Confinement and Heating of Plasma by

Nonlinear Interaction with Laser Radiation

H. Hora

INSTITUT FÜR PLASMAPHYSIK

GARCHING BEI MÜNCHEN

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Abstract

At ruby or neodymium glass laser intensities exceeding $L^* \approx 10^{14}$
W/cm^2 a ponderomotive force is produced towards low electron densi-
ties in inhomogeneous plasma surfaces near the cutoff density.
Under steady-state conditions, the final velocity of the ions is
integrated, details of the density profile being cancelled. The
energy of the ions accelerated to the vacuum is equal to the mean
oscillation energy of the electrons if the elevated electromagnetic
energy density in the plasma due to collective effects is taken
into account. The pronounced onset of the nonlinear, electrodynamic
acceleration mechanism at the threshold energy L^* is due to the
fact that the ion energy rises with the fourth power of the light
intensity. Above $L_o \approx 10^{15}$ W/cm^2 the total laser energy is con-
verted into directed ion motion only. Between L^* and L_o a D-T
plasma of solid-state density can be heated sufficiently with a
$10^5 j$ laser pulse of length 0.5 nsec to achieve the Lawson criterion
to within a factor of 3.

I) Introduction

The nonlinear interaction of electromagnetic radiation with a collisionless inhomogeneous plasma produces a force towards lower electron density /1,2/. In a plasma with collisions, the resulting force is similar if the electron density generates a plasma frequency ω_p smaller than or very close to the frequency ω of the incident radiation /3/. Higher densities produce a force with a component parallel to the light, which can be interpreted as a kind of radiation pressure /3/. Integration of the force density to evaluate the transferred momentum shows greater compression of the overdense plasma compared with the usual radiation pressure owing to a recoil of the nonlinearly blown off inhomogeneous surface /4/. A derivation of the basic equation was given by P. Javel on the basis of the microscopic plasma theory /5/.

Here we shall discuss an integration of the equation of motion to find the maximum ion energies. First we have to evaluate the conditions under which the processes due to the interaction of the radiation with the plasma exceed the thermokinetic processes. Comparison of the resulting ion energies with the electron oscillation energies yields quite a plausible relation between the energies.

The ion energies resulting from nonlinear interaction allow evaluation of the amount of energy consumed by the nonlinear process. This absorption in the surface region is a loss of energy required for heating of the plasma interior beyond the surface region. In order to obtain conditions for plasmas for thermonuclear fusion, the heating of the interior has to be large enough while the amount of plasma nonlinearly emitted from the surface has to be small enough, and the recoil of this emission has to increase the radiation pressure sufficiently to confine the interior of the plasma. We shall evaluate relations to satisfy all of these conditions.

II) Limitations to the predominance of nonlinear over thermo-
   kinetic processes.

The time averaged force density f in a stratified inhomogeneous
plasma with perpendicularly incident electromagnetic waves with an
amplitude E_v of the electric field strength in the vacuum, and under
WBK conditions is /3/

$$f = -\nabla_x \left[p + \frac{E_v^2}{16\pi} \left(\frac{1}{|\eta|} + |\eta| \right) exp(-kx) \right] . \tag{1}$$

x is the coordinate of depth in the layer. The complex refractive
index η is given by

$$\eta^2 = 1 - \frac{\omega_p^2}{\omega^2 + \gamma^2} \left(1 + i \frac{\nu}{\omega} \right) \tag{2}$$

with the plasma frequency ω_p

$$\omega_p^2 = 4\pi e^2 n_e / m_e \tag{3}$$

where e is the charge and m_e the mass of the electrons, and n_e is
the electron density; the collision frequency ν

$$\nu = \frac{\omega_p^2 \, \pi^{3/2} \, m_e^{1/2} \, Z \, e^2 \, \ln \Lambda}{8\pi \, g_E(Z) \, (2 \, K \, T)^{3/2}} \tag{4}$$

is determined by the ion charge Z, the Coulomb logarithm $\ln \Lambda$,
Spitzer's correction /6/ of electron-electron collisions $\gamma_E(Z)$, and
the electron temperature T. We use gauss units and express T in
electron volts. K is then 1.602×10^{-12} erg/eV. Other dimensions
used are specially noted. The integral absorption coefficient **k** in
Eq.(1) is

$$k(x) = \frac{1}{x} \frac{\omega}{c} \int^x Im(\eta(\xi)) d\xi \tag{5}$$

and the thermokinetic pressure p is

$$p = \left(1 + \frac{1}{Z} \right) n_e \, K \, T. \tag{6}$$

In the surface of a plasma with a temperature of 100 eV or more, we find in Eq.(1) for $\omega_p \approx \omega$ that the absorption constant k (Eq.(5)) is negligible, $|\eta| << 1$, and

$$|\eta|_{min} = \frac{a}{T^{3/4}} \quad ; \quad a = \left(\frac{\omega_p \pi^{3/2} m_e^{1/2} Z e^2 \ln \Lambda}{8\pi \gamma_E(Z)(2\varkappa)^{3/2}} \right)^{1/2} \quad (7)$$

The electron density $n_e = n_{eco}$ is then the cut-off density given by $\omega_p = \omega$ in Eq.(3). The electrodynamic part of the force density (Eq.(1)) is more effective than the thermokinetic part if $E^2/(16\pi|\eta|) \geq (1 + 1/Z)n_{eco}\varkappa T$, which gives

$$E_v > E_v^* = 4 (\pi a \, n_{eco} \varkappa (1 + 1/Z))^{1/2} T^{1/8} \quad (8a)$$

This limitation is expressed by the light intensity L of the radiation for <u>ruby lasers</u> and deuterium plasma

$$E_v > E^* = 3.65 \times 10^8 T^{1/8} V/cm; \quad L > L^* = 3.5 \times 10^{14} T^{1/4} W/cm^2; \text{ using } n_{eco} = 2.3 \times 10^{21} cm^{-3} \quad (8b)$$
$$a = 4.02 (eV)^{3/4}$$

and for <u>neodymium glass</u> lasers

$$E_v > E^* = 2.17 \times 10^8 T^{1/8} V/cm; \quad L > L^* = 1.26 \times 10^{14} T^{1/4} W/cm^2; \text{ using } n_{eco} = 0.49 \times 10^{21} cm^{-3} \quad (8c)$$
$$a = 3.25 (eV)^{3/4}$$

In the interior of the plasma, the electrodynamic part of the force density vanishes because of absorption due to collisions. But with respect to the differentiation in Eq.(1), the force densities are effective only in inhomogeneous regions, especially in the surface; it can therefore be concluded that the expansion process of a plasma is dominated by the electrodynamic part of the force density if $E_v > E_v^*$ in Eqs.(8).

III) Ion energy from the nonlinear blast wave process

If the electric field strength E_v of the incident laser radiation exceeds the value E_v of the Eqs.(8), the nonlinear force f_n of Eq.(1) produces a force towards lower plasma density up to depths in the plasma, where $\omega_p \approx \omega$ at electron temperatures $T > 100$ eV. The momentum transferred by this process has already been evaluated /3/. Here we shall evaluate the energy ε_o transferred to the ions.

A necessary condition for the following is that the density profile of the plasma surface should not change noticeably during the complete acceleration process of the ions. The time of this acceleration is of the order of 10^{-11} to 10^{-12} seconds, which may be short enough to consider the blast wave mechanism of the electromagnetically driven surface acceleration as being of the quasi-stationary kind. Neglecting the thermokinetic pressure p at $E_v > E^*$ in Eq.(1), the force density /3/ is given by

$$\underset{\sim}{f}_n = m_i n_i \frac{d}{dt} \underset{\sim}{v}_i = \begin{cases} -\underset{\sim}{i}_1 \dfrac{E_v^2}{16\pi} \dfrac{\partial}{\partial x} \dfrac{1}{|\eta|} & \text{at } \omega_p \approx \omega \text{ because } |\eta| \ll 1 \\[3em] -\underset{\sim}{i}_1 \dfrac{E_v^2}{16\pi} \dfrac{\omega_p^2}{\omega^2} \dfrac{\partial}{\partial x} \dfrac{1}{|\eta|} & \text{at } \omega_p < \omega \end{cases} \tag{9}$$

Using the relation $n_e = Z n_i$, we find the acceleration $\underset{\sim}{b}$

$$\underset{\sim}{b} = \frac{d}{dt} \underset{\sim}{v}_i = -\underset{\sim}{i}_1 \frac{E_v^2}{16\pi} \frac{Z}{m_e c_o} \frac{\partial}{\partial x} \frac{1}{|\eta|} \tag{10}$$

The necessary fulfilment of the WBK condition restricts our consideration to

$$\Theta = \frac{c}{2\omega} \left| \frac{\partial}{\partial x} \frac{1}{|\eta|} \right| \ll 1 \tag{11}$$

The total thickness of the surface layer Δx can be derived from Eq.(11)

$$\Delta x = \frac{c}{2\omega\Theta} \left[\frac{1}{|\eta|_{min}} - 1 \right] \approx \frac{c}{2\omega\Theta} \frac{1}{|\eta|_{min}} \tag{12}$$

where $|\eta|_{min} << 1$ is satisfied at $T > 10^2$ eV (Eq.(7)) and the de-
confining acceleration is effective from low density only to about
$\omega_p \approx \omega$, at which the minimum of $|\eta|$ results for $\nu << \omega$. At higher
densities, the interior of the plasma is compressed /3,4/.
Expressing the acceleration $\underset{\sim}{b}$ of Eqs.(10) by Eq.(11)

$$|\underset{\sim}{b}| = \frac{E_v^2}{16\pi} \frac{Z}{m_e c_o} \frac{2\omega\Theta}{c} , \tag{13}$$

we find the final velocity v_o of the ions after falling through the
inhomogeneous surface owing to the ponderomotive force to be

$$v_o = \sqrt{2\Delta \times |\underset{\sim}{b}|} = \frac{E_v}{2} \sqrt{\frac{Z}{2\pi\, m_e c_o\, m_i \cdot |\eta|_{min}}} \tag{14}$$

It can be seen that the special profile of the plasma density as
described by the value Θ has been cancelled. The maximum ion energy
ε_i is given by

$$\varepsilon_i = \frac{m_i}{2} v_o^2 = \frac{E_v^2}{16\pi} \frac{Z}{|\eta| m_e c_o} . \tag{15}$$

ε_i is the energy gained by the ion for a directed motion after being
nonlinearly accelerated through the inhomogeneous plasma surface.
This motion is driven by the electromagnetic field, where each
particle describes a moving eight-like track owing to the electric
field and the Lorentz force producing a longitudinal oscillation
with the frequency 2ω.

We shall show that the kinetic energy ε_i of the ion after being
shaken electromagnetically through the surface is Z-times the
oscillation energy ε_e^{osc} of an electron in the electromagnetic field
in the plasma,

$$\varepsilon_e^{osc} = \frac{m_e}{2} \overline{v_e^2} = \frac{e^2}{m_e\omega^2} \frac{E^2}{4} = \frac{1}{16\pi} \frac{\omega_p^2}{\omega^2 m_e} \frac{E_v^2}{|\eta|} . \tag{16}$$

Here we make use of the relation between the actual amplitude of
the field strength E in the plasma and the value E_v in vacuum /1,3/,
$E = E_v/\sqrt{|\eta|}$, and find at $\omega_p \approx \omega$ that

$$\varepsilon_i = Z \varepsilon_e^{osc} \tag{17}$$

The temperature of the electron used in $|\eta|_{min}$ in Eq.(11) is composed of the thermokinetic temperature T_{th} and of the mean energy ε_e gained by the electron from the electromagnetic field.

$$T = T_{th} + \varepsilon_e^{osc}/\varkappa \tag{18}$$

This virtual increase of the "temperature" is well known in plasmas and induces a decrease of the collision frequency /7/. From Eqs. (7) and (16) we find an equation

$$\varepsilon_e^{osc} = \frac{E_v^2}{16\pi} \frac{1}{m_e c_o a} \left(T_{th} + \frac{\varepsilon^{osc}}{\varkappa}\right)^{3/4} \tag{19}$$

which cannot be solved generally by algebra. By the formulation

$$\varepsilon_i = \begin{cases} z \dfrac{E_v^2}{16\pi} \dfrac{T_{th}^{3/4}}{m_e c_o a} & \text{if} \quad E_v < E^*(T_{th}) \\[2mm] \dfrac{z\, E_v^8}{(16\pi a\, n_{e c o}\varkappa^{3/4})^4} & \text{if} \quad E_v > E^*(T_{th}) \end{cases} \tag{20}$$

we find an appropriate approximation of the kinetic energy ε_i in erg of the ions that is exact for $E_v \gg E^*$ and $E_v \ll E^*$.

Equation (20) states that a very steep increase of the ion energies ε_i by the fourth power of the light intensity is to be expected at light intensities L larger than that given by Eqs.(8). Intensities of the order of magnitude mentioned are available at present /8,9/.

A necessary condition is the approximate fulfilment of the stationary state, i.e. that the light should interact long enough. As is well known from the initial processes of the transmission of electromagnetic waves /10/, the increased power density of electromagnetic energy in matter has to be built up during a certain time. This may be the reason why at light pulses of 10^{-11} sec /11/ the ion energies of the value of Eq.(20) do not have to be reached. For the processes considered only the electron temperature is of interest. Delays due to the energy transfer to the ions are not effective here. With long laser pulses it is also possible that the storing of energy in the surface front needs more time to reach the energy ε_i of Eq.(20) than the nonlinear blow-off of the ions; but no matter what limitations exist for the validity of the

relation (20) towards higher intensities, one should observe the onset of a highly superlinear increase of the ion energy around $E^{\#}$.

The possibility of the electrodynamic blow-off mechanism also being present at measured lower average light intensities cannot be excluded in view of a spontaneous picosecond spike structure of the Q-switched laser pulses, which are sufficient to get the higher intensities /12/. Some experiments show completely the properties of Eq.(20):

1) the mass independence of ε_i /13,14,15/,
2) the linear dependence of ε_i on Z /15,16/,
3) the superlinear dependence of ε_i on the light intensity, where an increase of T_{th} with increasing light intensity is implied /14,17/.

IV) Conditions for plasma confinement and heating

From previous work /3,4/ we know the momentum transfer to the plasma surface and the confining recoil to the interior of the plasma, expressed in multiples of 100 to 1000 of the usual radiation pressure. Using the ion velocity v_o of Eq.(14), we can calculate the amount of plasma blown off nonlinearly to achieve confinement. Furthermore, we can calculate the amount of energy of the light which is consumed by the surface, and we find what remains to heat the confined interior of the plasma. In this section we derive the expressions of all the conditions which are necessary to achieve both heating and confinement of the plasma interior.

The first condition to be fulfilled is that the electron density in the interior of the plasma be larger than the cut-off density

$$\text{(I)} \qquad n_e > n_{eco} = \frac{\omega^2 m_e}{4\pi e} \qquad (21)$$

Furthermore the laser intensity L has to be so large that in the plasma surface with $\omega_p \approx \omega$ the electrodynamic force density is larger than the thermokinetic, Eqs.(8), or

$$(II) \qquad L > L^* = 4 a c n_{eco} \mathcal{K} (1 + 1/Z) T_{th}^{1/4} \qquad (22)$$

The nonlinearly increased radiation pressure P_s has to balance the thermokinetic pressure in the plasma

$$P_s = \frac{L}{2c|\eta|} = \frac{L}{2ca} T^{3/4} = 2 n_e \mathcal{K} T_{th} \qquad (23)$$

The factor 2 at the right-hand side is the value $1 + 1/Z$ for hydrogen. For $Z > 1$, P_s is a lower bound for an always compressing radiation process. We shall always use $Z = 1$ in this and the following sections. T is composed of the thermal energy T_{th} and the oscillation energy ε_e^{osc} of the electrons. For the condition (II) we can neglect T_{th} relative to ε_e^{osc}. Using Eqs.(7), (16), and (23) we get the condition of confinement at the increased radiation pressure

$$(III) \qquad L = 4 a c \mathcal{K} T_{th}^{1/4} n_e^{1/4} n_{eco}^{3/4} . \qquad (24)$$

T_{th}, like all temperatures T, is given in electron volts and a has the dimension of $(eV)^{3/4}$.

Starting from the momentum $\mathcal{P}$ of the accelerated plasma of the surface /3/

$$\mathcal{P} = \frac{\varepsilon_L}{2 c |\eta|_{min}} \qquad (25)$$

and using $\mathcal{P} = M_{NL} v_o$ we get the nonlinear mass loss

$$M_{NL} = \frac{\varepsilon_L \sqrt{m_i} L}{4 a^2 c^2 \sqrt{2} n_{eco} \mathcal{K}^{3/4}} \qquad (26)$$

We compare this mass with the total mass M_{tot} of the plasma heated to an average temperature T_{th}

$$M_{tot} = \frac{m_i \, \varepsilon_L}{2 \varkappa T_{th}} \tag{27}$$

using a factor α:

$$\alpha = \frac{M_{NL}}{M_{tot}} = \frac{T_{th} \, L}{2\sqrt{2} \, a^2 c^2 \, n_{eco} \, \varkappa^{1/2} m_i^{1/2}} \tag{28}$$

We shall have to check whether condition

$$\text{(IV)} \qquad \alpha \ll 1 \tag{29}$$

is fulfilled.

We compare the energy of the incident laser radiation ε_L with the energy consumed by the nonlinearly accelerated surface layer $\varepsilon_{NL} = \mathscr{C} v_0/2$. The parameter β, evaluated by Eqs.(7), (20), (25), and $v_0 = \sqrt{2\varepsilon_i/m_i}$

$$\beta = \mathscr{C} v_0 / 2 \varepsilon_L = \frac{\sqrt{2} \, L^5}{(4 \, a \, c \, \varkappa^{3/4})^6 \, m_i^{1/2} n_{eco}^5} \tag{30}$$

has to be

$$\text{(V)} \qquad \beta \leq 1. \tag{31}$$

The sign of equality in Eq.(31) is the case where we can assume a 50 % heating of the plasma interior by the incident radiation, taking into account the difference of the assumed linear decay of intensity against the real exponential decay due to the absorption process. The highest acceptable intensity for $\beta = 1$ is

$$L \leq L_0 = 2^{-1/10} (4 \, a \, c \, \varkappa^{3/4})^{6/5} \, n_{eco} \, m_i^{1/10} \tag{32a}$$

For D-T plasma we find in the case of ruby lasers

$$L_0 = 2.36 \times 10^{15} \text{ W/cm}^2 \tag{32b}$$

and of neodymium glass lasers

$$L_0 = 7.94 \times 10^{14} \text{ W/cm}^2. \tag{32c}$$

Any confinement by the nonlinear surface acceleration process at sufficiently high heating of the plasma interior is possible only if $L^* \leq L_0$. From Eqs.(22) and (32a) we find

$$\frac{L_0}{L^*} = (4ac\varkappa^{3/4})^{1/5}(m_i/2)^{1/10}/(1+1/Z)\,T^{1/4} \geq 1 \qquad (33a)$$

From this relation (33a) we find a limitation for ruby and neodymium glass lasers respectively

$$T \leq 4.06 \text{ keV} \quad \text{and } 3.1 \text{ keV respectively.} \qquad (33b)$$

V) D-T plasma

In accordance with the conditions of the last section we calculate the confinement and heating of a spherical D-T plasma of a 50-to-50 mixture to find the parameter $n_i\tau_L$ of the Lawson criterions. We start from the density $n_i = 1.6 \times 10^{22} \text{ cm}^{-3}$ in vacuum. If the light of a neodymium glass laser of a total energy ε_L is incident from two opposite sides or from four corners of a tetrahedron simultaneously and in equal parts, we can then neglect the spherical modification of the material because the electrodynamic forces are mainly radially directed /3/. This is also valid when the incidence is so oblique that total reflection occurs, as will be shown in a later paper.

In order to produce a plasma of a temperature $T_{th} = 3 \times 10^3$ eV, the radiation intensity L needed for achieving confinement by the nonlinearly increased radiation pressure has to be

$$L = 8 \times 10^{14} \text{ W/cm}^2 \qquad (34a)$$

The intensity then simultaneously fulfils the conditions (II), (III), and (V), while condition (I) is fulfilled by the used density $n_i = n_e$. Condition (IV) results in a value

$$\alpha = 0.35 \qquad (34b)$$

and expresses that 35 % of the plasma are lost by the nonlinear acceleration mechanism.

The laser pulse length τ_L is determined by the time during which the laser intensity L passing the surface of the sphere heats up the interior to a temperature T_{th}. Longer heating would result in higher temperatures. The relation of this surface process and the volume heating with illumination from two sides only

$$2\pi L \tau_L r_o^2 = 2 \frac{4\pi}{3} r_o^3 n_e \mathcal{K} T (1-\alpha) \qquad (35)$$

together with the sphere radius $r_o^3 = 3\varepsilon_L/4\pi n_e$ KT$(1-\alpha)$ yields

$$\tau_L = B (\varepsilon_L)^{1/3} T_{th}^{5/12} n_e^{5/12} n_{eco}^{-3/4} \alpha^{-1} (1-\alpha)^{2/3} \qquad (36a)$$

where

$$B = 1.172 \times 10^{-7} \quad \text{with} \quad [T_{th}] = eV; \ [a] = (eV)^{3/4}; \ [\varepsilon_L] = erg \qquad (36b)$$

and τ_L is in sec and n_e and n_{eco} in cm^{-3}. The value

$$n_e \tau_L = (\varepsilon_L)^{1/3} 4.8 \times 10^9 \ \text{cgs} \qquad (37)$$

leads with $\varepsilon_L = 10^7$ joule $= 10^{12}$ erg to

$$n_e \tau_L = 4.8 \times 10^{13} \ \text{cgs} \qquad (38)$$

This value is compared in Fig. 1 with other experimental values of $n_e \tau_L$. We find that the value deviates from Lawson's D-T criterium by a factor of three. In addition, we find that $\tau_L = 3 \times 10^{-9}$ sec and that the radius of the initially solid D-T sphere is $r_o = 2.5$ mm.

VI) Conclusions

At ruby and neodymium glass laser intensities of $L \approx 10^{15}$ W/cm^2 (Eqs. (8)) we expect a very pronounced start to the nonlinear deconfining acceleration of the inhomogeneous plasma surface owing to the interaction with light, which overcomes the thermokinetic properties. The ion energy increases with the fourth power of the laser radiation and the surface acceleration produces by recoil a confinement of the plasma interior in the form of a superlinearly increased radiation pressure. The surface acceleration consumes only a small part of the interacting energy for light intensities up to a factor ten higher than the threshold intensity L^*. At intensities a little higher than L^* it is possible to heat and confine a D-T plasma of 1.6×10^{22} cm^{-3} ion density, the Lawson criterion being reached within a factor of three. The amount of plasma which is blown off by the nonlinear acceleration of the surface is about 35 %. This loss increases at higher temperatures and lower light frequency as shown by Eq.(28) with allowance for the relation $a \propto \omega^{1/2}$. This reason exludes an application of microwaves for confinement on the basis of the described mechanism. Only at higher ion masses can better conditions be expected, but these cases are of less interest for thermonuclear fusion.

The applied laser intensities of a few 10^{16} W/cm^2 in the experiments of laser produced fusion reactions /11/ are higher than the upper limit of Eq.(32c). So a higher thermal effect can be expected at lower intensities and longer laser pulses, because under the present conditions most of the radiation energy should accelerate the surface only in directed way if the interaction times are long enough.

VII) Acknowledgments

References

1   H. Hora, D. Pfirsch, and A. Schlüter, Z. Naturforschung 22a, 278 (1967).

2   A. Schlüter, Plasma Physics 10, 471 (1968).

3   H. Hora, Phys. Fluids 12, No. 1 (1969).

4   H. Hora, Ann. Physik (to be published).

5   P. Javel (to be published).

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

7   P.K. Calw, and A.R. Salat, Phys. Fluids 11, 2223 (1968); R.E. Kidder, Paper at the AIAA Symp. on Laser Produced Plasmas, Los Angeles, Calif., June 24, 1968.

8   F.P. Küpper, Euratom-FOM Rijnhuizen Rep. 68-44 (Febr. 1968).

9   P.E. Faugeras, M. Mattioli, and R. Papoular, AIAA Fluids & Plasma Dynamics Conf., Los Angeles, Calif. June 24-26, 1968.

10   L. Brillouin, Wave Propagation and Group Velocity, Academic Press, New York, 1960.

11   N.G. Basov, S.D. Sakharov, P.G. Krjukov, Ya.W. Senatskij, and S.W. Tschekalin, Lebedev Inst. Rep. 63 (July 1968).

12   J.A. Fleck, Jr., Phys. Rev. Lett. 21, 131 (1968).

13   W.I. Linlor, Appl. Phys. Lett. 3, 210 (1963); Phys. Rev. Lett. 12, 383 (1964); A. Ducauze, G. Tonon, and P. Veyrie, Compt. Rend. 261, 4039 (1965); S. Namba, P.H. Kim, and A. Mitsuyama, J. Appl. Phys. 37, 3330 (1966).

14   N.R. Isenor, Appl. Phys. Lett. 4, 152 (1964); S. Namba, P.H. Kim, T. Itoh, T. Arai, and H. Schwarz, Scientif. Papers of Phys. Chem. Res. (Japan) 60, 101 (1966); in Record of the IEEE 9th Annual Symp. on Electron, Ion and Laser Beam Techn., Berkeley 9-11 May, 1967, p. 86.

15   B.E. Paton, and N.R. Isenor, Can. J. Phys. <u>46</u>, 1237 (1968).

16   B.C. Boland, F.E. Irons, and R.W.P. McWhirter, Proc. Phys. Soc., London 13 (to be published).

17   A.G. Engelhardt, H. Hora, T.V. George, and J.L. Pack, Phys. Fluids (submitted).

18   J.G. Linhardt, A Note on Several Different Approaches to the Problem of Controlled Fusion, Euratom-C.N.E.N., Frascati (1967).

19   A.F. Haught, D.H. Polk, Phys. Fluids <u>9</u>, 2047 (1966).

20   R.G. Tuckfield, and F. Schwirzke, Plasma Physics <u>11</u>, 11 (1969); T.V. George, A.G. Engelhardt, J.L. Pack, H. Hora, and G. Cox, Bull. Amer. Phys. Soc. <u>13</u>, 1553 (1968).
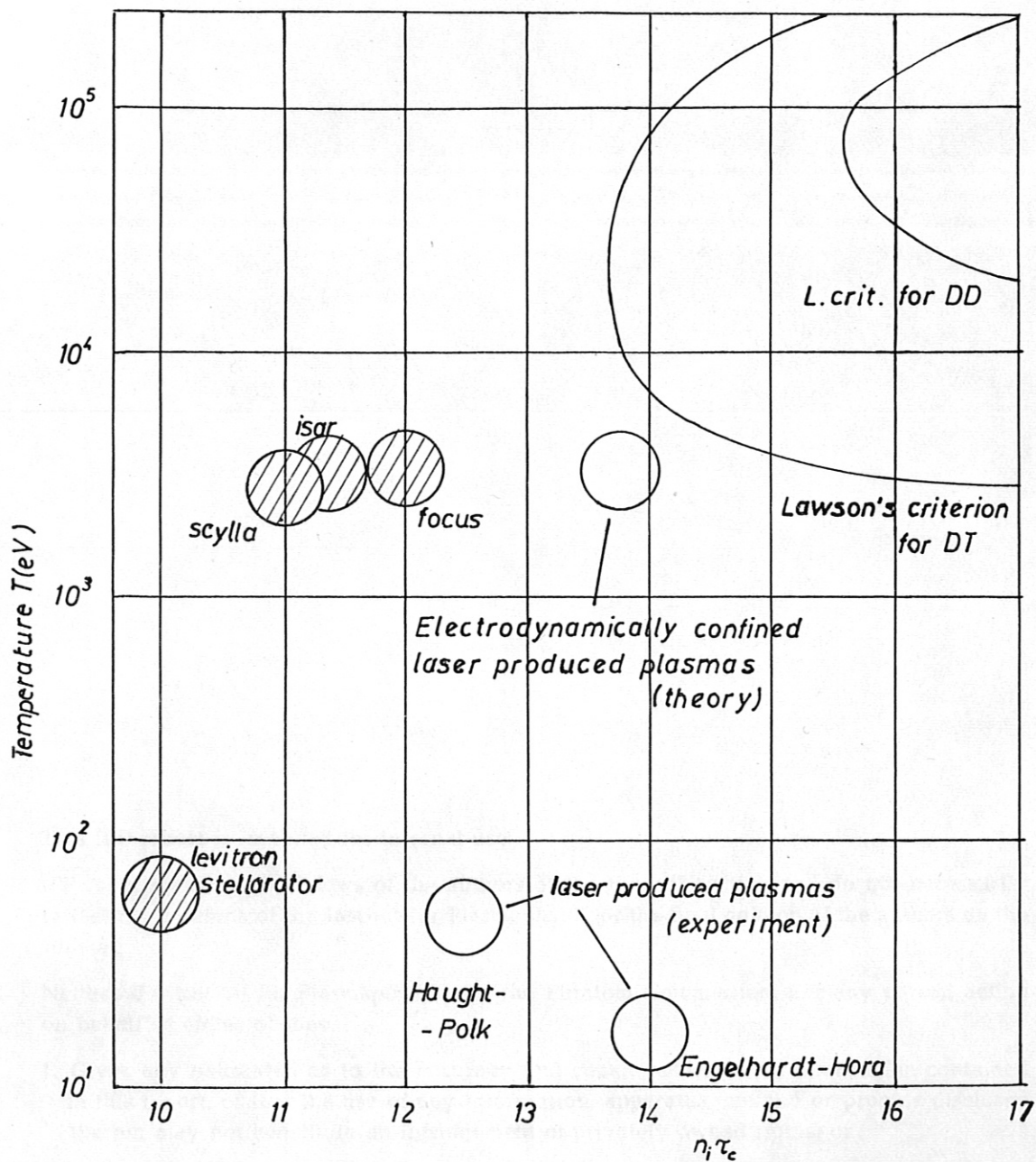
Fig. 1

Diagram to compare temperatures and $n_i \tau_L$-values of plasmas with the Lawson criterion /18/. The experimental values of laser produced plasmas are based on measurements and conclusions on the basis of similarity expansion models for the cases of Haught and Polk /19/ and the evaluated results at Westinghouse (Engelhardt, Hora et al.) /17,20/. The theoretical value is based on the confinement by the nonlinearly increased radiation pressure of a D-T plasma of 5 mm diameter and 1.6×10^{22} cm^{-3} ion density by a 10^5 joule 3 nsec pulse of neodymium glass lasers.