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A programmable, multichannel power supply for SiPMs with temperature compensation loop and Ethernet interface

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ABSTRACT: Among the different techniques available, the SiPM power supply described in this paper uses output voltage and sensor temperature feedback. A high-resolution ADC digitizes both the output voltage and an analog signal proportional to the SiPM temperature for each of its 16 independent outputs. The appropriate change in the bias voltage is computed in a micro-controller and this correction is applied via a high resolution DAC to the control input of a DC/DC module that produces the output voltage. This method allows a reduction in gain variations from typically 30% to only 0.5% in a 10ºC range.

The power supply is housed in a 3U-height aluminum box. A 2.8” touch screen on the front panel provides local access to the configuration and monitoring functions using a graphical interface. The unit has an Ethernet interface on its rear side to provide remote operation and integration in slow control systems using the encrypted and secure SSH protocol. A LabVIEW application with SSH interface has been designed to operate the power supply from a remote computer.

The power supply has good characteristics, such as 85 V output range with 1 mV resolution and stability better than 2 mV_P, excellent output load regulation and programmable rise and fall voltage ramps. Commercial power supplies from well-known manufacturers can show far better specifications though can also result in an over featured and over costly solution for typical applications.

KEYWORDS: SiPMs; Modular electronics; Front-end electronics

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Contents

1. Introduction

Silicon Photomultipliers (SIPMs) are replacing PMTs in a growing number of high-energy, nuclear and medical physics applications where the reduced cost and size, small operating voltage, mechanical robustness and insensitivity to magnetic fields, overcome a number of drawbacks (like higher noise, reduced active area and greater temperature dependence).

One key element in the use of this technology is the power supply. SiPMs from different vendors require bias voltages ranging from 20 V to 90 V and the type of application will imply current demands ranging from microamps to milliamps. Good output load regulation will ensure a uniform response in the dynamic range, while temperature compensation is a must in applications that require high gain stability or are subject to temperature variations. Temperature compensation, being device specific, usually requires some sort or adjustment or configurability. Multiple-output capability (as well as remote monitoring and control) is desirable in applications with large SiPM arrays. These features and requirements are discussed in the next sections.

1.1 Temperature dependence compensation

SiPMs are avalanche photodiodes operated in Geiger mode, reverse biased at a small overvoltage (V_{ov}, typically 1.5-3.5V for Hamamatsu devices [1] and 1-5V for SensL [2]) beyond the breakdown voltage (V_{bk}). The gain (G) of the device is a linear function of the bias voltage, $V_{bias}=V_{bk}+V_{ov}$. As V_{bk} has a relatively large variation with temperature (its temperature coefficient is typically 20-70 mV/ºC [1,2]), the device gain changes 1-10%/ºC [3]. Consequently, some sort of compensation (that results in adjusting V_{bias} when temperature changes) is required for most applications.

A survey of different temperature compensation techniques is presented in [3]. Some techniques are based on SiPM dark current control, which has a negative exponential relation with temperature at a given gain value. A thermistor (which has a negative exponential response too) is used in the bias circuit to compensate for the gain variation. However, these techniques are limited to low temperature and/or low intensity of light if high accuracy is sought, in addition to requiring changes in the thermistor circuit if the SiPM model is changed.

A more flexible and accurate family of methods are based on direct bias voltage control. Our group presented in 2011 [4] a direct bias voltage control method in which the output of a high-resolution DAC is connected to the control input of a high-voltage module in order to provide a compensated V_{bias}. A temperature sensor and characterization data for the SiPM are used to compute the DAC output in a microcontroller. Other works referenced in [3] have been implemented later using a similar approach.

The power supply presented in this work inherits the temperature compensation from [4]. In order to determine the V_{bias} required for a given temperature (T), two characteristic curves need to be measured [4,5] and fitted to straight lines: dG/dV and dG/dT. The former allows to determine a, b coefficients in the expression $G = a + b \cdot V$, while the latter renders coefficients c, d in the expression $G = c - d \cdot T$ (showing a negative dependence of gain with T). The relation between a change in temperature ΔT and the required change in V_{bias} (ΔV) can be easily inferred as $\Delta V = -(d/b) \cdot \Delta T$. Finally, taking as a reference room temperature (25 ºC), the applied voltage is $Vbias = V_{bias25^{o}C} + \Delta V$.

2. Design specification

2.1 Target application

NEXT [6] is an underground experiment for neutrino-less double-beta decay searches that combines an excellent energy resolution with tracking capabilities merging PMTs and SiPMs. The detector is a time-projection chamber with sensor planes in opposite ends. PMTs are used for energy measurement in one of the detector planes, while the other consists of a large SiPM array for topology reconstruction.

The SiPM detector plane and associated readout electronics for the first NEXT phase (called NEW) are described elsewhere [7]. Energy accuracy requirement in this plane is not stringent, as the application is tracking and not calorimetry. Due to radio-purity concerns, only the SiPM sensors are placed inside the detector. A total length of 5 m cable connect a group of 64 sensors (see figure 1) to a front-end electronics module, based on gated integrators with a 1-µs integration time. On-board ADCs and an FPGA produce sub-event data which are transferred to the DAQ system.

The bias voltage for the SiPMs is fed through the same cables via the front end. The two terminals of a temperature sensor are also available in this cable. Three 16-channel external power supply units (described in this work) feed the bias voltages to the 28 front-end boards and read out the temperature sensors using a 4-pin LEMO connector.

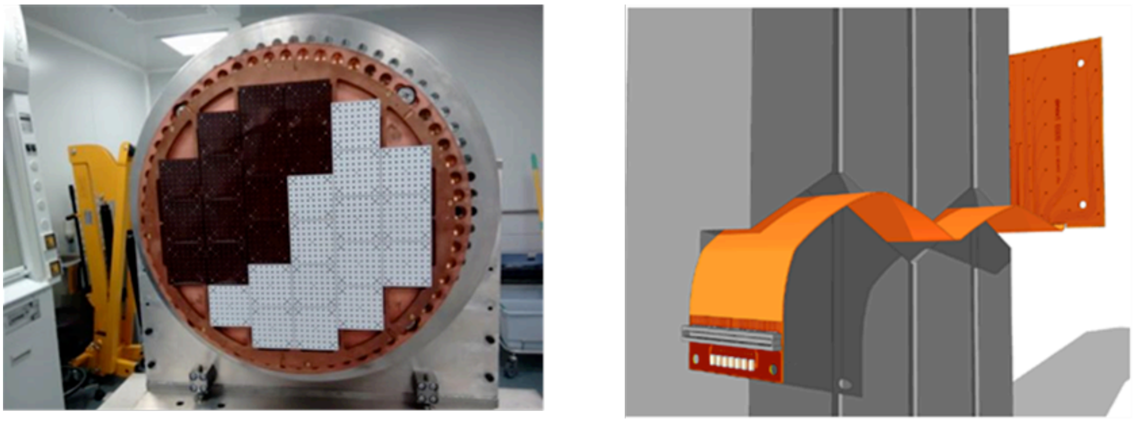


Figure 1. Left: the 1800-SiPM tracking plane in the NEW detector. Teflon masks (white) are mounted on the tracking plane to improve light collection. SiPMs are arranged with a 1-cm pitch on 8x8 kapton carriers. Right: kapton carriers' pigtails traverse a 12-cm copper shield.

2.2 Requirements

In terms of integration, the power supply must be 3U-rackable, as the front end boards are 3U Eurocard form factor. Remote monitoring and control via Ethernet is a must, in order to integrate the power supply in the experiment's LabVIEW-based Slow Control system. Multiple outputs are required (16 is considered a good factor) to reduce the overall power supplies volume. Due to the already existing low-voltage power supplies' characteristics, the SiPM power supply must accept ±12V as input voltages.

In terms of bias voltage output, a 0-85 V is required to accommodate both Hamamatsu and SensL devices. Voltage resolution must be better than 5 mV for accurate gain stabilization with temperature. Output current per channel up to only a few μA is required (a result from calibration tests on the 64 SiPMs on a kapton carrier with the expected illumination in the experiments), though the source actually has good load regulation up to 5 mA.

Gain stability with temperature in the SiPM must be better than 1% in a 10 ºC range (the underground laboratory is kept at a constant 21-22 ºC).

3. Power supply design

3.1 Block diagram of an output channel

Each of the 16 channels are based on the LT3482 [8], a 90V boost DC/DC converter with control input and current monitoring aimed at APD applications. It provides a direct current monitor signal (I_{mon} in Figure 2, with a maximum error of 12 μA) to a low-noise ADC, which also digitizes the output voltage (via a resistor divider) and the temperature sensor signal. A Raspberry Pi module uses these data to compute the required correction in the bias voltage output, which is fed to the DC/DC converter's control input via a 16-bit DAC, closing the control loop. Both ADC and DAC are connected to the Raspberry Pi via a SPI bus. The resulting closed-loop control allows a precise SiPM gain stabilization (see section 4).

The LT3842 module includes a number of convenient features like overcurrent, overvoltage and overheat protection, as well as automatic power off.

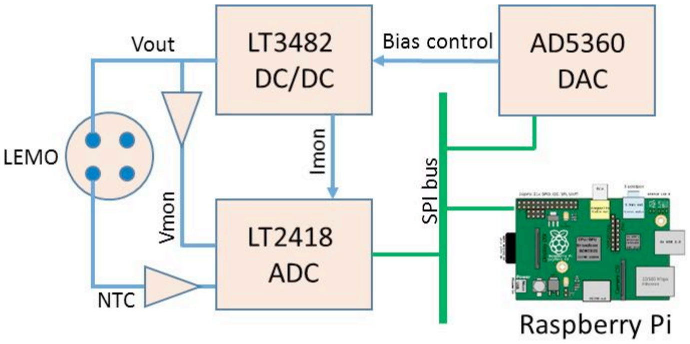


Figure 2. Block diagram of an output channel.

For remote SiPM temperature sensing in the NEW detector, a Murata NTC sensor (reference NCP18XH103F03RB) is mounted on each 8x8 kapton carrier. In order to improve the sensor behaviour, a second-grade polynomial is fitted in the range from 15ºC to 35ºC. The results obtained with this method show a 0.06 ºC (1.32 mV) maximum fit error. With the SiPM SensL MicroFC-10035-SMT-GP, currently used in NEW, this corresponds to 0.037% maximum gain compensation error due to the fit. To avoid calibrating each NTC sensor in the tracking plane, the response of 30 NTC sensors was fitted, and the maximum error with a general fit is of 0.259 ºC (5.7 mV). This produces a 0.16% maximum gain compensation error.

3.2 I/O interfaces and mechanical design

The front panel is equipped with a 2.8” color touch screen (see figure 3). A graphical user interface provides in-field monitoring and control of the source parameters, a convenient feature for stand-alone applications or for quick in-field troubleshooting. A USB memory can be plugged into the rear USB connector to store the diary reports, measurements and channel configuration data.

The small size design provides a compact solution fully compatible with the NEW tracking plane readout, which consists of 28 groups of 64 SiPMs (making a total of 1792 SiPMs). A 19” 3U crate accommodates a programmable power supply and 12 front-end boards (see figure 4). As a result, the whole tracking plane is read-out with three 3U crates.

Figure 3. The SiPM power supply for the NEXT experiment, front and rear views. It is a 3U rackable unit with (front) touch screen, on/off switch, reset button and (rear) 16 4-pin LEMO connectors, ±12V power input, Ethernet and USB connectors.

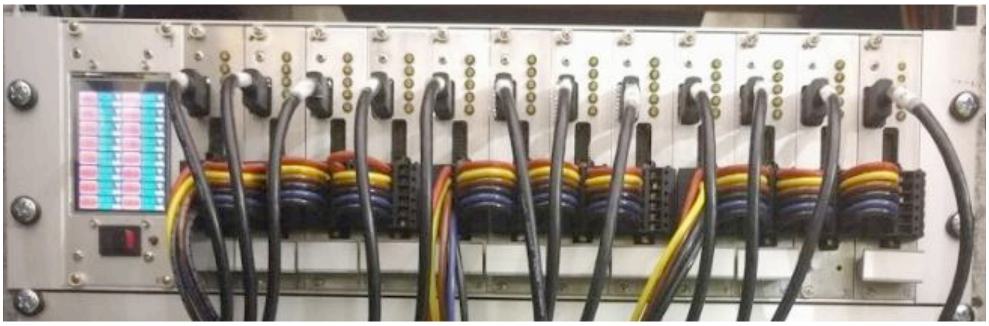
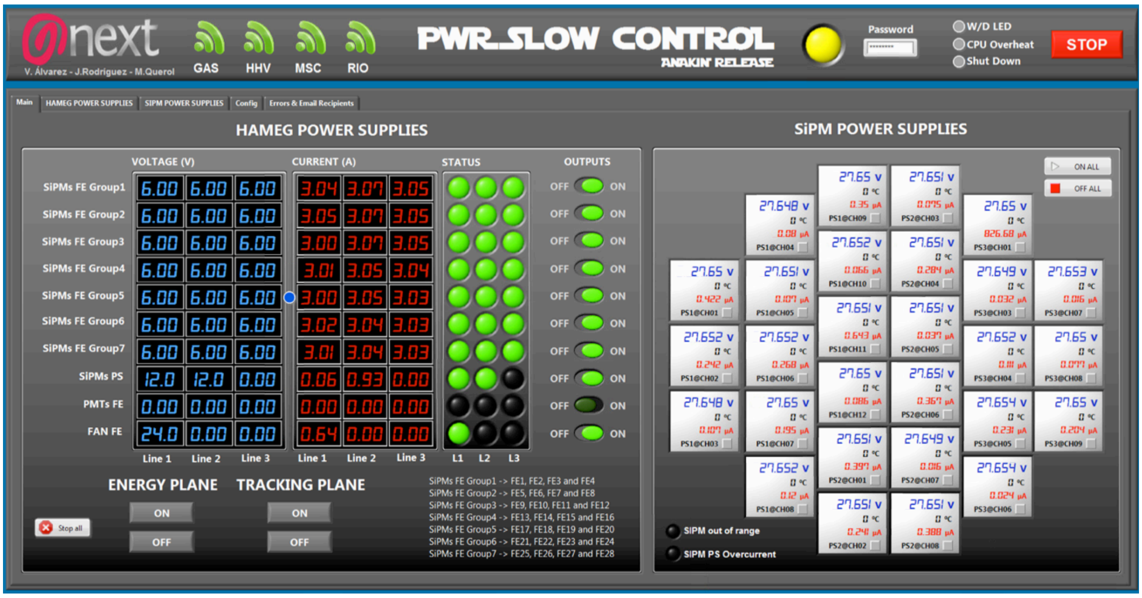


Figure 4. A 19” Eurocard crate equipped with a SiPM power supply (left) and 12 SiPM front-end modules (reading out 768 channels) for the NEXT experiment.

An ethernet interface allows remote monitoring control of the power supply using the SSH secure protocol [9]. A Labview VI (Virtual Instrument) has been created as an interface to the power supply from Labview using SSH. A monitoring tool has been developed in LabVIEW (figure 5). The right side of the image shows the SiPM plane where voltage, current and temperature for each group of 64 SiPM sensors is displayed.



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HAMEG POWER SUPPLIES

	VOLTAGE (V)			CURRENT (A)			STATUS			OUTPUTS
	Line 1	Line 2	Line 3	Line 1	Line 2	Line 3	L1	L2	L3	
SiPMs FE Group1	6.00	6.00	6.00	3.04	3.07	3.05	🟢	🟢	🟢	ON
SiPMs FE Group2	6.00	6.00	6.00	3.05	3.07	3.05	🟢	🟢	🟢	ON
SiPMs FE Group3	6.00	6.00	6.00	3.00	3.07	3.05	🟢	🟢	🟢	ON
SiPMs FE Group4	6.00	6.00	6.00	3.01	3.05	3.04	🟢	🟢	🟢	ON
SiPMs FE Group5	6.00	6.00	6.00	3.00	3.05	3.03	🟢	🟢	🟢	ON
SiPMs FE Group6	6.00	6.00	6.00	3.02	3.04	3.03	🟢	🟢	🟢	ON
SiPMs FE Group7	6.00	6.00	6.00	3.01	3.04	3.03	🟢	🟢	🟢	ON
SiPMs PS	12.0	12.0	0.00	0.06	0.93	0.00	🟢	🟢	⚫	ON
PMTs FE	0.00	0.00	0.00	0.00	0.00	0.00	⚫	⚫	⚫	OFF
FAN FE	24.0	0.00	0.00	0.64	0.00	0.00	🟢	⚫	⚫	ON

ENERGY PLANE: ON / OFF

TRACKING PLANE: ON / OFF

SiPMs FE Group1 -> FE1, FE2, FE3 and FE4
SiPMs FE Group2 -> FE5, FE6, FE7 and FE8
SiPMs FE Group3 -> FE9, FE10, FE11 and FE12
SiPMs FE Group4 -> FE13, FE14, FE15 and FE16
SiPMs FE Group5 -> FE17, FE18, FE19 and FE20
SiPMs FE Group6 -> FE21, FE22, FE23 and FE24
SiPMs FE Group7 -> FE25, FE26, FE27 and FE28

SiPM POWER SUPPLIES

PS1@CH01	27.65 v	0 °C	0.422 µA
PS1@CH02	27.652 v	0 °C	0.242 µA
PS1@CH03	27.648 v	0 °C	0.107 µA
PS1@CH04	27.648 v	0 °C	0.08 µA
PS1@CH05	27.651 v	0 °C	0.107 µA
PS1@CH06	27.652 v	0 °C	0.268 µA
PS1@CH07	27.65 v	0 °C	0.195 µA
PS1@CH08	27.652 v	0 °C	0.12 µA
PS1@CH09	27.65 v	0 °C	0.35 µA
PS1@CH10	27.652 v	0 °C	0.066 µA
PS1@CH11	27.651 v	0 °C	0.643 µA
PS1@CH12	27.65 v	0 °C	0.086 µA
PS2@CH01	27.651 v	0 °C	0.397 µA
PS2@CH02	27.651 v	0 °C	0.241 µA
PS2@CH03	27.651 v	0 °C	0.075 µA
PS2@CH04	27.651 v	0 °C	0.284 µA
PS2@CH05	27.651 v	0 °C	0.037 µA
PS2@CH06	27.651 v	0 °C	0.367 µA
PS2@CH07	27.649 v	0 °C	0.016 µA
PS2@CH08	27.651 v	0 °C	0.388 µA
PS3@CH01	27.65 v	0 °C	826.68 µA
PS3@CH03	27.649 v	0 °C	0.032 µA
PS3@CH04	27.652 v	0 °C	0.111 µA
PS3@CH05	27.654 v	0 °C	0.231 µA
PS3@CH06	27.654 v	0 °C	0.024 µA
PS3@CH07	27.653 v	0 °C	0.016 µA
PS3@CH08	27.65 v	0 °C	0.077 µA
PS3@CH09	27.65 v	0 °C	0.204 µA

⚫ SIPM out of range

⚫ SIPM PS Overcurrent

Figure 5. *Part of the NEW slow control software. On the right side 28 channels of 3 programmable power supplies are being monitored for voltage, current and temperature.*

4. Results

A Lecroy WaveRunner HRO 64zi oscilloscope (12-bit vertical resolution, set to infinite persistence, AC coupling, 1 Mohm input impedance) has been used to measure output voltage stability in a 2-hour interval. Stability is better than 2 mV_P (see figure 6), measuring the difference between desired and actual output voltage. Output voltage resolution, after calibration, is better than 1 mV over the full range. Other relevant specifications are summarized below:

- Maximum output voltage of 85 V
- Power consumption between 5W (typical) and 29W (max)
- Controlled rise and fall slopes
- Self-calibration algorithm

In the NEW detector, each power supply channel provides the bias voltage to the 64 SiPMs in an 8x8 kapton carrier. Sensors for each group have been selected for minimum parameter dispersion, and the temperature compensation feedback was adjusted to the mean of the group.

Figure 7 shows the first results of the NEW tracking plane on April 2016. As can be seen, the gain variation with temperature has been reduced just to less than 0.5% in the whole tracking plane in a 10 ºC range, and the single photon spectrum is clear enough to perform the SiPM calibration using the dark count events.

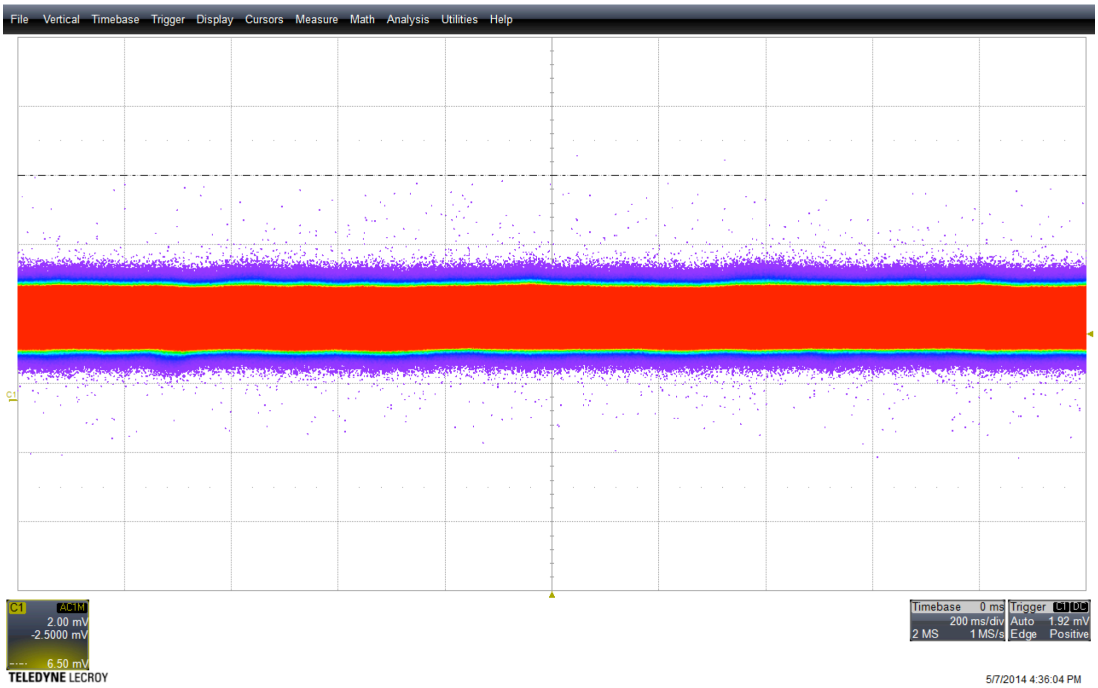

Figure 6. *Stability of the programmable power supply output. Vertical scale is 2 mV/div.*

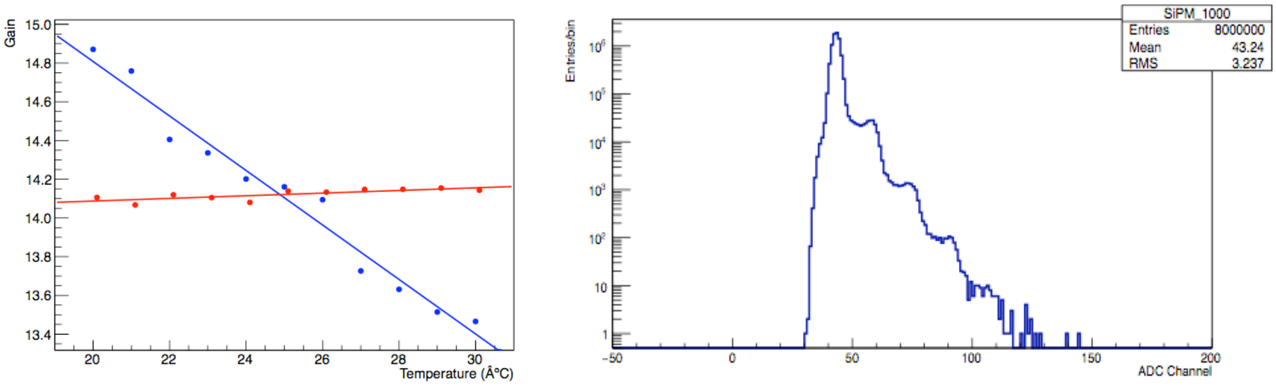

Figure 7. Left: *Gain vs Temperature without compensation (Blue) and with a compensation of 22mV/ºC (red).* **Right:** *Single photon spectrum obtained from the dark count of a NEW SiPM.*

5. Summary and outlook

This paper presents a solution for SiPM bias supply with temperature compensation without introducing additional complexity to the bias circuit, which may be interesting for applications with high density of SiPM or other applications where there are space or heating constraints and active circuits with operational amplifiers are not desirable.

The device produced provides gain stability for the SiPMs in the NEW detector of 0.5% in the operation range, with output voltage stability better than 2 mV_P. Three power supplies are being used in the NEW detector since spring 2016, whose tracking plane is made of ~1800 SiPMs, and they allowed a full sensor calibration ready for the data taking. As the design is fully scalable together with the front-end electronics a new batch will be built for the NEXT-100 detector, containing ~8000 SiPMs.

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