NUCLEAR FUSION BY MECHANICAL ADIABATIC COMPRESSION OF A DENSE PLASMA

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ABSTRACT

Thermonuclear fusion rates for particles of a single species are proportional to n^2, where n is the number density of the reacting particles. Standard magnetic confinement techniques employ relatively thin plasmas with $n \approx 10^{15}$ cm^{-3} and therefore require temperatures of the order of 10^8 K. We propose a method to exploit the n^2 factor and hence to attain appreciable fusion rates at lower temperatures. We consider a dense gas of deuterium to undergo a rapid, adiabatic compression by a piston in an adiabatically insulated reaction chamber. A reduction in the degrees of freedom of the plasma particles, such as may be effected by an electric discharge during the compression or by application of suitably disposed external magnetic fields, results in a higher final temperature for a given energy input. In model calculations we consider the adiabatic compression of one mole of deuterium initially at room temperature and pressure and we compare the fusion energy release with the work done by the piston. We examine the effects of varying degrees of freedom and of varying compression ratios in both an ideal gas and a van der Waals gas. Additional fusion-enhancement factors such as the adiabatic insulating environment are discussed.

1. INTRODUCTION

Thermonuclear fusion rates for particles of a single species are proportional to n^2, where n is the number density of the reacting particles. Standard magnetic confinement techniques employ relatively thin plasmas with $n \approx 10^{15}$ cm^{-3} and therefore require temperatures of the order of 10^8 K. We propose herein a method to exploit the n^2 factor and hence to attain appreciable fusion rates at lower temperatures. Principal features of the method include the rapid, adiabatic compression by a piston of a dense gas of deuterium in an adiabatically insulated reaction chamber and a reduction in the degrees of freedom of the plasma particles. We emphasize that certain concepts and calculations presented herein contain simplifying assumptions and idealizations and that the conditions corresponding to them may not easily be realized in practice. In this respect one might regard the results as limiting cases to be attained under ideal conditions.

2. FUSION PROCESS

2.1 Adiabatic compression of an ideal gas

Consider an adiabatically insulated chamber as depicted in Figure 1 with a movable piston as one of its walls and containing one mole of deuterium gas initially at atmospheric pressure and room temperature. Since one mole occupies 2.24×10^4 cm^3 at T = 273 K, the volume at 300 K is

V_0 = 2.46 × 10^4 cm^3 and the initial number density of deuterons is $n_0 = 2N_A/V_0 = 4.90 \times 10^{19}$ cm^{-3} where N_A is Avogadro's number and the factor of two appears because there are two deuterium atoms per molecule. We now subject this gas to a rapid compression by driving the piston by some external means such as an explosive device. The process is, in a limited sense, analogous to that of shock-compression by a magnetic piston [1,2]. Upon the resulting rise in temperature, we expect the deuterium molecules to dissociate into atoms and subsequently to form a plasma of deuterons and electrons.

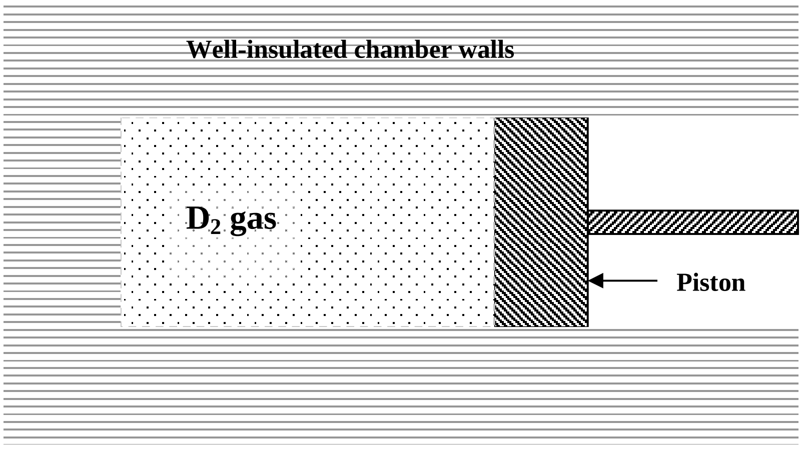

Figure 1. Compression of deuterium gas by a piston.

For an adiabatic compression, the thermodynamic relationships among the final pressure, volume and temperature for an ideal gas are

$$PV^{\gamma} = \text{ constant}, \quad TV^{\gamma-1} = \text{ constant}, \tag{1}$$

where γ is the specific heat ratio. Expressing the constants in terms of initial values P_0, V_0, T_0, and introducing a volume compression factor $\beta = V_0/V$ yields

$$P = P_0\beta^{\gamma}, \quad T = T_0\beta^{\gamma-1}. \tag{2}$$

We note that the final temperature varies with the compression factor and depends exponentially upon the specific heat ratio.

The work to perform the compression is given by the negative of the integral of the pressure taken over the volume of the gas from its initial value V_0 to its final value $V = \beta^{-1}V_0$. Upon introduction of P from the first of Eqs. (1), the integral becomes

$$W = -P_0V_0^{\gamma}\int_{V_0}^{V} V^{-\gamma}dV = \frac{P_0V_0}{\gamma-1}(\beta^{\gamma-1}-1). \tag{3}$$

2.2 Degrees of freedom

The specific heat ratio γ is related to the number f of degrees of freedom of the gas particles by $\gamma = (f + 2)/f$. With this relation, the second of Eqs. (2) becomes

$$T = T_0 \beta^{2/f} \ . \qquad (4)$$

Thus we see that if the particles are deprived of some of their freedom of motion, a larger temperature rise results from a given energy input. For a monoatomic gas $f = 3$ and the exponent on the compression factor is 2/3. For two degrees of freedom, the exponent increases to one and a further constraint on the motion increases the exponent to two.

We propose that, concomitant with the adiabatic compression. a reduction in the degrees of freedom be effected by an electric discharge through the plasma in the direction of the moving piston with the piston serving as one electrode and the chamber wall toward which the piston is headed serving as the other. We justify this assertion by transforming our frame of reference from the laboratory to that of the moving plasma; in that reference frame, the deuterons possess only the two degrees of freedom transverse to their motion in the electric discharge. In addition, we would expect the discharge to produce a pinch effect [3]. It is well known that the degrees of freedom can be controlled by suitably disposed external magnetic fields [4] and we propose that such techniques be employed in addition to the electric discharge.

Rewriting Eq. (5) in terms of the degrees of freedom yields

$$W = \tfrac{1}{2} P_0 V_0 (\beta^{2/f} - 1) \approx \tfrac{1}{2} P_0 V_0 \beta^{2/f} \ . \qquad (5)$$

We note that the work to compress the plasma also increases with reduction of degrees of freedom.

2.3 Nuclear fusion energy release

The thermonuclear reaction rate per unit volume for particles of a single species is given by

$$r = \tfrac{1}{2} n^2 \langle \sigma v \rangle \qquad (6)$$

where σ is the reaction cross-section and v is the relative velocity of the interacting nuclei. Empirical data for D-D reactions provide a relation for σ as a function of v which, when averaged over all possible relative velocities, yields

$$\langle \sigma v \rangle_{DD} = 2.33 \times 10^{-14} T^{-2/3} \exp(-18.76\, T^{-1/3}) \quad \mathrm{cm}^3 - \mathrm{s}^{-1}, \quad T < 50 \ \mathrm{keV}, \qquad (7)$$

for a Maxwellian distribution and for T expressed in keV [5]. The reaction power density is the product rQ where Q is average energy released per reaction so that in a volume $V = \beta^{-1} V_0$, the corresponding fusion energy release in a time interval δt is

$$\delta E = rQV\delta t \ . \qquad (8)$$

The fraction of the total supply of fuel which reacts in this volume and time interval is given by

$$\frac{rV\delta t}{n_0 V_0} = \frac{r\delta t}{n_0 \beta}. \tag{9}$$

The reactions of interest are the primary reactions

$$\begin{aligned} &\mathrm{D + D \rightarrow T + p + 4.03\ MeV} \\ &\mathrm{D + D \rightarrow {}^3He + n + 3.27\ MeV} \end{aligned} \tag{10}$$

and the secondary reactions

$$\begin{aligned} &\mathrm{D + T \rightarrow} \alpha \mathrm{+ n + 17.6\ MeV} \\ &\mathrm{D + {}^3He \rightarrow} \alpha \mathrm{+ p + 18.3\ MeV.} \end{aligned} \tag{11}$$

In the calculations below we consider only the primary reactions. Since these reactions occur at approximately equal rates, we use an average energy release of Q = 3.65 MeV = 5.85×10^{-5} ergs.

3. FUSION RATES FOR AN IDEAL GAS

Although fusion reactions occur at all instants during the compression, for simplicity we calculate the fusion energy generated only in the final state of the process, i.e. that of maximum compression where $n = \beta n_0$, $V = \beta^{-1} V_0$ and $T = T_0\, \beta^{2/f}$. To compare the energy generated by fusion with that expended to drive the piston, we form the ratio $\delta E/W$ which, for given Q and δt, depends only upon β and f. With $P_0 = 1.01 \times 10^6$ dyne-cm^{-2}, T_0 = 300 K = 2.59×10^{-5} keV and δt = 0.001 s we obtain values of $\delta E/W$ which are shown in Table 1 for various compression factors and for one, two and three degrees of freedom. Also tabulated for each case are the final temperature, reaction rate, reaction power density and the fuel burnup fraction.

f	β	T (K)	r (cm^{-3}-s^{-1})	rQ	$\delta E/W$	$r\delta t/\beta n_0$
3	100	6.46×10^3	3.9×10^{-68}	$\sim 10^{-67}$	7.4×10^{-86}	$\sim 10^{-92}$
3	200	1.03×10^4	1.6×10^{-53}	$\sim 10^{-52}$	9.2×10^{-72}	$\sim 10^{-78}$
2	100	3.00×10^4	2.6×10^{-50}	$\sim 10^{-49}$	1.5×10^{-68}	$\sim 10^{-74}$
2	200	6.00×10^4	5.9×10^{-38}	$\sim 10^{-37}$	8.5×10^{-57}	$\sim 10^{-62}$
1	100	3.00×10^6	1.1×10^{17}	$\sim 10^{17}$	1.3×10^{-3}	$\sim 10^{-8}$
1	200	1.20×10^7	9.6×10^{21}	$\sim 10^{22}$	1.4×10^1	$\sim 10^{-3}$

Table 1. Values of final temperature, reaction rate, power density, fuel burnup fraction and the ratio $\delta E/W$ are computed for a time interval of 0.001 second and for various values of compression factor and degrees of freedom in an ideal gas.

The table shows how temperatures and reaction rates increase with higher compression ratios and with lowered degrees of freedom. Note that for β = 200 and f = 1 the nuclear energy release exceeds the work required to effect the compression.

4. NON-IDEAL GAS BEHAVIOR

For simplicity, the previous analysis was carried out for an assumed ideal gas. A more realistic approach is to consider non-ideal gas behavior and for this purpose we consider the van der Waals equation of state

$$\left(P + a\frac{N^2}{V^2}\right)(V - Nb) = NRT \qquad (12)$$

in which N is the number of moles, R is the Universal gas constant and the constants a and b are determined empirically. The pressure correction considers the long range attraction of the particles while the volume correction arises from their finite size. For an adiabatic compression, the analogs to the previous equations for the temperature increase are

$$\begin{aligned} T &= T_0\left(\frac{V_0 - Nb}{V - Nb}\right)^{\gamma-1} \\ &= T_0\beta^{2/f}\left(\frac{V_0 - Nb}{V_0 - \beta Nb}\right)^{2/f} \\ &= T_{ideal}\left(\frac{V_0 - Nb}{V_0 - \beta Nb}\right)^{2/f} \end{aligned} \qquad (13)$$

in which we note that the first factor is the temperature increase for an ideal gas and that the factor multiplying it exceeds one. Thus the van der Waals gas attains a higher final temperature and hence a higher fusion reaction rate than does the ideal gas. We note also that the denominator expression limits the compression factor to values $\beta < V_0/Nb$.

The work to compress the gas is again the negative of the volume integral of the pressure. Solving Eq. (11) for P and using Eq. (12) to eliminate T, we obtain.

$$\begin{aligned} W &= -NRT(V_0 - Nb)^{\gamma-1}\int_{V_0}^{V}(V - Nb)^{-\gamma}dV + aN^2\int_{V_0}^{V}V^{-2}dV \\ &= \frac{NRT}{\gamma-1}\left[\left(\frac{V_0 - Nb}{V - Nb}\right)^{\gamma-1} - 1\right] - aN^2\left(\frac{1}{V} - \frac{1}{V_0}\right). \end{aligned} \qquad (14)$$

With substitution of $V = \beta^{-1}V_0$ and γ-1 = 2/f, Eq. (14) becomes

$$\begin{aligned} W &= \frac{NRT_0 f\beta^{2/f}}{2}\left[\left(\frac{V_0 - Nb}{V_0 - \beta Nb}\right)^{2/f} - \beta^{-2/f}\right] - \frac{aN^2}{V_0}(\beta - 1) \\ &= W_{ideal}\left[\left(\frac{V_0 - Nb}{V_0 - \beta Nb}\right)^{2/f} - \beta^{-2/f}\right] - \frac{aN^2}{V_0}(\beta - 1) \end{aligned} \qquad (15)$$

in which we recognize the first factor as the work to compress an ideal gas.

Detailed computations of *T* and *W* require numerical values for the van der Waals constants for deuterium. For our purposes, we assume the value of *b* for deuterium to be close to that of hydrogen, namely $b \approx 0.027$ liters per mole. The constant *a* appears only in the subtracted term in the expression for *W* and we will ignore this term so as to overstate the value of the work to compress the gas. Using Eqs. (12) and (14) we compute values of *T*, *r*, *rQ* and $\delta E/W$ as well as the fuel burnup fraction for the same values of β, *f* and δt employed for the ideal gas. These results are contained in Table 2.

f	β	T (K)	r (cm^{-3}-s^{-1})	rQ	$\delta E/W$	$r\delta t/\beta n_0$
3	100	7.8×10^{3}	2.4×10^{-62}	$\sim 10^{-67}$	3.8×10^{-80}	$\sim 10^{-86}$
3	200	1.6×10^{4}	4.1×10^{-42}	$\sim 10^{-52}$	2.4×10^{-60}	$\sim 10^{-67}$
2	100	3.9×10^{4}	2.8×10^{-45}	$\sim 10^{-49}$	1.7×10^{-63}	$\sim 10^{-69}$
2	200	1.2×10^{5}	7.1×10^{-29}	$\sim 10^{-37}$	1.0×10^{-47}	$\sim 10^{-53}$
1	100	5.2×10^{6}	1.1×10^{19}	$\sim 10^{17}$	1.2×10^{-1}	$\sim 10^{-6}$
1	200	4.5×10^{7}	2.9×10^{24}	$\sim 10^{22}$	4.1×10^{3}	~ 0.3

Table 2. Values of final temperature, reaction rate, power density, fuel burnup fraction and the ratio $\delta E/W$ are computed for a time interval of 0.001 seconds and for various values of compression factor and degrees of freedom in a van der Waals gas.

Although values of both *T* and *W* for the van der Waals gas exceed those of comparable cases for the ideal gas, the increased reaction rate for the van der Waals gas more than compensates the increase in the work done. Comparison of the highest values of $\delta E/W$ shows that the van der Waals gas value exceeds that of the ideal gas by a factor of almost 300. Clearly the perfect gas idealization understates the efficacy of the process.

5. DISCUSSION

5.1 Caveats and additional considerations

Since these calculations suggest the possibility of achieving better than breakeven conditions, one should be aware that we have assumed that all the energy released by the explosive charge served to drive the piston and that we have considered neither frictional energy losses associated with the motion of the piston nor energy expended to establish both the electric discharge and the magnetic fields required to reduce the degrees of freedom. To compensate for these omissions, we have taken care to avoid weighting the results unduly in the direction of high yields. Thus we assumed that fusion occurs only at the moment of maximum compression but this understates the case since some fusion will certainly occur at all instants in the compression with release of energy resulting in a temperature rise exceeding that of our calculation. More realistic results would obtain with computations based on the kinetics of the reactions considered over a continuous time interval. We have also ignored the secondary reactions Eqs. (11) whose energy releases exceed those of the primary reactions by a factor of ≈ 5. We have left out of account various enhancement processes such as special coatings of the interior walls of the reaction chamber which, when vaporized by the high temperatures, would increase the number of deuterons available for fusion reactions. We have also ignored the volume compression and temperature rise associated with the pinch effect as well as the shielding effects of the electron gas which reduce the nuclear potential barrier and thereby increase the probability of fusion.

5.2 Applications

If the reaction chamber is adiabatically insulated so that no energy is lost to the external environment, then both the work to compress the plasma and all the energy released, whether by nuclear processes or radiation from charged particles in the plasma, serve to increase the thermal energy of the plasma and thereby to increase the fusion reaction rates still further. In such a device all the energy expended to create the fusion conditions should soon be compensated and there would be a net energy gain. Applications can be based either on a single compression or on a reciprocating engine undergoing multiple compressions. A single compression device could provide a burst of neutrons such as may be required to initiate fission reactions. A reciprocating device in which a piston moves between identical cylinders could provide pulsed sources of neutrons or electromagnetic radiation, be coupled mechanically to external devices or induce electric currents in externally wound coils as depicted in Figure 2. Only the initial compression need be actuated externally since subsequent compressions in one chamber would result from excess pressures developed in the other chamber and energy breakeven need not be attained in the initial compression.

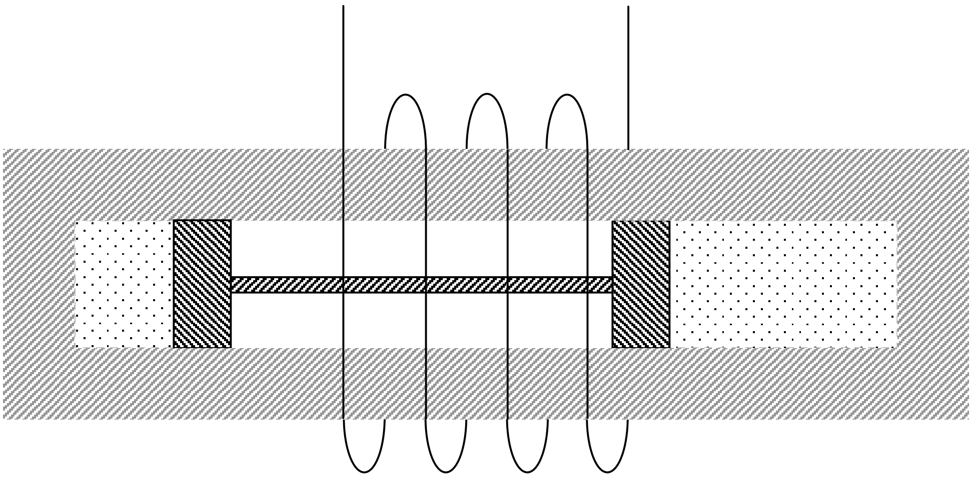

Figure 2. Dual piston reciprocating device with externally wound coils.

5.3 Implementation

The proposed process is relatively simple in concept and it should be possible to test the process in a short time and at relatively little cost. However, it is anticipated that ingenuity will be required to overcome the technical challenges facing successful operation of a practical device. For example, leakage of plasma particles through the space between the chamber wall and the piston must be arrested. Such leakage can be minimized by the rapidity of the compression and by coating the chamber walls with high-temperature, self-lubricating bearing materials such as those used in supersonic transport applications. Damage to the reaction chamber walls is another concern. Here the pinch effect arising from the proposed electric discharge can serve to keep plasma particles away from chamber side walls. It will also be useful to draw upon the work of Gross [1,2] and of Feinberg and Gross [6] who studied plasma-wall interactions and damage to wall materials in chambers containing plasmas subjected to shock-compression by a magnetic piston. It is of interest to note the assertion by Gross that under suitable conditions "wall evaporation may not be the catastrophic problem that is often intuitively imagined" and that the temperatures of his plasmas reached $\approx 5 \times 10^6$ K [6].

6. SUMMARY

We propose a fusion process based on the adiabatic compression by a piston of a dense plasma with reduced degrees of freedom. Our calculations indicate that substantial fusion yields can be obtained at temperatures lower than those commonly associated with fusion devices. We caution, however, that owing to simplifying assumptions, the results should be regarded as ultimate targets to be attained under the ideal conditions assumed.

7. ACKNOWLEDGMENTS AND DEDICATION

Prof. J. R. Roth informed the author of the work on shock compression by a magnetic piston and Dr. Robert Butler provided helpful comments. The basic ideas elaborated herein were conceived by the late Prof. Lloyd Motz and this work is dedicated to his memory in grateful recognition of his contributions, guidance and friendship.

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