Boost for Laser Fusion

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The exciting break-through in laser fusion experiments announced by Chiyoe Yamanaka at the 7th Conference on "Laser Interaction and Related Plasma Phenomena" in Monterey on 30 October, 1985 has prompted a number of reappraisals at the major laboratories.

The two largest experiments in the world are the Gekko XII laser at the Institute for Laser Engineering at the University of Osaka and the NOVA laser at the Lawrence Livermore National Laboratory. The latter which had recently become operational uses ten neodymium-glass laser beams of 78 cm diameter as source, each of which is fired through crystals that can double or triple the laser frequency and deliver a total peak power in the range of 50 TW on to the target pellet. This contained a deuterium-tritium mixture, but the exact design is classified. The frequency multiplying is to give better coupling to the target and reduce non-linear effects which simplifies the analytical problem. Efficiencies of production are about 70% for the second and 45% for the third harmonic. J.T. Hunt reporting on the first experiments with NOVA confirmed that with a laser pulse in the range of 30 kJ in the second harmonic, good agreement with theoretical expectations was obtained. The pulse energy employed was however less than half the value originally planned, as there are problems with the glass which contains a few parts per billion of platinum in metallic form (impurities from the crucible used in manufacture). This puts a limit on the intensity as at higher powers, absorption by the platinum would lead to damage. Replacement would take two years and cost 8-10 M$. Moreover glass manufacturers indicate that reliable methods for producing glass without this disadvantage are still not developed.

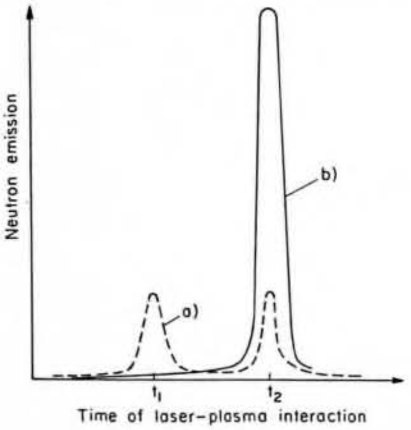

Fig. 1 — Time resolved neutron emission from laser irradiated pellets (a) with first central compression and later volume compression; (b) with single volume (soft-volume) compression of Yamanaka.

The Gekko XII laser, operating with frequency doubling cells, provides laser pulses of about 100 ps duration and delivers an energy to the target pellet of about 8 kJ. The targets giving the high fusion neutron gains reported by Yamanaka were thin shell glass micro-balloons of 1 mm diameter filled with 3 atm DT. Their success was the culmination of a large series of shots done under a wide range of conditions: different wavelengths, pulse duration, and target type. The highest compression achieved (5 G atm) was an absolute record and the highest neutron production (1.2×10^{12} per shot) was ten times higher than the preceding record held by the Institute of Laser Energetics of the University of Rochester (April 1985). However, this figure was topped in January of this year at Livermore where 1.1×10^{13} neutrons per shot have been produced from similar pellets using the third harmonic and 18 kJ pulses.

As was explained to the Monterey conference, the key lies not only in having direct drive coupling into a glass balloon target, but also a kind of a soft volume-ignition instead of the "pusher" or "ablation" regimes aimed for in earlier experiments. In most experiments, in recent years the aim has been compression of the pellet centre which should lead to a self-sustaining combustion wave. In practice, two temporally separated neutron emission peaks of only modest intensity are observed at times t_1 and t_2 (Fig. 1a). Numerical calculations as shown in Fig. 2a give the same result. First, one has the hydrodynamic shock-compression of the pellet core at time t_1 producing the first neutron peak, followed by compression of the whole pellet up to a minimum radius at time t_2, resulting in the second peak. However, by changing the temporal profile of the irradiating pulse, the central core peak can be avoided, and we have only one ignition as illustrated by the follow-up computation in Fig. 2. Experimentally, this gives the highest output, a fact now confirmed by many shots. The new objective is thus volume ignition of the pellet that strictly avoids core ignition. Yamanaka stated that he fully expects neutron gains of 10^{15} per shot before 1990 — the "scientific" break-even value — but on present evidence this might be achieved much earlier.

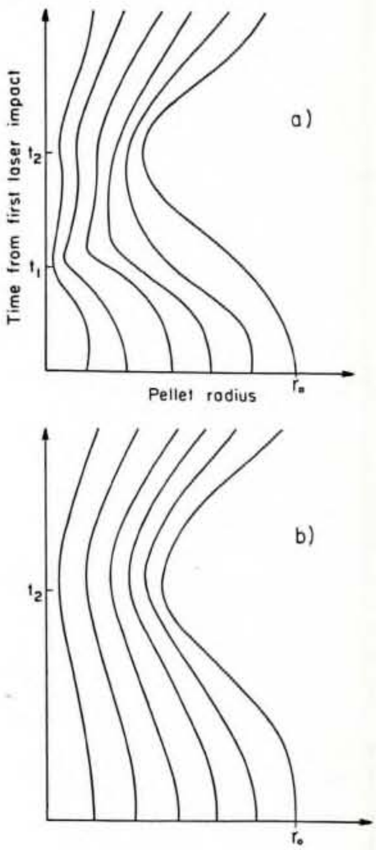

Fig. 2 — Time development of radial shells computed for the cases (a) and (b) of Fig. 1.

Experiments using a "cannon-ball" target scheme with the Gekko XII laser have also been very successful giving a density and confinement time product (with a lower plasma temperature) that is less than one order of magnitude from the goal of scientific break-even.

Reactions to Yamanaka's Result

Producing core compression and igniting a fusion combustion wave had run into serious problems and although the slow progress made does not necessarily signify that this approach is impracticable it does suggest that it is not the best in the immediate future. Difficulties with central ignition in connection with the equation of state had also been demonstrated earlier by "Eliezer's scape goat" and this had cast a shadow over laser fusion in general.

A basic problem of central ignition is that a high density homogeneously compressed plasma of sufficiently high temperature cannot easily be achieved because the laser light can penetrate only relatively low plasma densities. Heating of the pellet interior is thus by thermal conduction from the hot corona, and compression occurs only by mechanical recoil from the fast ablating corona. It is nevertheless still hoped to reach at 10 keV a central plasma density of a thousand times that of the solid state. The core should then ignite and produce a self-sustaining fusion combustion wave moving outwards, burning the surrounding lower density nuclear fuel. Compression to 100 times may well have been achieved, but the core temperature has been too low, one reason being that the thermal conduction from the hot corona is between 1/10 and 1/100 that of the ordinary thermal conduction of plasma electrons. Even if the high temperature and compression in the centre is reached, there are doubts from a number of theoretical considerations that the self sustained fusion combustion wave will really materialise.

Hence the very great interest in the overall volume compression results. Other approaches aiming at the same objective are the cannon ball variant and the snow plough system where the fuel pellet is surrounded by a mantle of heavy material that contains the radiation pressure that builds up in the intermediary space. While Yamanaka depends on hydrodynamic forces, volume ignition may also be achieved through direct electrodynamic laser-plasma interaction, but that is further in the future. For the moment laboratories will be wanting to emulate Yamanaka's results and go on from there.

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