Performance characteristics of the new detector array for the SANS2d instrument on the ISIS spallation neutron source

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ABSTRACT: The performance of the new position sensitive neutron detector arrays of the Small Angle Neutron Scattering (SANS) instrument SANS2d is described. The SANS2d instrument is one of the seven instruments currently available for users on the second target station (TS2) of the ISIS spallation neutron source. Since the instrument became operational in 2009 it has used two one metre square multi-wire proportional detectors (MWPC). However, these detectors suffer from a low count rate capability, are easily damaged by excess beam and are then expensive to repair. The new detector arrays each consist of 120 individual position sensitive detector tubes, filled with 15 bar of $^3$He. Each of the tubes is one metre long and has a diameter of 8 mm giving a detector array with an overall area of one square metre. Two such arrays have been built and installed in the SANS2d vacuum tank where they are currently taking user data. For SANS measurements operation of the detector within a vacuum is essential in order to reduce air scattering. A novel, fully engineered approach has been utilised to ensure that the high voltage connections and preamps are located inside the SANS2d vacuum tank at atmospheric pressure, within air tubes and air boxes respectively. The signal processing electronics and data acquisition system are located remotely in a counting house outside of the blockhouse. This allows easy access for maintenance purposes, without the need to remove the detectors from the vacuum tank. The design will be described in detail. A position resolution of 8 mm FWHM or less has been measured along the length of the tubes. The initial measurements taken from a standard sample indicate that whilst the detector arrays themselves only represent a moderate improvement in overall detection efficiency ($\sim$20%), compared to the previous detector, the count rate capability is increased by a factor of 100. A significant advantage of the new array is the ability to change a single tube in situ within approximately one day with a relatively small staff effort. The results obtained from the first user trials are reported.

KEYWORDS: Neutron detectors (cold, thermal, fast neutrons); Neutron diffraction detectors; Gaseous detectors
1 Introduction

The ISIS spallation neutron source [1], located at the Rutherford Appleton Laboratory, produces neutrons and muons for fundamental research in the physical and life sciences using the techniques of diffraction, reflection and spectroscopy. Neutrons are produced when a high intensity beam of protons (accelerated to 800 MeV) is fired at a tungsten target. The neutrons are then moderated to lower energies by cold materials such as liquid hydrogen before being collimated down a variety of beamlines to sample positions enabling the various science techniques to thus be applied. Two target stations exist on ISIS, TS1 and TS2, of which 18 instruments view target one and another seven view the second target with the capacity to increase this by a further 11 instruments. The second target station became operational in 2009 and SANS2d [2] was one of the seven phase 1 instruments built. SANS2d is a second generation Time Of Flight (TOF) small-angle scattering instrument combining the advantages of white beam techniques with two large independently moveable area detectors. The instrument can be used to examine size, shape, internal structure and spatial arrangement in nanomaterials, ‘soft matter’, and colloidal systems, including those of biological origin, on length scales between 0.25–300 nm. The technique of small angle neutron scattering does not locate individual atoms but rather looks at the larger structures they form. This gives important insights into many everyday materials and biological systems.

Two one metre square Ordela [3] detectors have been used to capture the SANS data, since the instrument became operational. However, these detectors suffer from low count rate capability, are easily damaged and are expensive to repair. The design and performance of a new position sensitive detector array is presented. The new arrays each consist of 120 individual position sensitive detector tubes. The detector tubes have an active length of one metre, and a diameter of 8 mm giving an overall detector area of ~ one square metre for each array. Two such arrays have been installed into the SANS2d vacuum tank where they are currently taking user data, some of which is presented here. Similar detector arrays have already been constructed for SANS instruments at other facilities including D22 [4] and BRISP [5] at the ILL and SANS1 at FRM2 [6], and indeed similar arrays already exist at ISIS on the WISH instrument [7].
The position sensitive detectors used to form the SANS2d detector arrays are single wire proportional tubes, which have been supplied by GE Reuter-Stokes [8]. The detector tubes are made from thin walled stainless steel which acts as the detector cathode. A thin resistive wire runs along the length of the tube which serves as the detector anode. The tubes are made neutron sensitive by using $^3\text{He}$ as the detector gas through the nuclear reaction:

$$\frac{1}{3}\text{He} + \frac{1}{0}n \rightarrow \frac{1}{1}\text{H} + \frac{3}{1}\text{H} + 764\text{keV}$$

The tubes are filled with 15 bar of neutron sensitive $^3\text{He}$. Argon is also added as a stopping gas to reduce the range of the proton and triton and to minimise the wall effect, typical of this type of detector [9]. The detectors have a theoretical detection efficiency of 50% for 1 Å neutrons, which is adequate for the detector requirements of SANS2d.

2 Design of the detector array

The large range of scattering vector ($q$) offered by the SANS2d instrument necessitates the use of a large evacuated tank to minimise the scattering of neutrons by air. This requires the detector to either be operable in vacuo, or be suitably engineered with its own atmosphere within the vacuum tank in order to avoid any high voltage breakdown. Either way, the problem associated with the air/vacuum interface needs to be addressed. The previous detector used on SANS2d had a 15 mm thick entrance window, which produced a significant amount of scatter. Thin window designs have previously been utilised, but such windows deflect when atmospheric pressure is present on only one side of the window. Such deflections result in the path length of the neutron through air differing as a function of scattering angle which is undesirable. Measurements performed with a test set up indicated that we could not operate the tubes at the rough vacuum level used in the SANS2d vacuum chamber due to high voltage (Paschen) breakdown occurring. This vacuum level is used ($\sim 1 \times 10^{-3} \text{mbar}$) as it is sufficient to reduce neutron air scattering to the desired level and can be attained relatively quickly ($\sim 30 \text{ mins}$). A high vacuum rated chamber is then not needed. In order to sustain the high voltage in a vacuum level of $1 \times 10^{-3} \text{mbar}$ the high voltage connection to the detector was encased inside a plastic pipe, with the inside of the pipe being held at atmospheric pressure. The implication of this is that the preamplifiers also need to be operated at atmospheric pressure (which is desirable from a heat removal point of view). This was achieved by mounting the electronics in a sealed housing and feeding the detector output signals through a series of KF vacuum hoses. These hoses then provide the necessary atmospheric conditions and were connected to an air blower to provide additional cooling for the preamplifiers.

The detector tubes are precision mounted onto a support panel which in turn is mounted to an assembly jig. Each panel carries 120 of these tubes and also houses the preamplifiers and high voltage connections necessary for the operation of the tubes. The tubes are supported at four points along their length and the supports are aligned within 300 $\mu\text{m}$ in order to guarantee that the wires sit in the centres of the tubes to avoid damage under high tension. The tubes are connected at both ends via their HT connection to preamplifiers, which are housed in a screened air box. At the end of each detector tube a right angled connector has been spot welded to the tube by the manufacturer to our design. These can be seen in the photograph in figure 1(a). The right angled connector facilitates the removal and replacement of individual detector tubes. In order to provide air paths
for the HT leads which are inside the vacuum tank, a fillet of glue is applied around the welds of the right angled connectors and the connector legs are fitted into the right angled connectors with O-ring seals. Standard Swagelok [10] fittings are clamped to the ends of the right angled connectors and to the preamplifier housings. These fittings form vacuum tight connections to the plastic tubes. The detector HT connections are kept at atmospheric pressure as they pass through the right angled connectors, plastic tubes and the Swagelok fitting to the preamplifier housings. These details are highlighted in the photographs shown in figure 1(b) and 1(c). Boron carbide shielding is mounted onto the support panel, behind the tubes in order to reduce neutron backscatter, resulting in a total weight for one panel of approximately 120 kg. Once assembled and leak tested the panels are then source tested before transfer and installation into the SANS2d vacuum tank.

Figure 2 shows a photograph of the backside of a detector panel showing the air box arrangement. Each detector has its own separate air boxes in order to keep the central region empty for a potential “high resolution central detector” as well as to avoid any high energy neutron background in the straight though beam direction. A series of vacuum hoses can also be seen connected to the air boxes which have the high and low voltage cable running through them as well as a SCSI cable for the amplified signals. These 40 m cables take the signals from the preamplifiers to a remote counting house where custom made readout electronics boards process the data, ready for analysis. The modularity of the array and the staggering of the modified legs, allows for easy access for maintenance purposes, all of which can be done inside the vacuum tank. The detectors can be moved in the vacuum tank both along the beam direction (to vary sample-detector distance between 2 and 12 m) and sideways to give an offset (to extend the scattering vector (q) range at a given detector distance) of up to 1200 mm. The front detector can also be rotated to face the sample.

2.1 Preliminary detector testing

The initial evaluation of this design of tube was conducted during the development of the WISH detector array, reported in [11], which was performed on the ROTAX beam line [12] at ISIS. The beam tests evaluated the position resolution of the tubes as well as the rate performance under intense illumination. The tests were also used to develop the signal processing and the gamma/neutron discrimination algorithms. The resistive anode wire (∼8 kΩ) is read out at both ends by means of a bipolar amplifier with a 200 ns integration time. The differential output signals are then digitised with custom built ADC boards with a 33 MHz sample rate and 14 bit resolution. A number of FPGAs are mounted on each ADC board which are used for various functions including signal filtering, optimisation routines and base line restoration. The position of the neutron interaction, which is also performed in the FPGA, is determined by the charge centre of gravity method. Figure 3 shows the response of one of the tubes under test with a collimated neutron beam illuminating the centre of the tube. A position resolution of 7 mm FWHM is obtained in the centre of the tube at the nominal operating voltage of 1450 V, rising to 8 mm towards the ends of the tube. The digital signal processing needs to preserve the position resolution of the detectors up to the maximum count rate of the tube, which has been shown experimentally to be 150 kHz [11]. Thus the global rate limit of our proposed detector array of 120 such tubes should be greater than 10 MHz. This compares favourably with the D22 and SANS1 detector arrays [4, 6]. In comparison the Ordela MWPC had a much lower global rate limit of $2 \times 10^5$ counts per second [3].
The flexibility afforded by the use of the FPGAs in the ADC boards also permits the pulse height distribution of the tubes to be measured, albeit not simultaneously with the position data. This is an important diagnostic tool for determining the working condition of the tubes. Figure 4 shows the pulse height distributions from two tubes when illuminated by an $^{241}$Am:Be source. The figure clearly indicates that one of the tubes is running with a slightly higher gain than the other.
Figure 2. Photograph showing the air hoses connected to the rear of a one square metre detector array with the array installed in the 3 m wide SANS2d vacuum tank.

Figure 3. Position distribution from a tube at 1450 V, illuminated by a 2 mm collimated neutron beam at the centre of the tube.
even though both tubes are nominally identical and are running at the same voltage. This difference in gain is acceptable (∼6%), but much larger differences have been measured (> 50%) which were clearly unacceptable. In fact any tubes showing a gain variation more than 10% were removed and those tubes not used in the final array. The reason for the difference could be due to mechanical tolerances in the alignment of the tubes, either internal to the tube or external, or could be due to a slight difference in gas composition.

The pulse height distribution is measured for each tube on the detector array using the Am:Be source for illumination, which enables rogue tubes and faulty preamplifiers and cables to be highlighted and subsequently replaced if necessary. Figure 5 shows the pulse height spectra from both detector arrays. Each image has been formed from three different scans as only two ADC boards were available with the test set up. Panel 1 shows a tube with a higher gain (tube 94), which was the ‘tube with higher gain’ distribution used in figure 4.

Panel 2 shows three tubes that have some ‘noise’ issues (tubes 26, 96 and 97). Whilst this is of no great concern, these spurious ‘low energy’ pulses could be indicative of underlying problems with the tubes, so this needs to be monitored closely during the operation of the detector arrays. Figure 6 shows position data sets for the two panels which can also be used to highlight any problem tubes or issues. In fact panel 2 shows some mis-positioning in channels 41, 45, 47, 89, 93 and 95. These are due to a fault with the SCSI cable connecting the preamp to the ADC.

Figure 6 also indicates that several tubes on panel 1 show events at the tube ends, generally associated with sparking tubes. This is exactly what they are, the cause of which turned out to be insufficient insulation around some of the solder joints where we had extended the detector HT cables. The solder joints are visible in figure 1(b) and one of the joints is highlighted by a black circle. Initially we had used single sleeves of heat shrink over these joints. Once it was realised that this was sometimes inadequate, an extra layer of insulation was added to the detector HT leads.
Figure 5. Pulse height spectra obtained from both panels under Am:Be illumination.

Figure 6. Position data obtained from both panels under Am:Be illumination.

on panel 2. Figure 6 shows that there is considerably less sparking on the second panel compared to the first panel. Once tested, the two panels were installed into the SANS2d vacuum tank as can be seen in the photograph in figure 7.

3 Experimental measurements on SANS2d

Once the detector arrays were installed a series of commissioning and calibration runs were performed to verify the performance of the detectors. A polymer mixture is routinely used on the SANS2d instrument as a baseline standard. The polymer is a mixture of deuterated and hydrogenous polystyrene polymers of molecular weight around 70000 g/mole, with about half of the polymers fully deuterated. Figure 8 shows a comparison of the data obtained from the rear detector panel (panel 1) to that obtained by the Ordeja detector placed in the rear detector position, at the same sample to detector distance. The figure indicates that the new detector array represents a moderate improvement in overall detection efficiency $> 20\%$. This increased efficiency is partly due to the fact that there is no thick aluminium window to attenuate the long wavelength neutrons.
and partly due to the increased $^3$He pressure at the shorter wavelengths. The major advantage of the new array over the previous detector is the increased count rate capability which is a factor of $\sim 100$ for a comparable position resolution.

With both detector arrays now operational excellent data is now being produced from the instrument. Figure 9 shows the scattering patterns obtained from a solution containing 26 nm diameter silica particles. The image labelled (a) in figure 9 is obtained from the front detector, 8 m from the sample position and the image labelled (b) is from the rear detector, 12 m from the sample. Figure 10 shows the scattering vector as a function of intensity, showing the presence of fluffy aggregates of the nanoparticles, at $q = 0.04 \text{ A}^{-1}$, obtained by merging the data sets from both detectors.

The two dead channels observed in figure 9(a) have since been repaired or replaced (one was a broken tube, one was a malfunctioning preamplifier channel), the turnaround time for the repair being $\sim 3$ hours, justifying the mechanical design in terms of ease of repair.

The problem of insufficient insulation around the solder joint of the detector HT leads, evidenced in figure 6, is now even more apparent in figure 9(b). In fact this detector array will be removed from the vacuum tank and modified to include the extra insulation around the HT solder joint during a scheduled shutdown period of the ISIS source.

4 Discussion and future work

The two detector arrays recently installed and commissioned on the SANS2d instrument are now employed in the full ISIS TS2 user program. The increased rate capability afforded by these new detectors increases the overall experimental throughput of the SANS2d instrument resulting in a more efficient use of the facility by the wider scientific community. The detector array represents a modest improvement in overall detection efficiency and the design ensures that the detectors can be quickly and easily maintained. We intend to use a similar detector design to meet the needs of ZOOM, the next SANS instrument being constructed at ISIS.
Figure 8. Comparison of the performance of the new detector array and the Ordela detector for the deuterated polymer sample.

Figure 9. SANS data from solution containing 26 nm silica particles from (a) front detector and (b) rear detector. The bright spots at the tube ends in (b) are due to the lack of insulation on the HT leads.
Figure 10. Subsequent plot of the scattering vector versus intensity, with a peak at 0.04 Å⁻¹ showing the presence of the fluffy aggregates of the nanoparticles.

Acknowledgments

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