LBL-14380

Lawrence Berkeley Laboratory
UNIVERSITY OF CALIFORNIA

Accelerator & Fusion Research Division

Presented at the International Workshop on Computed Tomography and Multidimensional Digital Technology, (KAIST), Seoul, Korea, May 6-7, 1982

IMAGING USING ACCELERATED HEAVY IONS

RECEIVED
LAWRENCE
BERKELEY LABORATORY

JUN 15 1982

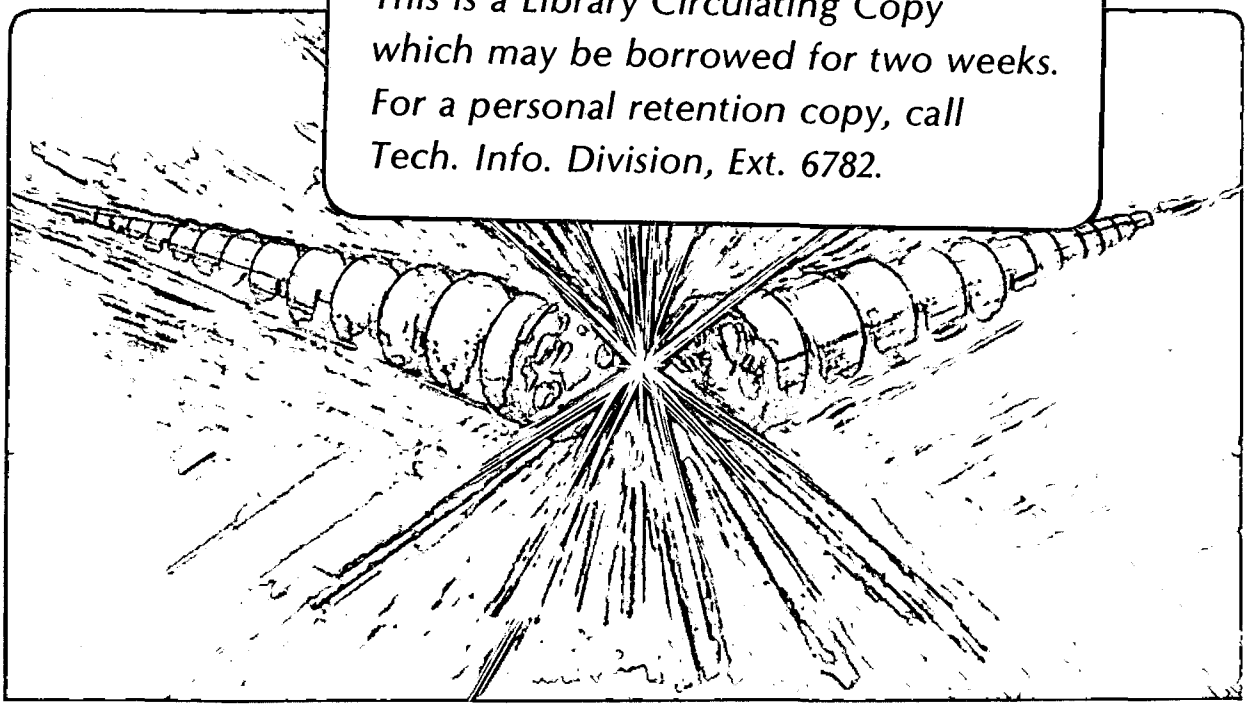
LIBRARY AND
DOCUMENTS SECTION

William Tongil Chu

May 1982

TWO-WEEK LOAN COPY

This is a Library Circulating Copy which may be borrowed for two weeks. For a personal retention copy, call Tech. Info. Division, Ext. 6782.



Prepared for the U.S. Department of Energy under Contract DE-AC03-76SF00098

LBL-14380 c.2

DISCLAIMER

This document was prepared as an account of work sponsored by the United States Government. While this document is believed to contain correct information, neither the United States Government nor any agency thereof, nor the Regents of the University of California, nor any of their employees, makes any warranty, express or implied, or assumes any legal responsibility for the accuracy, completeness, or usefulness of any information, apparatus, product, or process disclosed, or represents that its use would not infringe privately owned rights. Reference herein to any specific commercial product, process, or service by its trade name, trademark, manufacturer, or otherwise, does not necessarily constitute or imply its endorsement, recommendation, or favoring by the United States Government or any agency thereof, or the Regents of the University of California. The views and opinions of authors expressed herein do not necessarily state or reflect those of the United States Government or any agency thereof or the Regents of the University of California.

IMAGING USING ACCELERATED HEAVY IONS*

William Tongil Chu
Lawrence Berkeley Laboratory, University of California
Berkeley, CA 94720

Several methods for imaging using accelerated heavy ion beams are being investigated at Lawrence Berkeley Laboratory. Using the HILAC (Heavy-Ion Linear Accelerator) as an injector, the Bevalac can accelerate fully stripped atomic nuclei from carbon ($Z = 6$) to krypton ($Z = 34$), and partly stripped ions up to uranium ($Z = 92$). Radiographic studies to date have been conducted with helium (from 184-inch cyclotron), carbon, oxygen, and neon beams. Useful ranges in tissue of 40 cm or more are available. To investigate the potential of heavy-ion projection radiography and computed tomography (CT), several methods and instrumentation have been studied[1].

Nuclear Track Detectors (E. V. Benton, J. I. Fabrikant, W. R. Holley and C. A. Tobias) - The plastic foils used in heavy-ion imaging are LEXAN and cellulose nitrate[2]. They are insensitive to the passage of low-LET particles; high-LET particles cause lesions in the plastic that can be developed in concentrated sodium hydroxide until tiny conical impressions or holes form. By bringing a beam of heavy ions into a stack of these plastic foils, the stopping points of the ions, and thereby their residual ranges, may be determined.

A nearly paralled beam of monoenergetic heavy ions crosses the object to be imaged and stops in a stack of plastic foils placed downstream of the object and normal to the beam direction. The stopping point distribution in the stack corresponds to the residual range distribution of the particles, which can be expressed in terms of the distribution of the integral stopping power of the object. Individual plastic foil may be viewed qualitatively as radiographs, or the entire stack sheets may be digitized and an image in terms of its integral stopping power may be synthesized. Heavy ion radiographs have been made of human breasts, extremities, and brains.

The accuracy of determining the residual range is limited by straggling of the stopping ions, a dispersion in path length distribution as a result of statistical fluctuation in energy loss processes. Since the atomic composition of soft tissue is similar to that of water, the variance in the path length in tissue is approximated by that for water, where R is the range and A is the atomic mass. For typical value of $R = 20$ cm, $\sigma_s = 2$ mm for protons and $\sigma_s = 0.46$ mm for neon ions.

$$\sigma_s\,(\text{cm}) = 0.012\ R^{0.95}\ A^{-0.5}\ ,$$

Transverse spatial resolution is dominated by multiple Coulomb scattering, and the scatter parameter for heavy ions in water is

$$\sigma_t\,(\text{cm}) = 0.03\ R^{0.9}\ Z^{-0.2}\ A^{-0.4}\ ,$$

where Z is the atomic number. For $R = 20$ cm, $\sigma_t = 4.3$ mm for protons and $\sigma_t = 0.8$ mm for neon ions.

For a given dose, heavy ion beams can achieve better density resolution than x-rays, and slightly poorer spatial resolution. To achieve the same density resolution, the heavy ions have a factor of two to fifty dose advantage over x-rays depending on the size of the object imaged.

Because of the quantitative character of the heavy-ion radiographs, computer tomography is a logical extension of the heavy-ion radiography. A thin slice of an object is radiographed using a heavy-ion beam collimated by a narrow slit, then the object is rotated by a small fixed angle, 1 to 3 degrees, and the process is repeated. The resulting CT is the distribution of electronic stopping powers, expressed in terms of the heavy-ion number, T,

$$T = 1000\left(\frac{\sigma_t}{\sigma_w} - 1\right) \approx 1000\left(\frac{n_t}{n_w} - 1\right)\ ,$$

where σ_t and σ_w are linear stopping power values and n_t and n_w are the electron densities of the target and water, respectively. This information may be compared with the x-ray CT number, (Hounsfield number),

$$H = 1000\left(\frac{\mu_t}{\mu_w} - 1\right)\ ,$$

*This work was supported by the Assistant Secretary for Health and Environmental Research Division of the U.S. Department of Energy under Contract DE-AC03-76SF00098 and by the National Institute of Health Grants CA15184 and CA27021.

where μ_t and μ_w are the average or "effective" linear x-ray absorption coefficients of target and water, respectively. Heavy-ion CT of plastic and water phantoms, preserved human heart and spinal column, and the brain of a human patient have been made[3].

Multiplane multiwire Ionization Chamber (W. T. Chu, J. R. Alonso, and C. A. Tobias) - A 16-plane multiwire proportional chamber has been developed to accurately map intensity profiles of heavy ion beams at the Bevalac, 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. 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 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 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, 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.

If a heavy ion beam with a spread Bragg peak 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 stopping power of the object along the path of the beam. In other words, the reconstructed image of a 3-dimensional object using a heavy ion beam with a suitably modified Bragg peak is a 2-dimensional projection radiograph of the object, each pixel of which gives the integrated electron density seen by the beam particles arriving at the pixel's coordinates.

For imaging purpose, a special filter was constructed to produce a spread Bragg peak with a constant resolving power. The filter modifies and spreads the Bragg peak of 670 MeV/amu neon-20 ions and produces a modified peak of 13 cm width of an approximately constant slope from 13 cm to 26 cm of water-equivalent penetration depth.

Heavy-ion CT of plastic phantom and the thorax of a live dog have been made. Approximately 2×10^4 particles/cm^2 of broadened and modified 670 MeV/amu neon-20 ions were used per exposure. To average out any pulse to pulse variation in the beam structure, the intensity of the extracted beam from the Bevalac was sufficiently lowered, so that an exposure spanned 5 Bevalac pulses (approximately 20 seconds). Projections from sixteen different angular directions are made by rotating the object by 11.25 degrees between the exposures. By choosing slices at the same level in these 16 reconstructed projections, a transverse tomograph of the slice is computed. By repeating the process at all levels, the entire 3-dimensional representation of the object is obtained.

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. It is estimated that MEDUSA images a 3-dimensional object in pixel size of 8 mm with the reconstructed electron density to an accuracy of approximately 7 percent while exposing the object to about 2.4 rad of heavy ion radiation.

Although it is a low spatial resolution device, MEDUSA 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 improved by a larger number of wire planes, finer wire spacings, and to a lesser extent by increased pressure of the chamber gas.

Solid-State Detectors (J. Llacer and C. A. Tobias) - Recent developments in solid-state radiation detectors have provided accurate information on the identity, position, and energy of individual heavy ions before and after they tranverse an absorber. Thin silicon detector strips have been developed which, when positioned transverse to the beam path, can detect the LET of a particle, separate primary beam particles from fragmented nuclei, and indicate beam position with an accuracy better than 0.15 mm, before and after they traverse an object. Similarly, the recent development of a stable surface treatment for germanium detectors, with no dead layers, allows the use of long, flat detectors for full absorption of the heavy ions without having to construct expensive detector telescopes. With the new geometry, the energy of heavy ions can be determined with better than 0.2 percent accuracy, even if as few as 100 particles enter the detector.

A preliminary experiment in heavy-ion image CT reconstruction using the solid state detector system has been carried out. A polyethylene disc (approximately 1.5 cm thick) was used as a phantom. The phantom is 7.3 cm in diameter and contains seven copper pins of 1 mm diameter separated by 1 cm from each other placed along a diameter line in the disc. A 1-mm diameter void is also drilled at the periphery. This configuration for the phantom was chosen to allow easy determination of position detector linearity, centering of the CT reconstruction and diagnosis of error. The phantom also contained two peripheral, larger voids filled with liquids of density approximately 1.

Data were taken with a 425 MeV/amu ^{20}Ne beam passing through a 6 cm water absorber; the range of the beam fell entirely inside the flat germainum detector without the use of any water bath. The phantom was displaced in six steps past the detector array fixed at beam center, and rotate through 30 angles (6 degree steps). A total of 150 to 200 primary particles were accepted in each 1-mm bin. The slice thickness was 4 mm. An initial detailed examination of the complete reconstruction process provides explanation of the obtained results, without any fundamental flaws in the original reasoning. We are, therefore, quite encouraged by the results, and these studies are continuing.

Reference

1. "Biological and Medical Research with Accelerated Heavy Ions at the Bevalac 1977-1980", M. C. Pirruccello and C. A. Tobias, editors, Lawrence Berkeley Laboratory Report 11220, 423 pp (1980).

2. R. M. Cassou and E. V. Benton, "Properties and Applications of CR-39, Polymetric Nuclear Track Detector", J. Nucl. Track Detectors, 2, 173-179 (1978).

3. W. R. Holley, J. I. Fabrikant, C. A. Tobias, and E. V. Benton, "The Physics of Heavy Ion Radiography and Heavy Ion Computed Tomography", presented at International Workshop on Physics and Engineering in Medical Imaging, Pacific Grove, CA, March 15-18, 1982 (to be published).

4. W. T. Chu, J. R. Alonso, and C. A. Tobias, "Imaging with a Multiplane Multiwire Proportional Chamber Using Heavy Ion Beams", ibid; Lawrence Berkeley Laboratory Report LBL-14143 (1982).

5. J. Llacer, E. E. Haller, W. L. Hansen, J. T. Walton, and E. K. Batho, "Semiconductor Detectors for Medical Tomography with High-Energy Heavy Ions," IEEE Trans. Nucl. Sci., NS-28, 161-165 (1981).

This report was done with support from the Department of Energy. Any conclusions or opinions expressed in this report represent solely those of the author(s) and not necessarily those of The Regents of the University of California, the Lawrence Berkeley Laboratory or the Department of Energy.

Reference to a company or product name does not imply approval or recommendation of the product by the University of California or the U.S. Department of Energy to the exclusion of others that may be suitable.

TECHNICAL INFORMATION DEPARTMENT
LAWRENCE BERKELEY LABORATORY
UNIVERSITY OF CALIFORNIA
BERKELEY, CALIFORNIA 94720