Detector Development in NMI3

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Detector performance is still a limiting factor for many neutron instruments, and with new higher power pulsed sources coming on-line, these limitations will become even more acute. It is therefore obvious that detector development would be a high priority within the NMI3 Joint Research Activities. The work was structured in two separate projects, though there was a considerable amount of interaction between the different groups, including regular common meetings.

The DETNI (Detectors for Neutron Instrumentation) project was coordinated by Burckhard Gebauer from the Helmholtz Centre Berlin (Germany previously: Hahn Meitner Institute). The other partners were FZ Jülich (Germany), CNR INFM (Perugia, Italy), Heidelberg University (Germany) and AGH University ((Cracow) Poland). Brookhaven National Laboratory participated in meetings as an observer. The ambitious goal of this project was to develop prototypes of three different single-event counting neutron area detectors, together with the novel high-rate and high-resolution electronics for their operation. Two of the DETNI prototypes were micro-strip detectors developed for 10^8 s^{-1} counting rate and 50–100 µm spatial resolution, while the third was somewhat simpler and built for rates of 10^7 n s^{-1} and 1 mm spatial resolution.

All three of the DETNI detector types consisted of a few µm thick solid converter layer, which captures a neutron and promptly emits at least one quantum of detectable secondary radiation, in combination with fast, high resolution two-dimensional position-sensitive detectors for the secondary radiation. In both micro-strip detector types ^{157}Gd converter layers were used in the central detector plane. These emit at least one fast (29–182 keV) conversion electron for each captured neutron, with 87% probability, but in a random direction, and so they are sandwiched between two two-dimensional position-sensitive detectors to achieve the maximum detection efficiency.

Micro-Strip the DETNI detectors

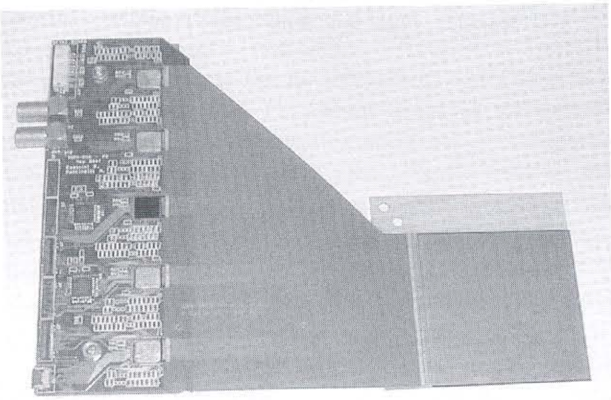

Figure 1. DETNI Si-MSD prototype segment (Picture courtesy of INFM).

In the first Si-Micro-Strip detector (Si-MSD) type each (Fig. 1) module has four segments comprising 53.3×53.3 mm^2 double-sided silicon micro-strip detectors either side of the converter, with 640 micro-strips of 80 µm pitch in each of their two x and two y detection planes. The strips of each plane are read out via five novel 128-channel 'n-XYTER' ASIC (Application Specific Integrated Circuit) chips developed in DETNI, connected to a powerful multi-ADC-FPGA (Analogue Digital Converter – Field Programmable Gate Array) board. For each hit the digitized strip coordinate, a 2-ns wide, 14-bit deep time stamp and the corresponding analogue amplitude fraction deposited on the strip, is recorded. The spatial resolution is improved, relative to direct digitized strip coordinate readout, by calculating the centre of gravity of the amplitude distribution on adjacent strips for each event and in each detection plane. In addition, the background is suppressed by energy gating. A prototype of the Si-MSD detector was made operational and is presently under test.

The second Micro-Strip Gas Chamber (MSGC) detector type (Fig. 2) contains a central composite converter foil with 4.5 mm deep three-stage low-pressure (20 mbar) gas avalanche multiplication gaps on either side; these are enclosed by novel multilayer two-dimensional position-sensitive plates. The novel composite converters consist of 1 µm ^{157}Gd layers coated with 1 µm thick columnar CsI secondary electron (SE) emitter layers either side of a Kevlar support foil. After neutron capture, each fast conversion electron emits a detectable cluster of slow SEs into the adjacent gas volume. These SEs are extracted and pre-amplified by means of an 8–10 kV cm^{-1} electrical field

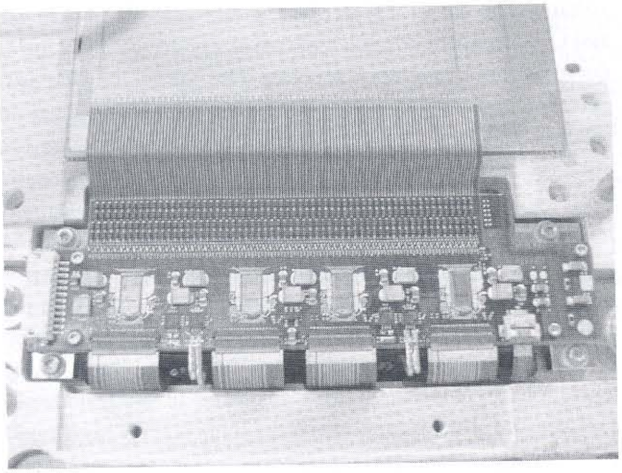

Figure 2. The Prototype MSGC ASIC board developed in DETNI wire-bonded to a MSGC plate in a prototype detector. (Picture courtesy of HZB).

applied over a depth of 250 µm between the converter and extraction grids mounted on either side. The number of SEs scattered through the grid is further multiplied in the subsequent 3.75 mm deep constant field region, until the avalanche reaches the rising field region in the last 0.5 mm to the MSGC plate anodes, where additional micro-strip amplification occurs. The MSGC plates were optimized for low-pressure operation by widening the high-field region between the anode and cathode micro-strips by field shaping to attain higher micro-strip amplification. In addition, through a controlled diffusion widening of the avalanche head, for each event hits are induced on 3.5 adjacent strips on average, thus giving optimal conditions for precise position calculation using the centre of gravity method. The MSGC detector is read out via the 32-channel 'MSGCROC' variant of the novel DETNI ASIC family, which has variable amplification and a five times higher counting rate capability of 900 khit s^{-1} per micro-strip than n-XYTER. With DETNI MSGC prototype detectors the predicted very fast and high signals necessary for reaching the planned very high counting rates and resolutions and so far spatial resolutions of a few tenths of a millimeter were measured.

The third detector type is called CASCADE, because it contains stacks of up to five Cascaded GEM (Gas Electron Multiplier) foils 2 mm apart in a gas pressure vessel, on either side of a central two-dimensional position-sensitive signal induction and readout electrode. The GEM foils are 50 µm thick insulating Kapton foils with copper cladding on both sides, perforated with a regular structure of holes of 70 µm diameter at 140 µm pitch by double-sided etching. 1 µm thick ^{10}B neutron converter layers are deposited on either side of each foil; these emit prompt ^{7}Li ions and α particles in the 1 MeV range following neutron capture. The latter release secondary electrons into the gas volume along their stopping tracks; these drift through the GEM holes towards the central readout electrode without gas amplification. Only when passing through the last GEM foil are they sufficiently amplified for detection by applying higher field strength. The n-XYTER ASIC is again used, optimized for low-charge signal readout. With CASCADE prototype detectors so far as preliminary results position resolutions <1.3 mm (at 2.5 bar overpressure) and counting rates of several Mcps were reached.

DETNI has developed unique channel-wise triggered ASIC chips for high-rate micro-strip readout. These have also been used as prototypes for high-energy heavy-ion detectors for FAIR/GSI and as the basis for developing a dedicated radiation hard version. The DETNI ASIC and readout board developments could also be used for synchrotron and X-ray detection and, after some small modifications, for slower thermal neutron and X-ray detector types like multi-wire chambers with single-wire readout.

MILAND (Millimetre resolution Large Area Neutron Detector) project

The MILAND (Millimetre resolution Large Area Neutron Detector) project was coordinated by Bruno Guerard (ILL) with partners from ISIS, GKSS, LLB, FRM-II, BNC and LIPC (Portugal) and observers from Tokyo University and SNS. The main goal was to build a new detector (not just a prototype) that would significantly improve the performance of single crystal diffraction and reflectometry instruments in terms of sensitive area, counting rate, and position resolution. The specific aims were to improve the previously available angular resolution by a factor of two, by creating a 32 cm × 32 cm area detector with 1 mm FWHM (full-width half maximum) position resolution, and to achieve 1 MHz count rate capability at 10% efficiency loss. This is a factor of 10 better than current detectors. This improvement is greatly due to the 640-channels parallel readout electronics.

The project started with the evaluation of three different techniques of neutron gas detectors – MWPC (Multi-Wire Proportional Chamber), MSGC (Micro-Strip Gas Chamber), and GSPC (Gas Scintillation Proportional Chamber). These have different levels of potential performance and associated technological risk. The MWPC has been used in neutron detectors since the beginning of the 1970's. Its main drawback is the difficulty of keeping the anode wires stable under applied voltage. The MSGC overcomes this by using lithographic techniques, the

Figure 3. The MILAND Detector (Picture courtesy of ILL).

wires in the MWPC being replaced by strips engraved on the surface of a glass substrate. This technique has been used since the late 1980's. It is intrinsically superior to MWPC but suffers from the limited size of the MSGC plate. The GSPC comes from High Energy Physics and has never been used on a neutron instrument.

Despite very promising results for the GSPC, there were still too many open questions to select this technique for a large-area detector. To overcome the MSGC size restriction it was initially proposed to mount four 16 cm × 16 cm plates without dead space between them and all the connections at the periphery of the sensitive area. However, a suitable mechanical design could not be developed. We also tried to mount 10 cm × 10 cm plates side by side with no dead space, but with conductive holes in the glass to connect the strips. Unfortunately, we did not succeed in manufacturing conductive holes without dead space, and the fabrication quality was not high enough. For these reasons, neither GSPC nor MSGC options could be retained for the fabrication of the MILAND detector. However, given the promising results that had been obtained, it was decided to study a new detector combining the two techniques in a single device where the light emitted by a MSGC is read out by a matrix of Photo Multiplier Tubes (PMT). Experimental tests have been made concerning light yield and the spatial resolution of parameters such as the MSGC layout, the gas composition and the MSGC to PMT photocathode distance.

For MWPC the main challenge is to halve the relative distance between the anode wires (the pitch divided by the length); this requires a higher quenching gas pressure (to reduce the ionisation track length) and higher operating voltage. The detector was filled with a gas mixture of ^{3}He and CF_4 at 15 atm. We have obtained a good result by introducing a new mounting process. The wires are first soldered on two printed circuit boards, which are mounted on rotating supports. By moving the supports the wires are stretched by 0.5 mm from both ends, passing the elastic limit and hence being maintained at the maximum mechanical tension. This produces uniform tension between the wires independently of the soldering procedure. The wires are positioned with an accuracy of ± 20 μm using ceramic combs. The 640 readout channels are individually connected to fast amplifiers and comparators to deliver Time-Over-Threshold signals which are transferred to the processing electronics for determination of the longest TOT signal and X-Y coincidence.

The resulting detector nearly matches the specification. The measured counting rate is 0.7 MHz with 10% neutron loss due to the electronic dead time, and fare beyond 1 MHz without taking into account the neutron loss. The spatial resolution FWHM is 1.2 mm for the cathodes and 1.4 mm for the anodes. All these values, close to the specification, will be improved by optimising the signal processing. Other parameters such as the detection efficiency, gamma sensitivity and counting stability have been maintained at the level of the state-of-the-art.

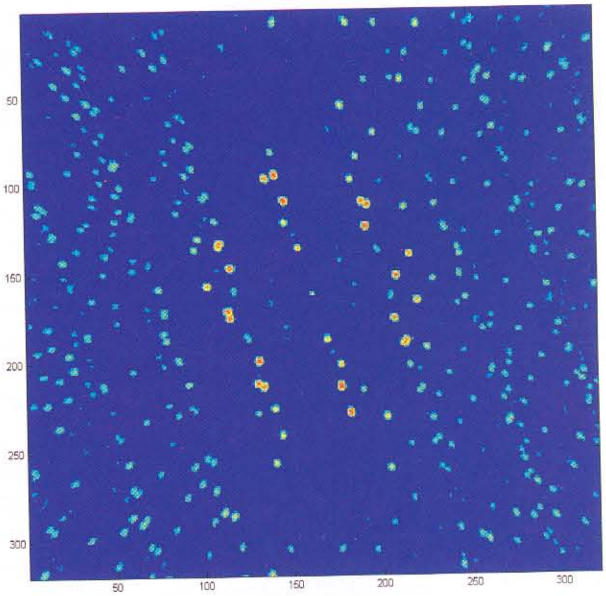

Figure 4. Image of a Lysosyme crystal obtained on the 320 mm × 320 mm MILAND detector demonstrating the high spatial resolution at 32 cm sample to detector distance.

The angular resolution as defined in the MILAND specification does not reflect the accuracy with which the position of a spot signal can be determined, but rather the ability to separate two neighbouring spots. We have studied the position centroid accuracy (PCA), defined as the standard deviation of errors from beam position measurements given by fitting the detector response. For MILAND we measured an accuracy of 11 microns on the anodes, and 15 microns on the cathode. These values are a factor of two better than previously measured with state-of-the-art detectors.

Another important parameter is the parallax error – the FWHM and the PCA increase with the angle of incidence. This effect is often neglected and rarely quantified, but it plays a decisive role when the sample-detector distance is decreased in order to increase the angular coverage. To minimize it, the MILAND detector has been designed to sustain a very high gas pressure to compensate for the reduced efficiency due to the small conversion gap. In addition, the internal electrodes allow two modes of operation. Firstly, applying for single-crystal diffraction, the conversion gap is only 5 mm so that the parallax error is strongly reduced even for sample-detector distances up to 30 cm. Secondly, the conversion gap is increased from 5 to 20 mm in order to maximise the detection efficiency. The user can choose the mode depending on the type of experiment. To our knowledge, this is the first time that a neutron detector allows such flexibility. In future, different operation modes may also be defined by setting the acquisition parameters according to priorities such as the counting rate versus background noise.

The MILAND detector has been installed on the D16 diffractometer at the ILL for further evaluation and real experiments. Figure 4 shows the first image acquired with a lysozyme crystal. Experimental conditions were as follows: the sample size is 2 mm × 2 mm × 2 mm; it is rotated by steps of 1° from 0° to 90°; the distance between the sample and the entrance window is 32 cm; the monochromatic neutron beam (4.76 Å) is collimated with several slits to limit angular divergence; a final diaphragm of 1 mm diameter is mounted at 10 cm from the sample; the neutron flux on the sample is $4 * 10^4$ n/sec; the detector is operated with the 5 mm thick conversion gap. Total acquisition time is 16 hours. The same measurement has been performed with the standard Bidim26 MWPC of D16 (260 mm × 260 mm sensitive area, 2 mm × 2 mm pixel size, 30 mm absorption gap) for comparison. Several spots in the image seen as single peak with the Bidim26 are seen as double peaks with MILAND.