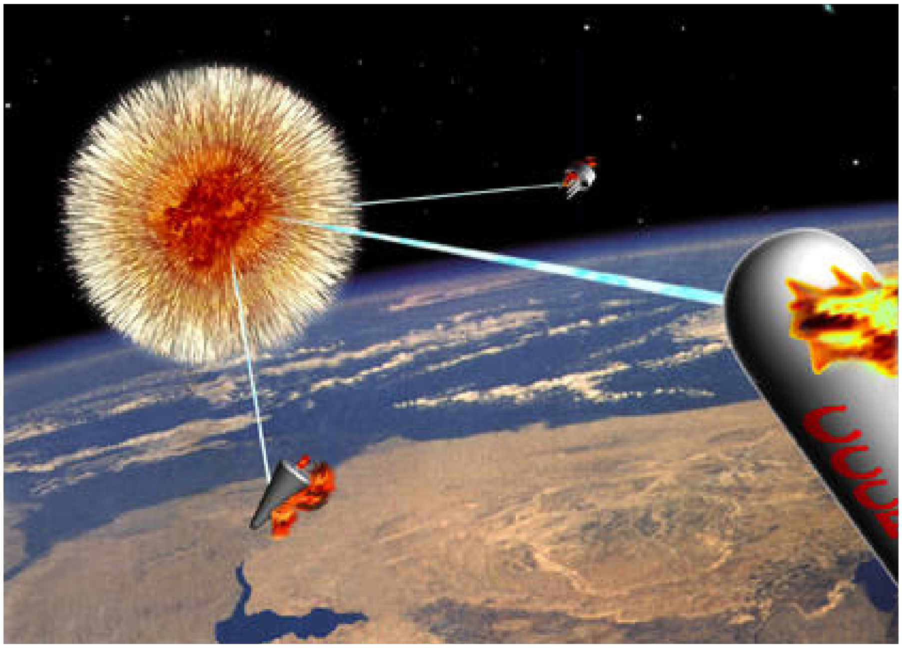
Legacy of the X-Ray Laser Program



The X-Ray Laser Program, which was stimulated by a vision of a laser system that could provide strategic defense against Soviet missiles, has left a legacy of new technologies for industrial and medical use.

INTEREST in producing shorter wavelength lasers that reached into the x-ray region began soon after the first ruby laser was operated in 1960. With the advent of the large lasers for inertial confinement fusion in the early 1970s, several groups, including those at Lawrence Livermore National Laboratory, proposed studies of nuclear and nonnuclear pumped x-ray lasers.

On March 23, 1983, President Reagan challenged the scientific community to find a defense against nuclear-tipped ballistic missiles. As the technical committees formed in response to this challenge focused largely on antiballistic missile systems, an alternative approach proposed accelerating an LLNL research program that was working on a nuclear-pumped x-ray laser system. If successful, such a system might offer a shield for the United States in the event of nuclear war. Thus began the funding of the x-ray laser effort and numerous other research activities (such as the efforts in free-electron and chemical lasers and Brilliant Pebbles, a nonnuclear anti-ballistic missile concept) under the Strategic Defense Initiative (SDI).

Since 1983, the world has changed dramatically. The Berlin Wall has fallen, Germany has been reunited, and the Soviet Union has collapsed. Because of these changes and the various technical difficulties involved in developing the x-ray laser into an antiballistic missile system, the X-Ray Laser Program has been eliminated. However, many of its technical and physics achievements live on in areas unrelated to strategic defense.

We are finding that much of the x-ray laser technology originally developed for strategic defense can be used to advance research in biotechnology, materials science, and materials analysis.[1] This rich legacy includes a better understanding of x-ray laser physics; an array of sophisticated computational tools for modeling plasma physics; a laboratory x-ray laser for biological imaging; the development of such advanced materials as aerogel and SEAgel;

a unique, world-class research facility, called the electron-beam ion trap (EBIT), for performing atomic physics experiments; new measurement techniques for characterizing materials; and a superior mammographic technique for early detection of breast cancer.

Advancing the Laboratory's Research Goals

To achieve the goals of SDI as it was first envisioned, scientists needed to overcome many of the obstacles they had encountered in trying to better understand the atomic physics of highly charged ions. They also needed more exact measurement systems for nuclear tests and more sophisticated computer programs to process and model the data. Many of our efforts not only improved the quality of our research for SDI but were also transferred to research in other areas.

Diagnostics

In the 1970s, most measurement systems for nuclear tests relied on coaxial cables connected to single x-ray diodes. As electronics technologies were improved, coaxial cables were replaced by fiber optics, streak cameras, multiplexing, and other new technologies. With the advent of the x-ray laser effort, scientists suddenly needed vast quantities of high resolution data that could not be gathered by using conventional techniques. This need for more detailed data pushed the immense growth in the development of advanced electro-optic devices used in nuclear tests.

Transmission Crystal Spectrometer

A good example of the tremendous progress in measurement systems technologies is the transmission crystal spectrometer (TRACS). Before the development of this spectrometer, hard x rays were measured in the nuclear environment using absorption-edge filters and fluorescers to define bandpass regions of the x-ray spectrum. This diagnostic approach could accommodate very few data channels, and therefore, the amount and type of data that could be gathered were severely restricted. For example, a standard instrument like the SPECTEX had 10 spectral-energy channels. The TRACS solved the crystal spectroscopy problem by providing a way to measure short wavelength x rays (i.e., hard x rays) by using a crystal with the planes perpendicular to the crystal surface, as shown in Figure 1, and then measuring the transmission spectroscopy of the x rays. The x rays still have small Bragg angles with respect to the Bragg planes, but now they strike the crystal at near-normal incidence. Using the TRACS one can now have 1000 channels of time-resolved data covering the same spectral range as the SPECTEX, an increase of two orders of magnitude (100 times) in resolution.

High-Precision Spatially Resolved X-Ray Spectrometer

Measuring the electron temperature of a plasma is very important to our understanding of the dynamics of nuclear-driven plasmas. To gather this type of information, a high-precision spatially resolved x-ray spectrometer was developed that measures the free-bound continuum emission from radiative recombination. In one particular experiment, four samples were imaged simultaneously with subnanosecond time resolution. This required very stringent pointing tolerances that were not previously possible. A 20-μrad pointing accuracy was achieved, which was 5 times better than the 100-μrad resolving power of the spectrometer. The electron temperatures of both the K- and L-shell nuclear-driven plasmas were determined to an accuracy of better than 10%.

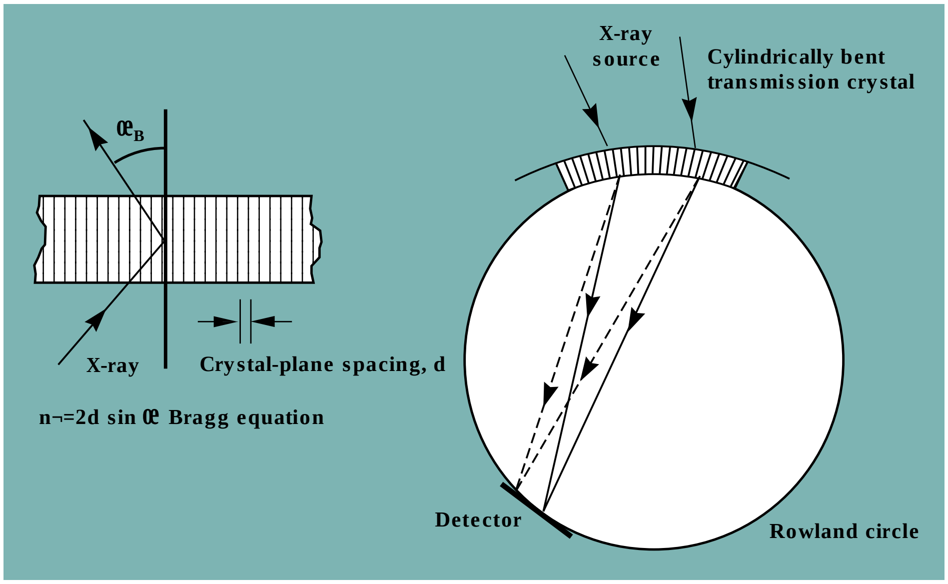


Figure 1. Transmission crystal spectrometer (TRACS) for measuring hard x rays underground. The TRACS uses a crystal with the planes perpendicular to the crystal surface, and measures the transmission spectroscopy of the x rays.

Fast X-Ray Detectors

A new generation of fast x-ray detectors was developed to meet the challenges of diagnosing plasmas in a nuclear environment. The new detectors are based on microchannel plate-intensified detectors developed for diagnosing laboratory x-ray lasers. These detectors have a 400-ps time resolution and convert the x-ray signal into an optical signal 1000 times brighter than the x-ray signal. This is a million-fold conversion efficiency enhancement when compared with the passive phosphors and scintillators used previously. Figure 2 shows a schematic of the detector with the photocathode that converts x rays to photoelectrons, the microchannel plate (MCP) that amplifies the photoelectrons, the electrostatic focusing electrode that compresses the electron current in one dimension, the fast phosphor that converts the electron's kinetic energy to light, and the fiber-optic face plate that transmits the light out of the vacuum system.

A Laboratory X-Ray Laser

Research on the laboratory x-ray laser began as part of the effort to improve our understanding of x-ray laser physics and to develop laser physics computation codes. To design this laser, we needed very complex atomic models that could be used for solving plasma kinetics. As a result, we developed several computer codes, such as YODA, ADAM, and XRASER. In the first experiments, we used the Novette laser, a prototype for the Nova laser, to study x-ray laser physics. In 1984, we demonstrated the first laboratory x-ray laser.

As a result of these tests, the Defense Sciences Department funded a second target chamber on the Nova laser that would allow two beams for x-ray laser experiments. This two-beam facility has been in use for 10 years and has demonstrated many new x-ray lasers, with wavelengths ranging from 32.6 nm in neon-like titanium to 3.5 nm in nickel-like gold.

X-Ray Imaging

One potential use of a laboratory x-ray laser is in imaging. X-ray lasers are being coupled with x-ray microscopes to image biological samples. Using x-ray lasers as a light source, we may be able to use x-ray microscopes to image live hydrated organisms to better understand the structure of a living organism. Our goal is to use this technology to create three-dimensional (3-D) holograms of living organisms. As the first step toward making these images, we have constructed an x-ray microscope that uses a 4.483-nm nickel-like tantalum x-ray laser as the light source. The wavelength of this laser is ideal for biological imaging because it provides good contrast between the carbon in the living organism and the water in which the organism lives. A spherical multilayer mirror condenses the light onto the target, and a zone plate lens projects the image onto the microchannel-plate detector (Figure 3).

We are using this technology to study how DNA is organized inside a sperm cell. Figure 3b shows an image of rat sperm that was taken with our x-ray microscope; this particular microscope is powerful enough to detect features as small as 50 nm.

To improve the coherence and power of x-ray lasers, we demonstrated multipass amplification at 20.6 nm in a neon-like selenium laser. We placed a flat multilayer mirror made of

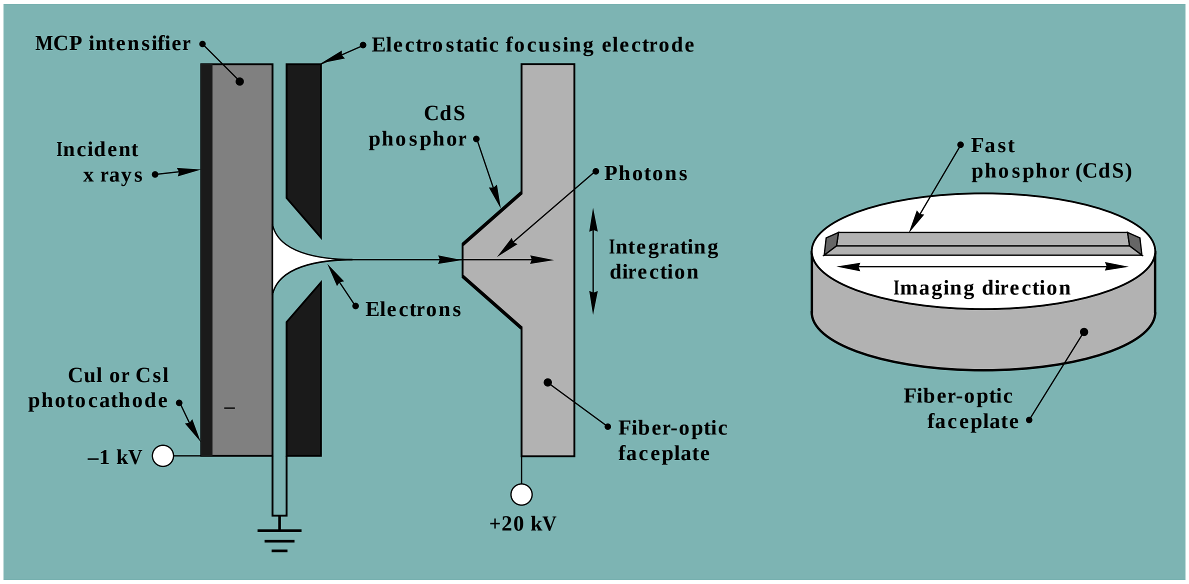


Figure 2. Time-resolving intensified detectors for low-level x-ray detection. The photocathode converts x rays to photoelectrons and the microchannel plate (MCP) intensifier amplifies the photoelectrons. The electrostatic focusing electrode compresses the electron current in one dimension, and the CdS phosphor converts the electron's kinetic energy to light. Finally, the fiber-optic faceplate transmits the light out of the vacuum system.

30 molybdenum–silicon pairs 2.75 cm from the end of the laser medium. Data collected at the right end of the laser (Figure 4) showed both the amplified spontaneous emission (ASE) pulse from x rays that originated at the left end of the laser (these x rays were amplified as they propagated down the length of the laser) and a second pulse created by x rays starting at the right end. This second pulse was observed after it propagated down the laser, was reflected by the mirror, and then was reamplified during its second pass through the gain medium (Figure 4a). The double-pass amplified signal was seven times more intense (Figure 4b) than the single-pass ASE. This experiment demonstrated the first step toward making an x-ray laser cavity, which offers the potential for producing the highly coherent output required to do holography.

Multilayer mirrors have also been important in developing new diagnostics in the soft-x-ray regime, where crystal spacings are too small to allow measurements to be made. The multilayer mirrors are essentially crystals with layer spacings that are matched to the long wavelengths being diagnosed. A variation of the multilayer technology is the Fresnel zone plate, which is essentially a multilayer mirror rotated 90 degrees.

A tabletop x-ray microscope that achieves 10-μm resolution has been built using 8-keV Fresnel zone plates. This microscope creates images of a sample by scanning it with a focused x-ray spot that is produced by a phase-modulating zone plate and a copper K-α source. The picture of the ant shown in Figure 5 is an example of an image made using this microscope.

New Materials

Another outgrowth of the X-Ray Laser Program was the research and development done in very low-density foams, such as silica aerogels, organic aerogels, and safe-emulsion agar gel (SEAgel). Aerogels are solid foams so low in density that they are mostly empty space. They are open-cell structures, like a sponge, with tiny pores (< 50 nm in diameter). Because both the particle and pore sizes are much smaller than the wavelengths in the visible spectrum (350 to 800 nm), aerogels are transparent to visible light.

Silica aerogels—highly porous forms of silica or silicon dioxide (SiO_2)—were first prepared in the 1930s at Stanford University, but they were not put to practical use until the 1970s, when they were used in nuclear-particle detectors. In the 1980s, Laboratory scientists working in the X-Ray Laser Program extended aerogel technology by creating superlight silica aerogels (with densities of 1 mg/cm^3) and by producing organic aerogels.

Aerogels have outstanding thermal insulating and acoustic properties. Because they transmit heat at only one-hundredth the rate of full-density glass, a 1-cm-thick aerogel panel insulates as effectively as a 4-cm-thick batt of fiberglass. They are natural candidates for insulation in window glass, refrigerators, and other appliances. Figure 6 vividly illustrates the insulation value of aerogel. In this photograph, a person is holding a piece of aerogel foam while he heats it with a blowtorch. The aerogel foam effectively protects his hand from the flame of the torch.

Aerogels also can be used in space to collect fast-moving particles, such as micrometeoroids (cosmic dust).

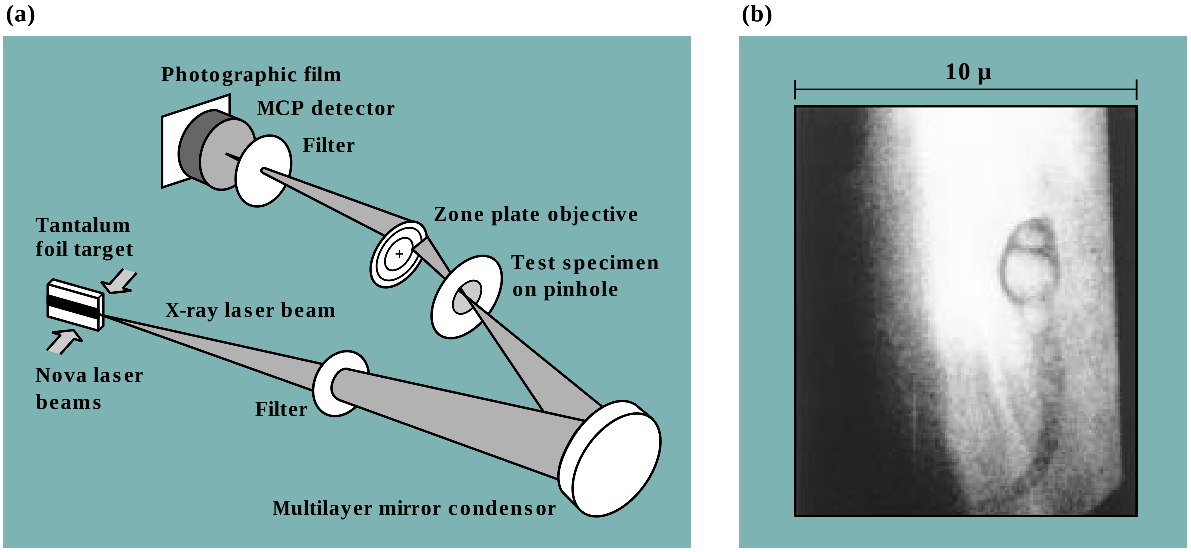


Figure 3. (a) Diagram of the x-ray microscope. The light source is a nickel-like tantalum x-ray laser. The x-ray laser beam is condensed using a spherical multilayer mirror, and a zone plate projects the image onto the microchannel-plate detector. (b) Image of rat sperm captured using the x-ray microscope. This image shows 50-nm features.

Organic aerogels are likely to be used as gas filters in chemical processing, as catalyst beds for the petroleum industry, and as thermal insulators for cryogenic applications.

SEAgel, a very low-density, organic-based foam (Figure 7), is a natural material made from agar—a component of red algae that is used to thicken ice cream and other foods. SEAgel is made by dissolving agar in water and adding an organic solvent and emulsifier that disperse the agar evenly throughout the liquid. Then the mixture is freeze-dried to extract the water and solvents. SEAgel can be made with densities from 1 to 300 mg/cm^3 and with cell sizes from to 2 to 3 μm.

Laboratory scientists are using SEAgel as targets for x-ray laser experiments on Nova because it can be doped with other materials, such as selenium. If we can fabricate an x-ray laser target with a density that is less than the critical density of laser light (4×10^{21} electrons/cm^3 for 0.53-μm light), we can eliminate the violent hydrodynamics that take place when a solid-density target explodes before it reaches the density required for lasing. Using SEAgel will help us achieve a more uniform plasma, which will improve the quality of the x-ray laser beam.

Because SEAgel is safe enough to eat, it could be used as food packaging or as encapsulating material for timed-release medication. SEAgel could also be used instead of balsa wood to insulate supertankers and to provide sound damping in high-speed trains.

The Electron-Beam Ion Trap

The X-Ray Laser Program required a new level of understanding and new measurements of the atomic physics of highly charged ions. The electron-beam ion trap (EBIT) was developed and built at LLNL to study

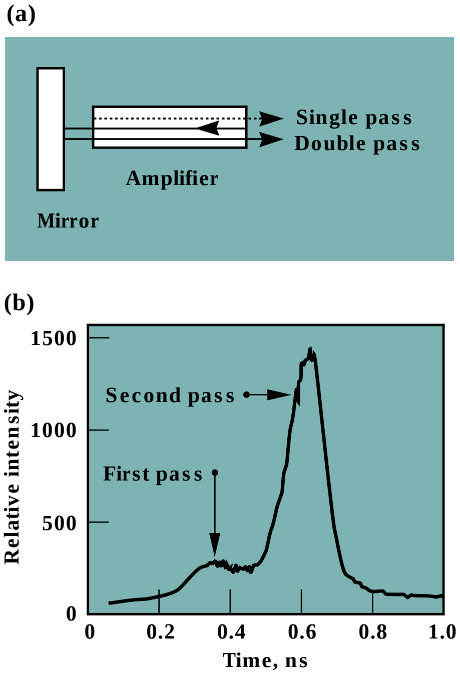


Figure 4. (a) Multipass amplification process and (b) measurements from multipass amplification of the x-ray laser. X rays in the first pulse originated at the left end of the laser and were amplified as they propagated down the length of the laser. X rays in the second pulse originated at the right end of the laser, were reflected by the mirror, and then were reamplified during their second pass. As the measurements show, multipass amplification increased the coherence and power of the laser—the double-pass amplified signal was seven times more intense than a single-pass signal.

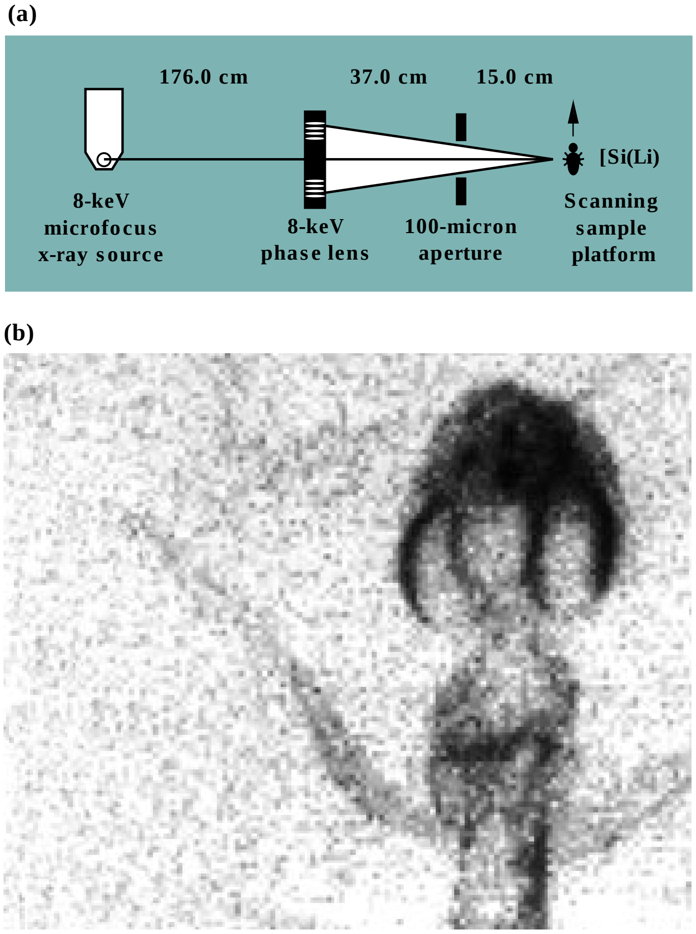


Figure 5. (a) Schematic of the 8-keV scanning x-ray microscope geometry and (b) image of an ant made with this microscope. The tabletop x-ray microscope creates images by scanning a sample with a focused x-ray spot that is produced using a phase-modulating zone plate and a copper K-å source. The image of the ant shows features as small as 50 µm; each pixel = 15 µm.

Figure 6. Tom Tillotson, a chemist at LLNL, applies a propane torch to the top of a 2.5-cm-thick silica aerogel brick. His hand remains totally unaffected by the heat.

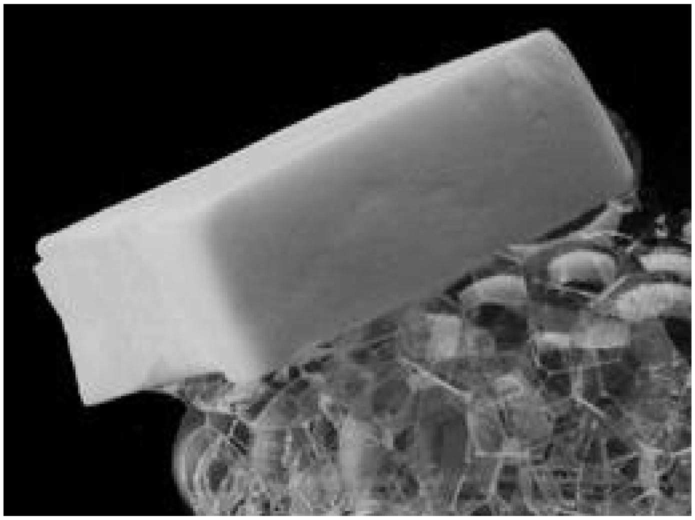


Figure 7. A piece of SEAgel floating on soap bubbles in a beaker. This very-low-density organic-based foam, made from the food-thickening agent agar, is safe enough to eat and could be used as food packaging or encapsulating material for timed-release medication.

the behavior of these ions (Figure 8). Currently, EBIT can produce highly charged ions up to neon-like uranium, in which 82 of uranium's 92 electrons are removed (leaving 10 electrons, like neon).

In EBIT, the ions are electrostatically trapped for minutes to hours in a narrow cylindrical volume that is defined by biased electrodes in the axial (longitudinal) direction and by a high-current-density electron beam in the radial direction. The energy of the electron beam can be varied reliably from 2 to 25 keV. This is sufficient to strip all electrons from elements up to molybdenum (creating a +42 charge state) and to make any naturally occurring element neon-like (10 electrons remaining, up to a +82 charge state).

EBIT allows us to measure directly processes that are crucial to understanding high-temperature plasmas. These processes include electron-impact ionization, excitation, and recombination. Before EBIT, only a few measurements of ionization cross sections were available for charge states of 50 or less, and direct measurements of electron impact excitation, dielectronic recombination, and radiative recombination cross sections were possible only for charge states of 6 or less.

The physics of these highly charged ions is of interest as we strive to obtain a fundamental understanding of matter. With EBIT, we can obtain experimental data that allows us to confirm or disprove theoretical predictions. Specifically, we use high-resolution, well-calibrated spectrometers to measure the x rays that result from the inelastic collisions of the highly charged ions with the free electrons in the EBIT electron beam.

We have used EBIT to measure the dielectronic recombination cross section for neon-like xenon (xenon stripped of all but 10 of its 54 electrons, in a +44 charge state). The EBIT measurements are in good agreement with the theoretical calculations for this cross section. This is an important finding since dielectronic recombination is an important process in theoretical models of the ionization balance in plasmas of neon-like and nickel-like lasers. Before EBIT, measurement of cross sections was possible only for ions with a few electrons removed; now highly ionized materials, such as these plasmas, can be studied. The agreement between calculation and measurement gives us confidence that our theories about the behavior of plasmas and highly charged ions—and essentially our basic understanding of matter—are correct.

With the recent construction of the new super-EBIT, which has beam energies up to 200 keV, we can now strip all the electrons from any ion, including uranium, and therefore study any charge state of any ion. This ability allows the study of even more fundamental tests of quantum electrodynamic (QED) theory.

Materials Analysis

When we build experiments like those to be included with a nuclear test, we must follow strict manufacturing tolerances. To meet these tolerances, we have developed several characterization techniques that can handle thousands of new parts a year, and many of them, our radiographic methods in particular, have applications in the biomedical industry. For example, we have used our diagnostic technique for finding tiny flaws in SDI components to detect flaws in samples of material used for artificial heart valves. This application is extremely important, considering that 1.5 million people have artificial heart valves and that even the slightest flaw in these valves can be fatal. In these diagnostic experiments, the sample material is placed in a vacuum chamber and bombarded with a 10-MeV proton beam. The sample is then analyzed by a detector that measures the beam's energy. The thickness of the material is determined by the amount of energy loss in the beam. In recent experiments, we were able to detect a minute scuff in the core of a sample of carbon-based heart valve material.

Three-dimensional x-ray computer tomography (CT), which was originally developed to inspect weapons parts, now has medical and industrial

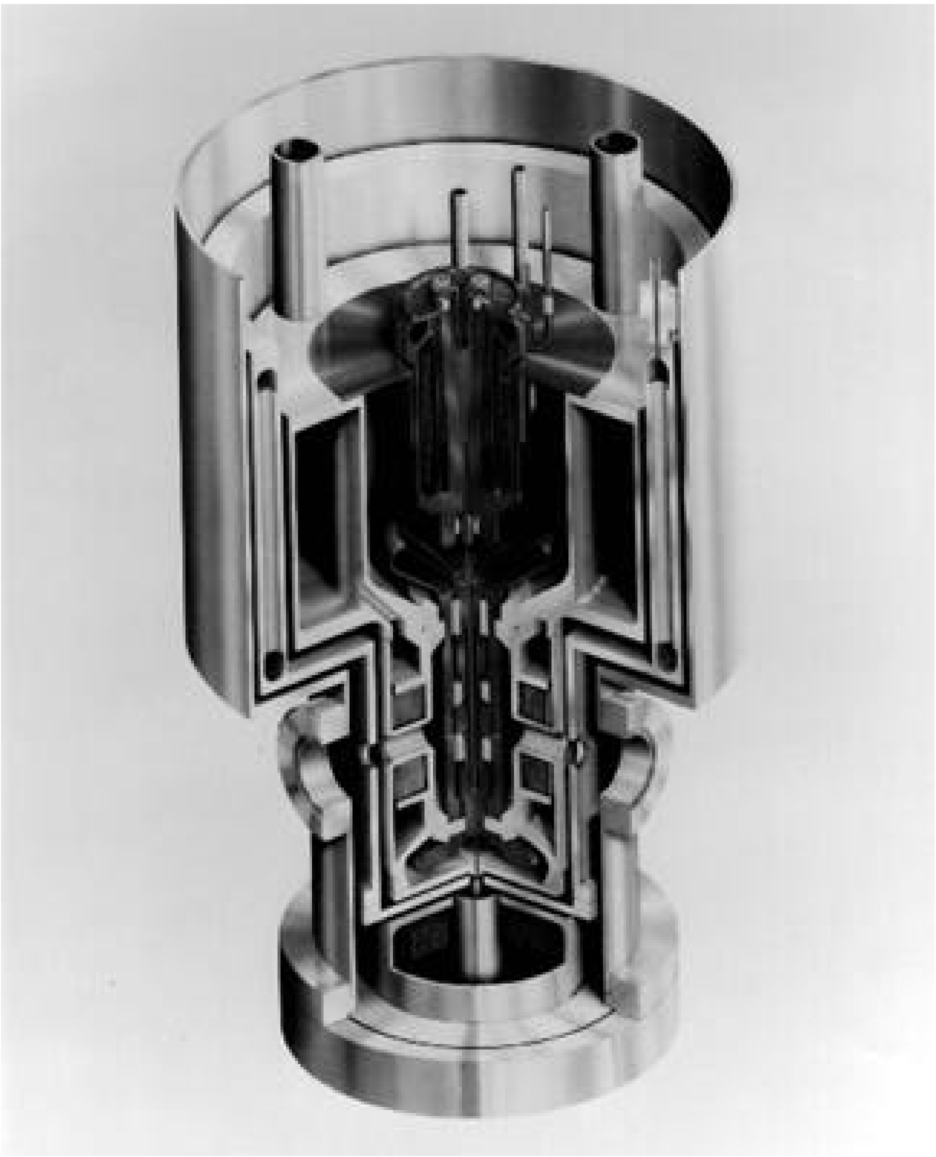


Figure 8. The EBIT (electron-beam ion trap), developed and built at LLNL to obtain direct measurements on highly charged ions. With this device, we can create very highly charged ions (up to a +82 charge state, for neon-like uranium) and then measure the x rays produced by the ions when they interact with the free electrons of EBIT's electron beam. These measurements provide data, which when compared with theoretical predictions, allow us to extend our understanding of the nature of matter.

applications. The basic technique involves illuminating a sample with a collimated monochromatic x-ray source to create a two-dimensional image. By using x-rays between 5 and 35 keV and rotating the sample in small angular increments through 180 degrees, we obtain enough data to reconstruct a three-dimensional image of the sample with 2- to 3-μm resolution. This technology is similar to the CT (or CAT) scan done at a hospital, but it has a much higher resolution. It is being used to look for pores in ceramic composites, to identify potential fatigue areas in tensile loading of aircraft wings, and to study the demineralization of dentin, which leads to tooth decay.

A continuum x-ray gauging technique has been developed for nondestructive elemental analysis of materials with known constituents. For many applications, the quantitative distribution of the components must be known. By measuring the transmission of photons at different energies, the abundance of different components can be mapped.

X-Ray Image Enhancement

As an outgrowth of our radiography activities, we are developing a superior mammographic technique that may increase the early detection of breast cancer. Breast cancer is an important national health problem. In the United States, it kills 45,000 women each year, and the incidence of new cases increases annually, even when corrected for our aging population. To help mammographers screen the large number of mammograms, we developed a computer algorithm to locate microcalcifications in digitized mammograms. This improvement and others will help doctors detect breast cancer at an early stage, when treatment is more successful, and thus increase the survival rate.

Breast x-ray imaging, or mammography, in combination with physical examinations, is the most effective means for detecting breast cancer at an early stage. Mammography is the only method to detect microcalcifications, which often accompany breast cancer before it is palpable—that is, when the cancer is too small to feel in a physical exam. Because microcalcifications absorb x rays more strongly than soft tissue, they are visible in a transmission x-ray image.

To detect these microcalcifications, mammographers must systematically search the traditional x-ray film using a magnifying glass. This task is tedious, time consuming, and subject to errors caused by fatigue or distraction.

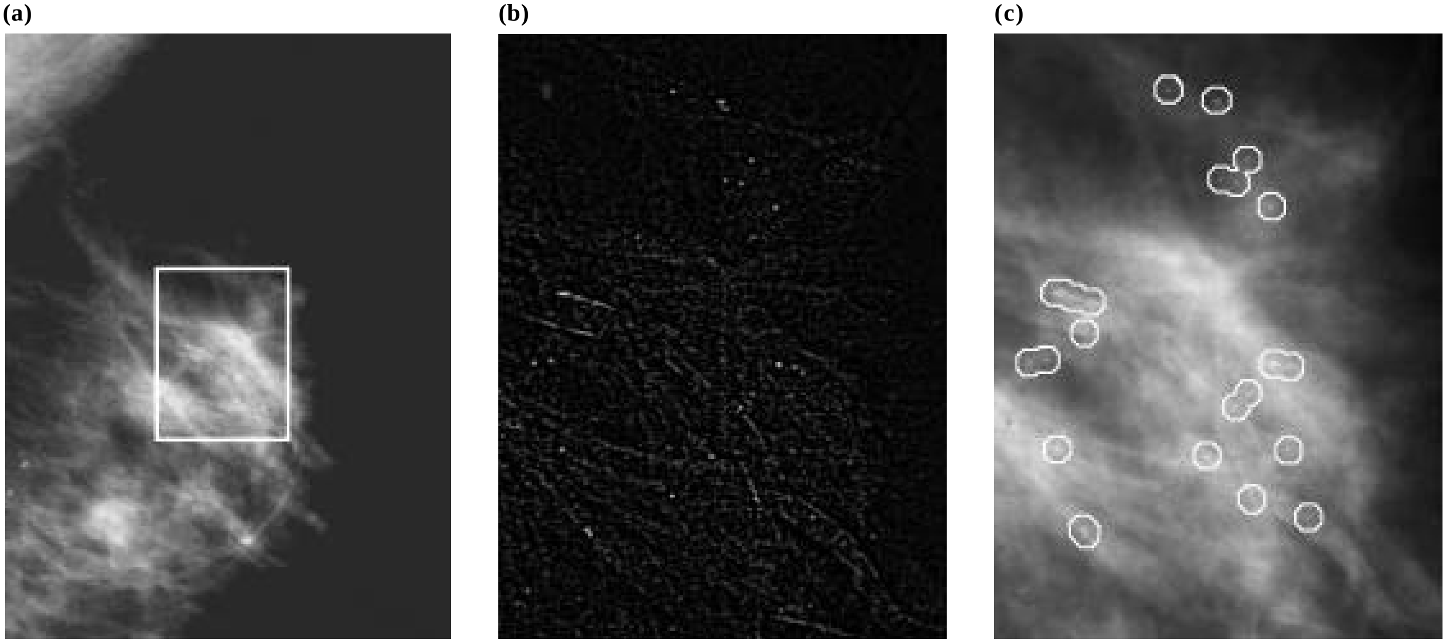


Figure 9. (a) A digitized mammogram. For reference, part of the pectoral muscle is visible at top left. (b) High-frequency image of the same breast—the area bordered by a rectangle in (a)—with the soft-tissue structure absent. This image was obtained after applying our algorithm. With data displayed in this manner, the pattern of calcification is evident without any distracting background information. (c) Using part of the original digital image bordered by the rectangle in (a) as background, we can highlight the most suspicious microcalcifications with circles. A mammographer can focus on the circles in the context of the overall breast structure.

"Missed" malignancies are relatively common. For example, one study found that in 320 cases of breast cancer, 77 cancers (24%) were missed by screening mammography.

The quantitative radiography techniques developed at LLNL use a computer algorithm to locate microcalcifications in digitized mammograms. Figure 9 shows an example of a digitized x-ray mammogram. The calcifications identified by the computer program are highlighted with circles. Our computational approach can best be thought of as a "mammographer's associate," because it objectively and reproducibly detects and flags microcalcifications for the mammographer. This work may free mammographers from the routine and tedious search task, thus allowing them to concentrate on diagnosis.

Conclusion

The world has changed dramatically during the last decade, and the part of the X-Ray Laser Program that President Reagan proposed is no longer being pursued. But the decade of work on x-ray lasers has produced a rich and important legacy that includes a better understanding by physicists of x-ray lasers; sophisticated computational tools for modeling plasma physics; a laboratory x-ray laser for biological imaging; advanced materials, such as aerogel and SEAgel; unique, world-class facilities like EBIT for performing atomic physics experiments; and a superior mammographic technique for early detection of breast cancer. During the last decade, hundreds of people have participated in these efforts and helped to reshape LLNL. Their achievements have made LLNL a world leader in many fields of science and technology.

One of the newest and most sophisticated uses of x-ray lasers is as a probe for studying large, high-density plasmas. In an upcoming issue of *Energy and Technology Review*, we will describe several diagnostic techniques being developed by LLNL researchers. Our techniques include plasma imaging and, most recently, interferometry, which directly measures electron density in plasmas of the sort created by the Nova laser.

Key words: Aerogels—SEAgel, silica, organic; biological imaging; digital mammography; laboratory x-ray laser; multilayer mirrors; three-dimensional x-ray computer tomography; x-ray diagnostic techniques—electro-optics devices; x-ray gauging technique; x-ray laser microscopes; x-ray laser physics—electron-beam ion trap (EBIT); Strategic Defense Initiative (SDI).

Reference

1. Technical descriptions of and related references on the research described in this article are given in Joseph Nilsen's *Legacy of the X-Ray Laser Program*, Lawrence Livermore National Laboratory, UCRL-LR-114552 (1993).

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