SAVONIA

Development of High Voltage Power Supply for a Photomultiplier

Vihtori Virta

Bachelor's Thesis

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Bachelor's degree (UAS)

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Tiivistelmä

Koulutusala Tekniikan ja liikenteen ala			
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Toimeksiantaja/Yhteistyökumppani(t) University of Hawaii at Manoa, Instrumentation Development Laboratory			

Tiivistelmä

Tämän opinnäytetyön tarkoituksena oli kehittää 4-kanavainen korkeajännitetehonlähde tuomaan tehoa Hamamatsun SL10-valomonistinputkille iTOP-detektorissa. iTOP detektori on osa Belle 2--detektoria, joka on kehitetty tunnistamaan kaaoneita ja piioneita (K/π). Belle 2 -detektori on kehitetty tunnistamaan varautuneiden hiukkasten violaatioita Super KEKB -hiukkaskiihdyttimessä, joka sijaitsee Tsukubassa, Japanissa. Super KEKB on KEK High Energy Accelerator Research Organizationin alainen projekti.

Opinnäytetyön tavoitteena oli suunnitella tehonlähde, joka tuottaa jokaisessa kanavassa säädettävästi 0 - (-4 000) V jännitteen, joka on seurattavissa erilliseltä monitorointietupaneelilta. Työ tehtiin PADS-piirilevynsuunnitteluohjelmistoa käyttäen Manoan yliopiston mittalaitteiden kehityslaboratoriossa Havaijilla, Yhdysvalloissa.

Työn tuloksena syntyi piirikaavio sekä ensimmäinen prototyyppi tehonlähteestä. Tehonlähteen testausvaiheessa havaittiin piirilevynsuunnitteluun koskevia virheitä sekä epästabiilisuutta ulostulossa sekä korkeajännitteen monitoroinnissa. Tästä syystä tehonlähteestä aloitettiin tekemään toista versiota, jossa kaikki havaitut ongelmat tullaan korjaamaan. Tuotteen jatkokehityksen pääpaino tulee olemaan toisen prototyyppiversion suunnittelussa, valmistamisessa ja testaamisesta.

Avainsanat
Super KEKB, Belle 2, iTOP

Julkinen

SAVONIA UNIVERSITY OF APPLIED SCIENCES **THESIS**
Abstract

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Abstract

The purpose of this thesis was to develop a 4-channel high voltage power supply for powering Hamamatsu SL10 photomultiplier tubes in the iTop detector. The iTop detector is part of the Belle 2 detector and it is made for detecting Kaons and Pions (K/π). The Belle 2 detector is made for detecting charged particle violations in the Super KEKB particle accelerator which is located in Tsukuba, Japan. The Super KEKB particle accelerator research project belongs to the KEK High Energy Accelerator Research Organization.

The goal of this thesis was to design a power supply which can generate variable 0 - (-4 000) V for each channel. The voltage can on seen by the monitoring front panel. The development was done at the Instrumentation Development Laboratory in University of Hawaii at Manoa using the PADS circuit board design software.

As a result, the schematic and the first prototype of the power supply were made. At the testing part of the power supply some issues were found concerning the PCB (Printed Circuit Board) design. There was also instability in high voltage output and monitoring. Because of these reasons another prototype version of the power supply was started. In this version all the detected problems are going to be fixed. The main focus in further development is going to be on designing, fabricating and evaluating the next version of the power supply.

Keywords
Super KEKB, Belle 2, iTOP

Public

PREFACE

This thesis was done for Instrumentation Laboratory in University of Hawaii at Manoa – Department of Physics and Astronomy during the period from 9 January 2012 to 6 July 2012.

I would like to thank everybody in the Instrumentation Development Laboratory for the support and guidance during this project. Especially I want to thank my supervisor, Professor Gary Varner for this possibility to do my thesis in IDLab and all the support during this project. Special thanks go also to my thesis supervisor, Ari Suopelto, who gave me lot of support and feedback. I would also like to give special thanks to Matt Andrews who helped me with the problems during the project

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SYMBOLS, TERMS AND ABBREVIATIONS

MILS	A unit of measurement used in electronics. One mill equals one thousands of an inch
PADS	PCB designing software created by Mentor Graphics
PID	Particle Identification
HV	High Voltage
iTOP	Imaging Time of Propagation
Ω	Ohm, a symbol for SI derived unit of electrical resistance
BOM	Bill of Materials

1 INTRODUCTION

iTOP stands for imaging Time-of-Propagation. It is a detector which has been developed for detecting Kaons and Pions (K/π) in the Belle 2 detector. The Belle 2 detector is an upgraded version of the Belle detector which was designed and constructed to carry out quantitative studies of rare B-meson decay modes with very small branching fractions using asymmetric e^+e^- collider in the KEKB factory. Belle 2 aims to continue studying the properties of b-quark with increased luminosity. The increased luminosity is achieved by upgrading the electron-positron collider to Super KEKB.

The upgrade depends on the new iTOP particle identification (PID) system. The system upgrade consists of many smaller projects. On this project the main focus was on Hamamatsu SL10 Photomultipliers. These photomultipliers need proper high voltage to function. To generate the voltage, a proper power supply needed to be developed.

This thesis includes the development process of the power supply for the Hamamatsu SL10 photomultipliers in the iTOP project. The very first prototype version of the power supply was developed, manufactured and tested. The power supply was designed to have four channels and each channel has to generate -4000 V to make the photomultipliers to work.

2 PROJECT ASSIGNMENT

The aim of the project was to design, fabricate and evaluate a 4-channel variable high voltage power supply for the operation of high performance Hamamatsu SL10 Micro – Channel Plate Photomultiplier Tubes (MCP-PMTs). This project is part of the Imaging Time of Propagation Particle Identification system upgrade for the Super B factory project. This improvement is necessary due to the upgrade of the Super – KEKB particle accelerator, already the world's highest luminosity accelerator. This luminosity is needed for the upgraded BELLE 2 detector at the KEK High Energy Physics Laboratory in Tsukuba Japan. The BELLE 2 upgrade will allow the physics experiments and search for the physics beyond the standard model of particle physics in the field of Kobayashi and Maskawa theory to continue. The PID (Particle Identification) depends on these new MCP - PMT devices and their proper high voltage operations. The Belle 2 detector is located in point 7 A in Figure 1.

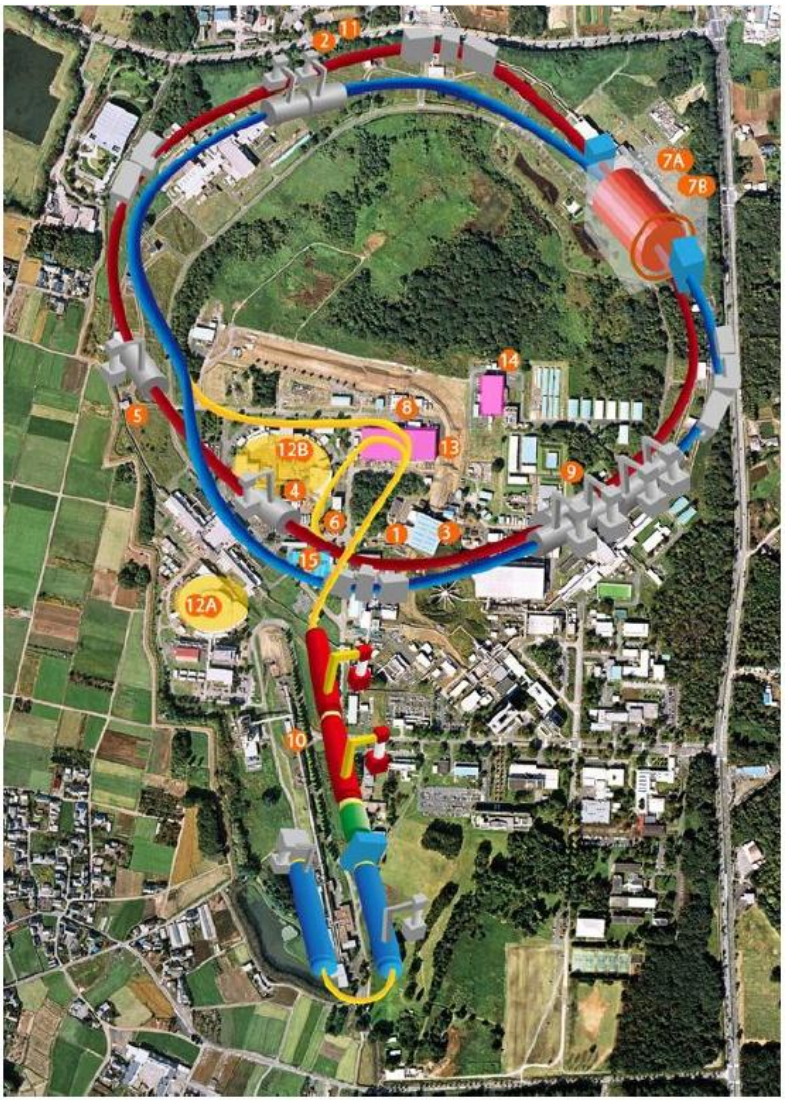

FIGURE 1. KEKB facilities and components (Malin, J. 2012, 8)

2.1 iTOP

This power supply is designed for powering the SL10 – MCP-PMTs in the imaging Time-Of-Propagation (iTOP) system in the Belle 2 detector. This system is designed for charged particle identification (PID), particularly K /π (Kaon/Pion) separation for momenta up to 4 GeV/c. Photons emitted from charged particle interactions in Cerenkov radiator bar are internally reflected to the end of the bar, where they are collected on a compact image plane using photodetectors with spatial segmentation in two dimensions. This can be seen in Figure 2. (Nishimura, K., Browder, T., Hoedlmoser, H., Jacobson, B., Kennedy, J., Rosen, M., Ruckman, L., Varner, G., Wong, A., Yen, W. 2009, 1.)

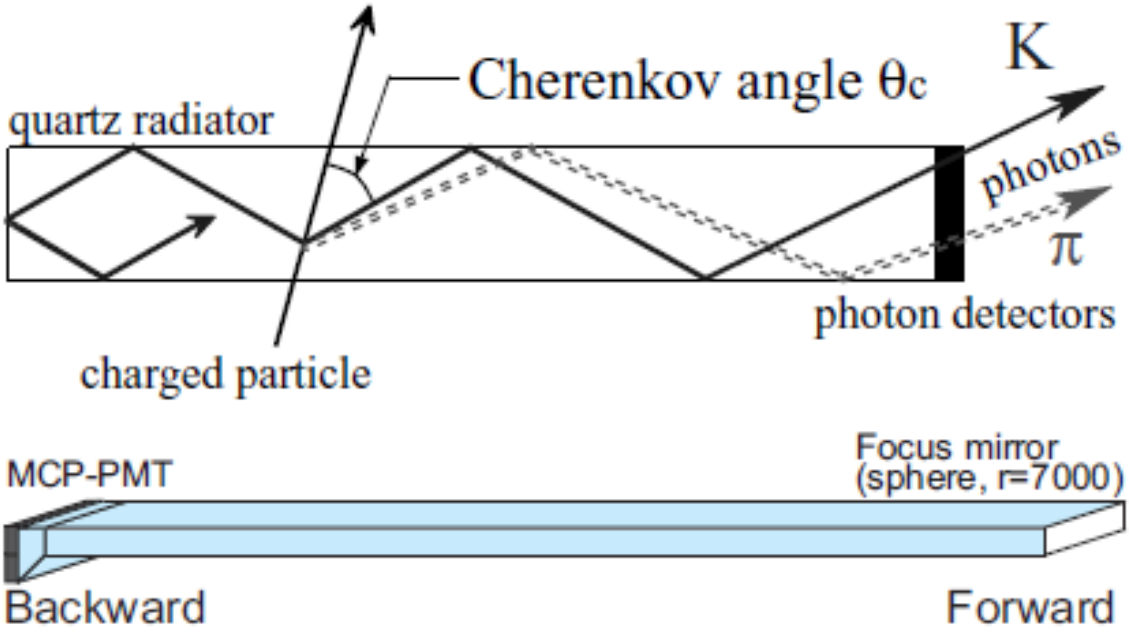

FIGURE 2. (Above) A side way schematic of a Time-of-Propagation (TOP) concept as used to distinquish Kaons from Pions. (Below) A single Belle 2 TOP module (readout electronics not shown). (Andrew, M., Gao, X., Macchiarulo, L., Nishimura, K., Ridley, L., Warner, G. 2011, 2)

As shown in Figure 3 the iTOP detector consists of three main parts. The biggest part of the device is a quartz bar (Figure 2 below). The quartz bar is 2.85m long and it is made to reflect the Cherenkov photons emitted from the Kaons and Pions to the photodetectors on the left end of the bar. On the right end of the bar there is the focusing mirror. This mirror is made to reduce chromatic dispersion on the measured timings. (Nishimura, K. et al. 2009, 2)

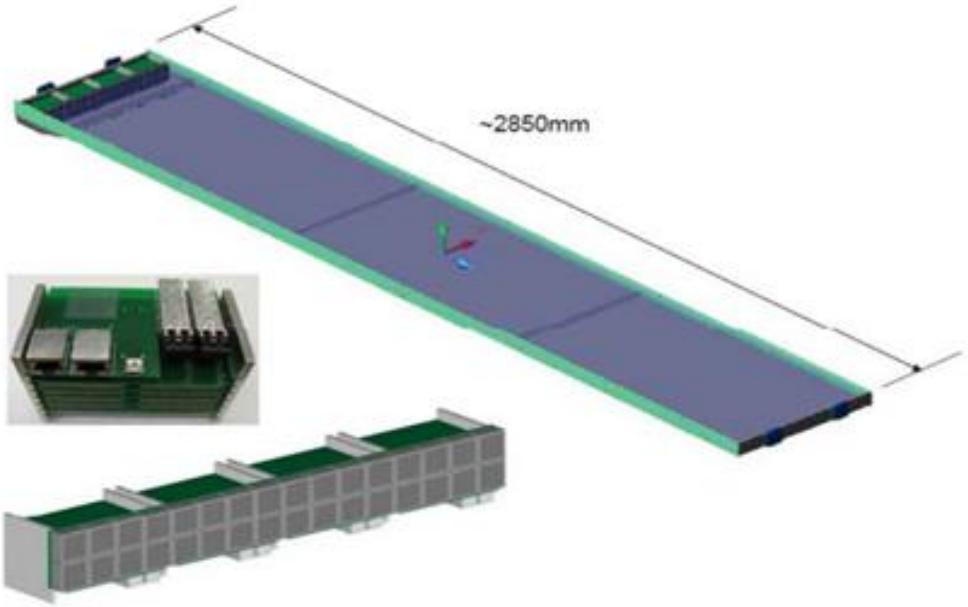

FIGURE 3. Parts of the iTOP system (Varner, G. 2012, 1)

Figure 4 presents the front end board stack. These stacks are used as readout electronics. The readout electronics read and digitize waveforms from SL10 PMTs. On one quartz bar there are four stacks. The photodetectors are mounted on these stacks and they are made to control the collected data coming from photodetectors. One board stack carries eight photodetectors so there are 32 photodetectors in one iTOP detector. (Nishimura, K. et al. 2009, 4)

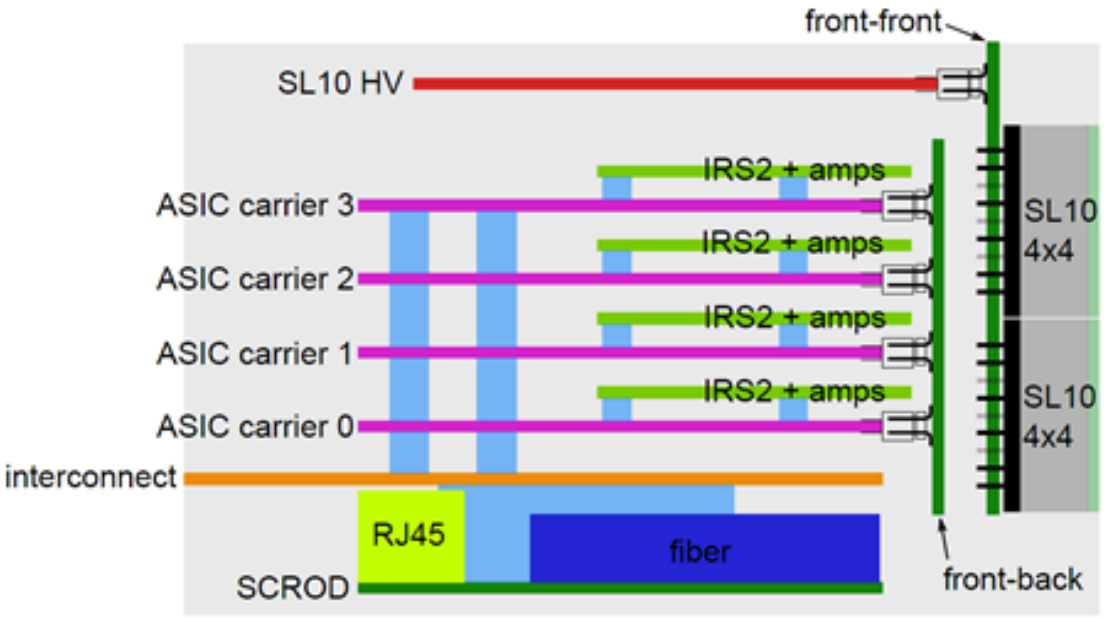

FIGURE 4. Front end board stack. (Nishimura, K. et al. 2009, 6)

2.2 Hamamatsu SL10 MCP - PMTs

MCP-PMT stands for Micro Channel Plate-Photo Multiplier tube. SL10 PMTs (Image 1) are designed by Nagoya University in co-operation with Hamamatsu Photonics, K.K. which is a Japanese company, established 1953, manufacturing optical sensors. The SL10 is a super bi-alkali PMT with photon timing resolution of 40ps and 4X4 anode channels. (Nishimura, K. 2010, 2)

IMAGE 1. SL10 Micro Channel Plate – Photo Multiplier Tube (MCP-PMT)

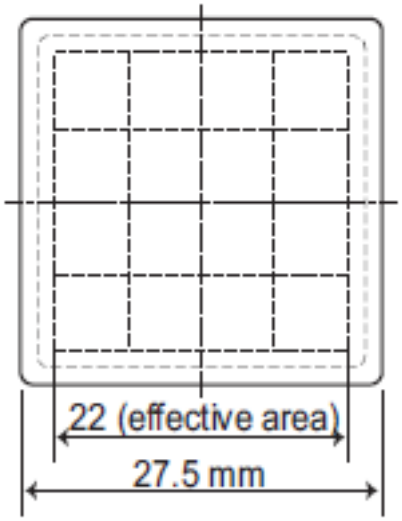

FIGURE 5. Anode structure diagram of SL10 (Nishimura, K. 2010, 3)

MCP-PMT is a modern version of the traditional PMT. The main difference between these PMTs is that the MCP-PMT uses micro channel plates to replace dynodes in traditional PMTs. This means that when the electron hits the wall of the MCP it emits electrons. The other differences are that SL10 is a multi-anode PMT. It has 4x4 anode channels (Figure 5) which means that in one TOP module there are 512 channels in total. The operation of the MCP-PMT is shown in Figure 6 and the schematic drawing is shown in Figure 7. (Kazuhito, S. 2011)

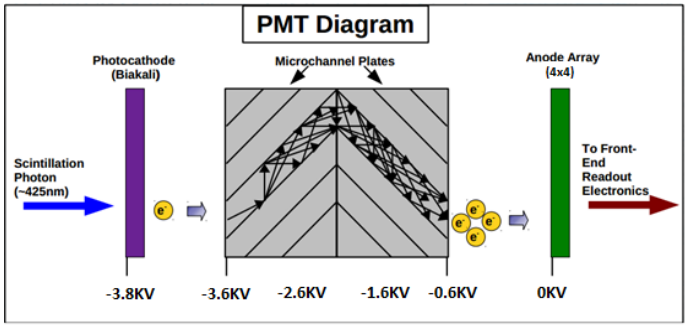

FIGURE 6. The operation of MCP-PMT

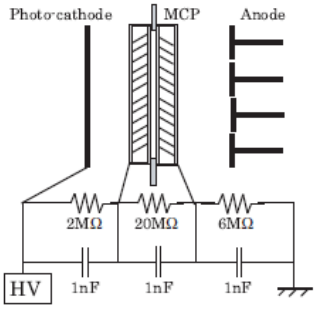

FIGURE 7. Schematic drawing of the internal structure and the HV-network of SL10 (Inami, K., Mori, T., Matsumura, T. 2008, 4)

The main reason for developing these PMTs for this project was that the PMT should have high gain with compact size in square shape. Table 1 shows that comparing to two other square shaped PMTs, Hamamatsu SL10 is smaller and has much bigger geometrical efficiency than the other two. The other advantages of using SL10 are fast time response, 2D detection with high resolution and that they are operative under magnetic field. (Kazuhito, S. 2011, 6) (Montgomery, R. 2010)

TABLE 1. MCP – PMT Comparison (Montgomery, R. 2010)

	Burle 85011	Burle Prototype	Hamamatsu SL10
Pore size (μm)	25	10	10
Number of pixels	8 x 8	8 x 8	4 x 1
Active area (mm^2)	51 x 51	51 x 51	22 x 22
Total area (mm^2)	71 x 71	69.5 x 69.5	27.5 x 27.5
Geometrical efficiency	0.44	0.47	0.61
Peak quantum efficiency	At 400nm	At 400nm	At 300nm

2.3 Requirements and objectives for power supply

Originally the aim of the project was to develop 8 - channel high voltage power supply for powering SL10 PMTs in iTOP detector. The power supply was designed in University of Hawaii at Manoa for KEK High Energy Accelerator research organization. There were some requirements and restrictions to consider when designing the power supply.

The first assignment for the project was to design a power supply which takes 15 V as Input voltage and generates variable 0 - (-4000) V for each channel in output. The high voltage transform from 15 V to -4000 V had to be done with proportional EMCO E40 high voltage module. It had to have potentiometer adjustment for voltage and low voltage monitoring with maximum +-1 V fault in measurement. Also the voltage monitoring should have been done completely separated from high voltage with inverting operation amplifier connection. The low voltage monitoring means that when there is -4000 V in output it shows -4000 mV in display. The very first block diagram can be seen in Figure 8. The block diagram below shows the designed actions at the beginning of the designing process.

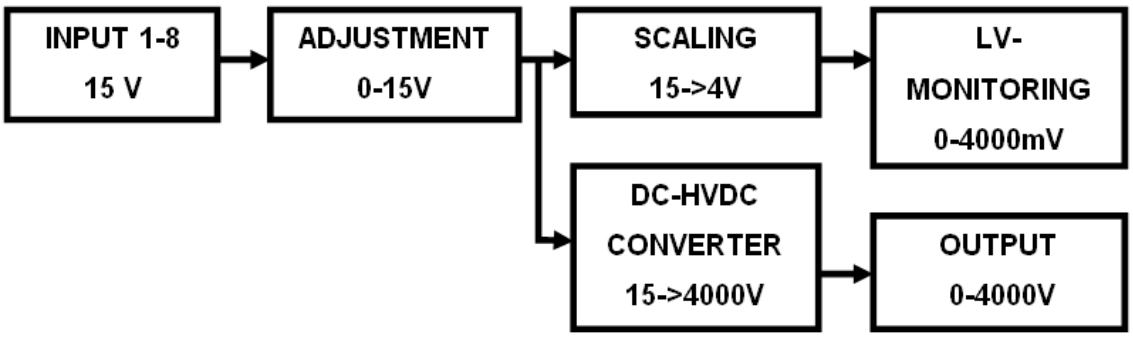

FIGURE 8. Project block diagram

Later on the aim of the project changed into designing a compact 4 - channel power supply with separate high voltage board and monitoring front panel so it would be more universally usable and easier to transport. Also the dimension restrictions were set. The power supply had to be designed to fit into standard rack which is 16” in width. In the University there were already some standard cases which meant that the PCBs (Printed Circuit Boards) should fit in those cases. The case dimensions were 16” in width and 1.6” in height.

3 SCHEMATIC DESIGN OF POWER SUPPLY

The Schematic design was done by using the PADS Logic designing tool by Mentor Graphics. The schematic design is the first phase when designing a new electric device. At first the schematic was designed so that all the components would have been on one PCB. Displays, potentiometers and switches would have been wired from the front panel to the PCB. In this design the inside of the case would have been too tightly packed. After struggling with the problem for a while the design was split on two separate boards. One board would have all the high voltage components and the other would work as a monitoring front panel board with most of the low voltage components. These two boards would be connected together with connectors. When using two boards, displays can be soldered directly to the monitoring board requiring fewer wires. It also allows monitoring board to be universally used in other projects in the future.

3.1 Connections

The very first schematic design was made by using block diagram shown in Figure 8. This project has few critical connection designs that needed some extra attention. The first problem was the low voltage monitoring connection. At first the connection was supposed to be built by using the inverting operation amplifier connection as shown in Figure 9. The schematic drawing of the inverting operation amplifier connection can be seen more closely in Figure 10.

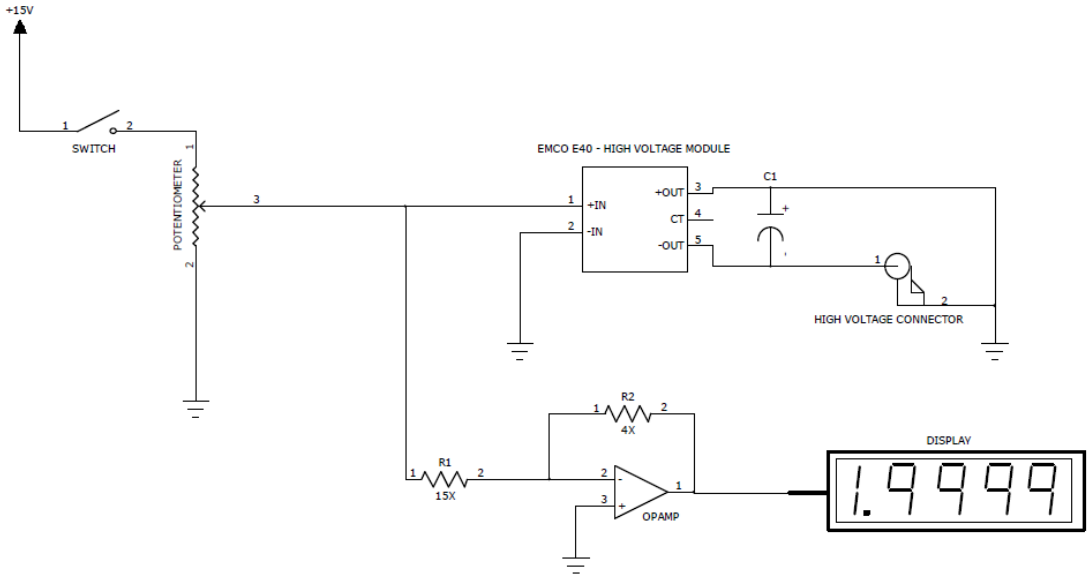

FIGURE 9. First schematic for one channel.

The problem with this connection was that it inverts the positive voltage to negative. The displays need positive voltage to work so this connection could not be used. The voltage invert is described by the formula

$$V_{out} = -\frac{R_f}{R_{in}} * V_{in} = -\frac{4K\Omega}{15K\Omega} * (0 - 15)v \quad (1)$$

where Rin is an input resistor and Rf is a feedback resistor.

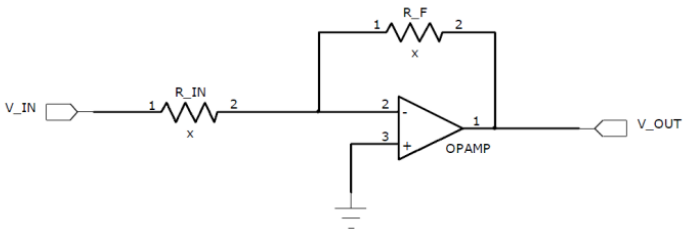

FIGURE 10. Inverting operation amplifier connection.

In the new design a simple voltage divider was used to replace the operation amplifier (Figure 11). The voltage divider calculation is described by the formula

$$V_{out} = \frac{R_f}{R_{in}+R_f} * V_{in} \quad (2)$$

where the ratio between the resistors Rf and Rin adjust the output voltage.

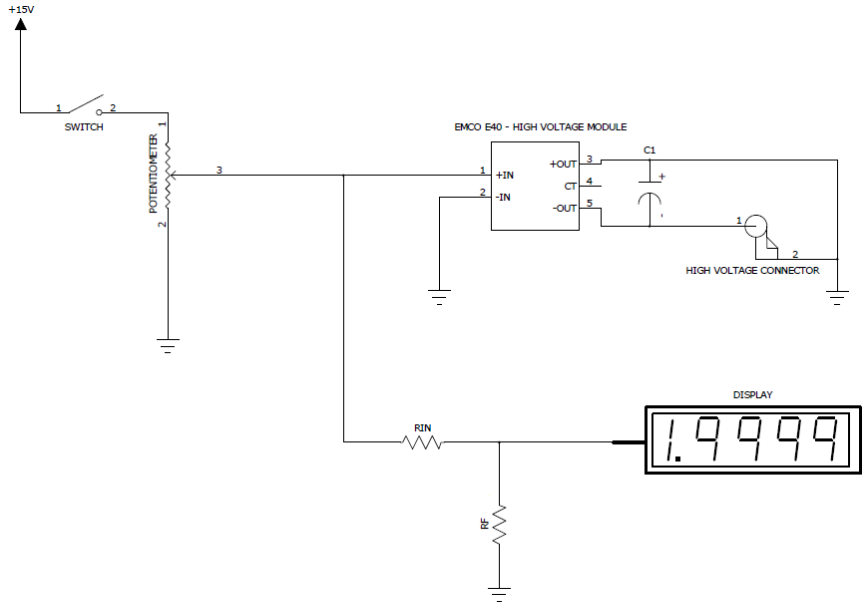

FIGURE 11. Schematic design for one channel with voltage divider.

To make the board more universal, one of the resistors was replaced by a potentiometer as seen in Figure 12. This connection allows the display values to be fine tuned for the required voltage range.

For this project the potentiometer was set to be 2KΩ and the resistor for voltage divider is 13KΩ. The final display connection is shown in Figure 13. This figure shows how the signals were connected to the display pins.

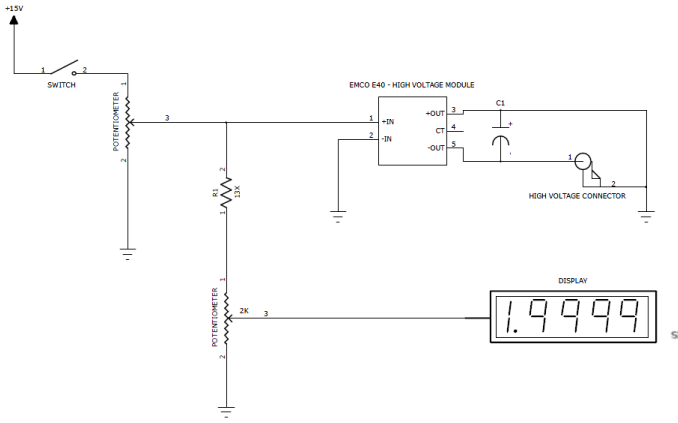

FIGURE 12. New connection for low voltage monitoring

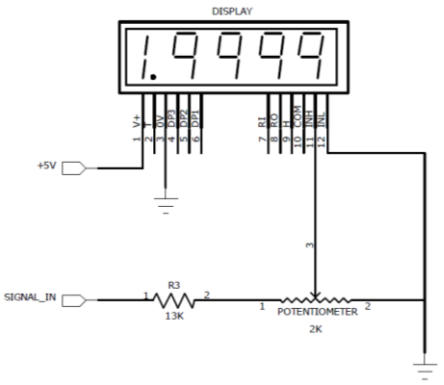

FIGURE 13. Specific display connection

Another critical connection was the operation amplifier connection for the EMCO E40 DC-HVDC converter. This connection was done to buffer more current to high voltage modules. The connection can be seen in Figure 14.

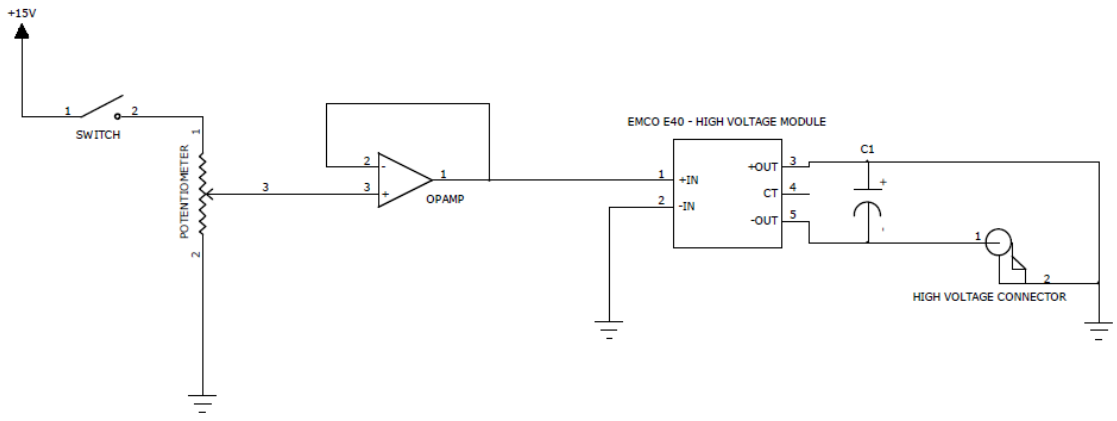

FIGURE 14. EMCO E40 – High voltage module connection

3.2 Final design

After making many different versions of the schematic and having chosen the main components, the final schematic for the power supply was ready. Block diagrams for both boards of the power supply can be seen in Figures 15 and 16. Figure 15 shows the block diagram of the display board. This board has most of the low voltage components like displays, potentiometers and operation amplifiers. Figure 16 shows the high voltage board block diagram. The goal was to keep the board as simple as possible; it has only the required components for generating high voltage. These components are the DC-HVDC converters, safety fuses and high voltage capacitors. The final schematic designs for both boards can be seen in Appendices 1 and 2.

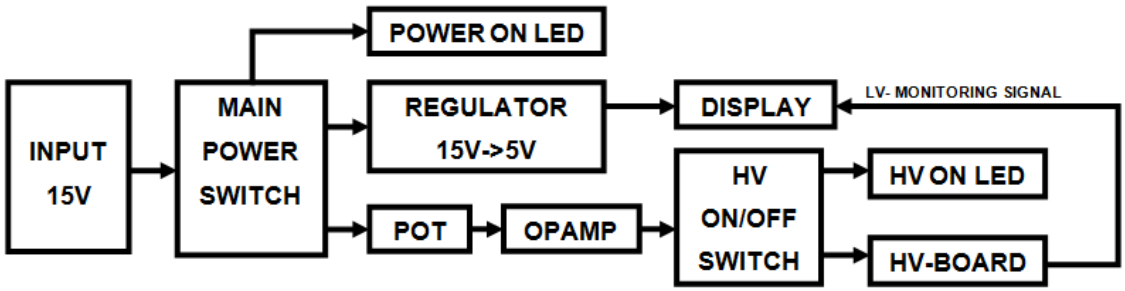

FIGURE 15. Block diagram for display board

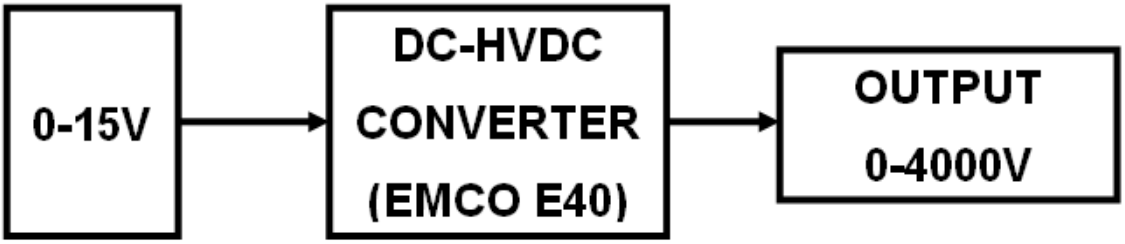

FIGURE 16. Block diagram for high voltage board

3.3 Component choosing

BOM (Bill of Materials) can be seen in Table 2. The Bill of Materials lists all the components used in a project.

TABLE 2. BOM (Bill of Materials)

Quantity	Component	Manufacturer	Model	Description
4	A1-4 (HV- Board)	EMCO High Voltage	E40	DC-HVDC Converter
4	J1-4 (Display Board)	Molex Inc.	15-24-7040	Molex connector (female)
4	J1-4 (HV- Board)	Molex Inc.	0015249044	Molex connector (Male)
1	POW_1 (Display Board)	Molex Inc.	39-30-2047	4Pin_RA_Molex-Power connector
4	DISPLAY_1-4 (Display Board)	Murata Power solutions Inc	DMS-40PC-1-RL-C	LED-Display
2	REG1, REG2 (Display Board)	Fairchild Semiconductor	LM7805CT	15 -> 5V Regulator
4	PS1-4 (HV- Board)	TE Connectivity	RXEF025	72V/40A Fuse
2	OPAMP1-2 (Display Board)	Micrel Inc	MIC7122	Buffer opamp
4	POT1 POT3 POT5 POT7 (Display Board)	Bourns Inc	3950S-2-103L	10 K Precision Potentiometer
4	POT2 POT4 POT6 POT8 (Display Board)	Bourns Inc	3313J-1-202E	2 K Potentiometer
5	S1-5 (Display Board)	C&K Components	7205SYCQE	Switch
4	R1-4 (Display Board)	-	-	13K Resistor
5	R9-13 (Display Board)	-	-	1.3K Resistor
4	C1-4 (HV- Board)	-	-	1nF HV-Capacitor
2	C2 C6 (Display Board)	-	-	0.1uF Capacitor
2	C1 C5 (Display Board)	-	-	0.33uF Capacitor
1	D1 (Display Board)	-	-	Power-ON LED (Green)
4	D2-5 (Display Board)	-	-	HV-ON LED (Red)

The operation amplifiers, displays and high voltage modules are the most critical components and they must be chosen carefully. The operation amplifiers were needed in the design because the first voltage divider looses current and the DC-HVDC converters needs a minimum of 175 mA to work. This means that the operation amplifiers need to work as current buffers. The reason of choosing the Micrel Inc. MIC7122YMM TR 2-channel buffer operation amplifiers was that they are able to drive 250 mA for each channel which is more than the minimum requirements and enough for the modules to work.

Micrel Inc. offers also 1- and 4-channel models of the operation amplifier. The reason for choosing 2-channel operation amplifiers was that using 1-channel version would require double amount of components which would mean increased costs and wasted space. With the 4-channel version, the traces would have been too long. (Micrel Inc. 2005)

The displays for this project were chosen based on the project specifications. The displays were supposed be able to show at least 4000 mV on the screen. This means that the displays should have 4.5 digits on the display. Murata Power Solutions Inc. was chosen because they offer this kind of display in reasonable price. (Murata Power Solutions. 2011)

EMCO E40 is the most critical component on this project. It was chosen for this project because it has proved its reliability in previous projects in IDLab. Everything on the project was constructed around these components. The EMCO E-series module can be seen in Image 2. (EMCO High Voltage Corporation. 2012)

IMAGE 2. EMCO E- series module

4 PCB- DESIGN AND MANUFACTURING

PCB Stands for Printed Circuit Board. The PCB- design of this project was done by using Mentor Graphics PADS Layout and Router designing tools.

After designing the schematic, the PCB design has two phases. In the first phase the schematic of the power supply has to be transferred into the layout design which is the outline of the oncoming PCB. In this phase the PCB outline is designed, but it also includes a lot of component footprint design which consists of component outline and pin-out design. In the second phase, when the components are placed, the copper routes have to be routed.

4.1 Layout design

The Layout design was done by using PADS Layout designing program. In the layout design process the circuit board is made to its digital form. This means that the real circuit board is theoretically going to look the same as in the layout design.

In the layout designing process the outlines of the boards were done first. The power supply was supposed to fit into a standard rack which is 16” wide. The IDLab had some standard rack cases in stock and so the PCBs were designed to fit in those cases. In this project the dimension restrictions for the high voltage board was 16” for wideness and as small as possible in depth. The reason for the depth restriction to be as small as possible was the length of oncoming copper routes. The copper routes should be as short as possible to avoid voltage loss. The display board had the same wideness restrictions but it could only be 1.5” high because that was the maximum height that can fit inside the case. Figure 17 shows an example of the PCB outline.

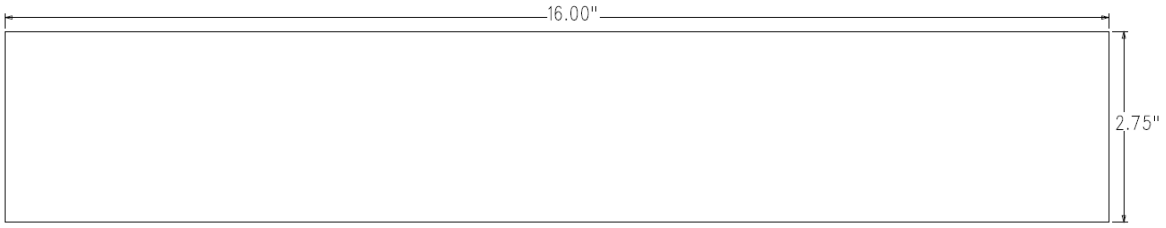

FIGURE 17. Outline of the High Voltage board with dimensions

After the outlines of the PCB are done the footprints of components must be drawn. The component footprints describe the component outlines on the design and they define the pinout from the schematic. Figure 18 shows the footprint design of the display.

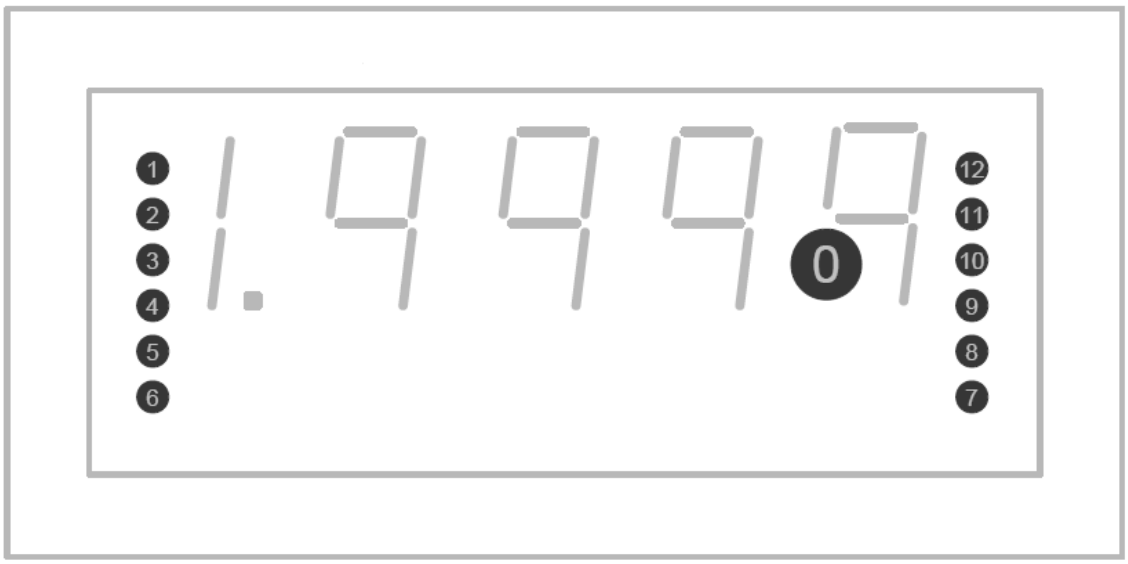

FIGURE 18. DMS-40PC-1-RL-C footprint

4.1.1 PCB design rules

The design rules are determined before placing the components and routing the traces to help the designing and manufacturing process. Design rules make designers work easier by making sure that the components, traces and vias won't be too close to each other. Manufacturing companies also have their own design rules that are based on the equipment they are using. At this project the company called Advanced Circuits from Denver, Colorado was chosen. One of the reasons this company was chosen is that they offer free PCB file check software. It is possible for customer to upload their designs to their web site and have them checked for free. IDLab also has good experiences about ordering the PCBs from there.

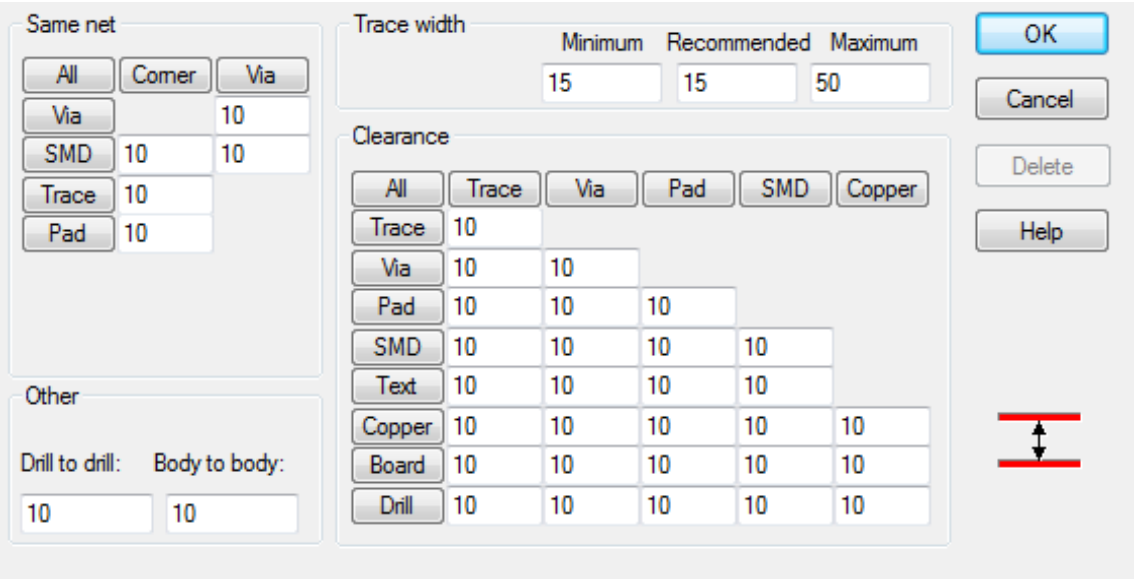

FIGURE 19. Display board default design rules

As can be seen in Figure 19 all the clearances have been set to 10 mils on the display board. This was done to make sure the traces will not cross talk together and there is enough space on the board to do this without extending it. The minimum clearance for Advanced Circuits is 6 mils. The trace width setting has been set to 15 mils which is the minimum and recommended value. Smaller traces could make the signal too weak. The 50 mil maximum trace width allows the copper route width to be changed during the routing process by hand between 15 to 50 mils.

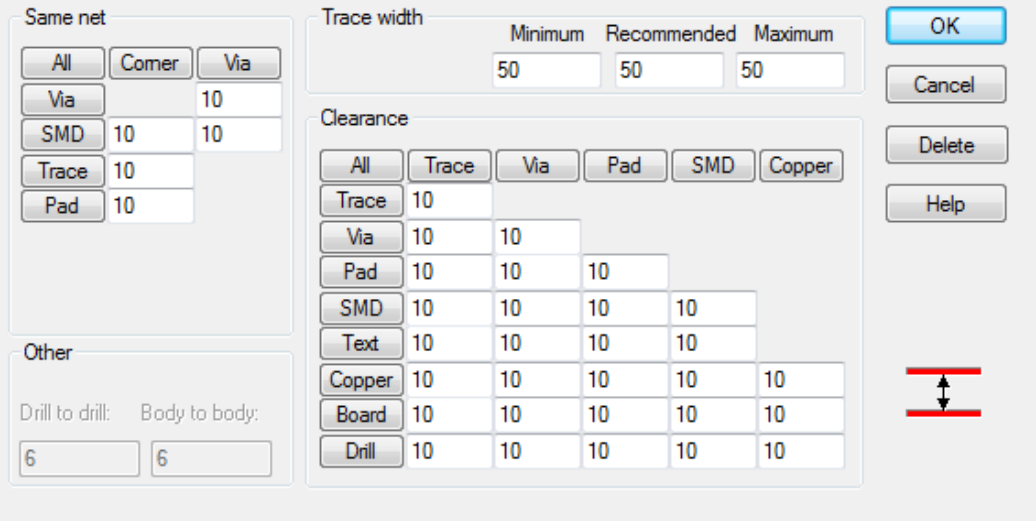

FIGURE 20. Design rules for high voltage traces.

With the HV-Board the default design rules were the same as with the display board. The only exeption was the high voltage traces which are shown in Figure 20. This was done by creating a class of its own for high voltage traces with different design rules. This way the design rules can be changed without changing the rules for other components. This exeption was made because too small high voltage traces can cause too much voltage loss.

Another main design rule factor is the layer definition. In these design rules the number of electric layers can be modified. Also the layer setups can be set here. The plane and copper areas can only be set on the certain type of layers. Figure 21 shows the layer definition rules for two different layers on the display board. This board was designed to have four layers. Top and bottom layers are for traces and two layers between are only for ground and power planes.

The high voltage board was designed to have only two layers, top and bottom. This was done to make the board cheaper. The board does not have many components so it was possible to be designed in this way. The top layer is designed to have all component copper routes and the bottom layer has only the ground plane.

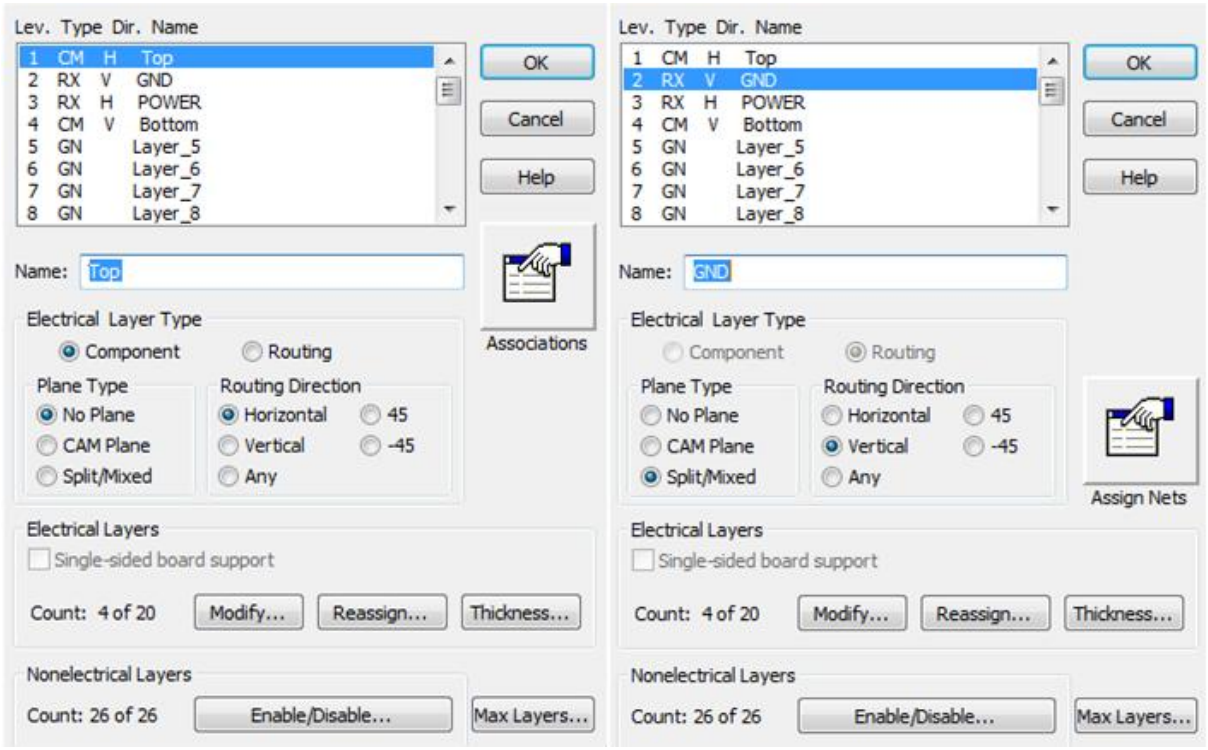

FIGURE 21. Layer setup rules with Top and GND layers

As can be seen from the GND layer definition rules on Figure 21, with the Split/Mixed layer the certain nets can be assigned for this layer. If the nets are assigned for this layer, only the defined nets can be used on this layer. Also the plane areas can only be set on Split/Mixed layer. This ability will help the routing process especially when the auto router is used. In the Figure 22 can be seen the assigned nets for the GND layer of the display board.

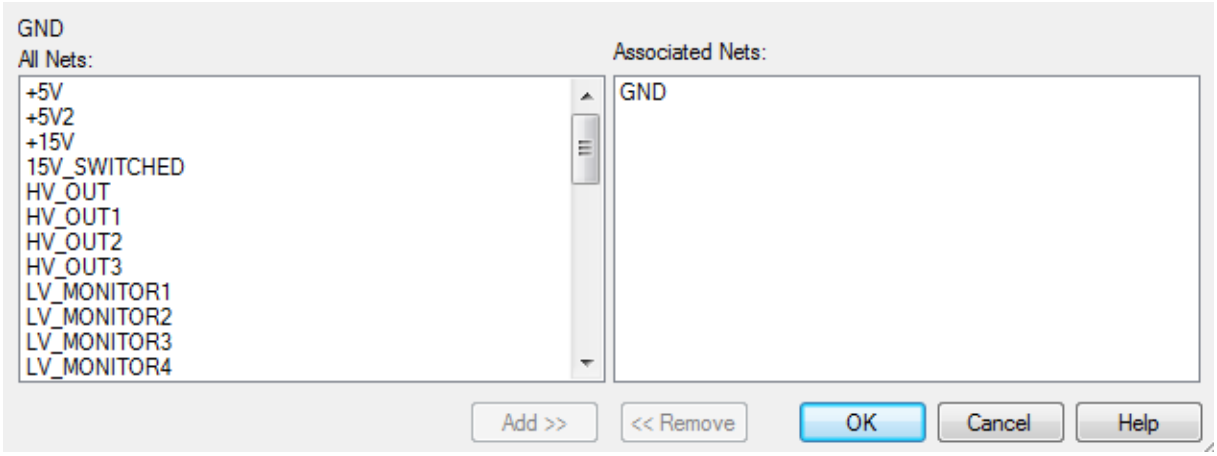

FIGURE 22. GND Layer net setup on Display Board

4.1.2 Component placing

After the design rules are set the components can be placed on final form of the PCB. When placing the components on the high voltage board, there were a couple of things that needed special attention.

Every component or trace that carries high voltage needs a lot of space around it. The first real issue with this board was the high voltage output traces coming from the components that generate the high voltage. The traces must be thick, short and as far as possible from the other components and traces. Also the traces cannot have sharp corners or turns. Otherwise cross talking, sparkling or voltage loss can occur.

Another major problem with the high voltage board was the Molex connectors between the boards. These connectors need to be at the same locations on both boards. Otherwise the boards will not fit together inside the case. This restricted the rest of the design since if the connectors are moved during the designing process; also the other board needs to be modified. This restriction was a bigger problem on the display board which has most of the components. The unrouted version of the high voltage board can be seen in Figure 23.

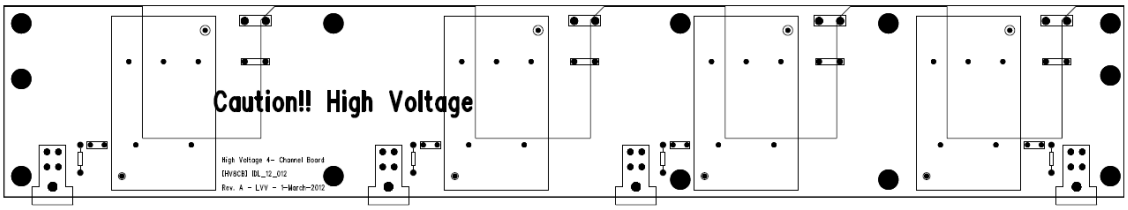

FIGURE 23. High voltage board design with placed components

On the display board there were more issues to consider while placing the components. Since the display board has the most of the components and more layers it was more complex to design. The distance between displays, high voltage switches and potentiometers needs to be constant to make the power supply look good and to be easy to use. In addition the two operation amplifiers needed to be between two channels they were buffering to make sure the traces were not too long for either channel. The unrouted version of the Display Board can be seen in Figure 24.

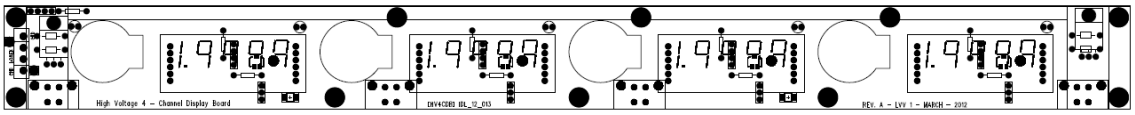

FIGURE 24. Display board design with placed components

The next issue was the precision potentiometers for the voltage adjusting which were too big to fit between the display board and case. This problem was solved by making holes for the potentiometers. The holes took a lot of space from the board and made the designing and routing process more difficult. The holes for potentiometer are located on the left side of each display. The hole on the circuit board can be seen in Image 3.

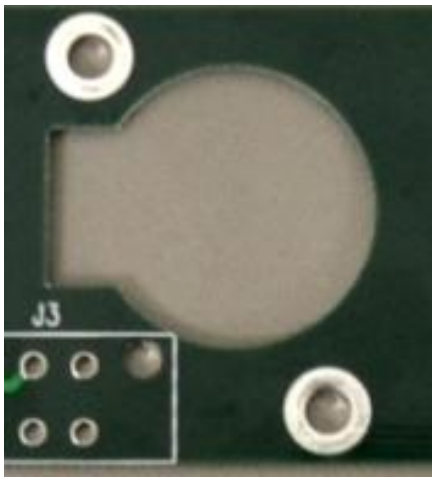

IMAGE 3. Hole for potentiometer

4.1.3 Plane areas and routing

The plane areas are made to ease the routing process. In this project the plane areas are made for power and ground. The display board was designed to have four layers. The top and bottom layers are for component placing and signal routing. The two layers between were determined as ground and power layers. The power layer has only the power plane which is designed to carry the operating voltage for every channel after the main power switch. This plane also makes sure that the input voltage is the same for every channel. The ground layer has only the ground plane. All ground signals go through this plane.

For the two layer high voltage board, only one plane area was made. Since the board has only the necessary components for generating high voltage, it was possible to design it to only have two layers. All the traces and components are placed on the top side of the board and the bottom side has the ground plane only. This was done to ease the routing process and to make sure there is enough space for the thick high voltage traces.

4.2 Finalized board design

When the schematic and layout designs were ready, the boards were tested with CAM file checking program and the Revisions A of the boards were ready to be manufactured. The finalized board layout designs for both boards for one channel can be seen in Figures 25 and 26. The final designs can be found in Appendix 3.

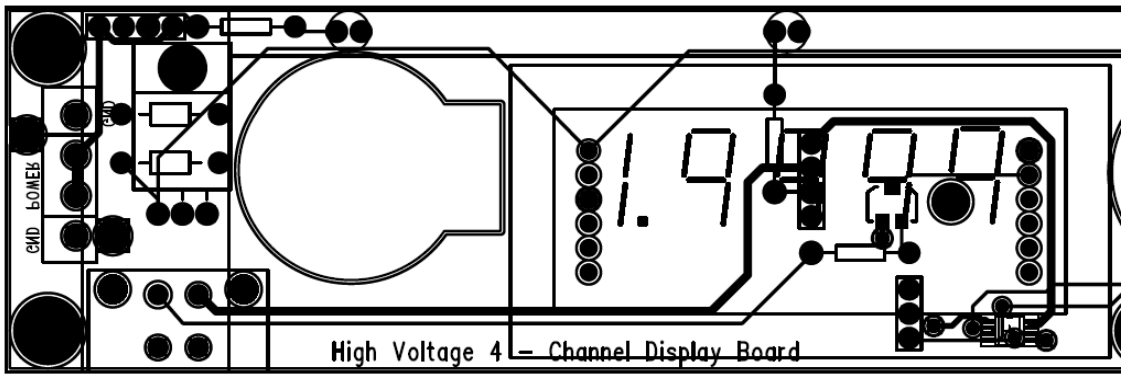

FIGURE 25. Final display board design for one channel

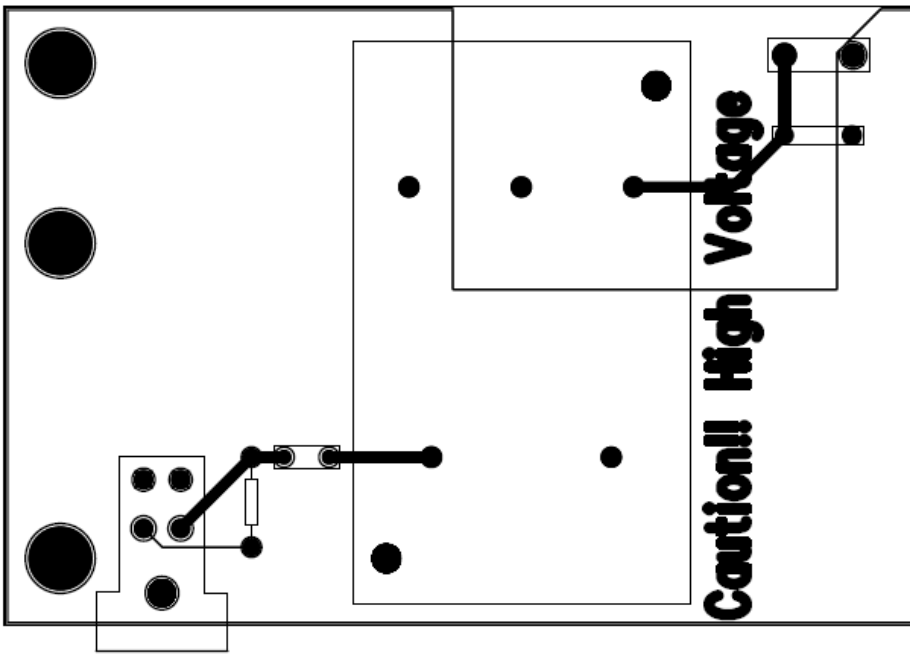

FIGURE 26. Final high voltage board design for one channel

4.3 Revision A

Revision A is the first prototype build of the power supply. The first prototype is very important for the whole product development process. The first prototype tells if there have been some flaws in the design or if there have been errors in the manufacturing process.

The first prototype should have the most of the functionalities and properties of the final product. This includes the raw version of schematic design with bill of materials and the circuit board outline design and shape. Changes might be needed after the testing process has taken place, since very rarely the product is perfect after building the first prototype. These changes usually cannot affect to the shape and size of the product anymore. Changing the shape and size parameters at this point could mess the visual design of the product. The images of the Revision A circuit boards are shown in Images 4-7.

IMAGE 4. High voltage board, top view

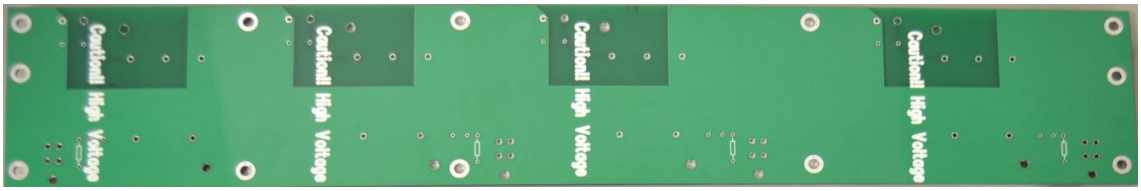

IMAGE 5. High voltage board, Bottom view

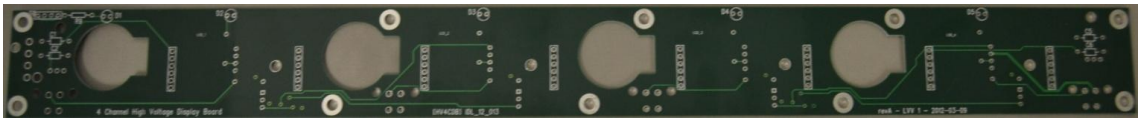

IMAGE 6. Display board, top view

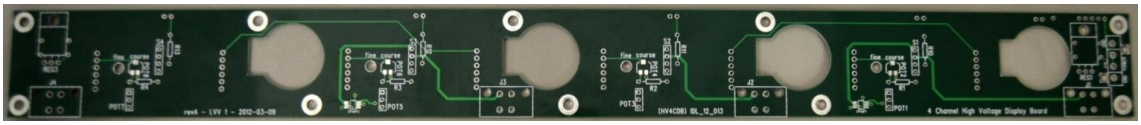

IMAGE 7. Display board, bottom view

4.4 Problems in Revision A

The problems in Revision A were found during the assembly and testing processes. The circuit board designing problems can be seen in Figure 27 and 28. The first problem with the display board was the cross-talking problem between the regulator and power connector. These components were designed to be too close to each other. This problem occurred at the assembling process when it was realized that the regulator has metal plating on the bottom side of the component. The problem is shown in Figure 27. This problem was fixed on Revision B by moving the regulator lower on the board.

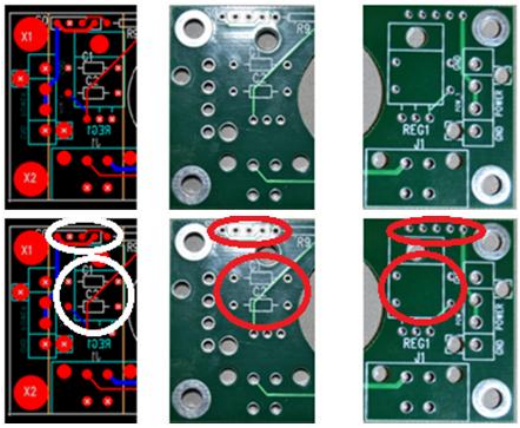

FIGURE 27. Problems between regulator and power connector in display board.

The second problem on the display board was between regulator and capacitors shown in Figure 28. The capacitors were designed to be through hole components and they were coming under the regulator. The regulator has the metal plating on the bottom side of the component and so there could be a sparkling problem between these components. This problem was solved on Revision B by changing the capacitors to surface mount components.

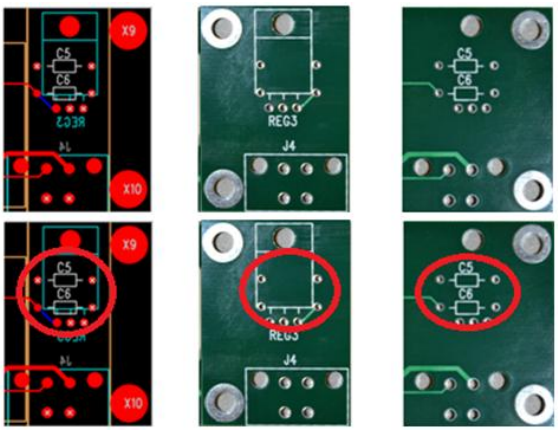

FIGURE 28. Problems between regulator and trough hole capacitors in display board.

The designing flaws on the display board did not prevent the testing because the problems could be temporally fixed. The regulator was coated with dielectric tape so it would not contact with other components. With this solution the prototype could be tested.

The only circuit board designing flaw in the high voltage board was with the EMCO E-40 footprint. The footprint was designed as a mirror image and so the voltage was connected into the ground plane. The problem did not affect the testing part because the components could be assembled on the bottom side of the board. This problem was fixed on the Revision B.

The testing process showed some instability problems in the high voltage output and fault in voltage monitoring in Revision A. The problems with the high voltage output instability were on the EMCO high voltage modules. In the high voltage stability-testing phase, it was found that the voltage changes with a longer period of usage. The maximum voltage change in a one-hour testing period was 84 V with the EMCO E-50 module, where the maximum voltage with this specific module was 5124 V.

This instability is based on the heat that the EMCO module produces. The component is molded inside the glass-filled epoxy case and the cooling outside the component case will not affect the values. (EMCO High Voltage Corporation. 2012)

One instability problem occurred in monitor values. The displays are fine tuned before plugging in the high voltage modules to avoid voltage shock. The first problem with displays occurred when the high voltage modules were plugged in. The values changed approximately 5-15% after plugging in the high voltage modules.

Another problem occurred in display stability testing. Like the output values, display values changed during the one hour stability testing phase. The maximum fault was 90 V. The maximum fault for the monitoring was set on +-1 V so this was the major problem and must be fixed in Revision B. The problem that makes the values to change is probably some kind of display loading problem. The test results are analyzed more specifically in Chapter 5.

5 TESTING

Testing was done to verify that the power supply works as it should and is safe to use. Different kinds of testing were done for the power supply to test all the basic functions and to find out if some functions do not work. The testing process was divided into six different phases. The testing part includes safety testing, high voltage function testing in two phases, stability testing for voltage and monitoring and ripple voltage testing phases.

5.1 Phase 1 - Safety Testing

The first safety testing was done for one channel. The channel was tested without a high voltage board to test that the operating voltage goes to display (Image 7). The next step in safety testing phase was to plug the high voltage board in without the high voltage module to test that the operating voltage goes to high voltage modules and the system still work correctly before plugging in the high voltage module.

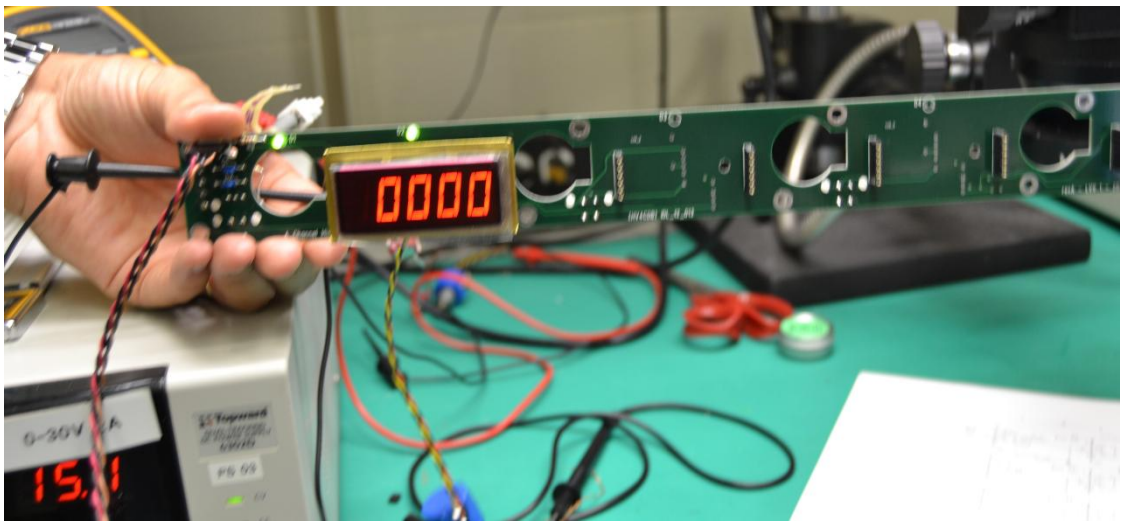

IMAGE 7. Basic function testing with one channel without high voltage board

5.2 Phase 2 - High voltage function testing with one channel

In high voltage function testing phase one, high voltage channel was tested with EMCO E50 module with 15 V input voltage. Current draw was 290 mA with full load. The test result can be seen in Table 3.

TABLE 3. High voltage testing with one channel and E50 module.

Input voltage (V)	Current draw (mA)	Output voltage (V)
15,1	290	-5171

Table 3 shows that the output voltage (-5171 V) differs only 3,4% from the value given in the datasheet (-5000 V). The result was expected.

5.3 Phase 3 - High voltage function testing with four channels

Testing phase 3 was made with all four channels. The testing was made with the E30 module in first channel and the E50 modules in three others. In testing phase 3 two different samples were taken. First sample was taken with various voltages (first line, Table 4). This sample was done only for safety testing before continuing with full values. After this safety check, next sample was taken with full values (second line, Table 4).

In high voltage function testing with 4 channels the input voltage was 15 V and current draw 690 mA. The results show that the power supply can actually generate the required voltages. The test results are shown in Table 4.

TABLE 4. Testing with 4 channels and E30/50 modules

Output voltage (V)			
Channel 1 (E30)	Channel 2 (E50)	Channel 3 (E50)	Channel 4 (E50)
-2012	-4010	-3007	-1011
-3053	-4986	-5026	-4905

5.4 Phase 4 - High voltage stability testing

In testing phase 4 the stability of high voltage modules were tested. This was done by driving the output voltages to the maximum and taking samples after every 10 minutes for 1 hour. The testing was done with 15 V input voltage. The testing results can be seen on Table 5.

TABLE 5. Testing 1 hour with 4 channels and E30/50 modules

Output voltage (V)				
Time	Channel 1 (E30)	Channel 2 (E50)	Channel 3 (E50)	Channel 4 (E50)
0 min	3092	5102	5121	5040
10 min	3047	5137	5061	5089
20 min	3047	5151	5080	5109
30 min	3048	5162	5091	5118
40 min	3048	5164	5092	5123
50 min	3048	5167	5095	5124
60 min	3047	5167	5095	5124

Table 5 shows that the high voltage modules are unstable. The maximum change for the voltage was in channel 4 where the voltage increment during the testing phase was 84 V. As described in Chapter 4.4, the instability problem was due to the heat produced inside the EMCO module.

5.5 Phase 5 - Display stability testing

In testing phase 5 the stability of the displays was tested. This test was done to find out if the display values change during a longer period of use. The testing was done with the 15 V input voltage. The results are shown in Table 6.

TABLE 6. Display stability testing.

Display (V)					
Time	Channel 1	Channel 2	Channel 3	Channel 4	Current draw(mA)
0 min	3133	4472	4427	4471	680
10 min	3139	4514	4462	4506	680
20 min	3143	4528	4484	4515	670
30 min	3143	4559	4495	4521	660
40 min	3150	4571	4498	4523	650
50 min	3151	4577	4500	4526	660
60 min	3152	4582	4502	4526	660

As can be seen in Table 6 above, the display values changed during the testing. The maximum allowed error in display measurements was +- 1 V. The reason for the changing values on displays is unknown. The problem could be some kind of display loading problem on the power supply. This problem is part of product development in future and it is going to be fixed in the next versions of the power supply.

5.6 Phase 6 - Ripple voltage testing

Ripple voltage testing was made with the EMCO E30 module to check how much the ripple voltage is. For this test the voltage divider needed to be build. This was done because the oscilloscope input could handle only +-300 V. The voltage divider was built with 5MΩ (left) and 512,2KΩ resistors to make the high voltage output be approximately 9% from its maximum value. The voltage divider can be seen in Image 8. The testing result is shown in Table 7.

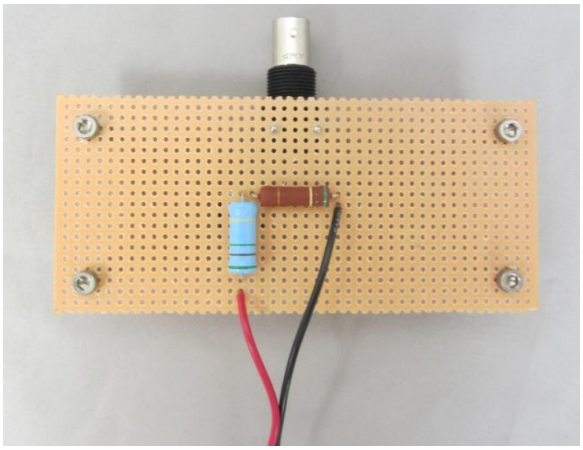

IMAGE 8. Voltage divider.

TABLE 7. Ripple voltage testing with one channel and E30 module.

Input voltage (V)	Current draw (mA)	Output voltage (V)	Ripple voltage (mV)
15	350	-2555	330mV

6 TECHNICAL SPECIFICATIONS AND PRICES

The Technical specifications and price information can be seen in Tables 8 and 9. From the Table 9 below can be seen that the power supply is very cost effective. The price for one channel is 298 $. This is very competitive price comparing to other high voltage power supply manufacturers. For reference Stanford Research Systems offer high voltage power supplies with similar output voltage ranges starting from 1395 $ for one channel power supply. (Stanford Research Systems. 2013)

TABLE 8. Technical specifications

Input Voltage	15 V
Input Current	250 mA/ Channel (1A for 4 channel)
Input Power	3,75 W/ Channel (15W for 4 channel)
Output Voltage	0 – (-4000) V
Output Current	0,75 mA
Max output Power (EMCO E - series)	3 W
Mechanical dimensions, High voltage board	16,15” x 2,75”
Mechanical dimensions, Display board	16,15” x 1,5”

TABLE 9. Price information.

Price			
Component	Price / component	Quantity	Price total
HV- Board	53,18$	1	53,18$
Display Board	47,34$	1	47,34$
EMCO E40	118$	4	472$
Display	78$	4	312$
Case	216$	1	216$
Precision potenti-ometer	11,27$	4	45,08$
Power supply	20,52$	1	20,52$
Other components	~25$	-	~25$
Total		~1191,12$	

7 FURTHER DEVELOPMENT

The first prototype build of the power supply has already been manufactured and tested. Some issues that need extra attention were detected in display monitoring stability and PCB designing. The issues considering PCB design are already fixed and the proposed layout designs for Revision B PCBs are shown in Figures 29 and 30. With the short terms of further development the main focus is going to be on fixing the display problems in Revision A. The proposed layout designs are not in manufacturing yet because the stability problem may cause some updates in the schematic and layout design.

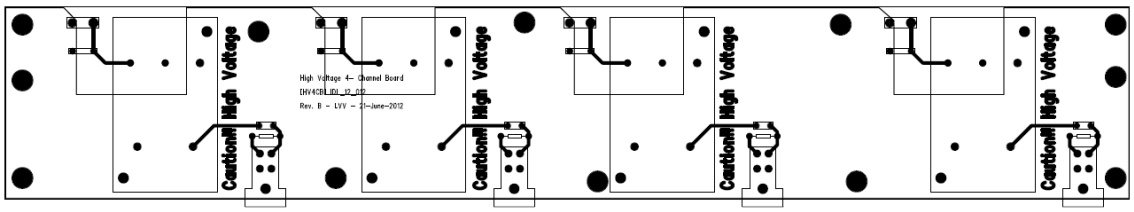

FIGURE 29. Revision B design of the high voltage board

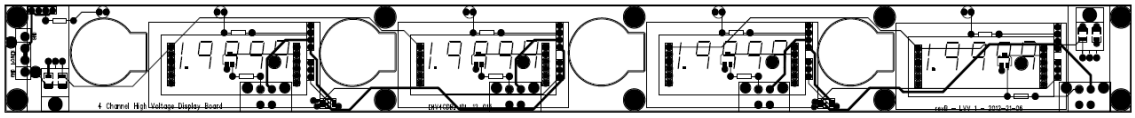

FIGURE 30. Revision B design of the monitoring board

The designing and prototyping of the power supply will continue until all the detected problems are solved, tested and approved. The main focus of further development is on fixing the problems in Revision A and manufacturing the Revision B in short term. In the longer period of time, many prototype versions are going to be built. When the power supply reaches all its goals it is going to be manufactured and sent to Japan.

8 CONCLUSION

The goal of the project was to design, fabricate and evaluate a 4- channel variable high voltage power supply for the operation of high performance Hamamatsu SL10 Micro – Channel Plate Photomultiplier Tubes (MCP-PMTs) in the Imaging Time of Propagation Particle Identification system upgrade for the Super B factory project. The first prototype build (Revision A) of the power supply was designed, manufactured and tested while doing this thesis. The power supply design included schematic and layout designing with PADS PCB designing tools, component selection, purchasing and managing the bill of materials (BOM) of the components, fabricating and testing the first prototype.

Revision A still has some issues concerning display stability and circuit board designing. The problems concerning the PCB designing are already fixed on the proposed version of the Revision B. Fixing the instability problems is part of the further development process in next prototype versions and they may cause some updates in schematic and layout designs.

During the project a lot of information and new skills were gained. In the field of PCB designing, schematic, PCB layout designing and routing were learnt and PADS PCB Cad designing tools were mastered. Also the knowledge about how to manage the bill of materials (BOM), choose and purchase components was increased. Abilities related to high voltage product designing, soldering surface mount components and analogue electronics as well as product testing skills were advanced. The experience of working on a big international project in a foreign language was very useful for the future.

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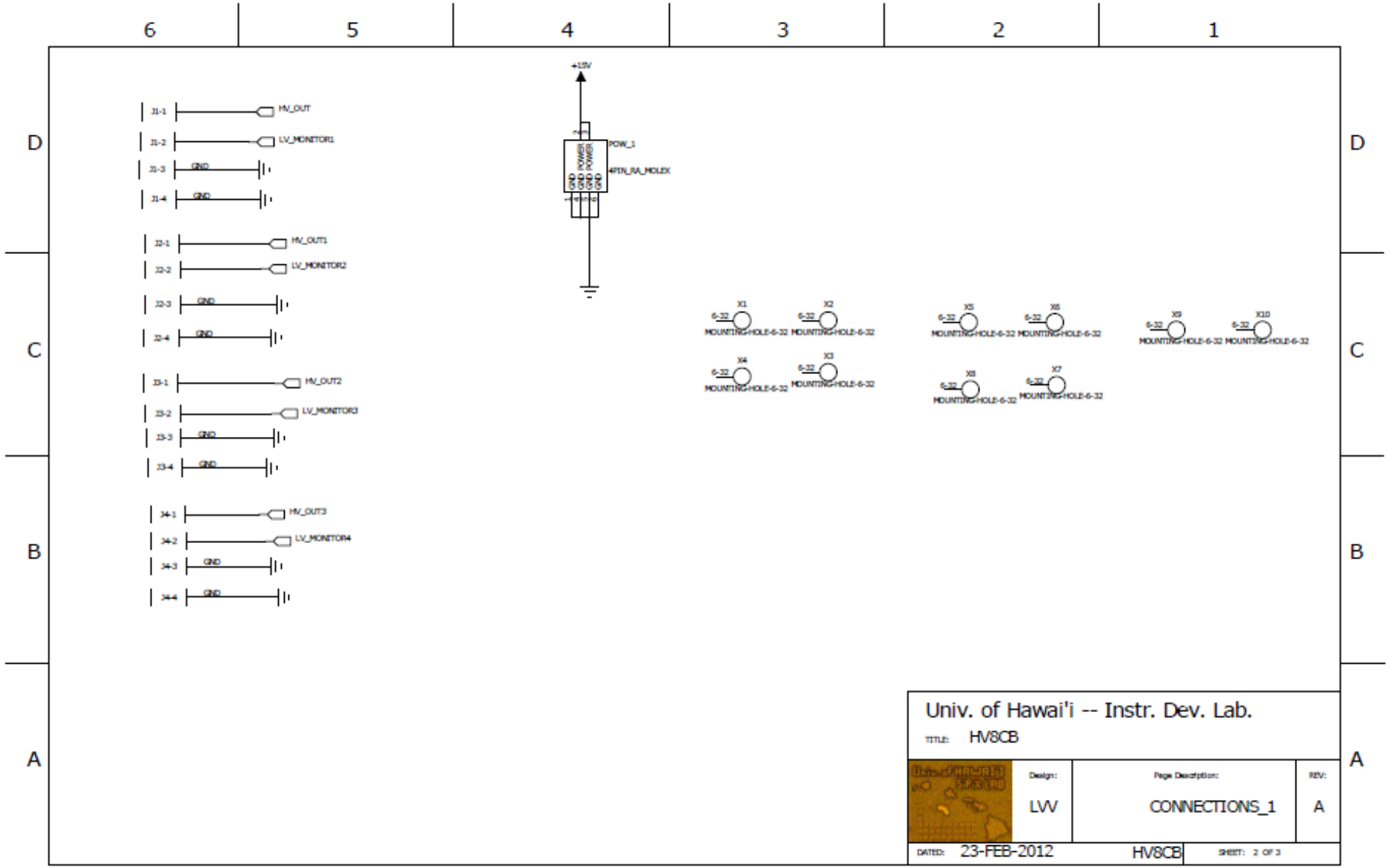
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GND
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GND
J3-1
HV_OUT2
J3-2
LV_MONITOR3
J3-3
GND
J3-4
GND
J4-1
HV_OUT3
J4-2
LV_MONITOR4
J4-3
GND
J4-4
GND
+15V
POW_1
4PIN_RA_MOLEX
GND
POWER
GND
POWER
X1
X2
X3
X4
X5
X6
X7
X8
X9
X10
6-32
MOUNTING-HOLE-6-32
Univ. of Hawai'i -- Instr. Dev. Lab.
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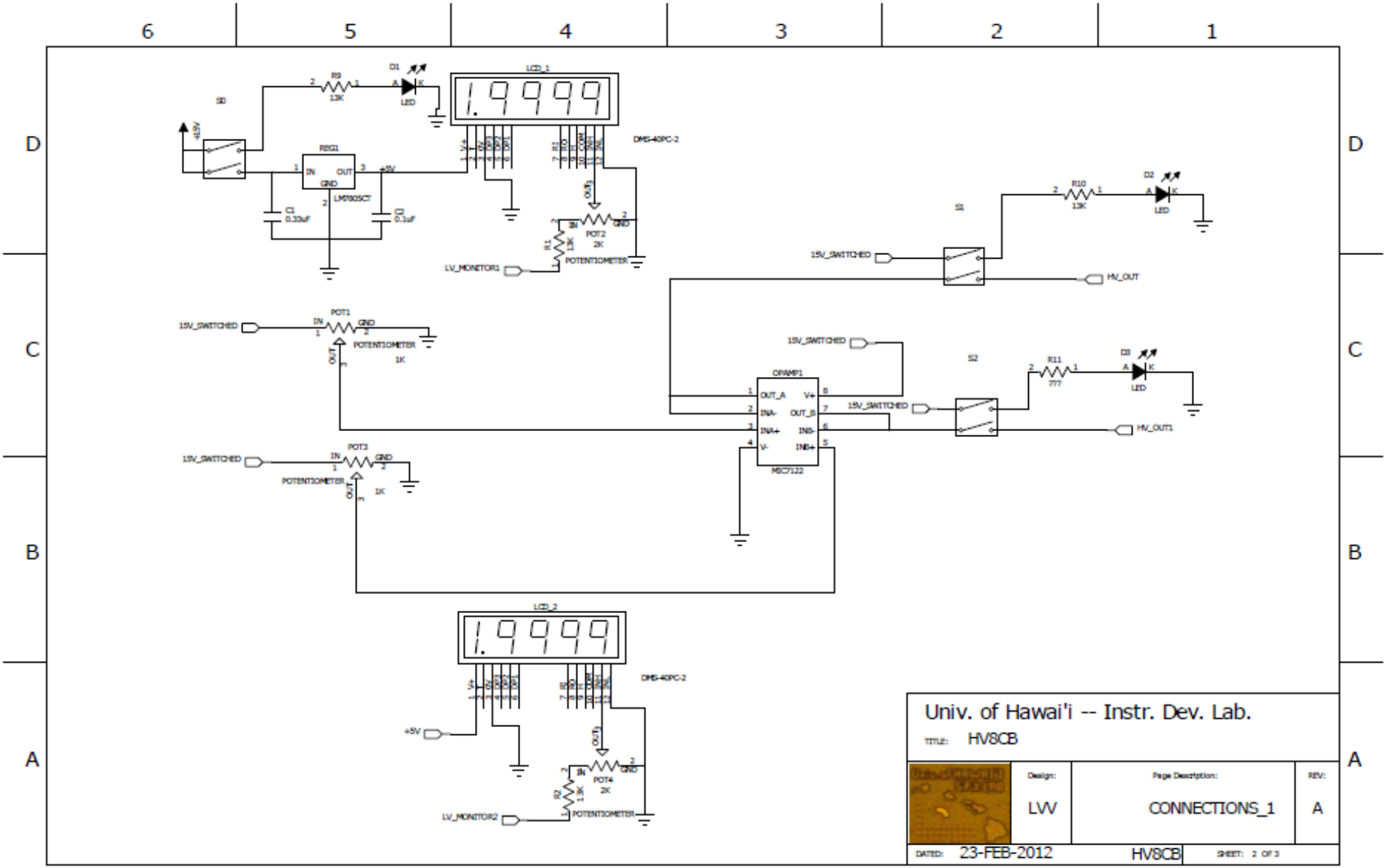

Univ. of Hawai'i -- Instr. Dev. Lab.

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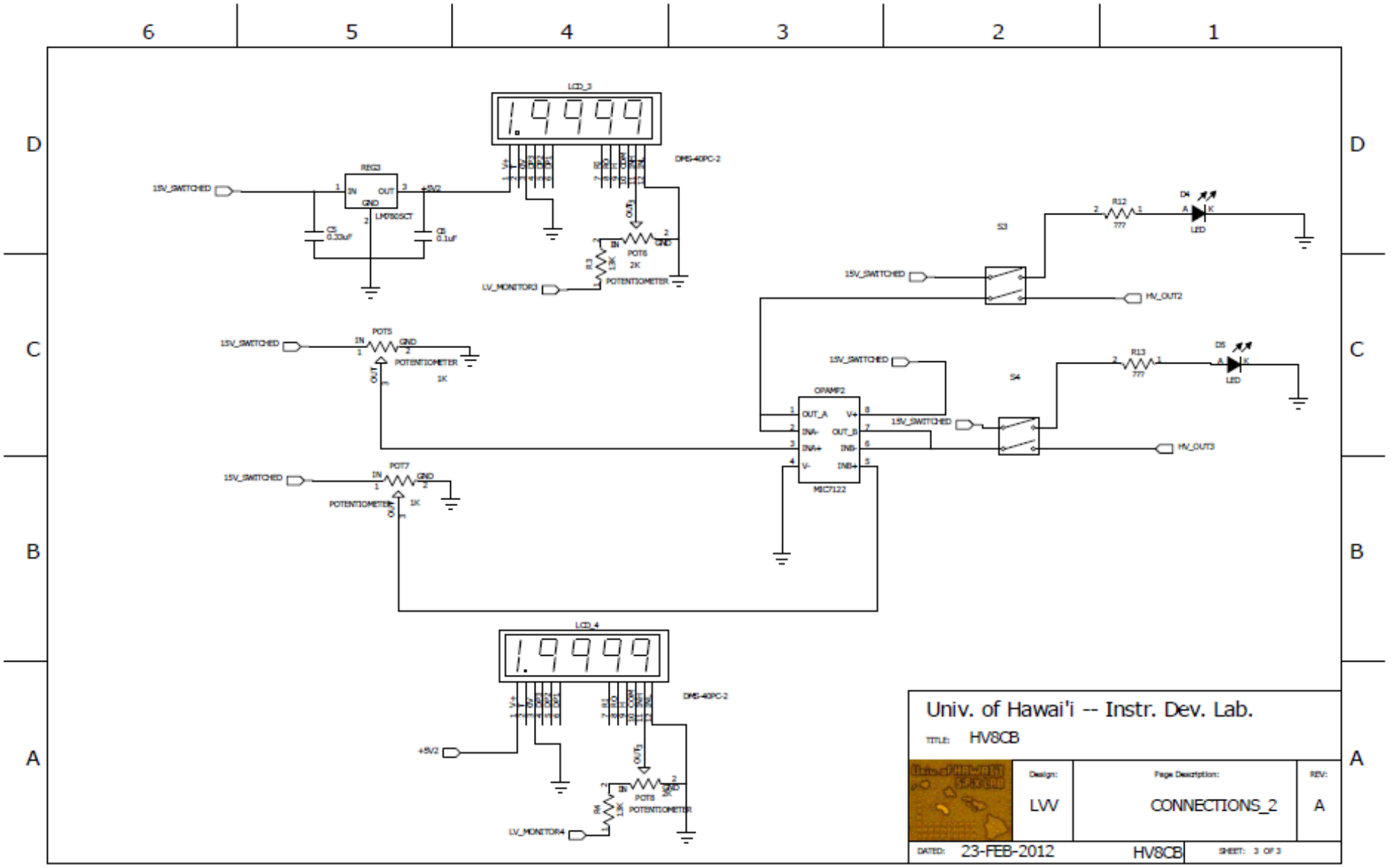
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5
4
3
2
1
D
C
B
A
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1.9999
DMS-40PC-2
REG3
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IN
OUT
GND
+5V2
LM7805CT
C5
0.33uF
C6
0.1uF
OUT3
POT6
2K
R3
1K
POTENTIOMETER
LV_MONITOR3
POT5
1K
POT7
OPAMP2
OUT_A
V+
INA-
OUT_B
INA+
INB-
V-
INB+
MIC7122
S3
S4
R12
R13
777
D4
D5
LED
HV_OUT2
HV_OUT3
LCD_4
POT8
LV_MONITOR4
Univ. of Hawai'i -- Instr. Dev. Lab.
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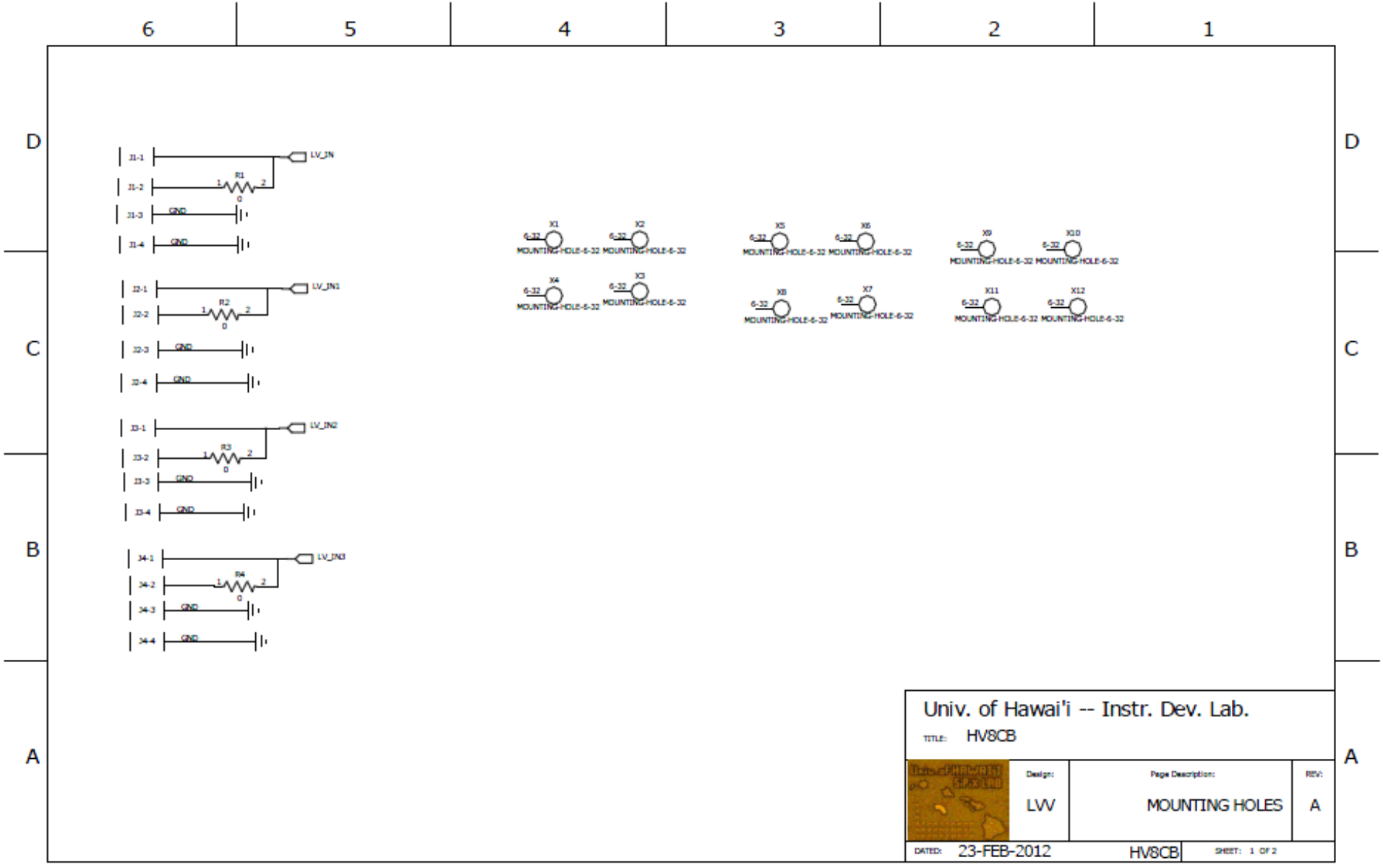
6
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2
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C
B
A
J1-1
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J1-3
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R1
GND
J2-1
J2-2
J2-3
J2-4
LV_IN1
R2
J3-1
J3-2
J3-3
J3-4
LV_IN2
R3
J4-1
J4-2
J4-3
J4-4
LV_IN3
R4
X1
X2
X3
X4
X5
X6
X7
X8
X9
X10
X11
X12
6-32
MOUNTING-HOLE-6-32
Univ. of Hawai'i -- Instr. Dev. Lab.
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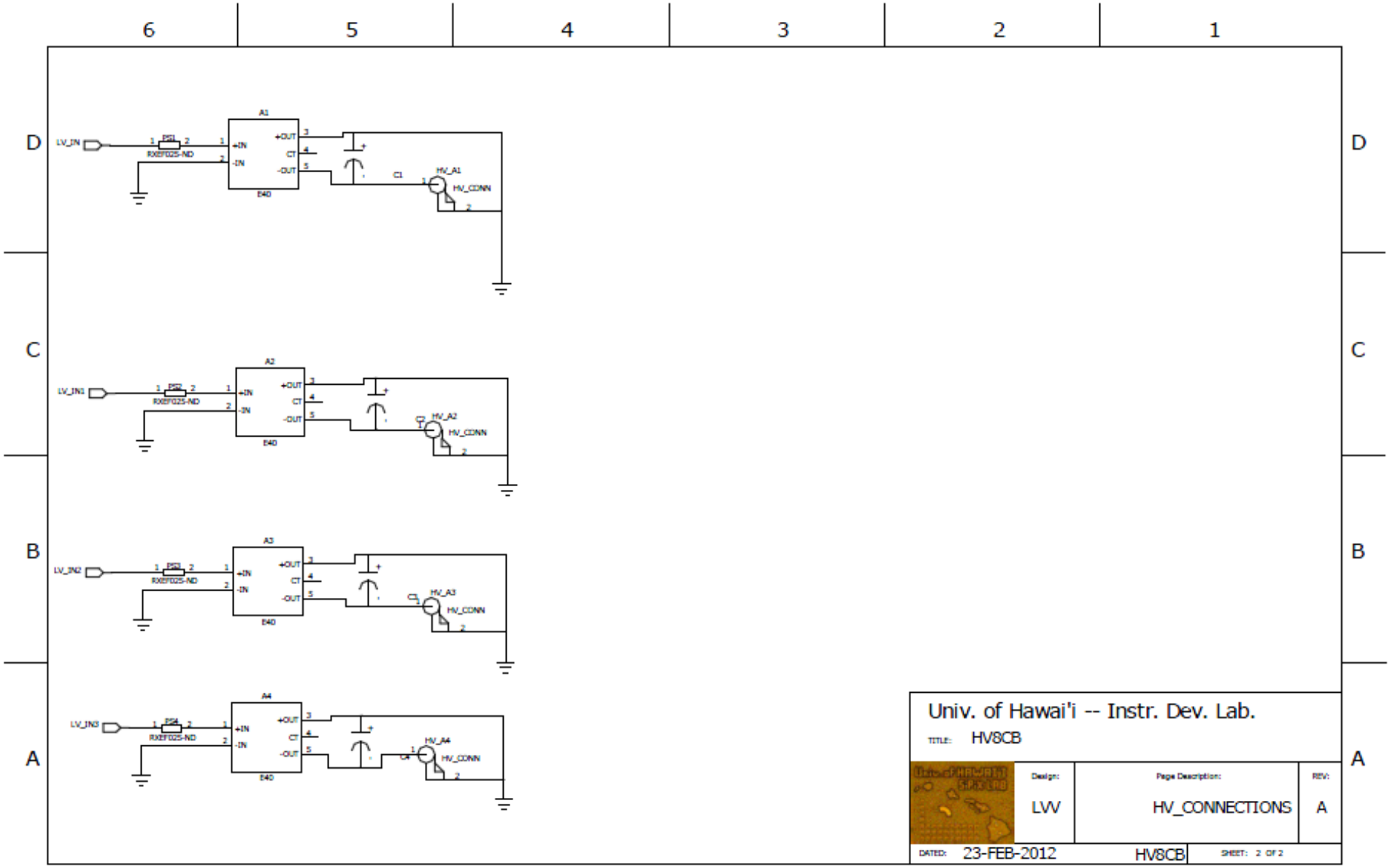
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C
B
A
LV_IN
LV_IN1
LV_IN2
LV_IN3
RXEF025-ND
A1
A2
A3
A4
+IN
-IN
+OUT
CT
-OUT
E40
C1
HV_A1
HV_A2
HV_A3
HV_A4
HV_CONN
Univ. of Hawai'i -- Instr. Dev. Lab.
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HV8CB
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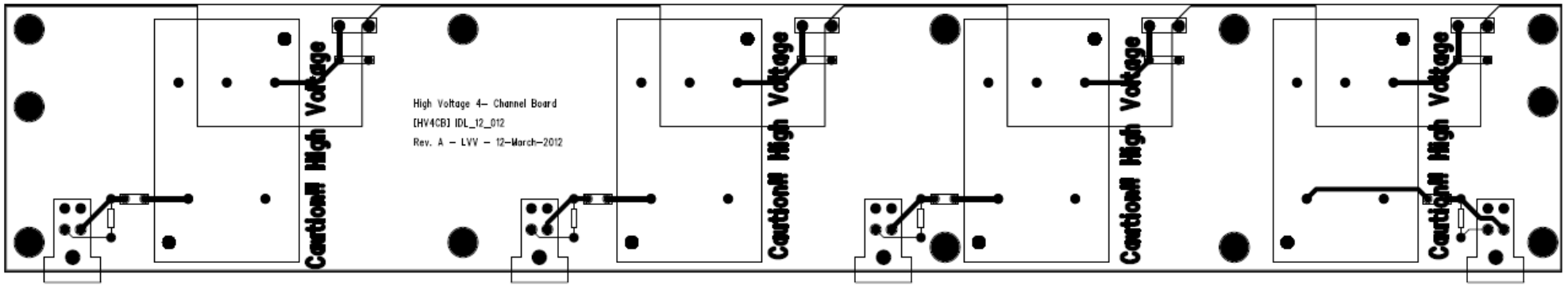
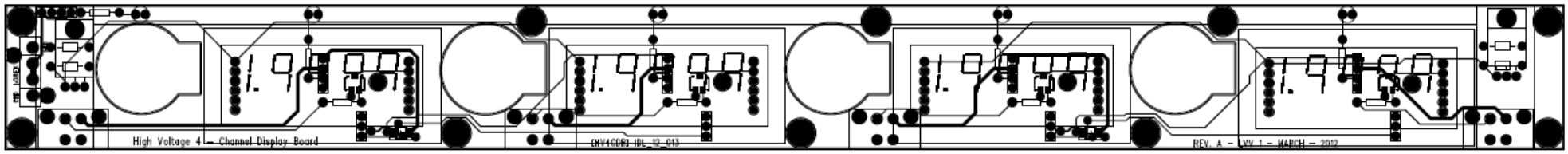


High voltage board revision B



Display board revision B

Varner, G. 2012. About my thesis and pictures [email]. Recipients: Ari Parviainen; Janne Himanen; Jussi Kangaskoski; Lauri Karppinen; Vihtori Virta. Sent 30 Maay 2012 [accessed 30 May 2012].


SAVONIA