

DEVELOPMENT AND APPLICATIONS OF
A PULSED NEUTRON RADIOGRAPHY SYSTEM

Stephanie Woodward

Thesis submitted for the degree of Doctor of Philosophy

Imperial College of Science and Technology

University of London

ABSTRACT

A prototype pulsed neutron radiography detector had previously been constructed and initial tests on it had been started. The development of the detector system from that time is described, together with three experiments on potential applications of it.

The system uses a time-of-flight technique to distinguish between neutrons of different energies from a pulsed source (the 136MeV linac at Harwell). The detector is based on a lithium glass scintillator viewed by two photomultipliers which provide timing information and, via a mirror and lens, by an Imaging Photon Detector (IPD) which provides positional information. Spatial information about neutron transmission through a sample in eight preset timing gates is recorded for subsequent analysis.

A series of investigations and subsequent modifications designed to improve the detector performance are described. These include changes to the scintillator, photomultipliers, mirror, lens, IPD and the signal processing electronics. Data analysis and image plotting programs have also been written.

The detector had, originally, been designed for Resonance Radiography in which images of nuclide distribution in a sample are obtained from measurements of neutron transmission at appropriate resonance energies. Several resonance radiographs are shown. The system may also be used to measure neutron beam profile as a function of energy; this is demonstrated successfully at low energies. The final application to have been investigated is Strain Radiography, in which shifts of Bragg edges in time-of-flight spectra are measured and then analysed to produce a plot of strain across the area of a sample. A strain radiograph is shown and the results are compared with other data.

Moderate success has been achieved with all three applications, but the experimental results indicate areas in which further improvements to the detection system must be made.

CONTENTS

ABSTRACT	2
CONTENTS	4
FIGURES	7
TABLES	9
ACKNOWLEDGEMENTS	10
CHAPTER1 - INTRODUCTION	11
1.1 HISTORICAL PERSPECTIVE	11
1.2 THE HARWELL PNR PROJECT	13
1.3 RADIOGRAPHY	13
1.4 THE TIME-OF-FLIGHT TECHNIQUE	16
1.5 PULSED NEUTRON RADIOGRAPHY	17
1.6 APPLICATIONS	20
CHAPTER 2 - DEVELOPMENT OF THE DETECTOR SYSTEM	22
2.1 THE NEUTRON SOURCE	22

2.1.1 The Linac	22
2.1.2 The Flightpath	29
2.2 THE PNR DETECTOR	37
2.2.1 The Scintillator	39
2.2.2 Optics	49
2.2.3 The Mirror	54
2.2.4 The Lens	56
2.2.5 The Photomultipliers	58
2.2.6 The IPD	62
2.3 THE DATA - HANDLING ELECTRONICS	68
2.3.1 The Time-of-Flight System	72
2.3.2 The Imaging System	72
2.4 DATA PROCESSING	74
2.5 SUMMARY OF DETECTOR PERFORMANCE	78
 CHAPTER3 - APPLICATIONS	 80
3.1 RESONANCE NEUTRON RADIOGRAPHY	81
3.1.1 Theory	83
3.1.2 Method	84
3.1.3 Data Processing	88
3.1.4 Results	88
3.2 BEAM PROFILE RADIOGRAPHY	92
3.3 STRAIN RADIOGRAPHY	94
3.3.1 Theory	96

3.3.2 Method	101
3.3.3 Data Analysis and Results	107
3.3.4 Transmission Measurements	110
3.3.5 Numerical Comparison of Radiography and Transmission Data	116
3.3.6 Discussion	119
 CHAPTER4 - CONCLUSION	 124
4.1 RESONANCE RADIOGRAPHY	125
4.2 BEAM PROFILE RADIOGRAPHY	127
4.3 STRAIN RADIOGRAPHY	127
4.4 DETECTOR CONSIDERATIONS	128
 REFERENCES	 132

FIGURES

Figure Title.....	Page
1.1 A schematic view of a radiography system.....	14
1.2 A typical time-of-flight spectrum.....	18
2.1 The layout of the Harwell linac.....	23
2.2 The condensed matter target.....	26
2.3 A section of the moderated CMT spectrum.....	28
2.4 The transmission flightpath.....	30
2.5 The geometrical unsharpness of a radiography system.....	33
2.6 The strain radiography flightpath.....	36
2.7 The detector layout.....	38
2.8 Scintillation mechanisms in lithium glass.....	42
2.9 The PHD electronics as used for measurements of scintillator pulse height spectra.....	44
2.10 Pulse height spectra from three scintillators.....	45
2.11 The ratio of spectra for 5mm and 1mm Ne902 scintillators...	47
2.12 The emission spectrum of ^{137}Cs	50
2.13 The reflectivity of aluminium as a function of wavelength..	50
2.14 The percentage of scintillator light transmitted by various lenses.....	55

2.15	The 2mA photomultiplier base chain.....	60
2.16	The 5mA photomultiplier base chain.....	61
2.17	The Imaging Photon Detector.....	63
2.18	The silicon resistive anode.....	63
2.19	The data handling electronics.....	69
2.20	Pulse trains for the production of an 'enable' for the IPD.	70
2.21	A radiograph demonstrating the optical resolution of the PNR detector.....	79
3.1	Radiograph of a silver cross and plate.....	89
3.2	Radiographs of an indium and gold sample.....	90
3.3	Radiograph of the 'LINAC' sample.....	91
3.4	A series of beam profile measurements.....	93
3.5	A time-of-flight transmission spectrum showing Bragg edges edges due to lead and iron.....	98
3.6	The strain radiography double-V weld sample.....	100
3.7	A time of flight spectrum for iron showing (approximately) the gate settings for the strain radiography experiment....	102
3.8	Schematic diagram of the gate settings about an edge.....	103
3.9	Strain radiographs from the 5meV edge data.....	108
3.10	Strain radiographs from the 15meV edge data.....	109
3.11	Strain calculated from transmission measurements across the sample.....	115
3.12	Comparison of strain radiography data with previous measurements.....	122

TABLES

Table	Title.....	Page
2.1	Specifications of the Harwell Linac.....	24
2.2	Specifications of the Condensed Matter Target.....	27
2.3	"RESULTS".....	76
2.4	"TOFRUNS".....	77
3.1	Some examples of cross sections for resonance radiography..	82
3.2	Results from Transmission Measurements.....	114
3.3	Results from Measurement Comparison Analysis.....	120

ACKNOWLEDGEMENTS

Firstly my thanks are due to my colleagues on the resonance radiography project: Dr Mike Sowerby, Miss Eleanor Bowey and Mr Mark Bailey and my supervisor at Imperial College: Prof Tony Goddard. I am very grateful to Mr Mick Moxon for answering many and diverse questions and also to Dr Colin Windsor and Dr Roger Sinclair for advice on strain radiography, to Mr John Brisland for help with the data collection system, to Mr Dave Endacott for advice on computing and to the Linac operations crews and workshop staff. In particular I would like to thank Dr Jim Riddle for giving so much time to help and encourage me. The work was carried out with the financial support of the United Kingdom Atomic Energy Authority.

CHAPTER1 - INTRODUCTION

Pulsed Neutron Radiography (P.N.R.) is a potentially versatile experimental technique for non-destructive testing. It is a recent development of thermal neutron radiography, incorporating the feature of energy selection as well as two-dimensional spatial sensitivity.

1.1 HISTORICAL PERSPECTIVE

The first radiograph was taken in 1895 when Roentgen used the newly discovered X-rays to produce an image of a hand on photographic film. The potential of the new technique was soon realised and many workers contributed to its rapid early development. By the 1930's X-radiography was used routinely for medical imaging. It was in 1932 that the neutron was discovered by Chadwick. Early experiments on the particle were concerned mainly with its properties, but in 1935 the first neutron radiography was carried out by Kallman and Kuhn in Berlin (ref 1). They used a small accelerator source to radiograph a wide range of objects and their work laid down most of the basic principles of neutron

radiography. Little progress was made in the following years until the advent of nuclear reactors gave access to very high thermal neutron fluxes. The first reactor radiography was carried out by Thewlis and Derbyshire at Harwell in 1956 (ref 2,3), but it was not until the early 1960's that the method was widely investigated. Major contributions were made by Berger (ref 4), Barton (ref 5) and Hawkesworth (ref 6).

Most present-day neutron radiography utilises the high thermal flux available from nuclear reactors, though accelerator and isotopic sources are also used. The technique is essentially complementary to that of X-radiography - neutrons are used for imaging substances which are transparent to X-rays and for 'looking through' substances which are opaque to them. A typical example is the radiography of a hydrogenous material through a metal. The major applications of neutron radiography are in the imaging of active materials for the nuclear industry and the inspection of high reliability systems for such faults as incorrect assembly, missing seals and possible contamination. Various more specialised neutron radiography techniques have also been investigated, such as cold neutron radiography, neutron computed tomography and zone plate encoded neutron holography as well as pulsed neutron radiography.

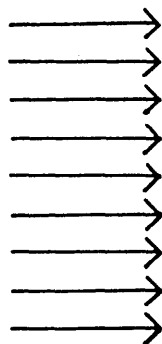
1.2 THE HARWELL PNR PROJECT

The Harwell pulsed neutron radiography project began in 1979 with the design of a detector for resonance neutron radiography. This was constructed and the first test radiographs were produced in 1982 (ref 7). The aim of this thesis is to describe the work carried out from that time. The development of various aspects of the detector, data handling system and image processing codes is described in Chapter 2. The experiments carried out to test the feasibility of three applications - Resonance Radiography, Beam Profile Measurement and Strain Radiography - are reported in Chapter 3. The conclusions which may be drawn from the results of these and their implications for the further development of the detector are discussed in Chapter 4.

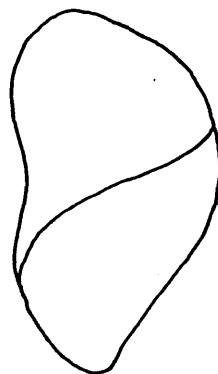
1.3 RADIOGRAPHY

The basic principle of all forms of radiography is shown in fig 1.1. A sample placed in a beam of radiation of uniform intensity causes the beam to be attenuated unequally across its area. This variation in intensity is subsequently recorded by a position sensitive detector and

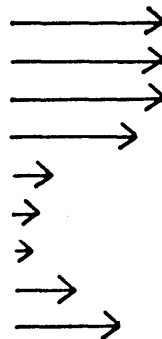
UNIFORM
RADIATION
BEAM



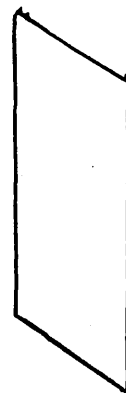
SAMPLE



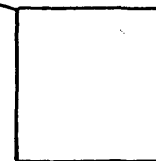
ATTENUATED
BEAM



POSITION-
SENSITIVE
DETECTOR



DATA
PROCESSING
SYSTEM



IMAGE



Fig 1.1 A schematic view of a radiography system.

the information is then processed to produce a two-dimensional image of the sample. The degree of attenuation depends on the thickness of the sample and the material of which it is composed.

The mechanisms causing attenuation are, of course, different for different radiations but the effect can generally be described by an equation of the form:

$$I = I_0 e^{-\alpha X}$$

where I = detected beam intensity, I_0 = initial beam intensity, α = linear attenuation coefficient and X = sample thickness. The linear attenuation coefficient for neutrons is a function of the atomic density (n_i) of each of the sample components and its total neutron cross-section (σ_i). (N.B. The above equation is valid only when multiple scattering into the beam may be assumed to be negligible. This is the case in radiography experiments where the radiation beam is collimated and the sample is thin.) For a sample composed of N different elements i of thickness X_i the above equation may be written:

$$I = I_0 \exp(-\sum n_i \sigma_i X_i)$$

The sample is often made up of several different materials, the aim being to produce a radiograph from which it will be possible to distinguish between them and show the shape of each, i.e. to produce a radiograph with good contrast. In order for this to be practicable the

attenuation coefficients must be different for each of the sample components. The greater the difference between them, the greater the variation in transmitted intensity and the better the contrast in the image produced .

1.4 THE TIME-OF-FLIGHT TECHNIQUE

The energy selection capability of the detector is based on the time-of-flight technique, a standard method of observing energy dependent phenomena with a pulsed neutron source. The pulse from the source is a short intense burst of neutrons with a 'white' energy spectrum. The time taken for the neutrons to travel down a flightpath to a distant detector depends upon their energy:

$$t \approx 72.3 L/\sqrt{E}$$

where t = time (μ s), L = flightpathlength (m) and E = neutron energy (eV). (This equation is simply obtained from the non-relativistic expression for kinetic energy $E = \frac{1}{2}mv^2$. Relativistic effects are negligible for neutron energies below a few MeV). The result of this relation is that the neutrons are spread out in time when they reach the detec-

tor, so at particular times neutrons of particular energies can be detected.

In an experimental system a time-of-flight scaler is started when the neutron pulse is produced and as the neutrons are detected they are recorded in a series of time bins. In this way a histogram is built up (fig 1.2). The resonances at the high energy end of the spectrum correspond to the resonances in the neutron cross-sections of the sample materials; the 'steps' at the low energy end are Bragg edges. The energy selection capability of the detector allows for timing gates to be set across these features so that any changes in them may be observed as a function of position across the sample.

1.5 PULSED NEUTRON RADIOGRAPHY

The two techniques just described - radiography and time-of-flight energy selection - are combined in the Harwell pulsed neutron radiography system, so that radiographs can be produced using neutrons of chosen energies. This allows energy dependent features of neutron time of flight spectra to be utilised. For example, several sample constituents may have equally high thermal neutron cross-sections, but with

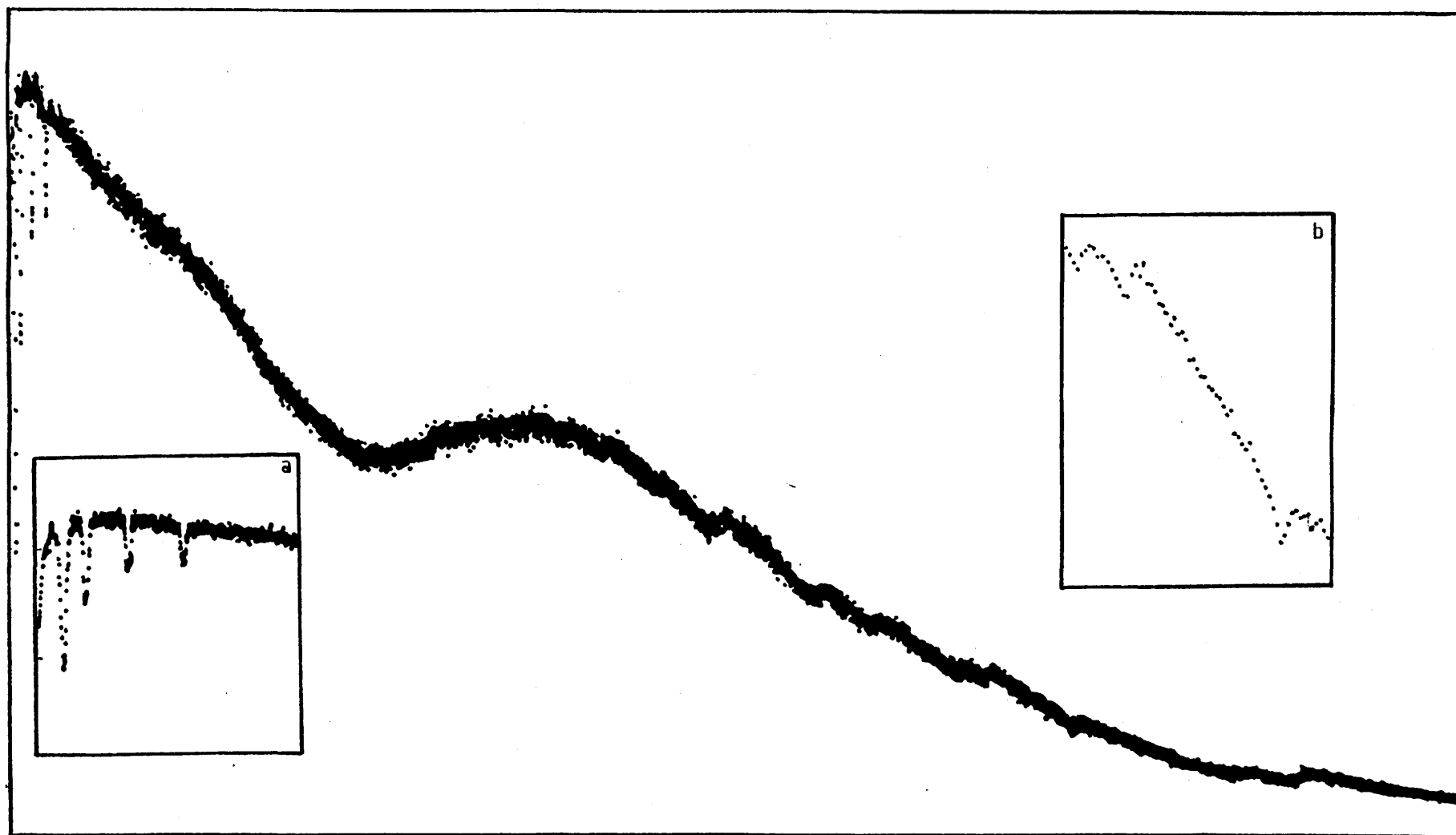


Fig 1.2 A typical time-of-flight spectrum.

Two regions of the spectrum have been expanded to show (a) resonances and (b) bragg edges due to a steel sample

resonance peaks at different energies. By observing neutrons of different energies independently, these constituent elements may be imaged separately.

The neutron source for the Harwell Pulsed Neutron Radiography system is a target on the Harwell electron linac. A burst of neutrons from the target will travel down a collimated flightpath to the sample, where it is attenuated due to scattering and absorption. The detector is situated closely behind the sample. It is based on a lithium glass scintillator viewed by two photomultipliers and, via a mirror and lens, by a position sensitive imaging photon detector. The photomultiplier pulses are used to produce a time-of-flight spectrum and are also fed into a series of eight timing gates. The pulses from these are used to 'enable' the imaging photon detector, so that eight separate images can be produced.

The image data is built up in a camac store and then kept on computer disc for subsequent retrieval and processing. A series of flexible analysis programs is used to extract the required information from the raw data. The eight images are often complementary and two or more of them may be used together with other data in the production of each radiograph.

1.6 APPLICATIONS

Three potential applications of the system have been investigated - resonance neutron radiography, beam profile measurement and strain radiography.

In resonance radiography the presence of resonances in neutron cross-sections is utilised for the imaging of nuclide distribution. A resonance of a sample nuclide is chosen, so that this nuclide's absorption coefficient is much higher than those of the others at this resonance energy. Hence, resonance energy neutrons are removed from the beam preferentially by the nuclide in question, leaving a 'shadow' which is recorded by the system.

For beam profile measurements the detector simply measures beam intensity as a function of position in predetermined energy ranges. This information can then be used to test experimental assumptions about beam uniformity.

Strain radiography is a technique for investigating the distribution of strain in a sample. The presence of residual stress causes strain; i.e. changes the lattice spacings of the crystallites, which has the effect of shifting the Bragg Edges in the time-of-flight spectrum. Thus,

by recording neutron transmission at an edge, the relative shift and hence the strain may be plotted as a function of position.

CHAPTER 2 - DEVELOPMENT OF THE DETECTOR SYSTEM

The pulsed neutron radiography system may conveniently be divided in to four sections which will be considered in turn :-

- The neutron source
- The detector
- The electronic data collection and handling systems
- The data analysis and processing programs

2.1 THE NEUTRON SOURCE

2.1.1 THE LINAC

The neutron source for this experiment was the condensed matter target on 'Helios' the 136MeV electron linear accelerator at AERE Harwell; see fig 2.1. The linac is of the travelling wave type in which electrons are accelerated by the longitudinal component of the electric

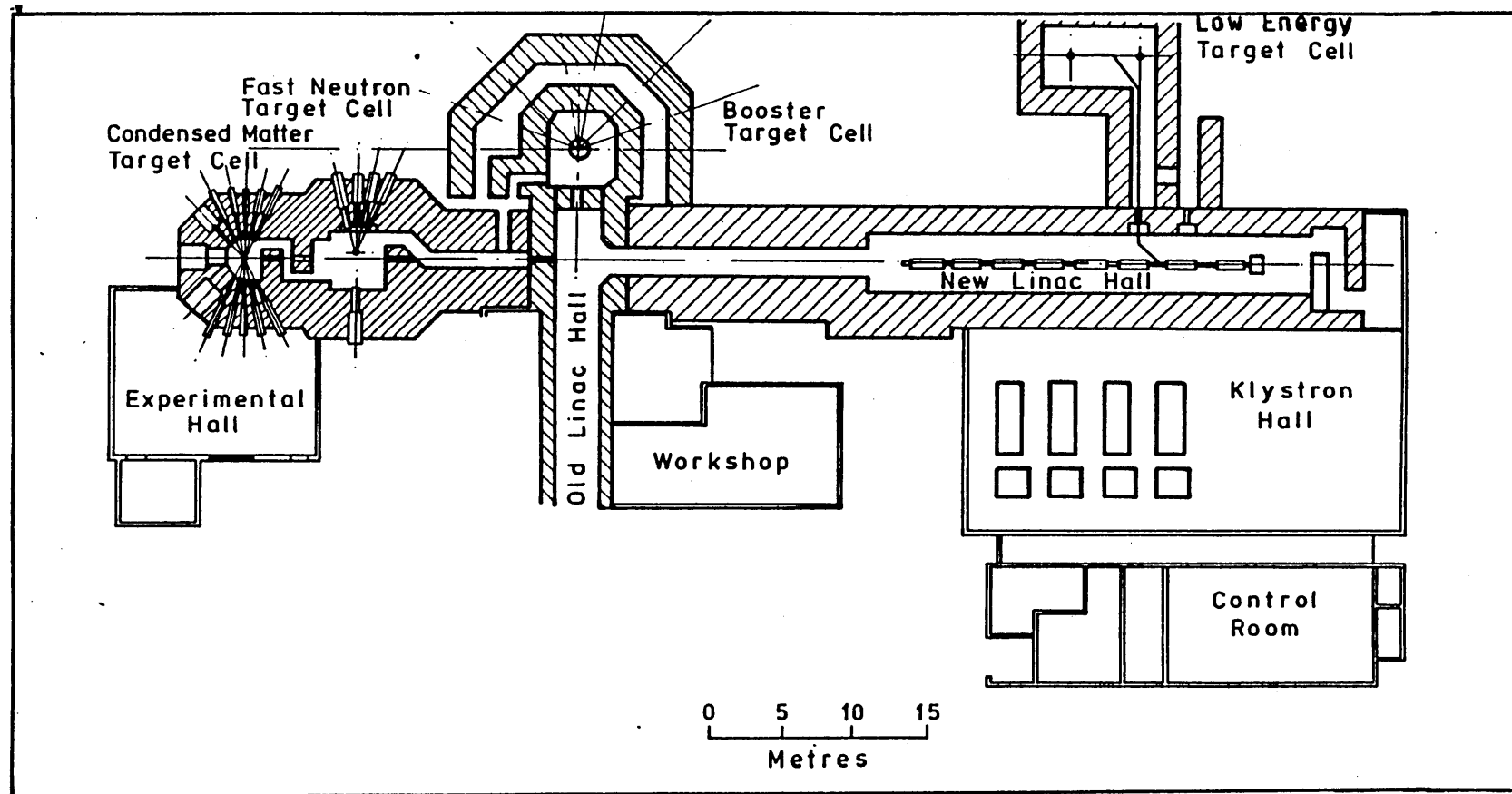


Fig 2.1 The layout of the Harwell electron linac (ref8)

Table 2.1 SPECIFICATIONS OF THE HARWELL LINAC

Operating Frequency	1300 MHz (L Band)
Klystrons	4 Thomson CSF type TV2022
RF Peak Power	80 MW (4 x 20 kW)
RF Maximum Average Power	160 KW (4 x 40 kW)
Acceleration Length	16 m
Pulse Length	5 ns - 5 μ s
Pulse Currents (short pulses)	6 - 11 A
Pulse Currents (long pulses)	0.6 - 1 A
Max. Unloaded Electron Energy	136 MeV
Max. Power (short pulses)	30 kW
Max. Power (long pulses)	90 kW
Max. PRF	2000 pps

field of travelling electromagnetic waves. The electrons are produced in a triode gun which injects them into the bunching section of the first of eight corrugated waveguides. These eight waveguides are driven in pairs by four klystrons. The dimensions of the irises that load them are such as to give the waves a phase velocity equal to the velocity of light. Since the electrons rapidly reach relativistic energies, they can then gain further energy by moving synchronously with the wave. The design specifications of the Harwell linac are listed in table 2.1.

The electron beam produced by the LINAC may be directed into any of the four targets shown in fig 2.1. The condensed matter target, which is used for the PNR experiment, is designed for the production of slow neutrons with energies of a few eV or less. A time resolution of a few microseconds is acceptable for the long flight times of such neutrons, so the target has been designed to accept the 5 μ s pulse of maximum power from the accelerator. Its performance specifications are listed in table 2.2 and its configuration shown in fig 2.2. Two targets have been used in the condensed matter cell: one of tantalum, the other of uranium.

The electromagnetic field produced by the target nuclei causes incident electrons to lose energy by bremsstrahlung. These γ -rays then interact with the nuclei to produce neutrons by photonuclear reactions, and by photofission in the uranium target. All these reactions are es-

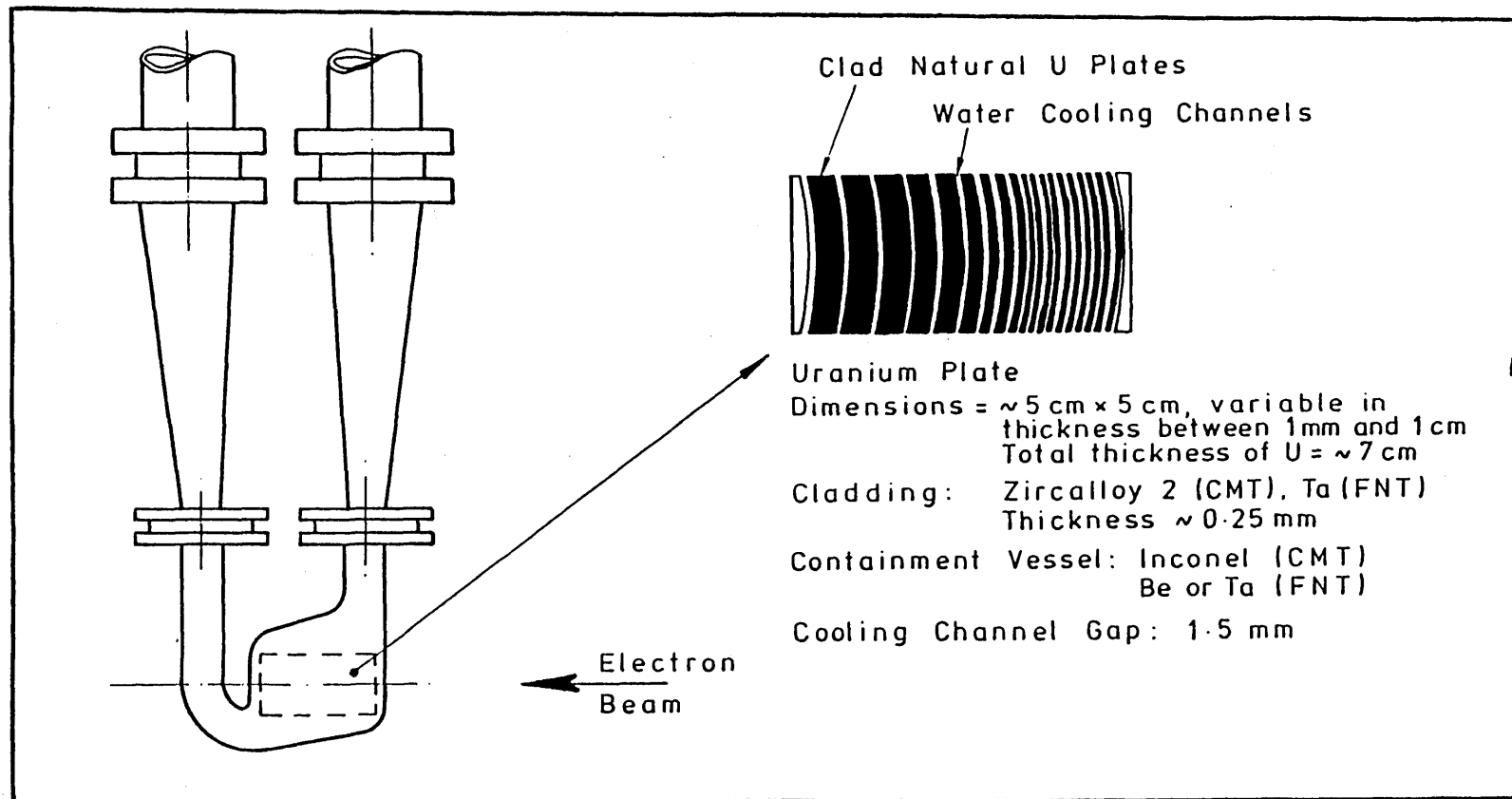


Fig 2.2 The condensed matter target (ref8)

Table 2.2 SPECIFICATIONS OF THE CONDENSED MATTER TARGET

Typical Electron Pulse Duration	5 μ s
Mean Electron Energy	60 MeV
Pulse Repetition Frequency	300 pps
Peak Current	1 A
Beam Power	90 kW
Mean Neutron Output per Pulse	1.2×10^{12}
Peak Neutron Output per Pulse	2.4×10^{17}

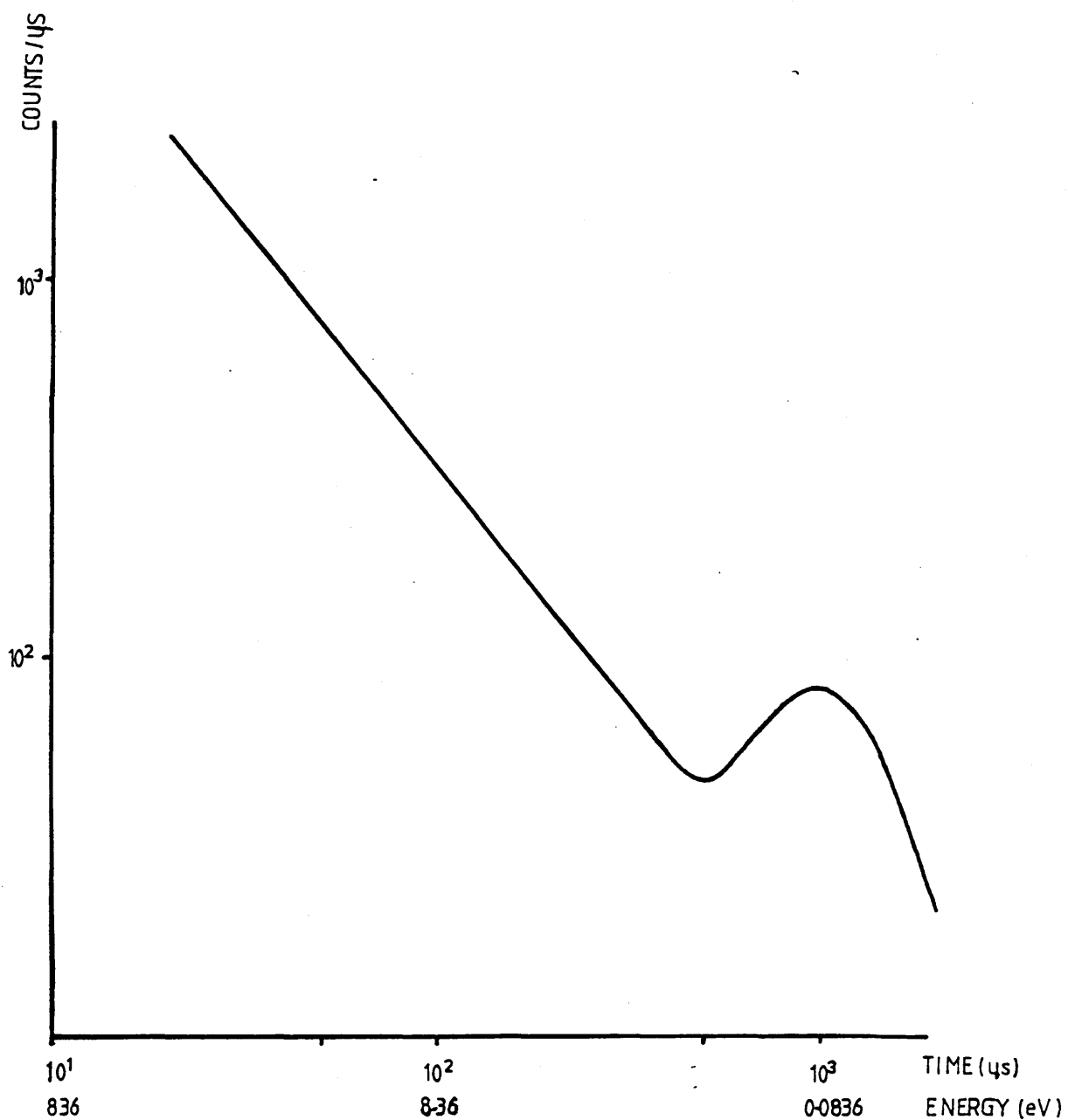


Fig 2.3 A section of the moderated CMT spectrum

entially instantaneous, but the neutron pulse is longer than the original electron pulse due to neutron interactions within the target and the varying times taken for neutrons to travel across it. At this stage the neutron energy spectrum takes the form of a Maxwellian with a characteristic temperature of about 1 MeV. The slow neutron output is enhanced by a series of water moderators around the target. The moderated target spectrum takes the form shown in fig 2.3.

2.1.2 THE FLIGHTPATH

Neutrons produced in the Condensed Matter Target reach distant detectors by travelling down the flightpaths that radiate outward from the cell. The configuration of the flightpath collimation depends on the nature of the experiment for which it is being used. The ideal collimation for PNR produces a parallel beam of the maximum possible flux which just covers the sensitive area of the detector. In practice this is never quite achieved. Early experiments on PNR had to be carried out on a 19m flightpath shown in fig 2.4. The neutron beam was not parallel, due to the converging - diverging collimation geometry and the lack of collimators in the last section. The flux was very low because of the small aperture in the narrowest collimator and the attenuation

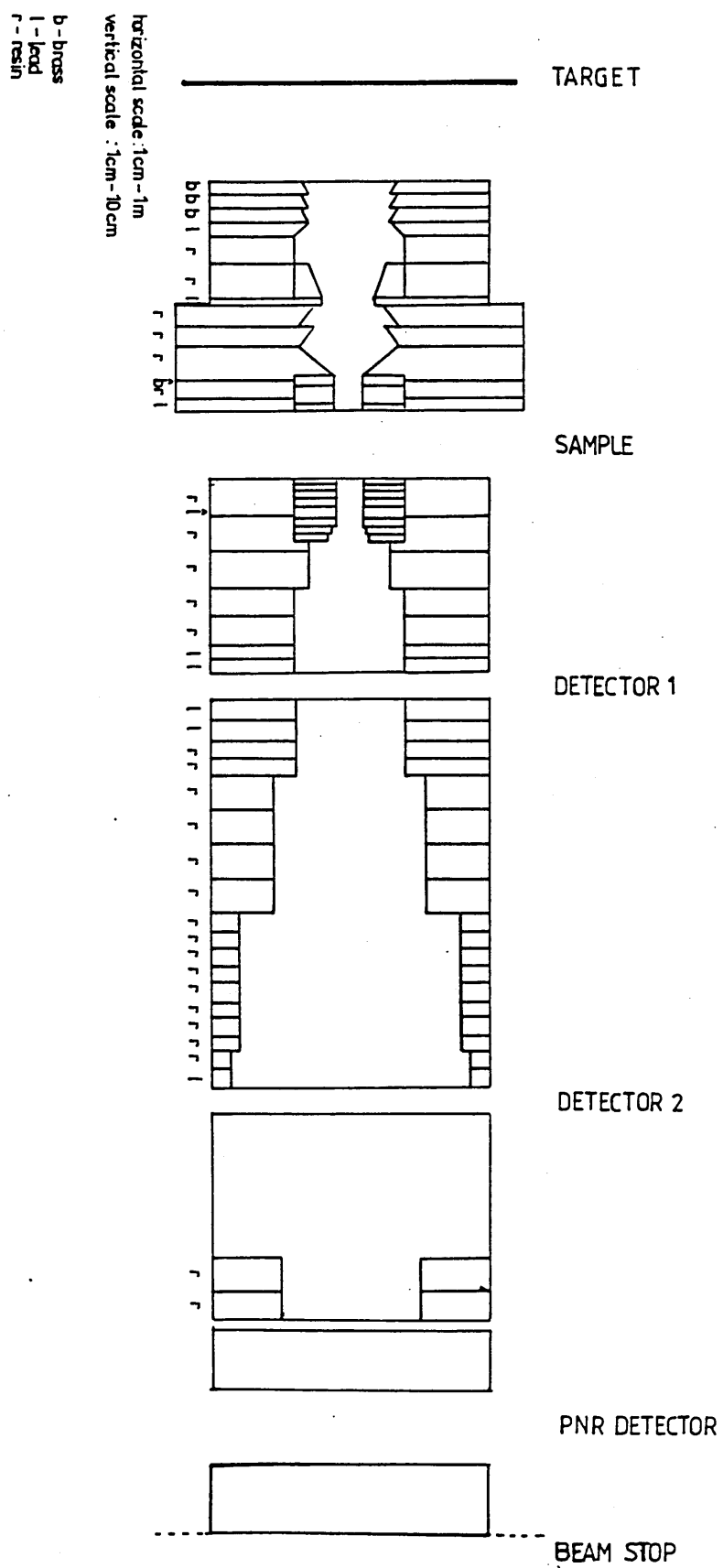


Fig 2.4 The transmission flightpath

due to the samples and detectors of the other experiments on the flightpath. The beam covered a large area of the detector - which caused neutrons to be scattered into the scintillator from the walls of the detector, and thus resulted in an increased background. The poor flightpath adversely affected the quality of the radiographs produced on it, but no other flightpath was available at the time. Later it was possible to recollimate one specifically for the radiography experiment.

Three main factors are involved in the design and construction of a flightpath - the optimum length, the optimum beam profile and the shielding.

2.1.2.1 Flightpath Length

The calculation of optimum flightpath length for a PNR system involves the consideration of timing resolution, spatial resolution and beam intensity.

The timing resolution function of the PNR system includes components due to electronic jitter, timing channel width, electron pulse width, the angle between the flightpath and the moderator and the moderator re-

solution function (see section 3.4.2). The flight time, and hence the flightpath length, must be of sufficient magnitude that the separation between any two features of interest is greater than the timing resolution. The energy range of interest for strain radiography extends from a few meV to several tens of meV. In this region the timing resolution is dominated by the moderator decay term and has a width of ≈ 40 ps. However, the Bragg edges are isolated and much more widely separated in time, even for the minimum possible flightpath length of 1.5 m (imposed by the cell geometry). In this particular case, therefore, the timing resolution imposes no constraints on flightpath length.

The geometrical resolution of the system due to the flightpath should be better than 1mm in order to meet detector specifications; the limiting factor on the spatial resolution is then the pixel size. The geometrical unsharpness (U_g) is given by :

$$U_g = Dl/L$$

where D = source diameter, l = sample - detector distance and L = source - sample distance (see fig 2.5). It is not possible to minimise the unsharpness merely by reducing the sample - detector distance. Elastic neutron scattering is approximately isotropic, so the nearer the detector is to the sample, the more scattered neutrons will be detected and the poorer the image contrast. In order for the scattered flux at the detector to be less than 1% of the direct flux for a 1cm sample of iron, the sample - detector distance must be at least 10cm (ref 7). The beam

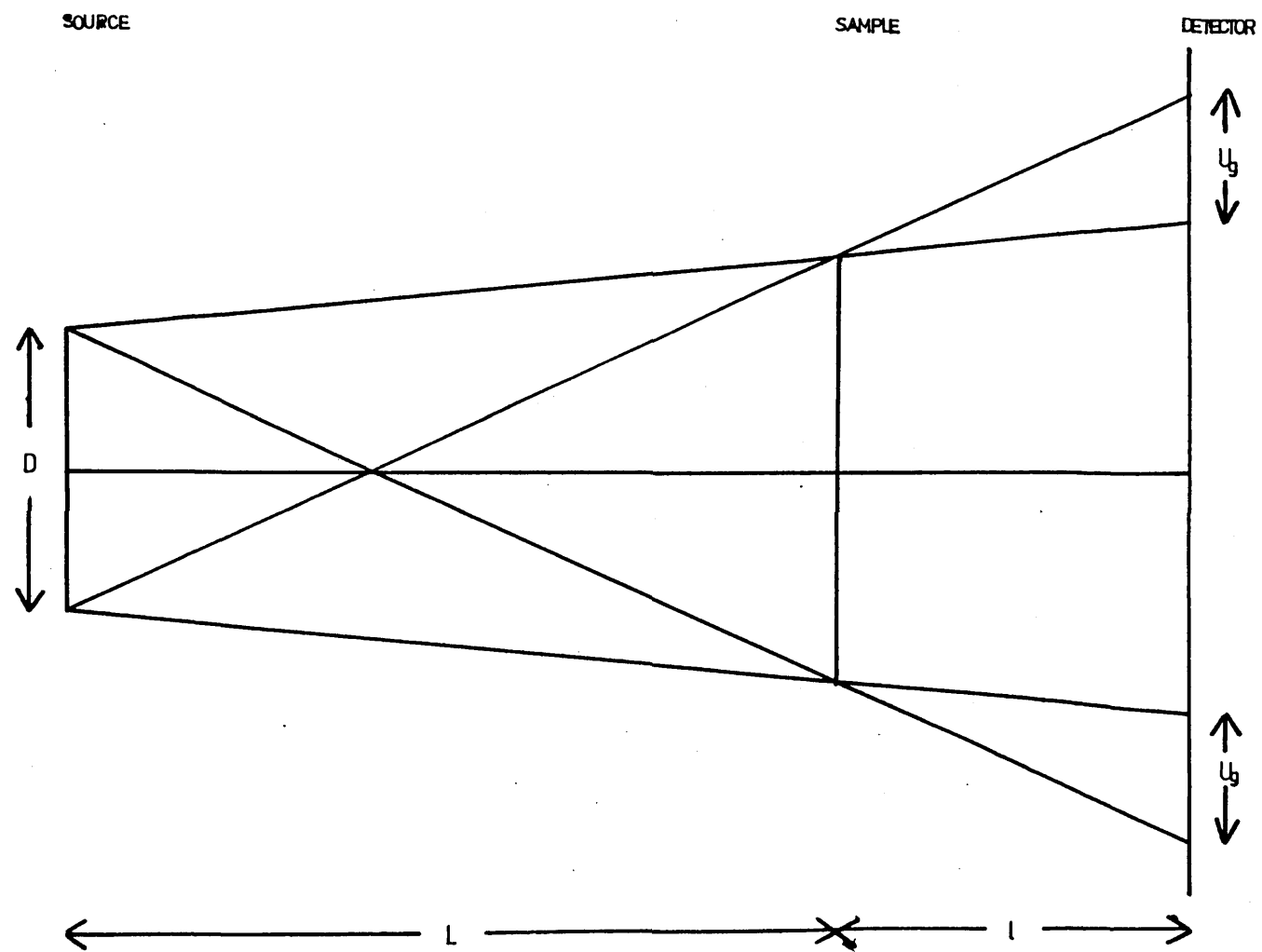


Fig 2.5 The geometrical unsharpness of a radiography system

profile requirements (see section 2.1.2.2) limit the size of the defining collimator, and hence the source diameter, to 10cm. Thus, for the required resolution, the minimum flightpath length is 10m.

Beam intensity must be as high as possible in order to minimise counting time without losing accuracy. Intensity increases with the square of the source diameter and decreases with the square of the flightpath length.

Consideration of all these criteria lead to the result that the optimum flightpath length for the strain radiography experiment is 10m. The flightpath actually used was 9.7m long.

2.1.2.2 Beam Profile

The ideal beam profile for radiography is a completely uniform beam just covering the sensitive area of the detector. In practice it is impossible to achieve this, but the collimation must be arranged so that the umbra covers the scintillator as nearly as possible and the penumbra is as small as possible. Unfortunately the whole beam line could not be recollimated, but the best layout achieved gave an umbra of 5cm diameter

and a penumbra of 10cm diameter. This was sufficient for the purposes of the strain radiography experiment - the sample was less than 5cm wide and the scintillator diameter was 10cm, so the beam would not be scattered by the front wall of the detector.

2.1.2.3 Collimation and Shielding

The collimation had to be designed to absorb neutrons of a wide range of energies and also γ -rays. Three different materials were used - brass, lead and borated resin, to collimate the fast neutrons, γ -rays and slow neutrons respectively; γ -rays produced in the brass as a result of neutron capture were also absorbed in the lead. The thickness of collimation required was based on 1Mev neutrons (the peak of the unmoderated spectrum from the CMT) and a required reduction in neutron flux of the order of 10^4 . The flight tube was evacuated and it was surrounded by a further 20cm of concrete for biological shielding.

Initial test showed that the γ -flash and the high fast neutron flux in the first few microseconds of each pulse were of an intensity such that the detector saturated and did not recover for 10ms (which was too late for the observation of Bragg edges). As these fluxes were due to

Target +
Moderator

Shadow
Bar

Lead
Wall

Scintillator

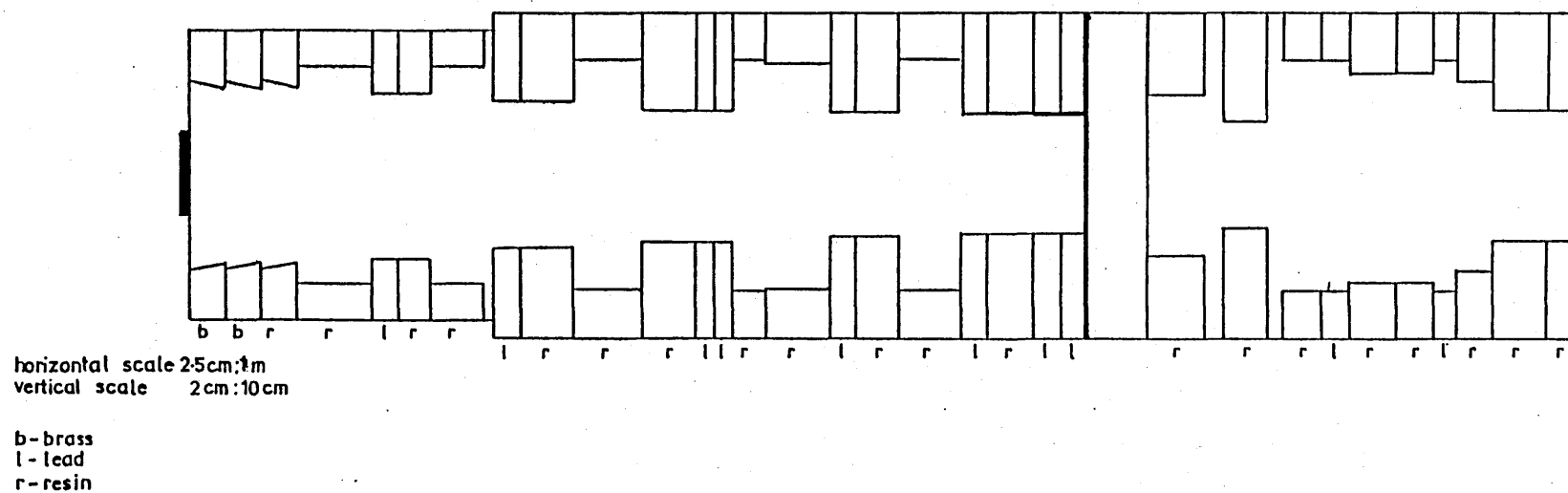


Fig 2.6 The strain radiography flightpath

the bremsstrahlung and fast neutrons produced in the target, the detector had to be shielded from the target in some way. This was achieved by placing a shadow bar of heavy metal in the centre of the beamline in the cell and a 2 inch thick lead wall across the flightpath. The shadow bar screened the detector from radiations coming directly from the target, whilst allowing neutrons produced in the moderator to pass at either side. The lead wall then absorbed 90% of the remaining γ -rays, but only 16% of the 5meV neutrons. The final flightpath configuration is shown in fig 2.6.

2.2 THE PNR DETECTOR

The layout of the detector is shown in fig 2.7. The neutron sensitive part of the detector is a 10cm diameter Lithium glass scintillator, positioned normally to the neutron beam. Other components are positioned as far out of the beam as possible in order to avoid radiation damage and minimise the background due to scattering. The only other component directly in the beam is a plane mirror positioned at 45° to the vertical which reflects the scintillation photons up to the lens. This focusses a reduced image of the scintillator onto the photocathode of the position-sensitive IPD (Imaging Photon Detector) above it. The

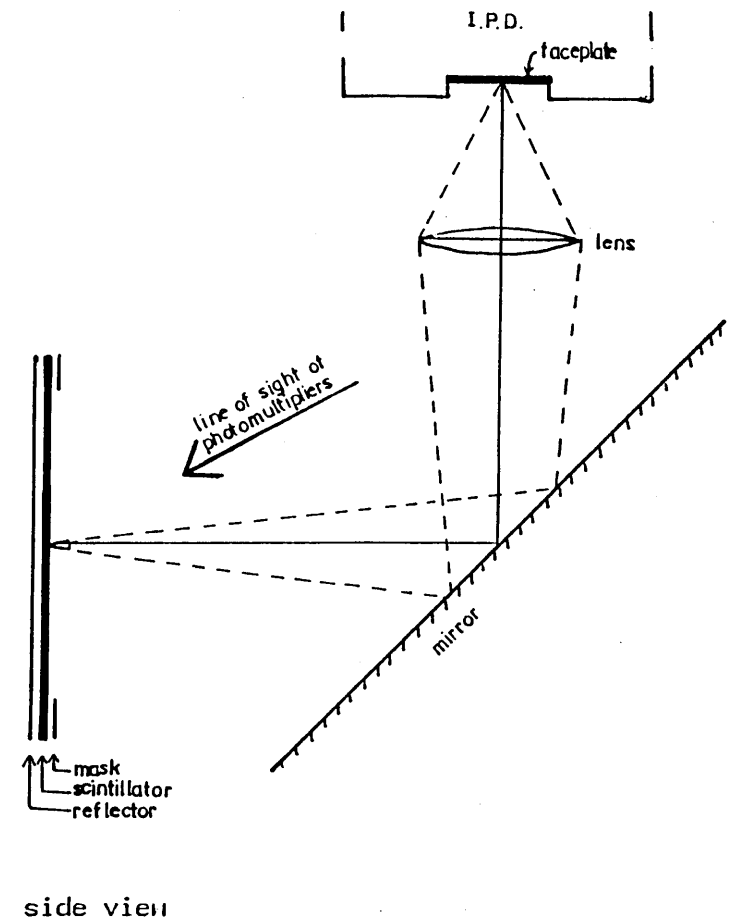
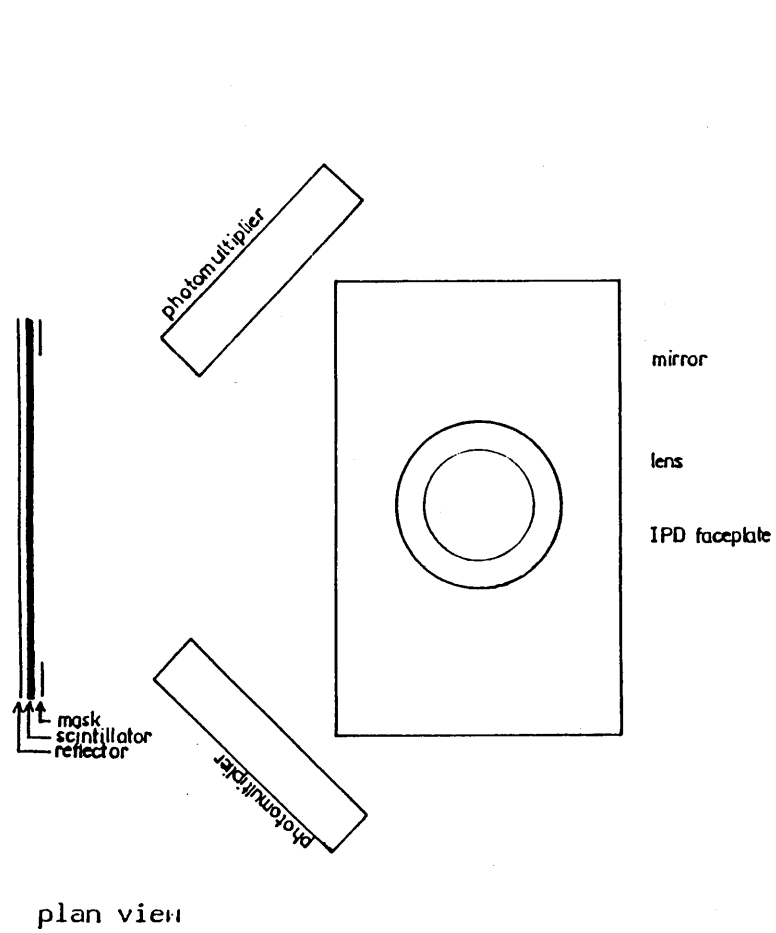


Fig 2.7 The detector layout

scintillator is also viewed by two fast photon counting photomultipliers. The components are housed in an aluminium box, coated on the inside with optical black paint to absorb any 'stray' photons. A thin aluminium foil reflector was optically coupled to the outer surface of the scintillator and an aluminium covering over this ensured that the system was light tight.

2.2.1 THE SCINTILLATOR

The choice of scintillator for the PNR detector involved the consideration of the following criteria:

- High efficiency.
- Smoothly varying neutron cross-section: the presence of resonances, for instance, would render it useless for observing resonances of other materials in that energy region.
- Low γ -sensitivity, or the possibility of discrimination against γ -rays.
- High light output.
- Short decay time ($<1\mu\text{s}$), which would not limit the count rate capability of the detector.
- Capability for good spatial resolution.

Most scintillators used for neutron detection in the energy region of interest are based upon one of three interactions: ${}^6\text{Li}(n,\alpha)t$, ${}^{10}\text{B}(n,\alpha){}^7\text{Li}$ or $\alpha{}^{158}\text{Gd}(n,\beta){}^{159}\text{Tb}$. The gadolinium scintillators could not be used for the radiography system, because the resonance region of gadolinium extends to 1eV, well within the energy range used for resonance radiography. The response of ${}^{10}\text{B}$ and ${}^6\text{Li}$ based scintillators is very similar, but the Q-value of the (n,α) reaction for Lithium is 4.8 MeV, compared with only 2.3 MeV for Boron, so the amount of light produced per scintillation is much greater for the former than for the latter. It was, therefore, decided that ${}^6\text{Li}$ scintillators should be used for the PNR detector. Such scintillators are available in several forms: as a lithium glass containing a cerium activator, as doped Lithium halide crystals or combined with $\text{ZnS}(\text{Ag})$. This last has a long decay time, and even when impurities are added to the mix to reduce afterglow, more than 10% of the light is emitted after 100 μs (ref 9). $\text{LiI}(\text{Eu})$ crystals have a higher light output than lithium glass, but are less efficient and could not be used at energies above 20eV due to neutron capture by the iodine, which has resonances in this region. They are also hygroscopic and very fragile and it is difficult to manufacture thin crystals with large enough areas for the detector requirements. Lithium glass scintillators were, therefore, chosen - in particular types NE902 and NE905 as these have been shown to have the largest peak pulse height of the commercially available scintillators when used with a standard photomultiplier (ref 10). 1mm and 5mm thick 10cm diameter

discs of NE902 equivalent and a 1mm thick disc of NE905 equivalent were obtained.

Scintillation mechanisms in Li glass are based on the ${}^6\text{Li}(n,\alpha){}^3\text{H}$ reaction; both the scintillators used were enriched in ${}^6\text{Li}$. The α -particle and triton liberate ion pairs in a columnar region around their tracks (fig 2.8). The electrons produced migrate outwards and are widely scattered, giving rise to secondary electrons some of which excite cerium centres which then de-excite by luminescence. 95% of the photons are emitted within 500ns (ref 7).

Compton scattering of γ -rays may also give rise to electrons of sufficient energy to produce a scintillation, indeed the γ -sensitivity of Lithium glass scintillators can be a considerable problem. The relation between γ -sensitivity and thickness is not linear. Jensen & Czirr (ref 11) observed that increases in γ -induced background go as three times the respective increases in scintillator thickness, whereas Spowart (ref 12) reports an increasing rate of change of γ efficiency with increasing thickness. The advantages of using a thicker scintillator for higher neutron efficiency must be weighed against the disadvantages of a higher γ background.

In order to determine which of the three scintillators should be used, a pulse height spectrum was obtained for each and their relative

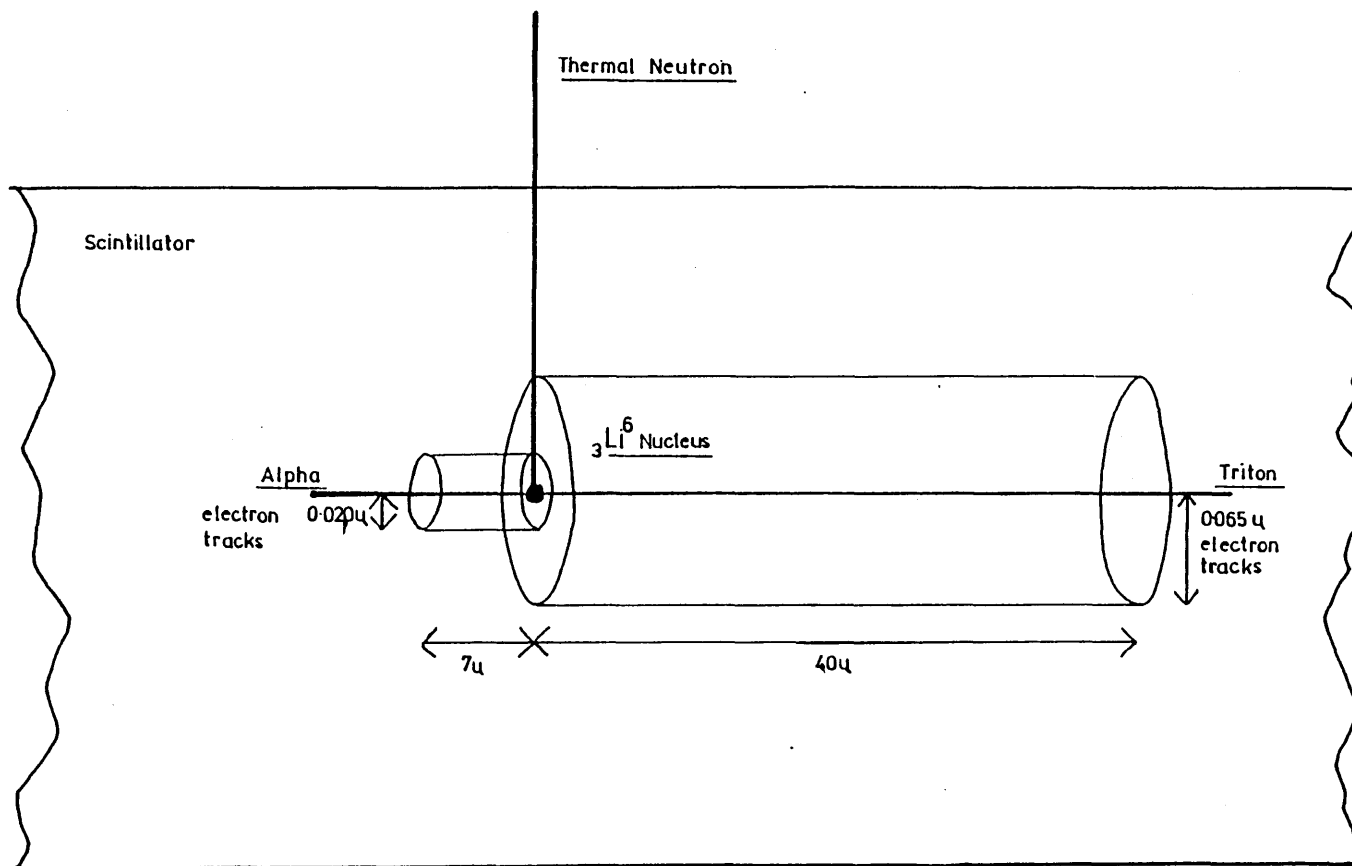


Fig 2.8 Scintillation mechanisms in lithium glass (ref 10)

efficiencies were measured. This was done with each of the scintillators in place in the detector, using the pulse-height discrimination electronics shown in fig 2.9. A polythene moderated ^{252}Cf source which produced thermal neutrons and γ -rays was used. The results for the three scintillators are shown in fig 2.10. The first (smaller) peak is due to the γ -rays - this was checked by observing the pulse height spectra with γ sources. The NE905 was rejected at this stage because of the large overlap between the γ and neutron peaks which would have rendered pulse height discrimination against γ 's impossible. Comparison of graphs (b) and (c) shows some unexpected results. The neutron peak pulse height for the 1mm NE902 appears to be 12% higher than that for the 5mm NE902 though the γ peaks occur in the same place. The total number of neutron counts, and hence the efficiency, for the 5mm glass is a factor of 1.3 greater than that for the 1mm glass. Initially we had expected the same pulse height for each, as the scintillations are produced by the same mechanisms; and an efficiency approximately proportional to the thickness of the glass (ref 13).

It is possible that impurities exist in the 5mm glass which have high neutron absorption cross-sections and would, therefore, compete with the ^6Li . As most elements have resonances in the epi-thermal region of the energy spectrum, the efficiency of the glass might be expected to vary in that region. In order to investigate the energy dependence of the efficiencies, a time-of-flight spectrum was obtained

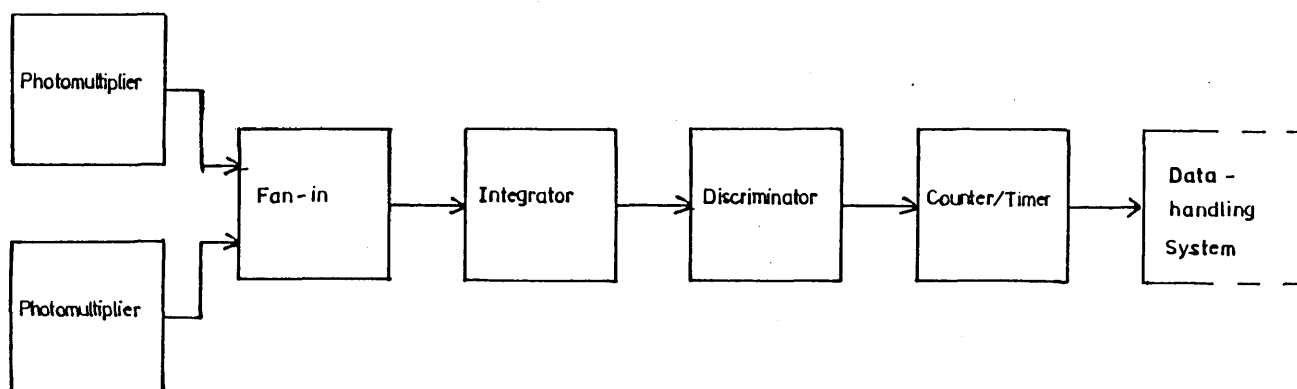


Fig 2.9 The pulse height discrimination electronics used for scintillator pulse height spectrum measurements

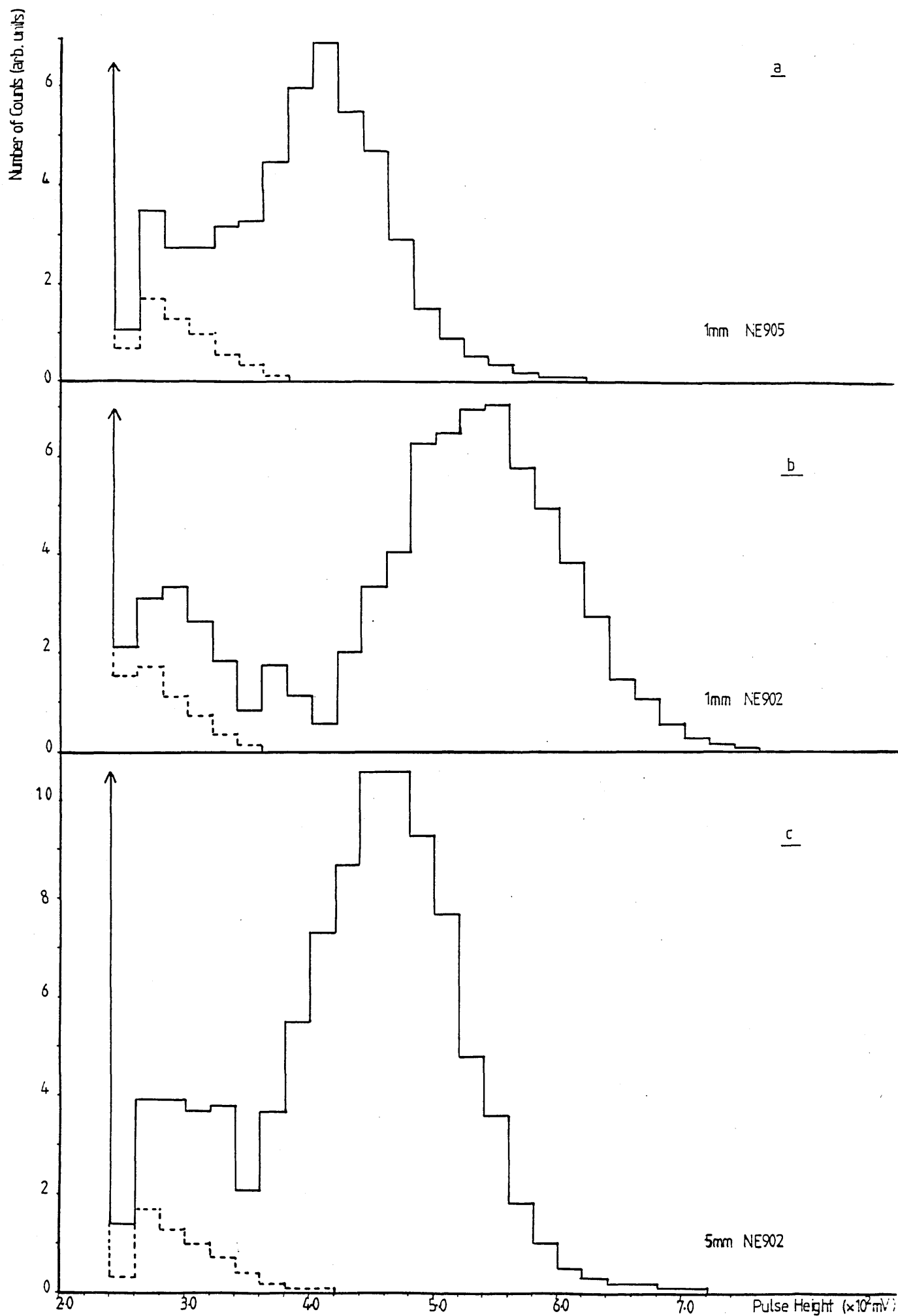


Fig 2.10 Pulse height spectra for three scintillators
 (The dashed line indicates 'background' pulse height, measured without a source)

with each of the scintillators in turn in the detector on a 9.5m flightpath on the CMT. After normalisation and subtraction of background, the runs were divided. As shown in fig 2.11, the ratio of efficiencies is independent of energy.

The effect is, therefore, unlikely to be due to competing neutron absorption processes. An alternative explanation is low ^6Li content in the 5mm glass. Measurements of the neutron transmission of each of the scintillators were made on another CMT flightpath using scintillation detectors at 8m and 16m and the lithium content of each glass was calculated. A small variation in lithium content was found:- 4.8% for the 1mm and 3.4% for the 5mm glass, but this would only account for a decrease in efficiency of 30%. It is possible that the lithium in the glasses was very non-uniformly distributed. The transmission measurements were made over an area of 3cm^2 and the lithium content of the glasses may by chance have been the same there, whereas it could have varied widely over the whole area of each of the scintillators. Such non-uniformity has been reported by Spowart (ref 10).

The difference in peak pulse height may be accounted for by self-absorption. ^{140}Ce , iron, magnesium and aluminium, which are all present in glass scintillators, have been shown to affect the pulse height (ref 10, 14, 15). The peak pulse height of the 1mm glass is a factor of 1.12 higher than that of the 5mm glass. This gives a mean

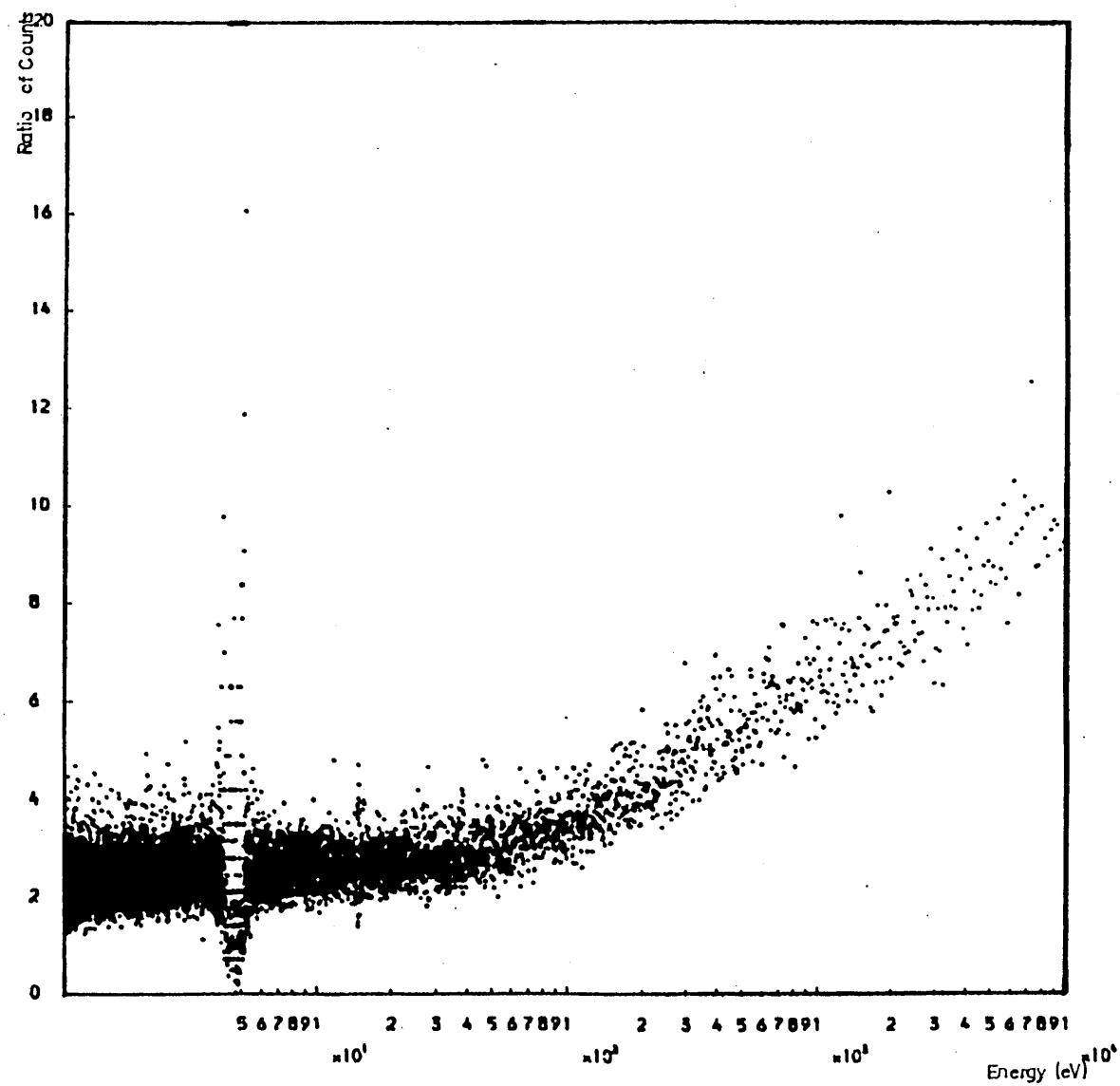


Fig 2.11 The ratio of spectra from 5mm and 2mm NE902 scintillators. The structure near 5eV is caused by a resonance due to a background filter. The slope above 50eV is due to extra γ -ray absorption in the thicker scintillator.

absorption coefficient of 0.06, in good agreement with the value of 0.08 obtained by Bollinger et al. for light of wavelength 390nm in a similar Lithium glass scintillator.

It was decided that the 1mm NE902 scintillator should be used in the detector because of its greater neutron peak pulse height, which permitted pulse height discrimination against γ 's to be used - the method is described in section 2.2.5.

Subsequent work on the detector indicated that low light levels were a major problem (see section 2.2.2). One solution to this could be the use of a $^6\text{LiI}(\text{Eu})$ crystal scintillator which would have a light output about 12 times that of the Lithium glass (ref 16). Though $^6\text{LiI}(\text{Eu})$ scintillators are more sensitive to γ -rays than are Lithium glasses, the higher light output should allow for successful pulse shape discrimination. Another advantage is that the emission spectrum peaks in the visible region, which would result in more light reaching the IPD through the mirror and lens. The long decay time of such a scintillator ($>1\mu\text{s}$) would limit the count rate of the system, but in the energy range used for strain radiography this should not be a problem, due to the relatively low slow neutron flux. A $^6\text{LiI}(\text{Eu})$ crystal was ordered but, due to manufacturing difficulties, its delivery was considerably delayed, so it could not be used in this work.

2.2.2 OPTICS

Despite the use of a high light output scintillator, problems due to low light levels were still encountered. Due to the effects of total internal reflection, most of the light from each scintillation event was transmitted through to the edges of the glass and only 20% passed through the front face. Only a small fraction of this transmitted light then reached the IPD and the photomultipliers. This was a result of the geometrical arrangement of the components in the detector: because they were positioned out of the neutron beam they were relatively distant from the scintillator and only subtended small solid angles there. Light intensity at the IPD was further reduced by the mirror and lens which, like most optical components, had been optimised for use with visible light, whereas the scintillator emission spectrum peaks at 390nm in the near u.v. (see fig 2.12). The worst results of the low intensity were that the photomultiplier pulses were small and indistinguishable from noise and that 85% of neutron events were not registered at all by the IPD. The various measures taken to reduce this light loss will now be considered :

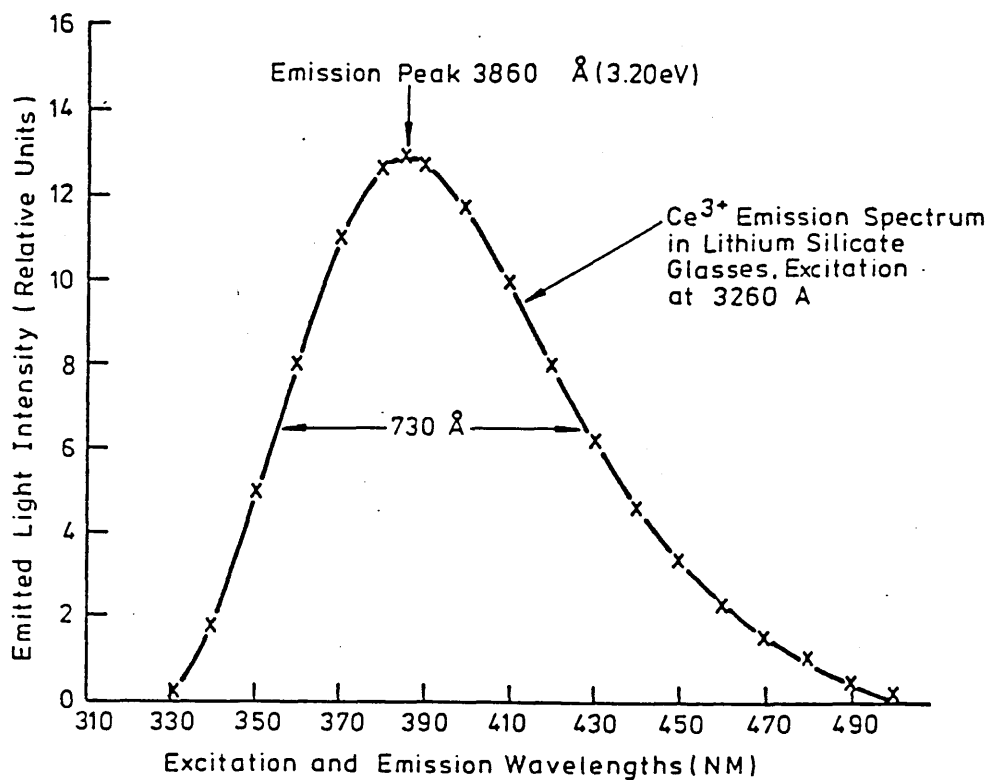


Fig 2.12 The emission spectrum of ³⁺Ce - the scintillator used in lithium glasses.

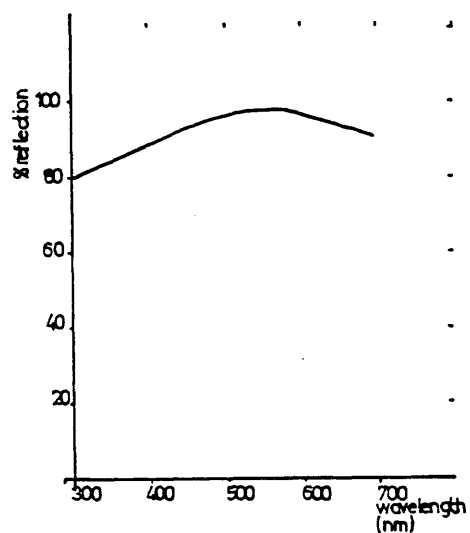


Fig 2.13 The reflectivity of aluminium as a function of wavelength

2.2.2.1 Light Collection by the Photomultipliers

The two photomultipliers had windows of 5.3cm diameter and viewed the plane face of the 10cm diameter scintillator from a distance of 17cm centre to centre at angles of 30° to the horizontal and vertical. Assuming that the 6×10^3 photons (ref 17, 18) were emitted isotropically, and allowing for refraction at the scintillator / glass interface and 50% reflection from the reflector behind the scintillator, the mean number of photons per event reaching each photomultiplier was 21. The variation in countrate of the sum of the photomultiplier pulses was less than 10% across the scintillator. The photocathode efficiency for light of 390nm wavelength was 25% (ref 19), so an average of 5 photons per event were recorded by each photomultiplier - clearly far too few to allow for any discrimination against noise or γ -ray pulses. Two modifications were made to improve the situation :-

Firstly parabolic reflectors of 7.5cm diameter coated with aluminised film were positioned around the windows of the photomultipliers to reflect any incident photons into the tubes. The solid angle subtended by the reflectors was double that subtended by the photomultipliers alone, but due to losses in the foil and imperfect geometry, the measured increase in countrate was only 20%. An alternative modification was, therefore, made. The photomultipliers were moved for-

ward to a distance of 12cm from the centre of the scintillator, which again doubled the solid angle at the centre of the scintillator, but also doubled the variation in solid angle across it. This was considered to be unacceptable, so the scintillator was masked to 8cm diameter which reduced the variation back to 10%. The measured increase in countrate was indeed a factor of 2 within the experimental errors, so the total number of photons registered for each event was 20.

This proved to be sufficient for pulse height discrimination.

2.2.2.2 Light Collection by the IPD - Lens - Mirror System

The mean number of photons per neutron event detected by the IPD in the original detector configuration was calculated as a product of factors due to each component of the detector. The 6×10^3 photons were again assumed to be produced isotropically and the reflectivity of the back reflector of the scintillator was assumed to be 50%. The original mirror was surface silvered but had become tarnished and scratched. Its reflectivity was estimated at 85%. The original 50 mm f/1 lens was positioned at 25cm from the object to give 4:1 diminution; its transmission was measured as 37%. The fractional forward solid angle

subtended by the lens at the centre of the scintillator can be shown to be

$$\frac{1}{16(m+1)^2 N^2}$$

where m = magnification and N = effective $f/\#$. The transmission of the IPD itself was limited by the transmission of the faceplate (90%), the efficiency of the photocathode (25%) and the efficiency of the micro-channel plates (60%). The product of these factors gives the mean number of photons per event as 0.15 ± 0.05 , which is in good agreement with a measurement of efficiency of the IPD relative to the photomultipliers of 12%.

Various steps were taken to improve the overall efficiency of the IPD and optical systems. A second IPD was purchased which had a u.v.-transmitting faceplate and a higher efficiency photocathode (see section 2.2.6). Modifications were made to the mirror and lens, as described below.

2.2.3 THE MIRROR

The original mirror was front silvered, but over two years it had become tarnished and scratched, so a replacement had to be found. The obvious choice for a reflective material was aluminium, because of its high reflectivity in the near u.v. (see fig 2.13). The first alternative mirror to be tested was constructed in the laboratory from aluminised 'melinex' film stretched over an aluminium former. This had the advantages of being easily replaceable and very cheap, but there was no measurable increase in countrate when it was used in the detector. This was probably due to the thinness of the aluminium coating which became even thinner when the film was stretched. A conventional glass mirror was, therefore, purchased. It was front aluminised with a protective coating of silicon oxide. The reflectivity was specified as 90% at 390nm. The IPD/optic system efficiency was increased by 10% when it was incorporated into the detector.

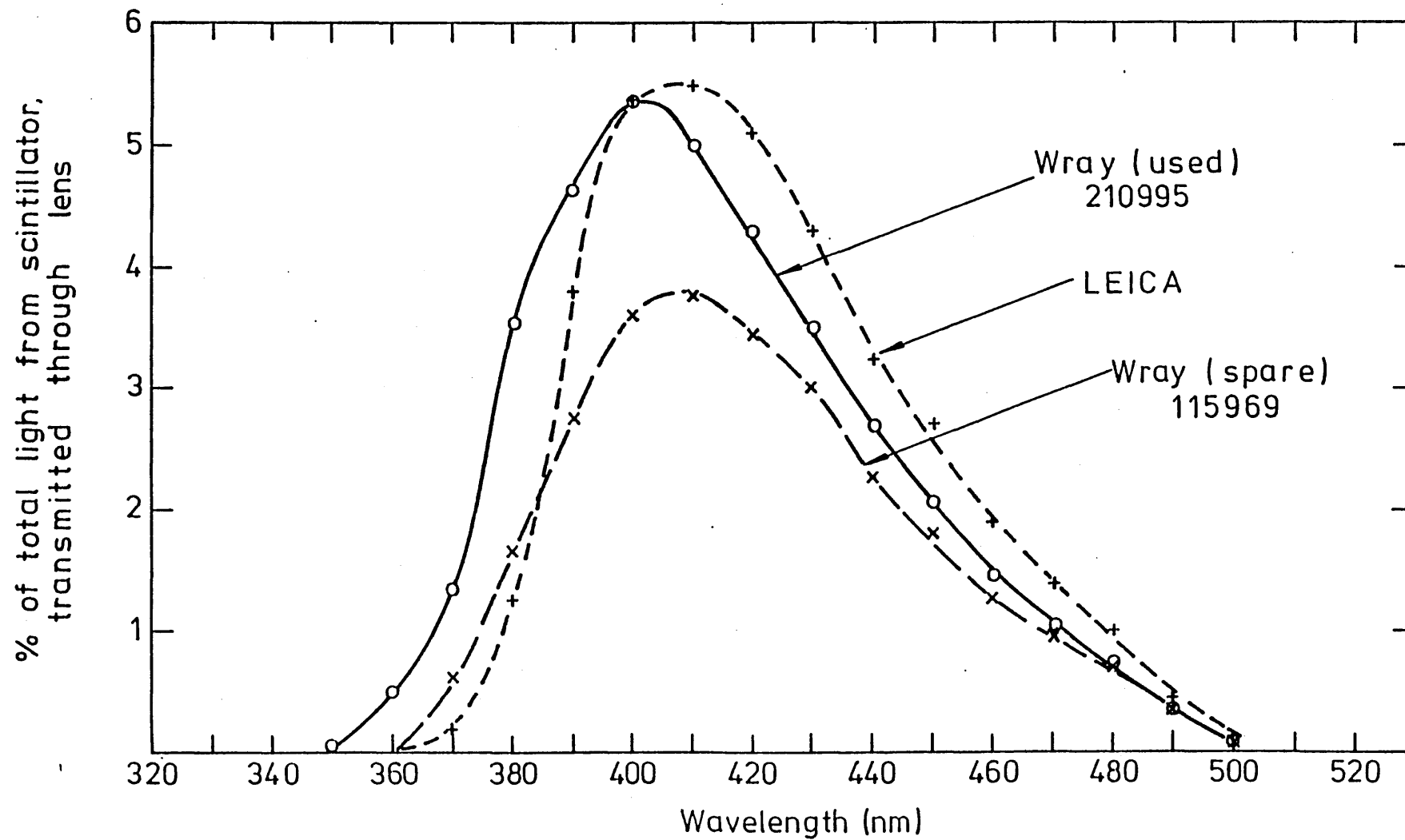


Fig 2.14 The percentage of scintillator light transmitted by various lenses

2.2.4 THE LENS

The original detector lens was a 50mm f/1 Wray copier lens. It had good image formation properties at small object distances for which it was used, but had two major disadvantages: it was designed for use with visible light and had poor transmission properties in the near u.v. and it was also slightly radioactive. It emitted light photons, probably Cerenkov radiation produced in the decay chain of Thorium - an element often used in the manufacture of lenses. The photons were detected by the IPD and gave rise to a 50% increase in background. This was unacceptable so an alternative lens was sought. The requirements it had to meet were:

- Good transmission properties in the near u.v., at least comparable with the original lens.
- Good image formation properties at short object distances ($\approx 25\text{cm}$).
- Focal length $\approx 50\text{mm}$ for 4:1 reduction in image size with conjugates fixed by the detector geometry.
- Large aperture for maximum light collection. i.e. minimum f/# for given focal length.

The lowest f/# for a commercially available 50mm lens was f/1 for a Leica Noctilux-M camera lens. The next lowest was f/1.2, but as the light collected is inversely proportional to the square of the f/# the transmission through such a lens would have to be 44% higher to give the same light collection efficiency as the f/1. A Leica Noctilux-M lens

was purchased and its transmission as a function of wavelength was measured using an ultraviolet spectrometer at the Blackett Laboratory, Imperial College with the help of Dr. B.L. Morgan. The transmissions of the original Wray lens and a similar Wray 50mm f/1 copier lens were also measured.

The transmission spectra obtained were multiplied by the emission spectrum of the NE902 scintillator (fig 2.12) to give the relative light collection capabilities of each in the PNR detector. The resultant spectra are shown in fig 2.14 - the total efficiency may be obtained by integrating over the whole spectrum. The percentage of scintillator light transmitted by each lens was :-

Wray I (used) $37.1 \pm 0.7 \%$

Leica $36.4 \pm 0.7 \%$

Wray II (spare) $25.5 \pm 0.5 \%$

Though the transmission of the new Leica lens was no greater than that of the old one, it had the great advantage of not being radioactive. It was, therefore, installed into the detector. The masking of the scintillator to 4cm radius (see section 2.2.2.1) allowed the diminution of the image to be reduced; the lens was finally positioned to give a diminution of 3:1 which increased the transmission by a factor of 1.8.

It may be possible for a lens to be designed specifically for this experiment with the correct imaging properties and also good transmission in the near u.v.. Alternatively, the light collection of the IPD/optics system may be further increased by using a scintillator with an emission spectrum in the visible region such as $^6\text{LiI}(\text{Eu})$, though this has some undesirable properties such as high γ -sensitivity. The lens and mirror could be replaced by one large aspheric mirror, though such mirrors tend to have poor image forming properties with considerable aberrations.

2.2.5 THE PHOTOMULTIPLIERS

The most important criterion in the choice of photomultipliers for the PNR detector was high sensitivity, since the timing resolution requirement ($\approx 20\text{ns}$) was easily satisfied by a number of readily available tubes. The photomultipliers used were a pair of fast single photon counting tubes, type EM19883B, with bialkali photocathodes to give high sensitivity in the near u.v. (25% at 400nm).

The original divider chains for these tubes gave poor performance - the output pulse was very noisy and showed considerable ringing. New

base chains were constructed based on the EMI recommended voltage dividers for photon counting applications featuring decoupling of the last three stages and increasing voltage steps over the last three stages (see fig 2.15). The operating potentials and k-d1 voltages were optimised experimentally. The γ -flash seen on the strain - radiography flightpath was considerably greater than that seen on the first radiography flightpath and caused the photomultipliers to saturate. New bases were, therefore, constructed to the same design but allowing higher currents, up to 5mA, to be drawn (see fig2.16). The heat generated in the high current bases was dissipated by air cooling - the divider chains were mounted externally to the detector. With these bases the photomultipliers took approximately 1ms to recover from the γ -flash, which was sufficient for the strain radiography experiment where the first features to be observed occurred at 10ms.

The anode pulses from the photomultipliers were clean and relatively free from ringing but it was still difficult to distinguish 'real' neutron events from noise. The low light levels and the long decay time of the scintillator meant that each photomultiplier received only 10 photons per event spread over 500ns. In order to distinguish the neutron events a pulse height discrimination (PHD) system was set up as was shown in fig 2.9. The photomultiplier pulses were summed, which improved the counting statistics and reduced the effect of scintillation position on efficiency. The summed pulses were then fed into a 'Link

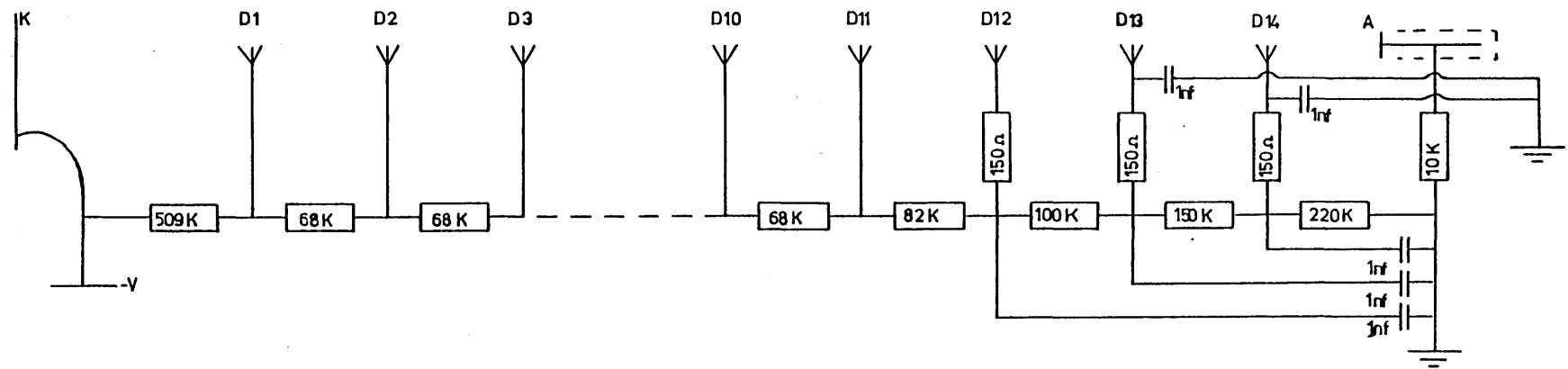


Fig 2.15 The 2mA photomultiplier base chain

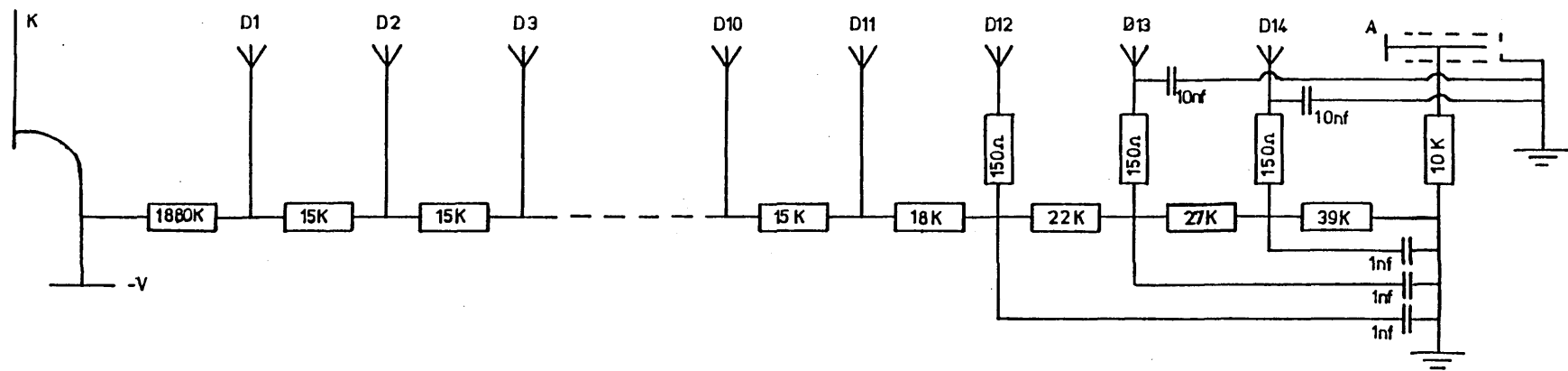


Fig 2.16 The 5mA photomultiplier base chain

systems PSD-5010' PSD unit, part of which acted as an integrator over a period of 500ns. The pulse height spectra obtained showed clearly separated noise, γ and neutron peaks as was shown in fig 2.10. The discriminator was set in the valley just below the neutron peak.

2.2.6 THE IPD

The imaging photon detector (manufactured by ITL) is a position sensitive, single photon counting device based on a microchannel plate image intensifier and a resistive anode with the associated processing electronics.

A schematic diagram of the detector head is shown in fig 2.17. An incident photon passes through the faceplate and hits the photocathode, thereby releasing a photoelectron which is accelerated towards the microchannel plates by a strong electric field. There are three plates arranged in a 'Z' configuration. Each consists of a sheet of lead glass pierced by a matrix of small channels which act as an array of miniature electron multipliers. The lead glass is treated to optimise secondary emission and to render the channel walls semiconducting, so that the charge can be replenished from the external voltage source. A conducting

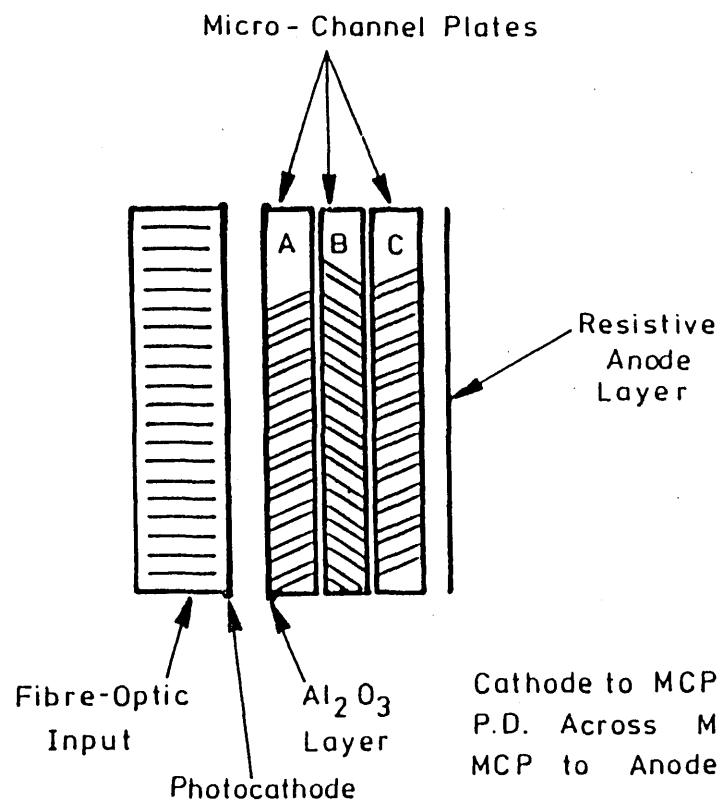


Fig 2.17 The Imaging Photon Detector

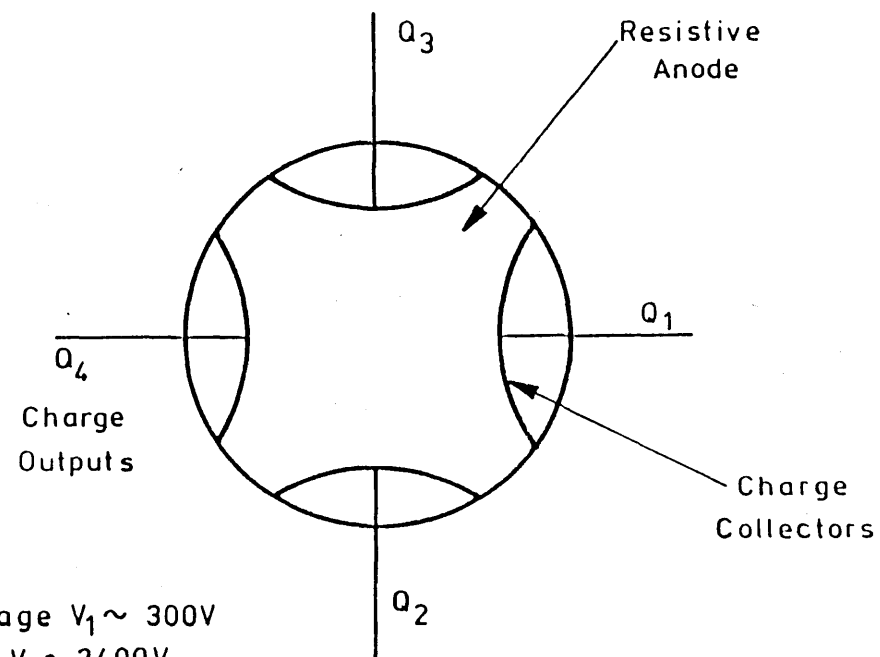


Fig 2.18 The resistive anode

coating on the flat surfaces of the plates ensures that the voltage across each channel is the same. The electron multiplication factor of the plates is about 10^6 . Ion feedback is reduced by the 'Z'-configuration and by a thin aluminium oxide layer on the front surface of the first plate. A good pulse height distribution is obtained by running the last plate in a saturated gain mode so that space charge effects limit the gain. The electron pulse from the plates is drawn onto a resistive anode which has four arc-shaped terminating resistors connected to virtual earth (see fig 2.18). The charge collected at each of these is converted into a voltage pulse, amplified, shaped and buffered and then fed into the separate signal processing unit. Here the summed pulses are fed into sample and hold circuits and also into a summing circuit so that pulses which do not fall within preset limits (e.g. small noise pulses or large pulses due to ions or to multiphoton events) may be rejected. The four anode signals are then converted into a pair of X-Y coordinates which are fed into ADC's, the outputs of which are buffered. The event position is thus presented as two 10-bit words; the analogue signals for X and Y and a data-ready pulse are also available. The IPD was used in an 'enabled' mode in which only those pulses coincident with externally generated enable pulses (see section 2.3) are processed.

Two IPD's have been used on the detector - the second was manufactured to slightly different specifications from the first in order to

achieve higher efficiency. The chief modifications were:- The fibre-optic faceplate was replaced by a u.v.-transmitting glass one and the second photocathode was u.v.-sensitive bialkali rather than S20 type. The second IPD was operated at a higher potential than the first in order to improve its sensitivity and the uniformity of response of the photocathode. The dead-time of the IPD signal processing electronics was reduced to $< 10\mu\text{s}$. These changes produced a factor of 3 increase in efficiency over the old IPD, the performance of which had by then been reduced considerably by the effects of age and exposure to high light levels.

The IPD is essentially a single photon counting device - the thresholds on the summing circuit are set up to exclude not only noise, but also multiphoton events. This ensures that pulses from 2 or more photons due to different but simultaneous neutron events are rejected, because they would cause a false position (the 'mean' of the true event positions) to be recorded. In the present system this is quite satisfactory as an average of 0.75 photons per neutron event are recorded and very few events give rise to more than one photo-electron from the photocathode. If, however, the detector were improved so that many more photons per event reached the IPD, then problems could arise. With the present settings a large fraction of IPD summed pulses would be rejected because they would fall outside the single photon peak. If the thresholds were reset so that multiphoton events were accepted, then simul-

taneous neutron events in the scintillator would give rise to wrongly recorded event positions. The seriousness of this problem would obviously depend on the probability of simultaneous neutron events taking place, i.e. on the efficiency of the scintillator and the strength of the source. In general, the single photon counting regime of the IPD imposes constraints on the maximum light output and the maximum efficiency of the scintillator, though in the present system there is still considerable scope for improvement of both before any of these problems are encountered.

A problem which was evident with both IPD's was that of noise. The noise rate was very high - several tens of counts per second when the device was free-running and blacked out. This rate increased by up to an order of magnitude when the IPD was strongly illuminated and in the period immediately after it was switched on. The manufacturer's recommended settling time after initial switch on was 24 hours, but it was found that approximately 72 hours was required for the noise rate to reach a steady level. The reason for this long settling time is not clear, but it is probably related to the similar effect which has been observed in conventional photomultiplier tubes and may be due to some metastable excitation mechanism in the photocathode.

A pulse height analysis confirmed that the noise pulses fell within the single photon peak, so they were indistinguishable from 'real'

events and could not be removed by resetting the discriminator thresholds. This would tend to confirm the hypothesis that the pulses originated in an early stage of the IPD, such as the photo-cathode, and then passed through the rest of the tube in the same way as a genuine event pulse.

During experiments on the LINAC, it was found that the γ -flash at the start of each machine pulse caused a considerable increase in the noise level. The seriousness of this effect depended on the strength of the γ -flash on the flightpath in question. The most obvious method of dealing with this problem would be to gate the IPD off during the first few microseconds of the machine pulse. Unfortunately this solution was not viable, as the action itself generated an increase in the noise level. Alternatively, a gateable device could be fixed in front of the IPD faceplate, but any such device would absorb some photons and thus reduce the efficiency of the system. In practice, the problem of γ -flash was solved by modifying the flightpath (see section 2.1.2.3).

2.3 THE DATA - HANDLING ELECTRONICS

The data handling electronics is described with reference to fig 2.19. The detector station was next to the flightpath where the experiment was carried out; the data collection station was in a laboratory some 100m away. This arrangement was necessary because the position of the data collection computer was fixed, but much of the pulse processing had to be done near to the detector in order to avoid as far as possible the problems of sending analogue signals up long cables. The horizontal line of circuitry at the top of the diagram is the part that generates the enable pulse for the IPD, the rest takes data and converts it into a form suitable for the CAMAC data collection system. All start pulses come from the LINAC MTU (master timing unit).

The photomultiplier pulses are amplified, fed to a fan-out unit (to allow them to be scaled) and then summed in the fan-in unit. The sum pulse is fed into a 'Link systems 5010' PSD unit, two sections of which are used. One provides a fast timing pulse when an input pulse is accepted, the other is a charge integrator. The fast timing pulse is fed into a fan-out unit, from where it is sent to a scaler, to the time-of-flight system (see section 2.3.1) and to an octal fan-out which provides the 8 inputs required for the timing gates. The gating unit (designed by P.E.Dolley, AERE Harwell) consists of eight digital gates

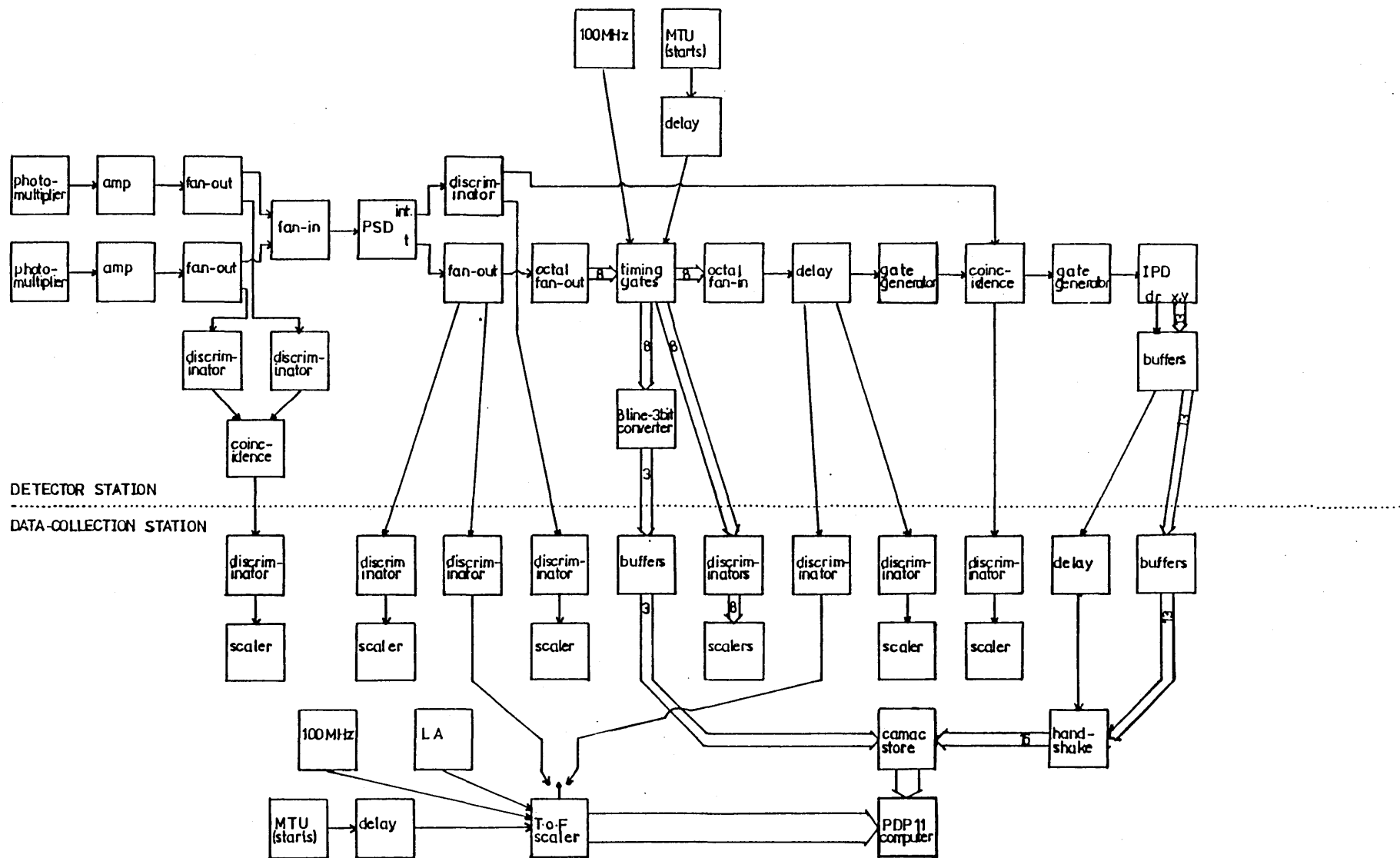


Fig 2.19 The data-handling electronics

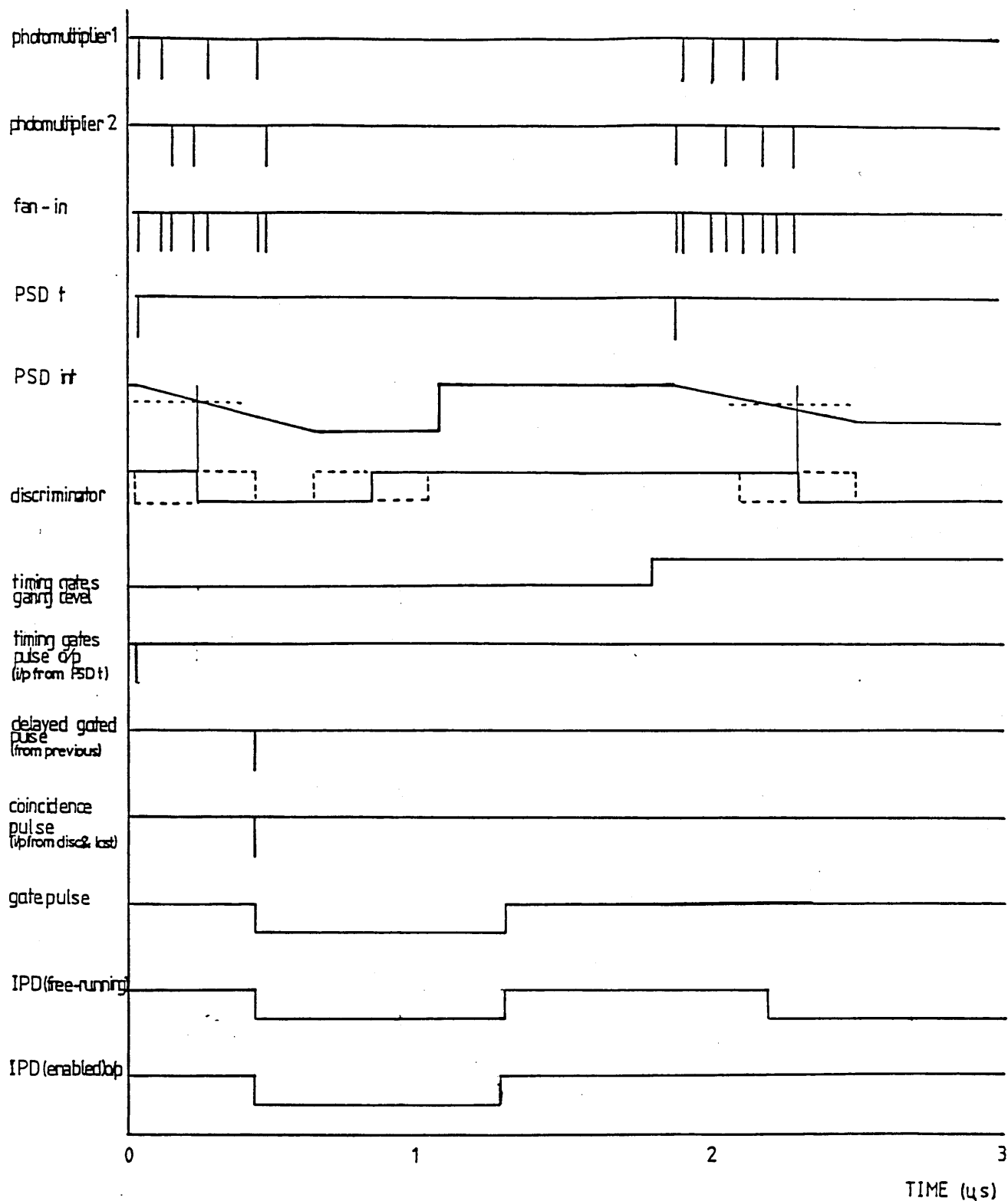


Fig 2.20 Pulse trains for the production of an 'enable' for the IPD

(The dashed lines on the discriminator pulses indicate jitter)

which can be preset independently to any time interval between 10ns and 9.99999ms after the start pulse, the smallest increment being 10ns. Each of the eight gates has three outputs. One provides a level which switches to positive when the gate is open, the other two provide pulses when an input pulse is received during the 'gate-open' time. One of these outputs from each gate is scaled, the other is fed to an octal fan-in and then into delay and gate generators to provide pulses of the required length for a coincidence. The output of this gate unit thus gives all the photomultiplier pulses which have passed through the gates and has good timing resolution ($<10\text{ns}$) but includes noise and unwanted γ pulses. These are removed by using a coincidence with a pulse train which excludes unwanted signals, though it is ungated. These come from the PSD integrator. The integrator output takes the form of a 500ns ramp up to a maximum voltage which is maintained for a further 400ns. A discriminator after the integrator provides pulse height discrimination to remove 90% of the noise and γ pulses. The output of the discriminator has considerable jitter ($\approx 300\text{ns}$) with respect to the original photomultiplier pulses because of the variable slope of the ramp input. This is the pulse which is fed into the coincidence unit with the gated timing pulses to give gated neutron pulses with good timing resolution. These are delayed and converted to TTL to supply an 'enable' to the IPD. The pulse train is shown in fig 2.20. The time-of-flight and imaging systems are completely separate from this point.

2.3.1 THE TIME-OF-FLIGHT SYSTEM

The timing pulses from the integrator, either before or after gating, are fed into the time-of-flight data acquisition system (designed by D.Morris, AERE Harwell). This time-of-flight scaler converts times into 16 bit words in a rapid access buffer memory, from where they are transferred, via a CAMAC interface, into the PDP11 computer. A histogram of neutron flight times is thus built up on disk and then written to magnetic tape at the end of a data collection period.

2.3.2 THE IMAGING SYSTEM

The two X,Y coordinate words from the IPD are fed into buffers, then along two cables to another buffer unit in the counting station to provide the positional information about neutron events. The data-ready pulse from the IPD is also fed up to the counting station. These data must be divided into eight groups corresponding to the eight timing gates. The 'gate-open' levels from the gating unit are used for this purpose. They are fed into an 8-line to 3-bit converter unit whose outputs indicate the number of the open gate. Between gates the three bits

are set to 0 0 0, the same code as for the first gate. The converter unit also acts as a buffer and a level stretcher - each of the 'gate-open' pulses may be stretched by up to 25 μ s, so that the appropriate levels are still present in the counting station when the positional information arrives. Positional information arriving after the gate will be associated with code 0 0 0 and assigned to the first gate. The required 'stretch' has been found empirically to be 20 μ s. The gating levels are fed into a CAMAC store.

Positional information is also fed into the store, via a handshake system. Only 13 bits of positional data (7X,6Y) can be used because the store is limited to 16 bits of input data. The main advantage of using the store is its rapid access time - 1 μ s for the 16 bit word compared with 40 μ s for direct access to the PDP11 computer. The data in the store is periodically transferred to a disk histogram in the computer and then written to magnetic tape at the end of a data collection period. Data on magnetic tape is transferred to the Harwell site IBM3084Q computer, in which it is stored for subsequent processing.

2.4 DATA PROCESSING

The original data-handling programs that had been written for the resonance radiography project were rather primitive and inflexible, so new data processing codes had to be created. Two sets of processing programs were written to deal with the data - one for image data (RESULTS) and the other for time-of-flight data (TOFRUNS). The aim was to create flexible data manipulation and analysis code which could easily be modified or extended. In addition to this a series of programs were written specifically for the strain radiography experiment; these are described in sections 3.3.4.2 and 3.3.5 .

The task of the imaging code RESULTS was to manipulate and finally produce images from run data. The data for resonance radiography, beam profile radiography and strain radiography had to be processed independently, yet many stages in the procedures (e.g. addition of runs, normalisation, summation of pixels etc.) were common to all. The data from each run was stored as a partitioned dataset, each member of which contained 8192 integers representing the counts in each pixel of an image from one gate. The code is run from a clist which prompts for commands and then causes the appropriate load module to be run; it also deals with entry and exit to the code and with errors and attention exits. There are 26 primary programs which may be called by the clist

(see table 2.3). Each of these relies on the 3 secondary programs to manipulate the datasets - to read data in or write the output of the program to a stream for temporary storage or to a new dataset for permanent storage. The resultant array of any primary program that modifies the data is written to 'last' so that a series of sequential operations can easily be performed on the same data. A simple processing operation to convert a series of runs into an image might be:

ADD all runs of the same sample together

NORMALise LAST array by dividing by a stored RUNSUM dataset

KEEP this temporarily

CIRCLE - create a circular mask data-array

MASK the KEPT array by the LAST array

PLOT the LAST array

The actual use of the code is described in Section 3.1.3.

The time-of-flight program TOFRUNS works on the same principles as RESULTS. Its members are listed in table 2.4.

Table 2.3 "RESULTS"

Primary Programs

Processing Programs

ADD	to add arrays
CIRCLE	to create a circular mask
DIV	to divide one array by another
MASK	to multiply by a mask array
MULTI	to multiply together several data arrays
SHIFT	to shift the position of the image
STRAIN	to calculate and plot strain arrays
SUB	to subtract one array from another
SUM	to sum groups of pixels

Information - giving Programs

CHECK	to check for certain errors in data
QUERY	to obtain titles of data-arrays
STATS	to calculate the sum, mean and st.dev. of an array and plot frequency distribution
TOTAL	to calculate the total number of counts in an array

Plotting Programs

IMAGE	high resolution plotting
LINE	to plot one row or column
NPLOT	number plotting
PLOT	greyscale plotting
SUMPLOT	greyscale plotting with pixel summation

Data Handling Programs

KEEP	to store an array for the duration of the program
------	---

Secondary Programs

IN	to read in data from files
OUT	to output data to files
TOLAST	to store data in 'LAST' array for duration of program

Table 2.4 "TOFRUNS"

Primary Programs

ADD	to add arrays
BKGD	to subtract a flat background
DIVIDE	to divide one array by another
ENQUIRE	to obtain the titles of arrays
EPLT	to plot a time-of-flight array on an energy scale
ESCALE	to plot a time normalised array on an energy scale
GATES	to calculate the number of counts in gate regions
MCMRUN	to plot a time-of-flight array with variable channels
NORM	to normalise an array by monitor counts
PLOT	to plot a histogram
SAVE	to write data to a permanent file
STORE	to store data for duration of program
SUBT	to subtract one array from another
SUM	to sum channels

Secondary Programs

IN	to read in data from files
TOLAST	to store an array in 'LAST' for the next operation

2.5 SUMMARY OF DETECTOR PERFORMANCE

The detector has been demonstrated successfully and radiographs of a variety of samples have been produced. The detector performance, in quantitative terms, is summarized below.

Dead time - 10 μ s due to the IPD processing electronics. The dead time of the photomultiplier timing system is limited by the PSD integrator to 1 μ s.

Timing resolution - 500ns limited by the decay time of the scintillator.

Efficiency - 15% of scintillator efficiency. This gives 10% for 5meV neutrons, but only 1% at 1eV, falling still further at higher energies.

Spatial resolution - < 1mm. This was completely dominated by the pixel size (0.8x1.6mm) which was constrained by the limitations of the number of bits that could be handled by the data acquisition system. The flightpath was set up so that the geometric unsharpness was less than the pixel size (see section 2.1.2.1) and other factors were negligible relative to these. (N.B. A detailed analysis of the

spatial resolution would be necessary if the pixel size were significantly reduced.) A radiograph demonstrating the spatial resolution of the detector is shown in figure 2.21. In order to remove any resolution effects due to the neutron source or sample, this radiograph was obtained by fixing a mask behind the scintillator, inside the detector. A moderated Cf^{252} source was used so that the experiment could be performed in the laboratory.

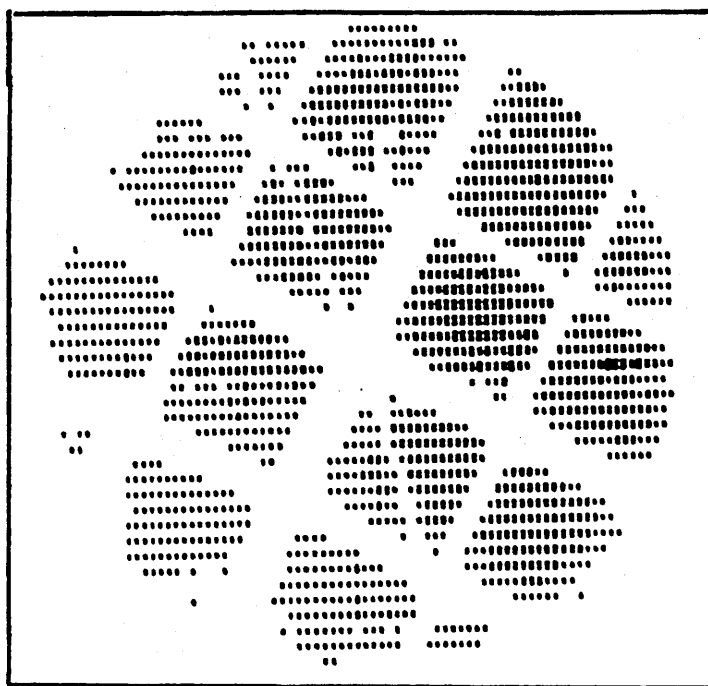


Fig 2.21 A radiograph demonstrating the optical resolution of the PNR detector. The bars are 4mm, 2mm and 1mm wide.

CHAPTER3 - APPLICATIONS

The PNR detector had originally been designed for use in Resonance Neutron Radiography (PNR) - a non-destructive testing technique for producing separate images of the distributions of nuclides in a sample. Several experiments have been carried out to demonstrate this. The PNR system, however, is potentially versatile and with suitable data collection and processing methods, may be used in other ways. A straightforward application of the system is beam profile measurement, in which the intensity of a neutron beam is measured across its area at different energies. A more complex problem to which the PNR detector may be applied is strain radiography. A prototype strain radiography system has been set up, in which the detector is used to measure the strain resulting from residual stress in a sample. These three applications will now be discussed.

3.1 RESONANCE NEUTRON RADIOGRAPHY

This technique uses the resonances in the total neutron cross sections of different sample materials to discriminate between them and produce images of each.

The data in table 3.1 indicates that RNR could be used to distinguish between iron, cobalt and nickel and it may be utilised to check low activity waste for the presence of re-useable structural materials. Other possible applications include the assay of fuel rods to test for the anisotropic distribution of actinides and the radiography of steel components to check for the presence of pockets of sulphur which weaken them.

The standard techniques of X-radiography and thermal neutron radiography will almost certainly continue to dominate this area of non-destructive testing for the foreseeable future, but each has its limitations :- X-ray cross-sections vary only slowly with atomic number, so that nuclei of similar atomic number are difficult to distinguish; similarly, the majority of thermal neutron cross-sections are of the same order of magnitude, so whilst thermal neutron radiography is extremely useful in particular cases (e.g. the imaging of hydrogenous materials) it cannot be used generally to distinguish between different

Table 3.1 SOME EXAMPLES OF CROSS SECTIONS FOR RESONANCE RADIOGRAPHY

<u>Energy</u> <u>(eV)</u>	<u>Cross section(b)</u>				<u>Macroscopic cross section(cm⁻¹)</u>					
<u>Actinide Isotopes</u>										
	U235	U238	U239	U240	U235	U238	U239	U240		
1.1	100	10	55	1x10 ⁵	48	5	27	5x10 ⁴		
6.6	35	7x10 ³	22	20	17	3x10 ³	11	10		
7.9	20	15	2x10 ³	30	10	70	1x10 ³	15		
8.8	1.2x10 ³	10	18	50	580	5	9	24		
<u>Structural Materials</u>										
	Cr	Fe	Co	Ni	Cr	Fe	Co	Ni		
130	5	12	7x10 ³	18	4	10	6x10 ³	16		
15000	3	4	3	140	2	3	3	130		
50000	45	5	2	5	37	4	2	4		
<u>'LINAC' sample</u>										
	Co	U238	Ta	Ag	Pt	Co	U238	Ta	Ag	Pt
5.2	9.4	14	40	1x10 ⁴	12	8	7	22	6x10 ³	8
6.6	9.2	4x10 ³	13	58	12	8	3x10 ³	7	34	8
10.3	9.0	15	3x10 ³	9.8	19	8	7	2x10 ³	6	13
11.9	9.0	13	10	8.2	2x10 ³	8	6	5	5	1x10 ³
132	7x10 ³	13	30	6	16	6x10 ³	6	17	4	10

nuclides. Thus although PNR is a more complex and more expensive technique, it has the advantage that it can succeed in situations where other methods fail and it is likely to be used for unusual, 'one-off' imaging tasks, as well as the other applications that have been mentioned.

3.1.1 THEORY

Resonances are present in the epi-thermal region of the total neutron cross-sections of most nuclides. Their energy, height and width depend on the allowed levels of the compound nucleus which is formed from the target nucleus and incident neutron. These are different for each nuclide, so the pattern of resonances is also different for each. For a sample composed of several nuclides it is almost always possible to find energy regions for each of them where only that one has a resonance. The resonance cross-section may be up to 1000 times greater than that between resonances, which is of the same order of magnitude (a few barns) for most nuclides. Thus, in the chosen energy region, the neutron cross-section of one of the sample nuclides will be much greater than those of the others and so a radiograph made with neutrons from that en-

ergy range will show the nuclide in question with good contrast against the rest of the sample.

Consider, for example, a sample made up of structural materials - Iron, Cobalt and Nickel. In the energy range from 100eV to 3keV each of these has an easily distinguishable resonance with a peak cross-section much higher than the cross-sections of the other materials (see table 3.1). The resonance energies and peak cross-sections of some other nuclides, which have been used in experiments, are also listed. Note that the macroscopic cross-sections (Σ) allow for a simple estimate of the relative thicknesses of sample components which could be distinguished, as the attenuation (I/I_0) for each is given by

$$I/I_0 = \exp(-\Sigma x)$$

where x is the thickness of the sample nuclide.

3.1.2 METHOD

In RNR the timing gates are set on appropriate resonances to allow images of up to eight sample nuclides to be obtained simultaneously. The

first stage in producing resonance radiographs is to obtain a time-of-flight spectrum of the whole energy region of interest. The flightpath length (L) and start delay (t_0) of the time of flight scaler are known to a first approximation and so the energies (E) of resonances seen at times (t) on the spectrum may be calculated, using the equation:

$$\sqrt{E} = 72.3 L / (t+t_0)$$

(see section 1.4). The resonances can then be identified and the sample composition verified. From the established values of the resonances, the flightpath length and start delay may be calculated more accurately and then the settings for the gates may be worked out. They are usually positioned between the half-maximum points of relevant resonances.

The system is then ready for data collection. The length of time required for runs may be calculated as follows: -

Given a sample of n components (c) with densities $\rho_1, \rho_2, \dots, \rho_c, \dots, \rho_n$, thicknesses l_c etc. and atomic numbers A_c etc.; the attenuation due to one component at energy $E_{c\text{res}}$ where it has a resonance is:

$$\alpha_c = N_c / N_0 = \exp(-N_A \rho_c l_c \sigma_{c\text{res}} / A_c)$$

where σ is the cross-section of component c at $E_{c\text{res}}$, N_0 is the number of counts that would be recorded in a gate set at $E_{c\text{res}}$ without the sample and N_c is the number that would be recorded in the gate with only compo-

ment c present. N_A is Avogadro's constant. The total attenuation of the beam due to all the other components at this energy is:

$$\alpha_R = N_R/N_0 = \exp\left(\sum_i (-N_A \rho_i l_i \sigma_{i_{res}}/A_i)\right) \quad (i \neq c)$$

so the total attenuation at $E_{c_{res}}$ is:

$$\alpha_c \alpha_R = N_T/N_0$$

where N_T is the total number of counts recorded in the gate with the sample present. The data must be normalised in order to remove the effects of detector and beam nonuniformity - this is done by dividing the data by a sample-out run with N_0 counts in the gate. In order to show the presence of component c with 99% certainty, the error on this ratio must be less than 1/3 of the magnitude of the effect. i.e.

$$\sigma([N_R - N_T]/N_0) < [N_R - N_T]/3N_0$$

if $N_0 \gg N_R, N_T$ then this reduces to

$$(N_R + N_T)^{1/2} / N_0 < (N_R - N_T) / 3N_0$$

$$\Rightarrow N_0 > 9 (1 + \alpha_c) / \alpha_R (1 - \alpha_c)^2 \quad \text{for each pixel.}$$

The counting time necessary to achieve this value of N_0 may be found from a preliminary run.

In practice the images were much worse after the calculated counting time than had been expected. This was found to be due to a high level of noise, which was non-uniformly distributed across the IPD. In order for the noise counts to be statistically insignificant, a much longer counting time was needed, but it was not always possible to achieve

this: the PNR experiments were carried out on a 19m flightpath on the CMT shown in fig 2.4. The collimation of this beamline was far from ideal and the PNR detector was situated behind two other transmission detectors so the flux reaching it was very low. The quality of the radiographs obtained would certainly have been higher if a better flightpath had been available, or if the IPD had been less noisy.

The timing resolution of the system has components due to the scintillator, electronic jitter in the detector, timing channel width, electron pulse width, the rise and decay of neutrons in the target and the slowing down time of neutrons in the moderator. In the resonance energy region the electron pulse width (typically 5 ps) dominates, so the timing resolution is independent of energy. The relation between resolution and timing resolution may be derived from the equation for kinetic energy:

$$E = 1/2 m v^2 = (m/2) \cdot (l/t)^2$$

where E is kinetic energy, m is neutron mass, v is neutron velocity, l is flightpathlength and t is flight time. Hence

$$\delta E / \delta t = -m l^2 / t^3 = -(m/l) \cdot (l/t)^3$$

$$\Rightarrow \Delta E = -\Delta t (m)^{1/2} / l \cdot E^{3/2}$$

Thus the resolution function broadens with increasing neutron energy and it is more difficult to resolve resonances at higher energies. In the epithermal energy region, where the detector is used for resonance

radiography, the energy resolution has not limited the performance of the detector in any of the experiments that have been carried out.

3.1.3 DATA PROCESSING

After the run, data must be transferred to the main IBM computer and processed. To obtain images, the program RESULTS is used (see section 2.4). All the runs for the same sample must first be added together. Each resonance gate data-array is then normalised by division by the appropriate sample-out run to remove the effects of detector and beam non-uniformity. A mask data-array of the same shape as the sample is then created and the normalised data are multiplied by this. Finally the datasets can be plotted.

3.1.4 RESULTS

Some of the resonance radiographs obtained are shown in the following pages. Fig 3.1 represents a silver cross and plate. The scale is ≈ 1.5

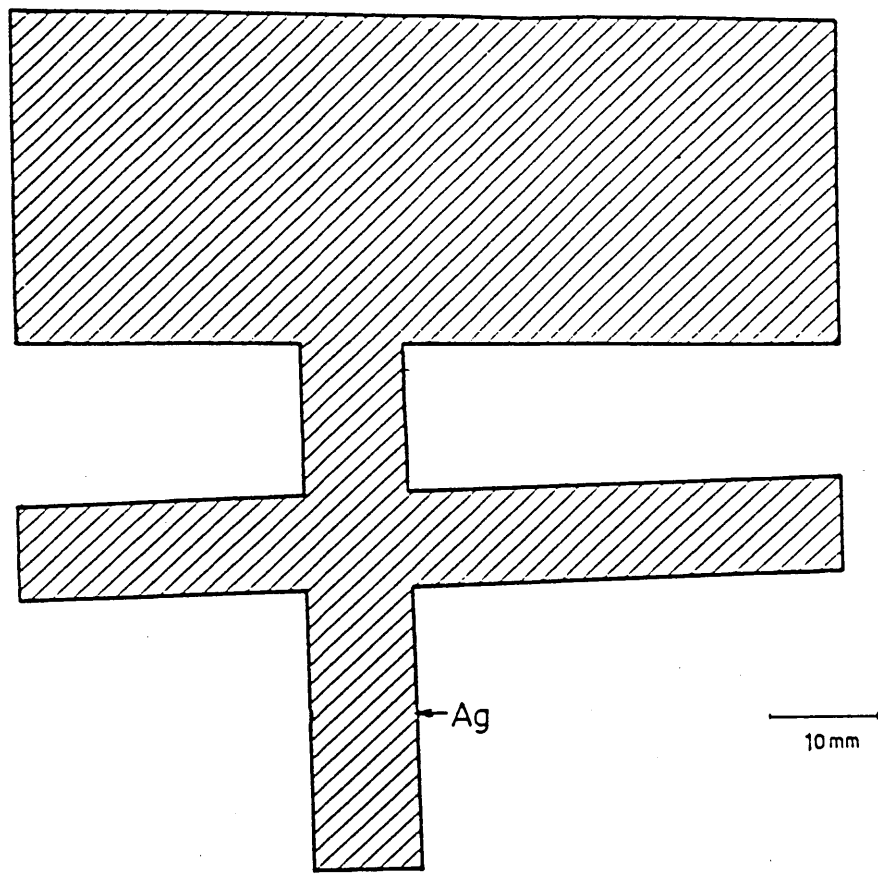


Fig 3.1 Radiograph of a silver cross and plate together with a diagram of the sample

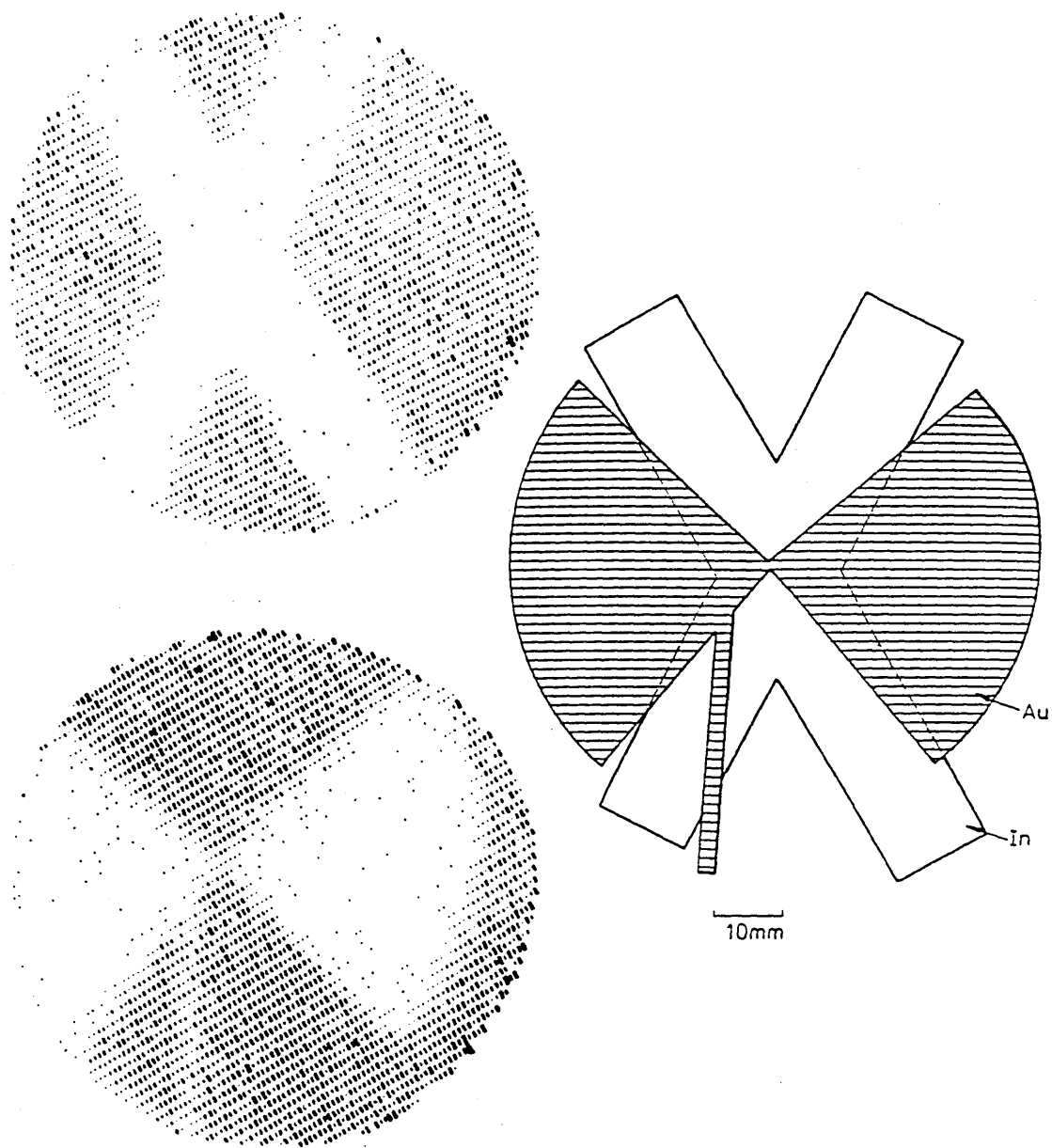


Fig 3.2 Radiograph of a gold and indium sample together with a diagram of the sample

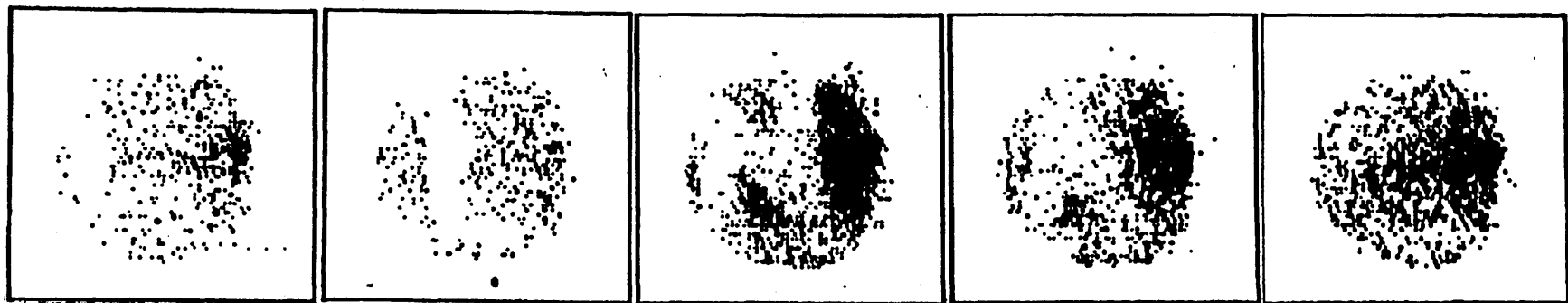


Fig 3.3 Radiograph of the 'linac' sample - the letters were superposed on one another in the sample

x natural size. Fig 3.2 shows an indium cross and gold quadrants and bar. These components were positioned in the sample as shown - the two radiographs were taken simultaneously. Fig 3.3 again demonstrates the ability of the detector system to produce several images at one time. The sample was composed of 5 components in the shapes of the letters of the word 'LINAC', which were superposed onto one another. The elements used were: uranium (L), platinum (I), silver (N), tantalum (A) and cobalt (C). The resonances that were used for each element are listed in table 3.1. All the components were $\approx 1\text{mm}$ thick - the problem of sample thickness is discussed in section 4.1.

The radiographs which have been produced demonstrate that the technique can work. However, due to the lack of availability of a suitable flightpath, it was impossible to test the method rigorously. The conclusions from this work are discussed in section 4.1.

3.2 BEAM PROFILE RADIOGRAPHY

The method used to obtain radiographs of the neutron beam itself is similar to that used for resonance radiography. The length of time required for each run depends on the magnitude of the variations which are

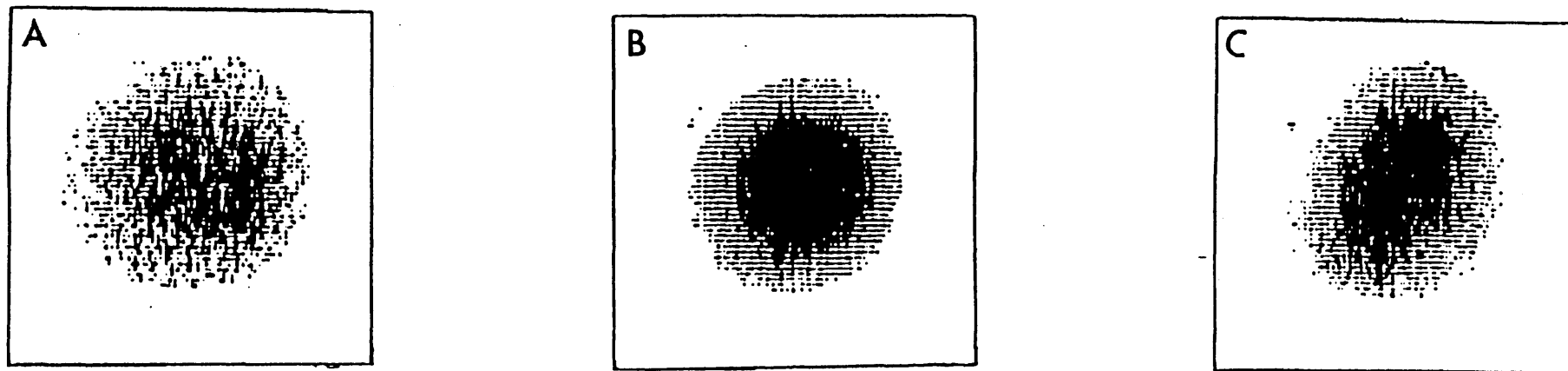


Fig 3.4 A series of beam profile measurements for a 10m flightpath on the CMT.

The energy ranges shown are: A 5.0 - 9.0 meV , B 19 - 30 meV , C 2.1 - 4.2 eV

to be observed. Initially data is collected in the ungated mode in order to obtain a time-of-flight spectrum. A thin filter is put into the beam for this run so that identifiable resonances may be seen and from this data the flightpath length and start delay may be calculated as before. The filter is then removed and the eight gates are set to the required energy regions for the next run. Finally a neutron source is set in front of the detector and an ungated run is obtained with at least as many counts as in any of the previous gates. The source distance must be at least 50cm to obtain 1% uniformity across the scintillator. After retrieval of the data each of the eight gates is normalised by the source-run and masked to a circle. The resultant arrays are then plotted. Examples of beam profile measurements from a beam line on the CMT are shown in fig 3.4. The radiographs do indeed show a variation of the neutron beam profile with energy. The results are discussed in section 4.2.

3.3 STRAIN RADIOGRAPHY

The strain radiography experiment was set up to test the feasibility of using the PNR detector to measure mean strain through a sample as a function of position across it. The technique is based on the measure-

ment of shifts in the wavelength of neutrons that are diffracted - which are related to stress induced shifts in the spacings of crystal planes (i.e. strain).

The Bragg equation:

$$2 d^{hkl} \sin \theta^{hkl} = \lambda$$

relates the angle of diffraction θ^{hkl} , for radiation of wavelength λ being diffracted by crystal planes $\{h,k,l\}$, to the interplanar spacing d^{hkl} . It indicates that changes in interplanar spacing, such as those due to strain, are associated with changes in the diffraction angle. This is the basis of two of the most widely used strain measurement techniques - neutron diffraction and X-ray diffraction. However, if the diffraction angle (θ) is fixed, changes in lattice spacing cause neutrons of different wavelengths to be diffracted, and a fixed, energy sensitive detector may be used to measure the wavelength and hence the strain. The PNR detector is suitable for this purpose and, in a transmission geometry (i.e. source, sample and detector aligned in the beam), its spatial sensitivity should permit the measurement of mean strain through the sample as a function of position. Such a system would have the advantage of combining 3 useful features - non-destructive evaluation, measurement of mean strain (as opposed to surface strain) and spatial sensitivity - which are not found together in any of the strain measurement methods in general use. It was decided to set up a prototype strain radiography

system based on the PNR detector to test the practical feasibility of the technique. A series of transmission measurements were also carried out in which a narrow neutron beam was used to obtain measurements of edge position at 19 points across the sample. This was done in order to provide data with which to assess the radiography results.

3.3.1 THEORY

The technique of strain radiography relies on the coherent scattering of neutrons by crystalline solids. Planes of atoms in a crystal are designated by their Miller indices h,k,l , which give their orientation relative to the crystal axis (see ref 20, 21). The interplanar spacing of a set of parallel planes $\{h,k,l\}$ is d^{hkl} , where:

$$d^{hkl} = a_0 / \sqrt{(h^2+k^2+l^2)}$$

a_0 being the lattice constant for the material in question. (e.g. for iron $a_0 = 2.87 \times 10^{-10}\text{m}$). Radiation scattered by this regular array of atoms may interfere constructively. The wavelength for diffraction is given by Bragg's Law:

$$2 d^{hkl} \sin \theta^{hkl} = \lambda$$

$$\Rightarrow \lambda = 2 a_0 \sin \theta^{hkl} / \sqrt{(h^2+k^2+l^2)}$$

Not all sets of planes produce diffraction, however; the positions of the atoms may be such as to produce destructive rather than constructive interference. The values of h,k,l for which diffraction occurs depend on the type of primitive cell of the crystal (see ref 20, 21). The primitive cell for iron is body centered cubic and constructive interference occurs when $h+k+l$ is even, e.g. $\{1,1,0\}$, $\{2,0,0\}$, $\{2,2,0\}$ etc..

For a polycrystalline sample with randomly oriented crystallites all angles of θ are present so, for a given plane, the maximum wavelength for which diffraction can take place occurs when $\sin\theta = 1$ i.e.

$$\lambda = 2d = 2 a_0 / \sqrt{(h^2+k^2+l^2)}$$

Thus the transmission of neutrons through a sample would be expected to increase at this wavelength due to a particular set of planes $\{h,k,l\}$. This can indeed be observed on a transmission time-of-flight spectrum (which may be thought of as a plot of transmission vs. neutron wavelength). Fig 3.5 is part of such a spectrum, showing a series of Bragg edges from different sets of planes. Their finite widths are due almost entirely to the resolution function of the detection system. The exact position of any edge depends on the mean value of the interplanar spacing of the associated set of planes. The first iron edges occur at :

$$\lambda = 4.0\text{\AA} \Rightarrow E = 5\text{meV}$$

$$\lambda = 2.9\text{\AA} \Rightarrow E = 10\text{meV}$$

$$\lambda = 2.0\text{\AA} \Rightarrow E = 15\text{meV}$$

etc.

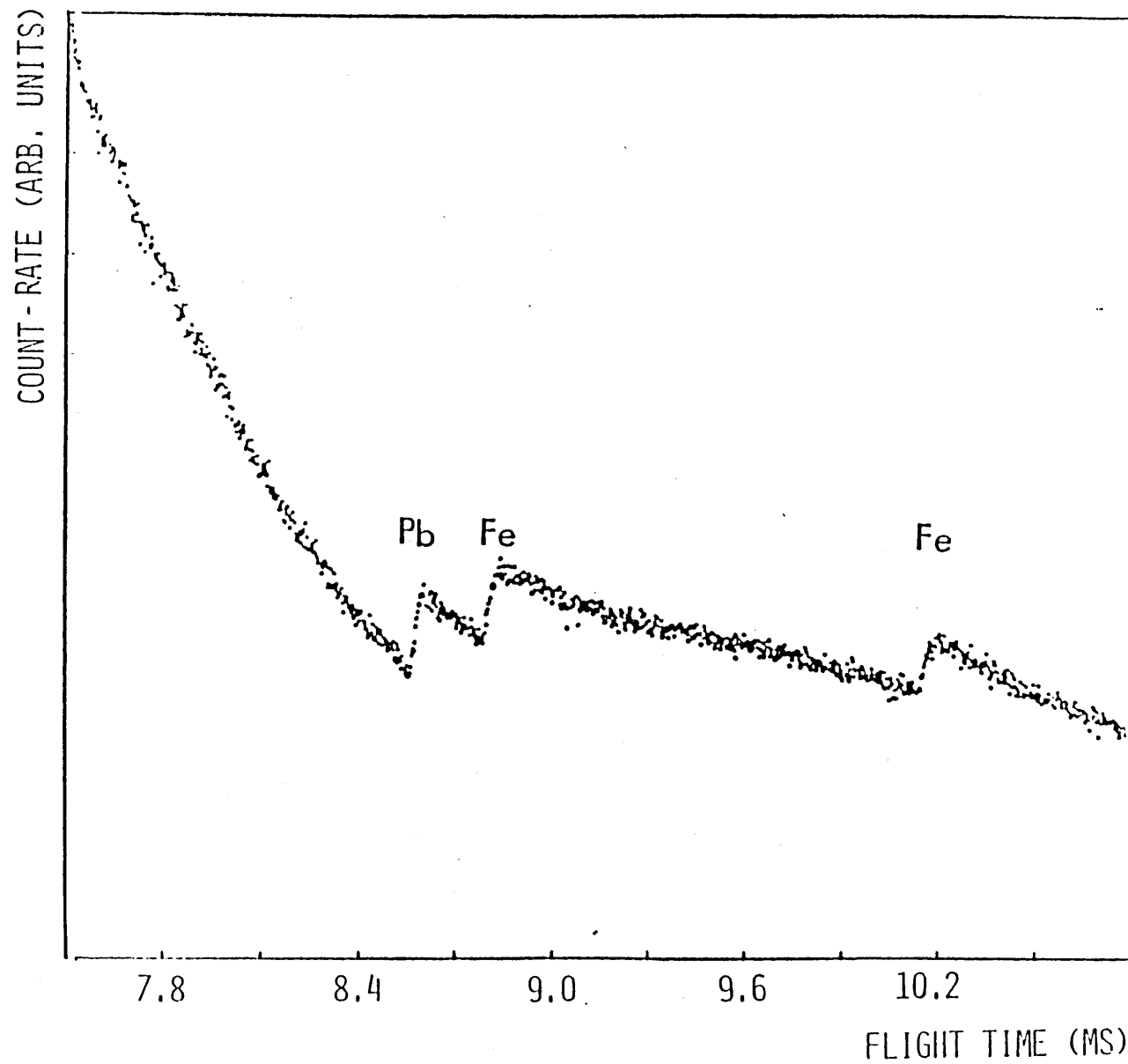


Fig 3.5 A time-of-flight transmission spectrum showing Bragg edges due to iron and lead

Any change in this spacing, such as that caused by strain, is reflected in a shift of the edge:

$$\Delta\lambda = 2\Delta d$$

or, in terms of change in flight time:

$$\Delta t = 2 m L \Delta d / h$$

where m is the neutron mass, L is the flightpath length and h is Plank's constant.

When external stress is applied to an object and then removed, some internal stress may remain. Three orders of this residual stress are conventionally recognised. First order stress is uniform on the scale of a few grains, second order stress is uniform on the scale of one grain and third order stress is uniform over a few interatomic spacings. First order stress produces macrostrain which results in a shift of the Bragg edge, whereas second and third order stress produce microstrain and edge broadening. It is macrostrain that is of chief interest in engineering, and it is this that is measured by the system. Microstrain is generally smaller in magnitude than macrostrain; the edge broadening produced by microstrain in the strain radiography experiment was negligible.

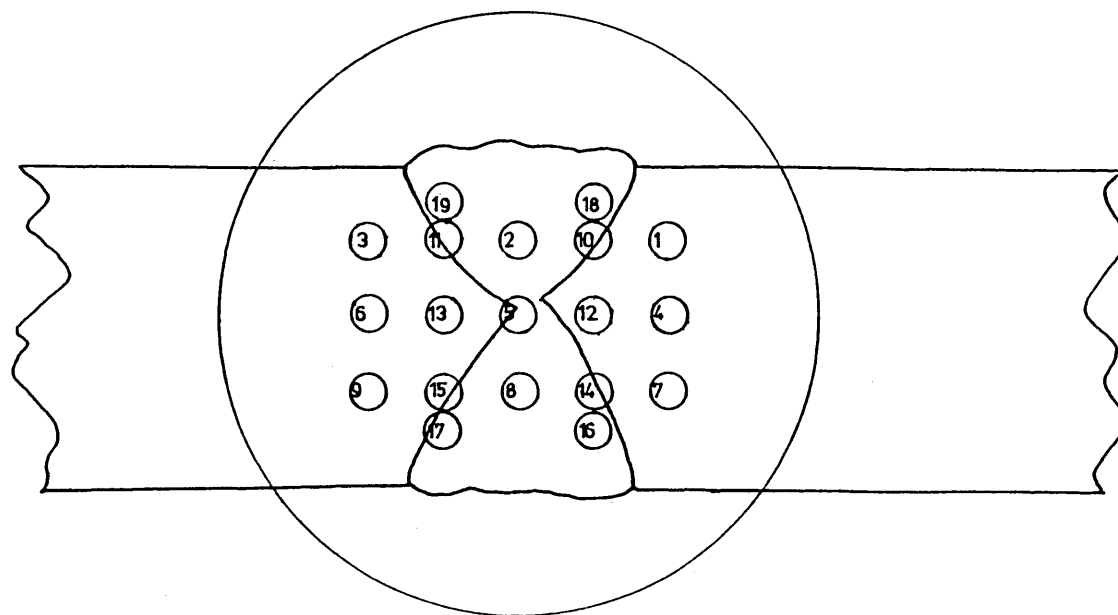


Fig 3.6 The strain radiography double-V weld sample

The small circles indicate the areas of the transmission measurements

The large circle indicates the area of the radiography measurement

3.3.2 METHOD

The sample used for this experiment was a double V weld specimen made of 50-D-C-Mn steel 14mm thick (see fig 3.6). It was chosen because its dimensions were suitable and previous measurements (ref 22, 23) had shown residual stress up to the yield stress through the weld. The experiment was carried out on a 9.7m flightpath on the CMT, (see section 2.1.2).

The transmission through the sample was measured on and at either side of bragg edges by appropriate setting of the timing gates. A small shift of the edge caused the transmission in the central 'edge-gate' to change, whilst the transmission into the other gates remained constant. By using these outer gates for normalisation, the relative strain across the sample could be calculated and plotted. The gate settings used are shown in fig 3.7. The gate length and separation were determined by the requirements of high countrate (gates as long as possible) and maximum uniformity of efficiency and background (gates as close as possible), together with the limitation that they had to be at least 20ps apart in order to prevent the 'overlapping' of pulses from one gate into the next. Gate1 was not used because, due to the logic of the data-handling system, any stray pulses that were detected between gates would be recorded there (see section 2.3.2). Gate5 was set on a flat section of

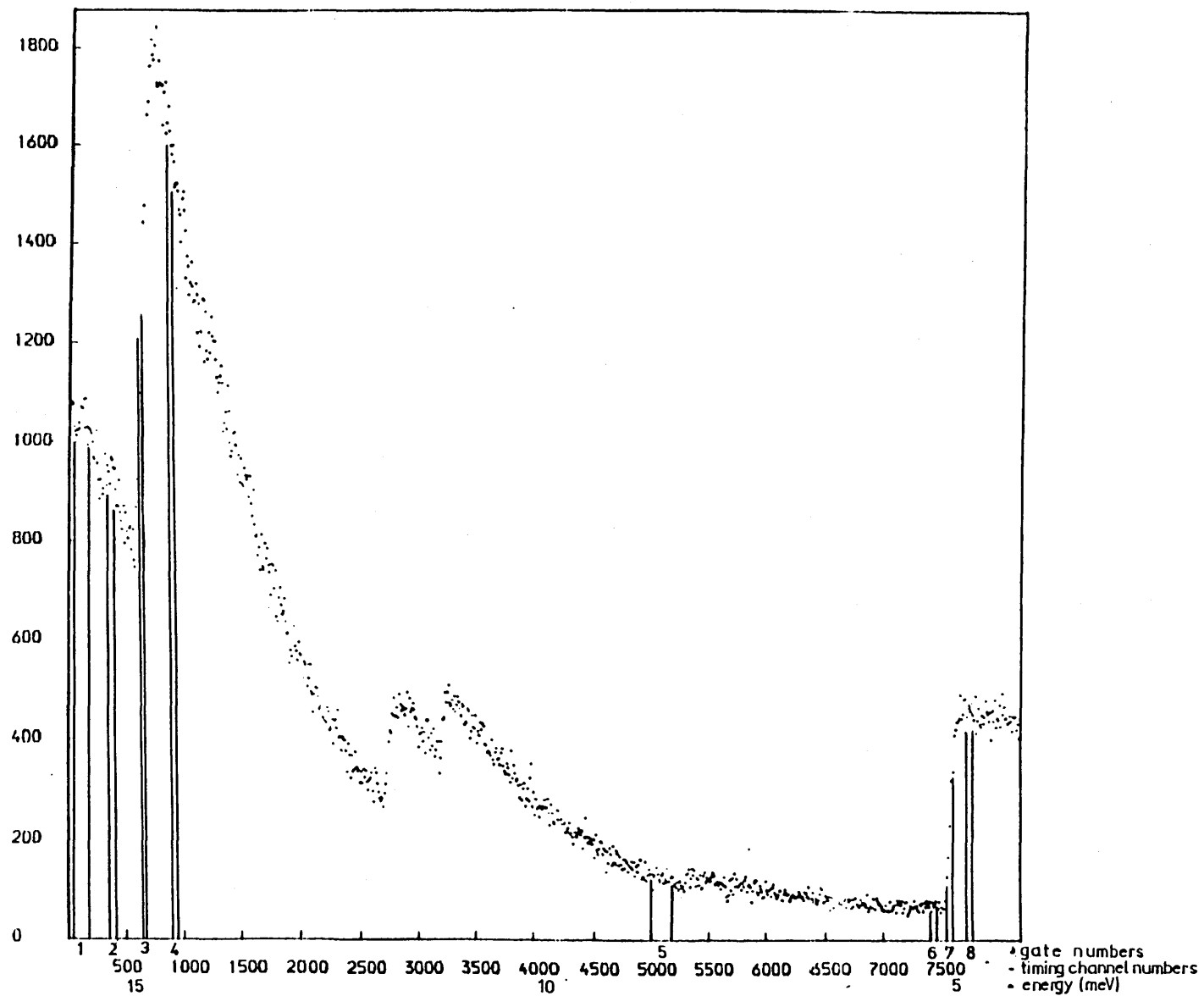


Fig 3.7 A time-of-flight spectrum for iron showing (approximately)
the gate settings for the strain radiography experiment

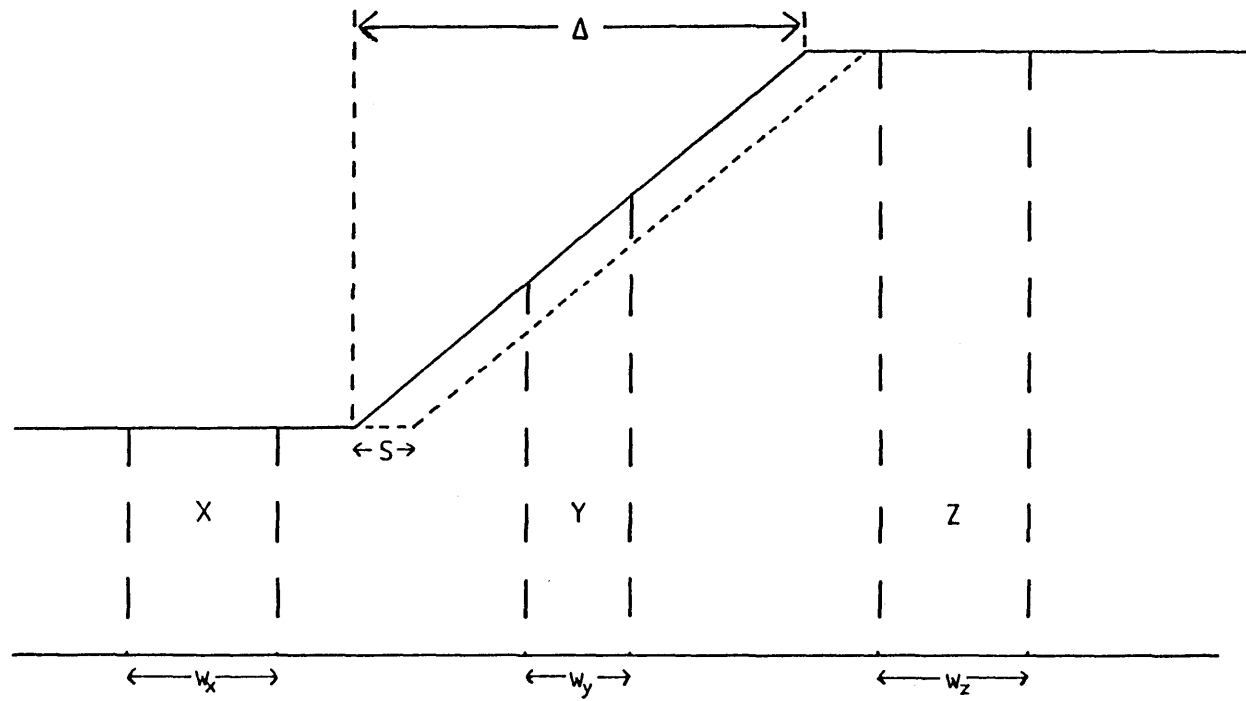


Fig 3.8 Schematic diagram of the gate settings about each edge

the spectrum in order to provide an image of the sample without any strain effects. The 5 and 15meV edges were chosen for the other gates because a preliminary run had indicated that these were clearest.

Assuming that the edge can be approximated by a straight line and that the spectrum at either side of it is flat, (see fig 3.8), then the strain can be related to the counts N_x, N_y, N_z in each of the three gates across the edge in the following way:

If the second gate (Y) were positioned exactly halfway along an edge, then N_0/w_y would be equal to the mean of N_x/w_x and N_z/w_z . Its position is not known exactly, but the value of N_0/w_y can be said to be proportional to that mean. i.e.

$$N_0/w_y = \alpha(N_x/w_x + N_z/w_z)$$

When the edge shifts by $S \mu s$, the change in counts per microsecond gate width in Y ($[N_0 - N_y]/w_y$) is equal to the shift multiplied by the slope (i.e. width/height) of the edge ($\Delta/[N_z/w_z - N_x/w_x]$). So

$$N_0 - N_y = w_y S \Delta / (N_z/w_z - N_x/w_x)$$

Thus the strain is given by:

$$\epsilon = \frac{S}{t} = \frac{\Delta}{t} \cdot \frac{1}{(N_z/w_z - N_x/w_x)} \cdot [\alpha(N_x/w_x + N_z/w_z) - N_y/w_y]$$

where t is the flight time.

The counting time was calculated for a strain of $\Delta t/t = 1/2900$ which corresponded to half of the maximum expected strain in the sample. The error on the strain measurement was calculated from the equation for strain given above: the uncertainties in the flight time and edge width are small with respect to the uncertainties on the other terms in this equation and are, therefore, ignored.

The standard deviation of the strain is given by:

$$\sigma(\varepsilon) = (\sigma^2(A)/A^2 + \sigma^2(B)/B^2)^{1/2} \cdot (A/B) \cdot (\Delta/t)$$

where

$$A = \alpha (N_x/w_x + N_z/w_z) - N_y/w_y$$

$$B = N_z/w_z - N_x/w_x$$

The absolute errors on the terms A and B will be approximately the same as the countrate in each gate is similar and $\alpha \approx 1/2$ due to the gate settings. The first term itself, though, is smaller than the second term by at least a factor of 3, so its fractional error will be much larger and will dominate the expression for the standard deviation of the strain. So:

$$\sigma(\varepsilon) \approx (\sigma(A)/A) \cdot (A/B) \cdot (\Delta/t) = (\sigma(A)/B) \cdot (\Delta/t)$$

Assuming that $\alpha \approx 1/2$, and that the height of the edge (B) is proportional to the counts in Y for each pixel - k being the constant of proportionality - then:

$$\sigma(\varepsilon) \approx \left[\frac{3N_y}{2w_y^2} \right]^{1/2} \cdot \frac{k w_y \cdot \Delta}{N_y t}$$

This must be less than one third of the expected strain (ϵ) in order for the strain to be measured with 99% certainty. Thus:

$$(3/2N_y)^{1/2} \cdot (k\Delta/t) < \epsilon/3$$

$$\Rightarrow N_y > (3k\Delta/t\epsilon)^2 \cdot 3/2$$

Now, $N_y = C_y w_y T$ where C_y is the counting rate per microsecond gate width in Y with the sample and T is the counting time. So:

$$T > (3k\Delta/t\epsilon)^2 \cdot (3/2C_y w_y)$$

The counting time for a shift of $1/2900$ was calculated. Δ was obtained by fitting a straight line to an edge due to an unstressed iron sample; the value obtained was $36.9\mu s$. The values of k , t , C_y and w_y from a preliminary run were: 1.0 , $9.9ms$, $0.0125 \text{ counts pixel}^{-1}\mu s^{-1}hr^{-1}$, $24\mu s$ and 1.22 , $5.7ms$, $0.085 \text{ counts pixel}^{-1}\mu s^{-1}hr^{-1}$, $14\mu s$ for the $5meV$ and $15meV$ edges respectively. Substituting these values into the last equation gives:

$$T > 219 \text{ days} \quad 5meV$$

$$T > 247 \text{ days} \quad 15meV$$

This was obviously unacceptable, so it was decided that neighbouring pixels should be summed to obtain a higher countrate per pixel at the expense of spatial resolution. By summing 18 pixels together, the resolution falls to $6mm$, but the counting time is:

$$T > 12 \text{ days} \quad 5meV$$

$$T > 14 \text{ days} \quad 15meV$$

The actual running time available was 12 days.

3.3.3 DATA ANALYSIS AND RESULTS

The raw data from the strain radiography experiment was in the form of 2 sets of 3 radiographs from gates before, on and after each of two edges. This was converted into 2 images representing the strain measured at each edge using the algorithm derived in section 3.3.2:

$$\epsilon = \frac{\Delta}{t} \cdot \frac{1}{(N_z/w_z - N_x/w_x)} \cdot [\alpha(N_x/w_x + N_z/w_z) - N_y/w_y]$$

The value of Δ in each case was obtained by fitting a straight line to the edge. The value of α which gave zero mean strain across the sample was used. The strain calculated from each edge was then plotted as a function of position as is shown in figs 3.9 and 3.10. Areas of high strain can be seen at the centre and the edges of the welds, as expected.

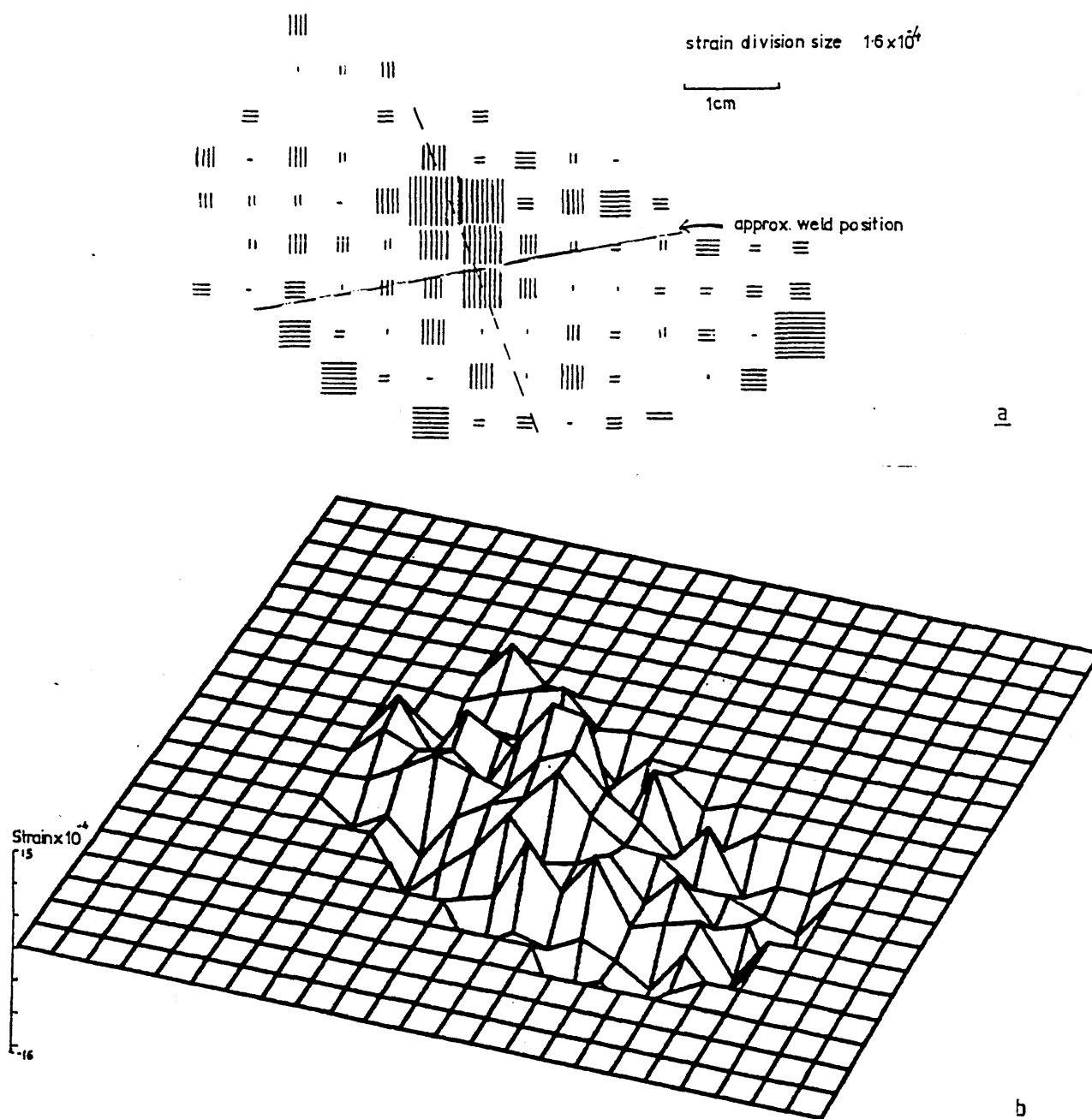


Fig 3.9 Strain radiographs from the 15meV edge data. a) Greyscale strain plot. Horizontal lines indicate negative (compressional) strain, vertical lines indicate positive (extensional) strain. b) 3-D strain plot. N.B. The calculated values of strain at any point may be found in the data array from which these images were plotted.

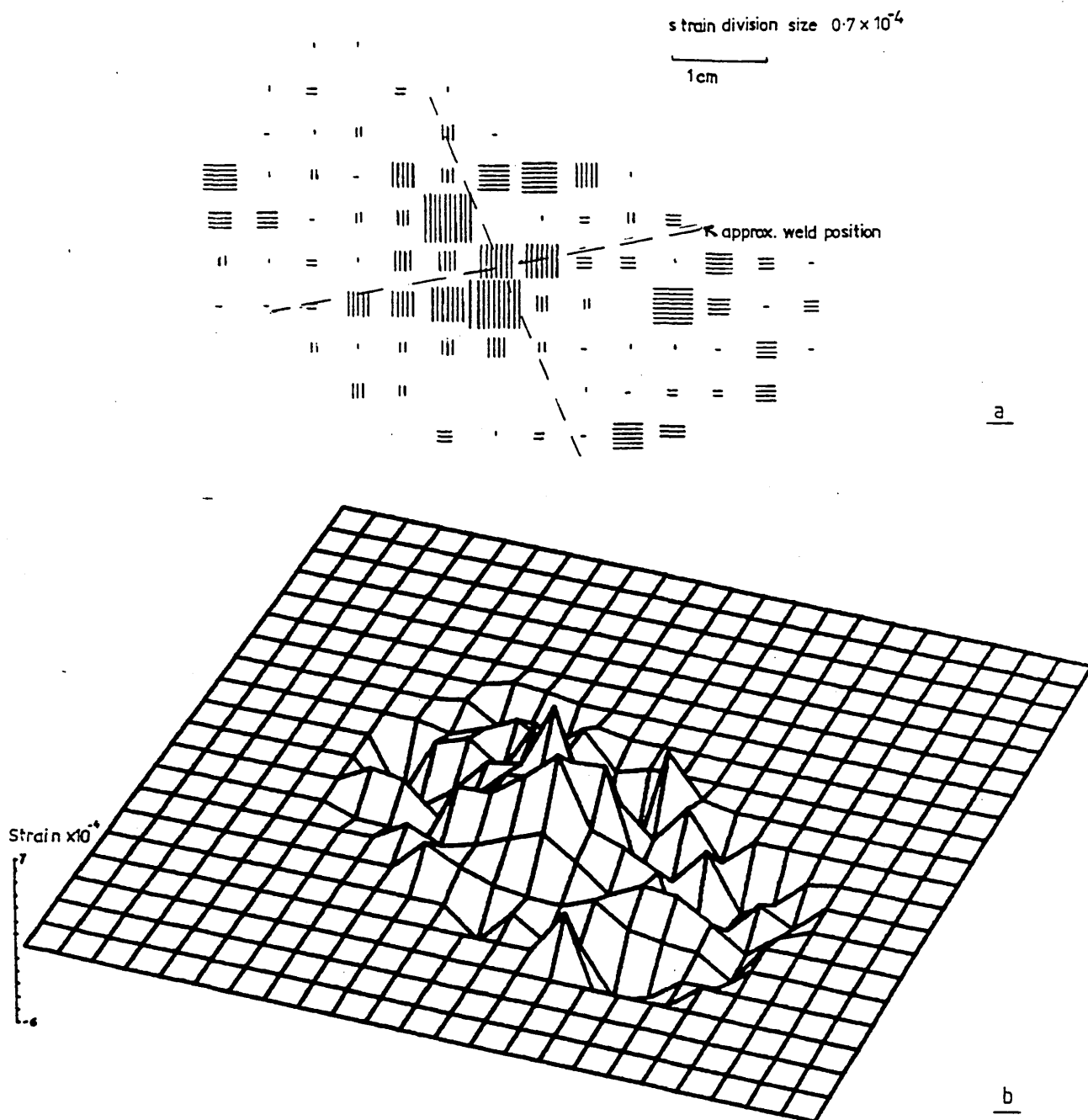


Fig 3.10 Strain radiographs from the 5meV edge data, a) Greyscale strain plot. Horizontal lines indicate negative (compressional) strain , vertical lines indicate positive (extensional) strain, b) '3-D' strain plot N.B. The calculated values of strain at any point may be found in the data array from which these images were plotted.

3.3.4 TRANSMISSION MEASUREMENTS

In order to test the results of the strain radiography experiment, a series of neutron transmission measurements were carried out on the sample. A narrow neutron beam was used to obtain time-of-flight spectra from 19 positions across the sample in turn. The relative strain in these areas could then be calculated for comparison with the radiography data.

3.3.4.1 Method

The measurements were carried out on an existing transmission system using a lithium glass detector on a flightpath on the CMT (see fig 2.4). The sample was situated at 5.2m from the target, 3.7m away from the detector. A converging - diverging collimation geometry was used, with the smallest collimator of 5mm diameter 3cm before the sample. A time-of-flight spectrum was obtained for each of the 19 measurement positions shown in fig 3.6.

The counting time necessary for the observation of a fractional shift of $\Delta t/t = 1/2900$ in the 5meV and 15meV edges was calculated. In order to measure the shift with 99% accuracy, the error must be:

$$\Delta x < \Delta t/3$$

where

$$\Delta x = \sigma/\sqrt{\sum n_i}$$

(σ is the resolution and $\sum n_i$ is the sum of the counts in an edge after the background has been subtracted).

As the resolution function is strongly dominated by the effect of the moderator at these energies, its shape may be approximated by a gaussian, for which:

$$\sigma \approx 0.43w \quad (w = \text{fwhm of resolution function})$$

The shape of an edge is the integral of the resolution function, so the width, and hence the resolution could be estimated from a preliminary run. Then, writing flight time in terms of flightpath length (L) and energy (E), the total number of counts required in an edge is:

$$\sum n_i > (3 \times 0.43 \times 2900 w \sqrt{E} / 72.3 L)^2$$

The flightpath length was 8.9m and the edge widths were 25ps. So:

$$\sum n_i > 100 \quad \text{for the 5meV edge}$$

The preliminary run had shown a countrate of 10 counts per hour in the edge, so the required running time was 10 hours for each measurement.

3.3.4.2 Data Analysis and Results

Initially the transmission data was analysed to produce a plot of strain across the sample for visual comparison with the radiography plots. This was done by calculating the integrated resolution function and fitting it to bragg edges on the time-of-flight spectra from each of the 19 measurement positions. In this way the edge position and hence the fractional shift and finally the strain was found for each.

The first stage in this process involved the calculation of the integrated resolution function. The resolution function has components due to the scintillator, electronic jitter in the detector, timing channel width, electron pulse width, the rise and decay of neutrons in the target and the slowing down time of neutrons in the moderator. In the energy region of interest, the effect of the moderator dominates. The fwhm of the moderator term is about 25 μ s, whereas the electron pulse width is 5 μ s, the channel width 0.4 μ s and the other effects contribute less than 0.1 μ s each. In particular, the moderator term changes the shape of the resolution function, as it has a tail about 40 μ s long. This may be due to neutrons being stored in the moderator. The resolution function was calculated using the algorithm given by Ikeda & Carpenter (ref 24), which includes this effect:

The time distribution of neutrons emerging from a hydrogenous moderator may be approximated by the slowing-down time distribution for neutrons in an infinite medium of free protons at rest with no absorption; which is a chisquare distribution with 6 degrees of freedom:

$$\phi(v,t) = \frac{1}{2} \Sigma v (\Sigma v t)^2 \exp(-\Sigma v t) \quad t > 0$$

where ϕ = flux, v = neutron velocity, t = time and Σ = macroscopic neutron scattering cross-section. This approximation works well above thermal energies but at lower energies another term must be introduced, giving:

$$\psi(v,t) = \int dt' \phi(v,t') [(1-R)\delta(t-t') + R\beta\theta(t-t')\exp(-\beta(t-t'))] \quad (t > 0)$$

where ϕ is the function given in the last equation, δ is the Dirac delta function, θ is the Heaviside function [$\theta(x < 0) = 0, \theta(x > 0) = 1$], R is the ratio of the area of the second term to the total area and $1/\beta$ is the characteristic storage time of the moderator. This equation may be rewritten as:

$$\psi(v,t) = \frac{1}{2} \alpha \{ (1-R) (\alpha t)^2 \exp(-\alpha t) + 2R [\exp(-\beta t) - \exp(-\alpha t) (1 + (\alpha - \beta)t + \frac{1}{2}(\alpha - \beta)^2 t^2)] \alpha^2 \beta / (\alpha - \beta)^3 \}$$

where $\alpha = v\Sigma$ and Σ can be expressed as a function of wavelength :

$$\Sigma = (S_1^2 + S_2^2 \lambda^2)^{1/2}$$

A routine was written (using Harwell subroutines - ref 25) to calculate the integral of this equation and fit it to Bragg edges on the transmission spectra. A least squares fitting method was used with x (the

Table 3.2 RESULTS FROM TRANSMISSION MEASUREMENTS

Position Number	Strain ($\times 10^{-4}$)
1	-4.39
2	1.41
3	-0.03
4	-1.30
5	5.53
6	-0.51
7	-1.90
8	1.00
9	-0.27
10	1.50
11	-0.40
12	2.95
13	3.33
14	0.57
15	2.88
16	-6.54
17	-1.11
18	-5.99
19	1.16

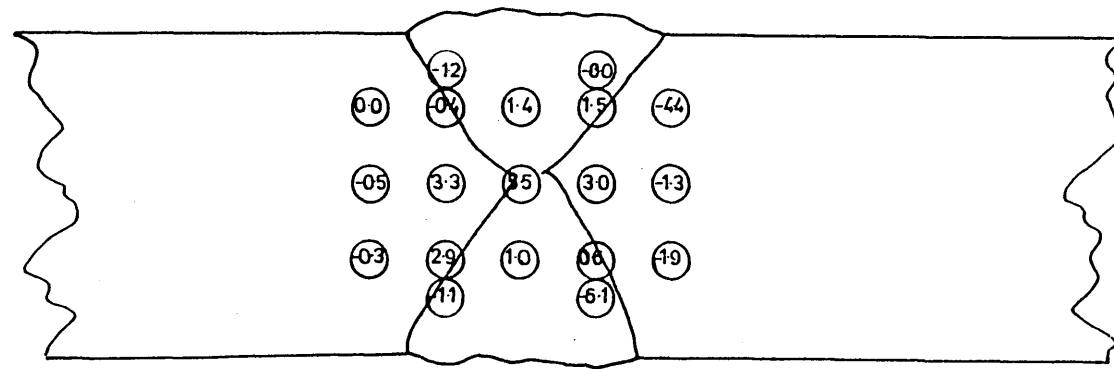


Fig 3.11 Strain ($\times 10^{-4}$) calculated from transmission measurements

edge position), k (the edge height), b (the background), S_1 , S_2 , R and β as variables. Five edges were fitted in this way, the best fit was obtained for the 5meV edge, for which the χ^2 per degree of freedom was 0.92. The values of the parameters S_1 , S_2 , R and β were taken from this. The other fits gave similar results.

The parameters that had been obtained were then used in the next stage of the analysis. A program was written (again using Harwell sub-routines - ref 25) to fit the integrated resolution function to the edges on the time-of-flight spectra for each measurement position, with the parameters b , k and x as variables. In this way the edge 'positions' for each measurement position were found. The best fits were again obtained for the 5meV edges. The mean edge position was calculated and the percentage shift of each measurement was obtained and plotted as a function of spatial position. The results are shown graphically in fig 3.11 and listed in table 3.2.

3.3.5 NUMERICAL COMPARISON OF RADIOGRAPHY AND TRANSMISSION DATA

The radiography and transmission data were also compared numerically. The sections of the transmission spectra corresponding to the 8

radiography gates and the positions on the radiography images corresponding to the 19 transmission measurement positions were calculated. Thus 19x8 pairs of equivalent measurements were identified and a least squares fitting method was used to compare them.

The 'gate-equivalents' of the transmission spectrum were identified by calculating the flight times for neutrons of the same energy in each system. In each case:

$$t - t_0 = 72.3 L / \sqrt{E}$$

where t = recorded flight time, t_0 = time-of-flight scaler start delay, E = neutron energy and L = flightpath length. So, for neutrons of the same energy in the two systems:

$$(t_R + t_{R0}) / L_R = (t_T + t_{T0}) / L_T$$

$$\Rightarrow t_T = (L_T / L_R) (t_R + t_{R0}) - t_{T0}$$

where the subscripts T and R refer to transmission and radiography data respectively. The values of t_0 and L for each system were obtained from the data using M.C.Moxon's code FPTOC - another least squares fitting routine, and the first and last channels of each gate were identified from the PNR time-of-flight data. The gate times and hence the number of counts per gate in each of the transmission measurement positions was then calculated.

The equivalent positions on the radiography images were identified by visual inspection and from records of the transmission experiment geometry. Six pixels were summed for each of the 19 positions to give equivalent measurement areas.

The data for the 'edge gates': - 2,3,4 and 6,7,8 were then compared. Suppose that the true count (N) for each position and each gate in each system is given by:

$$M = E N + B W$$

where E is the efficiency of the detector, M is the measured count, B is the background per microsecond and W is the gate width. The background for the transmission experiments was negligible and the efficiency and background across each set of 3 gates was assumed to be constant. Hence, the least squares fit of the two sets of data at either edge is obtained by minimising the following expression for χ^2 :

$$\chi^2 = \sum_p \sum_g [M_{pgT}/E_{pT} - M_{pgR}/E_{pR} + B_{pR} W_g/E_{pR}]^2 / [M_{pgT}/E_{pT}^2 + M_{pgR}/E_{pR}^2]$$

where subscripts p, g, T and R refer to positions, gates, transmission and radiography respectively.

The number of variables in this expression is too large for a least squares fit, so the relative efficiency $E'_p = E_{pR}/E_{pT}$ and the adjusted background $B'_p = B_{pR} W_g$ are used. Hence:

$$\chi^2 = \sum_p \sum_g (E'_p M_{pgT} - M_{pgR} + B'_p)^2 / (E'_p M_{pgT} + M_{pgR})$$

Another program using Harwell subroutines (ref 25) was written to calculate and minimise this expression. The goodness of fit of one set of data to the other was judged from the value of χ^2 per degree of freedom. The values obtained are listed in table 3.3.

3.3.6 DISCUSSION

Visual inspection of the radiography and transmission data indicated a reasonable degree of agreement between the two. This was confirmed by the results of the numerical comparison for 14 of the 19 points, which gave a χ^2 per degree of freedom of 2.0 for the 5meV edge and 1.4 for the 15meV edge. When the other 5 points were included, however, the fit between the sets of data became very much worse - the best values of χ^2 per degree of freedom were 9.2 and 6.3 for the 5meV and 15meV edges respectively. This was due to a high noise background generated in the IPD as a results of the intense flux of gammas and high energy neutrons at the start of each machine pulse. The noise was unevenly distributed across the detector and decreased with time, as can be see fom table 3.3.

Table 3.3 RESULTS FROM MEASUREMENT COMPARISON ANALYSIS

Transmission counts (8 gates x 19 positions)

1	10189	1544	1236	2354	1013	74	183	262
2	9123	1436	1133	2255	930	54	166	259
* 3	9108	1451	1170	2225	995	65	214	253
4	16315	2553	2096	3731	2502	124	421	585
5	16059	2488	1944	3868	2297	126	358	578
* 6	15621	2511	2040	3707	2463	144	471	572
7	10407	1684	1376	2527	1530	103	302	393
8	10160	1613	1292	2520	1215	100	288	379
* 9	9735	1589	1244	2285	1335	97	299	385
10	8800	1327	1191	2183	1310	81	252	340
* 11	8781	1403	1166	2083	1228	63	232	330
12	8948	1488	1151	2175	1372	65	203	334
13	8622	1419	1148	2080	1413	68	231	324
14	9170	1430	1182	2145	1171	90	277	316
15	8575	1404	1196	2034	1153	80	209	319
16	8393	1310	1130	2072	1066	84	192	289
17	7926	1254	1080	2040	1014	60	223	312
18	9900	1652	1320	2313	1345	77	278	336
* 19	9816	1487	1311	2423	1269	78	257	357

Radiography counts (8 gates x 19 positions)

1	49718	9059	7047	11443	9148	818	1805	2420
2	285949	54651	36528	49720	51144	6889	6879	6619
* 3	285949	54651	36528	49720	5114	6889	6879	6619
4	45802	8343	6419	10697	8091	706	1679	2137
5	29559	5271	4147	6666	4678	470	1013	1265
* 6	282963	53898	36312	49506	50388	6854	6986	6851
7	42089	7579	5794	9601	7048	762	1423	1955
8	25101	4633	3461	5782	4002	378	778	1101
* 9	116376	21642	15434	22363	19829	2479	3109	3637
10	45692	8269	6527	10635	7995	789	1631	2152
* 11	220741	41427	28367	38791	5327	5556	5550	
12	30414	5541	4180	6925	5329	443	990	1340
13	46890	8566	6704	10017	7534	846	1566	1804
14	28488	5164	3895	6674	4861	462	843	1239
15	38714	7073	5298	8757	6239	616	1281	1674
16	34458	6201	4653	7993	5628	599	1179	1611
17	40090	7270	5658	9256	6973	649	1462	1831
18	47520	8735	6526	10834	8184	817	1742	2183
* 19	244297	46720	31266	42489	44126	5917	5968	5880

χ^2 degree of freedom from 19 points: gates234 - 6.3 , gates 678 - 9.2

χ^2 per degree of freedom from 14 points (omitting those starred):
gates234 - 1.4 , gates678 - 2.0

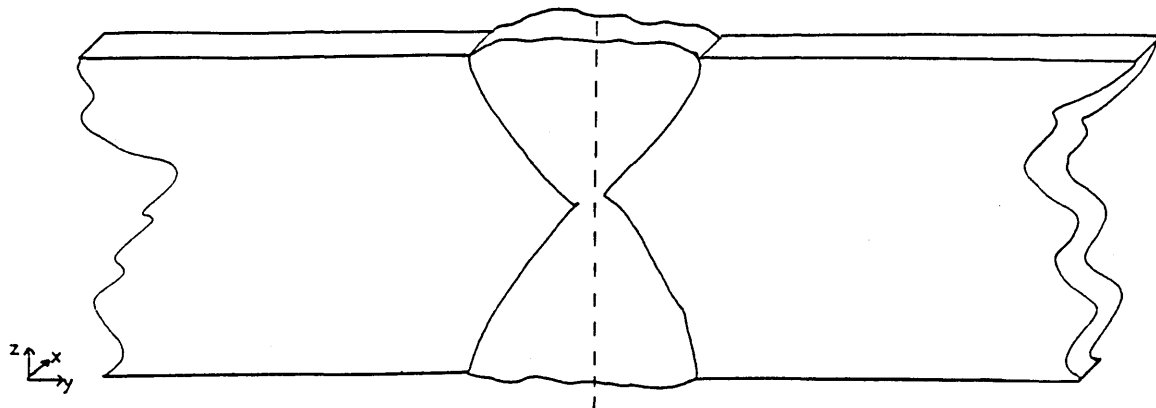
The assumption of a flat background across each set of three gates, as used in the data comparison calculations was, therefore, invalid in the high noise regions. A similar assumption was made in the analysis of the radiography data, in that α was taken as constant across the sample. Had more running time been available it would have been possible to find values of α for each pixel, from an unstressed sample. The effects of the non-uniform noise distribution could then have been accounted for and so a more accurate representation of the strain across the sample could have been obtained.

The radiography data may also be compared with earlier measurements on the sample performed by Allen et al. (ref 22). They used a neutron diffraction technique to measure residual stress in a series of positions along the axis of the welds. The strain may be calculated from the stress using the equations shown in figure 3.12. This was done and the results were plotted together with the equivalent data from the radiography experiment, which was from a 'low noise area'. A fair agreement can be seen between the sets of data. It was concluded that, in the areas where the detector was not too noisy, the strain radiography system gave the desired results in good agreement with other measurement techniques.

It appears then, that strain radiography is a feasible method of strain measurement. However, it is also evident that there are still

Fig 3.12 Comparison of strain radiography data with strain calculated from neutron diffraction stress measurements by Allen et al (ref22).

a) The line of diffraction measurements



The relation between stress (σ) and strain (ϵ) for plane stress is:

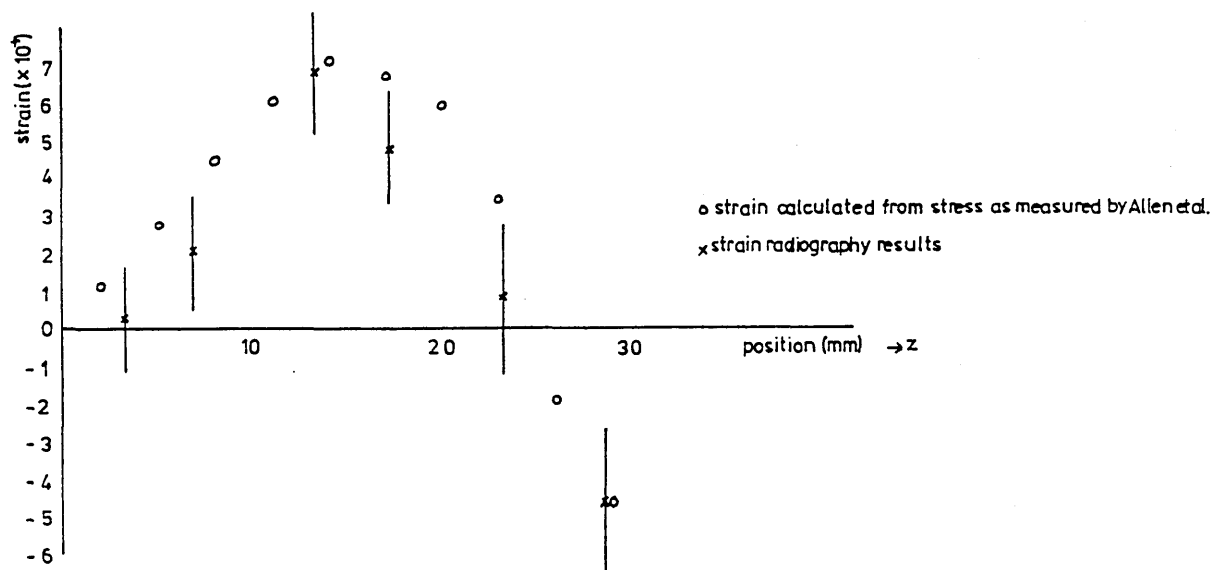
$$\epsilon_x = -\nu(\epsilon_y + \epsilon_z) / (1 - \nu)$$

$$\sigma_y = (\epsilon_y + \nu\epsilon_z)E / (1 - \nu^2)$$

$$\sigma_z = (\epsilon_z + \nu\epsilon_y)E / (1 - \nu^2)$$

$$\sigma_x = 0$$

where $\nu = 0.23$ and $E = 207$ GPa for 50 D C-Mn steel



b) Comparison of results

The two sets of data have been normalised in different ways. The diffraction data was normalised to zero by comparison with an area well away from the weld which was assumed to be unstressed. The radiography data was normalised so that the mean strain over the measurement area was zero. This may account for the slight vertical shift between the two sets of data.

problems to be solved: despite a very long counting time, the errors on the measurements were large. This was due to a combination of low detector efficiency and low beam intensity in the meV energy region, together with high detector noise and high beam intensity at higher energies. Alternative methods and possible solutions to these problems are discussed in section 4.5.

CHAPTER4 - CONCLUSION

The results obtained from the three radiography experiments not only demonstrate the feasibility of using the detector for resonance radiography, beam profile measurement and strain radiography, but they also indicate the main weaknesses of the present PNR system. The conclusions that can be drawn from the experiments will, therefore, be considered first and their implications for the development of the detector will then be discussed.

4.1 RESONANCE RADIOGRAPHY

Several resonance radiographs have been produced to demonstrate the potential viability of this technique. The quality of the images, however, is poorer than had been expected and the counting times were very long.

The poor image quality was caused by the unexpectedly high level of noise in some areas of the IPD. It appeared that this was generated by the intense γ and fast neutron fluxes which caused the IPD to be strongly illuminated with scintillator light at the start of each machine pulse. Because of the large noise background, it was necessary to record many more 'real' events than had been expected, so as to render the noise statistically insignificant. The beam conditions were such that this resulted in an impractically long counting time.

If it were possible to find a solution to the IPD noise problem, a better flightpath would be an essential requirement for making resonance radiography commercially feasible. With a purpose built flightpath the total flux into the scintillator would be much higher (≈ 10 counts per microsecond per machine pulse) and the counting rate for thin samples (a few millimeters thick) would be limited by the deadtime of the system, which is currently $\approx 10\mu\text{s}$. Resonances measured on a 10m flightpath are

mostly narrower than this, so the maximum counting rate into a resonance gate would be 1 count per machine pulse and the test radiographs could then be produced in minutes. For thicker samples (a few centimeters) of the same composition, the attenuation would be higher (it increases with the exponential of the sample length) and the counting time would, therefore, be longer. In practice the nuclide to be radiographed might form only a few percent of the sample and the required counting time would be longer again. Ideally the data from the detector would be used to provide information about the density of the nuclides, as well as their distribution, but this would extend the data collection period still further.

In order for a commercial system to be feasible the detector noise level would first have to be reduced and then the countrate capability would have to be increased by reducing the detector and data-collection system deadtimes to less than 1 μ s and by finding a scintillator with a higher efficiency above 1eV than the present one.

4.2 BEAM PROFILE RADIOGRAPHY

Radiographs have also been produced to demonstrate that the detector can be used to show changes in the beam profile as a function of energy. In the short running time that was available, it was not possible to record enough counts for a quantitative analysis of the data to be useful, although a visual inspection of the radiographs does indicate that changes occur. All the radiographs shown were taken at low energies ($<10\text{eV}$). The high γ and fast neutron fluxes at the start of each machine pulse caused the generation of considerable noise in the IPD which dominated the images for about $100\mu\text{s}$. The problem of noise in the IPD, particularly that generated by high light levels will have to be solved if this technique is to work at energies above a few tens of eV. At lower energies it should be able to provide useful information about beam profiles for experiments on pulsed neutron sources.

4.3 STRAIN RADIOGRAPHY

This is probably the most promising of the three applications which have been investigated. A plot of strain across the sample was produced

which agreed well with other results, except in those areas where the IPD noise was too high. This noise again seems to be generated by the high initial γ and fast neutron fluxes. A shadow bar and a lead wall were set in the beam in order to reduce these, but they also attenuated the low energy flux, so that a long counting time was necessary. If the system were used on a neutron source with a higher slow neutron flux and a lower fast neutron flux, the counting time would be considerably reduced. If the noise problem were solved, and with a flux of 10^5 neutrons per second across an edge (the maximum rate that the detector could record), the required counting time for the sample would be 35 hours. If, however the detector dead time could be reduced to 1 μ s, the measurement could be made in under 4 hours. Ideally the detector would record a time-of-flight spectrum for each pixel; this would require a dedicated computer for data collection, but the same measurement with maximum counting rate could then be made in half an hour.

4.4 DETECTOR CONSIDERATIONS

The review of the experimental results has shown up some major problems of the present PNR detector system. These are: the unacceptably high noise in the IPD, particularly when it is exposed to high light

levels, the long detector dead time, the low efficiency of the system above a few eV, the long dead time of the data-handling system and the restrictions imposed by the gating system. The light loss in the optical system could be reduced by the replacement of the mirror and lens by an aspheric mirror.

The effects of non-uniformity in efficiency were effectively removed by the data - processing techniques in each of the the three experiments, but the high and very non-uniform noise rate remained a problem. The source of the noise was not evident, though it was demonstrated that the pulses were generated within the IPD and were indistinguishable from 'real' events, in that the noise pulses entering the IPD processing electronics fell within the single photon peak on the pulse-height spectrum. In the laboratory, the noise rate was seen to increase following high illumination and to take several hours to return to its original level. On the flightpath, the illumination due to the γ -flash was sufficient to generate the same effect - which caused serious problems for the production of images. The solution to the IPD noise problem was outside the scope of this project, but it may be possible to find another commercial device to replace the IPD.

The low detector efficiency is largely due to two factors - the low efficiency of the scintillator to epithermal neutrons and the small amount of light from each scintillation event that reaches the IPD and

photomultipliers. The efficiency of a lithium glass scintillator increases with the concentration of ^6Li , as neutrons are captured by the $^6\text{Li}(n,\alpha)$ reaction. However, ^6Li also acts as a quenching agent, so increased lithium content causes a reduction in the light output per captured neutron. Because of these opposing effects, the detector efficiency cannot be increased significantly by increasing the lithium content of the scintillator. Higher light output could be achieved if a glass could be manufactured with reduced levels of Iron and other impurities, which have been shown to act as quenching agents (see section 2.2.1). The concentrations of these materials in the glass are already very low, however, and a further reduction is probably not practicable.

Another solution to the problem of low detector efficiency would be the use of a different scintillator with the same efficiency as the present one, but with higher light output, or with an emission spectrum that peaked in the visible region, so that fewer scintillation photons would be absorbed in the lens and more would reach the IPD. A $\text{LiI}(\text{Eu})$ scintillator may satisfy these requirements (see section 2.2.1). Alternatively, a scintillator with the same light output, but a higher efficiency at epithermal energies could be used. This last solution would be preferable as it would not give rise to unwanted multiphoton events in the IPD (see section 2.2.6).

If a dedicated computer were available, it could be set up to record a time-of-flight spectrum for each pixel. This would allow more data to be collected in the same counting time. If it were situated close to the detector, the problems associated with sending analogue signals through long cables would also be overcome and the data-handling system would work more effectively.

The system performance has been improved by the various modifications made to the detector, the electronics and the data processing programs. This has allowed the feasibility of three potential applications to be investigated. Moderate success has been achieved in each case, though it is evident that further developments, particularly to the IPD, are necessary if the detector is to be of practical use.

REFERENCES

- 1 Kallman H; Research I, 1948, p254
- 2 Thewlis J & Derbyshire R P T; AERE rpt M/TN 37, 1956
- 3 Thewlis J; British Journal of Applied Physics 7, 1956
- 4 Berger H; Neutron Radiography, Methods, Capabilities & Applications, Elsevier pub co, 1965
- 5 Barton J P; Applied Materials Research 4, no.2, 1965, p90
- 6 Hawkesworth M R & Walker J; Proc. First World Conf. Neutron Radiography, D Reidel Pub Co, 1981, p5
- 7 Robertson G; A Detector System for Neutron Radiography, PhD Thesis, Imperial College, 1983
- 8 Lynn J E; Contemporary Physics, Vol21, no.5, 1980, p483
- 9 Barton J C & Ranby P W; Journal of Physics E., Vol10, 1977
- 10 Spowart A R; Nuclear Instruments & Methods 135, 1976, p441
- 11 Jensen & Czirr; Nuclear Instruments & Methods 205, 1983, p461
- 12 Spowart A R; Nuclear Instruments & Methods 82, 1970, p1
- 13 Wraight et al.; Nuclear Instruments & Methods 33, 1965, p181
- 14 Bollinger et al; Nuclear Instruments & Methods 17, 1962, p97
- 15 Anderson et al; Nuclear Instruments & Methods 2, 1961, p616
- 16 Schelten J & Kurz R; Position-sensitive Detection of Thermal Neutrons, Academic Press, 1983, p203
- 17 Spowart A R; Nuclear Instruments & Methods 75, 1969, p35
- 18 Strauss M G; private communication

- 19 Thorn EMI Electron Tube Catalogue 1982/a
- 20 Kittel ; Introduction to Solid State Physics, Wiley
- 21 Ashcroft N W & Mermin N D; Solid State Physics, Holt Saunders
- 22 Allen A J et al; Advances in Physics, vol34, no4, 1985
- 23 Parlane A & Leggat R; Welding Institute Research Report, 1982, p1
- 24 Ikeda S & Carpenter J; Nuclear Instruments & Methods A239, 1985, p536
- 25 Harwell Subroutine Library; VA05A, MB11A - M J D Powell , MA04A - I G A Robinson, A B Smith, A R Curtis