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LASER FUSION: CAPITAL COST OF INERTIAL CONFINEMENT

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LASER FUSION: CAPITAL COST OF INERTIAL CONFINEMENT

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ABSTRACT

In the context of laser-induced fusion of solid pellets, a quadratic relation between peak laser power and the inertial confinement parameter ρR is derived and discussed. This relation is combined with the linear relation between laser system cost and peak output power to obtain an estimate of the capital cost of inertial confinement.

INTRODUCTION

In the context of laser-driven fusion, a laser pellet-compressor needs to accomplish two tasks: to bring the thermonuclear fuel to its ignition temperature T_b; and to provide sufficient inertial confinement, *measured by the ρR-product achieved in the fuel*, so that substantial fuel burn-up takes place. *(ρ and R denote the density and radius of the fuel at peak compression.)* Provided the maximum achievable efficiency of fuel burn-up $\epsilon_{max} \ll 1$, both ϵ_{max} and the Lawson confinement parameter $n\tau$ are directly proportional to ρR according to the relations

$$n\tau = \rho R/4M_i c_s, \tag{1}$$

$$\epsilon_{max} \lesssim \rho R/\{(\rho R)^* + \rho R\}, \tag{2}$$

$$(\rho R)^* = [8M_i c_s/\langle\sigma_{DT} v\rangle]_{min} = 7\ g/cm^2, \tag{3}$$

where M_i is the average ion mass, $\langle\sigma_{DT} v\rangle$ is the Maxwell-averaged DT reaction cross section, and c_s is the isothermal speed of sound in the fuel at peak compression.

The laser pulse energy W_L required to raise a mass M (= $4\pi\rho R^3/3$) of thermonuclear fuel (DT) to its ignition temperature T_b can be written

$$W_L(\text{joules}) \simeq 10^9(\rho R)^3 T_b/\epsilon_H \eta^2, \tag{4}$$

where ϵ_H is the efficiency of conversion of laser pulse energy into heat in the fuel, η is the ratio of the fuel density ρ to its normal solid density ρ_o (= 0.2 g/cm³), T_b is in kilovolts, and ρR is in units of grams *per square centimeter*. Taking T_b to be 10 keV and ϵ_H to be 0.03 as typical values, Eq. (4) becomes

$$W_L \simeq 4 \times 10^{11}(\rho R)^3/\eta^2. \tag{5}$$

We note that the laser pulse energy *required to achieve ignition temperature* at a specified value of ρR decreases as the square of the fuel compression η, this being the reason why extremely high fuel compression is required. If for example ρR is to exceed [illegible] g/cm², the minimum value for which spherically divergent thermonuclear propagation can occur, then η must exceed 10^3 if the laser pulse energy is not to exceed 10 kilojoules.

We shall see that a more direct relation exists between the laser pulse power P_L *and the inertial confinement parameter* ρR, at least in the case of isentropic *compression, than exists between the laser* pulse energy W_L and ρR as expressed by Eq. (4). *This* result is particularly useful, because the size and cost of a laser pellet-compressor is also more directly *related to its peak* power capability than to its output pulse energy.

RELATION BETWEEN CAPITAL COST AND OUTPUT POWER OF LASER-COMPRESSION SYSTEMS

The cost C of a large multibeam laser pellet-compression system is *proportional to its rated peak optical output* power P_L, because both the total cost and output power *are proportional to the* number of beams of given aperture, i.e.,

$$C(M\$) = \alpha P_L(\text{terawatts}). \tag{6}$$

The maximum useful power achievable in each beam is limited by nonlinear wavefront distortion accumulated in the laser medium and other optical elements in the beam, and is presently limited to less than 3 x 10^9 W/cm² of beam aperture. The maximum beam aperture is limited by superfluorescence and the disproportionate cost of large-aperture optics.

The coefficient α is currently estimated to be 0.7 M\$/TW, based on the \$17 M cost (excluding building) of the 25 TW neodymium-glass Laser Facility SHIVA now under construction at the Lawrence Livermore Laboratory. It is interesting to note that 25 TW is also the approximate output power of the most powerful of present pulsed electron beam machines, the AURORA Facility at the Harry Diamond Laboratory, White Oak, Maryland.

RELATION BETWEEN ρR AND PEAK OPTICAL POWER

It has been shown[1] that the mechanical power P_M required to homogeneously and isentropically compress an ideal ($\gamma = 5/3$) gas is proportional to the square of the ρR-product achieved by the compression. This result can be obtained very simply by making use of the property of such compressions that the internal energy W_i of the gas being compressed,

$$W_i = 2\pi\rho R^3 c_s^2, \quad (7)$$

doubles in a time τ proportional to the sound transit time

$$\tau \propto R/c_s. \quad (8)$$

The mechanical power supplied is then given by the proportionalities

$$P_M \propto W_i/\tau \propto \rho R^2 c_s^3 = (c_s^3/\rho)(\rho R)^2. \quad (9)$$

However, the factor (c_s^3/ρ) appearing on the right of Eq. (9) is constant along an isentrope, so that

$$P_M \propto (\rho R)^2. \quad (10)$$

If, in addition, we assume that the efficiency with which laser energy can be converted into compressive work does not depend significantly on the ρR-product achieved, we may write the proportionality above in terms of laser power P_L as

$$P_L \propto (\rho R)^2. \quad (11)$$

This result has indeed been derived from more detailed considerations elsewhere, based on a model of self-regulating pellet ablation by hot electrons of the pellet corona, and is supported by detailed computer calculations of the isentropic compression of solid, spherical fuel pellets by the absorption of laser light. These computer calculations also provide the value of the coefficient of proportionality

$$P_L(\text{terawatts}) = \beta\{\rho R(\text{g/cm}^2)\}^2 \quad (12)$$

$$\beta = 300\ \text{TW}/(\text{g/cm}^2)^2. \quad (13)$$

It must be stressed that the simple relation expressed by Eq. (12) is based on assuming the pellet corona to be a collision-dominated, quiescent plasma, an assumption that may well be false unless the wavelength of the laser light is quite short. (A wavelength of 0.265 μm was employed in the computer calculations of Ref. 1.) An alternative model treated by Rudakov[2] considers the corona to be a collisionless, turbulent plasma. This latter model may be more realistic for pellet compression with longer wavelength laser radiation, and according to Rudakov provides less efficient coupling between the laser beam and the compressed pellet core.

CAPITAL COST OF INERTIAL CONFINEMENT

Combining the results of Eq. (6) and Eq. (12), we arrive at the following estimate for the capital cost of a laser pellet-compression system having a given ρR rating:

$$C(\text{M\$}) = \alpha\beta\{\rho R(\text{g/cm}^2)\}^2, \quad (14)$$

$$\alpha\beta = (0.7)(300)\ \ 200\ \text{M\$}(\text{g/cm}^2)^2. \quad (15)$$

Values of estimated capital cost, together with optical power and fuel burn-up efficiency, are listed in Table 1 for selected values of ρR. A ρR-product of 3 g/cm^2 is thought to be required in the application of laser fusion to the production of electric power[3].

SUMMARY AND CONCLUSIONS

A significant property of the results listed in Table 1 is the quadratic increase of system cost with inertial confinement to be achieved. This property is based on a theoretical relation between peak laser power P_L and inertial confinement ρR that applies to the special case of nonturbulent, homogeneous, isentropic pellet compression, and which is as yet untested by experiment.

It is expected that inertial confinement will be largely determined by peak laser power, though perhaps not in accordance with the simple relation we have presented. We believe that an experimental investigation of this important relationship should be undertaken.

Table 1. Capital cost, optical power, and fuel burn-up versus compressor ρR-rating.

Compressor ρR-rating (g/cm^2)	Fuel burn-up (ϵ) (%)	Optical power (P) (TW)	Capital cost (C) (M$)
0.3	4	30	20
1.0	13	300	200
3.0	30	3000	2000

REFERENCES

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1. R.E. Kidder, Nucl. Fusion 14, 797 (1974).

2. L.I. Rudakov, JETP Lett. 19, 376 (1974).

3. J.H. Nuckolls, Laser Interaction and Related Plasma Phenomena, Schwarz and Hora, Eds. (Plenum Press, New York, 1974), p. 399.