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# Readout solutions for the VULCAN SiPMs

VULCAN is designed to take measurements of the reflection/transmission/fluorescence properties of material samples using SiPMs. The measurements will take place under a vacuum of 10$^{-3} \to$ 10$^{-5}$ mbar and at -100 $^{\circ}$C. There are a number of circuit boards in our lab which have the ability to be used to read out the SiPM signals in the final setup. These include a board borrowed from the XAMS lab, boards soldered by myself or Casimir, a board borrowed from the Zurich group, a board from Hamamatsu and boards designed and created in collaboration with Hans. This note will briefly touch on the majority of these boards for a comparison and will detail which to be used in the final configuration.

## SiPMs

The setup will use two different configurations for reflection/transmission or fluorescence measurements. Reflection and transmission measurements will detect the reflected light with a wavelength in the VUV range (128 or 178 nm). The SiPMs used for this measurement will be the Hamamatsu S13370-3050CN MPPC, with operational values, Vop=56 V, Iop<0.5 uA and RT dark counts 1*10$^6$ Hz. These are 3×3 mm SiPMs and 10 of these SiPMs are available to us, though some are not operational due to the bending of the pins when returning to the foam packaging. The table below shows which SiPMs are in working order, showing we have both visible-sensitive SiPMs and four VUV-sensitive SiPMs in working order. The spec sheet for these SiPMs is given on the wiki.

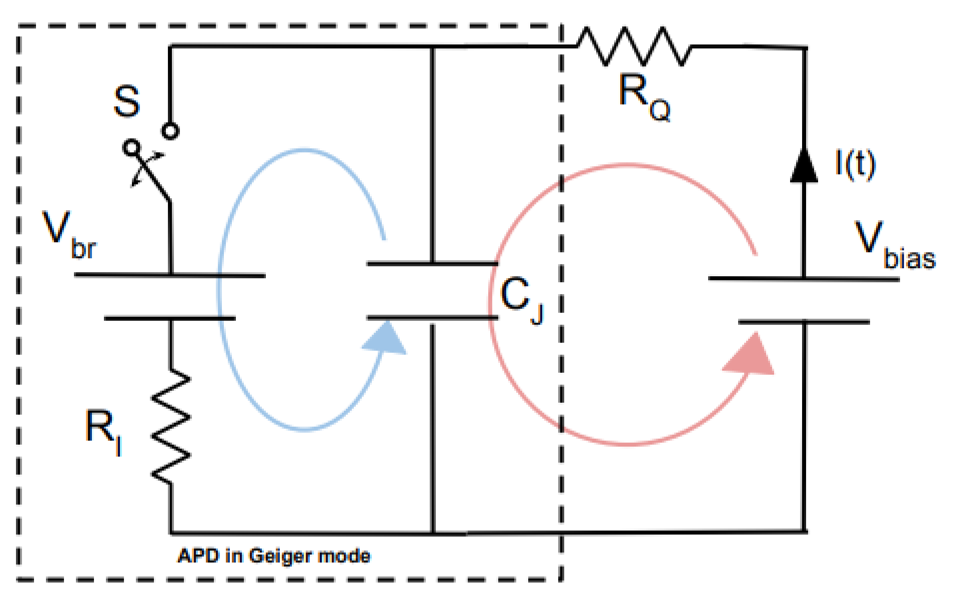
| SiPM type | SiPM number | Verdict | Notes |
|---|---|---|---|
| S13360-6075CS | 1 | Operational | 56V bias |
| S13360-6075CS | 2 | Operational | 56V bias |
| S13370-3050CN | 1805 | Current leak | |
| S13370-3050CN | 1810 | Current leak | |
| S13370-3050CN | 1812 | Operational | 58V bias, pins bent |
| S13370-3050CN | 1821 | Operational | 58V bias |
| S13370-3050CN | 1822 | Current leak | |
| S13370-3050CN | 1823 | Current leak | |
| S13370-3050CN | 1828 | Operational | 57V bias, pins bent |
| S13370-3050CN | 1829 | Operational | 57V bias, pins bent |
| S13370-3050CN | 1830 | Operational | 57V bias |

The fluorescence measurements will measure the emission of photons from the material after absorption, which will be of a longer wavelength than the exciting light. Therefore, these measurements will be detection photons in the near-UV to visible range and will use the Hamamatsu S13360-6075CS SiPMs with operating values of Vop=56 V, Iop<0.5 uA and RT dark counts 2*10$^6$ Hz. These are 6×6 mm SiPMs and we have 2 available for use. The spec sheet for these SiPMs is given on the wiki.

### Introduction to the detection mechanism

SiPMs are made up of many microcells of Avalanche PhotoDiodes (APDs) which are connected in series to a resistor. Each microcell can be modelled as shown below.

**Circuit diagram to represent the working of a SiPM.**



These APDs are supplied with a bias voltage which is larger than their breakdown voltage. When an electron-hole pair in the material is produced, the switch S closes and the current through C$_J$ and the bias voltage drops below the breakdown voltage again. This allows the avalanche to be quenched and the system to recover. The quenching resistor limits the current from an APD avalanche to order mA. This quenching resistor means that if multiple avalanches are initiated at the same time, the signal output will be the same as if only one avalanche had been initiated. The recharge time is defined via

$$\tau_r = R_Q C_J$$

and is on the order of ns.

The signal from a SiPM has some characteristic features.

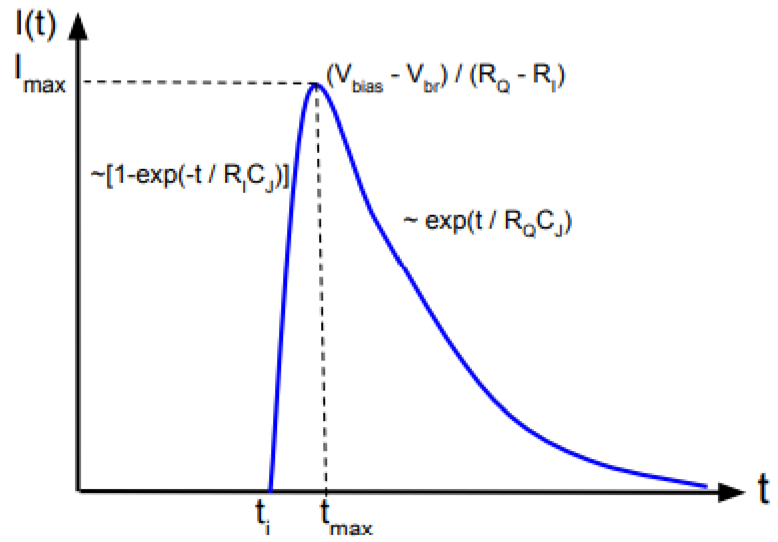
$$I_{max} ~ \frac{V_{bias}-V_{br}}{R_Q} = \frac{\Delta V}{R_Q}$$

$$t_{max}-t_i ~ 1-exp(\frac{-t}{R_I C_J})$$

$$Q_{tot}=\int^\inf_{t_i} I(t)dt = Q = C_J \Delta V$$

$$t_f-t_{max} ~-exp(\frac{t}{R_QC_J})$$

The first two characteristics arise since $R_Q \gg R_i$.

| **Example SiPM pulse shape, annotated** |
|---|
|  |

The Photon Detection Efficiency (PDE) is given by

$$PDE(\lambda, V_{bias}) = \eta(\lambda)*\epsilon(V_{bias})*F$$

where $\eta$ is the quantum efficiency of the SiPM material, $\epsilon$ is the avalanche initiation probability, and $F$ is the fill factor of active area over inactive area. Some of the SiPM is inactive due to inter-pixel trenches to minimise noise.

The gain is defined by

$$G=\frac{Q}{e} = \frac{\int I(t)dt}{e} = \frac{\Delta VC_J}{e}$$

and describes the multiplication of the initial charge (e) through the avalanche to the signal.

### Intrinsic noise

There are a number of origins for noise in a SiPM. The main culprets are dark counts, cross-talk and afterpulses.

Dark counts occur through two main methods. The Shocklet-Read-Hall process occurs due to impurities in the lattice which provide a 'stepping-stone' for the electrons to move from the valence band to the conductance band. These are highly dependent on temperature. The band-to-band tunneling occurs when the electron travels from the valence band to the conduction band due to energy aquired from the electric field in the depletion region. This is highly dependent on bias voltage.

The probability for dark counts is given as

$$p(T) = CT^{3/2}exp(\frac{-E_q}{2k_BT})$$

where T=temperature, $E_q$=the bandgap energy, and C=proportionality constant. C is generally dependent on the doping material used in the SiPM.

Cross-talk occurs when an avalanche produces a photon which travels out of that pixel and generates a new avalanche in either the depletion region of a neighbouring cell or the substrate material which goes on to create an avalanche in a different cell. This is reduced by the inter-pixel trenches.

Afterpulses occur when a charge-carrier gets trapped on impurities. It is later released (O(ns)) and generates a new avalanche during the recovery time of the cell, creating a pulse with a smaller amplitude on the decaying slope of a previous pulse.

### Using the SiPMs

The SiPMs used in this setup have very sensitive detection areas. Therefore, when handling, gloves are always worn and effort is taken to reduce the time that they are subject to open air environments. The pins on the VUV-sensitive SiPMs are difficult to manipulate since they get bent upon return to their casing. The polystyrene is too thick and bends the pins when they are inserted. This means that several of the SiPMs have bent pins already and care must be taken when inserting them to their storage or attaching them to the kapton cables.

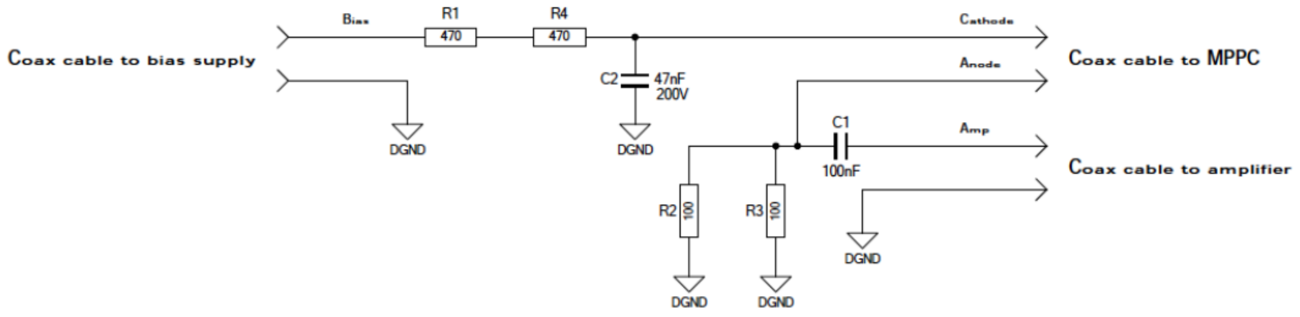
The visible-sensitve SiPMs have pins which are further apart than the VUV-sensitive SiPMs. When attaching these SiPMs to the setup, the cable should be unwound a little so that the pins are attached without any angular pressure.

Both SiPMs use the same bias voltage but cannot always be read out with the same board. For example, the Hamamatsu board discussed below requires changing some resistors and input junctions to read out different SiPMs.

## Readout boards

### XAMS pre-amp board

**Schematic of readout board borrowed from XAMS**

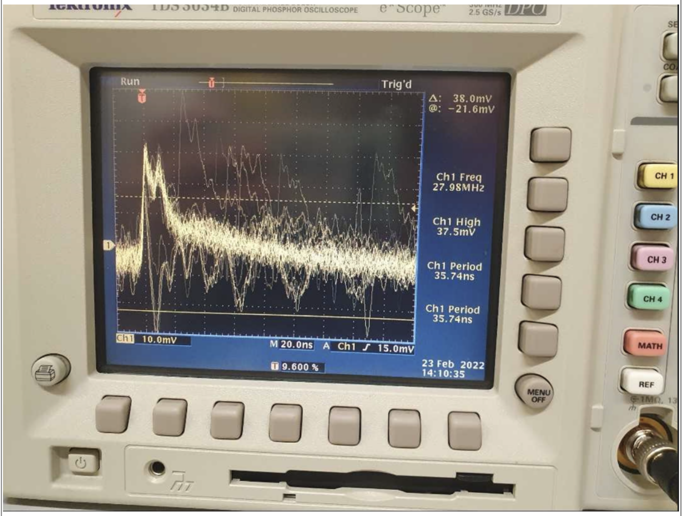
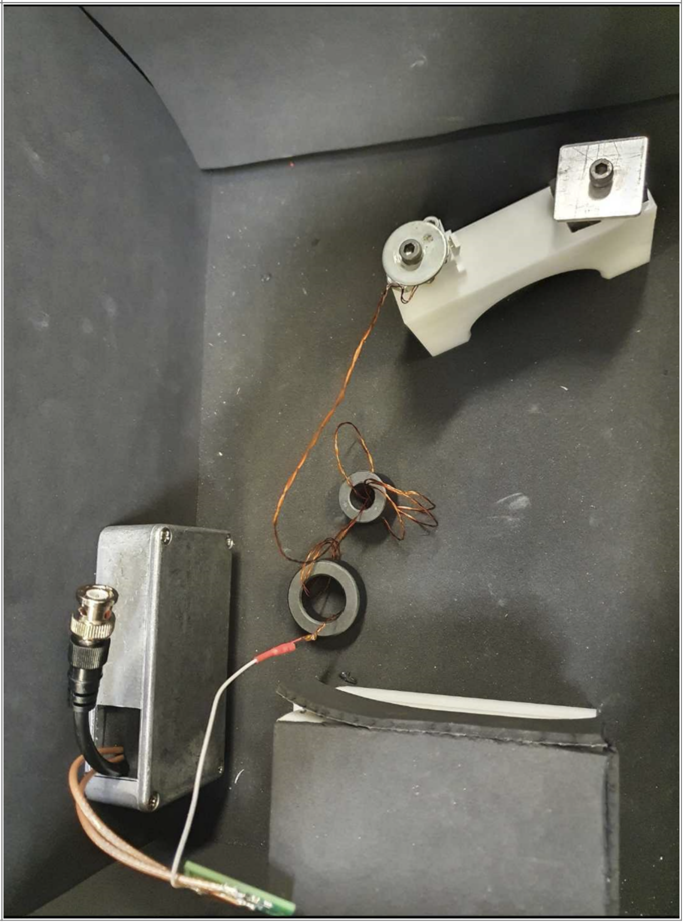


(c) PCB circuit diagram

The SiPMs used in VULCAN require a bias of 56 V, for which a dedicated power supply is used. The bias is supplied through a coaxial cable and passes through a low-pass filter. This is implemented to remove frequencies above a certain threshold, defined by the resistor-capacitor combination provided (R1+R4 and C2). There is also a secondary low-pass filter which removes high frequencies from the signal output of the SiPM (C1 and amplifier impedance of 50 $\Omega$). The threshold is defined via the equation

$$f_c=\frac{1}{2\pi RC}$$

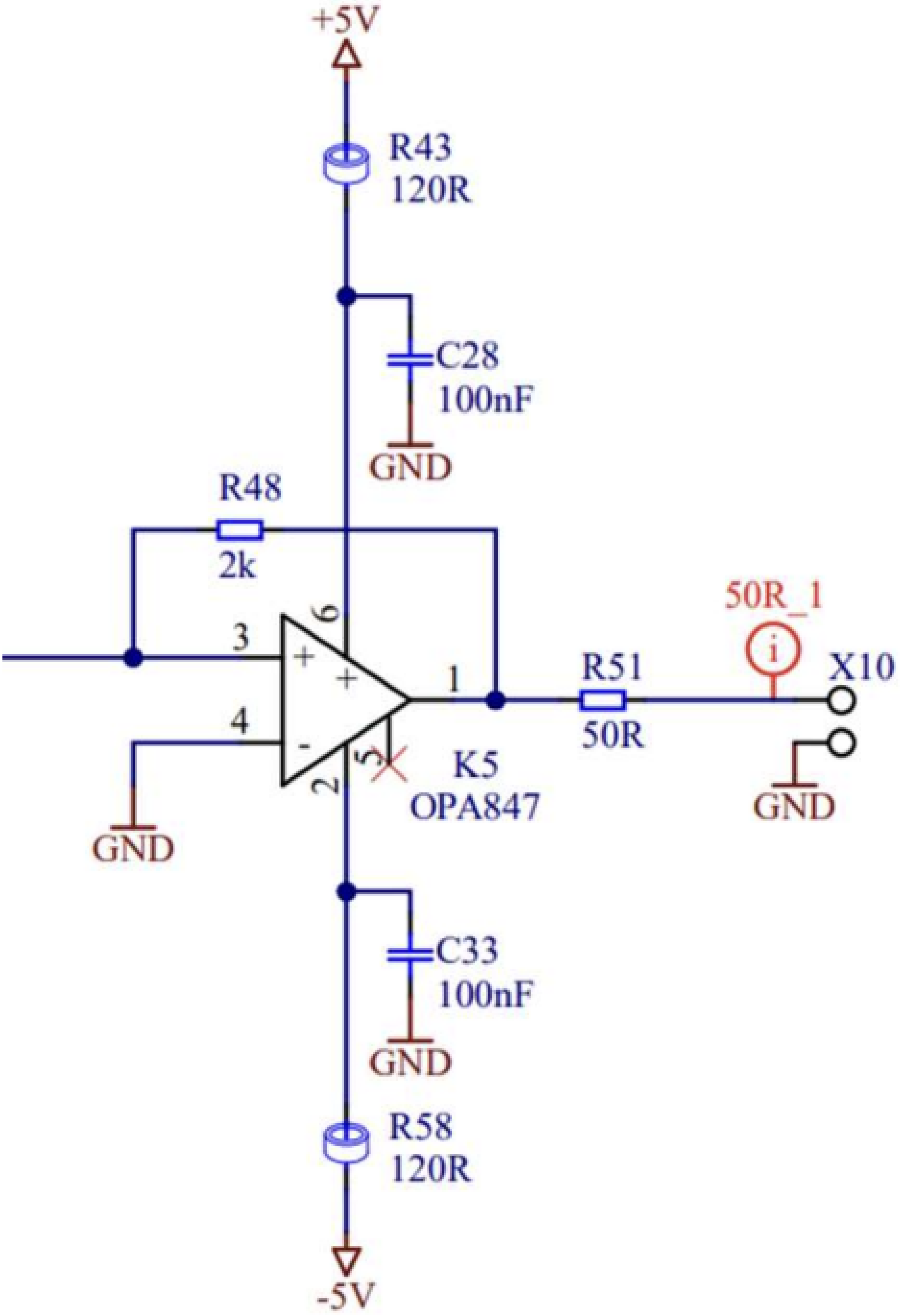
The resistors R2 and R3 also smooth the signal from the SiPM through their connection in parallel.

| **Testing setup** | |
|---|---|
|  |  |

Testing of the board was carried out in a dark box with the VUV SiPM 1822. The signals, as shown on the left, are multiple-photon waveforms and were very noisy. This was a characteristic of the setup seen in previous use in the XAMS lab, and was reduced by the use of two ferrite beads which were wound around the cable. An extra cable was used for the winding of these beads and for more manageable attachment to the SiPM.

The amplifier on this board (LMH6629) gives the signals a boost of 5x so that the single photon signals are on the order of 2mV. Further amplification is needed to use these signals with a digitiser. This board was set up for connections to SiPMs via a cable and for operation outside of a vacuum. This therefore also requires a separate feedthrough solution.

### Zurich pre-amp board

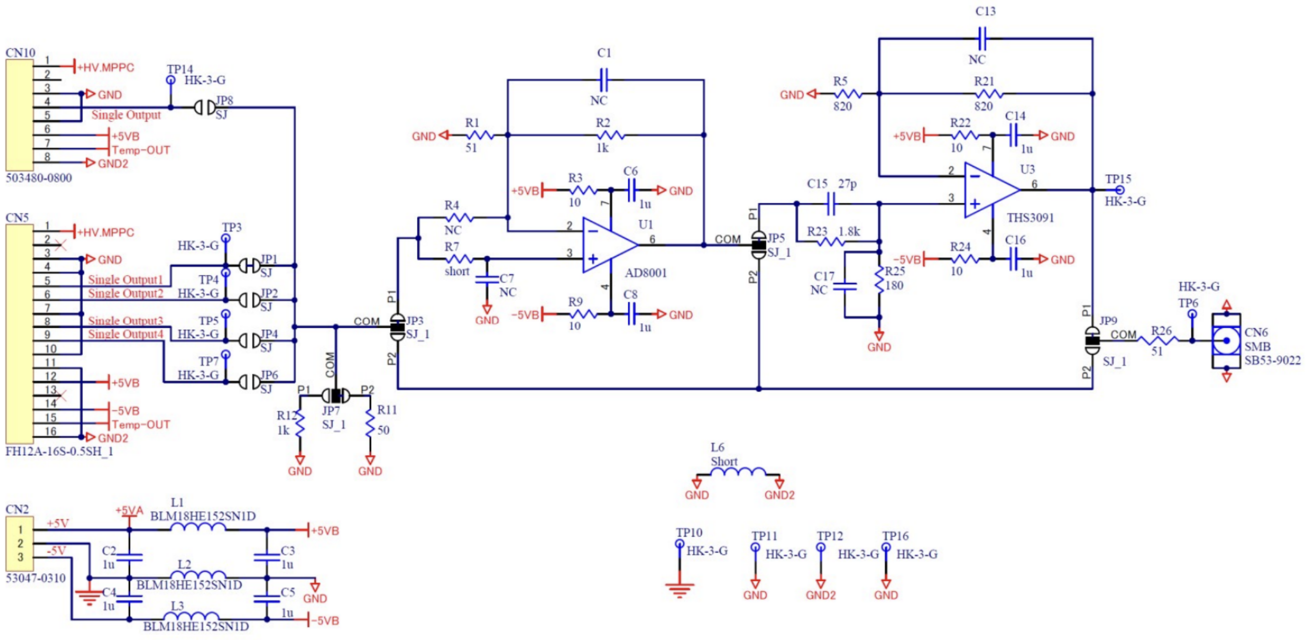
| **Schematic of readout board borrowed from the Zurich group** |
|---|
|  |

The board borrowed from the Zurich group was not operational upon arrival to the lab, so no signals are observed with this as of yet. After communication with Ricardo from the Zurich group, this is likely to be either a fried amplifier or damage in transit. In any case, a new board is being sent to our lab.

This board uses an OPA847 amplifier with low noise and supply voltages of $\pm$5 V which amplifies the SiPM signal by 10x. This is a transimpedence amplifier which works by first converting the signal to a voltage output and then amplifying it. It can also invert the signal (to a downwards pulse output).

Whilst this board wasn't operational, the amplifier has been used in the readout board developed at Nikhef (see Developed board).

### Hamamatsu evaluation board

| **Schematic of circuit board from Hamamatsu** |
|---|
|  |

The C12332-02 evaluation board from Hamamatsu was ordered alongside our visible-sensitive SiPMs. This board is laid out so that different SiPMs can be connected up in order to test their signals with an optional amplification and/or PZC circuit to shorten the length of the pulses. This board is therefore compatible with the visible-sensitive SiPMs but can also be modified to work with the VUV-sensitive SiPMs, although only one MPPC can be read out at a time. The testing of this board is carried out with the S1330-6075CS MPPCs.

The board comes set up for use with the S13360-3050CS MPPCs which we are not using. To modify the board for use with our SiPMs, the following components should be changed.

| **MPPC** | **R23 ($\Omega$)** | **R25 ($\Omega$)** | **C15 (pF)** |
|---|---|---|---|
| S13360-3050CS | 1.8k | 180 | 27 |
| S13360-6075CS | 3.9k | 390 | 39 |
| S13370-3050CN | 1.8k | 360 | 27 |

In addition to this, the amplifier/PZC can be switched on by soldering three junctions (JP3, JP5, JP9) to the correct configuration, as shown in the following table, so that the board is as shown below.

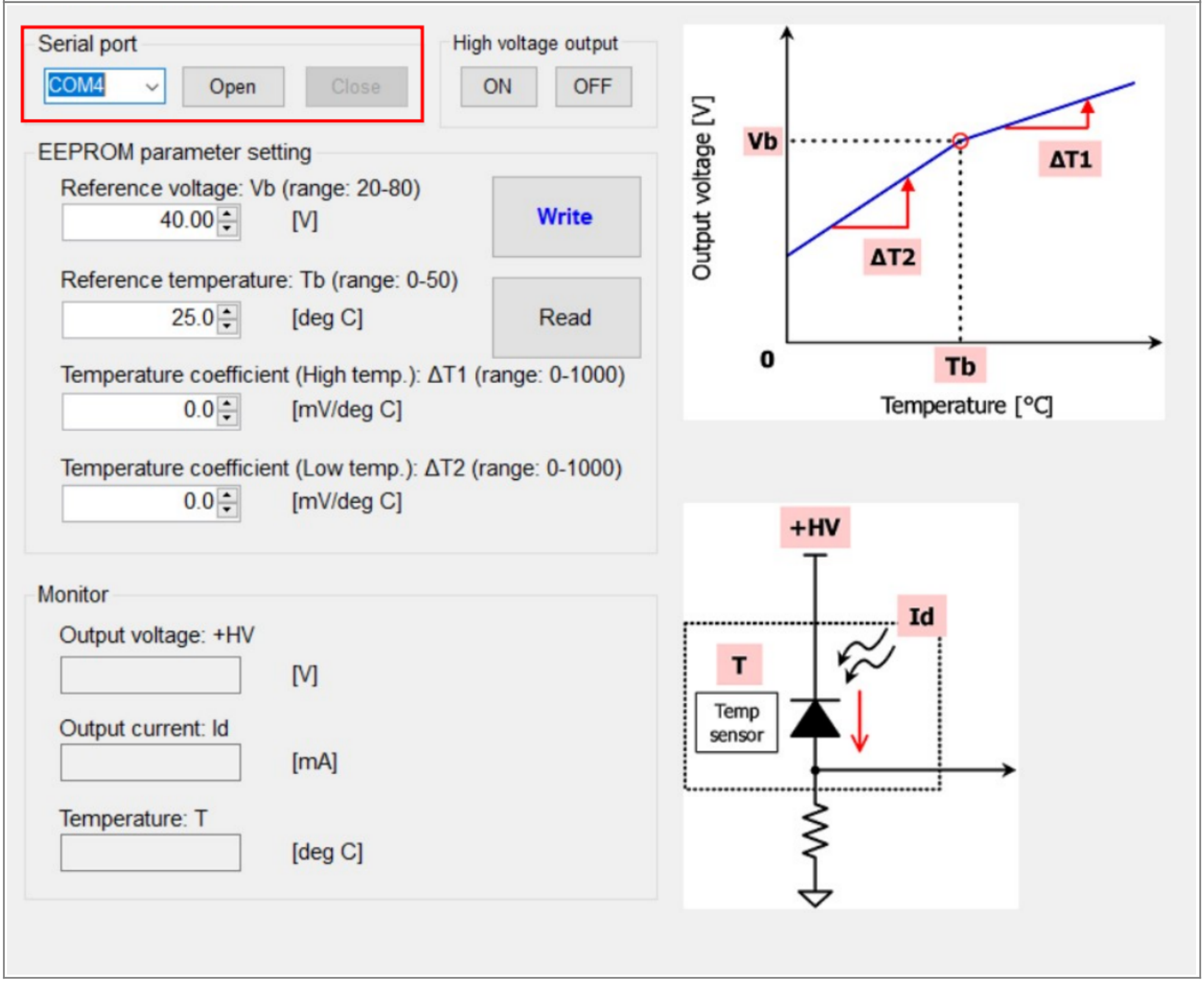
| **System activated** | **JP3** | **JP5** | **JP9** |
|---|---|---|---|
| Raw signals | Right | Not connected | Bottom |
| Amplifier | Left | Bottom | Bottom |
| Amplifier and PZC | Left | Top | Bottom |

After modifications, the amplifier is connected and the board is set up to read signals from S13360-6075CS.

The SiPMs are slotted straight into the board by design, but this will eventually be modified so that we can test the SiPMs from inside the sample chamber, through a feedthrough. Whilst both types of SiPMs use the same bias voltage, they cannot be read out by this board in the same configuration. The resistors must be changed as indicated above to change between SiPMs, and the junctions for the input signals should also be re-soldered. This is dependent on the size of the SiPM inserted to the board.

This board has a mini-USB connector which can be connected straight into a Windows computer. This enables the settings for the SiPM bias and the temperature response to be set via the software provided.

**Software page - set the port to COM3 (may change depending on computer/USB slot used).**



Serial port: COM4

Reference voltage: Vb (range: 20-80) 40.00 [V]

Reference temperature: Tb (range: 0-50) 25.0 [deg C]

Temperature coefficient (High temp.): ΔT1 (range: 0-1000) 0.0 [mV/deg C]

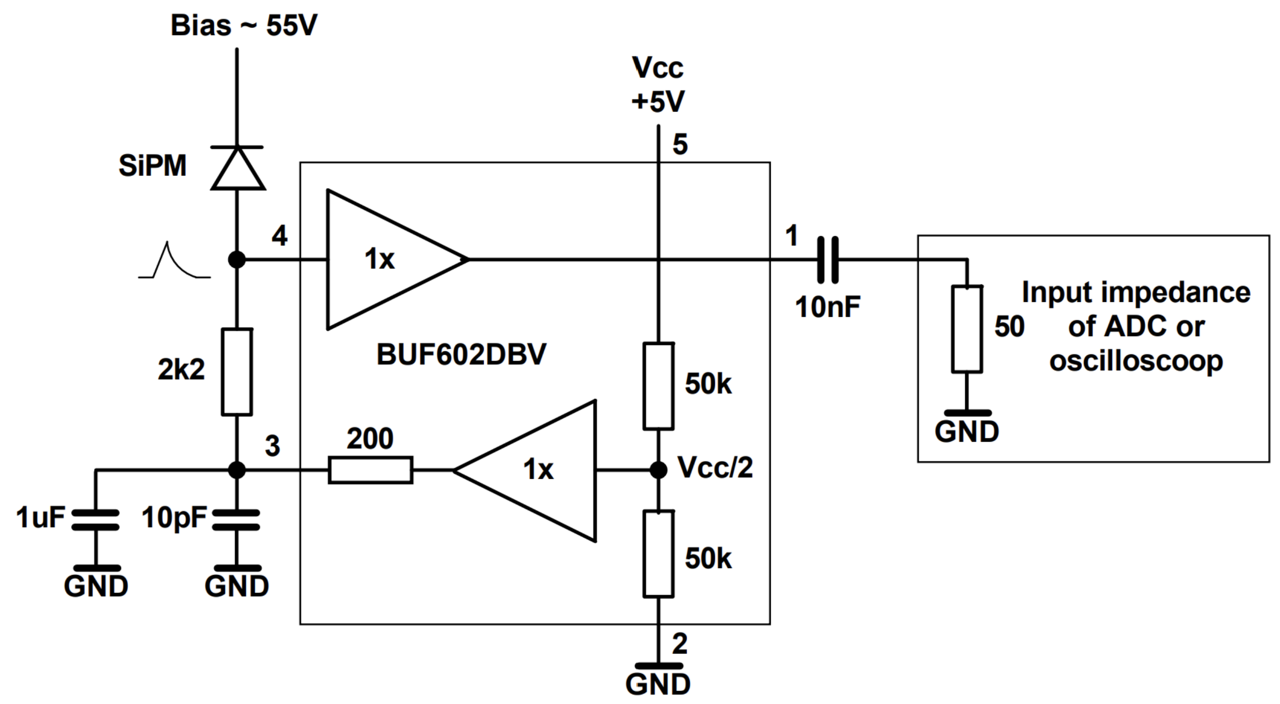
Temperature coefficient (Low temp.): ΔT2 (range: 0-1000) 0.0 [mV/deg C]

***This board is still being set up.***

### Developed board

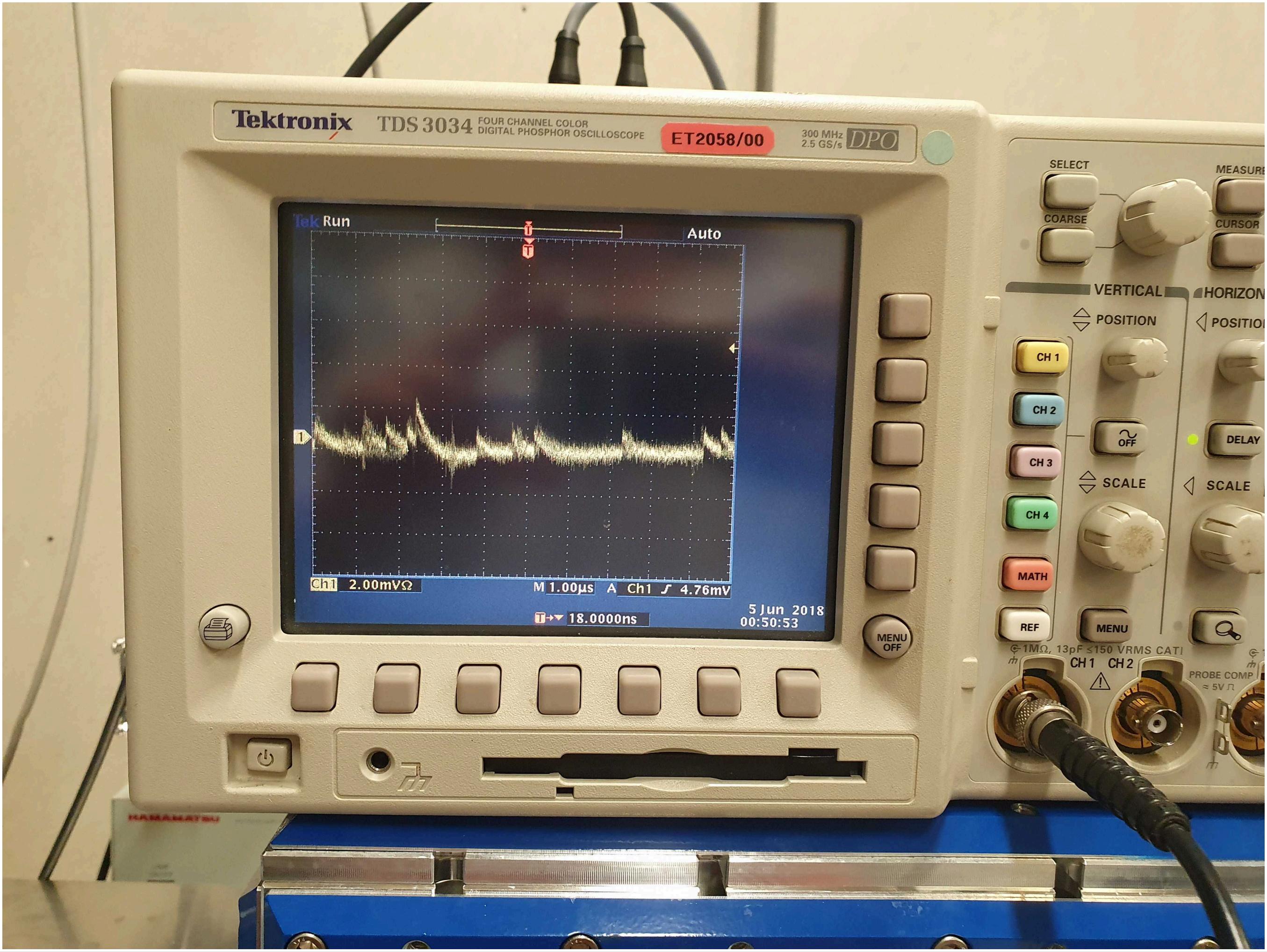
### Old schematic of buffer and bias supply for SiPM to be read out with oscilloscope

**Schematic of readout board developed in-house (old - Sept22)**



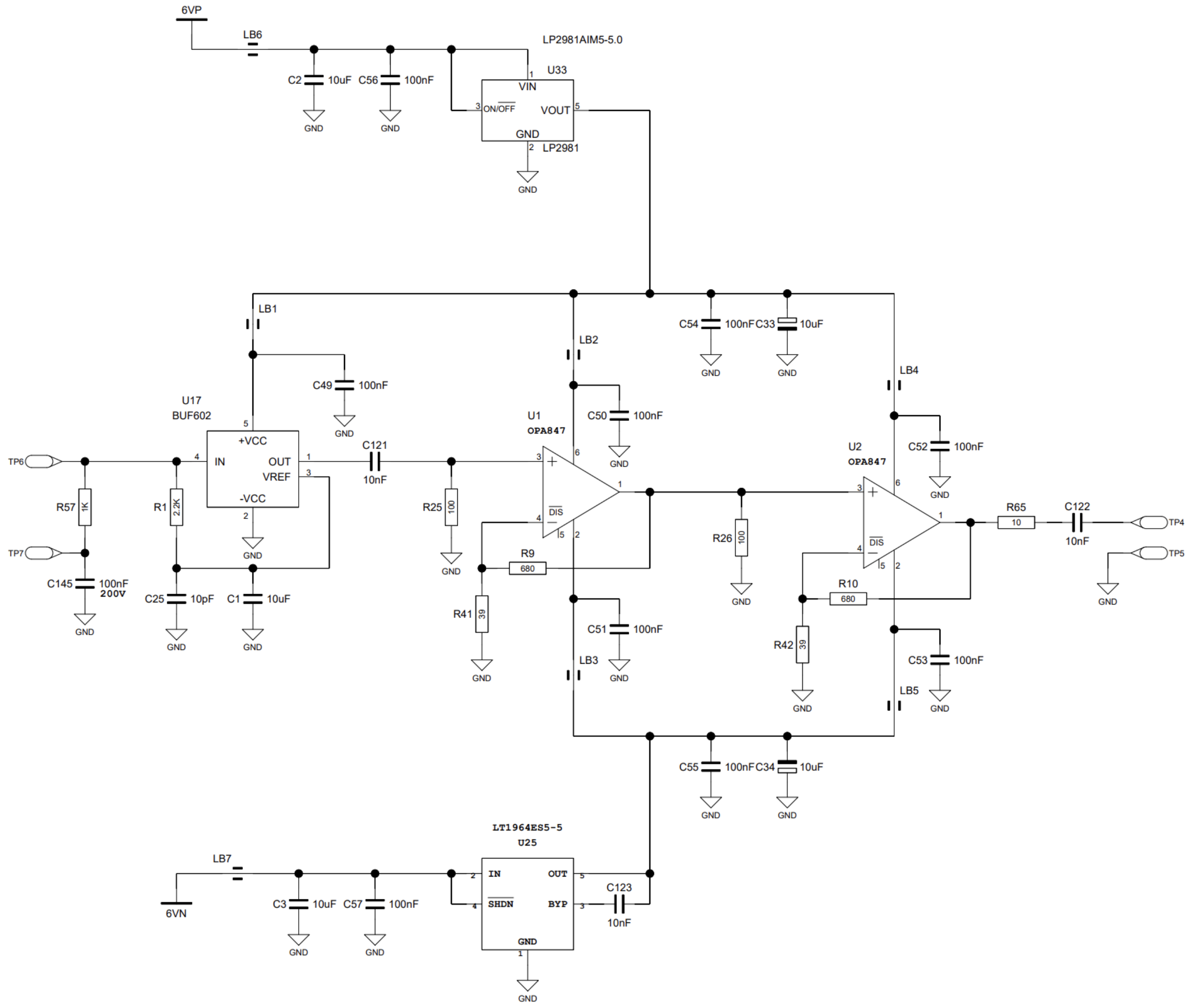
Working together with Hans from the electronics department, we developed new pre-amp and amplifier boards for use with our setup. This allowed us to modify the low-pass filter thresholds, connect nicely to the feedthrough and amplify the signals for use with the DAQ.

This board provides the ~55V bias voltage to the SiPM through a buffer (BUF602) which ensures that the impedance of the scope doesn't affect the signal. The signal from the SiPM is then passed through a low-pass filter (threshold defined as above) and another buffer is used for the Vcc/2 voltage (5V/2) so that the voltage level isn't affected by anything after it. With this board, the signals are ~1.5mV in height and visible above the noise. These are shown below. The feedback resistor on this board can be changed to modify the amplification gain and the filter threshold. This resistor was changed a number of times to achieve a nice balance.

| Un-amplified signals |
|---|
|  |

## New schematic of circuit including buffer, voltage regulators, supply bias and amplifiers

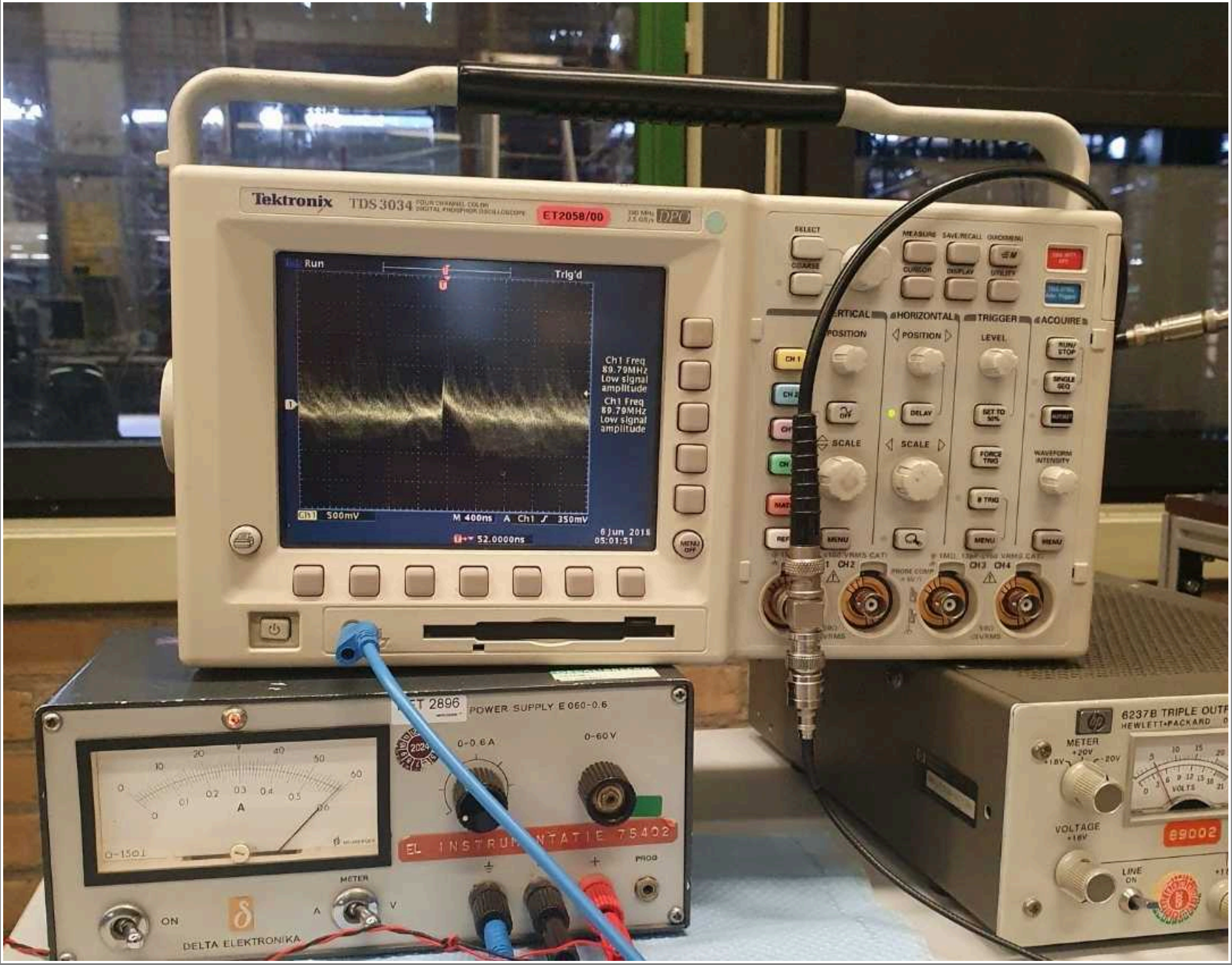
## Schematic of readout board and amplifier board developed in-house (new - Nov22)



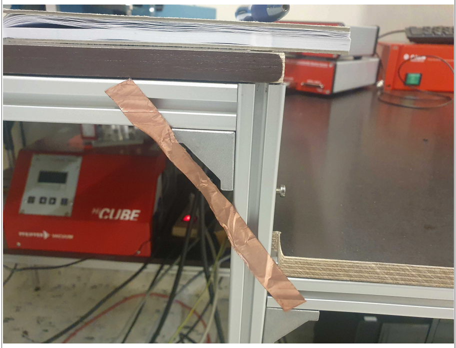
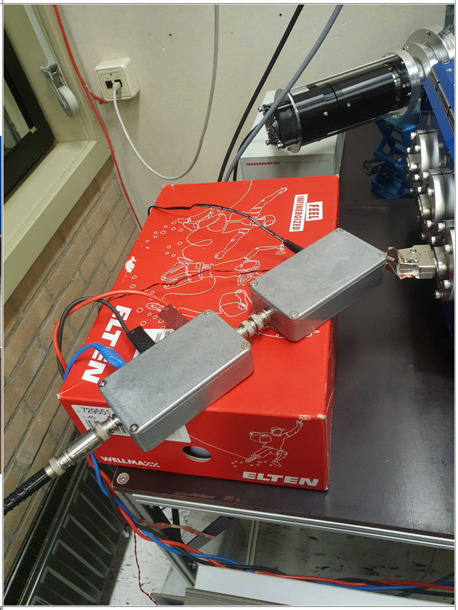
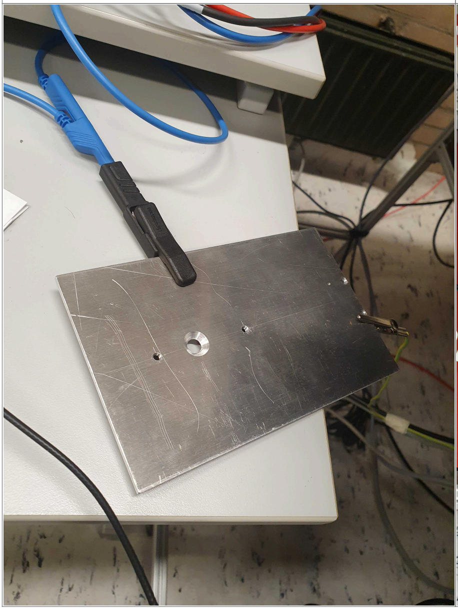
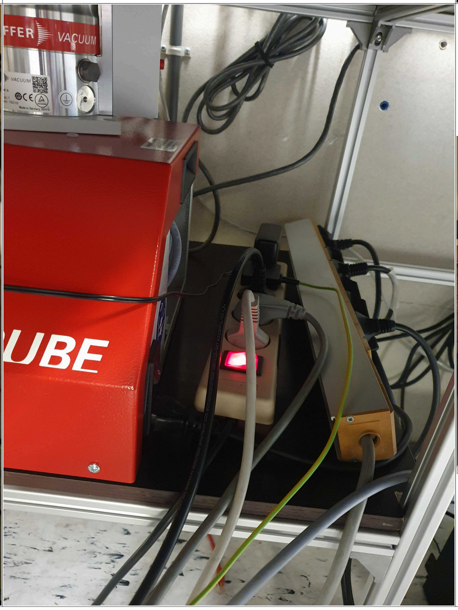
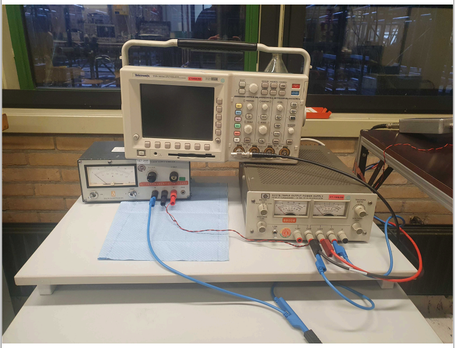
This schematic is an update to the bias board shown above. Here, the same buffer can be seen on the left which takes an input SiPM signal from TP6 at point 4 and provides the signal for amplification at point 1. This is input to the amplifier in two rounds, and the output signal is sent through TP4 on the right of the schematic. Two voltage regulators are shown at the top and bottom of the schematic to ensure smooth supply voltages.

For noise-reduction purposes, these boards were put into two separate metal boxes, as shown in Figure labelled 'Noise reducing solutions' below. The first box contains the SiPM bias supply and buffer stage. This stage requires the SiPM voltage bias of ~56V and the wall-socket power supply for the buffer. This fits directly onto the outside of the feedthrough, as shown below. The signal retrieved from the SiPM is passed to the second metal box which contains the amplification steps, requiring a supply voltage of +-5V.

The amplifier stage of the setup takes the signals from ~1mV to ~340mV and these are shown below. The gains of the amplifiers are obtained by dividing the feedback resistor in place (R9 and R10) by the resistor to ground (R41 and R42) +1. So the gain for each amplifier is given by $$1+ \frac{680}{39} = 18.4$$ and in total is $$18.4 * 18.4 = 338.6$$. This nicely reflects the amplification that we see on the oscilloscope.

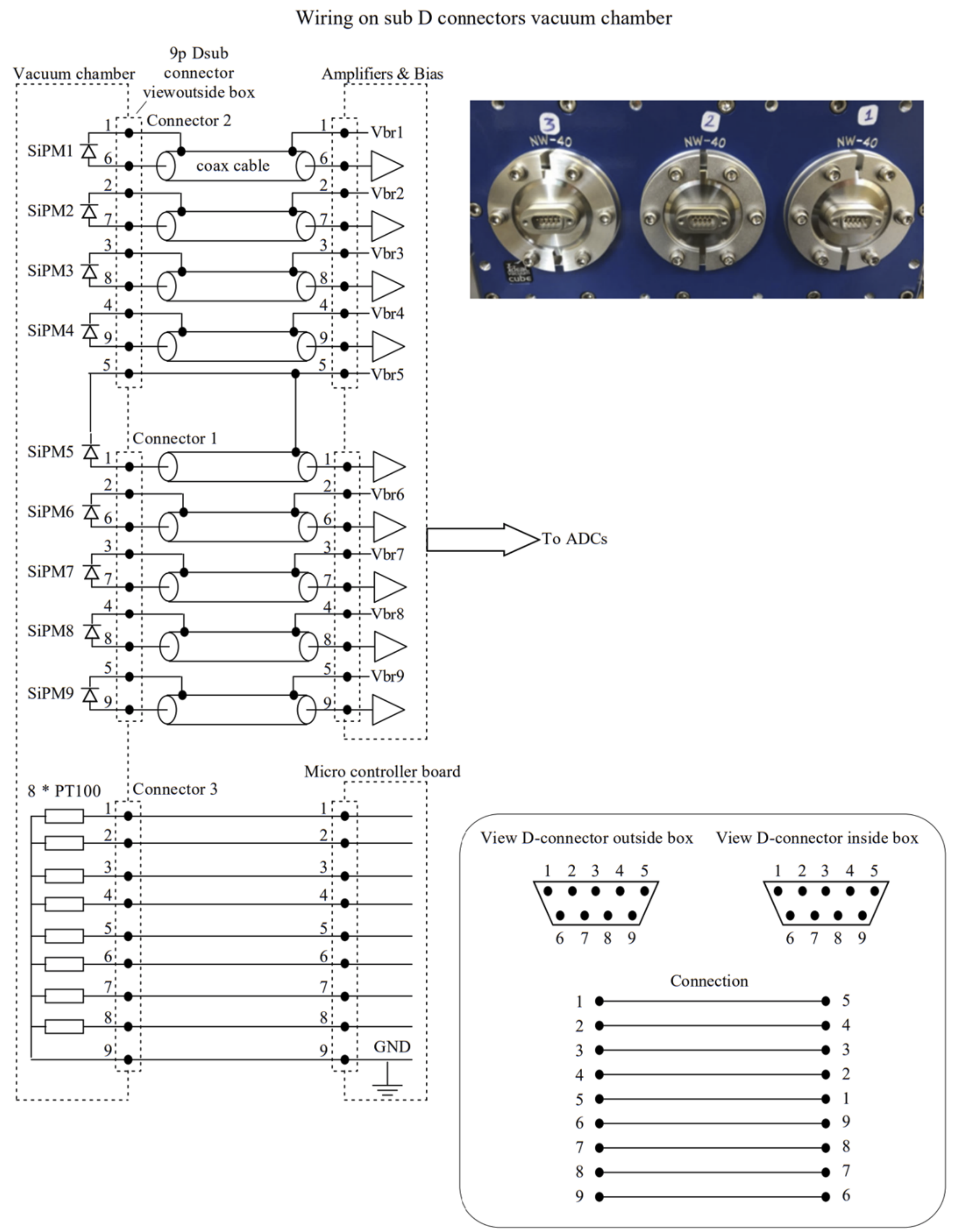
| **Amplified signals** |
|---|
|  |

The power supplies for all electronics are connected to the same power outlet to reduce noise from different sockets. The power outlet in question is connected to a metal plate which is used as a common ground for the rest of the electronics. Many noise-hunting crusades were undertaken for each change that was made to the board. These included using copper tape to connect the sample chamber to the ground or the two parts of the table together, moving the power supplies and oscilloscope to a different table, remaking some connectors and moving the power outlets to the pump level. Both the readout board and the amplifier board were put into metal boxes to help to shield from the atmospheric noise and these boxes were placed onto a non-conducting box above the table.

| **Noise-reducing solutions** | | |
|---|---|---|
|  |  |  |
|  |  |  |

The SiPM inside the sample chamber is connected via kaptop wires to match impedance with the rest of the circuit. These wires are tightly twisted to reduce interference and are soldered to a connector which slots onto the feedthrough from the inside. The feedthrough schematic is shown below for the SiPM connections and temperature connections.

## Feedthrough schematic



The DAQ is connected via a BNC splitter at the oscilloscope so signals can be seen both on the oscilloscope and the DAQ. This setup has been tested with the lamp on and off, with both the slits closed and a little open, and with the pump turned on and a pressure down to 1*10$^{-3}$ mbar. The signals from the SiPMs remain visible and the pumping improves the small light leak which has been associated with the different levels that the monochromator and sample chamber sit at, causing a sheer pressure on the connection. This was modified during cleaning and reassembly and the light leak is now minimal.

More specific information on the lab work relevant to this board can be found here: https://wiki.nikhef.nl/vuv/Status_updates.

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