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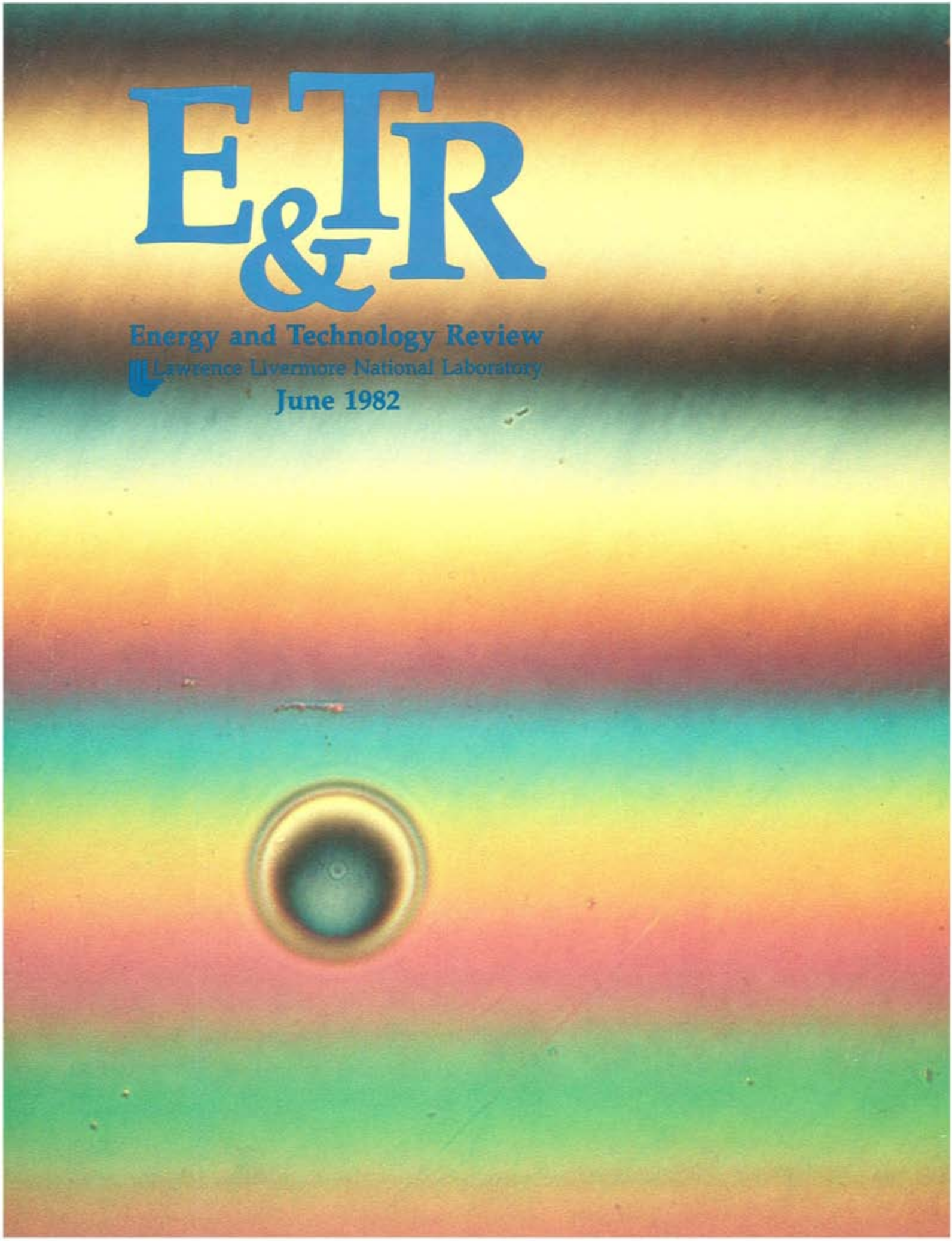

Measuring Microsphere Targets for Fusion Experiments

Microsphere targets used in inertial-confinement fusion experiments must satisfy precise tolerances. We have developed a variety of measurement techniques that enable us to quickly and systematically examine individual microspheres for fabrication defects.

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In inertial-confinement fusion (ICF) experiments, a high-power laser or particle beam is used to implode a tiny target containing deuterium-tritium (D-T) fuel, compressing and heating it until it ignites and burns (in the thermonuclear sense). A typical direct-drive ICF target consists of a fuel core surrounded by a spherical shell. The shell has two layers: an outer ablator of a material such as Teflon and an inner pusher of a higher density material such as glass. As the ablator is heated by a laser or a particle beam, it blows off, producing a rocket-like inward thrust that implodes the pusher, compressing and heating the fuel to the high densities and temperatures necessary to ignite it. For efficient thermonuclear burn, the fuel must stay together long enough to let a large fraction of the nuclei react.

It is crucial to this process that the implosion proceed symmetrically. A symmetric implosion is possible only with a target that has very smooth, uniformly thick walls, so the target must be fabricated to precise tolerances. We have developed several techniques that enable us to measure targets with the necessary precision.

Measurement Techniques

To permit trade-offs among speed, accuracy, and comprehensiveness, we need a variety of target-measuring techniques. Measurements to provide information about a fabrication process, for example, must be accurate but not necessarily rapid or nondestructive. Sorting the output of a low-yield production process requires high-speed, nondestructive measurements, but of only a few common kinds of defect. Final target measurements, to be used for correlating the results of implosion experiments, must be accurate, comprehensive, and nondestructive but need not be faster than an hour or so per target. Depending on the materials used, the various layers in a target may be either opaque or transparent. Each type demands a different measurement technique. As no single technique satisfies all of these requirements, we use several complementary approaches.

At present, our primary techniques of target measurement are optical interference microscopy, microradiography, and scanning electron microscopy. Each has unique assets and limitations.

Optical Interference Microscopy

In interferometry, we deduce the amplitude (depth or thickness) of a defect by measuring an optical phase shift. This technique is highly sensitive to defects with a low aspect ratio (see box on p. 7). Optical interferometry has become the technique of choice for measuring transparent targets such as hollow glass and polymer microspheres. Measurements can be made quickly, sample preparation and handling are quite simple, and the technique is available in many variants.

To rapidly inspect a large number of target spheres, we use white-light interference microscopy. The interference pattern produced by light incident on a transparent microsphere of uniform thickness appears as a set of concentric rings perfectly centered on the sphere. Any deviation from uniformity shows up as as a distortion of this pattern (Fig. 1). With this technique, we can rapidly measure the uniformity of microsphere thickness within 0.05 μm, about 0.1 of the wavelength of visible light.

Initial inspection with interference microscopy tells us whether a batch of

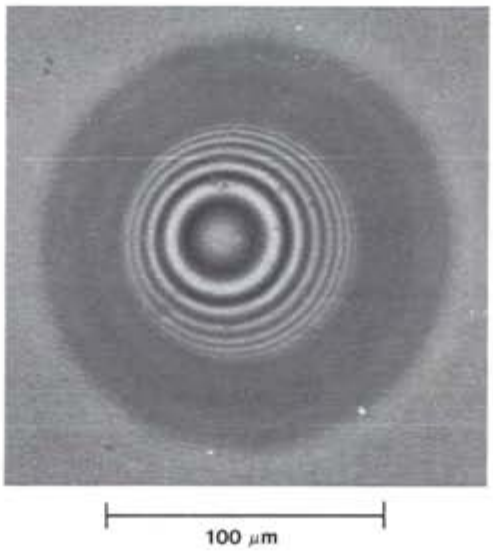


Fig. 1

Pattern produced in a nonconcentric microsphere by optical interference. The mis-centering of the fringe pattern is a measure of nonconcentricity.

microspheres contains target-quality fuel capsules. If most have only a few isolated defects, we sort the batch for prospective capsules. Those with no immediately visible defects are then selected for detailed individual examination.

Full Surface Examination

To meet the exacting specifications for ICF targets, we must inspect the entire surface of the sphere for defects or contaminating layers and measure the uniformity of wall thickness. We have combined a modified interference microscope with a computer-controlled micromanipulator—the Topo I system—that enables us to systematically inspect the entire target. The microsphere is held in the field of view by two soft, flat, silicone-rubber pads, each fixed at the tip of a tiny stalk (Fig. 2). By moving the pads equal distances in opposite directions along either the x or the y axis, we roll the microsphere about its center, which remains fixed. A programmed microcomputer controls the tip motion. With Topo I, we visually scan the target for defects through the interference microscope.

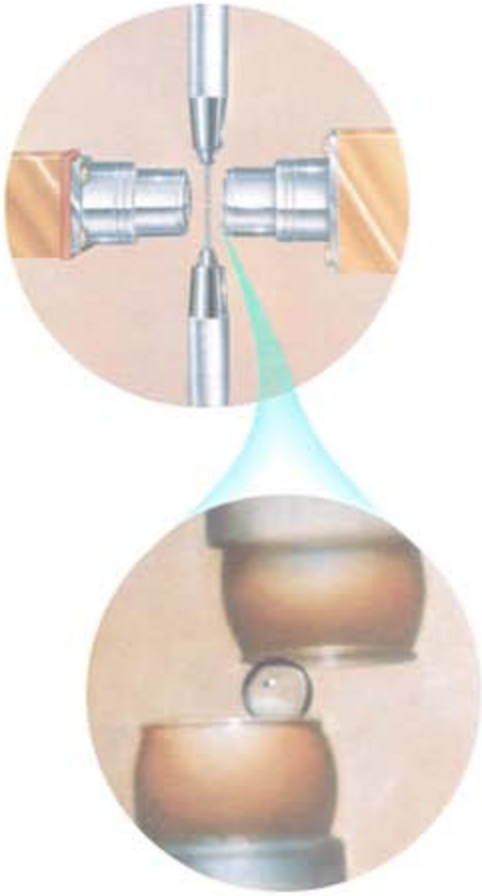


Fig. 2

(a) In the Laboratory's Topo I and Automated Sphere Mapper (ASM) optical interference system, a microsphere target is held in the microscope's field of view by two soft, flat, silicone-rubber pads, each at the tip of a tiny stalk. (b) When the pads are moved equal distances in opposite directions along either the x or the y axis, the microsphere rolls about its center, which remains fixed. A programmed microcomputer controls the tip motion.

To make more accurate measurements than can be made by eye and to eliminate the need for an observer, we have automated the interferometric sphere-measuring process. The Automated Sphere Mapper (ASM), our most sophisticated optical measuring device, combines automated heterodyne interferometry with a computer-controlled manipulator to map the surface of targets. In the ASM (Fig. 3), a microcomputer controls the sphere-rotator system and coordinates rotation with interference phase measurement of the surface topography. The topographic data are stored on a disk and displayed in graphical form in real time. The graphics display can be permanently copied for comparison with other target spheres.

The ASM has several novel features: the optical system that performs heterodyne interferometry, the manipulator that positions the sphere during measurement, and provisions for computer control, data acquisition, and data display.

In heterodyne interferometry, an optical phase shift in the measurement beam is converted to an electronic phase shift that can be measured very rapidly and accurately. The ASM embodies this principle in a novel design that measures the amplitude of surface features with an accuracy of 10 nm while requiring sphere position to be maintained only within a few micrometres. In an ordinary reflection interferometer, where the measuring beam is simply focused at one point on a sphere, any motion of the sphere along the beam axis has the same effect as a surface defect. A manipulator able to maintain sphere position with the required 10-nm accuracy would be extremely expensive.

To map the surface of an opaque target with the ASM, we first focus the measuring beam to a point on the front surface of the sphere (Fig. 4). The

reflected beam is routed around the target to its rear surface and focused toward the center of the sphere so that it is again reflected, this time from a broad area of the rear surface. With this arrangement, any surface feature or irregularity in the diameter of the sphere causes a change in the path length of the measuring beam. The system measures local defects as they pass under the part of the beam focused on the surface. When these defects pass under the broadly focused beam on the rear surface, they are "averaged out" with a negligible effect on the beam.

The primary advantage of this interferometer lies in its relative insensitivity to changes in the position of the target sphere. Small motions of the sphere along the beam's axis cause no change in the path length, so that sphere position need be maintained only within 1 to 2 μm.

The manipulator we developed for the ASM is based on the same operating principle as the Topo I manipulator. In the Topo I, each tip is driven independently with a stepping motor, but this technique is neither fast nor accurate enough for the ASM. In the ASM, equal and opposite motion of the manipulator tips is achieved by a mechanical coupling that eliminates the need to simultaneously drive two stages at precisely the same rate.

As shown in Fig. 5, two flat plates are coupled by a set of three balls held in bearings that allow them to rotate but not to translate. The motion of the lower plate, which is driven by a set of x-y stages, drives the coupled plate an equal distance in the opposite direction. The motion of the plates is transmitted through holding arms to the manipulator tips, which then move in opposite directions to rotate the spherical target about its center.

The controlling microcomputer builds up a point-by-point map of the target sphere by driving the sphere rotator system while acquiring data from the interferometer. Figure 3 shows a microradiographic image of the target and a representative section of such a map. Map data are stored for subsequent

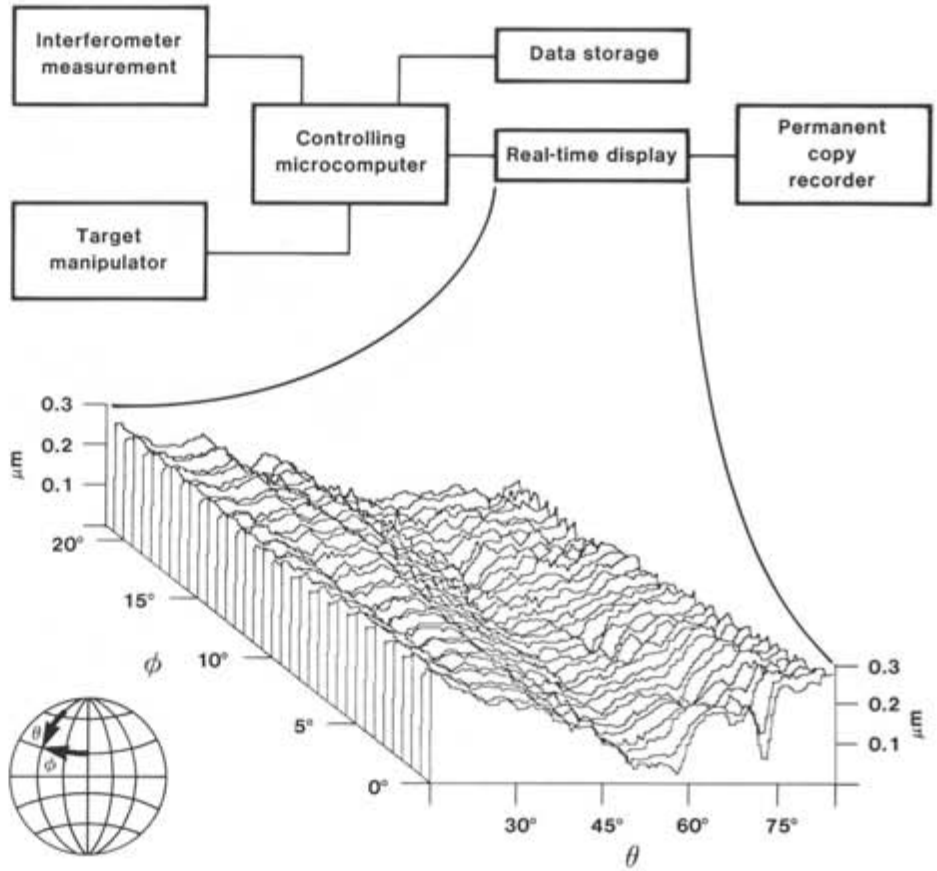


Fig. 3

In the ASM, a microcomputer controls the sphere-manipulator system and coordinates rotation with interference phase measurement of the surface topography. The topographic data are stored on a disk and displayed in graphical form in real time. The pull-out shows a three-dimensional target-surface map produced by heterodyne interferometry using the ASM system. The sphere is manipulated by the device shown in Fig. 5.

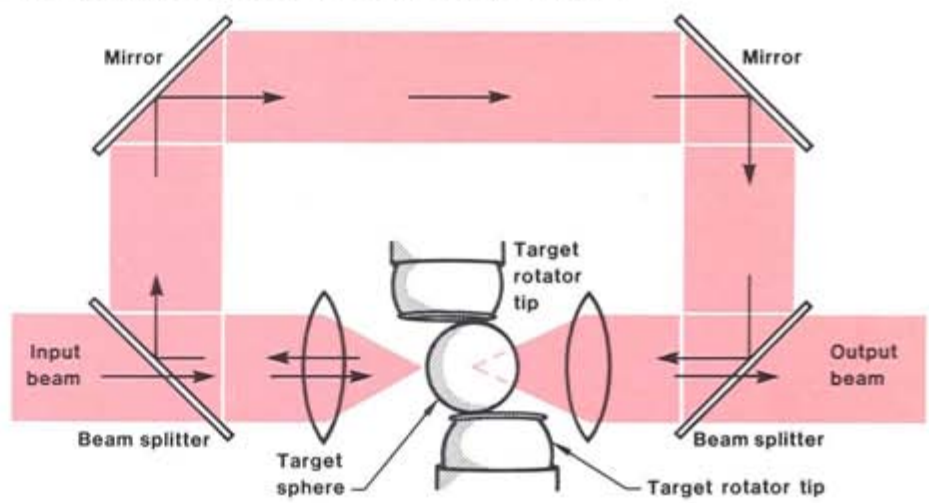


Fig. 4

The ASM uses optical interferometry to map the surface of an opaque target. The measuring beam is focused on a point on the front surface of the sphere and reflected and routed around the target to its rear surface; here, it is focused toward the center of the sphere and again reflected, this time from a broad area of the rear surface. An irregularity of the surface or change in diameter causes a change in the path length of the measuring beam.

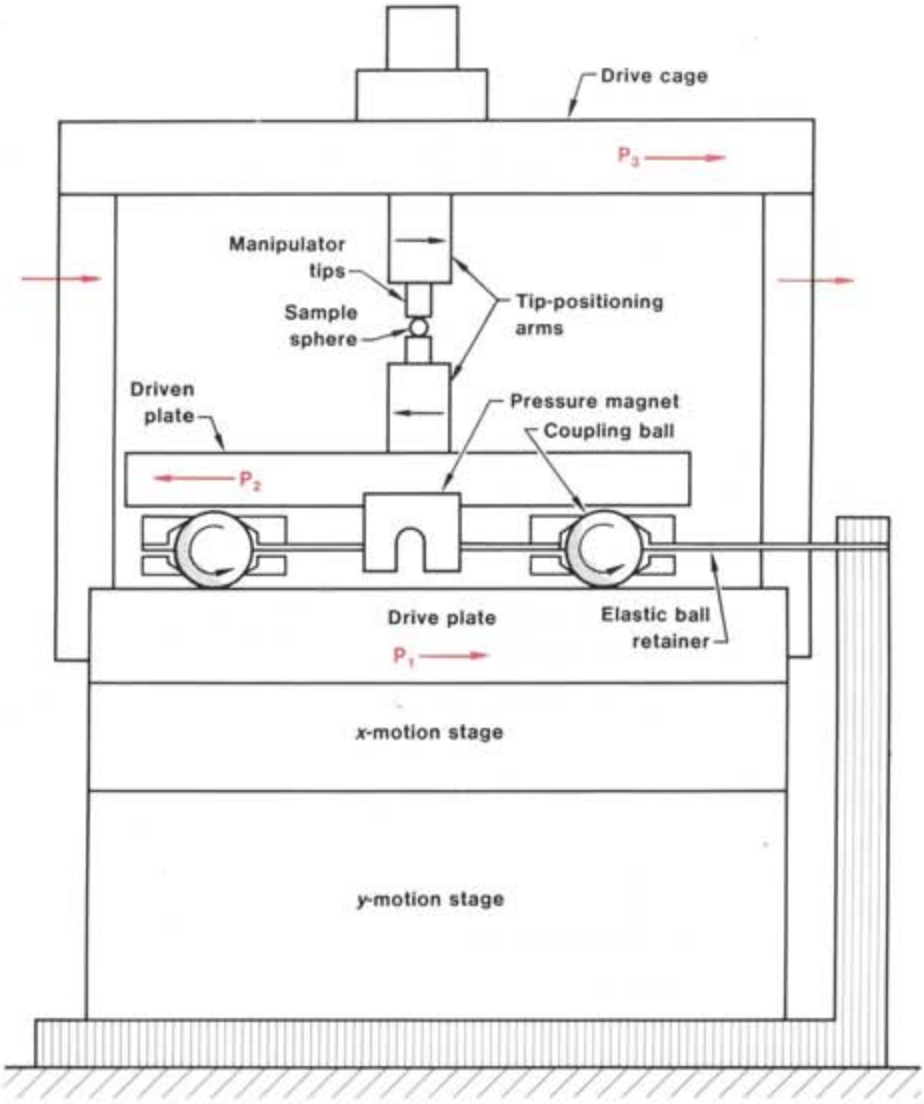


Fig. 5

Target manipulator developed for the ASM. To rotate the target sphere for inspection without moving its center, the tips of the manipulator must move equal distances in opposite directions. Three balls rotating about their fixed self centers are used to mechanically couple the motion of two flat plates. When the drive plate (P_1) is moved in one of two orthogonal directions, the coupled plate (P_2) moves the same distance in the opposite direction. The motion of the drive plate is transmitted directly to the upper plate (P_3), which moves in the same direction. The net result is rotation of the target about its self center.

analysis. We can retrieve the stored data at random to display full or partial mappings in various formats.

The ASM embodies several substantial improvements over other sphere-measuring systems:

- 10-nm thickness resolution and 2-μm spatial resolution.
- Total mapping time of less than 60 s for a sphere 150 μm in diameter.
- Computerized data acquisition that eliminates human measurement errors and biases.
- Complete sphere mapping in a single data-acquisition scan, minimizing sphere handling.
- Interactive software that allows the operator to tailor a measurement to specific requirements.
- Real-time contour plots and pseudo-three-dimensional data plots plus hard copy of any display.
- Data written on flexible computer disk for permanent, detailed, transportable storage.
- Ability to enter scan data into LLNL's timesharing computer system for more extensive analysis and display.

These features make the ASM the most advanced target-measuring device currently available.

Microradiography

For transparent targets, optical-interference measurements provide excellent thickness and uniformity data. For opaque targets, microradiography is the technique of choice. As almost all advanced target designs contain one or more opaque layers, accurate radiographic measurements are crucial to obtaining target-quality microspheres.

In microradiography, we illuminate a target with a small, very bright x-ray source. The unmagnified shadow of the target is cast onto a high-resolution photographic emulsion (Fig. 6). We obtain two views of the target by sandwiching it between two thin films, one of which is translated by a micromanipulator to roll the target 90 deg between exposures. By examining the resulting x-ray images with a high-resolution microscope, we can measure target features to an accuracy of about 1 μm.

Much more accurate information can be obtained by digitizing and computer processing the x-ray image. This process, when done conventionally with a flatbed densitometer, is very slow, requiring extremely careful alignment of the optics for each digitization. The result is a data tape that must be transferred to another computer for analysis.

To circumvent these problems, we developed the AXIAS (Automated X-ray Image Analysis System). In this system, the image is rapidly digitized by a microprocessor and then analyzed by a dedicated microcomputer. We use a television camera to examine, through a high-power optical microscope, a film plate containing x-ray images of an

array of targets. The video image of each target is digitized at high speed and stored in a special-purpose random-access memory from which it is computer processed.

We use a very bright xenon light to illuminate the x-ray image through the microscope. This enables us to set the camera to minimize the shading error and latent error of the vidicon tube. The microscope has several objectives of different powers to examine target images of various sizes with maximum resolution. At its lowest magnification, the system can view images up to 700 μm in diameter. At high magnification, the spatial resolution is less than 0.5 μm.

The camera that records the image incorporates a logarithmic amplifier to detect optical densities in a linear fashion. Because of its very high signal-to-noise ratio, the camera can detect an optical density range of 3 (a light-transmission range of 1000). The video image is digitized in 1/30 s and stored directly in a random-access memory. To reduce electronic noise, the digitizer-processor sums and averages sequential frames of video images. Shading error from the xenon light source is subtracted directly from the image.

To provide fast and precise measurements of target thickness and uniformity, the digitized image is next transferred to computer memory. We have developed a very fast data channel for transmitting information from the digitizer's memory to the microcomputer. An entire image consisting of more than 250 000 points can be transferred in 1.4 s. The stored image is analyzed using noise-reduced scans, operator-controlled cursors, and least-squares fitting for maximum sensitivity.

To make a measurement, we extract a horizontal cross-sectional scan through the center of the target image. Sphere diameter and wall thickness are determined by locating the edges in the cross section. The accuracy of edge location is limited by film-grain noise. We can reduce grain noise by averaging several immediately adjacent cross-sectional scans (Fig. 7a.) This procedure reduces resolution, however, as only one scan passes directly through the center of the sphere and thus represents a true cross section. We reduce grain noise without losing resolution by averaging along an arc (Fig. 7b). This method, which we call wedge-scan averaging, considerably reduces grain noise over that in an unaveraged cross section, providing much more accurate edge measurements.

To rapidly measure the diameter of a feature, we place operator-controlled cursors at its edges. The computer automatically reads out the distance between them. To make more accurate measurements, we use a least-squares fitting routine to analyze the x-ray image. This routine does a four-parameter fit to the data from the

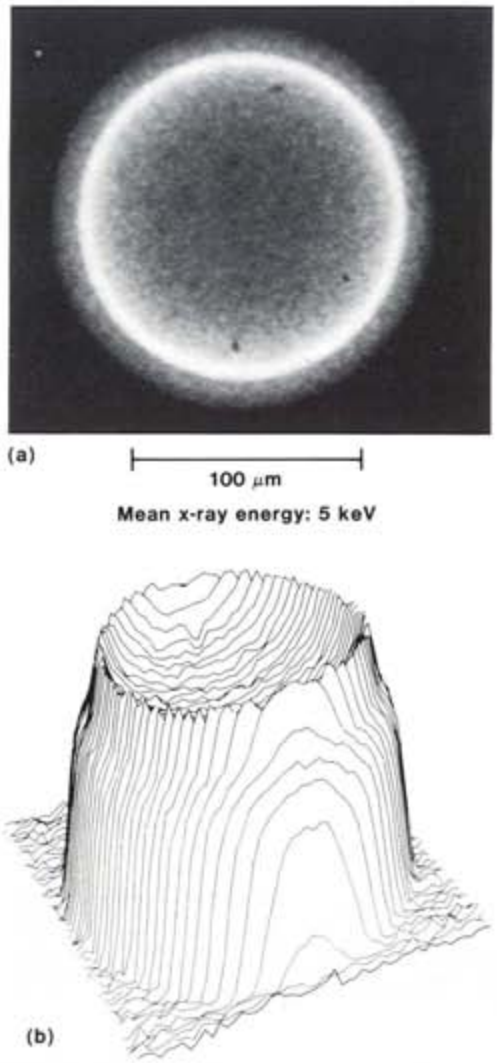


Fig. 6

(a) Microradiograph image of a hollow glass microsphere ICF target (hydrocarbon polymer coated). (b) Three-dimensional representation of the digitized image.

wedge-averaged density scan. Running on the same microprocessor system that acquires the data, the fitting routine calculates values of diameter, thickness, and nonconcentricity in 2 to 3 min.

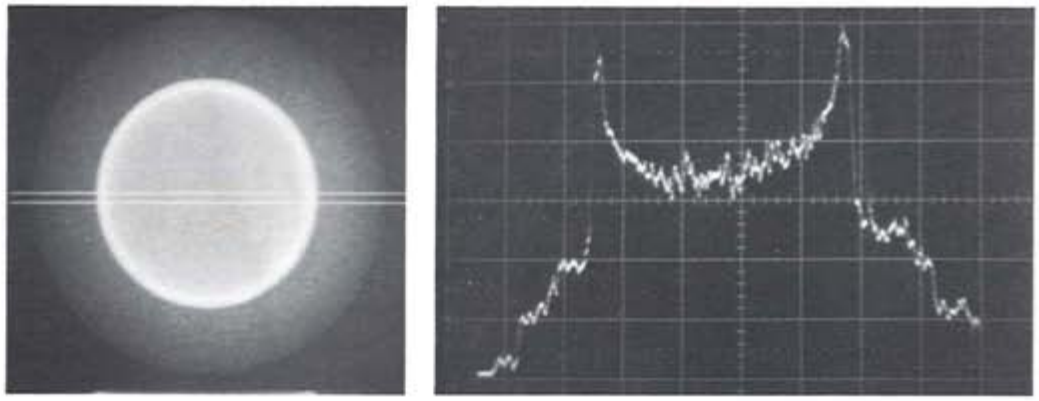
With this analysis, we can measure target diameter within 1%, wall thickness within 0.5 μm, and concentricity within 3% of the wall thickness. The entire process of image digitization, transfer, and analysis requires only a few minutes per image. We are developing a fully automated system that can rapidly scan and measure an array of target images.

Scanning Electron Microscopy

A scanning electron microscope (SEM) provides higher spatial resolution of ICF targets than either optical or radiographic methods. In an SEM, a highly focused electron beam generates an image of the surface with greater resolution than can be obtained with light. A good instrument can achieve a spatial resolution of less than 10 nm. With an SEM, we can measure not only surface features but also the thickness and internal structure of fractured or cross-sectioned samples. High-resolution surface measurements are especially important because small surface defects can nucleate the growth of much larger defects in a coating. The SEM is also widely used in composition and microstructure analysis, a distinct but equally important area of ICF target measurement. Finally, SEM measurements are used to cross check and calibrate interferometry and radiography measurements.

SEM full surface mapping. We have developed several techniques to apply the SEM to the measurement of ICF targets. One technique uses a target manipulator, similar to that used with our Topo I and ASM systems, that enables us to systematically inspect an entire target under completely automatic control, recording the SEM images and storing them permanently on a video disk.

(a)



(b)

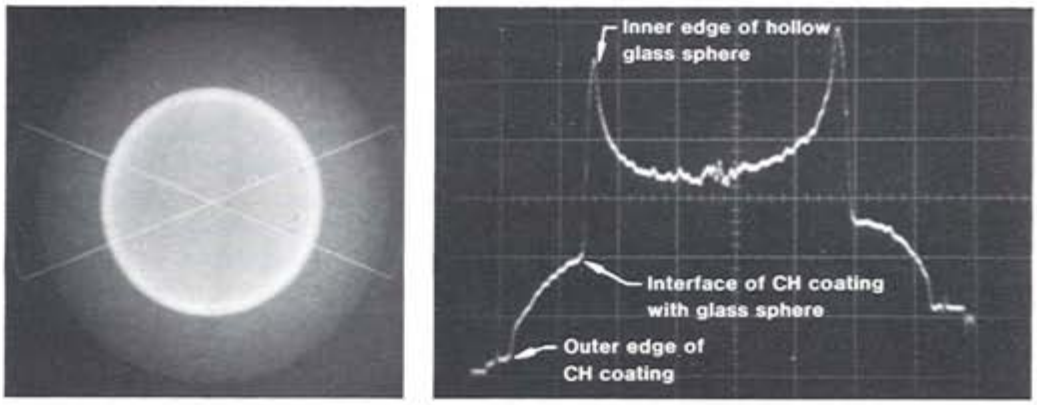


Fig. 7

(a) Left: the Laboratory's AXIAS x-ray microradiographic system extracts a horizontal cross-sectional scan through the center of a hollow glass sphere, coated with hydrocarbon (CH) polymers, shadowed on a photographic plate. Sphere diameter and wall thickness are determined by locating the edges in the cross section. Right: AXIAS-produced unaveraged cross section through a microsphere target. Grain noise is evident. (b) Left: Wedge-scan averaging along an arc eliminates noise while preserving resolution. Right: the same cross section analyzed by wedge-scan averaging. Grain noise is considerably reduced, providing much more accurate edge measurements. Least-squares fitting to these data provides very accurate measurements of thickness and diameter.

The target sphere is first coated with carbon to make it electrically conductive and then mounted between the manipulator tips. A microcomputer synchronizes stage motion, SEM scan, and the video-disk image recorder. The system records a series of partly overlapping images of the target surface, accumulating a montage that enables us to examine any point on the sphere. The recording time for an entire sequence (up to 1000 pictures) is as long as 36 h. Once stored, however, the data can be almost instantly retrieved for examination.

The SEM system must be stable enough to need no readjustment during the entire mapping operation. This requires careful adjustment of the electronics, control of contamination in the electron-focusing column, and a stable electron emitter. Normal tungsten filaments have a 40-h life, during which their emission properties may change

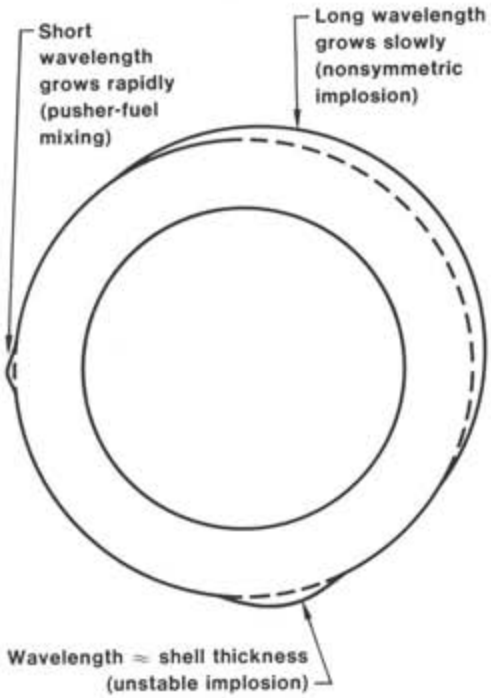
The Character of Target Defects

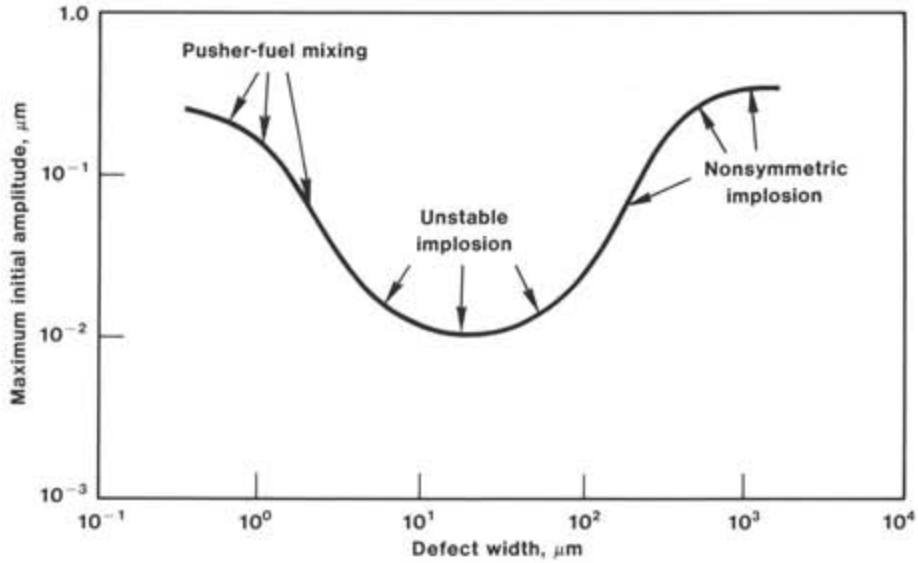
Microsphere targets are subject to a variety of defects resulting from the fabrication process or subsequent contamination. A defect is characterized by its wavelength (width) and amplitude (depth or thickness).

Different kinds of defects affect the implosion process in different ways (left-hand figure). If one side of the pusher or ablator layer is thicker than the other, for example, the implosion will be nonsymmetric. An imploding target is subject to fluid instabilities. During implosion, the amplitude of small thickness variations or perturbations (pits, grooves, and protuberances) in the target surface or in the interface between layers grows exponentially. Such defects can cause the imploding shell to break up. Finally, the growth of small perturbations on the inner surface of the pusher can result in mixing of the pusher material with the fuel. This effect quenches the thermonuclear burn and reduces target yield, even though the pusher remains intact and the implosion proceeds to high density.

These considerations have generated strict requirements for the initial smoothness and uniformity of each layer, surface, and interface in a target. As the growth rate of a perturbation depends on its wavelength, the requirements specify the maximum allowable initial amplitude for a defect of a given wavelength. The right-hand figure shows typical uniformity requirements for a target 600 μm in diameter with a wall 40 μm thick.

Because of the wavelength sensitivity of perturbation growth rates, we must be able to measure defects with a low aspect ratio (those with a small amplitude but a relatively long wavelength). In an extreme case (the minimum of the curve in the right-hand figure), we must detect defects with aspect ratios as low as 0.001. Such defects usually are invisible to measurements of surface contour. To effectively measure ICF targets, therefore, we need a set of techniques that resolves both wavelength and amplitude to cover the entire "defect space."





greatly. We stabilize emission by using a lanthanum hexaboride emitter, which, when properly adjusted, is bright and stable for more than 100 h.

Our SEM system effectively complements full surface inspection with an interferometer. Whereas the optical interferometer is more sensitive to broad, low-amplitude defects, the SEM can detect surface defects smaller than the spatial resolution of an optical microscope. Our paper describing the SEM system received the Microbeam Analysis Society's award for the best instrumentation paper of 1979.[1]

Backscattered electron mapping. We have developed another SEM technique that uses the differential detection of backscattered electrons to measure surface topography. This technique is especially sensitive to low-aspect-ratio defects, improving the detection limit to about 1:50. Surface roughness can also be quantitatively measured by this method.

We have developed another SEM technique that uses the differential detection of backscattered electrons to measure surface topography.

As backscattered electron flux is strongly dependent on the angle between the surface and the electron beam (the take-off angle), we can use the flux to measure local slope on a surface. Detectors on opposite sides of an electron beam incident on a sloping surface will see different signal levels. Our system consists of a conventional SEM with four backscattered-electron detectors placed radially around the primary electron beam at 90-deg intervals.

Because we use two detector sets, we can measure the slope in any direction. The computer controlling the SEM receives the slope data and calculates height differences, displaying them on a graphics terminal. By scanning a raster pattern over the sample, the computer builds up a topographic image of its surface (Fig. 8).

Future Work

Our present combination of measurement techniques is close to satisfying both resolution and speed requirements for transparent ICF targets. For opaque targets, much development work remains. For example, we still lack fast,

accurate techniques for scanning large numbers of opaque spheres, rapidly measuring the key parameters, and selecting acceptable targets. The prospect for developing such techniques is not promising. Future work on opaque-target selection, thus, may take a somewhat different direction. It may prove more feasible and economical to improve the fabrication process for opaque targets than to attempt to combine low-yield fabrication with rapid sorting. The availability of high-yield target-fabrication processes for a commercial ICF power reactor would permit more efficient use of production equipment and target materials and eliminate the need for fast, nondestructive sorting measurements. There are, of course, many intermediate possibilities. For example, sorting may be used at a point where it becomes neither feasible nor cost-effective to further improve the fabrication process.

Summary

Inertial-confinement fusion experiments require microsphere targets with walls that are extremely smooth and of a highly uniform thickness and concentricity. We have developed several new measurement devices and innovative techniques that enable us to measure such features quickly and precisely. These techniques lend themselves to a variety of applications, from rapid survey and sorting of large batches of fabricated targets to complete measurements of individual targets.

Although our techniques work well for transparent targets, much work remains to achieve the same results with opaque targets, for which the technical problems appear less tractable. Thus, for opaque targets, it may prove more feasible to improve fabrication processes.

Key Words: Automated Sphere Mapper (ASM); Automated X-ray Image Analysis System (AXIAS); inertial confinement fusion; microradiography; microsphere; optical interference microscopy; scanning electron microscopy; target analysis—ICF; Topo I.

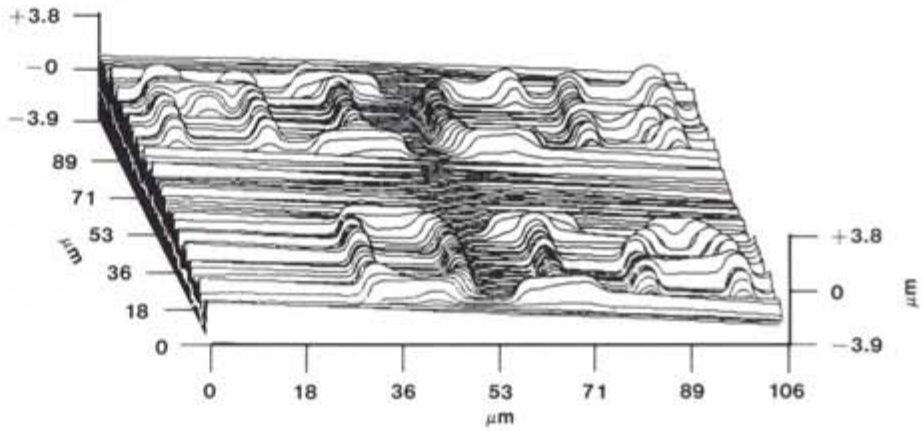


Fig. 8

Topographic surface map produced with backscattered electrons. The computer scans a raster pattern over the sample and calculates the height differences, displaying them on a graphics terminal. The inset shows a scanning electron microscope image of the same area.

Notes and References

1. C. M. Ward, D. L. Willenborg, and K. L. Montgomery, "Full Surface Examination of Small Spheres with a Computer-Controlled Scanning Electron Microscope," *Microbeam Analysis*, 1979.