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REAL-TIME LIQUID SCINTILLATOR CALIBRATION BASED ON INTENSITY MODULATED LED

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Abstract

In many nuclear applications such as nuclear/high-energy physics and nuclear fusion, sensors are widely used in order to detect high energy particles. One of the available technologies is the scintillator, which is generally coupled with a photomultiplier and pulse amplifier. The detector acquisition chain is not stationary; mainly, it changes its gain as a function of the temperature, the nuclear irradiation and the magnetic field on the photomultiplier; therefore it needs to be periodically calibrated during its operation. A calibration method reported in the literature is based on the use of a pulsed LED that flashes on the photomultiplier by generating a train of reference pulses. A new technique may be the use of an LED with continuous sinusoidal intensity emission. This provides as an output of the detector chain a small sinusoidal signal which can be digitally processed in real time, by measuring the gain and the delay time of the detector chain. Moreover, this sinusoidal background signal can be removed in real-time, before any processing or storage of data. This paper presents the technique, reporting its simulation and the main characteristics of the developed firmware and the hardware.

Keywords: (Liquid Scintillators, Neutron and Gamma Detection, Intensity Modulation, Real-Time Calibration, ITER Radial Neutron Camera, Digital Signal Processing)

INTRODUCTION

In many nuclear applications such as nuclear/high-energy physics and nuclear fusion, there is an extensive use of sensors, in order to detect high energy particle.

One of the available technologies is the scintillator, which is generally coupled with photomultiplier tube (PMT) and pulse amplifier (see Figure 1). The high energy particles incident on the scintillator produces electrical pulses as output of the PMT chain. The pulses have different shape and amplitude depending on the particle type and energy. In general, the pulses due to high energy particles are composed of a rising and a falling exponentials, having respectively little rising time and large falling time. The rising and falling constants depend on the particle type. Many algorithms can be used in order to discriminate the type of particles, such as Charge Comparison [1][2], or Pattern Recognitions [3].

Anyway, the detector acquisition chain is not stationary; mainly, it changes its gain as a function of the PMT temperature and sensor irradiation; this gain variation can cause distortions in the neutron Pulse Height Spectrum (PHS). For this reason, the acquisition chain containing the PMT needs to be periodically calibrated during its operation.

Classical Method: Pulsed Led Calibration

In the literature is reported a calibration method based on the use of a pulsed LED that flashes on the photomultiplier, so generating a train of reference pulses as output of the PMT chain [4].

This method is able to improve the spectrometer characteristics, but it also has intrinsic limitations due to the simultaneous effect of the LED pulses with the neutron and gamma pulses. The LED must induce on the photomultiplier a signal having different shape with respect the Neutron and Gamma, in order to distinguish the pulses corresponding to neutron, gamma or LED. In the energy spectra, the effect of the LED pulses is located in a different area than the physic particles; moreover, for algorithm not based on the spectra calculation, the LED pulses can be discriminated due to their shape, being larger than the particles ones [5].

Anyway, by increasing the LED pulse duration, the joint probability to have at the same time a LED pulse and a particle pulse increases. This can be a problem because, when this overlapping event is not recognized, an error is caused in the PMT chain gain estimation, especially when the particle flux is high.

Another limitation concerns the measurement rate for the PMT chain; because, by increasing the rate of the LED pulses, the coincidence between particles and LED pulses increases, and this reduces the functionality of the instrument.

In general, the LED pulse frequency is around 1KHz [4], therefore the relative gain measurement rate is lower; this may be inadequate in the case of rapid variations in particles flow.

PROPOSED METHOD: INTENSITY MODULATION LED CALIBRATION

The new technique is based on the sinusoidal modulation of the LED. The frequency and the intensity of the modulation can be changed, taking into account the effect on the algorithm.

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Hardware Description

The hardware proposed for this system implementation is shown in Figure 1; it contains:

- the PMT chain;
- the 12 bit 1.6Gbps A/D converter model ISTIPFN FMC-AD-1Gx, (set to 400Msps) developed by the Istituto Superior Técnico (Portugal);
- the 16 bit dual D/A converter AMS101;
- the current driver for the LED (currently not developed);
- the LED;
- the Xilinx development board KC705.

All components of the diagram in Figure 1, with the exception for the *current driver*, are already present in the ITER Radial Neutron Camera project [6].

The IM algorithm can be implemented in the FPGA XILINX kintek 7 XC7K325T [7] present on the Xilinx KC705 development board with the following main features:

- one PCIe bus used to communicate with a PC by two DMA channels;
- one XMC connector where can be placed a A/D converter board;
- one 20 pin XADC connector for the connection of the D/A board.

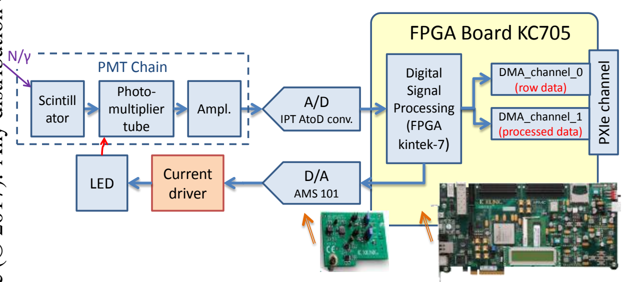

Figure 1: Scheme of the hardware proposed for the PMT chain gain calibration system.

Algorithm Implementation

The digital signal processing of the algorithm is implemented by FPGA. The main functions are:

- sinusoidal quadrature generator;
- quadrature demodulator;
- module estimation;
- quadrature modulator;
- signal subtraction.

The signal modulator generates the Sin modulation for the intensity of the LED and the Sin/Cos reference for the Quadrature Demodulator. The Quadrature Demodulator detects the amplitude and the phase of the sinusoidal echo superimposed to the PMT signal.

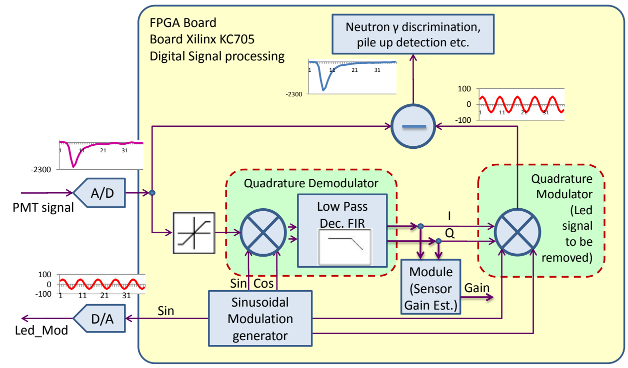

Figure 2: Fully Digital implementation for the calibration for the PMT chain gain, based on Intensity LED Modulation.

The Quadrature Demodulator consists of a complex multiplier and a double Low Pass decimation FIR. In the test shown in the next paragraph, the low pass decimation filter is a double cascade of five decimation FIR. In order to simplify the preliminary tests, FIR filters with limited requirements have been implemented:

- 5 FIR in cascade having identical coefficients;
- decimation factor: 2;
- Number of coefficients: 21 symmetrical (8 bits).

Figure 3 shows graphs derived from the System Generator for DSP™ Graphical User interface. Figure 3.a shows the floating-points coefficients of the FIR:

[0.672 , 2.772 , 5.334 , 4.326 , -4.242 , -17.22 , -21.252 , -1.386 , 42.728 , 89.824 , 110.18 , 89.824 , 42.728 , -1.386 , -21.252 , -17.22 , -4.242 , 4.326 , 5.334 , 2.772 , 0.672].

The Frequency Responses of the FIR Filters implemented with floating point and integer (8 bits) coefficients are showed respectively in Figure 3.b and c.

It is possible observe that the FIR filters do not have a severe out-of-band rejection.

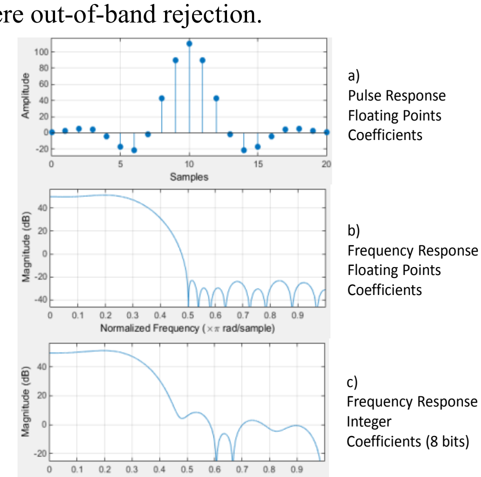

Figure 3: Graphs from the System Generator GUI during the design of the digital low pass FIR Filters.

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The module of the low frequency components (I, Q) corresponds to the Gain Amplitude. In our study, the I and Q components are used as modulation of the Quadrature Modulator in order to generate the sinusoidal signal, corresponding to the LED effect, to be subtracted from the A/D input. The LED signal cancellation could be removed by producing a simplified scheme; this can lead to reduced performance. However, the performance reduction is limited due to the small amplitude of the LED_mod signal, which is negligible when compared to the amplitude of the noise level and the pulses output of the PMT_signal caused by the particles, as it will be shown in the next paragraph.

SIMULATION

The automatic calibration system has been simulated in Simulink, by using the Vivado System Generator. This solution simplified the development of the final FPGA firmware after the simulations.

The signal used for the simulation (see Figure 4) has sampling frequency of 400Msps and contains true case pulse windows, acquired with trigger on a NE-213 liquid scintillator during the irradiation in Frascati Neutron Generator source. In particular, Figure 4 shows: (in blue) the simulated PMT signal composed of a double train of 4 pulses, (in red) the PMT signal due to the LED modulation (amplitude ±2.2 a.u and frequency 10MHz); for sake of simplicity the quantization effect is not represented in this graph.

The signal simulating the output of the PMT chain is the sum of the red and blue traces; moreover, it is necessary to introduce the quantization effect due to the A/D presence.

In order to simulate a continuous stream for PMT signal, a noise floor compatible with the real-case noise (amplitude ±2 a.u.) has been added between the pulse windows preliminarily acquired with triggered oscilloscope.

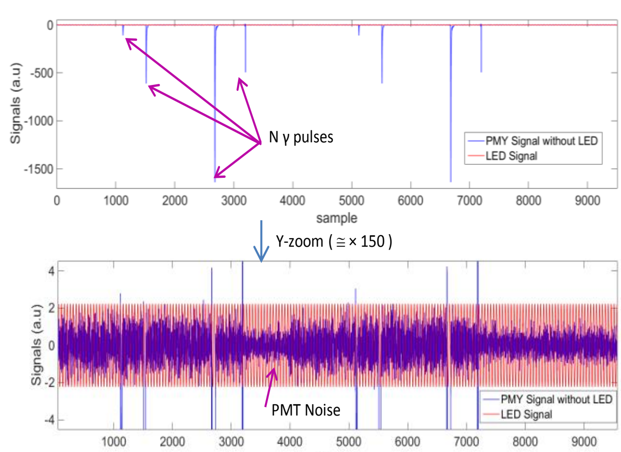

Figure 4: Simulation signals for PMT and LED modulation.

TEST RESULTS

Figure 5 shows the evolution of the PMT chain gain estimated by the algorithm. Due to the presence in the quadrature demodulator of 5 decimation-by-two filters, the gain values are upgraded every 2^5 samples @ 400Msps; this corresponds in a gain throughput of 12.5Msps (refresh time of 0.08us). Anyway, the presence of filtering and other digital processing causes a delay of about 1100 samples @ 400Msps (corresponding at 2.7 μs) in the gain estimation.

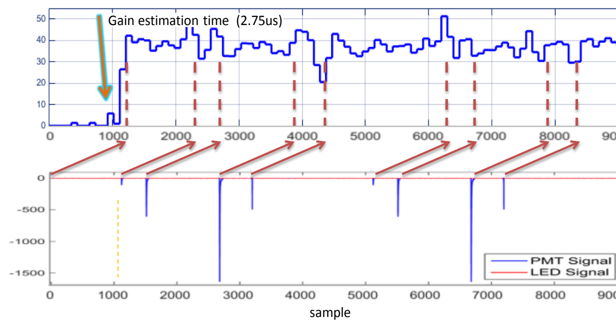

Figure 5: PMT Chain Gain estimation.

In the upper graph of Figure 5, some ripples on the gain are visible; considering the digital process delay, these mainly overlay with the presence of pulses in the PMT signal. In order to reduce the effect of the pulses on the gain estimation, during the process, the input signal has been saturated to a level higher than the LED modulation signal. Nevertheless, the artifact due to the presence of pulses is not completely eliminated.

The amplitude of the ripple in the estimated gain depends on many parameters:

- the ratio between peaks amplitude and LED modulation;
- the peaks duration;
- the frequency used for the LED modulation;
- the parameter of the low pass decimator filter;
- the saturation level set in the processing (±8 a.u. in the simulation);
- the phase of the LED sinusoidal signal at the moment of the pulse;
- the presence of other pulses before the present.

For example, the decrease of the cut-off frequency for the low-pass filter increases the immunity to particle pulses, but it delays the gain estimation.

The increase of the intensity in the LED modulation decreases the gain estimation error; anyway the LED signal cancellation can be more difficult, and the presence of residual LED signal can affect the subsequent processing.

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Figure 66 shows the difference between the PMT signal including the LED modulation (blue trace), and after the Led estimation and cancellation (red trace). The simulation includes the A/D (12bits) quantization effect.

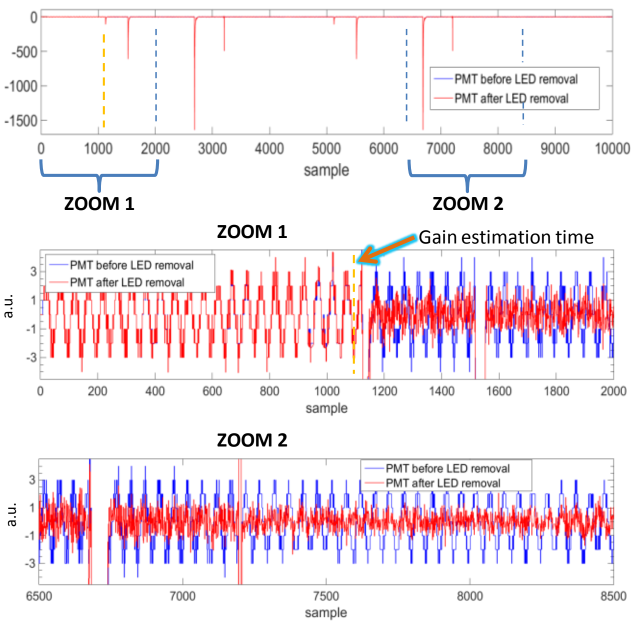

Figure 6: Pulse before and after LED removal.

The noise introduced by the calibration method is shown in Figure 7. In particular, the first three graphs in Figure 7 show the PMT signal without the LED modulation (blue trace), and the PMT signal when LED modulation is removed by the algorithm (red trace). The difference between these two signals is shown in the fourth graph; this corresponds to the noise introduced by the IM auto-calibration method. It is possible verify that, after the *estimation time*, the noise amplitude is less than ±2 a.u. , comparable with the noise floor present in the PMT, and then negligible for the subsequent digital processing (e.g. pulse detection, pile up detection, neutron gamma discrimination etc.)

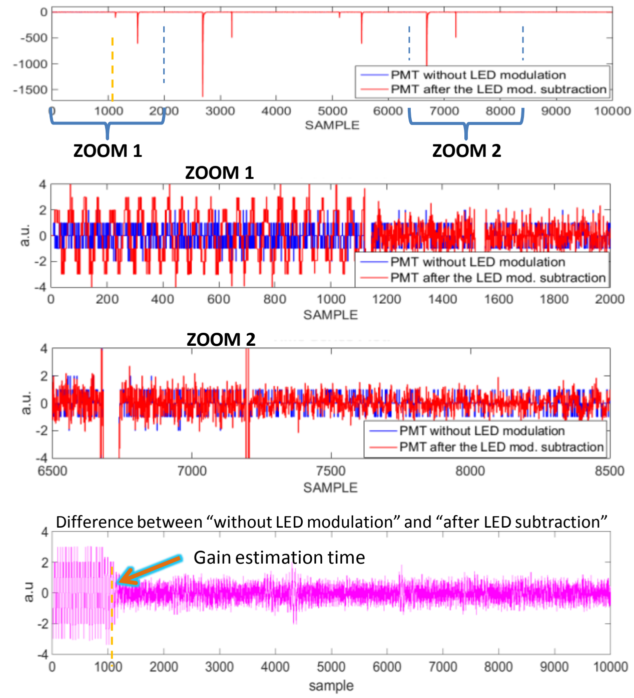

Figure 7: Analysis of the PMT signal: without the addition of LED modulation (blue) and after the LED modulation signal cancellation (red). Difference between the two signals, which corresponds to the noise introduced by the calibration system (pink).

FIRMWARE LOGIC ESTIMATION

Currently, the hardware system has not been completely implemented; in particular one of the analog components (LED current driver) has not been developed. Anyway, the firmware implementing the algorithm in Figure 2 has been completed, in order to verify the feasibility of the digital processing and to evaluate the logic resources necessary in the FPGA. The number of bits for the sinusoidal quadrature generator has been limited to 11, corresponding to a SNR of 66dB; a greater number of bits was not achievable at 400Msps due to timing constrains present in the FPGA in use.

The table 1 represents the resource occupied by the firmware inside the FPGA 7k325tfbg676-3 installed on the KC705 development board.

Table 1: Total Resources Occupied by the Firmware in the 7k325tfbg676-3 FPGA

Site	Used	Available	Utilized %
Slice LUTs	1310	203800	0.64
LUT as Logic	526	203800	0.26
LUT as Memory RAM + S Register	784	64000	1.23
Register as Flip Flop	2495	407600	0.61
DSP48E1 only	36	840	4.29
RAMB18	1	890	0.11

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Table 2: Main Firmware Components vs *Primitive_Type* Resources.

Main firmware components	F / F Latch	LUT	CARRY	MULT (DSP)	B Mem	D Mem	Others
Saturation and pulse detection	26	34	4				9
Sinusoidal quadrature generator,		19		2	1		11
Complex product,	390	30		2		360	66
Low Pass Dec FIR	1944	398		30		1034	350
Module estimation							
Quadrature modulator	91	31	8	2			27
Signal subtraction	32	32	8				12
Sincro_delay_block							
Total used resources	**2495**	**544**	**20**	**36**	**1**	**1406**	**478**

The percentages reported in the last column of table 1 show that just a small portion of the FPGA is used by the IM calibration algorithm. Moreover, by analyzing the single components and the relative *primitive_type* used in the firmware (see table 2), we can realize that most of the resources are used to implement the filtering chains.

Taking into account the presence of many resources still available in the FPGA, there are many possibilities to add data communication features or to add functionalities in the algorithm or to improve the present functions; for example, varying the filters or generator performances.

CONCLUSIONS

The use of additional modulated input signals can be a useful method to calibrate, in real time, sensors having non-stationary gain, such as in the case of the liquid scintillators. For the liquid scintillators, compared to the traditional method based on pulsed LED, there is an advantage for the absence of overlapping between LED and particle pulses. Moreover, changing the filters characteristics, the measuring time of the PMT gain can be easily set from few microseconds up to few milliseconds, also increasing the signal noise ratio and improving the stability of the measurement.

The power used for the sinusoidal LED modulation can be very small, due to the advantage of the dithering effect; the LED signal amplitude can be set at level comparable to the resolution of the A/D converter and generally below the noise present in the PMT chain. For this reason, the LED modulation signal does not affect dramatically the photodetector measure; anyway, a method based on the digital signal processing and usable to cancel the effect of the LED modulation has been developed and successfully simulated. The simulation model has been converted in firmware, and the FPGA resources necessary for its implementation have been estimated. They are not relevant in comparison with the medium FPGA size used in the project.

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