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First Tests of a new Fast Waveform Digitizer for PMT signal read-out from liquid Argon Dark Matter detectors

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Abstract

A new generation Waveform Digitizer board as been recently made available on the market by CAEN. The new board CAEN V1751 with 8 Channels per board, 10 bit, 1 GS/s Flash ADC Waveform Digitizer (or 4 channel, 10 bit, 2 GS/s Flash ADC Waveform Digitizer - Dual Edge Sampling mode) with threshold and Auto-Trigger capabilities provides an ideal (relatively low-cost) solution for reading signals from liquid Argon detectors for Dark Matter search equipped with an array of PMTs for the detection of scintillation light. The board was extensively used in real experimental conditions to test its usefulness for possible future uses and to compare it with a state of the art digital oscilloscope. As results, PMT Signal sampling at 1 or 2 GS/s is appropriate for the reconstruction of the fast component of the signal scintillation in Argon (characteristic time of about 4 ns) and the extended dynamic range, after a small customization, allows for the detection of signals in the range of energy needed. The bandwidth is found to be adequate and the intrinsic noise is very low.

Keywords: Dark Matter, liquid argon, fast waveform digitizer
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1. Introduction

Recently liquid argon has been one of the quickest developing detector technologies in neutrino and Dark Matter detectors. This is because argon detectors are able to register both the ionization and scintillation light resulting from particle interactions. The scintillation light is especially important in the case of Dark Matter detectors which try to measure extremely low energies (of the order of tens of keV or less) where the light gives a a precise measurement of the energy as well as a better capability of background discrimination.

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The low energy scale at which these detectors operate together with the properties of liquid argon make preparing the data acquisition setup a very challenging task.

First of all, liquid argon has a boiling temperature of 87 K, which means that the light collection active elements, usually PMTs, must be suited to operate in these temperatures. The second difficulty is due to the light emission mechanism in liquid argon, in which the scintillations are created by the deexcitations of argon dimolecules. There are two main molecular states: the singlet $^1\Sigma_u$ and the triplet $^3\Sigma_u$ [1]. The principal difference between the two components of the scintillation light is a result of the different decay times of the molecular states - 5-7 ns and 1.2-1.5 μs, respectively. The ratio of the relative amplitudes of these states is usually different for different types of particles and so it is often considered as useful for Pulse Shape Discrimination. To be able to perform this operation a very fast acquisition system is needed - the need for which is also amplified by the very fast response times of the PMTs used (several ns). Another thing required from such a DAQ setup would be to identify single photoelectrons, which for low energy events could compose a significant part of the event energy. For these reasons most of the experiments have chosen to employ fast waveform digitizers of up to 1GS/s sampling [2],[3][4].

We report here on the tests performed on a digitizer with such sampling - the new V1751 fast ADC board recently made available by CAEN SpA. The board has been tested extensively in working conditions in a liquid argon Dark Matter test detector. Its performance has also been compared to a state of the art oscilloscope capable of much higher sampling rates - up to 20 GS/s for four channels to check if the sampling implemented in the board is sufficient to reconstruct single photoelectrons.

First the tested board will be described, followed by the results of the initial tests obtained when using the board in a standard acquisition chain in a liquid argon detector. Finally the data obtained using the new board will be compared to runs taken with a LeCroy WavePro 735Zi oscilloscope to check whether its bandwidth and sampling are sufficient to acquire single photoelectrons in liquid argon.

2. The V1751 Fast Waveform Digitizer

In recent years CAEN has developed a complete family of digitizers that consists of several models differing in sampling frequency, resolution, form factor and other features. Each of these boards has been designed in order to satisfy the requirements of various applications involving different experimental setup and measurement constraints.

CAEN V1751 is a VME board housing a 8 channel 10 bit 1 GS/s Flash ADC waveform digitizer, see Fig. 1. The V1751 can also interleave couples of channel through the Dual Edge Sampling mode, acting as a 4 channel10 bit 2 GS/s digitizer.

The aim of this such a board is to sample the pulses of fast detectors with temporal behavior of the order of few tens of nanoseconds; examples of these devices are fast PMTs, even coupled to fast scintillators, APDs, SiPMs, RPCs etc.

Thanks to the high-speed sampling ADCs mounted on the V1751, it is possible to perform very precise timing measurements using interpolation methods on the digitized pulses; preliminary studies about these off-line techniques applied to signals generated by a pulser led to a timing resolution of less than 10 ps. For the same reasons, it is possible to reproduce the digitized waveforms with high accuracy letting the user to run further pulse processing algorithms as Pulse Integration or Pulse Shape Analysis, one of the most widely used particle identification techniques.

For these reasons, an ideal applications of V1751 is the acquisition of the pulses output by PMTs coupled to Liquid Argon Chambers. This application, in fact, requires fast, high-gain PMTs designed for low-light detection.

As previously said, the V1751 is a 6U VME board housing a 8 channel 10 bit 1 GS/s Flash ADC waveform digitizer with analog bandwidth of 500 MHz and input dynamic range of 1 Vpp. The single ended version of the board allows adjusting the DC offset of each channel by means of an internal 16-bit DAC in the range 0.5/+0.5 V. By interleaving couples of channels, the board can run in Dual Edge Sampling, hereafter DES, mode: in this way, the board works as a 4 channel 10 bit 2 GS/s digitizer. The V1751 has been designed with a mother-daughter boards configuration - see Fig. 2. The mother board is equipped

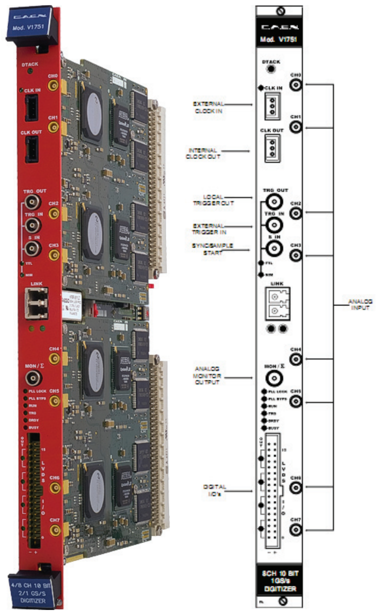

Fig. 1. CAEN V1751 4/8 Channel 10 bit 2/1 GS/s Digitizer and its front panel.

with an FPGA dedicated to the readout interfaces and the services as power supplies, clocks and I/Os. Each of the daughter boards houses 4 channels and contains the input amplifiers, the ADCs, the FPGAs for data processing; moreover, each channel has a SSRAM memory buffer (1.8 or 14.4 MS/ch according to the desired memory buffer size), with independent read-write access divided in 1 to 1024 buffers of programmable size. In DES mode the memory buffers of each couple of interleaved channels are shared doubling de facto the memory depth per channel.

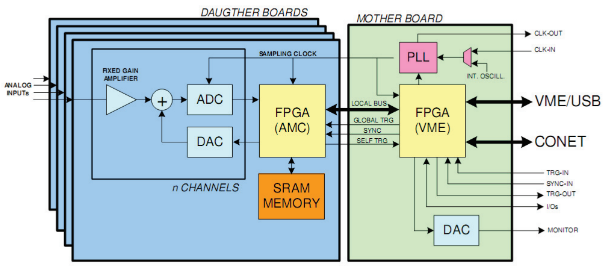

Fig. 2. CAEN Digitizer block diagram. The mother board defines the form-factor; it contains one FPGA for the readout interfaces and the services.The daughter board defines the type of digitizer; it contains the input amplifiers, the ADCs, the FPGA for the data processing and the memories

The trigger signal can be provided via the front panel External TRG IN input as well as via the VMEbus, but it can also be generated internally, allowing also the self-generation of a majority trigger. Being designed with multi-board synchronization capabilities, the trigger from one board can be propagated to the other boards through the front panel Trigger Output; in this way, it is possible to compose a complete DAQ system with a large number of channels.

A programmable Analog Output allows to reproduce the trigger majority, a test waveform and the buffer occupancy. The modules VME interface is VME64X compliant and the data readout can be performed in Single Data Transfer (D32), 32/64 bit Block Transfer (BLT, MBLT, 2eVME, 2eSST) and 32/64 bit Chained Block Transfer (CBLT). The boards houses a daisy chainable Optical Link able to transfer data at 70 MB/s through a CAEN proprietary protocol called CONET 2 [2] with a data transfer of up to 100MB/s, thus it is possible to connect up to eight ADC boards (64 ADC channels) per link by means of CONET-compliant optical controllers, (CAEN Mod. A2818 or Mod. A3818). Optical Link and VME access are internally arbitrated.

In order to adjust the dynamic range of the board with the PMT output in a way to be able to see single photoelectrons at the standard PMT gain used, a customization of the front end stage of the board has been required. Modifying the input amplifiers, the dynamic range has been reduced to 0.2 Vpp preserving the analogue bandwidth, see Fig. 3.

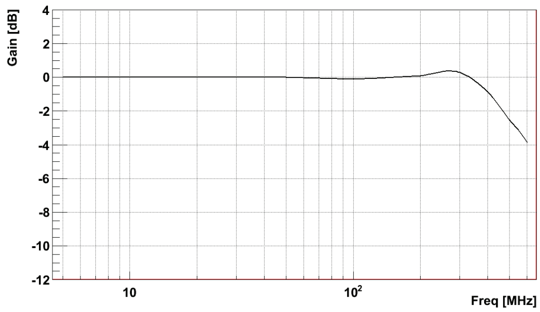

Fig. 3. Full Power Bandwidth graph of the modified front end stage. The 500 MHz bandwidth is preserved.

3. Experimental Setup and First Tests

From the point of view of a Dark Matter search the important parameters of the tested board were the sampling, full scale range, noise and triggering capabilities. The sampling and noise level of the board are important in order to observe single photoelectron pulses correctly and not lose them amongst the noise counts. The 10bit full scale range is useful in order to observe full events with a higher energy - which is imporant in high Light Yield setups with a small number of PMTs [5], even more so for WIMP-like recoil events that could occur in such a detector since these are dominated by the fast singlet light component and so a large part of the light arrives almost simultaneously which makes saturation more probable.

The 10 bit FS of the board allowed observing events in a range from 20 p.e. to 6000 p.e. for gamma like events in a 4PMT setup corresponding to a 3.3 - 1000 keVee at Light Yield equal to 6.1 [5] (20-1000 p.e. for recoil like events corresponding to 13 - 655 keV nuclear) energy range - more than sufficient for a Dark Matter detector.

3.1. The Experimental Setup

To our knowledge the setup used in this work, see Fig. 4, is the first use of the V1751 board in an experimental setup tailored for Dark Matter detection. The setup consisted of four high Quantum Efficiency (QE) Hamamatsu manufactured R11065 PMT with a negative bias on the cathode observing a liquid argon volume of 4.3 liters. The anode signals were fed directly into four of the V1751 input channels. An event was saved when 3 out the 4 channels registered a trigger of the order of 1 p.e. at a PMT gain of 0.8e6. In the first phase of the measurements this was done by feeding the majority trigger generated by the V1751 board into a threshold discriminator and feeding back the resulting NIM signal as a trigger into the board. In the second phase of the measurement the majority trigger was performed internally inside the ADC board by polling a board register address. The acquired events were then transferred via optical fibre into an A2818 CAEN PCI board connected to a PC computer.

[2] in the measurements reported here a board with an older version of the firmware using the CONET protocol was used.

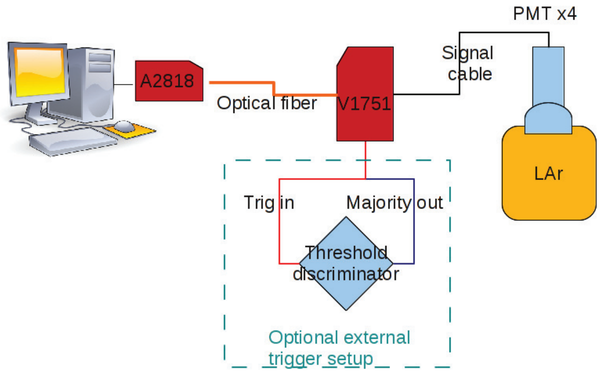

Fig. 4. The experimental setup used in these measurements.

The first tests with the board were concentrated on the basic quality of the acquired data. Among these were the registered noise defined as the RMS of the baseline measured in the pretrigger i.e. first $2\mu s$ of each signal. This quantity has been found to be under 1 ADC count i.e. under the LSB (Least Significant Bit) as declared by the manufacturer. The values were slightly worse when running in the 2GS/s DES mode, see Fig. 5. Average waveforms were also created by summing up consecutive events. This is usually done to estimate the purity of liquid argon [6, 7]. When observing these average waveforms a dephasing effect was observed in the baseline region, where the odd and even points seemed to be separated by an offset even when summing the 4 channels together, see Fig. 5. The reason for this behaviour is the way the board sends out the acquired samples in pairs. It should be noted that the observed offset in the average waveform is smaller than 1 ADC count per event and so should not cause problems for single waveforms and can be easily corrected for by software means.

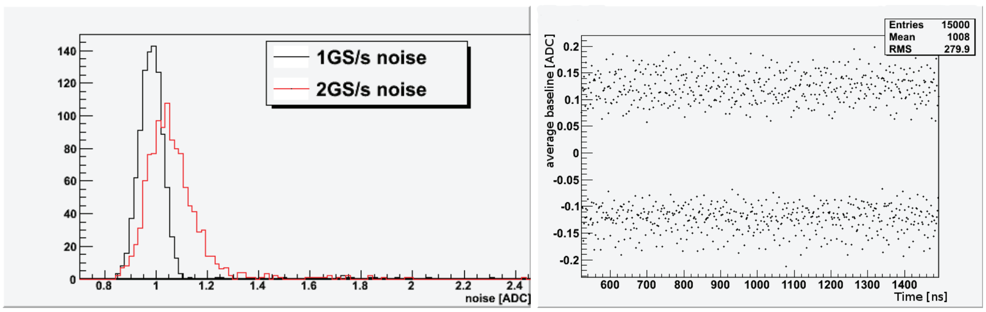

Fig. 5. The noise measured in the board (left) the dephasing effect observed when summing multiple events together(right).

Since two-phase liquid argon detectors, both currently operating [8] and future [4],[9], require long drift times and as a consequence longer waveforms, we have tested the data throughput obtainable with the board. We have found that acquiring with an automatic trigger results in a 17Hz acquisition rate for 8 channels at $400\mu s$ corresponding to a 49.6 MB/s data rate. This is less than the declared throughput of the CONET protocol used by the board to communicate with the PC. However the limit is set by the speed of writing to disk. Hence for a larger liquid argon detector, which will be characterized by a large background rate coming from the radioactive isotope ^{39}Ar [10] a second level trigger may be required.

The single electron response spectra SER obtained with the board were clear with a peak well separated from the steep exponential dark counts - Fig. 6. The new board showed an improvement with regard to the old DAQ setup used. This is attributed to the much better noise suppression in the V1751 board setup confirmed by an FFT transform on the acquired waveforms - Fig. 6 right.

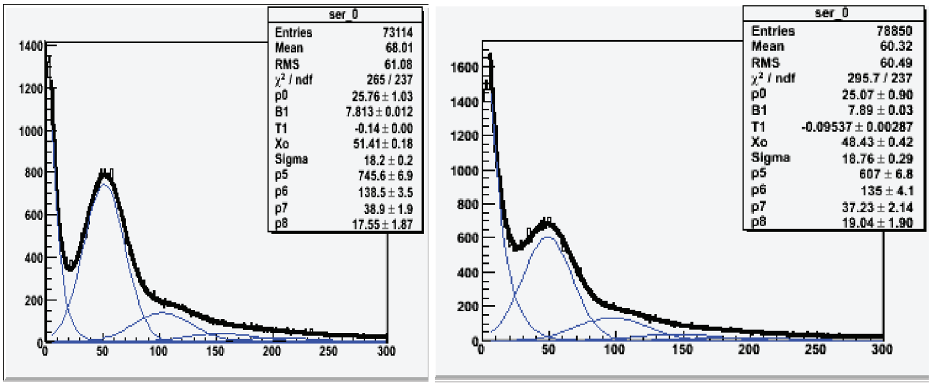

Fig. 6. SER spectrum obtained with the V1751 board (left) and previously used setup (right).

4. Liquid Argon Signal Readout at Higher Samplings

To fully test the performance of the V1751 board we decided to compare it to a state-of-the-art setup to see if the bandwidth and sampling rate ofthe V1751 board are really sufficient to register liquid argon signals. A LeCroy WavePro 735Zi oscilloscope was chosen as the reference. It is capable of achieving 20GS/s sampling (50ps/sample) simultaneously with 4 channels at a 3.5GHz analog bandwidth. However due to its price and operation mode it is not conceived to use for an actual data acquisition.

The first step was comparing the actual value of the single p.e. integral obtained by fitting the SER spectrum resulting from binning the single peaks found in the examined waveforms. For this measurement the PMTs were set to higher gain than in the usual data taking - 2×10^7 to focus on the single photoelectron signals. The data acquired with the PMTs was scanned using a simple peak finding algorithm and the integrals of the peaks found were binned into a spectrum. In this case multiple peaks were accepted and so the resulting spectrum was fit with a superposition of an exponential function to account for the component due to dark counts and multiple (N) gaussian peaks corresponding to the first and multple p.e. peaks. The position and variance of the nth peak was constrained to the values resulting from the single p.e. peak as in $x_n = nx_0$ and $\sigma_n = \sqrt{n}\sigma_0$. The N value was equal to 2 for the LeCroy data and 4 for the V1751 data. The resulting single p.e. peak positions, after converting to $V \cdot ns$, turned out to be in good agreement suggesting that the lower sampling rate of the V1751 board should not affect the collection of charge from PMTs capabilities of a potential DAQ setup. Actually the higher bandwidth of the LeCroy oscilloscope created problems by augmenting the fraction of noise peaks found by the algorithm and so making the single p.e. position determination more difficult - see 7. In this setting the CAEN SER peaks are in 10% agreement with those obtained at 20GS/s.

The next test was aimed at testing whether with 1GS/s some detail in the shape of the single p.e. signal is not lost. Using the peak parameters obtained from the the SER spectrum evaluation the data was rescanned to search for peaks with a sufficient amplitude and an integral in the range of $(x_o - \sigma, x_o + \sigma)$ from the first photoelectron peak, taking care to discard peaks too close together. For the V1751 data this operation was performed on a sample of 100000 un-triggered events. A similar procedure was performed for the LeCroy data, where waveforms encompassing the range between $5\mu s$ and $7\mu s$ after trigger were saved at samplings of 20GS/s, 10GS/s, 5GS/s and 1GS/s. Five thousand waveforms were saved for each PMT and sampling. The result of this comparison can be seen in Fig. 8, where the agreement between the different waveforms is quite satisfactory, it can even be seen that the V1751 waveforms actually have a slightly higher amplitude. This is attributed to the lower bandwidth of the V1751 board which results in less fast frequency noise that enters in to the waveform dilluting its amplitude. This effect has been confirmed by looking at single phe waveforms obtained with the LeCroy oscilloscope setting different bandwidth filter settings.

The last important test of the new setup was to check whether the lower sampling of the CAEN board might affect the Light Yield determined in the liquid argon detector. The Light Yield is an important parameter in a scintillation detector and signifies its efficiency in detecting light with respect to the energy deposited

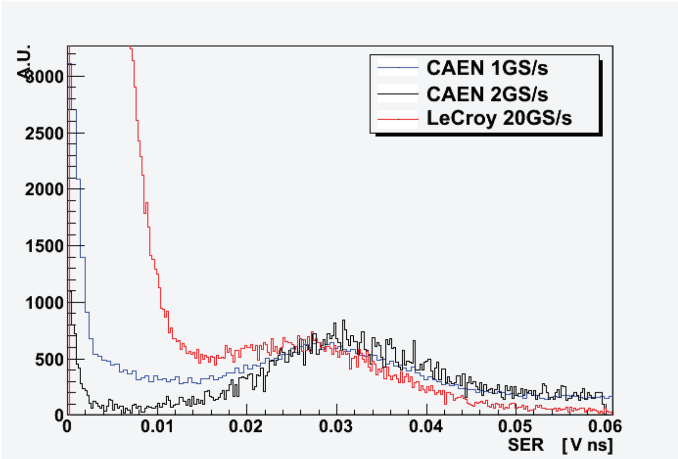

Fig. 7. Comparison of the Single Electron Response (SER) spectrum position for the 20GS/s SER spectrum taken with the LeCroy oscilloscope with the spectra obtained using the V1751 board at 2GS/s and 1GS/s

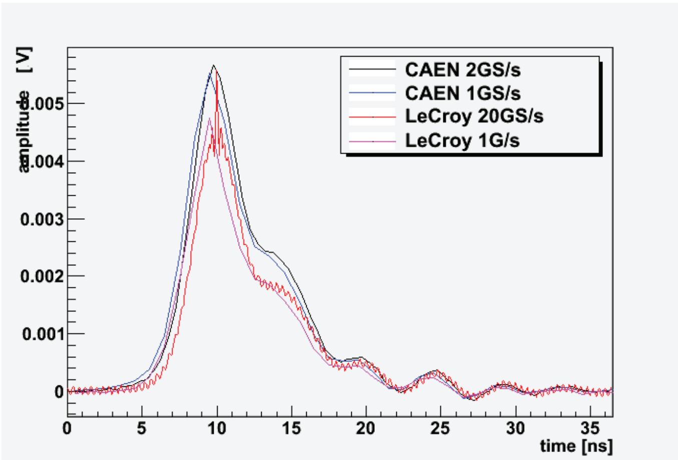

Fig. 8. Comparison of the single p.e. shape for the 20GS/s and 1GS/s p.e. waveforms taken with the LeCroy oscilloscope with the waveforms obtained using the V1751 board at 2GS/s and 1GS/s.

in the chamber. It is expressed in units of p.e./keV and usually measured by irradiating a chamber with a radioactive source of a known energy and calculating the detector response to this signal. In this case we used a ^{241}Am source with a monoergetic gamma peak at $59.5keV$. At this energy the emitted γ-rays undergo full photoelectric conversion depositing all of their energy in the liquid argon chamber. For details of this calibration we refer to [5]. The Light Yield (LY) is one of the most important parameters in a Dark Matter detector since the higher it is the lower the incident particle energies a detector can register and identify. The LY is mostly affected by detector components i.e. the PMT or wall reflection efficiency, but one can imagine that if the electronics setup were to miss a fraction of photoelectrons due to e.g. their shape or size - the effective LY could be diminished.

For this test analog waveforms of $8\mu s$ length with $1\mu s$ of pretrigger and $7\mu s$ of signal were acquired (about 5 times the triplet decay length). In this case, due to limited disk space, only 5GS/s waveforms were collected with the LeCroy oscilloscope. For each oscilloscope and V1751 run a SER spectrum was obtained in order to obtain the calibration factor in $ADC \cdot ns/p.e.$ or $V \cdot ns/p.e.$ for the V1751 board data and oscilloscope data, respectively. Once the calibration factor was known the total integral was calculated by summing only integrals of peaks three sigma above baseline to discard most noise peaks. For the selected peaks a local baseline was subtracted 50 ns before and after the signal. If in these windows of 50 ns another peak was found its integrating range was merged with the peak before it and the local baseline was recalculated. The total integral in $ADC \cdot ns$ or $V \cdot ns$ was then normalized to the reference SER in order to obtain the resulting spectrum in p.e.. The results of this operation for the V1751 board and LeCroy oscilloscope data is presented in Fig. 9. The obtained values were found to be in good agreement with each other - *about 3% loss of LY - well inside of measurement error (after rebinning/changing bandwidth)* suggesting both the satisfactory operation of the V1751 fast ADC board and the sufficiency of using 1GS/s sampling when acquiring data from a liquid argon scintillation detector.

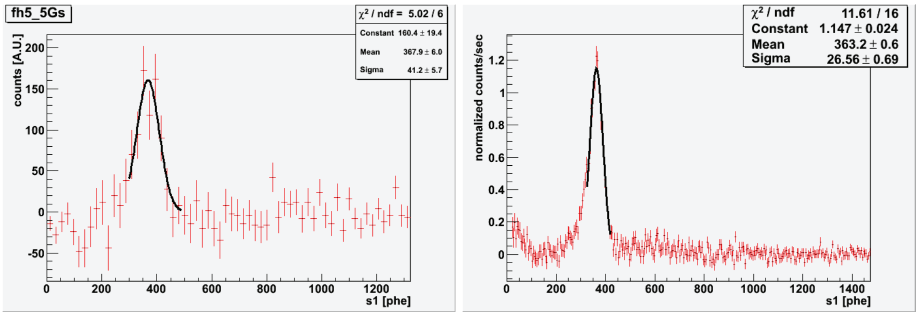

Fig. 9. LY obtained using the LeCroy oscilloscope at 5GS/s (left) and the V1751 board at 1GS/s (right).

5. Conclusions

We have tested the new V1751 fast ADC board manufactured by CAEN SpA in a setup with a liquid argon Dark Matter detector. We have found that the board is well suited for applications involving readout from such a detector where the board's fast sampling time and full scale range are neatly adequate. A further test was to check whether the 1GS/s and 2GS/s sampling capability of the board does not lose some information in the real data comparing it to a LeCroy WavePro 735Zi oscilloscope capable of up to 20GS/s sampling for four channels simultaneously. It has been found that 1GS/s sampling is fully sufficient to record single photolectron signals from cryogenic PMTs in liquid argon - it also seems that the V1751 bandwidth filter is well adjusted to this task.

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