Conf-751130--1

UCRL - 77079
PREPRINT

LAWRENCE LIVERMORE LABORATORY
University of California/Livermore, California

MASTER

Experimental Determination of DT Ion Temperatures in Laser Fusion Targets

H. G. Ahlstrom, V. W. Slivinsky, K. G. Tirsell, E. K. Storm, S. S. Glaros, and Don Campbell

October 8, 1975

This paper was prepared for submission to the APS meeting
St. Petersburg, Florida, November 10-14, 1975

UCRL-77079a

Abstract Submitted

for the St. Petersburg Meeting of the

American Physical Society

November 10-14, 1975

Physical Review
Analytic Subject Index
Number 52.50 Jm

Bulletin Subject Heading
in which Paper should be placed
Laser Produced Plasmas

Experimental Determination of DT Ion Temperature in Laser Fusion Targets.* H. G. AHLSTROM, V. W. SLIVINSKY, K. G. TIRSELL, E. STORM, S. S. GLAROS, and D. E. CAMPBELL, Lawrence Livermore Lab.--Using the time-of-flight technique, energy distribution measurements were made of the fusion produced α particles emitted from laser implosions of DT gas contained in glass microshells. The number of nuclear reactions was determined by an absolute measurement of both the number of α particles and the number of neutrons. From the FWHM of the α particle energy distributions, upper limits of the plasmas ion temperature have been inferred. By applying corrections for the broadening of the distribution due to the fuel and the pusher, ion temperatures of 2-3 keV have been calculated. These measurements constitute significant evidence that the implosions produced thermonuclear burn of the DT fuel.

*Research performed under the auspices of the USERDA.

To follow paper by J. Larsen, Computer Simulation of Laser-Driven Implosion of DT filled Glass Microballoons

Submitted by

Harlow G. Ahlstrom

Harlow G. Ahlstrom
APS Member

University of California
Lawrence Livermore Laboratory
Livermore, California 94550

Experimental Determination of DT Ion Temperatures in Laser Fusion Targets

A significant milestone in any fusion program which hopes to produce a reactor concept which will lead to a thermonuclear fusion power plant is the demonstration that the reactions produced in the machine are indeed thermonuclear, i.e., produced by a Boltzmann distribution of the reacting ions. As a demonstration of the importance of this the First Vugraph shows a number of nonthermonuclear fusion experiments. One of the first devices which was shown to produce fusion neutrons from the DD reaction was the Zeta machine which was built both in England at the Culham Laboratory and at Los Alamos in the United States. This machine produces an unstable plasma leading to accelerated deuterium ions which collide either with the low temperature background plasma or with other deuterons thus producing nonthermonuclear reactions. A second machine which held great promise as a possible thermonuclear reactor was the Z pinch which produced a column of plasma confined by the azimuthal magnetic field and pinched by the longitudinal current on the surface of the plasma column. This device produces a plasma which has magneto fluid dynamic instabilities which lead to very large electric fields in the plasma leading to accelerated deuterons which either collide with the cool background plasma or with stationary deuterium in the electrodes. This device also does not produce thermonuclear reactions. A third type of experiment in which the reactions are not thermonuclear is the irradiation of a slab of deuterated material, i.e., frozen deterium or CD_2 for example with a 1.06 um high power laser. These experiments have been performed in intensity ranges of $10^{13} - 10^{16}$ w/cm^2. In this case also we have deuterium ions accelerated to high energies - energies in the order of 50-150 kilovolts

Work performed under the auspices
of the U.S. Energy Research &
Development Administration under
contract No. W-7405-Eng-48.

and these deuterium ions produce reactions wth cold background deuterium ions. The determination of these nonthermonuclear nature of the neutrons has been performed in a number of ways, but primarily the method used was to measure the energy broadening of the reaction products and infer an ion temperature.

Vugraph #2 shows two examples where thermonuclear reactions have been proved. The first is the Scylla or theta pinch which has been shown to produce ion temperatures from 1-5 kilovolts and thermonuclear DD reactions which was verified by energy spectrum measurements of the 3 MeV protons from the DD reaction and the 1 MeV tritons produced by the DD reaction. The subject of this talk is the discussion in detail of the second example which is the laser implosion of DT filled glass microshells. The microshells are approximately 80 microns in diameter which were irradiated by 200 gigawatts per beam from the LLL Janus Nd:glass laser using f/1 optics for the two beams. The measurement was made by measuring the energy spread from the 3.5 MeV alphas which were produced in the DT reaction and these measurements indicate an ion temperature from 1 to 3 kilovolts. The lower part of the vugraph shows the 2.5 keV channel of the x-ray microscope showing the initial irradiated portion of the shell and the imploded region. Now one point which is covered in the next vugraph (Vugraph #3) is why we are concerned with whether or not the reactions produced in the implosion of these glass microshells filled with DT is indeed thermonuclear. What we show here is the ratio of the number of deuterons required to produce the reactions which are measured as a function of the energy of a beam of deuterons which could be accelerated through the core of the imploded target. You see that for 40 kilovolt deuterons, and a yield level of 10^6 neutrons we would require 8×10^9 accelerated deuterons and the number goes down to 1.3×10^9 at 130 kilovolts. Another way of looking at this is to ask how much of the energy has to reside in this accelerated beam and as shown here a 20 kilovolt beam would only have to contain 380 uJ of the energy absorbed from the laser, a 130 kilovolt beam would only have to contain 28 uJ and because this is a very small number and also because a large number of high energy ions - in the 40 to 100 kilovolt region had been measured in a number of experiments where lasers have been used to implode these type of targets there is significant concern that the reactions are possibly occurring due to a very small fraction of the energy being in an ion beam which is interacting with the deuterium/tritium fuel. The way we set out to determine the nature of the reactions is shown in Vugraph #4. The deuterium/tritium reaction goes to a 14.1 MeV neutron and a 3.5 MeV alpha particle. By examining the effects on the spectrum due to different energy distributions of the alpha particles we can arrive at a determination of the nature of the reaction or the nature of the distribution function which is producing the reaction. In the first case we consider a beam/beam reaction. In this case the distribution of the alphas which are produced is square and the equation for the broadening as a function of the energy of the beam is given as $75\sqrt{E_{D,T}}$ in the beam. If one of the reactants is stationary than we have a beam target reaction, again the energy distribution of the alphas produced will be square and in this case the broadening is $150\sqrt{E_{D,T}}$. Now if the reaction is thermonuclear, i.e., the distribution function of the deuterium and tritium ions is Maxwell-Boltzmann and the distribution function of the alphas produced will be Gaussian and its full width half maximum will be $177\sqrt{T_i}$. Therefore, what we set out to do is to measure the energy distribution of the alphas produced by the deuterium/tritium reaction.

Vugraph #5 shows the other possible effects that may influence the energy distribution of the alphas produced from the deuterium/tritium reaction. The first two are the effects covered on the previous slide. The next one we could have is the effect of doppler broadening due to the fuel motion, i.e., that the fuel is not stationary during the burn and we will get some additional broadening. We will also have energy loss due to the dE/dx of the fuel and the pusher, i.e., as the alphas pass through the fuel and the pusher they will lose energy. Also their energy distribution will be broadened due to the passage of the alphas through the fuel and the pusher. Finally there may be an affect due to symmetry if the implosion is not symetric and the distribution measured in different directions will be different.

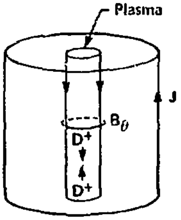
Vugraph #6 shows the alpha time of flight spectrometer which we constructed to make these measurements. The measurements were made on the Janus II laser which produces 400 gigawatts, 200 per beam with the target being irradiated by the f/1 lenses. Now in the laser fusion case we can use time of flight to determine the energy distribution function of the reaction products because the time scale or the time resolution of our detectors is of the order of nanoseconds and the reaction occurs in times of the order of 10 picoseconds so there is no measureable effect due to the time of the reaction. We use a baffled flight tube to reduce scattering of x-rays and electrons onto the detector. A 6 kilogauss magnet is used to deflect the alphas through an aperture onto a NE 111 fluor which is coupled to an Amperex 2106 photomultiplier. This combination gives us a time resolution of four nanoseconds full width half maximum. The energy resolution of a device of this type is given simply by $2E \frac{v}{d} t$. The important thing is that the measurement of the energy broadening of the alphas is a factor of 16 times more sensitive in energy resolution as compared to measuring the energy broadening of the neutrons. The reason for this is that the alphas have 1/4 the energy of the neutrons and their velocity is 1/4 the velocity of the neutrons giving a factor of 16 decrease in the ΔE_{FWHM} for a fixed Δt detector and fixed distance. Another way of saying this is that to obtain 130 kilovolt energy resolution which we have with the set up, one would have to increase the flight path for a neutron detector by a factor of 16 or to approximately 50 meters. The other factor of importance here is that the sensitivity of the detector is 5×10^{-6} alpha counts per target reaction. That is for a target which produces 10^{6} neutrons or alphas we would see 5 alphas into the detector thus indicating that a yield of somewhere around $4\text{-}5 \times 10^{6}$ should give reasonable statistics on the energy broadening of the alphas.

Vugraph #7 shows experimental data for three experiments. You see the oscilloscope traces in these cases. There was approximately 30 joules from the laser and approximately 8 joules absorbed. An important factor to note is the number of neutrons measured agrees very well with the number of alphas measured for all three experiments and the temperatures inferred are 2 and 2.5 kilovolts and by measuring the energy loss we calculate a compression of the target of 80 and 100. The third experiment shows a case in which DT fill in the glass microshell was 0 and we observed no neutrons and no alpha particles.

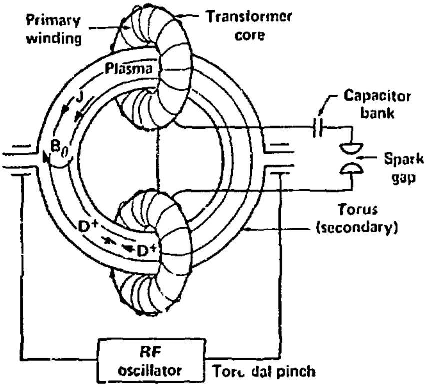
Vugraph #8 shows a summary of the uncorrected data for the experiments and we see points ranging 2 kilovolts up to 6 kilovolts for a number of different kinds of targets irradiated under different conditions.

Vugraph #9 summarizes the measurements and the conclusions of the measurements. First of all the time of flight detector was used to measure alphas on laser implosion of DT filled glass microshells. #2 the 3.5 MeV alphas were detected for target yields ranging from 2×10^5 up to 10^7 neutrons and alphas of course. Total yield of the alphas was equal the total yield of neutrons in each experiment. Another factor of importance is that the alphas lose from 180-300 KeV in energy which is consistent with the passage of the alphas through the DT fuel and the silica dioxide exploding pusher. Also the measured spread of the energy of the alphas would indicate an ion temperature of 2-6 kilovolts and when this data is corrected for the additional broadening effects it implies temperatures from 1-4 kilovolts which is in good agreement with the LASNEX calculation for these targets. Another important fact is that the alphas measured must come from the compressed core of the target because of their energy loss. And finally beam/beam or beam-target reaction seem very improbable at beam energies from 2-15 kilovolts in the target core. Therefore, we believe that these measurements have demonstrated that thermonuclear reactions are taking place in the compressed core of laser implosion of DT filled glass microshells.

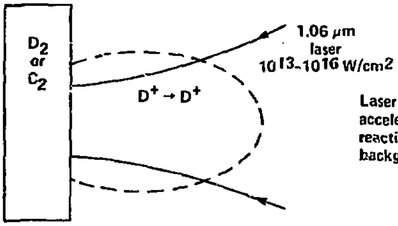
NONTHERMONUCLEAR FUSION EXPERIMENTS



z pinch
instabilities produce
accelerated D^+'s



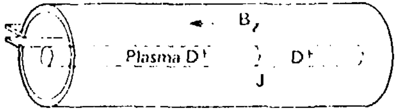
Instabilities
produce
accelerated
D^+'s



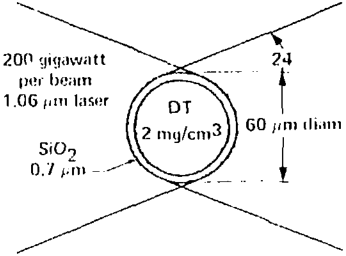
Laser irradiated slabs --
accelerated D^+'s produce
reactions with cold
background D^+'s

$$D + D \to \underset{2.45\text{ meV}}{n} + \underset{0.82\text{ meV}}{He^3}$$
$$\to \underset{3.02\text{ meV}}{p} + \underset{1.01\text{ meV}}{\tau}$$

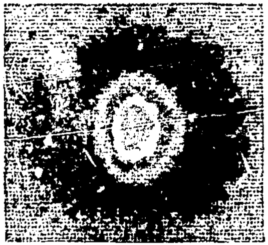
THERMONUCLEAR FUSION EXPTS



Scylla or θ pinch – produces T_i 1 - E keV and thermonuclear DD reactions verified by energy spectrum of 3 meV protons and 1 MeV tritons



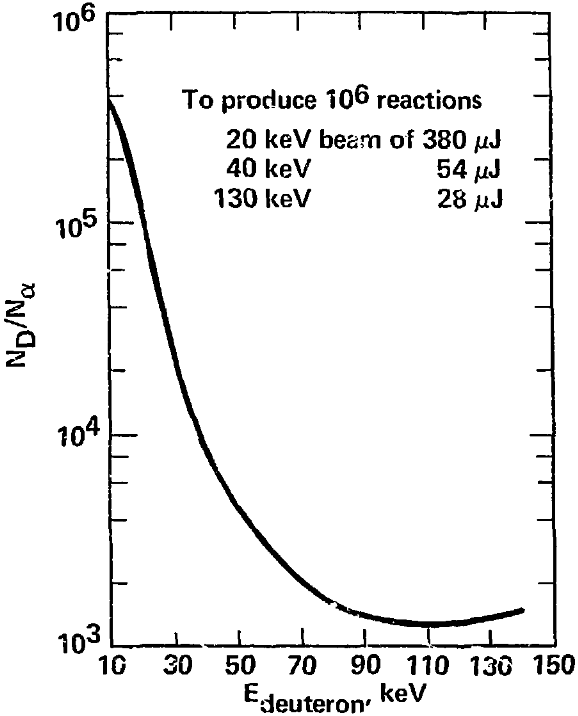
Laser implosion - produces T_i ~ 1 - 3 keV and thermonuclear DT reactions verified by energy spectrum of 3.5 meV α's



Compressed & heated DT plasma

2.5 keV
x-ray microscope

NUMBER OF HIGH ENERGY NEUTRONS REQUIRED FOR D + T REACTION



To produce 10^6 reactions

20 keV beam of 380 μJ
40 keV 54 μJ
130 keV 28 μJ

ENERGY SPECTRUM OF REACTION PRODUCTS

$$D + T \rightarrow \underset{14.1\ \text{meV}}{n} + \underset{3.5\ \text{meV}}{He^4}$$

Beam-Beam f(E) is square $\Delta E(\alpha) = 75 \sqrt{E_{D,T}} \sim \text{keV}$

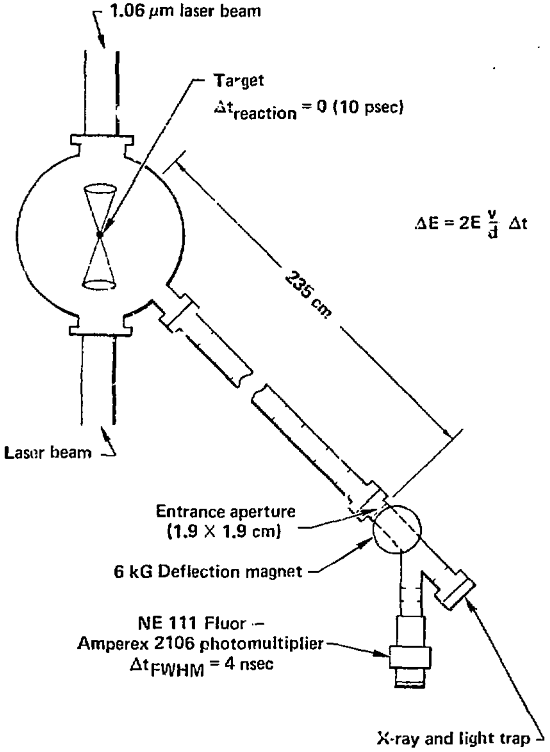
Beam-Target f(E) is square $\Delta E(\alpha) = 150 \sqrt{E_{D,T}} \sim \text{keV}$

Thermonuclear f(E) is Gaussian $\Delta E_{FWHM}(\alpha) = 177 \sqrt{T_i} \sim \text{keV}$

EFFECTS ON $f_\alpha(E)$ FOR LASER IMPLOSIONS

- Energy of reacting D and T
- $f_D(E)$ and $f_T(E)$
- Doppler broadening due to fuel motion
- Energy loss due to dE/dx of the fuel and pusher
- Energy broadening due to passages of α's thru the fuel and pusher
- Symmetry of implosion

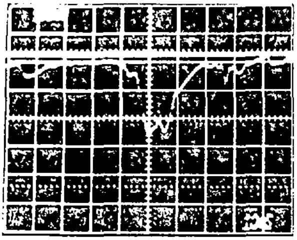
α TOF SPECTROMETER JANUS II
~ 400 GIGAWATT LASER



Total flight path = 276.75 cm ⇒ $\Delta E_{FWHM} = 130$ keV

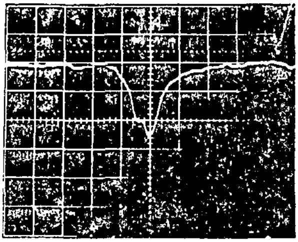
Sensitivity = 5×10^6 α counts/target reaction

α TOF RECORDS



Experiment 1

$E_E = 12.3$ J
$E_W = 13.3$ J
$E_{absorbed} = 6.2$ J
$N_n = 3.9 \pm 0.8 \times 10^6$
$N_\alpha = 4.0 \pm 0.8 \times 10^6$
$\Delta E_{FWHM} = 340$ keV
$T_i = 3.7$ keV
$\overline{E}_\alpha = 3.27$ meV
C = 50-100



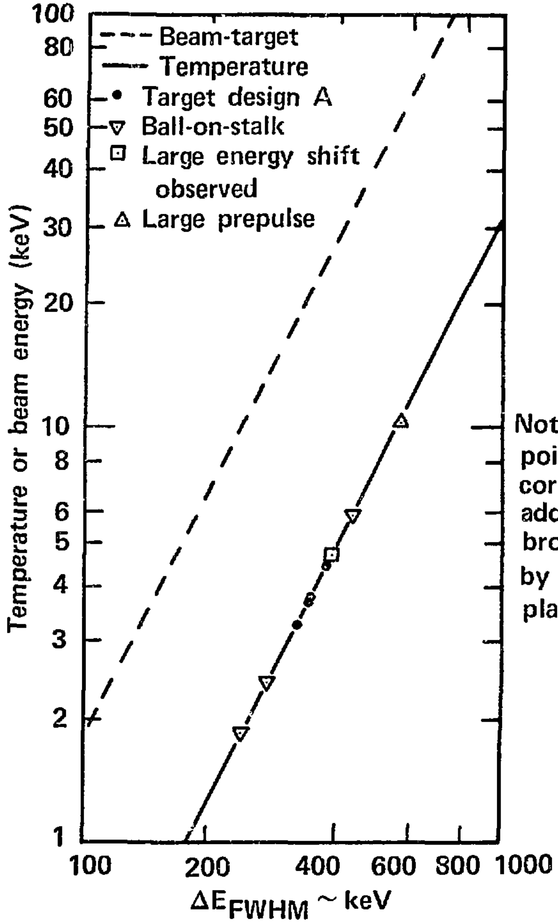
Experiment 2

$E_E = 15.7$ J
$E_W = 15.0$ J
$E_{absorbed} = 7$ J
$N_n = 4.7 \pm 1.0 \times 10^6$
$N_\alpha = 5.5 \pm 1.0 \times 10^6$
$\Delta E_{FWHM} = 315$ keV
$T_i = 3.2$ keV
$\overline{E}_\alpha = 3.36$ meV
C = 50-100

Experiment 3

$E_E = 15$ J
$E_W = 15$ J
$E_{absorbed} = 7$ J
$N_n = 0$
$N_\alpha = 0$
DT fill = 0 mg/cm^3

Ti AND E BEAM VS. ΔE_{FWHM} OF α



Note: Experimental points are not corrected for additional broadening caused by Doppler and plasma effects.

SUMMARY: α ENERGY SPECTRUM

- ToF α detector used on laser implosion of DT filled glass microshells.
- 3.5 MeV α's detected for target yields of 6×10^5 - 10^7 neutrons.
- Total yield of α's = total yield of neutrons.
- α's lose ~ 100-250 keV, consistent with passage of α's through DT fuel and SiO_2 exploding pusher.
- $\Delta E_{\text{measured}}(\alpha) \Rightarrow T_i(D,T) = 2\text{-}6$ keV
  $\Delta E_{\text{corrected}}(\alpha) \Rightarrow T_i(D,T) = 1\text{-}4$ keV
  which agrees with Lasnex calculations for these targets.
- The α's measured must come from the compressed core of the target because of their energy loss.
- Beam - beam reactions at $E_{D,T} = 6\text{-}22$ keV or beam - target reactions at $E_{D,T} = 1\text{-}6$ keV seem very improbable in the target core.