

Protons Reveal the Inside Story

Scientists are exploring the advantages of using protons instead of x rays as a radiographic probe to study the performance and aging of weapons.



ONE of the most important scientific breakthroughs in the past century was the discovery that a beam of x rays could penetrate matter and produce a radiograph that revealed the inside of objects.

X-radiography is today an indispensable tool for medicine, industry, and science. Scientists at Lawrence Livermore have long used x-radiography to obtain information about fleeting events that occur in experiments using high explosives to mimic the operation of a nuclear device. The resulting images yield important information on the hydrodynamic behavior, performance, and aging characteristics of weapon components.

While x rays have many favorable attributes, current x-ray technology will have difficulty meeting the long-term requirements of stockpile stewardship,

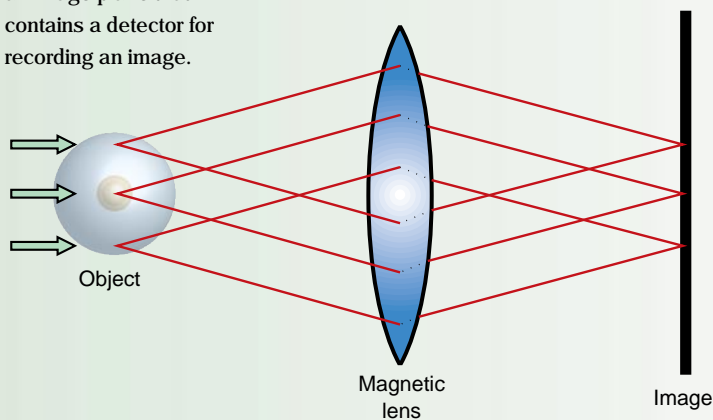
the Department of Energy's program to assure the safety and reliability of the nuclear stockpile without underground nuclear testing. In particular, providing views from multiple angles and at different times during one experiment will be a challenge for x rays.

For some time, physicists have considered using protons, the positively charged constituents of atomic nuclei, as a way to penetrate thick materials more effectively than x rays. Proton radiography has been used for medical imaging and to treat some types of cancer. Early tests with protons as a radiographic probe were not promising: the radiographs were blurred, an effect caused by the scattering of protons as they move through an object because of their electrical charge. The quest was largely abandoned until 1995, when physicists at Los Alamos National Laboratory came up with the idea of using a magnetic lens to focus the scattered protons into a clear image.

A team of Lawrence Livermore scientists soon joined their Los Alamos colleagues in a broad effort to determine if beams of high-energy protons focused with magnetic lenses could be used for stockpile stewardship to image deep inside dynamic systems. Over the past five years, the researchers have conducted a series of tests at Los Alamos and Brookhaven national laboratories.

The tests have centered on extending basic proton science and gauging proton

Proton radiography depends on magnetic lenses that focus scattered protons onto an image plane that contains a detector for recording an image.



radiography's ability to image and differentiate materials in both static and explosive situations. While more experiments are under way, the researchers have gained confidence that proton radiography offers a viable technology to meet future stockpile stewardship needs.

Seemingly Simple Technology

"At first glance," says Lawrence Livermore physicist Edward Hartouni, "proton radiography seems simple and obvious. High-energy protons are used directly as a radiographic probe to illuminate an object, are absorbed and scattered by the object, and then are brought to a focused image by a magnetic lens system for recording by an imaging detector."

Hartouni heads a research team drawn from Livermore's Physics and Advanced Technologies, Defense and Nuclear Technologies, and Engineering directorates, with funding by the Laboratory Directed Research and Development program. He notes that the Laboratory is well positioned to assess proton radiography because of its expertise in accelerators and detectors obtained in nuclear and high-energy physics research.

Hartouni says protons offer several advantages over x rays for studying the dynamics of imploding systems. For example, about 10,000 times fewer protons than x rays are needed to make

A Proton Radiography Primer

Protons are positively charged particles that, along with electrons and neutrons, comprise all matter. Protons interact with matter by way of strong and electromagnetic interactions. Because the strong interaction has a short range (about 1 fermi, or 10^{-15} meters), protons interact with other protons and neutrons by colliding with them. The probability of collision with the nuclei is indicated by a material's cross section and is dependent upon the number of protons and neutrons in the nucleus.

A proton interacting with a nucleus via the strong interaction can do so either elastically or inelastically. If the interaction is elastic, the proton scatters at some angle, retaining its identity as a proton and maintaining most of its original momentum. If the interaction is inelastic, the proton is "absorbed" in the interaction. That is, it transfers most of its energy to breaking up the nucleus, in the process producing subatomic particles called pions.

Because protons carry an electrical charge, they also interact with matter through long-range electromagnetic forces. This interaction takes two forms: with the electric field of nuclei and with the atomic electrons orbiting nuclei. The effects are quite distinct. Interacting with nuclei's electric field is termed elastic scattering and produces a small change in the proton's direction. The effects of each of the small scatters can accumulate, a phenomenon called multiple coulomb scattering. The consequence of multiple scattering for proton radiography is important, especially for dense materials, because ultimately it blurs a radiograph.

The proton interactions with atomic electrons are generally inelastic; that is, the proton loses a small amount of energy by ionizing atoms (kicking an electron out of its orbit). These interactions generally do not result in much change to the proton direction, but many scatters do reduce the proton energy. With dense materials, the energy loss can be quite large (100 to 500 megaelectronvolts). The amount of energy loss can be important, depending on the energy of the beam.

Protons travel a few centimeters to tens of centimeters through matter before they undergo a significant interaction with the object either through strong or electromagnetic forces. These so-called interaction or attenuation lengths are optimum for radiographing objects to extract precise physical characteristics such as density. In contrast, x rays have a maximum attenuation length of about 1 centimeter. For a 10-centimeter-thick slab of material, a beam of x rays is reduced by roughly one million (one in a million x rays makes it through the slab), whereas one in three protons makes it through. Because many more protons make it through than x rays, scientists say that protons are more penetrating.

the same quality radiograph. The greater penetrating ability of protons gives a much higher signal-to-noise ratio, which translates to higher resolution. Protons also have a better capacity to discriminate between two similar materials. X rays are sensitive to density only, so if the densities of two dissimilar materials are close, the radiograph will fail to differentiate the two clearly.

What's more, Hartouni says, using magnets to focus beams of charged particles is an established practice at accelerator laboratories. It is quite easy to split a single proton beam into a large number of separate beams for penetrating an object from different angles. Also, because protons are naturally pulsed in the accelerator, it is easy to produce pulsed beams that would permit multiple,

stop-action radiographs to be taken during a single dynamic experiment.

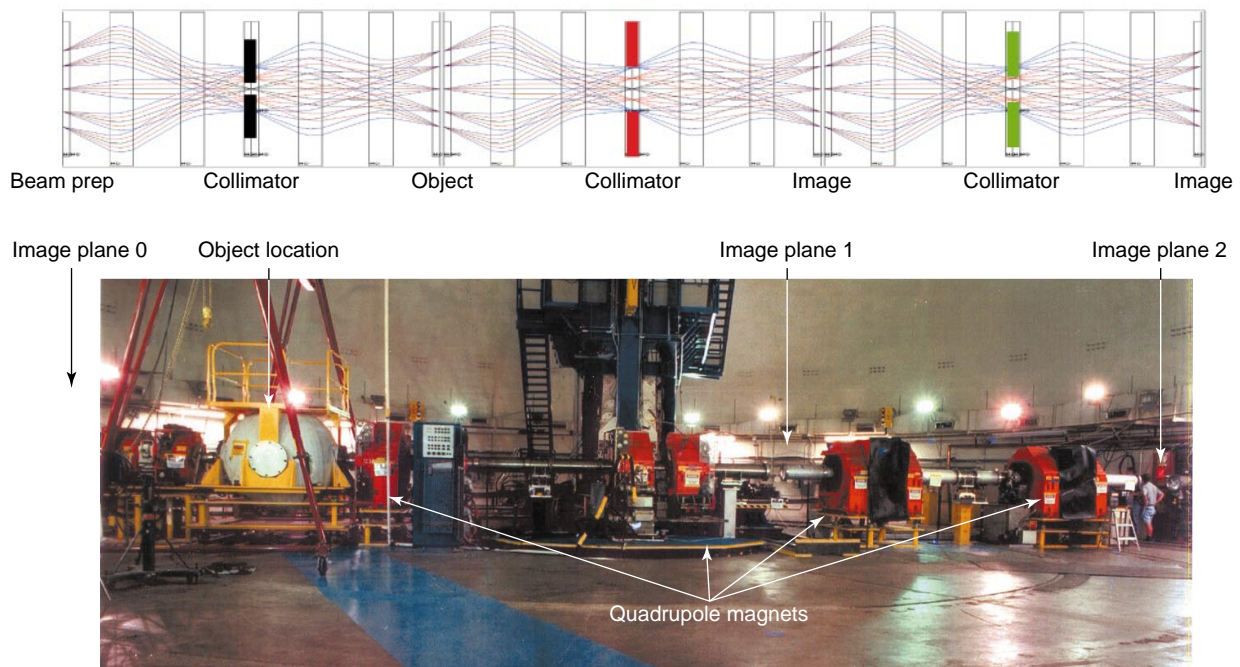
Finally, x rays are produced by first creating and accelerating a beam of electrons. These electrons are directed onto a target, where they decelerate, damaging the target in the process. The deceleration produces photons with a broad energy spectrum and with only some of the photons in the x-ray band. Protons offer a more efficient direct source of penetrating radiation.

Leading Candidate for New Facility

Because of these strong attributes, proton radiography is a leading candidate for the proposed next-generation stockpile stewardship hydrotest facility, called the Advanced Hydrotest Facility (AHF). Imaging a mock primary detonation at multiple vantage points

and at various times to form a three-dimensional movie will provide scientists more data to help verify the supercomputer codes that model the performance of a nuclear weapon.

Livermore scientists joined the proton radiography research effort shortly after Los Alamos physicists in 1995 successfully tested the concept of a magnetic lens. The Los Alamos scientists used a beam of 800-megaelectronvolt protons produced at the Los Alamos Neutron Science Center (LANSCE). The success at LANSCE encouraged tests using a much higher-energy (24-gigaelectronvolt) proton beam at Brookhaven National Laboratory's Alternating Gradient Synchrotron facility in New York. (A proton radiography facility would require



Explosive proton radiography experiments are conducted at the Los Alamos Neutron Science Center facility. In these experiments, a proton beam traveling inside a tube penetrates a target placed in a spherical vessel (left) to contain the explosion. Quadrupole magnets (orange) focus the scattered protons onto imaging detectors. This particular setup uses three imaging stations, including one installed in front of the target to examine the profile of the incoming proton beam. Collimators are located inside the beam tube.

Radiography Remains the Top Tool

In the absence of nuclear testing, advanced radiography is the most important experimental tool currently available to help maintain the nation's aging nuclear stockpile. Hydrotests use high explosives and surrogate nuclear materials to make up a mock primary (the first stage of a nuclear weapon). During the test, explosive pressures become so great that materials flow like liquids, that is, hydrodynamically. X-radiographs taken during the experiment allow physicists to study what happens to the different materials on very short time scales and deep within the mock primary.

Livermore's newly upgraded Flash X-Ray (FXR) machine, located at the remote Site 300 test center, will continue to be one of the premier flash x-ray capabilities once the Contained Firing Facility is completed in 2001. The upgraded machine will be able to take two radiographs along the same vantage point about a microsecond apart.

Los Alamos National Laboratory's Dual Axis Radiographic Hydrodynamic Test (DAHRT) facility, when fully operational, will offer higher resolution radiographs than FXR. The first arm of the facility, which uses a single-phase accelerator, is scheduled to become fully operational in the late fall of 2000. A second arm (for which Livermore scientists provided most of the design) will be situated 90 degrees to the first and is scheduled for completion in about two years. Although additional arms can be added, the expense would be considerable and the number of pulses per view is severely limited.

To meet the goals of the DOE's Stockpile Stewardship Program, scientists require much more information about the functioning and aging of primaries than either facility can provide. The work of the last five years by physicists from Lawrence Livermore and Los Alamos national laboratories has helped to advance proton radiography to the point where the technology is a serious candidate for the Advanced Hydrotest Facility (AHF).

Planning the Next-Generation Facility

Still in the conceptual stages, the AHF would be an important long-term goal of the Stockpile Stewardship Program. The facility would better reveal the evolution over time of a weapon primary under normal conditions and in accident scenarios. The AHF would be constructed at either Los Alamos or DOE's Nevada Test Site (NTS).

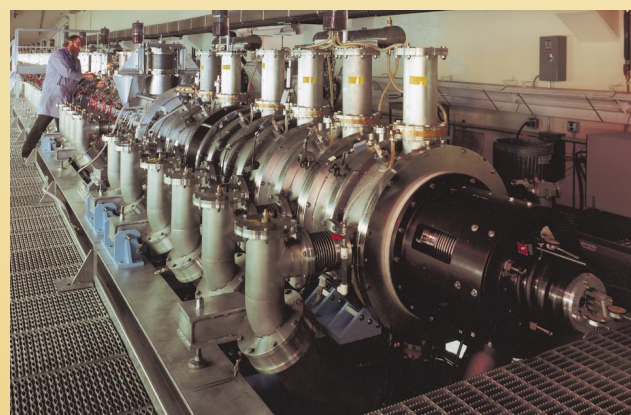
The facility would provide radiographs from between 8 and 16 directions and between 5 and 12 fleeting pulses per experiment. In this way, it would create a three-dimensional tomographic movie of the object as it implodes. Each image would last 50 nanoseconds, with 200-nanosecond to 2-millisecond intervals between images. A high spatial

resolution of 0.5 to 1 millimeter would allow experimenters to identify the amounts and types of material at each location inside the object. Says Livermore physicist Edward Hartouni, "Only three-dimensional radiographs can fully answer stockpile stewardship questions and verify our computer codes."

Hartouni says that the AHF would also provide a research and development base for industrial applications. Some of these applications might include the investigation of combustion in automobile engines and various nondestructive testing procedures, such as material identification.

Different approaches to achieving an AHF capability have been considered by the laboratories. Livermore physicists have studied ways of developing limited proton radiography capabilities quickly and at minimum cost by recycling components from the decommissioned main ring of the Fermi National Accelerator Laboratory.

At the same time, conceptual work is being done by Los Alamos scientists on the design of a complete AHF sited at Los Alamos and using the Los Alamos Neutron Science Center facility as the proton injector for the main accelerator ring. Some of their designs have drawn on concepts developed at Livermore for minimizing the cost of the facility and for producing, along the path to a full AHF radiography facility, more limited proton radiography. With this interim capability, scientists could conduct classified high-explosive-driven dynamic experiments using bursts of energetic protons, magnetic lenses, and particle detectors to produce radiographic images. Currently, because of classification, material, and safety issues, no suitable facilities exist in the U.S. to perform these experiments.



Livermore's upgraded Flash X-Ray machine will be one of the most capable radiographic facilities in the world.

20- to 50-gigaelectronvolt proton beams.) “The ease with which the experiment at Brookhaven was set up and run showed us that new technology does not have to be developed; current accelerators easily provide a source of protons for radiography use,” says Hartouni.

The early experiments were followed by increasingly more complex tests.

Livermore weapons physicist Lloyd Multhauf notes that the experimental program has been essential to learning the capabilities and limitations of proton radiography. “We can’t argue just on theory that proton radiography works,” he says. “There are always lots of practical problems and experimental details that can prevent achieving

needed accuracy.” But Multhauf points out that the research team “has learned with each experiment.”

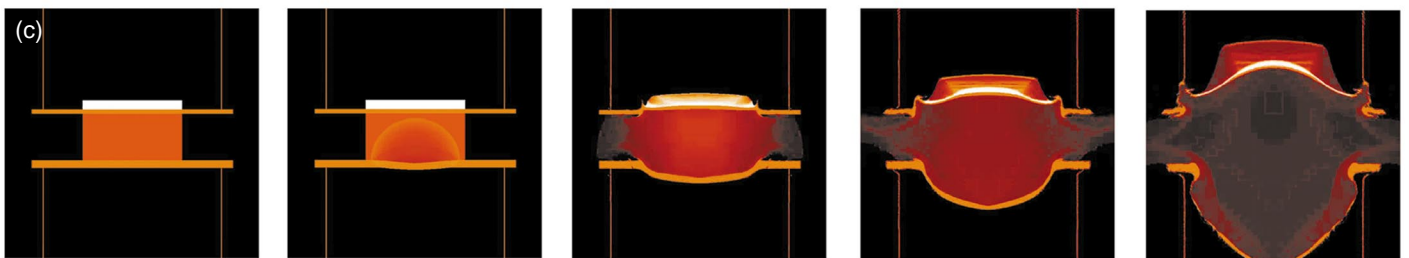
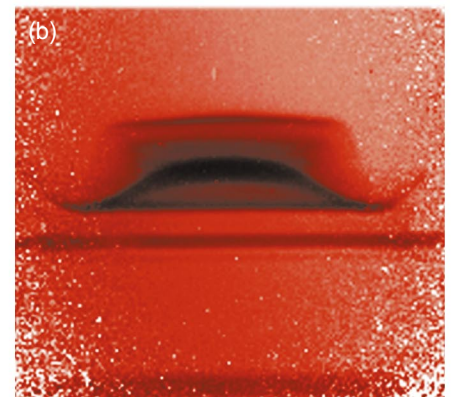
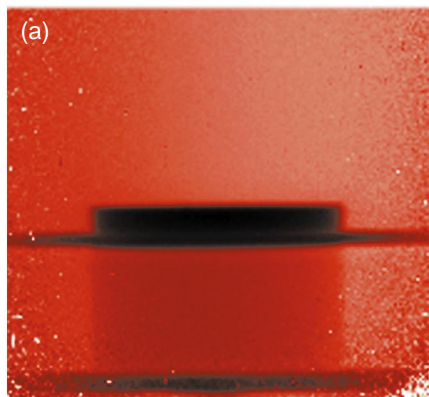
Basic science experiments, conducted largely at Brookhaven, have focused on understanding better how proton beams interact with different materials. In studies on a variety of materials and at proton energies from 1 to 10 gigaelectronvolts, a parameter was established for the cross section of a proton–nuclear interaction. Other experiments studied the momentum of scattered protons as well as the subatomic particles (namely pions) that inevitably are created when protons collide with nuclei.

Experiments also have been conducted on developing the systems to image objects with protons and refining components such as magnets and detectors. In the summer of 1999, a Livermore–Los Alamos experiment at Brookhaven radiographed static objects using a 20-gigaelectronvolt beam of protons and an advanced magnetic lens. The images were of static objects chosen to provide data on the density

Livermore physicists Doug Wright (foreground) and Hye-Sook Park and technician Eric Parker monitor experiments at the Los Alamos Neutron Science Center control room.



Some experiments have investigated the hydrodynamic properties of shocked metal. (a) A 4-centimeter-diameter tin disk sits on a block of high explosive that is sandwiched between two layers of aluminum. (b) Some 10 microseconds following the blast, a radiograph reveals how the top aluminum plate is bent by the blast and how the tin falls apart from the explosive shock wave. The radiographs also reveal how gas and small chunks of matter intermix. (c) A computer simulation of the proton radiography experiment in (a) and (b).



and composition of objects containing different materials.

Static, Explosive Systems Tested

In tandem with the Brookhaven experiments, tests have been conducted on both static and explosive systems at LANSCE using 800-megaelectronvolt protons. The collaborative experiments have helped scientists develop lenses and detectors and provided information on the hydrodynamics of the interfaces between shocked metals and gases.

One series of experiments involved pulsed protons aimed at a target of high explosives and tin. The bursts probed the exploding object by producing a series of images lasting from 40 to 100 nanoseconds, separated by about 1 microsecond, and with a resolution better than 500 micrometers.

In follow-on experiments at LANSCE, a Livermore team measured the hydrodynamic properties of tin when shocked by high explosives. In particular, the team examined the small pieces, or ejecta, that fly off the surface and the way the tin fails by spalling because a tension wave propagates through the tin from the

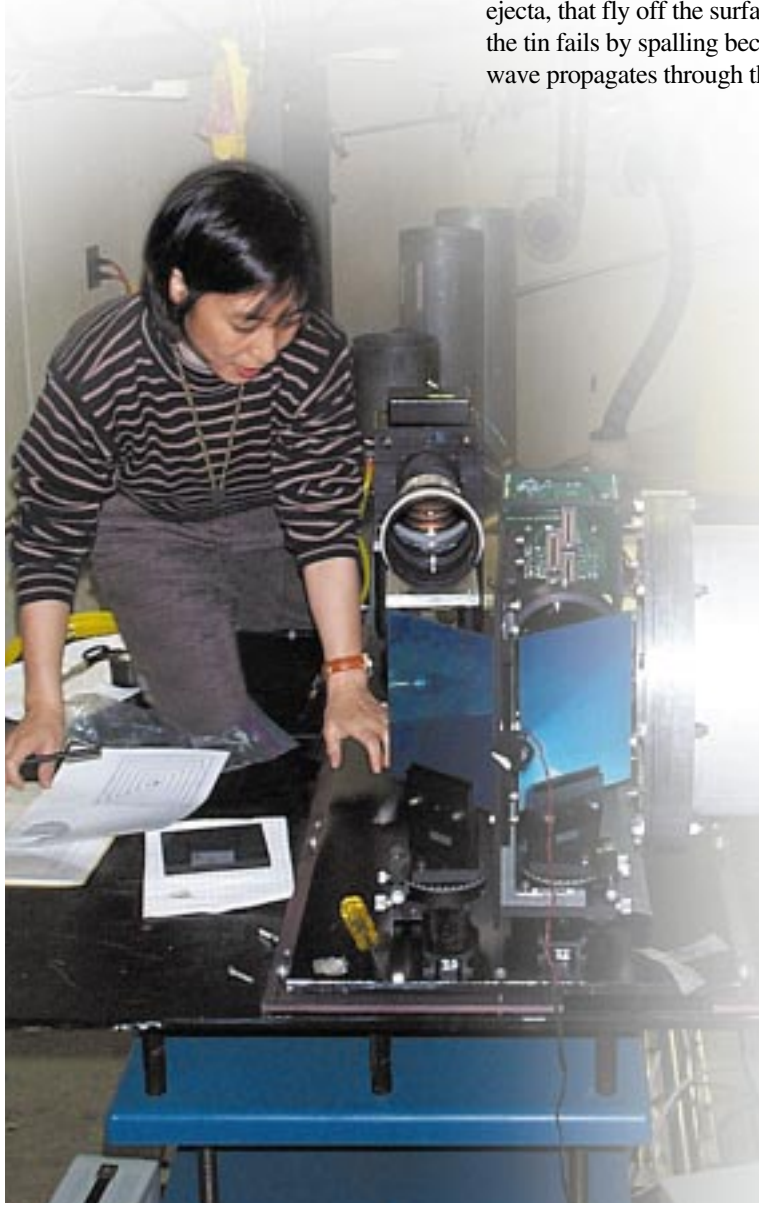
high explosives. Ejecta and spall are important phenomena for stockpile stewardship because they describe how plutonium can behave in a nuclear weapon's primary stage.

Dynamic experiments at LANSCE are expected to continue through next year. In early 2001, a Livermore-Los Alamos experiment at Brookhaven will perform three-dimensional tomography of objects and develop material composition analysis tools. Later in the year, experiments at Fermi National Accelerator Laboratory in Illinois will measure high-energy cross sections of protons interacting with various materials.

Magnetic Lens Focuses Protons

A major emphasis of the research effort is improving the all-important magnetic lenses that overcome the blurring of proton radiographs. Not only do these lenses focus scattered protons, but they also reduce the obscuring effect of secondary particles that cause an overall haze on proton radiographs.

Just as our eyes combine two images into one, so the magnetic lens reconverges diverging rays onto an image plane. When the lens is in focus, protons emerging from the object and traveling in different



Lawrence Livermore physicist Hye-Sook Park checks an imaging station at the end of the proton beamline at the Los Alamos Neutron Science Center. At the right are Livermore-designed detectors that record the differences in the focused proton beam's intensity through the target. One of the detectors is a charge-coupled device that images the experiment in two dimensions. The other detector is a one-dimensional streak camera that images the exploding target at 180-nanosecond intervals. A scintillating screen converts the proton beam intensity into visible light that is diverted by the turning mirrors onto the detectors.

directions are bent by the magnet to reconverge onto an image plane containing a detector, where a permanent image is recorded.

The simple magnets (quadrupole magnets) used for this purpose have four poles alternating in sign. The magnetic lens system allows for the addition of collimators, which can restrict the presence of protons scattered multiple times within the object. The spread in scattering angles depends on the material type, so by adding different collimators, a user can dial in the contrast for the object's region of interest.

Another critical element is the detector system, which records the spatial distribution of the protons that are transmitted through the object. Early experiments used traditional radiography detectors such as phosphor plates that act like photographic film (exposed when the protons penetrate the plate). Newer, more efficient electronic detectors take advantage of the protons' electrical charge. Hartouni notes that detectors for charged particles are commonly used in nuclear and high-energy physics experiments.

The new detectors have little effect on the proton beam so that multiple detectors can be placed in the beam downstream from the object being radiographed. In this way, sets of lenses and detectors can be used in tandem to allow researchers to obtain several simultaneous radiographs, each with a different angular "cut." By combining these images, it is possible to distinguish and identify

different materials in the radiograph. For example, Livermore physicists have observed the expected differences in materials at LANSCE in a test object containing Teflon, graphite, Lexan, and aluminum layers.

Livermore's detector development program is adapting the well-known charged-coupled device (used in home video cameras) for high-resolution images. These devices have a screen that scintillates when protons pass through it and can take measurements such as the proton intensity per area and the average energy of the protons. Images from the screen are stored in a computer file. The ultimate goal is to have a camera that allows multiple time frames of an image to be recorded during one experiment, with a frame-duration of 120 nanoseconds and a frame-to-frame spacing of 180 nanoseconds. Livermore engineers have also developed a solid-state streak camera for making proton radiographic movies of dynamic objects.

As the Livermore research team prepares for another year of experiments, its members are increasingly confident that they understand the science of proton radiography and its capabilities for stockpile stewardship. In short, says Hartouni, "We know enough to build a facility and run it. Proton radiography's scientific underpinnings are on solid ground."

—Arnie Heller

Key Words: Advanced Hydrotest Facility (AHF), Brookhaven National Laboratory's Alternating Gradient Synchrotron, Dual Axis Radiographic Hydrodynamic Test Facility (DAHRT), Fermi National Accelerator Laboratory's Main Ring, Flash X Ray (FXR), hydrotests, Los Alamos Neutron Science Center (LANSCE), multiple coulomb scattering, Nevada Test Site (NTS), proton radiography, quadrupole magnets, stockpile stewardship, x-radiography.

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About the Scientist



EDWARD HARTOUNI received a B.A in physics from the University of California at Berkeley in 1976 and an M.A., M.Ph., and Ph.D. from Columbia University in 1978, 1979, and 1984, respectively. He was a postdoctoral fellow at the University of Massachusetts from 1985 to 1988 and an assistant professor there from 1985 to 1994. He joined Lawrence Livermore in 1995 as a physicist involved in high-energy physics research. He is currently group leader of the Proton Radiography Group within the Physics and Advanced Technologies Directorate.