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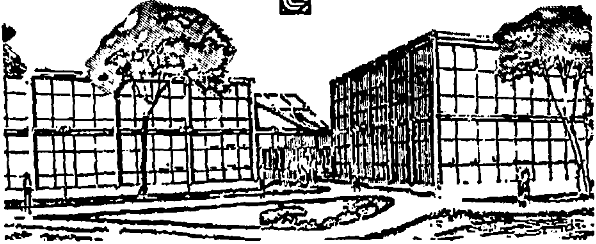

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CONCERNING THE GENERATION OF VERY HIGH PRESSURES FOR EOS STUDIES WITH ULTRA-HIGH POWER LASER PULSES*

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Introduction and Summary

Experimentally validated knowledge of the structure of matter is presently limited by our ability to bring materials to the upper limits of the regions where atomic structure dominates the properties of matter, within a laboratory environment. We propose here general techniques by which much of these regions may be experimentally explored, via rather obvious extensions of the fast adiabatic compression principle described earlier[10].

High Pressure Attainment via Chemical Means

The equality (to within order of magnitude) of the strengths of essentially all chemical bonds precludes the straightforward attainment of pressures significantly greater than the energy densities characteristic of such bonds, by means as diverse as static presses[1] and high explosives[2]. The upper limit of the pressure range accessible by these essentially chemical techniques is of the order of 1 megabar[3].

Physical Approaches to Very High Pressures: Rectilinear Stacks of Flat Plates

Fairly well-known physical-kinematic techniques may be employed to concentrate energy and momentum in a reasonably isentropic fashion to attain pressures of tens of megabars. Careful experimental technique results in the attainment of

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pressures at as low a temperature as may be desired. Examples of such techniques are multi-stage gas guns[4] and high explosive-driven flying flat plate experiments[5], in which momentum is concentrated in a plate as it is accelerated by collision with a considerably more massive plate--the flat plates rebound from each other at equal velocities in their center-of-mass, which, however, is already moving with nearly the lab frame velocity of the considerably more massive plate, so that the total final lab frame velocity of the lighter plate is nearly twice that of the initial velocity of the more massive plate.

The kinetic energy density of the lower mass flat plate may thus be increased relative to that of the more massive plate by half an order of magnitude, as a practical matter, and therefore the pressures generated when it is stagnated raised by a similar factor[11,12].

Moreover, it is obvious that such techniques may be applied repetitively in the same experimental arrangement--a succession of ever less massive flat plates may be stacked in a rectilinear sequence to produce a system that successively multiplies plate speed[6,7,11,12]. A five plate stack could, in principle, increase the velocity of the final plate by two orders of magnitude (and thus its specific kinetic energy by four), relative to the first plate. As a practical matter, the spacing of the flat plates, their surface finishes, thicknesses and compositions and other such details would have to be carefully chosen in order to avoid growth to ruinous extents of initial perturbations, via the Rayleigh-Taylor hydrodynamic instability, in the pressure-temperature regime in which the residual mechanical strength of the plates would no longer be sufficient to effectively damp this instability.

The interposition of one or more suitable "inter-plate buffer fluids" between such a rectilinear stack of flat plates permits the near-isentropic acceleration of the i^{th} plate by the $(i-1)^{th}$ plate, so that the kinetic energy densities of such plates (continued on next page)

may be maintained as much larger than their thermal energy densities as is desired. The conditions on such an interposed fluid layer are that the product of its density and thickness be small compared to those of the plates which bound it, but that its sound speed at essentially all times be larger than the relative velocity of the two bounding plates. The former condition is imposed simply to minimize unwanted inertial effects, while the latter one allows sub-sonic acceleration of the $(i+1)^{th}$ plate by the i^{th} one; this condition is morever rather automatically met by the interposed fluid, in that it will be shocked up to a sound speed comparable to the velocity of the i^{th} plate, if it doesn't have it intrinsically.

Ideally, one selects a high sound speed ($\Delta_{i,i+1} c_{s_{i,i+1}} \lesssim \Delta_{i+1} c_{s_{i+1}}$) fluid of low density ($\int \rho dr \ll \int \rho dr$) of an inter-plate thickness $v \sqrt{\Delta_{i,i+1}} \gtrsim c_{s_{i+1}} / \Delta_{i+1}$

where $v(i)$ is the maximum velocity of the i^{th} plate as it moves toward the $(i+1)^{th}$ plate, $c_{s_{i+1}}$ is the (cold, uncompressed) sound speed of the $(i+1)^{th}$ plate, Δ_{i+1} is the thickness of this plate, and $\Delta_{i,i+1}$ and $c_{s_{i,i+1}}$ are the inital thickness and sound speed of the inter-plate fluids. Satisfaction of these conditions essentially guarantees the isentropic acceleration of the $(i+1)^{th}$ plate by its buffered collision with the i^{th} one, as mediated by the inter-plate buffer fluid.

One such fluid whose feasibility for these purposes has already been experimentally demonstrated[8] is simply a gas of (transversely compressed) magnetic flux; its density-thickness product is zero for all thicknesses, and its sound speed is very high ($\lesssim c$). Its only disadvantage is that it must usually be generated in situ just prior to use, and is associated with magnetic field intensities H which are comparatively large ($H^2 \gtrsim \rho v^2$) if it is to act most effectively (i.e. if it is to be able to significantly accelerate the

$(i+1)^{th}$ plate during a substantial portion of the time interval that the i^{th} plate is rapidly approaching).

It should be realized, however, that the use of such inter-plate buffer fluids is not an unmixed advantage. The use of a (necessarily) lower density fluid between two plates i and (i+1) results in a Rayleigh-Taylor unstable interface between the inter-plate buffer fluid and $(i+1)^{th}$ plate[13], and care must be taken that the density variation at the interface, the plate strength and smoothness and the conditions of its acceleration are such that Rayleigh-Taylor unstable hydrodynamic motion does not become a major problem. This is also the case when magnetic flux is employed as the buffer fluid, except that the unstable motion at the interface is of a magnetohydrodynamic nature, and may be stabilized or effectively eliminated by employment of both appropriate density and electrical conductivity gradients. Such stability constraints may in general be met in both cases.

The application of this combination of physical-kinematic techniques permits the attainment of kinetic energy densities of the order of 10^{14} ergs cm^{-3}, at thermal energy densities not greatly in excess of those at ordinary temperatures, so that the properties of materials may be transiently studied at very substantial compressions, but at sufficiently low comoving temperatures that thermal ionization effects do not destroy atomic structure. Much higher ($\geq 10^{16}$ ergs cm^{-3}) energy densities may be generated by these linear plate stack techniques, if low temperature constraints are removed.

Super-High Pressure Generation via Geometric Means: Ablative Implosions

The use of geometric effects enhances the pressures which may be realized through chemical and physical means. Primary among such geometry techniques is that of the implosion, whose momentum- and energy-focussing properties and essentially isentropic nature have been widely discussed only relatively recently[9,10].

It is now generally appreciated that implosions function as energy-momentum lenses in space-time, and act to focus the energy density and momentum flux applied to an imploding mass over the space-time volume occupied by the mass during the implosion history into the generally much smaller spatial volume occupied by the imploded mass, over the comparatively very brief time interval of the implosion culmination[12]. It is also now widely realized that proper control of the implosion history allows the imploded mass to be essentially isentropically assembled; requiring the energy source driving the implosion to so interact with the surface of the imploding matter that the characteristics of the resulting hydrodynamic flow all intersect on the symmetry locus of the mass configuration (e.g., the axis of a cylinder, or the center of a sphere) and only there, is a necessary and sufficient condition for the optimally isentropic character of an implosion[10].

The multiplication of the implosion-driving pressure which may be realized in the imploded mass is limited only by practical considerations of the symmetry with which the driving pressure may be applied, and the degree of hydrodynamic stability which obtains, particularly during the early phase of the implosion. It has been postulated that implosions may be conducted over characteristic scale length ratios of $\lesssim 10^2$ in an essentially hydrodynamically stable fashion, if adequate driving symmetry is attained, and that peak pressures in the imploded mass of as much as 3 orders of magnitude greater than the peak driving pressure may be obtained. Such pressures are comparable to those in the cores of main sequence stars, and are sufficient to nearly completely pressure-ionize even the highest Z elements.

Laser-Energized Speed-Multiplying Flat Plate Tectilinear Stacks and Implosions

Power-tailored pulses of high frequency laser light are nearly ideal as driving sources for either rectilinear flat plate speed-multiplying stacks or implosions. While the momentum fluxes associated with focussed, state-of-the-art laser pulses are substantial ($\lesssim 10^2$ megabars), such energy is also readily convertible to kinetic and internal energy of evaporated (blown off) superficial layers of a material body, resulting in multiplication of the radiant momentum flux at such a surface of the order of c/v_{bo}, where v_{bo} is the velocity of the blown-off surface material. Under typical conditions,

$$3 \times 10^{-4}c \lesssim v_{bo} \lesssim 3 \times 10^{-3}c \quad ,$$

so that very substantial pressures--$\sim 10^4$ megabars--may be transiently generated at very high intensity laser focal spots, without employment of velocity multiplication or implosion techniques. However, due to the very severely limited nature of such high pressure regions in both space and time, and the large transverse pressure gradients associated with them, their utility in hyperbaric physics is not likely to be great. It seems much more likely that the requirements of the "bench-top" scale solid state experimental physicist in the 1 - 1000 megabar pressure regime will be met by speed-multiplying stacked plates and implosion techniques, energized by appropriate laser pulses (or perhaps by pulsed charged-particle beam generators, outputting well-focussed, high powered bursts of relatively short stopping length species).

It may be instructive to consider how the energy which drives the first flat plate in a speed-multiplying stack, or which drives the implosive motion of a homogeneous slab, cylindrical or spherical mass, should be optimally shaped in time. It is clear from above that, for the flat plate, the hydrodynamic characteristics associated with laser-energized blow-off of one side should all intersect just at its other side, in order to accelerate it most efficiently, i.e., to the highest velocity, and thus with the lowest internal energy due to irreversible heating. For the cylinder and sphere, the characteristics should likewise intersect only on-axis and at the center, respectively, as noted above, so that only very small volumes around such loci should be irreversibly heated. In all three of these one-dimensional geometries, maximum compressions and bulk material velocities are attained by avoiding the creation of phonons by irreversible (i.e. shock) phenomena, which must subsequently be compressed by the driving source, along with the matter in which they are entrained; it is of present interest to compress only electrons and ion cores, not entropy.

Consider (for simplicity) a homogeneous material mass whose pressure P may be represented as

$$P \subset \rho^{\gamma} \tag{1}$$

where ρ is the (initially uniform) density of the material mass and γ is a constant. This is a good approximation for a Fermi-degenerate fluid (with $\gamma = {}^5/_3$), and for condensed phase hydrogen along a zero temperature isentrope; it is a reasonable estimate for other materials along low temperature isentropes, particularly at elevated pressures (the conditions of interest to us here).

Then we may write the (adiabatic) sound speed c_s within the material as

$$c_s^2 = \frac{\partial P}{\partial \rho} \simeq \rho^{\gamma-1};\ c_s \simeq \rho^{(\gamma-1)/2} \tag{2}$$

Now consider the initial adiabat upon which the material will be put by (uniform) irradiation of its surface by the laser pulse at intensity I_0:

$$I_0 = {}^{\dot{E}_0}/{}_{A_0}, \tag{3}$$

where $\dot{E}_0$ is the initial laser power (of time-varying power $\dot{E} = \dot{E}(t)$), and A_0 is the initial surface area of the material (of time-varying area $A = A(t)$). Denote by t_0 the time it will require for the sound signal associated with this initialization of the adiabat to travel from the material's laser-ablated surface (initially at $x = x_0$) to the symmetry locus. Then the (optimal) isentropic condition that all characteristics of the flow associated with the surface ablation (simultaneously) intersect at the symmetry locus, and only there, is that

$$\frac{x(t)}{c_s(t)} = (t_0-t), \qquad (4)$$

where $x(t)$ and $c_s(t)$ are the time-varying coordinate of the ablating surface, and the sound speed just inside it, for all times $t < t_0$; the sound signal created at the surface at time t will clearly propagate all the way to the symmetry locus at (constant) velocity $c_s(t)$.

Moving toward quadrature, we seek a relation between the x coordinate of the surface and the material density ρ, and write this as

$$x \sim \rho^{-1/n} , \qquad (5)$$

where n indexes the (one-dimensional) geometry of the compressing homogeneous material:

$n \equiv 3 \leftrightarrow$ sphere

$n \equiv 2 \leftrightarrow$ cylinder

$n \equiv 1 \leftrightarrow$ plane slab.

For subsequent use, we also write the surface area A of the material in terms of the density as

$$A \propto x^{n-1} \propto \rho^{\frac{1}{n}-1} \qquad (6)$$

We have approximated the material density just inward of the ablating surface as the volume-averaged density by writing these relations in this fashion. This is an excellent approximation, particularly for the higher n geometries, as most of the volume of the material is indeed just inside the ablating surface, and the slope of the ingoing characteristic (e.g. the compressing material's sound speed) is relatively weakly dependent on the density-determined pressure, via (2).

Using (2) and (5), we may then re-write (4) as

$$\frac{x(t)}{c_s(t)} \propto \frac{\rho^{-1/n}}{\rho^{(\gamma-1)/2}} = \frac{1}{\rho^{[(\gamma-1)/2+1/n]}} \propto (t_0-t) \quad , \quad \text{or} \qquad (7)$$

$$\rho^{[(\gamma-1)/2+1/n]} \propto (t_0-t)^{-1} \propto P^{[(\gamma-1)/2+1/n]/\gamma} \quad , \quad \text{or} \qquad (7')$$

$$(t_0-t) \propto P^{-[n(\gamma-1)+1]/2n\gamma]} = P^{[(n+1)/2n\gamma-1/2]} \qquad (7'')$$

But P, the ablation-generated pressure, may be written

$$P \simeq \dot{m}c_s/A \propto \frac{\dot{m}\rho^{(\gamma-1)/2}}{\rho^{1/n-1}} = \dot{m}\rho^{(\gamma+1)/2-1/n} \quad , \qquad (8)$$

where $\dot{m}$ is the rate of mass removal from the ablating surface of the material, and we have made use of the fact that the velocity at which mass blows off this surface is proportional to c_s, the sound velocity just inside it (for the internal energy density of the ablating surface must be raised substantially--about 30-50% -- above its zero temperature value of $\rho\ c_s^2$ by heating from the outside before it blows off substantially and hydrodynamically sustains the compressive motion).

Now the required laser power $\dot{E}$ may be written as

$$\dot{E} \propto \dot{m}c_s^2 \propto \dot{m}\rho^{\gamma-1} \quad . \qquad (9)$$

where, for clarity of exposition, we have ignored the thermal power required for reheating of the blown off surface, which causes no serious error for material compressions to $\lesssim$ 10% gm cm^{-3}, which are of primary interest to us here.

From (8) and (9) we may write

$$\frac{\dot{E}}{P} \propto c_s A \propto \rho^{[(\gamma-1)/2+\frac{1}{n}-1]} = \rho^{[(\gamma-3)/2+\frac{1}{n}]} \quad \text{, or} \qquad (10)$$

$$\dot{E} \propto P\rho^{[(\gamma-3)/2+1/n]} \propto \rho^{[\gamma+(\gamma-3)/2+1/n]} = \rho^{[(\gamma-1)/2+\frac{1}{n}]}\rho^{[\gamma-1]} \qquad (10')$$

Recalling (7) and using (10'), we write

$$\dot{E} \propto \left[\frac{1}{(t_0-t)}\right]^{[1+2(\gamma-1)/((\gamma-1)+2/n]} \equiv \left[\frac{1}{t_0-t}\right]^{\delta} \qquad (11)$$

$$= (t_0-t)^{-2} \quad \text{for } \gamma = 5/3,\ n = 3 \text{ (sphere)}$$
$$(t_0-t)^{-9/5} \quad \text{for } \gamma = 5/3,\ n = 2 \text{ (cylinder)}$$
$$(t_0-t)^{-3/2} \quad \text{for } \gamma = 5/3,\ n = 1 \text{ (plane slab).}$$

We normalize the laser power $\dot{E}$ and eliminate all proportionality constants by writing

$$\frac{\dot{E}}{\dot{E}_0} = (t_0-t)^{-\delta} . \qquad (12)$$

We further note that this equation actually has only one free parameter, the laser power initially applied to the material surface in question, which, by determining the adiabat onto which the material is put for the subsequent compression, determines a unique minimum isentropic compression time t_0. As would be expected, the optimal value of t_0 corresponds to a time over which a sound wave would transit from the surface of the material to its symmetry locus at a signal velocity comparable to its zero-temperature sound speed.

It should be remarked that a material may certainly be isentropically compressed in times greater than t_0, simply by requiring that the hydrodynamic characteristics only intersect beyond the symmetry locus of the system. Such compression is, however, sub-optimally "slow", in that larger quantities of laser energy must be used to compress smaller masses of material up to the same density as could be obtained with the optimal pulse. Such "slow" pulses may, however, be quite useful in maintaining pressures and densities at and in the neighborhood of the symmetry locus for times long compared to the hydrodynamic relaxation time of the "optimal" pulses, by broadening the sharply peaked momentum flux of the "optimal" pulse into a much wider, comparatively lower and flat-topped one, as seen at the symmetry locus.

We note in passing that it may be desired to implosively compress some one dimensional geometry (such as a single slab, laser-ablated from one side, with the other side "exposed" to one or more probing techniques), and to maintain the cumulated condition for some time, to facilitate physical studies. The required laser pulse shape is again given by (11) up to a maximum power (and thus time) determined by (10) and the desired pressure to be attained and maintained. Beyond this time, the laser power must merely remain constant, so that the laser-energized ablation-generated momentum flux impunging on the symmetry locus remains constant. For $n = 1$, the non-ablated side of the slab then accelerates at a uniform rate just sufficient to "stall" the ingoing rarefaction wave at the exposed edge of the slab; for $n = 2$ or 3, the cumulated matter is pinned in the neighborhood of the symmetry locus, again through stalling of the rarefaction wave by the inward-directed momentum flux.

(We should also emphasize that the laser pulse shapes derived above are not at all suitable for laser induction of thermonuclear microexplosions, in that the derivation ignored many physics considerations crucial to successful microexplosion induction, such as blowoff reheat, central ignition requirements, laser-plasma interaction complications, etc. Optimal pulse shapes for super-high density laser CTR are considerably more complex in nature than these simple, moderate compression ones.)

Technological Considerations

It is worth noting that relatively modest laser powers and energies will suffice to compress materials to pressure conditions which

have not hitherto been suited to laboratory-scale physical investigations.

The laser intensities and powers of interest in such investigations are easily determined through dimensional analysis. A momentum flux P of the order of 10^{12} dynes cm^{-2} (1 megabar) is characteristic of those needed to launch strong sound (or weak shock) waves into most condensed phase matter, and the corresponding laser power (applied to a unit area) is the value of $\dot{E}_0$ in (3) above, as well as that which one desires to apply to the initial (most massive) plate of a velocity-exponentiating flying plate stack. This value is

$$\dot{E}_o = \frac{\dot{m}}{A} v_{bo}^2 = \rho v_{bo}^3 = \rho \theta_e v_{bo} = P v_{bo} \qquad (13)$$

where $\dot{m}/A$ is the specific rate of mass removal from the ablation surface (having a characteristic blow-off velocity v_{bo} at a density ρ), driven by an electron temperature θ_e (actually a specific thermal electron energy) at the laser-matter interaction critical surface. Since we know the laser wavelength λ_L, and thus the critical surface density (invoking momentum conservation, relative to the ablation surface, and ignoring divergence effects for the n = 2 and 3 geometries), we can solve for Θ_e, and find it to be ≈ 800 ev. for λ_L = 1 μm. The corresponding values of v_{bo} and $\dot{E}_o$ are ~ 2 x 10^7 cm sec^{-1} and ~ 8 x 10^{13} watts cm^{-2}.

A Nd-glass laser system (λ_L = 1 μm) delivering 3 kJ in 100 ps (30 TW) and 10 kJ in 1 nsec (10 TW) pulses is coming into existence this year at LLL (SHIVA). From (13), it is seen that such pulses may be employed crudely to launch 1 Mb shocks into 1 cm^2 area slabs, and to maintain such driving pressures while the associated shock waves move 10^{-2} cm distances into such slabs, resulting in the acceleration of ~ 10^{-2} gm mass to velocities of 1-2 x 10^6 cm sec^{-1}. A rectilinear "short stack" of speed-multiplying flat flyer plates would thus suffice to bring a ≤ 10^{-3} gm mass to velocities of 1-2 x 10^7 cm sec^{-1}, thereby permitting the attainment of multi-hundred Mb pressures upon stagnating such a high velocity slab. Since the acceleration distances of such a rectilinear flat plate stack would be ≤ 10^{-1} cm (a small multiple of the thickness of the initial plate), edge effects would result in quite acceptable degradation of the initial plate area by the time the final plate was up to speed.

The use of the laser pulse shape of (10) over a 1 mm x 1 mm area (e.g., of a single flat slab) would permit the attainment of peak intensities of 3 x 10^{15} watts cm^{-2}, and the attainment on its other side of multi-hundred Mb peak pressures, or pressures of 100 megabars maintained for an order-of-magnitude longer period (as noted above). Pressures well in excess of 10^4 Mb may be attained in the cores of spherically imploded masses, using such laser pulses as we have noted previously[10].

Other, much lower energy, very short pulse lasers could be used to flash-heat efficient x-ray emitting targets, whose (possibly time-sequenced) outputs could be employed to study (with x-ray pinhole camera "snapshots", possibly using monochromatized x-radiation) the material properties of objects compressing to high densities, with ≤ 10^{-11} second and ≤ 10^{-3} cm resolutions, as has recently been done successfully at somewhat lower compressions and on large spatial scales, by our experimental colleagues in the LLL Laser Fusion Program

Conclusions

The use of basic physical and geometric principles, coupled with current laser technology, seems likely to extend experimental hyperbaric physics investigations from the megabar region into the portions of parameter space in which the ideal (degenerate) Fermi gas approximation is valid for even the highest Z materials. Implosions and speed-multiplying rectilinear stacks of flat plates seem particularly apt techniques for the near-term, transient attainment of pressures of 10^9 atmospheres in the laboratory, and laser-energized, pulsed x-ray "cameras" appear suitable for analyzing the basic properties of matter under such conditions.

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