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IMAGING WITH A MULTIPLANE MULTIWIRE PROPORTIONAL CHAMBER USING HEAVY-ION BEAMS*  

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Abstract

A 16-plane multiwire proportional chamber has been developed to accurately map intensity profiles of heavy ion beams at the Bevalac. The imaging capability of the system has been tested for reconstruction of 3-dimensional representation of a canine thorax region using heavy ion beams.

Introduction

Accelerated heavy ions from the Bevalac are used for biomedical experiments. Often the radiation field areas are large, of diameters of 20 cm or larger, and the radiation intensities across the fields are desired to be uniform. To map the dose uniformity quickly, a 16-plane multiwire proportional chamber has been constructed and successfully used as a beam intensity monitoring device. It is named MEDUSA after Medical Dose Uniformity Sampler.

The 16 chamber planes, each of which has 64 parallel wires placed 4 mm apart, are stacked with their wire directions staggered in such a way that they cover the 180 degree space as shown in Fig. 1. When the heavy ions penetrate the chamber, the resulting ionization electrons are collected in each signal wire and stored in the integrating capacitor connected to the wire. The voltage on the capacitor is therefore proportional to the beam intensity over the area of a 4 mm-wide strip which is centered on the particular wire and extends midway toward the adjacent two wires. The voltage data collected on the 64 wires of a given chamber plane are the line integrals along the wires of the ionization resulting from the penetrating heavy ions. In other words, the data represent the one dimensional projection, along the direction of the wires, of the two-dimensional beam intensity profile. Based on the 16 projections, each at a different angle, the beam intensity profile is readily reconstructed. The reconstruction algorithm

Fig. 1. MEDUSA.  

is based on the filtered back-projection technique.

The heavy ion beams at the Bevalac are pulsed at every 4 seconds, and MEDUSA is reset immediately prior to a beam pulse. At the end of each data collecting cycle, usually one or a few pulses, the capacitor voltages are sequentially sampled, digitized, and stored in a buffer memory under the control of an LSI-11 microprocessor. Upon command, the data in the buffer are serially transmitted to the host computer, a PDP 11/34 computer. The 1024 data points (16 planes of 64 wires) are used to reconstruct the beam profile,

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usually in a 64 x 64 array with 4 mm pixel size. The reconstructed images are color coded according to the intensities and displayed on a RAMTEK 9351 system, which has a 512 x 512 pixel matrix with each pixel of 12-bit refreshable memory.

MEDUSA is used in the Biomedical facility of the Bevalac for routine beam intensity profile measurements and for new beam development. Imaging capability of MEDUSA using unmodified Bragg peak and spread Bragg peak have been also tested.

**Beam Preparation for Imaging**

Heterogenous 3-dimensional objects can be imaged using MEDUSA in the following way. If a heavy ion beam with a spread Bragg peak (spread by a specially designed filter, see below) is transmitted through a radiological object, MEDUSA positioned downstream of the object will detect the portion of the heavy ions in the peak that have excess energy after passing through the object. If the modified Bragg peak is shaped in such a way that the dose is a function of the penetration depth, then the measurement of the dose beyond an object represents the integral of the beam profile over the object. If one takes one horizontal slice from each of the 16 2-dimensional projections in Figure 3, which show the exposures of the canine thorax from 16 different angular directions, the process was repeated until 16 angular positions, each with 4 water column settings, were exposed. The beam profiles through the empty plastic cylinder were also taken for normalization purposes as the beam intensity profile was a broad Gaussian instead of a uniform flat distribution. For imaging an object with dimensions less than the spread Bragg peak width, 13 cm in this case, only one water column setting is needed for reconstruction; four water column settings were used for checking and calibration purposes. The reconstruction of 2-dimensional heavy-ion radiographs from these data are shown in Figure 3, which show the exposures of the canine thorax from 16 different angular directions.

If one takes one horizontal slice from each of the 16 2-dimensional projections in Figure 3 at a certain level, then a tomographic image may be reconstructed at that level. It is noted that...
Fig. 3. Two-dimensional projection heavy ion radiographs of a canine thorax from sixteen different angular directions.

Fig. 4. Transverse tomographs of a canine thorax showing the heart, the two lungs, and the body contour.

The sensitive area of MEDUSA is a circle of 25.6 cm diameter, and the canine thorax is projected in its entirety in not all 16 views at high and low parts of the circle as seen in Figure 3. This affects the accuracy of the reconstructions discussed below.

Transverse tomographs of the canine thorax are shown in Figure 4. Out of the 64 possible slices, 12th to 45th slices are shown at every third slice. For the reconstruction, the data from Figure 3 are averaged over 3 slices, i.e., 12 mm thick slices, and the transverse tomographs were reconstructed again through the filtered back-projection technique. In Figure 4, the contour of the body, the two lungs, the heart, and the spinal column are clearly visible.

Taking data from all 64 transverse sections, allowing the inaccuracies in top and bottom slices due to the limited view of MEDUSA as described above, the sagittal and coronal tomographs are reconstructed and shown in Figures 5 and 6, respectively. The sagittal slices in Figure 5 show 28th to 50th slice at every other slice, starting from left side and ending at right side of the dog. They clearly show the body contour, the lungs, the heart, and the diaphragm. The coronal slices in Figure 6 show 14th to 42nd slice at every other slice, starting at the frontal part and ending at the back of the dog. Again, they show the body contour, the lungs, the heart, and the diaphragm.

The uncertainties in the reconstructed electron density distribution stem mainly from two sources, namely, the statistics of the heavy
ions and the reconstruction based on data from a finite number of chamber planes and discrete spacings of signal wires of MEDUSA. The statistical error in the ionization due to the heavy ions in MEDUSA is analyzed in the following way. The dose-averaged linear energy transfer, \( <\text{LET} > \), for neon at midpeak of a 14-cm spread Bragg peak (used for therapy) is

\[
<\text{LET}> = 632 \text{ MeV/cm}^2/\text{g in water.}
\]

On the other hand, the neon ions transmitted through the thick part of the object, those with 5D HeV/amu of kinetic energy possesses the energy loss,

\[
\frac{\Delta E}{\Delta x} = 1263.5 \text{ MeV/cm} \cdot \text{g in water.}
\]

The dose-averaged linear energy transfer, \( <\text{LET} > \), for neon at midpeak of a 14-cm spread Bragg peak (used for therapy) is

\[
<\text{LET}> = 632 \text{ MeV/cm}^2/\text{g in water.}
\]

Since the absorbed dose of 1 rad represents \( 6.25 \times 10^7 \text{ MeV/g} \), 1 rad dose is given by \( 0.5 \times 10^5 \) neon ions/cm\(^2\). The dose per exposure in the middle of the object, where the ion flux is reduced to about one half of the incident beam, is estimated to be about 0.15 rad per exposure. Now each neon ion passing through 5 mm of argon gas (one plane of chamber) at STP, with the density of 0.66 \times 10^{-3} \text{ g/cm}^3 and mean excitation energy of 210 eV, has an energy loss of

\[
<\frac{\Delta E}{\Delta x}> = 688 \pm 71 \text{ keV, (FWHM = 141 keV).}
\]

Actually the distribution is not symmetric, with the skewness parameter \( K = 0.4938 \), but for our analysis it is assumed to be Gaussian. Since \( 2 \times 10^4 \) ions/cm\(^2\) is equal to \( 1.29 \times 10^4 \) ions/(8 mm)\(^2\), which represents the number of ions passing through a square made of two wire spacings, we take a half of the value, \( 0.64 \times 10^4 \) ions/(8 mm)\(^2\), to represent typical number of ions detected in MEDUSA per exposure. The percent statistical error in the measurement of ionization in an area incident by \( N \) particles is then,

\[
\sigma_i = \frac{100}{\sqrt{N}} \left\{ 1 + \left( \frac{21}{1689} \right)^2 \right\}^{1/2} \%
\]

or \( \sigma_i = 1.3 \% \) for \( N = 0.64 \times 10^4 \) ions/(8 mm)\(^2\).

The uncertainty due to the reconstruction is estimated following the analysis by Huesman\(^2\). For MEDUSA, with 16 angular projections, each with 64 wires, and wire spacing of 4 mm, the uncertainty in the reconstructed electron density, \( \sigma_p \), is related to \( \sigma_i \) as,

\[
\sqrt{\frac{\sigma_p^2}{\sigma_i^2}} \approx 2.4 \times \langle \sigma_i \rangle ,
\]

which is approximately 3%. In the above estimate, the reconstructed pixel size \( d = 8 \text{ mm (2 wire spacings), and the reconstructed image size} \) \( D = 14 \text{ cm are used.} \)

MEDUSA's imaging capability has been tested and demonstrated. Although it is a low spatial resolution device, it has the advantage of imaging the 3-dimensional object at once, instead of in a slice-by-slice way as in the case of CT scanners. Its resolution can be increased by a larger number of wire planes, finer wire spacings, and to a lesser extent by increased pressure of the chamber gas. Such a system, if used in conjunction with the heavy ion therapy program, will make it possible to assess the patient anatomy in relation to heavy ion beams with patient in the treatment position at the time of treatment.

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