MAX-PLANCK-INSTITUT FÜR PLASMAPHYSIK

GARCHING BEI MÜNCHEN

Optimized Laser Pulses for Pellet Heating at Refuelling Stellarators

(Optimierte Laserpulse bei der Pellet-Heizung zur Füllung von Stellaratoren)

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IPP IV/50 January 1973

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.

IV/50 H. Hora

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ABSTRACT

Refuelling of stellarators with solid pellets of deuterium (or tritium mixtures) has the advantage of an undisturbed motion of the solid material at penetration of the hot magnetoactive plasma. Only ablation processes can disturbe the motion by generating a "comet tail" of plasma. Time constants for the motion of these comet tails are derived. The generation of plasma at a desired point in the stellarator by interaction with a laser pulse is discussed extensively on the base of present experiments and their consistent interpretation. The applicability of the self-similarity model is proved and from this calculated, what laser pulses of optimal duration τ^* for numbers N_o of pellet ions and laser pulses E_o are necessary to generate desired ion energies ε_i , taking into account the transparency of the plasma after passing the cut-off density. Cases for neodymium glass and CO_2 lasers indicate the necessity of short high energy pulses to reach ε_i in the fusion region.

1. INTRODUCTION

The development of high power lasers offers two different applications for solving the problem of controlled thermonuclear fusion: (1) heating of inertially confined plasma and (2) heating of plasma in systems of magnetical confinement. The concept of inertial confinement is of interest only if the laser energy E_o^B for break-even of fast heating of a solid deuterium-tritium pellet can be reduced from its value /1/ of 1.5 M Joule, by application of a laser induced compression to densities 10^4 times than the initial value as calculated by Nucholls, Wood and Teller /2/ and Brueckner /3/, which reduces E_o^B simply /1,4/ by a factor 10^8. The experimental verification of this compression is still open and some aspects to this problem will be touched also by this paper.

The second application which will mainly be discussed here, starts from the success of confining plasma by magnetic fields especially in stellarators /5/ but also with the view of tokomaks /6/, where an increase of confinement times was achieved by the Pfirsch-Schlüter diffusion/7/. While the advances of confinement and heating of the plasma are evident, one of the future technological problems will be the refuelling of the apparatus by deuterium and tritium. One proposed way is to produce spheres of 10 to 100 µ diameter of these solid hydrogen isotopes, accelerate and guide them into the plasma and heat them by a laser pulse at a desired point within the plasma to reach ion energies up to 10 keV.

Besides of the problems of motion of the pellets within the hot magnetoactive plasma of the apparatus, the present knowledge of the laser interaction with the pellet will be discussed and the results of the self-similarity /8,9/ model will be used to find relations for the duration τ^* and energy E_o of the laser pulses to be fired towards the pellet. Obviously a too long pulse will be ineffective if the plasma sphere expands too early to densities below cut-off, when the laser beam crosses the plasma with nearly no absorption. The laser systems available for this purpose at present are neodymium glass lasers and CO_2 lasers. The next interesting iodine laser /10/ has a wavelength close to that of the neodymium glass laser that a separate treatment is not appropriate within the following simplifying assumptions.

II. PROBLEMS OF PELLET INJECTION

If the pellet is injected in vacuum into the magnetic field of the stellarator or any other configuration before any plasma has been generated, the motion will not be influenced. In the case of refuelling when plasma of high temperature and moderate density is present, however, the pellet surface interacts with the plasma. The generated high density plasma of the pellet boundary interacts with the magnetic field as will be shown down within the field. Plasma will be generated behind the moving pellet in the same way as a comet tail, because the surrounding hot plasma has a sufficient electric conductivity.

The details of the ablation mechanism at the pellet boundary are highly complex. From several considerations of Spitzer e.a. /11/, Rose /12/ concluded deviations due to the irrelevant assumption of secondary electron emission coefficients for the pellet which were assumed remarkably larger than unity by Spitzer e.a. While Rose /12/ assumes the main energy transfer to the pellet by plasma electrons, the generation of a Debye sheath at the pellet surface should prevent the penetration of the plasma electrons into the pellet and the ablation should be determined by the ions preferably.

The generation of the comet tail has been observed in the case where a pellet has been injected into the arc plasma of an E x B - machine. The plasma generated at the pellet surface was put into rotation immediately similar to the stationary arc plasma. In this case a comet tail in front of the pellet could be seen /13/. For the comet tail behind the pellet if its velocity $\underline{v}$ is higher than any convection in the hot plasma of the stellarator, the characteristic time τ_c for the slow down process of the ablated surface plasma within the magnetic field $\underline{B}$ can be calculated.

Assuming simplifying a homogeneous pellet plasma, moving with a velocity $\underline{v}$ perpendicularly to a magnetic field $\underline{B}$, then an electric field $\underline{E}$ is generated

$$\underline{E} = \underline{v} \times \underline{B} \tag{1}$$

We assume a sufficient electric conductivity of the resting lower density stellarator plasma which shortcircuits the polarized sides of the plasma. Using the specific electric conductivity σ of the pellet plasma, the current density is $\underline{j} = \sigma \underline{E} = \sigma \underline{v} \times B$ and the time derivative of the ohmic energy density $\mathcal{E}$ is

$$\frac{\partial \mathcal{E}}{\partial t} = \underline{j} \cdot \underline{E} = \sigma \underline{E}^2 = \sigma \underline{v}^2 \underline{B}^2 \tag{2}$$

The distance $\partial \underline{s}$ of the pellet passed during the time ∂t is $\partial \underline{s} = \underline{v}\, \partial t$ and results with the preceding equation at the force density

$$\underline{f} = -\sigma \underline{v}\ \underline{B}^2$$

Using the plasma density $\varrho = m_i n_i$ with the mass m_i and density n_i of the ions, the acceleration $\underline{a}$ is

$$\underline{a} = \frac{\partial \underline{v}}{\partial t} = \sigma \underline{v}\ \underline{B}^2 / \varrho \qquad (3)$$

Solving the differential equation we find an exponential decrease of the plasma velocity within the magnetic field

$$v = \exp(-\ (\sigma/\varrho)\ \underline{B}^2 t) \qquad (4)$$

with a caracteristic time

$$\tau_c = \varrho / (\sigma \underline{B}^2) \qquad (5)$$

Using the electric conductivity of a plasma with a Coulomb logarithm of 10 and a number Z=1 for the number of ionization, the characteristic time is

$$\tau_c = 380\ \varrho / (B^2 T^{3/2})\ \text{sec.} \qquad (6)$$

where MKQS units and T in Kelvin is used. In the cases considered, the electron density $n_e = n_i$ of the ablated deuterium plasma at the pellet surface (pellet plasma) is higher than 10^{16} cm^{-3} and may not exceed that of solid density ($n_i = 10^{22}$). Therefore it can be concluded for reasonable magnetic fields of 10 to 100 k Gauss that the slow down time of the pellet plasma is short enough in dependence on the plasma temperature (Fig. 1).

A further question is that the slow down process causes friction when the ablated plasma moves away from the "comet head" around the pellet sphere. Because of the anisotropy of the viscosity, the final form of initially spherically plasma will be a rotational ellipsoid when heated by the laser pulse. We shall show the applicability of the self-similarity model /8,9/ of interaction. In this case the geometry of the pellet does not change the results principally, as shown by Dawson, Kaw and Green /14/. The processes or retarding the pellet by the viscosity processes will be treated otherwhere /15/.

III. MODELS OF PLASMA HEATING BY LASERS

The interaction of the laser radiation with the pellet has to be distinguished between linear absorption processes of the laser radiation, for which the usual collision processes /16/ or the method of Dawson and Obermann /17/ can be used, - and between nonlinear processes. Nonlinear processes are e.g. the deviation of the collision frequency at high light intensities /18/, anomalous heating or parametric instabilities /19/ and nonlinear acceleration of the plasma boundary by dielectric collisionless interaction with the laser radiation /20/. These processes have thresholds of about 10^{14} W/cm^2 for neodymium glass laser radiation and of about 10^{12} W/cm^2 for CO_2 lasers. However, even below these thresholds self-focussing can occure /21/ which may cause a highly complicated heating process of the irradiated plasma.

A highly transparent numerical model for the hydrodynamic processes in the irradiated plasma and solid pellet was developed by Mulser /22/ for the special case that no nonlinear processes shall occure and the interaction is describable one-dimensionally conserving always plane fronts with perpendicularly incident radiation. Using a one-fluid code for the ion density n_i, the temperature T and plasma velocity v one finds a solution of their dependence on the coordinate x and the time t from the equation of continuity

$$\frac{\partial n_i}{\partial t} + \underline{\nabla}(n_i \underline{v}_i) = 0 \tag{7a}$$

the equation of motion

$$n_i m_i \left(1 + \frac{m_e}{m_i}\right) \frac{d}{dt} \underline{v} = - \nabla n K T \tag{7b}$$

and the equation of energy conservation /23/

$$\frac{\partial}{\partial t} \frac{n_i m_i}{2} \left(1 + \frac{m_e}{m_i}\right) \underline{v}^2 = -\left(\frac{\partial}{\partial t} 2 n_i K T\right) - \varkappa \Delta T + \overline{W}(x,t) \tag{7c}$$

with the Boltzmann constant K thermal conductivity $\varkappa$ and the masses of the deuterium ions m_i and the electrons m_e. The quantity $\overline{W}$ describes the input of laser energy in which variation the spatial distribution of the laser intensity is involved as described by the optical constants of the plasma resulting in the absorption and reflection of the laser light.

The solutions of Eqs. (7) cover very generally the assumed conditions which can be distinguished between two extreme cases: (1) Is the laser beam incident onto a thin foil of deuterium, the thermal conductivity permits a nearly instantaneous distribution of the laser energy to the pellet, and a nearly symmetric expansion of the plasma nearly with a Gaussian density profile occurs.

(2) For thick foils (or bad thermal conductivity), the laser energy is absorbed in the surface region what causes an ablation of the plasma and a shock wave towards the solid material as a reaction of ablation. Similar results were derived by Rehm with a complementary method /24/.

The two extreme cases could also be treated analytically. The shock wave mechanism was describable by similarity solutions /25/, while the case of good thermal conductivity is the solution of the self-similarity model /8,9/. In the case of spherical pellets, this means a homogeneous heating of the whole sphere and an expansion with a linear (radial) velocity profile. The exact derivation of this model from the hydrodynamic equations (7) was shown /23/, analyzing the conditions of averaging the plasma density. At a constant input power $\overline{W}$, distributed always sufficiently fast the whole plasma sphere, the radius of the sphere follows the relation

$$r = \left(r_0^2 + \frac{10}{9} \frac{\overline{W} t^3}{N_i m_i} \right)^{1/2} \tag{8}$$

Non-constant laser power needs numerical treatment, in general. For a constant laser input within a constant focus cross section and varying pellet size, an analytic solution could be derived /23/.

The decision between the two cases may be based on a comparison with experiments. The excellent agreement of the self-similarity model with laser interaction with aluminum spheres /26/ may be caused by the good thermal conductivity of the metal. The special observation of a fast group of plasma with nonlinear properties had to be discussed separately. Similar observations of a fast group are known from Yamanaka e.a. /27/, using LiH-pellets, and an excellent behaviour of the central plasma core according to the self-similarity model in the case of Yamanaka /27/ and in the pioneering work of Haught and Polk /28/ are of more interest because LiH has no metallic properties. One question, however, is the fact that the nearly spherical symmetric expansion of the plasma /28/ can be reproduced only if a taylored pre-pulse is incident /29/. The most interesting results, however, are that of measuring the transmission time of the laser radiation at hydrogen foils /23/, where the rigorous application of the hydrodynamic calculation with the conditions of a shock wave /22/ results in thirty times longer transparency times while the self-similarity model /23/ reproduces the experimental results immediately. Because the treatment of Mulser /22/ is completely exact, the conclusion can be drawn that the assumptions either of Spitzer´s thermal conductivity at that extreme high densities are not applicable or/ and that of the plane fronts are not realized because of self-focusing and a turbulent and homogeneous transfer of the laser energy to the whole plasma. These facts should also be considered for the case of inertially confined laser produced fusion plasmas where the compression effect is based on undisturbed interaction fronts.

Taking into account the complexity of these processes, where nonlinear effects even at the considered low laser intensities can be involved with respect to self-focusing or other observations /31/, or the special behaviour of the two groups of plasma at expansion into magnetic fields /32/, here we can give only a rough calculation of the optimized properties of the laser pulses needed to estimate the parameters for next experiments.

IV. SELF-SIMILARITY MODEL: OPTIMIZED PULSES

Following these considerations it may be justified to base an estimation of laser properties for heating the pellet on the self-similarity model. For this case, always pulses of rectangular shape are assumed as is obvious from the knowledge of negligible reflection of light /26/. The laser power $\overline{W}$ to be transferred into the pellet is assumed constant, what is a consequence of the concluded homogeneous energy dissipation within the sphere. Limitations for very short laser pulse durations τ and large initial pellet radii r_o will be subject of further experiments.

Following Eq. (8), the expansion of the pellet during irradiation up to a certain time τ^* reaches a radius r^*, where the averaged density is the cut-off density n_{eco}. It is one of the not completely understood results of the experiments and their consistency with the theory of the self-similarity model that the energy transfer of the laser works for electron densities n_e of the pellet where the plasma frequency ω_p

$$\omega_p^2 = \frac{4\pi e^2 n_e}{m_e} \tag{9}$$

exceeds the value of the laser frequency ω. For $\omega_p \ll \omega$ the absorption of the laser radiation /16/ in the plasma of the pellet is very low, therefore it can be concluded in agreement with the measurements discussed in the preceeding section, that only laser pulses of a duration when the cut-off density is reached are optimized. With an initial density $n_o = 6 \times 10^{22}$ cm^{-3} of the solid pellet and a cut-off density n_{eco} derived from n_e from Eq. (9) where $\omega_p = \omega$,

$$n_{eco} = \begin{cases} 10^{21}\ \text{cm}^{-3} & \text{for Neodymium glass lasers} \\ 10^{19}\ \text{cm}^{-3} & \text{for CO}_2\ \text{lasers} \end{cases}$$

we find

$$\frac{r^*}{r_o} = \left(\frac{n_o}{n_{eco}}\right)^{1/3} = \begin{cases} 3.91 & \text{for Neodymium glass lasers} \\ 18.2 & \text{for CO}_2\ \text{lasers} \end{cases}$$

The time $\tau^* = t$ in Eq. (8) described the optimized laser pulse duration

$$\tau^* = \left[(r^{*2} - r_o^2) \frac{9 N_i m_i}{10 \bar{W}} \right]^{1/3} \tag{10}$$

where r_o and N_i are related by

$$r_o = \left(\frac{N_i}{m_o} \frac{3}{4\pi} \right)^{1/3}. \tag{11}$$

Using the laser energy E_o transferred to the pellet plasma, the optimum pulse duration is

$$\tau^* = \left[\left(r^{*2} - \left(\frac{3 N_i}{4\pi m_o} \right)^{2/3} \right) \frac{9 N_i m_i}{10 E_o} \right]^{1/2} \tag{12}$$

where Eqs. (10) and (11) have been used.

The Figures 2 and 3 demonstrate the results of Eq. (12) for neodymium glass lasers and CO_2 lasers respectively. For the cases of an ion number N_i (complete ionization assumed; the recombination for low energy pulses at large targets was discussed rigorously by Sekiguchi and Tanimoto /30/), corresponding to an initial pellet radius r_o, we find the optimized pulse length τ^* in dependence on the energy E_o of the laser pulse. The energy of the ions of the pellet ε_i after the laser interaction and after expansion of the plasma is

$$\varepsilon_i = \frac{E_o}{2N_i} \tag{13}$$

where the factor 2 takes into account the energy transferred to the electrons. This ion energy ε_i is expected to be rethermalized when the created plasma is confined by the magnetic field of the stellarator. Figure 4 shows the results in a way as interesting for stellarators: For various ion numbers N_i, the achieved ion energy ε_i is given to evaluate the corresponding input laser energy E_o of the optimized pulse duration τ^*.

It should be noted that the temperature of the laser produced plasma is each lower then ε_i by factors up to 4 and the identification of ε_i with a temperature is possible only after rethermalization in the magnetic field. Only pulses shorter than τ^* preferably with a taylored shape, may produce temperatures up to ε_i and can generate fusion neutrons similarly to the purely inertial confinement, after which processes the fusion at magnetical confinement becomes effective.

Though there are some essential differences, a consideration of the results of filling stellarators with laser produced plasmas from solid targets at the walls may be added /33/, where /34/ the generation of 100 eV ion energies was observed with neodymium glass laser pulses with an energy of up to $E_o = 6$ Joules at effective pulse length of not much longer than 10 nsec. The generation of 100 eV corresponds to 10^{17} ions in Fig. 4 at 10 Joule laser pulses ion temperatures of only 10 eV or less were observed, which possibly indicate a too large number of ions (10^{18}) causing too high densities in the stellarator. A comparison of the results of the self-similarity model used here and as its preference could be demonstrated in the detailed discussion above, with the results of a pure shockwave model of Caruso and Gratton /25/ is possible by the evaluation of that numbers by Büchl /35/ which shows optimized pellet radii of about half the value calculated here. This difference is of a well-known magnitude for cases of the different models.

V. CONCLUSIONS

If the assumptions of the self-similarity model are applicable - as discussed within the present knowledge of experiments and their consistent interpretation -, the concept of filling stellarators with 10^{19} to 10^{20} Ions of energies of 1 to 10 keV will need laser pulses of few keV energy and of pulse durations about 10 nsec for neodymium glass (or iodine) lasers and of about 50 nsec for CO_2 lasers. Intermediate experiments for filling with 10^{18} ions of few 100 eV energy will need pulse energies of about 100 Joules with pulse lengths of 5 nsec for neodymium glass (or iodine) lasers and of 20 nsec for CO_2 lasers.

These laser intensities exceed mostly thresholds for nonlinear effects. These may, however, be of not such influence for refuelling stellarators than in the case of inertial confinement.

FIGURE CAPTIONS

Fig. 1 Slow down time τ_c of Eq. (6) for the high density plasma generated by ablation of the pellet moving in a hot low density plasma with magnetic field B (10 kG (Fig. 1a); 100 kG (Fig. 1b)).

Fig. 2 Optimized laser pulse duration τ^* for heating pellets of a given ion number N_i and a solid pellet radius r_o by laser pulses of an energy E_o for Nd glass lasers.

Fig. 3 Optimized laser pulse duration τ^* for heating pellets of a given ion number N_i and a solid pellet radius r_o by laser pulses of an energy E_o for CO_2 lasers.

Fig. 4 Nomogram relating the optimized laser energy E_o and pulse duration τ^* with the pellet radius r_o or atom number N_i and the resulting ion energy ε_i for neodymium glass or CO_2 laser radiation.

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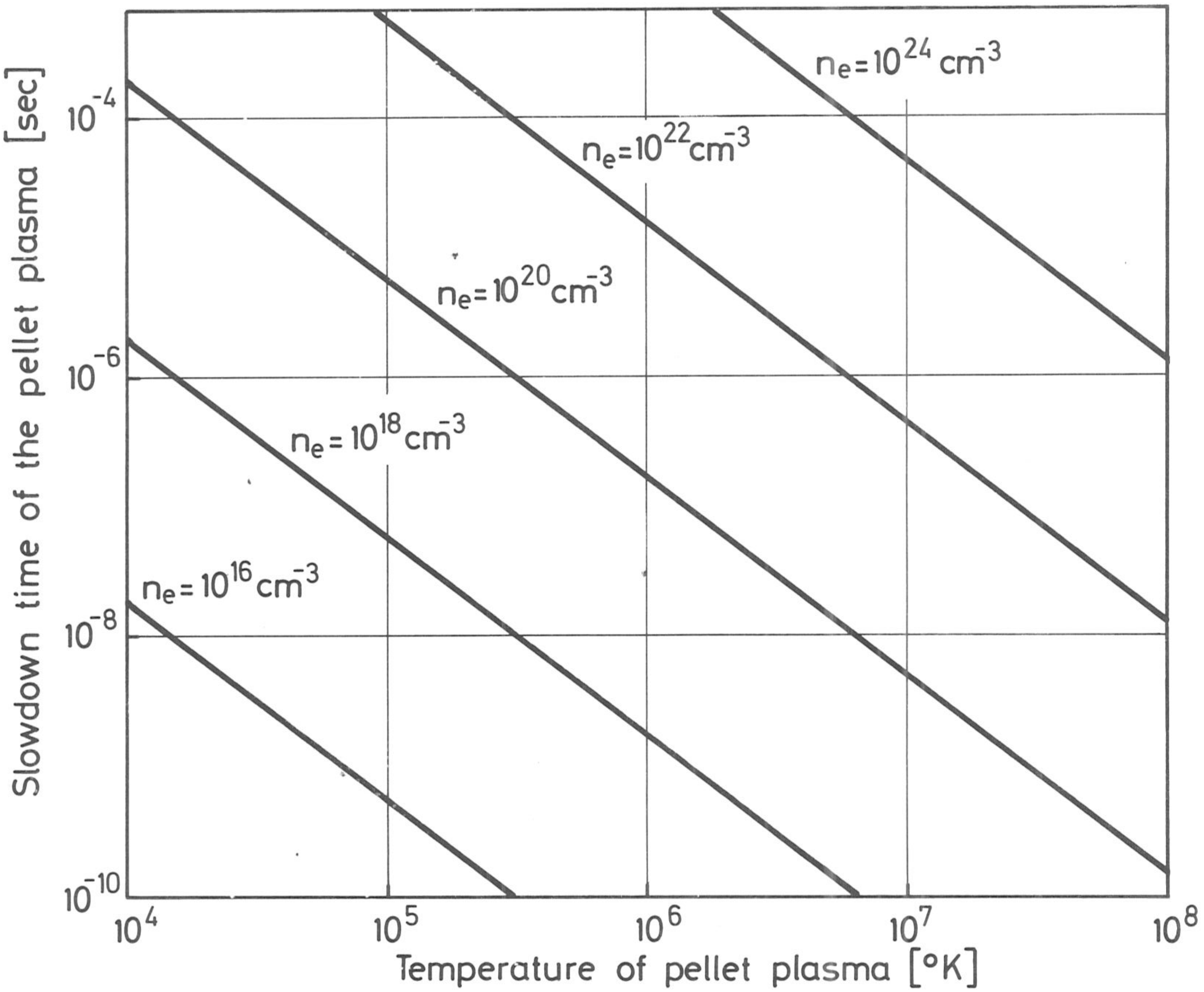
$n_e = 10^{24}\ cm^{-3}$
$n_e = 10^{22} cm^{-3}$
$n_e = 10^{20} cm^{-3}$
$n_e = 10^{18} cm^{-3}$
$n_e = 10^{16} cm^{-3}$
Slowdown time of the pellet plasma [sec]
10^{-4}
10^{-6}
10^{-8}
10^{-10}
10^{4}
10^{5}
10^{6}
10^{7}
10^{8}
Temperature of pellet plasma [°K]

Fig. 1a

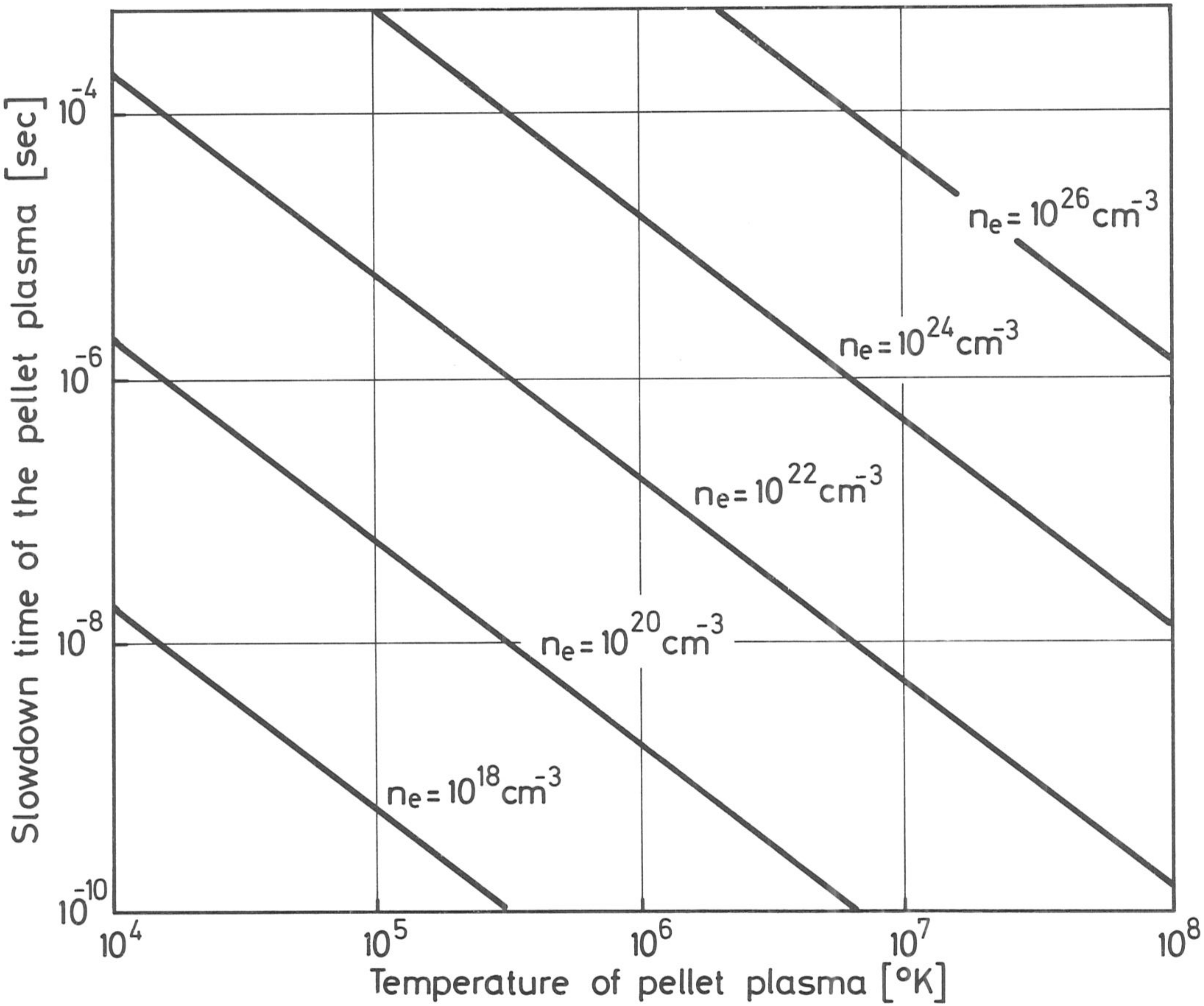
Slowdown time of the pellet plasma [sec]
10^{-4}
10^{-6}
10^{-8}
10^{-10}
10^{4}
10^{5}
10^{6}
10^{7}
10^{8}
Temperature of pellet plasma [°K]
$n_e = 10^{26} cm^{-3}$
$n_e = 10^{24} cm^{-3}$
$n_e = 10^{22} cm^{-3}$
$n_e = 10^{20} cm^{-3}$
$n_e = 10^{18} cm^{-3}$

Fig. 1b

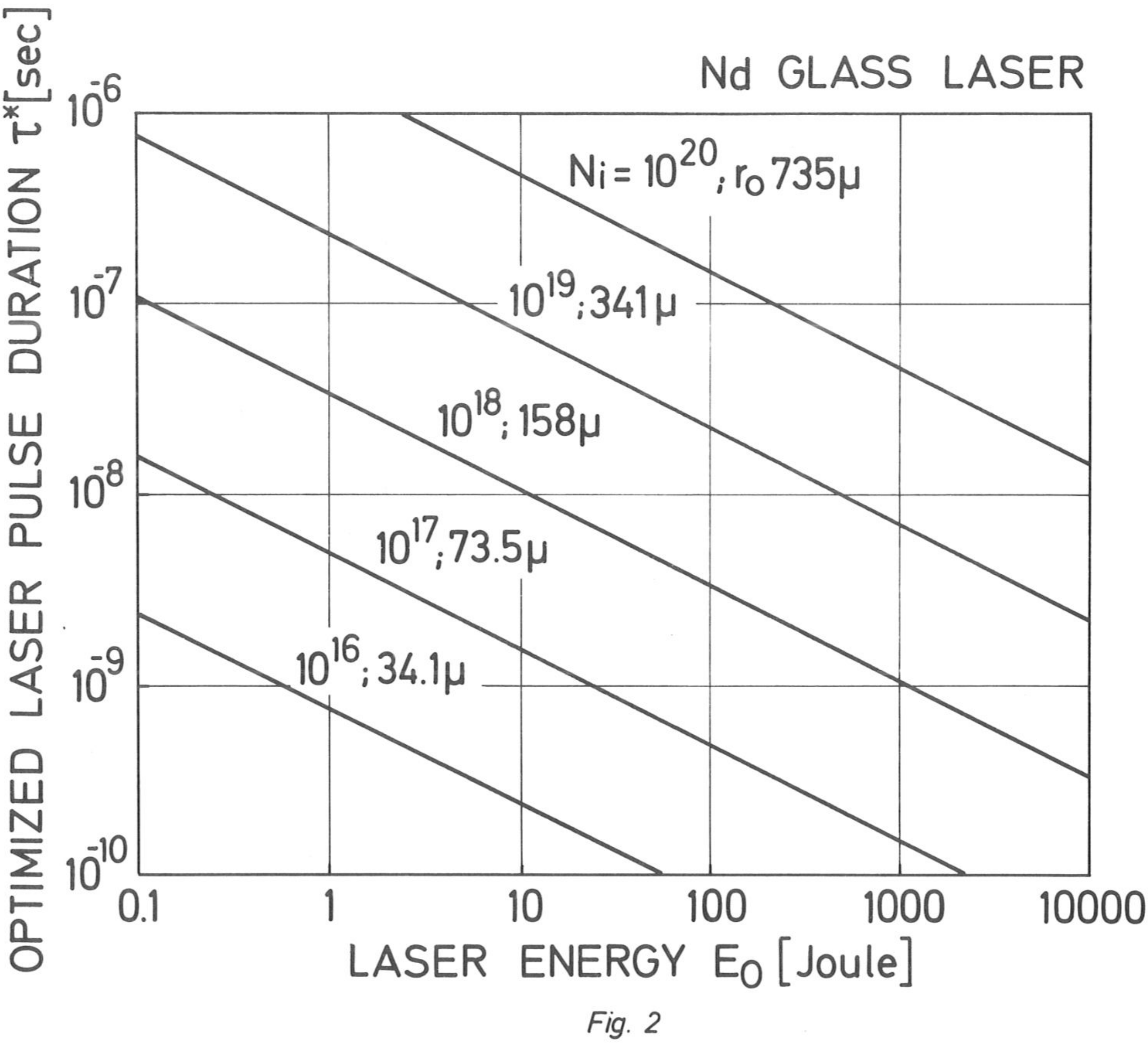
Nd GLASS LASER
OPTIMIZED LASER PULSE DURATION τ*[sec]
10⁻⁶
10⁻⁷
10⁻⁸
10⁻⁹
10⁻¹⁰
Ni = 10²⁰; r₀ 735µ
10¹⁹; 341µ
10¹⁸; 158µ
10¹⁷; 73.5µ
10¹⁶; 34.1µ
0.1
1
10
100
1000
10000
LASER ENERGY E₀ [Joule]

Fig. 2

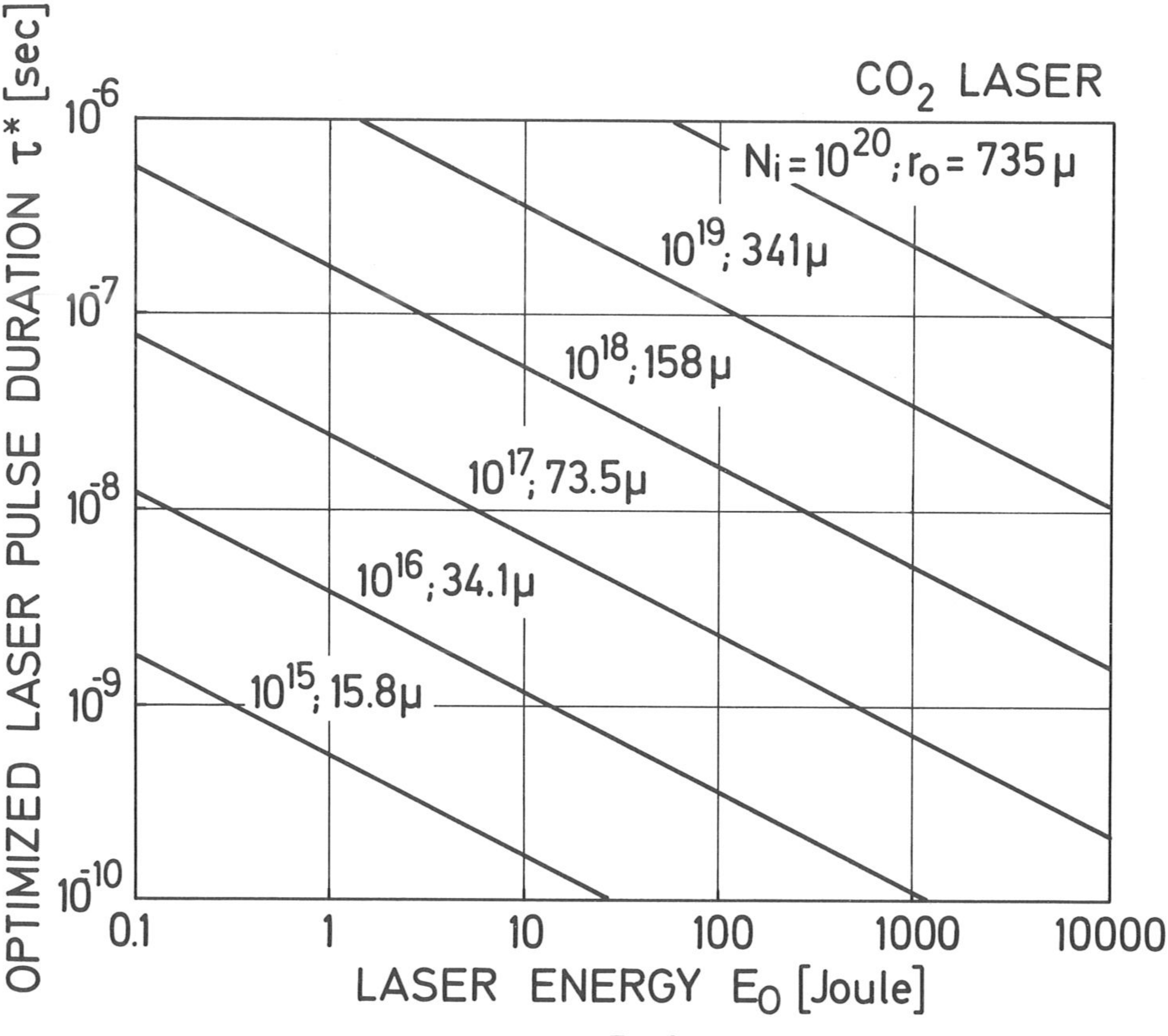
CO$_2$ LASER
OPTIMIZED LASER PULSE DURATION τ^* [sec]
10^{-6}
10^{-7}
10^{-8}
10^{-9}
10^{-10}
0.1
1
10
100
1000
10000
LASER ENERGY E_0 [Joule]
$N_i = 10^{20}$; $r_0 = 735\mu$
10^{19}; 341μ
10^{18}; 158μ
10^{17}; 73.5μ
10^{16}; 34.1μ
10^{15}; 15.8μ

Fig. 3

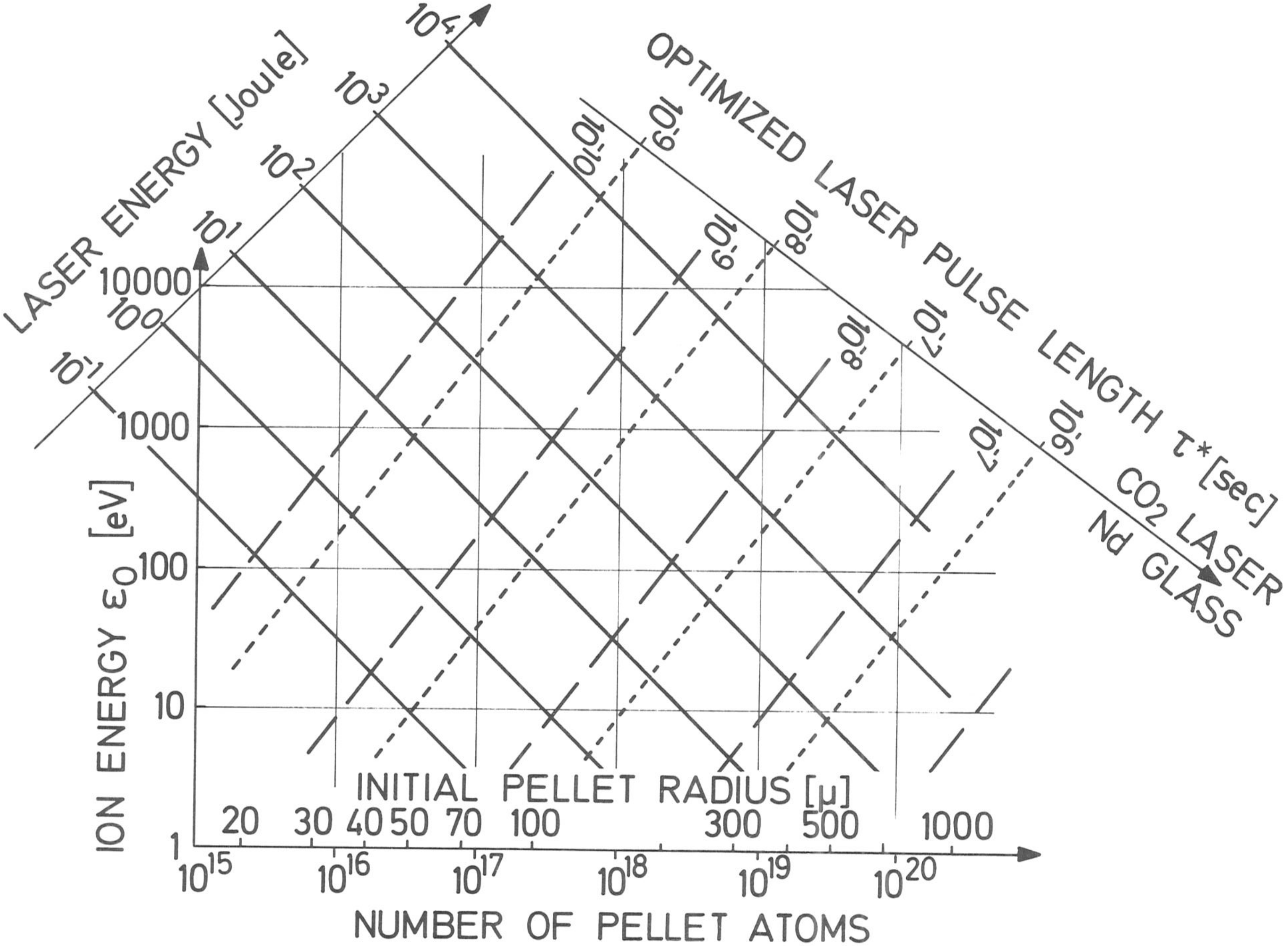
LASER ENERGY [Joule]
10^{-1}
10^{0}
10^{1}
10^{2}
10^{3}
10^{4}
OPTIMIZED LASER PULSE LENGTH τ^* [sec]
10^{-9}
10^{-8}
10^{-7}
10^{-6}
CO$_2$ LASER
10^{-10}
10^{-9}
10^{-8}
10^{-7}
Nd GLASS
ION ENERGY ε_0 [eV]
10000
1000
100
10
1
INITIAL PELLET RADIUS [μ]
20
30
40
50
70
100
300
500
1000
10^{15}
10^{16}
10^{17}
10^{18}
10^{19}
10^{20}
NUMBER OF PELLET ATOMS

Fig. 4