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New Horizons with Position Sensitive ^{3}He Detectors

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Abstract

We describe the design and performance of position sensitive detectors based on resistive wire ^{3}He detector tubes that have been designed for inelastic single crystal measurements on chopper spectrometers at a pulsed source. An array of 26 of these detectors was installed on HET in May 1997, and approximately 600 of them will be used on the new inelastic single crystal spectrometer, MAPS, currently under construction at ISIS.

Introduction

The use of direct geometry time-of-flight chopper spectrometers for measurements of the magnetic inelastic response of polycrystalline samples is a well established technique. More recently, the availability of high-flux pulsed spallation sources like ISIS have enabled the extension of this technique to single crystal measurements. The chopper spectrometers HET and MARI have been at the forefront of these investigations and have made substantial contributions to many areas in contemporary magnetism. A new instrument, MAPS, is currently under construction at ISIS that aims to build on this success and has been specifically designed for single crystal experiments. A key part of its design is the use of position sensitive detector arrays that are based on resistive-wire ^{3}He detector tube technology. These will enable the experimentalist to construct scans in any direction in reciprocal space and optimise the instrumental resolution for that measurement.

Several position sensitive detector systems already exist on time-of -flight instruments: the GLAD spectrometer at IPNS, Argonne National Laboratory, USA [1] and VEGA and SIRIUS at KENS, National Laboratory for High Energy Physics (KEK), Japan [2]. The detector systems designed for these instruments are, however, optimised for measurements of elastic neutron scattering from polycrystalline, liquid or amorphous samples making them unsuitable for use on the MAPS spectrometer.

A position sensitive detector array for use on an inelastic neutron spectrometer using the time-of-flight technique has to be designed to cope with two characteristics of the neutron response in a typical single crystal experiment. The first is that high intensity Bragg peaks can occur as a result of the orientation of the single crystal sample and choice of incident neutron energy; the second is that the typical cross section for the inelastic response of the sample is often many orders of magnitude lower than these Bragg reflections. The detector system therefore has to have a short dead-time so that the highly intense Bragg reflection does not impede the measurement of the inelastic response and it has to have a low background count. In addition we required that the detectors had good stability, both temporally and spatially, a linear positional response, a comparable efficiency at all neutron energies with the standard ^{3}He detectors on MARI and HET and a resolution along the detector comparable to its width (of 25.4mm). The MAPS spectrometer will also require of the order of 600 such detectors so that a low maintenance system is highly desirable.

As part of the ongoing instrument upgrade program at ISIS, and as a prerequisite test to enable experimentalists to gain experience in the use of PSDs prior to the construction and commissioning of the MAPS instrument, half of the 4m detector banks on the HET spectrometer at ISIS were replaced with 26 PSDs in May 1997. This array providing an additional 1536 individual detector channels and has now been in successful operation for almost a year. In this paper we aim to describe the PSD system and its implementation on HET.

Section A - The PSD Detector System

A block diagram of the detector system is shown in figure 1. Its operation can be divided into three stages; physical neutron detection, pre-amplification of the detected signal and encoding of the neutron position.

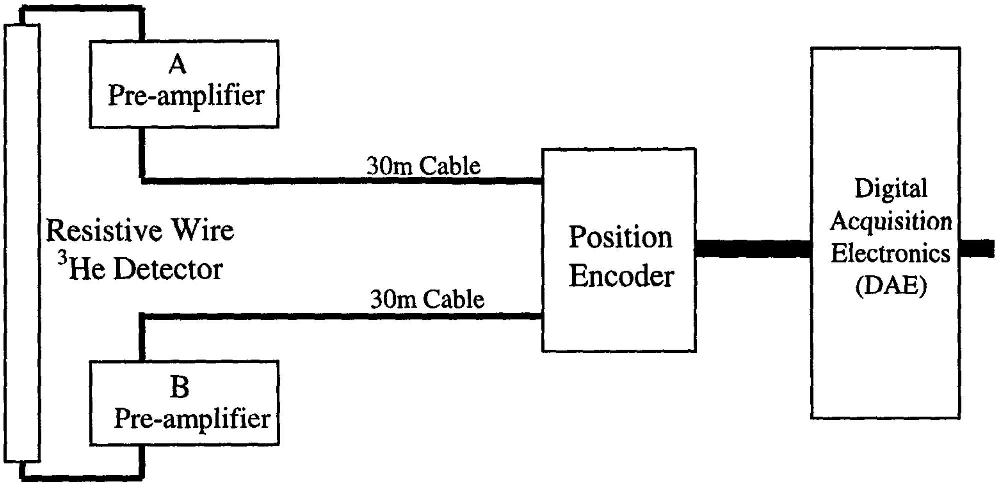

Figure 1: The PSD system

Neutron Detection

The position sensitive detector tubes are cylindrical ^{3}He resistive wire proportional counters each 25.4mm in diameter by 914mm active length filled with ^{3}He at a partial pressure of 6.5 atmospheres and other stopping and quenching gases. These tubes are operated in proportional mode by the application of a bias voltage of 1960V between the central resistive wire and the outer steel gas container.

Detection of a neutron is through the reaction

$$n + {}^{3}He \rightarrow {}^{1}H + {}^{3}H + 765keV$$

followed by ionisation of the stopping-gas by the proton and tritium, and gas amplification from the proportional mode of operation. This results in a charge being deposited on the central anode wire at the position of the incident neutron.

It is the division and measurement of this charge that allows the encoding of the position of the incident neutron to be determined. The accuracy of the determination of the neutron position is highly dependent upon the characteristics of the pre-amplifiers and encoding circuits.

Pre - Amplifier Circuit

The pre-amplifiers are charge amplifiers that convert the charge collected at each end of the tube resulting from a neutron event to two voltage signals that are compared in the position encoding circuit. Distortion of the charge signal by these circuits degrades the resolution of the system and can also lead to systematic errors in the final encoded position of the incident neutron.

The pre-amplifiers developed at ISIS for HET were designed with two criteria in mind. The first was to ensure that the detector and pre-amplifier electrical characteristics should have a minimal effect on the detected signals and the second was that the design should be simple.

To implement the first of these criteria, the design addressed three properties that could adversely affect the encoded position.

The first consideration is that the resistance of the anode wire within the detector is likely to vary from detector to detector. Our design incorporates a pre-amplifier with low impedance, low enough so that the anode resistance tolerance becomes negligible, which means that there is no need to match detectors to electronics. Different length tubes, with different anode resistances, can also be connected to the same electronics.

Secondly, we considered that the pulse shape from a detected event may have fast or slow rise-time, depending on the position and angle of the created triton and proton to the anode wire. The variation in rise-time meant that we used a pre-amplifier with wide bandwidth and flat response.

The third consideration was the potential error that could occur if the gains from pre-amplifiers either side of the detector are mismatched. To overcome this we ensured that the gains of the amplifiers were precisely matched by using precision 0.1% resistors. The amplifiers used in the pre-amplifier circuit were also chosen to have low internal offsets and low noise.

Our second criteria, simplicity, was in response to the fact that MAPS will require approximately 600 PSD detectors. Simplicity of design, with minimal components, increasing reliability and reduced maintenance. In the past the ^{3}He proportional counter pre-amplifiers have been built at ISIS on an individual basis. To vastly reduce the number of interconnections it was decided to group together the low impedance pre-amplifier stage, a 50Ω cable driver stage, and the filtered HT and pre-amplifier power supplies for several PSD detectors into a single module. For the implementation of PSDs onto HET this module was for thirteen detectors.

The pre-amplifier design also incorporates a method for electronic injection of test pulses into the circuit. This is used to test for cable connectivity and as a crude method of simulating an encoded neutron event. A more accurate electronic method was excluded because it was prohibitive in cost, requiring a test pulse generation and delivery system that would have to be extremely accurate and stable.

Position Encoding Circuit

The position encoding circuit's function is to take the two analogue outputs from the pre-amplifier stages and convert them to a 6-bit digital *word* representation of the position of the incident neutron for use by the standard ISIS digital acquisition electronics (DAE).

The theory of the encoding of the incident neutron's position on the detector is basically the same in all restive wire detector systems. If we label the ends of the detector tube ***a*** and ***b***, and the position at which the neutron is incident *x*, then the position *x* can be thought of as also dividing total resistance of the resistive wire into two. Measurement of the charge collected at each end of the resistive wire (A at ***a*** and B at ***b***) which results from the division of the charge created by the incident neutron event by the resistance paths from ***x*** to ***a*** and ***b***, allows the position ***x*** to be calculated. The position along the detector from the B end is given (as a fraction) by

$$x = \frac{A}{A+B}. \qquad [1]$$

In the ISIS HET position encoding electronics (a block diagram is shown in figure 2), the two pre-amplifier outputs are buffered by receiving amplifiers, one of which has an adjustable gain. The adjustment is used to compensate for the slight variations in impedance that are a consequence of tolerance of the 30m interconnecting cables. It should be highlighted that this is the *only* adjustable part of the whole system. The outputs from these amplifiers are then used by three amplifiers to provide outputs representing the charge collected at the A, B ends of the tubes and their sum, A+B. The B signal is not subsequently used but is incorporated to ensure that the A and B inputs are treated symmetrically by the electronics. The A+B signal, which in a single-ended tube represents the dynamic range of the input, is used in the discrimination process.

The discriminator uses the differentiated A+B signal to first cross a threshold value, in a similar way to a normal low level discriminator, and then to provide a switch at the peak of the A+B signal. The peak of A+B is easily determined by detecting when the differentiated A+B signal crosses zero. This method gives a better timing performance than the standard threshold crossing technique, whose timing may depend on the amplitude of the signal.

The peak values of A and A+B are then converted to 8-bit digital words using high speed FLASH architecture analogue-to-digital converters (ADC's). With this type of ADC there is minimal analogue voltage set-up and hold-time before digitisation. These words are then input into a 64Kbyte FLASH lookup table containing the fractional position of the event (c.f. equation [1]) and its output is a 6-bit position word (figure 3). A second FLASH memory device is used to reject any events that are computed as being outside the Lookup table map. The purpose of the second memory is to allow the first memory to be expanded to output an 8-bit word in future configurations.

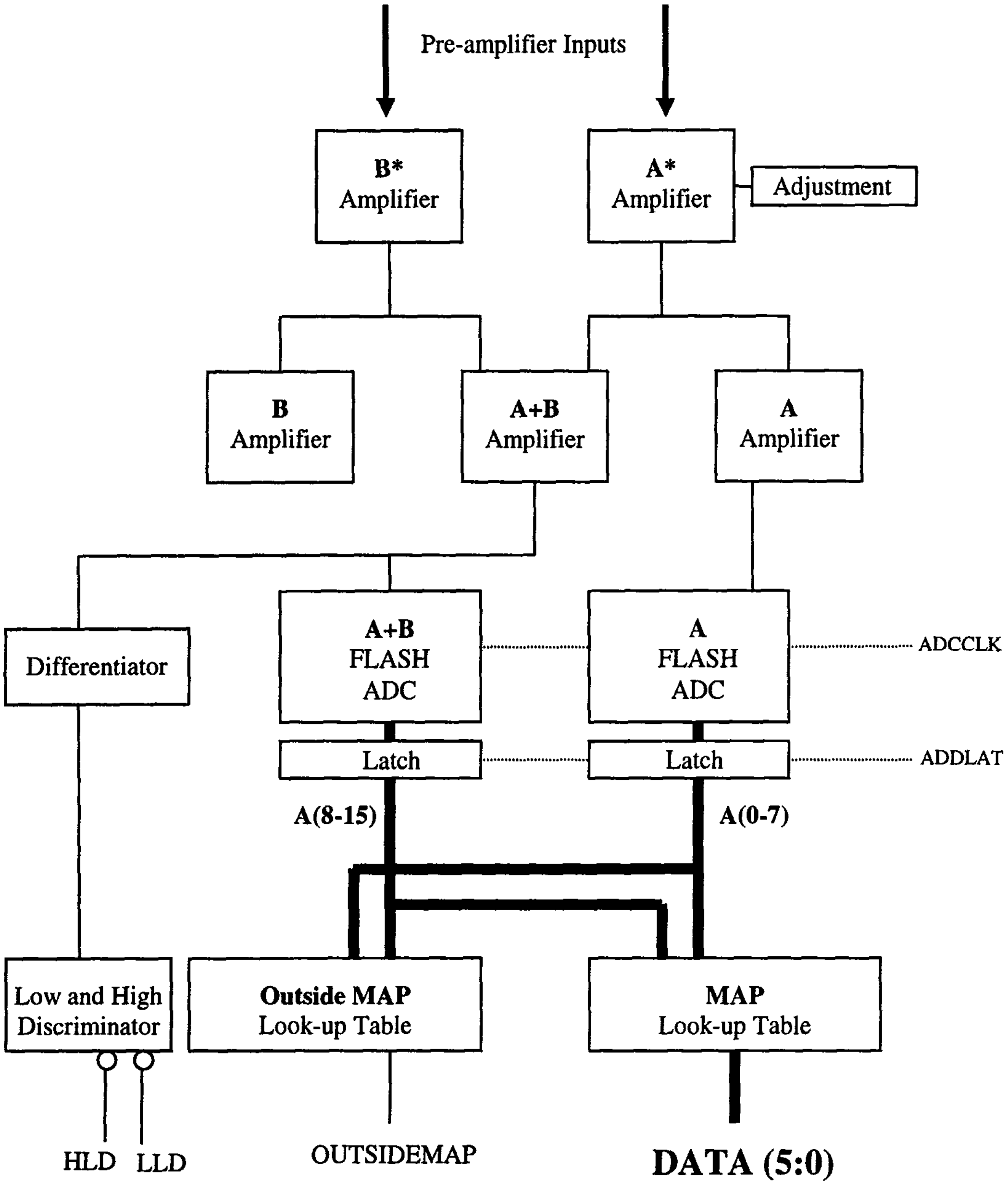

Figure 2: Diagram of the Position Encoding

The timing of the digitisation and encoding process is achieved through a single complex programmable logic device of approx. 5 thousand gates.

The ADC circuit is fabricated on a 6U multi-layer printed circuit board and is able to accommodate two PSD tubes. The 6-bit outputs are multiplexed onto a 7-bit output word plus strobe either as differential ECL or single-ended TTL. With the low detector event rates on HET the board is further multiplexed by multiplexing pairs of ADC cards using the back-plane of the ADC Crate, thus creating an 8-bit output.

We would like to emphasise two things about the system design. The first is its simplicity requiring only one amplifier to be adjusted to match the electronics to any particular detector. This is the result of using low noise, low impedance amplifiers with a wide bandwidth. The second is that the FLASH ADC's do not require long hold times for the analogue voltages, as is the case when the comparison of the A and A+B *analogue* signals is carried out *directly* with a ratiometric ADC. The comparison of the A and A+B signal *after* digitisation is at the heart of the ISIS design and has enabled us to build a high speed device.

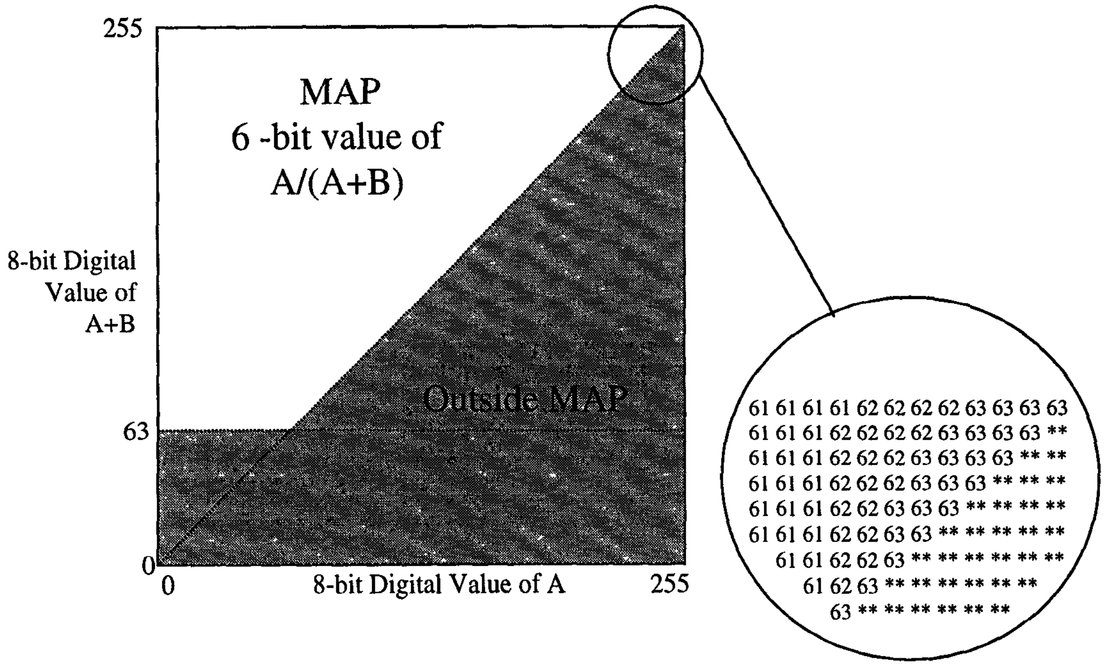

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Figure 3: Diagram of the MAP contained in the FLASH 16-bit Memory

Section B - Performance of the PSDs

Characterisation of the performance of the whole detector system has been carried out in two ways; dedicated tests of PSD tubes were carried out on a test experimental set-up followed by the installation, commissioning and on-going monitoring of an array of 26 PSD tubes installed on the HET spectrometer in May 1997.

The testing facility, installed on the ROTAX beamline at ISIS allowed us to test the tubes using a variety of samples and shielding configurations. In this way many of the operational parameters such as spatial resolution, positional linearity, efficiency when compared to a standard HET or MARI detector tubes could be accurately determined under controlled conditions. Illumination of the tubes with different neutron fluxes including intense Bragg peak reflections also allowed us to measure the tubes performance under near operational conditions.

In addition to these measurements, periodic measurements have been made on the PSD installed on HET. A movable calibration bar, made with neutron absorbing material, that can be placed at any position along the PSD array had been installed for this purpose. With this device the temporal stability of both the position and resolution of the PSD tubes have been monitored since the installation of the system. We have in addition checked the linearity and efficiency of the tubes.

Table 1: Summary of PSD Parameters and Performance

Physical Parameters	
Tube dimensions	25.4mm∅ × 1050mm
Active length	914mm
^{3}He Pressure	6.5 Atmospheres
Pixel Size (64 pixels per tubes)	14.3mm× 25.4mm
Performance	
FWHM	23±4mm
Efficiency (w.r.t. standard HET/MARI detector)	80% E_i>50meV rises to 100% below 30meV
Quiet Count	0.2623 counts/hour/channel
Total circuit deadtime	1µS individual 5µS multiplexed
Pulse Pair Resolution	<4µS
Positional Stability (change in the measured position of the calibration bar)	< ±0.2 channels in 4 months (≈ 3mm)
Resolution Stability (change in the FWHM measured at the same position)	≈0.15 channels in 4 months (≈ 2mm)

The MAPS detectors are longer (having an active length of 1000mm) and contain a higher partial pressure of ^{3}He (at 10 Atms). They have been tested alongside the HET tubes and show almost identical characteristics except that the high ^{3}He content makes them 100% efficient when compared to a standard HET/MARI detector.

Section C - Scientific Experiments with PSDs

The replacement of two of the 4m detector banks on the HET spectrometer at ISIS by 26 PSDs with characteristics given in Table 1 has opened up new scientific opportunities.

On HET the data from the PSD array is collected in the digital acquisition electronics, which bins it according to the time of flight of arrival and into which particular pixel element of the PSD detector array it arrived. Knowledge of the time of flight (~2000 bins) and the position of the pixel elements (1536 elements) allows us to construct, in software, a volume of reciprocal space that is divided into many thousands of small reciprocal space volume elements. Each volume element results from the particular trajectory through reciprocal space of the PSD pixel elements as a function of the time of flight.

Software can then be used to bin these reciprocal space volume elements together and project the results onto planes within reciprocal space to obtain intensity maps of the neutron scattering from the sample under investigation.

Figure 4 is an example of the use of the HET PSD for the investigation of magnetic scattering in a high temperature superconductor. In this experiment the magnetic zone centre around which the magnetic excitations were expected was placed in the centre of the reciprocal space volume measured by the PSD array. The figure shows a slice taken on a high symmetry plane through this volume that reveals the magnetic excitations that surround this magnetic zone centre. This particular cut was taken in an out of plane direction (because of the necessity for *l* in the reciprocal space co-ordinate (*hkl*) to be non-zero to give a non-zero structure factor for the excitations). This measurement was not possible before the installation of the PSDs.

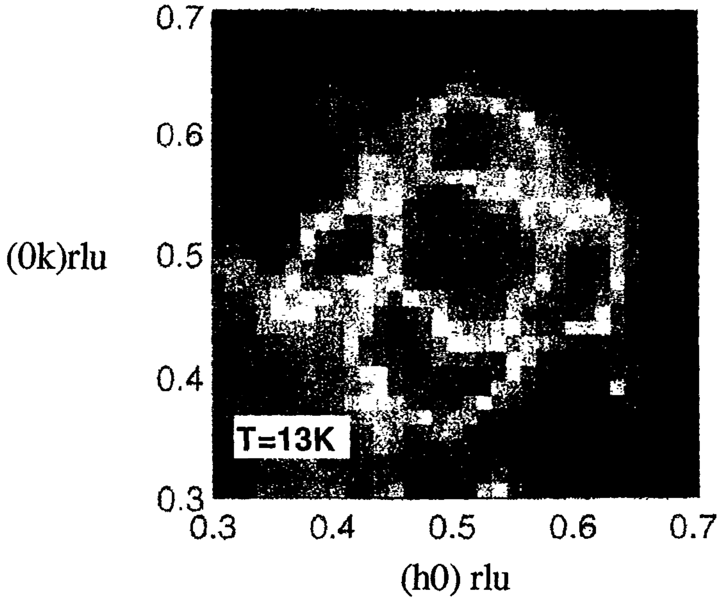

Figure 4: Magnetic Excitations from $YBa_2Cu_3O_{7-\delta}$ measured in PSD array on HET with an incident energy of 34meV from reference [3].

Section D - Concluding Comments

The installation of PSD onto HET has already led to new results in the area of contemporary magnetism. The flexibility that they provide for exploring the inelastic excitations of materials has led to an increasing demand for experimental time on HET at ISIS. The new spectrometer MAPS, due to be commissioned at the end of 1998, will incorporate over 600 such detectors and is expected to provide unique opportunities for scientific experiments and truly represent the next generation of inelastic chopper spectrometer.

References

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