Real-time liquid scintillator calibration based on intensity modulated LED

Fabio Pollastrone[a], Gian Carlo Cardarilli[b], Marco Riva[a],

[a] *ENEA - FSN (Nuclear Fusion and Fission and Related Technologies Department) – Frascati, Italy*

[b] *University of Rome "Tor Vergata" - Department of Electronics Engineering - Roma, Italy*

Introduction

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 photomultiplier tube (PMT) and pulse amplifier (Fig. 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 temperature, the nuclear irradiation and the magnetic field on the photomultiplier; 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. 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. The new calibration method proposed is based on the use of a 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. Here we present this new technique, the relative hardware, the simulation and the main characteristics of the developed firmware.

Classical Calibration based on Pulsed led

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 signals corresponding to neutron or gamma particles from the LED [5]. 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 distinguished due to their shape, being larger than the particles ones.

By increasing the LED pulse duration, the probability to have at the same time a LED pulse and particle pulse increases. This can be a problem because if this overlap event is not recognized it can cause an error in the PMT chain gain estimation, especially when the particle rate is high. Another limitation is due to the measurement rate for the PMT chain, because by increasing the rate of the LED pulses, it results in an increase in the coincidence between particles and LED pulses. In general, the LED pulses frequency is about 1KHz [4], and this may be inadequate in case of rapid variations in particles fluxes.

Proposed Calibration based on Intensity Modulation Led

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.

Hardware description

All components in the diagram in Fig. 1, except the Current driver, are present in the ITER Radial Neutron Camera project. The main hardware components are: the PMT chain, the 12 bit 1.6Gbps A/D converter (400Msps) developed by the *Instituto Superior Técnico* (Portugal) [6], the 16 bit dual D/A, the current driver (currently not developed), the LED, the Xilinx development board KC705.

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

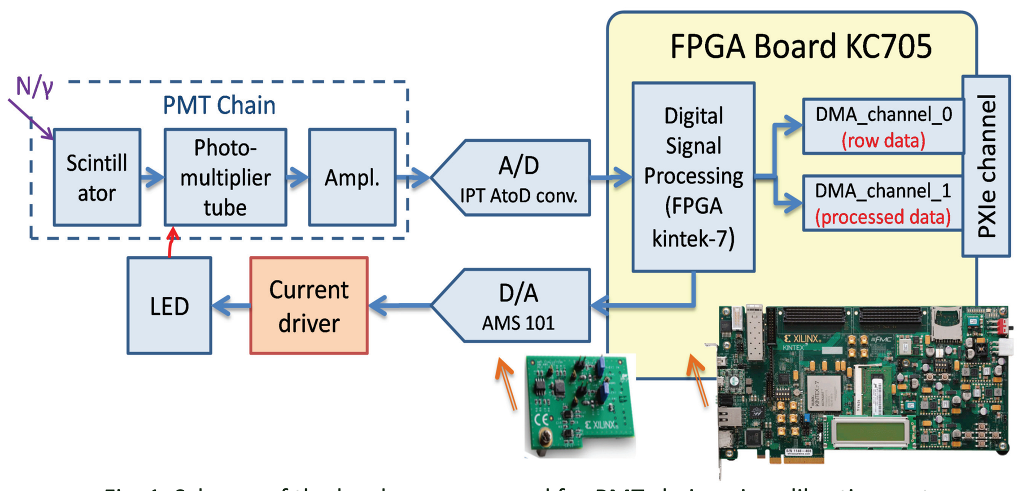

Fig. 1. Scheme of the hardware proposed for PMT chain gain calibration system.

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.

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.

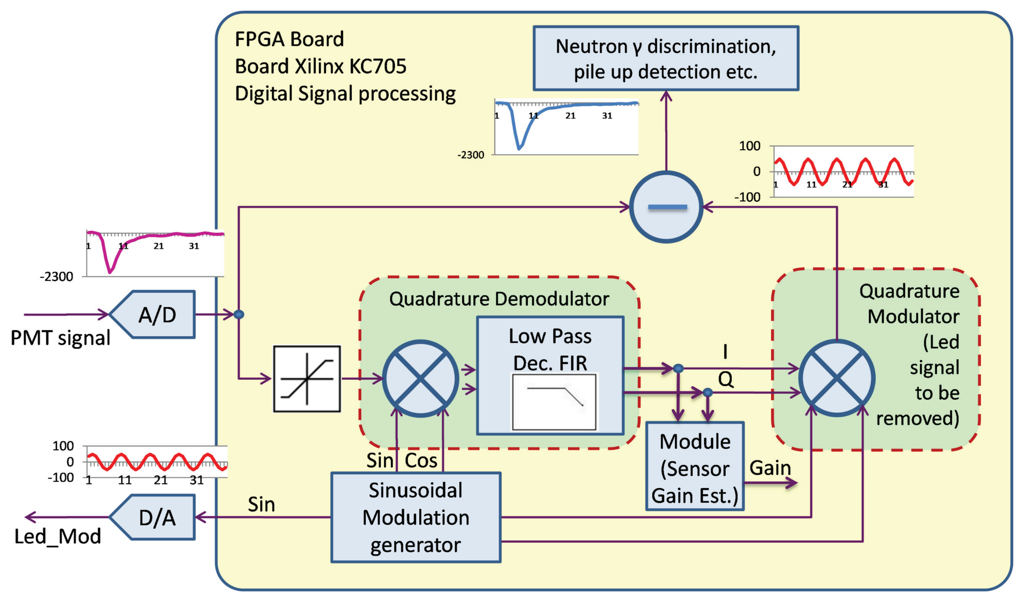

Fig. 2. Fully Digital implementation for the calibration for the PMT chain gain, based on Intensity LED Modulation.

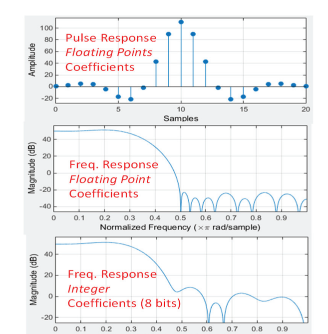

Fig. 3. Graphs from the System Generator GUI during the design of the digital low pass FIR Filters

The *Quadrature Demodulator* detects the amplitude and the phase of the sinusoidal echo superimposed to the PMT signal; it consists of a complex multiplier and a double Low Pass decimation FIR. In the preliminary tests performed, each low pass decimation FIR filter consists of a cascade of 5 filter. In order to simplify these tests, FIR filters with limited requirements have been implemented: identical coefficients for all the filters (21 symmetric taps), decimation factor = 2.

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. Fig. 4 shows: (in blue) the PMT signal, composed of two train of 4 pulses, (in red) the PMT signal due to the LED modulation (ampl. ± 2.2 a.u freq. 10MHz). 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. The signal used for the test in Fig. 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. Between the pulses windows has been added a noise floor compatible with the real case noise (ampl. ±2 a.u.) in order to simulate a continuous stream for PMT signal.

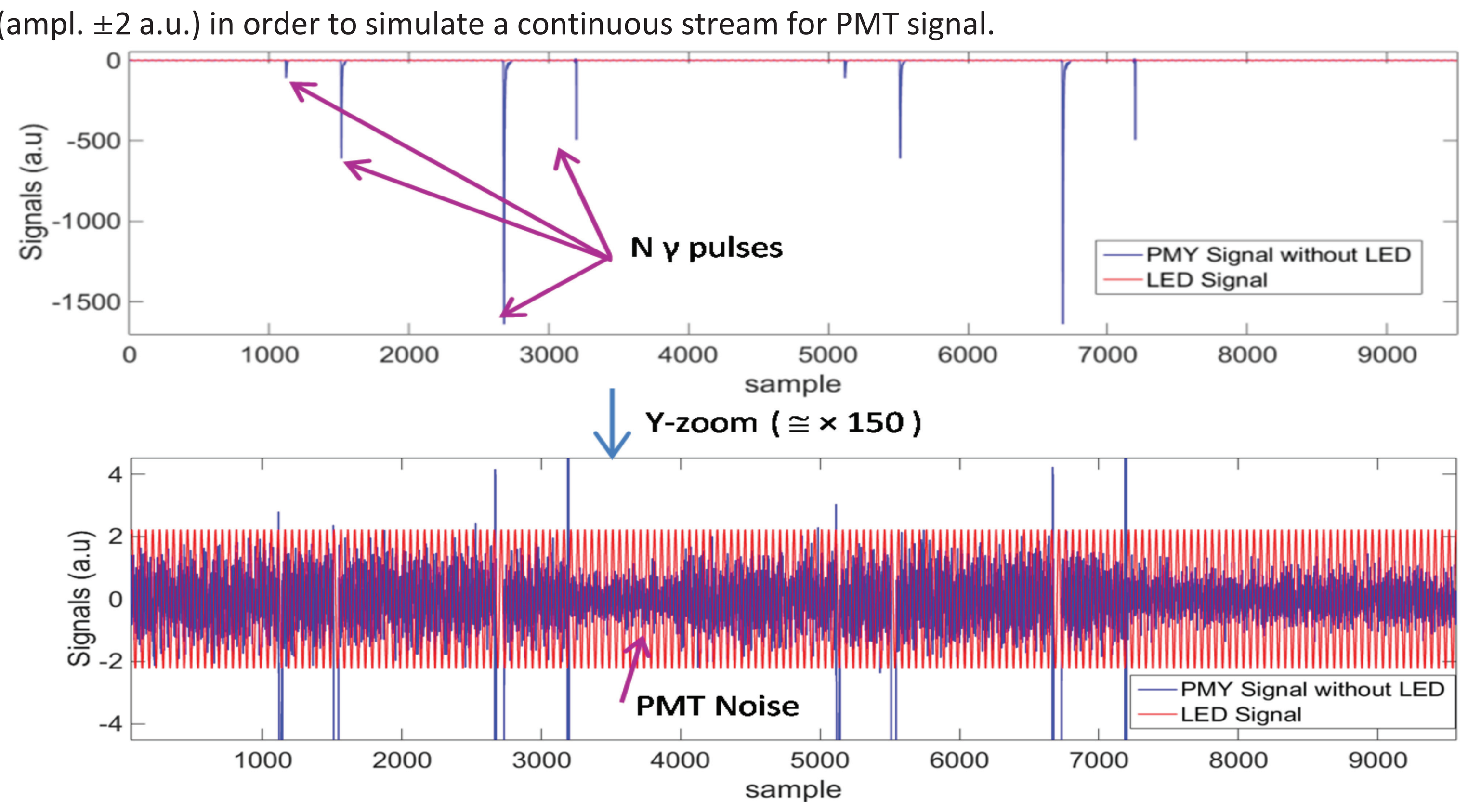

Fig. 4. Simulation signals for PMT and Led modulation (without taking into account the quantization effect).

Test results

Fig. 5 shows the evolution of the PMT chain gain estimated by the algorithm. The presence of filtering and other digital processing causes a delay of 1100 samples (corresponding at 2.7 µs @ sample clock 400MHz) in the gain estimation.

Some ripples on the gain are visible; taking into account of the digital process delay, these coincide with the presence of pulses in the PMT signal.

In order to limit 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 artefact 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 intensity, the peaks duration, the LED modulation frequency, the low pass decimator filter, the saturation level set, the effect of other pulses that precedes the current.

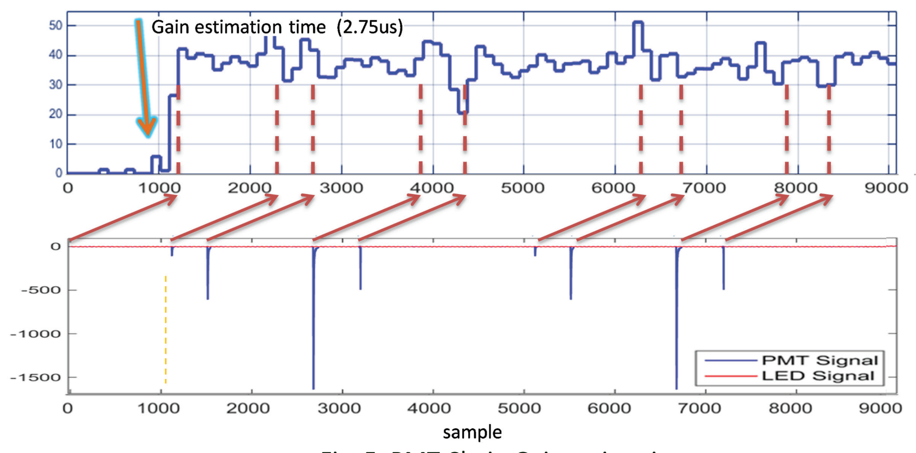

Fig. 5. PMT Chain Gain estimation.

Fig. 6 shows the difference between the PMT signal including the LED modulation (blue trace), and after the Led estimation and removal by the algorithm (red trace). The simulation includes the A/D (12bits) quantization effect.

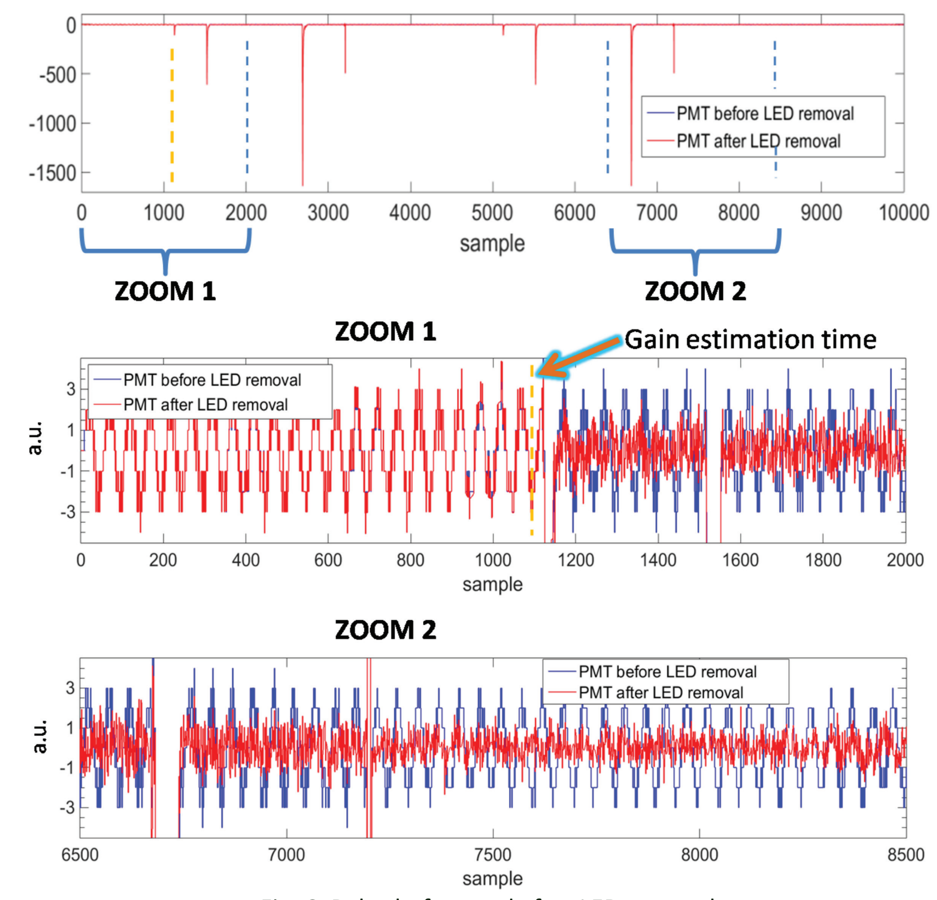

Fig. 6. Pulse before and after LED removal.

The noise introduced by the calibration method is shown in Fig. 7. In particular, the first three graphs in Fig. 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 the absence of LED and its cancellation by the algorithm is shows in the fourth graph; this difference corresponds to the noise introduced by the auto-calibration method. It is possible verify that, after the *gain 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.) .

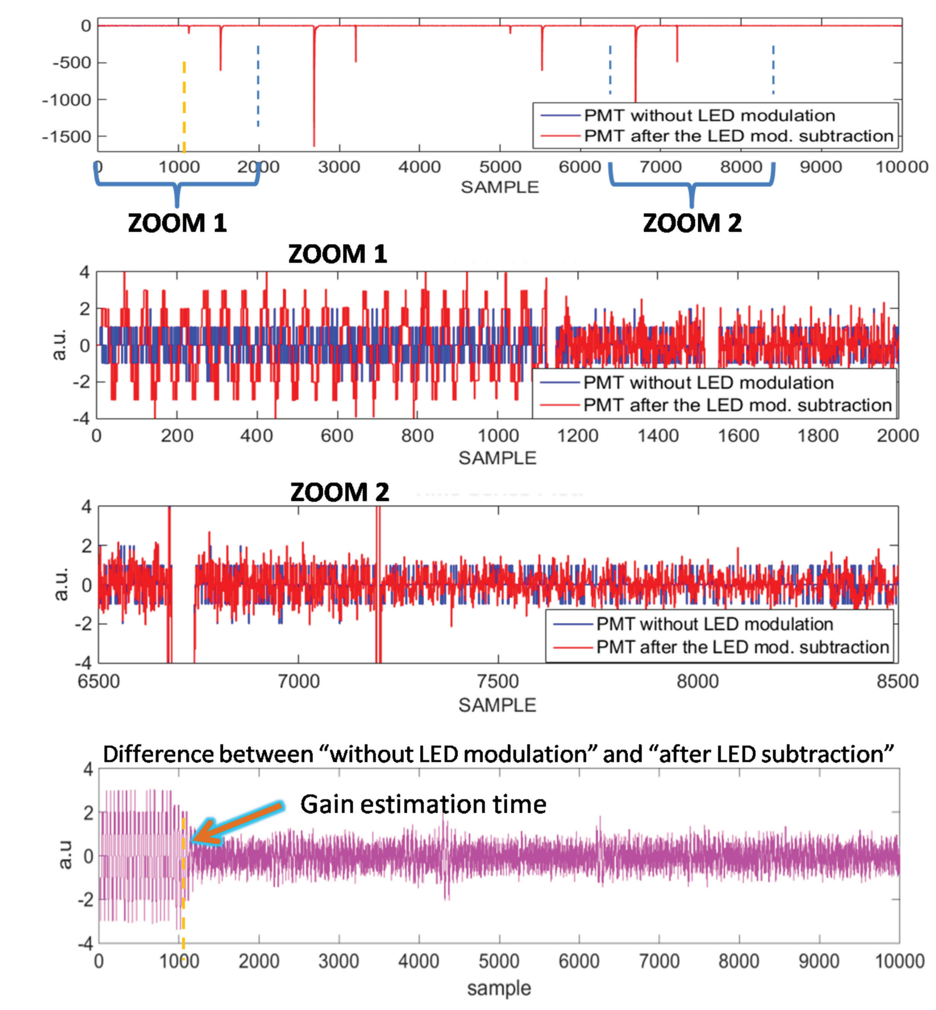

Fig. 7 Analysis of the PMT signal: without the addition of LED modulation (blue) and after the LED modulation signal cancellation performed by the algorithm (red). Difference between the two signals, corresponding to the noise introduced by the calibration system (pink).

Firmware logic estimation.

The firmware implementing the IM algorithm (Fig. 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 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.

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

Many resources are still available, this allows the presence in the same FPGA of data communication features or the improvement of the algorithm functions; for example, varying the filters or generator performances.

Conclusion.

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. In comparison 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 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 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 FPGA resource necessary for its implementation have been estimated. They are not relevant in comparison with the medium FPGA size used in the project.