the high densities n_b obtained by this technique may lead to ballooning modes [2,3] and other instabilities [25].

(ii) In poloidal field systems, such as in some internal ring [26,27] and rotating plasma devices [8,20], the magnetic field strengths are relatively low and the beta values comparatively high. This often leads to values of N_b and N_{na} of the order of unity, thus being near or within the transition range between cases (I) and (II) of Fig.2. It also results in high densities n_b, n_{na} at which operation within the cold-blanket domain is readily achievable. In some of these cases one should even expect the lower power limit of Figs. 5-8 to become important. It is therefore of great interest to design special model experiments in which the parameters can be varied within the entire cold-blanket domain, such as by gas puffing to approach the lower power input limit, and by rapid vacuum pumping to approach the upper power limit [28].

(iii) Especially at small values of N_b and β, as well as in presence of impurity radiation, the width of the cold-blanket domain may even shrink to zero, as illustrated by Fig.9.

(iv) An additional power input by externally imposed heating mechanisms, such as by induced currents, affects the balance conditions of eq. (24) and displaces the power limits in parameter space (see e.g. Refs. [2,7]). Also turbulence within the plasma blanket [8] changes the heat balance.

Provided that the results of Figs. 3-9 represent correct orders of magnitude, it is thus seen that cold-blanket conditions should become realizable in full-scale reactors like UWMAK [29] and in model experiments with certain internal conductor devices and rotating plasmas [8,9,20,26], but only at beta values being at least of the order of a few percent. Also in large tokamaks like JET [30] and in devices with fast gas injection such as ALCATOR [21,22] operation in the cold-blanket domain may become possible, just inside the upper power input limit. On the other hand, such operation can hardly be realized in present medium-size tokamaks without fas gas injection.

7. Stability

According to earlier investigations there is a strong stabilization mechanism due to the joint viscosity-resistivity-pressure effects in the partially ionized boundary layer of a fully developed cold-blanket system [31-34]. This stabilization is of crucial importance to the over-all stability of several confinement schemes, not only because of the stabilization effects within the boundary layer itself, but also due to the fact that the existence of such a layer changes the boundary conditions of the fully ionized plasma core and permits a finite pressure at the "edge" of the latter [7,35].

This "boundary layer stabilization" mechanism becomes effective within specific density limits of a well-defined partially ionized layer [32-34], such as outlined in connection with Fig.1 and with the power balance illustrated by Figs.2-8. To exemplify the corresponding stability condition, we shall in this section restrict ourselves to the flute-type MHD instability in the case of strong plasma-neutral gas coupling. In the boundary layer localized analysis then yields the stability condition [7,31]

$$\theta = \gamma k m_e k_{ei} \kappa^6 C_s / 6 c_{sn} e^2 B^2 T k_n \sigma_{nn} \kappa_z^2 \kappa_\Gamma^2 \gtrsim 1 \qquad (54)$$

where

$$\kappa_\Gamma^2 = (B'/B)\left[(p'/p) - 2\gamma(B'/B)\right] \tag{55}$$

Here C_s/c_{sn} is given by eq. (26), κ_Γ represents the driving force of an instability having the total wave number κ and the wave number κ_z in the direction being perpendicular both to $\underline{B}$ and to the spatial gradients B' and p' of the magnetic field and the pressure, and the definitions $k_{ei} = \nu_{ei}T^{3/2}/n$, $\nu_{ei} = e^2 n\eta/m_e$, and $k_n = w_n/\sqrt{T}$ have been adopted.

It is seen from expressions (54) and (55) that the density dependence and its corresponding viscosity effects enter into the present stability criterion only through C_s. Especially in the range (I) of Fig.2 we then have $C_s \propto (k_B B n_b)^2$. Therefore the earlier deduced strong boundary layer stabilization mechanism [7,31-35] should prevail, as long as operation within the cold-blanket domain becomes possible at values of N_b not being too small compared to unity. Thus, high beta values should favour this mechanism, through the corresponding high values of $N_b = n_b/k_B B$. The parameter ranges of Figs. 3-4 and 5-8 may serve as an illustration of the available values of n_b and n_{na} in this connection.

8. Conclusions

With the reservation that the coefficients of the present theory are subject to some uncertainty, as well as the detailed numerical results being presented as illustrations, the following general conclusions can be drawn:

(i) The particle and momentum balance within the partially ionized boundary layer of an impermeable plasma leads to a relation between the ion density n_b at the inner layer "edge" and the wall-near neutral density n_{na}. In a first approximation this relation depends only on the magnetic field strength and the type of plasma diffusion taking place in the layer, but becomes independent of the layer thickness and the detailed spatial extensions of the "diffusion" and "ionization" subregions.

(ii) Within the density range of plasmas being impermeable to neutral gas, there are two subranges. There is a lower range (I) within which the plasma diffusion is dominated by Coulomb collisions leading to $n_{na} \propto n_b^3/B^2$, and an upper range (II) within which ion-neutral collision are important and lead to $n_{na} \propto n_b$.

(iii) The impermeability condition and the relations obtained from the particle and momentum balance are, however, not sufficient to specify the conditions of existence of a cold-blanket system. The latter becomes determined first when the heat balance is taken into account. This results in a subdivision of impermeable plasmas into classes which are not identical with the ranges (I) and (II), but become determined by a lower and an upper limit of the heating power which is transmitted from the hot plasma into the boundary layer. These limits are affected also by an extra imposed heating power, as well as by additional heat losses from impurity radiation.

(iv) If the power input becomes smaller than the lower limit, there is no equilibrium layer thickness for which the available heat supply into the layer can cover the total heat losses. The layer is then expected to grow such as to replace the fully ionized body by a partially ionized plasma of low temperature.

(v) If the power input becomes larger than the upper limit, the ionization region will on the other hand expand such as to replace the diffusion region. Then, no cold partially ionized region will remain between the fully ionized body and the surrounding walls.

(vi) In parameter space the lower and upper power input limits therefore define a restricted domain for cold-blanket operation. The width of this domain shrinks when the beta value decreases, or when the radiation losses increase due to the effects of impurities. In certain cases the same domain even disappears completely.

(vii) At beta values of some percent and under pure plasma conditions, a cold-blanket state is likely to exist for a large class of confinement systems. Thus, cold-blanket conditions should be satisfied by many of the present reactor models as well as in model experiments with a main poloidal magnetic field, but not in earlier tokamak experiments of small and medium sizes being operated at moderately high ion densities and low beta values. It is likely that the cold-blanket regime can just be reached in JET, and also in devices like Alcator when making use of fast gas injection.

(viii) To keep also the cold-blanket sufficiently clean, it may become necessary to introduce a neutral gas flow velocity $v_{n\parallel}$ parallel with the wall surface in Fig.1, to "wash away" a considerable part of the blanket impurities.

(ix) Boundary-layer stabilization by the joint viscosity-resistivity-pressure effects should open up new possibilities of over-all plasma stabilization for a large class of magnetic confinement schemes. This stabilization mechanism becomes important to most cold-blanket systems.

(x) The problems of the radiation balance of cold-blanket systems need further detailed analysis.

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Figure Captions

Fig.1. Crude outline of a quasi-steady fully developed cold-blanket system, consisting of a cylindrical plasma column being confined by an axial magnetic field $\underline{B}$. The local plasma density and temperature are n and T, and the densities of slow and fast neutrals are n_{ns} and n_{nf}. In the case of a fusion reactor, the reaction rate is larger than the bremsstrahlung loss in the region defined by $r < r_t$. The boundary layer consists of an outer "diffusion region" within which the ionization rate can be neglected, and an inner "ionization region" within which the "residual" incoming neutral gas flux becomes "absorbed" by a strong ionization rate.

Fig.2. The relation between the normalized ion density N_b at the inner edge of the partially ionized region and the normalized neutral gas density N_{na} at the outer edge of the same region being defined by a wall or limiter surface. The branches corresponding to the asymptotic cases of Section 4.1 are indicated by (I) and (II).

Fig.3. The relation between the plasma density n_b at the inner "edge" of the boundary layer and the wall-near neutral density n_{na}, in the case of Pfirsch-Schlüter diffusion at $q = 3$, $T_o = 10^7$ K, $T_b = 10^5$ K, and $\alpha = 1/4$. The curves have been obtained with the magnetic field strength B as parameter and the dashed lines refer to the beta value.

Fig.4. Similar to Fig.3, but with classical diffusion and $T_o = 3 \times 10^5$ K.

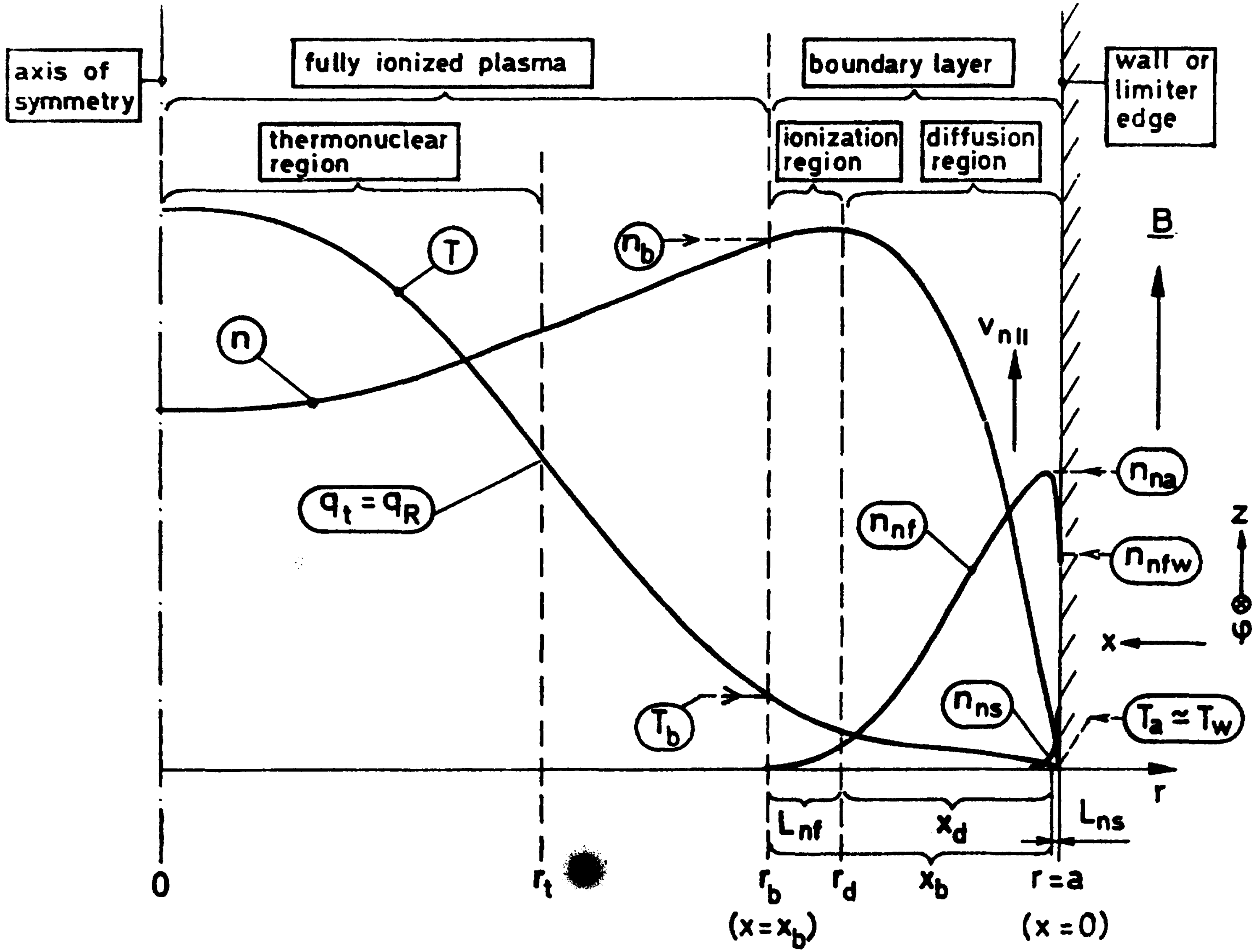
Fig.5. The domain of existence of a cold-blanket system, as defined by the lower and upper power input limits. The power input Q_b is treated as an independent variable, $\beta = 3 \times 10^{-2}$, and the data of Fig.3 are adopted. Normalized density $N_b > 10^{-2}$.

Fig.6. Similar to Fig.5, but with a power input depending on N_b and of the radius a, as defined by eq. (44). The dashed line represents the special impermeability "limit" obtained from $L_{nf}(T_b, n_b) = a$. Normalized density $N_b > 10^{-2}$.

Fig.7. Power input limits with Q_b as independent variable, $\beta = 0.1$, and with the same data as in Fig.4. Normalized density $N_b > 10^{-2}$.

Fig.8. Similar to Fig.7, but with a power input depending on N_b and the radius a. Normalized density $N_b > 10^{-2}$.

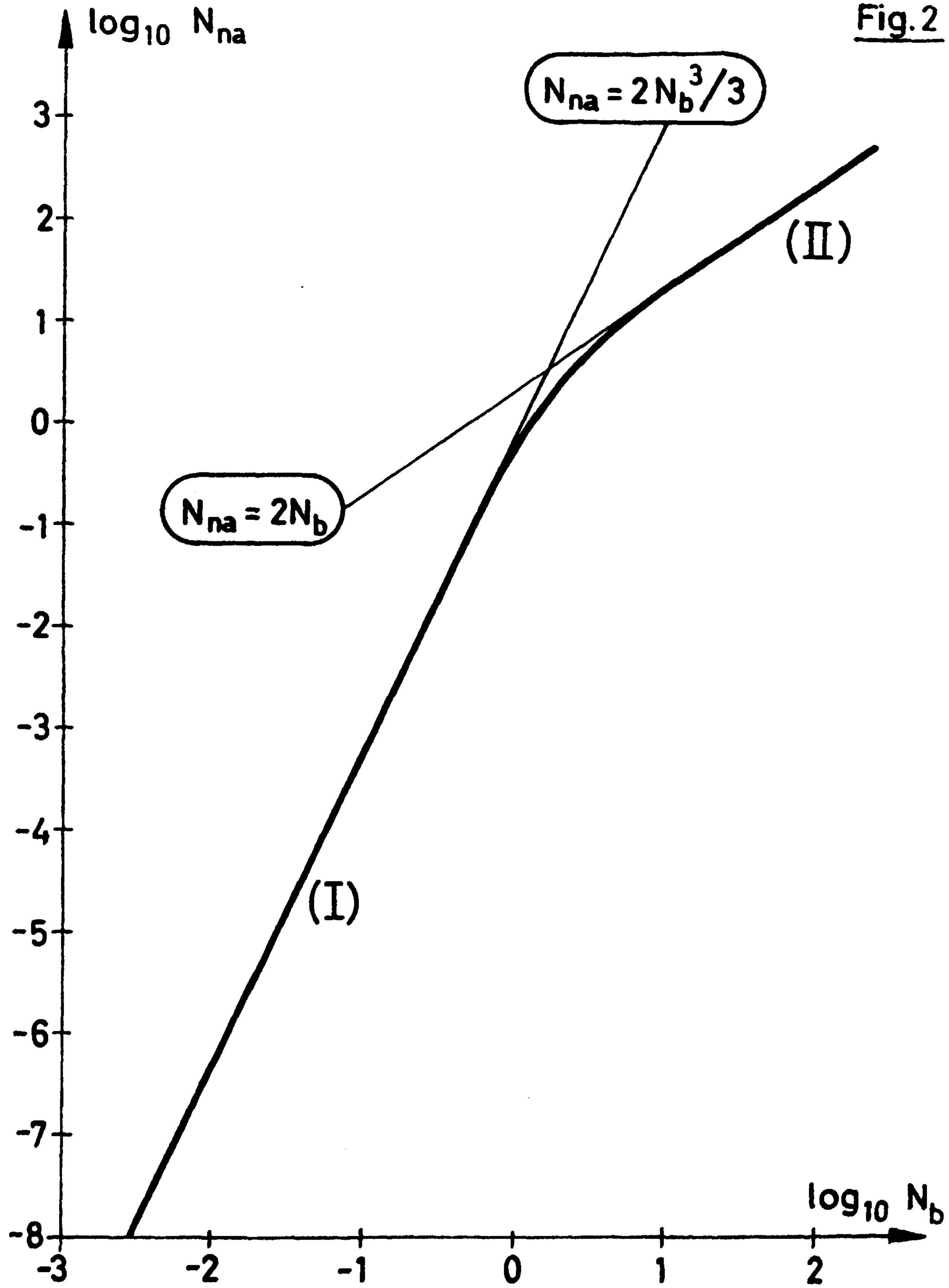
Fig.9. The ratios $f = x_{bmax}/x_{bmin}$ and $F = Q_{bmax}/Q_{bmin}$ between the limits of thickness and power input of the boundary layer, as functions of the normalized plasma density $N_b \propto \beta B$. Data given by Sections 4.2.1 and 5.4.1, at the magnetic field strength B = 3 tesla. A cold-blanket state exists only within the range $f > 1$, $F > 1$.



axis of symmetry
fully ionized plasma
boundary layer
wall or limiter edge
thermonuclear region
ionization region
diffusion region
B
T
n
n_b
$v_{n\parallel}$
$q_t = q_R$
n_{na}
n_{nf}
n_{nfw}
z
φ
x
T_b
n_{ns}
$T_a \simeq T_w$
r
L_{nf}
x_d
L_{ns}
0
r_t
r_b
$(x = x_b)$
r_d
x_b
$r = a$
$(x = 0)$

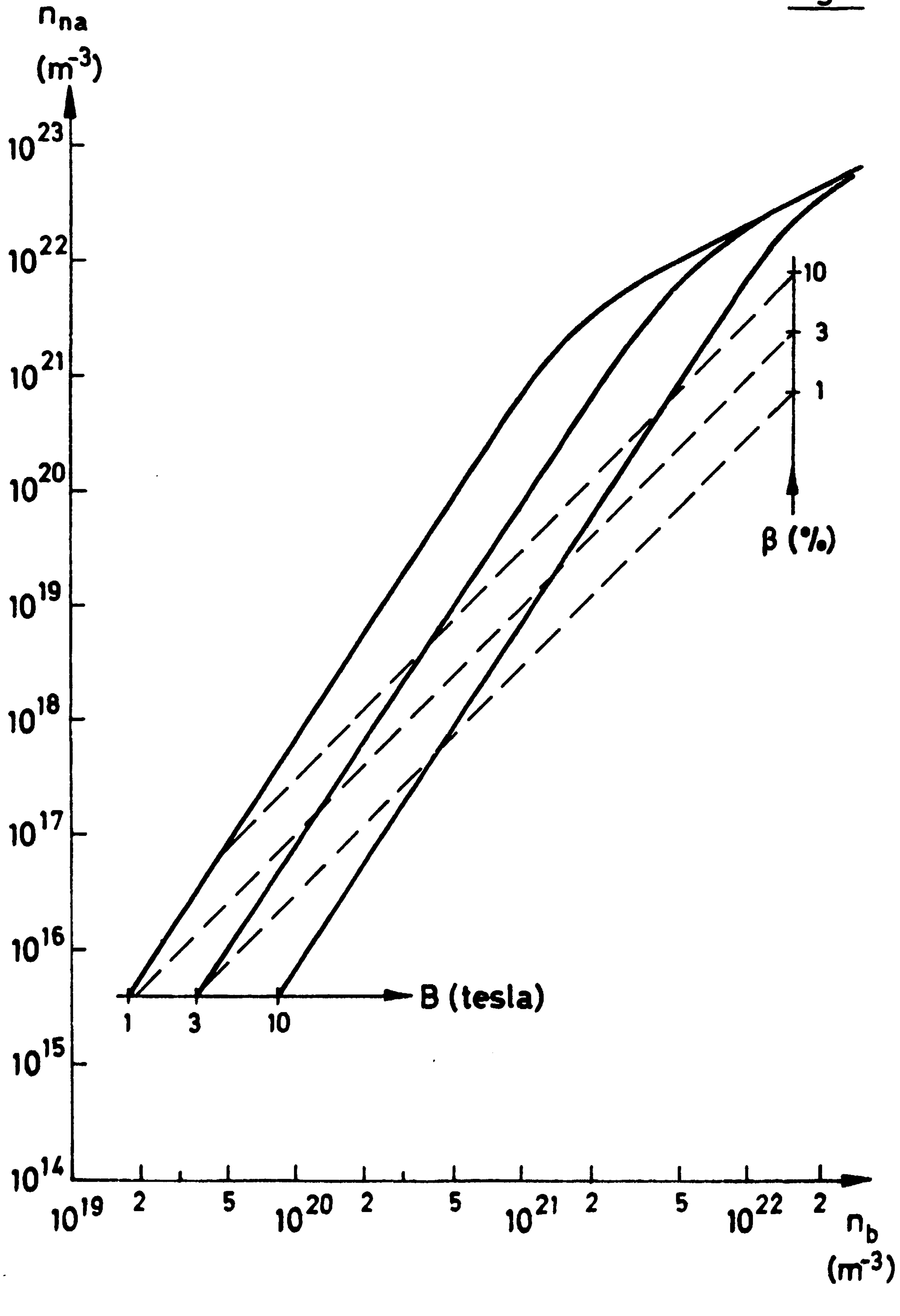
Fig. 1

Fig. 2



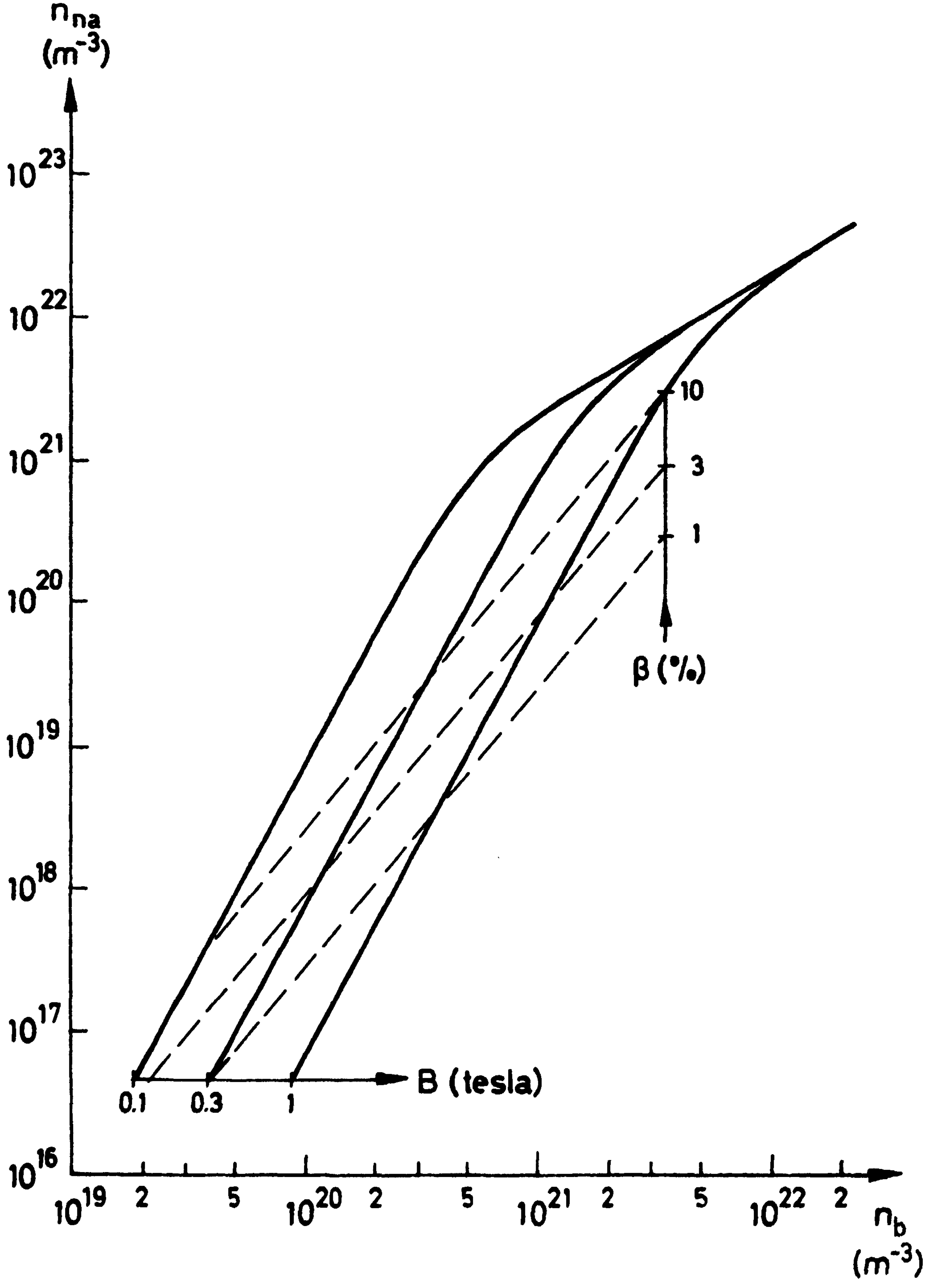
log10 Nna
Nna = 2Nb3/3
(II)
Nna = 2Nb
(I)
log10 Nb
3
2
1
0
-1
-2
-3
-4
-5
-6
-7
-8
-3
-2
-1
0
1
2

Fig. 3



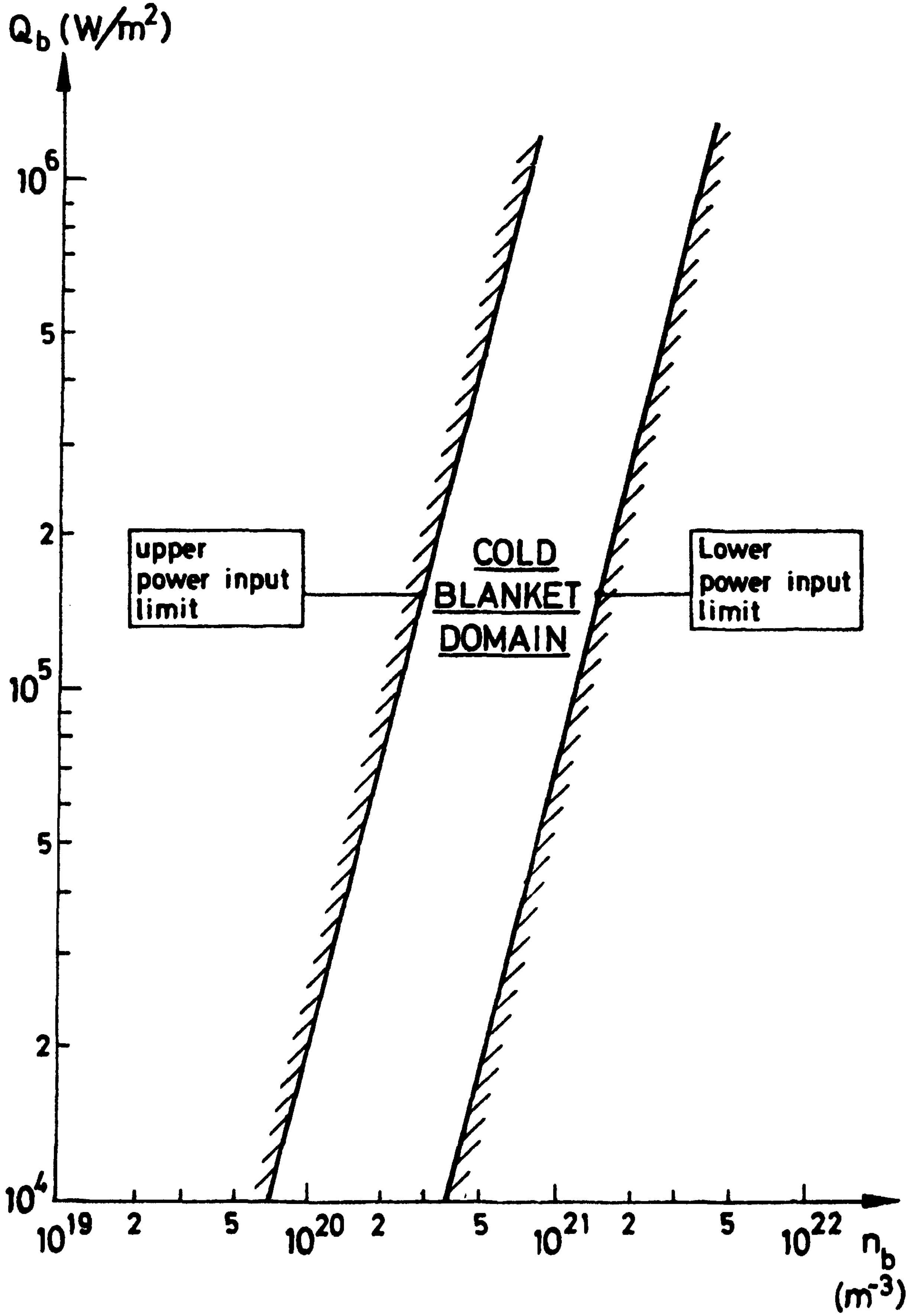
n_{na} (m^{-3})
10^{23}
10^{22}
10^{21}
10^{20}
10^{19}
10^{18}
10^{17}
10^{16}
10^{15}
10^{14}
10
3
1
β (%)
B (tesla)
1 3 10
10^{19} 2 5 10^{20} 2 5 10^{21} 2 5 10^{22} 2
n_b (m^{-3})

Fig. 4



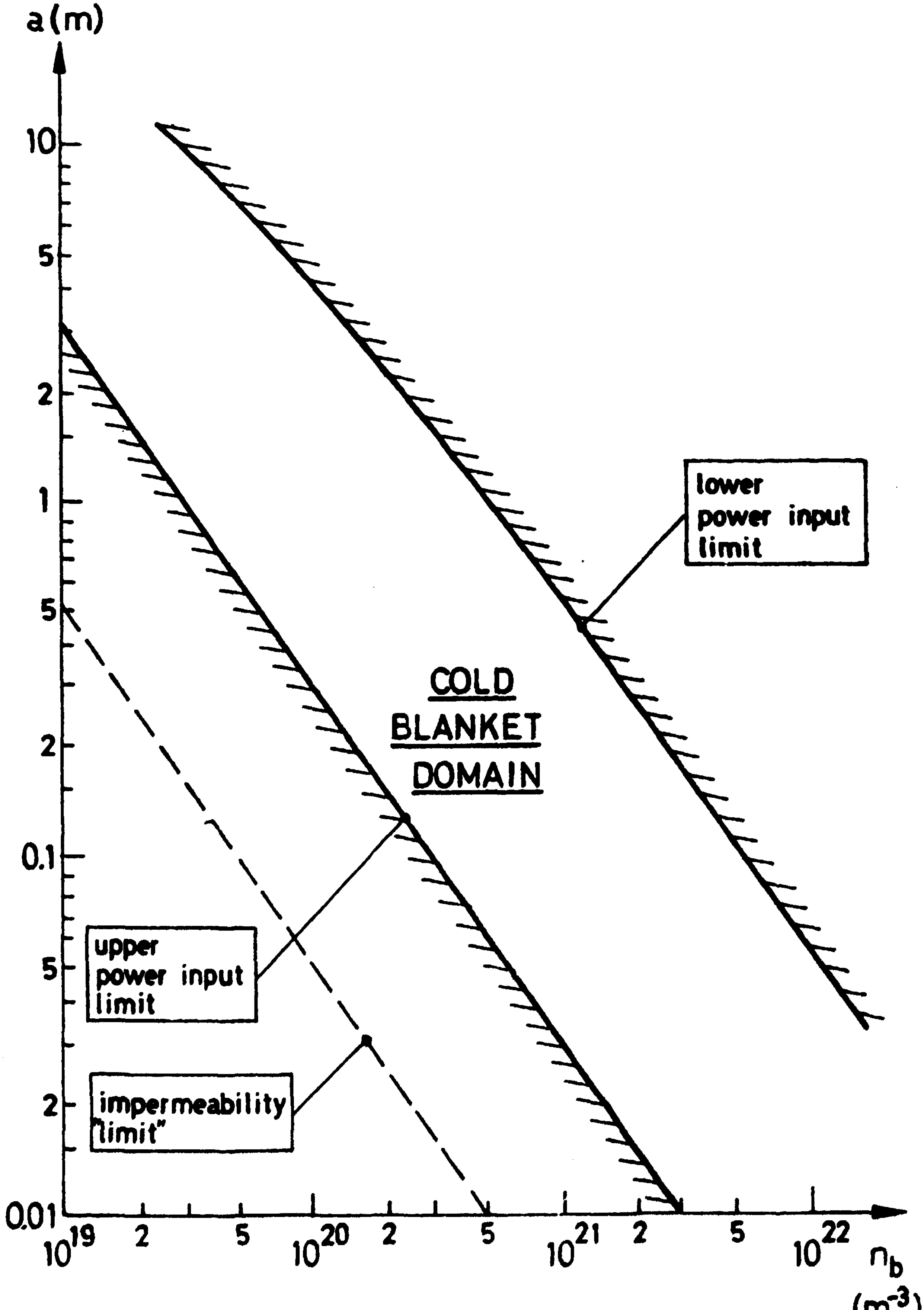
n_{na} (m^{-3})
10^{23}
10^{22}
10^{21}
10^{20}
10^{19}
10^{18}
10^{17}
10^{16}
10
3
1
β (%)
B (tesla)
0.1
0.3
1
10^{19}
2
5
10^{20}
2
5
10^{21}
2
5
10^{22}
2
n_b (m^{-3})

Fig. 5



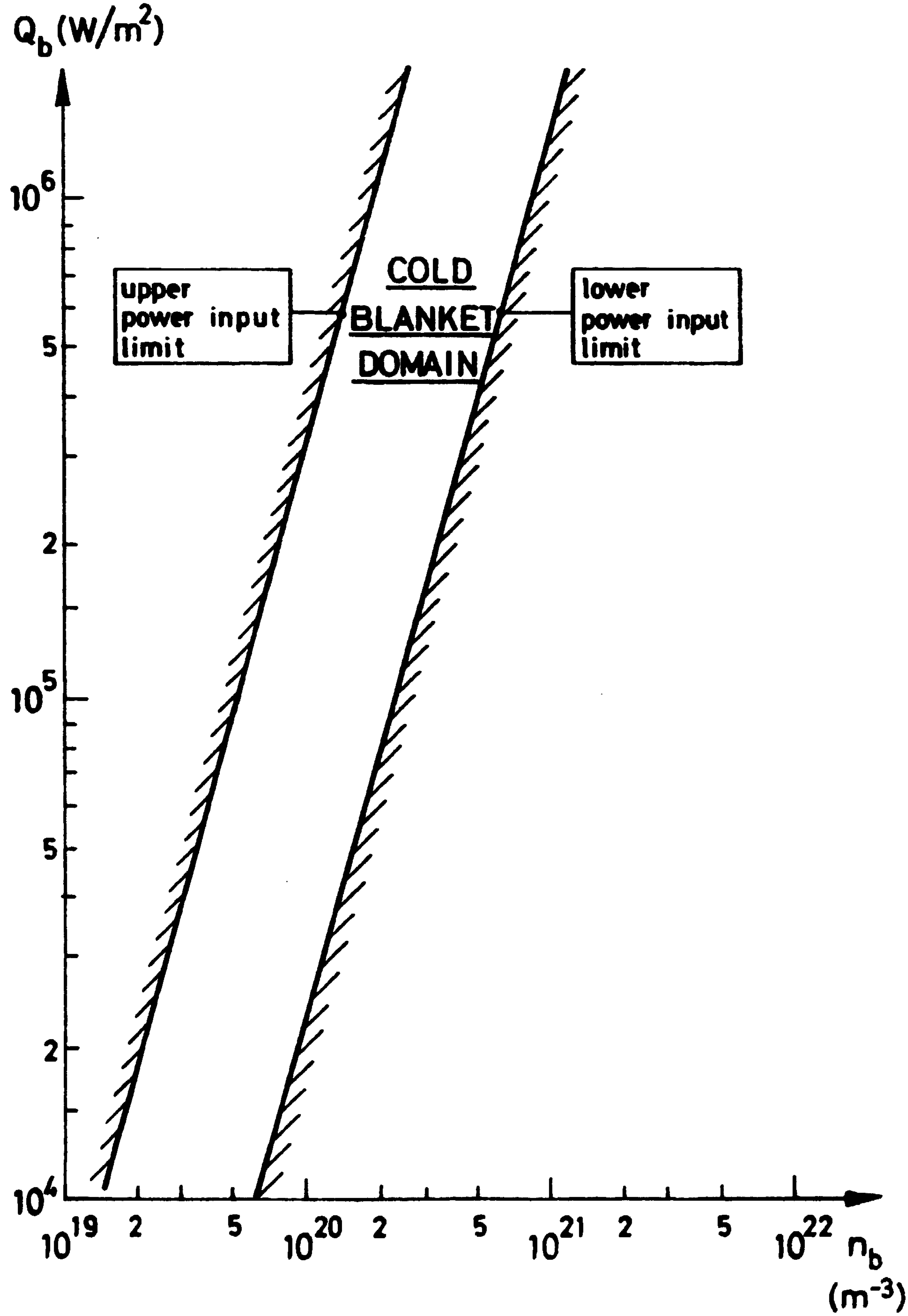
Q_b (W/m^2)
10^6
5
2
10^5
5
2
10^4
upper power input limit
COLD BLANKET DOMAIN
Lower power input limit
10^19
2
5
10^20
2
5
10^21
2
5
10^22
n_b (m^-3)

Fig. 6



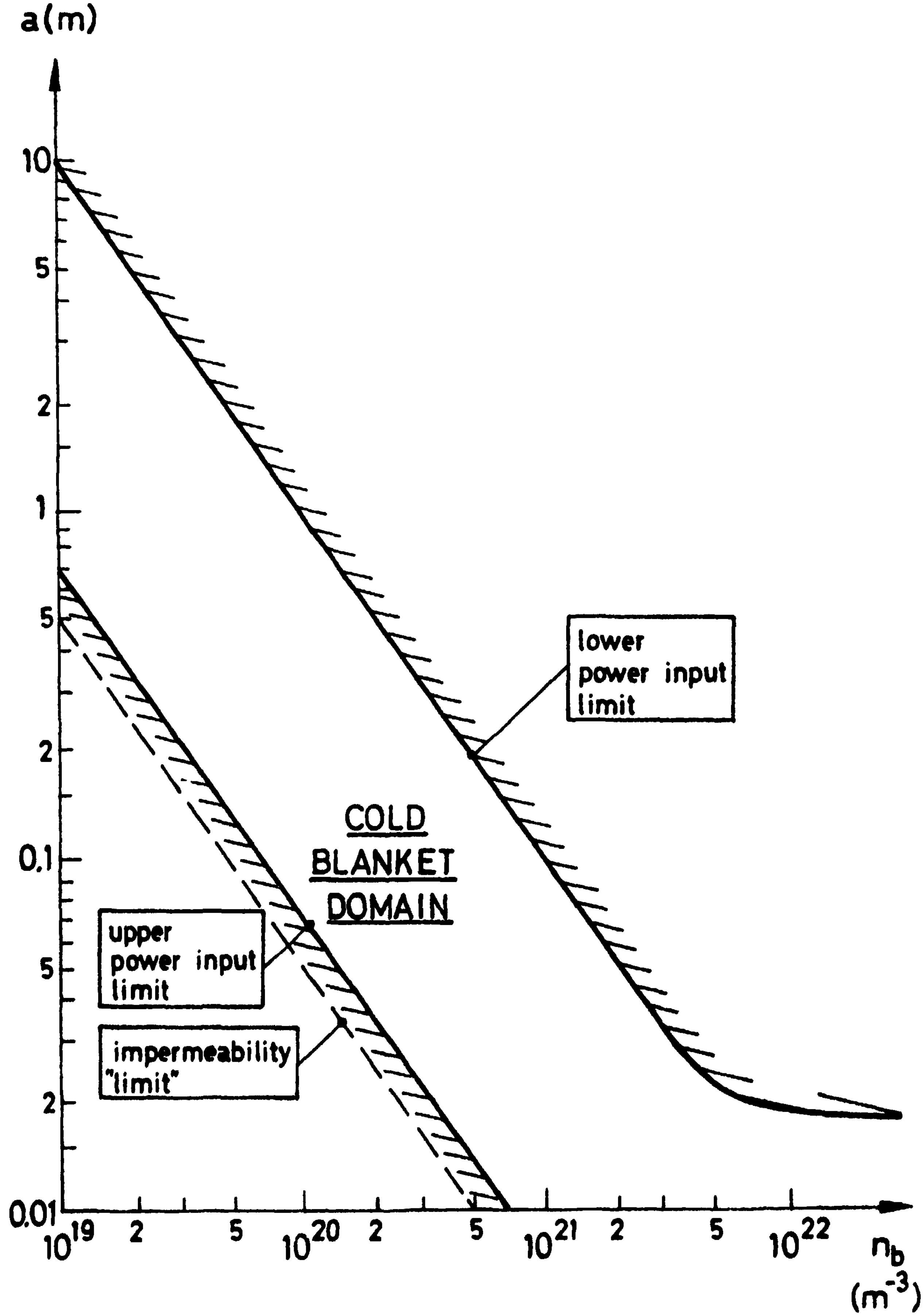
a (m)
10
5
2
1
5
2
0.1
5
2
0.01
10^19
2
5
10^20
2
5
10^21
2
5
10^22
n_b
(m^-3)
lower power input limit
COLD BLANKET DOMAIN
upper power input limit
impermeability "limit"

Fig. 7



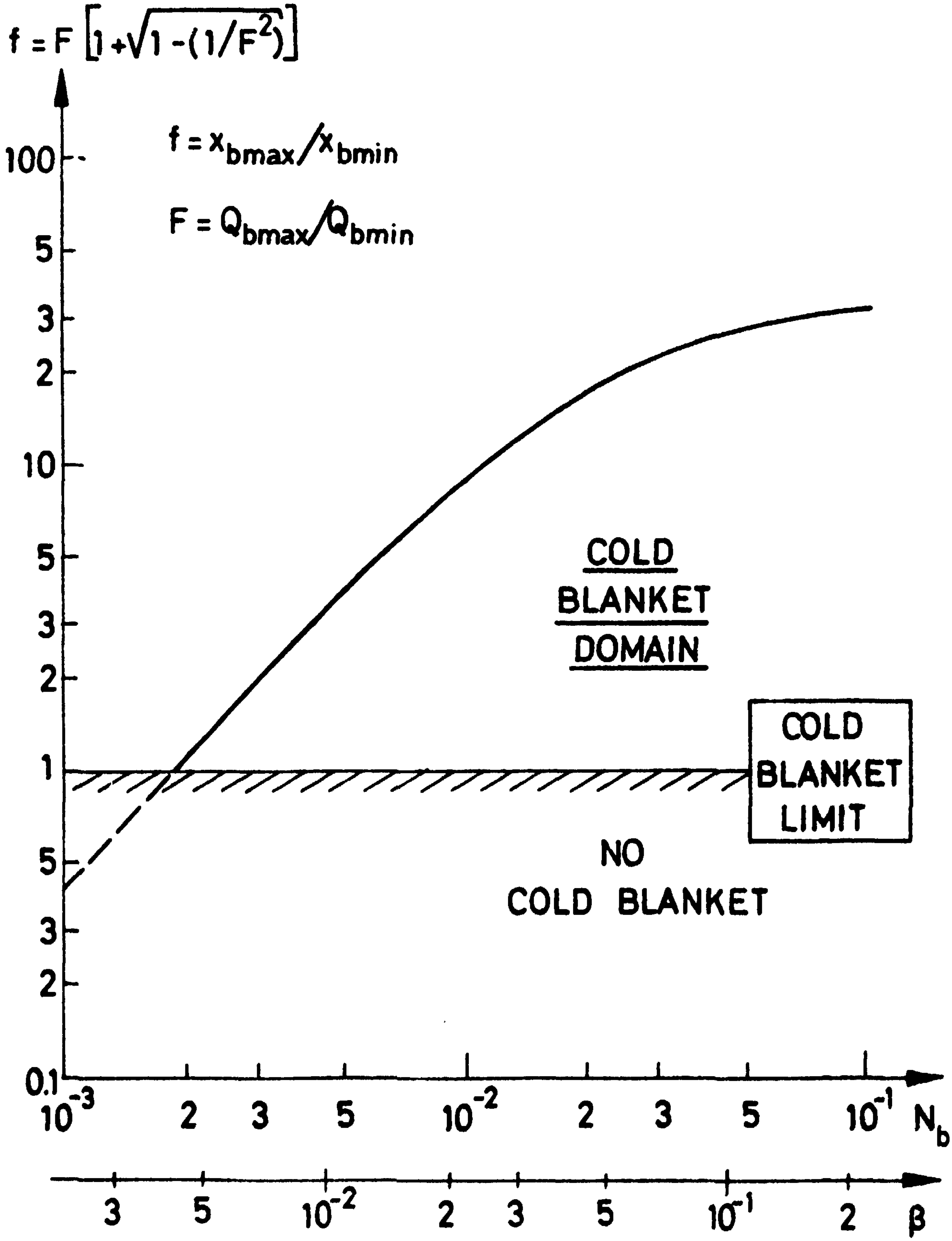
$Q_b (W/m^2)$
10^6
5
2
10^5
5
2
10^4
upper power input limit
COLD BLANKET DOMAIN
lower power input limit
10^{19}
2
5
10^{20}
2
5
10^{21}
2
5
10^{22}
n_b (m^{-3})

Fig. 8



a(m)
10
5
2
1
5
2
0,1
5
2
0.01
10^19
2
5
10^20
2
5
10^21
2
5
10^22
n_b
(m^-3)
lower
power input
limit
COLD
BLANKET
DOMAIN
upper
power input
limit
impermeability
"limit"

Fig. 9



f = F [1 + √(1 - (1/F²))]
f = x_bmax / x_bmin
F = Q_bmax / Q_bmin
100
5
3
2
10
5
3
2
1
5
3
2
0.1
10^-3
2
3
5
10^-2
2
3
5
10^-1
N_b
3
5
10^-2
2
3
5
10^-1
2
β
COLD BLANKET DOMAIN
COLD BLANKET LIMIT
NO COLD BLANKET

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Royal Institute of Technology, Department of Plasma Physics
and Fusion Research, Stockholm, Sweden

ON THE CONDITIONS OF EXISTENCE OF COLD-BLANKET SYSTEMS

B. Lehnert, December 12, 1977, 45 p. in English

An extended analysis of the partially ionized boundary layer of a magnetized plasma has been performed, leading to the following results:

(i) In a first approximation the ion density at the inner "edge" of the layer becomes related to the wall-near neutral gas density, in a way being independent of the spatial distribution of the ionization rate.

(ii) The particle and momentum balance equations, and the associated impermeability condition of the plasma with respect to neutral gas penetration, are not sufficient to specify a cold-blanket state, but have to be combined with considerations of the heat balance. This leads to lower and upper power input limits, thus defining conditions for the existence of a cold-blanket state. At decreasing beta values, or increasing radiation losses, there are situations where such a state cannot exist at all.

(iii) It should become possible to fulfill the cold-blanket conditions in full-scale reactors as well as in certain model experiments. Probably these conditions can also be satisfied in large tokamaks like JET, and by fast gas injection in devices such as Alcator, but not in medium-size tokamaks being operated at moderately high ion densities.

(iv) A strong "boundary layer stabilization" mechanism due to the joint viscosity-resistivity-pressure effects is available under cold-blanket conditions.

Key words: Cold-blanket, plasma-neutral gas interaction, magnetic confinement.