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Consequences of Intensity Constraints on Inertial Confinement Fusion

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Consequences of Intensity Constraints

on

Inertial Confinement Fusion*

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ABSTRACT

It is shown that the conflicting requirements of high implosion efficiency ([illegible] corona temperature) and adequate energy transport (high corona temperature) can, together with other effects, limit useful infrared light intensities to values on the order of 100 Tw/cm^2. Increased interest in ultraviolet lasers, for which this intensity constraint is expected to be less severe, and the entry of charged-particle drivers in the inertial confinement fusion (ICF) competition are consequences of this limitation.

Analytical results based on a simple model are presented which show how the gain of an ICF target is modified by the existence of an arbitrary intensity constraint.

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1. INTRODUCTION

In 1962 it was estimated that DT ignition by laser-driven implosion would require a pulse energy of 100 kJ (at 0.69 μ) and an intensity on target of 500 Tw/cm^2 [1]. These requirements, though far beyond the state of the art at that time, were deemed feasible, with the result that a research program with this objective in view was begun at Livermore.

Progress in laser development led to the availability in 1967 of focused intensities as high as 10^5 Tw/cm^2 (at 1.06 μ) [2]. Theoretical calculations predicted that intensities in the range $10-10^5$ Tw/cm^2 would be capable of exciting a large variety of light-driven plasma instabilities and other nonlinear effects, including the generation of anomalously energetic suprathermal or "hot" electrons [3-7].

In 1971, experiments at Livermore indicated that a hot-electron component with an apparent temperature of 40-50 keV was being generated in a 1-2 keV CD_2 plasma at an intensity of 200 Tw/cm^2 (at 1.06 μ) [8-9]. These experiments also suggested that stimulated Brillouin scattering, for which the threshold intensity was estimated to be approximately 10 Tw/cm^2 [9], was responsible for the observed back-reflection of the incident laser light.

Although the prospects of utilizing such high light intensities did not seem favorable in view of the existing theoretical and experimental picture, it was nonetheless proposed in 1972 that intensities on the order of 10^5 Tw/cm^2 might be used to achieve 10,000-fold compression and central ignition of a bare droplet of liquid DT [10]. The authors of this proposal advised that "the Basov (Soviet) team is likely to reach the so-called break-even point within the next year, slightly ahead of the

Americans" [11]. KMS Fusion Inc. advised its shareholders: "Your company predicted to the U. S. Atomic Energy Commission that it would reach breakeven in energy before December 31, 1973" [12].

At the same time that these sanguine predictions were being broadcast, it was pointed out that the transport of energy within the laser-heated plasma might be limited to a value nearly two orders of magnitude less than had been previously assumed [13]. This effect, which has been observed experimentally, together with the generation of hot electrons, corona-core decoupling [14], and the excitation of various plasma instabilities, act to limit the focused intensity that can be effectively used to drive implosions. A result of these limitations is that the "breakeven" predicted with a kilojoule of light in 1973 is now thought to require at least 100 kilojoules, focused to an intensity of a few hundred terawatts/cm^2, values remarkable similar to those initially estimated in 1962.

The focused light intensity that can be effectively used to drive implosions is clearly a matter of primary importance to laser-driven fusion. In this paper we shall consider the factors that limit that intensity, the limits they impose, and the consequences of these limits for inertial confinement fusion generally.

2. INTENSITY CONSTRAINTS

The least laser pulse energy W_L (joules) required to achieve a "pellet gain" G_p by imploding and centrally igniting a DT target is given by [15]

$$W_L = (G_p/115)^{12/5} \alpha^3/\varepsilon_{LW}{}^{17/5} \quad \text{joules}, \qquad (1.1)$$

where α is the ratio of the internal energy of the compressed DT to that which would result from isentropic compression at minimum entropy, and ε_{LW} is the ratio of internal energy W_F (of compressed DT) to laser pulse energy. The "pellet gain" is defined as the ratio of the thermonuclear energy yield W_{TN} to the energy of the laser pulse W_L.

The property of this result to which we wish to draw attention is its sensitivity to the efficiency ε_{LW} with which the laser pulse energy is converted to internal energy W_F of the DT fuel. A factor of two reduction in the efficiency ε_{LW} results in a ten-fold increase in the laser pulse energy required to achieve the same gain. It is therefore important that the implosion be efficient.

An estimate of the efficiency of a laser-driven implosion is provided by the efficiency ε of a "rocket" ablatively propelled by a steady, planar isothermal expansion. This efficiency is easily found to be-

$$\varepsilon = (\beta/2)^2/(e^{\beta} - 1) \quad , \qquad \beta = 2u/c_i \quad , \qquad (1.2)$$

$$c_i = (2.2 \times 10^7) \sqrt{T_e(\text{keV})} \;\; \text{cm/sec} \; (Z = 2A >> 1) \quad , \qquad (1.3)$$

where u is the velocity of the "rocket", i.e., imploding shell, and c_i is the exhaust velocity, i.e., isothermal sound speed. The isothermal expansion is actually spherical rather than planar, and for this reason the efficiency will be overestimated by Eq. (1.2). This overestimate can be severe if a substantial part of the absorbed laser light is wasted in maintaining the isothermality of a divergent supersonic flow.

If the efficiency ε as given by Eq. (1.2) is to exceed 10%, for example, then

$$c_i \le (2.23)u \quad , \qquad (\varepsilon \ge 0.1) \quad . \tag{1.4}$$

If we assume a typical implosion velocity u of 3×10^7 cm/sec, it follows from Eqs. (1.3) and (1.4) that

$$T_e < 9 \text{ keV} \quad , \qquad (\varepsilon \ge 0.1, \quad u = 3 \times 10^7 \text{ cm/sec}) \quad , \tag{1.5}$$

that is, if we are to achieve adequate propulsive efficiency, the temperature of the laser-heated corona must be limited.

The maximum power density that can be transported by the electrons of a plasma is the saturated intensity

$$F_{sat} = n_e[2(kT_e)^3/\pi m]^{\frac{1}{2}} \quad . \tag{1.6}$$

Bickerton [13] first pointed out that this result may overestimate the maximum achieveable power density by a factor ~ 60 ($= \sqrt{M/Zm}$) if the velocity of thermal energy transport is limited to the ion acoustic velocity by the unstable excitation of ion sound, a possibility that arises when $ZT_e >> T_i$ as is often the case. Recent experimental results are consistent with transport inhibition factors of this magnitude [16].

If we assume a transport inhibition factor of 60, then the maximum power density F that can be transported to the ablation front from the critical surface is

$$F = (1/60)F_{sat}(n_e = n_{ec}) = (3.15)T_e^{3/2}(\mathrm{keV})/\lambda_L^2(\mu) \qquad (1.7)$$

$$\lesssim 85\ \mathrm{Tw/cm}^2 \ ; \quad T_e < 9\ \mathrm{keV} \ , \quad \lambda_L > 1\mu \ ,$$

where the critical electron density n_{ec} is given by

$$n_{ec} = \pi/r_o\lambda_L^2 \qquad (r_o = e^2/mc^2) \qquad (1.8)$$

for light of wavelength λ_L.

The efficiency ε will therefore be less than 10% if the absorbed infrared ($> 1\mu$) light intensity is as great as 85 Tw/cm^2, a limit based on the conflicting requirements of adequate energy transport and low "rocket" exhaust temperature. The wavelength dependence exhibited in Eq. (1.7) suggests that the same 10% efficiency might be achieved at a 10-fold greater intensity if ultraviolet light (1/3 μ) were used instead of infrared light (1.06 μ).

This intensity constraint based on the need for efficient ablative implosion, together with other intensity constraints imposed by plasma instabilities, hot electron generation, self-focusing, corona-core decoupling, etc., suggests that light intensities useful for driving implosions may be limited to values less than $\sim$ 100 Tw/cm^2 (at 1.06 μ or greater) [17]. More generally, we shall assume that the maximum useful light intensity is I_L, and examine the consequences of this assumption.

3. LEAST MECHANICAL POWER DENSITY NEEDED TO ACCELERATE A THIN SHELL TO A SPECIFIED VELOCITY

We consider a thin, hollow, spherical shell of solid DT fuel with an initial density ρ_0(= 0.2 g/cm^3) and aspect ratio ζ(= $R_0/\Delta R_0$ >> 1). The mechanical power density I_F transmitted into this shell is the product pu of pressure and velocity at the outer surface of the shell. The least peak mechanical power density needed to implode the shell to a desired velocity u is achieved when I_F is constant in time. An elementary calculation :ows this least value to be

$$I_F = \rho_0 u^3/\zeta \quad . \tag{3.1}$$

The efficiency with which the incident light intensity I_L is converted into mechanical intensity I_F supplied to the fuel will be denoted by ε_{LI}. This efficiency will usually be comparable to the efficiency ε_{LF} with which light energy W_L is converted into internal energy of the compressed fuel, i.e.,

$$I_F = \varepsilon_{LI} I_L \ , \quad W_F = \varepsilon_{LW} W_L \ , \quad (\varepsilon_{LI} \sim \varepsilon_{LW}) \quad . \tag{3.2}$$

For example, if ε_{LW} = 0.05 (half the incident light is absorbed and the implosive efficiency is 10%), then a laser intensity I_L of 400 Tw/cm^2 is required to accelerate a solid DT shell, having an aspect ratio of 27, to an implosion velocity of 3 × 10^7 cm/sec.

4. LEAST PULSE ENERGY NEEDED TO ACHIEVE IGNITION

The mean internal energy (per gram of fuel) of the imploded fuel at ignition time is the sum of the energy w_S needed to create the central ignition "spark" and the energy w_C required to compress the fuel. This energy is approximately equal to the maximum specific kinetic energy attained by the shell during implosion, i.e.,

$$w = w_S + w_C \simeq u^2/2 \quad . \tag{4.1}$$

The energy of compression w_C is, for DT,

$$w_C = \alpha w_0 \eta^{2/3} \quad , \qquad (\eta = \rho/\rho_0 >> 1) \quad , \tag{4.2}$$

where the constant w_0 equals 0.178 MJ/g for DT, and α is defined as in Eq. (1.1).

The ignition "spark" energy w_S is

$$w_S = f_S e_S \quad , \qquad f_S = M_S/M = (H_S/H)^3 \quad , \tag{4.3}$$

where ϵ_S (= 116 T_S (keV) MJ/g for DT) is the internal energy of the spark, f_S is the fraction of the total fuel mass M encompassed by the spark, and H and H_S denote ρR and ρR_S of the fuel and spark, respectively.

The total internal energy W_F in the compressed fuel can be written as follows in terms of H^3

$$W_F = (4\pi w/3\rho^2)H^3$$
$$= (4\pi w/3\rho_0{}^2)(\alpha w_0 H/w_C)^3 \quad . \tag{4.4}$$

The quantities w and w_C can be eliminated from Eq. (4.4) using the relations

$$w_C = w - (e_S H_S^3)/H^3 \quad , \tag{4.5}$$

$$w = (\zeta I_F/\rho_0)^{2/3}/2 \quad , \tag{4.6}$$

so that W_F is expressed in terms of H, the ρR of the compressed fuel.

The least energy $(W_F)_{MIN}$ we needed to achieve fuel-ignition is obtained by minimizing $W_F(H)$, given by Eqs. (4.4-4.6), with respect to H. The result obtained is that

$$(W_F)_{MIN} = 2\pi(8/3)^4(\alpha w_0)^3 e_S H_S^3/(\zeta I_F)^2 \tag{4.7}$$

when H equals H_{MIN}

$$H_{MIN} = 2(e_S H_S^3)^{1/3} \, (\rho_0/\zeta I_F)^{2/9} \quad . \tag{4.8}$$

$W_F(H)$ also has the property

$$W_F \xrightarrow[H \to H_\infty]{} \infty \quad , \qquad H_\infty = H_{MIN}/2^{2/3} \quad , \tag{4.9}$$

which implies that the conditions specified cannot be simultaneously satisfied at any finite energy W_F if $H \leq H_\infty$.

The properties of the ignition spark are contained in the factor $e_S H_S^3$ appearing in Eqs. (4.7) and (4.8). To ensure ignition, this factor should not be less than $\sim 6 \times 10^{14}$ cgsu, corresponding to a spark temperature T_S of 20 keV and spark H_S of 0.3 g/cm^2 [15].

We note that the least fuel-energy needed to achieve ignition <u>decreases as the square</u> of the mechanical intensity I_F delivered to the fuel, according to Eq. (4.7). A restriction to lower light intensities therefore implies a requirement for strongly increased light-pulse energy to achieve ignition and burn.

We also note that $(W_F)_{MIN}$ decreases with the square of the aspect ratio ζ. The ratio α, however, tends to increase with ζ, the least values achieved in a series of WAZER computer program [18] runs, spanning a large range of aspect ratios, being given by [19]

$$\zeta \approx 3\alpha^3 \quad . \tag{4.10}$$

If this effect is accounted for, $(W_F)_{MIN}$ still decreases with increasing ζ, but only as the first power.

5. INFLUENCE OF INTENSITY CONSTRAINTS ON PELLET GAIN

The "fuel gain" G_F is shown in Fig. 1 as a function of H, the ρR of the compressed fuel. G_F is related to the "pellet gain" G_p according to

$$G_p = \varepsilon_{LW} G_F \quad , \tag{5.1}$$

the "pellet gain" denoting the ratio of the thermonuclear energy yield to the energy of the incident laser pulse. The solid curves show G_F versus H for a sequence of values of the fuel energy W_F, and are taken directly from Fig. 2 of Ref. [15] where the details of their derivation is described. The curves apply to the case in which the parameter α, defined in Section 2 above, is assumed equal to 2. The solid straight line appearing in Fig. 1 represents the limit of G_F vs H as W_F tends to infinity.

The dashed curves shown in Fig. 1 show G_F vs H for three values of the mechanical intensity I_F. They are obtained by substituting $W_F(I_F)$ given by Eqs. (4.4)-(4.6) into the relations defining $G_F(H;W_F)$ in Ref. [15], and apply to the case in which the aspect ratio ζ of the fuel-shell equals 24. The three values of I_F were chosen so that $(W_F)_{MIN}$ equals 50, 1600, and 50,000 joules, with the result that the dashed curves are tangent to the solid curves having these values of W_F.

To translate the results shown in Fig. 1 into laser pulse energy W_L and intensity I_L, it is necessary to specify the conversion efficiencies ε_{LW} and ε_{LI}. If we assume 50% light absorption and 10% efficiency in converting absorbed light energy into fuel internal energy, then ε_{LW} equals 0.05. The energies W_F listed in Fig. 1 should therefore be multiplied

20-fold to obtain the corresponding laser pulse energies W_L, which then range between one kilojoule and one megajoule. If ε_{LI} equals ε_{LW}, then the listed values of I_F should similarly be multiplied 20-fold to obtain the light intensities I_L that apply to the dashed curves (A), (B), and (C), namely

(A) 3.5×10^{14}

(B) 2.0×10^{15} (w/cm^2)

(C) 1.1×10^{16}

We see that if central ignition and burn are to be accomplished with as little as one kilojoule of laser light the light intensity used must exceed 10^{16} w/cm^2 (with $\zeta = 24$), and the maximum pellet gain G_p achievable at this energy is approximately 10. These conditions are reminiscent of those postulated to provide "breakeven at a kilojoule" in the early 70's.

On the other hand, if effects such as those considered in Section 2 should limit the useful light intensity to less than 3×10^{14} w/cm^2, then at least one megajoule of laser light will be needed to achieve ignition and burn under the conditions we have specified. However, the pellet gain that is required for commerical electricity generation via pure-fusion ($G_p > 200$) then becomes potentially possible.

6. SUMMARY AND CONCLUSIONS

Limitations on useable light intensity (at 1.06 μ or greater wavelength) have resulted in increased light-pulse energy requirements for laser-driven fusion. Breakeven is no longer thought possible at a kilojoule. Indeed, current estimates are that breakeven will require pulse energies in the range 100-400 kilujoules, to be provided by the SHIVA-NOVA facility in the early 1980's. These considerations have led to increased interest in shorter wavelength lasers, such as KrF (0.250 μ) and XeCℓ (0.306 μ) for which focused intensity constraints are expected to be less severe.

The limitation of useable light intensity to a few hundred terawatts/cm^2 has allowed charged-particle drivers, especially ion beams, to enter the ICF competition, since it is projected that such intensities may be achievable with these drivers. These drivers can also more readily provide the multi-megajoule pulses that appear to be needed for commercial ICF, have high energy-conversion efficiency, demonstrated pulse repetition rate capability (in the case of heavy ion drivers), and appear to enjoy markedly superior target-coupling characteristics.

Heavy-ion accelerators are projected to be capable to achieveing sufficiently low emittance at high power that their beams, like laser beams, can be focused to high intensity in vacuum at the stand-off distances required for ICF reactor survival. They are late entries in the ICF race, but at the moment seem to show considerable promise for the commerical production of ICF power, and for the breeding of fissile fuels [20].

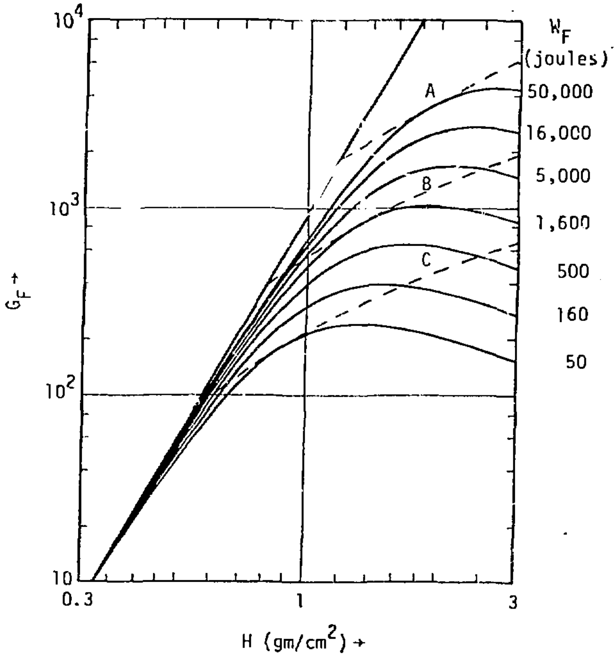

Fig. 1

Fig. 1 Fuel gain G_F versus inertial confinement parameter H for fuel energies W_i of 50-50,000 joules (solid curves), or for mechanical intensities I_T of $1.70\times10^{[illegible]}$ (A), 9.83×10^{13} (B), 5.56×10^{14} (C) watts/cm^2 (dashed curves).

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