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LASER-HEATING OF HYDROGEN PLASMA

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ABSTRACT

The possibility of creating a fully ionized hydrogen plasma to investigate the capture of slow antiprotons is discussed. Laser heating of the initially discharge created arc or Z pinch plasma is proposed. Within the framework of a simple 1 dimensional model based on the energy balance equation alone it is shown that plasma equilibrium can be sustained for 10μs. A simple pulsed CO_2 laser with this pulse duration and an energy of about 10 30 J is sufficient for heating.

И.Б. Фёлдеш, П.Н. Игнац, Г. Кочиш: Лазерный нагрев водородной плазмы. KFKI-1990-51/D

АННОТАЦИЯ

Исследуются возможные способы создания полностью ионизированной плазмы водорода для изучения захвата медленных антипротонов. Предлагается метод лазерного нагрева, индуцированного дуговым или Z-pinch - разрядами плазмы. При помощи простой одномерной модели, основывающейся на уравнении энергетического баланса, доказана возможность сохранения равновесия плазмы в течение 10 мкс, что является необходимым условием для вышеуказанного исследования. Нагрев может быть обеспечен простым импульсным CO_2 лазером с длительностью импульса 10 мкс и энергией 10-30 Дж.

Földes I.B., Ignácz P.N., Kocsis G.: Hidrogén plazma lézeres fűtése. KFKI 1990 51/D

KIVONAT

Megvizsgáljuk annak a lehetőségét, hogy miként lehet teljesen ionizált hidrogén plazmát létrehozni lassú antiprotonok befogásának vizsgálatához. Egy ív vagy Z pinch kisüléssel keltett plazma lézeres fűtését javasoljuk. A csupán az energia megmaradáson alapuló 1 dimenziós modell számítás segítségével megmutatjuk, hogy lehetséges a plazma egyensúly 10μs on keresztül történő fenntartása, ami a vizsgálatokhoz szükséges. A fűtéshez elég egy egyszerű impulzus CO_2 lézer használata a fenti impulzushosszal és mintegy 10 30 J energiával.

1. Introduction

Laser heating of plasmas has become a subject of increasing interest in the past two decades with the availability of high power lasers. Lasers are used to heat high density plasmas in order to reach thermonuclear conditions [1,2]. Another field of interest is the heating of lower density (underdense) preformed plasmas with lasers [3,4]; this is an area which offers numerous applications.

On the other hand, fully ionized Z–pinch hydrogen plasmas have been created in order to investigate laser–plasma interaction processes [5,6]. Hydrogen discharge plasmas were produced to study the interaction of heavy ion beams with dense plasmas [7]. Interest arose however, in studying the interaction of other particles, e.g. antiprotons with plasmas [8]. Antiprotons are slowed down with an anticyclotron [9]. The fully ionized plasma must be created outside or, if it is possible, inside the anticyclotron. In that current flows and electrical noise are to be avoided, laser heating of the plasma is suggested. Very high power is required to generate and ionize the plasma, therefore the heating of an initially discharge created plasma is considered. In the case of initial neutral atom pressures around 1 torr the CO_2 laser seems to be the best candidate to obtain efficient heating.

In this work calculations are presented on the heating and sustaining of a plasma in the fully ionized regime during a 10 μs period.

2. Plasma properties

2.1. General properties

In order to estimate the temperatures needed to fully ($\geq 99\%$) ionize the hydrogen plasma local thermal equilibrium (LTE) is assumed and the Saha equation has been used. In order to utilize the LTE model the plasma electron density must be sufficiently high for collisional de–excitation: it should in fact be at least ten times more probable than radiative decay for all transitions. In an optically thin plasma it means [10]:

$$n_0 \geq 1.6 \cdot 10^{12} T^{1/2} (\Delta W)^3_{max} cm^{-3} \qquad (1)$$

where $(\Delta W)_{max}$ is the largest interval between adjacent energy levels of the atoms and ions in the plasma in eV and T is in K. In the case of hydrogen ΔW is the Lyman α level, consequently $n_0 \geq 3.5 \cdot 10^{17} cm^{-3}$ for a 5 eV hot plasma. We can see that in the case of densities $2 \cdot 10^{17}$ which will be discussed here in detail, we are slightly below the applicability of the LTE model (but only for the Lyman α line): however, this is not a bad approximation [11]. Thus in the following the Saha equation is used to calculate the degree of ionization of the plasma. For $\alpha = n_e/n_0$, i.e. for the ratio of the number of free electrons per original atoms, it gives

$$\frac{\alpha^2}{1-\alpha} = 2u_0 \frac{1}{n_0} \left(\frac{2\pi m_e kT}{h^2} \right)^{3/2} e^{-I_1/kT} \tag{2}$$

Here n_0 is the initial density of atoms, m_e is the mass of the electron, $I_1 = 13.6eV$ is the ionization energy of hydrogen. The factor u_0 is obtained from the electronic partition function which, for hydrogen atoms (the hydrogen gas is assumed to be atomic throughout this work, i.e. molecular excitations, dissociation, etc. are neglected) is:

$$u_0 = \sum_{n=1}^{n^*} 2n^2 exp\left[-\frac{I_1}{kT} \left(1 - \frac{1}{n^2} \right) \right]. \tag{3}$$

The summation must be carried out until the electron orbit becomes equal to the distance between the atoms, i.e. $n^* = \left(\frac{1}{n_0^{1/3} a_0} \right)^{1/2}$ with $a_0 = 0.53 \cdot 10^{-8}$ cm Bohr radius [11]. This somewhat arbitrary cutoff limits the accuracy of the calculations, as will be discussed later. It is taken into account that the ionization energy is shifted by $\Delta I = E_{n^*} = 7 \cdot 10^{-8} n_0^{1/3}$ eV, i.e. with the binding energy of an electron moving in the limiting orbit [11].

Figure 1 shows the results of some Saha calculations. It can be seen that at $6.6 \cdot 10^{16} cm^{-3}$ initial density at 5 eV temperature the degree of ionization is higher than 99%. In the case of $5 \cdot 10^{17} cm^{-3}$ the required temperature is already 8 eV for a similar degree of ionization. If the density is increased, higher and higher temperatures are needed for similar ionization. Thus it can be seen that at these low pressures a relatively low temperature is sufficient to obtain fully ionized hydrogen plasma.

2.2. Producing the plasma

It is difficult to produce a plasma simply by laser breakdown of the gas because laser breakdown requires laser intensities in the $10^{14} W cm^{-2}$ range. This has recently been realized [6], but it can be done only in a very small volume otherwise the necessary laser power is unrealistically high. Thus in the following we shall deal with an initially discharge created plasma, and discuss how to heat and sustain it by a laser beam. For low densities a laser with a long wavelength can efficiently be utilized so the CO_2 laser seems to be an optimal choice with its $10.6 \mu m$ wavelength.

The main absorption mechanism in such an underdense plasma is the inverse bremsstrahlung [12]. In this work we use simple analytical expressions [13]. In the case of a homogeneous plasma the electromagnetic radiation propagating along the x–axis attenuates in accordance with

$$\frac{dI}{dx} = -KI \tag{4}$$

with

$$K = \frac{2\omega}{c}\sqrt{\frac{1}{2}(A - B)}; \tag{5}$$

$$B = 1 - \frac{\omega_p^2}{\omega^2 - \nu_{ei}^2}; \qquad A^2 = B^2 + \frac{\nu_{ei}}{\omega}\left(\frac{\omega_p^2}{\omega^2 + \nu_{ei}^2}\right). \tag{6}$$

Here $\omega_p^2 = \frac{4\pi n_e e^2}{m_e}$ is the plasma frequency and ν_{ei} is the electron–ion collision frequency [14]:

$$\nu_{ei} = 8.64 \cdot 10^{-7} \frac{n_e}{T^{3/2}} ln\left(1.55 \cdot 10^{10} \frac{T^{3/2}}{n_e^{1/2}}\right) \tag{7}$$

for hydrogen (Z=1), with [T]=eV and $[n_e] = cm^{-3}$.

Equation (5) is valid for fully ionized plasmas. It can however be well applied for a not fully ionized hydrogen ($T > 1eV$ in our case) as well, because even at relatively low temperatures the collisions of electrons with ions dominate over the electron-neutral atom collisions. The electron-ion collision frequency in our range of interest is in the order of $10^{11} s^{-1}$.

2.3. Energy loss mechanisms

Three main mechanisms for losing the thermal energy have been taken into account. The power lost by bremsstrahlung emission per unit volume in all directions in both polarizations (see [12]) can be given by a simple equation:

$$P_{out} = 1.66 \cdot 10^{-32} g n_e n_i T^{1/2} W cm^{-3}, \tag{8}$$

where T is in eV, n_e and n_i in cm^{-3} and g is the Gaunt factor with $1.45 > g > 1.1$ for all temperatures above 1 eV. In the following, we take g=1.2.

The second loss mechanism is diffusion the treatment of which is more troublesome. We assume a longitudinal magnetic field of $B_T = 1T$. Either classical or Bohm diffusion is taken into account. In the case of classical diffusion [15] the $D_\perp$ diffusion coefficient is given by

$$D_\perp = 5.47 \cdot 10^{-13} \frac{n_e ln\Lambda}{\sqrt{T} B_T^2} \frac{cm^2}{s} \tag{9}$$

with B_T in Tesla, T in eV; Spitzer resistivity has been used here; Λ is the Coulomb logarithm.

For this case, Bohm diffusion gives a diffusion coefficient with

$$D_B = \frac{1}{16} \cdot 10^4 \frac{T(eV)}{B_T} \frac{cm^2}{s} \tag{10}$$

It is well known [15] that Bohm-type diffusion describes more correctly the diffusion in the plasma. In our range of interest we shall see that classical diffusion gives a higher diffusion coefficient and correspondingly higher losses.

Thermal heat conduction is perhaps the most important factor to be taken into account when considering loss mechanisms. In the case of the parameters used in these calculations no strong gradients, and thus no flux limiting effects, are expected in view of which heat conduction can be treated classically. Classical heat conduction is described by

$$Q = -\kappa \nabla T \tag{11}$$

We use an order of magnitude estimation following Max [16]:

$$\kappa \nabla T \simeq \left(\frac{\lambda_{mfp}}{r}\right)(nT)\sqrt{\frac{T}{m}} \tag{12}$$

Here T is in energy units, m is the mass of the electrons as electron heat conduction dominates, the gradient scalelength is taken to be equal to r, i.e. the radius of the plasma, and λ_{mfp} is the electron mean free path, for which

$$\lambda_{mfp} \approx 30\mu m \left(\frac{T}{1000eV}\right)^2 \left(\frac{10^{21} cm^{-3}}{n_e}\right)\left(\frac{10}{ln\Lambda}\right) \tag{13}$$

is valid. This gives

$$Q \simeq \frac{200}{r}\frac{T^{7/2}(eV)}{ln\Lambda}\frac{W}{cm^2}. \tag{14}$$

Throughout this work the Bohm-type diffusion coefficient has been used. In this case thermal heat conduction causes the largest losses, whereas radiation losses are usually negligible. In the case of using the classical diffusion coefficient, diffusion losses are even higher then the thermal ones. The qualitative behaviour is similar even in that case, the only difference is that in order to sustain the same temperature significantly higher laser intensity is necessary.

3. The model

A laser beam with I_0 initial power is propagating along the x–axis in a plasma of initial temperature T_0 from x=0 to x=L. The laser and the plasma are assumed to be radially uniform within a radius of $r = 1cm$; n_0 is the number density of the atoms. The light energy is absorbed in accordance with eq(4). The absorption from the light beam causes an increase in the internal energy of the plasma in accordance with

$$\frac{dE(x,t)}{dt} = KI(x,t)\Delta x - P_{out}(x,t)\Delta x r^2 \pi - \frac{D}{\Lambda_d^2} E(x,t) - 2r\pi Q \Delta x. \qquad (15)$$

Here the above mentioned loss mechanisms are taken into account. The Λ_d diffusion length is taken to be equal to r. It is assumed that heat conduction losses take place through the cylindrical surface of the heated volume. The internal energy of the gas can now be written [11]:

$$\frac{E(x,t)}{(r^2 \pi \Delta x)} = \frac{3}{2} n_0 (1+\alpha) T(x,t) + n_0 \alpha I_1. \qquad (16)$$

The term from the electronic excitation energy has been neglected. In this one dimensional model we have neglected all the transport phenomena as well as heat conductivity along the x–axis. Thus, the system of equations does not serve as a hydrodynamic code but as an expression of the energy conservation law.

The calculation procedure is the following: A spatial grid is obtained by dividing the 0 to L distance into a number of cells (typically l$\simeq$ 60). At each time step, eqs (4) and (15) are calculated in order to obtain the change in the internal energy. Then eq (16) is solved self-consistently together with the Saha equation in order to obtain the new T and α values which serve as the initial conditions for the next time step. The simple calculations can be carried out on a personal computer.

4. Results

Calculations were carried out in a hydrogen plasma of $3cm$ length with $n = 6.6 \cdot 10^{16} cm^{-3}$ atomic density. The pulse of the $\lambda = 10.6 \mu m$ laser light is constant during its $10 \mu s$ duration. We varied its full energy and the initial temperature of the plasma. As an example, in a plasma with an initial temperature of 3 eV in the case of a 10 J laser pulse the temperature remained practically constant corresponding to a degree of ionization a little below 99%. The approximately constant temperature and degree of ionization were obtained in space and in time. This laser intensity is sufficient to heat an initially colder (e.g. 2 eV temperature) plasma to the same temperature within a few microseconds. In order to reach or to sustain higher temperatures more laser energy is needed. The laser beam is not significantly attenuated along the plasma at this density and that is why the temperature remains nearly constant along it. The same is true below $3 \cdot 10^{17} cm^{-3}$ density where the temperature difference along the x–axes reaches 10% as a consequence of the attenuation of the laser beam. Further increasing the density leads to a dramatic increase in reaching 100% at $6.6 \cdot 10^{17} cm^{-3}$.

If the attenuation of the laser beam can be neglected, it is possible to carry out the calculation with an initial temperature gradient along the x-axes. In this case a single calculation and corresponding single figure can illustrate the temperature and ionization development at a given laser intensity for different initial temperatures. Thus it can be seen whether the 99% degree of ionization can be reached or sustained in the next 10 μs depending on the original arc or Z–pinch discharge parameters for a given laser intensity. Figure 2 shows the results of such calculations with 10^6 and $3 \cdot 10^6 W$ laser intensities.

In these calculations the initial temperature was 5 eV in the first and 1 eV in the last cell corresponding to different temperatures of the initially discharge–created plasmas. The temperature profiles are shown every microsecond. It can be seen in both cases that at initial temperatures above a certain value the calculated temperature decreases in time monotonically, whereas below these values it increases. This means that according to our model there exists an equilibrium tenperature (T_{eq}) for a given laser intensity which will be reached after a certain time. This equilibrium temperature is slightly above 4 eV for a laser intensity of $3 \cdot 10^6 W$, which corresponds to a full ionization of the plasma (i.e. higher than 99%).

On the other hand we can also look for an equilibrium laser intensity, which can be defined as the laser intensity at which a given temperature can be reached as T_{eq}. The equilibrium intensity (I_{eq}) can easily be found from eq(15) if we take the derivative of the internal energy of the plasma to be equal to zero, i.e. $\frac{dE}{dt} = 0$.

In principal it is easy to solve now eq(15) in order to obtain I_{eq} necessary for a 99% of ionization as a function of the initial density. In this case, however, T_{eq} must be inversely calculated from the Saha equation (2). It must be noted that the cutoff in the electronic partition function (see comment following eq(3)) which is density dependent may cause a serious rounding error. It manifests itself in a stepwise $T_{eq} - n_0$ and a corresponding stepwise $I_{eq} - n_0$ dependence as an artifact. Our choice of the number of terms to be included in the electronic partition function following Zeldovich and Raizer [11] probably overestimates the actual number of levels. Some authors [11] terminate the partition function summation at a level where the electron binding energy is equal to kT. This overestimation of the electronic partition function results in a pessimistic I_{eq} of our calculation, i.e. the equilibrium intensity will be lower if one makes a stronger cutoff. Due to the stepwise shape of the $I_{eq} - n_0$ curve we preferred to show the equilibrium intensity as a function of temperature for $6.6 \cdot 10^{16}$ and $2.64 \cdot 10^{17}$ cm^{-3} initial neutral atom densities, see Fig.3. The equilibrium intensity for 4 eV temperature which corresponds to 99% of ionization at $6.6 \cdot 10^{16}$ cm^{-3} density was found to be $3 \cdot 10^6 W$ (as in Fig. 2b.), whereas it is less than $2 \cdot 10^6$ W for 6 eV temperature at $2.64 \cdot 10^{17} cm^{-3}$ density (corresponding to the same degree of ionization). Note that here the term "equilibrium" does not mean a real plasma equilibrium, only the necessary conditions for sustaining constant temperatures within the frames of our model, i.e. the conditions of energy conservation in 1 dimension. The hydrodynamic motion as well as the lateral transport, i.e. the streaming of the particles out of the heated volume, are neglected.

5. Summary

The possibility of creating a fully ionized hydrogen plasma for investigating the capture of slow antiprotons has been discussed. Laser heating of the initially discharge-created arc or Z-pinch plasma is proposed. Within the framework of a simple 1-dimensional model based on the energy-balance equation alone it was shown that it is possible to sustain plasma equilibrium for a period of $10\mu s$ which is necessary for the investigations. A simple pulsed CO_2 laser with this pulse duration and with the energy of about $10 - 30J$ is sufficient for heating, if the initial pressure of neutral hydrogen is between 1 and 4 torr.

Acknowledgements

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Figure Captions

Fig.1. Degree of ionization as a function of plasma temperature for densities $6.6 \cdot 10^{16}$ (solid line), $1.32 \cdot 10^{17}$ (broken line) and $2.64 \cdot 10^{17} cm^3$ (dotted line).

Fig.2. Temperature development of plasma along the propagation axis of the laser beam in every μs for an initially linearly decreasing temperature profile with 5 eV in the first and 1 eV in the last cell. The laser intensity was $10^6 W$ (a) and $3 \cdot 10^6 W$ (b), $n_0 = 6.6 \cdot 10^{16} cm^{-3}$.

Fig.3. Equilibrium intensity as a function of temperature for $6.6 \cdot 10^{16}$ (upper curve) and $2.64 \cdot 10^{17} cm^{-3}$ (lower curve).

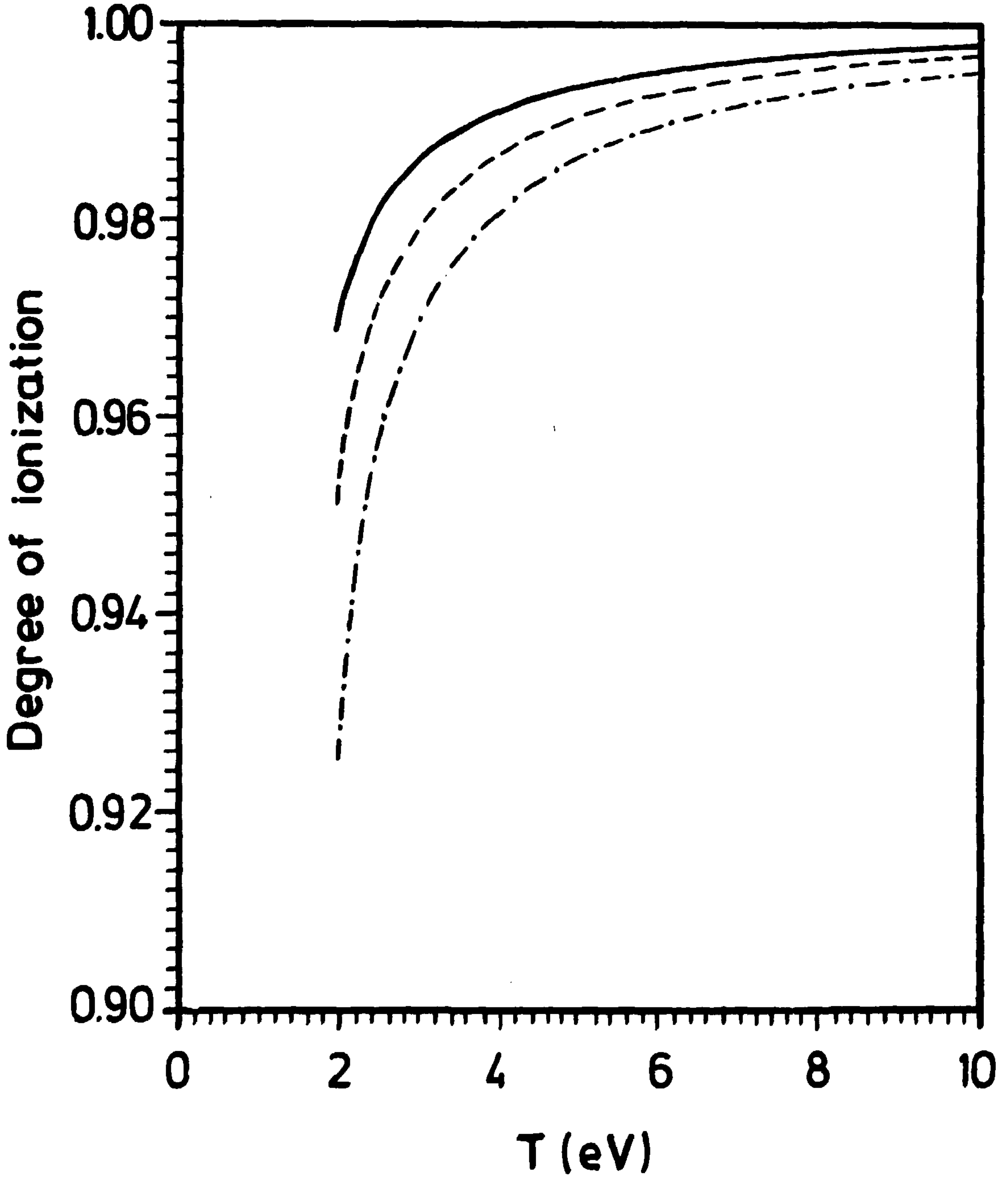

Fig. 1

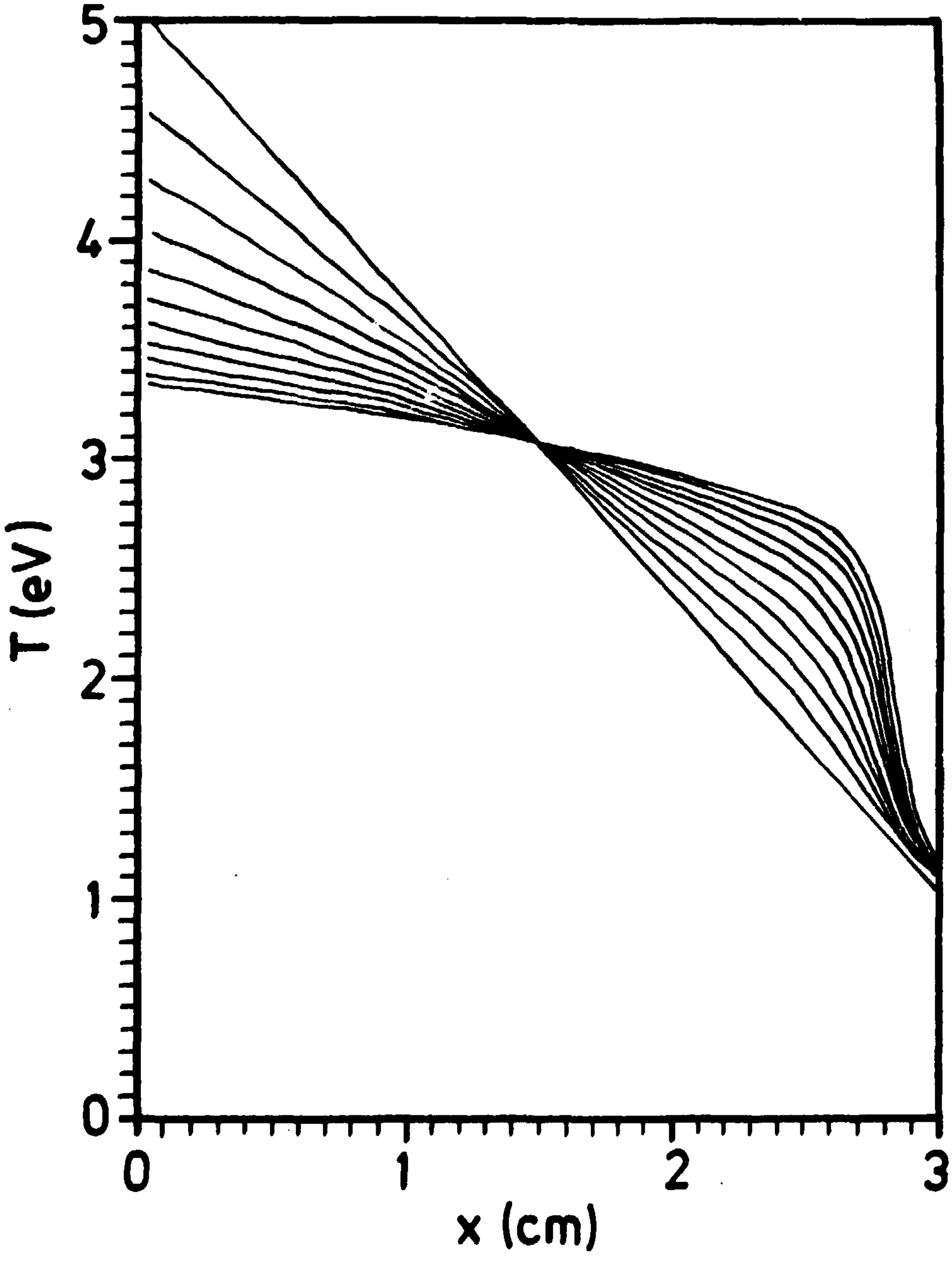

Fig.2a

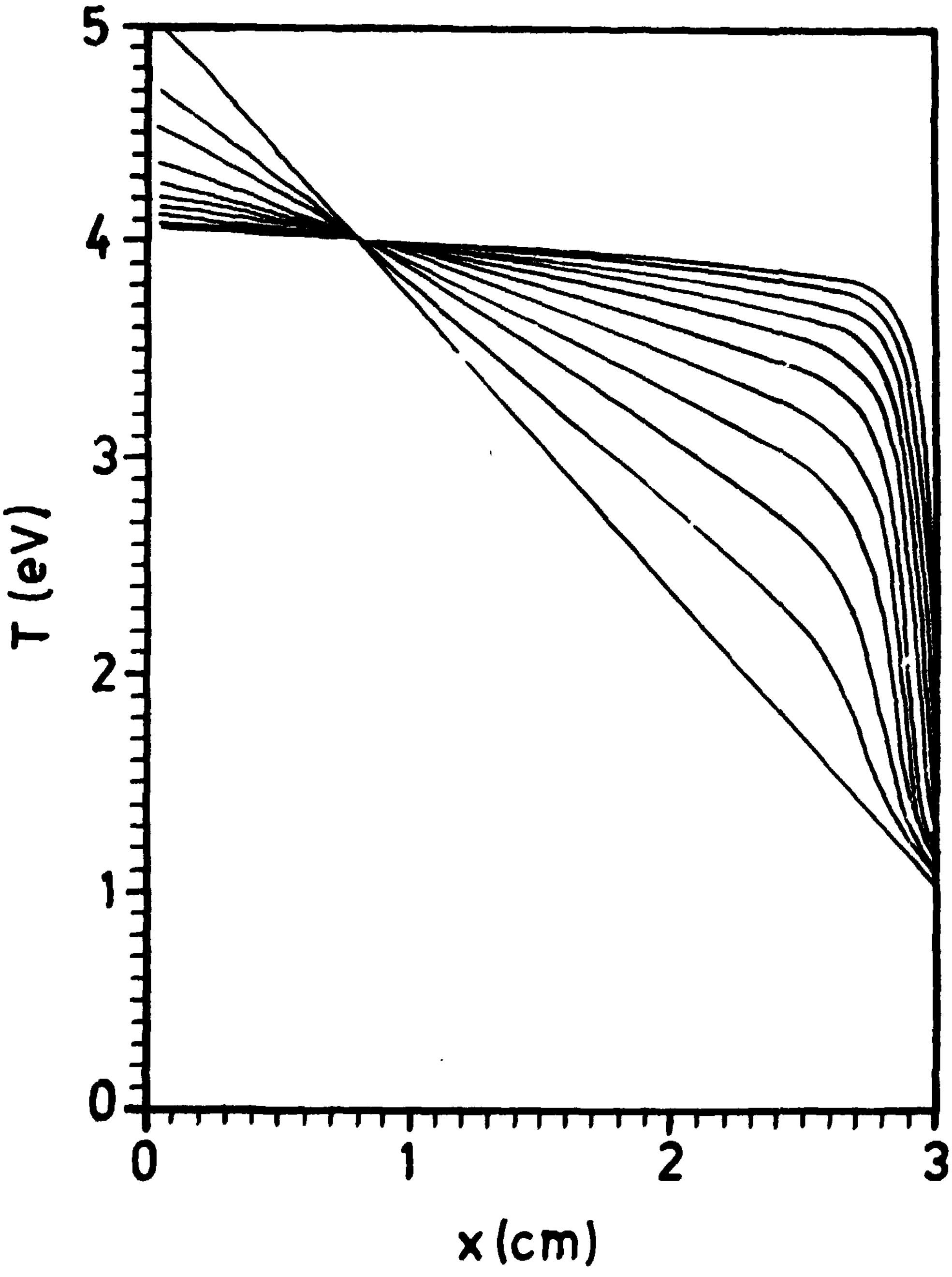

Fig. 2b

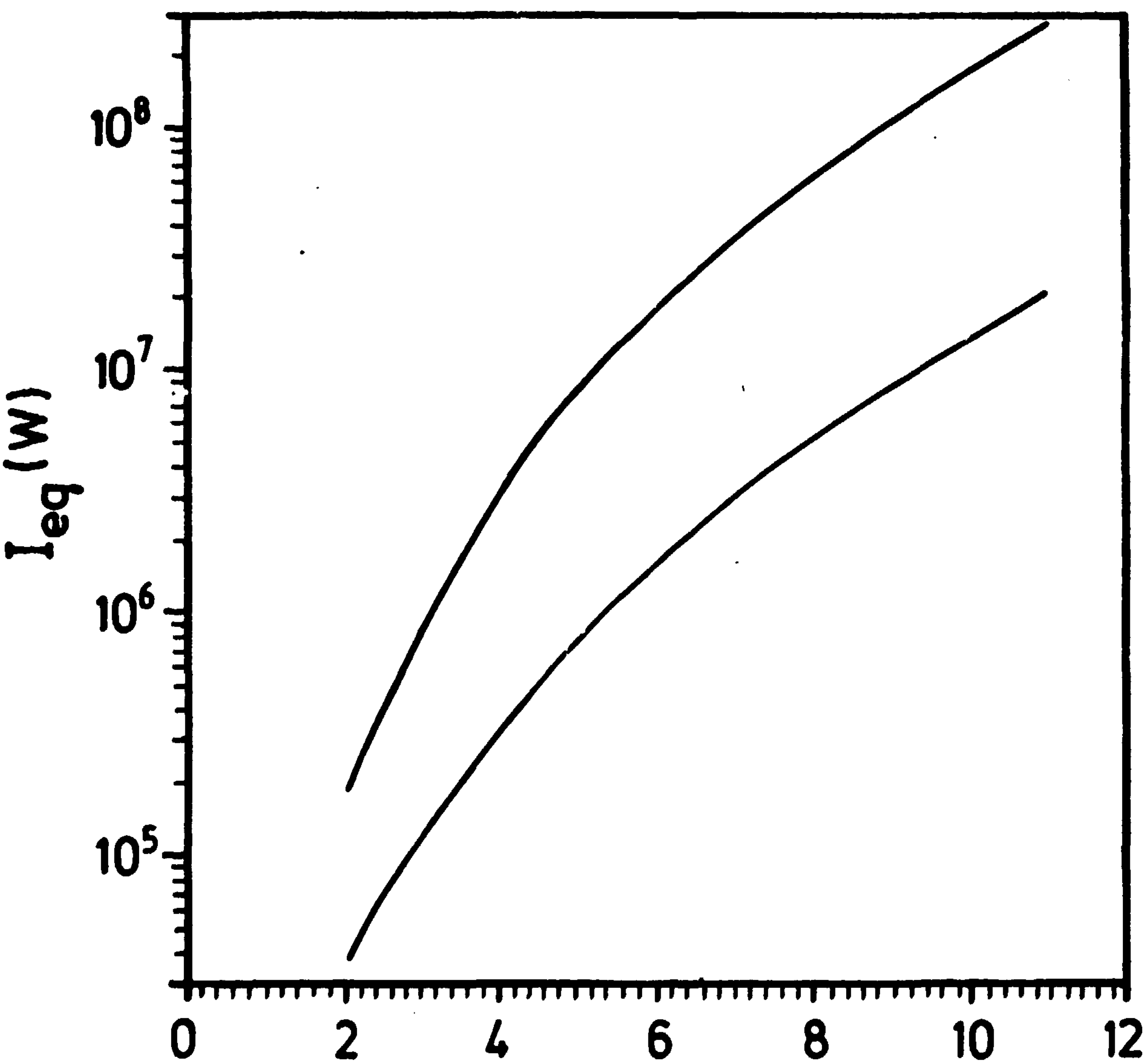

Fig.3

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