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LASER FUSION IMPLOSION AND TARGET INTERACTION PHYSICS

Harlow G. Ahlstrom and John H. Nuckolls

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LASER FUSION IMPLOSION AND TARGET INTERACTION PHYSICS†

Harlow G. Ahlstrom and John H. Nuckolls

University of California, Lawrence Livermore Laboratory
Livermore, California 94550
(415) 447 1100 x4245

The goal of the Laser Fusion Program is to produce useful energy from the fusion of the hydrogen isotopes, deuterium and tritium. This energy is released in the form of a neutron with 14.1 MeV of energy and an alpha particle with 3.52 MeV of energy. The concept is then to convert the energy of the reaction products through a thermodynamic cycle into electricity. The approach which we employ is that of inertial confinement of the thermonuclear fuel. In this concept the inertia of the medium itself is used to provide the confinement time necessary to provide significant burnup of the thermonuclear fuel. The fuel must be raised to temperatures of the order 100 million degrees Kelvin and it must remain at a high enough density for a sufficient time to provide the necessary reactions. In the concept of laser inertial confinement fusion which was first proposed by John Nuckolls in 1961 one uses the laser to not only heat the fuel but to compress it to high densities so that the amount of energy released from a specific reaction is appropriate to the containment capability of a reactor vessel and to the energy/power capability of a practical size laser. Therefore, the laser is used to efficiently compress and heat the thermonuclear fuel to densities of 10,000 times the normal liquid density of deuterium tritium and to the reaction temperatures of several 100 million degrees Kelvin.

We first began laser implosion experiments in 1974 with the Janus laser system at power levels of .2 TW.* Since then we have progressed to operations

* 1 TW is 10^{12} watts which is equivalent to the power generating capacity of the electrical utilities in the U.S. Our fusion lasers only generate this power for a billionth of a second.

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at .4 TW with the Janus system and equivalent powers with the Cyclops laser system. Those results were reported at CLEA in 1975 and to summarize the level of the attainment of the experiments at that time we list the following achievements in those early laser implosion experiments:

The number of neutrons achieved in a single implosion experiment was 10^7

The DT ion temperatures achieved were 2 keV

The DT density was approximately one half that of liquid density

The DT gain was 10^{-4} - the DT gain is defined as the ratio of the thermonuclear energy released by the pellet experiment to the thermal energy invested in the DT fuel.

Since then we have begun utilizing the Argus laser, the world's most powerful laser system, which produces over 3 TW for target experiments. The number of neutrons from a single experiment has gone up by two orders of magnitude to greater than 10^9 . The DT ion temperatures have been increased by more than a factor of 4 up to 8 keV and the DT gain has been increased to 1%. This is the most efficient fusion reaction ever achieved in a laboratory experiment. In separate experiments utilizing the Janus spherical illumination system we have traded temperature for density in the imploded fuel and have achieved densities of approximately 5 times that of liquid density. All of these target experiments utilize spherical glass microshells which are suddenly exploded to drive the implosion of the gaseous fuel in the form of equal molar deuterium tritium typically at initial densities of 2 mg/cm^3 . Thus, the compression ratios which have been achieved to date vary from approximately 50 to 500.

Since the last CLEA meeting we have also made a number of significant advances in our diagnostics of the laser fusion target experiments. In the area of neutron yield we have implemented radiochemistry diagnostics which

now allow us to improve the accuracy of our fusion yield measurement to approximately 15% certainty. In this case we use the neutron activation of a Cu^{63} disk and then observe the decay of the radioactive copper isotope, Cu^{62} , which is formed under the bombardment of the neutrons from the target experiment. We have also been able to implement neutron time of flight diagnostics to measure the energy broadening of the neutrons which gives us further proof of the thermonuclear nature of our implosion experiments. In addition this gives us an additional measurement of the DT ion temperature of the thermonuclear burn in the fuel. We have further confirmed this temperature by substituting DHe^3 for DT fuel and measuring the number of protons generated by DD and DHe^3 reactions. We have also implemented an x-ray streak camera with a imaging capability which has allowed us to make a direct measurement of the implosion history of the glass pusher in these exploding pusher target experiments. This measurement is in good agreement with the LASNEX calculations and typically yields approximately 30 cm per microsecond for the implosion velocity.

We have also implemented an x-ray spectrometer with very high resolution to look at the broadening of the x-ray lines from a seed material inside the fusion capsule. The purpose of this spectrometer is to allow us to measure the density of the DT fuel by using the broadening of the x-ray lines emitted by the high Z seed material. These experiments were performed on the Janus system with a pair of ellipsoidal mirrors to distribute the laser light over the target surface and produce a reasonably spherical implosion of the DT fuel. The analysis of the broadening from these experiments imply that we have achieved densities of approximately $1/2 \text{ g/cm}^3$ or approximately 2-3 times liquid density of DT fuel.

Figure 1 shows a summary of some of the experimental data and projections of results we expect to obtain in future Argus, Shiva and Shiva Nova experiments.* The chart shows the product of the density of the fuel times the confinement time (the parameter $\tau\rho$) plotted against the DT ion temperature in kilovolts. Cross plotted are two additional parameters, the DT gain and the number of times liquid density of the imploded fuel. The results which we have just quoted are the box called Janus C in 1976 and Argus Hyperion 1976. The Argus Hyperion results show a DT ion temperature of the order of 10 kilovolts and densities equal to liquid density and a DT gain of 1%. The chart also shows that our next goal is to use the Argus laser to achieve densities of 100 x liquid density and then with the Shiva laser to achieve DT gain of 1 at 100 x liquid density and then to further increase the density of the fuel, and finally with the Nova system to achieve net energy gain.

An extremely important quantity which must be measured in the fusion experiments is the final size and shape and distribution of reactions in the imploded fuel region. Imaging hot x-rays from the stagnated pusher has given some indications of the shape and size of the imploded core in experiments done by all of the laboratories which have successfully imploded glass microshell targets, however, this information can be ambiguous and difficult to interpret. A more unique method to determine the size, shape and distribution of reactions is to directly image the reacting particles. We were able to image the alpha particles from the DT reaction region because they readily pass through the exploded pusher in these experiments.

* Shiva and Shiva Nova are discussed in paper 11.6 by John Holzhrichter. Shiva will produce > 20 TW and will be operational in 1978. Shiva Nova is designed to produce > 200 TW with an operational date of 1983.

Figure 2 shows the data for an 85 μm diameter target from two imaging techniques and shows the alphas were emitted from a nearly spherical region of approximately 28-30 microns in diameter. The resolution of the imaging devices do not provide the capability of determining the true shape and distribution of the alpha particles at this time, however, with further developments in these techniques and utilizing the Shiva target in 1978 we expect to make measurements of the thermonuclear burn region using the alpha particles which will provide detailed information on the size and in addition on the shape and distribution of the alpha particle emission.

We have also devoted significant resources to understanding the laser plasma interaction, to better design the implosion targets for our future high gain and high density experiments.

Figure 3 shows a summary of a large amount of data for the temperature of the suprathermal portion of the x-ray spectrum which is typically produced for laser irradiated targets. The data appears to have a scaling with the intensity on target times the wave length squared. However, the data also shows that this simple scaling does not provide the whole answer. There is additional variation with target material and the target configuration. More important even with this scaling, the hot electrons generated by CO_2 light have ten times the range of those produced by Nd light, since the range varies as energy squared. Because of preheat effects, CO_2 lasers may suffer a large penalty in the fusion application.

During the past year we have also accumulated significant evidence on the role of resonance absorption in the laser fusion targets. For example, the distribution of the plasma energy at large distances from the target implies the existence of resonance absorption. In addition, measurements of the absorption as a function of the focal position for spherical targets also is evidence of the role of resonance absorption. However, to provide

conclusive evidence we did a set of experiments which unequivocally demonstrates the importance of resonance absorption. In these experiments we used a long focal length lens, $f/10$, and placed the target at the focus of the laser beam; this provided a nearly parallel beam which was incident on a flat target. We then varied the angle of incidence of the laser beam on the target for both s and p polarized light. For s polarized light, the absorption should decrease monotonically as the angle of incidence increases. However, with p polarized light, if resonance absorption is important, the absorption should increase with the angle of incidence up to some maximum resonance condition and then decrease. Figure 4a and 4b show a summary of our data for these experiments. The data clearly demonstrates the effect of resonance absorption with the resonance angle appearing at approximately 25 degrees for the p polarized light.

In summary, the laser plasma experiments at the Lawrence Livermore Laboratory have progressed very rapidly and have achieved new milestones in both the implosion and DT gain in laser fusion targets. We have also developed new diagnostic methods for determining the state of the compressed fuel and the plasma processes which are occurring in the absorption and scattering of the laser light incident on the laser fusion pellets.

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LASER FUSION - [REDACTED], PROJECTIONS

Figure 2a

ALPHA ZONE P. AND IMAGE OF TARGET IN ALPHAS

Alpha emission
density
counts/cm²

Alpha emission
density
counts/cm²

ALPHAS

Figure 2b

OBSERVED AND CALCULATED SUPRATHERMAL X-RAY TAIL SLOPE, θ_h , SCALES WITH THE INCIDENT INTENSITY TIMES THE WAVELENGTH SQUARED

Figure 3

ANGULAR DEPENDENCE OF P-POLARIZED LIGHT ABSORPTION

4/77

Figure 4a

ANGULAR DEPENDENCE OF S-POLARIZED LIGHT ABSORPTION

4/77

Figure 4b