

# Experimental setup and data acquisition software for scanning TCT

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## Abstract

The Transient Current Technique is a powerful tool to probe semiconductor detectors for high energy physics at different bias voltages and temperatures. By scanning the detector one is able to determine the spatial dependence of the detector and to test its quality. This article shows how to set up a TCT experiment for semiconductor detector testing, which experimental requirements are to meet and how to acquire data using a LabVIEW Virtual Instrument.

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# 1 Introduction

The Transient Current Technique (TCT) allows to test semiconductor detectors for high energy physics with little effort in the local lab. A source is placed in front of the detector in question, the detector is biased with a high voltage and the signal is read out using a digital oscilloscope. This setup allows to analyse the shape and the amplitude of the signal this detector gives at different temperatures and bias-voltages for different radiation sources. By knowing the particle specific signal shapes, one is later able to identify detected particles. By scanning the detector, one is also able to determine the spatial dependence of this signal and to detect local inhomogeneities in the semiconductor. By carefully analysing the shape of the signal and its temperature dependence some intrinsic properties of the semiconductor can also be figured out: The stopping power, (temperature dependent) drifting velocity and mobility and from this scattering lifetimes and the amount of lattice defects and impurities.

## 2 Physical background

### 2.1 Principles of semiconductor physics

The atoms of an ideal crystal are placed in a periodic pattern without inhomogeneities. This periodic structure has various consequences on the body's properties, e.g. well-grown crystals break preferred along plains of high symmetry, they refract X-rays in special patterns that depend on their lattice structure and special electronic properties arise.

In the last century quantum mechanics has proven to describe physics on atomic level pretty well. For single isolated atoms like hydrogen, discrete isolated Eigenenergies arise which can be directly observed in means of spectroscopy. These Eigenenergies denote to Eigenstates which are solutions to the kinematic equation for electrons near the atom. In the easiest way to treat the hydrogen atom, these solutions are rotational invariant. When putting a second atom in, this symmetry will break as there is no symmetry left along the axis between the atoms. The Eigenstates of the two single atoms mix and form molecular states which can be either symmetric or antisymmetric with respect to the axis. The energy of symmetric and antisymmetric states is not anymore the same as it would have been for two completely separated atoms, the atomic energy levels split up due to the interaction between the two atoms.

When you add more atoms, the energies will further split up. In a solid state body there are in the order of  $10^{23}$  atoms which all interact. Therefore the former discrete atomic levels are split up to broad quasi-continuous energy bands. This effect is larger, the less localised the interacting atomic levels are. Strongly bound core-levels in solid states are nearly the same as in isolated atoms.

The structure of the electronic levels determines the electronic properties of any material. In metallic bodies electrons can easily be excited to unoccupied states as the topmost energy band is only partially occupied. This band is called valence band (VB). When excited to free energy states, electrons can flow and contribute to a net current.

In isolators there is an energetic gap between the fully occupied valence band and the lowest unoccupied band, the conduction band (CB). Electrons first have to be excited to the CB before they can be considered to be free charge carriers. At room temperature there are very few free charge carriers that have been thermally excited and the isolator has a very high resistance.

In semiconductors there is a band gap present too. However this gap is small enough that electrons at room temperature can be excited to the CB. This is called intrinsic conductance.

The highest energy to which the states are occupied at 0 K is called Fermi-energy. When above zero degree there is always some thermal excitation of electrons states above the Fermi-

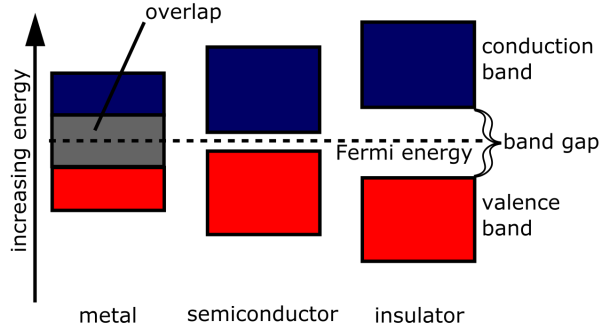


Figure 1: Schematic of the electronic structure of metals, semiconductors and insulators near the Fermi energy [wik(2014)].

energy present. This excitation becomes larger at higher temperatures.

When electrons are excited to the CB they leave free states in the VB behind. These can be treated as 'missing electrons' or as 'holes'. Holes then carry positive charge and have the negative mass of an electron. However the motion of electrons or holes in semiconductors can not be described by their mass alone but one has also to take the band structure into account.

By putting foreign atoms inside a semiconductor (doping), additional electronic levels inside the band gap can be added. If for example phosphorus, which has five valence electrons, is added to a silicon crystal, which has four valence electrons, the phosphorus is integrated in the crystal and the fifth electron is only weakly bound to the phosphorus nucleus. To say it within the band model: Phosphorus adds a new occupied electronic state inside the band gap which is spatially located near the atomic core. The energy of this state is slightly below the energy of the CB, the electron is weakly bound. This electron can be easily excited to the CB and can then be considered a free negative charge carrier (n-doping). Doping the semiconductor the other way around also works: By adding e.g. boron (3 valence electrons) to silicon a unoccupied level slightly above the VB edge is created. Therefore holes can be easily 'excited' to the VB and can be considered free positive charge carriers (p-doping).

When putting a p- and a n-doped semiconductor together a diode can be created: Electrons and holes at the interface start to recombine and a zone which is depleted of free charge carriers arises. This area thus has a very high resistance. By biasing the diode in one direction (reverse bias), the depletion zone further increases and no current can flow through it. When biasing the diode in the other direction (forward bias), the depletion zone decreases and the resistance does as well.

## 2.2 Peltier effect

When looking at different disconnected materials their vacuum-energy will be all the same but their Fermi-energies will differ as the materials have different binding energies for electrons. However, when bringing those materials in electric contact, the charge carriers will move to the material with the highest binding energy. This will increase the binding of the remaining electrons in the material with the lower binding energy, the Fermi-energy drops, and will decrease the binding energy for further electrons in the material with higher binding energy, the Fermi-energy rises. Thus, the Fermi-energies of materials in contact align and in this very simple model a step-like structure in the conduction-band as well as in the valence-band arises at the interface.

Electrons have to gain energy to 'climb' that step when passing from one material to the other. This energy is taken from lattice vibrations, the contact cools down. On the other

side the electrons will have more energy than the band minimum when the 'drop' down such a step. They will relax to the band minimum, typically again by inelastic scattering with lattice vibrations, thus heating up the contact.

By appropriate stacking of alternating p- and n-doped semiconductors, a structure can than be assembled, which heats up on one side while cooling down the other when a current zig-zags through it.

### 2.3 Charge transport in semiconductors

The energy of electrons in a semiconductor depends on its momentum  $\vec{k}$ . As the crystal itself is anisotropic in general so is the energy dispersion  $E(\vec{k})$  of the electrons inside it. When one wants to describe the motion of electrons the band structure of the crystal has to be taken into account. This can be easily done by using Newton's law together with the effective mass  $m^*$  of the charge carriers

$$\begin{aligned}\frac{d\vec{v}}{dt} &= \frac{1}{m^*}\vec{F} \\ \frac{1}{m_{ij}^*} &= \frac{\partial E(\vec{k})}{\partial k_i \partial k_j}\end{aligned}$$

where  $\vec{v}$  is the charge carriers velocity and  $\vec{F}$  is an external force. In general the effective mass is a tensorial quantity. For small electron momenta it can be considered to be constant. One can think of the effective mass as of taking the electric fields inside the crystal into account when applying Newton's law.

From this, Ohm's law can be derived which is

$$\vec{j} = \sigma \vec{E}$$

with the current density  $\vec{j}$ , the conductivity  $\sigma$  and the electric field  $\vec{E}$ . The conductivity is an intrinsic quality of the semiconductor and is given by

$$\sigma = ne\mu$$

where  $n$  is the density of free charge carriers and  $\mu$  the mobility, which depends in the effective mass of the charge carriers as well as on scattering lifetimes. Note, that the mobility can depend on the spatial position, the momentum of the charge carriers and the electric field. By determining the temperature dependent mobility one is able to distinguish between different scattering processes (as they have a different temperature dependencies) that dominate the charge transport and to check the quality of the semiconductor.

### 2.4 Semiconductor detectors

A semiconductor detector consist of a diode which is reverse biased by a high voltage. By reverse biasing it, only a small leakage current flows while there is a strong electric field inside the crystal. When a high energetic particle hits the detector, the particle loses some energy due to inelastic scattering and some electrons are excited to the CB. The amount of generated charge carriers might depend on the type of particle, its energy, the semiconductor material, its temperature and so on. Due to the strong electric field inside the reverse biased diode, the charge carriers start to drift and induce a current to metallic contacts. This current signal can then be detected e.g. by using a digital oscilloscope.



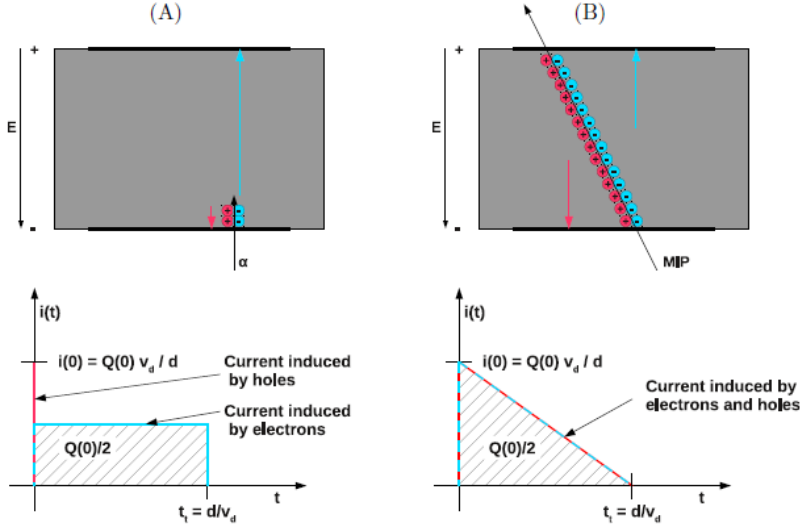


Figure 2: Schematics of different possible signal shapes [Jansen(2014)]. **A** When a particle is stopped near one surface of the detector, it will deposit its energy in a small spatial area and steep pulse edges arise. In this example, holes are created near the contact so they give only a short pulse while they are drifting. Electrons need a much larger time to traverse the detector and give a much longer signal. **B** If a particle traverses the detector, it will deposit energy all along its way. As the particle moves near speed of light, all the charges start to drift nearly at the same time and give rise to a current pulse. However, some of the charge is absorbed by the metallic contacts over time and the signal decreases.

In case of a flat diode which is sandwiched by two metallic contacts, the electric field can be considered to be homogenous and the detected current  $i_{det}$  is

$$i_{det} = Q_{drift} v_{drift} \frac{1}{d}$$

$Q_{drift}$  is the amount of drifting charge which is amount of excited free charges minus at the contacts collected charge.  $d$  is the detectors thickness and  $v_{drift}$  the drifting velocity of the charge carriers. The drifting velocity is proportional to the electric field inside the detector as well as to the charge carrier's mobility. Neither of them has to be constant, the mobility is different for electrons and holes and depends on the (anisotropic) effective mass.

The shape and the amplitude of the signal depends on various parameters and tells many properties of the detector: The width of the pulse usually tells the time the charge carriers need to reach the metallic contacts of the semiconductor. Therefore it depends on the spatial location, the position at which the charge has been excited, the electric field, the mobility and the geometry of the detector. The edge of the signal will also depend on the spatial location where the charges have been created. The area of the pulse depends on the total amount of created charge and thus on the energy the incoming particle deposited inside the detector.

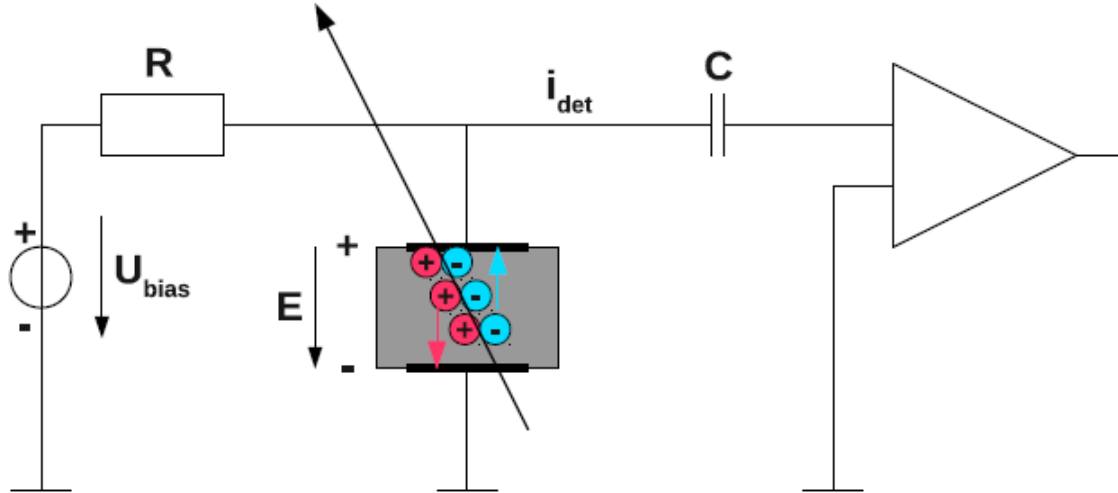


Figure 3: Scheme of the TCT setup [Jansen(2014)]. A semiconductor is biased by a high voltage. By placing a source in front of the detector, it will create a signal, which can be read out via an AC-coupling and an oscilloscope.

### 3 The experimental setup

The experimental setup used for scanning TCT measurements of semiconductor detectors is shown in fig. 4. The setup has been purchased from *Particulars, advanced measurement systems* and extended at some points. It is placed inside a box which can be seen in fig. 5 for various reasons: Due to safety instructions, the setup has to be light-tight as there is a strong laser inside. But the reduction of environmental light also reduces the detector background and the housing allows for a better control of temperature and humidity as well.

The detector that is supposed to be tested is mounted on top of a peltier-element whose backside is connected to a heat sink. By controlling the current that flows through the peltier element, the detector can be either cooled down by heating up the heat sink or it can be heated up.

By exciting the detector with a pulsed laser, free charge carriers are created inside the detector volume and a signal pulse arises. This signal is AC-coupled to an outgoing wire, pre-amplified and read out using a digital oscilloscope.

The laser can be remotely controlled via USB-connection and its repetition rate can be set to a value between 50 Hz and 500 kHz. The light pulse is fed into an optical fiber. By using a beam splitter, the majority of the light can be focused on the detector while a part of the light is detected by a photodiode. By measuring the signal of the diode one is able to detect fluctuations of the laser's intensity during acquisition. This is necessary, as the amount of generated charge carriers inside the detector under study depends on the intensity of the exciting light.

#### 3.1 Dry air supply

The detector is supposed to be cooled down to around  $-20\text{ }^{\circ}\text{C}$ . As there must be no ice in the setup, the humidity inside the box has to be decreased. This is done by flushing the box with dried compressed air.

On the outside of the box a precision valve has been mounted as can be seen in fig. 6. This valve can be connected to any compressed air supply by plugging in a hose. On the output side of the valve, a gauge and a pinhole is added through which the air has to flow. The pinhole is

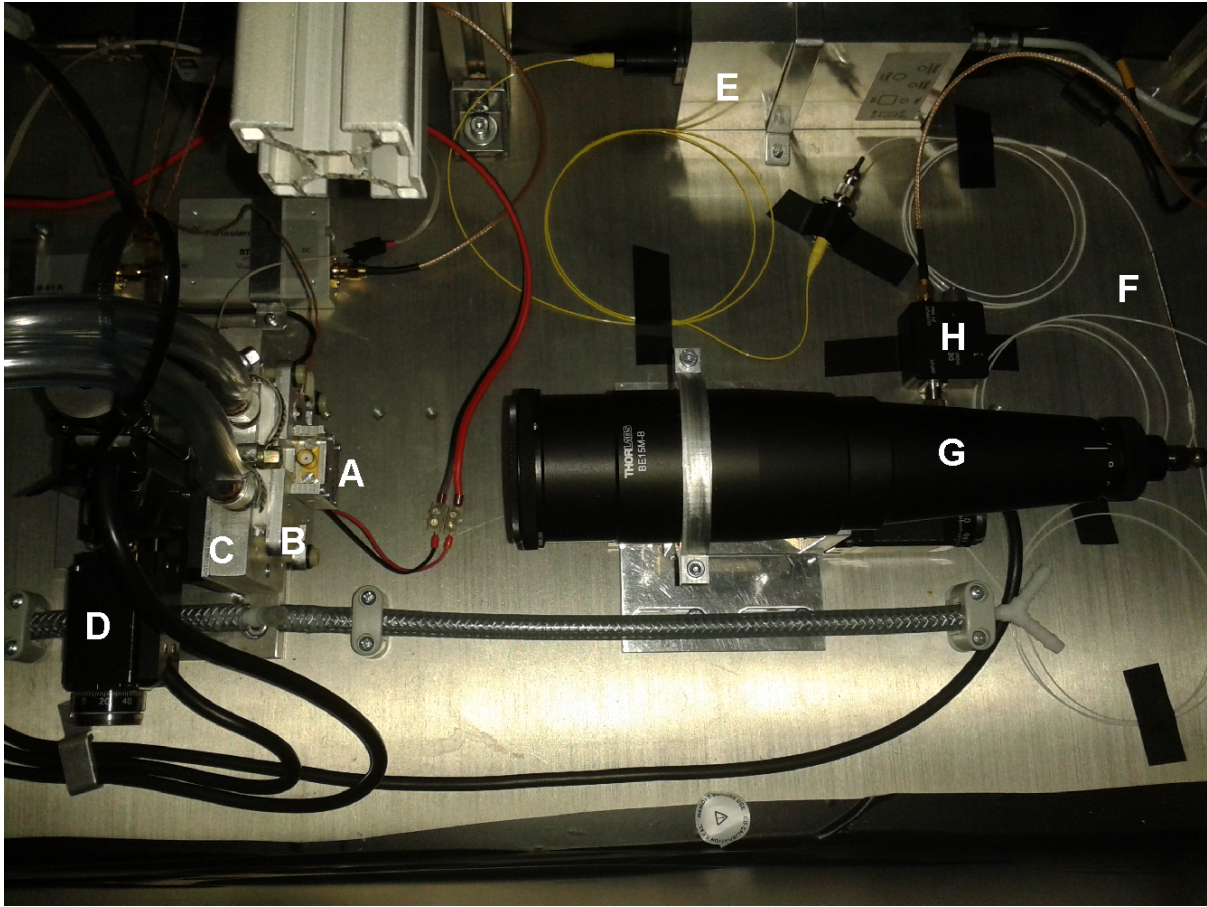


Figure 4: Picture of the TCT setup. **A** detector **B** peltier-element **C** heat sink **D** stages **E** pulsed Laser **F** 90/10 beam splitter **G** outcoupling optics **H** photodiode

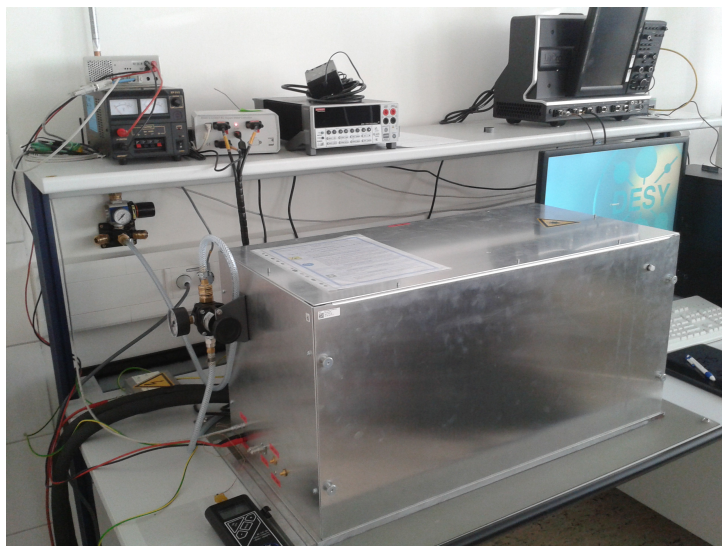


Figure 5: Picture of the TCT setup.

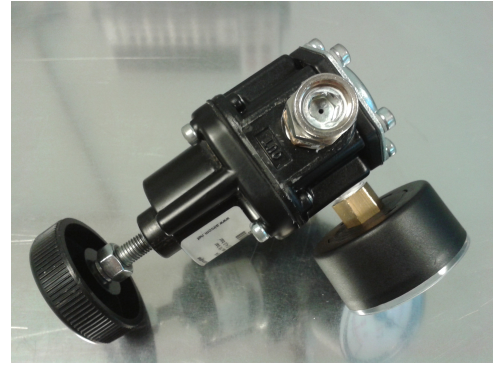
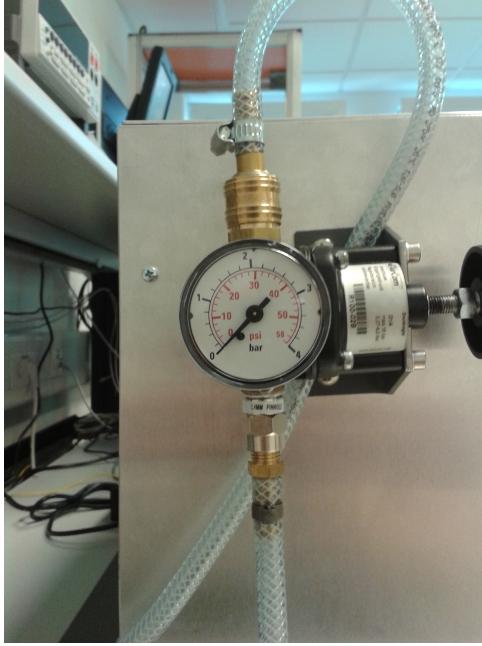


Figure 6: Precision valve used to control the dry air supply

put in place to artificially increase the air resistance behind the gauge to increase the pressure. This way one can have a decent flow of air to the box while still having a high pressure which can be measured by the gauge. The flow can then easily be controlled by hand.

After some measurements of the dew-point inside the box, it turns out that flushing the box for five minutes with a pressure of 4 bar at the gauge and afterward reducing the pressure to 0.2 bar allows for quickly reducing the dew-point below  $-40\text{ }^{\circ}\text{C}$  and even less.

### 3.2 Temperature control

As can be seen in fig. 7 the detector under test is mounted on top of a peltier-element. The heat is dissipated by a water cooled heat sink. The temperature of this water is controlled by an external chiller. At the detector mount a PT1000 temperature sensor is attached.

The sensor is connected to a temperature controller (fig. 8), which controls the current  $I(t)$  at the peltier element. The controller reads the temperature from the sensor and regulates the peltier element proportional to the deviation  $e$  from a set-temperature, proportional to the integrated deviation and as well proportional to the derivative of this deviation (PID-controller):

$$I(t) = K_p e(t) + K_i \int_0^t e(\tau) d\tau + K_d \frac{d}{dt} e(t)$$

The values of the three gains  $K_p$ ,  $K_i$  and  $K_d$  determine the stability and the tracking behaviour of the controlled value, the temperature. The proportional gain  $K_p$  determines for example the change of the current proportional to the temperature error. If  $K_d$  is too small, the output might be too small to reach the set temperature in a decent time. If  $K_d$  is too high on the other hand the temperature might overshoot the set temperature. The temperature starts to oscillate and the system becomes unstable.

Temperature fluctuations less than  $0.1\text{ }^{\circ}\text{C}$  are achieved by carefully tuning the PID-controller



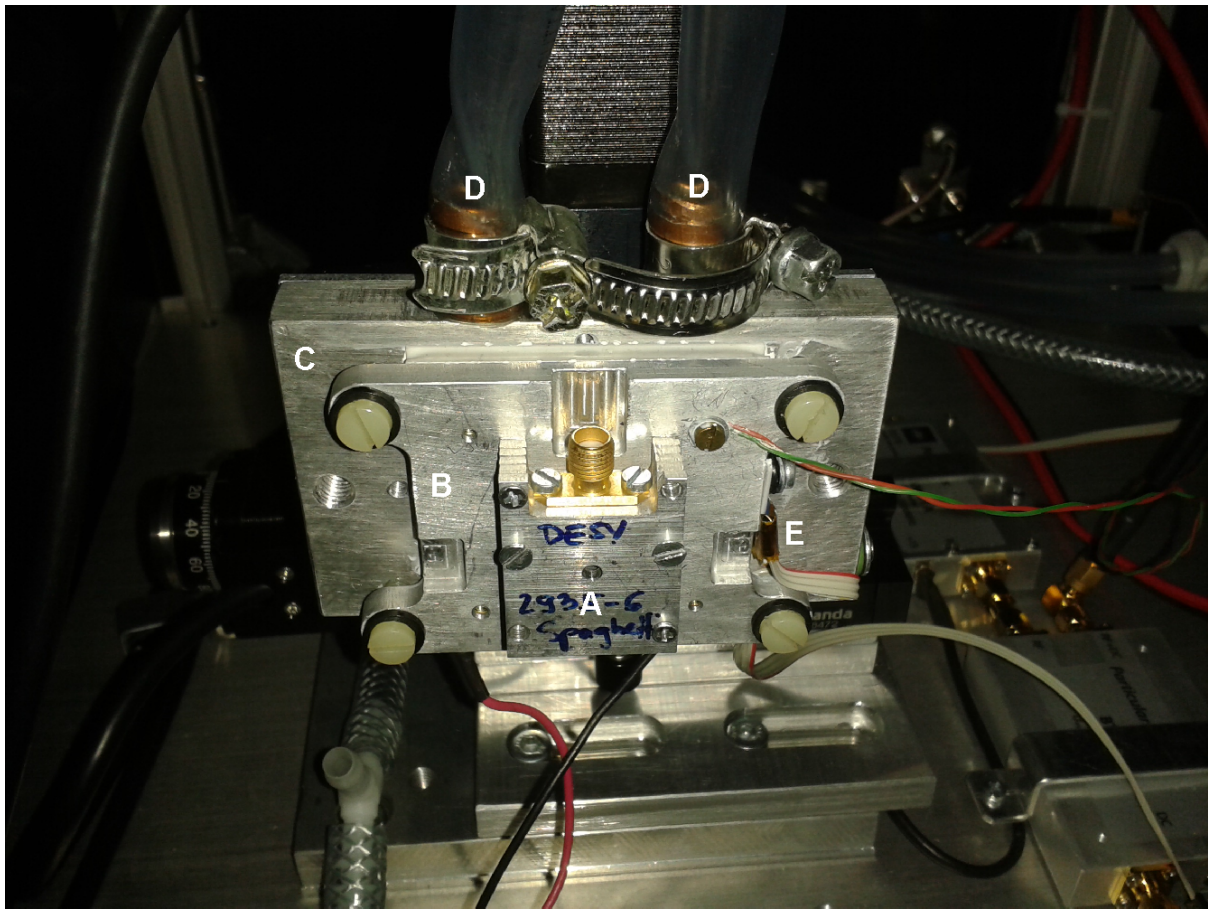


Figure 7: View on detector and cooling mount. **A** detector **B** peltier element **C** heat sink **D** water cooling **E** temperature sensor

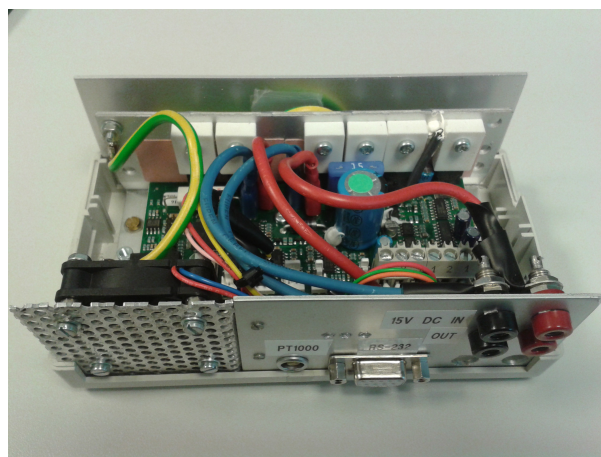


Figure 8: View on the opened temperature controller.

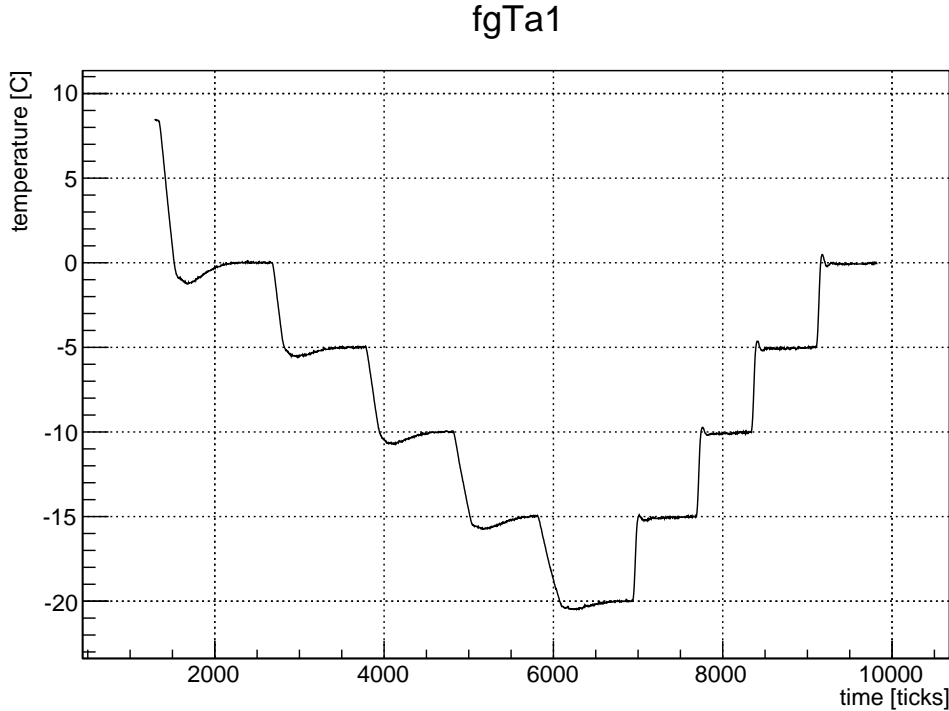


Figure 9: Temperature tracking at the detector after the PID-controller had been tuned. Ten ticks correspond to one second. Cooling water temperature 5 °C.

using Ziegler-Nichols method. The parameters were chosen as follows:

$$\begin{aligned} K_p &= 60 \\ K_i &= 5 \\ K_d &= 0 \quad 234 \end{aligned}$$

After tuning, the temperature tracking of the peltier-element locks like in fig. 9. The temperature of the controller can be easily set to -20 °C. It takes about one to two minutes until the set temperature is reached. From this point on it remains stable. The minimum temperature that can be reached is limited by the power of the peltier-element and the temperature of the cooling water which dissipates the heat from the element. At a water temperature of 5 degrees, a minimum temperature around -30 °C could be reached at the detector.

The temperature control has been tested up to 25 °C. With the PID parameters given above it works well if the temperature of the cooling water is higher than the set temperature at the detector.

## 4 Data acquisition

The detector's signal after pre-amplification is read out using a digital oscilloscope (LeCroy Waverunner 640Zi). The data acquisition software (DAQ) that was shipped with the experimental setup supports only GPIB-devices. Since the faster Ethernet connection should be used, a new LabVIEW Virtual Instrument (VI) was developed which takes care of the communication with the scope and is supposed to be integrated to the DAQ (fig. 10).

The new VI provides algorithms to connect to the oscilloscope as well as to change the most important oscilloscope settings. The VI can be used to acquire either a single event from the

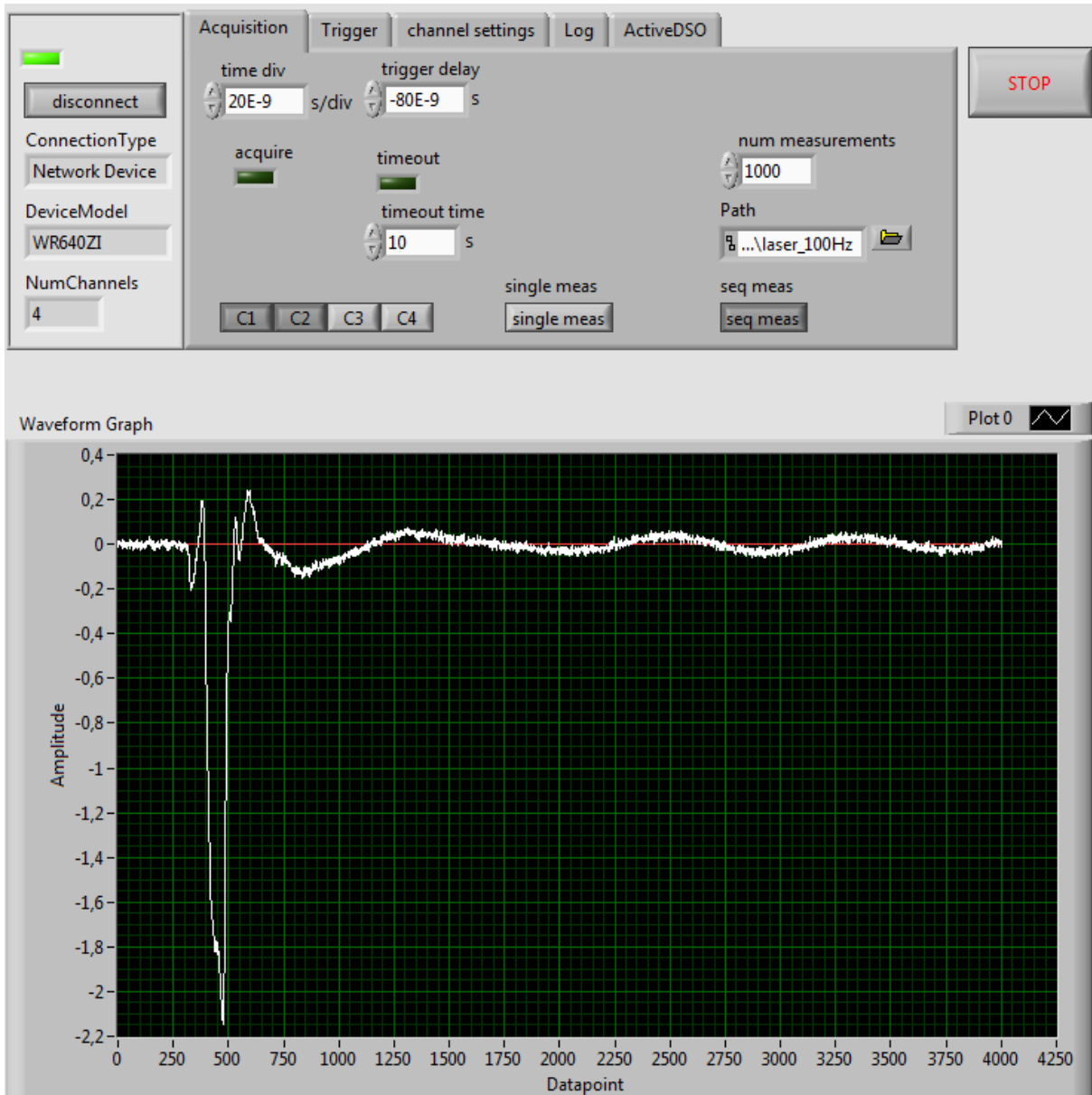


Figure 10: Overview over the VI's GUI.

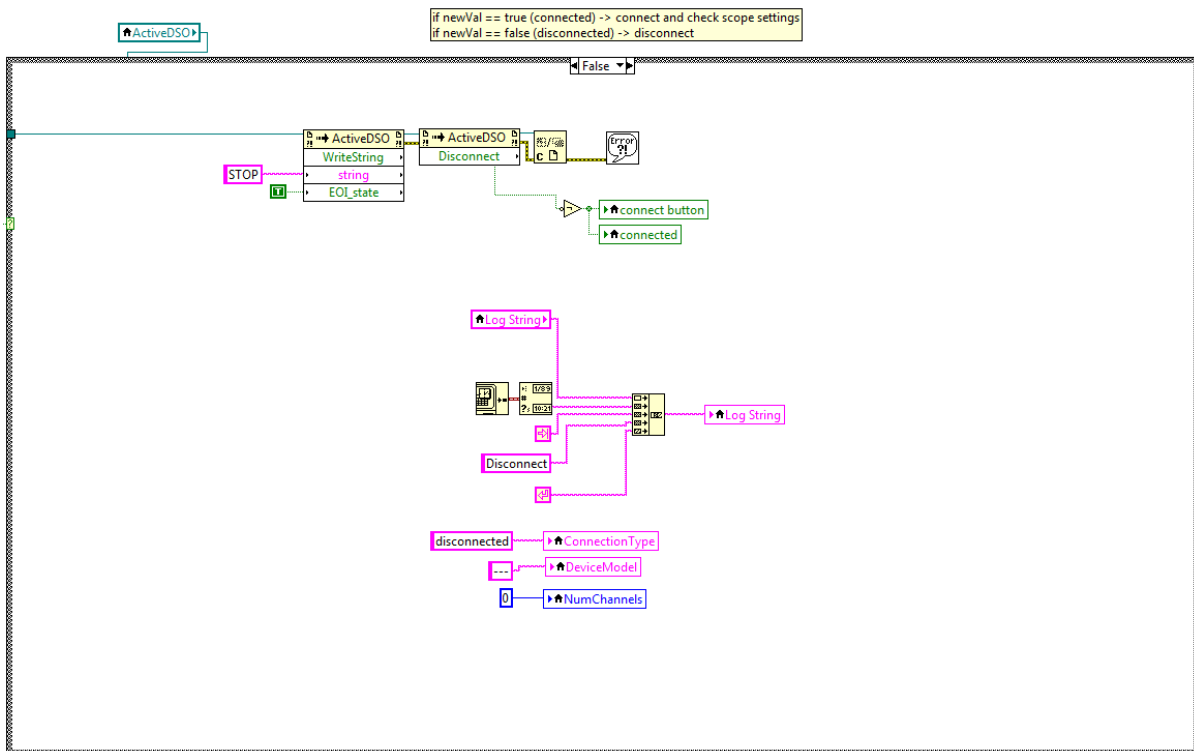


Figure 11: Blockdiagram used for disconnecting.

oscilloscope or to acquire a series of events. In the current state the developed VI is able to reliably set any oscilloscope parameter and to take about ten acquisitions per second.

#### 4.1 ActiveDSO

The low-level communication with the scope is done using LeCroy's ActiveDSO interface. This can be used as an embedded control within other programs. ActiveDSO provides methods to connect to an oscilloscope, to set parameters, to send commands and to read waveforms. ActiveDSO communicates with other programs by using Microsoft's ActiveX standard.

It can easily be integrated to any LabVIEW VI by using an **ActiveX Container** from LabVIEW's ActiveX palette. By adding ActiveDSO to a container, one gets a reference to the ActiveX object. By wiring the reference to a **Property Node (ActiveX)** or a **Invoke Node (ActiveX)** from the ActiveX palette any properties or methods of the automation can be used.

#### 4.2 Connecting / Disconnecting

The VI is constructed in an event-based way. When a button is pressed or a parameter is changed, the corresponding event is called. When e.g. the connect-/disconnect-button is pressed, the corresponding event, whose blockdiagram is shown in fig. 11, will be executed. The state of the button is first checked. If the state is true, the VI will connect to the scope, otherwise it will disconnect.

When disconnecting, the VI will stop the current acquisition and then disconnect. This is done with ActiveDSO's method **WriteString** by using **Invoke Node**. **WriteString** writes any string to the oscilloscope. Valid commands and queries can be taken from LeCroy's Remote Control Manual [rem(02/2005)]. By sending the command *STOP* the current acquisition will



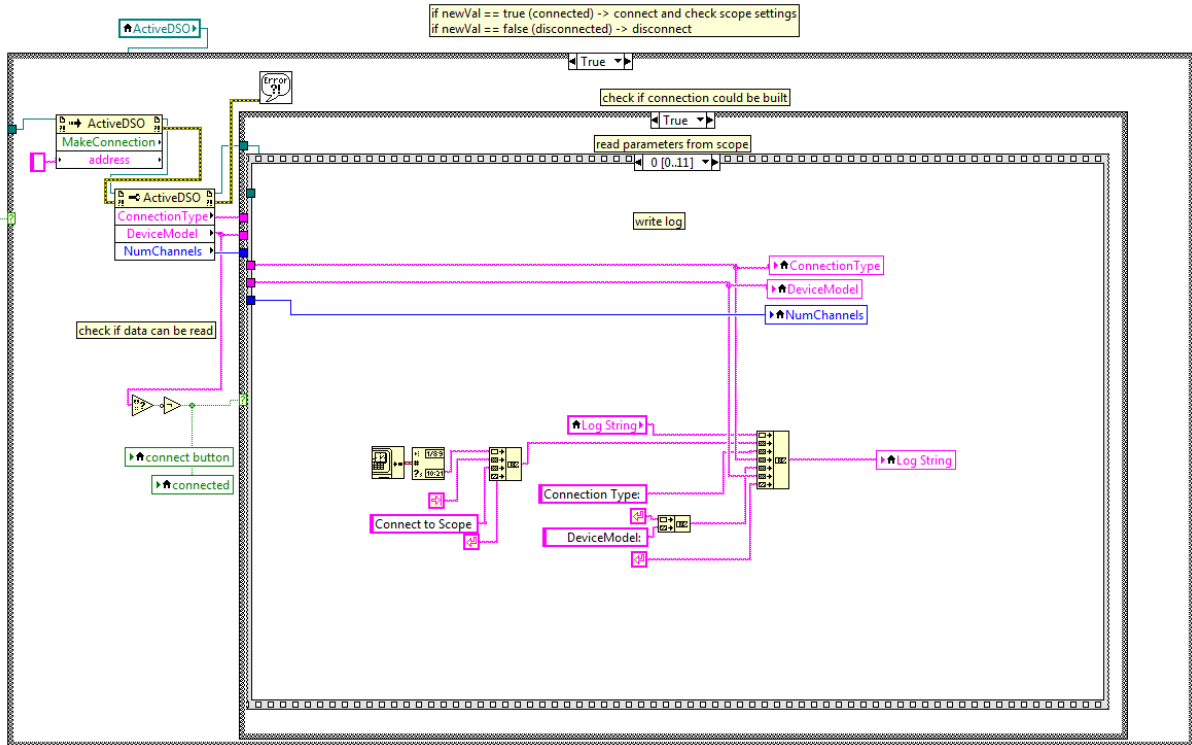


Figure 12: Blockdiagram used for connecting.

be stopped. Afterwards ActiveDSO disconnects by using the method **Disconnect** together with **Invoke Node**.

If the buttons state is true the VI will attempt to connect to the oscilloscope by using ActiveDSO's method **MakeConnection**. ActiveDSO will then prompt for choosing a connection type and address. Afterwards the VI tries to read the connection type and device model by using **Property Node**. If these can't be read, the connection could not be built and the algorithm breaks at this point. Thus one has to try to make another connection. If a connection could be built, the VI reads all the relevant settings from the oscilloscope. This works exactly the same as after setting these parameters, which will be described in the next sections. The corresponding blockdiagram is shown in fig. 12.

### 4.3 Changing parameters

The algorithm used to change any oscilloscope parameter is explained at the example of changing the channel offset. The corresponding GUI-element is shown in fig. 13 and the blockdiagram in fig. 14 & 15.

First a command string has to be constructed, which is to be sent to the scope: To change channel specific settings, the channel followed by a command and the new value has to be sent. E.g. the command *C1:OFST 1* sets the offset of channel one to 1 V. Thus, to change the channel offset the command string is made up of the channel, which is chosen by the combo box *ch settings channel*, followed by a colon, the actual command *OFST* and a whitespace followed by the value, which is chosen by a selector. The whole command is then sent to the scope via **WriteString**.

It then has to be checked whether the changing has been adapted. This is done by sending the query *<channel>:OFST?* which asks for the offset of channel *<channel>*. The answer

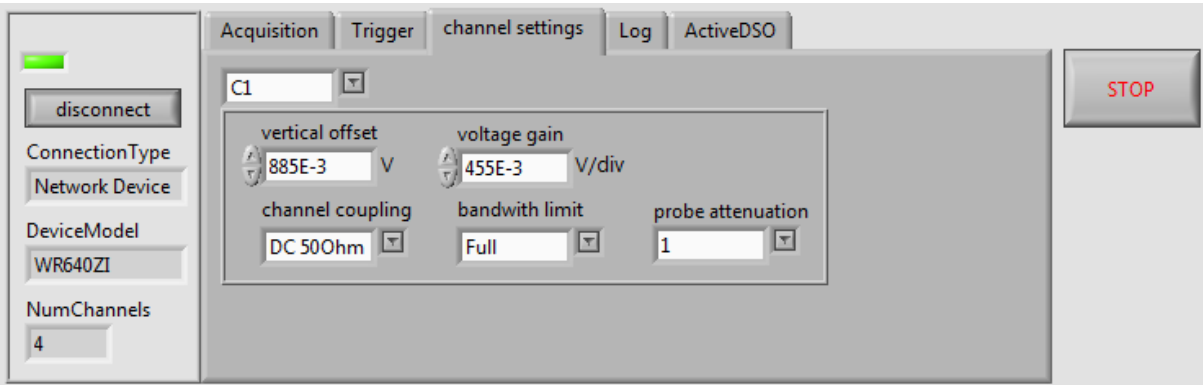


Figure 13: GUI-elements to change channel settings.

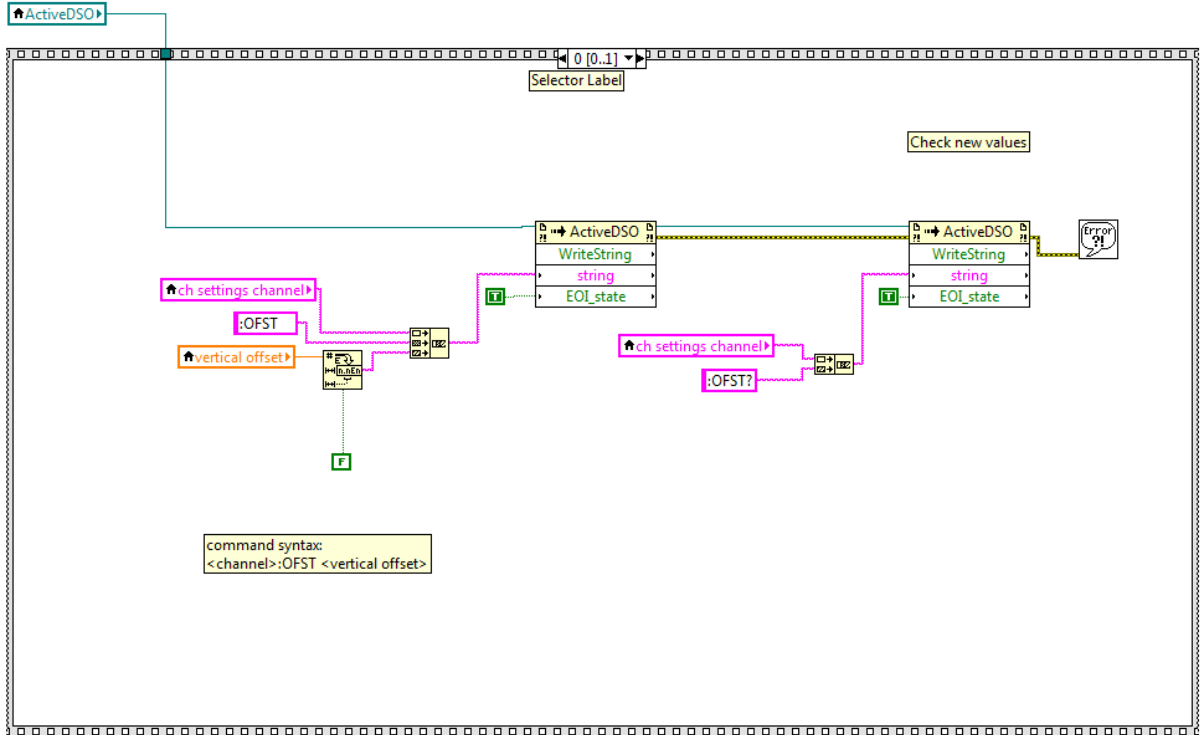


Figure 14: First part of the blockdiagram used to change channel offset.

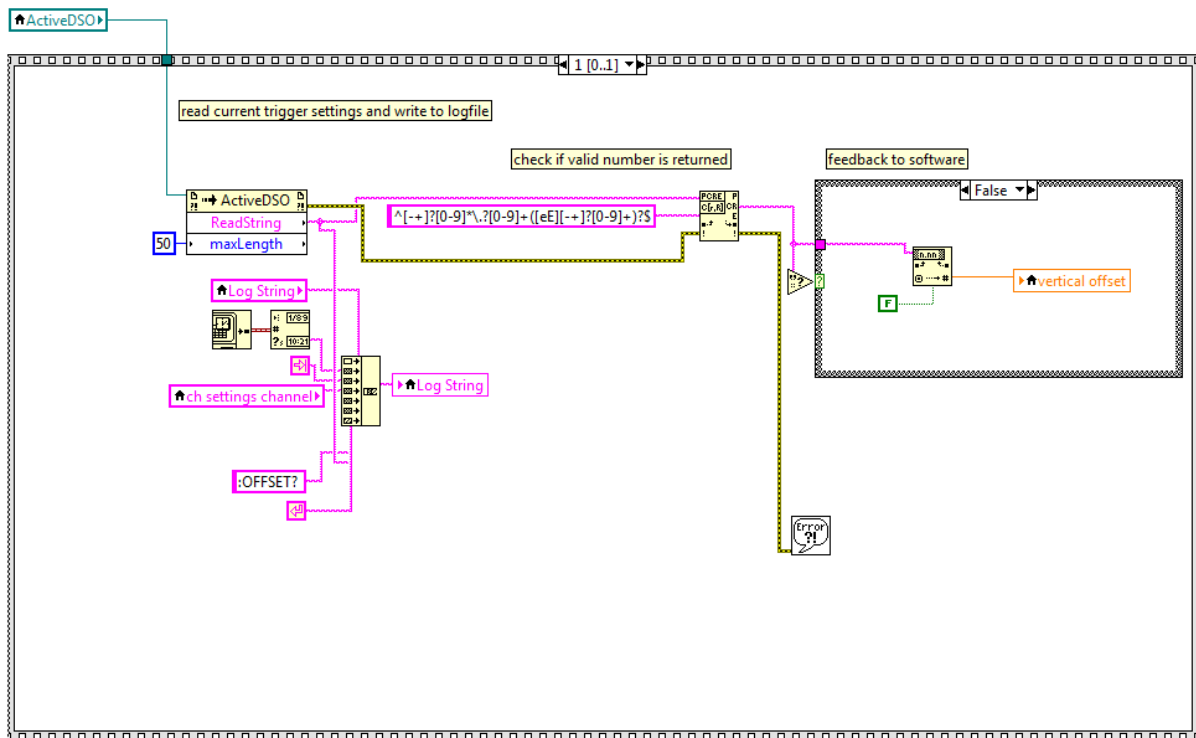


Figure 15: Second part of the blockdiagram used to change channel offset.

is read with the method **ReadString**. The VI then checks, whether the response is a valid floating point number by using regular expressions. If it is a valid number, the value displayed by the VI is set to the value returned from the oscilloscope. This way the VI always displays the correct parameters, even if one tries to set a parameter to an invalid value which is not accepted by the oscilloscope. If the answer is not a number or if there is no answer at all, the value is set to default.

The other parameters are set in the same way. When the channel for which the changes are to be made (*ch settings channel*) is changed, all the settings for the chosen channel are read from the oscilloscope for correct display of the current values in the VI. Other parameters are the trigger-type, -mode, -value, -slope, -channel, -holdvalue, and coupling, vertical channel setting, horizontal settings, coupling and bandwidth limit just to name a few.

#### 4.4 Single acquisition

When starting a single acquisition, the trigger is armed and an entry to the logstring is written. After arming the trigger, the VI waits until the oscilloscope has acquired an event. The trigger mode will then switch from *SINGLE* to *STOP*. Thus, the VI repeatedly checks the trigger mode, until it is set to *STOP*. In case of no event, there has also is a timeout implemented in order to prevent the VI from waiting forever.

If no timeout has occurred, the descriptor of the waveform is read out. The descriptor contains any relevant information needed to interpret waveform data.

If the trace of the corresponding channel is set active (the data from this channel is supposed to be acquired), the channel's data is read by using ActiveDSO's method **GetScaledWaveform**. Values passed by ActiveX objects are of the type *Variant* which contains data as well as metadata which tells how to interpret the data. To use the data with LabVIEW it has to be parsed to a LabVIEW compliant data type, e.g. an array of floating point numbers. To get

the waveforms timing information, one has to get the step size between two data points which is written to the waveform descriptor. The acquired data can then be displayed in the VI and written to an ASCII file.

## 4.5 Sequential acquisition

When executing a sequential measurement, the VI loops over single acquisitions. One has to give a number  $N$  of acquisitions as well as a folder. The VI then automatically writes  $N$  data files to this folder, each file one single acquisition.

This way of doing the acquisition might seem to be pretty straight forward, but it proves to be a very robust method while being sufficiently fast. In its current state, the VI is able to take ten acquisitions per second, each with four traces of 4000 data points.

There are still some ways to improve the VI as well as the acquisition speed. First of all, one has to change the file format. By saving the data in binary format instead of ASCII, one is able to decrease the data size by a factor of about 20. The data can also be directly attained in binary format from the scope, which further increases acquisition speed due to smaller data size.

## 5 Data analysis

The new data acquisition creates data files in a format that has not been used before: The files contain a descriptor as well as four columns of data, one column for each trace. A C++ method was implemented to read these files. The method was then integrated to more advanced TCT analysis software.

The descriptor is circumscribed by two delimiters at the beginning and the end. These delimiters tell the method, which lines belong to the descriptor. Each line of the descriptor holds a pair of a parameter name and its value, separated by a colon and whitespace. Therefore, the parameter names can be easily matched and the parameter values can be written to the corresponding variables that are used within the analysis software after trimming and parsing.

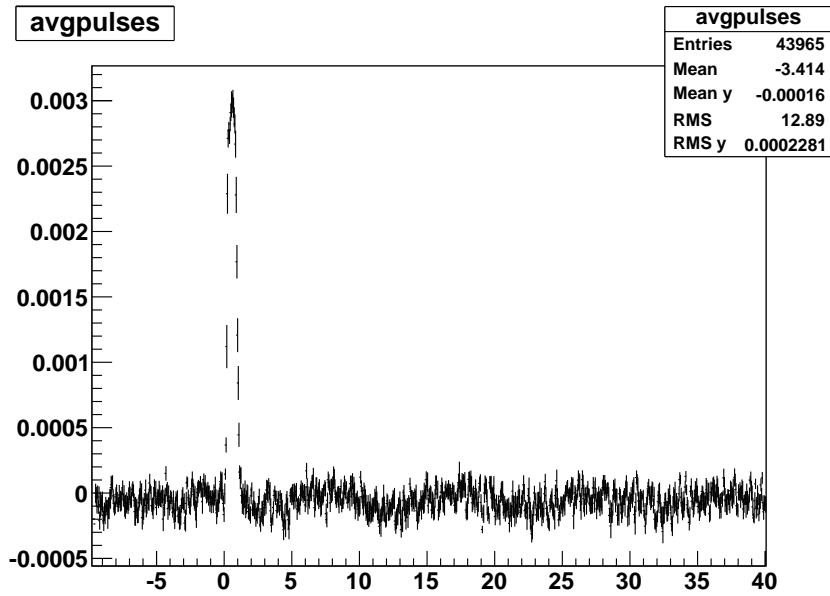
After the header there are four columns of data, separated by whitespaces. These can then also be easily separated and parsed to floating point numbers. The current analysis software only supports single channel data. Therefore the new method reads out only one channel which can be chosen via a parameter. The data itself contains only vertical information. The timing information has to be read out from the descriptor, which tells the time difference between two data points (usually 50 ps) as well as the offset between the first point and the trigger.

The data is then put to an array and feed to existing analysis software. This software reads all the files in one folder, averages them and does some analysis, e.g. it calculates the noise, searches for pulses, calculates rise time, pulse width, amplitude and so on. The results are then saved to a root file [roo()].

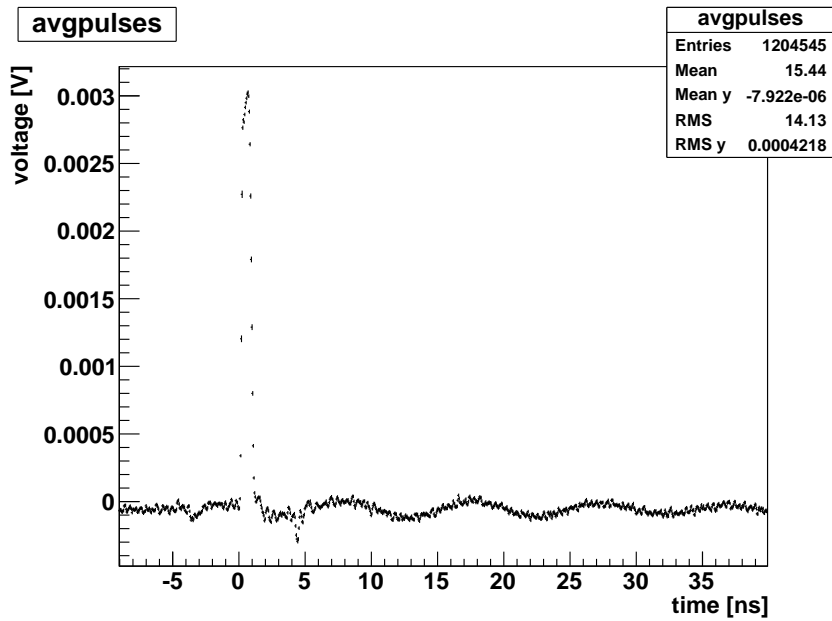
An exemplary acquisition is shown in fig. 16 which is the photodiode's signal when illuminating it with the pulsed laser. Averaging the signal over many single acquisitions significantly increases the signal to noise ratio which is the reason for the desired high number of single acquisitions. Taking 300 acquisitions with the VI takes about 30 s.

## 6 Conclusion

The Transient Current Technique (TCT) allows to test semiconductor detectors for high energy physics with little effort in the local lab. A source or laser is placed in front of the detector in question, the detector is biased with a high voltage and the signal is read out using a digital



(a) 10 acquisitions



(b) 300 acquisitions

Figure 16: Signal of the photodiode when the laser is operated at 100 Hz. The average of 10 and 300 single acquisitions is shown. The error of each point has been calculated from the variance of the single acquisitions.

oscilloscope. This setup allows to analyse the shape and the amplitude of the detector's response for different sources, bias voltages, temperatures and incident positions of the radiation. By carefully analysing the shape of the signal and its dependencies, information about the most important detector properties, the environmental conditions in which it can be used and the dependence of the signal on those conditions can be extracted.

During this work I have taken care of a dry air supply which is necessary for dew-point regulation. In the next step the temperature control itself was managed: The temperature of the detector is set via a peltier element which is controlled by a PID-controller. A housing for this controller was built and the controller was tuned for a good temperature tracking as well as for high temperature stability, which is necessary for temperature dependent TCT measurements.

The experimental setup also came with a data acquisition software (DAQ) which only supported GPIB devices. Therefore I developed a data acquisition, which is supposed to be integrated to the shipped DAQ. The software is compatible with the used oscilloscope and supports various connection types, especially Gigabit LAN, which is used for fast acquisition. It is able to set most of the oscilloscope's parameters as well as to do multiple automated acquisitions in a decent time.

Additionally also an new method has been implemented in the current TCT analysis software to read in the new data format.

At this point one is now actually able to perform TCT experiments as the experimental conditions can be controlled, the data can be taken fully automated in a decent time and it can also be analysed with existing software.

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