

Digital to analog converter operating at cryotemperature

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Abstract

Trapped-ion systems are one of the most promising approaches to build a quantum computer. To trap these ions, it is important to have accurate analog voltages at the electrodes creating the potential. In experiments the analog voltages for trapping are created using DAC. Moreover to construct such a quantum computer, the system has to be scalable. To make the up scaling easier, it is an idea to put the DACs closer to the ions. For example to put them inside the cyrochamber. One downside of putting the DACs inside, is the low temperature of 4 K which brings difficulties, since they are not constructed for such low temperature. In this experimental project we tested the analog voltage output of DACs operating at cryotemperature.

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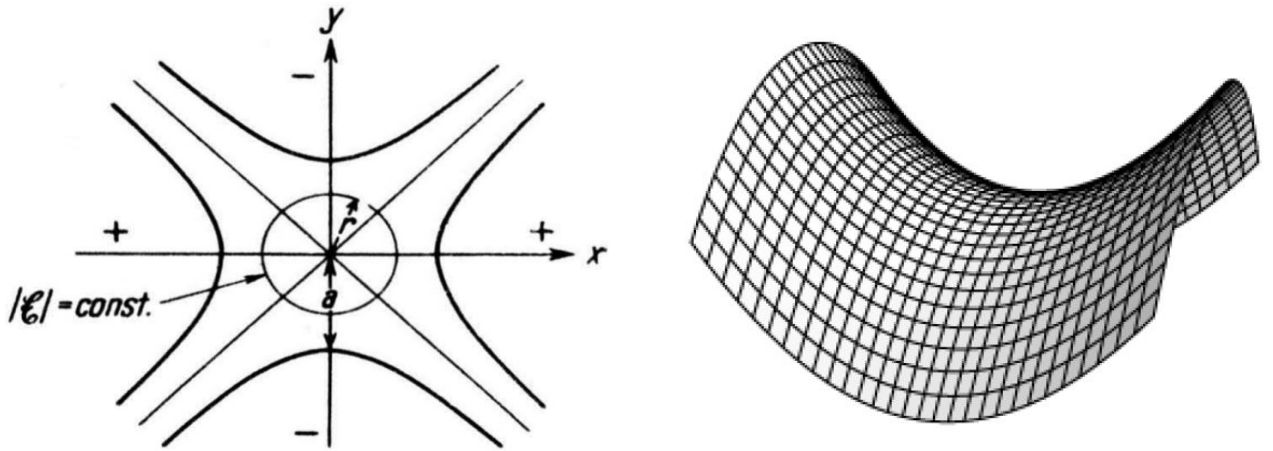
1 Introduction

1.1 Approaching quantum computers with trapped ions

Quantum computers promise to solve certain tasks exponentially faster than classical computers. Trapped ion systems are one of the most promising approaches to build such a quantum computer [1]. They currently demonstrated the highest fidelity for fundamental operations. According to Earnshaw's theorem it is not possible to use an electrostatic potential to maintain charged particles within a region [2]. Instead charged particles like ions can be trapped using dynamic fields like the Paul trap, invented by Wolfgang Paul [3]. He describes a trap which uses an electric AC field, of which the absolute of the field strength is proportional to the distance of a fixed axis, for example the z-axis. These ions are confined in the z-axis by a field with the potential

$$\phi(x, y, t) = \frac{U + V \cos(\omega t)}{a^2} \cdot \frac{x^2 - y^2}{2} \quad (1)$$

This field is created by four hyperbolic electrodes with a distance a from the z-axis. They have the alternating voltage $\pm \frac{1}{2}(U + V \cos(\omega t))$ thus between two neighbouring electrodes there is a DC voltage of U and an AC voltage of $V \cos(\omega t)$ (see figure 1.1a). At a given point of time the equipotential of the Paul trap is shaped like a saddle (illustrated in figure 1.1b). To confine the ions in all three directions the saddle rotates around its own axis (z-axis in this example). The frequency of the rotation has to be faster than it takes the particles to escape the field. Therefore typically radio frequency is used.



(a) Electric field with the potential $|\xi| = \frac{U + V \cos(\omega t)}{a^2} \cdot r$. The equipotential surfaces of the electrodes are drawn with the bold lines. The + and the - stand for $+\frac{1}{2}(U + V \cos(\omega t))$ and $-\frac{1}{2}(U + V \cos(\omega t))$ [3].

(b) 3D drawing of Paul's equipotential saddle-shaped surface at one moment. This saddle is rotating with radio frequency, to avoid the ions from moving outside the potential [4].

Figure 1.1: These two pictures illustrate the equipotential of Paul's trap.

Paul's description of the quadrupole is the simplest way to get such an electric field, however other geometries are also possible to build such a trap. For example cylindrical electrodes can be used since they provide a similar potential but are easier to fabricate. There are also two kinds of Paul traps, for one type the oscillation potential confines the

ions in all three direction and for the other type it only confines in two directions. The latter is called a linear Paul trap and the confinement in the third direction is provided by a static electric field (see figure 1.2 for a schematic of these two types of traps). To obtain a desired trapping potential it is crucial that the electrodes get precise voltage signals. By using digital to analog converters (DACs) we are able to obtain high resolution analog voltage signals.

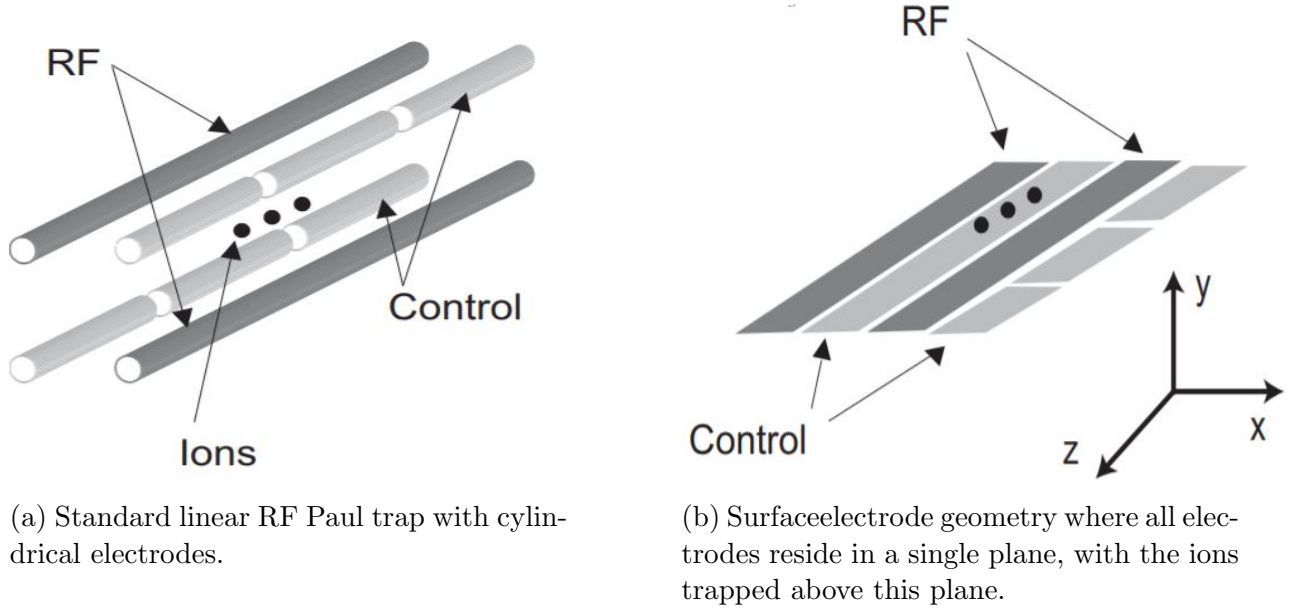


Figure 1.2: There are two types of Paul traps, one confining the ions in all three direction like in figure a) and second the a linear Paul trap like in figure b) [5].

1.2 Why testing a DAC at cryotemperature?

For constructing a quantum computer the system has to full fill a list of requirements called the DiVincenzo criteria. The first condition is that the quantum computer has to be a scalable physical system with well characterized qubits [6]. To make this up scaling easier there is the idea to have the DACs inside the cryochamber. So far the digital signal gets converted into an analog signal outside of the cyrochamber and has to get inside via feed through and long cables. Yet for many tens of qubits a lot of wires would be needed to control the ions. This would be hard to realize and expensive. Therefore placing the DACs inside the cryochamber would result in less wires which makes it easier to build the system. For example one could control a FPGA inside the cryochamber which then communicates with all the DACs directly. Furthermore there might be an improvement of the signal since the analog signal travels less distance and therefore there is less chance to pick up some noise [7].

The biggest challenge for having a DAC inside a cyrochamber is probably the temperature, since DACs are usually not fabricated for such low temperatures. However because of the mentioned reasons it is attractive to test if a DAC is working at cryotemperature and still is precise enough to fulfil the demands. Moreover the output range of the DAC may not fit the required range, so an amplifier and some resistors have to be added which also have to be tested at cryotemperature.

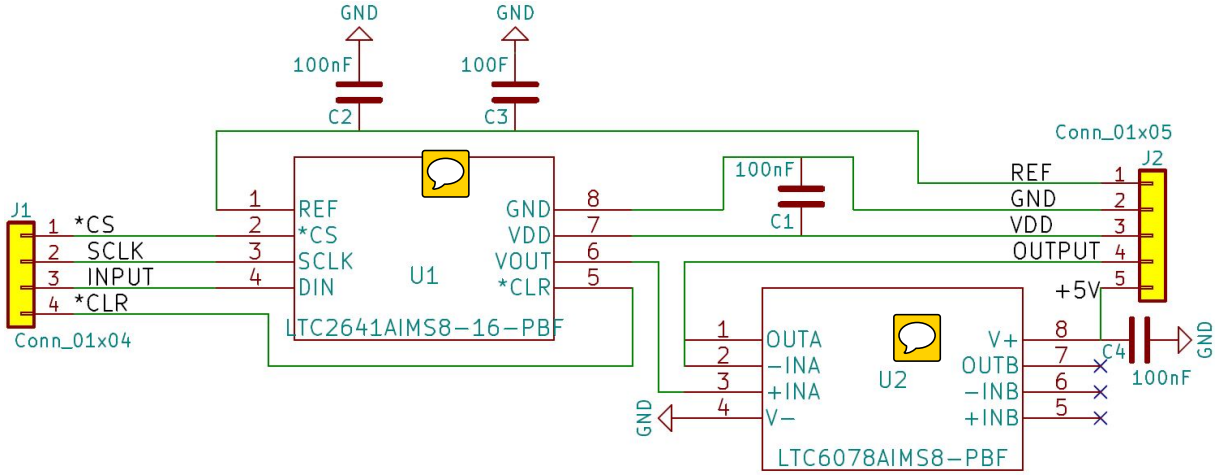
2 Setup

2.1 First setup for basic testing

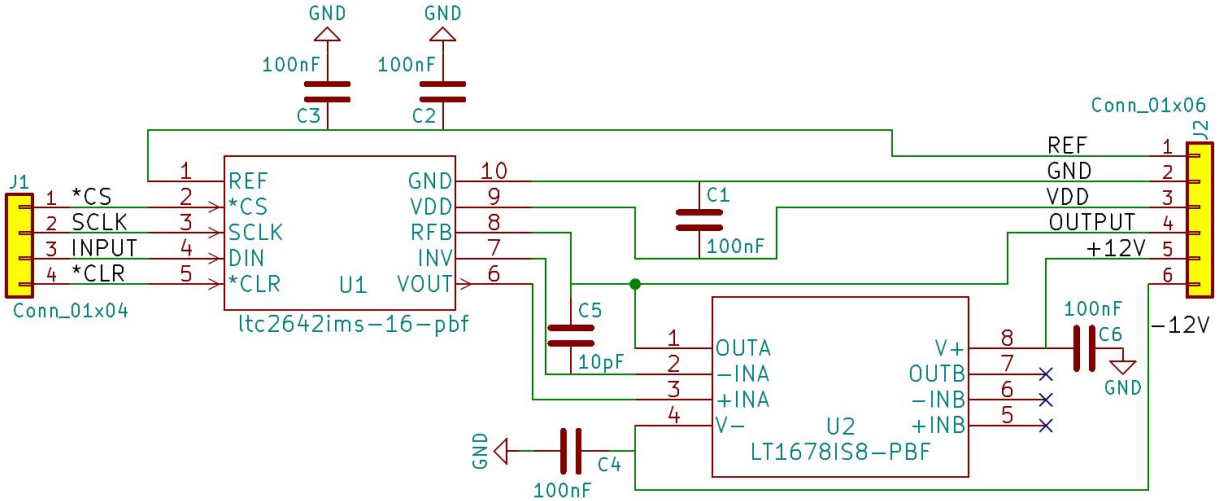
For testing the basics, like controlling the DAC and measuring the analog voltage outputs, we first created two simple setups for two DACs. To increase the chances of success we picked a model which has already been tested at cryotemperature by a research group at the University of Sydney [8]. The measurements of the research group shows the performance of a DAC produced Linear Technology with the name LTC2641 16-bit and MSPS package [9]. Their measurements show that the non-linearity of the device gets worse when it is cooled. Therefore the paper suggests DAC calibration to improve the linearity. The research group also test a more complex DAC but this one showed more noise when cooled to 4 K. Therefore for building our own setup we choose the LTC2641ACMS8-16#PBF.

The downside of the LTC2641 is its polar and small voltage output range of 0 V to 5.5 V. For our trapped ions experiment is typically a bipolar range of -10 V to 10 V needed. A solution about the unipolar voltage output, is using a similar model of this DAC also produced by Linear Technology but with unipolar output. The LTC2642 [9] has an output range of -5.5 to +5.5 V by applying an OpAmp. In our setup we use the LTC2642CMS-12#PBF. By studying the schematic of this DAC we see that it uses two resistors inside the DAC to create a reference voltage which is necessary for the op-amp to get the bipolar output. There would still be the challenge of increasing the output range by a factor of two. Nevertheless if this one works we could apply a second amplifier to increase the output range. Therefore we are motivated to test this model as well.

As the very first step, we only test the control and readout of the DAC at room temperature. For doing so we designed a PCB according to the application schemes shown in the data sheet of the two DACs LTC2641/LTC2642 [9]. Part of the schemes is a precision voltage source as a reference and an amplifier. On our PCB we did not include the voltage reference directly but instead connected an external reference via a pin connector. Since we do not know of an op-amp which is working at 4 K, we used the ones suggested by the application schemes to avoid unforeseen mistakes. Fig. 2.1 shows the schematics of the two PCBs for our first test. The names of the DAC in the schematics are not the same as we used for our testing. It is not required to use exactly these models for the experiment. For printing the PCB it is only important to have the matching footprint to the package of the DAC and not on the exact model. In fact we printed two kinds of PCBs for the MSOP package and the DD package. In the end we used the MSOP package since it is easier to solder on the PCB. Pictures of the PCBs are shown in the appendix B.



(a) Using the LTC2641 for an output range of 0 V to 5 V. One can also use this PCB for testing the DAC only, by shorting pin 6 of the DAC with pin 4 of the pin connector on the right and also not including an amplifier.



(b) In this schematic the theoretical output range is increased to 0 V to 10 V due to the operational amplifier and the additional two pins coming from the DAC LTC2642 which are labelled with INV and RFB, they are a center tap of the scaling resistors and the latter is a feedback resistor.

Figure 2.1: The left box named U1 is the DAC with the name LTC2641AIMS8-16-PBF in a) and ltc2642ims-16-pbf in b) which are specific models produced by Linear Technology. The box on the right named U2 is the amplifier. The amplifier in schematic a) acts as a buffer. In b) in the other hand is the amplifier needed to amplify the output range to -5 V to 5 V. The capacitors are used to filter the voltage signals.

2.2 Communication

To communicate with the DAC using the SPI protocol, we use a raspberry pi 3 which runs a code written in python. The code is shown in the appendix A. A python package called spidev can send byte lists with the desired voltage input to the DAC and also sends data to the other three pins of the left pin connector in 2.1 as well. The bytelist for the voltage input consist out of 12 to 16 bits, depending on the resolution of the DAC model. The number of the byte list converts linearly to the voltage output with the following two end

points. When the input is all set to 0 it gives the lowest voltage output and with the highest number as an input it gives the highest voltage. The digital-to-analogue transfer function is [9]:

$$V_{OUT} = \frac{k}{2^N} V_{DD} \quad (2)$$

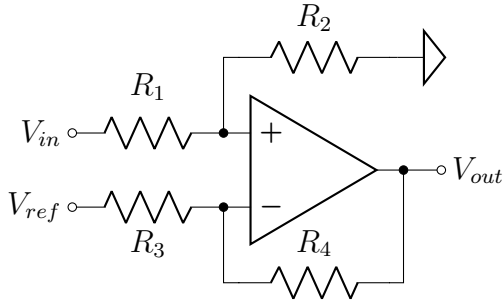
where N is the resolution of the DAC, k is the decimal equivalent of the byte list and the maximal output is the same as the voltage supply V_{DD} .

2.3 Advanced Setup

The testing of the two circuits discussed before were successful. The communication between the raspberry pi and the DAC worked for both models and the voltage output had a deviation of 1% to the desired voltage. Our next goal is to build a setup with the desired output of -10 V to +10 V. This can be realized by building a differential amplifier with 4 resistors and an Op-Amp. To calculate in which way the resistors have to be set on the circuit to give the desired amplification, we do use the properties of an ideal op amp which can be summarized to the two golden rules on an ideal op-amp:

1. The output attempts to do whatever is necessary to make the voltage difference between the inputs zero.
2. The inputs draw no current.[10]

The circuit to add between the DAC output and the output pin to measure the voltage is drawn below. Notice that the positive and negative power supply for the amplifier are omitted in the drawing, but are necessary to amplify the signal. In our measurements we used +12 V and -12 V.



The ratios of the resistors have to fulfil certain relations so that V_{out} has the desired range. The output range of the LTC2641 is from 0 V to V_{DD} , while V_{DD} can be chosen to have a value between 2.7 V and 5.5 V. First we use the property of the operational amplifier that the inputs virtually draw no current. Therefore all current I_1 goes from V_{in} to ground through R_1 and R_2 , and all current I_2 goes from V_{ref} to the op-amp output through R_3 and R_4 . According to Ohm's law the following equations can be obtained.

$$I_1 = \frac{V_{in}}{R_1 + R_2} \quad (3)$$

$$I_1 = \frac{V_+}{R_2} \quad (4)$$

$$I_2 = \frac{V_{ref} - V_-}{R_3} \quad (5)$$

$$I_2 = \frac{V_- - V_{out}}{R_4} \quad (6)$$

Solving 6 for V_{out} and substituting I_2 using 5 we get.

$$V_{out} = V_- - I_2 R_4 \stackrel{(5)}{=} V_- - \frac{(V_{ref} - V_-)R_4}{R_3} \quad (7)$$

A second property of an ideal op amp is that V_+ and V_- are virtually equal. Using the additional equation $V_+ = V_-$ we can substitute V_- with V_+ in equation 7. Then let us use equation 4 and reorganize the terms.

$$V_{out} = V_+ - \frac{(V_{ref} - V_+)R_4}{R_3} \stackrel{(4)}{=} I_1 R_2 - \frac{(V_{ref} - I_1 R_2)R_4}{R_3} = I_1 R_2 \frac{R_3 + R_4}{R_3} - \frac{R_4}{R_3} V_{ref} \quad (8)$$

Finally by using equation 3 we get the following:

$$V_{out} \stackrel{(3)}{=} \frac{R_2}{R_1 + R_2} \frac{R_3 + R_4}{R_3} V_{in} - \frac{R_4}{R_3} V_{ref} \quad (9)$$

For easier calculations lets set $V_{DD} = 5$ V and $V_{ref} = 2$ V. Other numbers would also work but the solution would not be natural numbers as ratios and if V_{ref} is too high the result would have a negative value for one resistor. By setting the mentioned numbers into equation 9 and looking at the endpoints with the lowest input converting to -10 V and the highest input to +10 V. The results are the following relations of the resistors:

$$V_{out}(V_{in} = 0V) = -\frac{R_4}{R_3} 2V = -10V \quad (10)$$

$$\Rightarrow \frac{R_4}{R_3} = 5 \quad (11)$$

$$V_{out}(V_{in} = 5V) = \frac{R_2}{R_1 + R_2} 6 \cdot 5V - 10V = 10V \quad (12)$$

$$\Rightarrow \frac{R_2}{R_1} = 2 \quad (13)$$

These ratios of resistors and setting $V_{ref} = 2$ V amplifies the voltage range by factor 4 and shifts it by -10 V. The circuit drawn above with these ratios of resistors is added on a new PCB, so this construction can also be tested. For the second row of testing we were only interested in LTC2641, because anyway one op-amp is used to expand the output range, so LTC2642 has no advantage over LTC2641. For our testing we use the LT1678IS8#TRPBF [11] amplifier. Fig. 2.2 shows the scheme of the new circuit and a picture of the PCB is in appendix B.

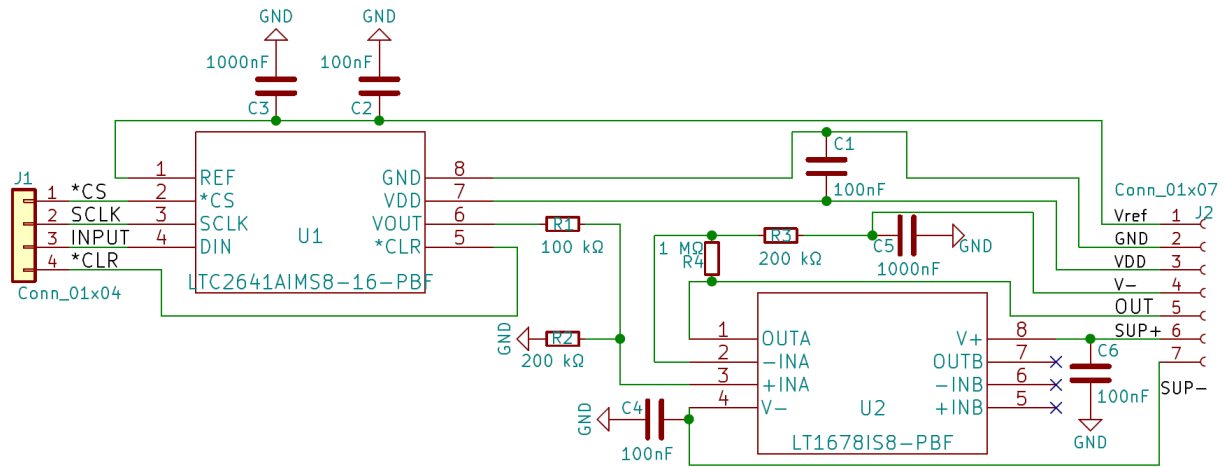


Figure 2.2: The left box named U1 is the DAC with the name LTC2641AIMS8-16-PBF. The box on the right named U2 is the amplifier, in combination with the four resistors R1, R2, R3 and R4 it amplifies the voltage signal to the desired output range of -10 V to 10 V. The capacitors are used to filter the voltage signals.

3 Measurements


3.1 LTC2641 without an amplifier

To only test the DAC at 4K we used the more simple setup for the LTC2641 discussed in section 2.1. But here we had the amplifier omitted and the output of the DAC is shorted to the output pin of the PCB. So all the components which got cooled are three capacitors, the DAC, the PCB itself and the wires connecting to the pinholes.

The first 10 data points were taken at room temperature and then the same cooled to 4 K by dumping the PCB with the components into liquid helium. The measurements are presented in the table below. The first row lists the expected voltage while the second and third row list the measured voltage output at room temperature and 4 K respectively. The last row shows the difference of the voltage measured at the two different temperatures.

V_{expected} [V]	V_{out} [V] at 300 K	V_{out} [V] at 4 K	ΔV_{out} [V]
0.0	$(1.01 \pm 0.01) \cdot 10^{-4}$	$(1.2 \pm 0.02) \cdot 10^{-4}$	$(1.9 \pm 0.3) \cdot 10^{-5}$
0.5	$0.49895 \pm 1 \cdot 10^{-5}$	$0.49945 \pm 1 \cdot 10^{-5}$	$(5.0 \pm 0.2) \cdot 10^{-4}$
1.0	$0.99798 \pm 1 \cdot 10^{-5}$	$0.99864 \pm 1 \cdot 10^{-5}$	$(6.6 \pm 0.2) \cdot 10^{-4}$
1.5	$1.4969 \pm 1 \cdot 10^{-4}$	$1.4975 \pm 1 \cdot 10^{-4}$	$(6 \pm 2) \cdot 10^{-4}$
2.0	$1.9959 \pm 1 \cdot 10^{-4}$	$1.9965 \pm 1 \cdot 10^{-4}$	$(6 \pm 2) \cdot 10^{-4}$
2.5	$2.4949 \pm 1 \cdot 10^{-4}$	$2.4954 \pm 1 \cdot 10^{-4}$	$(5 \pm 2) \cdot 10^{-4}$
3.0	$2.9939 \pm 1 \cdot 10^{-4}$	$2.9942 \pm 1 \cdot 10^{-4}$	$(3 \pm 2) \cdot 10^{-4}$
3.5	$3.4929 \pm 1 \cdot 10^{-4}$	$3.4931 \pm 1 \cdot 10^{-4}$	$(2 \pm 2) \cdot 10^{-4}$
4.0	$3.9919 \pm 1 \cdot 10^{-4}$	$3.9920 \pm 1 \cdot 10^{-4}$	$(1 \pm 2) \cdot 10^{-4}$
4.5	$4.4909 \pm 1 \cdot 10^{-4}$	$4.4911 \pm 1 \cdot 10^{-4}$	$(2 \pm 2) \cdot 10^{-4}$
5.0	$4.9900 \pm 1 \cdot 10^{-4}$	$4.9902 \pm 1 \cdot 10^{-4}$	$(2 \pm 2) \cdot 10^{-4}$

Table 3.1: LTC2641 without an amplifier tested at 300 K and at 4 K.

Secondly we tested a cold start of the device. To do so we shut down the raspberry pi  so that there is no supply for the DAC and it can completely cool down. After starting the raspberry pi the DAC was able to start and gave the same output as measured before the restart.

3.2 LTC2641 with the operational amplifier LT1678

After seeing the DAC successfully working at 4 K, without significant change of the voltage at 4 K, we are motivated to test the amplifier as well. The setup contains the LTC2641 DAC, the LT1678 amplifier, six times the 100 nF capacitors, and $R_1 = 100 \Omega$, $R_2 = R_3 = 200 \Omega$ and $R_4 = 1 \text{ k}\Omega$ resistors. It is important that the ratio of the resistors are as discussed in section 2.3. The supply and reference voltage of the DAC are set to 5 V. The positive and negative power supply for the amplifier are set to 12 V and -12 V respectively. Finally the reference voltage V_{ref} of the amplifier is set to 2 V.

Measuring the output at room temperature results in a disappointing 0.25 V for all voltage

inputs above 0.25 V. At 0 V the output was more or less correct. After investigating the problem we found the source of it. The DAC output resistance is 6.2 k Ω and the combined resistance of R_1 and R_2 is only 300 Ω . This results in a power drain of the DAC output. To overcome that problem one has to use higher resistors.

Unfortunately there were no resistors with higher resistance and the correct ratios available, therefore we used slightly different ones, namely $R_1 = 100$ k Ω , $R_2 = R_3 = 220$ k Ω and $R_4 = 1$ M Ω . This results in the theoretical output range of -9.09 V to 9.97 V which is not the desired range but it does not matter very much for now, since we only want to test the function of the setup. The result is seen in the table below. First we took some data points at room temperature and later at 4 K. Unfortunately the set up did not function at 4 K. The measured output was always 1.5375 V. However as soon as everything got warmer it worked again. Therefore the low temperature did not damage the set up, instead it only stopped functioning while being cold.

V_{expected} [V]	V_{out} [V] at 300 K
-9.09	$-9.0880 \pm 2 \cdot 10^{-4}$
-9	$-8.9988 \pm 2 \cdot 10^{-4}$
-8	$-8.0184 \pm 1 \cdot 10^{-4}$
-7	$-7.0381 \pm 1 \cdot 10^{-4}$
-6	$-6.0578 \pm 2 \cdot 10^{-4}$
-5	$-5.0776 \pm 1 \cdot 10^{-4}$
-4	$-4.0974 \pm 2 \cdot 10^{-4}$
-3	$-3.1171 \pm 2 \cdot 10^{-4}$
-2	$-2.1368 \pm 2 \cdot 10^{-4}$
-1	$-1.1566 \pm 1 \cdot 10^{-4}$
0	$-0.1763 \pm 1 \cdot 10^{-4}$
1	$0.8039 \pm 1 \cdot 10^{-4}$
2	$1.7841 \pm 3 \cdot 10^{-4}$
3	$2.7640 \pm 2 \cdot 10^{-4}$
4	$3.7445 \pm 2 \cdot 10^{-4}$
5	$4.7248 \pm 2 \cdot 10^{-4}$
6	$5.7050 \pm 1 \cdot 10^{-4}$
7	$6.6852 \pm 2 \cdot 10^{-4}$
8	$7.6656 \pm 2 \cdot 10^{-4}$
9	$8.6457 \pm 2 \cdot 10^{-4}$
9.97	$9.5981 \pm 2 \cdot 10^{-4}$

Table 3.2: The measured voltage output of the advanced setup with the LTC2641 DAC and amplified by the LT1678.

4 Conclusion

4.1 The DAC

Looking at ΔV_{out} in table 3.1 one observes that as the set voltage increases, the actual voltage acquired at 4 K gets closer to the voltage measured at 300 K. In general the difference is quite low and for some data points it is even inside the uncertainty of the measuring device. Therefore we can conclude that the DAC does not lose much functionality when cooled to cryogenic temperatures. Moreover the relative deviation between the input and output has an offset of 0.2 % for all measured data points above 0 V (if the desired voltage is zero there is a small deviation of $(1.01 \pm 0.01) \cdot 10^{-1}$ mV).

4.2 Advanced set up

The advanced set up got some differences between the expected and measured voltage at room temperature as seen in table 3.2. Since the communication, voltage supply, and voltage reference stayed the same as in the simpler setup, the source of error should lay with the resistors, the amplifier or the different circuit. For further experiments it might be better to use bigger resistors, because the resistors in the experiment probably are still too low, resulting in a drainage of the output voltage.

At cryogenic temperature the advanced system failed to fulfil its task. This might be because the amplifier stopped working. Another source of the problem could be that the resistance of the resistors changed due to the cold temperature and therefore the voltage of the DAC got drained.

5 Outlook

It was shown that the LTC2641 works without any difference if operating at room temperature or at 4 K. The deviation of the expected to the measured analog voltage is a relative offset of 0.2%. This strongly looks like a systematic error which could be corrected by adjusting the bytelist input. Instead of using the ideal equation 2 one could correct this formula with the measured offset. Furthermore an amplifier which works at cryogenic temperature needs to be found. Another solution would be to find a DAC which already gives the desired output range and also works at 4 K.

References

- [1] P. Schindler et al., *A quantum information processor with trapped ions*, arXiv:1308.3096 (2013).
- [2] S. Earnshaw, *On the Nature of the molecular forces which regulate the Constitution of the Luminiferous Ether*, Transactions of the Cambridge Philosophical Society, Vol. 7, pp. 97-112, 1842.
- [3] W. Paul, H. Steinwedel, *Ein Neues Massenspektrometer Ohne Magnetfeld*, DOI: 10.1515/zna-1953-0710 (1953).
- [4] F Major, V. Gheorghe, G. Werth, *Charged Particle Traps* (Springer Berlin Heidelberg, 2005) p.26. ISBN 978-3-540-22043-5.
- [5] S. Seidelin, et al. *Microfabricated Surface-Electrode Ion Trap for Scalable Quantum Information Processing*, arXiv:quant-ph/0601173 (2006).
- [6] D. DiVincenzo, *The Physical Implementation of Quantum Computation*, arXiv:quant-ph/0002077v3 (2000).
- [7] J. Conway Lamb, et al. *An FPGA-based instrumentation platform for use at deep cryogenic temperatures*, DOI: 10.1063/1.4939094 (2016).
- [8] Conway Lamb, Ian, Master thesis, University of Sydney, 2016, <http://hdl.handle.net/2123/17046>
- [9] Data sheet of the LTC2641/LTC2642. 14 October 2018, www.linear.com/LTC2641
- [10] P. Horowitz, W. Hill, *The Art of Electronics* (Cambridge University Press, 2015) Vol. 3, p. 225.
- [11] Data sheet of the LT1678. 14 October 2018, www.linear.com/LT1678

A Code for the communication

```
import spidev

resolution= 16
vRef = 5

def setVoltage(voltage):
    voltage = (voltage + 10) / 4    #to convert the amplified range to [0V, 5V]

    if voltage > vRef or voltage < 0:
        return

    if voltage == vRef:
        dacSetting = 2**resolution - 1
    else:
        dacSetting = (voltage / vRef) * 2**resolution

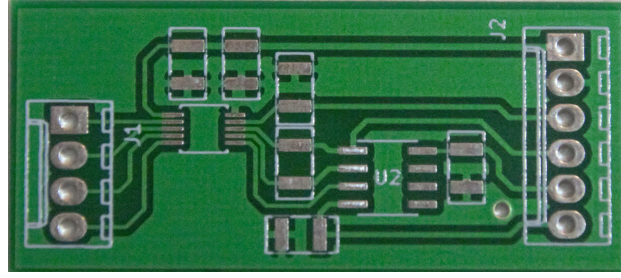
    INPUT_CODE = int(dacSetting)
    SHIFTED_CODE = INPUT_CODE << (16-resolution)
    data = [0xff&(SHIFTED_CODE >>8), 0xff&SHIFTED_CODE]

    SendCommands(data)

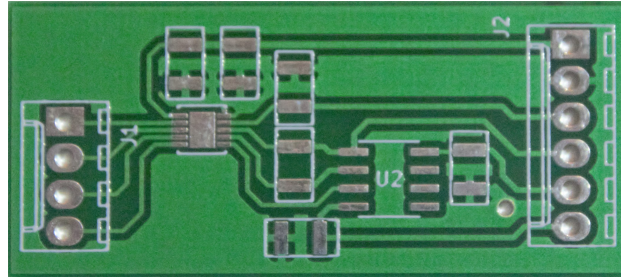
def SendCommands(byteList):
    spi = spidev.SpiDev()           #create spi object
    spi.open(0, 0)
    resp = spi.xfer2(byteList)
    spi.close()
    print("Communication successful",resp)
    return resp

if __name__ == "__main__":
    setVoltage(8)
```

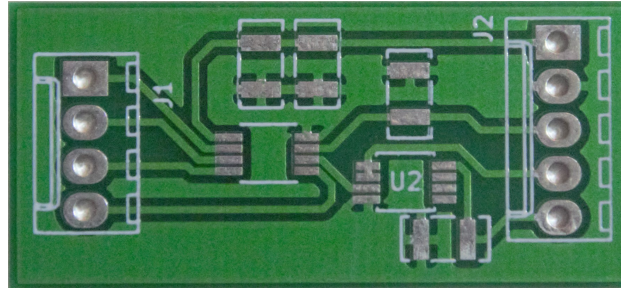
B Pictures of the PCBs



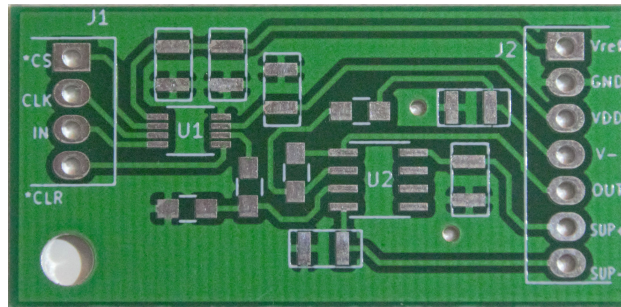
(a) PCB with the LTC2642 setup for the MSOP package.



(b) PCB with the LTC2642 setup for the DFN package.



(c) PCB with the first setup of the LTC2641 DAC for the MSOP package.



(d) PCB of the advanced setup for the MSOP package.

Figure B.1: These for PCBs are used to solder the components on them. For further informations about the PCBs compare them with the schematics in figure 2.1.