Volume Ignition in Pellet Fusion to Overcome the Difficulties of Central Ignition

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Dedicated to Professor Dieter Pfirsch on his 60th Birthday

Z. Naturforsch. **42 a**, 1239–1240 (1987);
received July 14, 1987

Since C. Yamanaka et al. demonstrated that the best fusion gains from laser irradiated pellets result only when central shocks are avoided and an ideal volume compression is achieved, the problems of the central (spark) ignition with necessary densities of 1000 times the solid state may be overcome. Based on an analytical formula of volume ignition, the new conditions should provide reactor adequate laser fusion with compression to 50 to 100 times solid state.

Yamanaka et al. [1] reported that laser fusion from laser irradiation of thin glass shell pellets of about 0.8 mm diameter filled with about 3 atm 1:1 deuterium tritium gas mixtures produced the highest fusion gains if the usually aimed central shock compression was avoided and an ideal volume compression was used. The significant role of the adiabatic compression was well known [2, 3], only the experimental verification was not evident before the Yamanaka-compression was achieved. This result simplifies the broad stream of attempts since 1969 [3] to compress the pellet by the lasers in such a way that a central shock produces a very small 100 Million degrees plasma of 1000 times solid state density which ignites a self sustained fusion combustion wave to burn the surrounding plasma. Though a revision of this spark ignition with the recent results of electric double layers [4] may improve the conditions and the necessary density may possibly go down to 500 times the solid state, the problems of very precisely reaching the spark conditions and to control instabilities apart from insufficient knowledge of the basic mechanisms in the fusion combustion wave indicate how far away we are from verification of central ignition [5].

The widely ignored volume compression resulted in an ignition-free burn formula of the fusion gain [6] G if an energy

$$E_0 = 8\pi R_0^3 n_0 kT_0/3 \tag{1}$$

was homogeneously distributed to a DT mixture of initial density n_0 of a spherical volume V_0 with an initial radius R_0 resulting then in an initial (average energy related) temperature T_0 using the Boltzmann constant k, of

$$G = (E_0/E_{BE})^{1/3} (n_0/n_s)^{2/3}, \tag{2}$$

where E_{BE} is the break-even energy (1.6 MJ for DT), and n_s is the solid state density, if the initial temperature was of the optimum value

$$T_{opt} = 10.4 \text{ keV}. \tag{3}$$

This was the result of numerical calculations using the empirical fusion cross sections averaged over Maxwellian velocity distributions and using the self-similarity model of the adiabatic hydrodynamic expansion [3]. Using (1), Eq. (2) results in the algebraically identical formula published later by Kidder [7]

$$G = C n_0 R_0 \tag{4}$$

where the completely independent derivation arrived at a constant C which differed from (2) by a factor of about 2. This was fully within the numerical acuracy test on which (2) was derived and mutually confirmed the correctness of the derivations of (2) and (4).

Kidder was aware [7] of the insufficience of the formulas since the interaction of the alphas of the fusion reactions with the pellet and the resulting "self-heat" as not included. The inclusion of self-heat by the fusion neutrons is not yet included in the following discussions; while these do not result in any improvement for spark ignition it was estimated that the self heat by neutrons may improve the volume compression results by a factor 2 according to Goel [8]. Performing the computations of G with inclusion of the fuel depletion, bremsstrahlung loss with inclusion of the radiation transport process based on the classical absorption constants [3] and including the alpha self-heat including the alpha transport process, and using a stopping power in agreement with the numerous other models in the relevant temperature range [9], resulted in the discovery of the *volume ignition* process at volume compression, first published in 1978 [10]. It was observed numerically that the optimum temperature (3) decreased and that the fusion gain curve for constant initial volume V_0 as parameter

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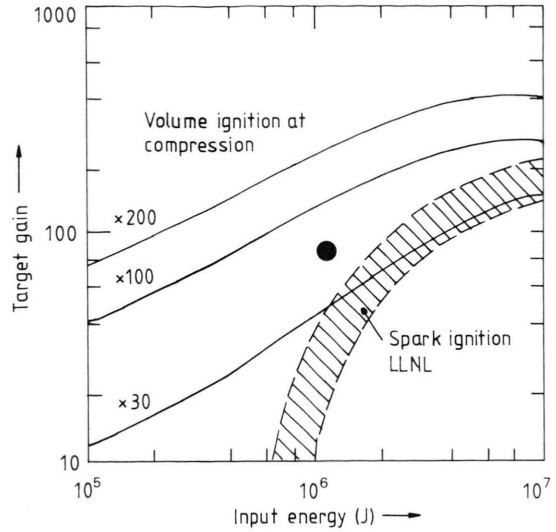

Fig. 1. Target gains for pellet fusion based on the energy incident from the laser (to distinguish from the transmitted energy E_0) for central spark ignition according to the result of LLNL [11] and the 20% hydrodynamic efficiency calculations of volume ignition (fully drawn lines) for densities given in multiples of the solid state density. The big dot is the computed result for Yamanaka compression according to Takabe [14].

nearly made a discontinuous jump to values 10 to 100 times higher than values without ignition.

I view of Yamanaka's result, we derived now the first analytical formula for the fusion gains with alpha self-heat from the numerical-empirical results of the following kind

$$G = \left(\frac{E_0}{E_{BE}}\right)^{1/3} \left(\frac{n_0}{n_s}\right)^{2/3} \frac{E_0/(7.1 \times 10^3\, n_s/n_0)^2}{[1 + E_0/(5 \times 10^3\, n_s/n_0)^2]^{1/2} - 1}, \quad (5)$$

where E_0 is in J and the optimum temperature is

$$T_{opt} = 10.4\, \frac{\{[25 + 10\,(E_0/E_{BE})^{1/3}(n_0/n_s)^{2/3}]^{1/2} - 5\}}{(E_0/E_{BE})^{1/3}(n_0/n_s)^{2/3}}\ \mathrm{keV} \quad (6)$$

for $G < 200$ otherwise the corrections for fuel depletion will need a further modification. These new formulas (5) and (6) are possible only since a systematic structure of the optimum fusion gain curves with a change for the volume ignition at G of about 5 could be identified and understood from the physics resulting then in a stopping range of about 3 to 5 g cm^{-2} (which stopping process has nothing to do with Kidder's constant in Eq. (4) apart from the same dimension).

From the results in Eq. (5) we can derive that the volume ignition can result in reasonable target gains in the range of 80 with compressions of 50 to 100 times the solid state at incident laser energy in the MJ range only (Figure 1). This is to be compared with the gains calculated by the Lovermore Laboratory LLNL [11] for spark ignition with compression to 1000 to 10000 times the solid state density. Since target gains of 23 are necessary only for a reactor under optimistic conditions [5], gains of 80 will come into the realistic range for the basically straight forward pellet fusion reactors.

The extensive checking of the reported formulas (5) and (6) by Shalom Eliezer, Gordon-Godfrey-Visiting Professor at UNSW on leave from the SOREQ NRC in Tel Aviv, Israel, in March 1987 and discussions during a special conference with Prof. Sir Ernest Titterton, Canberra, and Prof. K. Mima (Osaka) are gratefully acknowledged.

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Verantwortlich für den Inhalt: A. KLEMM
Satz und Druck: Konrad Triltsch, Würzburg