# Proton radiography with a range telescope and its use in proton therapy

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Because of the advent of relatively high energy (245 MeV) proton accelerators for proton therapy, we were lead to re-explore the old idea of proton radiography, as first used by A. M. Koehler in 1968, and by Hanson et al. in the 70's, now in the light of present (high-energy) nuclear physics techniques. The basic idea is to make use of the proton beam per se to help position the patient/tumor relative to the beam. We describe results of recent tests done at proton energies of 70 MeV to measure density variation (like tumors) in an relatively homogeneous material like water or plastic (biological tissue). These tests were specifically designed to deal with simple, but realistic, shapes and geometries, so that we could compare the experimental results with Monte Carlo simulations. Extensions of the method at 245 MeV are discussed.

1) On our involvement (circa 1993)

-- UC Davis, together with LBL, are (were?) joining efforts to build a proton cancer treatment facility in Sacramento. NCI was considering at the time building two similar facilities, the other one located at Massachusetts General Hospital.

-- We (Crocker Nuclear Laboratory and Physics at UCD) were approached by Del Kubo (UCDMC) to see if there is a simple way, other than the usual x-ray method, to position accurately (to within perhaps 5 mm) the proton beam in the tumor of the patient.

-- "Why not use a sample of the beam itself and make use of energy loss sensitivity to surface density of the medium?", we asked ourselves.

-- Preliminary Monte Carlo simulations showed us that there was a good possibility. Also, we soon found out about the pioneering work by others on proton radiography... (see below).

-- At this point, we established a collaboration group to explore these ideas.

Collaborators

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2) Earlier work on proton radiography

The value of using beams of high-energy charged particles, in particular proton beams, as sensitive probes to detect small density variations has been recognized for many years. In 1968, Koehler used 160 MeV protons from the Harvard University cyclotron to obtain radiography of fabricated phantoms *[7]*.
*[7] A. M. Koehler, Proton radiography, Science  160 (1968) 303.*

Koehler showed that density differences as small as

0.05% could be detected. Working with Steward in the early 1970s, they obtained proton radiography of real tumors of the breast *[1]* and brain *[2]*.
*[1] V.W. Steward and A.M. Koehler, Surg. Neurology ,2 (1974) 283-284.*
*[2] V.W. Steward and A.M. Koehler, Radiol. 110 (1974) 217-221.*

In the late 1970s, Hanson et al. used a 240 MeV proton beam from the Los Alamos Meson Production Factory (LAMPF) to obtain computed tomography of the highest quality and sensitivity to density variation of the order of 0.013 g/cm$^2$ *[3,4]*
*[3] K. M. Hanson, IEEE Trans. on Nucl. Sci. N3-26 (1979) 1635.*
*[4] K. M. Hanson et al., IEEE Trans. on Nucl. Sci. N3-25 (1978) 657*.

They also compared proton radiography with conventional x-ray radiography and showed that for similar quality images, protons resulted in a much lower dose to the patient than did x-rays, and that treatment doses could be located more accurately and away from sensitive areas.

A general discussion on the physics of imaging with ionizing radiations is found in Kouris, Spyrou and Jackson *[5]*
*[5] Kypros Kouris, Nicholas M. Spyrou and Daphne. F. Jackson, "Imaging with ionizing radiations", Surrey University Press, 1982*.

## 3) Description of method

### Principle of proton radiography

For a given incident proton energy and a given density variation, the residual (detected) energy changes much faster near the range of the incident proton as anywhere else (about 10 times for 245 MeV protons).

## Range-straggling

Fig. 1 presents the well-known relationship between the proton energy and the range in water and also the corresponding range straggling . It is seen that for water, straggling is typically 1% of the range. For a specimen of 40 cm of water, straggling is about 4 mm.

## Multiple (Coulomb) scattering

... of the proton beam with the atoms of the material affects the lateral precision. However, a determination of the trajectory of the proton, measured before and after traversing the phantom, allows us to correct for this effect. Typically, one expects to correct the lateral component of the proton trajectory position to within 1 mm.

## Conceptual design

Considering the above, a conceptual design of a detector array to obtain a radiography of a patient tumor or phantom structure, by measuring the range of a high energy proton beam is sketched in Fig. 2. A (very) low intensity proton beam passes an X-Y position-determining device such as a multi-wire proportional chamber, impinges on a patient, traverses a density anomaly such as a tumor or bone structure, emerges through a second X-Y device and finally is stopped in a total energy detector, such as the range telescope. In this case, if one uses 1 mm scintillating detectors, the typical average error in determining the range (or depth sensitivity ) is 0.05 g/cm$^2$.

4) Experimental setup

## Geometry and detectors

Fig. 3 shows the experimental set-up we used at CNL. Use was made of existing DE detectors and available wire chambers to assemble a fast range telescope. The low intensity proton beam impinges on a phantom and onto the detecting telescope, where it stops. The fast range telescope consists of 5 thin DE detectors (DE1, DE2, ..., DE5), with thicknesses ranging from 0.8 mm to 2 mm. An adjustable energy degrader and a trigger DE detector are located before the phantom. Wire chambers WC1 and WC2, located before and after the phantom, respectively, are used to determine more precisely the individual proton trajectory. The multiwire chambers give position (one standard deviation) close to s= ±1 mm, and also allow corrections for the effects of multiple Coulomb scattering.

## Electronics

The anode signal from each  DE  detector is fed to a fast discriminator. The threshold for the latter is set in a separate calibration run using full energy protons (67.5 MeV), guaranteeing in this way the detection of low energy protons when the phantom is used. The output from the fast discriminator is fed into a CAMAC  coincidence register, which establishes how many of the five DE  detectors are in coincidence with the  trigger detector. The latter initiates the sequence of electronic coincidences for each event. The coincidence register and the X and Y signals from the wire chambers are stored event-by-event onto magnetic tape for off-line analysis. In this manner, each individual proton is registered as an electronic coincidence between the trigger detector and at least one of the five DE  detectors.  For example, an event that has a coincidence register set to detectors 1, 2 and 3  is accepted in the analysis. A coincidence register set to detectors 1, 2, 3 and 5 is rejected. In the next section, we present results from events that have consecutive hits starting from detector 1.

5) Results of experiment and simulations at 70 MeV

## Results  to test general idea of the method

Fig. 4 (right) presents the results corresponding to an acrylic phantom shaped as in Fig. 4 (left). The phantom has, as shown, a raised pattern 1.6 mm in thickness on top of an acrylic cube 30 mm in thickness. The very low intensity proton beam (about 160 protons/sec with an energy at the phantom of  66.0 MeV) impinged normal to the phantom along the Z direction. Each panel in Fig. 4 shows the distribution of events stopped in the corresponding  ΔE detector. The X, Y values correspond to the hits in WC1 placed upstream of the phantom, as in the setup in Fig. 3. The sequence of scatter plots of positions at the entrance wire chamber for the cases where the proton stopped in the first, second, ..., and fifth detector is an excellent illustration of both the principle and sensitivity of the method. This radiography of the phantom was obtained with about $3 \times 10^4$ protons and it took 3 minutes. It is seen that most of the protons incident on the thin raised pattern are stopped in ΔE2, while most of the protons incident outside are stopped in ΔE4. Straggling, beam energy width ($\sigma \approx$ 0.3 MeV), wire chambers resolution ($\sigma \approx$ 1.3 mm) and multiple scattering produce diffuseness in depth (as measured by the detector where the proton stopped) and in the X,Y position (as measured by the hit in WC1). The rather good depth sensitivity allows us, in the present configuration, to distinguish thickness differences of at least 0.05 g/cm$^2$ (see below).

## Results to test simulations

Another set of measurements were made using a variety of simple phantoms. The purpose here was to explore the capability of our simulation code to reproduce the experimentally observed results. Here we discuss the results using the phantom and geometry shown in Fig. 5.

## Simulations

Briefly, the Monte Carlo simulations are done as follows: Individual protons, each with an energy of 66.0 MeV, are sent along the beam direction, the Z-axis, at random X,Y points, so they span the phantom. The incident energy is smeared according to a Gaussian distribution corresponding to a beam energy resolution with $\sigma$= 0.3 MeV. Each proton is then propagated through the phantom and, incrementally (in the beam direction) the new energy (decreased due to energy loss) and new position due to multiple scattering are calculated. The latter is done in 3-dimensions, so at each increment in the Z-axis a new position (X,Y,Z) and a new energy is obtained. This process is continued until the proton energy is zero (normally it stops in one of the $\Delta$E detectors). At the point of stopping, the final position is determined by smearing the stopping position according to the range-straggling curve, using a Gaussian distribution with a standard deviation obtained from Fig. 1. Finally, the X,Y hits at the location of the wire chambers are also smeared according to the expected resolution of the wire chambers ($\sigma$= 1.3 mm). The process is repeated for the desired number of protons.

## 6) Predictions at 245 MeV

### Bone structure (Fig. 9)

The good agreement observed between the data and the simulations for 66 MeV protons gives us confidence in our Monte Carlo simulations and allows us to make predictions on the quality of the method for higher energy protons. An example of such predictions is presented in Fig. 9. The setup corresponds to that of Fig. 2. The phantom, shown on the left on Fig. 9, is (for simplicity) a cylinder, 2 cm in diameter and 3 cm in depth, and positioned at the center of a surrounding media consisting of $H_2O$ (35 cm in depth, r = 1.0 g/cm$^3$). We assume the cylinder to have a composition similar to that of bone, i.e., $CaO_2$ (r = 1.5 g/cm$^3$). The proton beam, with an energy of 245 MeV, impinges perpendicular to the main axis of the cylinder (Fig. 9). We send $3x10^5$ protons over an area of 7 cm (horizontal) by 3 cm (vertical). The X-Y positions correspond to that of WC1 (s=1.3 mm). The data is binned in X-Y areas of 1 mm$^2$, and every 100 hits are averaged in each bin, to take advantage of statistical sampling.

**Increased resolution with beam intensity (fig. 10)**

The top part of Fig. 9 (right) shows the average (100 hits per bin) X-Y distribution at WC1 corresponding to protons stopping in detectors DE10 through DE16. The cylindrical bone was positioned with its center at X= 6 cm. The bottom panel of Fig. 9 (right) plots the detector where each proton stops (average over 100) versus the X position, and provides another way of displaying the results. (This is possible because of the symmetry of this phantom along the Y-axis.) The bone structure is discerned quite well even with much less statistics, as seen in Fig. 10, where we compare the results with the case corresponding to averaging only every ten hits (i.e., 10 times less integrated beam intensity, or $3x10^4$ protons). As mentioned above, a more involved tomographic reconstruction has not been pursued, since we have dealt with rather simple phantoms in our tests and simulations. Future work should involve more complex phantoms and possibly tomographic reconstruction.

## 7) Recent results by the group at PSI

The group at the Paul Scherrer Institute, in Switzerland have also pursued proton radiography as a tool in proton therapy. Their ideas are very similar to what we have explored, illustrating again that when technology is ready, ideas/methods pop up simultaneously in many places.
*Uwe Schneider and Eros Pedroni, " Proton radiography as a tool for quality control in proton therapy", Med. Phys. 22 (4), April 1995.*

Their studies differ from ours in several respects. Here are the most important ones:

-- use of a 219 MeV proton beam
-- use of a range shifter
-- use of a NaI detector to measure residual energy (75 mm in diameter, 100 mm thick)
-- they took proton radiography of the Alderson phantom
-- counting rate limited to only 1000 protons per second, which implied long running times, ≈ 2 h.
-- they used the spatial information of the two wire chambers to reconstruct the intercepts of the most likely proton trajectory of every event at every point between the two chambers. Then they used the intercept coordinates of the calculated proton trajectory and the plane to be reconstructed to form images at different depths in the phantom.

This is an important work. They also have done detailed studies of multiple scattering and range uncertainties.
They are setting up a system like ours, with a range telescope, to speed up the data rate at least 2 order of magnitude.
They are also starting a Monte Carlo simulation program.

## 8) Final remarks

We have described a method to locate density variations in phantoms that makes use of high energy proton beams.

The method is thought to be applicable to the positioning of a patient in a proton therapy facility.

The method makes use of a proton range telescope for density variation and X-Y position sensitive detectors for planar positioning.

We have tested the principle of the method with measurements at a proton energy of 66 MeV.

Good visual quality is seen in the tests. We have compared the measurements with detailed Monte Carlo simulations and achieved good agreement.

Further simulations with high energy proton beams (245 MeV) show that the method should provide good visual quality and sensitivity for positioning. In the case of a proton therapy facility, the latter could be achieved by using the proton therapy beam *per se* in a (very) low intensity mode.