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MiniHV V2
A modular, remote controlled high voltage system

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Abstract

A compact, extendable high voltage system for low currents, with local intelligence is described. It is remote controlled via a CAN bus. This first production series is a 1000 V, 5 µA type.

A CANbus is used to ease the integration with other systems in an experimental set-up. This paper describes the specifications and hardware design considerations in MiniHV V2.

How to use the various functions is described in an other paper by Henk Boterenbrood [5].

Check for the most recent version of this paper:
http://www.nikhef.nl/pub/departments/et/high_voltage/v2/MiniHV_V2.pdf

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1 Contents

1.1 Introduction

Several types of remote controlled high voltage supplies have been build at Nikhef [1]. These are mainly used as supplies for photo multipliers. It utilizes a Cockcroft Walton (CW) circuit to multiply the input voltage, where the circuit contains more stages than the number of outputs needed. In this way the choices of voltage steps between the dynodes is more flexible.

More recent is the use of gas-filled silicon detectors. These do not require so many outputs, but precisely monitoring the current becomes more important. Voltages used here range from 500 V to more than 2000 V. For some configurations voltages are stacked and currents may run “the wrong way” [2]. MiniHV V2 has a single output that can be set from close to 0 V to 1000 V. The current measurement range is 5 µA with a resolution better than 1 nA.

A CANbus is used to ease the integration with other peripherals in an experimental set-up. The CANopen protocol is used.

This paper describes the hardware design considerations in MiniHV V2. How to operate the system is described in [5] (the software description). The paper describes the functions, various types of ramping, how to set limits and more.

1.2 System set up

The prototype system was fed by an external 24 V adapter. This is replaced by a box having a 220 V input. This requires less components and ensures a clear ground definition. It is also more safe and CE conform. In the HV supplies the circuit ground is connected to the housing.

The *miniHV PS/split* converts the 220 V to +/- 12 V and 60 V. Older types convert the external supplied 24 V to these voltages. These are combined with the CANbus signals. The CANbus is connected via the standard DB9 connector and then distributed from this box via RJ45 cables. The CAN standard allows to split the bus into two strings. In that case the system should be terminated with 180 Ω at the three ends. The supply box monitors the proper cabling and termination and enables the 60 V only if this is correct. Error Leds on the supply box indicate this. The terminations in the diagram make part of the system. Terminating the DB9 bus is up to the user, though not very critical.

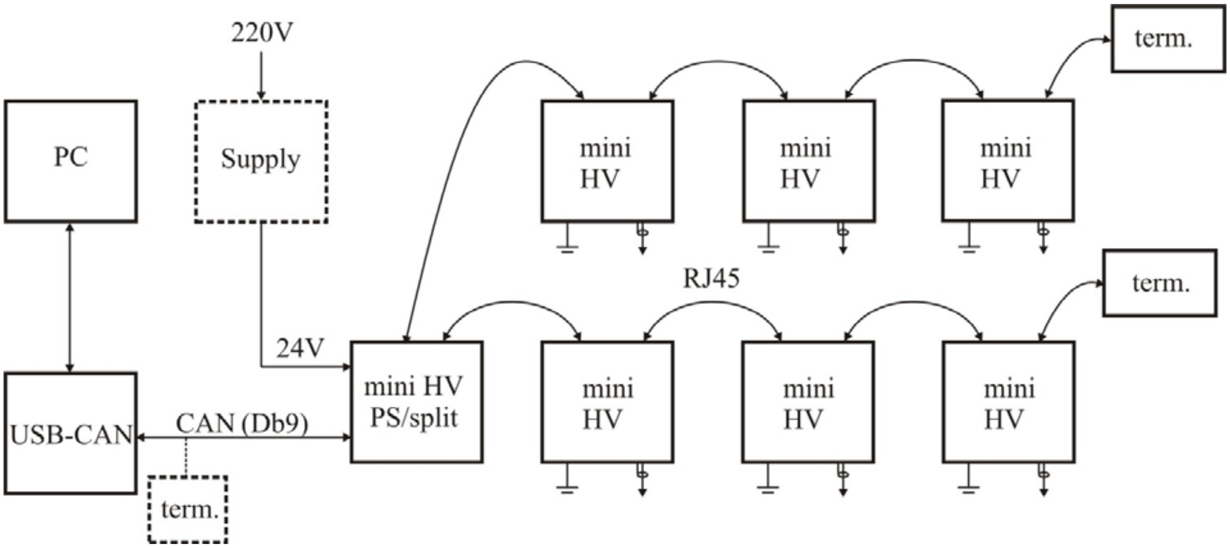

Figure 1: system set up

The picture shows a small set up with only one HV supply. The white box contains the CAN termination and a loopback circuit to check this termination. A larger set up can contain 10 MiniHV units.

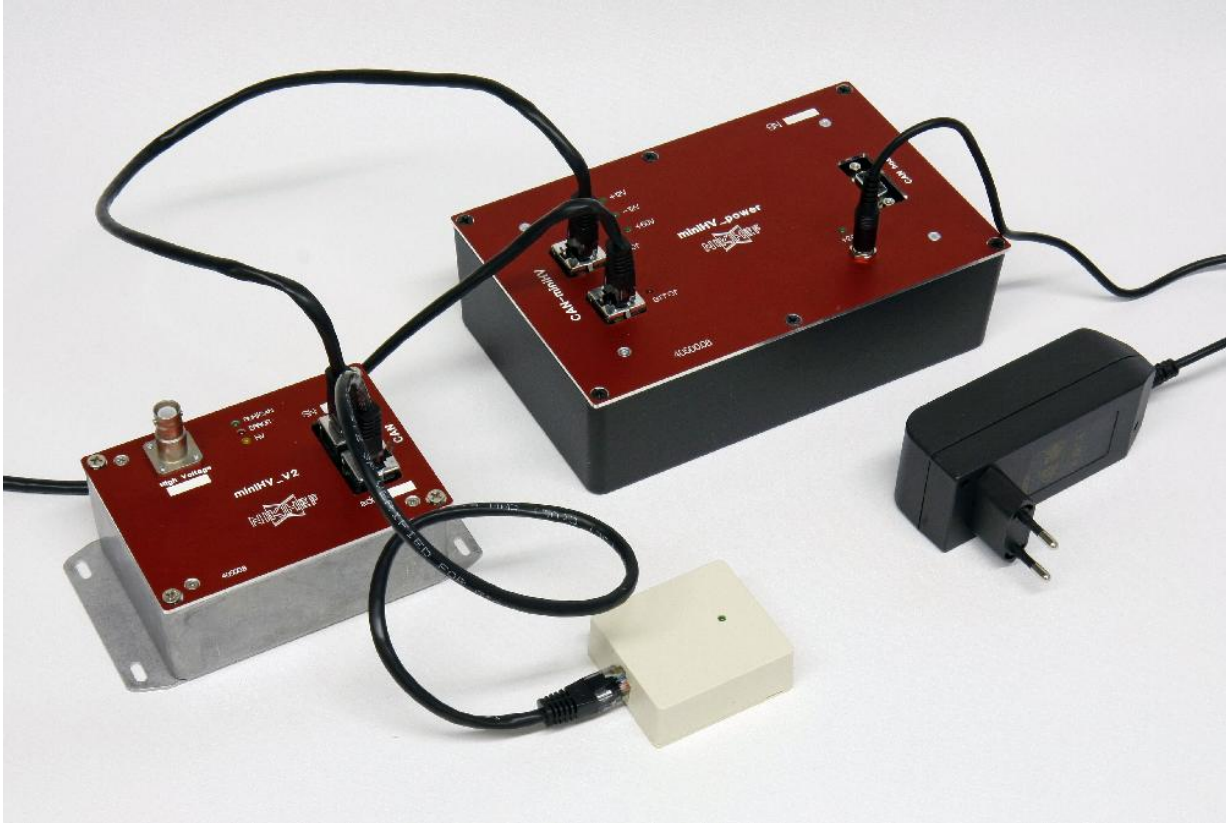

Figure 2: system set up, components

On the right one sees the power adapter (prototype only) and *miniHV PS/split* box with CAN splitter from DB9 to RJ45. On the left is the actual *miniHV V2*, of which can be several chained on the bus. The white box contains the terminator. The power adapter is replaced by a direct connection to the mains from the *miniHV PS/split* box to ensure connection to ground of all boxes. When the prototype power supply is used, the user should at least ground one of the miniHV housings.

1.3 Specifications

1.3.1 Power

Power consumption of the miniHV V2	
+ 12 V	30 mA
-12 V	20 mA
+ 60 V	7 mA

MiniHV power (temporarely)	
± 12 V	830 mA
+ 60 V	830 mA

Due to rush-in currents, the total number of miniHVs connected to a supply box is limited to app. 10. This rush in current includes the checking of the supplies for new software versions, which take a lot of CAN messages.

1.3.2 Dimensions

[mm]	length	width	height	see also
miniHV box	110	83	44 *	Hammond 1590 BFL
box + flange	140	-	-	
miniHV supply	188	120	54 *	Hammond 1590 DBK
Terminator	58 *	51	21	
*: connectors/ cables not included				

Please note that the current *miniHV supply* is a temporarily solution.

1.3.3 Terminator

pin	signal	components
1	CANH	180 Ω
2	CANL	
6	Interlock (-)	green LED + 2k2
8	+12 V	

1.4 MiniHV V2

The high voltage unit *miniHV V2* is described. The power unit will change and will be described in a later stage.

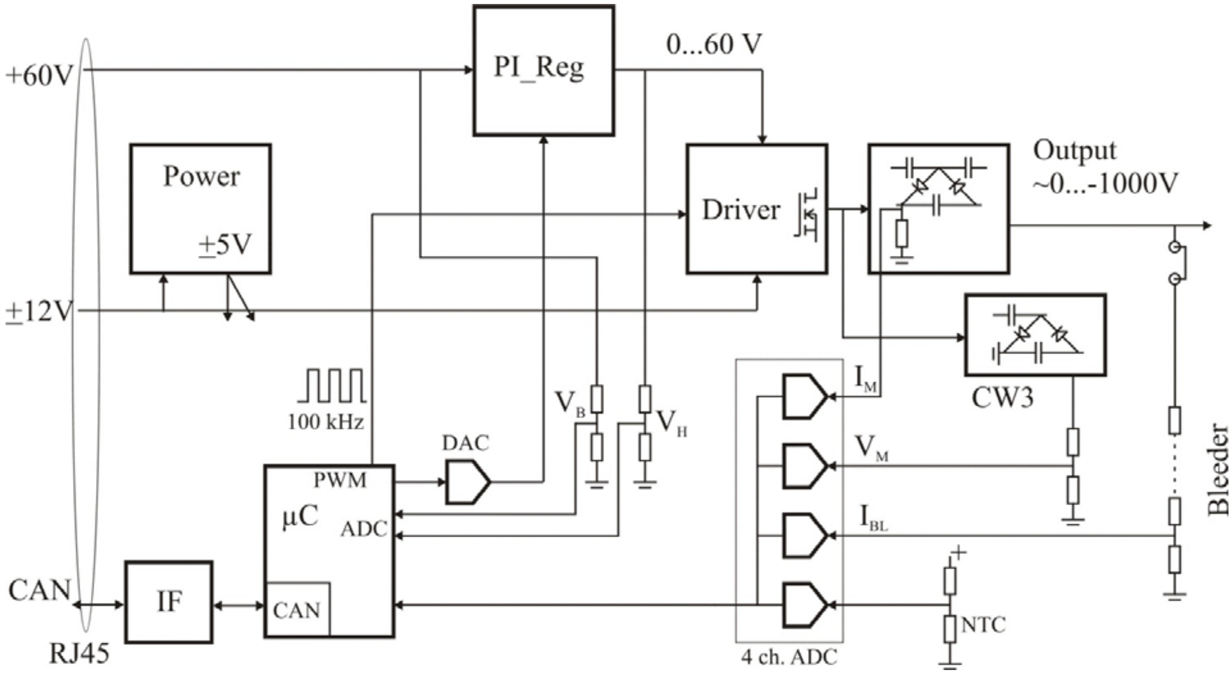

Figure 3: block diagram MiniHV V2

Power and control comes in via an RJ45 connector. CAN via RJ45 is an industrial standard, spare lines are used for power and monitoring proper cabling. The CAN protocol is handled by the micro-processor, just an electrical interface is needed. The DAC defines the setting of the sub-circuit that generates the voltage for the driver circuit (0 to 60 V). The driver is a switch that toggles between the regulated input voltage and ground. The toggle frequency is determined by the processor. This generates two complementary, non overlapping clock signals.

The combination of diodes and capacitors, the Cockcroft Walton circuit (CW), multiplies the driver output. The frequency is not critical, but it influences the output impedance. A low frequency slows down the CW response. A high frequency introduces higher losses in the driver and CW. 100 kHz shows a good performance. When setting the DAC to a high value and disabling the control loop, the output voltage is 1040 V without load. This is measured with a non contacting high voltage probe. When a load of 200 MΩ is added (~5µA), the voltage drops due to the output impedance. The table below shows the effect of the frequency on the impedance. This value increases when less current is drawn.

f [kHz]	Vout [V]	Z [MΩ]
25	983	11.5
50	1004	7.2
100	1012	5.6
200	1007	6.6

There is a current limitation between the driver section and the CW circuit which also reduces noise in the system. This does not contribute to the output impedance. The software corrects for the voltage drop thus reducing the output impedance.

The current measurement (I_M and I_{BL}) use a 24 bit ADC. Not all these bits are stable, but the natural fluctuation (noise) makes it possible to average the results at the host. V_M is a representation of the high voltage without loading the main CW. The temperature measurement enables to correct the other measurements. At the moment it is not used in the control loop and there seems to be no reason to do so. V_H is merely used in the debugging of hardware problems. It is measured by a 10 bit ADC. V_B is used in two ways: to see if it useful to start the module in the first place. And it generates an interrupt to the microcontroller when there are problems with this supply voltage. The processor disables that supply by setting the DAC to zero. And it sends a message to the host.

1.4.1 Current measurement

A simple way to measure the output current is to measure the power that goes into the driver circuit and calibrate at several points (different currents) how this relates to the output current. This is not accurate enough with the dynamic range required here. Also the ambient temperature and thus the leakage current of the diodes plays a role.

An other method is to place the measuring circuit directly at the output of the supply. This requires to bring power at the high voltage level for this circuit, containing amplifiers, an ADC and circuitry to isolate the communication between this circuit and the microprocessor. This may introduce noise at the output. It can also introduce voltage shifts due to imbalances in the power circuit and/ or the digital interface. It also would require a lot of components.

Measuring the return current, at 0 V, is not a good approach, for safety reasons for example. Especially in high voltage systems or when supplies may be coupled. The definition of ground becomes unclear and large measurement errors may be introduced..

The solution for this lies in the fact that the DC current that goes out to the load also flows through the first diode in CW circuit, the one normally connected to ground. This diode is now connected to a current to voltage converter via a two stage low pass filter. The converter itself again is a low pass filter because there is a large AC component that must be suppressed before the signal can be digitized. The circuit acts as a virtual ground for the first diode of the CW.

For the diodes in the multiplier, very low leakage types are chosen. In parallel to the CW, a second, single stage CW generates the same voltage as the first stage of the original CW but with opposite polarity. The leakage current of this circuit is hardware subtracted from the leakage current of the original CW. This reduces the error in the current measurement. It also compensates the increasing leakage current when the temperature rises.

For the current to voltage converter a chopper stabilised OpAmp is used. This ensures a low and temperature stable offset. This is smaller than 1 μV. The same circuit is used to measure the bleeder current. Since the high value resistors (in total 180 GΩ) may not be very accurate nor stable, the current trough the bleeder is measured. Here the low bias current of the OpAmp choosen is of importance. The current measured is 5 nA full scale. The bias current is 4 pA typical, 60 pA maximum. In practice, the stability is rather good since the components are used well below the maximum specifications. The measured value is subtracted from the CW current measurement to determine the load current. This is done by the microprocessor. The bleeder current is also used to see whether there is still high voltage on the output after switching of (more than 50 V). This is indicated by the LEDs on the module. For the definition of the LED indication see the software description **Error! Reference source not found.**.

1.4.2 Stabilisation

To stabilize the high voltage, a control loop is needed. The feedback for this circuit is usually taken from one of the lower taps of the CW. This has the advantage that the voltage divider does not need extreme high impedance components. More important, the delay of a change at the input of the CW increases with the amount of stages. In the case of this 1000 V supply, there are 18 stages. So it takes at least as many clock cycles of the driving circuit before the feedback circuit gives the full representation of that change. To compensate for a true delay in a closed loop requires a complex

PID design. In this case, where the control loop is implemented in software, this is less difficult. It is still possible to choose this implementation since the bleeder current is measured.

A feedback from a lower tap also draws current, which is relatively constant at a given high voltage. This works fine when the load at the output is also reasonably constant. This is the case when the bleeder resistance (fixed resistor from output to ground) takes most of the current. This is correct for photo multiplier supplies, where the highest taps draw the smallest current and is relatively small compared to the bleeder current. For this design we want to have a small bleeder current or, in some cases, no bleeder at all. For this version we have chosen a current (I_{BL}) of app. 5 nA. This already is high compared to the desired resolution for current measurement. In this design it means 36 resistors of 5 GΩ in series. That is 10 GΩ per stage. For the feedback a buffer circuit with an input resistance of 100 MΩ is reasonable. This already takes much more current than the bleeder circuit or a small load at the output. Therefore the feedback at the lower tap of the CW gives a less accurate representation of the output voltage, especially at low output currents.

The current of the bleeder could be used as feedback for high voltage stabilisation. But then again, we have the feedback delay. Also the impedance is extremely high (180 GΩ) and possibly not stable enough. Therefore a 3rd CW is introduced; a single stage, driven by the same driver circuit. This removes the load of the feedback circuit from the main CW, giving the same measurement results. For more details see [6].

What is left is the problem that, if the real HV output is not directly monitored, how to determine the relationship of the ideal output voltage which is influenced by the load. So, we monitor a single stage (CW3), extrapolate this to (in this case) an 18 stage CW and correct it with the CW current. Temperature also plays a role here, but the feedback circuit CW3 employs the same diodes as the main CW and the load of the buffer circuit is small enough to neglect the heating of the diodes from this effect. In the circuit is the same leakage current compensation as in the main CW. Assuming this, there is a simple relationship of: $HV = n * V_M - b * ln(I_M) – c * I_M$, where n is the number of stages, V_M is the feedback voltage from the 3rd CW and I_M is the current in the main CW. The logarithmic term comes from the diodes, the linear term is the impedance of the capacitors at the pumping frequency. V_M must be corrected for the load of the measuring circuit. This load is a simple resistor, but the current varies with the voltage setting. Summing things up we get:

CW: $HV = n*V_0 – b*ln(I_M) – n*c* I_M$, with V_0 being the ideal (no load) voltage.

CW3: $V_M = V_0 – a*ln(V_M/R_{FB}) – c*(V_M/R_{FB})$, with R_{FB} being the input impedance of the measuring circuit.

Assuming that $b = n*a$ and multiply the CW3 formula with n, we get:

$HV = n*V_0 – n*a*ln(I_M) – n*c* I_M$ and $n*V_M = n*V_0 – n*a*ln(V_M/R_{FB}) – n*c* (V_M/R_{FB})$

By subtracting this, V_0 drops out, which is not really know or measured. (This is probably close to V_H). Reordering gives:

$HV = n*V_M – n*a*ln(I_M) – n*c* I_M + n*a*ln(V_M/R_{FB}) + n*c* (V_M/R_{FB})$ or

$HV = n*(V_M – a*ln(I_M) –*c* I_M + a*ln(V_M/R_{FB}) + c* (V_M/R_{FB}))$

All values are known (n, R_{FB}) or measured, which leaves the calibration factors ‘a’ and ‘c’ to be determined.

The current in the bleeder is also measured, but this is only used to determine the load current ($I_{LOAD} = I_M - I_{BL}$). It does not play a role in the control loop.

1.4.3 Output impedance (more)

Since the voltage feedback and regulation is not directly connected to the high voltage output, the supply shows a noticeable impedance. In this design this effect is rather strong since the low leakage diodes have a rather high threshold voltage. There is a “build-in” potential which makes a diode, below the so-called threshold voltage a nearly perfect isolator. Above that voltage the V-I curve is exponential. This curve is temperature dependant. The diode current is given by:

$I = \left(a^{V/n*V_T} - 1\right)$. Here V_T is the thermal voltage. Factor n lies between 1 and 2 and is often omitted since it is 1 most of the time. This may not be truth in the case of the low leakage diodes. $Vt = k * T/q$, so temperature dependant. All terms are equal for the main CW and single stage CW3, used for the feedback. The temperature difference due to different currents in the different sections can be neglected. This is calculated, not tested. If the software correction is disabled the impedance is around 5 to 12 MΩ, depending on the oscillation frequency. Since the correction is done in software this is what one will experience at first instance. Shortly after that the DAC setting is corrected using the calibration values. It will be corrected at a rate of app. 2 Hz. Since there is usually a large filter externally of the supply, this is probably adequate.

1.5 Pitfalls

- Changing anything in the chains of supplies in a running system will cause all supplies to shut down.
- A short circuit in any supply may cause a 60 V auxiliary supply dip (not very likely because of current limiting). This may or may not be detected by all HV modules. So some will shut down and others may not. This should be handled by the host.
- For the moment all modules will have a bleeder installed. Still, it will take time before the high voltage goes down after lowering or disabling the supply via software. We have chosen to have a very low bleeder current. The modules monitor the bleeder current and will indicate that there is still high voltage by a Led indication. This can also be monitored via the host by checking this current. The time constant is in the order of 20 minutes. This means that after switching of 1000 V, after 20 minutes there is still 300 V and another 20 minutes later still 100 V. When the user adds more filtering this becomes even more. The energy stored is not large, but may feel rather unpleasant.
- The scheme of grounding relies on the grounding of the HV boxes themselves in the prototype set-up. This is changed now, but may give some unpleasant surprises until then.

References

[1] “A remote controlled high voltage supply for photo multiplier tubes” Nikhef, ETR 94-11
Stacked sensors example: triple GEM detector for COMPAS, CERN-EP/ 2002-008 [4]

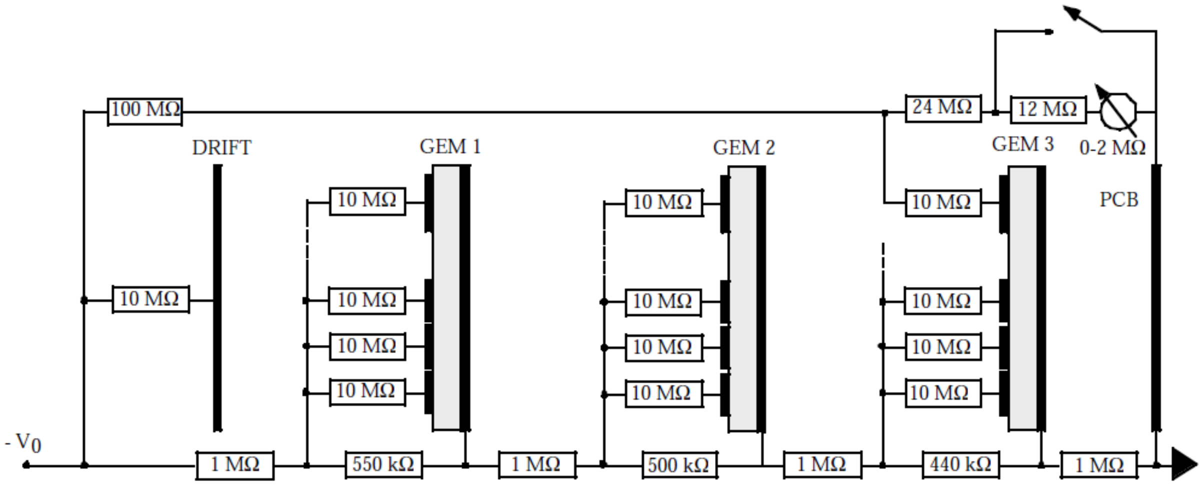

Fig. 19: The resistor chain used for high voltage distribution. A remote-controlled switch allows to activate/de-activate the central beam region.

[2]

Figure 4:Voltage distribution using resistive divider

[3] The Frascati HV system
[4] CERN-EP/ 2002-008
[5] Henk Boterenbrood: MiniHV manual
[6] Tests on various aspects of a high voltage module