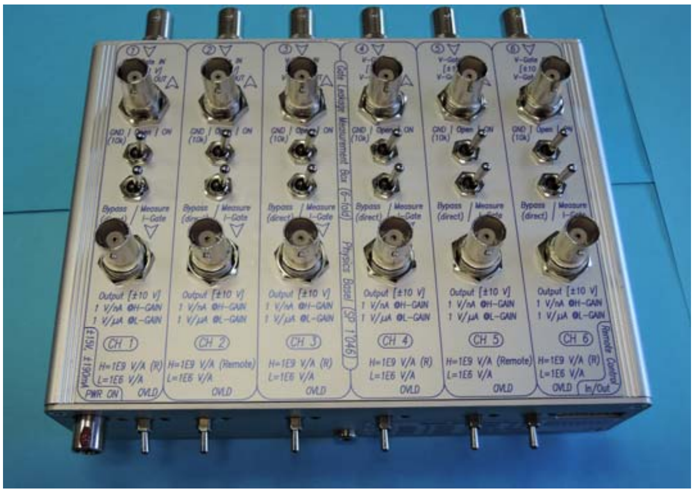
Gate Leakage Measurement Box (6-fold)

Physics Basel SP 1’046

User’s Manual
Revision 1.2



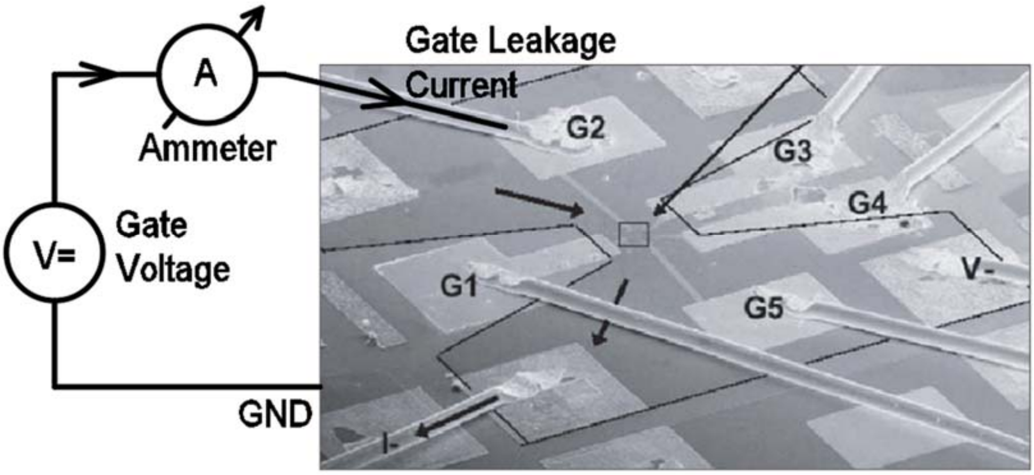
Michael Steinacher | July, 2020

University of Basel

1. Motivation

In low-temperature physics experiments many different gate voltages has to be applied to a sample. These gate voltages must be stable, low noise and adjustable with a high resolution. They are often generated by using our Low Noise / High Resolution DAC (LNHR DAC) which was designed to control up to eight gate voltages in a range of ±10 V. The gates of such low-temperature samples are normally very high-ohmic (>100 MOhm) and almost no current is flowing. A higher leakage current on one or more gate(s) is often an indication for a defective gate on sample or a problem in the wiring of the cryostat.

Before running the experiments, the qualities of the gates are often checked by using a commercial Source Measurement Unit (SMU) which are quite expensive. The leakage current of each gate is tested within the typical voltage rang (e.g. ±10 V). After passing these tests, the gates are hooked up to the multi-channel voltage source (e.g. LNHR DAC) and the experiment can be started. But now, the gate leakage can longer be monitored. During a running experiment gate leakage is hard to detect. Measuring the very small gate leakage currents (e.g. by an ammeter) without strongly deteriorate the quality of the gate voltages is challenging. The principle of a gate leakage current measurement is shown below:



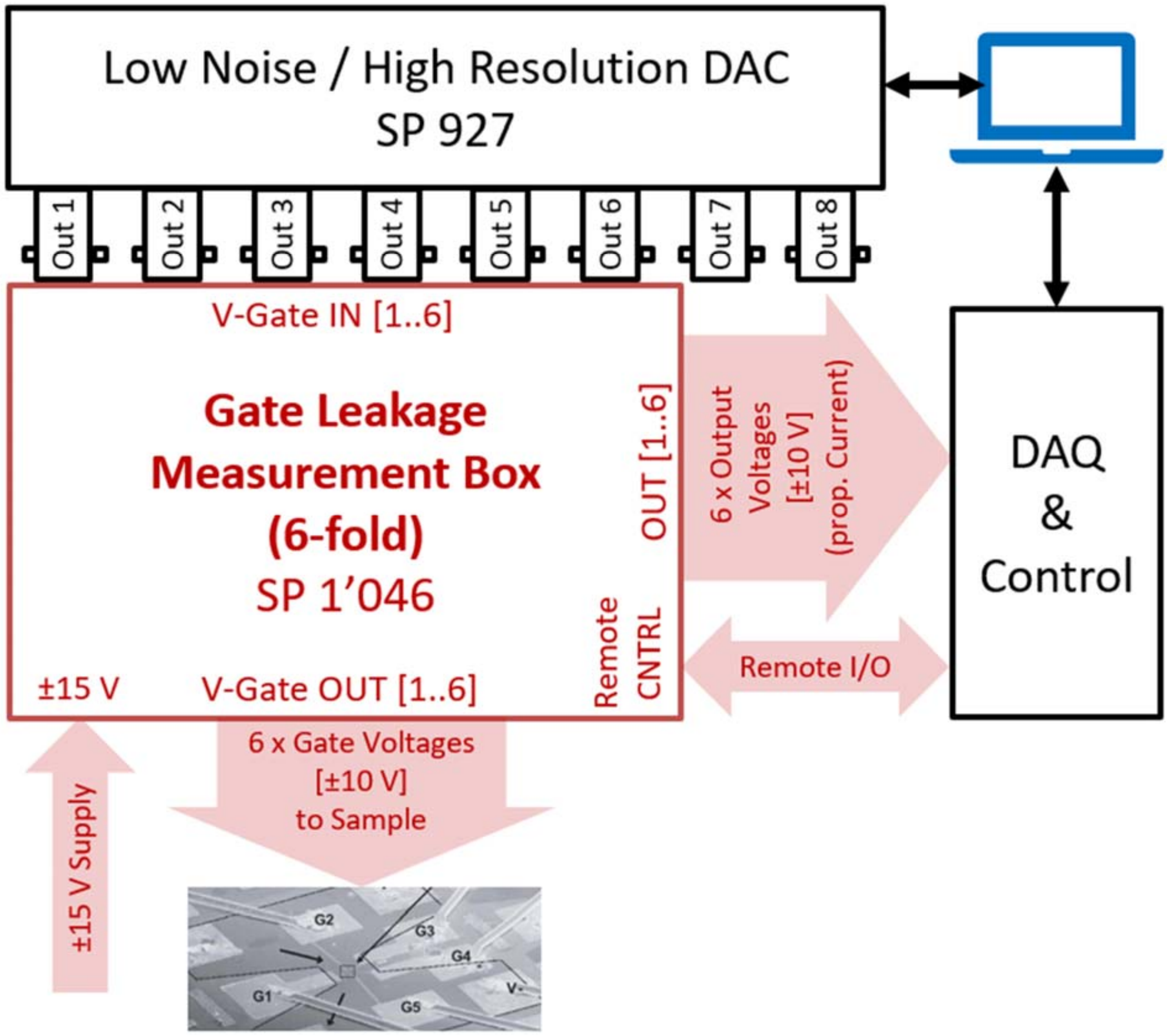
To overcome all these problems the Gate Leakage Measurement Box (GLMB) has been developed at the Physics Department of the University Basel. During an ongoing experiment, up to six gate leakage currents can be measured in parallel without strongly degrading the quality of the gate voltages.

2. Overview

The GLMB allows to monitor six gate currents during a running experiment. The device can be mounted directly in front of the LNHR DAC; then the six output voltages from the LNHR DAC are straightly connected by six BNC adapters to the input voltages (V-Gate IN) of GLMB. That reduces the cabling effort and allows a compact setup. The gate voltages (V-Gate OUT) have to be wired to the sample – often inside a cryostat – by using high quality and low noise BNC-cables.
By installing the GLMB between the gate voltage source (e.g. LNHR DAC) and the sample, the gate leakage currents can be measured without greatly increasing the noise level and deteriorating the stability of the gate voltage.

Gate voltages in a range of up to ±10 V can be precisely current monitored from the pA-range up to the 10 µA-range. This large measurement range is realized by two different current measurement ranges which have a scaling of 1 to 1’000.

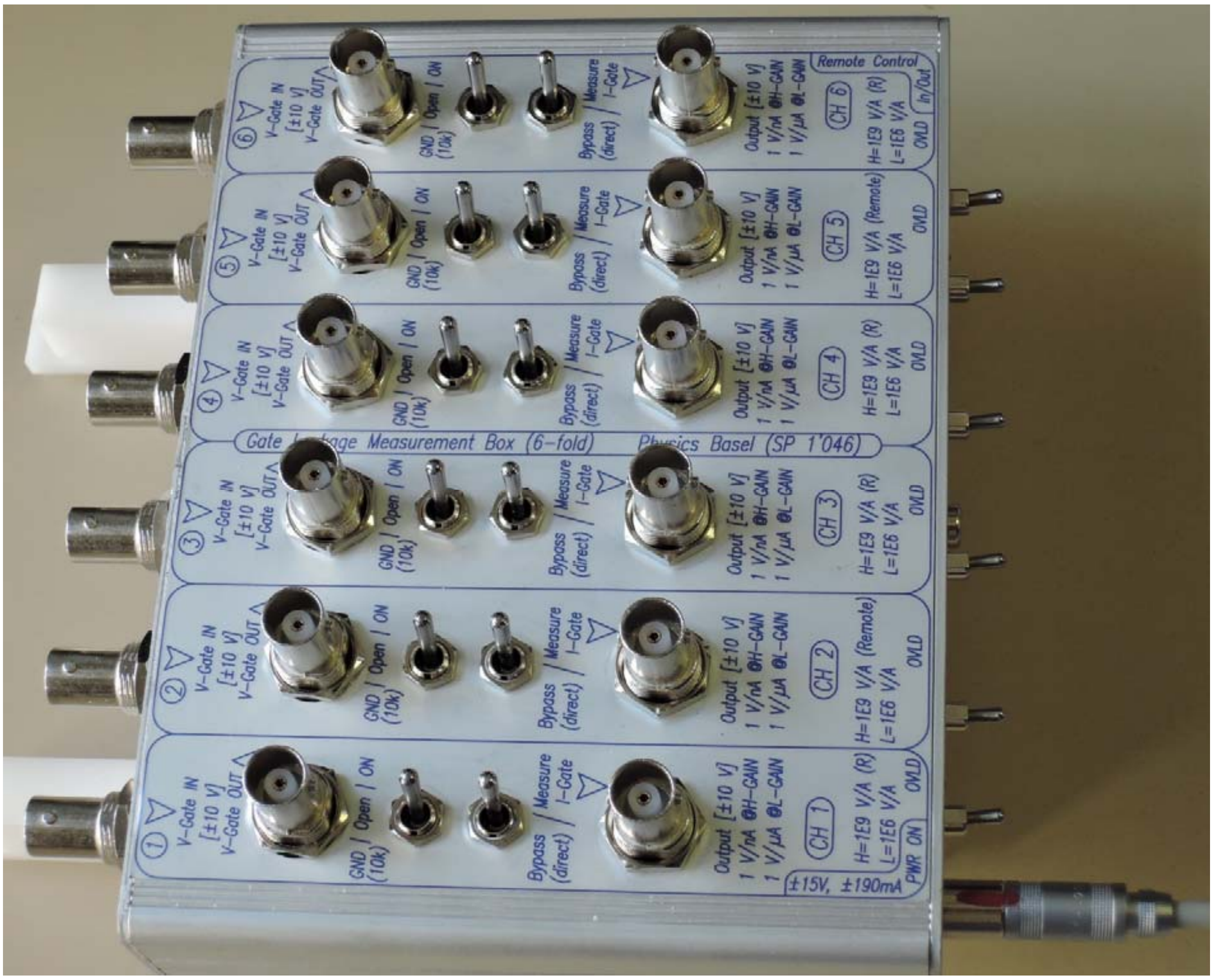
The bandwidth of the current measurement is 10 Hz and therefore only DC leakage currents can be detected. The six analog output voltages – which are proportional to leakage currents – can be readout by a data-acquisition (DAQ) or by several digital volt-meters (DVM). Such a typical setup for gate voltage control with the GLMB is schematically given below:



Two different current measurement ranges can be selected either manually or by remote control (which is galvanically isolated):
The HIGH-gain range has a scaling of 1 V/nA (gain = 1E9 V/A) while the scaling of the LOW-gain range is 1 V/µA (gain = 1E6 V/A). The gate leakage current is converted in a ground-referenced output voltage (Output [±10V]) in a range of ±10 V. The sign gives the direction of the leakage current; a positive output voltage corresponds to a gate current sourced from the GLMB.

An optical (red LED) and an acoustical alarm (beeper) notifies the user if the gate current has reached its maximum of ±10 nA at HIGH-gain (1E9 V/A) respectively ±10 µA at LOW-gain (1E6 V/A). If the user is only interested that the gate currents remain below ±10 nA, the GLMB can be used as alarm only. Then all the ranges have to be set to HIGH-gain and the digital overload information can be monitored via the remote control I/O. Doing so there is no need for continuously reading out the six analog output voltages which are proportional to leakage current. In the event of an overload alarm, the corresponding channel can be examined more closely.

The photo below shows the top front-panel of the device. The six BNC connectors for the gate input voltages (V-Gate IN) are located on the left side-panel while the six gate output voltages (V-Gate OUT), the six signal outputs (Output [±10V]) and the 12 function switches are on top of the box. On the right side-panel the six gain selection switches, the six overload LEDs (red), the ±15 V power-supply connector (4 pin Lemo 0S) and the Remote Control In/Out connector (14 pin, 2 rows, 2mm) is located. The mechanical channel to channel spacing is 25 mm which is compatible to the LNHR DAC. The total weight of GLMB is about 1 kg:



While measuring the leakage current (toggle switch in the position Measure I-Gate) the maximum DC gate current gets restricted by the GLMB to ±25 nA in HIGH-gain respectively to ±25 µA in LOW-gain range. This gives some protection to the sample and the wiring of the cryostat.
When the toggle switch in the position Bypass (direct) no current limitation is coming from the GLMB, since the gate voltage input (V-Gate IN) is directly wired to the gate voltage output (V-Gate OUT).

Note: Capacitances to ground (GND) – coming from cabling and low-pass filters – must be charged/discharged when the gate voltage is changed. This charge current is also measured by the GLMB and a fast-changing gate voltage, in combination with a larger capacitance to ground, can lead to an overflow warning (LED and beeper). This overflow warning can be ignored since it will be automatically turned off after the capacitance has been charge completely to the demanded gate voltage. However, make sure that the DAQ waits at least 1 second after the overload is turned off before starting a gate leakage measurement – otherwise a too high leakage current is measured.

For a given gate voltage step (ΔV) the charging-time (t_c) of a load-capacitor (C_L) at the gate voltage output can be calculated by:

$$t_c = \frac{\Delta V \cdot C_L}{I_C}$$

By assuming a mean charging current (I_C) – which is depending on the selected gain – the charging-time (t_c) can be estimated. In the HIGH-gain range a mean charging current of 10 nA (max. 25 nA) can be assumed and 10 µA (max. 25 µA) in the LOW-gain range. Taking these typical currents in account, the charging-time (t_c) can be estimated to:

- HIGH-gain range: t_c = 100 ms per ΔV = 1 V and per C_L = 1 nF
- LOW-gain range: t_c = 100 µs per ΔV = 1 V and per C_L = 1 nF

This shows that manly in the HIGH-gain range the charging-time (t_c) can reach noticeable values.

For example, a gate voltage step (ΔV) of 5 V in combination with a load-capacitor (C_L) of 10 nF leads to charging-time (t_c) of around 5 second in the HIGH-gain range, but only 5 ms in the LOW-gain range.

Since the output of the GLMB has a time-constant of 16 ms (bandwidth 10 Hz) only charging-times longer than around 30 ms are able to trigger the overflow warning (red LED and beeper).

3. Principle

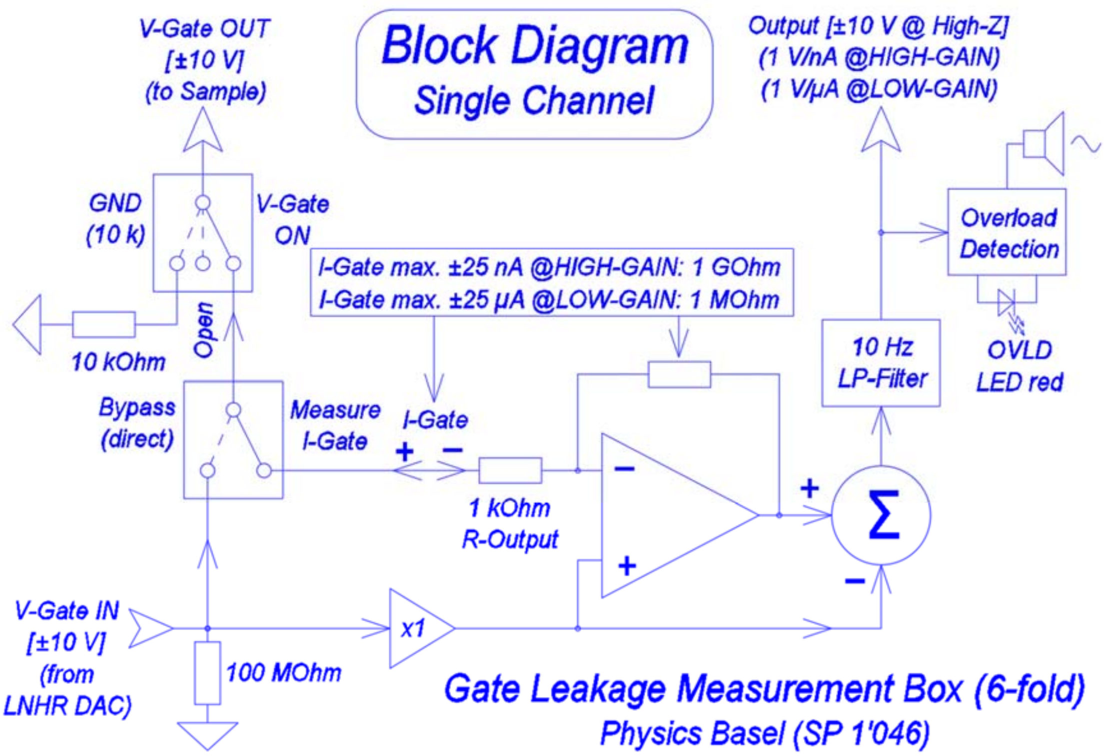
The GLMB consists of six independent and identical channels; only the supply voltage (±15 V, ±190 mA) and the overload beeper is common for all channels.

In order to achieve high stability, low noise and low leakage performance, precision components in combination with a sophisticated design and a proper PCB-layout are combined in the GLMB.

Each channel is based on a current to voltage converter (I to V converter) which can be individually voltage-biased up to ±10 V. The gate voltage input (V-Gate IN) is buffered and biases the I to V converter which has a selectable gain of 1E9 V/A (HIGH-gain, Rf= 1 GOhm) or 1E6 V/A (LOW-gain, Rf = 1 MOhm). To maintain the full dynamic range, its bipolar supply voltage must be shifted according to gate voltage input. The input of the I to V converter is wired to the gate voltage output (V-Gate OUT) where the leakage current is measured.

By precisely subtracting the bias voltage from the output of the I to V converter, the output voltage (Output [±10 V]) is proportional to the leakage current only. A suppression ratio (V-Gate IN/Output) of 80 dB makes sure that only the leakage current is measured. In the HIGH-gain range the theoretical current error due to a varying (±10 V) input gate voltage is only around ±1 pA and ±1 nA in the LOW-gain range. Coming from internal leakage (V-Gate OUT = open) the measured gate current varies by approximately ±10 pA (HIGH-gain range), while the gate input voltage changes by ±10 V. This corresponds to an internal leakage resistance of around 1E12 Ohm (1 TΩ).

The block diagram of a single channel is given below; it also printed on the back of the housing of the GLMB:



The gate voltage input (V-Gate IN) is high-ohmic; it is loaded by a 100 MOhm in parallel with a 10 nF capacitor to ground, which is not shown on the block diagram.

With the two toggle switches on the top of the GLMB the user can select the function of the gate voltage output (V-Gate OUT):

- The 3-position toggle switch (GND / Open / ON) allows to ground the gate output (by a 10 kOhm resistor), open the gate or switch ON the gate voltage.
- With the 2-position toggle switch (Bypass (direct) / Measure I-Gate) the gate voltage output (V-Gate OUT) can be either wired directly to the gate voltage input (V-Gate IN) or to the input of the I to V converter, which is the normal position and allows measuring the gate leakage current.

The I to V converter has an input resistor of 1 kOhm which is in series with gate voltage output and forms the internal DC source-resistance. The voltage drop across this resistor is at maximum ±10 mV while measuring the maximum gate leakage current of ±10 µA in the LOW-gain range. In the Bypass (direct) position no additional noise and drift, coming from the GLMB, is added to the gate voltage.

In the frequency range from 0.1 Hz to 2 kHz the GLMB has a typical gate noise voltage of around 800 nV_{RMS} in the HIGH-gain range and 700 nV_{RMS} in the LOW-gain range.
These values are about the same as the typical noise voltages on the outputs of the LNHR DAC (SP 927). Measuring the gate current with the GLMB attached to the LNHR DAC will therefore increase the gate voltage noise by a factor of around square root of two (1.414). This is because two independent noise voltages build the geometric mean. Therefore, the total typical gate voltage noise (LNHR DAC with GLMB) can be estimated to around 1 μV_{RMS} in the frequency range from 0.1Hz to 2 kHz.

By the GLMB a typical temperature drift of ±150 nV/K is added to the gate voltage output (V-Gate OUT) while measuring the gate leakage current (Measure I-Gate).

Note: A leakage current flowing from the GLMB to the sample is a source current and it results in a positive output voltage. Therefore, a resistor at the gate voltage output (V-Gate OUT) to ground leads to positive output voltage (Output [±10V]) when a positive gate voltage (V-Gate IN) is applied.

With the 2-position toggle switch on the side-panel the current measurement range can be switched between HIGH-gain (±10 nA, Rf = 1 GOhm) or LOW-gain (±10 µA, Rf = 1 MOhm). If the gain is controlled remotely the manual toggle switch has to be in the upper position (HIGH-gain range).

The output signal of the current measurement (Output [±10 V]) has a bandwidth of 10 Hz (time-constant 16 ms) and drives at minimum ±10 V into high-impedance loads; the output resistance is 500 Ohm. The following typical noise voltages [equivalent current noise] are present on the output measured in a frequency range from 0.1 Hz to 400 Hz:

- HIGH-gain range: 70 μV_{RMS} [70 fA_{RMS}]
- LOW-gain range: 4 μV_{RMS} [4 pA_{RMS}]

Assuming a noise crest-factor (peak-peak/RMS) of 6.6, the current measurement of the GLMB has the following typical peak to peak current fluctuations:

- HIGH-gain range: 462 fA_{PP}
- LOW-gain range: 26.4 pA_{PP}

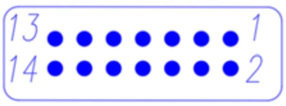
These are the broadband current fluctuations measured with an oscilloscope – they are significantly lower when the DAQ or the DVM makes an integration over a longer period (e.g. 1 second).

4. Remote Control

Via the Remote Control In/Out connector (14-pin, 2 mm, see left) the six gains (GAIN1...6) can be controlled (HIGH/LOW-gain) by an external source (e.g. computer). Further the six overloads (OVLD1...6) can be readout by an external device (e.g. computer). All the remote control signals are galvanically isolated with optocouplers from the electronics of the GLMB. Therefore, no ground-loops or interference can occur by using these remote control lines. Nevertheless, make sure that the TTL control signals are clean and do not carry any high-frequency noise. High-frequency noise may capacitive coupling into the sensitive electronics. If this is observed, low-pass filtering the TTL control signals may be necessary before these noisy signals entering the device.

Note: When the gains are remotely controlled the manual gain toggle switch has to be in the upper position (HIGH-gain range).

A 14-pole flat cable connector Amphenol/FCI 2x7P (type 89947-714LF) fits into the socket of the Remote Control In/Out. In low-interference laboratory environment an unshielded flat cable up to a length of around five meters can be connected between the GLMB and a computer. The assignment of the remote control connector is the following:



PIN1	PIN2	PIN3	PIN4	PIN5	PIN6	PIN7	PIN8	PIN9	PIN10	PIN11	PIN12	PIN13	PIN14
G1	OVLD1	G2	OVLD2	G3	OVLD3	G4	OVLD4	G5	OVLD5	G6	OVLD6	COM_IN	COM_OUT

The six inputs G1…G6 are used for the programming the six gains (HIGH/LOW-gain) of each channel separately. The COM_IN (PIN 13) is the common ground (0 V of the computer) of the remote TTL input signals. A logic high (1) needs a voltage lager than +2.5 V and a logic low (0) a voltage smaller than +0.8 V. The remote control inputs are therefore compatible with 3.3 V logic output levels. Each remote control input signals is loaded by a 1.8 kΩ resistor to the common input ground (COM_IN). Do not apply voltages higher than +7 V and no negative voltages to these remote control inputs.

The logic of these six input signals is inverted: A logic high (1) selects the LOW-gain (1E6 V/A) while a logic low (0) selects the HIGH-gain (1E9 V/A) range. The typical gain-switching time is around 1 ms.

The six outputs OVLD1…6 can be used to readout the overload information of each channel separately. The COM_OUT (PIN 14) is the common ground (0 V of the computer) for these OVLD output signals. These open-collector outputs (from optocouplers) must be externally pulled-up to +3.3 V (or +5 V) to generate a TTL-level signal. A pull-up resistor of 10 kOhm is suggested; at maximum a current of 2 mA can be drawn to ground. The logic of these six output signals are active low; this means 0 V (low) is read when the corresponding channel is overloaded (OVLD).

Note: To generate a global overload signal (active low) all the output signals (OVLD1…6) can be connected in parallel. Due to the open-collector outputs, an OR-function is built automatically: If one or more channels show an overload warning this global overload signal gets active (low).

5. Supply Voltage

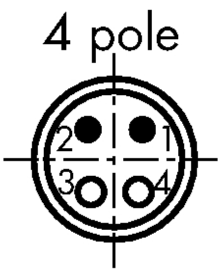
The supply voltage of the GLMB is ±15 V with a tolerance of ±5 %. The green LED (PWR ON) lights up when the supply voltage reaches ±14 V. The typical quiescent current is around ±150 mA, but it can rise to ±190 mA during normal working conditions.

It is very important that the GLMB is powered by a floating, low noise, low ripple and stable supply voltage. Linear regulated laboratory power supplies (e.g. Keithley 2230) or our Floating Supply ±15 V (SP 874) are suitable for powering this device. Our low noise switching power supply, called Universal ±15 V Power Supply (SP 1’052), can also be used.

Note: Only when using a high-quality and low noise power supply the low noise performance of the GLMB can be reached.

To prevent from ground-loops, via the shield of the gate voltages, the power supply must be floating from earth/ground. Further the earth/ground leakage current should be less than 2 μA_{RMS}. Inside the GLMB the ground (GND, 0 V) of the power supply is connected to the housing and therefore also to the shield of the power supply socket. To prevent from noise pick-up on the long power supply cable a shielded one is strongly recommended.

The connector for the ±15 V supply voltage is a 4-pole LEMO series 0S with the following part number: LEMO FFA.0S.304.CLAC44

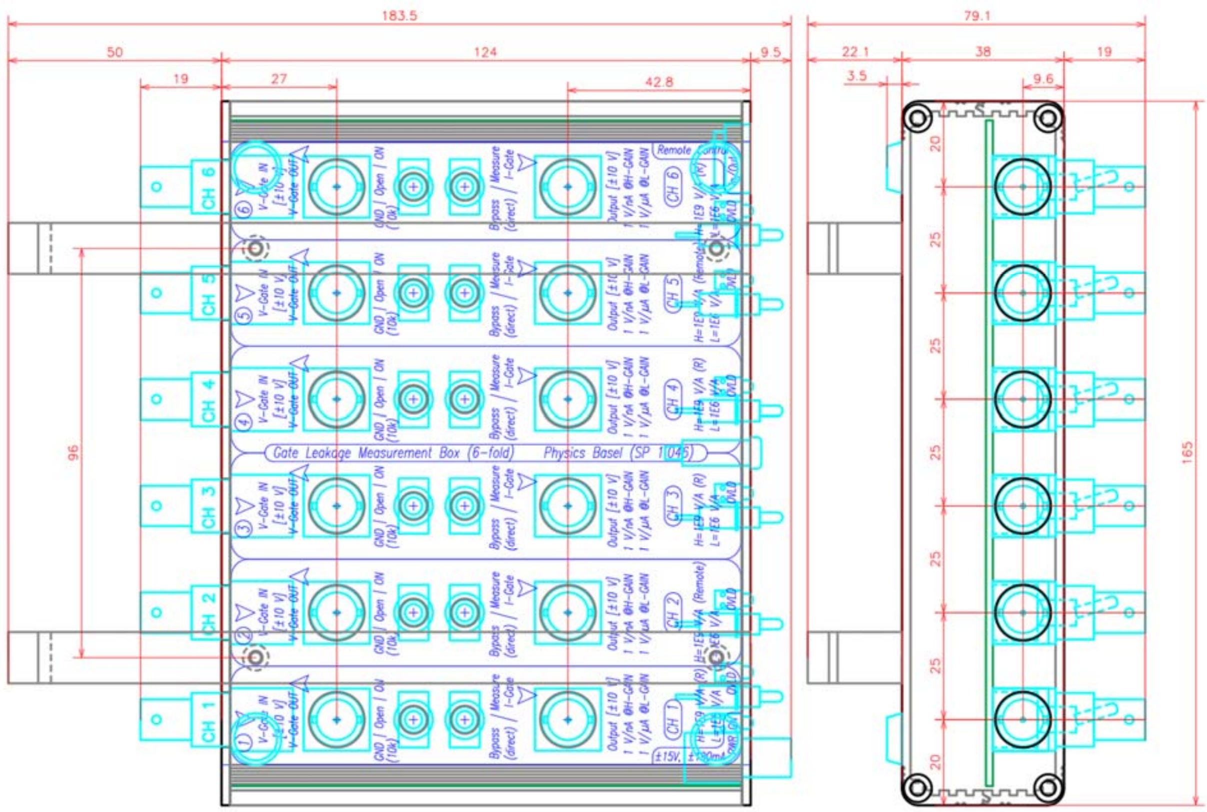


The pin assignment of the power connector is the following:

PIN 1: +15 V / +190 mA maximum
PIN 2: -15 V / -190 mA maximum
PIN 3: not connected
PIN 4: 0 V / Ground
(Shield is connected to housing and 0 V)

6. Mechanics

Below the mechanical dimensions of the GLMB are given in mm:



The mechanical channel to channel spacing is 25 mm which is compatible to the LNHR DAC. The total weight of the device is about 1 kg.

With the two mounting rails, together with the six BNC plug-to-plug adapters, the GLMB can be fixed directly in front of the LNHR DAC. These mounting rails support the GLMB to the front-panel of the LNHR DAC and prevent from bending the BNC adapters. Since the gate output voltages of the LNHR DAC are floating from earth/ground (front-panel), the mounting rails must be made out of isolating plastics. Otherwise the ground of the GLMB would be connected to the front-panel of the LNHR DAC which is connected to earth/ground.

With the two rails for directly mounting on the LNHR DAC the overall dimensions are:
183. 5 mm x 165 mm x 79.1 mm

The overall dimensions of the GLMB (without the mounting rails) are:
152.5 mm x 165 mm x 60.5 mm

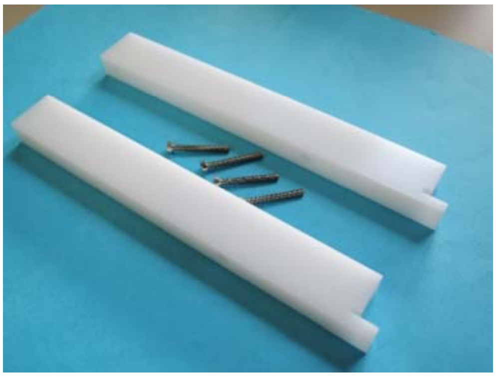
7. Mounting GLMB on LNHR DAC

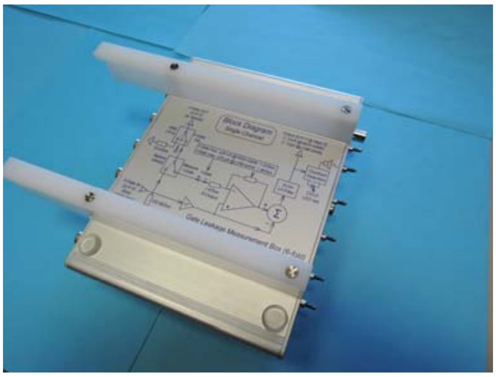
As already mentioned, the GLMB can be mounted directly in front of the LNHR DAC (SP 927) by using six BNC adapters and two mounting rails. The advantages are reduced number of cables and a compact setup which makes it less prone for noise pickup. The picture below shows the GLMB mounted in front the LNHR DAC:

The mounting set consist of six BNC plug-to-plug adapters (length = 31.5 mm, Cinch 27-8130), two isolating plastic mounting rails and four M3-screws (length = 25 mm).

Please follow the instruction below to mount the GLMB in front of the LNHR DAC:

1. Fix the two mounting rails with the four M3-screws at the bottom of the GLMB so that they jut out on the side with the six BNC connectors (V-Gate IN):

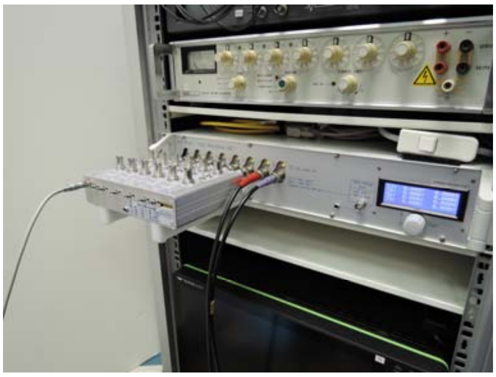




2. Switch off the LNHR DAC and attach the six BNC plug-to-plug adapters on the channels 1 to 6 of the LNHR DAC. Make sure that the slots of the BNC adapters are exactly vertical so that the GLMB can be smoothly slide-in:

3. Insert the BNC connectors of the GLMB to BNC adapters and press the box until the BNC connectors are completely inside and the two mounting rails touch the front panel of the LNHR DAC; perhaps you have to wiggle the GLMB slightly. Now fix the BNC adapters on the GLMB side by turning them counter-clockwise until they are all locked:


4. Power on the GLMB and switch on the LNHR DAC; now you can start cabling your setup. The not occupied DAC outputs channels 7 and 8 can be used for other purpose. The tandem-pair (GLMB and LNHR DAC) can be operated on the table (photo left) as well as inside a 19”-rack (photo right):

8. Typical Specifications @ $T_{ambient}$ = 25°C

- **Independent Gate Leakage Measurement Channels**: 6
- **Gate Voltage Input Range**: ±10 V
  Input Impedance: 100 MOhm (5%) || 10 nF (5%)
- **Gate Voltage Output Range**: ±10 V
  DC Output Impedance @Position Measure I-Gate: 1 kOhm (0.5%)
- **Resistance to GND @Position GND**: 10 kOhm (2%)
- **Current Measurement Output Voltage (@High-Z Load)**: >±10 V
  Output Resistance: 500 Ohm
- **Current Measurement Range / Accuracy**
  HIGH-gain: ±10 nA (1E9 V/A) / ±2%
  LOW-gain: ±10 µA (1E6 V/A) / ±1%
- **Overload indication (red LED & beeper)**
  HIGH-gain Range: >= ±10 nA
  LOW-gain Range: >= ±10 µA
- **Maximum DC Gate Current (V-Gate OUT shortened to GND)**
  HIGH-gain: ±25 nA
  LOW-gain: ±25 µA
- **Current Measurement Bandwidth / Time-Constant**: 10 Hz / 16 ms
- **Current Measurement Noise (0.1 Hz… 400 Hz) RMS / Peak-Peak**
  HIGH-gain: 70 fA_{RMS} / 462 fA_{PP}
  LOW-gain: 4 pA_{RMS} / 26.4 pA_{PP}
- **Current Measurement Offset @V-Gate IN = 0 V, @V-Gate OUT = open**
  HIGH-gain: ±5 pA
  LOW-gain: ±100 pA
- **Gate Voltage to Output Suppression**: 80 dB
- **Internal Leakage Current @V-Gate IN = ±10 V**: ± 10 pA
- **Gate Voltage Output Noise (0.1 Hz… 2 kHz)**
  HIGH-gain: 800 nV_{RMS}
  LOW-gain: 700 nV_{RMS}
- **Gate Voltage Output Drift VS. Temperature**: ±150 nV/K
- **Power Supply Voltage / Current**: ±15 V (±5%) / ±190 mA
- **Remote Control Gain Input Voltages**
  High-Level: Minimum +2.5 V, Maximum +7 V / Low-Level: Maximum 0.8 V
- **Remote Control Overload Output Current (Open Collector)**: Maximum 2 mA
- **Overall Dimensions**
  With mounting rails for LNHR DAC: 183. 5 mm x 165 mm x 79.1 mm
  Without mounting rails: 152.5 mm x 165 mm x 60.5 mm
- **Ambient:** Dry Laboratory Conditions between 15°C and 35°C
- **Weight**: 1 kg