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INITIAL TEST OF A PROTON RADIOGRAPHIC SYSTEM*

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Summary

Protons have a well defined range in matter. A detector, therefore, placed near the end of range of a monoenergetic proton beam becomes a very sensitive measure of changes in the mass of material which the beam has traversed. This property of protons can be exploited in a variety of ways to make radiographs of solid objects. The experimental radiography system we have built to use with the 200 MeV booster synchrotron of the Zero Gradient Synchrotron (ZGS) is described. In addition, there is a brief description of a more elegant system which would operate with a suitable source such as the proton diagnostic accelerator proposed by R. Martin.[1]

Theoretical Considerations

Medical diagnostic applications of proton radiography require proton ranges up to ~ 25 g/cm^2 which necessitates proton energies up to ~ 200 MeV. The interaction of protons in matter below 200 MeV is well known, so it is possible to calculate any physical parameter of proton radiography.

Figure 1 shows a theoretical range curve for a 200 MeV monoenergetic proton beam. A detector placed at the end of range will see large intensity changes for any small mass changes in the sample being radiographed. This is the crucial property of protons for radiography. One of the problems of radiography, on the other hand, is that if the mass changes are too large then the detector is driven out of the sensitive region. Range straggling is between ± 1 - 1-1/2% of the range for ranges of medical interest. In its simplest conception, therefore, radiography is limited to mass changes within 2-3% of the proton range. In practice, there are various ways around the problem so it has become more of a nuisance than a real difficulty.

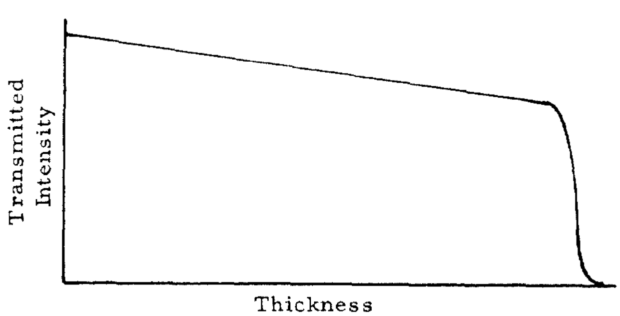

Figure 1 - Proton Range Curve

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Since the range of the protons is a gaussian distribution, it is straightforward to derive an approximate expression for the radiation dose required to detect a given mass change. The result[2] is

$$D = \frac{\pi r^2 RE}{\Delta t^2 AC} \left(\frac{\sigma}{R}\right)^2,$$

where D = dose in rads, averaged over the whole volume being radiographed, required to detect a change in thickness, Δt in cm, with r standard deviation precision

R = range of protons in cm

σ = standard deviation of range straggling in cm

E = incident proton energy in MeV

A = area of object to be detected in cm^2

C = conversion coefficient from energy deposited to dose = 6.25 x 10^7 MeV/cm^3/rad, where the mean density is assumed to be 1 g/cm^3.

The above expression makes the approximation that the proton range equals the thickness of the object being radiographed and it neglects the effect of nuclear interactions.

Tumor detection is the principal medical application which we foresee. The density differences, therefore, between tumor tissue and the surrounding normal tissue are the crucial biological data needed for dose calculation. Measurements made by one of us (Steward) suggest a representative density difference of 3%. This number is quite variable, however, depending on the tumor type and its location. Assume we wish to detect, with 6 standard deviation precision, a cube shaped tumor, 3 mm on a side, which has a 3% density difference from the surrounding tissue. Using the tables of Janni[3] and the dose formula above, we find for two cases:

Proton Range, R	5 cm	16 cm
Proton Energy, E	79 MeV	152 MeV
Range Straggling, $\frac{\sigma}{R}$	0.013	0.012
Dose	16 mrad	90 mrad
Protons/cm^2	64,000	580,000

The 5 cm case could represent a compressed breast and the 16 cm case a skull radiograph. Present x-ray techniques would deliver 1000 mrad or more and probably could not detect such a tumor directly. There is one very important qualification, however. This dose calculation is highly idealistic. It assumes a well defined tumor located in a homogeneous medium. Biological material is, of course, much more compliciated.

Multiple coulomb scattering of the incident proton beam causes loss of beam quality and, therefore, loss of spacial resolution. Using the usual multiple scattering expression, $\theta_{rms} = \frac{15}{p\beta}\sqrt{\frac{\ell}{\ell rad}}$, and the empirical range-energy relation, $E = kR^n$, it is possible to calculate[4] the following approximate expression for the beam spread:

$$2\,Z_{rms} = 0.057\,R^{0.94}\left(\frac{t}{R}\right)^{1.5},$$

where $2\,Z_{rms}$ = projected rms beam spread in cm

R = proton range in cm

t = object thickness in cm

This expression should be accurate to about 20% for all biological material near density 1.0.

In general, it should be possible to make two 180° radiographs so the worst case for scattering is at the center of the object being radiographed. Since the range, R, of the protons should be normally only slightly greater than the thickness of the object, this means the worst scattering case is about t/R = 1/2. Using this, we find $2\,Z_{rms} = 0.9$ mm for R = 5 cm and $2\,Z_{rms} = 2.7$ mm for R = 16 cm. Since the beam size corresponds roughly to the spacial resolution, we find proton radiography capable of detecting objects as small as about 1 mm in diameter in the compressed breast case (noted above) and 3 mm in diameter for the skull case. This also means that in scanning beam radiography, the beam should be 1-2 mm in diameter at most.

The above resolution calculation assumes a radiographic system in which the positions of the entering protons are measured. If one only measures the exit positions, as is the case for a nonelectronic system such as photographic film, then the spacial resolution in the center of the object is worse. This is because the position of each proton is measured after traversing the entire object. A nontrivial calculation shows the resolution is 2-1/2 times worse at the center of an object. For this reason, in part, we have discarded film as a detector.

The Present Argonne Experimental Radiographic System

This system was designed to operate with the 200 MeV booster synchrotron of the ZGS. This accelerator delivers about 10^{11} protons in 0.1 μs every 67 ms. A collimation system (see Fig. 2) produces four 1 mm² beams stacked vertically 2-1/2 in apart. The purpose of four beams is to collect data four times faster. The scan is made by stepping the mechanical stage 1 mm after each pulse. The command to step is given only if the last booster pulse exceeds a certain intensity threshold. Typical intensities used are: 5000 protons per 1 mm beam per pulse. The stage scans horizontally 10 in and then steps down 1 mm and scans back. A complete 10 in wide scan takes 18 min. Another mode of operation allows a horizontal scan to be followed by a 2° rotation of the object inside the specimen box. This allows studies of 3-D reconstruction problems.

The proton beam intensity upstream and downstream of the specimen box is measured by light

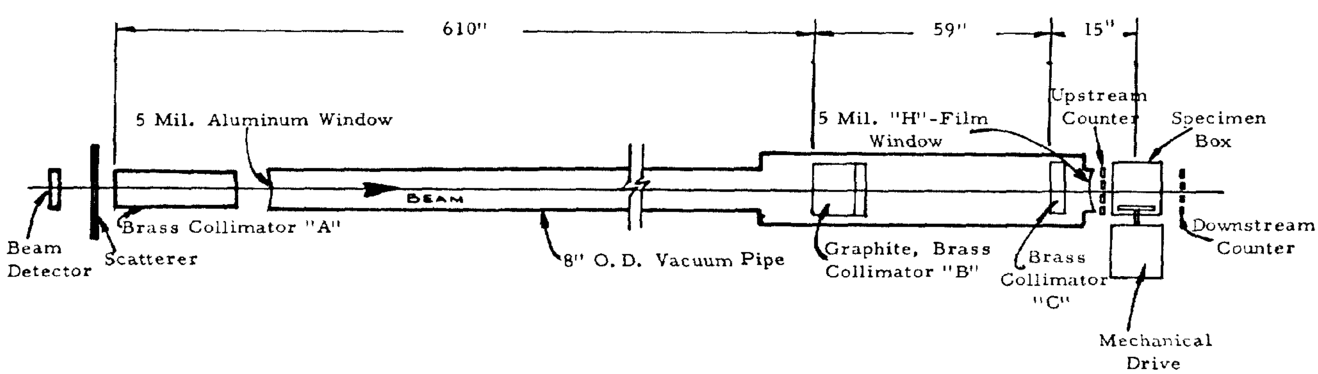

Figure 2 - Proton Radiography Beam

integrating scintillation counters. The pulse from each photomultiplier tube is integrated, amplified and then sent to a sample and hold. The sample and hold output goes to the control room where it is digitized and written on magnetic tape along with the specimen box position and other parameters.

The pulse to pulse energy stability of the booster of ± 1/4% is inadequate for proton radiography. To monitor energy shifts the top pair of counters always has a fixed amount of material between them arranged so that the downstream counter is at the end of range. This monitor is then used to correct the other three pairs of counters for these shifts. This, unfortunately, increases our statistical fluctuations.

The pulse amplitude in the upstream counters is directly proportional to the number of protons in the beam burst. The downstream counters, however, are sensitive to the number of protons times the average proton energy deposited. The transmissions, ratios of the downstream to upstream counters, therefore, give a Bragg curve when plotted as a function of the thickness of material in the specimen box rather than the curve in Fig. 1. Calculations indicate, however, that this does not substantially affect the conclusions drawn above, about sensitivity, dose, etc.

We have accumulated a number of magnetic tapes of engineering data, physical test objects, and biological specimens. The one standard deviation statistical fluctuation in the transmissions is about 1-1/4% of the maximum transmission. This means that there are about 80 levels of grey associated with each square millimeter. For this reason it has been difficult to create "pictures" from these tapes. One system we have relied on is storing the transmissions in a scan converter tube. The data in the scan converter can easily be read out as a video signal to make a TV picture. This system is easy to use, however, it is

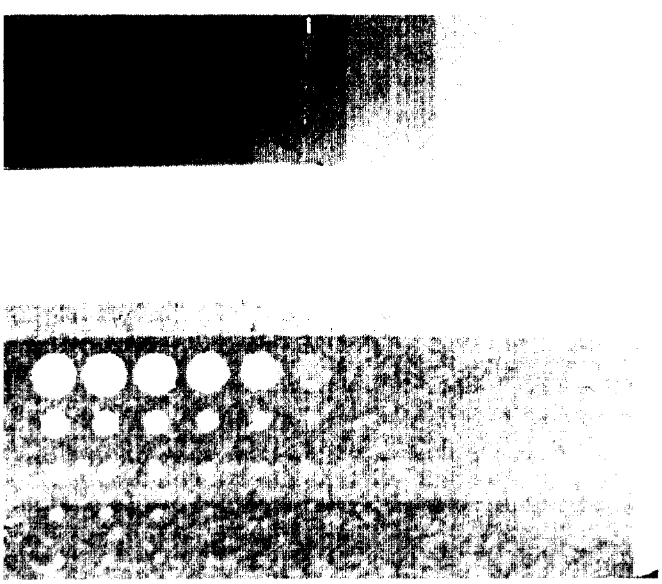

Figure 3 - Proton Radiograph of Burger Phantom

capable of only about ten levels of grey. Figure 3 is a picture made this way of a Burger phantom. This test object is an array of holes drilled in a piece of Lucite. The top row of holes is 1/2 in in diameter. Each succeeding row is half of the diameter of the one above. The fifth and bottom row is 1/32 in in diameter. All of the holes in the left column are 0.320 in deep. Each succeeding column is half the depth of the column to its left. The seventh and rightmost column holes are all 0.005 in deep. The picture you see here is a copy of a copy of a Polaroid of the TV monitor. In our most recent radiograph of this test object, the 1/8 in diameter, 0.005 in deep hole is visible. This corresponds to a density change of 0.06% as it was made through 8 in of Lucite. An x-ray of this test object through only 2 in of Lucite and using several rad instead of the approximate 0.1 rad used in the proton radiograph reveals less detail than the proton radiograph.

The Ideal System

The ideal accelerator for proton radiography should deliver a small ($\leq$ 1 mm) pencil beam dc or with at least a 1 s spill and with an intensity of about 10^8/s. It should have an energy spread of less than 1/4% and a short term energy stability of better than 1/200%. With such a source the detector becomes quite simple. It consists of a magnet which would scan the beam over the object being radiographed in about 1 s and a single large integrating scintillation counter downstream of the object being radiographed to record the transmission.

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