DEFENSE PROGRAMS

Zone-Plate Coded Imaging of Thermonuclear Burn

The first high-resolution, direct images of the region of thermonuclear burn in laser fusion experiments have been produced using a novel, two-step imaging technique called zone-plate coded imaging. This technique is extremely versatile and well suited for the microscopy of laser fusion targets. It has a tomographic capability, which provides three-dimensional images of the source distribution. It is equally useful for imaging x-ray and particle emissions. Since this technique is much more sensitive than competing imaging techniques, it permits us to investigate low-intensity sources.

In the Laboratory's laser fusion program, we are experimenting with thermonuclear explosions on a microscopic scale using focused, high-power laser beams. A typical experiment focuses multiple laser beams onto a spherical glass pellet about 100 μm in diameter that is filled with a high-pressure mixture of deuterium-tritium gas. The incident laser radiation heats and compresses the target, driving it to thermonuclear burn conditions.

To obtain a more detailed understanding of the physical processes involved in laser-driven implosions, advanced diagnostic devices are used to collect and analyze the x-ray and particle emissions from such targets. Recently, a new diagnostic device, a Fresnel zone-plate camera employing coded imaging principles, was used to image the alpha-particle emission (one of the fusion reaction by-products) from imploded fusion targets, and thereby to produce the first high-resolution, direct images of thermonuclear burn in such experiments. These measurements provide an explicit demonstration that the thermonuclear burn produced by laser-driven implosions does indeed occur within a compressed core of the imploded target.

Use of the zone-plate-coded imaging (ZPCI) technique in laser fusion experiments involves a simple two-step procedure, which is outlined below and illustrated in Fig. 1.

Step 1—Shadowgraph Recording. A Fresnel zone-plate camera views the laser-irradiated target. The zone-plate camera is a simple shadow device containing no lenses or shutters. It uses a Fresnel zone plate—a concentric array of alternately transparent and opaque rings of equal area—as an aperture at the front, an appropriate recording film at the rear, and filter foils to keep unwanted radiation from reaching the film. The radiation emitted from the target casts a geometrical shadow through the transparent rings of the zone plate onto the recording film, producing a shadowgraph. This shadowgraph, also called a coded image, contains all the necessary information about the spatial distribution of the source, but that information is scrambled, or coded.

Step 2—Image Reconstruction. Unscrambling or decoding information that has been recorded in the shadowgraph is accomplished by shining a laser beam through the shadowgraph and viewing the diffracted laser light at the appropriate planes downbeam, much in the same way one would reconstruct an image from a hologram. At each plane, there is a high-resolution, optical, real image of the radiation emitted from the corresponding plane of the target. The simplicity

Contact Natale M. Ceglio (422-8251) for further information on this article.
of the ZPCI optical reconstruction procedure is due to the choice of the Fresnel zone pattern as the aperture on the shadow camera (Fig. 2). No other aperture pattern would permit the use of such a simple optical procedure for image reconstruction.

The Fresnel zone pattern operates in two distinct ways in the two steps of the ZPCI procedure.

In step 1, the radiation passing through the zone plate has wavelengths very much smaller than the minimum zone width. In this case, diffraction effects are negligible, and the zone plate acts merely as a coded aperture for casting shadows. In step 2, the wavelength of the reconstruction laser light is comparable to the minimum zone width so that

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Fig. 1. Basic principles of the two-step ZPCI technique. Step 1: a zone-plate shadow camera views the imploding target. The emitted radiation—appropriately filtered—casts a shadow through a Fresnel-zone-plate aperture onto a recording film. Each source point will cast a separate shadow onto the recording film, producing a shadowgraph. Each zone-plate shadow uniquely characterizes, by its size and position, the spatial position of its associated point. Step 2: the processed shadowgraph transparency is illuminated with a low-power, visible-light laser beam. Each zone-plate shadow focuses the incident laser light to a diffraction-limited spot—the inversely located image of its associated source point.
diffraction effects dominate in image reconstruction. Each individual zone-plate shadow in the coded image acts as a circularly symmetric diffraction grating, focusing the incident laser light.

We can illustrate the significance of the Fresnel zone pattern more fully by considering how the technique works. We choose for illustration a hypothetical, incoherent radiation-source distribution composed of three separated point sources. The points may emit any incoherent radiation—electrons, x rays, alpha particles—that travels in a straight line from the source through the zone-plate aperture to the recording film. Each source point will cast a separate zone-plate shadow onto the film (see Fig. 1). Note that each zone-plate shadow uniquely characterizes, by its size and position, the spatial position of its associated source point. That is, off-axis points cast off-axis shadows, more distant points cast smaller shadows, and closer points cast larger shadows. Thus, the spatial distribution and size of the zone-plate shadows encode on the shadowgraph the information about the spatial distribution of the source.

The unique focusing properties of the Fresnel zone-plate pattern are used in the image reconstruction. Each zone-plate shadow focuses the incident laser light to a diffraction-limited spot, the image of its associated source point. In this way the three zone-plate shadows focus the incident laser light to a three-point image of the original three-point source. This simple concept of point-by-point reconstruction from zone-plate shadows can be extended to understand how a more complicated source distribution is imaged by the ZPCI two-step technique.

Fig. 2. Micro-Fresnel zone plates. The Fresnel zone plate is a pattern of alternately transparent and opaque, equal-area, annular zones. High-resolution coded imaging requires the use of free-standing, metallic zone plates having zone widths of microscopic size. These are fabricated at LLL using ultraviolet photolithography and microelectroplating techniques. (a) A free-standing gold zone plate in which the gold zones are supported by a series of radial struts. The zone plate is 5 \( \mu \text{m} \) thick, its diameter is 1 mm, the outermost zone is 2.5 \( \mu \text{m} \) wide, and the plate has 100 zones. (b) Scanning-electron micrographs of sections of a similar gold zone plate before it was lifted off the substrate on which it was fabricated.
SPECIAL FEATURES OF THE
ZPCI TECHNIQUE

Three particular features of the ZPCI technique make it especially attractive for diagnostic measurement of laser fusion plasmas:

- Tomographic capability—it produces three-dimensional images of three-dimensional sources.
- Broad radiation applicability—it can be used to image any incoherent radiation (x rays, electrons, alpha particles, etc.) that travels in straight lines.
- Efficient information collection—it can see small, low-intensity sources better than conventional imaging techniques.

Tomography. ZPCI produces three-dimensional images in much the same way as holography, except that there is no coherence requirement for the source. We record three-dimensional source information on the two-dimensional coded image and then retrieve it by viewing the reconstructed image distribution in separate reconstruction planes (Fig. 3). Ideally, there is a one-to-one correspondence between each reconstruction plane and each source plane. Thus, a complex three-dimensional source distribution can be ideally synthesized plane by plane.

The tomographic capability of ZPCI has been experimentally demonstrated. Shown in Fig. 3 are...
reconstructed images of the thermal x-ray emission from a glass microsphere target, irradiated from two opposite directions by a low-power neodymium-glass laser pulse. Because of the low power on target, no compression was achieved. The images show the x-ray emission from the outer glass shell of the target as it is heated by the two laser beams. The three images are contour maps representing the x-ray emission from three separate planes within the target.

There are, of course, practical resolution limits to the tomographic capability of ZPCI. In alpha imaging experiments, for example, the small size of the compressed target core (about 25 µm) precluded the possibility of three-dimensional images of the thermonuclear burn region. The zone-plate camera used had an aperture with 100 zones and a tomographic resolution of only 70 µm. Since tomographic resolution improves with the number of zones, work is under way to produce a zone-plate camera with a 1000-zone aperture, having a tomographic resolution of about 10 µm.

Broad Radiation Applicability. Zone-plate coded imaging is an extremely versatile technique for imaging small x-ray sources as well as alpha-particle emission. The attractiveness of ZPCI for x-ray imaging is enhanced by its high-energy x-ray capability. In this application, ZPCI complements the high-resolution capability of the grazing-incidence-reflection x-ray microscope that operates below about 6 keV. The ZPCI technique has been used to image fusion target x-ray emissions in the range 12 to 24 keV. (In these experiments, the high-energy limit was determined by x-ray transmission through the solid zones of the gold zone plate used, and the low-energy limit was set by the x-ray filter foils used.)

Information Collection Efficiency. The zone-plate shadow camera has a very high information collection efficiency that allows it to see small, low-intensity sources with a much greater signal-to-noise ratio than conventional imaging techniques. For example, to improve resolution, a conventional pinhole camera must sacrifice radiation collection by reducing pinhole diameter. The zone-plate camera, on the other hand, can maintain both high resolution and high collection efficiency by merely increasing the number of zones in its zone-plate aperture.

The radiation collection efficiency of the zone-plate shadow camera has made it particularly well suited for imaging thermonuclear burn in current laser fusion experiments. The thermonuclear burn region has been small (typically less than 25 µm in diameter), and the total alpha emission has been limited. In one of the alpha-imaging experiments to be discussed, the imploded target emitted only 300 million alpha particles. The zone-plate camera collected roughly one-half million alphas and yielded a reconstructed image with resolution of about 3 µm. A conventional pinhole camera having the same nominal resolution would have collected only two alpha particles—a number insufficient to produce an image of the burning thermonuclear fuel.

ALPHA-IMAGING TARGET EXPERIMENTS

Imaging thermonuclear burn in laser fusion presented us with three primary challenges: the microscopic dimensions of the source required a high resolution capability; the relatively low yield of current target experiments required efficient collection of the alpha-particle emission; and the very high level of background radiation accompanying the alpha emission required extraordinary radiation discrimination in image recording. We have already seen how the zone-plate shadow camera served to obviate the first two of these requirements. The procedures used to achieve the appropriate radiation discrimination in these experiments are outlined below.

There was approximately 100 000 times more energy in background radiation (x rays, electrons, ions) from the target experiments under discussion than in the alpha-particle emission. We successfully recorded the alpha-particle coded image without interference from the intense radiation background by using a very thin (about 6 µm) layer of red plastic (cellulose nitrate) instead of photographic film. The thin plastic layer was placed close behind a beryllium filter foil about
8 \mu m thick that served to stop all heavy ions from reaching the plastic, while letting the alpha particles through. The cellulose nitrate acted as a highly discriminating alpha-particle recording film. Each alpha incident on the plastic produced a microscopic damage channel, which upon subsequent etching produced a pinhole all the way through the 6-\mu m layer. None of the other radiation reaching the cellulose nitrate produced pinholes through the film. The final coded image appeared as an array of pinholes—each produced by an alpha-particle track—through the red cellulose nitrate layer. This pinhole pattern was then contact-printed, using green light for maximum contrast, onto a photographic glass plate and optically reconstructed as detailed earlier.

The reconstructed images of the alpha-particle emission from two different target experiments are presented in Fig. 4. Shown are isoe mission contour maps of the burn region. Each contour line represents a locus of constant alpha-emission density, time-integrated over the duration of the burn (less than 15 ps). The incremental change in alpha emission is constant between successive contours, with the lowest emission level represented by the outermost contour.

These experiments were conducted using the Argus laser, which produces a dual-beam, multi-terawatt pulse of 1.06-\mu m light. The laser output was focused onto the target from two opposing, parallel directions by a pair of f/1 aspheric lenses. Typical pulse lengths for these experiments were 25 to 60 ps (full width, half maximum), with 50 to 80 J per beam. Microsphere target diameters ranged from 80 to 100 \mu m, and the target implosions produced alpha-particle yields ranging from 300 to 800 million.

The images of Fig. 4 show that the burning fuel was compressed into an egg-shaped core at the center of the spherical target. The eccentricity of the oval core was found to increase (core became less spherical) as the laser power on target increased. The dimensions of the burning fuel region are given in Table 1. Nominal image resolution is 10 \mu m. (Using more advanced procedures, we have recently achieved higher resolution images; see Fig. 5.) From these measurements, we can infer a fuel-volume compression factor of 150 and an estimated compressed-core fuel density of $3 \times 10^{22}$ ions/cm$^3$. Fuel temperature was measured independently at about 7.3 keV.

The alpha-particle images confirm for the first time that the thermonuclear reactions in laser implosion experiments do indeed occur within a compressed core of the target. They provide direct information about thermonuclear burn geometry.

**Table 1. Burning fuel dimensions.**

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<thead>
<tr>
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<th>Shot A</th>
<th>Shot B</th>
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<tbody>
<tr>
<td>Outer dimension, \mu m</td>
<td>$29 \times 26$</td>
<td>$26 \times 22$</td>
</tr>
<tr>
<td>FWHM dimension, \mu m</td>
<td>$16 \times 16$</td>
<td>$18 \times 15$</td>
</tr>
<tr>
<td>Alpha yield</td>
<td>$300 \times 10^6$</td>
<td>$800 \times 10^6$</td>
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Fig. 4. Reconstructed images of the thermonuclear burn region for two representative laser target shots. The images shown are isoe mission contour maps of the burn region. The alpha yields for shots A and B were 300 and 800 million, respectively. Nominal planar image resolution is 10 \mu m. These results show that the thermonuclear burn occurred within a compressed target core about 25 \mu m in diameter.
that can be compared with complex computer-code calculations. Thus, they provide an important test of the basic physics described in the codes.

RECENT IMPROVEMENTS IN IMAGING CAPABILITIES

We are continuing to improve and extend the imaging capability of the ZPCI technique. Since our primary concern is the microscopy of laser fusion plasmas, our efforts are directed toward improving the planar (two-dimensional) and tomographic (three-dimensional) resolution of the technique and toward extending its spectral range to higher x-ray energies. The zone-plate coded imaging capability can be improved by increasing the quality of information collection during shadowgraph recording (step 1) and by improving the quality of information extraction during image reconstruction (step 2). We have made significant progress in both areas.

The imaging characteristics of the zone-plate shadow camera are strongly dependent on the dimensions of its zone-plate aperture. The planar resolution of the camera improves as the minimum zone width of the aperture is reduced.4

Fig. 5. Image of the thermonuclear burn in a laser fusion target, reconstructed in first and third order. A zone-plate coded image acts as a generalized diffraction grating, focusing incident laser light into multiple, well-separated, reconstructed images—each image a complete, three-dimensional representation of the source. Each separate reconstructed image is designated by an order number, M. Higher order (shorter reconstruction distance) images are reduced in intensity by \(1/M^2\)—therefore, reduced signal-to-noise ratio—but their resolution is improved \(M\) fold. A third-order image, having a threefold resolution improvement, allows us to see spatial detail not apparent in a first-order image.
Tomographic resolution improves as zone number increases. The high-energy x-ray capability increases as the x-ray opacity of the solid zones of the zone-plate aperture is increased, that is, thick zone plates of high atomic-number material are required. We are extending the technology of micro-Fresnel zone-plate fabrication to meet these needs. We are currently fabricating zone plates with minimum zone widths of 2.5 \(\mu\)m, thicknesses of 10 \(\mu\)m (gold), and 240 zones. We expect soon to be fabricating zone plates having 1000 zones with widths of 1 \(\mu\)m and thicknesses of 20 \(\mu\)m.

Significant improvement in image resolution may also be achieved by higher order reconstruction of coded images. A coded image, acting very much like a generalized diffraction grating, will focus the incident laser light into multiple, well-separated reconstructed images (see Fig. 5). Higher order reconstructed images have a reduced intensity (therefore, reduced signal-to-noise ratio) but a higher resolution. The \(M\)th order image will have a better resolution by a factor of \(M\) (both transverse and tomographic). The \(M\)fold improvement in resolution derives from the fact that for the \(M\)th order the effective \(f/\)number of the coded image is reduced by a factor of \(M\), while image magnification is independent of reconstruction order. This is illustrated in Fig. 5, which shows an image of the thermonuclear burn in a laser fusion target reconstructed in first and third order. The third-order image, having a threefold resolution improvement, allows us to see spatial detail not apparent in the first-order image.

The improvement in zone-plate fabrication technology along with the use of higher order image reconstruction techniques has extended the ZPCI capability to about 1-\(\mu\)m planar resolution, 10-\(\mu\)m tomographic resolution, and 40-keV x-ray energy.

**Key Words:** alpha emission; alpha measurements; plasma—diagnostics; radiation—measurements; x-ray emission; x-ray images; zone-plate coded imaging; ZPCI.

**NOTES AND REFERENCES**