Laser Compression of Matter to Super-High Densities: Thermonuclear (CTR) Applications

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Hydrogen may be compressed to more than 10,000 times liquid density by an implosion system energized by a high energy laser. This scheme makes possible efficient thermonuclear burn of small pellets of heavy hydrogen isotopes, and makes feasible fusion power reactors using practical lasers.

THERMONUCLEAR burning occurs extraterrestrially in stars and terrestrially in nuclear explosions[1]. The specific thermonuclear burn rate is proportional to density

$$\dot{\varphi} \sim \rho \overline{\sigma v}$$

where $\dot{\varphi}$ is the fractional burnup, ρ is the density, and $\overline{\sigma v}$ is the Maxwell velocity-averaged reaction cross-section. Consequently, except at high fuel depletions, the thermonuclear energy production at a fixed ion temperature is proportional to the Lawson number, a product of density and confinement time[2]. In conventional controlled thermonuclear reactor (CTR) approaches, the density is limited by material properties, and the objective is to achieve sufficiently long confinement times by the use of electromagnetic fields[3]. In the laser-fusion approach to CTR, the objective is to achieve sufficiently high fuel densities, while the confinement time is determined by the inertia of matter. Spherical compression of 10^4-fold via the laser implosion scheme described here reduces the laser energy required for CTR by more than one thousand-fold, from more than 10^8–10^9 J—which is so large as to be currently impractical—to $\sim 10^5$–10^6 J, assuming laser and thermal/electric efficiencies of 10% and 40% respectively[4]. One kJ of laser energy may be sufficient to generate an equal thermonuclear energy.

Compression

Hydrogen in the centre of the Sun is believed to exist at more than one thousand times liquid density, and at pressures greater than 10^{11} atmospheres (temperature $\sim$1–2 keV)[5]. These pressures are maintained gravitationally by the overlying enormous solar mass, $\sim 10^{33}$ g. Matter in the cores of white dwarf stars is believed to exist at more than 10^5 g cm^{-3}, and at pressures greater than 10^{15} atmospheres[6].

The electrons in white dwarf cores are Fermi-degenerate, so the pressure is a minimum determined by the quantum mechanical uncertainty and exclusion principles[7]. The pressure of dense hydrogen with Fermi-degenerate electrons is[8]

$$P = \frac{2}{3} n_e \varepsilon_F \left[\frac{3}{5} + \frac{\pi^2}{4}\left(\frac{kT}{\varepsilon_F}\right)^2 - \frac{3\pi^4}{80}\left(\frac{kT}{\varepsilon_F}\right)^4 + \cdots \right]$$

where n_e is the electron density; $\varepsilon_F = \frac{h^2}{8m}\left(\frac{3}{\pi} n_e\right)^{2/3}$ is the Fermi energy; kT is the thermal energy; h is Planck's constant, and m is the electron mass. At 10^4 times liquid density ($n_e = 5 \times 10^{26}$), the minimum hydrogen pressure occurs when $kT \ll \varepsilon_F$, and is $\sim 10^{12}$ atmospheres.

Pressure: Implosion, Ablation

To compress hydrogen on Earth to these stellar densities, the required pressures must be generated by means other than gravitational. The pressures generated mechanically or chemically are generally limited to $\lesssim 10^6$ atmospheres by the strengths of chemical bonds, although chemical explosive pressures have been multiplied from less than 10^6 to more than 10^7 atmospheres by implosion. The pressure applied to an implosion system does PdV work generating kinetic energy which is converted near isentropically to internal energy concentrated in the compressed volume. Because pressure is energy per unit volume, the maximum average pressure equals the applied pressure multiplied by the compression ratio. Additional pressure multiplication occurs near the centre because of convergence effects[9]. The pressure multiplication factor may be increased by implosion of hollow spheres, since the externally applied pressure acts over a larger volume[10].

Laser light has been focused to intensities greater than 10^{17} watts cm^{-2} (ref. 11). At such intensities the "light pressure" (momentum flux) is almost 10^8 atmospheres ($P \simeq I/c$ where I is the intensity, and c the velocity of light). Much higher pressures can be generated with intense light by a combination of ablation and implosion. The momentum flux (and pressure) associated with laser-driven ablation is much greater than that of the light for the same reason that matter-ejecting rockets develop greater thrust than photon-drive rockets of equal power. Typical matter velocities associated with laser intensities of 10^{17} W cm^{-2} are 10^8 cm s^{-1} ($\sim$sound speed at temperature of 10 keV), or $\sim 3 \times 10^{-3}$ c. Hence the momentum flux and pressure, which are proportional to laser energy flux divided by reaction velocity, can be increased by several hundred-fold to more than 10^{10} atmospheres. The ablation pressure can then be further multiplied to more than 10^{12} atmospheres by a laser-driven ablative implosion in which high compressions occur.

Pulse Shape

The Fermi-degenerate state—which minimizes the required implosion pressure—may be achieved by shaping the laser pulse in time. When implosion begins, laser power is set so that the initial shock speed in the imploding matter is comparable to sound speed (pressures of 10^5–10^6 atmospheres) and subsequently so that the compression is near-isentropic; the hydrodynamic characteristics intersect only near the centre of the sphere. Owing to the extreme convergence effects, and by adjusting the pulse shape so that the characteristics intersect just before the centre is reached, a small fraction of the pellet mass in the central region is compressed and strongly heated, producing thermonuclear ignition. The laser power history which generates an optimal, isentropic compression of a degenerate hydrogen sphere is approximately *

$$\dot{E} = \dot{E}_0 \, \tau^{-s}$$

where $\tau = 1 - t/t'$, t is time, t' (which is $>t$) is the transit time to the centre of the sphere of the initial shock (generated by application of $\dot{E}_0$), $s = \frac{3\gamma}{\gamma+1} = 15/8$ for dense hydrogen with degenerate electrons ($\gamma = 5/3$). Such a pulse shape may be generated with sufficient accuracy with a practical laser system. Implosion calculations show that the optimal power history can be satisfactorily approximated by a sequence of about ten pulses. Starting with the final shortest, most intense pulse (which need not be accurately shaped) the preceding pulses can be generated with sufficient accuracy with beam splitters, attenuators, and optical paths of various lengths. More sophisticated pulse shaping schemes are probably feasible.

Symmetry

To implode matter to high densities the implosion pressure must be applied with sufficient symmetry, both spatially and temporally, and hydrodynamic instabilities must be adequately controlled. In compression of a sphere by 10^4 times, the radius decreases rather more than 20 times. If, after compression, spherical symmetry is required to within 1/2 the compressed radius—or 1/40 the initial radius—then the implosion velocity (and time) must be spatially uniform (and synchronized) to better than one part in 40, or a few per cent. In general, for a spherical implosion in which the ratio of initial to final volumes is η, and in which the tolerable error in the final radius r is wr, the associated tolerable fractional error in the product of velocity and time is

$$\frac{\Delta(vt)}{vt} \simeq \frac{w}{\eta^{1/3}}, \quad \eta \gg 1$$

Implosion errors may be reduced to 10–20% by a many-sided irradiation system, consisting of beam splitters, mirrors, lenses, and other optical elements. For example, the entire surface of a sphere may be irradiated—with an intensity variation less than $\pm 20\%$—by 6 beams oriented along the 6 Cartesian directions, each focused with f/1 optics to a point about one radius beyond the centre of the sphere, and with overlapping edges blocked out. The intensity variation may be reduced by use of more beams. The error of 10–20% can then be reduced to less than 1% by means of an atmosphere (generated by ablation with a laser prepulse) extending to several pellet radii with density slightly greater than the critical density (at which the laser frequency equals the plasma frequency). Laser light is absorbed and heats electrons in the outer atmosphere by inverse bremsstrahlung and plasma instabilities[12]. Asymmetries are reduced during energy transport by electrons through several mean free paths of atmosphere to heat the surface of the pellet. In addition, each point on the relatively small pellet is heated by, and averages over, a large fraction of the hot absorbing region in the outer atmosphere.

Stability

The implosion of the pellet by diffusion driven ablation-generated pressures is hydrodynamically stable, except for relatively long wavelength surface perturbations which grow too slowly to be damaging. The amplitude of a perturbation on the droplet surface grows during implosion as $A_0 e^{-i\sigma t}$, where A_0 is the initially present amplitude of surface roughness, and

$$\sigma^2 = -ak + \frac{k^2 P_A}{\rho}$$

for acceleration a, wavelength $\lambda = 2\pi/k$, ablation pressure P_A, and density ρ. The first term ak is associated with the well-known Rayleigh-Taylor instability[13]. If Δx is the thickness of a shell of matter, then using $a = P_A/\rho\Delta x$ (from $F = ma$), σ^2 is positive (implying stable acceleration) for $\lambda \lesssim 2\pi \, \Delta x$. In part, ablative stabilization occurs because the peaks of surface perturbations are effectively closer to the heat source (radius at which the critical density occurs) so that the temperature gradient is steeper. Consequently more rapid ablation occurs, and higher pressures are generated which reduce the amplitude of the perturbation. "Fire polishing" may also be a significant mechanism.

In the compression scheme which has been described, the spherical pellet is accelerated inwardly by the reaction forces associated with the outwardly expanding ablated material. In effect, this scheme is a spherical ablation rocket implosion system, externally energized by an optimally power-programmed high energy laser.

Thermonuclear Burn

The inertial confinement time of a sphere of hot plasma is proportional to the radius divided by the sound speed. Therefore since the burn rate is proportional to density, the burn efficiency is proportional to the product of the density and radius, ρr. In spherical compression ρr increases because the density increases more rapidly than the radius decreases. At constant ρr, the spherical mass is inversely proportional to the density squared.

Spherical compression reduces the minimum pellet mass and laser energy required for efficient thermonuclear burn. In addition, very high spherical compressions produce a product of radius and density so large that the energetic charged particles from the fusion reaction are absorbed within the dense pellet†, and the ion-electron coupling time becomes

* Computer calculations of spherical implosions show that this power history generates a near optimal pressure history, and that this pressure history is (for a Lagrangian surface):

$$P = P_0 \left(\frac{h}{h_0 \tau}\right)^{2/3\, s}, \quad h = \int_0^R \rho \, \mathrm{d}r$$

It may be shown analytically (via the hydrodynamic characteristics) that this pressure history also generates an optimal compression of a plane slab (where $h = h_0 = $const.). As expected $P \sim \dot{E}^{2/3}$, since $\dot{E} \sim Px$ velocity, velocity $\sim P^{1/2}$.

† In DT at 10 keV electron temperature, the effective range of the 3.6 MeV alpha particles produced by DT fusion is ~ 0.3 g cm^{-2}. A liquid density DT sphere with this ρr has a mass of 3 g, and requires 3×10^9 J to heat to 10 keV. At $10^4 \times$ liquid density and the same ρr, the mass and energy are reduced by 10^8-fold.

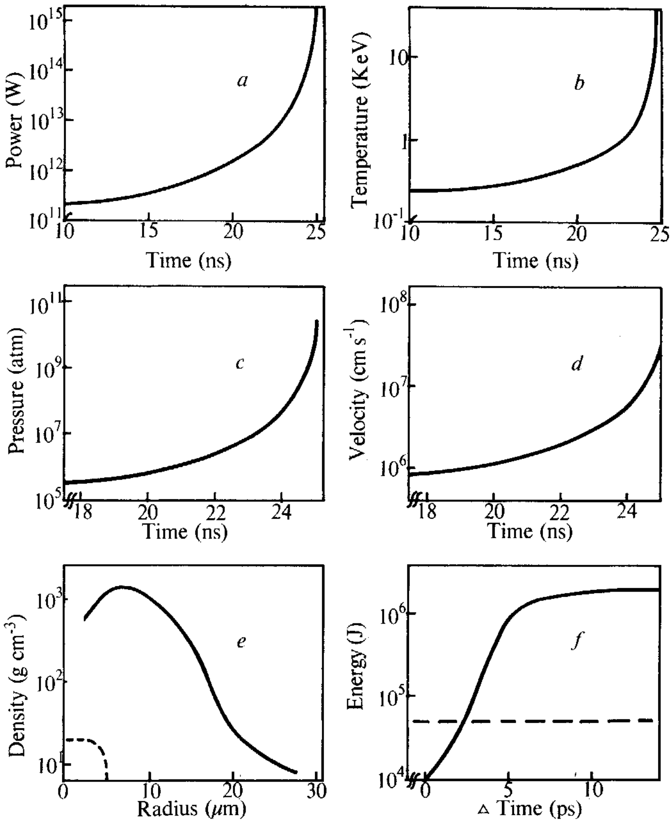

Fig. 1 Computer calculations of microexplosion resulting from 10,000-fold compression of a fusion pellet. A 60 kJ, 1 μm, laser is assumed to implode a 0.4 mm radius sphere of equimolar deuterium/tritium. *a*, Laser power. *b*, Electron temperature. *c*, Pressure. *d*, Velocity of shell. *e*, Density (—) and ion temperature (- - -) during thermonuclear ignition. *f*, Energy production; —, fusion; - - -, laser.

shorter than the inertial confinement time[14]. The resulting self-heating further reduces the laser energy required for effective fuel ignition. Compression also provides a means of heating the fuel ions to ignition temperatures. Except in very low density matter, only electrons are significantly heated by absorption of laser light[15]. These considerations preclude CTR applications with uncompressed pellets using practical lasers. The advantages of compression are partially offset by energy losses associated with escaping ablated material. These losses are related to the implosion and blow off velocities by the rocket equation.

Computer Calculations

Laser compression and fusion have been explored with the LASNIX computer program. LASNIX simulates by a Lagrangian finite difference scheme a wide variety of physical processes including hydrodynamics (by the von Neumann-Richtmeyer technique); (flux-limited) spatial energy transport and cross-field coupling between thermal ions and photons and up to 50 velocity groups of electrons; thermal radiation generation and absorption via bremsstrahlung and bound-free processes; laser-matter interaction via inverse bremsstrahlung and a variety of non-linear processes, involving appropriate electron spectral inputs to the electron velocity groups for each interaction (determined for non-linear processes by plasma simulation code studies); thermonuclear burn, including non-local time-delayed transport and appropriate electron-ion couplings of charged fusion reaction products. Realistic properties of matter are utilized, including equations of state, such as opacities, pressures and specific heats and transport coefficients which take into account nuclear coulomb, degeneracy and partial ionization effects.

Computer calculations of a 10,000-fold compression of a fusion pellet and the resulting thermonuclear microexplosion are shown in Fig. 1. In these calculations a 60 kJ, one micron wavelength laser implodes a 0.4 mm radius spherical liquid drop of equimolar deuterium-tritium (DT) located in a vacuum chamber. A laser prepulse ablates the pellet generating an atmosphere of DT which extends to a radius of $\sim 1,000$ microns with a density greater than 4×10^{-3} g cm^{-3}. The applied laser power then optimally increases from $\sim 10^{11}$ to $\sim 10^{15}$ W in ~ 20 ns (Fig. 1*a*).

The laser light is absorbed in the outer atmosphere, heating electrons. In this calculation the electrons are assumed to be strongly coupled by possible plasma instabilities to form a near Maxwellian distribution. These hot electrons heat the atmosphere to electron temperatures which increase from $\sim 10^7$ to $\sim 10^8$ K during the implosion (Fig. 1*b*). The surface of the pellet is heated and ablated, generating pressures which increase optimally from 10^6 to 10^{11} atmospheres (Fig. 1*c*). The many order of magnitude increase in implosion pressure occurs during the transit time of the initial shock to the droplet centre, so that the unablated outer part of the pellet is gradually compressed into a spherical shell with density >100 g cm^{-3}, while at the same time this shell is inwardly accelerated to velocities which increase from 10^6 to 3×10^7 cm/s (Fig. 1*d*). As the internal pressures become larger than the ablation pressures, the rapidly converging shell slows down and is compressed, still near-isentropically at sub-degeneracy temperatures, to densities greater than 1,000 g cm^{-3}. At the same time the low density non-Fermi degenerate central region is compressed by the shell to densities approaching 1,000 g cm^{-3}, and heated in the process to ion and electron temperatures greater than 10^8 K, initiating thermonuclear burn (Fig. 1*e*). About 1,800 kJ of fusion energy is produced in less than 10^{-11} s (Fig. 1*f*). Since a 60 kJ input of laser light was used, net electrical energy production would be possible with a 10% efficient laser and a 40% thermal-electric efficiency.

Calculations with non-Maxwellian electrons and linear electron coupling show that suprathermal electrons generated by laser plasma instabilities preheat the fuel during compression and effectively decouple from the atmosphere. Decoupling of thermal electrons may also occur[16]. These effects are worst with long wavelength lasers, such as CO_2, because absorption occurs at a lower density. Generation of suprathermal electrons can be minimized by using inverse bremsstrahlung absorption of the laser light. The instability thresholds can be increased, and inverse bremsstrahlung absorption enhanced, by use of ultraviolet lasers and by seeding the pellet with small amounts of high Z material (~ 0.1 atom %). Decoupling limits the maximum ablation pressure. This can be compensated for by use of hollow pellets if suprathermal electron preheat is avoided. In non-Maxwellian linearly coupled calculations with ultraviolet lasers and seeded pellets, results similar to those described above have been achieved.

Fig. 2 shows the scaling of the gain, G_L (ratio of fusion energy to laser light energy) with compression and laser light energy. Gains approaching 100 are predicted for laser energies of 10^6 J. At compressions less than $\sim 10^3$, the gain increases strongly with increasing compression because of increasing burn efficiency and alpha particle self-heating of the fuel. The gain decreases with compressions much greater than 10^4 because of depletion (of the DT) and because ablative energy losses increase and the energy of compression (against degeneracy pressures) becomes dominant.

The electrical gain, G_e (ratio of electrical energy outputted to electrical laser pumping energy), is

$$G_e = G_L \varphi_t \varphi_L$$

where φ_t is the power plant thermal efficiency and φ_L is the laser pumping efficiency. If $\varphi_t = 40\%$ and $\varphi_L = 10\%$, $G_e > 1$ if $G_L > 25$, which occurs for a laser energy, L, less than 100 kJ for $\eta = 10^4$

(Fig. 2). Also < 1 kJ of light energy is sufficient to generate an equal quantity of thermonuclear energy, if optimally employed (Fig. 2).

Pellet Cost

Cheap fuel pellets are required for commercial power production. Ten million joules of electrical energy is currently worth roughly one cent, and most of this cent must be used to pay capital and operating costs of the power plant. In the scheme described here the pellet may be a droplet of DT (or deuterium, using multi-megajoule lasers) ejected from a sophisticated eye dropper and spheroidized by surface tension and viscosity effects, while freely falling in an evacuated drop tower. The pellet may also be a hollow sphere of fusion fuel (although very small ratios of shell thickness to radius are precluded by symmetry and stability requirements). Hollow pellets require lower peak laser powers (but not less laser energy) and may be advantageous for lasers with wavelength ≥ 1 µm (because of electron decoupling effects). The high cost of tritium can be overcome by regenerating the consumed tritium with neutron reactions in lithium blankets, or by burning essentially pure deuterium (with only a small tritium content).

Reactor Economics

Thermonuclear microexplosions producing of the order of 10^7–10^8 J (5–50 pounds TNT equivalent) are suitable for commercial power production. Multigigawatt-electric average power levels may be achieved by burning about 100 pellets per s, perhaps 10 per s in each of 10 explosion chambers.

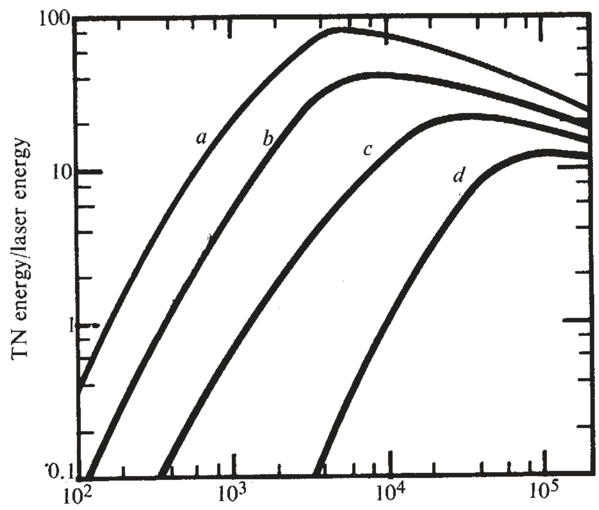

Fig. 2 Energy gain plotted against compression: *a*, 10^6 J; *b*, 10^5 J; *c*, 10^4 J; *d*, 10^3 J.

The electrical power P is related (through energy conservation) to the laser energy, L, explosion frequency, N, gain G_L, thermal-electric efficiency φ_t, and laser efficiency φ_L by

$$P = LN(G_L\varphi_t - \varphi_L^{-1})$$

where we assume the laser is electrically pumped and the hot gas exhausted from the laser is not used to generate electricity. It is desirable that $G_L\varphi_t \geq 2\varphi_L^{-1}$ to avoid marginal designs. Hence, if $\varphi_t = 0.4$, $\varphi_L = 0.1$, then G_L must be greater than 50, which occurs for $L \sim 10^5$–10^6 J (Fig. 2). Then if $P = 10^9$ W, $L = 10^6$ J and $N = 100$ s^{-1}.

The explosive impulse from a small fusion explosion is much smaller than that from a TNT explosion of the same energy, because the fusion explosive weight is $< 10^{-6}$ that of the TNT explosion, and the impulse generated is proportional to the square root of the explosion débris mass. A specially designed explosion chamber is required, however, to withstand the neutrons, X-rays, and hot plasma generated by the fusion explosion. Such an explosion chamber appears to be feasible[17,18].

Conventional thermal cycles may be used to generate electricity if fusion neutrons are absorbed in lithium blankets, and the hot plasma cooled to manageable temperatures[17,18]. If relatively large DT pellets or essentially pure deuterium pellets are burned (requiring a multi-megajoule laser energy), the fusion neutrons will deposit much of their energy in the fuel plasma, which may be expanded against a magnetic field, to convert much of the fusion energy directly to electricity[19,20], achieving very high electricity generation efficiencies. With deuterium pellet burning, lithium utilization and tritium storage and cycling may be greatly reduced. Net tritium is generated by deuterium burn.

Hybrid reactors, in which the 14 MeV DT neutrons which escape from the explosion chamber are used to fission natural uranium, or thorium, may generate more energy than used to pump the laser even with low efficiency, low energy lasers, such as 1% efficient, 10 kJ Nd glass lasers.

Problem of Realization

Important areas requiring future study include suprathermal electron coupling and pellet preheating; effects of magnetic fields generated by laser driven gradients in the plasma temperature and density; engineering design of a sufficiently cheap reactor system which will function for more than 10^{10} microexplosions; and development of the required lasers.

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