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Dedicated power supply system for silicon photomultipliers

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Silicon photomultipliers (SiPMs) have replaced traditional photomultiplier tubes bit by bit in high-energy physics experiments in the last years. This includes the scientific fields where the demand for highly efficient and stable photo sensors outweigh the need for large active areas. Silicon photomultipliers offer a high photon detection efficiency, low supply voltage and stable operation even under harsh environments, for example bright moon-light conditions. The temperature dependence, however, presents a challenge to the power supply system which has to compensate for this effect along with biasing the SiPMs with a stable voltage with mV precision at up to 100 V (10^{-5} accuracy).

Here, we present an intelligent power supply system for silicon photomultipliers. Up to 64 SiPM channels can be driven with one module, where more than 1 mA of power can be drained per channel. The operating-voltage can be changed in 1 mV steps to allow for temperature variations of the power supply system itself, which is well below 1 mV K^{-1}. A built-in micro-controller applies the voltage correction for temperature changes on the SiPM automatically using up to 64 analogue temperature sensors. The data, like the mean current per channel, temperature and applied voltage is communicated via Ethernet, while the user is able to set the bias-voltage to his needs. Measurements concerning the performance of the power supply system are being shown.

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1. Introduction

Silicon photomultipliers (SiPMs) have been introduced in many fields of physics in the last years. Compared to other devices capable of detecting faint photon fluxes, SiPMs show a high photon detection efficiency and mechanical as well as electronic robustness. This makes them suitable for applications in high-energy and astro-particle physics even in harsh environments, including imaging telescopes. As the SiPM shows temperature dependencies, it is the job of a power supply to keep the gain of the SiPM constant to less than 1%. This leads to requirements on the power supply, like 10^{-4} to 10^{-5} accuracy, temperature-dependent adjustment of the bias voltage, current measurement and stability. To understand these demands it is to understand the electronic basics of a SiPM.

Important electronic values of a SiPM are the breakdown voltage v_{bd} defining the point where the SiPM starts to operate in Geiger-mode, the overvoltage v_{ov} which is directly proportional to the gain, and the sum of both, usually called the bias voltage

$$v_b = v_{bd} + v_{ov} \tag{1.1}$$

which is applied across the SiPM. This voltage has to be known usually to about or less than 10^{-3}. This is due to the following: The gain is directly proportional to v_{ov} which is typically in the single Volt range; for older SiPM generations from Hamamatsu this is for example 1.4 V. If the gain needs to be kept constant to the 1% niveau, the bias voltage v_b has to be known to at least 14 mV. This resolution corresponds to $2 \cdot 10^{-4}$ and thus below 10^{-3} for a bias voltage of 65 V (typical value).

Furthermore, the temperature dependence of the SiPM represents a challenge to the power supply system. The temperature dependence of the breakdown voltage is found to be linear in a wide range [1] and can be thus expressed as

$$v_{bd}(T) = v_{bd}(T_0) + \beta(T - T_0). \tag{1.2}$$

The constants $v_{bd}(T_0)$ and β depend on the properties of the device and vary from manufacturer to manufacturer but are otherwise mostly independent from other physical quantities (e.g. temperature, light, current). The breakdown voltage at room temperature $v_{bd}(25\,^\circ\mathrm{C})$ can be as small as 25 V and as large as 95 V depending on the manufacturing process [2, 3, 4, 5] but it varies usually only a few percent (or even less) within the same SiPM series [5]. The linear progression factor β also depends on the device and is typically found between $20\,\mathrm{mV\,K^{-1}}$ and $90\,\mathrm{mV\,K^{-1}}$ – which is also constant to below one percent within the same SiPM series.

As already mentioned above, one requirement to a power supply is to keep the gain of the optical device (here, the SiPM) constant or at least at a known state. As the gain of a SiPM is directly proportional to the overvoltage v_{ov}, the gain *decreases* linearly with increasing temperature if the bias voltage is kept constant, seen by combining equations (1.1) and (1.2). To avoid this problem,

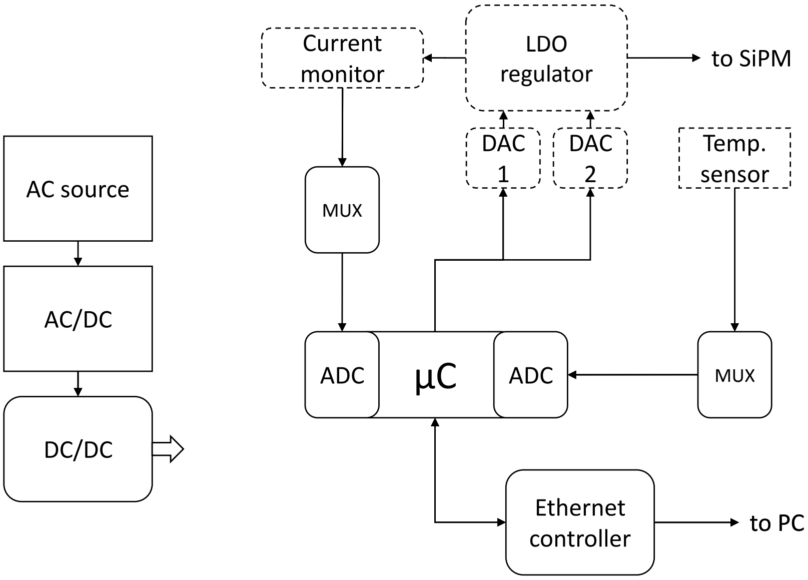

Figure 1: This figure shows a functional diagram of one PSU module. The pattern of the boxes specify the *nature* of this component. Sharp-edged boxes are external elements like the AC/DC module on the left. Round-edged boxes indicate that these components are located on the PSU module. Solid boxes are implemented once. Dashed boxes are installed 64-times. Details are given in the text.

the gain will be kept constant if the bias voltage is *increased* linearly with temperature. The temperature has to be measured in close proximity to the SiPM device. At the end, the only variable the user wants to change is the gain, i.e. the overvoltage v_{ov}.

2. Overview

The power supply system (PSU) is an autonomously operating 64 channel power supply made specifically for applications with SiPMs exposed to high constant light fluxes, i.e. high currents up to a few mA on the bias voltage lines. This includes fluorescence and Cherenkov telescopes. The PSU can be controlled by a micro-controller and read out via Ethernet. The user can set two parameters for each channel individually, which are $v_b(T_0)$ and β, defined above. A schematic drawing of the power supply system can be found in figure 1. Figure 2 shows a photo of the bottom side of an assembled 64-channel PSU module. The board dimensions are $225 \times 200\,\mathrm{mm}^2$. On the next pages some features and performance measurements of a fully tested 8-channel module (the same PCB as the 64-channel version but only eight channels assembled) are described. The technique developed for the PSU has already been implemented in several applications, see section *Applications* at the end of this proceeding.

2.1 Input voltages and power consumption

The module itself needs two voltages to operate; a voltage for the SiPM supply which should be a few volts (1.5 V minimum) larger than the desired maximum voltage needed by the SiPMs (for example +75 V for a maximum voltage of +70 V is a good starting point) and a voltage for the

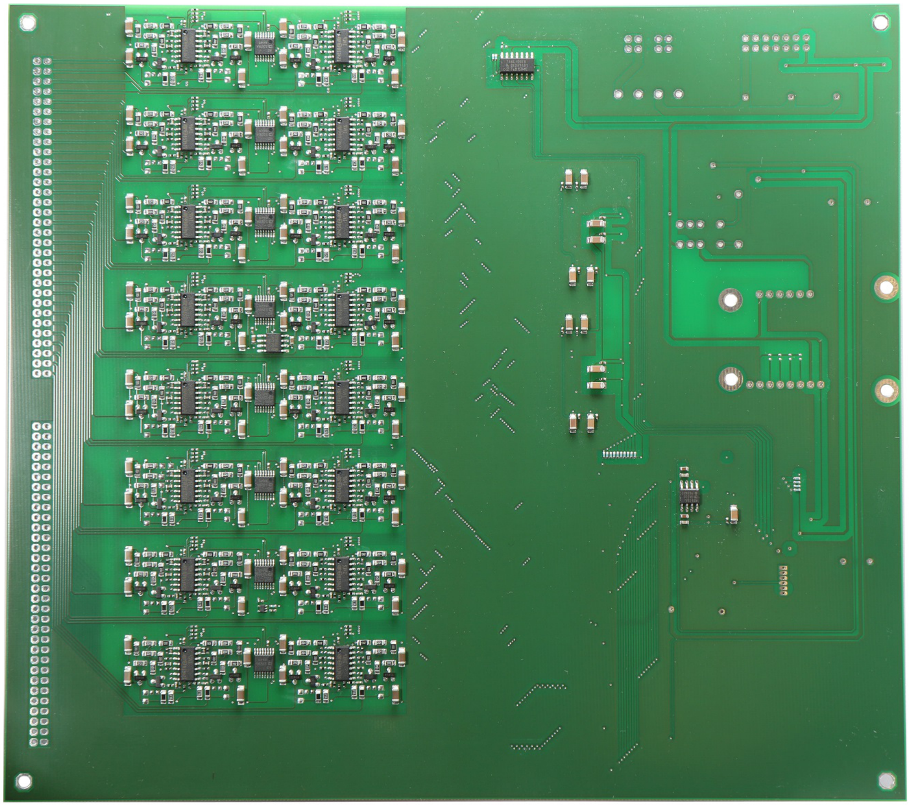

Figure 2: Bottom view of the first partially equipped 64-channel PSU module developed and assembled at RWTH Aachen University in May 2015. The SMD components in the mid-left are 32 regulators for the SiPM bias voltage channels. The other 32 channels are located on the top-side of the PCB and can not be seen here. Two connectors can be mounted on the very left side with 64 pins each which offer connections for the 64 temperature sensors (bottom) and SiPM cathodes (top), respectively. The Ethernet RJ45 jack will be placed on the very right side of the PCB (center). Dimensions: $220 \times 200\,\mathrm{mm}^2$. Photo courtesy of L. Middendorf (RWTH Aachen University).

supply of the digital and analogue peripherals of the power supply itself (+6.5 V to +27 V). The current consumption on the high voltage line depends on the output voltage and ranges typically between $300\,\mu$A and $1000\,\mu$A per channel (corresponding to +30 V to +100 V output voltage). The low voltage supply is loaded with 135 mA (Ethernet module) and 30 mA (8-channel version, all other components) during operation. The power supply uses linear regulators on-board and no switching regulators to avoid switching noise. If power saving is an issue, the user should operate the low voltage line with the minimum voltage of +6.5 V to reduce power dissipation.

2.2 Regulation

The regulation of the bias-voltage of the individual channels has been implemented by a self-composed low-dropout (LDO) linear regulator. It has been modified with proportional and integral capabilities to be able to regulate the voltages fast and efficient with a minimum amount of voltage noise coming from the digital components. A high value decoupling capacitor has been chosen at the output connected to GND to buffer the voltage for current pulses of the SiPM and to reduce

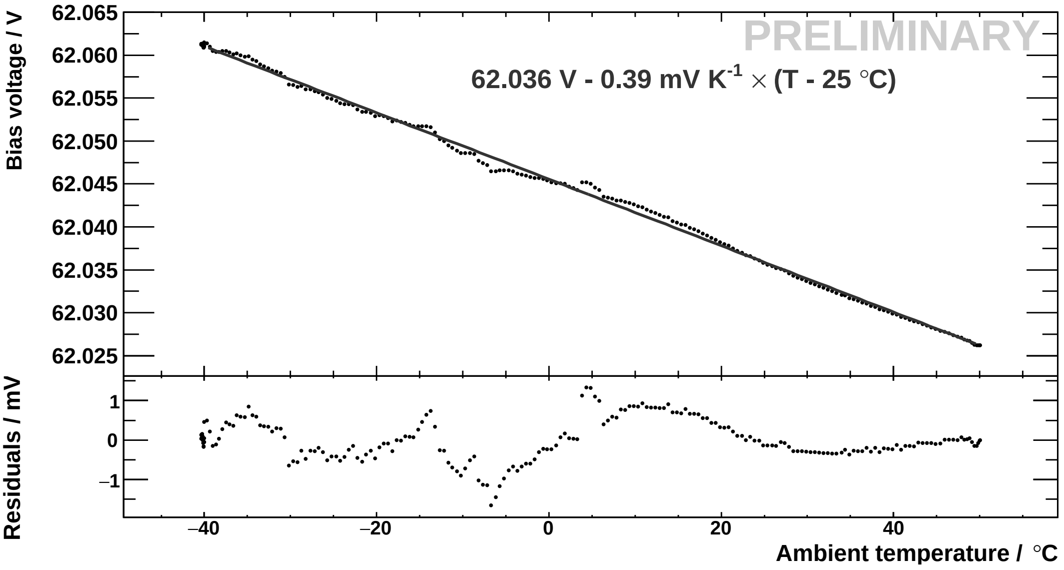

Figure 3: Shown is the temperature effect of the PSU module itself: The bias voltage has been set to $+62\,\mathrm{V}$. The ambient temperature has been ramped up by 90 K using a commercial cooling chamber. The electronic components like DACs and resistors show a small temperature drift. This can be seen by applying a linear equation fit to the data which gives roughly $0.4\,\mathrm{mV\,K^{-1}}$. Since the DACs are very sensitive it is possible to reduce this effect by regulating on this very temperature effect using the on-board sensors.

the noise to 4 mV RMS. The maximum current per channel is limited to 2 mA by software (configurable) and to about 10 mA by hardware. The latter is implemented by a resistor in series with the regulating chain[1]. If the current drawn by the SiPM on this line exceeds a value such that the voltage drop at the resistor becomes larger than the overvoltage of the SiPM, the SiPM will stop drawing current and is shut down. This means that the current drawn by the SiPM is limited to a value depending on the SiPM type. The operation can be described as a constant current mode known from stabilised DC power supplies in the lab.

Two DACs are used for each channel, both being temperature-compensated to $5\,\mathrm{ppm\,K^{-1}}$. The first DAC (16-bit) is used to set the desired range of the bias voltage, for example from 54 V to 70 V. The second DAC (14-bit) is used for the bias voltage regulation. The implementation of this technique increases the resolution of the bias voltage step size since the bias voltage has only to be regulated in a small range on top of the offset voltage: 90 K temperature swing is equal to less than 6 V (assuming $\beta = 60\,\mathrm{mV\,K^{-1}}$ progression of the SiPM). A 16 V swing has been chosen which guarantees a step-size of 1 mV and also tolerates variations of the breakdown voltage of devices from different SiPM series.

Typical for LDO regulator circuits is the very low series resistance at the output located behind the regulation chain. The regulator consequently does not need any corrections for the current drawn by the SiPM like other power supply systems do, due to voltage drop at a series resistance. However, it is recommended to implement a low-ohmic, low-capacitive RC low-pass filter as close to the SiPM cathode as possible to reduce external noise picked up from the cables. This also allows

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[1] Located such that the regulating circuit is not affected by the additional resistance, e.g. independent of any current loads.

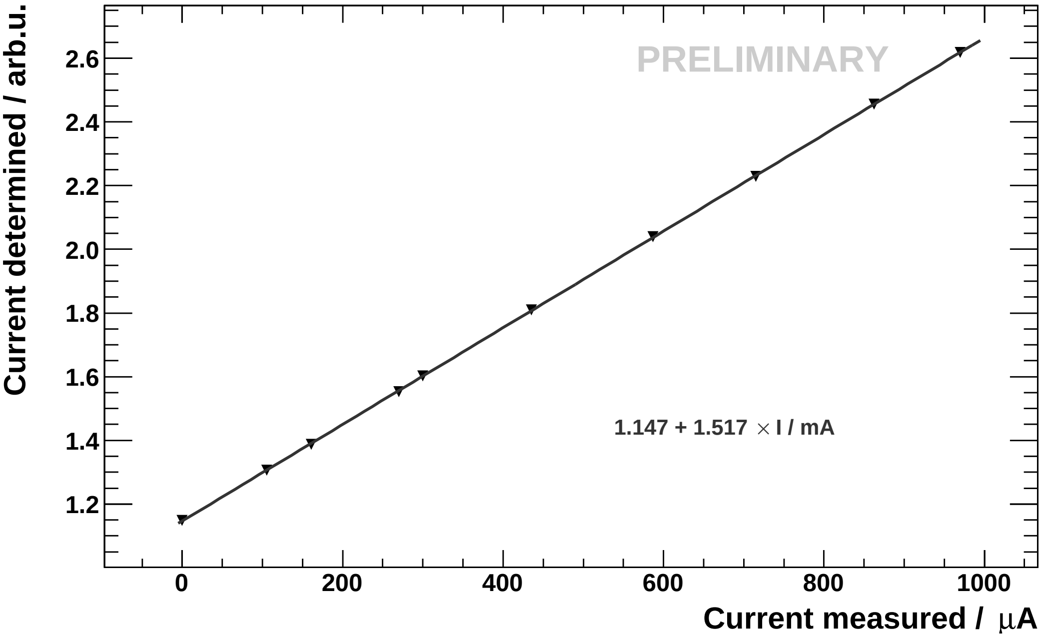

Figure 4: A measurement showing the current determined by the power supply system on one bias channel compared to the current measured with a multi-meter. The load has been changed continuously using a variable resistor at the output. The response is linear in a wide range but depends on the bias voltage resulting in an offset. This can be calibrated and corrected for in the PC software.

the SiPM to draw charge of short and small pulses from the capacitors directly. A two stage RC low-pass filter with $R_1 = R_2 = 4.7\,\Omega$ and $C_1 = 4.7\,\text{nF}$, $C_2 = 100\,\text{pF}$ has proven to be useful resulting in a cut-off frequency of about 7 MHz[2].

To be able to regulate a high bias voltage of several tens of Volts depending on the temperature measured near the SiPM, the power supply itself should not show any temperature dependence (or at least it must be known and corrected for). A measurement has been made where the ambient temperature of the power supply module has been changed from $-40\,^\circ$C to $+50\,^\circ$C equal to a 90 K rise. The power supply has been programmed such that it will keep the voltage stable. The offset DAC has been set to an equivalent of $+54$ V at the output and the regulating DAC has added another $+8$ V giving $+62$ V in total. The results are shown in figure 3. As one can see, the temperature dependence of the PSU itself is roughly $0.4\,\text{mV}\,\text{K}^{-1}$. This is equal to less than $10^{-5}\,\text{K}^{-1}$ or less than 0.1% on the full 90 K scale. Translating this to a SiPM gain stability of an assumed 1.4 V overvoltage, the variation is equal to roughly 3% on the full temperature scale. Note, that this effect can be reduced significantly by correcting on it using the on-board micro-controller and temperature sensor.

2.3 Current monitor

The current on the high voltage line of each channel is measured by a voltage divider using

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[2] this will of course implement a voltage drop at the low-pass resistors of roughly 1 mV in total for 100 μA which is acceptable.

temperature compensated resistors ($25\,\mathrm{ppm\,K^{-1}}$) and a differential amplifier. The sense resistor is $1\,\mathrm{k\Omega}$[3] which means that a current drawn by the SiPM of $1\,\mu$A translates to a voltage drop of 1 mV. This is further amplified with a gain of 1.5 and digitised by an ADC channel of the micro-controller. The current measurement includes the quiescent current of the regulator which depends on the bias voltage. This offset has to be taken into account. If precise knowledge of the current is necessary, the current measurement can be characterised for each channel individually. The resolution of a single current measurement is $12\,\mu$A RMS. The PC read-out software implements a moving average on the current measurements to achieve a high resolution on a statistical basis down to below $1\,\mu$A, theoretically. A linearity measurement is given in figure 4. One can see that the response of the PSU is linear in a wide range. The dependence of the bias voltage results only in an offset which can be calibrated and compensated in the PC read out software.

2.4 Communication

All the data described above, like current, bias voltage set point and temperature, is available via an Ethernet connection on a RJ45 jack. Once a connection is established, the PSU system will periodically[4] push data through the network line using the TCP standard. The system also reads commands from the Ethernet connection. The data format sent from the PSU is simple to parse. It consists of the voltages set by the DAC (in DAC counts), the total current drawn on each channel (in ADC counts) the temperature measured by the analogue temperature sensors (in ADC counts) and the value of two additional sensors located on the PSU itself (in ADC counts).

3. Applications

Applications of the power supply system include fluorescence and air-Cherenkov telescopes. The First Auger Multi-pixel photon counter camera for the Observation of Ultra-high-energy air Showers (FAMOUS) Project aims on detecting fluorescence light by implementing a silicon photomultipliers based camera on a refractive telescope design [6]. At the moment of this writing, the camera of this telescope is planned to be upgraded from seven to 64 channels [7]. The PSU module described here will be operated in the upgraded FAMOUS telescope this year. Cherenkov telescopes based on SiPMs are another interesting option. A 61-pixel refractive telescope prototype based on the FAMOUS design is currently in development in Aachen [8]. In contrast to the FAMOUS application, it will be used for air-Cherenkov light detection. Apart from imaging telescopes, the technique used in the power supply has already been implemented successfully in 1-channel SiPM modules operating from 12 V battery supplies.

4. Conclusions

The power supply system described here fulfils the requirement from most astro-particle physics experiments using SiPMs. This includes in particular the stability over a wide temperature range spanning $-40\,^{\circ}$C to $+50\,^{\circ}$C, see figure 3. The range of the SiPM bias voltage can be set between

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[3] In fact, it is the very same resistor also used for the current limiting feature, described above, i.e. there is no artificial voltage drop of the bias voltage introduced here.

[4] Currently, this is below 1 Hz, artificially increased.

0 V and up to 100 V which includes the operating range of most SiPMs [2, 3, 4, 5]. The power supply system has additional features like current measurements, Ethernet communication and independence from the DAQ system which makes it modular and applicable especially to imaging telescopes. The costs can be estimated to less than $10 per channel.

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