Proton Radiography

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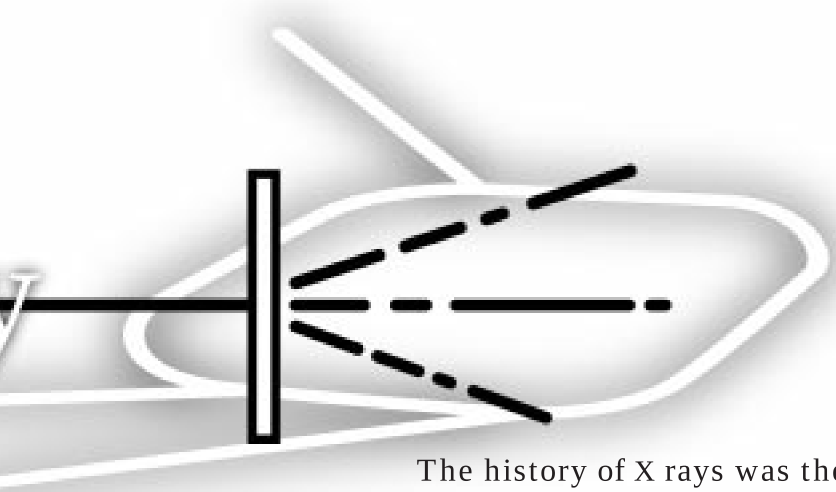
BOOM! As beam arrives to your experiment the target is reduced to a twisted pile of rubble in an impressively energetic explosion, this after months of planning and hard work. Later inspection of the target reveals little information about how it got that way. Fortunately, your experiment is part of a plan to study the physics of explosions that push metal hard enough to make it flow hydrodynamically. Not only does this process happen on very short time scales, but much of what is interesting takes place deep within the moving metal itself. Further complexities arise when the exploding experiment is composed of many different materials, the behavior of each providing important clues as to what is happening in the system. This is a key problem faced by practitioners of the Department of Energy's Science Based Stockpile Stewardship, an ambitious program to allow our Nation to maintain its nuclear stockpile in a safe and reliable state and simultaneously support the Comprehensive Test Ban Treaty.

A solution to this experimental challenge lies in the use of radiography. Both Los Alamos and Lawrence Livermore National Laboratories have used X-ray radiography for many years to glean information about transient events occurring in exploding systems. To meet the goals of the Science Based Stockpile Stewardship program will require much more information about these systems. While X rays have many favorable attributes for radiography, using high energy protons as a radiographic probe has a number of exciting possibilities. Current accelerator technology could easily provide a source of protons for use in radiography.

Our work on proton radiography has applied ideas, measurements, and technology from nuclear and high energy physics. These applications were unanticipated when Los Alamos and Livermore initiated basic science programs in these fields. The laboratories had a vision that supporting basic science would provide a cadre of workers whose broad range of skills could be applied to programs of national



importance related to the mission of the laboratories. Proton radiography verifies this vision.

The application of proton radiography to a national need is another example of physicists applying their particular skills in the service of the Nation. It is important that physicists remain engaged at all levels of developing policy to insure sensible solutions are found to address important problems.

The history of X rays was the topic of the *Beam Line's* Summer 1995 issue (Vol. 25, No. 2). The realization that X rays could penetrate matter led almost immediately to the idea of a radiograph, an image produced by radiation other then visible light. The application of Wilhelm Konrad Roentgen's discovery to medical diagnostics gave doctors the ability to look within a living body. Over the last century, X-ray radiography has been applied to a number of applications in which the interior state of an object must be "viewed" without disturbing or destroying the object (nondestructive testing). X rays have also been used in investigating transient phenomena.

The method of making an X-ray radiograph is largely unchanged from Wilhelm Roentgen's technique (though the technologies for making and detecting X rays have changed greatly). A source of X rays is directed at an object, generally from a "point source." Behind the object is placed an X-ray detector (film, for example). The detector produces an image of the shadow cast by the differential absorption of the materials that compose the object.

The use of protons for medical radiography has been studied since 1954. Low energy protons (100–300 MeV) beams have been used at a number of locations throughout the world to treat various medical conditions. In conjunction with the treatments, the proton beams have also been used to radiograph the internal elements of the patients as part of the treatment planning. In these medical settings, the means of making a radiograph are similar to what was described above for X-ray radiography. The difference between X ray and proton differential absorption distinguishes the information contained in the radiographs.

PROTONS ARE FAMILIAR OBJECTS to nuclear and particle physicists. They comprise the charged component of nuclei and are (along with electrons) the fundamental objects of matter in the present day Universe.

They have one unit of positive charge, plus they have a precisely known mass. They have one unit of "baryon number" and are the isospin partner to the neutron. They interact with other particles primarily through the electromagnetic and strong interactions. While physicists now regard the proton as composed of quarks and gluons, this level of detail is irrelevant to radiography.

The fact that protons and electrons are stable (do not undergo radioactive decay) and are readily available in ionic form (for example, ionized hydrogen, H^+) has allowed physicists to devise a number of ways to accelerate them to increasingly higher energies. Electrons were originally accelerated in cathode-ray tubes in experiments performed over a century ago. Protons have a more recent history in accelerators.

The strong interaction binds the nucleus together. The current theory of this interaction is Quantum Chromodynamics which, together with the Standard Model, explains much of particle physics. What is important to radiography is the phenomenological observation that the strong interaction has a very short range (roughly 1 fermi, equal to 10^{-15} meters). Since the proton and nuclei have dimensions of the same order (1 fermi) this means that the proton and other nuclei interact by hitting each other, something like billiard balls. The probability of collision is indicated by the quantity termed "cross section" and is measured in units of barns (a term taken from the quip "...couldn't hit the broad side of a..."). For proton-nuclei interactions, the cross section is approximately equal to the cross sectional area of the nucleus (given by the nuclear radius, r, as r^2, nuclei being, to very good approximation, spherical).

For readers wishing to pursue issues in more detail related to the Science Based Stockpile Stewardship and the Comprehensive Test Ban Treaty programs, the following URLs may be helpful:

SBSS

http://www.dp.doe.gov/dp_web/public_f.htm

http://nepa.eh.doe.gov/eis/nometa/eis0236/toc.htm

CTBT

http://www.state.gov/www/ global/arms/ctbtpage/trty_pg.html

Another part of particle physics phenomenology is that the proton interaction cross sections are very nearly independent of the proton's energy at high energy (greater then 1 GeV). This fact makes interpreting proton radiographs easier because the probability of survival of the high energy proton is not affected by a change in its energy from other scattering processes.

Because the proton is charged, it interacts with matter through the electromagnetic interaction. As high energy protons traverse matter, they interact with the electric field of the nuclei, and with the atomic electrons orbiting those nuclei. The effects of these interactions are quite distinct. When the proton scatters off of the nucleus by way of the electromagnetic interaction, the effect is a small change in the proton's direction. These interactions are termed "elastic" scattering. Because the proton can scatter off of many nuclei as it makes its traverse, the effects of each of the small scatters can accumulate. This effect is called multiple Coulomb scattering because it is the result of many scatters off of the nuclear electric field which is described by the Coulomb potential. Because of many complications in this system (for example, the atomic electrons "screen" the nuclear potential from the protons) physicists use approximate formulas to describe the scattering involving bulk characteristics of the material to represent the probability of such a scattering process.

The consequence of multiple scattering for proton radiography is quite significant, especially for dense materials. That part of the beam which is not absorbed by the material is scattered by it. Straight-line rays no longer exist, and the shadow made by the object is blurred. In fact, the farther behind the object the detector is located, the more blurred the image. An innovative way around this multiple scattering was found to make it possible to separate the object from the detectors.

The proton interactions with the atomic electrons generally do not result in much change to the proton direction, but many scatters do reduce the proton energy. This is because the electrons might scatter so violently as to become unbound to the atomic nucleus. This process is known as ionization energy loss. With dense materials the energy loss can be quite large (100–500 MeV).

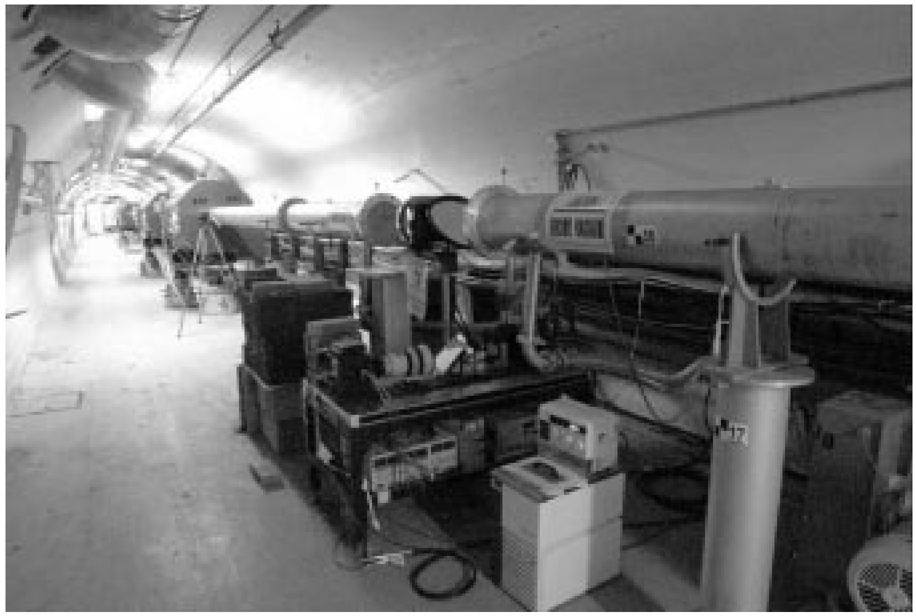
THE IDEA that protons could be used as a radiographic probe for thick dense objects to support the goals of the Science Based Stockpile Stewardship program originated at Los Alamos National Laboratory (LANL) in 1995. The LANL physicists realized that the blurring of the object's shadow cast in the radiograph could be corrected by using a magnetic lens. Using magnets to focus beams of charged particles is common place at accelerator laboratories. The simplest magnets used for this purpose, called quadrupole magnets, have four poles alternating in sign. When used in combination, these magnets will bend charged particles of a particular momentum so that the rays which are multiply scattered going through the object will re-converge at a point downstream of the object to form an image. This was the innovative idea that opened the door to new applications for proton radiography.

The LANL physicists quickly tested their ideas at the Los Alamos Neutron Science Center (LANSCE), a proton linear accelerator capable of producing a beam of 800 MeV protons. The beam can be pulsed and have a large number of protons, depending on the number of pulses produced. Their initial experiments led them in two directions. The first was to propose a more elaborate facility for proton radiography at LANSCE. The other direction was to test their ideas in a high energy beam of protons at Brookhaven National Laboratory's Alternating Gradiant Synchrotron (AGS) facility in New York.

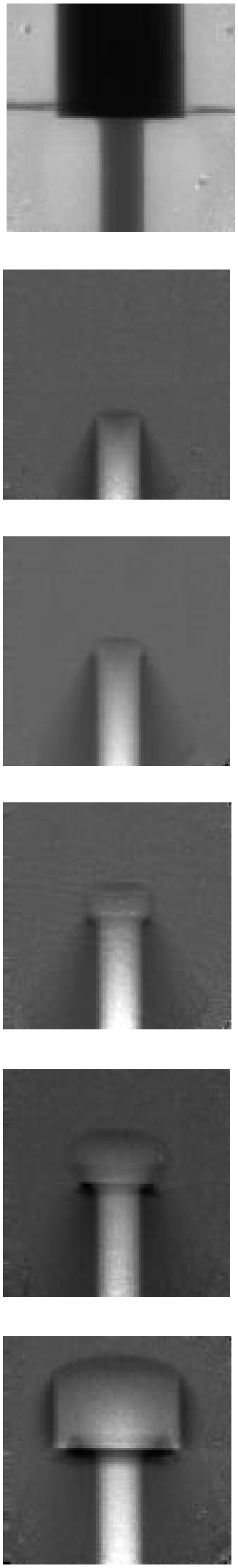
The AGS experiment (E290), a collaboration of physicists from both LANL and Lawrence Livermore National Laboratory, was conducted in the A1 beam line in the summer of 1996. The beam line was rapidly converted to provide a magnetic lens consisting of four AGS beam line quadrupoles (8Q48's). The particles in this secondary beam had a 10 GeV/c momentum and consisted of 70 percent protons and 30 percent pions, the most common meson. The entire experiment took two weeks to set up and run. The images confirmed the physicists' expectations that their ideas would work at high energy.

The ease with which this experiment was set up and run also points to the fact that proton radiography utilizes mature accelerator technology; existing accelerators and beam line technologies are adequate to meet the needs of proton radiography. E933, a follow up experiment to E920, is shown in the photograph above. It is located in the U-Line at the AGS.

The detectors used for proton radiography can be designed to take advantage of the fact that protons are charged. This means that detectors used in nuclear and high energy physics experiments can be applied for radiography. In particular, these



The E933 beam line at Brookhaven National Laboratory's Alternating Gradient Synchrotron. The view is looking downstream. The quadrupole magnets (octagon-shaped) are part of the first magnetic lens. The break in the beam pipe allows detectors to be set up at the first image station. Two camera systems are viewing the same scintillating fiber plane.



A time sequence from the Los Alamos LANSCE PRAD-50 experiment of a high explosive burn to determine how detonation waves propagate around geometric features. The first photo on the left shows two high explosive cylinders of different diameters before detonation. The high explosive is detonated from the bottom and the detonation wave propagates vertically. The figures are taken with different charged-coupled detector cameras at different times from 17.26 milliseconds to 23.70 milliseconds.

detectors will have high efficiency in detecting protons and at the same time have little effect on the proton beam. This enables multiple detectors to be placed in the radiography beam line to make multiple measurements of the radiographic image.

Some traditional radiography detectors have been used for proton radiography. These include imaging phosphor plates which act like photographic film (exposed when the protons penetrate the plate) and charged coupled device cameras that view a screen which scintillates when the protons pass through.

A new set of detectors is being designed and tested at Lawrence Livermore and Los Alamos national laboratories that allow multiple time frames of an image to be recorded. The frames have a duration of 50 nanoseconds (1 nanosecond is 10^{-9} seconds), a frame-to-frame spacing of 250 ns, and the ability to take tens or hundreds of frames.

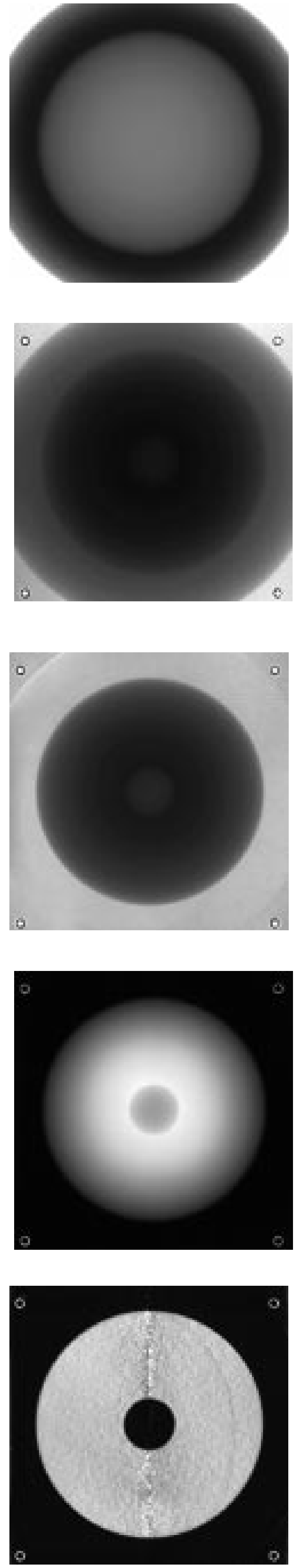
Making a movie to follow the internal dynamics of objects is one of the goals of applying proton radiography to the SBSS program. Along with detectors, accelerators must be capable of producing pulses of beams with a large number of protons in each pulse. Protons circulating in synchrotrons have a pulsed structure because of the fact that the radiofrequency (rf) accelerating cavities must have a well defined frequency in order to accelerate the beam. As the protons circle around the accelerator, they arrive at the rf cavity at some well-defined time depending on their velocity. The rf cavity is setup to give the protons a little acceleration "kick." As the protons move faster, the rf frequency and phase is adjusted to give the kick at just the right time. Because the rf is sinusoidal in the cavity, the kick can occur at each period of the rf, which means that if the period is short compared to the orbit time of the proton beams, many proton beam bunches can be accelerated simultaneously.

Once the protons achieve their maximum energy, the beam bunches can be extracted from the synchrotron by way of a well practiced set of beam gymnastics. These pulses fall on the changing object at different times and are detected at various image points in the radiography beam line, one image for each pulse. In this way a radiographic movie is made with the pulses of protons from the accelerator. The photographs on the left show the time sequence radiographs from a LANSCE experiment investigating the behavior of a high explosive burn.

The changing shapes of the object are only part of the information proton radiography can provide. Both the density of the material in the object and the identity of that material may be obtained. To make these measurements we require some information about the nuclear scattering length and the radiation length of the material. We obtain this information by making radiographs of objects varying in thickness made of known materials with known densities. We can predict what the radiograph will look like and adjust the scattering and radiation lengths to make the prediction agree with the radiograph. This procedure takes into account a particular radiography beam line setup.

The density of the radiographic object can then be found given the

Steps in reconstructing the volume density of the French Test Object from the Brookhaven National Laboratory E933 data. A model of the overlaying, partially seen material (mostly foam and copper) is formed into a "synthetic radiograph" in the top right image. This is ratioed with the actual data (second image), for which the beam and the detector artifacts have been removed, resulting in the third image. The logarithm of the ratio image is then normalized by the scattering length to give the "areal" density (fourth image). Finally a mathematical procedure uses the fact that the object has cylindrical symmetry to reconstruct the volume density of the French Test Object. A slice through the reconstruction is shown in the bottom image.



beam path length through different parts of the object and the scattering constants. Finding the path lengths involves making a three-dimensional reconstruction of the object. This procedure, known as tomography, may use many different views of the object taken simultaneously, or some known property of the object's shape (for example, the object might be spherical). The measured intensity of the object depends on the product of the density and the path and the scattering lengths. Knowing the path length and the scattering length, the density is then recovered. The images on the right show the steps reconstructing the French Test Object, a series of nested spherical shells made of plastic foam, copper, tungsten, and air.

Identifying the material is somewhat more difficult and involves two different but simultaneous measurements. The multiple scattering depends on the radiation length of the material. A material with a large radiation length scatters the beam less then a material with a short radiation length. The material identification is the result of comparing a radiograph which sees different amounts of the multiple scattering angles. This can be arranged by putting two magnetic lenses, one after the other, in the beam line. The first lens sees all multiply scattered protons from the object and records them at the lens' image location. The protons pass unaffected through the first detector and into the second lens. The second lens contains a collimator that absorbs protons with large scattering angles (collimators can be made to absorb only small angle scattered protons too). The second lens images the protons at the second detector. When these two images are compared, the relative amount of intensity of the images is used to extract the ratio of the path length-to-radiation length. Knowing the path lengths of the protons through the object allows the radiation lengths to be determined. The radiation lengths then provide the information about materials.

THE WORK of the last five years by physicists from Los Alamos and Lawrence Livermore national laboratories has helped to develop proton radiography to the point where the important Science Based Stockpile Stewardship facility, the Advanced Hydrotest Facility, is considered to be devoted to proton radiography. It will be capable of investigating the behavior of the Nation's nuclear stockpile safety and reliability. This facility is in the conceptual stages of development and will be located at the Los Alamos site. Physicists from both laboratories will perform many tests and experiments in support of their Science Based Stockpile Stewardship activities.

This facility will also provide a research and development base for the industrial applications of proton radiography. Some of these applications might include the investigation of combustion in automobile engines and various non-destructive testing procedures, such as material identification.