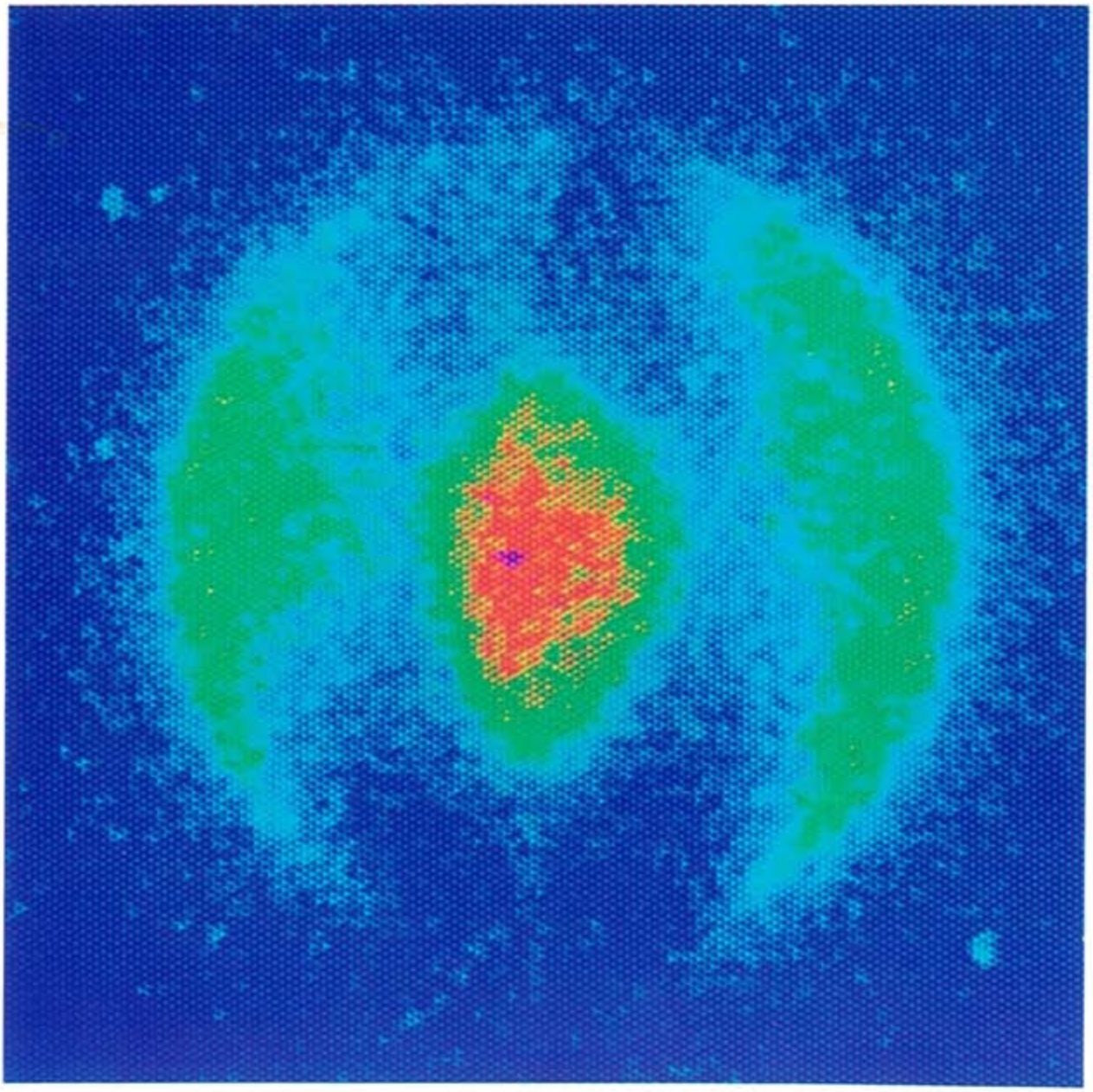
UCRL-52000-76-12

Energy and Technology Review

DEC. 1976

Prepared for U.S. Energy Research & Development Administration under Contract No. W-7405-Eng-48



LAWRENCE
LIVERMORE
LABORATORY

LASER IMPLOSION DYNAMICS

LASERS AND LASER APPLICATIONS

IMAGING IMPLOSION DYNAMICS: THE X-RAY PINHOLE/STREAK CAMERA

We have combined a Livermore-developed x-ray-sensitive streak camera with a unique x-ray pinhole camera to make dynamic photographs of laser-irradiated fusion target implosions. These photographs show x radiation emitted from the imploding shell during its 100-ps implosion; they are the first continuous observations of an imploding laser-driven fusion capsule. The diagnostic system has a time resolution of 15 ps and a spatial resolution of about 6 μm. Results agree very well with those predicted by our LASNEX calculations, confirming that the essential physics are correctly described in the code and providing further confidence in the soundness of our approach to inertial confinement fusion.

In the study of laser-driven implosions of hollow glass microspheres, our goal is to compress the encapsulated deuterium-tritium fuel to a high enough density and temperature to ignite a thermonuclear reaction that produces more energy than it takes to charge the laser. So far, we have achieved modest compressions and detected thermonuclear fusion reactions.[1]

Because of the high densities and temperatures involved in these laser-driven implosions, x-ray emission from the compressing target provides an opportunity to diagnose the dynamics of the implosion process. Our implosion experiments involve compressing a 100-μm-diam target to a fraction of its original size within 100 ps or less. Thus if the x-ray measurements are to accurately describe the heating and implosion process, they must be made with a spatial resolution of a few micrometres and a time resolution of a few picoseconds. Figure 1 gives a schematic layout of the pinhole/streak camera combination that makes this possible.

Contact David T. Attwood (Ext. 4210) for further information on this article.

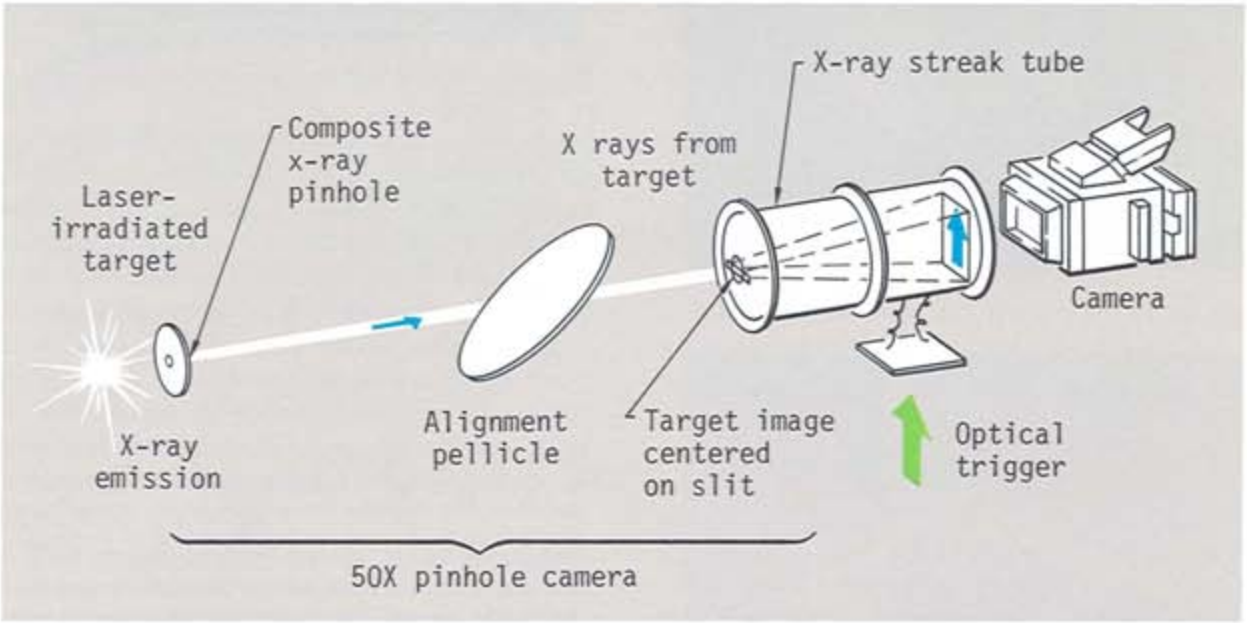
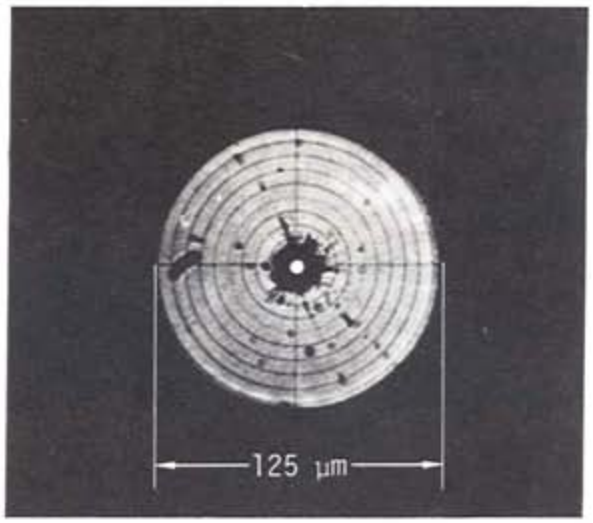


Fig. 1. Schematic layout of the x-ray pinhole/streak camera. The composite x-ray pinhole is 1 cm from the laser-irradiated target and 50 cm from the streak camera's slit photocathode, making the image magnification 50×. Since both the compressed target and the pinhole can be smaller than 10 μm, moving either of them more than 5 μm above or below the optical axis would throw the enlarged pinhole image of the compressed target clear off the streak tube slit. We had to devise special techniques to align the x-ray image precisely. The streak camera is based on a modified image converter tube. X rays falling on the slit-shaped gold photocathode release slow electrons. Shaped electrostatic fields accelerate and focus these electrons, forming a line image on the output phosphor screen. A fast-rising voltage pulse on the deflection electrodes sweeps the image vertically across the screen.

Previous diagnostic techniques have been unable to simultaneously provide the space and time resolutions required to make such measurements. Pinhole cameras and grazing-incidence-reflection x-ray microscopes, for example, provide time-integrated images that can show us the initial and final states of the implosion.[2] However, these photographs cannot provide details on the dynamics of the compression process.

The cover photograph is such a time exposure of a target implosion, taken with an x-ray microscope. The Janus laser system irradiated the target simultaneously from two sides. The outer partial ring in the picture shows the x rays generated at the surface of the target as it starts to implode. The bright spot in the center was formed by x rays from near the center of the highly compressed target. The relative lack of x rays during the compression permits these two images to be recorded without interference. The picture shows where the implosion started and where it stopped, but it doesn't show what happened along the way – i.e., the velocity history.

While the x-ray microscope provides spatially resolved data, our x-ray streak camera gives us time-resolved x-ray data, data that we have been able to interpret in terms of target implosion times.[3] Although in some circumstances these separate space and time data can lead to the average shell implosion velocity, they do not provide a direct measure of this velocity. We have now developed a capability for temporally recording x-ray images with sufficient resolution to continuously follow the implosion process of laser-compressed targets. These



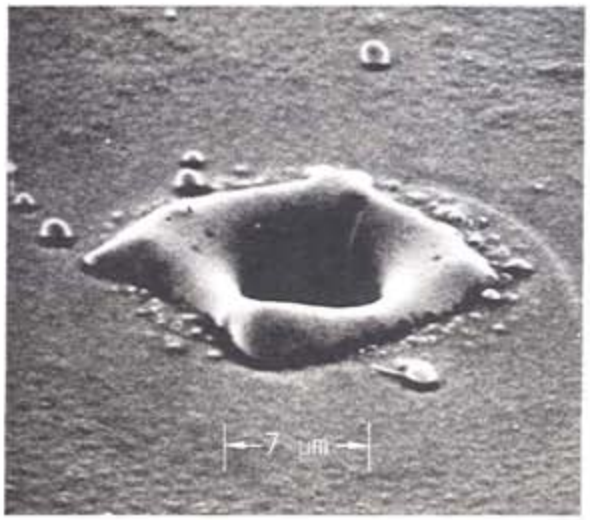


Fig. 2. Three views of a typical composite x-ray pinhole assembly. The 16-gauge hypodermic needle, above, forms the body of the pinhole. We cut the end of the needle off, square it up, and epoxy on a 12-μm-thick gold foil. Then we drill a 125-μm-diam hole in the foil, forming the visible-light pinhole. This we cover with a 9-μm-thick disk of special glass that is opaque to x rays but transparent to visible light. Punching a concentric 3- to 10-μm hole through this glass disk with a laser completes the composite pinhole. The greatly enlarged reticle pattern, upper left, is superimposed on the glass disk during laser drilling. The electron-microscope view, lower left, shows one of the x-ray pinholes close up.

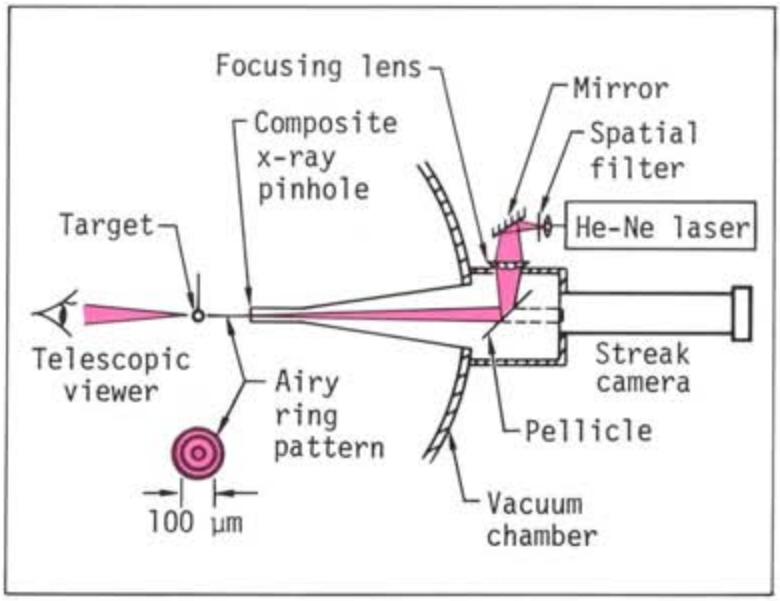


Fig. 3. Alignment scheme for space-time studies of x-ray emission with the pinhole streak camera. Light from a helium-neon laser goes through a system of lenses, a filter, and a diagonal mirror to an x-ray-transparent pellicle that reflects about 50% of the alignment-laser beam. The angle of the pellicle is adjusted to make the laser beam appear to come from the center of the streak-camera slit. The beam passes through the glass of the composite x-ray pinhole assembly, through the transparent laser target, and into a telescopic viewer. We adjust the focusing lens and the beam clipping to produce a diffraction pattern between the pinhole and the laser target. Then both the pinhole assembly and the laser target can be centered accurately on the diffraction pattern.

measurements provide time-dependent implosion velocities, the best data for meaningful comparisons with numerical simulations.

A new pinhole/streak camera arrangement (Fig. 1) gives us time and space resolution in the same picture, i.e., velocity information. At the left, next to the imploding target, is the x-ray pinhole that forms a 50-times-magnified image of the target on the front slit of the streak camera. The x-ray streak camera, on the right, is based on a modified image converter tube.

X rays from the laser-irradiated target – striking the 10-nm-thick, slit-shaped gold photocathode of the image converter tube – release slow secondary electrons from the cathode. Shaped electrostatic fields accelerate these electrons and focus them into a horizontal line image on the output phosphor screen. Meanwhile, a rapidly rising voltage pulse applied to deflection electrodes in the tube sweeps the line image vertically across the phosphor screen, so things that happen at different times appear at different places in the resulting streaked image. The time resolution of the camera is 15 ps.

When we use the streak camera without the pinhole, the streak data reveal the history of the x-ray intensity emitted during the implosion, but the record contains no detailed information about the spatial motion of the target envelope. Only with the addition of x-ray imaging can we obtain the additional important data on implosion speed.

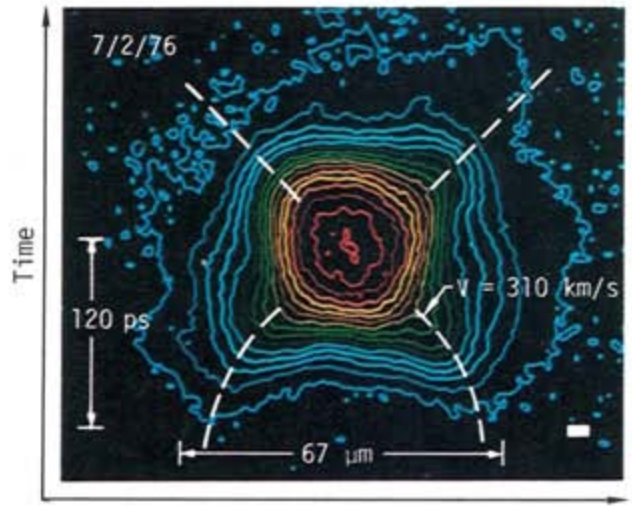
The pinhole/streak camera combination provides accurate data only when all the elements are aligned within a few micrometres. As can be seen in Fig. 1, raising the pinhole just a few micrometres would displace the diameter of the compressed-target image far enough from the streak camera slit that accurate implosion data would not be obtained. Alignment to such precision is difficult, but we have developed the techniques that make it possible.

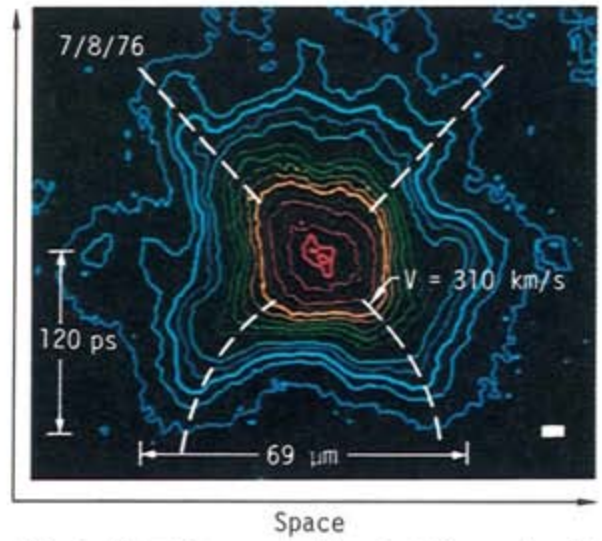
The alignment problem is composed of several interrelated factors. To start with, the glass microsphere targets are small, and the implosion compresses them to a fraction of their original diameter. The small size of the compressed target means that the pinhole must be as small as possible to be able to image details on the target. The use of short-wavelength x rays makes it possible to use very small pinholes to obtain high resolution without losing image quality because of diffraction.

Unfortunately, there are no sources of suitable x rays intense enough to be used for alignment. When we try to use our standard helium-neon laser to align the small pinhole, we run into severe diffraction problems. The wavelength of this laser's red light is too large a fraction of the pinhole diameter, and the resulting image is too diffuse to permit accurate alignment.

We solved this problem by making pinholes that look small at x-ray wavelengths and large in visible light. This is feasible using a special glass. A 9-μm-thick piece of this glass transmits only 0.001% of the x rays but is relatively transparent to visible light, transmitting 13% of the helium-neon laser light.

Figure 2 gives three views of the finished pinhole assembly. The body of the assembly is a 16-gauge hypodermic needle with the end cut off squarely. We





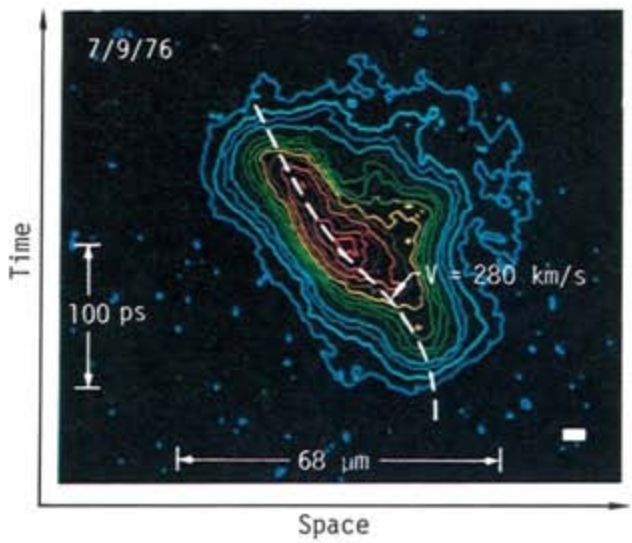


Fig. 4. Space-time record of three implosions made with the pinhole/streak camera combination. The colored lines are contours of equal film density, *i.e.*, of equal x-ray intensity. Vertical arrows indicate implosion times; horizontal arrows show initial target diameters. The small white rectangle in each frame shows the resolution element, 6 μm wide and 15 ps tall. The dashed white lines correspond roughly to trajectories of the target surfaces in space-time; curved trajectories indicate acceleration.

In the implosions recorded on July 2 and 8 (above) the target was irradiated from both sides. These symmetrical implosions reached speeds of 310 km/s and generated 10^6 neutrons. In the experiment of July 9 (lower left) the beam on the left was purposely blocked. The implosion reached a velocity of 280 km/s and generated about 2×10^5 neutrons. Although the implosion was one-sided, the subsequent explosion was two-sided, in agreement with numerical simulations.

mount a 12-μm-thick gold foil across the end of the needle and mechanically drill a 125-μm-diam hole in it. This forms the visible-light pinhole. Then we cement a 9-μm-thick disk of the x-ray-absorbing glass over the gold foil and laser drill a tiny hole in the glass, concentric with the 125-μm hole. This forms the x-ray pinhole.

Having made the composite pinhole, we still have to align all the elements of the system. We do this by inserting an x-ray-transparent optical beam splitter as shown in Fig. 3. We adjust the focusing lenses and the angle of the beam splitter so that the laser light projected through the 125-μm pinhole appears to be coming from the center of the streak-camera slit.

We also clip the light beam at the focusing lens in such a way as to produce a diffraction pattern – a bull's-eye array of light and dark concentric rings – midway between the pinhole and the laser target. We can then move the holder assembly until the 125-μm pinhole is centered on this pattern. This centers the small x-ray pinhole on the line-of-sight to within the 2- to 3-μm concentricity error. Then we move the laser target until it is also centered on the diffraction pattern, completing the alignment to an overall accuracy of 5 μm.

With the pinhole camera aligned with the streak-camera slit, the streak camera records both x-ray production and x-ray source position, separating events in time so that the entire implosion and subsequent explosion can be followed. Figure 4 presents the records of three different implosion events, taken on different days last July. The original black-and-white images have been analyzed with a microdensitometer, and the resulting contour lines have been color coded to reveal details of the density distributions.

All three of these events took place on the Janus laser system, which generates 0.45-TW pulses of 1.06-μm light 70 ps long (FWHM). In the experiments of July 2 and 8, the targets were irradiated with two beams coming from opposite sides, making symmetrical implosions.

Several features of these records are evident. The colored lines are contours of equal density, i.e., x-ray intensity. The small rectangle in the lower right corner indicates the resolution element, about 6 μm wide and 15 ps tall. The scale along the bottom of each picture indicates the initial diameter of the D-T target.

The diagonal dashed lines represent the trajectories of peak x-ray emission in space-time. As such they provide characteristic velocities of the implosion process, which, according to our computer simulations, agree closely with the velocity of the target surface. The two incoming trajectories are curved, indicating that the surface was accelerating throughout the laser pulse. Straight trajectories would indicate a constant velocity.

The experiment on July 9 was purposely made asymmetrical. One of the laser beams was blocked so that the target was irradiated from the right only. The target thus is heated and implodes essentially from one side, with only one incoming trajectory. After convergence near the target center, there is a highly asymmetric expansion with two lobes. The slopes of these trajectory lines indicate the compression and expansion velocities of the glass envelopes. (The camera observes radiation primarily from the shell rather than from the enclosed fuel.) In the one-sided implosion the incoming velocity was 280 km/s. In the symmetrical implosions the measured velocity reached 310 km/s, in good agreement with LASNEX calculations.

All three of these events produced neutrons, but the symmetrical implosions were more efficient, each producing 10^6 neutrons. The asymmetrical implosion produced only 2×10^5 neutrons.

Experiments such as these allow us to study the implosion process in much more detail and with far greater accuracy than ever before. They also provide basic data, for example implosion velocities, that can be compared with the predictions of theoretical calculations. These comparisons give us new information confirming the validity of the basic physics described in our codes. This information is already having an impact on our calculations and target designs and has increased confidence in our inertial confinement approach to fusion.

Key Words: implosions – measurement; laser-induced fusion; streaking cameras; x-ray microscopes.