MAX-PLANCK-INSTITUT FÜR PLASMAPHYSIK

GARCHING BEI MÜNCHEN

Recombination Effect on the Expansion Process of the Laser-Produced Plasma in the Absence and Presence of an External Magnetic Field

S. Sudo

IPP 4/177 May 1979

Die nachstehende Arbeit wurde im Rahmen des Vertrages zwischen dem Max-Planck-Institut für Plasmaphysik und der Europäischen Atomgemeinschaft über die Zusammenarbeit auf dem Gebiete der Plasmaphysik durchgeführt.

IPP 4/177

Recombination Effect on the Expansion Process of the Laser-Produced Plasma in the Absence and Presence of an External Magnetic Field

S. Sudo

May 1979

Abstract

The change of the ionization ratio of the laser-produced plasma during expansion is calculated with a simple model.

The results for expansion in the absence of a magnetic field are compared with the experimental results obtained by Baumhacker et al. The recombination is not negligible and it takes place mainly in the first stage of expansion.

The ionization ratio of the expanding plasma remains distinctly higher in the presence of a magnetic field. However, in order to maintain full ionization in the plasma during the filling process in a magnetic container, the lower initial density is more favorable and the use of a CO_2 laser (at least in the final stage of plasma heating) seems necessary in the range of currently possible parameters.

I. Introduction

Plasma production by means of high-power-pulsed laser beam(s) from a solid deuterium pellet has some advantages compared with other high-temperature plasma production methods, particularly in connection with the problem of filling magnetic confinement devices with a clean hot plasma. Nevertheless, the method has not proved reliable until now because several difficulties involved in the method have not been completely resolved. The main problems of this method can be classified under three headings:

(1) full ionization of the deuterium pellet,

(2) maintaining full ionization in the plasma expansion process,

(3) avoiding instabilities (including $\vec{E} \times \vec{B}/B^2$ drift motion, where $\vec{E} = \vec{v} \times \vec{B}$) due to the characteristics of the laser-produced plasma in a magnetic field.

Recently, plasma production has been drastically improved by the double pulse method /Baumhacker et al. 1979/, and full ionization at the end of the main laser pulse may be considered possible in practice at a certain laser energy (in the experimentally reasonable parameter range). As to problem (3), two-beam irradiation has much improved the homogeneity of the plasma expansion /Baumhacker et al. 1979/, although it is not yet clear if this homogeneity is enough to suppress the instabilities.

Problem (2) is studied here. The initial density of the laser produced plasma is very high, being near the laser cut-off density (10^{21} cm^{-3} for Nd-glass laser), and through rapid plasma expansion the plasma quickly cools down. If the final density of the plasma is 10^{14} cm^{-3}, the temperature of the plasma decreases by a factor of 5×10^4 through an adiabatic process. Such a rapid decrease of the temperature may cause strong recombination in the plasma. This may take place even in the presence of a magnetic field because the β value in the initial phase of the plasma expansion is very high (e.g. $\beta = 4 \times 10^4$ if $n = 10^{21}$ cm^{-3}, T = 50 eV, B = 1 T) and the plasma expands almost freely. The recombined neutral atoms cannot be captured by the magnetic field. This results in loss of plasma.

Numerical calculations of the expanding process of the laser produced plasma, including recombination phenomana, have been made by several authors /e.g. G.L. Payne et al. 1978/. Payne et al. calculated the ionization ratio in the case of beryllium ions with different charge states in the absence of an external magnetic field. We concentrate here on deuterium plasma only and the initial density of the plasma is considered to be rather lower than the cut-off density because at the outset of the main laser pulse the target gas cloud is produced from a deuterium pellet by the pre-pulse laser in the double pulse method and this is a very important point for reasonable plasma production.

In Sec. II, the recombination process in the absence of a magnetic field is studied. The numerical results are compared with the experimental results /Baumhacker et al. 1979/ of the interferogram and the Faraday cup measurements in Sec. IV. In Sec. III, the recombination process in the presence of a magnetic field is studied with a simple model.

II. Plasma Expansion in the Absence of a Magnetic Field

The question here is how many particles in the initially fully ionized plasma are recombined through the plasma expansion process in the absence of an external magnetic field. The detailed process of plasma production is not considered. It is assumed that the density and temperature are spatially homogeneous and are the same for ions and electrons.

The basic equations are as follows:

$$\frac{dN}{dt} = - \alpha_c \left(\frac{N}{V}\right)^3 V + S \left(\frac{N_o}{V}\right) \left(\frac{N}{V}\right) V - \alpha_r \left(\frac{N}{V}\right)^2 V, \qquad (1)$$

$$P \frac{dV}{dt} = \frac{1}{2} M \frac{d}{dt} \left\{\left(\frac{dR}{dt}\right)^2\right\}, \qquad (2)$$

$$\frac{3}{2} (2N+N_o) \frac{dT}{dt} = -P \frac{dV}{dt} - \left(13.6 + \frac{3}{2} T\right) \left\{-\alpha_c \left(\frac{N}{V}\right)^3 V + S \left(\frac{N_o}{V}\right) \left(\frac{N}{V}\right) + \alpha_r \left(\frac{N}{V}\right)^2 V\right\} - \alpha_B \left(\frac{N}{V}\right)^2 V, \qquad (3)$$

where

$$P = \frac{2N + N_o}{V} \cdot T , \quad (4)$$

$$M = \frac{3}{5} N_t \quad m_D , \quad (5)$$

$$N_t = N + N_o , \quad (6)$$

N and N_o being the numbers of ions and neutral particles. N_t is the total particle number defined by eq. (6) and is constant in time. R and V are the radius and volume of the plasma blob, which is assumed to be spherically symmetric. T is the temperature of the particles. (It is assumed that neutral particles also have the same temperature T.) The coefficients α_c, S and α_r are of the three-body collisional recombination, collisional ionization and radiative recombination /Menzel and Pekeris 1935/. The coefficient α_B denotes bremsstrahlung loss /Spitzer 1956/. The 'effective' mass M of particles is introduced from the self-similarity model /Hora 1969/ and the factor 3/5 in eq. (5) comes from integration on the assumption of a spatially linear velocity distribution, that is, $v(r) = r/R \cdot dR/dt$, where r is the variable radius in the plasma blob /Hora 1969, Dawson 1964/. The symbol m_D is the mass of the ion (deuterium in our case). The equation (1) of particle number conservation indicates the change of the ion number (= the electron number) through collisional and radiative processes. The equation (2) of momentum conservation states that thermal pressure brings about the outward motion of the plasma blob. Equation (3) gives the energy balance. The equation of state is (4). In order to calculate the collisional ionization rate, the experimental data of the ionization cross-section by Fite and Brackmann (1958) is used. The integration in energy space to obtain the rate of the collisional ionization is carried out on the assumption that the energy distribution of particles is Maxwellian. The rate for the inverse process, i.e. three body collisional recombination, is calculated with the above collisional ionization rate and Saha's formula. The ionization rate calculated is compared with another analytic formula /Burgess 1961/ and the discrepancy is always within a factor of 2 at least in the region Te = $10 \sim 100$ eV. A distinct difference between final results with these different rates has not been found with the parameters used here. When the temperature becomes less than 0.5 eV through the expansion process, the three-body recombination rate from Gurevich and Petaevskii (1964) is used (because the calculation method mentioned above is not accurate below the lower temperature) and

the ionization rate is negligible in this temperature region.
The initial particles are assumed to be fully ionized. When neutral atoms in the gaseous state are mixed with the plasma and the initial temperature is higher than about 10 eV, the ionization rate of these atoms is very large owing to the high density in the initial phase and such a condition merely corresponds to that for a lower initial temperature and fully ionized plasma (e.g. when $n_e \sim 10^{20}$ cm^{-3}, $v_e \sim 10^8$ cm/s and $\sigma_c \sim \pi$ 10^{-16} cm^2, the collision time $1/(n_e\ \sigma_c\ \ v_e)$ is less than 1 ps.). When neutral atoms are in the solid state, the effective rate is naturally much less than the above value owing to the 'shielding' effect and this is just the problem of pellet burning, which is beyond the scope of this report.

In order to approach the experimental conditions /Baumhacker et al. 1979/, the initial radius R(1) is defined as the plasma radius at the beginning of the main laser pulse and the plasma is assumed to expand with the thermal velocity to the radius $R(\tau) = R(1) + \ \tau\,(T/m_D)^{1/2}$, where τ is the time interval of the dominant laser absorption (taken here as 20 ns), after which it expands freely into vacuum. For example, if T = 50 eV and R(1) = 0.15 cm, one has $R(\tau)$ = 0.25 cm. Such a somewhat artificial initial condition is necessary because the plasma radius at the beginning of the laser pulse is roughly doubled near the end of the laser pulse, as shown in the shadow photographs by Baumhacker et al. Alternatively, the above assumption can be interpreated from the way that the plasma with the temperature T, the radius $R(\tau)$ and the expansion velocity $(T/m_D)^{1/2}$ begins to expand into vacuum from $t = \tau$.

The numerical calculations with the set of equations (1) to (6) are carried out by the 4th order Runge-Kutta method. Figure 1 shows the result with parameters $N_t = 1.5 \times 10^{18}$, the initial radius of the plasma R(1) = 0.15 cm and the initial temperature T(1) = 50 eV. It should be noted that the temperature rapidly decreases in 50 ns,while the recombination (mainly due to the three-body collisional recombination) takes place somewhat later. The main part of the recombination process takes place in the narrow time interval (from t = 100 ns to t = ∿ 200 ns), and it can be said that the ionization ratio is almost 'frozen' after t = ∿ 1 μs. The expansion velocity of the plasma remains constant after t = ∿ 30 ns. At R = 20 cm (t = 1.2 μs), the ion number remains at 65 % of the initial number. For comparison, the results with other initial temperatures are shown in Figs. 2 and 3. In the case of Fig. 2, the initial temperature is 25 eV (half of that in Fig. 1), the other conditions being unchanged. The ion number remains at 45 % of the initial number at R = 20 cm (t = 1.7 μs). When the initial temperature is 100 eV, the ion number remains at 85 % at R = 20 cm (t = 0.9 μ), as shown in Fig. 3. It should be noted that the recombination phenomenon is not negligible even in the case that the initial temperature is 100 eV, in spite of the fact that the initial plasma density is much less than the cut-off density (owing to the double pulse method in the experiment), and this situation is very favorable for suppressing the recombination compared with the case of plasma production near the cut-off density. When the initial radius of the plasma blob in the case of Fig. 1 is doubled and the other conditions are not changed, the ion number remains at 83 % at the same position indicated in Fig. 4 and the ionization ratio is improved by 18 % compared with the former case. This indicates that the lower initial density is more favorable for preventing recombination if the initial temperature is the same. However, when the laser wavelength is fixed, the initial density cannot be chosen arbitrarily because the absorption coefficient /e.g. Dawson and Oberman 1962/ is almost in proportion to n^2 below the cut-off density and thus the laser absorption in the plasma with lower density becomes ineffective at the reasonable dimensions of the target plasma. The absorption lengths in the cases of Nd-glass laser and CO_2 laser are shown in Table 1. Here, the total particle number is fixed and both the diameter of the plasma and the temperature are varied as parameters. When the Nd-glass laser is used and the electron temperature is 50 eV, the absorption length is 1/10 of the plasma diameter if the latter is 0.3 cm, while the absorption length is larger than the plasma diameter if the latter is 0.5 cm. (In the table, the broken line indicates that the absorption length is smaller than the plasma diameter on the left side of the line and larger on the right side.) In this case, the minimal reasonable density for laser absorption is estimated at about 10^{20} cm^{-3}. When the CO_2 laser is used and the electron temperature is 100 eV, the absorption length becomes larger than the plasma diameter between 1.0 cm and 1.2 cm of the plasma diameter. The minimal reasonable density for laser absorption is estimated in this case at about 2×10^{18} cm^{-3}. The CO_2 laser is then more favorable than the Nd-glass laser for suppressing recombination. We have so far studied the recombination phenomena in the plasma expansion process under the condition without an external magnetic field. This may be applied to the interpretation of the experimental results, which will be discussed in Sec. IV.

How is the recombination suppressed in the presence of a magnetic field? Plasma production with the Nd-glass laser may also be useful from the viewpoint of the ionization ratio in the reasonable parameter range. This will be studied in the next section.

III. Plasma Motion in the Presence of a Magnetic Field

The magnetic field is assumed to be homogeneous and spherically symmetric. Making this assumption, Bhadra (1968) studied the motion of a resistive plasma without the recombination process. His method is followed here for the terms relating to the magnetic field

The basic equations in the presence of the magnetic field are as follows:

$$\frac{dN}{dt} = -\alpha_c\left(\frac{N}{V}\right)^3 V + S\frac{N_o}{V}\frac{N}{V}V - \alpha_r\left(\frac{N}{V}\right)^2 V, \quad (7)$$

$$P\frac{dV}{dt} = \frac{1}{2}M\frac{d}{dt}\left\{\left(\frac{dR}{dt}\right)^2\right\} + \int_V |\vec{j}\times\vec{B}|\frac{dr}{dt}dV, \quad (8)$$

$$\frac{3}{2}(2N+N_o)\frac{dT}{dt} = -P\frac{dV}{dt} - (13.6 + \frac{3}{2}T)\ \{-\alpha_c\left(\frac{N}{V}\right)^3 + S\frac{N_o}{V}\frac{N}{V}\cdot V,$$

$$+\alpha_r\left(\frac{N}{V}\right)^2 V\} - \alpha_B\left(\frac{N}{V}\right)^2\cdot V + \int_V \eta j^2 dV, \quad (9)$$

$$\frac{d\Phi_M}{dt} = -\int \eta\vec{j}\cdot\vec{ds}, \quad (10)$$

$$\vec{j} = \frac{1}{\mu_o}\vec{\nabla}\times\vec{B}. \quad (11)$$

Here, $j = |\vec{j}|$ is the diamagnetic current and $B = |\vec{B}|$ is the magnetic field, and it is assumed that $B = B_o e^{-\frac{R-r}{\lambda}}$, where B_o is the undisturbed magnetic field and λ is the skin depth of the magnetic field into the plasma. Φ_M is the magnetic flux and η is the resistivity which is given by Spitzer (1956).

Bhadra's expression for the magnetic pressure term is found to be inadequate. When the resistivity becomes 0 in the extreme case, his expression gives the magnetic pressure $\frac{B_o^2}{\mu_o}4\pi R^2\frac{dR}{dt}$, which is twice the correct value. For simplicity, the set of equations (8) and (9) without recombination gives the simple energy conservation equation, i.e. $\frac{d}{dt}(2\cdot\frac{3}{2}NT + \frac{1}{2}M\left(\frac{dR}{dt}\right)^2 + \frac{B_o^2}{\mu_o}V) = 0$, where the last term in the parentheses should be corrected to $\frac{B_o^2}{2\mu_o}$ V. This failure is caused by the fact that he calculated the volume integral of the magnetic pressure term without the configuration of the velocity distribution, which is not self-consistent with his assumption (e.g. by his expression, $M = \frac{3}{5} N_i m_i$).

The correct expression is introduced as follows:

$$\int |\vec{J} \times \vec{B}| \frac{dr}{dt} dV$$

$$= \int |\vec{J} \times \vec{B}| \frac{r}{R} \frac{dR}{dt} 4\pi r^2 dr$$

$$= \frac{dR}{dt} \frac{1}{R} \int_0^R \frac{B_o^2}{\mu_o \lambda} e^{-2(R-r)/\lambda} 4\pi r^3 dr$$

$$= \frac{2\pi B_o^2}{\mu_o} \frac{dR}{dt} [R^2 - \frac{3}{2} R\lambda + \frac{3}{2} \lambda^2 - \frac{3}{4} \frac{\lambda^3}{R} \{1 - \exp(-\frac{2R}{\lambda})\}] . \qquad (12)$$

In the extreme case that the resistivity equals 0, the above expression gives the correct value

$$\frac{B_o^2}{2\mu_o} 4\pi R^2 \frac{dR}{dt} (= \frac{B_o^2}{2\mu_o} \frac{dV}{dt}).$$

In another extreme case that the resistivity becomes very large or λ/R is very large, the above expression becomes $\frac{B_o^2}{2\mu_o} 4\pi \frac{R^3}{2\lambda} \frac{dR}{dt}$, which, of course, approaches zero as λ becomes very large.

The set of equations above is also calculated by the 4th order Runge-Kutta method. The time step of the calculation is carefully chosen to maintain a certain accuracy.

The calculation result with the magnetic field strength 10 T (the other parameters are the same as those in Fig. 1) is shown in Fig. 5. This shows the periodic motion of the plasma and this bouncing time remains nearly constant (about 100 ns), while the mean value of the periodic penetration depth slowly increases with time. The maximal temperature in the compressed phase of the plasma is higher than the initial temperature. This is caused by the fact that the initial plasma has internal and kinetic (expanding) energies, while the plasma in the compressed phase has only internal energy because the expanding valocity is 0. The temporal variation of the ionization ratio is drastically changed from that shown in Fig. 1. The ionization ratio remains 1.0, while the ratio in the latter case decreases to 0.8 in 200 ns. The effectiveness of the strong magnetic field to suppress recombination phenomena is thus clear. However, the experimental value of the applied magnetic field strength ranges up to about 1 T in our group so far /Baumhacker et al. 1977/. The result calculated with the magnetic field strength 1 T (the other initial parameters are not changed) is shown in Fig. 6. In the initial expansion phase, the temperature rapidly decreases. Then, however, when the temperature becomes very low, the resistivity becomes very large and this causes ohmic heating by the diamagnetic current circulating in the plasma-magnetic field interface. The temprature increase of the plasma blob causes, in turn, a decrease of the resistivity. The behavior of the temperature change is thus like self-regulation. In the compressed phase ($t = \sim 530$ ns) the temperature becomes higher not owing to ohmic heating but to adiabatic compression. In the initial expansion phase, the ionization ratio decreases very slowly compared with the case in the absence of a magnetic field (as shown in Fig. 1), while the expansion velocity is about the same in the initial phase (up to $t = \sim 150$ ns). In the presence of the magnetic field, the ionization ratio is even restored to 1.0 in the period of the first bouncing time ($t = \sim 270$ ns). This is very favorable for suppressing recombination. However, near the end of the first period of the bouncing ($t = \sim 470$ ns), the penetration depth of the magnetic field suddenly becomes very large, as a result, the plasma expands almost freely because of the low magnetic pressure. The plasma cannot be trapped under this condition. This is a very dangerous aspect for containing the plasma in a magnetic field. This situation is very different from the case $B_0 = 10$ T (as shown in Fig. 5).

For comparison, the motion of the plasma without resistivity is shown in Fig. 7, the other initial parameters being the same as those in Fig. 6. Until $t = \sim 350$ ns, the change of the ionization ratio is similar to the case of free expansion (Fig. 1) rather than to the case in the presence of the magnetic field including resistivity (Fig. 6). Near the compression phase, the ionization ratio is restored to 1.0. In reality, this cannot happen because neutral particles are not influenced by the magnetic field and thus they expand freely without bouncing and re-ionization. On the other hand, the recovery to full ionization in the case of Fig. 6 is reasonable because the recovery is already completed before the compression phase. Another important difference between the cases of Fig. 6 and Fig. 7 is that the bouncing of the plasma continues in the case of

Fig. 7, while the plasma in the case of Fig. 6 expands almost freely after t = ∿ 600 ns. Thus, the resistivity has two major effects. One of those is suppressing the recombination by recovering the temperature with the diamagnetic current (favorable aspect), and the other is the rapid penetration of the magnetic field into the plasma, and under certain conditions the plasma expands almost freely without being trapped in the magnetic container (unfavorable aspect).

The possibility of preventing adverse behavior shown in Fig. 6 is explored for reasonable experimental parameters. One example is shown in Fig. 8, where the initial radius of the plasma is chosen as 0.5 cm, the other parameters being the same as those in Fig. 6. At least in two bouncing phases, the almost free expansion of the plasma as shown in Fig. 6 does not take place. The ionization ratio always remains 1. This indicates that the lower initial density is more favorable for containing the plasma in the magnetic field.

IV. Discussion

It may be interesting to compare the results obtained in Sec. II with the experimental results in the absence of an external magnetic field /Baumhacker et al. 1979/. In the experiment, some Faraday cups are placed 20 cm distant from the origin of plasma production. The time of the maximum of the ion flux (the rise time is very short 100 to 200 ns) is typically t = ∿ 1.2 μs after the main laser irradiation. The calculated time taken by the radius of the plasma to reach 20 cm is also 1.2 μs. The initial temperature assumed in the case of Fig. 1 is then adequate for comparison with the experimental results. When the initial temperature is 25 eV (half of that in the case of Fig. 1), one gets t = 1.7 μs at R = 20 cm, as shown in Fig. 2. When the initial temperature is 100 eV, one gets t = 0.9 μs at R = 20 cm, as shown in Fig. 3. It thus becomes clear that the relation between the initial temperature (not directly measured in the experiment) and the expansion velocity of the plasma blob (from the time-of-flight method based on the Faraday cup measurement) is sensitive enough for our experimental accuracy (∿ 10 %).

In the experiment, the number of electrons measured by interferometry near the end of the main laser irradiation is compared with the number of ions obtained in the same shot from the mean value observed by 8 to 12 Faraday cups. The mean value of the ratio of the former to the

latter is 1.5 ± 0.1 when the pre-pulse laser power is 4 x 10^9 W/cm^2 and the main pulse laser parameters are 40 J, 25 ns and the temporal interval between two pulses is ∿ 250 ns and the focal diameter is 0.3 cm.
As shown in Fig. 1, the ion number calculated at t = 1.2 μs (R = 20 cm) remains at 65 % of the initial number and the value corresponding to the above ratio is 1.5. The difference between the electron number observed by interferometry and the ion number observed with the Faraday cups thus becomes comprehensible. The two numbers should be the same without recombination phenomena.

In Sec. III, the magnetic field is assumed to be sperhically symmetric. Here, we consider the plasma in a toroidal magnetic container.
If the plasma is very small, the above assumption may be admissible. Until what time is the method applicable? In order to estimate this situation, it is considered how many particles run away from the sphere of the plasma blob in a certain time. The loss flux streams through the area S_B, where the magnetic field penetrates the plasma. Here, only the region where the skin depth is much less than the plasma radius is considered (typically up to the first 3/4 period of the bouncing).
One then has $S_B = \pi R^2 - \pi(R-\lambda)^2 \sim 2\pi R\lambda$. The total number N_t equals $n \frac{4}{3}\pi R^3$, where n is the density. The loss flux F is written as follows:

$$F = 2 n v S_B$$

(there are two 'outlets').
The lifetime τ_ℓ of the plasma in the spherical volume of the magnetic field is roughly given by

$$\tau_\ell = N_t/F = \frac{R^2}{3v\lambda}.$$

Here, we consider only the case of Fig. 6. When typical values R = 2 cm, λ = 0.2 cm and v = 10^7 cm/s are used, τ_ℓ becomes 0.7 μs. Thus, up to half a period (t = ∿ 270 ns) of the first bouncing, the particles in the spherical volume remain at about 60 % of the initial total number.

Then, for the plasma filling process in the torus container, the initial plasma is assumed to be cylindrical in shape (but very similar to the sphere) with a diameter of 5 cm and a length of 5 cm along a magnetic field line. The initial temperature of this cylindrical plasma is assumed to be 10 eV (the value in the first 3/4 phase of the bouncing as shown in Fig. 6). We now need the final density $n(\tau_f)$. We assume that the container volume is 4 x 10^4 cm^3. Then, if there is no particle loss, one gets

$n(\tau_f) = 1.5 \times 10^{18} / 4 \times 10^4 = 4 \times 10^{13}$ cm^{-3}. In turn, we check the effect of recombination in the first filling phase in a torus field using the above parameters. The number of the recombined atoms ΔN is given by

$$\Delta N = \int dN = \int \frac{dN}{dt} dt \ ,$$

$$\left|\frac{dN}{dT}\right| = C_1 \ T^{-4.5} \ n^3 V \ .$$

The recombination in our parameter region is mainly due to three-body collisional recombination. For the adiabatic expansion, one gets $T = C_2 n^{2/3}$. It then follows that

$$\Delta N = C_1 \ C_2^{-4.5} \ N_t \int_0^{\tau_f} n(t)^{-1} dt,$$

where τ_f is the filling time.
We assume $n(t)$ in the form

$$n(t) = \frac{N_t}{S_o(r_o + vt)} = \frac{C_3}{C_4 + t} \ .$$

As described above, it is assumed that $n(o) = 1.5 \times 10^{18}/(\pi \times 2.5^2 \times 5) = 1.5 \times 10^{16}$ (cm^{-3}), $n(\tau_f) = 4 \times 10^{13}$ (cm^{-3}). And if τ_f is assumed to be 50 μs (typical value in the experiment /Baumhacker et al. 1977/), then $C_3 = 1.3 \times 10^{-7}$ and $C_4 = 2.0 \times 10^9$.
From the adiabatic equation, one obtains $C_2 = T(o) \ n(o)^{-2/3}$. One also has $C_1 = 3.2 \times 10^{-27}$ /Gurevich and Pataevskii 1964/, and so it follows that

$$\Delta N = C_1 \ C_2^{-4.5} \ N_t \int_0^{\tau_f} \frac{C_4 + t}{C_3} dt$$

$$= C_1 \ C_2^{-4.5} \ N_t \left(\frac{C_4}{C_3} \tau_f + \frac{\tau_f^2}{2C_3}\right)$$

$$= 3.2 \times 10^{17}$$

or $\Delta N/N = 0.21$. This value is not small enough to neglect recombination phenomena. As ΔN is almost in proportion to $T(o)^{-4.5} \ n(o)^3$, it is very effective for suppressing recombination to make the initial temperature higher and the initial density lower. It seems that there is a possibility of suppressing recombination sufficiently in our reasonable experimental parameter region because some extension of the parameters mentioned above is not so severe. (In fact, our Nd-glass laser energy has now almost been doubled, and additional heating by CO_2 laser is also being planned. For example, if somewhat later after the stopping phase the temperature is doubled, i.e, $T(o) = 20$ (eV), and the density is reduced to half, i.e. $n(o) = 7.5 \times 10^{15}$ (cm^{-3}), then the value $\Delta N/N_t$ becomes 10^{-3}.)

On the other hand, without re-thermalization at the local bouncing time, i.e. if the initial density $n(o) = 2.4 \times 10^{19}$ (cm^{-3}) and the initial temperature $T(o) = 50$ (eV) and the plasma expands adiabatically to fill the container, the value $\Delta N/N_t$ of the above formula becomes large and thus most of the charged particles recombine before filling the magnetic container. Local thermalization in the linear magnetic field has been experimentally observed by Sudo et al. (1978). We thus believe that the former estimate is more valid. For greater accuracy, the initial expanding phase should be coupled to the filling phase in a toroidal field, which requires three-dimensional calculation.

V. Conclusion

The expansion of the laser-produced plasma with recombination phenomena is studied. The results in the absence of an external magnetic field indicate that recombination phenomena are not negligible in the expanding process. This also agrees with the experimental results.

When the plasma expands in the presence of an external magnetic field, the plasma is heated by the dissipation of the diamagnetic current and recombination is drastically suppressed. In turn, penetration of the magnetic field can take place very rapidly under certain conditions and the plasma expands almost freely. In order to prevent this unfavorable behavior, it is effective to make the initial density lower and this is possible under reasonable conditions. In order to suppress recombination phenomena in the filling phase (for a toroidal field), it is necessary that the initial temperature be higher and the initial density be lower (than our previous experimental values). In spie of the fact that the double-pulse Nd-glass laser method drastically improves the number of ions produced (= electrons), the use of the CO2 laser seems absolutely necessary from the above results.

Acknowledgement

The author thanks M. Salvat for kind encouragement and useful discussions. He is also indebted to H. Brinkschulte, L. Lengyel and H. Baumhacker for valuable discussions.

References

H. Baumhacker, H. Brinkschulte, R.S. Lang, W. Riedmüller, M. Salvat, Appl. Phys. Lett. 30, 461, 1977.

H. Baumhacker, H. Brinkschulte, W. Riedmüller, M. Salvat, S. Sudo, 1979 to be published (in J. Phys. D), see also Jahresbericht 1978 vom M.P.I. für Plasmaphysik.

D.K. Bhadra, Phys. Fluids 11, 234, 1968.

A. Burgess, Mém, Soc. Roy. Sci. Liège, [5], 4, 299, 1961.

J.M. Dawson and C.R. Oberman, Phys. Fluids 5, 517, 1962.

J.M. Dawson, Phys. Fluids 5, 517, 1964.

W.L. Fite and R.T. Brackmann, Phys. Rev. 112, 1141, 1958.

A.W. Gurevich and L.P. Pataevskii, Soviet Phys. JETP 19, 870, 1964.

H. Hora, Laser Interaction and Related Plasma Phenomena, p. 365, 1969 (Plenum Press, New York-London).

D.H. Menzel and C.L. Pekeris, Mon. Not. Roy. Astron. Soc. 96, 77, 1935.

L. Spitzer, Physics of Fully Ionized Gases (Interscience Publishers, Inc., New York, 1956).

G.L. Payne, J.D. Perez, T.E. Sharp, B.A. Watson, J. Appl. Phys. 49, 4688, 1978.

S. Sudo, K. Sato, T. Sekiguchi, J. Phys. D; Appl. Phys. 11, 389, 1978.

Figure Captions

Fig. 1 Temporal variations of the ionization ratio, radius and temperature of the laser-produced plasma in the absence of an external magnetic field. The constant total number of particles is 1.5×10^{18}. The initial temperature is 50 eV and the initial radius is 0.15 cm.

Fig. 2 Only the initial temperature is changed to 25 eV, the other parameters being the same as those in Fig. 1.

Fig. 3 Only the initial temperature is changed to 100 eV, the other parameters being the same as those in Fig. 1.

Fig. 4 Only the initial radius is changed to 0.30 cm, the other parameters being the same as those in Fig. 1.

Fig. 5 Temporal variations of the ionization ratio, radius, temperature and skin depth in the presence of a homogeneous magnetic field. The magnetic field strength is 10 T. The other parameters are the same as those given in Fig. 1. The initial skin depth is assumed to be the same size as the initial plasma radius.

Fig. 6 Only the strength of the magnetic field is changed to 1 T, the other parameters being the same as those given in Fig. 5.

Fig. 7 The results without resistivity, the parameters being the same as those given in Fig. 6.

Fig. 8 Only the initial radius of the plasma is changed to 0.50 cm, the other parameters being the same as those given in Fig. 6.

Table I

Absorption length
N = 1.5 x 10^{18} (fixed) deuterium

a) Nd-glass laser (λ_L = 1.06 μm)

D (cm) / n_e (cm-3) / Te (eV)	1.5 x 10^{-1} 8.5 x 10^{20}	2.0 x 10^{-1} 1.1 x 10^{20}	5.0 x 10^{-1} 2.3 x 10^{19}
50	6.6 x 10^{-5}	2.8 x 10^{-2}	6.25 x 10^{-1}
100	1.8 x 10^{-4}	7.4 x 10^{-2}	1.8
500	2.1 x 10^{-3}	8.3 x 10^{-1}	2.0 x 10^{1}

b) CO_2 laser (λ_L = 10.6 μm)

D (cm) / n_e (cm^{-3}) / Te (eV)	8.0 x 10^{-1} 5.6 x 10^{18}	1.0 2.9 x 10^{18}	1.2 1.7 x 10^{18}
50	4.6 x 10^{-2}	2.9 x 10^{-1}	1.0
100	1.3 x 10^{-1}	8.1 x 10^{-1}	2.84
500	1.5	9.1	3.2 x 10^{1}

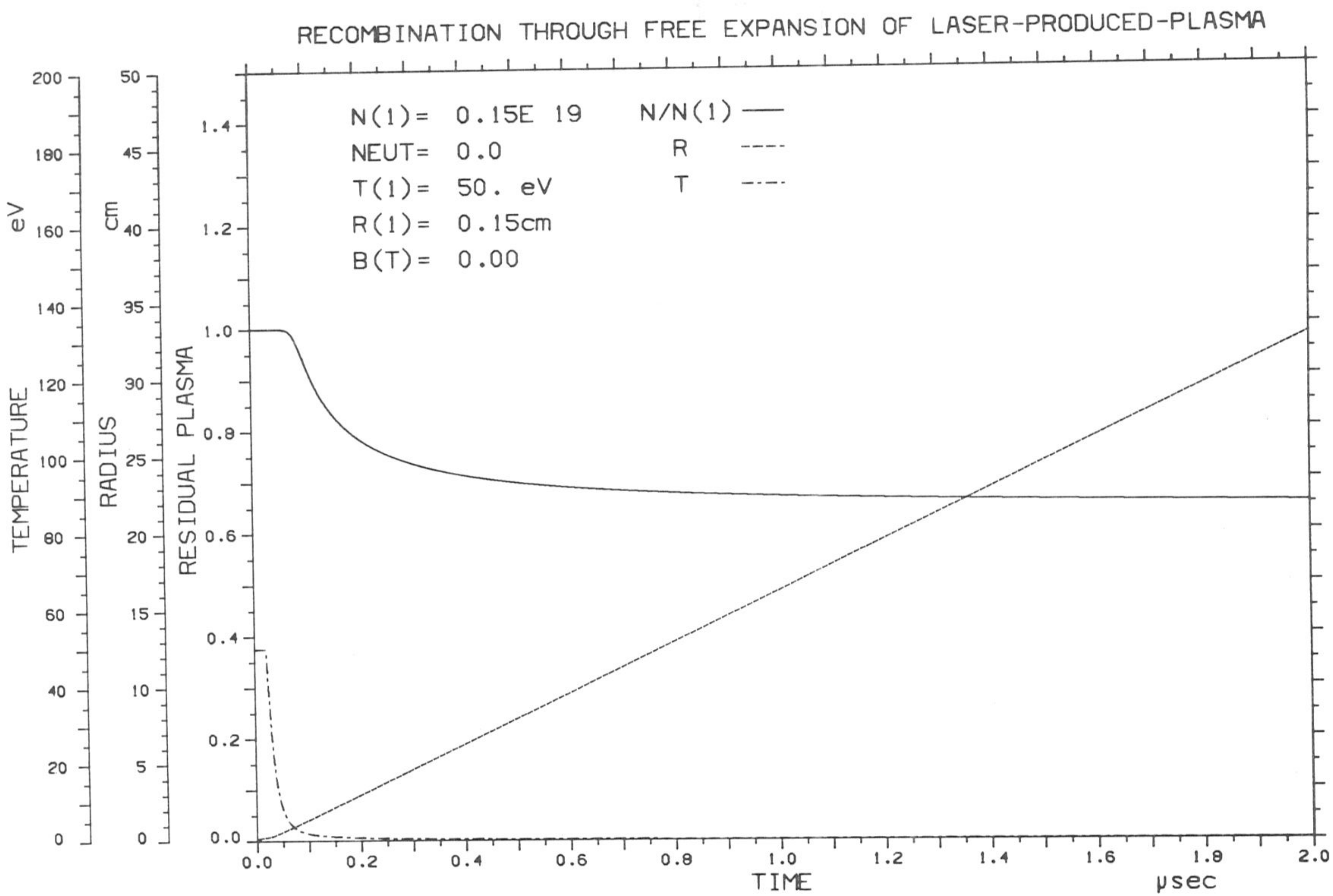
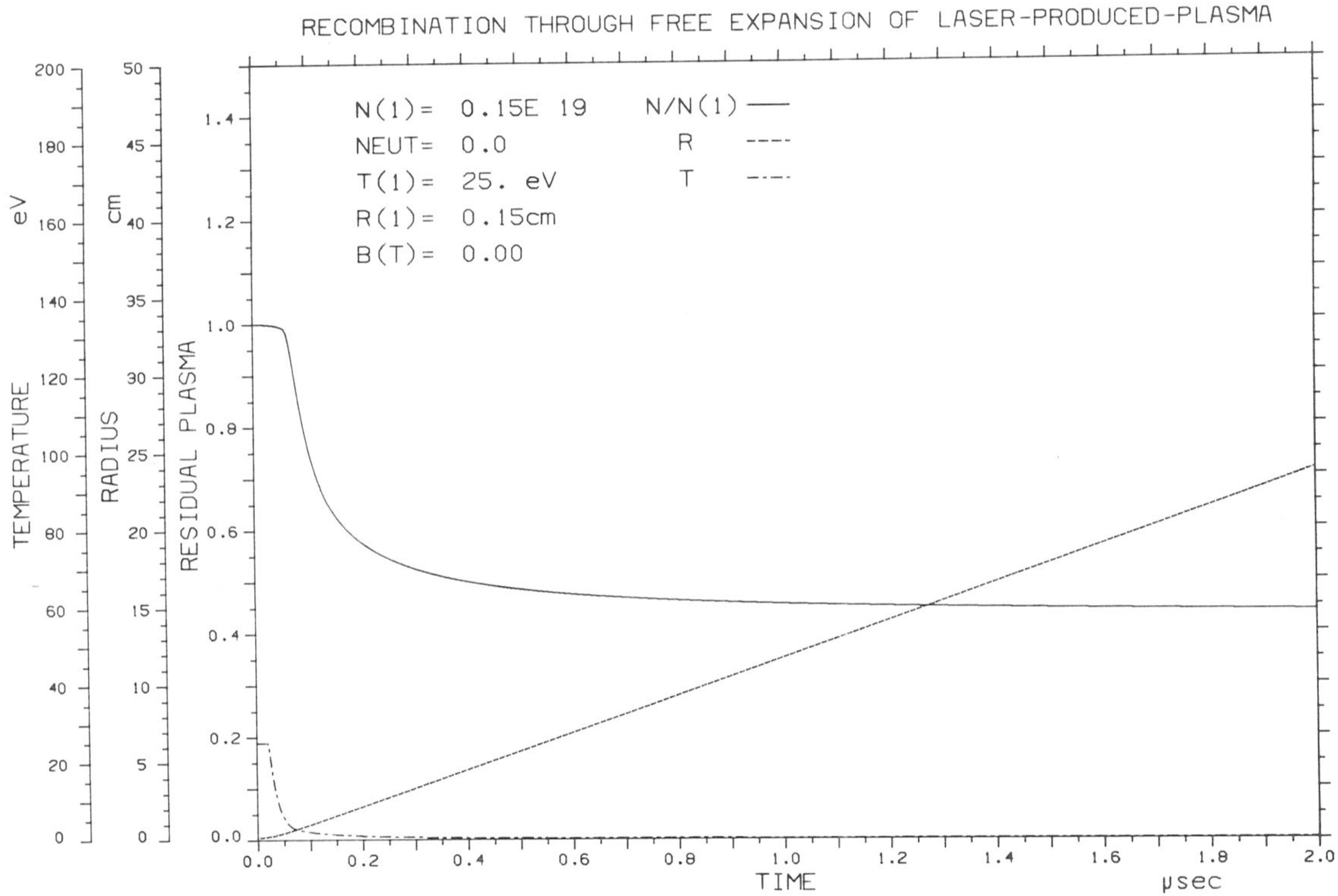

RECOMBINATION THROUGH FREE EXPANSION OF LASER-PRODUCED-PLASMA
N(1)= 0.15E 19
NEUT= 0.0
T(1)= 50. eV
R(1)= 0.15cm
B(T)= 0.00
N/N(1)
R
T
TEMPERATURE
eV
RADIUS
cm
RESIDUAL PLASMA
TIME
μsec
0.0
0.2
0.4
0.6
0.8
1.0
1.2
1.4
1.6
1.8
2.0
0
20
40
60
80
100
120
140
160
180
200
5
10
15
20
25
30
35
40
45
50

Fig. 1



RECOMBINATION THROUGH FREE EXPANSION OF LASER-PRODUCED-PLASMA
N(1)= 0.15E 19
NEUT= 0.0
T(1)= 25. eV
R(1)= 0.15cm
B(T)= 0.00
N/N(1)
R
T
TEMPERATURE eV
RADIUS cm
RESIDUAL PLASMA
TIME
μsec

Fig. 2

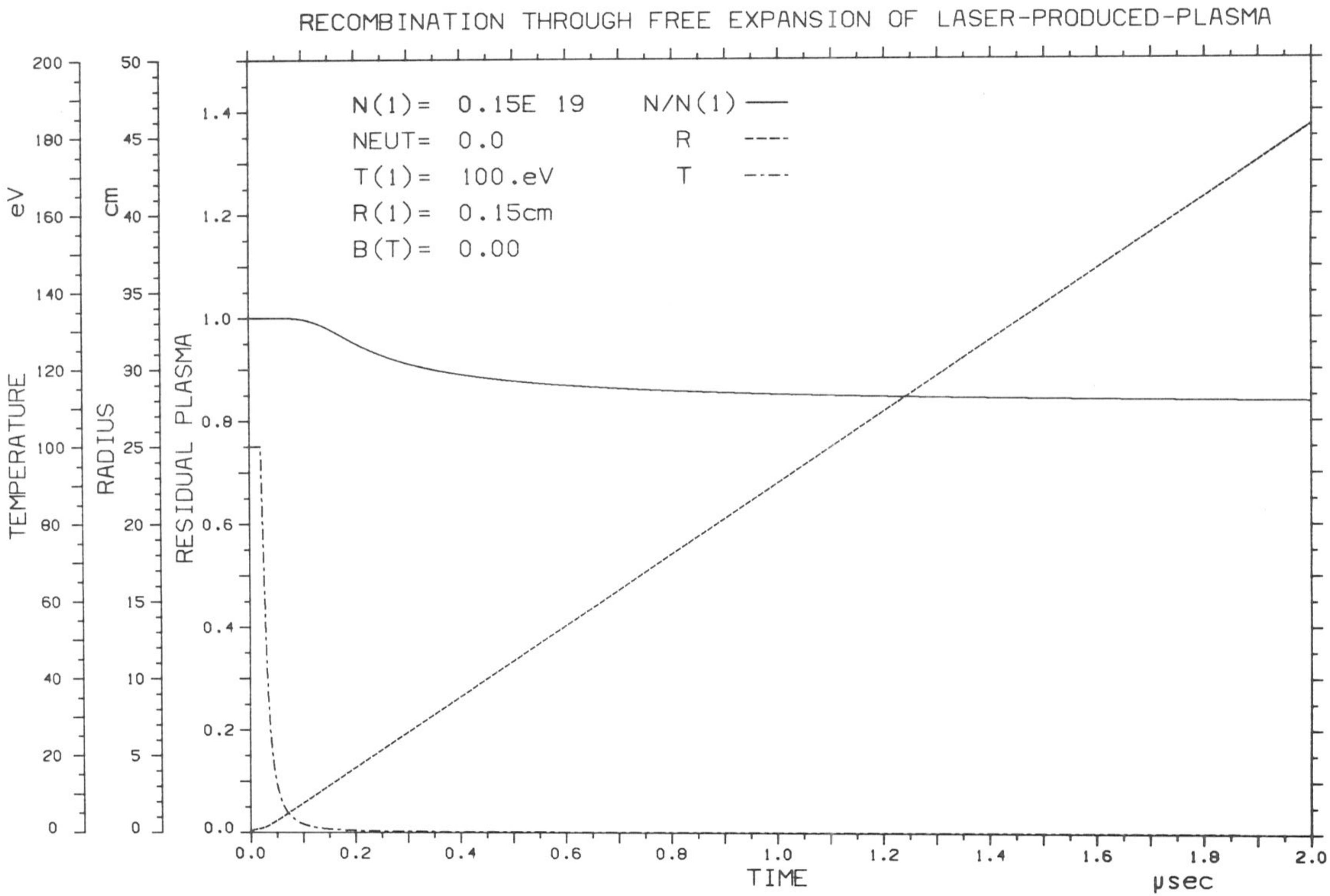

RECOMBINATION THROUGH FREE EXPANSION OF LASER-PRODUCED-PLASMA
N(1)= 0.15E 19
NEUT= 0.0
T(1)= 100.eV
R(1)= 0.15cm
B(T)= 0.00
N/N(1)
R
T
TEMPERATURE eV
RADIUS cm
RESIDUAL PLASMA
TIME
μsec

Fig. 3

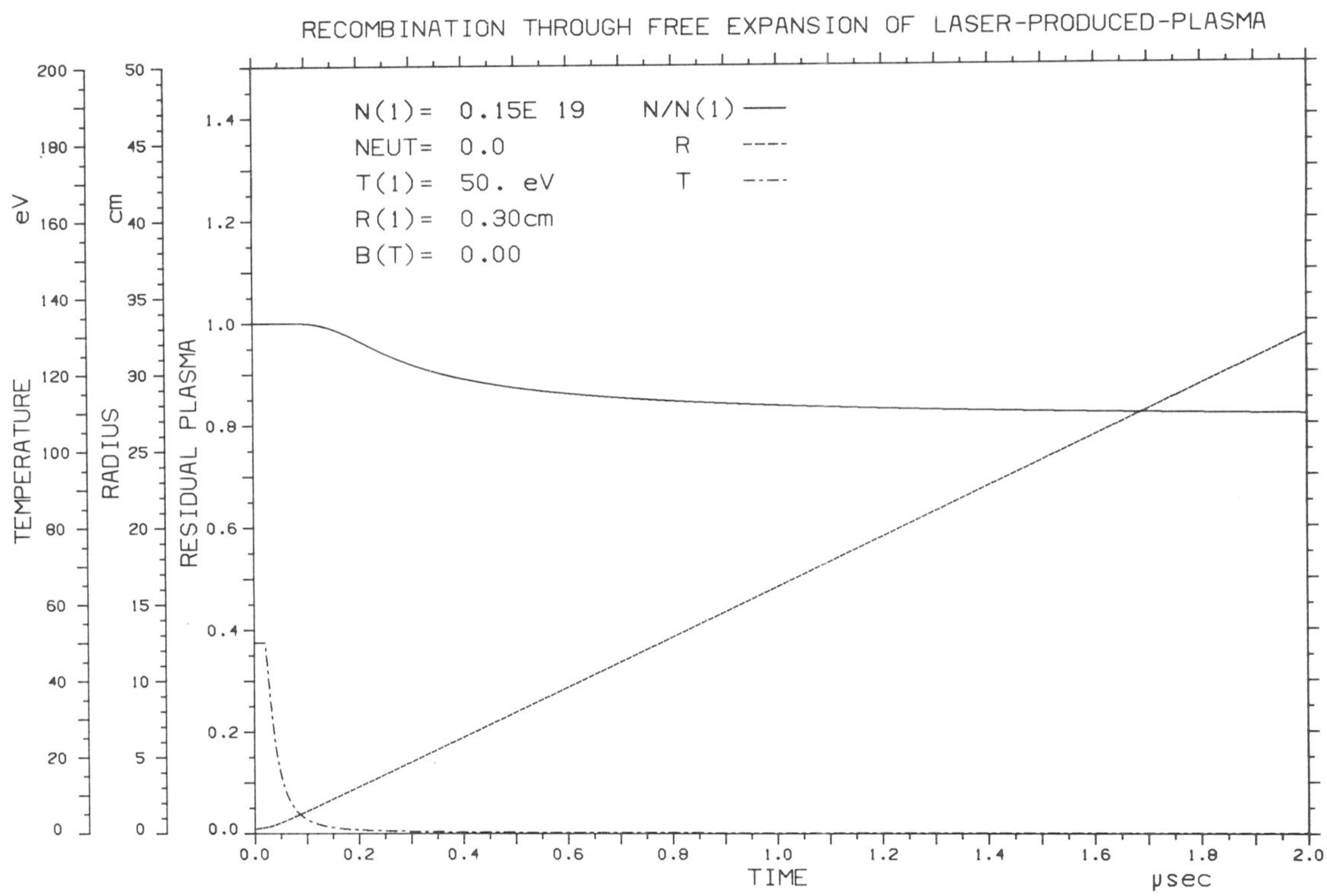
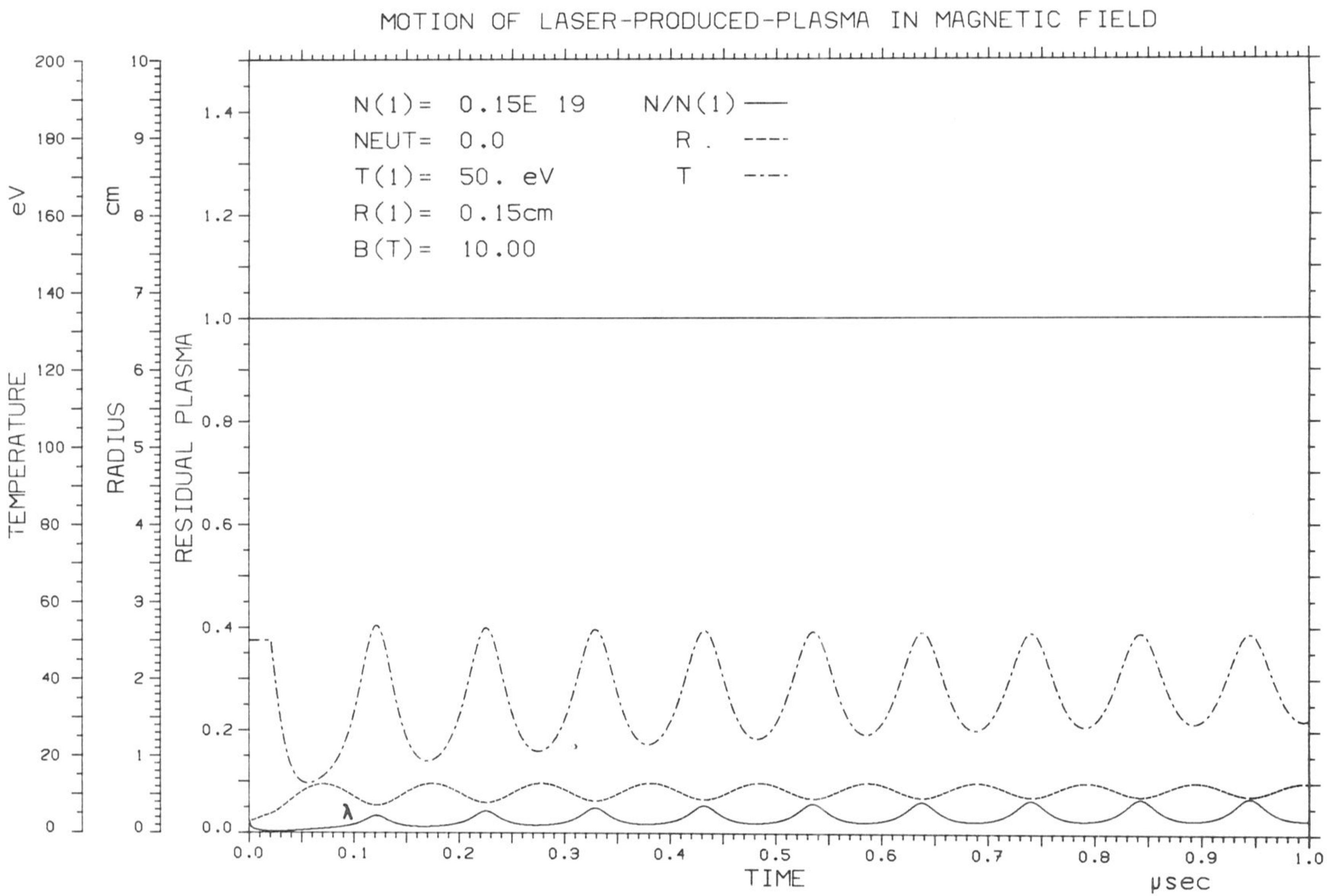

RECOMBINATION THROUGH FREE EXPANSION OF LASER-PRODUCED-PLASMA
N(1)= 0.15E 19
NEUT= 0.0
T(1)= 50. eV
R(1)= 0.30cm
B(T)= 0.00
N/N(1)
R
T
TEMPERATURE
eV
RADIUS
cm
RESIDUAL PLASMA
TIME
μsec
0
20
40
60
80
100
120
140
160
180
200
0
5
10
15
20
25
30
35
40
45
50
0.0
0.2
0.4
0.6
0.8
1.0
1.2
1.4
0.0
0.2
0.4
0.6
0.8
1.0
1.2
1.4
1.6
1.8
2.0

Fig. 4



MOTION OF LASER-PRODUCED-PLASMA IN MAGNETIC FIELD
N(1)= 0.15E 19
NEUT= 0.0
T(1)= 50. eV
R(1)= 0.15cm
B(T)= 10.00
N/N(1)
R .
T
TEMPERATURE eV
RADIUS cm
RESIDUAL PLASMA
TIME
μsec
λ

Fig. 5

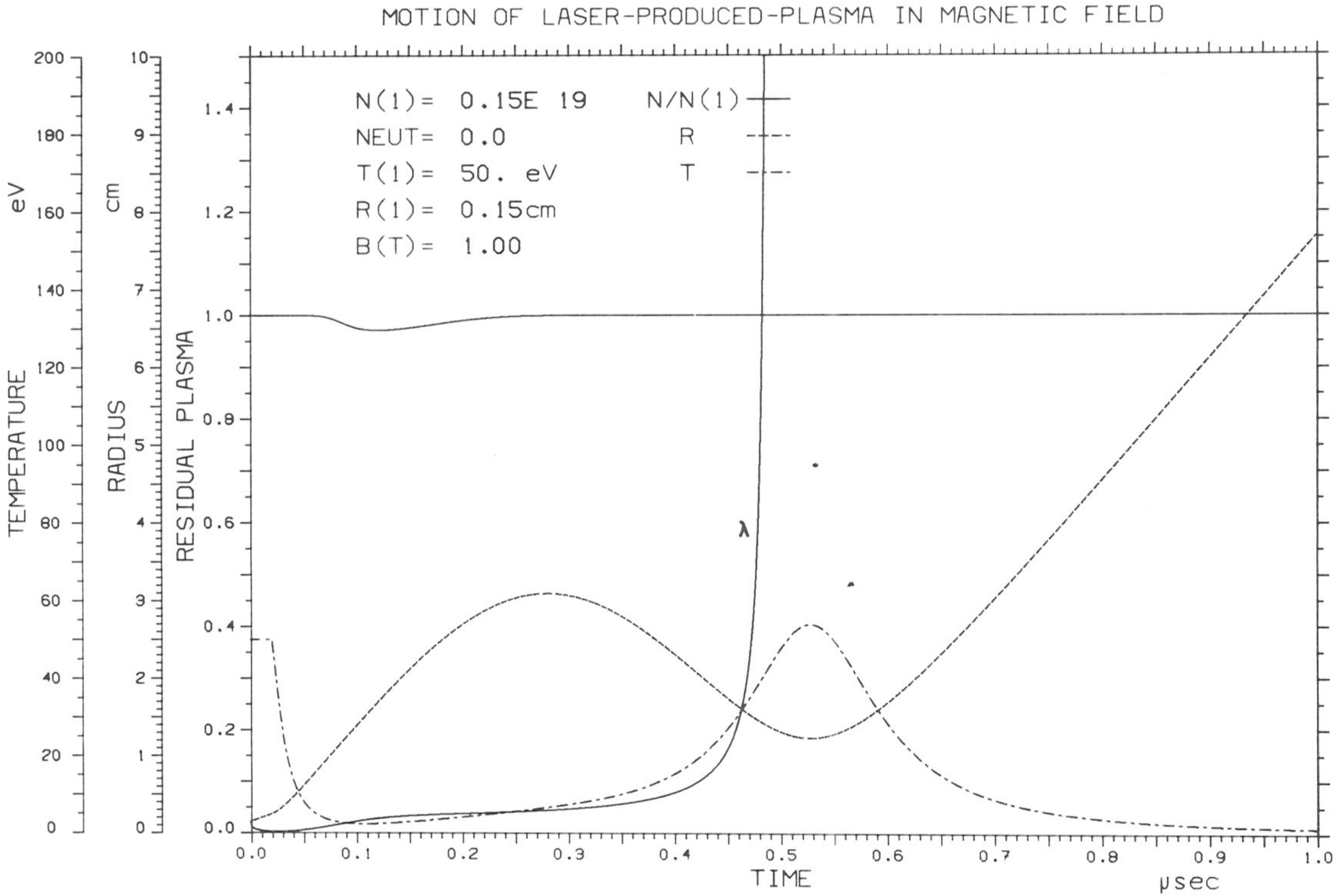

MOTION OF LASER-PRODUCED-PLASMA IN MAGNETIC FIELD
N(1)= 0.15E 19
NEUT= 0.0
T(1)= 50. eV
R(1)= 0.15cm
B(T)= 1.00
N/N(1)
R
T
TEMPERATURE eV
RADIUS cm
RESIDUAL PLASMA
TIME
μsec
200
180
160
140
120
100
80
60
40
20
0
10
9
8
7
6
5
4
3
2
1
0
1.4
1.2
1.0
0.8
0.6
0.4
0.2
0.0
0.0
0.1
0.2
0.3
0.4
0.5
0.6
0.7
0.8
0.9
1.0

Fig. 6

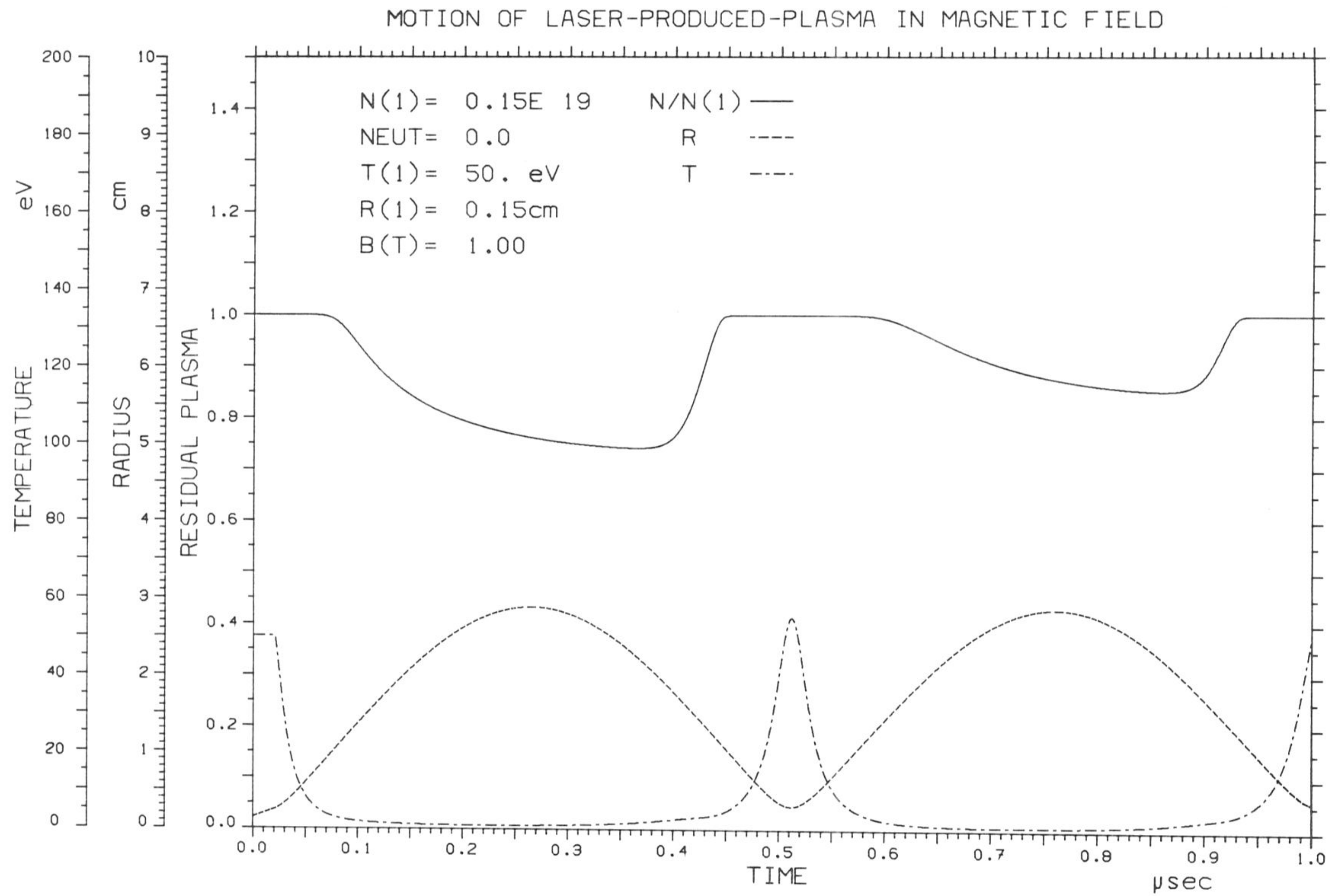
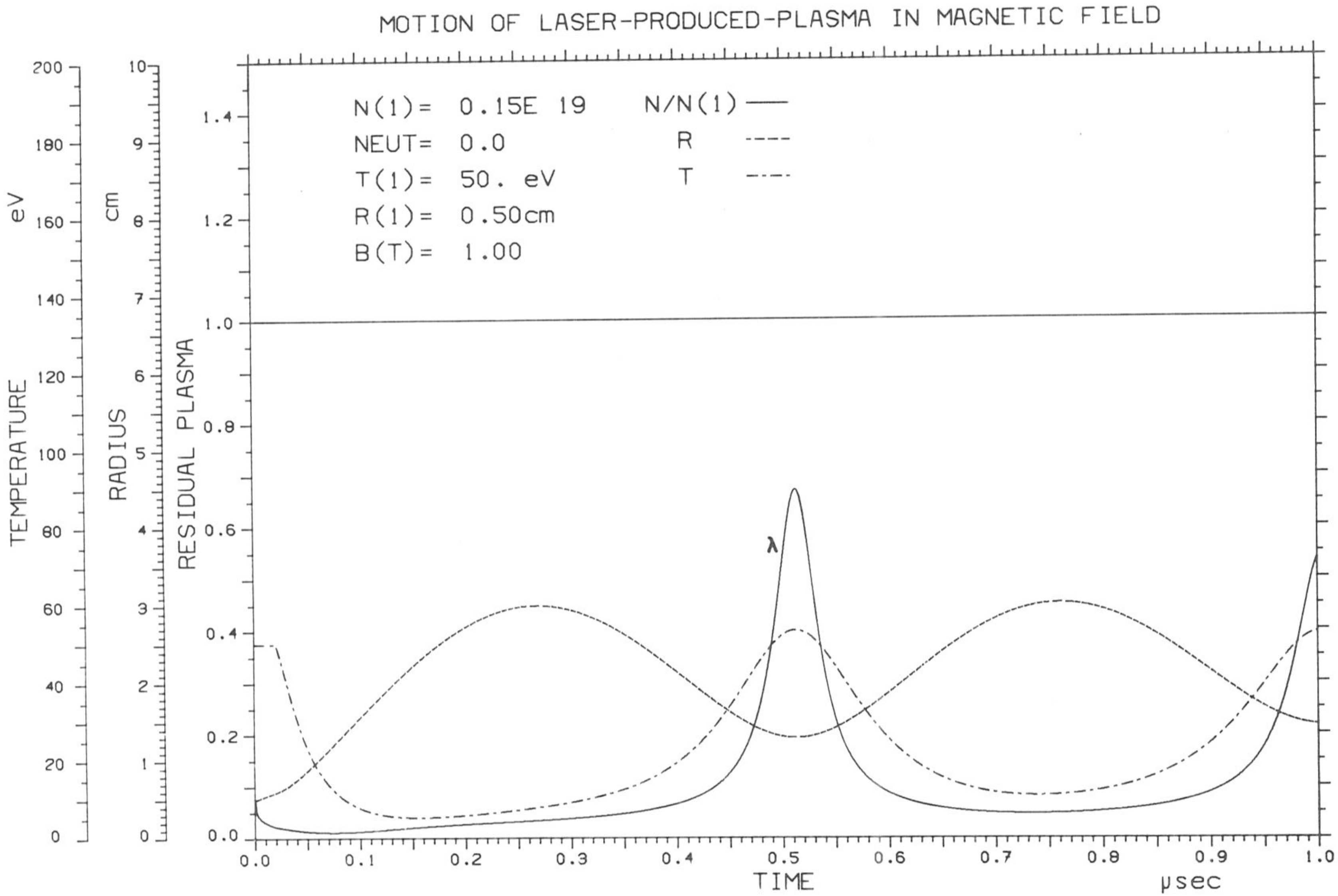

MOTION OF LASER-PRODUCED-PLASMA IN MAGNETIC FIELD
N(1)= 0.15E 19
NEUT= 0.0
T(1)= 50. eV
R(1)= 0.15cm
B(T)= 1.00
N/N(1)
R
T
TEMPERATURE eV
RADIUS cm
RESIDUAL PLASMA
TIME
μsec

Fig. 7



MOTION OF LASER-PRODUCED-PLASMA IN MAGNETIC FIELD
N(1)= 0.15E 19
NEUT= 0.0
T(1)= 50. eV
R(1)= 0.50cm
B(T)= 1.00
N/N(1)
R
T
λ
TEMPERATURE
eV
RADIUS
cm
RESIDUAL PLASMA
TIME
μsec

Fig. 8