Conversion of laser radiation into fast electrons in the LTF problem

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A simplified version of the "Luch" program was used to compute the target-irradiation regime that makes CO_2 lasers competitive with short-wave lasers.

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The CO_2 lasers have been considered for a long time to be the most probable systems for use in future thermonuclear laser reactors, since their efficiency is high (5–10%) and they are capable of prolonged operation in the repetition-frequency regime. However, recent studies[1-3,5-7] showed that the physics of the interaction of CO_2-laser radiation with the target plasma is highly unfavorable for LTF purposes. Because of the long wavelength of CO_2 lasers and hence low critical plasma density, the absorption of laser radiation is inefficient, and the laser radiation is absorbed only because of the resonance effect, which converts the absorbed energy into fast electrons. As a result, the fraction of absorbed radiation is reduced (compared with Nd lasers) and the hydrodynamic characteristics of the target are drastically degraded, since the fast electrons transfer a large amount of energy to the thermonuclear fuel by heating the entire target, which makes it impossible to obtain a high compression. According to the data of Ref. 4, about 20% of the energy is absorbed at CO_2-laser power of 3×10^3 J, of which 90% is converted into fast electrons with a characteristic temperature of 50 keV. To absorb these electrons, a thick layer of evaporable material must be used in the target (the aspect ratio of the target is $R/\Delta R\approx 2$); as pointed out, this results in poor target hydrodynamic characteristics. According to some estimates, the attainment of the same effect in terms of compression and neutron yield by using CO_2 lasers requires a power that is several times greater (almost an order of magnitude) than that used for Nd lasers.

On the basis of the foregoing discussion, a short-wave laser with a wavelength in the 0.25–0.5-μ range is promising for a thermonuclear reactor. The advantages of such a laser in terms of physics of the interaction of radiation with the target are the high level of absorption due to the inverse braking process, the absence of a penetrating radiation (hard electrons and x-rays), and, most importantly, the high hydrodynamic transfer coefficient η (the fraction of absorbed laser energy that is converted into the kinetic energy of the inward-moving part of the target).[8–10]

The purpose of this paper is to focus attention on the selection of a target-irradiation regime by long-wave lasers (primarily CO_2) for which the fast electrons generated in the corona have an energy (and hence moderation range) at which the energy is liberated only in the outer part of the evaporable target sheath, which includes rather dense layers with above-critical density. The dimensions of the region of energy loss must be optimized for compression and subsequent heating of the target. In this case, there is no preliminary heating of the thermonuclear fuel. Under these conditions the long-wave laser behaves as a short-wave laser, since the fast electrons transfer the energy to the deep, dense layers of the target. An important effect in the analyzed scheme is the reflection of fast electrons from the outer vacuum boundary of the corona. Just as in the case of a short-wave laser, the optimum regime is characterized by an irradiation pulse time that is equal to the target compression time and by moderate fluxes in the 10^{13}–10^{14}-W/cm^2 range.

In absolute terms, the fast electrons are not completely like the short-wave radiation. The most important difference is that the electrons transfer energy to the plasma approximately uniformly in terms of mass,[11,12] whereas the photons transfer energy proportionally to the local density. In the case of electrons, therefore, the target corona is almost isothermal, which is obvioulsy unsuitable for hydrodynamic efficiency.

To verify these effects, we carried out numerical calculations using a simplified version of the "Luch" program. The calculations were performed for a target of DT ice and a light ablator with an aspect ratio of 100, and the absorbed laser radiation energy was about 100 kJ. Figure 1 shows the dependence of the thermonuclear gain coefficient for CO_2-laser irradiation, referenced to the gain coefficient for a Nd laser,

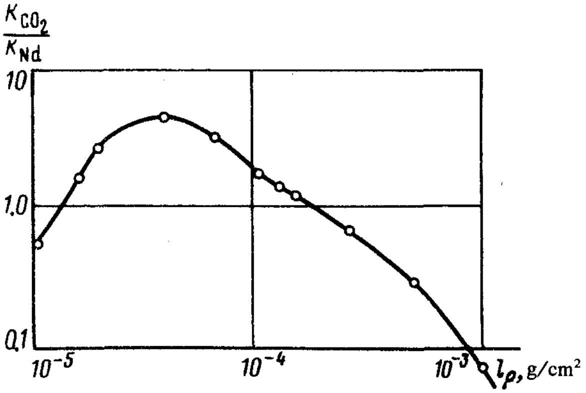

FIG. 1. Ratio of the gain coefficients of the target irradiated by CO_2 and Nd lasers as a function of the moderation range of hard electrons.

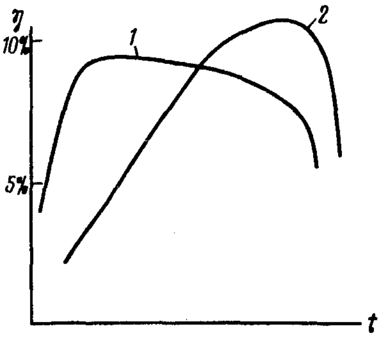

FIG. 2. Hydrodynamic efficiency of the target as a function of time: 1, CO_2 laser, electron range 5×10^{-4} g/cm^2; 2, Nd laser.

on the optical thickness of the region in which the energy is released. The right part of the curve corresponds to uniform heating of the entire target ("explosive" sheath); the left part of the curve corresponds to the energy concentration near the outer boundary. A well-defined maximum, which exceeds the result obtained for an Nd laser is observed, at certain optical thicknesses. Figure 2 shows the dependence of the hydrodynamic-transfer coefficient on time for electrons with a range $l\rho = 5\times10^{-4}$ g/cm^2 and for Nd-laser radiation. Notice the rapid increase of η in the case $l\rho = 5\times10^{-4}$ g/cm^2, which is attributed to the penetration of electrons into the dense layers of the target; this quantity subsequently becomes saturated due to nonoptimum evaporation of the sheath. The deep electron-penetration effect can also be observed in the r,t diagrams of the energy-absorption boundaries and in the electron heat-conduction wave (Fig. 3).

According to the result of Ref. 6, the energy (temperature T_H) of the fast electrons is related to the radiation flux and the wavelength by the relations

$$E_H = T_H = \begin{cases} 7.75\times10^{-10}\,(q\lambda^2)^{2/3} & 10^{11} \leqslant q\lambda^2 \leqslant 10^{15} \\ 1.38\times10^{-3}\,(q\lambda^2)^{1/4} & 10^{15} < q\lambda^2 \leqslant 10^{17}. \end{cases}$$

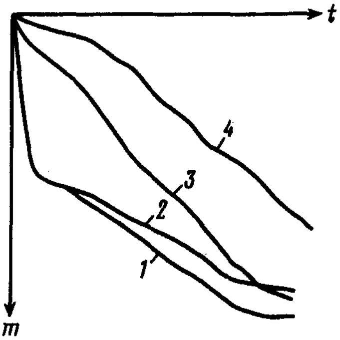

FIG. 3. Thermal-wave zone for target irradiation by CO_2 laser (curve 1, electron range 5×10^{-4} g/cm^2) and by Nd laser (3). Boundary of the energy absorption region (2, CO_2 laser; 4, Nd laser), m is the mass coordinate.

The measurement units are: [q] – W/cm^2, [λ] – μm, and [T_H] – keV. According to Refs. 11 and 12, the electron range before moderation with allowance for scattering is

$$l_p = (3-9)\times 10^{-6}\, T_H^2 \text{ g/cm}^2.$$

The optical thicknesses of 10^{-3}–10^{-4} g/cm^2 correspond to a fast-electron temperature in the 5 to 20-keV range (Fig. 1).

On the other hand, the flux near the critical surface is equal to 3×10^{14} to 3×10^{12} W/cm^2 for a laser pulse energy of $\approx 2\times10^5$ J and duration of ≈ 5 nsec. The temperature of hot electrons for such flux values is in agreement with the aforementioned values of 5 to 20 keV.

Thus, a reasonable choice of target irradiation conditions with a CO$_2$ laser provides the possibility, in principle, of making these lasers competitive with short-wave lasers from the viewpoint of using them in reactors in the LTF problem.

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