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Preliminary tests of detector prototypes and front-end electronics integration in MIRACLES (ESS)

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Abstract. This work reports on preliminary tests and results for the neutron detection system of the MIRACLES instrument, the time-of-flight backscattering spectrometer at the European Spallation Source (ESS). Several prototypes consisting of two tubes connected in series using a U-connection (doublets) were designed, manufactured and tested. The purpose is, on one hand, to tests the robustness of the serial U-connection, and on the other hand, the integration of the doublets with the front-end electronics (preamplifiers and digitizer). Two models of multichannel charge-sensitive CAEN preamplifiers have been used during the experiments. These preliminary tests were essential to characterize the detectors and gain insight into the parameters for data acquisition chain prior to integration into the ESS data management.

1. Introduction

MIRACLES is the time-of-flight backscattering spectrometer at the European Spallation Source (ESS).[1-3] The neutron detector system of the MIRACLES instrument consists of 96 ^{3}He tube detectors, arranged in two arrays of 48 tubes, configured in a semicylindrical layout around the sample environment (see Figure 1) with a cylinder radius of ~230 mm, above and below the sample plane (vertical gap sample plane detectors: ~95 mm). It is expected a maximum neutron rate up to 6×10^3 n/s per ^{3}He tube, achieved in the highest-flux mode of quasielastic measurements. The electronic components are directly connected to the tubes located above and below the scattering vessel.

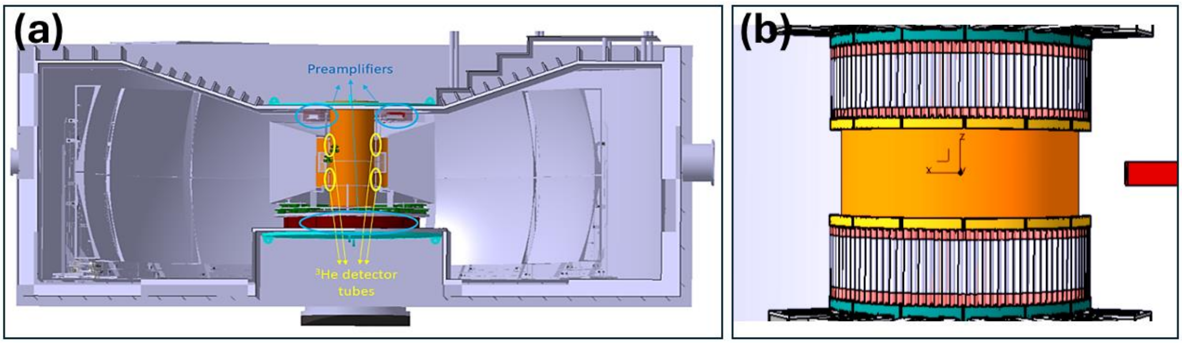

Figure 1. (a) Scattering system and (b) Detectors layout of the MIRACLES backscattering spectrometer.

Based on the conceptual design of the MIRACLES scattering characterization system, the 96 tube detectors will be arranged in 48 doublets, 24 in the upper bank and 24 in the lower bank covering a scattering angle (2θ) from 9.5º to 165º. The tubes in the doublet are connected in series (U-shape layout); this connection is located in the extreme closer to the sample plane.

An experimental plan was drafted as an approach to have a preliminary validation of the detection system of MIRACLES. To this purpose, a doublet assembly formed by two ^{3}He tubes were designed and manufactured to check the robustness of the U-shaped connection in terms of thermal stability, ground and RF isolation; two preamplifier modules were also tested. Finally, integration tests between the electronic devices included different cable lengths.

2. Experimental setup

Figure 2 shows the schematic experimental layout for the tests. These tests were carried out using an Am-Be neutron source at the Nuclear Engineering Department of the Polytechnical University of Madrid.[4] The source has an activity of 2 Ci with a neutron emission of 5.2×10^6 n/s, and for the experiment; this source was placed at the bottom of a container filled with paraffine acting as neutron moderator. The detectors are placed inside one of the ports designed for this container, and the thermal neutron yield detected ranges ~10^3 n·s^{-1}·cm^{-2}.

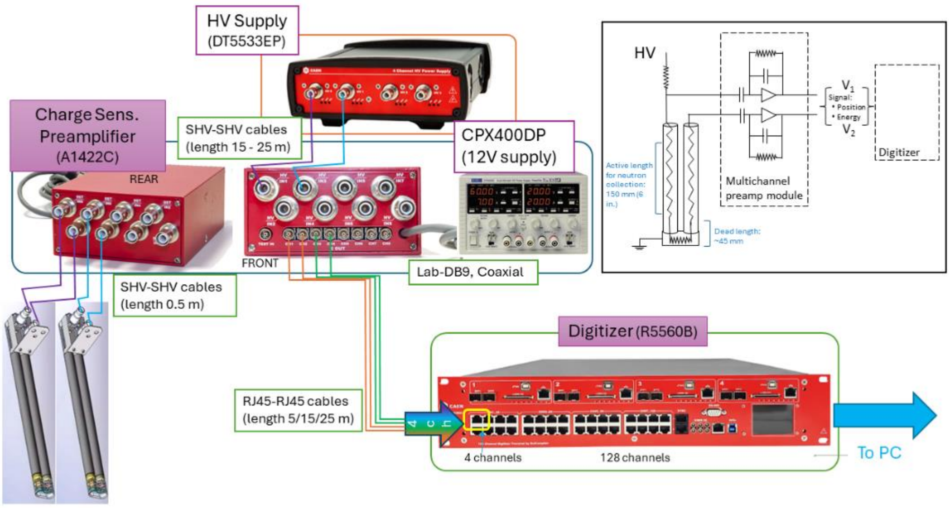

Figure 2. Basic layout of the experiments and test.

The ^{3}He tubes selected for the tests are from Reuter Stokes, model RS-P4-0406-276 (12.7 mm diameter 152 mm length). The cathode is made of 304 stainless steel and the tube walls are 0.25 mm thick. The anode is a Ni-Cr wire of ~15 μm diameter, yielding an average measured resistance of 1.16 kΩ. The resistance of the U-shape connection was set to the order of ~kΩ (the doublets show an average measured resistance of 2.85 kΩ). Additionally, to mimic the design specifications of the detectors for MIRACLES, the "dead length", which is the non-active detection zone of the detector at the U-shaped connection, shall be minimized (below 45 mm), and the separation between the tubes was minimized (~ 0.5 mm).

A partial ^{3}He pressure was set to 10 bars to provide efficiencies of >90% for $\lambda > 6$ Å neutrons. In a ^{3}He gas tube with P = 10 bars, the stopping power for ^{1}H (proton) is 5-6 mm and for ^{3}H (triton) is ~1.6-2 mm, yielding a total distribution of centroids (thus, an idea of position sensitivity) of 6.6-8 mm.[5]

Two charge sensitive preamplifiers were tested. On one hand, the CAEN 8-channel A1422C preamplifier module,[6] in which the charge sensitivity was set to R_S =90 mV/MeV (thus a gain of the preamplifier of G=2.03 V/pC). On the other hand, the CAEN 32-channel R1443A preamplifier module,[7] recently designed to provide an optimized response for ^{3}He tubes, displays a gain of G = 2.25 V/pC. The ^{3}He detectors are powered through CAEN multichannel charge-sensitive preamplifier modules using high voltage (HV) supply (CAEN DT-5533EP). In addition, the A1422C has an external preamp power (±12 V), supplied by a CPX4000P power supply.

The raw signal from the preamplifiers was directly processed using the CAEN R5560B digitizer,[8] following the same strategy as other ESS instruments. The R5560 is based on Xilinx Zynq-7000, and a Dual Core 1GHz ARM processor; it has 128 differential analog inputs and hosts 128 ADCs operating in simultaneous sampling at 125 MS/s, 14 bit. The Digital Pulse Processing solution provides several advantages related to a better correction of pile-up, low dead time and subsequently an appropriate management of high-count rate.[9] The CAEN SCI 55XX readout software is used to control the signal acquisition.[8]

The length of the SHV coaxial cables to connect the tubes to the preamps was 50 cm, although it has been demonstrated, using R1443 preamp modules, that no loss of signal amplitude has been observed with cables up to 2 m.[10] The connection of the preamp to the digitizer is carried out using 8-wire ethernet cables with RJ45 connectors were used forming 4 differential channels for every cable. Three different lengths (5, 15 and 25 m) were tested, giving the same results without visible signal loss.

3. Results and Discussion

During the tests to validate the preamplifier option, two doublets were used with different connection configuration: one of the doublets is connected as a counter mode (one end connected, one channel); the other doublet is connected for position sensitive mode (two channels connected to the two SHV connectors of the doublet).

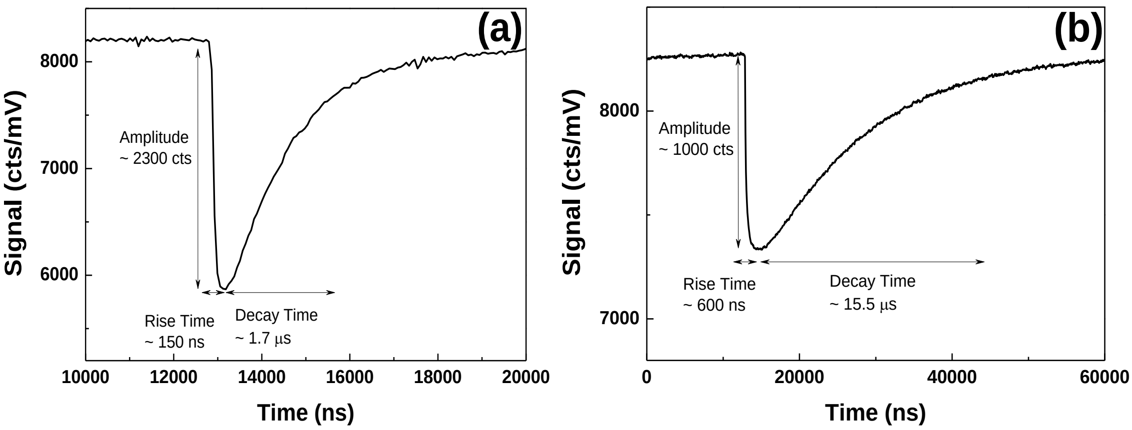

Figure 3. Output raw signal (oscilloscope) obtained for (a) the R1443A preamplifier module and (b) the A1422C preamplifier.

Raw signals captured for both preamplifiers are shown Fig. 3. The difference in the output of the preamplifiers is noticeable. Whereas the R1443 preamp displays an average decay time of ~1.5 µs (Fig. 3a), the A1422 preamp shows a decay time of one order of magnitude larger (~15 µs Fig. 3 b). A similar situation is observed in the rise time: the R1443 preamp has a faster rise time, ~150 ns, than the A1422 preamp risetime, ~600 ns. Finally, the amplitude of the signal present also significant differences: the R1443 preamp reveals amplitudes beyond 2000 counts, whereas the A1422 preamp displays smaller amplitudes of the order of the ~1000 counts. Therefore, the R1443 preamplifier module is more suitable to manage the high flux rates of MIRACLES, with a faster response and higher gain.

3.1 Spectra vs Peaking Time

Independent trapezoidal energy filter on each channel was implemented for energy calculation and realization of pulse height analysis (PHA) of the signal received. Although a different filter strategy might be needed in the flux-variable MIRACLES spectrometer, the trapezoidal filter works well in these tests carried out in a continuous source with no significant fluctuation in the incident count rate, The trapezoidal filter transforms the exponential decay signal generated by a charge sensitive preamplifier into a trapezoid whose flat top height is proportional to the amplitude of the input pulse (the energy released by the particle in the detector). The height of every signal is directly related to the energy deposited by the nuclear reaction (neutron capture) to the detector.

Captured raw signal is processed by the digitizer to generate the pulse height spectra (PHS) of the tubes. The energy resolution is given by the formula: $\delta E = \frac{\sigma[channels]}{\mu\{channels\}}$, where $(\sigma[channels])$ and $(\mu\{channels\})$ are the full width at half maximum (FWHM) and the position of the full-energy maximum peak, respectively. As shown in Figure 4a, counter mode has a clear height spectrum, with clean peak of energy corresponding to the full energy deposition; results also show an energy resolution in both devices below 10% for peaking times ≥400 ns, reaching an optimized value of 7.7% at peaking times of 800 ns. Also, at first glance it is shown that wall effects (proton and tritium escape contributions), gamma events and alpha events were hardly visible despite the small diameter of the ^{3}He tubes. In the position sensitivity mode, the evolution with peaking time is similar (Fig. 4b); however, the spectral peaks are much broader than the ones displayed by the counter configuration.

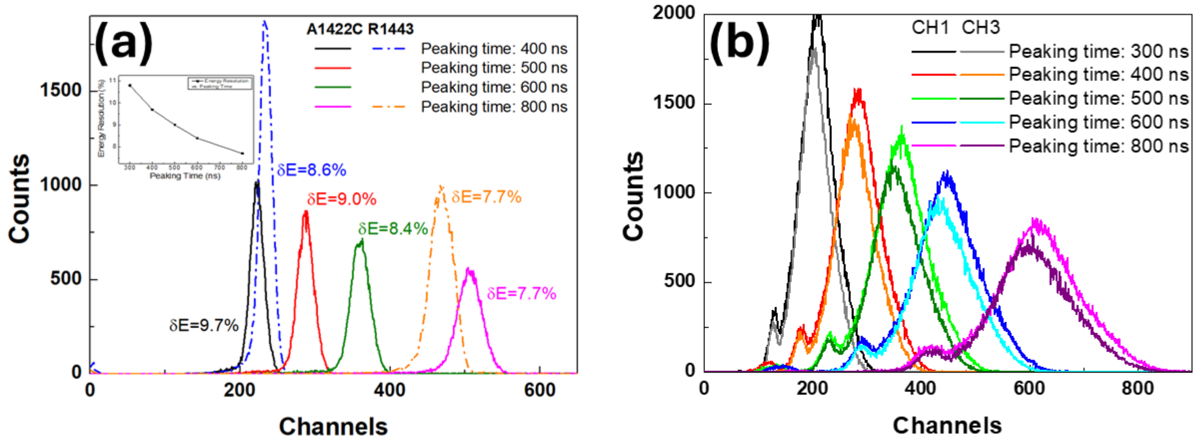

Figure 4. Pulsed height spectra vs peaking time using the A1422C preamp module as a function of peaking time (a) in the counter configuration, including results from the R1443 preamp for comparison (inset: evolution of the energy resolution with peaking time); (b) in the position sensitive configuration.

3.2 Spectra vs Voltage

The evolution of the neutron signal and pulsed height spectra at different high voltage supply values can be harnessed to characterize the gas gain of ^{3}He tubes. A gaussian fit will be carried out in the full energy peak, only considering the right side (avoiding the distortion observed in the left side, mainly at the highest voltages). Here, experimental results from the A1422C preamp module (Fig. 5a) and the R1443 preamp module (Fig. 5b) were displayed. The peaking time for the trapezoidal filtering was fixed in both preamps to 600 ns.

The position of the peak is directly related to the gas gain, considering a fixed value for preamp gain and digital gain. However, at V ≥ 1600 V the spectral peak starts to lose its well-defined shape, losing height and showing a clear peak asymmetry and broadening in the left side (i.e., reduction of the amplitude of the raw signals). This is likely due to predominant space charge effects, that arises when the slow ions generated during the avalanches distort the electric field to impede the growth of further avalanches. Also, the gain follows an exponential curve with increasing voltage (see Fig. 5c) as observed in other works; however, results detach from this trend significantly in the R1443 preamp.[11] Finally, the energy resolution remains below or about 10% until voltage increases above 1550 V (Fig. 5d). All the results displayed confirm that the optimized operative bias is about 1500-1550 V.

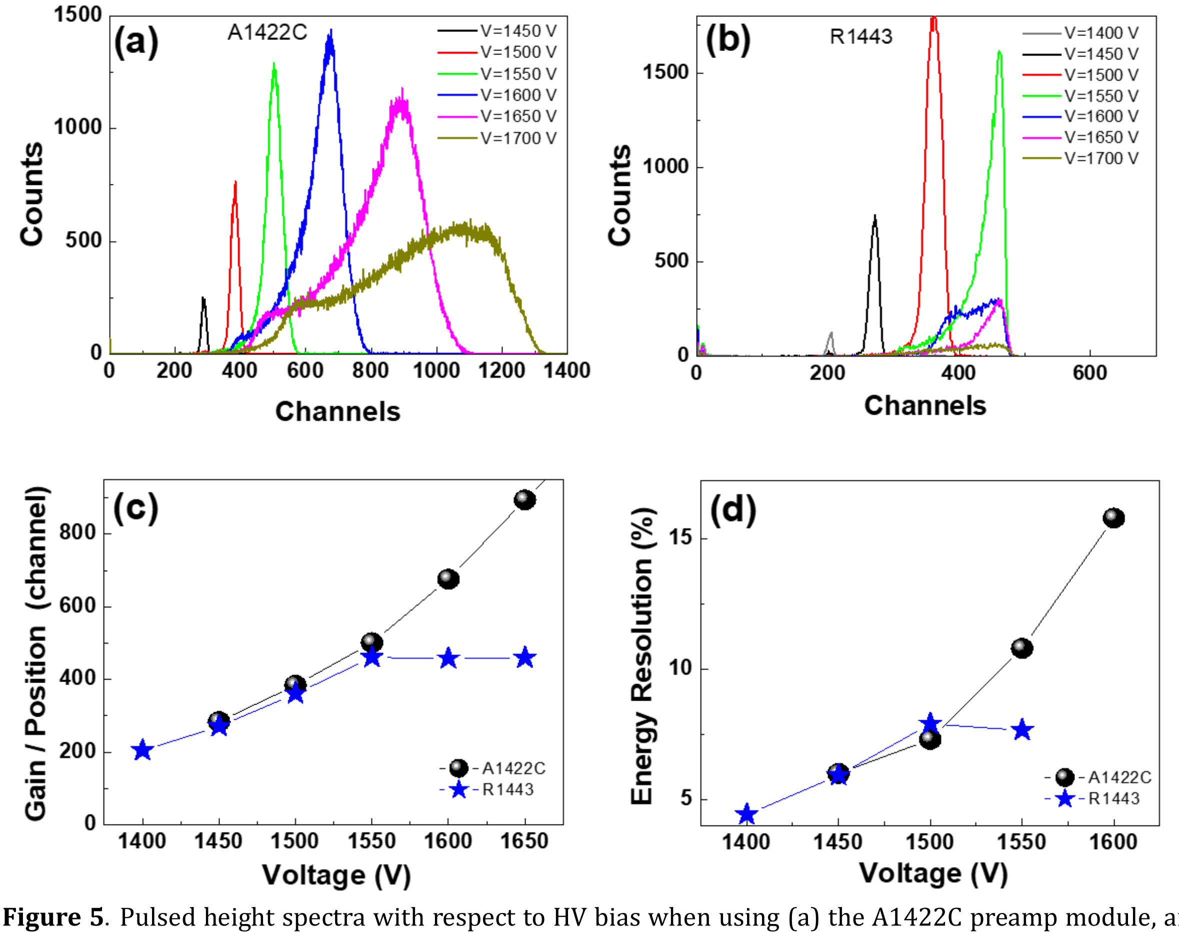

Figure 5. Pulsed height spectra with respect to HV bias when using (a) the A1422C preamp module, and (b) the R1443 preamp module; (c) peak position (gain), and (d) energy resolution of the spectra with respect to HV bias.

Once that we have established the optimized parameters in terms of energy resolution and neutron-gamma discrimination, future work in the MIRACLES detectors will consider position resolution determination. To this purpose, the position will be calculated event by event with timestamp associated, using the voltage division formula. Centroid shift of energy spectra from

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slit positions gives information of the position of neutron incidence. Although position resolution is not a paramount requirement for a backscattering spectrometer, it will be a good test to complete the characterization of the MIRACLES detectors.

4. Conclusions

Several tests were carried out to evaluate and validate the design approach to the detection system of the MIRACLES spectrometer. The MIRACLES detection unit consists of two ^{3}He tubes connected in series, forming a U-shaped doublet. Prior to signal processing by the digitizer, the signal was magnified using a preamplifier module. In these tests, two types of preamp module were evaluated: on one hand, an 8-channel CAEN A1422C module, with preamp gain of 2 V/pC; on the other hand, the 32-channel CAEN R1443A, recently developed, with a preamp gain of 2.25 V/pC. Both preamp modules are suitable for ^{3}He doublet detection, showing an energy resolution ~10%. However, the difference in the height of the raw signal and the significant difference in the decay time confirms that the R1443 device is more suitable for the high-count rates expected in MIRACLES with respect to the A1422C one. The processing parameters such as peaking time and the working HV bias for the front-end detection system, in terms of spectral shape, energy resolution, gas gain and space charge effects, have been optimized. Results suggest an adequate operative bias ranging between 1500 and 1550 V.

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