A Fast Monolithic System for Proton Imaging

**Purpose:** Proton radiography would be the most direct method of image guidance for proton therapy. There is a need to enable more complex treatments delivering a high dose to the tumor with reduced uncertainty. There is also a need to maintain patient throughput and improve the cost-effectiveness of proton therapy relative to conventional radiation therapy. The use of a proton beam for both imaging and treatment streamlines patient setup and quality assurance procedures, reduces alignment uncertainties, and reduces proton range uncertainties. We aimed to develop a high-performance, low-cost proton radiography system based on well-established fast scintillator technology.

**Methodology:** We established the feasibility for both a residual range detector and a tracking detector. The design of our system is based on requirements that the final clinical detector system be:
- Simple and lightweight.
- Easily scaled to large field sizes.
- Capable of operating at high speed to maximize patient throughput.
- Expose the patient to the minimum possible radiation dose for a given resolution.

Our specific aims were to construct and test a prototype high-speed residual range detector and a prototype tracking detector.

**Conclusion:** The combination of high performance, simple monolithic construction and reduced electronics channel count will enable us to develop a clinically practical system.

---

**Introduction**

From joint DOE-NCI workshop on ion beam therapy:

“A better method of determining the stopping power, be it through proton CT or other means, would greatly increase the accuracy of the treatment, particularly when 1 mm range precision is desired. This is an important area for further R&D.”

**Benefits of Proton Imaging for Proton Therapy**

1. A direct measurement of proton stopping power, reducing range uncertainties.
2. The use of a proton beam for both imaging and treatment can streamline patient setup and quality assurance procedures
   a. Reduces alignment uncertainties.
   b. Range check before treatment.
   c. Improve delivery accuracy of Pencil Beam Scanning (PBS) fields.
3. Goals: Achieve both of the following for proton therapy:
   1. Reduce set-up and range uncertainty margins.
   2. Improve cost-effectiveness

**Principle of Proton Imaging (CT or radiography):**

1. Tracking detectors measure the position of protons before and after the patient.
2. A residual range detector measures the proton energy absorbed within the patient.
3. With one direction: Form image showing proton range across the field.
4. With all directions: 3D image from tomography.

Proton Imaging immediately before treatment: Use protons with enough energy to traverse patient. Use ultra-low intensity beam:
- Lower dose than equivalent x-ray image.

Subsequent treatment beam uses:
- Lower energy, protons stop in tumor
- Higher intensity, delivers prescribed dose

**Methods**

Establish requirements:

1. Residual range resolution of 3 mm per proton.
   a. Resolution dominated by intrinsic fluctuations.
   b. Optimizes Dose / Resolution (< 100 μGy for an image)
   c. An image can average many protons to obtain:
      - range resolution of 1 mm or better per pixel (1 x 1 mm²)
2. Measure 10 million protons / second, resolving individual protons as close as 20 nsec.
   a. Image and treat with same system.
   c. Reduces cost and complexity of the detector.
3. Proton transverse position resolution (“hit” resolution) of 0.3 mm or better in the tracking detector.
   a. More optimal for dose.
   b. Keeps range detector thin.
   c. Reduces cost and complexity of the detector.
4. Proton Imaging provides the most direct method of image guidance for proton therapy.
   a. Higher intensity, delivers prescribed dose
   b. Lower dose than equivalent x-ray dose
   c. Merritt for dose.
5. Proton transverse position resolution (“hit” resolution) of 0.3 mm or better in the tracking detector.
   a. Multiple scattering limits spatial resolution.

**Design, build and test prototype range detector:**

- Monolithic design using fast scintillator and light sensors
- 20 x 20 x 10 cm³ active volume
- Test at Northwestern Medicine Chicago Proton Center with 20 cm WEPL phantom

**Test Beam Data**

- One dot = One proton
- Time differences are quantized from RF accelerating field.
- Clusters around 0.06V are single proton events.
- Clusters at 0.12V are two-proton events.
- Clusters at 0.09V are from protons sitting on a tail of a proton 10 nsec earlier.
- Nuclear scatter events fall below 0.06V.

**Conclusion:**

Our specific aims were to construct and test a prototype high-performance, low-cost proton radiography system based on fast scintillator technology. We developed a fast, lightweight, high-resolution proton imaging detector and a prototype tracking detector. The combination of high performance, simple monolithic construction and reduced electronics channel count will enable us to develop a clinically practical system.