JP0150573

JAERI-Conf 2001-002

ICANS-XV
15th Meeting of the International Collaboration on Advanced Neutron Sources
November 6-9, 2000
Tsukuba, Japan

15.6
The Development of Neutron Detectors for the GEM Instrument at ISIS

N J Rhodes*, M W Johnson, and E M Schooneveld

ISIS Facility, Rutherford Appleton Laboratory, Chilton, Didcot, Oxon. OX11 0QX UK
*E-mail n.j.rhodes@rl.ac.uk

Abstract

GEM is a new General Materials diffractometer now being commissioned at ISIS. To meet its broad based scientific programme GEM requires a large area position sensitive detector which covers a wide range of scattering angles and exhibits a high neutron count rate stability. This paper discusses the design of a $ZnS/^6Li$ fibre coupled detector array that meets the GEM requirements. Typical detector characteristics are documented together with the current status of the project. Two thirds of the detector array are operational and from the results obtained to date it is already obvious that the impact of this instrument on neutron scattering studies will be profound.

1. Introduction

GEM is the latest of 17 neutron scattering instruments to be commissioned at ISIS, the pulsed neutron and muon facility at the Rutherford Appleton Laboratory, UK. GEM is a general materials diffractometer designed to study the structure of both crystalline and liquid and amorphous samples [1]. To meet the wide range of scientific applications, GEM combines high resolution over a wide Q range together with a high count rate. These requirements are achieved by using a relatively large moderator to sample distance of 17 m while operating a large position sensitive detector array. This paper discusses the design and development of the detector array for GEM.

2. Principle beam line components

The GEM diffractometer views the liquid methane moderator. Neutrons from this moderator pass through both static and adjustable collimation to the sample position, which is at 17 m from the moderator. Two disc choppers define the neutron energy incident on the sample, while a nimonic chopper suppresses the background due to fast neutrons. The sample is contained in a complex sample tank, which is in turn located inside a well-shielded blockhouse. The sample tank is specifically designed with large apertures to accommodate the wide area of detector coverage required by GEM. Extensive secondary collimation, both within the sample tank and surrounding the detectors minimises neutron detector background. Eventually the inside of the sample tank will be equipped with a rotating collimator to further improve sample to detector collimation. A wide range of sample environment equipment can be used including sample changers, cryostats, furnaces, CCRs and cryomagnets. A polycold allows the sample tank to be held at a cryogenic vacuum. There are four neutron beam monitors positioned at intervals along the instrument flight path to measure neutron beam profiles. A beam stop absorbs the neutron beam transmitted from the sample tank. Most of the blockhouse is taken up by the large detector array.

3. The GEM Detector Array

The detector array required for GEM is approximately resolution focussed and covers a scattering angle from 1.1° to 169.3°, with a spatial resolution of 5 mm. The azimuthal angle of the array is generally ± 45 degrees on both sides of the sample position, leading to an overall detector area of 10 m^2. For ease of construction the detector array has been divided into 8 different banks, labelled 0 to 7. Details of the distances from the sample position and scattering angles subtended by these banks are given in Table 1.

Table 1. Positions of the GEM detector banks with respect to the sample position. L2 is the sample to detector distance of a detector bank and min 2θ and max 2θ are the scattering angles of the end elements of a detector bank. ϕ is the azimuthal angle subtended by a detector bank. The last two columns show the calculated and measured ΔQ/Q resolutions.

Detector Bank	L2 / m	Min 2θ / °	Max 2θ / °	ϕ / °	ΔQ/Q Calc.	ΔQ/Q Meas.
0	2.8 – 2.9	1.1	3.2	± 90	$5\text{-}10\times10^{-2}$	
1	2.2 – 2.4	5.6	13.5	± 45	$3\text{-}5\times10^{-2}$	
2	1.48 – 2.10	13.8	21.0	± 45	$2.0\text{-}3.0\times10^{-2}$	$1.2\text{-}2.5\times10^{-2}$
3	0.65 – 1.40	24.8	45.0	± 45	$1.7\text{-}2.0\times10^{-2}$	
4	1.04	49.9	74.9	± 45	$1.5\text{-}1.7\times10^{-2}$	$4.7\text{-}6.6\times10^{-3}$
5	1.38	79.0	104.0	± 45	$4.5\text{-}6.5\times10^{-3}$	$3.1\text{-}4.9\times10^{-3}$
6	2.0 }	141.9	149.2	± 45	$2.0\text{-}3.0\times10^{-3}$	$2.4\text{-}2.6\times10^{-3}$
7	1.0 }	149.3	169.3	± 45	$2.0\text{-}3.0\times10^{-3}$	

To achieve a 5 mm spatial resolution and to match Debye Scherrer cones of diffraction at small and large scattering angles, the GEM detector array has been based on fibre coupled $ZnS/^6Li$ scintillation technology. This technology has been used on a number of other instruments at ISIS including the backscattering detector for the High Resolution Powder Diffractometer, HRPD, [2]. A schematic showing the layout of the GEM detector banks, based on $ZnS/^6Li$ fibre coupled detectors is shown in Figure 1.

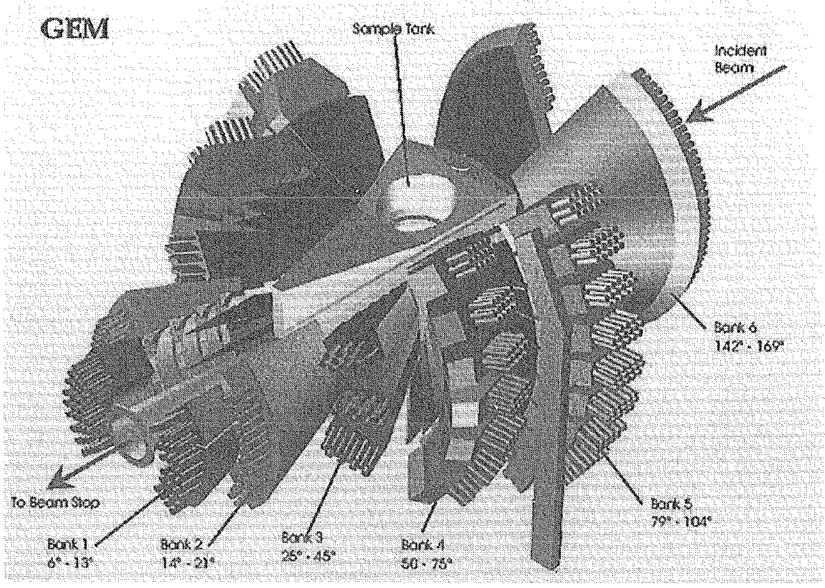

Figure 1. A schematic layout of detector banks 1 to 7 of the GEM detector array. Bank 0 is not shown, but is situated inside the get lost tube.

4. New challenges presented by the GEM detector array

The design and construction of the GEM detector array presented a number of new challenges. At 10 m^2 the size of the GEM detector array is 10 times greater than any scintillation detector previously constructed at ISIS. Both the scale and rate of production required a significant investment in skilled manpower. Neutron scattering studies of liquid and amorphous samples necessitates very high detector stability such that variations in detector count rate remain within count rate statistics. For the large GEM detector array this requires changes in detector performance limited to values in the order of 0.1% over the duration of an experiment, which may be several days. An effective method of minimising neutron scattering from the bulk of the acrylic fibre optic light guides was needed. Finally magnetic studies are to feature strongly in the GEM instrument programme and it was important that stray magnetic fields from the 7 tesla cryomagnet, available as a routine piece of sample environment equipment, did not contribute significantly to detector instabilities.

5. GEM detector developments

Prior to the development of the GEM detector, a dedicated team of ISIS personnel had constructed all previous scintillation detectors. To meet both the scale of the project and the stringent delivery times required, production of the fibre optic detector heads was transferred to outside manufacturing companies. The experience of the in house team in constructing these types of detectors ensured a smooth transition and other detector projects at ISIS are already benefiting from this experience.

Detector count rate stability is particularly difficult to optimise in this type of detector where the scintillator is opaque. Under these conditions pulse height discrimination is not available to minimise systematic changes in gain. To cope with the required increase in the detector stability over that previously obtained, the electronic processing of the light output from these types of detectors was carefully reanalysed. The main contribution to detector instability was shown to be the variation in gain of the photomultiplier tubes, PMTs, which is strongly temperature dependent. A new signal processing system has been designed which minimises the effect of gain changes of the PMTs on detector count rate. Details of this system are described in section 7.

In previous scintillation detector designs, shielding of the fibres from scattered neutrons has been accomplished by painting the fibre supports with gadolinium oxide paint. This works effectively on instruments operating at neutron energies below the gadolinium cut-off. However for GEM where the incident neutron energy is greatly in excess of the gadolinium cut off, an improved absorber was required. This was achieved by fabricating the fibre supports from mixtures of boron carbide and resin and by employing various techniques to pot the fibres in the boron carbide resin. Although the neutron absorption cross section of natural boron is very much less than that of gadolinium this is compensated by the increased thickness of boron containing material incurred by fabricating the whole of the fibre support from this material. Boron has a 1/v dependency of neutron absorption with neutron velocity and therefore remains effective at energies greater than that of the gadolinium cut off.

To cope with the effects of stay magnetic fields on the PMT gain, it was necessary to instigate careful shielding of the PMTs with both mu metal and low carbon steel.

6. Details of the different types of GEM detector modules.

All of the GEM detector modules are $ZnS/^6Li$ scintillation detectors fibre-optically coupled to arrays of PMTs. All modules within one detector bank are of the same design. Modules in different banks are designed specifically to match the corresponding 2θ scattering angle and differ in the number of active channels and the spatial arrangement of the detector elements. There follows a description of a GEM bank 5 detector. Details of the other detector modules and the number of detector modules in the different detector banks are given in Table 2.

Table 2. Details of the distribution of the detector modules and the detector elements for the whole of the GEM detector array. The present status of the GEM detector installation is given. Also indicated are the number of detector facets and the number of PMTs in the whole of the GEM detector array.

Detector bank	No. of modules per bank	No of modules installed to date	No of elements per module	No of elements per bank	No of elements installed to date	No of facets per element	No of facets per bank	No of PMTs per bank
0	1		80	80		5	400	14
1	2	2 in const.	160	320		3	960	68
2	2	2	160	320	320	1-2	560	56
3	10		90	900		1	900	140
4	14	3	100	1400	300	1	1400	210
5	18	18	120	2160	2160	1	2160	288
6	14	14	40	560	560	3-5	2240	140
7	10	10	80	800	800	1-3	2000	140
Total	71	47		6540			10620	1056

A bank 5 detector module consists of 120 individual detector elements, each 5 mm wide and 200 mm long. These elements are fibre optically encoded to 16 PMTs. Each element consists of a 0.4 mm thick strip of $ZnS/^6Li$ scintillator, folded into the shape of a 'V'. The 'V' shape is arranged to point at the GEM sample position and, compared to a flat strip of the same scintillator, provides an increased neutron path length whilst maintaining a constant path length for emitted scintillation light. In this way neutron detector efficiency is enhanced without seriously impairing light collection efficiency. Hence the ability to discriminate neutron from gamma radiation is maintained. Each 'V' scintillator is encapsulated in its own diamond shaped foil reflector, open at the base. A row of 1 mm diameter fibre optic light guides view each 'V shaped scintillator strip through the apertures in the base of the associated foil reflector. Each row of fibres is supported on a moulded boron carbide / resin separator, which also serves to support the foil reflectors. The scintillators, foil reflectors, fibre optic supports and the fibre optic array are contained in a light tight box. The fibre array is coded into 16 bundles and these bundles are potted into one face of the light tight detector box and their ends polished. A PMT is coupled to the end of each fibre bundle. Each row of fibres is coded to a different pair of PMTs such that adjacent fibres in any one row are connected to different PMTs. Thus the first detector element in the module is coded to PMTs 1 and 2, the second element to PMTs 1 and 3 etc. In this way the detector module can be coded via a $2C_n$ code such that all 120 detector elements are read out by 16 PMTs and their associated electronic chains.

The PMTs each have their own mu metal shield and are individually housed in low carbon steel tubes. These tubes contain the voltage divider network of the PMT and the first comparator in the detector electronics chain. This arrangement provides a light tight environment and magnetic and electronic screening for the PMT. Further details of the detector electronics are given in section 7.

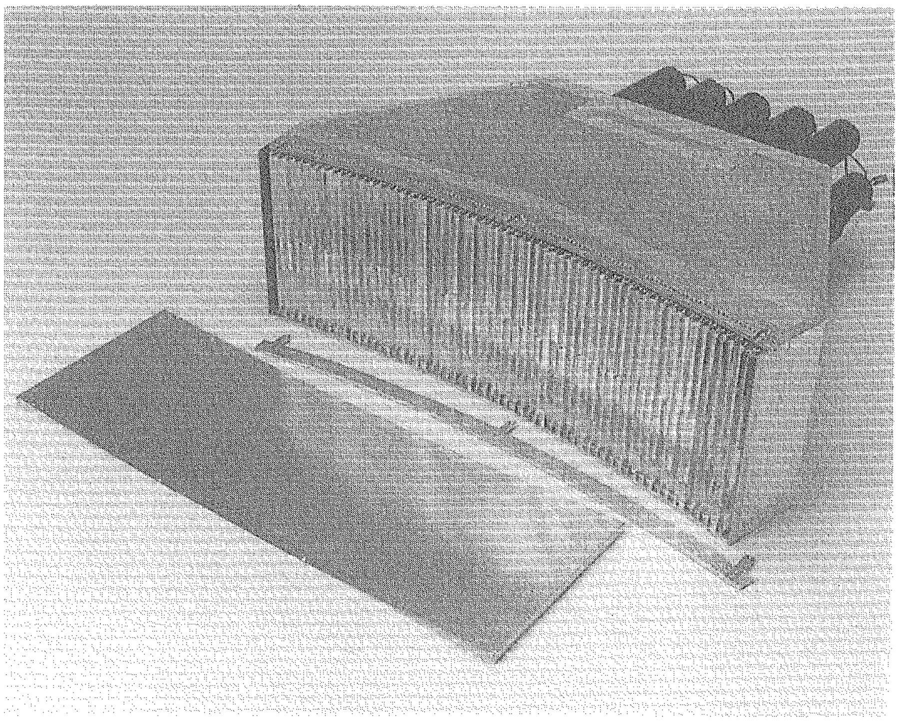

Figure 2. Photograph of a GEM bank 5 detector with the front cover removed. Visible are the foil reflectors of the 120 detector elements.

Table 2 also shows the number of PMTs used in each detector bank. Overall the number of PMTs in the GEM detector array is reduced by a factor of six compared with the number of individual detector elements. This reduction occurs as a result of the $2C_n$ code and varies for different detector modules depending on the geometric design constraints which effect optimisation of the fibre coding.

In detector banks 3, 4 and 5, the detector elements are arranged in straight rows, 200 mm in length. In the detector banks of the forward and back scattering arrays the lengths of the detector elements are shortened and oriented to match the Debye Scherrer cones of diffraction. While each of these shorter elements can be read out individually, it is not always necessary to do so and may not significantly improve the detector resolution. Under these conditions detector elements have been divided into a two or more facets, with each facet normal to a Debye Scherrer cone of diffraction. All facets within an element are coded to the same pair of PMTs. On average the number of PMTs in the GEM detector array is reduced by a factor of ten compared with the number of detector facets in the GEM detector array.

7. GEM detector characteristics

Characteristics of the GEM detectors are shown in Table 3.

Table 3. GEM detector characteristics.

Detection Efficiency at 1 Å	50 %
Gamma sensitivity ^{60}Co	10^{-7}
Intrinsic detector background	12 c hr^{-1} per element
Spatial resolution	5 mm
Pulse pair resolution	2.5 μs
Stability	0.1 % $°C^{-1}$

Detector efficiency is ~ 50 % at 1 Å and is very comparable with that of a 12.5 mm diameter 10 bar 3He detector. Figure 3 shows a time of flight spectrum from such a gas detector compared to a corresponding spectrum from a $ZnS/^6Li$ GEM detector element. These spectra have not been normalised for detector solid angle and the actual detector efficiency of the GEM scintillation detectors has not yet been determined definitively. Nevertheless, the spectra closely match over a wide energy range indicating similar neutron detection efficiencies.

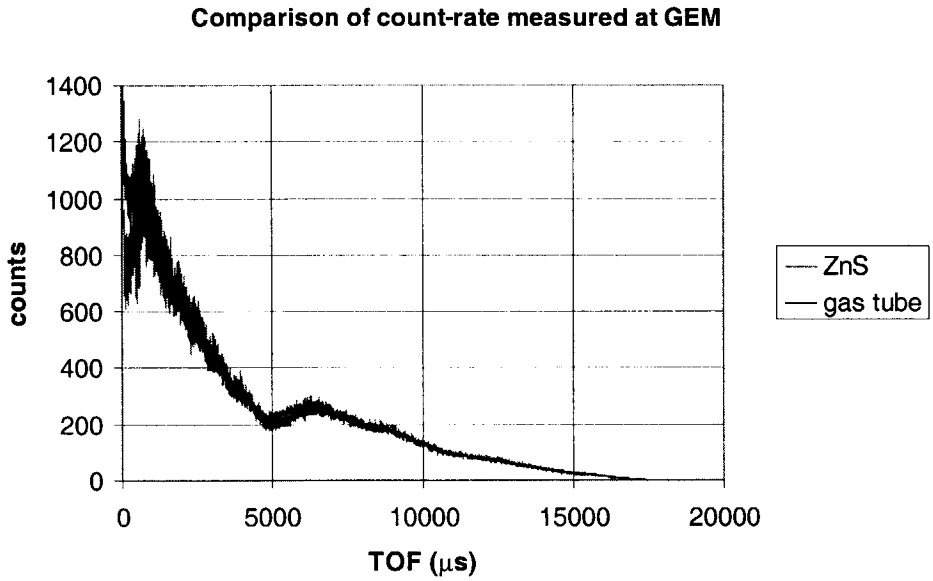

Figure 3. Time of flight spectra for a 12.5 mm diameter 10 bar 3He detector and a GEM $ZnS/^6Li$ detector element. The data has not been normalised for subtended solid angle, but similar profiles over a wide energy range imply similar detection efficiencies.

A measure of gamma sensitivity is obtained by determining the ratio of the number of ^{60}Co gamma rays detected by a detector element and the number incident on that detector element. At 10^{-7} this ratio is remarkably low whilst intrinsic detector background is also very low.

The spatial resolution of the detector in the 2θ direction is determined by the 5 mm width of the $ZnS/^6Li$ scintillation elements. At 2θ angles of 90° the height of the detector elements is 200 mm. At higher or lower scattering angles the height of detector elements is reduced and suitably oriented to allow adequate approximation to the Debye Scherrer cones of diffraction. Calculated and measured ΔQ/Q resolutions for the GEM detector banks are given in Table 1.

$ZnS/^6Li$ has a principal time constant of 200 ns and with the integration time constants currently in use, pulses separated by 2.5 μs can be resolved. However, there is also a long time constant associated with the light output from $ZnS/^6Li$ and light from a bright event can extend beyond 100 μs. $ZnS/^6Li$ detectors will not be able to sustain a 2.5 μs pulse pair resolution when subjected to high neutron rates.

Neutron detector count rate stability of these detectors has been measured both on ISIS and in the laboratory and is ~ 0.1% $°C^{-1}$. The first stage of the electronics system, which enables this stability to be achieved, is based on the RAL 10 comparator chip. This comparator is mounted on a card immediately behind the PMT voltage distribution card. The lower level thresholds of the RAL 10 comparators are set just below the single photon response level of the PMTs. A neutron event in the scintillator gives rise to a number of multiple and single photon pulses which are converted into digital pulses by the RAL 10s. This effectively inhibits the dynamic range of the signal, minimising the effect of PMT gain variation on neutron count rate stability. Outputs from the RAL 10 comparators of one module are sent to a remote discriminator / decoder card. A further inhibition of the dynamic range of the PMT output is achieved by pulse stretching each RAL 10 output pulse to a fixed width. The digital pulses are then integrated and discriminated to separate neutron events from gamma events and intrinsic detector background. A schematic of the process is given in Figure 4. Pulses from the discriminators are sent to a $2C_n$ decoder. This unit assigns the appropriate position descriptor to coincident pulses from pairs of PMTs in the $2C_n$ code. The decoder output pulses are sent to the data acquisition electronics for time stamping, storage and subsequent analysis.

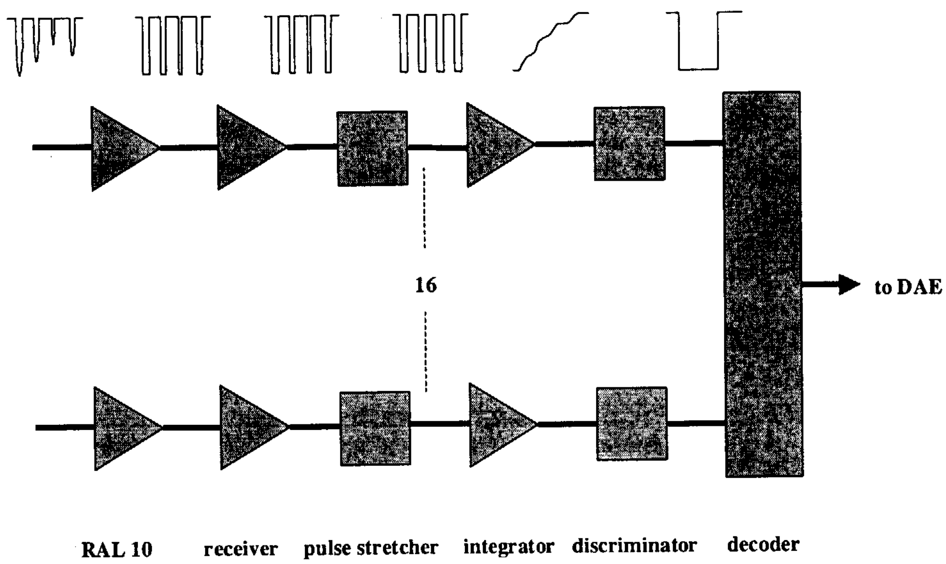

Figure 4. Block schematic of the electronics chain of the GEM detectors. Signals at the various stages of electronics chain are shown at the top of the diagram.

The GEM neutron detector count rate stability is illustrated in Figure 5. This represents a change in count rate of 0.12 % $^{o}C^{-1}$. Coolers in the GEM blockhouse keep the air temperature to within ± 1 °C and hence a count rate stability of ~ 0.1 % is achieved.

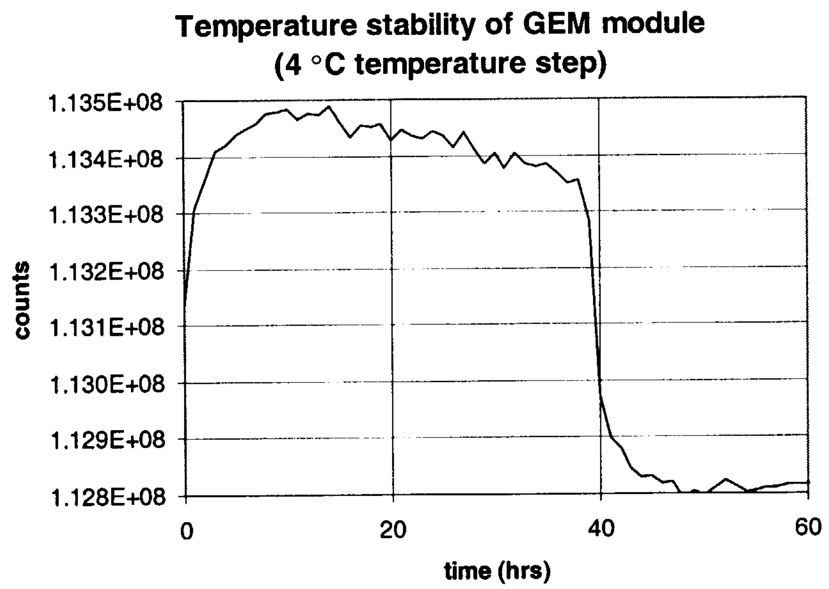

Figure 5. Count rate stability of a GEM detector module for a 4°C variation in ambient temperature.

8. Results

The first detector modules became operational on GEM in October 1999. Already a large number of experiments have been carried out. See [3] and references contained therein for further details. Areas covered include superconductivity and magnetism, ion disorder and migration and liquid and amorphous materials. Refinable powder diffraction data can be collected in just a few seconds while an overnight run has been shown to yield adequate data from a sample of only 3 mg. With the full detector compliment in place the minimum required sample may be reduced to as little as 200 μg for a 24 hour run.

9. Conclusion

Although not yet fully completed the high detector count rate and excellent detector performance has resulted is a tremendous start to the broad based science programme on GEM. A large area $ZnS/^6Li$ scintillation detector array based on fibre coupled readout has been designed and built to match the wide range of scattering angles required for GEM. Production of the fibre optically encoded detector heads has been successfully transferred to outside manufacturing firms, facilitating speed of detector construction. Despite being based on an opaque scintillator, development of new electronics has allowed excellent count rate stability to be achieved. Suitable screening has allowed the detector array to operate in high magnetic fields, an essential requirement of the science programme. This detector array will have a significant impact on the rapid measurement of data sets for kinetic studies using neutron scattering techniques. GEM provides a landmark for the design of future diffractometers for powder diffraction and liquid and amorphous studies.

References

[1] 'GEM - General Materials Diffractometer at ISIS.'
W.G.Williams, R.M.Ibberson, P.Day and J.E.Enderby, Physica B **241-243** (1998) 234-236.

[2] The future of scintillator detectors in neutron scattering instrumentation.
N.J. Rhodes, M.W. Johnson and C.W.E. van Eijk, J. Neutron Research **4** (1996) 129-134

[3] ISIS Facility Annual Report 1999 – 2000
Rutherford Appleton Laboratory Report, Report Number RAL-TR-2000-050