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PREPRINT UCRL- 78728

CONF-761140--1

Lawrence Livermore Laboratory

BASIC REQUIREMENTS OF LASER FUSION POWER PRODUCTION AND LASER
FUSION-FISSION PLUTONIUM BREEDING

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September 30, 1976

This paper was prepared for presentation at the
Japan-U.S. Seminar, University of Rochester, Rochester, New York,
November 2-5, 1976.

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Basic Requirements of Laser Fusion Power Production and Laser
Fusion-Fission Plutonium Breeding*

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Abstract

Required values of thermonuclear energy-gain, inertial confinement, laser-pulse energy and power for both electric power production by laser-fusion and for plutonium breeding by laser fusion-fission are obtained from simple considerations, and are tabulated for purposes of comparison.

It is found that breeder requirements are very significantly less demanding, suggesting that plutonium breeding is a much more feasible near-term goal of laser fusion.

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*Work performed under the auspices of the U.S. Energy Research & Development Administration under contract No. W-7405-Eng-48.

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I. INTRODUCTION

A central problem of laser-driven pellet fusion is achievement of the very large thermonuclear energy gain necessary to compensate for the low efficiency of short-pulse lasers and of the fuel-compression process. To achieve the required energy gain with the least amount of laser-pulse energy, a small amount of thermonuclear fuel must be highly compressed; its inertial confinement, measured by its ρR product, must attain a large, specified value. This minimum energy and required ρR product can be estimated by considering a simple model of the ignition and burn of the compressed fuel.^(1,2) It is found that isentropic fuel compression at near-minimum entropy is needed to avoid excessive laser-pulse energy requirements.

An elementary treatment of the hydrodynamics of isentropic compression shows that the ρR product that can be achieved is proportional to the square root of the peak hydrodynamic power expended.⁽³⁾ A more detailed consideration of the pellet ablation process shows that this square-root relation also applies, approximately, to the peak laser power absorbed by the pellet, the coefficient of proportionality being an increasing function of the pellet aspect ratio (inner radius divided by wall thickness).⁽⁴⁾ Thus there is a motivation to employ thin hollow shells, rather than the solid DT spheres originally proposed,⁽⁵⁾ to reduce the peak laser-pulse power required to drive the implosion. The reduction in peak power that can be achieved by this means, however, is limited by fluid instability of the Rayleigh-Taylor type.

We shall apply the relatively simple relations between thermonuclear energy gain, laser-pulse energy, ρR -product, and laser-pulse power to evaluate the basic requirements of laser fusion electric power production and of laser

fusion-fission plutonium breeding. We find that the breeder requirements are very significantly less demanding than those of electric power production.

II. REQUIRED PELLET GAIN

The basic energy-balance equation of a power plant based on laser-driven pellet fusion is

$$\epsilon_{\text{He}} f_e \epsilon_{\text{eL}} f_a G_p = 1 \quad (2.1)$$

where ϵ_{He} is the conversion efficiency of heat into electricity, f_e is the fraction of the total electric power generated that is supplied to the laser, ϵ_{eL} is the efficiency of the laser in converting its electrical input to light output, f_a is the fraction of the light output that is ultimately absorbed by the target pellet, and G_p is the pellet gain; i.e., the ratio of thermonuclear energy produced to the light energy absorbed by the pellet. A typical set of values for these factors might be: $\epsilon_{\text{He}} = 0.4$, $f_e = 0.25$, $\epsilon_{\text{eL}} = 0.10$, $f_a = 0.5$, $G_p = 200$.⁽⁶⁾

It is useful to write the pellet gain, G_p , as

$$G_p = \epsilon_{\text{LF}} G_F \quad (2.2)$$

where ϵ_{LF} is the fraction of absorbed laser light that has been converted into internal energy of the highly compressed core of thermonuclear fuel (DT) at the instant of fuel ignition. A typical value for ϵ_{LF} is 0.05,⁽⁶⁾ so that a fuel gain, G_F , of 4000 would be required to achieve a pellet gain of 200. The fuel gain is defined as the ratio of the thermonuclear energy yield to the internal energy imparted to the compressed core of DT.

III. REQUIRED INERTIAL CONFINEMENT

The inertial confinement necessary to achieve the large pellet gains required for laser fusion can be evaluated by means of a simple model.⁽¹⁾ The model used is that of a uniformly compressed pellet of DT ignited by a small, hot, central "spark." The spark is specified to be large enough and hot enough to ignite the remainder of the compressed fuel via an out-going thermonuclear detonation.

The fuel gain G_F is shown in Figs. 1 and 2 as a function of the inertial confinement parameter H_F denoting the density-radius product ρR of the compressed fuel for a sequence of values of the internal energy W_F supplied to the compressed core ranging from 50 J to 50 kJ. If ϵ_{LF} equals 0.05, and f_a equals 0.5, this corresponds to laser-pulse energies, $W_L (= W_F/f_a \epsilon_{LF})$ ranging from 2 kJ to 2 MJ.

Figure 1 applies to the most favorable case, that of minimum-entropy compression ($\alpha = 1$). Figure 2 applies when twice as much work ($\alpha = 2$) must be done to achieve the same compression. Inspection of Figs. 1 and 2 shows that H_F must amount to 2-3 g/cm² if fuel gains of several thousand are to be realized.

IV. REQUIRED LASER-PULSE ENERGY

Inspection of Figs. 1 and 2 also shows that laser-pulse energies of 200 kJ ($\alpha = 1$) to 1.6 MJ ($\alpha = 2$) are necessary if a pellet gain as large as 200 is to be achieved, again assuming the efficiency ϵ_{LF} to be 5% and f_a to be 50%.

The scaling of the least laser-pulse energy W_L^* required to achieve a desired pellet gain G_p , in terms of the principal factors describing the implosion and burn of the fuel, is found to be ⁽¹⁾

$$W_L^* = (G_p/q_{DT})^{12/5} H_B^{9/5} (A_S/\epsilon_{LF})^{2/5} / \epsilon_C^3 a \quad (4.1)$$

where

$$H_B = 8H_1/a \geq 7 \text{ g/cm}^2 \quad (4.2)$$

$$\sigma = \langle \sigma_{DT} v \rangle / c_s \quad (4.3)$$

$$A_S = T_S(\text{eV}) [H_S(\text{g/cm}^2)]^{3/540} \geq 1 \quad (4.4)$$

Here, M_1 is the average ion mass, c_s is the isothermal speed of sound in DT, $\langle \sigma_{DT} v \rangle$ is the Maxwell-averaged DT cross section, and q_{DT} is the energy of the DT fusion reaction. T_S and H_S are the temperature and ρR of the central ignition spark, respectively.

The factor ϵ_C is the compression efficiency defined as: the least possible work required to achieve a given compression (i.e., isentropically at minimum entropy), divided by the (absorbed) laser-pulse energy actually needed to achieve it. It is proportional to ϵ_{LF}/a , i.e., ⁽¹⁾

$$\epsilon_C \propto (7/5)(\epsilon_{LF}/a) \quad (4.5)$$

Compression efficiencies ϵ_C predicted by detailed implosion calculations are low, typically 1-2%. (Our choice of $\epsilon_{LF} = 0.05$ and $\alpha = 2$ implies that $\epsilon_C \sim 2\%$.)

We note that the laser-pulse energy W_L^* is a strong function of all factors appearing in Eq. (4.1) except the size A_S of the ignition spark.

The value of the confinement parameter H_F^* that minimizes the required laser-pulse energy scales as

$$H_F^* = (H_B^{3/4} A_{SGP} / q_{DT} \epsilon_{LF})^{4/15} \quad (4.6)$$

It is a far less sensitive function of the implosion parameters than is the laser-pulse energy itself.

V. REQUIRED LASER-PULSE POWER

A. Solid DT-Sphere Target

We demonstrate as follows that the mechanical power P_M required to homogeneously and isentropically compress an ideal ($\gamma = 5/3$) gas sphere is proportional to the square of the ρR product achieved by the compression:

$$P_M = 4\pi R^2 \dot{p} u = \underbrace{(4\pi/\gamma)}_{\text{const. } \sqrt{3}} (c_a^3/\rho) M(\rho R)^2 \quad (5.1)$$

$$\propto a^{3/2} (\rho R)^2 \quad (5.2)$$

$M (= u/c_a)$ is the Mach number of the compression, and c_a is the adiabatic sound speed. The quantity c_a^3/ρ is constant along an isentrope and is proportional to $a^{3/2}$.

The Mach number M is determined by our desire to minimize the laser-pulse energy required to drive the implosion, a result that is accomplished by carrying out the compression as rapidly as possible without the formation of shocks. This requires that the Mach number be equal to $\sqrt{3}$ for either homogeneous isentropic compression (HIC: compression-rate uniform throughout pellet volume^(7,8)) or centered isentropic compression (CIC: characteristics arrive simultaneously at the pellet's center^(8,9)).

The time-dependence of the mechanical power P_M required to carry out either HIC or CIC is given (at late times) by

$$P_M \propto (1 - t/t_c)^{-2}, \quad (1 - t/t_c \ll 1), \quad (5.3)$$

where t_c is the asymptotic time of "total collapse" ($= R_0/c_{s0}$ in the case of CIC).

A more detailed treatment that takes into account the nature of the pellet-ablation process⁽³⁾ leads to expressions for the peak laser power P_L , and for the time-dependence of P_L , that are closely similar to those given for the mechanical power P_M by Eqs. (5.2) and (5.3). They are

$$P_L \propto \alpha^{7/6} (\rho R)^{11/6} / f_a, \quad (5.4)$$

and

$$P_L \propto (1 - t/t_c)^{-11/6} / f_a. \quad (5.5)$$

Combining the results of Eqs. (5.4) and (4.6), and identifying H_F^* with ρR , we obtain the following scaling relation for laser-pulse peak power P_L^* ,

$$P_L^* \propto \alpha^{7/6} (H_B^{3/4} A_S G / q_{DT} \epsilon_{LF})^{1/2} / f_a. \quad (5.6)$$

We note that the required laser-pulse peak power is a considerably less-sensitive function of the implosion and burn parameters than is the laser-pulse energy.

B. Hollow DT-Shell Target

In the case of hollow shell targets, the coefficient of proportionality relating P_L and $H_F^{11/6}$ depends on the aspect ratio (t_u) of the unablated portion of the hollow shell; i.e., the aspect ratio of the payload of the

ablation-driven rocket. A semianalytical result, obtained by a best-fit to detailed computer runs of imploded shells with a wide range of aspect ratios (including solid spheres), is⁽⁴⁾

$$P_L(TW) = (160/\Omega f_a) \{H_F(g/cm^2)\}^{11/6}, \quad (5.7)$$

where

$$\Omega = \sqrt{1 + 3\zeta_u}. \quad (5.8)$$

A solid sphere is characterized by $\Omega = 1$. The ζ_u has, therefore, the physical significance of the factor by which the peak laser power can be reduced (by imploding hollow shells with aspect ratio $\zeta_u (\neq 0)$ instead of solid pellets).

We see that there is considerable advantage in imploding hollow shells instead of solid pellets. Not only is the peak power requirement reduced (by the factor Ω), but the intensity of the absorbed light will be lower, leading to reduced excitation of nonlinear optical effects and plasma instabilities, and improved corona-core coupling. However, we expect that the minimum feasible shell thickness will be limited by the growth of fluid instabilities during implosion.

Anticipating the result of the next section that fluid instabilities may limit the minimum shell thickness to aspect ratios $\zeta_u \sim 30$ and reduction factors $\Omega \sim 10$, and using the values $H_F = 2.7 \text{ g/cm}^2$ and $f_a = 0.5$, we obtain from Eq. (5.7) the required peak laser power

$$P_L \sim \begin{cases} 2000 \text{ TW (solid DT-sphere)} \\ 200 \text{ TW (hollow DT-shell)} \end{cases}, \quad (5.9)$$

VI. REQUIRED SHELL THICKNESS

The amplitude of a surface perturbation of a homogeneously and isotropically imploded shell increases, due to Rayleigh-Taylor instability growth, by the factor⁽⁴⁾

$$f_l = \frac{\cosh(\sqrt{l}\chi) - \beta^{2l} \cos(\sqrt{l}\chi)}{1 - \beta^{2l}} \quad (6.1)$$

where

$$\chi = \cosh^{-1} \eta^{1/3}, \quad \beta = R_{10}/R_{20}, \quad (6.2)$$

η is the compression of the shell, and $\beta (< 1)$ is the ratio of the inner and outer shell radii. The surface perturbation is described by the spherical harmonic $Y_{lm}(\theta, \phi)$. Equation (6.2) reduces to the following simple form for large values of η and l ,

$$f_l \approx \frac{1}{2}(8\eta)^{\sqrt{l}/3} (\beta^{2l} \ll 1, \eta \gg 1) \quad (6.3)$$

Application of these results to the question of shell break-up leads to the following limit on the shell aspect ratio τ_u

$$\tau_u < [3 \ln(5 \epsilon_0) / \ln \eta]^2 - 1, \quad (6.4)$$

and on the peak power reduction factor Ω

$$\Omega < 3\sqrt{3} | \ln(5 \epsilon_0) / \ln \eta |, \quad (6.5)$$

where ϵ_0 is the initial fractional surface perturbation amplitude $\delta R_{20}/R_{20}$. If $\eta = 10^4$, and $\epsilon_0 = 2 \times 10^{-5}$, for example, then τ_u must be less than 8 to avoid shell break-up, and Ω can therefore not exceed 5. (Since η and ϵ_0

enter Eqs. (6.4) and (6.5) only logarithmically, these results are relatively insensitive to the values of η and ϵ_0 chosen.)

In obtaining these results we have not taken into account the effects of ablation, viscosity, heat diffusion, or finite density gradient at the fluid surface, each of which will tend to decrease the growth rate of the shorter wavelength modes. This omission appears to be crudely justified by two-dimensional computer simulations of isentropically imploded shells that include the above-named effects.⁽¹⁰⁾ Such simulations exhibit growth rates amounting to 50 to 100% of the Rayleigh-Taylor values for wavelengths considered here ($\lambda \lesssim 10$).

If we assume that the actual growth rate is 50% as large as we have calculated neglecting these effects, then we conclude that the initial aspect ratio of the unablated or payload portion of the shell cannot exceed about thirty, which implies a ten-fold reduction in peak laser power as compared with the peak laser power required to implode solid spheres to the same density.

VII. REQUIRED LASER APERTURE

The useful aperture-averaged output light intensity that a laser is capable of radiating is limited by optical damage to laser materials and/or beam-quality degradation due to nonlinear propagation effects. If, for example, we consider this limiting intensity to be $3\text{-}6 \text{ GW/cm}^2$ as is presently the case for Nd-doped silicate glass,⁽¹¹⁾ then a 20 cm diameter output aperture is capable of radiating 1-2 terawatts of laser power. It follows that the number N_L of 20 cm diameter laser beams that are required to provide the

total peak laser power listed in Eq. (5.9) for pellet compression are

$$N_L \sim \begin{cases} 1000-2000 \text{ beams} & (\text{solid DT-sphere}), \\ 100-200 \text{ beams} & (\text{hollow DT-shell}). \end{cases} \quad (7.1)$$

These numbers clearly indicate the need for optical material capable of transmitting greater light intensity without deleterious effects.

VIII. SIGNIFICANCE OF FUSION-FISSION

The pulse-energy W_L^* and pulse-power P_L^* of Eqs. (4.1) and (5.6), respectively, can be written as

$$W_L^* \propto (A_S/\epsilon_{LF})^{2/5} / \phi^{12/5} \epsilon_C^3 f_a^3, \quad (8.1)$$

$$P_L^* \propto \alpha^{7/5} (A_S/\epsilon_{LF}\phi)^{1/2} / n f_a, \quad (8.2)$$

where

$$\phi = q_{DT} f_{He} f_e \epsilon_e f_a / H_B^{3/4}, \quad (8.3)$$

by eliminating G_p and generalizing P_L^* to the case of hollow shells (divide by Ω).

We note that a significant reduction in required laser-pulse power and a major reduction in laser-pulse energy could be made if the energy q_{DT} released per DT reaction could be substantially increased.

The energy q_{DT} can be increased approximately ten-fold⁽¹²⁾ by adding natural or depleted uranium to the lithium blanket that is needed anyway to breed replacement tritium. The nuclear reactions and energetics, with and without a fissionable blanket, are compared below.

PURE FUSION vs FUSION-FISSION

(22 MeV vs 224 MeV + 2Pu)

$$\text{PURE FUSION: } \text{H}^2 + \text{Li}^6 = 2\text{He}^4 + \underline{22 \text{ MeV}}$$

$$\begin{aligned} \text{FUSION-FISSION: } \text{H}^2 + \text{Li}^6 + 3\text{U}^{238} &= 2\text{He}^4 + \underline{224 \text{ MeV}} \\ (t = \infty) & \\ + \underline{2\text{Pu}^{239}(400 \text{ MeV})} &+ \{\text{Zr}^{90} + \text{Nd}^{145} + 12e\} + n \\ &\text{typical fission products} \end{aligned}$$

In addition to the ten-fold increase in energy produced directly, at least two fissile plutonium atoms can be created per DT-reaction with the potential for providing 400 MeV when burned in a fission reactor. This suggests a fissile-breeder mode of operation with zero net power output. In this mode of operation q_{DT} is increased ten-fold, and f_e is increased four-fold (from 0.25 to 1). We shall take advantage of the four-fold increase in f_e to reduce our assumed laser efficiency to 2.5%. The factor ϕ appearing in Eqs. (8.1) and (8.2) is then increased 10-fold, assuming that other quantities remain unchanged. The result is a 3-fold reduction in required peak laser power (to 60 TW) and a 250-fold reduction in required laser-pulse energy (to 6 kJ).

Since it may be more important to reduce pulse-power than to minimize pulse-energy, it may be desirable to operate at points in Fig. 2 other than the locus of curve-maxima. For example a fuel-gain of 400 is also obtained with $W_F = 500 \text{ J}$ and $H_F = 1 \text{ gm/cm}^2$, corresponding to a pulse-energy of 20 kJ and a pulse-power of 30 TW.

The requirements of pure-fusion electric power production and of fusion-fission plutonium breeding are summarized in Table I below.

Table I. Requirements^a for pure-fusion electric power production and fusion-fission plutonium breeding.

	Power Production	Plutonium Breeding
Laser-pulse power P_L (TW)	200	60 (30)
Laser-pulse energy W_L (kJ)	1,600	6 (20)
Laser efficiency ϵ_{eL}	10%	2.5%
ρR (g/cm ²)	2.7	1.5 (1.0)
Pellet gain G_P	200	20

^aAssuming 30:1 aspect ratio hollow DT-shell target

($\tau_u = 30$), compressive work equals twice minimum entropy value ($\alpha = 2$), 50% of laser output absorbed by pellet

($f_a = 0.5$).

IX. SUMMARY AND CONCLUSIONS

We conclude that a 200 terawatt, 1.6 megajoule, 10% efficient ($\epsilon_{eL} = 0.1$) laser may be required for practical ($\epsilon_{He} = 0.4$, $f_e = 0.25$) laser-fusion power production. In arriving at this conclusion we have assumed that half the laser output is ultimately absorbed ($f_a = 0.5$) by a hollow DT-shell target having a 30:1 (unablated) aspect-ratio ($r_u = 30$), and that the fuel-compression is accomplished within a factor of 2 of minimum entropy conditions ($\alpha = 2$) with an efficiency of 2% ($\epsilon_c = 0.02$). The uncertainty of our estimate of required pulse-energy (1.6 MJ) is considered to be much greater than that of our estimate of required pulse-power (200 TW), since it depends much more sensitively on implosion parameters whose values are uncertain.

We have also shown that these very onerous projected laser requirements are importantly relaxed in the case of a zero net power ($f_e = 1$) plutonium breeder. Here it appears that a 2.5% efficient laser providing 30 TW, 20 kJ pulses may suffice, requirements that are clearly far easier to meet.

It also should be noted that nothing has been said about the wavelength-dependence of these laser requirements. The values of the important parameters f_a , ϵ_c , and α all depend on the details of the light-plasma interaction and therefore are surely wavelength-dependent. There is, however, little agreement at present about this important dependence either theoretically or experimentally. The values we have employed are those that generally describe the results of one-dimensional, three-temperature, optimized computer runs with 0.25-1 micron laser light. Since these runs do not include hot-electron preheat, corona-core decoupling, anomalous electron transport, hot ion ejection, spontaneous magnetic fields, nonuniform illumination, etc., our values are almost certainly optimistic, perhaps grossly so.

We believe that the much-less-demanding requirements of the fusion-fission breeder, together with economic considerations (why use valuable 14 MeV neutrons merely to produce heat?), indicate that breeder development should be considered as the interim goal of laser fusion. (It tends to be forgotten that the possibility of plutonium breeding was an important motivation of the early CTR program, and the principal reason that the CTR program was originally classified.)

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FIGURE CAPTIONS

- Figure 1. Fuel-gain G_F versus inertial confinement parameter H_F for fuel-energies W_F of 50, 160, 500, 1600, 5000, 16000, and 50000 joules, assuming minimum-entropy compression ($\alpha = 1$).
- Figure 2. Same as Fig. 1 but with $\alpha = 2$. (Twice as much work must be done to achieve the same compression η .)

Figure 1

Figure 2