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Laser Fusion Experiments at 4 TW

E. K. Storm, H. G. Ahlstrom, M. J. Boyle, D. E. Campbell, L. W. Coleman, S. S. Glaros, H. N. Kornblum, R. A. Lerche, D. R. MacQuigg, D. W. Phillion, F. Rainer, R. Rienecker, V. C. Rupert, V. W. Slivinsky, D. R. Speck, C. D. Swift, and K. G. Tirsell
Lawrence Livermore Laboratory, University of California, Livermore, California 94550
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DT-filled glass microspheres have been imploded at power levels exceeding 4 TW using the Lawrence Livermore Laboratory 1.06-μm Argus laser. Thermonuclear neutron yields in excess of 1.5×10^9 have been observed implying a DT burn efficiency of 1.6×10^{-5}. Neutron and α time-of-flight measurements indicate DT burn temperatures of 4–8 keV, implying that a DT gain of approximately 10^{-2} and a $n\tau$ of 10^{12} were obtained.

As part of the effort to understand the physics of laser imploded targets, a series of experiments examining both basic laser-plasma interaction phenomena and the parameter space of exploding-pusher experiments have been performed over the last three years, both at Lawrence Livermore Laboratory and other laboratories.[1-8] A laser irradiated target is said to operate in the exploding-pusher[9] mode when the pusher significantly decompresses in the process of compressing the fuel. This is characteristic of a high rate of energy addition to the pusher. Laser absorption mainly by collective processes producing superthermal electrons, early energy deposition in the hsell by these superthermal electrons, a near supersonic electron thermal wave driven by electron thermal conduction from the laser-absorption region, and significant shock compression of the fuel causing a large entropy change are other characteristics of the exploding-pusher mode. This results in a limited density increase, but significant heating of the fuel. Early exploding-pusher experiments with DT-filled glass microshells indicated that for fixed DT fill, the target performance, measured in terms of neutron yield, should increase[10] as $r_0^{10/3}w^{2/3}\langle\sigma v\rangle T^{-1/2}$. Here r_0 is the target radius, w the shell wall thickness, T the time- and space-averaged final DT fuel temperature, and $\langle\sigma v\rangle$ the Maxwell averaged DT cross section. It is assumed that T is proportional to the useful specific absorbed energy, $\mathcal{E}_C$. The useful fraction is essentially the absorbed energy corrected for any temporal mismatch between the input laser pulse length and the characteristic target-implosion time scale, and is thus the time in the laser pulse beyond which further absorption can no longer influence the final implosion phase. This time is found empirically to be roughly determined by the amount of energy absorbed until the pusher has traversed ~30% of the initial target radius, with the instantaneous pusher velocity assumed proportional to the energy absorbed up to that time. Since pusher velocities are $\simeq(2.5-3.5)\times10^7$ cm/sec,[8,11] a 90-μm-diam target would find nearly all the energy "useful" for laser pulses with a full width at half-maximum (FWHM) $\lesssim$ 40 ps. Experiments performed at KMS Fusion, Inc. also gave results consistent with this description.[12] Targets irradiated at a fixed peak power, with pulse lengths increasing in steps of 40 ps up to 240 ps, showed no increase in neutron yield for pulse lengths beyond 80 ps. Both to confirm the "useful energy" hypothesis and to extend our data

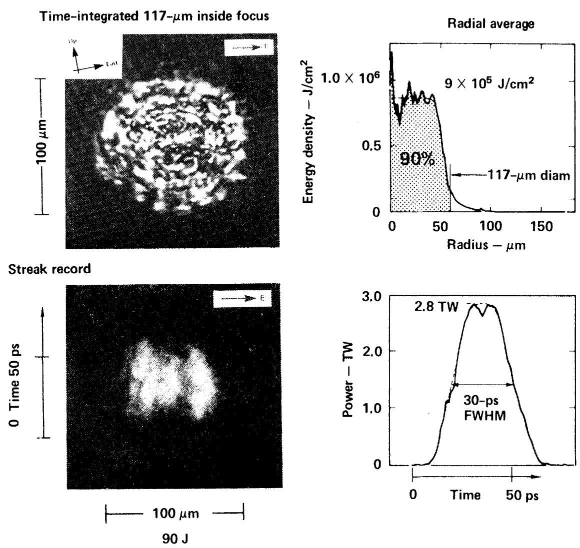

FIG. 1. Laser performance in the target plane for the Argus north beam on shot 36121004.

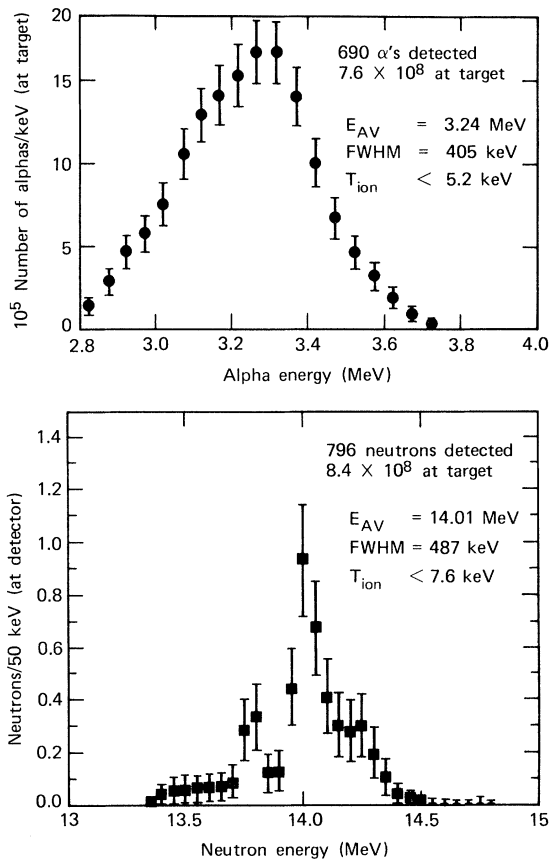

FIG. 2. Unfolded neutron and α time-of-flight data for the Argus shot in Table I.

base to higher power levels, exploding-pusher experiments were recently performed at the 2–4 TW level with pulse widths (FWHM) of 30–45 ps.

The Argus laser[13] routinely delivers greater than 4 TW in two beams that are of the order of 10 times diffraction limited. The spatial and temporal laser energy and power distribution in the target plane is recorded on each shot using an equivalent-plane imaging system. An example of the quality of the system output at the target plane is shown in Fig. 1.

The targets used in the experiments were typically 80–90-μm-diam SiO_2 microshells with a wall thickness of 0.8 μm and filled with an equimolar mixture of DT at a density of 2–3 mg/cm^3. Two $f/1$ lenses focused the beams such that in the target plane the beam diameters at $\sim\frac{1}{5}$ of peak intensity were equal to the target diameter. The laser and target performance for a typical shot are listed in Table I. This is compared with a typical result from the Janus system[2,3,11] (0.4 TW, $f/1$ lenses), also shown in Table I. We note $\mathcal{E}_C$ has increased by about a factor of 4 for the Argus experiment (M_p is the imploded fraction of the pusher mass, $\frac{1}{2}$ of the initial pusher mass M_T, and E_C is the useful fraction of the absorbed energy that is converted into kinetic energy of the pusher). This factor of approximately 4 is also relfected in the alpha[2] and neutron[14] time-of-flight (TOF) measurements. Figure 2 shows an example of the TOF data for the experiment in Table I.

In Fig. 3, we plot the normalized neutron yield both as a function of total specific absorbed energy and useful specific absorbed energy. The short-pulse (FWHM$\simeq$40 ps) high-power ($\gtrsim$2 TW) experiments have normalized yields in excess of approximately 5×10^7. Data are also shown for some low-power ($\simeq$0.4 TW) Janus experiments and a few experiments performed at $\gtrsim$2 TW, but with pulse lengths of 150–200 ps and target diameters of approximately 150 μm. The solid lines are proportional to $\langle\sigma v\rangle T^{-1/2}$ with T scaling with ϵ or $\mathcal{E}_C$. $\mathcal{E}_C$ was found by the prescription outlined in the beginning of this paper and detailed in Ref. 10. The ion temperatures indicated were found by normalizing to the neutron and α TOF data for the high-power, short-pulse experiments. Scaling target performance with useful, rather than total specific absorbed, energy is - obviously more appropriate.

The significantly higher neutron yields observed in the short-pulse, high-power Argus experiments is thus primarily due to the increase in final DT ion temperature caused by optimizing the laser pulse length with respect to the target-implosion time scale. This becomes particularly apparent when considering the large-diameter, long-pulse experiments. Even though the total specific absorbed energy was, in some case, equal to that of the short-pulse experiments, the mismatch between pulse duration and implosion time resulted in "wasting" a good fraction of the absorbed energy.

For the Argus experiment listed in Table I, the α-particle emission was imaged.[15] The spatial extent of the α-emission region indicated a density compression of about 100, a result which is comparable to those estimated for the Janus experiments based on x-ray microscope images and α-particle energy losses. This lack of increase in compression with increasing laser power is consistent with a target operating in the exploding-pusher mode, and further emphasizes the importance of useful energy in optimizing exploding-pusher yield. Figure 4 shows the time and space integrated continuum x-ray spectrum for the two experiments in Table I. We note the increase in both the thermal and superthermal "temperature" with increasing laser power. Figure 5 shows the time-integrated x-ray microscope image (2.5 keV) for the two experiments listed

TABLE I. Typical experiments.

	36 120 910 ARGUS	75 060 402 JANUS
Target	$r_0 = 44.0$ μm $w = 0.88$ μm D-T fill = 3.1 mg/cm^3	43.3 μm 0.70 μm 2.5 mg/cm^3
Laser	128 J 32 ps FWHM	28.3 J 70 ps FWHM
Abs.	$E_A = 28.2$ J (22%)	6.4 J (23%)
$\mathcal{E}_C$	$E_C/M_p = 0.123$ J/ng Useful fraction = 0.90	0.030 J/ng 0.73
Yield	$n = (8.0 \pm 1.4) \times 10^8$ $\alpha = (7.9 \pm 1.4) \times 10^8$	$(4.6 \pm 0.4) \times 10^6$ $(4.6 \pm 0.5) \times 10^6$
T_{ion}	n(TOF), (7.6 ± 1.4) keV α(TOF), (5.2 ± 1.5) keV	$\lesssim 2.0$ keV
$\int$ x-ray	(0.3 keV $\lesssim h\nu$ 17 kev) $E_x \simeq 3.9$ J	$\simeq 0.4$ J

in Table I. The uniformity of the heating is considerably improved at the higher intensity. Both experiments were performed with $f/1$ focusing optics. In the early exploding-pusher experiments[11] and the series of experiments utilizing the 4π illumination system,[7] it was also observed that both the heating and the implosion were more symmetric with increasing intensity on target.

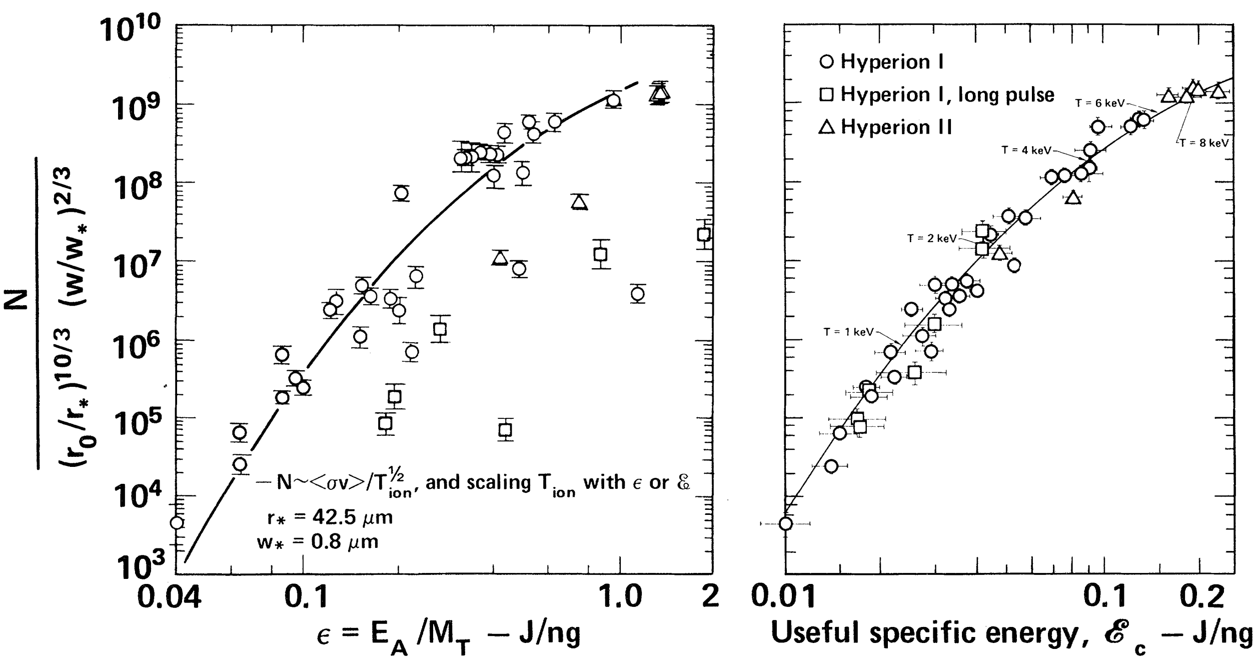

FIG. 3. Normalized neutron yield as a function of total specific absorbed energy and useful specific absorbed energy. Hyperion is the Lawrence Livermore Laboratory designator for exploding-pusher targets.

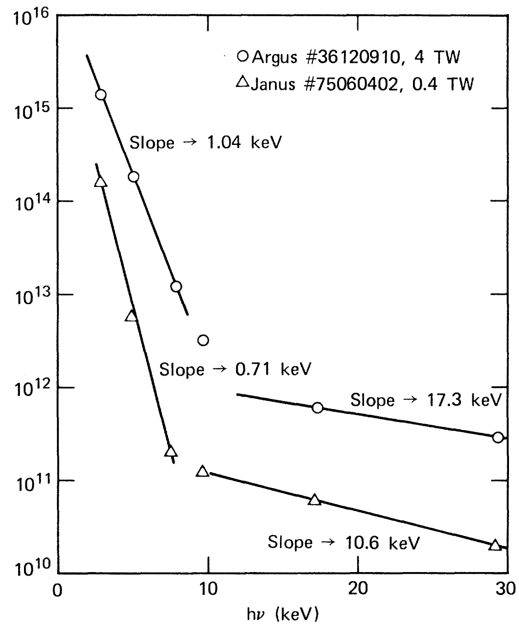

FIG. 4. Continuous x-ray spectra for the experiments listed in Table I.

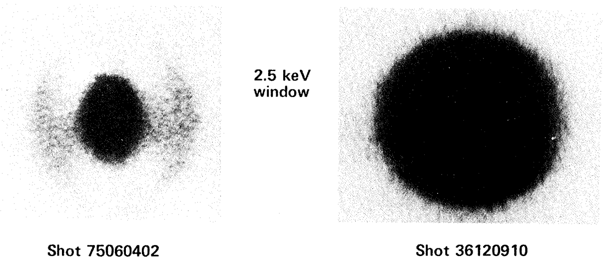

FIG. 5. X-ray microscope images from the two shots in Table I.

In summary, exploding-pusher experiments have been performed at the 2–4-TW, 40-ps level. In comparing the results to earlier low-power (~0.4 TW, ~70 ps) experiments performed on similar targets, we conclude that the increase in neutron yield was primarily caused by a more effective match of the laser pulse length to the target-implosion time scale. When high-power experiments were performed using longer pulse lengths (150–200 ps), no increase in target performance was observed. No increase in target compression with laser power was observed. The intensity-dependent symmetrization of implosions observed in earlier experiments was confirmed.

Appreciation is extended to the Argus crew for their many postmidnight efforts, to W. W. Simmons and J. F. Holzrichter for building Argus, to J. N. Nuckolls and J. T. Larsen and the Theoretical Group, and to C. D. Hendricks and the Target Fabrication Group. This work performed under the auspices of the U. S. Energy Research and Development Administration under Contract No. W-7405-Eng-48.

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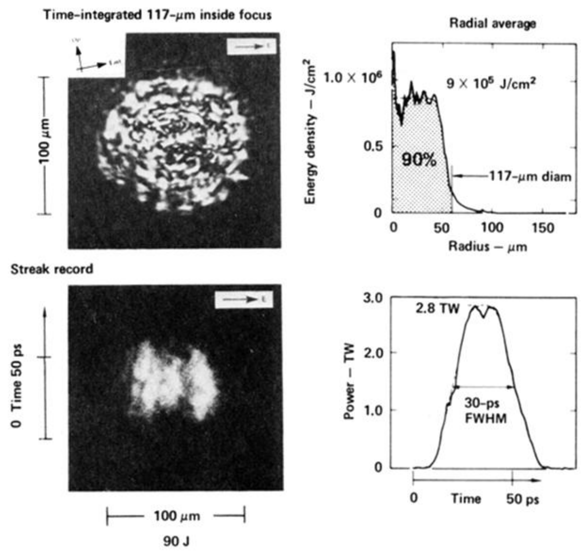

FIG. 1. Laser performance in the target plane for the Argus north beam on shot 36121004.

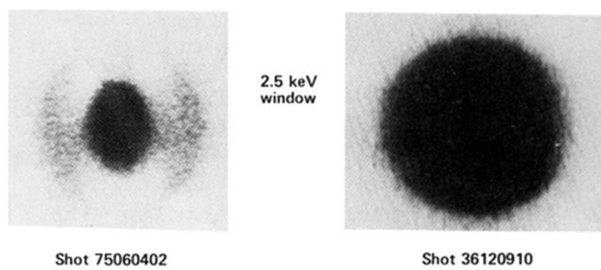

FIG. 5. X-ray microscope images from the two shots in Table I.