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Magnetless Magnetic Fusion

A.D. BEKLEMISHEV[a] and T. TAJIMA
Institute for Fusion Studies
The University of Texas at Austin
Austin, Texas 78712

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[a] Budker Institute of Nuclear Physics, Novosibirsk, Russia

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A.D. Beklemishev[a] and T. Tajima
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Abstract

We propose a concept of thermonuclear fusion reactor in which the plasma pressure is balanced by direct gas-wall interaction in a high-pressure vessel. The energy confinement is achieved by means of the self-contained toroidal magnetic configuration sustained by an external current drive or charged fusion products. This field structure causes the plasma pressure to decrease toward the inside of the discharge and thus it should be magnetohydrodynamically stable. The maximum size, temperature and density profiles of the reactor are estimated. An important feature of confinement physics is the thin layer of cold gas at the wall and the adjacent transitional region of dense arc-like plasma. The burning condition is determined by the balance between these nonmagnetized layers and the current-carrying plasma. We suggest several questions for future investigation, such as the thermal stability of the transition layer and the possibility of an effective heating and current drive behind the dense edge plasma. The main advantage of this scheme is the absence of strong external magnets and, consequently, potentially cheaper design and lower energy consumption.

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[a] Budker Institute of Nuclear Physics, Novosibirsk, Russia

I Introduction

If we need no (or few auxiliary) magnets and the plasma β is very high, such a configuration would be superior as a thermonuclear fusion reactor. Neutrons from the reacting plasma would not damage costliest components (usually superconducting magnets) and the design of the reactor would be much simplified and the cost much reduced.

One of the important figures of merit of a reactor is the energy density, which is defined as

$$\varepsilon \equiv \frac{P_{\mathrm{fus}}}{\Gamma_n} , \tag{1}$$

where P_{fus} is the energy production fusion power and Γ_n is the neutron flux (or fluence). The energy density is found to be inversely proportional to the size of the fuel core:

$$\frac{P_{\mathrm{fus}}}{\Gamma_n} \sim \frac{1}{a} , \tag{2}$$

where a is the size of the fuel core. The power of fusion energy P_{fus} is given as

$$P_{\mathrm{fus}} = n^2 \left< \sigma_{\mathrm{fus}}\, v \right> \varepsilon_R\, f_\alpha \propto \beta^2 B^4 , \tag{3}$$

where n is the density of the individual fusion fuel, σ_{fus} the fusion cross-section, ε_R the fusion reaction energy, and f_α the fraction of α particle trapping. The fusion power is proportional to the plasma β^2 and the containing magnetic field B^4. For the examples of $\beta = 0.06$ and $B = 6\,\mathrm{T}$, $P_{\mathrm{fus}} \sim 5\,\mathrm{MW/m^3}$ and $\beta = 0.02$ and $B = 20\,\mathrm{T}$, $P_{\mathrm{fus}} \sim 45\,\mathrm{MW/m^3}$, whereas a corresponding example of $\beta = 0.6$ and $B = 6\,\mathrm{T}$, $P_{\mathrm{fus}} \sim 500\,\mathrm{MW/m^3}$. The recent progress in advanced tokamak discharges has achieved high β in the core plasma (as much as 0.44)[1] and encouraging in avoiding ballooning instabilities.[2]

The gas-insulation of a hot plasma has been proposed by Alfvén and Småars[3] in 1960 as an alternative confinement scheme. Their initial estimates indicated practical feasibility of the approach in relatively simple conditions. However, later research[4] demonstrated that the bremsstrahlung, ignored in estimates of Alfvén, plays an important role and essentially forbids formation of steady-state discharges with $\beta \gg 1$. The energy sink in the power balance, associated with the bremsstrahlung, usually causes propagation of a cooling wave from the edge into the discharge,[5] so that now only transient configurations are being seriously considered for possible fusion applications. The gas-insulation was the central idea for the gas dynamic trap at Budker Institute of Nuclear Physics, where the gas dynamic trap is a multi-mirror device designed to operate at $\beta \gg 1$ and high enough density to make parallel flows collisional.

The worst problem of wall-confinement devices is the bremsstrahlung, which dominates the power balance at the edge[4] ($T \leq 2\,\mathrm{keV}$). For devices of moderate size ($R < 100\,\mathrm{m}$) the radiative collapse can be prevented only by steepening temperature gradients at the edge of the discharge. We propose a concept of thermonuclear fusion reactor, in which the plasma pressure is balanced by direct gas-wall interaction[3, 4] while the thermal insulation is provided by a relatively weak magnetic field, as an alternative confinement scheme. Previous studies of the subject indicated[5] that the thermal equilibrium can be achieved either in unrealistically large devices, or with sharp variation of the heat conductivity (magnetic field strength) within plasma volume. These restrictions can be relaxed by using nonlocal transport effects related to specific conditions in high-beta fusion plasmas. The nonlocal effects, such as shifted energy deposition profile from fusion alpha particles and reabsorption of radiation in the high-density regions, cause flatter temperature distributions and, thus, lower bremsstrahlung losses. A sample model of a spherical fusion device without magnetic coils is presented.

Our configuration includes:

1. The pressure ($\sim 100\,\mathrm{atm}$) is confined by walls of the container;

2. The temperature gradient is supported by a weak magnetic field of the self-generated plasma current, so that $\beta \gg 1$ but $\nabla\beta \approx 0$;
3. The overall magnetic configuration is toroidal and similar to spheromac's and FRC's, though supported by internal currents only.

The plasma/gas pressure is increasing or flat toward the outside, so that it is stable against MHD instabilities. Since there is no external magnetic field, the magnetic fields in the plasma do not have a particular orientation, and thus no tilt instability.[6]

II The Heat Transport Model and Thermal Equilibrium

We are interested in questions like:

(i) Is there a thermal equilibrium that can realize the burning regime?

(ii) What is the stability of the burning regime and how it can be controlled?

(iii) How can the burning regime be reached?

We look at problem (i) using a simplified heat transport model to make order-of-magnitude estimates. In order to consider problem (ii) we present qualitative arguments that the equilibrium will be at least one-dimensionally thermally stable, and discuss possible MHD relaxations. A method of RF control of the edge plasma is suggested. The third problem is always very difficult to answer and, probably, even more so with wall confinement.

Our heat transport model and thermal equilibrium are constructed, based on the following considerations. We choose a reasonable toroidal magnetic configuration, as shown below. The classical description of transport in the magnetized region of the central (or non-edge) plasma in two regimes are taken. The description of transport in the cold collisional plasma and matching into the neutral gas layer is taken at the edge region (near wall). We take into account alpha-particle production and redistribution of the heat source due to large particle orbits and heat transport. Bremsstrahlung and recombination radiation are considered as the heat sink and reabsorption is taken into account. The above processes are treated in one dimension with due account for flux-surface forms, and computed by using a one-dimensional transport code. Absent in this study is a self-consistent description of the magnetic field.

The magnetic configuration we consider is given by flux surfaces of the model magnetic field

$$\begin{cases} \mathbf{B}_\theta = \mathbf{e}_\phi \times \nabla f(\psi) \\ \psi = r^2 \exp(-r^2 - z^2) \ , \end{cases} \tag{4}$$

where the function $f(\psi)$ can be adjusted to simulate different profiles of toroidal current density. Sample flux surfaces from (4) are shown in Fig. 1. A sample field profile of $|B_\theta(x)|$ is shown in Fig. 2. For found thermal equilibria the magnetic intensity (at the edge) was in the range $1 \lesssim B \lesssim 10\,\mathrm{T}$, with broad current profiles. The decay of magnetic fields due to plasma current may be counteracted by an external rf current drive or by the current induced due to charged fusion products.[7]

The heat transport equations are now described. Introduce position x, which is a flux-function variable as long as the temperature is constant on magnetic surfaces, but x labels spherically symmetric surfaces at the edge. See Fig. 3. The transition point corresponds to the transition from magnetized to nonmagnetized plasmas and the flux tubes close to the vertical axis are considered to be filled with plasma at this transition temperature. (This situation might not be too dissimilar to that of the tokamak divertor region.) Now $T = T(x)$ and, consequently,

$$c_i \frac{\partial T}{\partial t} + T = \int_{x_{\mathrm{edge}}}^{x} \frac{dx'}{\overline{\chi}_\perp(x')} \int_{x_0}^{x'} (Q_\alpha - Q_r) D_v \, dx'' \ . \tag{5}$$

Here $\overline{\chi}$ and D_v depend on the metric characteristics of the temperature surfaces:

$$\begin{cases} \overline{\chi}_\perp = \int_{S_x} \chi_\perp |\nabla x| dS \ , & (6) \\ D_v = \int_{S_x} \frac{dS}{|\nabla x|} \ . & (7) \end{cases}$$

Although future studies may be needed, most microinstabilities such as drift instabilities and ballooning instabilities should be stable, as the plasma basically holds the good curvature in this configuration. The heat conductivity is then classically given by[8]

$$n\chi_\perp = \begin{cases} ncT/(eB(\omega_H\tau)_i)\ , & (\omega_H\tau)_i > 1 \\ ncT/eB \ , & 1 > (\omega_H\tau)_i > (m_e/m_i)^{1/2} \\ ncT(\omega_H\tau)_e/eB\ , & (\omega_H\tau)_e < 1 \end{cases} \tag{8}$$

where ω_H and τ are the cyclotron frequency and collision time of the respective species. The middle region has magnetized electrons but unmagnetized ions. The electron density is taken from $nT = \text{const}$, so that

$$n_e = n_i = 3 \times 10^{17}\, \frac{P(\text{atm})}{T(\text{eV})}\ . \tag{9}$$

Since the heat conductivity of a dense neutral gas is much smaller than that of a nonmagnetized plasma of comparable temperature, the neutral sheet is very thin and one can consider the radial position of the ionization temperature to be the effective edge of the device. This conclusion is supported by a separate model of ours on the thermal balance in the ionization region. The energy gains from α-particles and radiation losses as a function of temperature (at the given operating pressure $P = 100\,\text{atm}$) can be computed and shown in Fig. 4.

The α-particles and the bremsstrahlung powers can be written as functions of local temperature and density n which is approximately proportional to T^{-1}:

$$P_{br} = 2.10^4\, \frac{P}{T^{1/2}} \left(1 + \frac{13.6}{T}\right) n_e\ , \tag{10}$$

$$P_\alpha = 1.9.10^{14}\, PT^{-5/3} \exp\left(-\frac{199.4}{T^{1/3}}\right) n_i\ . \tag{11}$$

Figure 5 shows the fusion power as well as those in Eqs. (10) and (11). However, this does not mean that the profiles of the heat source and sink correspond to these formulas. The bremsstrahlung can be reabsorbed by dense plasma of the edge region (this effect is small for sharp temperature gradients), and the energy input from α-particles will be shifted into more dense regions along corresponding orbits. These effect are large if the temperature gradient length L_T is less than the gyroradius of an alpha particle $L_T \lesssim \rho_\alpha$, i.e. for sharp density gradients and weak fields and this is the case for our configuration. We model this process by allowing 1/2 of α's to slow down where they are born, while 1/2 is transferring energy to a point which is $2\rho_\alpha$-shifted away into the cold region.

We find that steady-state temperature profiles are found only for high central temperatures $\gtrsim 40\,\mathrm{keV}$ and exhibit sharp edge gradients of temperature. An example is shown in Fig. 6. The solutions we have found have the following significant features. The fact that the α-particles are lost from the outer edges of the discharge causes the energy input to be shifted outward. This is true for out-swinging orbits only and that may cause generation of toroidal current.[7] The flat-top radial profile of the temperature is caused by the hollow profile of the energy deposition (at high temperatures and $P = \mathrm{const}$ the thermonuclear power decreases). With increased temperature the thermonuclear power decreases more rapidly than the radiative losses. This ensures the thermal stability at least in one dimension. In plasma with $\beta \gg 1$ there is a natural process that causes a generation of sharp edge gradients due to the thermal wave.[9] The properties of the plasma are not very different from those of the solar transition layer (see for example, Ref. 10).

III Conclusion

In conclusion, the toroidal magnetic confinement configuration sustained by the plasma current but not by external magnets is proposed. This configuration may be maintained by an rf current drive or the fusion products themselves to fight against the resistive decay. By looking for a flat-top temperature ($\gtrsim 40\,\mathrm{keV}$) and sharp edge temperature gradient and by incorporating nonlocal bremsstrahlung power balance effects among other effects, we found steady-state burning regimes in a toroidal device with wall-confinement of pressure. These regimes are thermally stable for constant pressure but unstable with a fixed number of particles according to our one-dimensional model. The existence of steady-state regimes in devices of moderate size is heavily dependent on the asymmetric α-particle confinement.[7] The fusion exhaust may be taken out along the axis of the toroid as a form of a pair of jets. Moreover, some momenta of fusion products contribute to the azimuthal spin of the toroid. There is a serious problem of initial ignition and we still need much study on this. This project is still in a very formative stage and our preliminary results should be refined and verified in the future.

A similar consideration has been done recently.[11] The inertial confinement scheme proposed by Hasegawa[12] also takes a similar magnetic configuration and the role for magnetic heat insulation.

Acknowledgments

We would like to dedicate this paper to Prof. Norman Rostoker. He has been a conscience of the community as well as the signal contributor to this field. Moreover, he has been an excellent educator and one of the authors (TT) owes his scientific and moral growth to him.

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Figure Captions

1. Self-contained magnetic configuration described by Eq. (4). This represents plasma-produced fields. No external magnets are necessary. The decay of fields may be counteracted by external RF drive or by charged fusion product induced current.
2. Sample field profile of $|B_\theta(x)|$ given by Eq. (4).
3. The flux surface configuration and the coordinate x.
4. The energy source and sink as a function of the plasma temperature.
5. The fusion power, P_{fus}, cyclotron radiation P_c, and bremsstrahlung P_{br} as a function of T (in eV).
6. Steady-state temperature profile as a function of the magnetic surface coordinate.

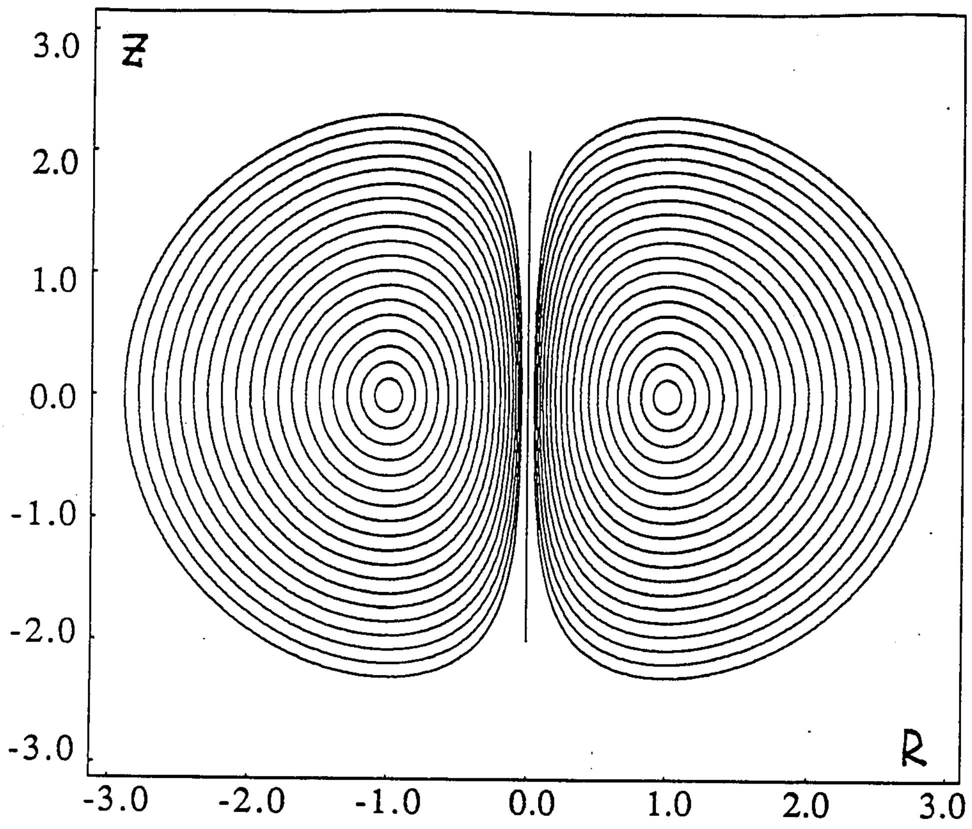
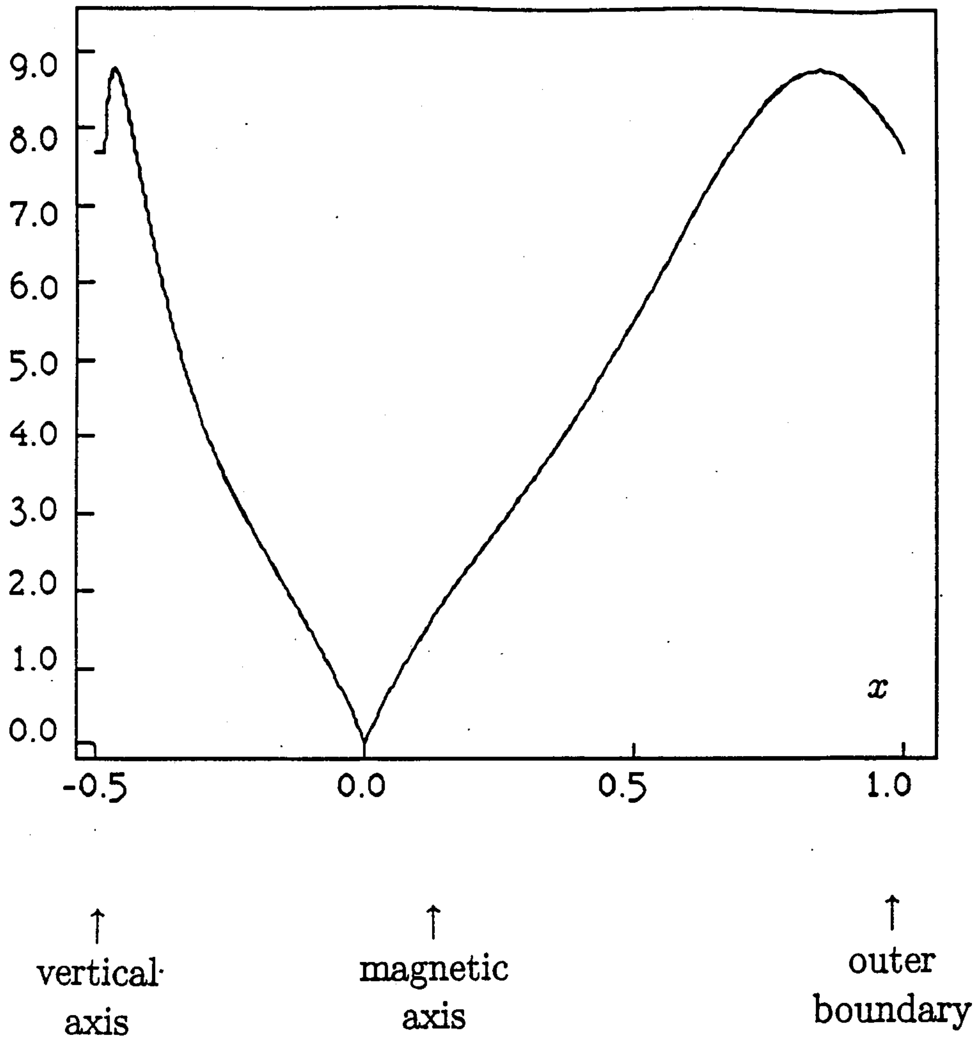


Fig. 1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8.0
7.0
6.0
5.0
4.0
3.0
2.0
1.0
0.0
-0.5
0.0
0.5
1.0
x
vertical axis
magnetic axis
outer boundary

Fig. 2

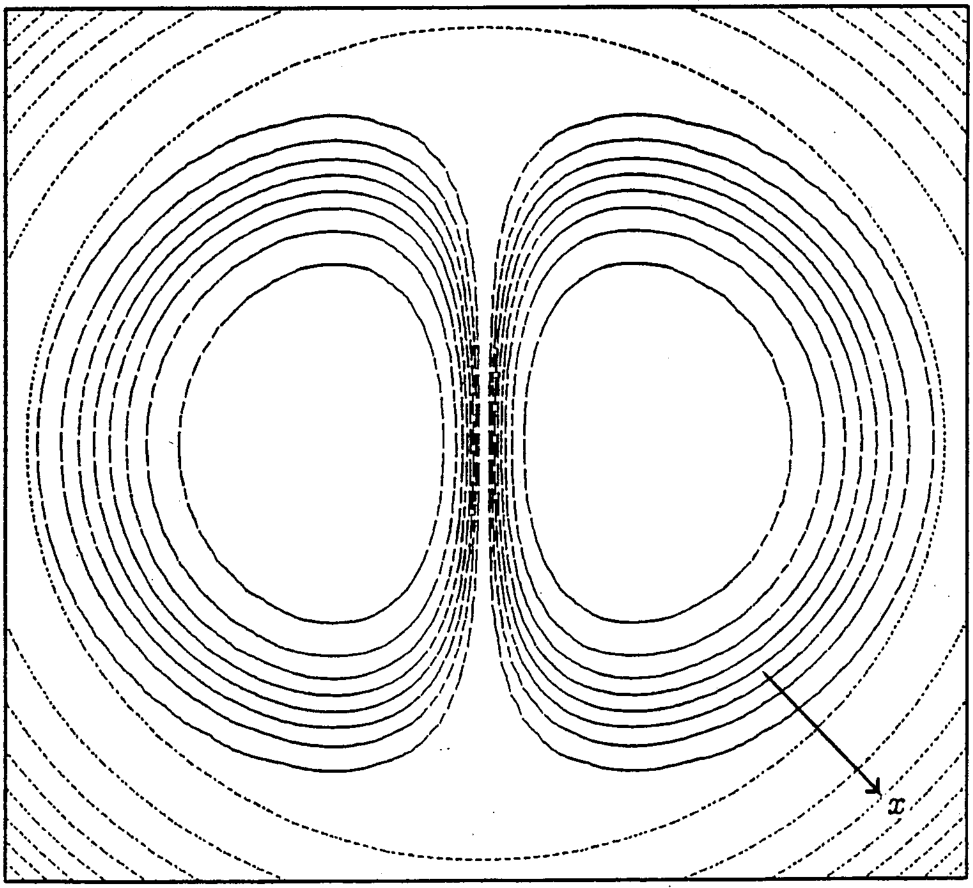

Fig. 3

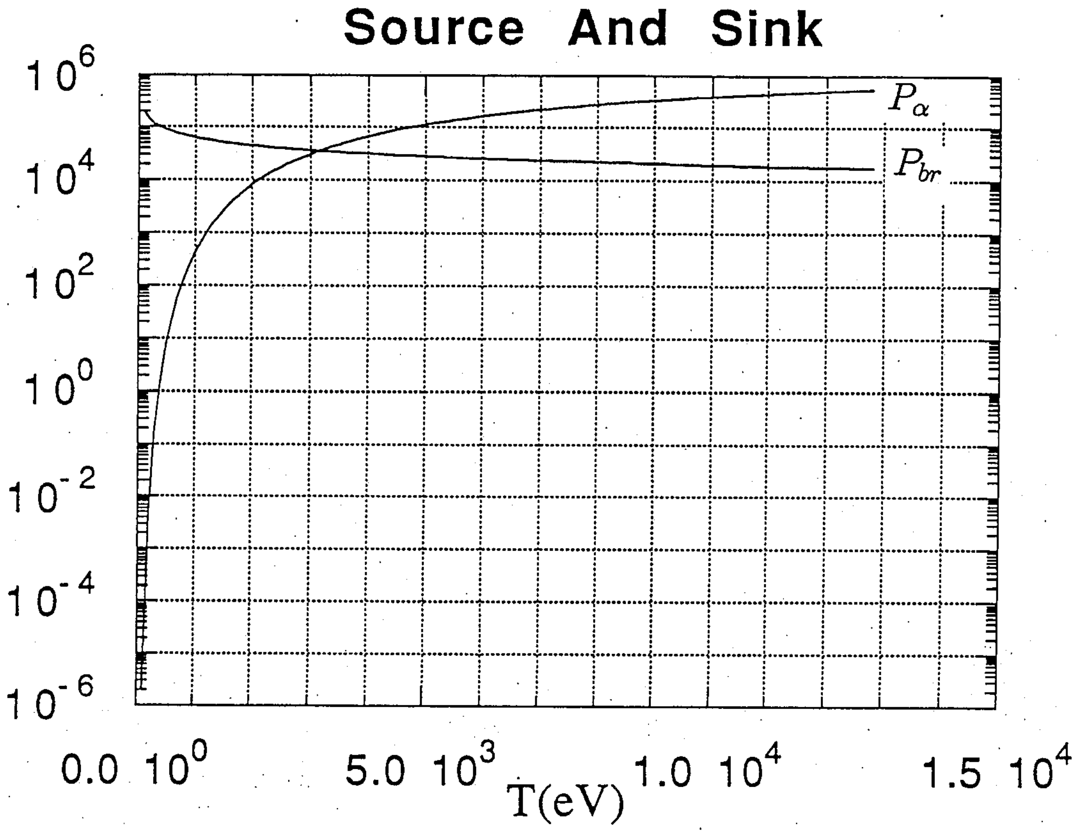
Source And Sink
10^6
10^4
10^2
10^0
10^{-2}
10^{-4}
10^{-6}
P_α
P_{br}
0.0 10^0
5.0 10^3
1.0 10^4
1.5 10^4
T(eV)

Fig. 4

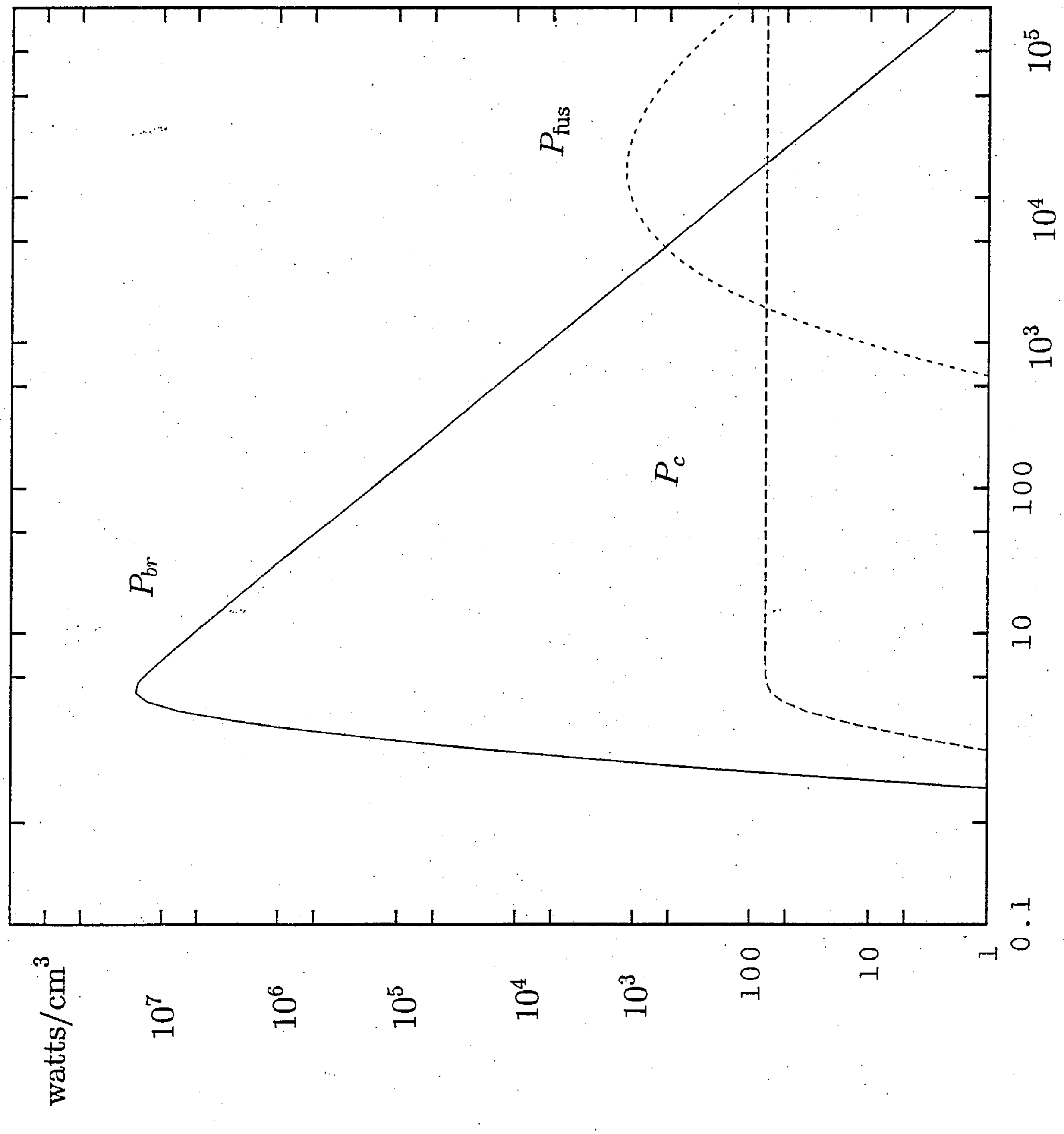
watts/cm^3
10^7
10^6
10^5
10^4
10^3
100
10
1
0.1
10
100
10^3
10^4
10^5
P_{br}
P_c
P_{fus}

Fig. 5

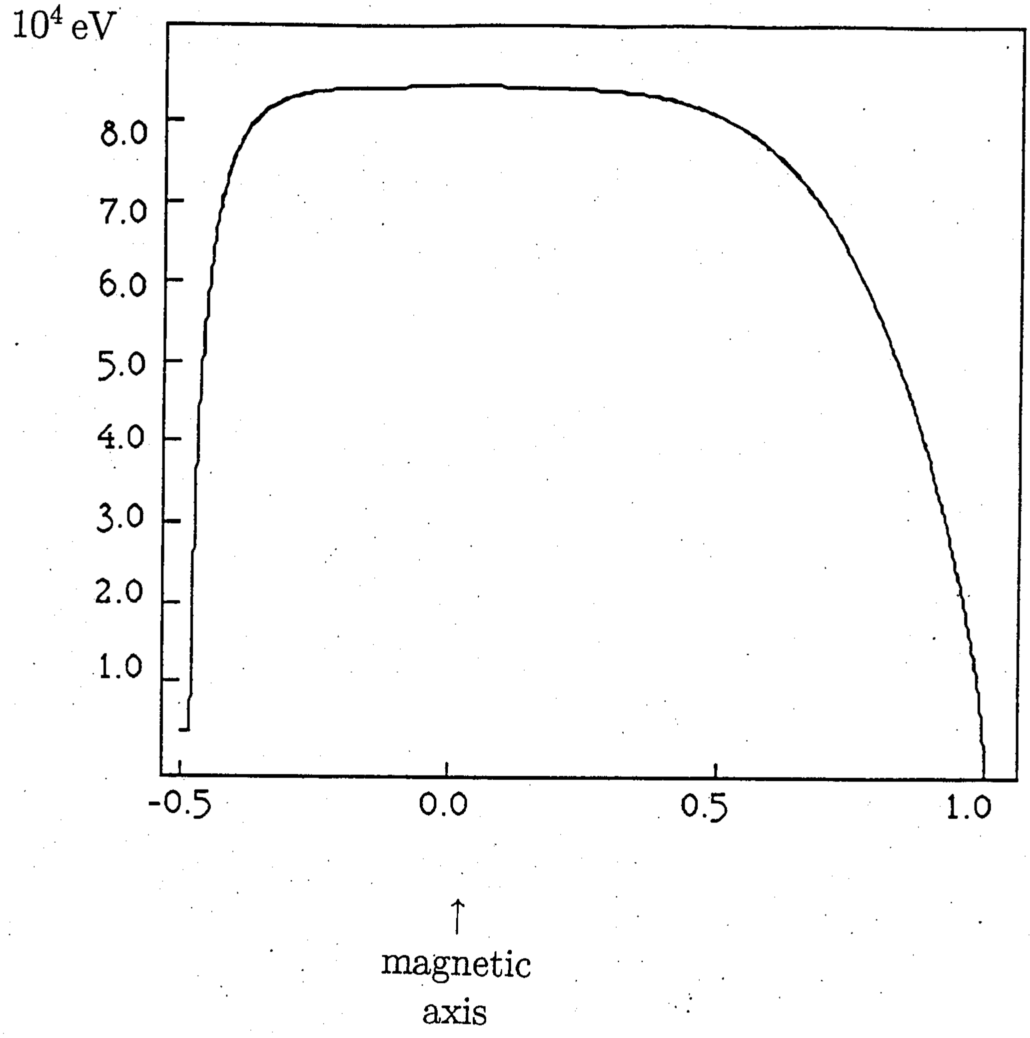

Fig. 6