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Low-Noise Current Source for Dilution Refrigerator Heat Switches

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<p>Low-temperature physics, or cryogenics, has fast returned to the forefront of technological advancement in recent years with the advent of the quantum computing processor. This experimental technology, which is still under development to discover a more stable outcome, requires extremely low temperatures in order to function properly.</p> <p>The need for a noiseless environment is obvious in this case, since at the lowest temperatures, even the slightest interference can throw off measurements wildly. Working with wiring and electronics, this thesis project aimed to make a cleaner current source for resistive heaters which are used to control thermally isolating heat switches within the devices, and also to literally heat up the device after tests have been performed. A prototype was developed based on a simple clean current source topology found in a white paper, and modified to fit the needs of the specific application.</p> <p>After multiple iterations, debugging and reworking, the current source prototype was found to function as planned. LTSpice simulations done alongside the physical implementation agreed with breadboard circuit testing results, and a schematic and layout were created. The prototype printed circuit board is now ordered, and components will be hand soldered in place before further testing, and then will be tested again in the dilution refrigerators themselves.</p>	
Keywords	Low Noise Current Source, Voltage Regulation, Current Source, Cryogenics

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List of Abbreviations

Abbreviation	Meaning
K	Kelvin (temperature scale)
MRI	Magnetic Resonance Imaging
Qubits	Quantum Bits
He-3	Helium isotope 3
He-4	Helium isotope 4
DC	Direct Current
AC	Alternating Current
PCB	Printed Circuit Board
LED	Light Emitting Diode
Op-Amp	Operational Amplifier
A	Ampere
V	Volt
MOSFET	Metal-Oxide-Semiconductor Field-Effect Transistor
SMD	Surface Mounted Device
DIP	Dual In Line (switch)
RefDes	Reference Designation

1 Introduction

Cryogenics was originally developed simply as a means to liquefy the permanent gases, which are classified as gases that require temperatures from 174 down to 0 Kelvin (K) to enter a liquid phase. They are named as such because they were originally considered to be unchangeable, and so permanently in a gaseous state. The last gas to ever be liquefied was helium, which has the lowest boiling point of any known substance. Helium-4 was finally liquefied in 1908 at a temperature of 4.2 K, by Dutch physicist Heike Kamerlingh Onnes. [1]

Onnes later turned his attention to lowering the temperatures of other elements, mainly metals, in a quest for lower resistances. It was theorized at the time that all resistance in metals would disappear when they reached absolute zero, also known as 0 K. This would have proved very useful for electrical applications, had 0 K temperatures been possible, as resistance is literally a loss of electrical power as heat. What he discovered, however, was that the electrical resistances in certain metals dropped quite suddenly at temperatures above the unattainable 0 K. The effect, known as superconductivity, proved to be invaluable in future applications such as particle acceleration and magnetic resonance imaging (MRI). [1]

In today's technological world, cryogenic research has applications in superconductivity, space technology, and even waste management, where rubbers or plastics are chilled to temperatures around 175 K and then crushed and ground into fine reusable granules. The newest arrival, quantum computing research, is still in its infancy, but quantum computational operations have been executed on small numbers of quantum bits (also known as qubits) already. Many governments as well as private companies continue to fund research of this technology, which would be far more powerful than conventional computing techniques. Quantum computing currently is only able to function at any useful capacity when it's at extremely low temperatures, however, since qubits require temperature that is much lower than their characteristic energy. As the temperature drops, the functions of the processors become more and more stable and accurate, and so more feasible. [1; 2]

To perform proper research on these quantum devices, a clean noise free environment is essential. It's exceedingly difficult to operate test equipment and perform actual measurement without electrical signals. The need for a clean current source for the cryostat heat-switches, which control movement of gases which thermally couple or decouple different temperature plates in the refrigerators, was born from this requirement, this being essential to a rapid cooling process achieving these low temperatures.

The focus of the project was to simply create a new current source for the heater switches, which would produce less noise and efficiently provide the needed heating power to control the required functions.

2 Theoretical Background of Current Source for Cryo-Systems

This section will explain the general idea behind this project and its motivations, as well as how it should work. First a brief explanation is given for dilution refrigerators, to help give some understanding of where this project is coming from. The second section describes how the heaters are used in the dilution refrigerators. Noise concerns are explained to give an idea of why this project aimed to redesign the current supply. Finally, the current source itself is covered, including then the voltage regulator which powers it. Appendix figure 6 shows the internal system of one of the refrigerators where this project will be implemented.

2.1 Dilution Refrigeration

In recent history, before dilution refrigeration, there were no available forms of continuous cooling to temperatures under $\sim 3\text{mK}$. Previous to this technology, the common method for reaching such low temperatures was to have a cold chamber submersed in a cryogen bath. The cryogens, liquid helium typically for very low temperatures, would be boiled off and essentially lost to achieve cooling. This system could become especially expensive when trying to reach any temperatures down to 1 K, because it re-

quires a second pot of helium-4 isotope, which would also be eventually lost. Though some helium recycling systems were developed, they could never maintain any temperatures below ~ 2 K.

Pulse tube refrigeration technology has made it possible to achieve low temperatures without losing helium-4 to evaporation. Two stage pulse tube refrigerators have reached temperatures below 2 K without the use of any cryogenes. The basic configuration is a metal cylinder with one open end and one closed off end. The open end provides low temperatures while the closed end accumulates the heat. Both are connected to their respective parts with heat exchangers. The tube works on a principle of gas compression within the tube which draws heat energy away from the open end of the tube and into the pressurized gas in the closed end. [3]

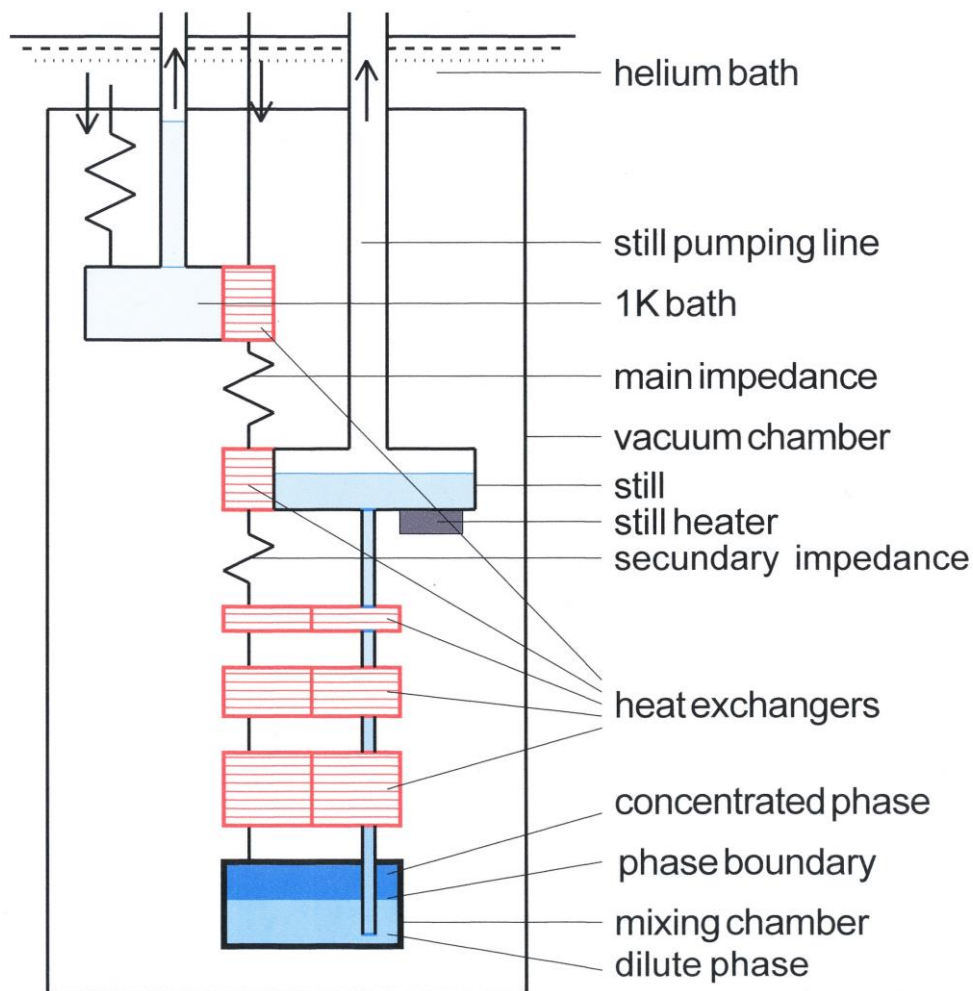


Figure 1. Schematic diagram of the low-temperature part of a dilution refrigerator.

The dilution refrigerator equipped with pulse tube technology was the solution for extreme cooling without the wasteful cryogen baths. They used the helium recycling systems to cool helium-4 and helium-3 to stable liquid state temperatures, then they combined them in a mixing chamber in the lowest level of the cooling chamber. By combining the helium-3 into the helium-4, they produce a sort of distillation process by which the helium-3 sinks from a higher phase of a nearly 100% He-3 into the isotope mixture phase, consuming heat energy in the phase change process. This occurs due to properties of the two isotopes which cause them to want to reach an equilibrium state of about 6.6% He-3 and 93.4% He-4 in the mixed phase. Any percentage of He-3 above that is pushed out and rises, cooling the incoming He-3 until it reaches the still, from whence it is sent through the cycle of cooling stages until it enters the mixing chamber once again, as seen in figure 1.

2.2 Project Concept

In dilution refrigerators, there is often need to either thermally couple, or thermally isolate different stage plates from each other. For this reason, the heat switches are essential to expedite both the cooling down and heating up of the refrigerator

These switches are operated by absorbing thermally conductive gas when they're cooled, effectively decoupling two surfaces from one another, or conversely by desorbing the same gas and coupling the surfaces instead. The heat required to activate these switches is minute, and since the chambers are being cooled during normal operation of the machines, the cooling is provided by the environment. The heat then needs to be provided, and small manganin coil heaters are used to do so.

The heaters used are typically powered with DC current fed through phosphor-bronze wires which lower their resistance as they are cooled. In order to produce heat, however, there is a manganin twisted wire loop tightly coiled around a gold-plated copper bobbin. Manganin has the special property that its resistance stays relatively stable even at extremely cold temperatures. This means that even in the low temperatures present in the fridge, the resistive manganin coil will still heat up sufficiently to operate the heat switches when a current is passed through.

Since there are currently three different heat switch wire configurations (single, double, and quad), with each acting as resistors in parallel, the proposed current source has been designed with different current output options included in the design. Each current can be selected using a small dual in line (DIP) switch on the printed circuit board (PCB), which supply voltage over differing resistances to produce desired values. Those currents are fed from the external heater controls into the device through hermetically sealed wire feedthroughs. That external heater control box is where the proposed circuit will be implemented.

2.3 Need for Low-Noise

In the cooled, ultra-low energy environment inside the refrigerators, there is a need for minimal interference of any sort. The lowest portion of the cooling chamber is so cold that in orders of magnitude, it is comparable to the difference between temperatures on earth versus temperature in the middle of our star, the sun. It takes immense amounts of energy to achieve these extraordinarily low temperatures, but the smallest amounts of stray energy released into such an environment can quickly vitiate the cooling achieved.

In addition to the low temperatures themselves being threatened by any sorts of stray radiation, the chambers are almost exclusively used to perform tests on materials or devices which are very sensitive to any sort of interference. The requirement for a super low-temperature environment is generally because there is need for a lack of any sort of external energy intrusions, as these would confound the hypersensitive results of such analysis.

Since direct currents can be easily isolated by physically disconnecting wires, and the heaters are powered by DC, the problem is with stray alternating currents causing radio interference, inductive coupling, or capacitive coupling. Limiting noise in components and the circuit as a whole helps to minimize these undesirable effects in the environment. Even though the circuit in question will be located outside the dilution chambers, the signals running through the lines will transmit much of the stray interference originating from the current supply.

2.4 Precision Current Source

Current sources are useful for a multitude of reasons. They provide a constant current over a load, even when the load resistance varies, to certain limitations, of course. Within those set limits, though, the steady current can be very advantageous in such applications as driving LEDs, where the colour temperature changes depending on the current. They can be used in battery charging applications, in multimeters to measure resistance, to bias a transistor, or in this case to power a resistive heater. [4]

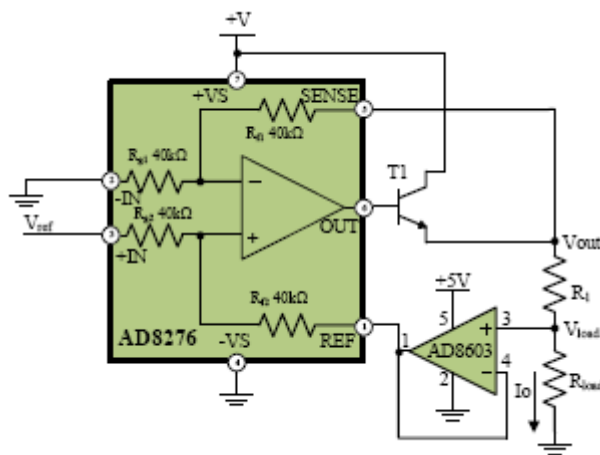


Figure 2. Difference amp and op amp form precision current source. [4]

A precision current source can be built using an Op-Amp (Operational Amplifier), resistors, and other discrete components. In the proposed current source, based on the AD8276 shown in figure 2, the output current can be calculated as follows: [4]

$$I_o = V_{ref} \frac{\frac{R_{f2}}{R_{g2}} + \frac{R_{f1}}{R_{g1}} * \frac{R_{f2}}{R_{g2}}}{R_1 \left(1 + \frac{R_{f2}}{R_{g2}} \right) + R_{load} \left(\frac{R_{f2}}{R_{g2}} - \frac{R_{f1}}{R_{g1}} \right)}$$

(1)

If the internal resistances are all equal, the equation can be reduced to: [4]

$$I_o = \frac{V_{ref}}{R_1} \quad (2)$$

The maximum output current is limited by the op amp input range, diff amp output range, and diff amp SENSE pin voltage range. The following three conditions must be met: [4]

$$V_{load} = I \times R_{load} \quad \text{Within op amp input range} \quad (3)$$

$$V_{out} = I \times (R_{load} + R_1) \quad \text{Within SENSE pin voltage range} = 2(-V_s) - 0.2 \text{ V to } 2(+V_s) - 3 \text{ V} \quad (4)$$

$$I \times (R_{load} + R_1) + V_{be} \quad \text{Within AD8276 output voltage range} = -V_s + 0.2 \text{ V to } +V_s - 0.2 \text{ V} \quad (5)$$

The SENSE pin can tolerate voltages almost twice as large as the supplies, so the second limitation will be very loose. [4]

Many alternate configurations were offered which could accommodate such requirements as eliminating the need for the feedback amplifier, significantly lower cost at the expense of accuracy, or simplified circuits for low current applications. The original precise composition was chosen, however, because it was the best suited to the goals of the project, which was noise reduction and reliable current output in the desired range of 30 mA to 90 mA.

The boost transistor needed to have a V_c (collector voltage) higher than the power supply voltage and I_c (collector current) higher than the chosen output current. The transistor MMBT2222 was selected from available parts in the workplace, and it held up in every step of design and testing.

2.5 Voltage Regulator

To properly run the proposed a current source, a steady regulated voltage is required. The simple and low-cost LM317 was chosen originally as it was easily available. It held up to scrutiny throughout development, and is used in the final circuit version.

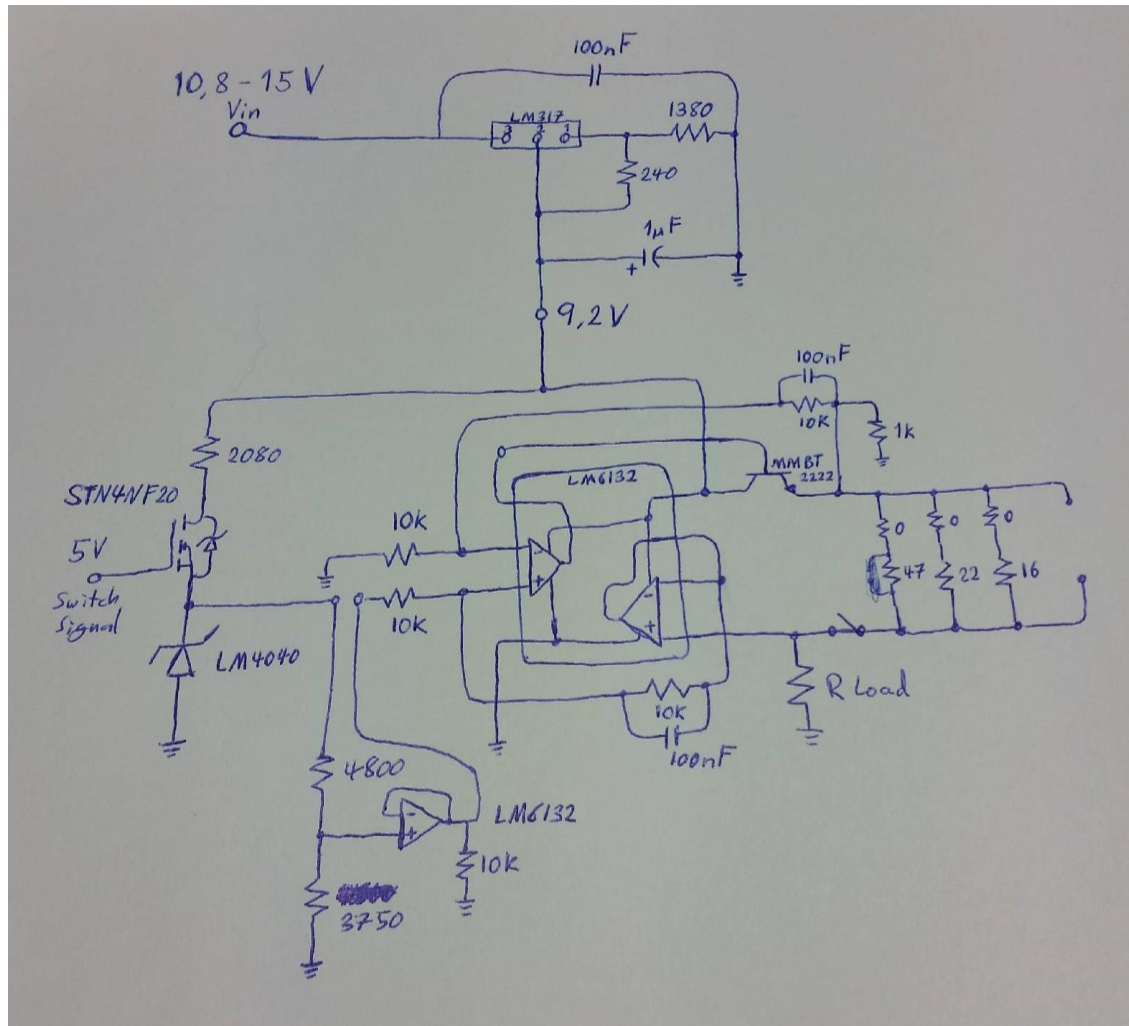


Figure 3. Final hand-drawn schematic of single source with voltage regulator and MOSFET switch.

The final single-source hand-drawn schematic can be seen in figure 3. The top portion, above the 9.2 V point, is the voltage regulator circuit, based around the LM317. This is a 3-terminal floating regulator. During operation, it develops and maintains a voltage of 1.25 V between its output and adjustment terminals. It is shown in the drawing with

output on the middle terminal and adjust on the right because the physical package is implemented this way, despite all design schematics showing them reversed.

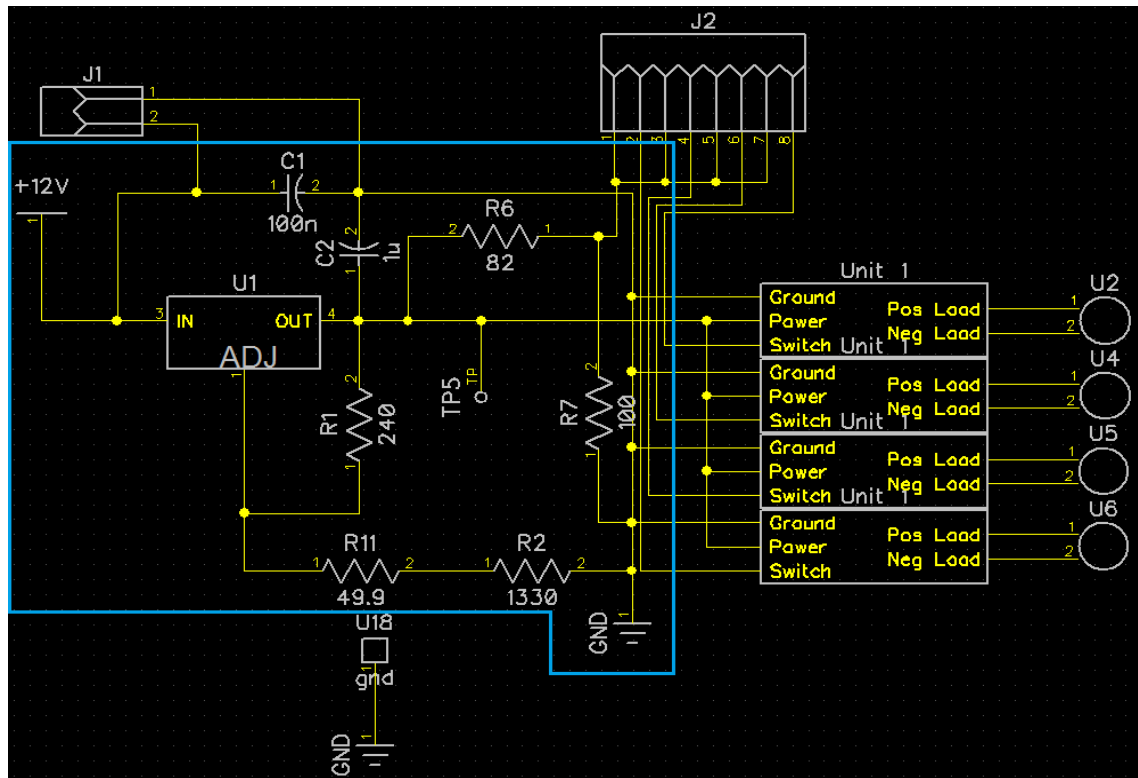


Figure 4. The highlighted regulator circuit surrounded by blue here, but excluding the voltage divider made up of R6 and R7.

In figure 4 is illustrated the voltage regulator sub-circuit. The pin on the left, pin 3, is where the input voltage is supplied, from the battery or otherwise. The right pin, pin 4, is the output in this diagram. This is connected to the ground with a tantalum capacitor in order to improve transient response in the circuit, meaning that the voltage level will oscillate less before returning to a steady state after the input has changed or the load resistance has change. Pin 1 is the adjustment pin which controls the output of the regulator. Reference voltage at the terminal is converted to a programming current by the 240 Ω resistor, and this constant current flows through the 1380 Ω resistor to ground. The output voltage is calculated from this current as follows:

$$V_{out} = 1.25V \left(\frac{R_2}{R_1} \right) + I_{adj}(R_2)$$

(6)

The adjustment terminal current represents an error term in the equation, and the LM317 was designed to control I_{adj} to less than 100 μA and keep it constant. To accomplish this, all the quiescent operating current, which is the baseline current drawn by the device when it's not loaded, is fed back to the output terminal. This imposes the requirement for a minimum load current. If the load current drops below the minimum, the voltage will rise. [5]

3 Design Process of the Low Noise Current Source

This section will cover the process which eventually led to the final circuit design explained below. The first part of design was replicating a functioning current source with individual components and then the voltage regulator. Afterwards switching was added and then multiple iterations of the current supply. All design was done originally on pen and paper and then schematics were created with DipTrace software on a computer.

3.1 Core Current Supply Circuit

The basis for the current source to be used in the devices was the AD8276 described earlier in the theoretical background portion of this report. The circuit was recreated at first using spare parts around the workplace which conformed roughly to the specifications, and some of the circuit worked well with these components. Later, however, some others needed to be replaced with more accurate parts.

The topology originally used the LM358, but in our configuration the difference amplifier was saturating and causing the voltage to hover some ~ 2 volts above the 0 V baseline when it was turned off, as well as inaccurate following and insufficient voltage outputs. The voltage was somewhat limited by a battery option which some customers request because they prefer to have no direct outside wiring leading into the room where they perform their testing. Though the battery is not the default option, the circuit would be

best designed to conform to the stricter limitations of the battery supply, as opposed to the directly wired supply.

The battery voltage would vary from around 13 V down to 10.8 V, and the LM317 voltage regulator stabilized the output voltage into the main circuit at 9.2 V. A rail-to-rail capable amplifier with a more stable architecture would be required to produce enough current from this voltage, to remedy the saturation issues, and to have higher accuracy in following the sense resistor to produce proper amperages. The LM6134 was ultimately chosen as the most suitable component package, with 3 out of the 4 op-amps being utilized.

3.2 MOSFET Controlled Switches and Multiple Current Supplies

Once the core circuit was functioning as was necessary, a MOSFET (Metal-Oxide-Semiconductor Field-Effect Transistor) switch was added to provide or cut input voltage into the difference amplifier's positive input, effectively turning the current on or off. This voltage was regulated by a shunt diode to around ~ 3.3 V, and passed through a voltage following amplifier to reduce current leakage. Different sense resistor values were wired to the previously mentioned DIP switch to produce the differing currents needed. The main voltage regulator will be used to power the four identical precision current sources, each of which can be turned on or off by whichever sort of external switch, which provides voltage to the MOSFET gates.

The prototype is able to power four separate heat switch wirings, each with different current, in the end. This satisfied the needs of the original goal and subsequent goal modifications during the design and development process.

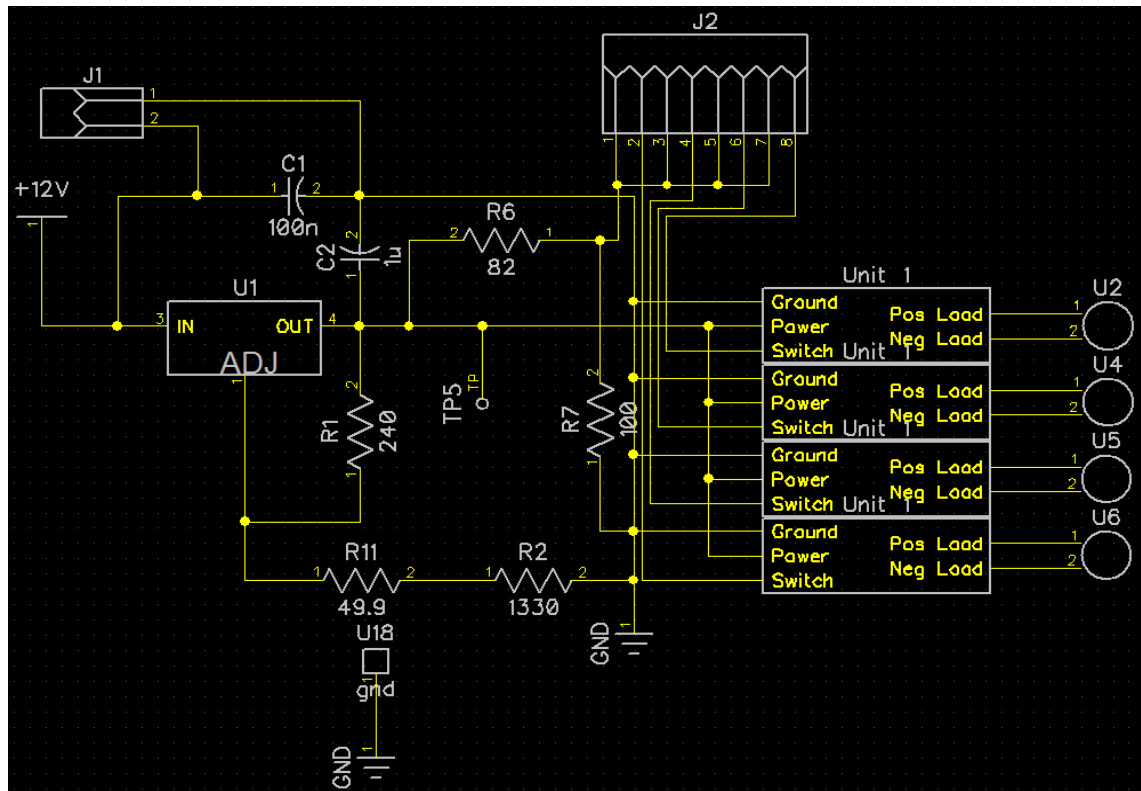


Figure 5. Simple voltage regulation circuit with LM317 and 4 attached current source circuits.

The schematic in figure 5 shows clearly how the 'Switch' terminals in the sub-circuit components labelled 'Unit 1' are wired to screw terminals in the J2 component at the top. These screw terminals can be connected to different external switching options, such as air pressure switches, which are used by some customers to avoid directly connecting the heaters to an external power source, and the noise or interference that may come with them. The voltage divider consisting of R6 and R7 is present to supply ~5 V to the MOSFET switches, which is the optimal voltage to operate the gate. J1 is another screw terminal to be connected to the power source, whether battery or otherwise, and an external ground, if necessary. There are test points, including a ground pad, as seen in figures 5 and 7, placed throughout the circuit to allow for easier debugging once the prototype PCBs are delivered. U2, U4, U5, and U6 are custom pads designed to fit connectors which are commonly used with the refrigerators in question.

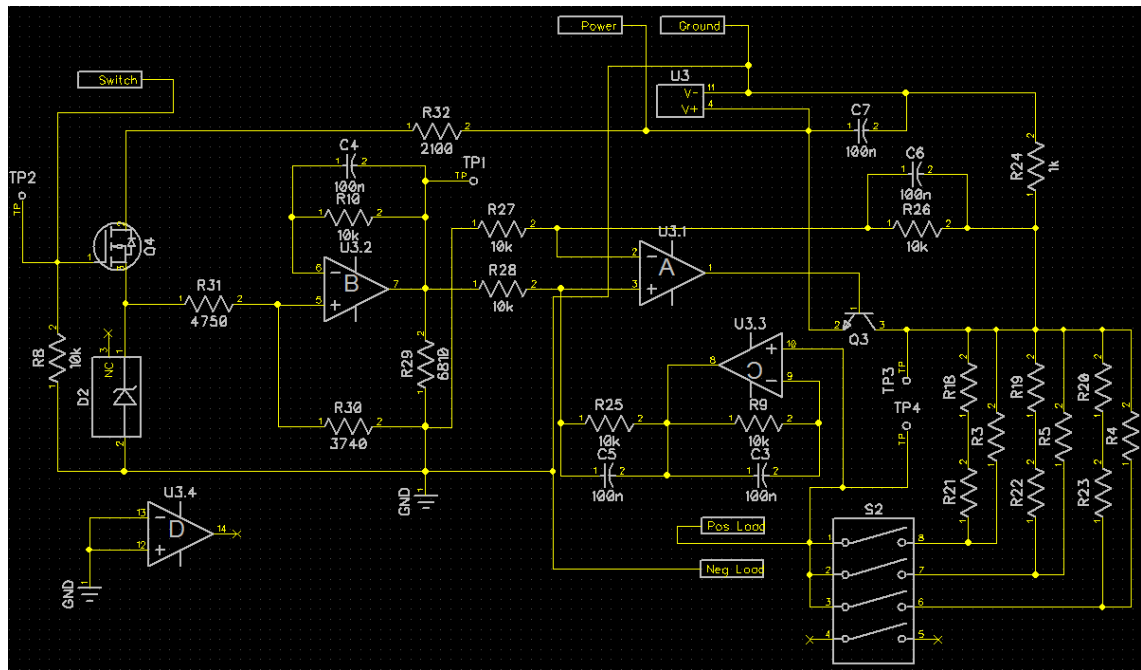


Figure 6. Current supply circuit with MOSFET switch on left and sense resistor switches on bottom right.

The current supplying sub-circuits represented as components in figure 5 can be seen as independent schematics in figure 6. The 'Pos Load' and 'Neg Load' lead to the special custom pads, power is supplied from the voltage regulator output, ground is connected universally, and the switch connects to the screw terminals to be controlled externally. The quad Op-amp package LM6134 is U3, with the power supply having simply that designation, and the individual amplifiers having dot plus number identifiers 1-4. You can see that the fourth amplifier is not yet in use in the circuit, and it may remain so, though it could potentially be useful in future iterations.

3.3 PCB Design

The board layout was done multiple times to suit evolving needs for the size and specific components and connectors available. The external connections are still not confirmed at the time of writing, but the general configuration will not be greatly altered. One can see the layout on all four planes in figure 7. The four separate current supply circuits are clearly laid out side by side, and the regulator and screw terminal connections at the top. The ground pad is located in the bottom left of the whole board, and test points, not to be confused with the connection pads, are scattered around where ever they could fit.

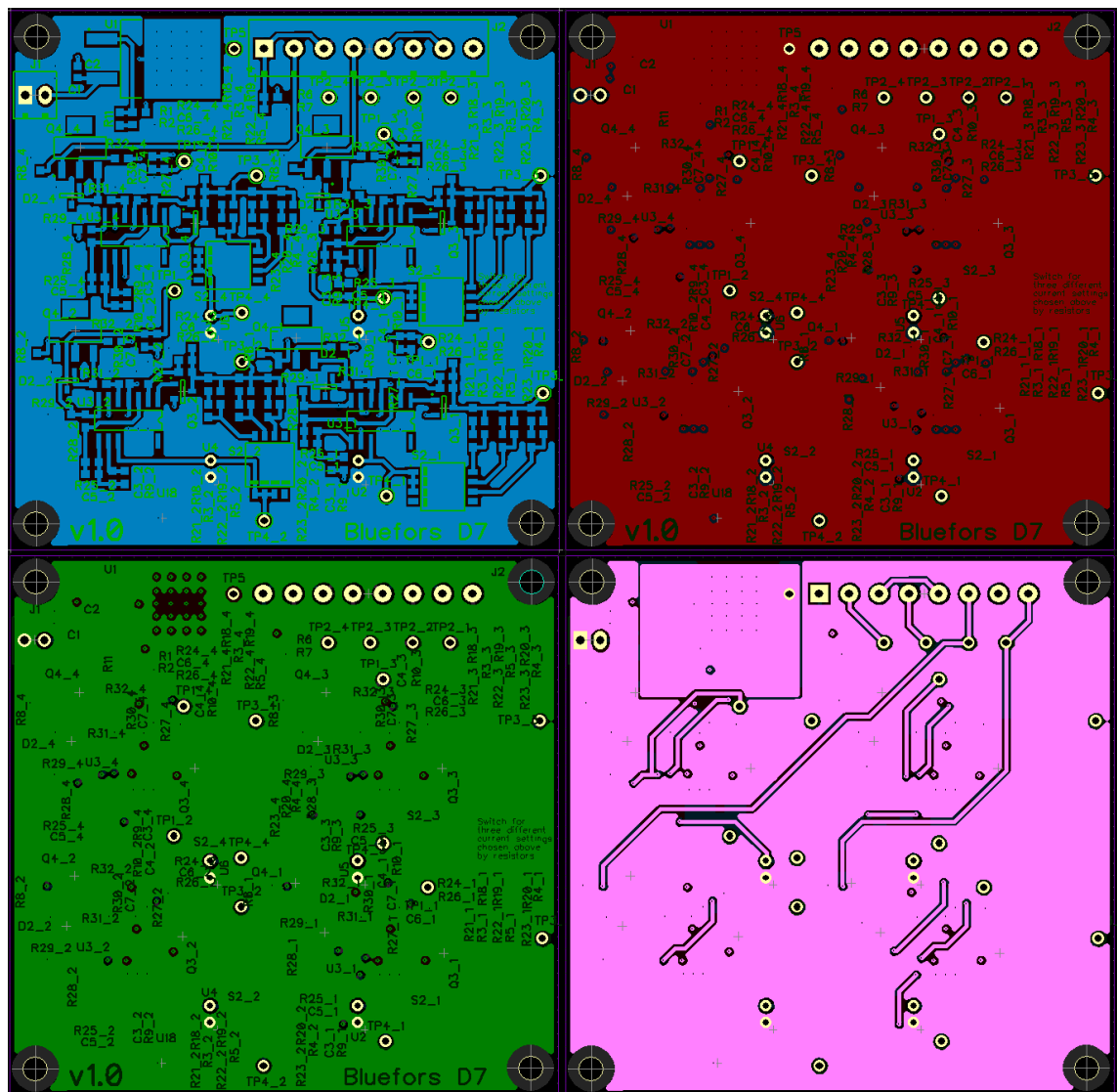


Figure 7. Board layout with Top (blue), Power plane (red), Ground plane (green), and Bottom (pink).

The board was designed to fit into a metal casing which conforms to other designs being implemented in company products. 7 cm x 7 cm was regarded to be small enough to fit and leave breathing room for any unanticipated differences. Using the DipTrace software, the components were laid in place one by one by hand. Ease of component soldering was taken into account, and so component designations (RefDes) will be printed on the board as close to their components as possible in the crowded top layer. The four duplicate circuits are also laid out independently from each other, and with as similar layout as possible for this reason.

The capacitor C1 is placed as close as possible to the input pin for the regulator. This helps it function as efficiently as possible. The power plane and ground plane were added to reduce common impedance coupling in their respective paths, as well as to simplify routing. The top and bottom layers were filled with copper pour and connected to ground for increased effectiveness.

The thermal component LM317 is connected with multiple vias, or holes with metal for conducting, to the power plane and a specially added heat dissipation plane on the bottom of the PCB. The 3D PCB layout design shown in figure 8 highlights the exposed pads where components will be soldered to the board. One can see that some pads are routed directly to the ground plane through vias, as well as to the copper pour on both top and bottom.

The placement of the specially designed connector pads needed to be specific so the connectors themselves would feed through predetermined holes in the front plate of the casing. They're equally spaced at about 28mm apart and equidistance from the sides, but oriented towards the bottom of the PCB. The screw terminals were required to be on the opposite, in this case top, end of the board so that wiring could easily be fed into the side of the metal casing. Screw holes at the outer corners of the board will be used to secure the board in the enclosure using M3 screws.

Do to both board size constraints and height of the casing constraints, all components were surface mounted devices (SMD), if possible. Through holes were used for external connectors such as the screw terminals and the connector pads mentioned, but otherwise unnecessary. Thusly the PCB could remain quite compact and fit easily according to specifications.

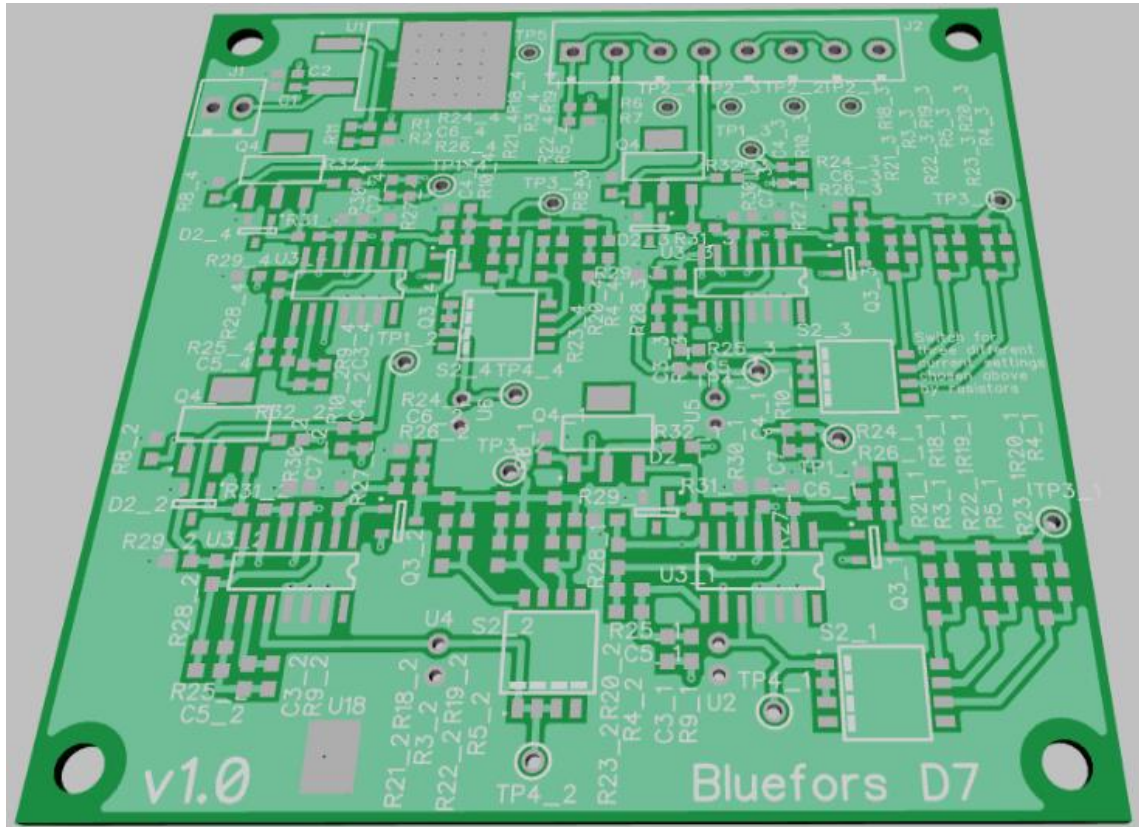


Figure 8. 3-dimensional representation of the PCB which better reveals the pads, copper pours, and silk.

The silk screen on the top of the circuit identifies all the components by RefDes numbering, outlines component and other package placements, and identifies the board designer and version.

3.4 Component Selection

Component selection was carried out initially mostly based on current stock availability in the company inventory. Cost was taken into consideration from beginning to end, but some components proved to be shoddy or noisy if too cheap. In the end a balance between price and quality was struck to maintain a cleanly and precisely operational design. Some components were confined to much stricter requirements and some func-

tioned effectively within the lower price ranges. The bill of materials for the PCB can be seen in appendix figure 1.

The operational amplifier was originally the LM358, after a mix-up with the LM393 at the start. The LM358 seemed to function correctly when testing began and the sense resistor was set to a larger value around $\sim 200 \Omega$. However, when the resistance needed to be lowered to increase current flow, the amplifier ran into multiple issues. Firstly, since it was not a rail-to-rail amplifier, it was unable to maintain currents high enough for some of the specifications based on the voltage provided to it. Secondly, the amps became saturated and could not return to 0V even when voltage to the difference amp was shut off at the MOSFET. The amplifier was upgraded to the LM6132 to deal with this, and later since 3 amps were required the LM6134 package, which contains 4 identical amplifiers. These amplifiers are a lot more expensive, but they function precisely in testing. They're planned to be used in the final implementation of the device.

The bipolar junction transistor was not to be subjected to high stresses, so a transistor available in inventory was chosen. The MMBT2222 NPN general purpose silicon transistor is quite generic and low cost impact. It showed no signs of failure in any of the testing, and so it will remain in the final circuit design.

The next major component was the LM317 linear voltage regulator. This is cost-effective but quite efficient and reliable in our application. Though a more expensive regulator could have possibly squeezed a few more tenths of a volt from the battery supply, it didn't seem necessary. After adjusting the output of the regulator from 8.9 V to 9.2 V using slightly adjusted resistor values, every part of the circuit managed to function effectively.

Giving the difference amp the proper input voltage to create the selected current across the load was the next task. To modify the main regulator's voltage output to an appropriately lower voltage was accomplished with the LM4040 precision micropower shunt voltage reference. This component comes with several options for fixed reverse breakdown voltages, of which 4.096 was chosen. The component behaved exactly as it should, and so no upgrades were necessary.

To control the on off functions, a simple MOSFET could be used before the shunt reference to connect or disconnect it from the supply network, thus controlling voltage to

the difference amplifier input. The STN4NF20 N-Channel low gate charge power MOSFET was chosen, and like the regulator and shunt reference, it worked as planned and was kept into the final design stage.

External connections in the form of screw terminals were chosen to be as low profile as possible and cost-effective, but durable. The Phoenix Contact EMC 1,5/ 8-G-3,81 conformed best to requirements, and has been ordered for implementation in the final design. Appendix figures 2 through 4 show a later update to the PCB design to accommodate new connectors.

A selection switch with a fairly low profile needed to be selected to choose between the sense resistor path options. The C & K Components TDP04H0SBD1 DIP / SIP Switch with 4 relays was used despite only needing 3. The fourth relay could possibly be implemented in later versions if more current levels are added.

The capacitors in most of the circuit are identical 100 nF ceramic capacitors. Price and availability led to the choice of Kemet multilayer SMD 0603 package capacitors. As far as any evidence shows, they have no functional deficiencies, and they are the final choice. Originally the capacitors used were indeterminate spares from inventory, but likely quite the same as the final orders. The one different capacitor, the tantalum 1 μ F capacitor, was used because of recommendation in the regulator datasheet. One large version was used on the breadboard from inventory initially, but in the final version a 0603-package version from AVX was ordered.

Resistors are the final and most numerous components on the board. To try and keep noise low in the overall circuit, all resistors were chosen as thin-film or metal-film. Most resistors were quite reasonably priced, but a few had higher prices due to unusual values, or in the case of the 10 K Ω resistors, higher quality. The 10 K Ω resistors are currently listed as Panasonic metal film 150 V 0603 package, but they may be changed for price considerations before final production.

4 Testing of System by Simulation and Physical Tests

This section will cover both the physical testing and the testing performed on LTSpice simulation software. All simulation testing was carried out on a laptop computer at the company. Testing for the voltage and current were also testing at the workplace, but using power supply, signal generator, and oscilloscope. The final noise testing was carried out at Metropolia's Albertinkatu campus using the network analysers available to students there.

4.1 LTSpice Testing

The LTSpice free-to-download software was used alongside the physical prototype to perform some preliminary testing with presumably fewer random variables.

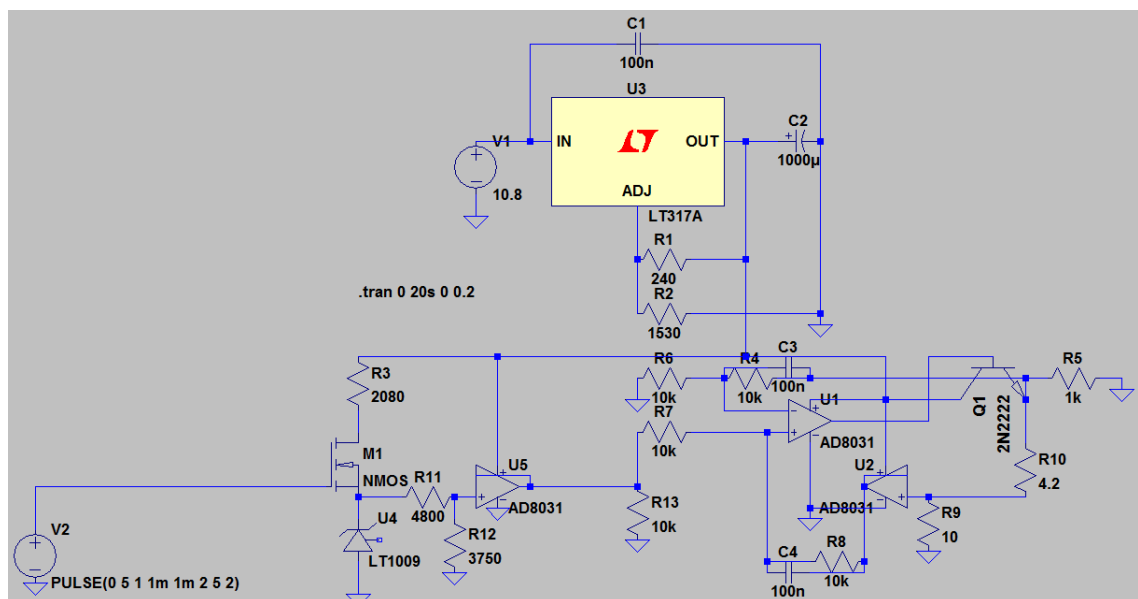


Figure 9. LTSpice schematic created for preliminary testing.

The simulation circuit shown in figure 9 used AD8031 op-amps as a substitute for the LM6134, which was not available for the program. They functioned quite the same in simulation as the others did in the prototype breadboard circuit. Since there was no

way to implement an external switch in the simulation, a pulse was generated at V2 to the MOSFET gate, which should switch the current source on and off, generating the desired currents to the load.

4.1.1 DC Voltage and Current

Testing was done on the LTSpice circuit to determine whether it would reliably produce the desired currents and voltages in at key nodes and across the load.

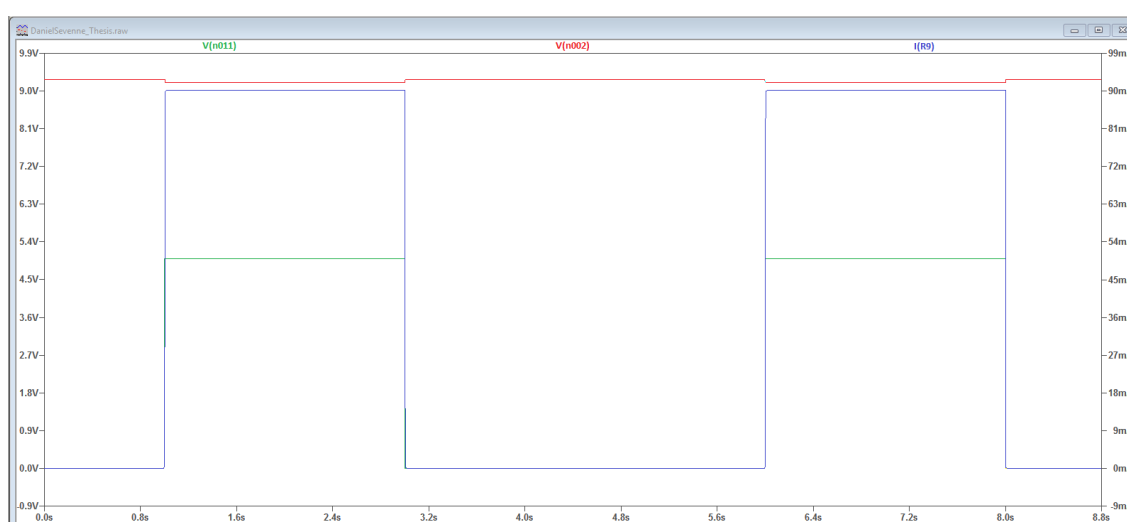


Figure 10. LTSpice simulation test measurements.

The measurement results from the LTSpice simulation can be seen in figure 10. The red line is the output voltage from the voltage regulator to the current source circuit, blue is the current at the load resistor, and the green line is the voltage at the MOSFET gate, shown to compare with the other two to determine response. You can see that the response in this circuit is flawless, though the physical model wasn't quite so perfect. The current output is also at the desired level for the heater load, which in this case was 90mA. The voltage from the regulator dips when the circuit is turned on, but the amount is negligible and it doesn't affect performance of the supply at all. The LTSpice simulations were successful and in agreement with the prototype, once it had been debugged and modified.

4.1.2 Noise

The LTSpice model was modified a bit at first to try to find the most accurate noise testing configuration. Though the AD8031 op amps used in the earlier simulations performed well as substitutes for the LM6134 behaviour regarding current output, they were discovered to be unacceptably noisy, producing nearly a full volt of noise below 100 Hertz. A spice model of the LM6132 (a two-pack version of the LM6134) obtained from the web was imported into the program to get more accurate results.

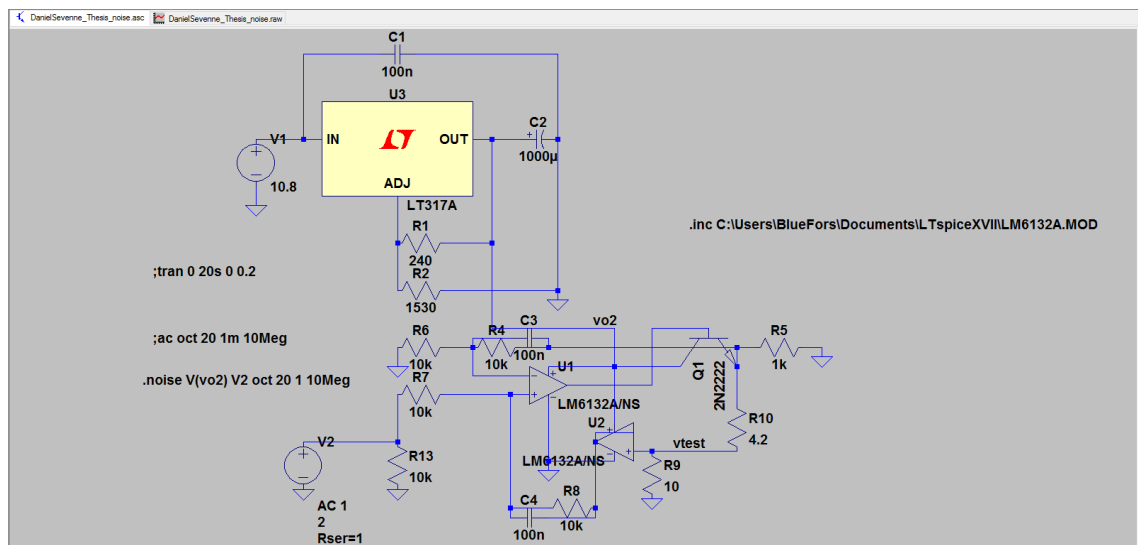


Figure 11. Updated LTSpice circuit with LM6132 op amps.

Figure 11 shows how the switch side of the circuit was cut off for simplicity and the more accurate op amps replaced the substitute AD8031. The noise test on the new circuit showed spectacular noise performance, around 2-3 nanovolts, as shown in figure 12.

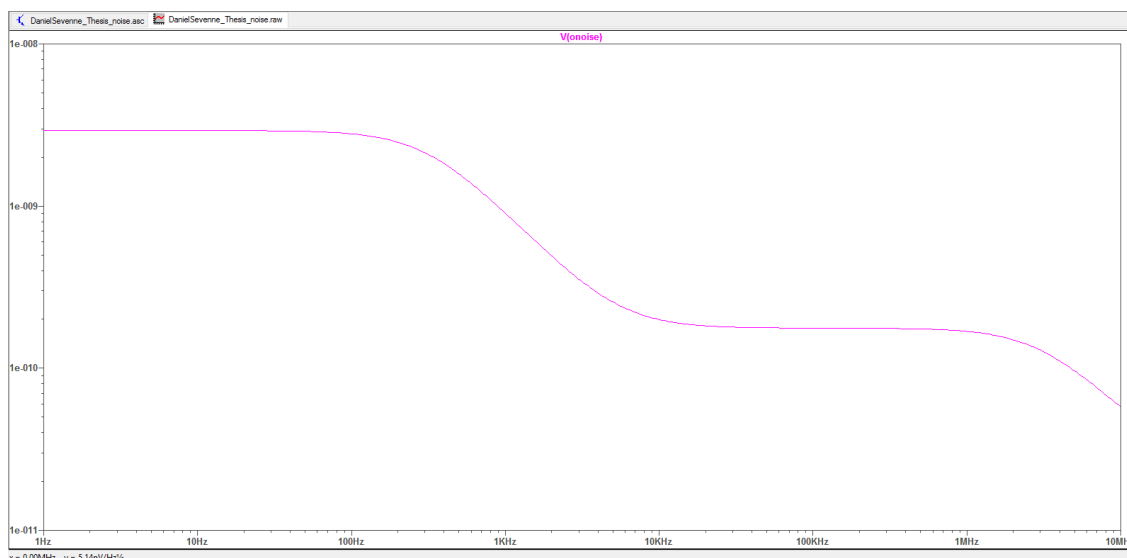


Figure 12. LTSpice noise measurement at output.

Despite not having proper spectrum analysis available for the real prototype, the results from the simulation seem to suggest project goals were likely achieved.

4.2 Prototype Testing

The prototype was tested repeatedly throughout the building of the breadboard circuit, and will be tested further after the completed printed PCB has arrived and components are soldered. The first tests done were to see that a constant voltage could be maintained to drive the current source circuitry. Once a stable voltage was achieved, the current source itself was tested for amplitude stability and response, which is where the most extensive testing was performed. There was a lot of debugging involved and component changes to finally get the desired results. Finally, noise measurements were carried out to determine whether the properly functioning architecture would indeed have reduced noise output as compared with the previous heater current supply.

4.2.1 Voltage Supply

The supplied voltage was originally calculated with a battery voltage range from ~13 V down to 10.25 V, and supplying a voltage of 8.96V to the rest of the circuit. The system performed as expected after a few resistor tweaks, and a steady voltage was main-

tained. Afterwards, however, the 8.96 V was deemed insufficient, and the battery range was reconsidered. 13 V down to 10.8 V would supply 9.2 volts continually, so the resistors were adjusted and tested again. Tests agreed with assumed values, and so this configuration was kept into the final design.

4.2.2 Current Output

Testing of the current output was carried out in the workplace where the circuit was designed and produced. The current output was one of the most important functions of the entire project, so it was tested extensively from the beginning to the current portion of implementation. Early testing showed that the amplifier was not responding to input at all, but it was discovered that the voltage to be input was in fact wired incorrectly. After correcting this issue, the device began to respond, but response was inadequate. Resistor values were re-evaluated, and eventually a secondary voltage follower was added before the difference amplifier input to attempt to mitigate saturation. Tests however demonstrated a need for a superior quality amplifier, because at lower sense resistor values the circuit could not fully turn off. Ultimately, with the improved components, tests did show the circuit was able to output appropriate currents with all resistor values, and able to drop to baseline effectively when turned off.

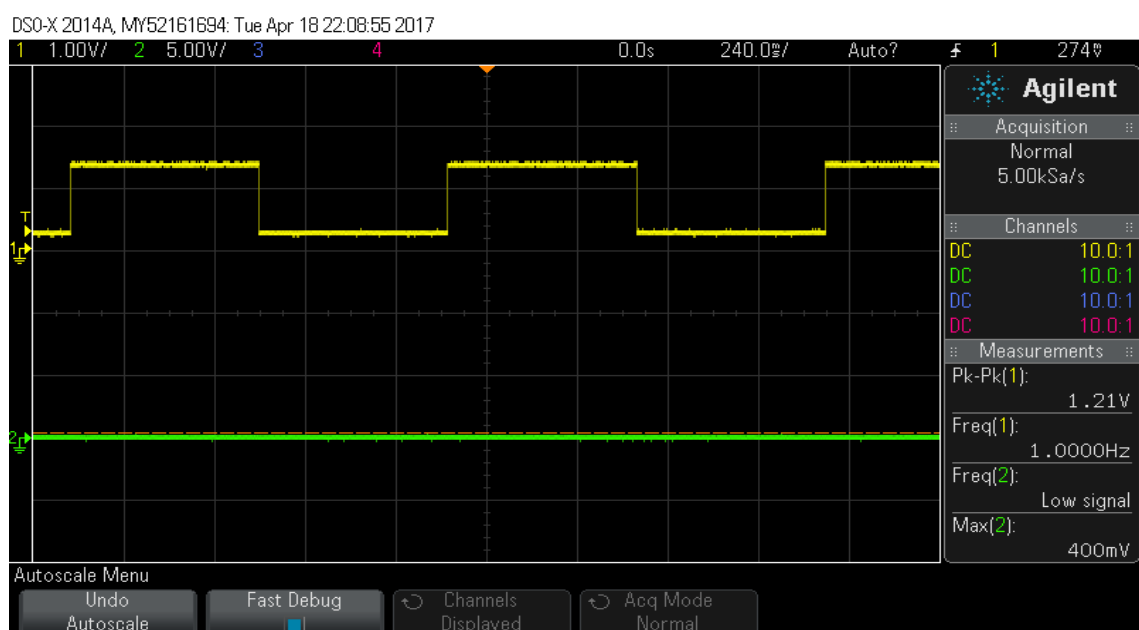


Figure 13. Oscilloscope measurement with input to op amp terminal in yellow and load voltage in green. This measurement is with the sense resistor removed.

Figure 13 shows that with the sense resistance left open, almost no voltage reaches the load, and no signal is transmitted whatsoever. In figure 14 the sense resistor is set at $15\ \Omega$, and the load is left open. This produces nearly maximum voltage of about 8.8 V across the load, but of course, no current flows in this case. These tests were carried out simply to make sure there were no shorts or other issues with the circuit.

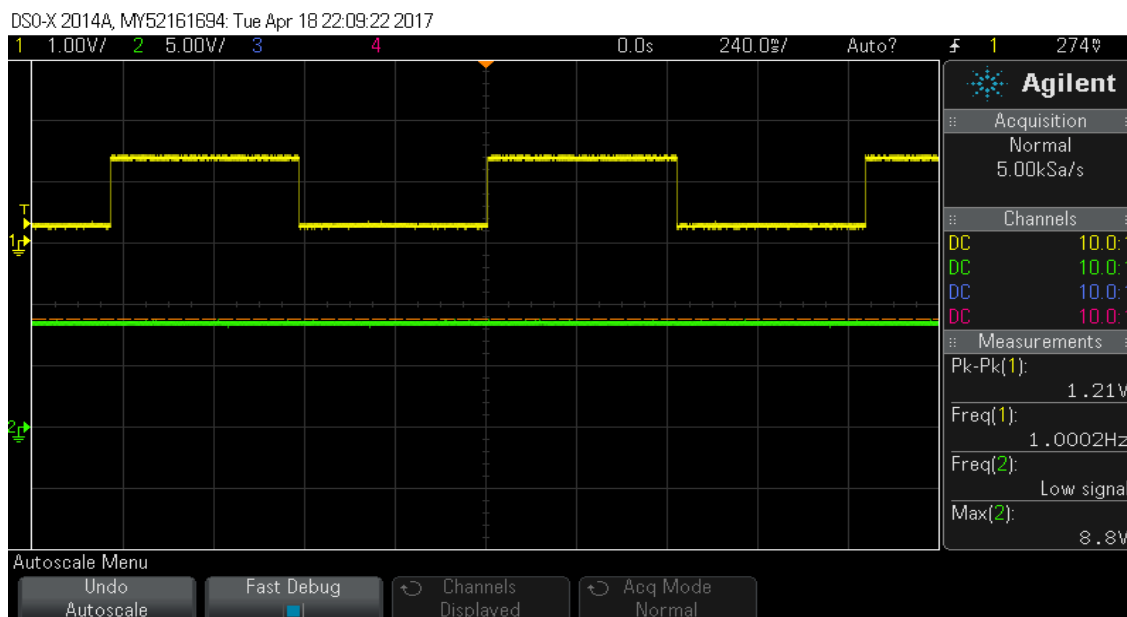


Figure 14. No load resistor, or open load. Voltage was quite high at 8.8 V.

After checking that the circuit behaved as expected with the load and sense resistances, testing proceeded to finding the desired currents across the three heater load configurations. The load voltage shown in green in figure 15 held steady at 4.2 V and responded cleanly to input signals. The voltage produced the correct amperage across the $140\ \Omega$ load resistance, at 30 mA. This can be simply attained using Ohm's law:

$$I = \frac{V}{R} \quad \text{or} \quad \frac{4.2V}{140\Omega} = 30mA$$

(7)

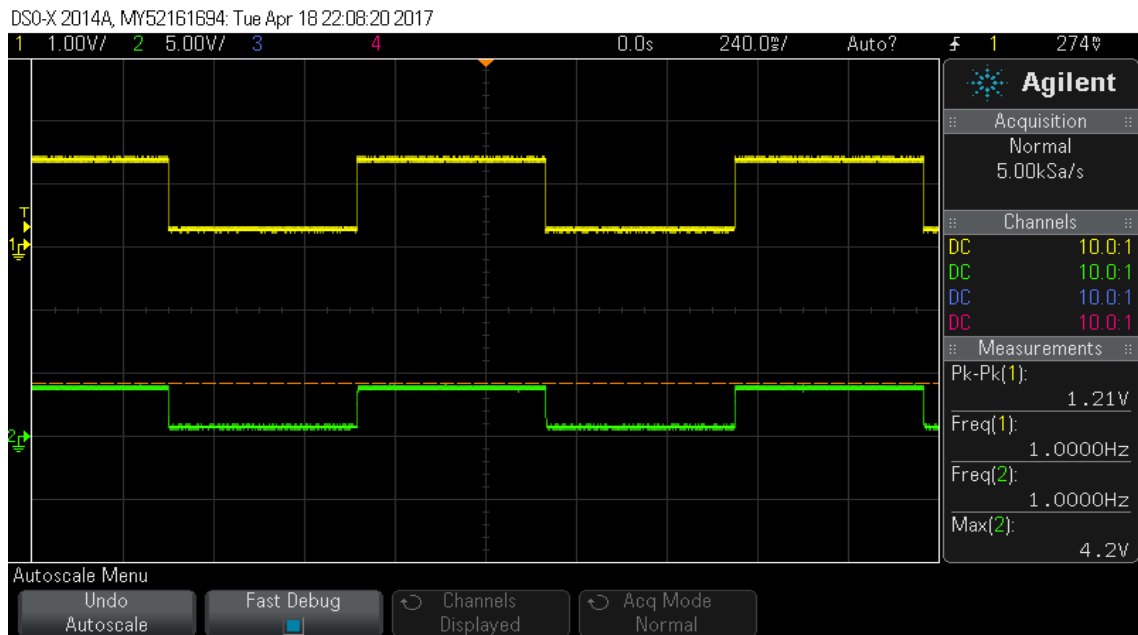


Figure 15. Voltage across 140 Ω load producing 30 mA current.

The next target current was 60 mA across 4 parallel heaters equalling about 90 Ω . You can see that the voltage level of 5.4 V in figure 16 coincides quite precisely with this expectation. This was achieved by adjusting the sense resistor value from the lower 10 Ω used in with the 140 Ω load. The value used for the 90 Ω double heater load was instead a 15 Ω sense resistor. The final sense resistor value was 35 Ω for the 50 Ω quad heater load.

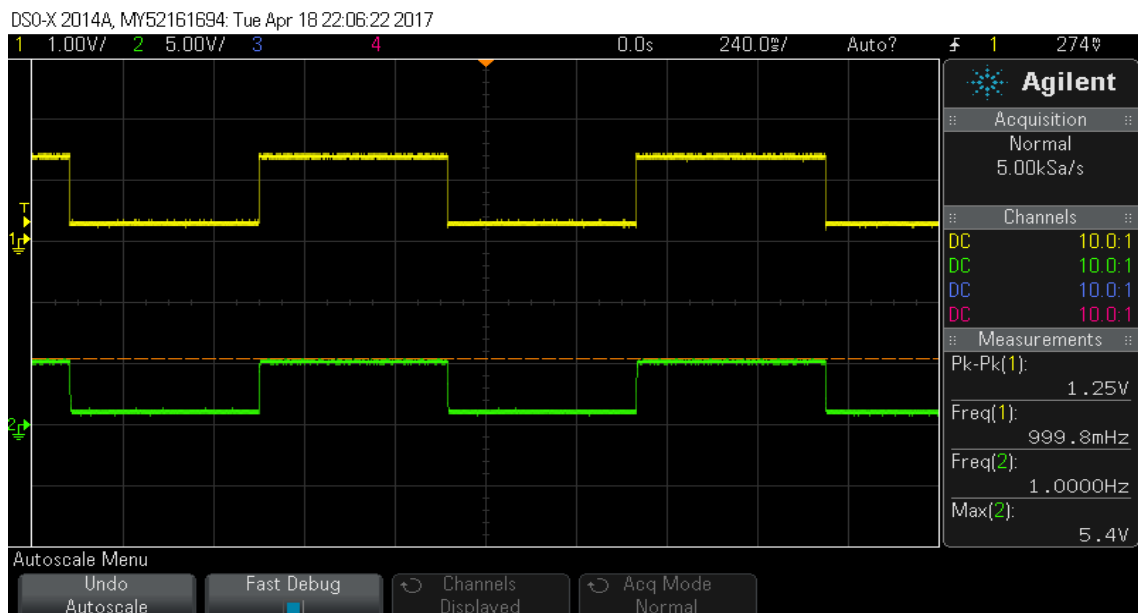


Figure 16. Voltage across 90 Ω load which produced the 60 mA current.

The final value needed was 90 mA across a load value of 50 Ω for 6 heaters in parallel. Again, the circuit performed well and produced the proper 4.48 volts over the load to give acceptable amperage, as seen in figure 17.

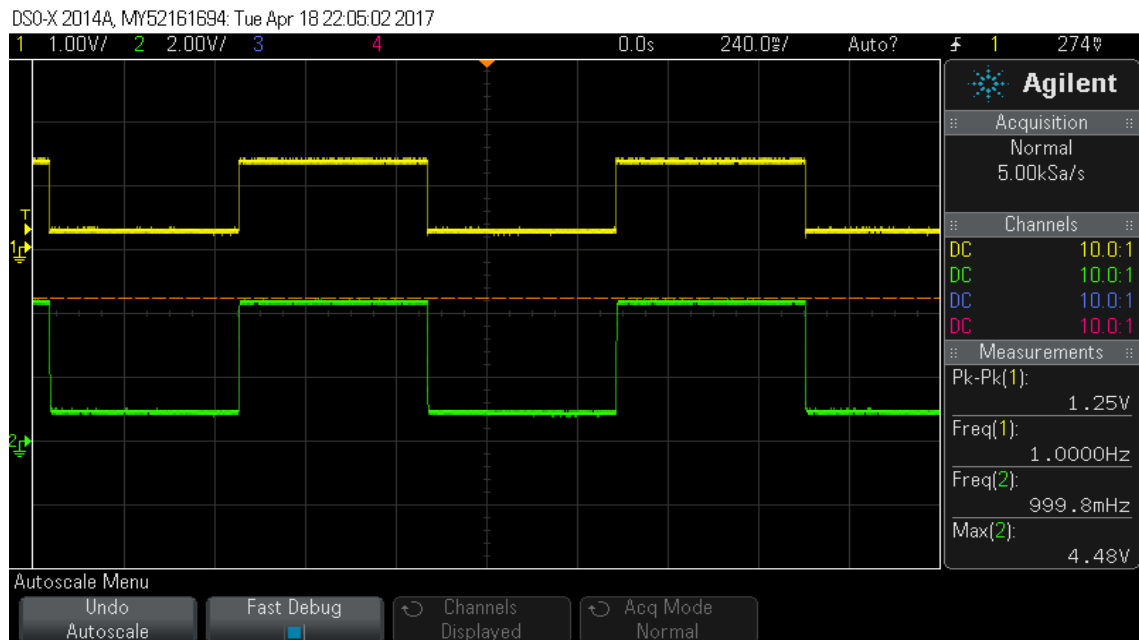


Figure 17. Voltage across 50 Ω load producing the final 90 mA required.

Earlier testing was carried out at many points during the design phase. The results were used to modify sense resistors and other components to finally reach the desirable results seen in the figures 11-15. Since the circuit was updated along the way, however, there was no time to backtrack and obtain the earlier results again for display in this report. The final testing demonstrates satisfactory circuit performance.

5 Conclusions on the Project

This project was carried out during the spring of 2017 for Bluefors Cryogenics company. The work time allocated for the project was generally around 6 or less hours a

week, during work hours. Other time was spent researching or writing at home, or sometimes testing at the Metropolia campus. The project managed to progress nearly to the completion of the product being designed, though further prototype verification will be required.

The handmade prototyping phase was completed, however, and the main desired characteristics were demonstrated to be satisfactory. The circuit appears to be stable and reliable. Voltages were measured to be correct where needed, and the most important current output was as required.

The goal of the project was mainly to produce a circuit design which would ultimately be used to efficiently and precisely power the heat-switches in the dilution refrigerator. Since the prototype already fulfils the requirements, it's reasonable to assume that any further issues with prototyping will be minimal. In the opinion of the author, this project has succeeded in providing what was asked.

Further debugging and testing will be carried out with the actual refrigerators, even after the final year project has been returned. The project has been a success in helping to improve techniques in design, research, time management, and meeting customer demands.

References

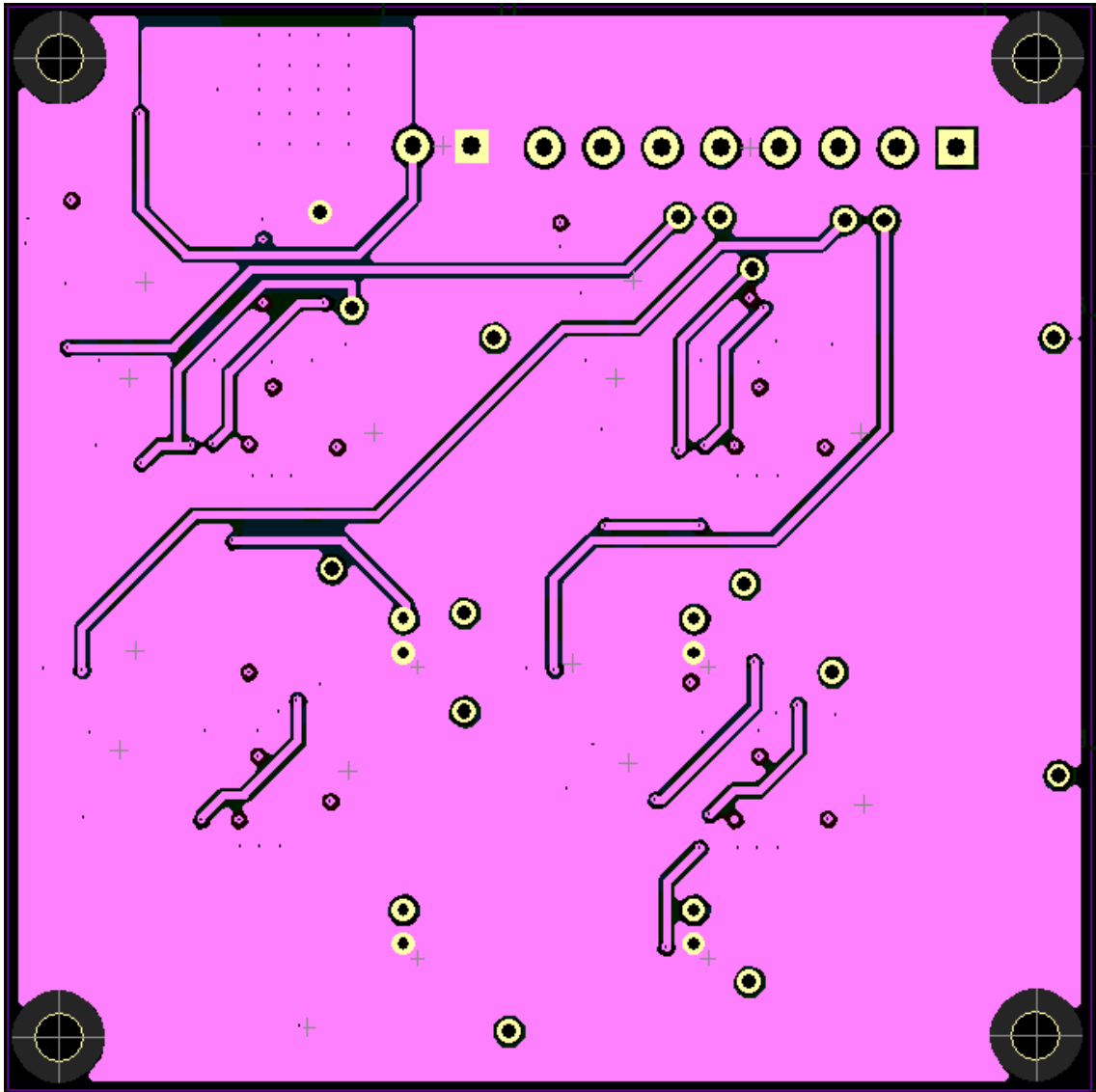
- 1 UXL Encyclopedia of Science COPYRIGHT 2002 The Gale Group, Inc.
URL: <http://www.encyclopedia.com/science-and-technology/physics/physics/cryogenics>
- 2 Eric Gershon January 14, 2013
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URL: <http://www.analog.com/en/analog-dialogue/articles/diff-amp-heart-of-precision-current-source.html>

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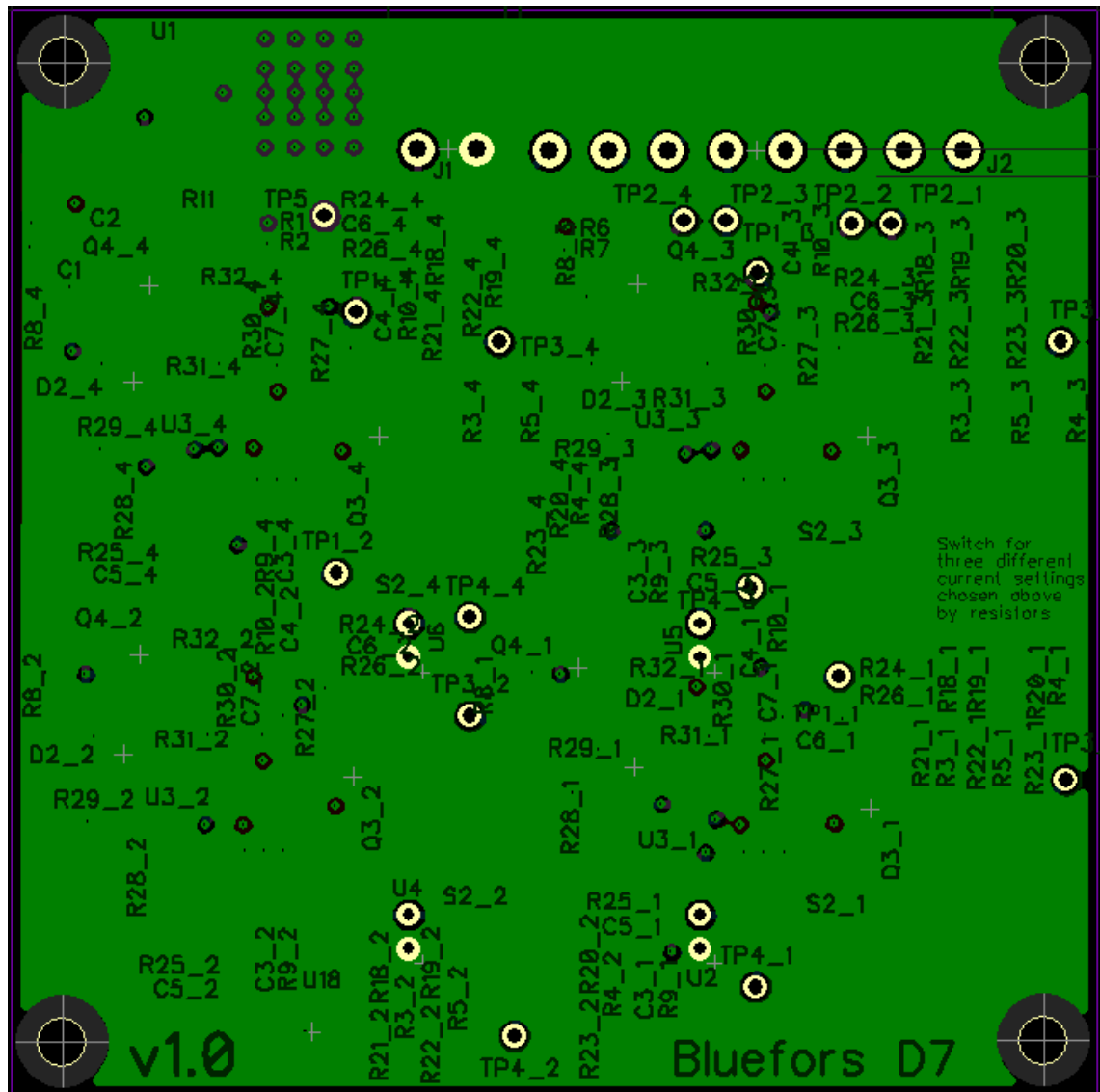
Additional Figures and Tables

Appendix Table 1. Bill of Materials.

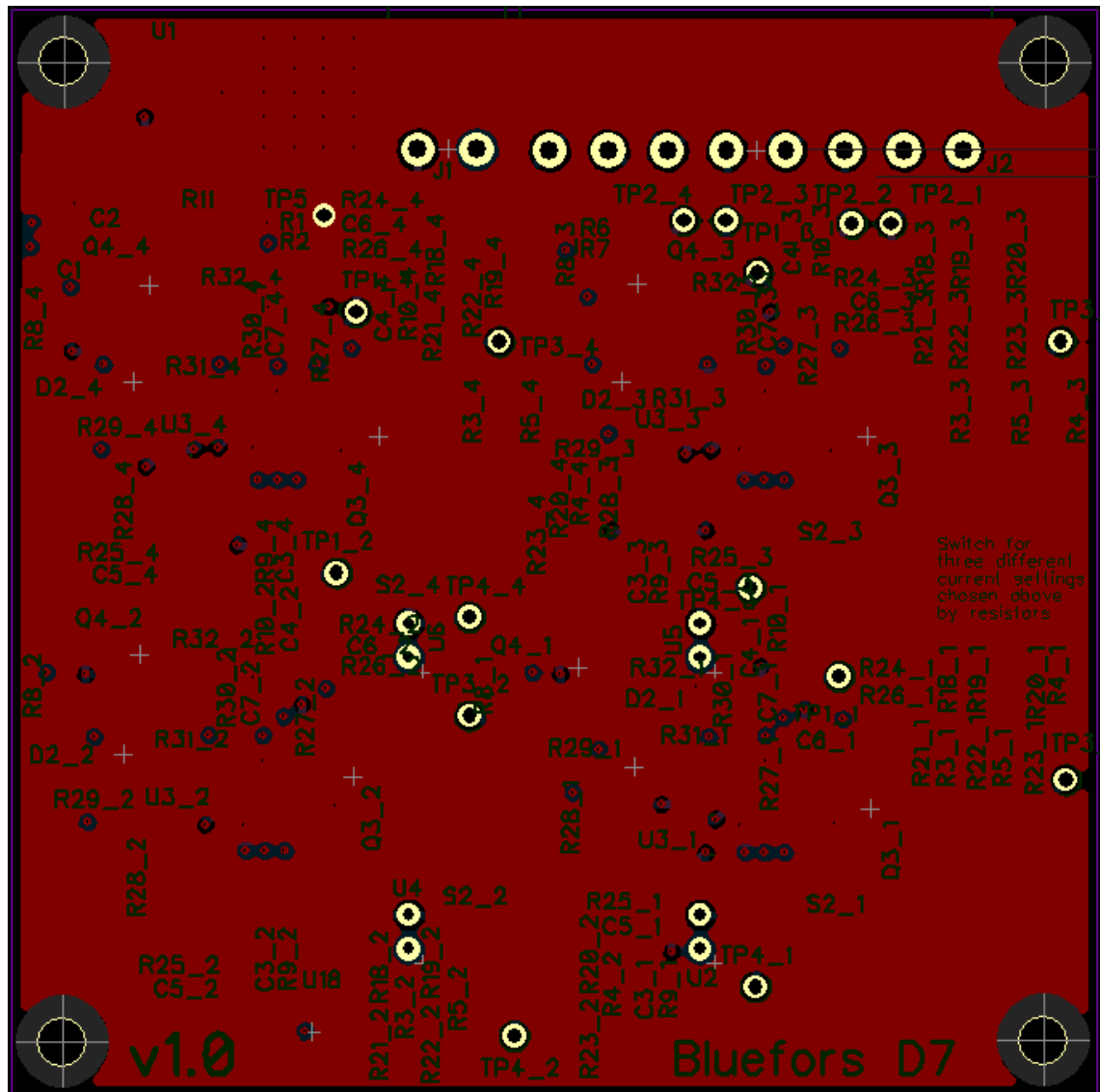
RefDes	Value	Digikey	Farnell	Quantity
C1, C3, C4, C5, C6, C7	100n		1414028	21
C2	1u		2408419	1
D2			1468840	4
J1			3041359	1
J2			3704634	1
Q3			1459098	4
Q4			2629750	4
R1		240	1670168	1
R2		1330	1809846	1
R3, R4, R5, R18, R19, R20, R21, R22, R23				36
R6		82	1577592	1
R7		100	1577593	1
R8, R9, R10, R25, R26, R27, R28	10k	RG16N10.0KWTR-ND	1717692	28
R11	49.9		1809605	1
R24	1k		1577605	4
R29		6810	2094645	4
R30		3740	1809791	4
R31		4750	2094611	4
R32		2100	2094535	4
S2			2435180	4
TP1, TP2, TP3, TP4, TP5				17
U1			1564300	1
U2, U4, U5, U6				4
U3		LM6134BIMX/NOPBCT- ND	9490027	4
U18	gnd	36-5016CT-ND		1



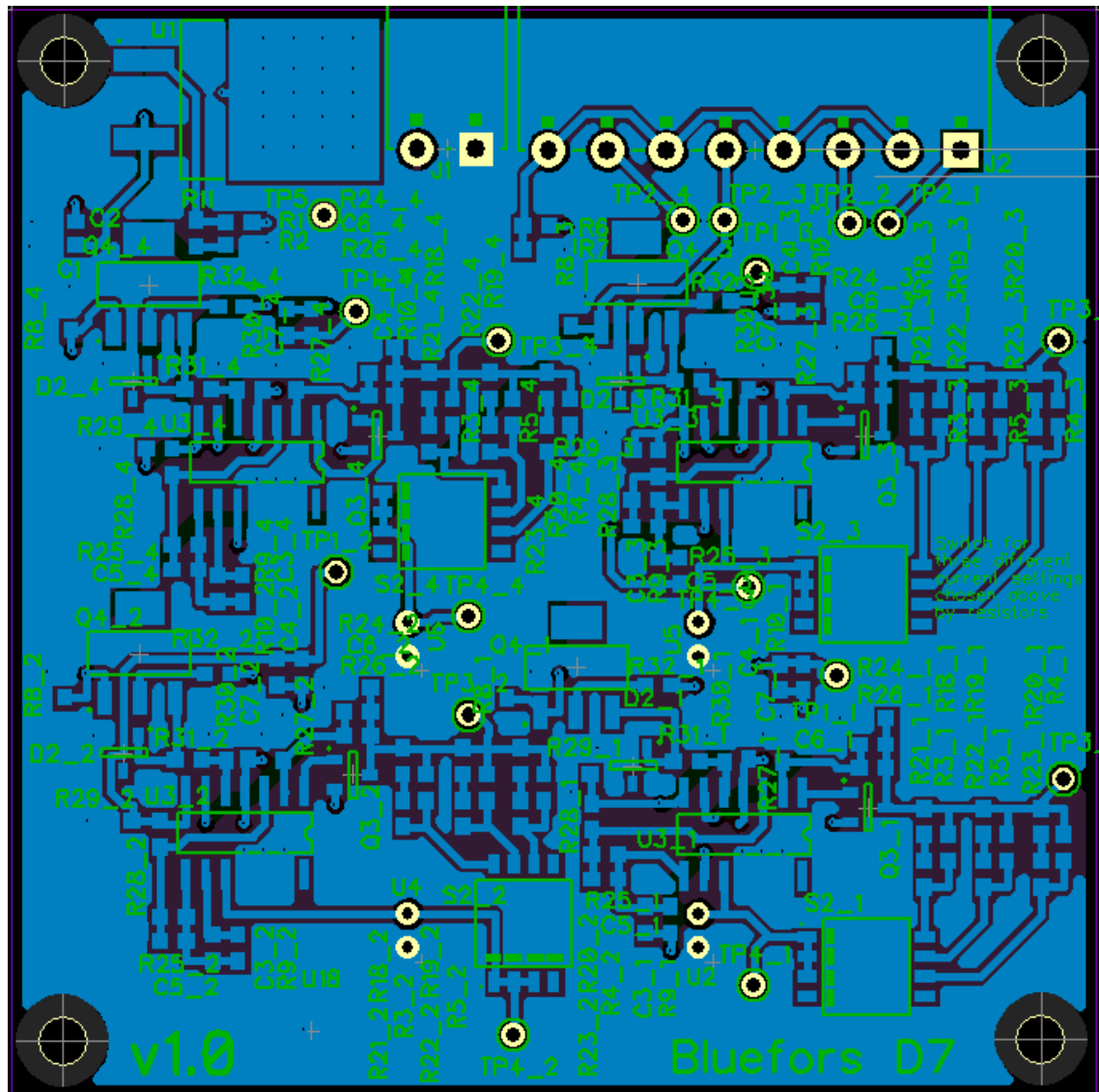
Appendix Figure 1. Bottom side of the updated PCB layout.



Appendix Figure 2. Ground plane of the updated PCB layout.



Appendix Figure 3. Power plane of the updated PCB layout.



Appendix Figure 4. Top side of the updated PCB layout.



Appendix Figure 5. Bluefors LD Dilution Refrigeration System. Copied from Bluefors Standard Range Models URL: <http://bluefors.com/index.php/ld-series>