A compact experiment to determine the efficacy of colliding macroscopic pellet fusion

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Abstract

Laboratory experiments are less than a factor of ten from the velocity required to initiate "pellet fusion" reactions. Means are proposed to close this gap.

Key words: Nuclear energy, fusion, inertial confinement.

Over the years and to the present day there has been considerable frustration with the progress made by orthodox plasma physics towards controlled thermonuclear experiments[1]. Out of this frustration Harrison[2] and others proposed a scheme which proports to circumvent many of the common difficulties. Briefly, the proposal is to collide solid (or gaseous) hydrogen isotope projectiles having velocities of nearly 10^6 m/s. To achieve ignition it is estimated that pellets of at least 10^{-5} kg are required[3].

The difficulty with such a scheme is obvious; to achieve such velocities requires conventional accelerators 10^4 meters long[4]. Because of the theoretical uncertainty inherent in such an ignition technique the necessary experiments have not been forthcoming.

In the present paper we propose a means for producing such large and energetic projectiles and argue that it can be attempted with very modest resources. The proposed technique[5] is to be considered a means for testing the efficacy of pellet ignition and studying the resulting physics and is not to be confused with a breakeven reactor design. However, since a thermonuclear detonation wave[6] is initiated, in principle at least the D–T target can simply be increased in size (independently of the trigger system) to achieve an arbitrary energy yield[7]. The basic components and geometry are shown in Fig. 1.

It is assumed that the target will have a cross-sectional radius greater than the mean free path of a thermonuclear alpha particle. At solid densities this implies cross-sectional areas of about 1 cm² in order for a one-dimensional ignition model to apply. In reality,
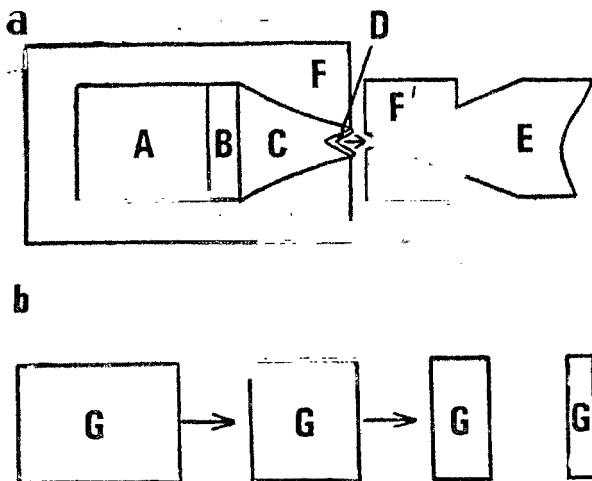
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FIG. 1. *a, b.* Thermonuclear experiment; A—High Explosive Fill, B—Driver, C—Accelerator Horn, D—Pellet, E—Target D-T Mix, F—Tamp, F'—Driver plates for radially compressing and tamping E, G—Flier Plate Masses.

however, we expect that the target will be compressed both by impact and by a cylindrical pre-compression. (Furthermore, any residual plasma instabilities will reduce the alpha mean free path length.) Compression in this cylindrical geometry should be only slightly less effective than the spherical compressions usually assumed. In this regard it is worth comparing the minimum energy required for ignition of a spherical laser heated DT pellet, E_L, with that required for a tamped cylindrical pellet, E_c. The former scales as[8]:

$$E_L \propto \frac{\beta^3}{\epsilon^4 \eta^3}$$

where β is the fusion energy gain desired, ϵ is the efficiency of coupling in the laser energy to the plasma, and η is the DT compression ratio. This is comparable to the scaling for cylindrical compression[8]:

$$E_c \propto \frac{\beta^3}{\epsilon^4 \eta \eta'}$$

where η' is the tamp compression ratio, we expect that $\eta' \approx \eta$.

Radial compression need be applied only at one end of the fuel stick so that ignition can occur at super-solid density and small cross-sectional area. The stick can then taper up to the steady state requirement of $\frac{1}{2}$ to 1 cm² (with tamp, perhaps, but no compression).

It seems reasonable to assume an ignition energy of 10 M Joules. Previously proposed fusion drivers (lasers, e^- beams, ion beams) have all involved beams of very low density and very high kinetic energy, as compared with the target thermal parameters. Under such conditions instabilities inevitably heat the plasma electrons predominantly. The confinement required (and, thence density) has then been largely determined by the time required for energy transfer from electrons to ions. This energy equilibration time actually much exceeds the energy confinement time (Lawson time) required for fusion breakeven.

In the present scheme we heat the ions directly and not the electrons. The reaction time appropriate to the thermonuclear detonation wave is:

$$\tau = \frac{1}{n \langle \sigma v \rangle}$$

where n is the fuel density and $\langle \sigma v \rangle$ is the fusion reaction rate coefficient. Since the Coulomb ion-ion equilibration time is shorter than τ (whereas the electron-ion equilibration time, τ_{ei}, is longer) the input energy will all go into an (initial) ion hot spot. Hence, we anticipate improved performance. We do not need such long confinement times or such high densities and compressions. Finally, the projectile has solid, or higher, density (*i.e.*, the projectile is itself compressed), and hence a " beam " kinetic energy of the same order as the required final plasma temperature. Under these conditions a relatively instability-free system should be possible.

The ion temperature equation appropriate to such a thermonuclear reaction wave is just:

$$\frac{\partial T_i}{\partial t} + u \frac{\partial T_i}{\partial x} = -\frac{2}{3} T_i \frac{\partial u}{\partial x} + \frac{2m_i}{3k_\rho} \mu_i \left(\frac{\partial u}{\partial x}\right)^2 + \frac{2m_i}{3k_\rho} \frac{\partial}{\partial x} \left(K_i \frac{\partial T_i}{\partial x}\right) + W_i + \frac{T_e - T_i}{\tau_{ei}}$$

and the electron temperature equation is:

$$\frac{\partial T_e}{\partial t} + u \frac{\partial T_e}{\partial x} = -\frac{2}{3} T_e \frac{\partial u}{\partial x} + \frac{2m_i}{3k_\rho} \mu_e \left(\frac{\partial u}{\partial x}\right)^2$$
$$+ \frac{2m_i}{3k_\rho} \frac{\partial}{\partial x} \left(K_e \frac{\partial T_e}{\partial x}\right) + W_e + \frac{T_i - T_e}{\tau_{ei}} - A_\rho T_e^{1/2}$$

where u is the mass velocity, governed by the equation of motion:

$$\frac{\partial u}{\partial t} + u \frac{\partial u}{\partial x} = -\rho^{-1} \frac{k}{m_i} \frac{\partial}{\partial x} \left[\rho (T_i + T_e)\right] + \rho^{-1} \frac{\partial}{\partial x} \left((\mu_i + \mu_e) \frac{\partial u}{\partial x}\right)$$

ρ is the mass density, $\mu_{i,e}$ are the viscosity coefficients, $K_{i,e}$ are the thermal conductivities and k is Boltzmann's constant. $W_{i,e}$ represent the power input to ions and electrons due to fusion reactions.

Once fusioning begins the fraction of the α particle energy absorbed by electrons should approach:

$$f = \frac{32}{32 + T_e}$$

(where T_e is given in keV) and the electron temperature (along with the ion temperature) will rise to approach a steady state high temperature burn (with T_e and $T_i > 10$ keV).

A conventional high explosive achieves a detonation wave velocity of approximately 10^4 m/s. An impedance matching driver plate (or series of layers of different materials having intermediate dispersion characteristics) might be used to couple the explosive output pulse into a tamped conical accelerator. (The energy coupling efficiency may hopefully exceed 20%[9].)

The accelerator itself operates on the principle of an acoustic concentrator or waveguide[10]. The approximate wave equation for any horn contour can be written as:

$$\frac{1}{S} \frac{\partial}{\partial z} \left(S \frac{\partial p}{\partial z} \right) = \frac{1}{c^2} \frac{\partial^2 p}{\partial t^2} \tag{1}$$

where p is the wave pressure, c the acoustic speed, and S the horn area, πR^2, with R, the horn radius, a function of z, the distance along the symmetry axis.

A wave launched into the wide base of the cone propagates toward the apex gaining both in intensity and speed. The fluid velocity along the axis of the horn is given by:

$$\frac{\partial v}{\partial t} = -\frac{1}{\rho} \frac{\partial p}{\partial z} \tag{2}$$

where ρ is the mass density, while the approximate wave pressure can be written[10]:

$$p \approx \frac{A}{R} \exp\, i\, (\omega t - kz) \tag{3}$$

where A is a constant, t is time, ω is the wave frequency, and k is the wave number.

The total alternating force exerted over an area S by an acoustic pressure p is pS, so with alternating particle velocity u the acoustic power flowing becomes[11]:

$$W = \langle up \rangle\, S. \tag{4}$$

Power balance through the accelerator demands that the alternating particle velocity at the apex (pellet position) be given by:

$$u_a = \beta u_0 \frac{R_0}{R_a} \tag{5}$$

where u_0 and R_0 are the initial alternating particle velocity (imposed by the explosive) and accelerator base radius, respectively, while R_a is the accelerator radius at the pellet location (apex). β is introduced to account for imperfect efficiency. Commercial ultrasonic horns (transmitting either a pulse or cw) yield beta values of about $0 \cdot 7$ for a multiplication of 4 to 5 times the incident sound speed[12].

As an acoustic disturbance approaches the apex (focus) of a cone its magnitude will increase until it reaches the structural limit of the material and the tip is "spalled" (detached and propelled) off. In plane geometry, when a sonic pulse approaches a material-vacuum interface the outermost layers spall off, taking part in the overall conservation of momentum and energy across the boundary[13]. If the surface layer (the "pellet" in our experiment) is very weakly bound at this point (and not too thick) it can attain approximately the alternating particle velocity u_a. In experiments in plane geometry the precursor spall actually achieves very nearly the incident pulse velocity[13].

The preformed interface of dissimilar pellet and accelerator materials, plus the effect of tamping reinforcement, should facilitate ejection of the properly sized pellet mass. A material like Beryllium is assumed for the accelerator in order to provide a sound speed in excess of 10^4 m/s and a high compressional strength. If a cylindrical driver is employed then a catenary horn shape is preferred[10] for coupling in $u_0 \gtrsim 10^5$ m/s.

There is an ultimate limitation on the pellet speed attainable in this device. Once the wave energy density becomes too high the compressive strength of the horn will be exceeded and the acoustic wave will be transformed into an evaporation wave[14]. This saturation will occur at about 3 to 5×10^4 m/s.

An additional factor of ~ 10 might be obtained in velocity amplification if Monroe focusing is employed[4]. Matter streams of at least 9×10^4 m/s have been achieved in the laboratory in just this way[15]. A concave accelerator apex and pellet are needed for Monroe focusing (Fig. 1 a) and a smaller pellet aspect ratio (diameter/length) results.

One can, in fact, use any number of further stages of shaped charge acceleration. An array composed of many-shaped charges with jets all impinging upon one another at an angle (*i.e.*, the jets all converging along a conical surface towards a focus) will lead to a second focusing and additional nonlinear acceleration.

The required pellet kinetic energy of $\lesssim 10^7$ Joules corresponds to the energy available from one or two pounds of common high explosive[13]. An overall energy conversion efficiency, β^2, can be computed from the coupling, horn, and Monroe cavity efficiencies of references 9, 12, 4, 16 and 17. A minimum explosive fill of about 500 pounds is suggested.

It is interesting to compute the fill required for yet another, simpler, accelerator model shown in Fig. 1 b. Here the impulse of the first, explosively driven, mass is delivered

through a chain of successively lighter and, thence, faster moving flier plates until the required pellet speed is reached. The speed of the pellet is just:

$$V = [(K)^{1/2}(2m_i/m_i + m_j)]^N V_0, \quad MR = m_i/m_j \tag{6}$$

where MR is the ratio of masses of the preceding and succeeding flier plates, N is the number of collisional stages employed, V_0 is the initial velocity input, and K is the coefficient of restitution of the collisions.

If it is assumed that 7 or 8 stages are used and K is about $0 \cdot 9$ then it is easy to show that about 1000 to 2000 pounds of explosive fill is adequate. Again we can see the importance of the compressional strength in limiting the pellet speed that can ultimately be developed by a shock focusing accelerator. In practice succeeding "flier plates" of different density materials (perhaps in the gaseous state) might be involved.

In conclusion, a prototype accelerator should be constructed out of conventional materials to determine if projectiles can be imparted with the requisite velocity *via* the variety of linear and nonlinear acceleration mechanisms available.

This can be accomplished with a sub-scale system at very low cost. If the result is promising then a full scale model should be built and an ignition experiment attempted

Acknowledgement

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