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DISSERTATION

Cool Science

ausgeführt am Atominstitut

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der Technische Universität Wien
Fakultät für Physik

unter der Anleitung von
Univ.Prof. Dipl.-Ing. Dr.techn. Gorge Hammond
und
Projektass. Dr.rer.nat Rodney MacKay MSc.
Projektass. Dr.techn. Dr.techn. Dr.techn. Dipl.-Ing. Samantha Carter

durch

Daniel Jackson

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Stadionallee 2
1020 Wien

Wien, am 04.05.2020

"The Setesh guard's nose drips."
TEAL'C

Contents

1 Cathodic Ray Tube Basics

This section features a quick explanation what a CRT is and what it's main components are, followed by a more detailed description on how these components are implemented in the CRT Heerlen D14-363GY, which was used in this project. It ends with a description of the important characteristics of the CRT and the requirement the theory poses on them.

1.1 Underlying Physics

Wikipedia states: "The cathode-ray tube (CRT) is a vacuum tube that contains one or more electron guns and a phosphorescent screen and is used to display images. It modulates, accelerates, and deflects electron beam(s) onto the screen to create the images."

There are three vital components to accomplish this feat: the electron gun, the electron lens and the deflection plates.

The electron gun extracts electrons from a cathode material, accelerates them onto a perforated anode and thereby produces a free electron beam (see fig. 1.1). One important characteristic in the selection of a cathode material is a low work function. The work function denotes the amount of energy needed to extract one electron from the material. The are two ways to overcome this energy barrier in an electron gun, one can either overcompensate it by applying a strong electric field ("field emission", "cold cathode", fig. 1.2b or one can heat the material until some electrons have enough thermal energy to overcome the energy barrier ("thermal emission", "hot cathode", fig. 1.2a. For our CRT, only thermal emission is relevant, more detail on this will be added later along with the description of our cathode's design.

The cathode itself is housed in a so-called Wehnelt cylinder, as the name suggests it is conducting cylinder, which is set to a slightly more negative potential than the cathode itself. This part implements two features, firstly it condenses the emitted electrons, leading to a smaller spot size, i.e. making the cathode a more point-like electron source. Secondly it enables us to regulate the beam current, the more negative the Wehnelt potential is, the less electrons are emitted by the electron gun. As we

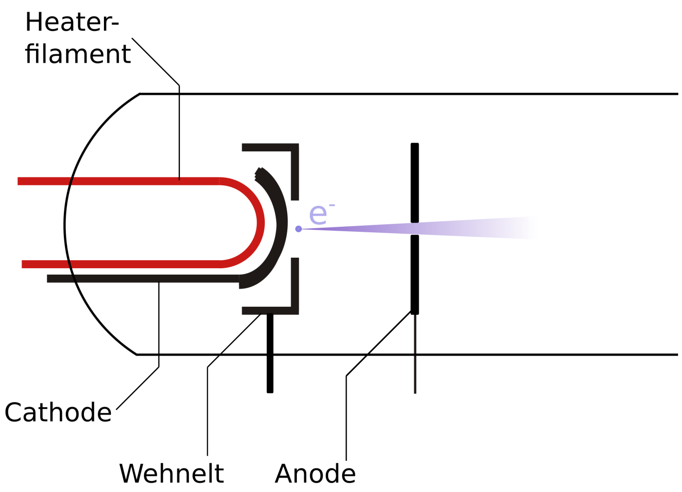
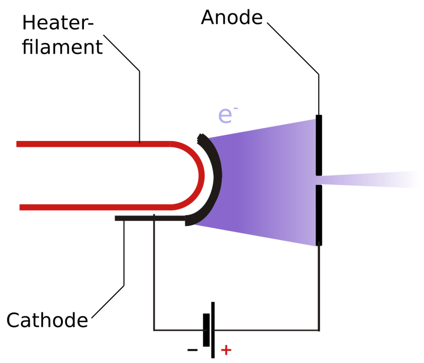
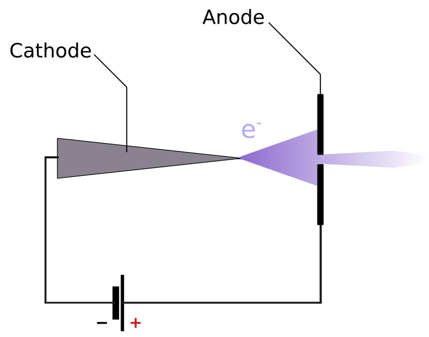


Figure 1.1: Schematic of an electron gun



(a) Schematic of a hot cathode



(b) Schematic of field emission cathode

Figure 1.2: Cathode types

make the Wehnelt potential more positive, the beam current increases and continues to rise even after it is more positive than the cathode itself. However the spot size reduction is lost in the process, along with the ability to properly focus the beam with electron optics.

The electrons that leave the electron gun are still divergent and need to be focused. For our 2 keV electrons it is still possible to use an electrostatic lens. Cylindrically symmetrical pieces of conductor, like rings and tubes, can be set to an electrical potential and act as a lens for the electrons. By combining several of them, one can (theoretically) engineer an electro-optical system with any combination of desired focal lengths f_1 and f_2. The field of this system is simply governed by Laplace's equation in cylindrical coordinates:

$$0 = \frac{1}{r}\frac{\partial \phi}{\partial r} + \frac{\partial^2 \phi}{\partial r^2} + \frac{\partial^2 \phi}{\partial z^2} \tag{1.1}$$

If we take the axis of the beam to be the z-axis, the position of the focal point in the x-y-plane can be shifted using the two pairs of deflection plates, one for the x- and one for the y-direction. The deflection is achieved by applying a voltage between the two parallel plates. (see: fig. 1.3) By starting with an electron with kinetic energy $e \cdot U_0$ which is accelerated in x-direction by a constant force $e \cdot U_x / d$ over the extent of the plates L, the deflection angle is approximately [**Demtroeder3**]:

$$\delta \approx \tan(\delta) \approx \frac{U_x \cdot L}{2U_0 \cdot d} \tag{1.2}$$

For the measures of our CRT ($L \approx 10\,\mathrm{cm}$, $d \approx 1\,\mathrm{cm}$, $U_0 \approx 2\,\mathrm{kV}$ and distance to screen $\approx 20\,\mathrm{cm}$) this amounts to a deflection coefficient of around $20\,\mathrm{V\,cm^{-1}}$, which is quite consistent with the value given in the CRT's manual.

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stimmen?

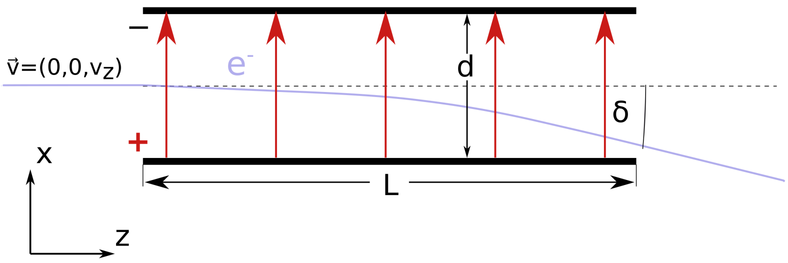


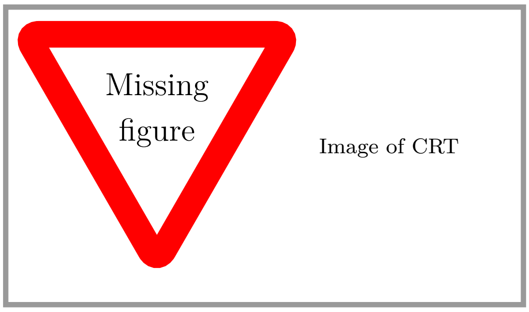
Figure 1.3: Deflection of an electron beam in a constant electrical field

1.2 Implementation in the Heerlen D14-363GY

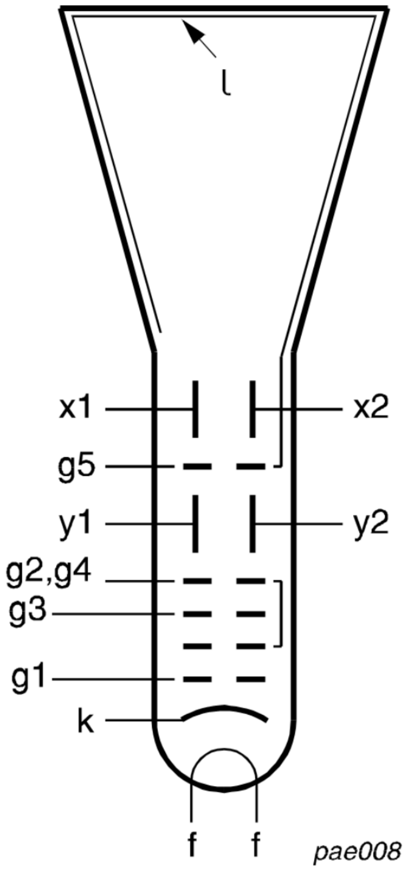
This section describes how the mechanisms described above are implemented in the CRT that was used in this project: the PDS/CRT Heerlen D14-363GY. Figure 1.4a shows an image of said CRT, fig. 1.4b shows a schematic depiction. The cathode is not visible, as it is fixed inside the Wehnelt cylinder (1), just a few millimeters from the exit of the wehnelt cylinder the electrons pass through the perforated anode (2) they gain their full final kinetic energy over this short distance. The electrons that go through the perforation and enter the electrostatic lens, have 2 keV and therefore move at a speed of approximately $0.08\,c$. The electrostatic lenses are realized using three conducting rings (3), that are set to the same potential but have varying radii: Each consectutive ring has a smaller radius than the previous one.

Between the electrostatic lens and the deflection plates, there is another aperture (4), which is internally connected to the anode and is thereby kept at the same potential. In our Setup, the deflection plates are not simply parallel but are shaped like funnels (5,7), between the two pairs of deflection plates, we have the final aperture (6), this ones potential can be regulated separately (usually it's on the same potential as the anode)

It is connected to the glass envelope of the CRT to prevent the glass from charging up and distorting the image. Finally the beam hits the phosphorous-coated screen which fluoresces on electron impact.



(a) Image picture of the Heerlen D14-363GY



(b) Schematic of the CRT from [**D14363GY123-manual**]

Figure 1.4

1.2.1 The Cathode

As already mentioned, we are using a hot cathode, where the electrons are exited thermally until some of them acquire enough energy to leave the material. Compared to cold cathodes, which work by field emission, this leads to a broader energy distribution. In fields like electron microscopy, where a high resolution is the goal, this in undesirable, as it leads to some degree of chromatic aberration in the electron optics, for our purposes, this should not be a problem. On the other hand, hot cathodes normally allow for higher current densities, which is very important to us. The electron current from this kind of emission is described by [**Whitaker**]:

$$I = A \cdot T^2 \cdot e^{-b/T} \tag{1.3}$$

Where b is proportional to the the work function of the material, T is temperature and A is a material-dependent constant. It is clear from this formula, that a low work function and a high melting point are important characteristics for a good cathode material.

The cathode from one of our Heerlen D14-363GY-tubes has been removed and examined with EDX (Energy-dispersive X-ray Spectroscopy). Nickel, barium, and strontium have been found, which suggests that it is a metal oxide cathode with barium-, strontium-, and possibly aluminum-oxide. This type of cathode is very common in low power electron tubes.

The “Power Vacuum Tubes Handbook” [**Whitaker**] describes a typical oxide cathode as a coating of barium and strontium oxides on a structure made from nickel alloys. Nickel is chosen for it’s strength and toughness, which it retains even at high temperatures. These cathodes are normally made by coating a case structure with a mixture of barium and strontium carbonates (typically 60 % Ba and 40 % Sr), suspended in a binder material and then baking the structure, causing the carbonates to be reduced to oxides.

These metal oxide cathodes normally operate at 700 °C to 820 °C and are capable of average emission densities of $100\,\mathrm{mA\,cm^{-2}}$ to $500\,\mathrm{mA\,cm^{-2}}$. Still higher peak emissions are possible for shorter periods of time, as already mentioned, one of the advantages of this type of cathode is its high emission current capability compared to cathodes made from other materials. Downsides to this cathode type are its greater susceptibility to so-called oxygen poisoning and to ion bombardment. The literature therefore recommends to avoid prolonged exposure to oxygen. Oxygen poisoning is the process in which oxygen adsorbs onto the cathode and increases its work function, effectively reducing its ability to emit electrons. Also the material from the oxide cathode will evaporate during the tube's lifetime and will travel to other parts of the tube, adsorbing to electron optics parts and turning them into additional emitters. The literature (also from [**Whitaker**]) therefore also advises against exceeding the design value for the heater voltage, as this reduces the lifetime of the cathode significantly. (However during the course of our project, we did drive the cathode with higher heater voltages on various occasions in order to increase the available beam current.)

1.2.2 Cathode Layout

Figure 1.5 shows how metal oxide cathodes for CRTs typically look, the depiction agrees very well with the layout of our cathode. On the image we see the cathode cylinder, which corresponds to the nickel support structure mentioned above. It is shaped into a cup, i.e. the cylinder is hollow and open on one side, where the heater filament (shaped into a heater coil) is inserted. The oxide disk, from where the electrons are emitted, is baked onto the top of the cathode cylinder. The cathode cylinder is mounted on an isolating support structure and inserted into the Wehnelt cylinder, which is called "grid cup" in the drawing.

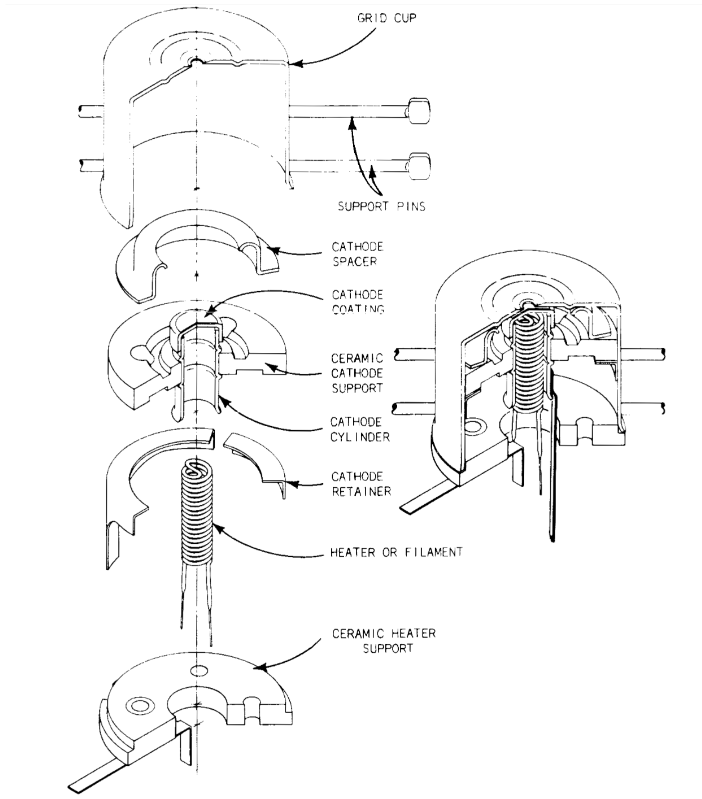


Figure 1.5: Schematic of the layout of a typical CRT-cathode from [**deVere69**]

2 Cicero Word Generator

This chapter describes the installation and initial setup of Cicero Word Generator[**keshet2013distribu** on a PC running Windows 10 with analog and digital cards from National Instruments (NI). The code is freely available on Github[**akeshet:Github**]. This chapter contains only differences, problems, and possible solutions encountered when Cicero was installed for the PC 'Fritz Fantom' which will be used for the QuaK experiment. It is therefore advised to use the technical and user manual[**akeshet:manual**] in conjunction. The titles in this chapter and font style with `Courier` and **Boldface** was mirrored to fit the manual.

2.1 Installation of National Instruments drivers

Before setting up the Cicero Word Generator, it is necessary to install the newest .NET Framework[**microsoft:download.net**] from Microsoft. For the first installation of NI drivers, NI-DAQmx (version 9.3), NI-VISA (newest version), and NI-4888.2 (newest version) should be downloaded from the National Instruments website[**ni:drivers**]. When installing the NI drivers it is possible to get an 'Runtime Error!'. In this case it is necessary to set the Regional format settings of Windows 10 to 'English (United States)'[**ni:runtimeerror**].

2.2 Installation of National Instruments Cards

After installation of the necessary drivers, the physical cards can be inserted into the PCIe slots on the motherboard. On 'Fritz Fantom' the digital card (NI PCIe-6537B) was installed in PCIe bus 3 while the analog cards (NI PCIe-6738) were installed in PCIe bus 4 and 5.

2.3 Configuring Atticus

After installation of the NI cards, Atticus should be launched for the first time and closed without changing any settings. After this, the NI-DAQmx drivers should be updated to the newest version. If version 9.3 was not used when launching Atticus in this step, it could result in an error. After this, “Configuring Atticus” on the user manual can be followed. The **Server Name** was set to ‘Fritz_Phantom’. **Dev1** to **Dev3** were set in the same ascending order as the physical installation on the motherboard.

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Phantom

2.3.1 Configure hardware timing / synchronization

For synchronization, a **Shared Sample Clock** was used with **Dev1** being the master card. The settings are summarized in table 2.1 and table 2.2. For **Dev3** ‘SampleClock-ExternalSource’ should be set to ‘/Dev3/RTSI7’. The ‘SampleClockRate’ is set to 350 kHz since this is the fastest rate with all 32 analog channels active. It is possible to raise this to 1 MHz by only using 8 channels (1 channel per bank).

Table 2.1: Settings for **Dev1**.

Setting	Value
MasterTimebaseSource	
MySampleClockSource	DerivedFromMaster
SampleClockRate	350000
UsingVariabletimebase	False
SoftTriggerLast	True
StartTriggerType	SoftwareTrigger

Table 2.2: Settings for **Dev2**.

Setting	Value
MasterTimebaseSource	
MySampleClockSource	External
SampleClockExternalSource	/Dev2/RTSI7
SampleClockRate	350000
UsingVariabletimebase	False
SoftTriggerLast	False
StartTriggerType	SoftwareTrigger

2.4 Configuration and Basic Usage of Cicero

After setting up the Atticus server, Cicero can be configured. In step 3.c. it is necessary to write the full IP address and not ‘localhost’. Once step 6 is finished, Cicero should run without any problems.

2.5 Saving of Settings and Sequences

The ‘SettingsData’ of the Server Atticus are saved in C:\Users\confetti\Documents \Cicero_Atticus\Cicero\SettingsData while the ‘SequenceData’ of Cicero are saved in C:\Users\confetti\Documents\Cicero_Atticus\Cicero\SequenceData.

2.6 Sequence length limit

The duration of a sequence is limited to $2^{32}/(16 * 32 * 350\,\mathrm{kHz}) = 23.967\,\mathrm{s}$ coming from a 32-bit application, 16 bit per channel, 32 channels in a NI PCIe-6738 card, and 350 kHz clock rate.

3 Electron beam setup

3.1 Charatarization of a working CRT

HAMEG HM507 oscilloscopes [**HM507-manual**] were used for testing purposes. These contain a D14-363GY/123[**D14363GY123-manual**] CRT hereinafter abbreviated as 'D14', 'tube', or 'CRT'. Although the HM507 has only a bandwidth of 0 MHz to 50 MHz, which is not sufficient for the hyperfine splitting frequency of 461.7 MHz of ^{39}K, it was used nevertheless because of its simple construction and availability. A schematic view of the device is shown in fig. 3.1 with the back pin arrangement in fig. 3.2.

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The voltages and currents of the necessary pins to drive the CRT were measured using a 2.5 kV probe with an attenuation ratio of and are summarized in table 3.1. It was not possible to measure pin g3 directly. Therefore a HVPS (section 3.2) was used to set a voltage and the beam diameter was observed. The best focus was achieved with the voltage mentioned in the table. The voltage offset of x-, and y-plates was not possible to measure directly, since it varies with time to draw the necessary image on the phosphor screen. The given values in table 3.1 are the mean of the minimum and maximum measured voltage. The deflection coefficient is summarized in table 3.2.

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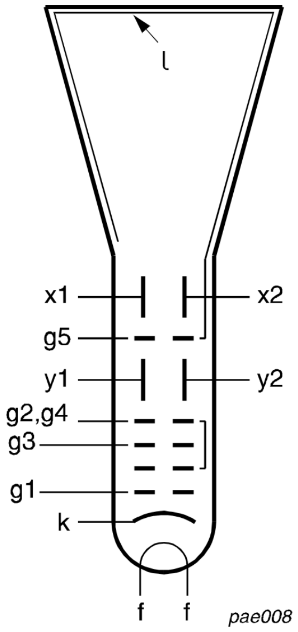

Figure 3.1: Electrode configuration (from [**D14363GY123-manual**])

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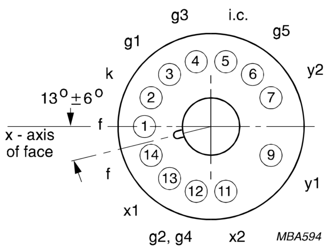

Figure 3.2: Pin arrangement, bottom view (from [**D14363GY123-manual**])

how to cite figure

Table 3.1: D14-363GY/123 CRT pin measurements

current empty or '-' symbol

number	pin	voltage/V	current/µA
1	f	-1.99×10^3	86.6×10^3
2	k	-2.00	-7.6
3	g1	-2.03	0
4	g3	-1.813×10^3	
5	i.c.	71.7	0.1
6	g5	64.0	7.2
7	y2	78	
9	y1	78	
11	x2	96	-
12	g2, g4	71.0	0
13	x1	96	-
14	f	-1.97×10^3	-86.2×10^3

Table 3.2: D14-363GY/123 deflection coefficient (from [**D14363GY123-manual**])

how to cite source

horizontal	M_x	19 V/cm
vertical	M_y	11.5 V/cm

3.2 High Voltage Power Supply HVPS

To produce high dc voltages to drive the CRT, four HCP 14-6500 power supplies[**fug-hcp-manual**] were used. They were named 'HVPS 1' to 'HVPS 4' and can provide up to ±6.5 kV and 2 mA. To connect the output to the CRT pins, BNC cables were refitted with a save high voltage (SHV) connector on one side while on the other end the BNC connector was kept (fig. 3.3). A 6 kV probe was used to obtain the breakdown voltage, which is around 3 kV caused by the coaxial cable which was not built do sustain high voltages.

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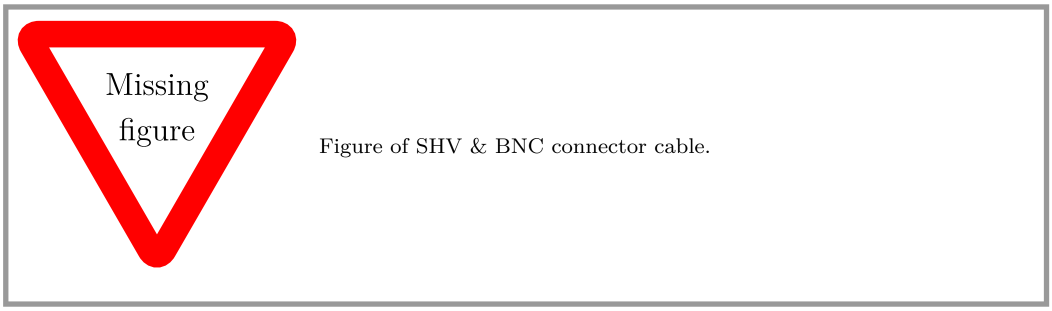


Figure 3.3: Coaxial cable with SHV and BNC connector.

3.2.1 Ripple measurement

Each power supply was measured for its ripple with a set voltage of 2 kV. A 2.5 kV probe (attenuation ratio)was connected to an oscilloscope set to ac coupling with a timescale of 1 ms. To get the electronic noise of the oscilloscope itself, the probe was shorted and the noise measured. A picture of a measurement is shown in fig. 3.4 with the values summarized in table 3.3.

100:1 or 1:100

Table 3.3: HVPS ripple

device	ripple/mV
short	116
HVPS 1	136
HVPS 2	138
HVPS 3	194
HVPS 4	204

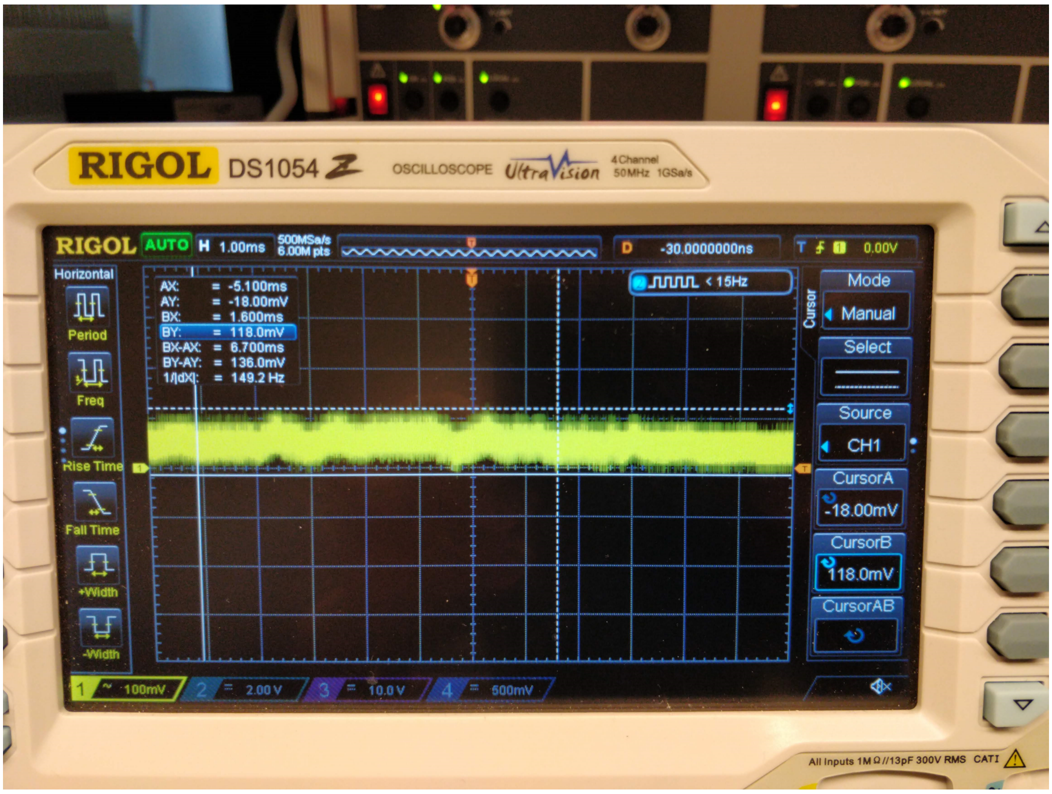


Figure 3.4: Measurement of HVPS ripple.

3.3 CRT wiring

A schematic of the supplied power is shown in fig. 3.5. A small ac or dc voltage is necessary to drive the heater filament f. This part of the setup is explained in section 3.4.

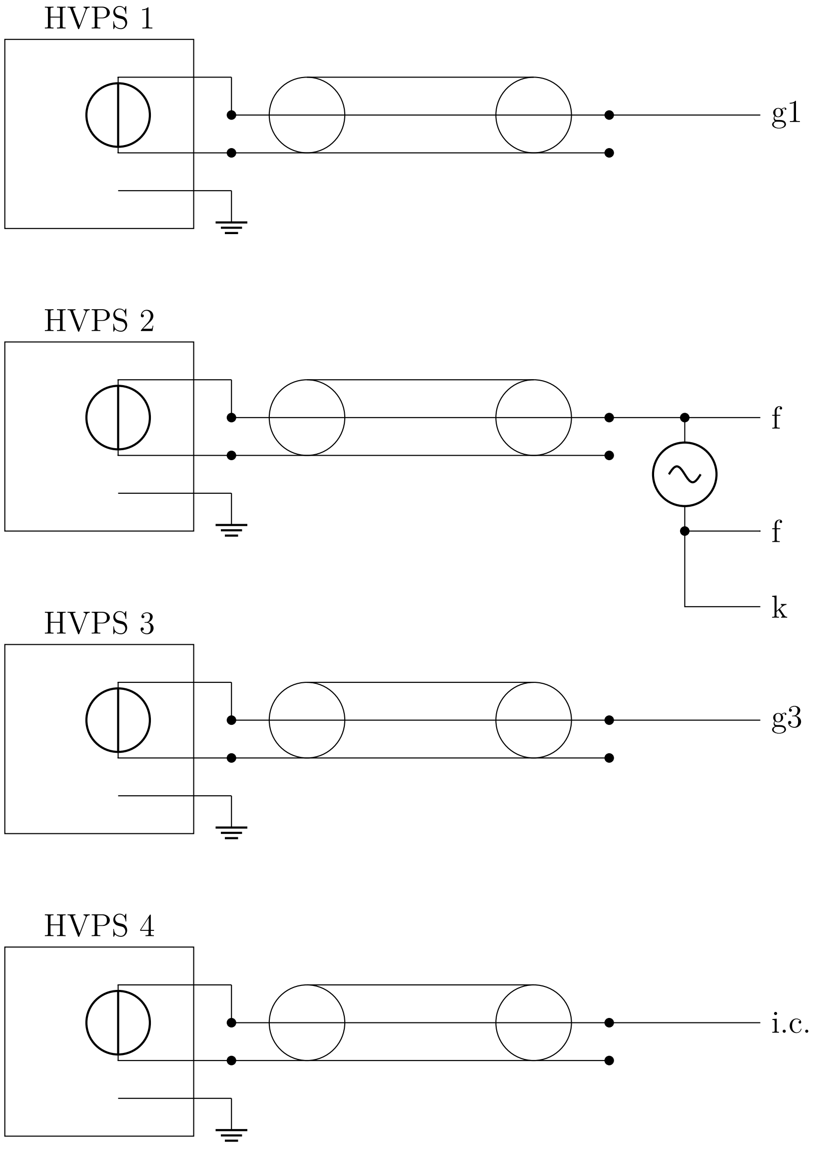


Figure 3.5: Schematics of supplying CRT pins with power.

3.4 Heater

The heater provides an adjustable ac voltage, which is used to regulate the temperature of the cathode. In the cold state, the heater filament has a an electrical resisitance of approximately 15 Ω, when the filament is hot, this value rises to 90 Ω. The normal heater voltage for the D14-363GY/123 during operation is 6.0 V to 6.6 V according to [**D14363GY123-manual**]. Our ac-power supply (figure 3.6 shows its circuit diagram)

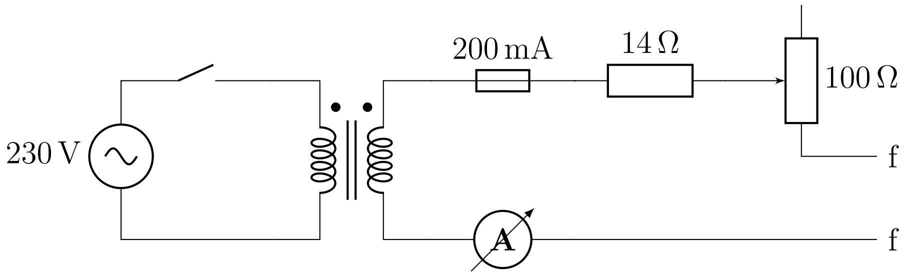


Figure 3.6: Circuit diagram of filament power supply.

check if really 14 Ω or if it event exists

consists of an isolation transformer (from grid voltage to 12 V), its primary and secondary circuits are isolated up to 4 kV [**DS44231-DataSheet**]. The power supply has two banana plug sockets to connect to the heater filament. It is connected to the transformer in series with a 100 Ω potentiometer. Using the full resistance, there is a voltage of approximately 5.7 V applied to the heater filament, by lowering the resistance this value can goes up to nearly the full voltage of the transformer. The current running through the filament is measured with an integrated amperemeter [**ACA-20PC-manual**] that measures currents up to two 2 A with mA accuracy.

At the beginning of operation it is recommendable to set the maximum resistance and slowly increase the current to the desired value once the filament is heated up. As the resistance of the cold filament is significantly lower, high onset currents could otherwise damage it.

4 CRT handling

4.1 Opening CRTs

In order to hit the ^{39}K cloud with an electron beam, it is necessary to cut open the CRT. This section explains the different methods which were tried and which resulted in clean and easy cuts. All slices were made in a glove box filled with nitrogen gas (fig. 4.1) to avoid oxygen poisoning of the cathode.

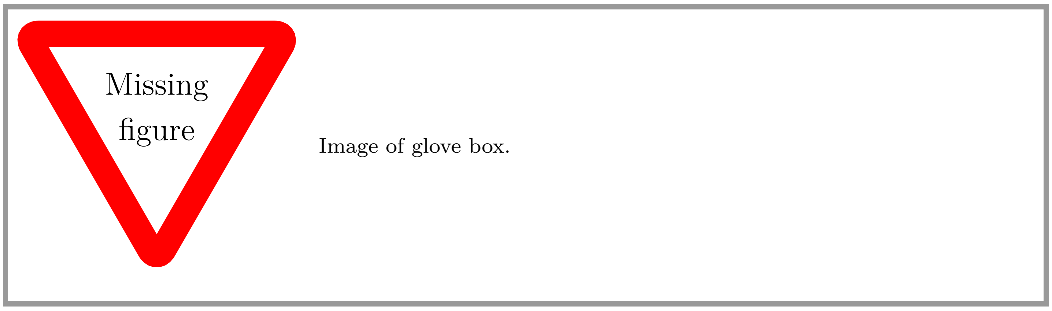


Figure 4.1: Glovebox filled with nitrogen gas to open CRTs.

4.1.1 Rotary tool

First, a small hole was drilled in the center of the CRT pins to pressurize the CRT with nitrogen. Then a diamond wheel attached to a rotary tool was used to cut the glass. This method was tried twice, but did not work well, as the method produced a lot of glass dust, which adhered to the electron optics. Another obstacle is the plastic box, since it is not fully transparent and therefore made more difficult to see inside.

4.1.2 Wire cutting

Higher success was achieved by cutting the glass with a heated wire. Two wires were put through the glove box, each ending in a ring terminal. A small height adjustable stage was built out of optical table parts (fig. 4.2) in which the CRT was put vertically and looped by an 0.25 mm steel wire (Fe 70/Cr 25/Al 5). It is important to keep a small gap in the loop to avoid an electrical short. Therefore two notches were made in which the wire was fixed.

The assembly was put inside the glove box which was subsequently filled with nitrogen. A current of approximately 2 A to 2.5 A was used to heat the thin wire which resulted in a breaking point inside the CRT glass. This method does not require a CRT pressurization before the cut. In order to not destroy a device by mistake, this procedure can first be tested on drinking glasses.

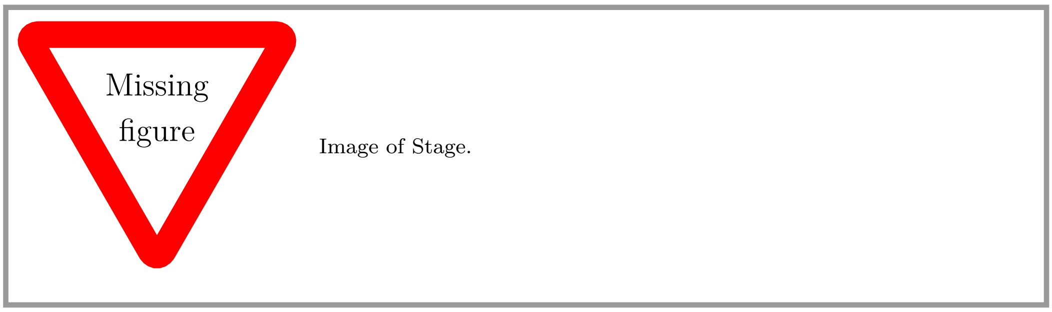


Figure 4.2: Stage to cut CRT with wire.

4.2 Oxygen poisoning

As mentioned in it is paramount to avoid contact of the cathode with oxygen. Therefore tests with a broken CRT were made to test on how well it can be isolated from air. where ?

The first experiment consisted of filling a drinking glass put upside-down with helium and putting a lighter after a set amount of time. If the fire goes off, it means that oxygen did not get inside. This was tested successfully from 0.5 min to 10 min.

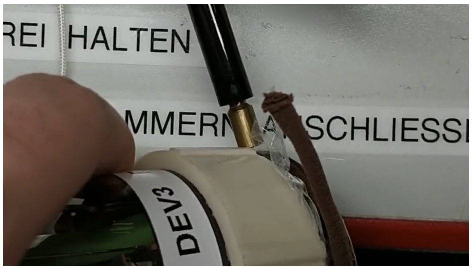
Next, plastic wrap was put on top of the glass filled with nitrogen by a rubber band. The glass was put with the open side up from 3 min to 10 min after which it was turned upside down and the foil was removed. A lighter was put inside and the flame went out again.

To improve the sensitivity, a He leak tester was used. For the first two tests, one plastic foil and one rubber band were used, for the third test three foils and two rubber bands, and for the last test an aluminum foil was hot glued on the CRT to seal it. The measurement locations are shown in fig. 4.3. As shown in table 4.1 using rubber band and clear foil results in the highest leakage while the glue seals much better (glue avg). But care needs to be taken in order ensure that the whole CRT is sealed since even a small leak can result in a rate around an order of magnitude above the background (glue max).

Table 4.1: He leak test.

location	leak rate/(10^{-5} mbar l/s)
1 plastic foil, 1 rubber band	
background	8
plastic foil	20
He gas cylinder	200
1 plastic foil, 1 rubber band	
background	7
plastic foil	20
rubber band	40
3 foils, 2 rubber bands	
background	20
plastic foil	30
rubber band	70
1 aluminum foil, hot glue	
background	6
glue avg	7
glue max	60
aluminum foil	8

(a) plastic foil



(b) rubber band

(c) glue

(d) aluminum

Figure 4.3: Measurement locations of He leakage.

5 Vacuum test chamber

ignore from here
2020-08-30 leak rate 2020-09-27 set voltages 2020-09-30 first successful external run 2020-10-07 spot vs pressure 2020-10-22 current measurement aluminum foil 2020-11-05 forgot to turn off filament heating 2020-11-14 assemble chamber with copper rings
to here

In order to be able to fit the CRT screen, CF160 flanges were chosen for the test chamber. At one point during testing, major changes were made which will be explained in section 5.2.

5.1 First iteration

A 3D render of the chamber is shown in (fig. 5.1). Without a CRT installed, it was possible to reach a pressure of 6.8×10^{-7} mbar, while with one the lowest was 2.0×10^{-6} mbar.

5.1.1 Parts

The center piece consists of a 6-way cross with view ports at the front and bottom. A valve was installed at the back in order to flood the chamber with nitrogen when installing a new CRT to avoid oxygen poisoning. On the right side, a HiCube 300 Eco turbo pump was installed and on the left side a wobble stick was attached with a wire. A nipple fitting was installed at the top with a 5 port cluster flange, each being of type CF63.

pure nitrogen name?

length

In the middle port, a VSH vacuum transducer was installed to measure pressure. This needs a 24 V dc power supply. On the left, a 19 pin connector was installed to supply the necessary voltages to the CRT. Two flanges were equipped with four BNC feedthroughs each. One of them was used to connect do the x-, and y-plates, while the other connected to the wobble stick and aluminum foil at the CRT screen. Further explanation will be given in . The last port was capped off by a blank flange.

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For the inside wires, stranded copper cables were used. The chamber was sealed by rubber gaskets.

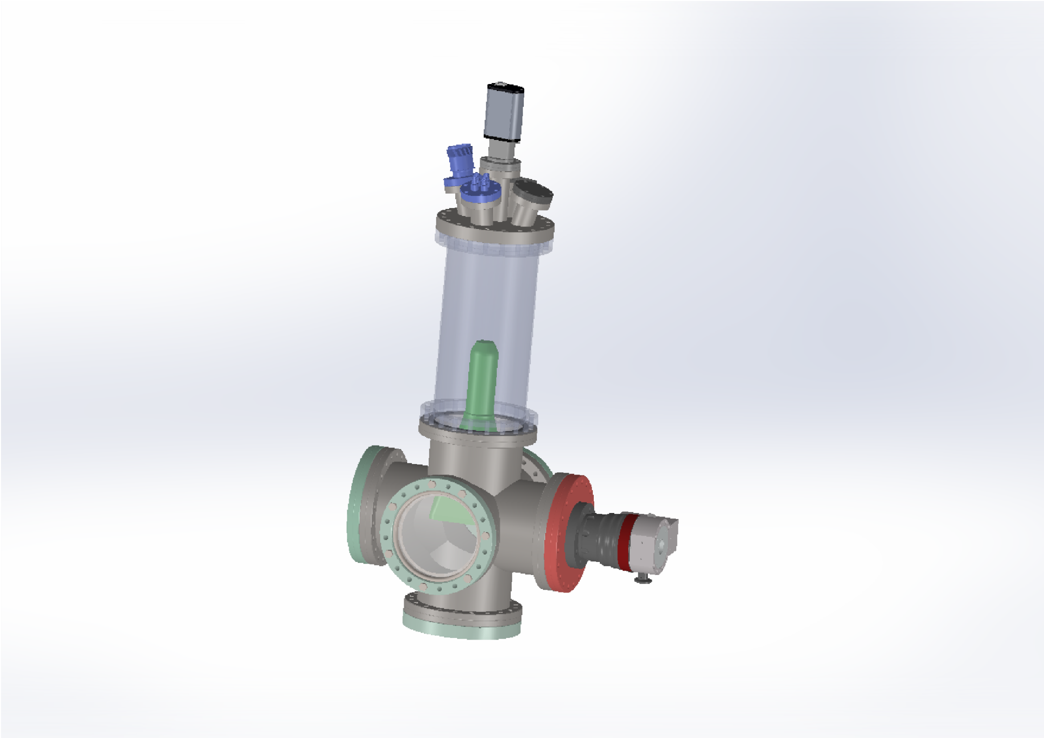

Figure 5.1: 3D rendering of test chamber.

5.1.2 CRT mounting mechanism

Two M8 rods of length were drilled into the cluster flange. On each, a L-piece was installed between two nuts and they were connected by a hose clamp. Two of these were used to secure the CRT inside the nipple facing the cross (fig. 5.2).

rod length?

5.1.3 Leak test

Before inserting a CRT, a leak test was performed. First, the chamber was set to a pressure of 10^{-5} mbar after which the pump was turned off. The pressure was measured once a minute for a duration 3 h. This is shown in fig. 5.3.

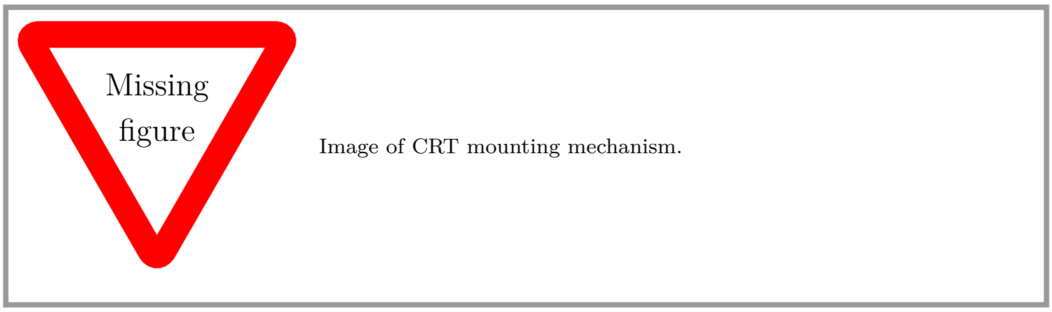

Figure 5.2: Image of CRT mounting mechanism.

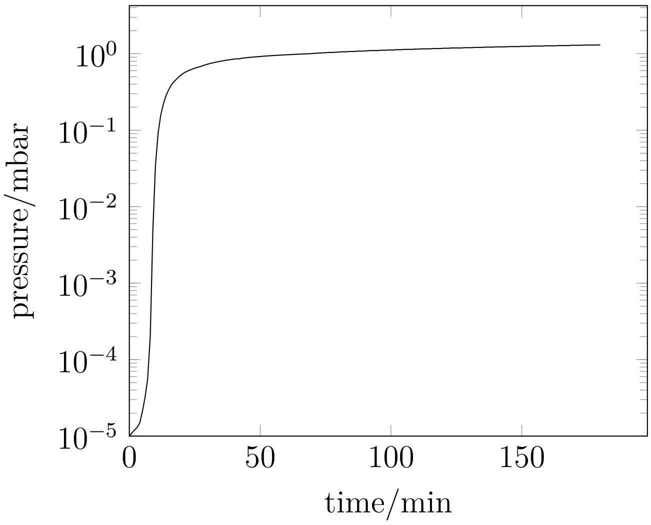

Figure 5.3: Leak rate of test chamber after turning off pump.

5.2 Second iteration

At one point during experimentation, major changes were made to the chamber. Thanks to these, it was possible to reach a pressure of 1.2×10^{-7} mbar.

5.2.1 Changes

First, every rubber gasket was changed to a copper one for a better seal, except at the cluster flange, since that spot will be opened and closed the most often. Each copper stranded cable inside was switched to a coaxial one and the mantle was connected to the chamber wall, which was set to ground. A Faraday cup was installed below the wobble stick, to accurately measure the beam current (further details in). The aluminum foil was extended to cover all four sides of the screen.

ref ch:Beam ch
terization

5.2.2 Fastening

When attaching flanges, it is important to start with a low torque and to fasten opposite screws to prevent too much force on one side of the gasket. For M6 screws, the torque was incrementally set to 6 N m, 10 N m, 15 N m and 20 N m and for M8 screws 8 N m, 16 N m and 25 N m. After finishing every opposite screw pair at a set torque, the procedure was repeated twice before going to a higher torque. This was done in order guarantee a tight and even seal.

Todo list