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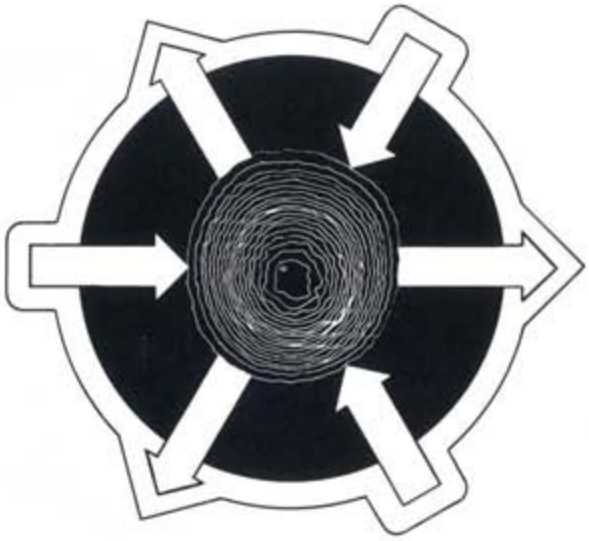

NATIONAL SECURITY

Diagnosis of Laser Fusion Targets

Our experiments on exploding-pusher targets have established several key facts about laser fusion and serve as benchmark tests for the predictive powers of the design codes. We used several experimental techniques to determine these characteristics of target implosions: the symmetry of laser heating and compression, evidence of thermonuclear burn, implosion dynamics, and fusion yield.

Exploding-pusher targets (Hyperion targets) were the first class of laser fusion targets to undergo extensive experimental verification. Through a series of highly diagnosed experiments on Hyperion targets, we have achieved, among others, the following objectives:

- Demonstrated implosion of the target and compression of the D–T fuel.
- Proved that the resulting reactions were truly thermonuclear and measured ion temperature.
- Determined implosion dynamics and compared them with LASNEX code predictions.
- Verified LASNEX predictions of how thermonuclear yield scales with laser power.

A preceding article titled "Laser Fusion Targets" includes a description of the design and calculated operation of exploding-pusher targets (see p.11). A short laser pulse rapidly heats a thin glass shell. This explodes, compressing the enclosed D–T fuel about a hundredfold to near-liquid density and to high temperatures (1 to 2 keV in early experiments and 5 to 8 keV in more recent experiments). The several measurements outlined above (yield, size and shape of the imploded fuel volume, implosion velocity, peak ion temperature of the compressed fuel) are keys to the understanding of the implosion dynamics.

In this article we discuss our experimental program as well as some of the more advanced instruments developed.

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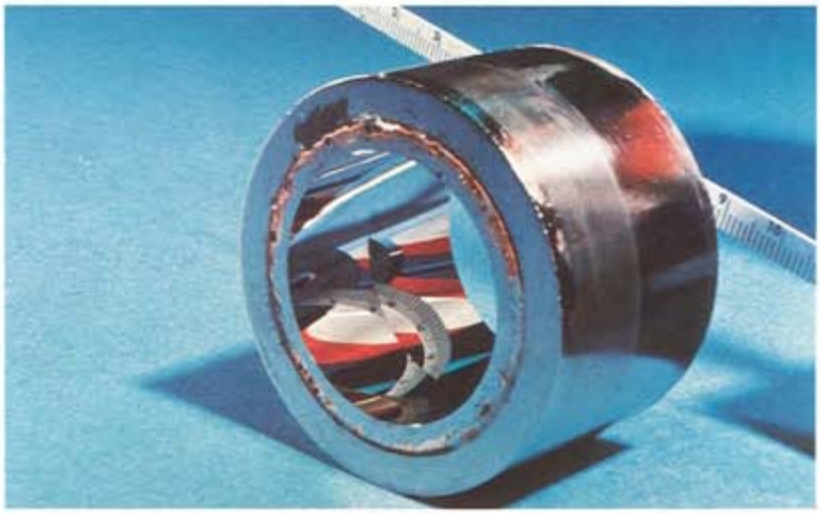

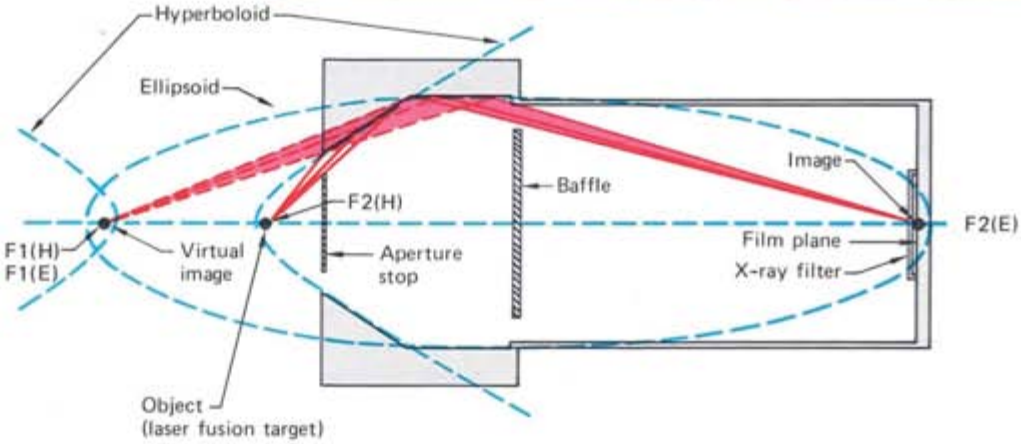

IMAGING X-RAY EMISSIONS

The most common method of imaging x rays is the pinhole camera. But in the soft x-ray regime pinholes cannot give the fine spatial resolution that we need to properly diagnose our implosion experiments.

We can, however, get high-resolution imaging of x rays by using pairs of conic sections in grazing incidence reflection. Paraboloid–hyperboloid x-ray mirrors used in x-ray astronomy programs have achieved resolutions of several arc seconds. We have designed and fabricated x-ray microscopes with paraboloid–hyperboloid mirror pairs that give perfect imaging from F2(H) of the hyperboloid mirror to F2(E) of the ellipsoid mirror (see the accompanying figures). Ray-trace analyses of this configuration indicate that we can achieve a resolution of better than 1 μm over a 400-μm field of view. Resolution, of course, depends on fabrication tolerances. For our requirements, the object distance is 30 cm. To achieve 1-μm resolution in the object plane, we need to achieve 25-nm surface-figure accuracy.

Using the numerically controlled diamond-turning lathe developed for the weapons program, we have been able to machine our 3-cm-diam microscope mirrors to an accuracy of ± 25 nm. We then polish this surface to produce a surface roughness of about 4 nm. At present, we are limited by errors introduced in the polishing process to about 4 μm resolution. But with improvements in the polishing process, we expect to achieve better than 1 μm resolution.

SYMMETRY OF LASER HEATING AND COMPRESSION

The symmetry of the target implosion is critically important for fuel compression and high yield. We can obtain information on the symmetry of laser heating and compression by imaging the x-ray emission of the laser-irradiated target onto photographic film. Time-integrated x-ray imaging is one of our best developed diagnostic techniques. (See the box on p. 24 for a description of one type of x-ray microscope.) For target temperatures around 10^7 K, radiation is emitted primarily as soft x rays with wavelengths of about 1 nm and energies of about 1 keV. Four simultaneous pictures are obtained, which correspond to four different x-ray energy channels centered at 0.8, 1.5, 2.5, and 3.5 keV.

Figure 1 shows two x-ray images for each of two Hyperion targets, the first irradiated on Janus at about 0.4 TW and the second on Argus at about 2 TW. In this figure, the x-ray-sensitive film has been processed by a computer to assign colors to different exposure levels. The outer ring in these images shows the emission from the glass shell where it was hit by the laser pulses coming from the right and left. The bright central emission occurs when the inward-moving pusher is stopped by the pressure of the D–T fuel, producing the high-temperature plasma from which neutrons and alpha particles originate.

Low-energy x-ray microscope images (at 1.5 keV) are good indicators of the heat distribution in the pusher as it is exploded by the laser pulse. The higher energy x rays (2.5 keV) originate from the hot stagnated pusher and show the symmetry of the compressed fuel. Figure 1 shows that the low-power irradiation of Janus did not heat the pusher uniformly, and an elliptical implosion resulted. The higher intensity Argus experiment produced a more uniform heating of the shell, resulting in a more spherical implosion. Comparing images such as these with LASNEX predictions tests the accuracy of LASNEX models of heat transport in the glass pusher.

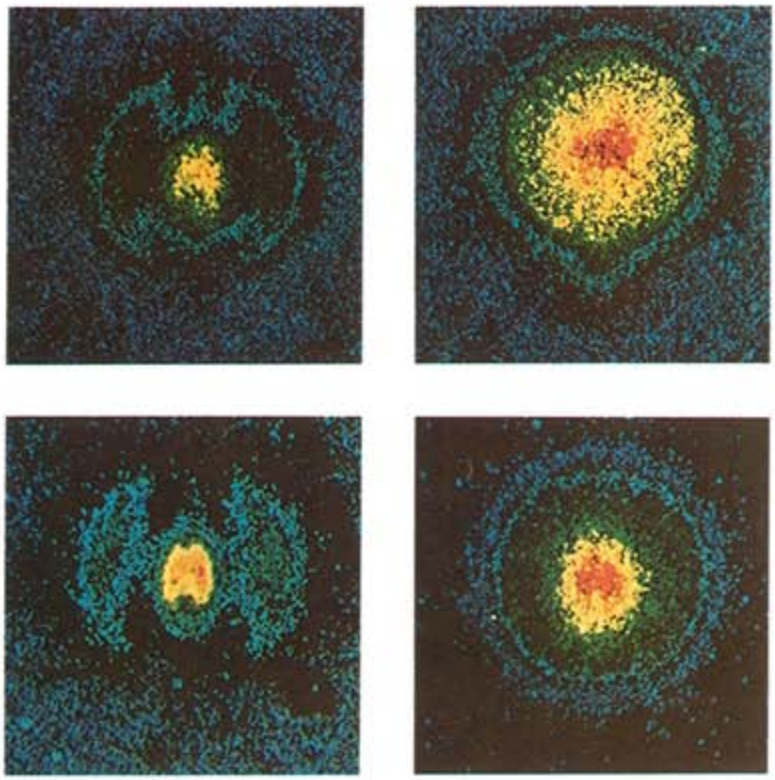

Fig. 1. Computer processing of x-ray microscope images produces these figures, in which colors denote levels of x-ray intensity. In these experiments, two laser pulses were incident on the target from left and right. The pictures at the top were taken through a filter that transmits x rays with energies near 1.5 keV. The bottom two pictures are from the 2.5-keV channel. The target on the left was irradiated at 0.4 TW with Janus; the one on the right was irradiated at 2.0 TW with Argus. The high-intensity irradiation produced a more uniform heating of the glass shell and a more spherical implosion.

Time-integrated x-ray images show intense emission from the compressed core, which indicates compression and heating of the fuel. However, there is an uncertainty in the fuel compression inferred from these x-ray images because the x rays are emitted principally from the imploded glass that may be mixed with the D–T fuel. We can measure fuel compression directly by imaging the alpha particles emitted from the D–T fusion. Since the D–T reaction rate increases rapidly with density and temperature, most of the reactions occur during a very short time at peak compression and temperature—about 10 ps. We have implemented two techniques for alpha imaging in our Hyperion experiments: pinholes, which image alpha particles exactly as a pinhole camera images visible light, and Fresnel zone plates.

The 2-mm-diam Fresnel zone plate shown on the right in Fig. 2 records a coded image that is later illuminated by laser light to reconstruct an image of the alpha-particle source. Isoemission contours shown in this figure were derived from an alpha image with resolution of about 10 μm, which may contribute significant blurring to the apparent 27-μm compressed reacting fuel region. Analysis of this image gives a direct measurement of the fuel compression. The compression of 125 is in good agreement with LASNEX calculations. We expect to improve the resolution of our zone plate imaging by tenfold, which will allow us to obtain both fuel compression and distribution of the burn region. The data in Fig. 2 are significant because they provide direct confir-

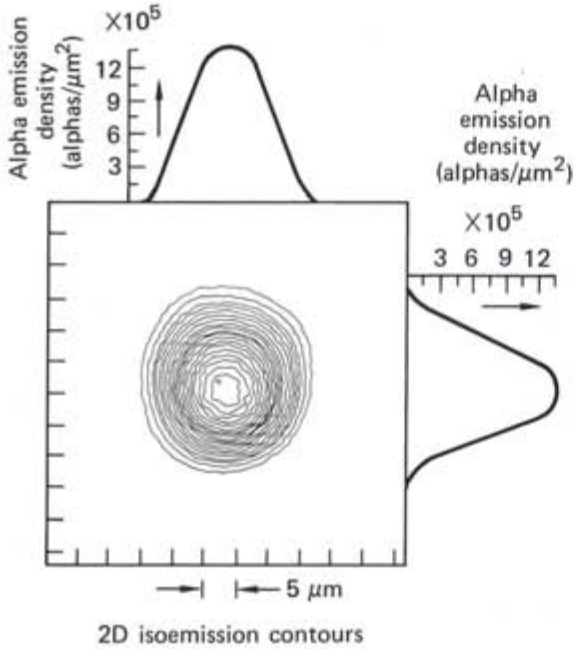

Fig. 2. The alpha-particle intensity contours on the left were reconstructed from a coded image of the alpha particles emitted from a Hyperion target. The Fresnel zone plate on the right produces the coded image by casting a shadow on an alpha-sensitive film located about 5 cm behind the zone plate. The zone plate, located about 1 cm from the target, is 2.5 mm in diameter with 100 zones, the smallest of which is only 5.3 μm wide. These plates are produced by ultraviolet photolithography and built up to the required 5-μm thickness by microelectroplating techniques.

mation that the reactions we see are produced in the hot compressed core of the fuel.

PROOF OF THERMONUCLEAR BURN

A number of fusion machines have produced copious fusion reactions that have been shown to result from high-energy beams from plasma instabilities. These beam–plasma reactions cannot be scaled up to useful yields; hence, an important issue in our experiments is whether the reactions we observe are truly thermonuclear—that is, whether the reactions occurred in a plasma that was confined and heated to ignition temperature. The energy distribution of the reaction products indicates the type of reaction produced and, for thermonuclear reactions, gives the fuel temperature—the width of the energy distribution is proportional to the square root of the temperature.

In May 1975 we first demonstrated that our fusion reactions were thermonuclear, using an alpha-particle time-of-flight spectrometer. In Hyperion targets, the pusher explodes as it compresses the fuel. The pusher material is nearly transparent to the alpha particles and allows them to pass through with little energy loss; therefore, the observed energy distribution is a valid indicator of the conditions of the fuel. In this experiment, as alpha particles and other reaction products passed through a 3-m tube toward a detector, the alpha particles were magnetically deflected onto a fluorescer–photomultiplier. By measuring the times of arrival of the alpha particles, we calculated the alpha-particle energy distribution. This agreed with LASNEX calculations, which indicate an ion temperature of 1 to 2 keV. Since the measured energy distribution cannot be reconciled with high-energy-beam reactions, this experiment verified the thermonuclear nature of the D–T fusion.

For reaction yields above 10^8, we can measure the time of flight of neutrons to indicate ion temperatures. Unlike alpha particles, neutrons are unaffected by magnetic or electric fields, and they can exit from higher density pushers. Thus, for high-yield targets they provide a more reliable and accurate measure of temperature without correcting for the broadening added in traversing the pusher. Hyperion experiments on Argus typically produced yields greater than 10^8 with ion temperatures between 5 and 8 keV, as measured by a neutron time-of-flight spectrometer. These ion temperature measurements are in good agreement with LASNEX predictions.

IMPLOSION DYNAMICS

The dynamics of the implosion are also critically important to understanding target performance. For Hyperion targets, the peak velocity of the pusher determines the final fuel temperature. The extremely short times and small dimensions of the implosion demand special diagnostic techniques to resolve the implosion dynamics. By combining a Livermore-developed x-ray-sensitive streak camera with a specially designed x-ray pinhole camera, we can simultaneously provide the space and time resolution to make such measurements. [1]

Figure 3 shows color contours of equal x-ray intensity from such a measurement. X-ray emission begins at the outside diameter of the target (bottom of the figure) and proceeds inward as the pusher accelerates toward a stagnation region where peak compression occurs. The target then flies apart, and x-ray intensity decreases as the material cools. Figure 4 shows a comparison of the data with a LASNEX calculation. The calculated and measured implosion velocities are 2.5×10^7 cm/s. Although the resolution of 15 ps and 6 μm does not permit a severe test of the LASNEX model, the broad agreement is encouraging.

TRENDS IN TARGET YIELD

A good overall indicator of agreement between LASNEX predictions and experimental measurements is the total yield of the various targets as indicated by the neutron count (see Fig. 2 on p. 9). Neutron yield has varied over 10^7 from our lowest detectable yields with Janus experiments to our most recent Argus results. Over the entire range of neutron yields, our calculations correctly predicted the yields to within a factor of 2 or 3. This agree-

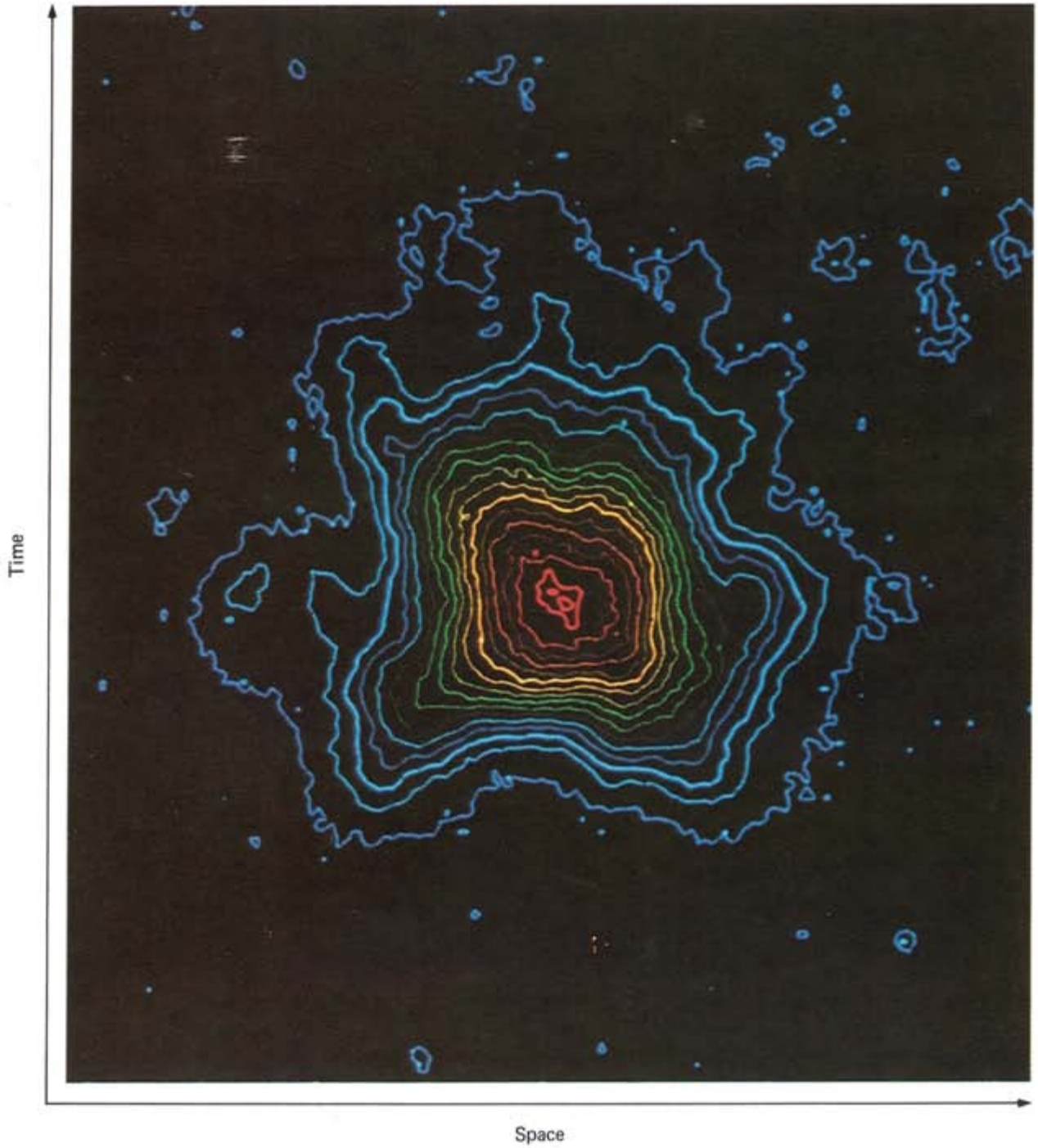

Fig. 3. Color contours of equal x-ray intensity reveal the motion of the pusher as a Hyperion target implodes and explodes. A combination of an x-ray imaging pinhole and an x-ray sensitive streak camera produces this space–time implosion picture, in which time increases toward the top of the figure. At early times (*bottom*) x rays are emitted from the outside diameter of the target. Near the center of the figure the inside of the pusher has moved in from both sides, compressing and heating the fuel, which results in intense x-ray emission. Near the top of the figure the target has exploded and cooled with x-ray emission occurring away from the center.

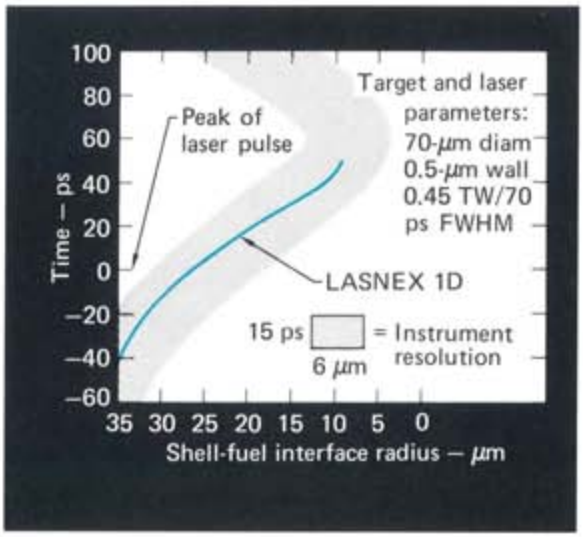

Fig. 4. **The data of Fig. 3 are plotted for comparison with one-dimensional LASNEX calculations. The distance from the center of the target to the x-ray emitting region (the glass/fuel interface) is shown as the grey band, which first decreases from the original target radius to about 10 μm during implosion and later increases as the target explodes. The solid line indicates the LASNEX prediction of the implosion history.**

ment for exploding-pusher targets gives us confidence that our predictions for much higher yield targets, up to those suitable for use in reactors, are based on an accurate model of the target physics.

Key Words: alpha measurements; alpha particles—measurements; lasers—diagnostics; neutrons—measurements; time-of-flight spectrometers; x-ray cameras; x-rays—measurements.

NOTES AND REFERENCES

1. For a discussion of the x-ray-pinhole-streak camera, see the *Energy and Technology Review* for December 1976 (UCRL-52000-76-12), p. 1.