Design and implementation of silicon photomultiplier characterization setup for plasma physics applications

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Abstract. Silicon photomultipliers are devices widely used and have direct applications in multiple scientific fields. Currently, the Universidad Antonio Nariño, Colombia, finance the research project Characterization of the coherent structures in the edge region of the plasma column in the TCABR tokamak using Langmuir probes in collaboration with Universidade de Sao Paulo, Brazil. In this project, we research plasma, and recently, we proposed a silicon photomultiplier to measure X-ray emissions from the plasma column. In this application, we have to know specific characteristics of silicon photomultiplier in behavior controlled conditions to establish its possible changes during exposure to radiation of plasma; one of silicon photomultiplier characteristics more important is gain due to its temperature dependence that generates disturbances on its response. To characterize the silicon photomultiplier in controlled conditions, we developed an analog integral proportional temperature automatic control system for the control of a silicon photomultiplier characterization setup that lets temperature variations from room temperature to 50°C reaching reference temperature in 1 minute with a steady-state error less than 2% and overshoot of 5.53%.

1. Introduction
In tokamak operation is very important the monitoring hard X-ray radiation produced by conversion plasma current to high energy runaway electrons (REs) stopped by plasma-facing components (PFCs). These REs could be dangerous for International Thermonuclear Experimental Reactor (ITER) and similar tokamaks because reduce life-time of PFCs [1]. Currently, we have the opportunity to develop experimental detect processes of the X-ray with silicon photomultipliers (SiPMs) on Research Project: Characterization of the coherent structures in the edge region of the plasma column in the TCABR tokamak using Langmuir probes, this project is financed by Universidad Antonio Nariño, Colombia, and developed in collaboration with Universidade de Sao Paulo, Brazil, and Universidad de Los Llanos, Colombia. SiPMs detect weak optical signals from only one photon to hundreds of photons [2, 3] and their spectrum response could be extended to X-ray using scintillators [4, 5].

However, photodetection processes require to characterize the silicon photomultiplier (SiPM) used to detect, especially, gain, breakdown voltage, biasing voltage, afterpulse, crosstalk, and...
dark noise [2,3,6]. Reports of characterization processes as Vacheret ensure temperature and SiPM gain are inversely proportion [7–9].

To introduce SiPMs in plasma physics is very important to characterize these devices to operate in environmental conditions of plasma experiments, especially, the temperature must be known due to SiPM sensitivity [10]. For this reason, we had to develop a SiPM characterization setup focused on temperature control. This SiPM characterization setup is a black box and contains a Peltier cell, solid-state temperature sensors, white light-emitting diode (LEDs), SiPM case, and isolated ports to external connections for signals acquisitions. Besides, an analog integral proportional temperature control reduces the settling time, the maximum peak, and guaranties reference temperature for SiPM behavior.

2. Experimental setup

2.1. Design and implementation of the experimental setup structure

The experimental setup was made by three stages. The first stage consisted of design and fabrication of the black box with dimensions and requirements given by the instrumentation workgroup: isolation of external light sources, external preamplifier stages, external temperature control system, external voltage signals for LEDs, and internal and external connectors for SiPM, LED, Peltier Cell and solid-state temperature sensors. Besides, SiPM is placed in a case on contact with a copper sheet, and LED light is not directly emitted to SiPM. Peltier cell is placed between a dissipator and a copper sheet. The black box was made with galvanized iron sheets, internally painted black to minimize weak light reflections of LED emissions. Inside of the black box is dark, the only light is from the LED. The second stage was the installation of anchoring elements as screws for dissipator and copper sheet that confine the Peltier cell, it is for easy replacement of any element and device. The third stage was the installation of connectors for external communication. Characterization setup is shown in Figure 1.

![Characterization setup](image)

**Figure 1.** Characterization setup.

2.2. Electronics characterization

To characterize temperature dissipation on the black box, specifically, over SiPM contact surface, we had to measure the current and voltage over the Peltier cell and temperature dissipation on the copper sheet in contact with SiPM. For Peltier cell current measurements, we used a shunt resistor with a high-side differential amplifier. It was possible because of the low voltage source
for biasing of the Peltier cell. For Peltier cell voltage measurements and temperature, we used a basic preamplifier dual channel and dual output. These voltage and current signals were acquired by using an analog to digital converter (ADC) ADS1115 connected to Raspberry Pi 3. Besides, these signals were plotted and fitting obtaining the temperature dependence of current/voltage.

2.3. Setup characterization and modelling
With the characterization setup implemented, we modeled it measuring the voltage of the Peltier cell, current of the Peltier cell, voltage biasing source of Peltier cell, and individual outputs of temperature sensors. To digitizing data, we used 16-bit multifunction IO device USB-6211 from National Instruments, with 250 kS/s sample rate; this device acquired all signals and we analyzed them using system identification toolbox from Matlab to obtain the model of setup.

2.4. Design and implementation of an automatic control system
The automatic temperature control system was designed by using the control system designer from Matlab. In this step, we had obtained the transfer function approximated from the system identification toolbox, and used it for the design of the control system; the parameters were conditioned by the instrumentation workgroup and consist of: variations from room temperature to 50°C, reaching reference temperature in 1 minute, steady-state error less than 2% and, overshoot of 5.5%. Block diagram of the temperature control system is shown in Figure 2.

![Figure 2. Block diagram of temperature control system.](image)

Block diagram describes the function of the system from the conversion of reference temperature to volts in the range of temperature sensor response to the output of the SiPM characterization setup, in fact, temperature response on SiPM. The system calculates the temperature error on each SiPM and the temperature control system activates the power driver of the Peltier cell to reach the reference temperature.

3. Results

3.1. Temperature dependence of bias voltage of Peltier cell
The solid-state temperature sensors were placed in the copper sheet on four different sides close to each SiPM to know its individual temperature and obtain a correct characterization of its gain dependent on temperature. Data acquisition was realized using the NI device and data were analyzed with a Matlab code. After data analysis, we conclude that temperature dissipation over the copper sheet is almost homogeneous close to all SiPM cases and sensors response was similar between them. The fitting curve was obtained by second-order polynomial fitting and Figure 3, shown the mean of the temperature sensors response vs bias voltage of Peltier cell and
a math quadratic model approximation. The equation describes the relation of copper sheet and Peltier cell response with its bias voltage.

![Graph showing temperature vs. bias voltage with the equation $0.6216x^2 + 3.792x + 25.55$](image)

**Figure 3.** Fitting curve of the mean of the temperature sensors response vs bias voltage of peltier cell.

### 3.2. Modelling the temperature vs time response of the silicon photomultiplier characterization setup

Once we knew the relation between temperature and bias voltage/current of Peltier cell [11], we can model the temperature vs time response of the SiPM characterization setup using different reference temperature as shown in Figure 4. This was made for twenty different reference temperatures and system responses were recorded including their delay time for a good identification system process. Figure 4 shown only six different system response.

![Graph showing temperature vs time with different steps](image)

**Figure 4.** System response to different reference temperature.
With these data, we obtained an approximation of transfer function using system identification toolbox of MATLAB recognizing gain, rise time, and delay as modeled in Equation (1).

\[
G(s) = \frac{0.992(e^{-2.44s})}{1 + 317.5s}.
\]  

(1)

3.3. Design and implementation of the temperature control system

Figure 5 shown normalized system response (blue line) because different reference temperatures (inputs) generated similar responses (outputs). We design a PI controller to minimize position error and maximize velocity of response. System response (orange line) was improved with implementation of PI controller being faster than without control, in fact, settling time changed from 1240 seconds to 497 seconds, rise time changed from 698 seconds to 105 seconds and overshoot was inside of plan, only 5.53%. Finally, transfer function of PI controller is shown in Equation (2).

Values of transfer function were used to design analog controller with commercial resistors and capacitors [12]. In this way, we design every block of all systems: Peltier cell driver, electronics feedback, electronics input, electronics sum point, and PI controller. Finally, we implemented the analog electronics systems, including PI controller, and Figure 6 shown details of these designs inside of the block diagram system.
4. Conclusions
The black box was designed the smallest possible; however, the inner space of the black box is very small to install all internal components, and they were installed very tight. Is necessary to add more space inside the black box. Additionally, a recommendation of evaluation of the system was installing more than one Peltier cell for increase performance of temperature dissipation and be able to obtain a faster steady-state system. The problem is that is not free space.

The identification process of the SiPM characterization setup yielded evidence of a poor electrical ground system that we solved with successful experimental tests obtaining an approximate model of the system. PI controller was designed based on the approximate model of the system reaching position error less than 2%, settling time of 497 s, and overshoot of 5.53%. These results of temperature control satisfy requirements for SiPM characterization procedures, for example, SiPM gain requires stable temperature with variations less than 1°C.

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