An Idealized Scenario for Energy Generation by Nuclear Fusion

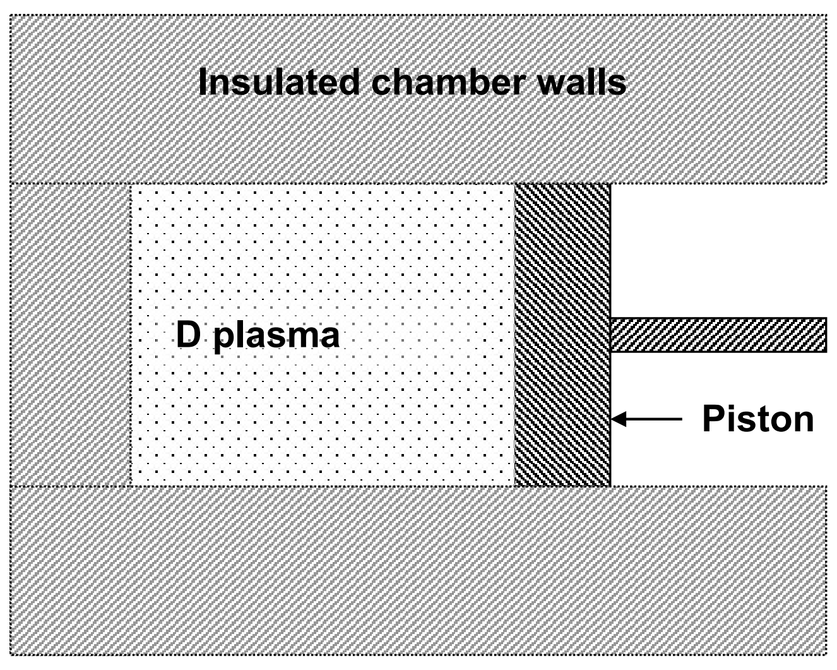
David W. Kraft and Issa Dababneh
College of Arts & Sciences, University of Bridgeport

Abstract

We study nuclear fusion processes in a deuteron plasma under a combination of conditions such that, for a given energy input, a maximum energy output can be attained. Specifically we consider fusion processes initiated by the rapid adiabatic compression by a piston of a deuteron plasma contained in a well-insulated chamber. To exploit the n^2 factor in the fusion reaction rate, we consider one mole of plasma which, at ambient temperature and pressure, provides a particle density of ~ 10^{19} cm^{-3}. Reaction rates are enhanced by the application of magnetic and electric fields to reduce the degrees of freedom of the plasma, thereby lowering its heat capacity and producing a higher temperature increase for a given energy input. Computations show that the combination of adiabatic operation, high particle density and reduced degrees of freedom can result in appreciable fusion rates at temperatures lower than those in magnetic confinement experiments. We consider both primary D-D and secondary D-T reactions. Conditions of energy break-even were found at temperatures of the order of 10^6 K.

Process description

One mole of a deuteron gas in a well-insulated chamber undergoes a rapid adiabatic compression by a piston. Adiabatic conditions mean that the energy is retained internally. Suitably disposed magnetic and electric fields can reduce the degrees of freedom of the gas, thereby decreasing its heat capacity with the result that higher temperatures are attained for a given energy input. Since nuclear fusion reaction rates are sensitive functions of temperature, the resulting energy release can exceed the energy required to compress the gas. Details of the computations follow.



Starting conditions One mole D at room P and T.

Apply compression. T increases.

Assumptions. Make simplifying assumptions.
Reversible adiabatic compression
Apply equilibrium thermodynamics
Treat as *van der Waals* (vdW) gas: $(P + aN^2/V^2)(V - Nb) = RT$

Degrees of freedom γ = specific heat ratio
Relate to degrees of freedom f of the gas: $\gamma = (f + 2) / f$.
For monoatomic gas: f = 3
Deprive particles of freedom of motion ⇒ larger T increase for a given energy input. Accomplish with
(1) External magnetic field(s)
(2) Electric discharge in direction of piston motion.
Also ⇒ Pinch Effect.

Adiabatic compression of a vdW gas

$$T = T_0\left(\frac{V_0 - Nb}{V - Nb}\right)^{\gamma-1} = T_0\left(\frac{\beta(V_0 - Nb)}{V - \beta Nb}\right)^{2/f}$$

Work to compress a vdW gas

$$W = -\int_{V_0}^{V} P\,dV = \frac{NRT_0 f}{2}\left[\left(\frac{\beta(V_0 - Nb)}{V_0 - \beta Nb}\right)^{2/f} - \beta^{-2/f}\right] - \frac{aN^2}{V_0}(\beta - 1).$$

Nuclear fusion reactions

Primary: $D + D \rightarrow T + p + 4.03\ \text{MeV}$ (T = tritium)
$D + D \rightarrow {}^3He + n + 3.27\ \text{MeV}$

Secondary: $D + T \rightarrow \alpha + n + 17.6\ \text{MeV}$
$D + {}^3H \rightarrow \alpha + p + 18.3\ \text{MeV}$

Energy release

Primary reactions occur with ≈ equal probability o
1st secondary reaction has much higher probability than 2nd.

Energy release in time Δt: $\Delta E = r\,Q\,V\,\Delta t$.
Q = av'g reaction energy release/reaction ; r = computed reaction rate

Expect fusion reactions to occur continuously throughout the compression. However, appreciable temperatures and hence fusion energies of interest are not attained until 99.99 % of available volume is traversed.

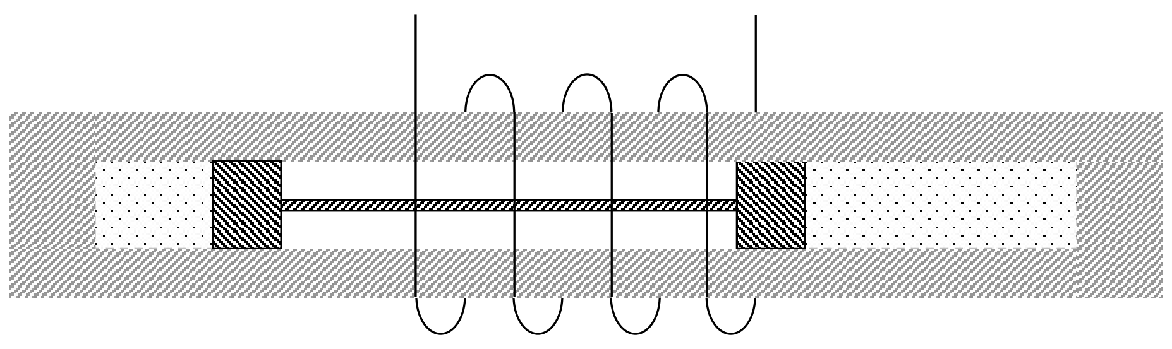
The volume was subdivided into discrete intervals. The temperature increase and the resulting energy releases from primary and secondary reactions were computed. The energy release results in an increase in temperature which is then used as the initial temperature of the next step.

Calculate $\Delta E / W$ for $\beta = 100$. f = 1. $\Delta t = 0.1$ s,
β = compression factor, f = no. degrees of freedom.
Results
Final Stage Compression: 99.99%
$T = 4.8 \times 10^6$ K, $\Delta E / W \approx 2.4$.

Energy break-even attained at $T \approx 4.5 \times 10^6$ K.

Applications

Single shot: Neutron source to initiate fission.
Multiple compressions in dual chambers – reciprocating engine.
Surround with coil to extract electrical energy.



Summary and Conclusions

Exploited effects of n^2 factor and reduced degrees of freedom.
Adiabatic conditions ⇒ energy retained internally.
Obtained energy break-even at temperatures lower than those in standard fusion experiments

To be more realistic:
Must consider particle losses via leakage.
Consider Pinch Effect.

Possible enhancements:
Coat chamber walls with deuterated compound to increase n.

References

David W. Kraft, *Nuclear Fusion by Mechanical Adiabatic Compression of a Dense Plasma,* Proceedings of the 13th International Conference on Emerging Nuclear Energy Systems, ICENES 2007, İstanbul/Türkiye (3 – 8 June 2007) S. Şahin (Ed.) ISBN-978-975-01805-0-7.

David W. Kraft and Robert G. Butler, *Multistage Fusion Reaction Rates In An Adiabatically Compressed Plasma*, Transactions of Fusion Science and Technology **61**, 475 (2012).

David W. Kraft and Robert G. Butler, *Secondary Fusion Reactions in the Mechanical Adiabatic Compression of a Dense Plasma*, Presented at 16th International Conference on Emerging Energy Systems, ICENES 2013, Madrid, Spain (26-30 May, 2013) .