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COMPUTED TOMOGRAPHIC RECONSTRUCTION OF BEAM PROFILES WITH A MULTI-WIRE CHAMBER*

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ABSTRACT

MEDUSA (MEdical Dose Uniformity SAmpler), a 16 plane multi-wire proportional chamber, has been built to accurately measure beam profiles. The large number of planes allows for reconstruction of highly detailed beam intensity structures by means of Fourier convolution reconstruction techniques. This instrument is being used for verification and tuning of the Bevalac radiotherapy beams, but has potential applications in many beam profile monitoring situations.

INTRODUCTION

The rapidly evolving radiotherapy program with heavy ions at the Bevalac[1] has disclosed the need for more precise beam monitoring and control. One of the key areas has been in measurements and verification of the flatness of the actual field used for therapy. The radiotherapists desire a uniformity of dose rate (number of beam particles per cm^2) of better than 1% over a 20 to 30 cm diameter field size.

There are several methods of effectively generating such fields, from the presently utilized scattering-foil occluding-ring system[2,3] to a computer-controlled beam scanning system.[4] With the present system experience has indicated that careful verification of the actual beam profile each day is very important since slight variations in beam alignment on the occluding rings can cause substantial skewing of the intensity distribution at the treatment site.[2]

In the past this verification has been performed by either of two techniques, film exposure followed by densitometer scans (with typically a minimum of several hours' turn around time), and the time-consuming process of scanning across the beam with a small ion chamber. Both of these techniques are cumbersome, and potentially subject to errors of the same order as the desired field flatness, so neither is considered a completely satisfactory solution to the verification question. In addition, the long time to gather and process the information precludes the use of either of these methods for interactive beam tuning.

The instrument to be described here, which is just being brought on line, has been designed to fill these needs. It is a fast (design turnaround of a few seconds), sensitive (single Bevatron-pulse data gathering) and accurate (better than ½% intensity resolution is expected) device which is easy to use and should fit well into the daily radiotherapy routine and in the process contribute greatly towards streamlining the program.

MEDUSA--CONCEPT

This instrument, called MEDUSA, is a multi-wire, multi-plane proportional chamber designed around the same operating principles employed in the highly successful Bevatron beam monitoring wire chamber system.[5]

The ionization produced by the Bevatron beam passing through a chamber is collected and stored on integrating capacitors connected to each of the signal wires. At the end of the sampling time (typically the whole Bevatron spill) the capacitors have collected charge

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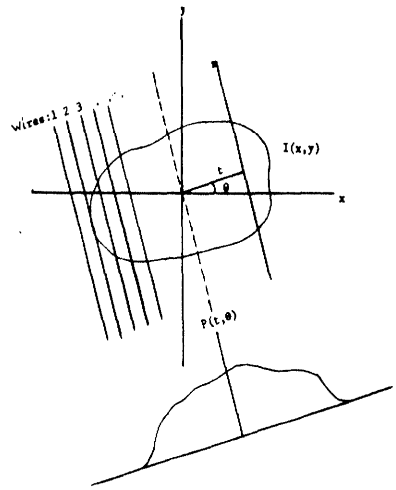

Fig. 1. Schematic diagram showing one of the sixteen signal wire planes and its projection of the actual beam profile, superimposed on the coordinate system used in reconstruction (see appendix). (XBL 793-8921)

proportional to the total beam flux passing by each signal wire. Thus the voltages on the capacitors of a given plane are a measure of the projection of the beam intensity profile at the angle of orientation of this plane (see Figure 1).

The Bevatron beam monitors use two planes; the horizontal and vertical projections are viewed directly, which is sufficient for steering and focusing of beams. A three-projection system at LAMPF described by Fraser[6] can provide more beam profile information, since these projections can be reconstructed algebraically into a fairly good representation of the beam image. However, with just three projections the reconstructed image is reasonably accurate only if the beam shape is regular and without sharp discontinuities. As one increases the number of projections the reconstruction accuracy improves. Modern medical diagnostic x-ray CT scanners measure projections at several hundred angles, collecting up to half a million data points for one image, and produce remarkably sharp and accurate cross section images of the human body. The algorithms and methods for reconstructing these data into images[7] (in just a few seconds!) are a great triumph for applied mathematics and computer techniques.

MEDUSA--DESIGN

The verification of radiotherapy beams requires good spatial resolution and accuracy, but not to the extreme degree available with these last instruments. Adequate resolution is possible with as few as 1000 measurements, provided they are divided according to a suitable ratio of number-of-projections to measurements-per-projection. Based on a study by Huesman[8] of the optimization of this ratio, the 1024 MEDUSA signal wires were divided into 16 planes equally spaced around 180°. Each plane has 64 wires, spaced at 4 mm intervals to cover an active beam diameter of 26 cm. The chamber (Figure 2) is made by alternating the 16 signal planes with high voltage planes. Gas inlet and exhaust ports are on the end window frames. The assembled chamber is shown in Figure 3a, Figure 3b shows the chamber with its data-gathering and control electronics.

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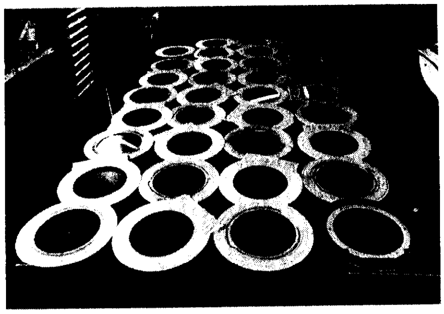

Fig. 2. Alternating high voltage and signal planes of MEDUSA prior to assembly of the chamber.

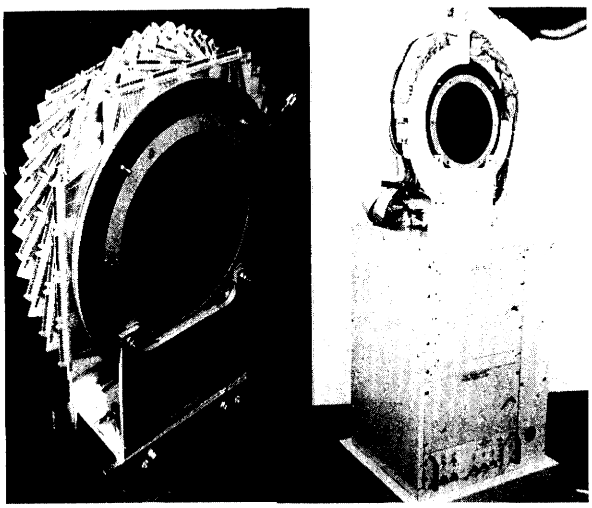

Fig. 3. a) Assembled chamber b) Chamber connected to electronics (data acquisition and LSI-11).

A block diagram of the electronics is shown in Figure 4. Ribbon cables connect the signal wires to the integrating capacitors on the 64 channel multiplex cards. After the end of the data collection period (established by the LSI-11) capacitor voltages are sequentially sampled, digitized and stored in buffer memory. Upon command, the buffer is serially transmitted to the host computer where the data are smoothed, normalized and finally reconstructed into the beam profile. Reconstruction into a 64 x 64 array (4 mm pixel size) is presently done on the PDP 11/34, and takes about 40 seconds. This time will soon be cut to just a few seconds when the array processor is brought on line. The algorithm employed for reconstruction is the Fourier convolution method [7,9] and is briefly described in the Appendix. Images are displayed on a Ramtek color CRT terminal attached to the 11/34, and can be viewed remotely by the accelerator operators to assist in beam tuning.

IMAGES

Figures 5 and 6 are examples of images produced by MEDUSA. Fig. 5a is an image of the beam before it has been broadened and shaped for therapy. Figure 5b is the fully shaped 20 cm diameter therapy beam before optimum tuning has been achieved, showing about an 8% intensity variation over the field. (The color display provides considerably more sensitivity than is visible in these figures.) Figures 6a and 6b were taken during initial commissioning studies of the chamber. A copper bar and lead brick were placed in front of the chamber so as to block out portions of the beam. The sharpness of the reconstructed edges is a good indication of the spatial resolution of the instrument (10% to 90% in 3 pixels), and of its ability to reconstruct

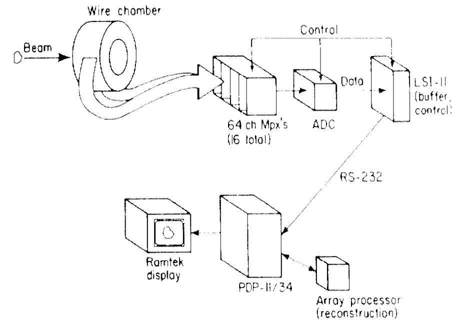

Fig. 4. Block diagram of information flow in MEDUSA.

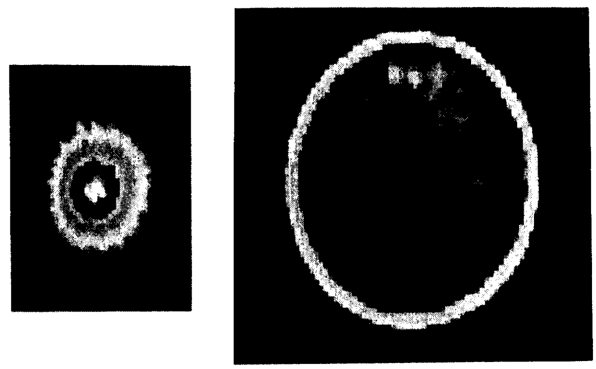

Fig. 5. Reconstructed images a) beam spot prior to shaping for therapy, b) shaped 20 cm therapy field before fine tuning to remove hot spot at upper corner.

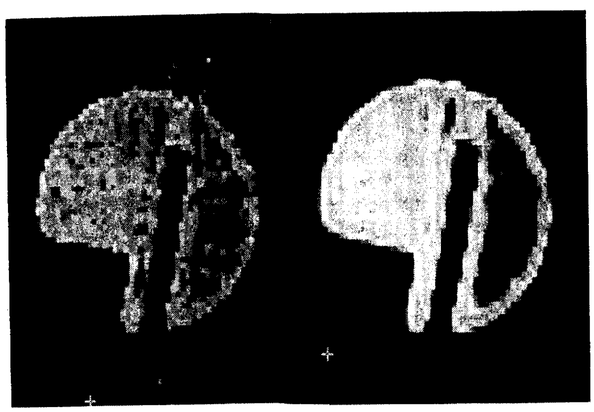

Fig. 6. Field obstructed by metallic absorbers. Reconstructions performed a) prior to, and b) after smoothing of the raw data.

asymmetric patterns. The two figures are reconstructions of the same data set, before and after smoothing of the data. Data must be smoothed to compensate for mismatching in capacitor values and other components, as well as to average out statistical variations. The optimization of smoothing algorithms is still being researched.

CONCLUSIONS

MEDUSA has already proven to be a highly useful tool for heavy ion radiotherapy beam tuning and verification. In addition, it can be used for the measurement of a wide variety of beams, from x rays and electrons, to neutrons (with slight chamber modifications), and thus could find widespread applications in industrial and medical therapy beam monitoring.

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REFERENCES

1. J.R. Alonso, J. Howard, T. Criswell. Preceeding paper.
2. A.M. Koehler, R.J. Schneider, J.M. Sisterson, Med. Phys. 4 (1977), p. 297.
3. K. Crowe, L. Kanstein, J. Lyman, F. Yeater, LBL-4235, August 1975.
4. Ch. Leemann, J. Alonso, H. Grunder, E. Hoyer, G. Kalnins, D. Rondeau, J. Staples, F. Voelker, IEEE Trans. Nucl. Sci. NS-24 (1977), p. 1052
5. J. Cuperus, R. Morgado, IEEE Trans. Nucl. Sci. NS-22 (1975), p.1561.
6. J.S. Fraser, 5th Conf. on Applic. of Small Accel., Denton, Texas, November 1978.
7. See for example, L.A. Shepp, B.F. Logan, IEEE Trans. Nucl. Sci. NS-21 (1974), p. 21.
8. R.H. Huesman, Phys, Med. and Biol 22 (1977), p. 511.
9. L. Wang, The Aerospace Corp. Report ATR-75 (8139)-1 (1975).
10. Z.H. Cho, IEEE Trans. Nucl. Sci. NS-21 (1974), P. 44.

APPENDIX

Fourier Convolution Reconstruction Algorithm

If we express the two-dimensional beam intensity profile as $I(x,y)$ in Cartesian coordinates, the electric charges collected on any given wire of the wire chamber is a line integral of $I(x,y)$ over that particular wire. (Actually it is proportional to the integrated value of $I(x,y)$ covered by the length of the wire and the width extending midway toward the adjacent wires.) If the normal to the wire through the origin makes an angle θ with the positive x-axis and the wire is at a distance t away from the origin, as shown in Figure 1, the equation of the wire is:

$$L(t,\theta) : x \cos\theta + y \sin\theta = t \tag{1}$$

The line integral of $I(x,y)$ over the wire is then,

$$P(t,\theta) = \int_{L(t,\theta)} I(x,y)\, ds = \int_{-\infty}^{\infty}\int_{-\infty}^{\infty} I(x,y)\, \delta(x \cos\theta + y \sin\theta - t)\, dx\, dy \tag{2}$$

where $\delta(x)$ is the Dirac delta function. We define the two-dimensional Fourier transform of the beam profile, $I(x,y)$, as

$$\hat{I}(\omega,\theta) = \int_{-\infty}^{\infty}\int_{-\infty}^{\infty} I(x,y)\, e^{-i\omega(x \cos\theta + y \sin\theta)}\, dx\, dy \tag{3}$$

and the Fourier transform of $P(t,\theta)$ as

$$\hat{P}(\omega,\theta) = \int_{-\infty}^{\infty} e^{-i\omega t}\, P(t,\theta)\, dt \tag{4}$$

The relationship between the two Fourier transforms which forms the basis of the reconstruction algorithm, is shown below.

$$\hat{P}(\omega,\theta) = \hat{I}(\omega,\theta). \tag{5}$$

If $P(t,\theta)$ is known for all t and θ, then the inverse Fourier transform gives $I(x,y)$ as

$$I(x,y) = \frac{1}{4\pi^2} \int_0^{\pi} d\theta \int_{-\infty}^{\infty} \hat{P}(\omega,\theta) \cdot e^{i\omega(x \cos\theta + y \sin\theta)}\, |\omega|\, d\omega \tag{6}$$

$$= \frac{1}{4\pi^2} \int_0^{\pi} d\theta \int_{-\infty}^{\infty} dt \int_{-\infty}^{\infty} P(t,\theta) \cdot e^{i\omega(x \cos\theta + y \sin\theta - t)}\, |\omega|\, d\omega \tag{7}$$

The integrand diverges when the range of ω extends from $-\infty$ to ∞; however, if the Fourier transform $\hat{P}(\omega,\theta)$ is band-limited, $I(x,y)$ can be approximately evaluated.

In our wire chamber, the line integrals $P(t,\theta)$ over the wires are known only over the discretely placed wires (64 wires per plane) at finite angular orientations (16 planes cover π radians at $\pi/16$ radian intervals). The line integrals are than written at $P(t_m,\theta_n)$, with $t_m = (m-32.5)d$, $m = 1,2,\ldots.64$, and d is the wire spacing (4 mm); and $\theta_n = n\pi/N$, $n = 0,1,\ldots.15$, and $N = 16$. Then the beam intensity profile is approximately evaluated by replacing the integrals in (7) by sums.

$$I_{\phi}(x,y) = \frac{d}{2N} \sum_{n=0}^{N-1} \sum_{m=1}^{64} P(t_m,\theta_n) \cdot \phi(x \cos\theta_n + y \sin\theta_n - t_m) \tag{8}$$

The subscript ϕ of I_{ϕ} in the above expression indicates the dependence of $I_{\phi}(x,y)$ over the weighting function of ϕ used in the computation. The meaning of ϕ is described below. The intensity $I(x,y)$ at (x,y) which lies on the line $L(t_{\ell},\theta_n)$, when reconstructed by back-projecting $P(t_{\ell},\theta_n)$, is blurred unless properly compensated by all other $P(t_m,\theta_n)$ values. The function ϕ establishes this mixing, and thus gives the extent to which each of the m wires contributes to the ℓth wire. This functional relationship can take various forms depending on the reconstruction algorithm employed; for the Fourier convolution method used here the compensated points $P'(t_{\ell},\theta_n)$ are given as follows,[9] where now t_m is expressed as $(m - 32.5)d$.

$$P'(\ell d,\theta_n) = \frac{1}{4d} P(\ell d,\theta_n) - \frac{1}{\pi^2 d} \sum_{m=\mathrm{odd}} P\{(\ell+m)d,\theta_n\}/m^2 \tag{9}$$

The beam intensity profile is then given by back-projection of these values;

$$I(x,y) = \frac{d}{2N} \sum_{n=0}^{N-1} \sum_{\ell=1}^{64} P'(\ell d,\theta_n) \cdot \delta(x \cos\theta_n + y \sin\theta_n - \ell d). \tag{10}$$

In actual computation, $I(x,y)$ is evaluated over the 64 x 64 matrix of square areas of d^2, i.e., $I(x_i,y_j)$ at $x_i = id$, $i = 1,2,\ldots.64$, and $y_j = jd$, and $j = 1,2,\ldots.64$, with $d = 4$ mm. Since an arbitrary matrix element (x_i,y_j) may include contributions from up to three $P'(\ell d,\theta_n)$, additional geometric compensating factors[10] must be used in the back-projection computation.