

X THE DEVELOPMENT OF γ -RAY EMISSION
TOMOGRAPHY FOR THE MEASUREMENT OF FISSION
PRODUCT DISTRIBUTIONS IN IRRADIATED NUCLEAR
FUEL ELEMENTS

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A B S T R A C T

Computerised γ -ray emission tomography has the potential to probe the three-dimensional fission product distribution within a fuel pin. The experimental procedures under development at Harwell are described. These procedures use equipment which is able to examine single fuel pellets by both the micro-gamma scanning and the tomographic scanning techniques. The design of a scanning unit capable of manipulating full size fuel pins is also discussed.

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INTRODUCTION

Knowledge of the fission product distribution within irradiated nuclear fuel provides important information regarding the neutron and thermal environment experienced by the fuel. These data may be used to estimate the fuel rating and performance, flux and fluence gradients, and safety requirements. A major application for this information has been the production of data for the establishment of core physics predictive codes.

A measurement of the distribution of a non-migrating γ emitting fission product (eg ^{95}Zr or ^{144}Ce) effectively records the relative burn-up of the fuel during irradiation. In contrast, that of a migrating fission product (eg ^{137}Cs) may be used as an indication of the temperature gradients within the fuel. The migration phenomenon itself could produce information associated with, for example, the interaction of caesium with fuel element cladding and other fission product release aspects under accident conditions.

Two dimensional fission product distributions may be obtained non-destructively using the technique of gamma-scanning as described later. Three dimensional fission product distributions have, so far, only been obtained destructively, by sectioning and scanning adjacent sections of a fuel element to build up the distribution. However, it would be more useful to obtain depth information and hence a full three-dimensional distribution non-destructively if possible. Computerised tomography has the possibility of providing such information in this way.

1.1 Gamma-Scanning

γ -scanning is a well established procedure which has been employed at Harwell and many other laboratories for over twenty years^[1]. During scanning, a fuel pin is mounted on a precision scanning chassis inside an adequately shielded cell. A collimator, usually fabricated from dense gamma shielding material such as lead or tungsten, is mounted through the cell wall, allowing a very small area of the pin to be presented

unshielded to a gamma-ray detector. The scanning chassis allows precisely controlled movements of the fuel element to be made thus exposing adjacent volumes of the fuel element to the detector through the collimator. High resolution detectors allow several γ emitting fission product nuclides to be measured at the same time.

Two modes of operation of the scanning system may be employed, commonly denoted as 'analogue' or 'digital'.

During analogue scanning, the count rate under a gamma-ray photo peak of interest is recorded relative to the position of the specimen during a continuous movement. A rectangular shaped collimator may be used to maximise the count rate, and the pin may be rotated continuously about its major axis to average the signal from the pin and reduce the effects of self-shielding of the fuel.

The digital scanning procedure provides information which is more suited to further processing. The specimen is driven to a preset pair of co-ordinates and held stationary whilst a statistically significant number of disintegration events is recorded under the gamma peak of interest. A second location is chosen and a second count accumulated. This stop-start cycle is repeated until the areas of interest have been covered. This approach is particularly suited to two-dimensional scans, in which a matrix of activity is measured across the scanned region. It is this mode of examination which has been adopted for use in micro-gamma scanning.

Micro-gamma scanning allows the study in finer detail of small specimens such as single pellet lengths or cross sections cut from a fuel element. The specimens are mounted on a small scanner, with the face of interest towards the collimator and a matrix scanning pattern is used to determine the relative activity distribution over that face, but integrated through the depth of the sample. Depth information can only be

obtained by repeated, destructive sectioning of the sample and micro-gamma scanning of adjacent sections.

2 TOMOGRAPHY

The principle of mathematically reconstructing an object from its projections is well known and well documented, particularly with reference to medical imaging applications (see, for example, Ref. 2). -

Transmission tomography uses external radiation sources to probe the object, and allows linear attenuation coefficients for small regions of space within the specimen to be calculated. X-ray brain and body scanners operate in this mode. Emission tomography requires internal radiation sources and enables activity levels in small regions of space within the specimen to be calculated. Radioisotope medical imaging scanners operate in this mode.

In both procedures, several projections of the object are obtained from different angles; two projections are illustrated in Figure 1 (1a for transmission and 1b for emission). It must be noted that although the signals are similar apart from their signs, the information obtained from the reconstructions is fundamentally different.

We may now consider the general experimental procedure involved in acquiring emission tomographic data. A detector and square collimator are arranged in a fixed orientation. The sample is mounted on a scanner chassis which can be rotated and also translated along orthogonal axes. A count of a fission product nuclide is accumulated, which is proportional to the activity contribution from each point in the sample, along the collimator's line-of-sight, neglecting scatter. This value may be designated a ray sum. The specimen is then translated by a small amount, usually equal to the collimator width, and a second count taken. This cycle is repeated until the complete specimen has passed the collimator. The set of ray sums thus acquired contributes a single projection. The sample is rotated by a few degrees, and the same lateral scan repeated

to generate a second projection. The scan-rotation cycle is repeated until the specimen has been rotated through 360°. If the number of projections is at least the same as the number of ray sums per projection, the mathematical reconstruction will yield a unique solution; the original specimen^[2].

2.1 Reconstruction Technique

A detailed discussion of the algorithm and its implementation is beyond the scope of this paper and is described elsewhere^[3]. Briefly, the sample is assumed to be a circularly symmetric, homogenous absorber and is reconstructed using a filtered back-projection algorithm incorporating a correction for self-absorption.

The back-projection technique is illustrated in Figure 2. In the form shown, the count obtained for a ray sum is assumed to apply to each point along the ray and all these back-projected ray sums are added together to obtain the "reconstruction". This simplified procedure yields inaccurate results because each region of high activity introduces a linear track into the reconstruction region when back projected. These tracks intersect at the high region itself, causing the production of a star-like pattern, as can be seen from Figure 2(b).

The projections may be mathematically modified, or filtered, so that when reconstructed, regions of space outside the original object receive both positive and negative contributions thus tending to be cancelled out. This development minimises production of the star effect and renders back-projection a more useful technique.

Comparison of the reconstruction of a known object (phantom) with the object itself is often used to give confidence in the performance of the algorithm (eg Ref. 4). It is also useful to compare a reconstruction with data obtained by other means, such as optical examination^[5], or as reported here, micro-gamma

scanning.

3 CURRENT EXPERIMENTAL PROGRAMME

The micro-gamma scanning equipment used in this development programme was originally designed to scan small specimens in the x,y plane only. The rotation capability was introduced to allow alignment of the axes of the specimens with the scanner axes, if required. The scanner is moved by precision stepper motors driving lead screws via reduction gearing for the linear axes, and by a stepper motor-driven rack drive for the rotation. Data are displayed as a colour matrix. The original equipment utilised a stepper motor controlled camera, wherein a plate camera was driven over a mask in parallel with the scanner's movement relative to the collimator. A wheel containing a number of coloured filters was rotated using a servo-amplified driver by amounts proportional to the count rate under the photo-peak of interest, and a photographic flash gun triggered at count rate equilibrium for each scanned point.

Two examples of results are shown in Figure 3. Figure 3(a) depicts a parallel-faced transaxial section, 1mm deep, through an AGR pellet and shows the central void and extremely significant ^{137}Cs migration. Figure 3(b) shows ^{144}Ce (top) and ^{137}Cs (bottom) distributions obtained from thin (1mm) axial sections of pellet fuel. The tendency for caesium to migrate to the pellet interfaces is clearly illustrated.

The scanner control equipment has recently been updated using a microprocessor-based system, in which the stepper motor drivers and scalers are controlled independently by dedicated microcomputers. Overall control is maintained by a sophisticated program running on a CBM 32K microcomputer. The control system, known as PISCES^[6], allows versatile scanning programs to be created and stored on diskette for repeated use.

The collimated gamma rays are detected by a high resolution, coaxial Ge (Li) detector (FWHM 1.9keV at 1332 keV). The pre-amplified signals are passed to a Kandiah-White pulse processor and successive approximation ADC^[7] which form a system with excellent gain stability

and which has a dead-time independent of pulse amplitude, both factors of importance during long term data acquisition. The peaks in the gamma-spectrum due to the fission products under study are isolated using digital group selectors, which permit precise channel identification and spectrum background (Compton continuum) subtraction. Total counts are recorded by scalers via the dedicated microcomputer mentioned earlier, and stored on diskette for subsequent processing.

The count data may be plotted in real-time on a colour graphics terminal under the control of the CBM. The colour of each pixel is determined by the total count accumulated under the peak of interest at the relevant point of the scan. The complete picture may be subsequently replotted. A colour slide video camera linked to the graphics terminal provides records for display purposes.

A schematic layout of the gamma scanning system is depicted in Figure 4.

3.1 Experimental Procedure for Tomography of Irradiated Fuel

At this early stage of development of the technique the radial ^{137}Cs distribution across a commercial AGR fuel pellet has been measured using both the micro-gamma and tomographic scanning techniques.

The pellet was mounted with its major axis aligned along the axis of rotation of the scanner and viewed using two orthogonal collimators, one studying the transaxial face, the other the side of the pellet. The positions are clarified in Figure 5. Separate micro-gamma and tomographic scans were carried out as described in 3.1.1 and 3.1.2 respectively.

3.1.1 Microgamma Scanning

A 60x by 60y scanning matrix was used with a 0.5mm square collimator. Counts were taken at 0.25mm intervals along the vertical tracks, each track being 0.25mm away from its neighbour. The count time was 30 seconds. The colour matrix

plot is shown in Figure 6a.

The picture is constructed from 16 colours, each depicting an equal proportion of the total count range; the picture is thus normalised relative to its maximum count.

3.1.2 Tomographic Scanning

A 55y by 85z scanning matrix was used. A tapered tungsten collimator in the form of a truncated pyramidal hole was employed, 2.5mm square at its outer face, 0.25mm square at its inner, with an overall length of 10cm. The centre of the pellet was 18cm from the inside face of the collimator, which was the minimum distance achievable with the current design of scanner. 100 second counts were taken at 0.25mm intervals along the vertical track. Thus, each projection consisted of 55 ray sums, 0.25mm apart. The pellet was rotated by 4.24° between each projection and hence 85 projections were acquired in total.

The data as collected are shown in Figure 6b. The vertical axis remains true, whereas the horizontal is used merely to display adjacent projections. The picture is normalised to its maximum count (see 3.1.1).

The reconstructed radial ^{137}Cs distribution is shown in Figure 6c, without a self-absorption correction, and in Figure 6d after self-absorption has been corrected.

4 RESULTS

Figure 6a clearly shows the pellet and its central hole. An activity gradient may also be qualitatively seen, from high at the top left to low at the bottom right. This represents a variation of approximately 30%.

Figure 6b shows the scans obtained from adjacent projections. The sinusoidal pattern indicates a small deviation of the pellet centre

from the rotation axis, and the projections can be seen to change somewhat as the pellet rotates.

The reconstruction obtained from Figure 6b (Figure 6c) is in good qualitative agreement with the micro-gamma scan results. The pellet is shown correctly shaped, with its central void well defined. The concentration gradient is also apparent, following the same trend as in the micro-gamma scan.

The results are highly encouraging, at this preliminary stage. Discrepancies between the reconstruction and the microgamma scan are attributed to inadequate collimation and possibly to depth effects in the micro-gamma scan.

5 FULL LENGTH FUEL PINS

A large-scanner with three degrees of freedom would be required to accommodate full size pins. Vertical and rotation movements are needed for the tomographic scanning procedure and horizontal motion to enable adjacent transaxial sections to be scanned. This should enable the complete fission product distribution within the pin to be determined non-destructively and automatically. A scanner meeting these criteria is under construction and will be operational soon.

The huge three-dimensional matrix which will be obtained after reconstruction will necessitate considerable software development to take the greatest advantage of the data. One such approach is mathematical sectioning, in which the data are processed to display axial sections at any point in the sample, using data calculated from the original set of transaxial tomograms.

6 CONCLUSIONS

The initial results of gamma emission tomography have shown the technique to be capable of measuring the fission product distribution within a fuel pellet. The distribution agrees qualitatively with that obtained from micro-gamma scanning and increases confidence

in the performance of the algorithms, which are still under development.

To complement the work on analytical reconstruction procedures, iterative algorithms are also being investigated at Harwell, to take advantage of their higher tolerance to incomplete data and the relative ease with which mathematical compensations, such as self-attenuation corrections, may be introduced.

REFERENCES

- 1 M F Banham, A J Fudge, R Causer and L Murphy
AERE-R5864 (1968)
- 2 R A Brooks, G Di Chiro
Phys. Med. Biol., 21 689 (1976)
- 3 J Huddleston, I G Hutchinson and G Davies
In preparation
- 4 G Ducros, Nuc. Tech. 68 370 (1985)
- 5 P R Betten and D M Tow
32nd Conference on Remote Systems Technology (Proceedings)
Vol 1 p46 (1984)
- 6 J Huddleston and I G Hutchinson
In preparation
- 7 F L Allsworth, J H Howes and G White
5th Symposium on X- and γ - Ray Sources and Applications (Proceedings)
June 1981

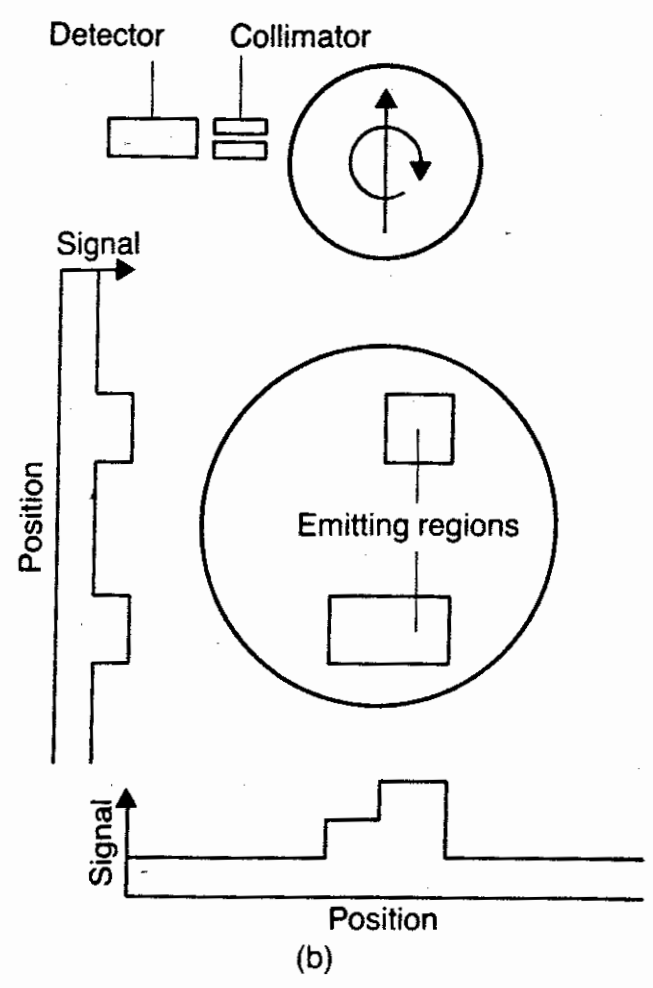
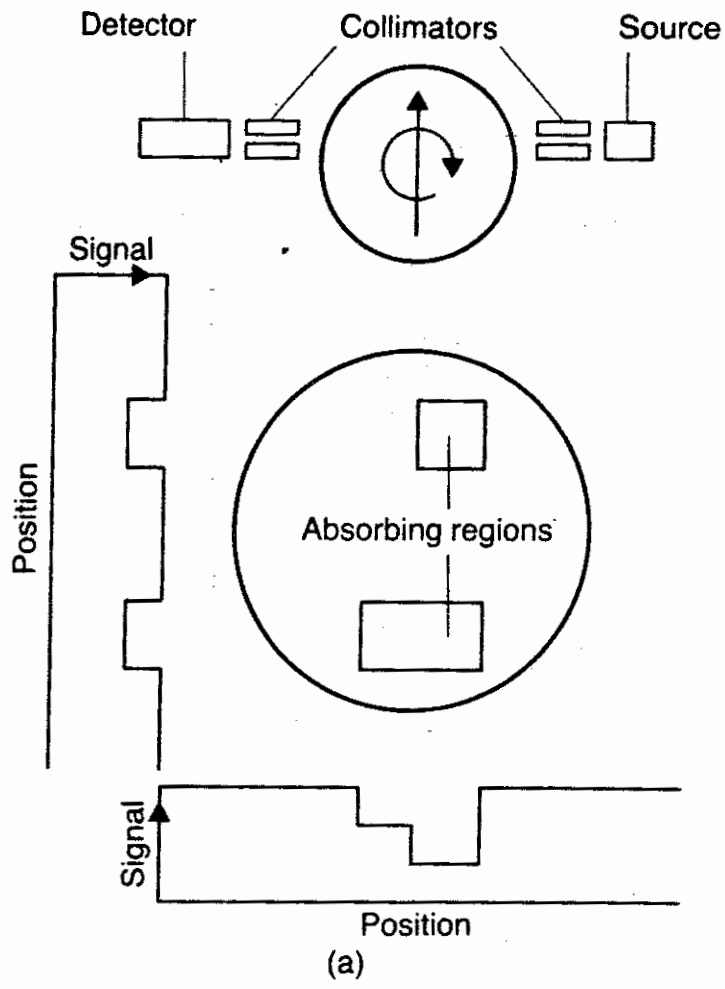
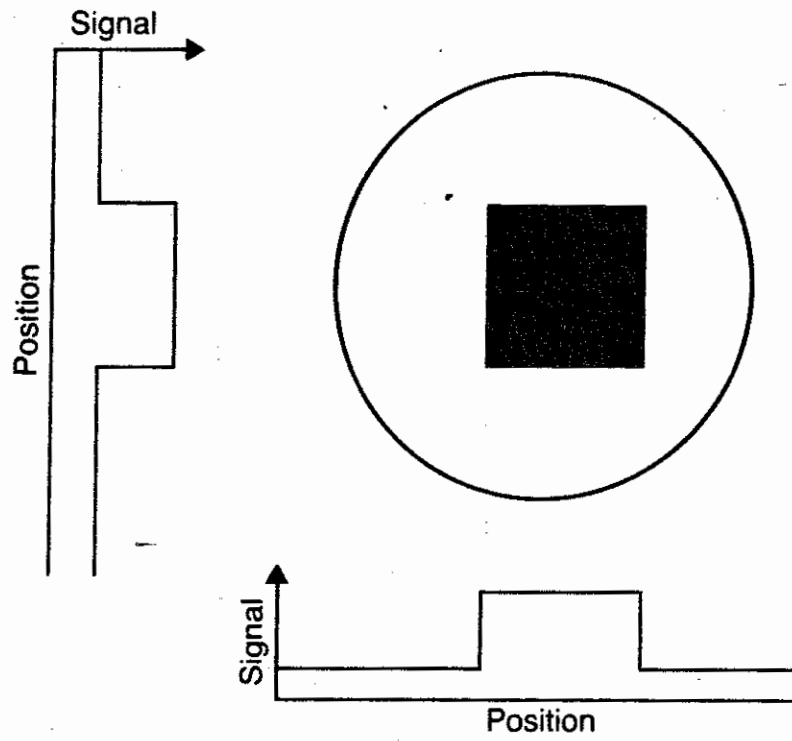
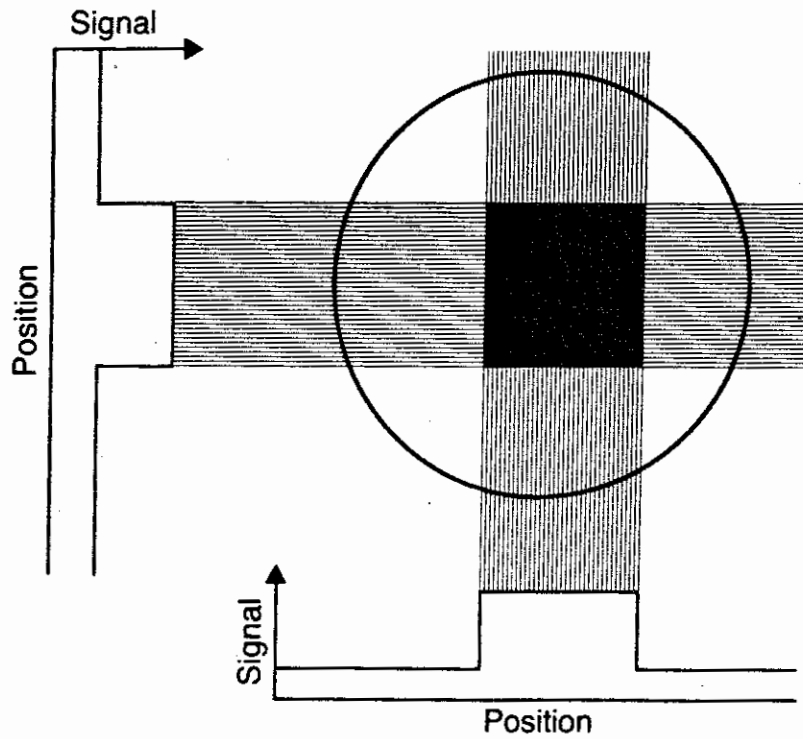


Figure 1 Illustration of scanning geometry and data acquired during (a) Transmission and (b) Emission tomographic scanning



(a)



(b)

Figure 2 Illustration of back projection technique
(a) Set of ray-sums taken
(b) Ray-sums back projected to form representation of original object

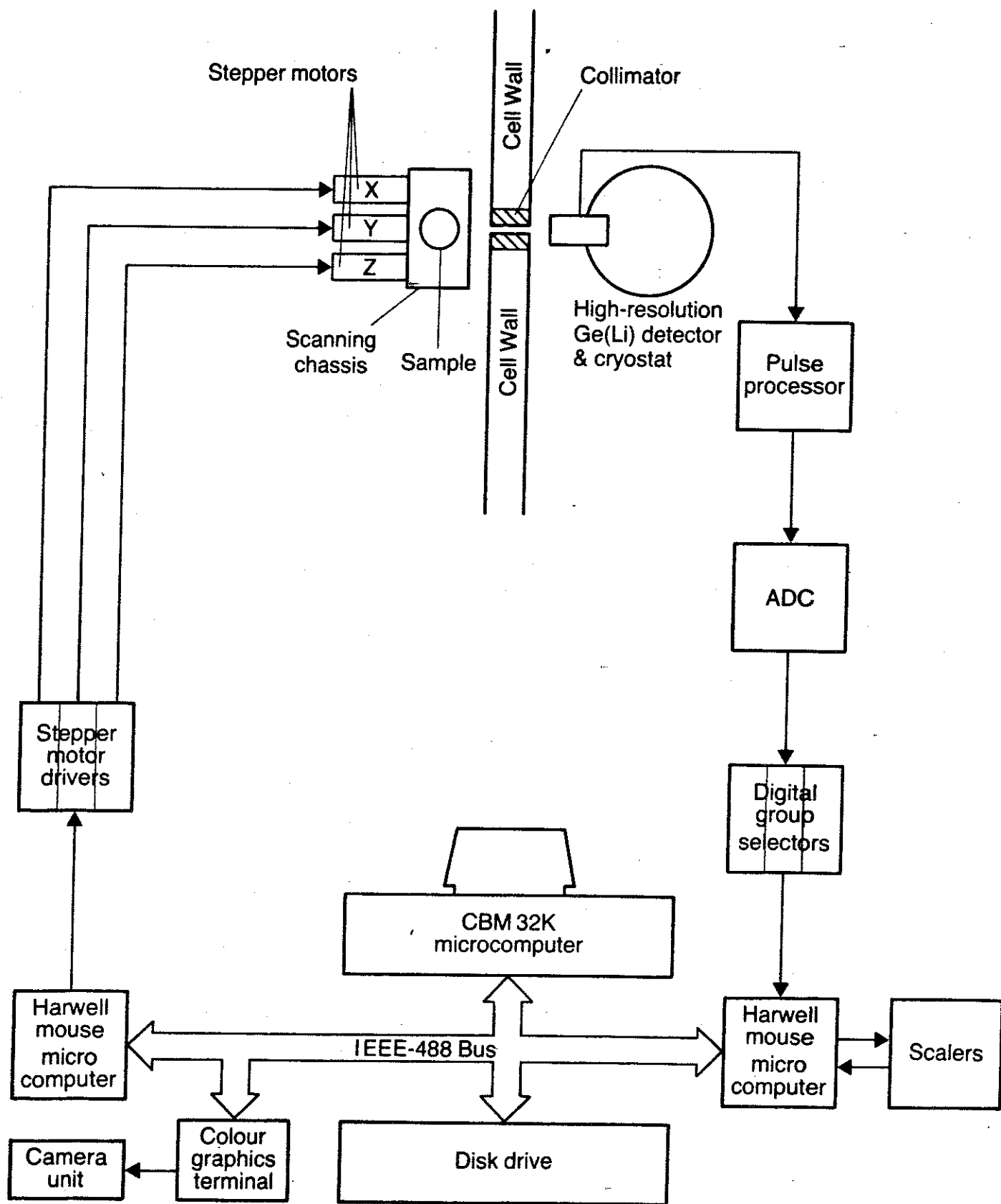


Figure 4 Schematic layout of γ -scanning system

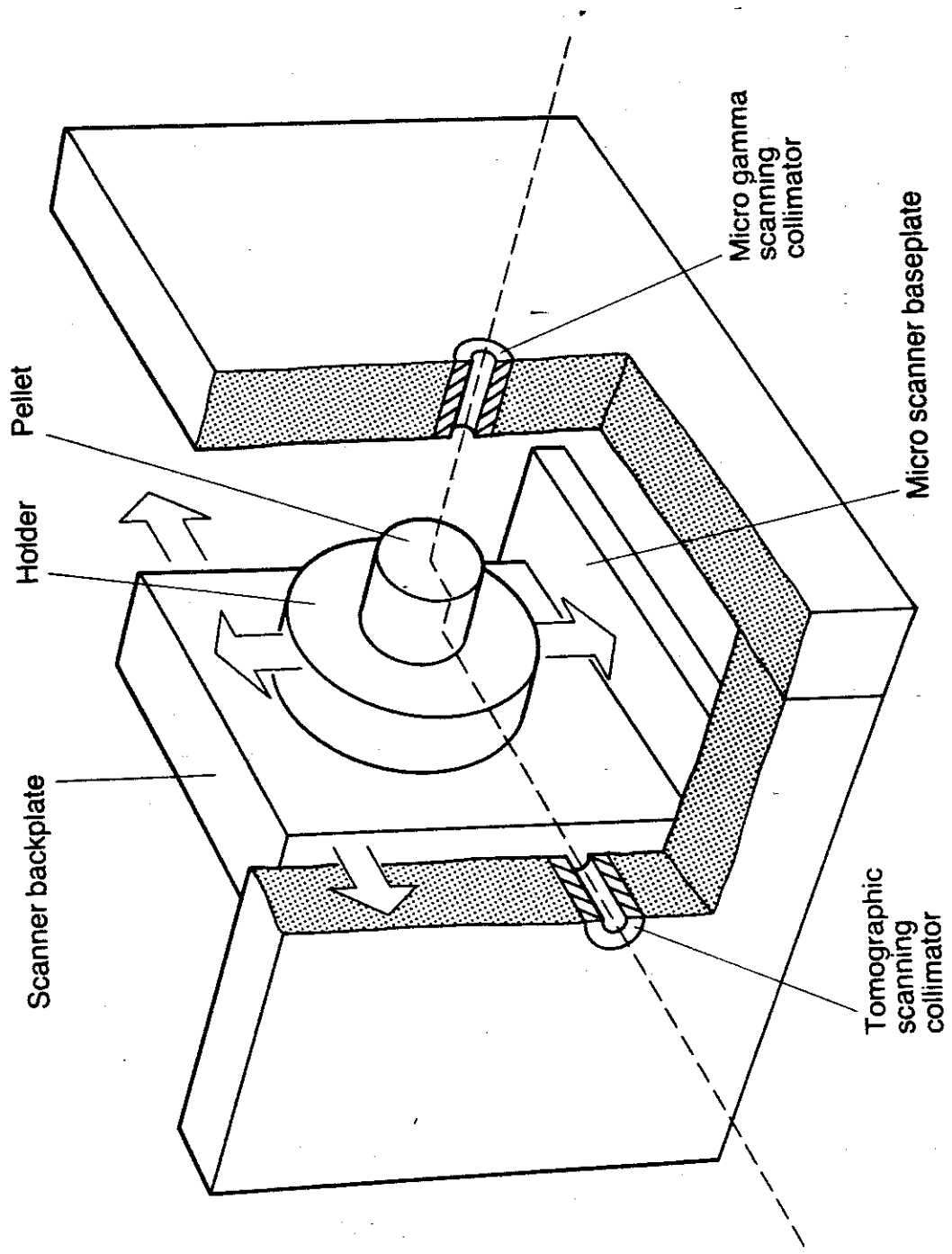


Figure 5 Micro scanner