



TECHNISCHE
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Project Report

Preliminary research on an electron beam setup for the QUAK experiment

performed at Atominstitut



at Technische Universität Wien
Faculty of Physics

under the supervision of
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and
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by _____

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Wien, am 05-01-2021

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¹ 1 Short introduction to QUAK

² The goal of QUAK (quantum klystron) is to drive Rabi oscillations between hyperfine
³ levels of ^{39}K which has a frequency of 461.7 MHz [1] using a classical electron beam.
⁴ For this, it is necessary to Doppler cool the atoms in a MOT (magneto-optical trap)
⁵ using lasers. Once the atoms are trapped, they will be exposed to the near-field of
⁶ the electron beam, which will be spatially modulated with the transition frequency.
⁷ In order to achieve this goal, the beam must allow for a current of $100\ \mu\text{A}$. The goal
⁸ of QUAK (quantum klystron) is to drive Rabi oscillations between hyperfine levels of
⁹ ^{39}K which has a frequency of 461.7 MHz [1] a classical electron beam. For this, it is
¹⁰ necessary to DOPPLER trapped, they will be exposed to the near-field of the electron
¹¹ beam, which will be spatially modulated with the transition frequency. In order to
¹² achieve this goal, the beam must allow for a current of $100\ \mu\text{A}$ and a beam waist of
¹³ $100\ \mu\text{m}$.

¹⁴ In our work, we conducted first experiments on how to accomplish an electron beam
¹⁵ fulfilling those requirements.

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2 Cathodic Ray Tube Basics

This section features a quick explanation what a CRT is and what its 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. This chapter features a quick explanation what a Cathodic Ray Tube (CRT) is and what its main components are. This is followed by a more detailed description on how the individual components are implemented in our used CRT, a Heerlen D14-363GY. The chapter ends with a description of the important characteristics of the CRT and the requirement the theory poses on them.

2.1 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.”

Wikipedia states: “The cathode-ray tube (CRT) is a vacuum tube that contains one or more electron guns, while 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 generates free electrons from a cathode material, accelerates them onto an anode and thereby produces an electron beam (see fig. 2.1). One important characteristic in the selection of a cathode material is a low work function. It denotes the amount of energy needed to extract one electron from the material. There are two ways to overcome this energy barrier in an electron gun; one can either apply a strong electric field (“field emission”, “cold cathode”) as seen in fig. 2.2b. Or one can heat the material until some electrons have enough thermal energy to overcome the energy barrier (“thermal emission”, “hot cathode”, fig. 2.2a).

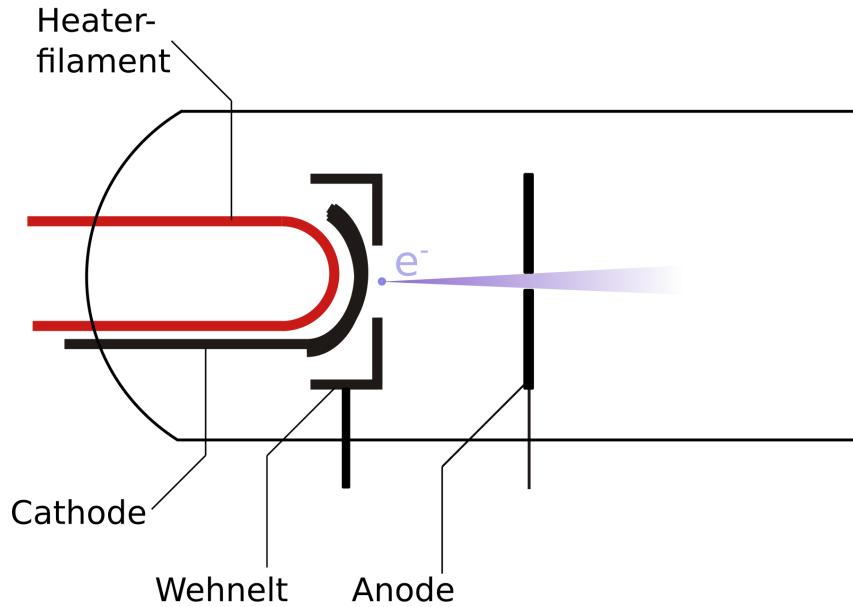
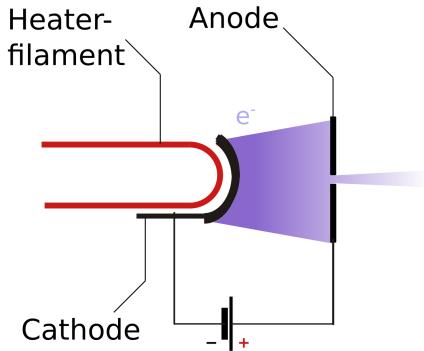


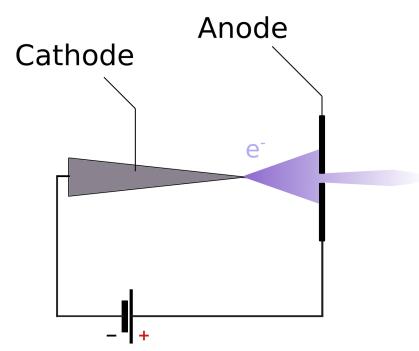
Figure 2.1: Schematic of an electron gun

1 The electron gun extracts electrons from a cathode material, accelerates them onto
 2 a perforated anode and thereby produces a free electron beam (see fig. 2.1). One
 3 important characteristic in the selection of a cathode material is a low work function.
 4 It denotes the amount of energy needed to extract one electron from the material.
 5 There are two ways to overcome this energy barrier in an electron gun; one can either
 6 overcompensate it by applying a strong electric field (“field emission”, “cold cathode”,
 7 fig. 2.2b); or one can heat the material until some electrons have enough thermal energy
 8 to overcome the energy barrier (“thermal emission”, “hot cathode”, fig. 2.2a). For our
 9 CRT, only thermal emission is relevant, more detail on this will be added later along
 10 with the description of our cathode’s design. For our CRT uses a hot cathode, more
 11 detail on this will be added later along with the description of our cathode’s design.

12 The cathode itself is housed in a so-called Wehnelt cylinder, as the name suggests
 13 it is conducting cylinder which is set to a slightly more negative potential than the
 14 cathode itself. This part implements two features; firstly it condenses the emitted
 15 electrons, leading to a smaller spot size, i.e. making the cathode a more point-like
 16 electron source. Secondly it enables us to regulate the beam current, the more negative
 17 the Wehnelt potential is, the less electrons are emitted by the electron gun. As we make
 18 the Wehnelt potential more positive, the beam current increases and continues to rise
 19 even after it is more positive than the cathode itself. However the spot size reduction



(a) Schematic of a hot cathode



(b) Schematic of field emission cathode

Figure 2.2: Cathode types

is lost in the process, along with the ability to properly focus the beam with electron optics. Normally the cathode itself is covered in beam direction in a so-called Wehnelt cylinder. Which is a conducting cylinder set to a slightly more negative potential than the cathode. 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 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 gets increased, while the proper beam focus is lost.

The electrons ,that leave the electron gun, are still divergent and need to be focused. For our 2 keV electrons an electrostatic lens is used. In the simples way these are cylindrically symmetrical pieces of conductor, like a ring or tube, set to an electrical potential. 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 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: The field of this system is simply governed by Laplace's

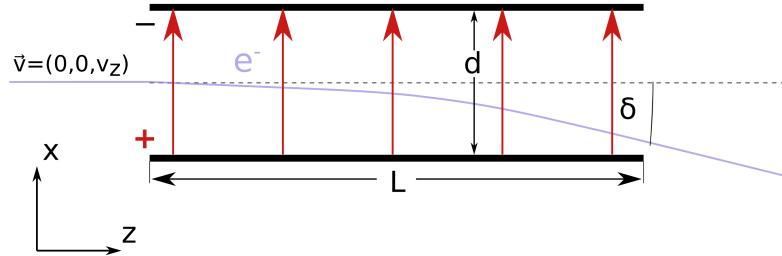


Figure 2.3: Deflection of an electron beam in a constant electrical field

¹ equation in cylindrical coordinates:

$$\frac{1}{r} \frac{\partial \phi}{\partial r} + \frac{\partial^2 \phi}{\partial r^2} + \frac{\partial^2 \phi}{\partial z^2} = 0 \quad (2.1)$$

³ If we take the axis of the beam to be the z-axis, the focal point position in the x-y-plane
⁴ can be shifted using the two pairs of deflection plates, one for the x- and one for the
⁵ y-direction. The deflection is achieved by applying a voltage between the two parallel
⁶ plates. (see: fig. 2.3) By starting with an electron with kinetic energy $e \cdot U_0$ which
⁷ is accelerated in x-direction by a constant force $e \cdot U_x/d$ over the extent of the plates
⁸ L , the deflection angle is approximately [2]: If we take the axis of the beam to be
⁹ the z-axis, the focal point position in the x-y-plane can be shifted using two pairs of
¹⁰ deflection plates, one for the x- and one for the y-direction. The deflection is achieved
¹¹ by applying a voltage between the two parallel plates. (see: fig. 2.3) For an electron
¹² with kinetic energy $e \cdot U_0$, which is accelerated in x-direction by a constant force $e \cdot U_x/d$
¹³ over the extent of the plates L , the deflection angle δ is approximately [2]:

$$\delta \approx \tan(\delta) \approx \frac{U_x \cdot L}{2U_0 \cdot d} \quad (2.2)$$

¹⁵ For the measures of our CRT ($L \approx 10$ cm, $d \approx 1$ cm, $U_0 \approx 2$ kV and distance to
¹⁶ screen ≈ 20 cm) this amounts to a deflection coefficient of around 20 V cm $^{-1}$, which is
¹⁷ quite consistent with the value given in the CRT's manual.

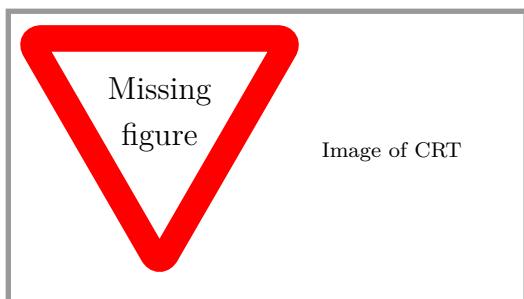
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2.2 Implementation in the Heerlen D14-363GY

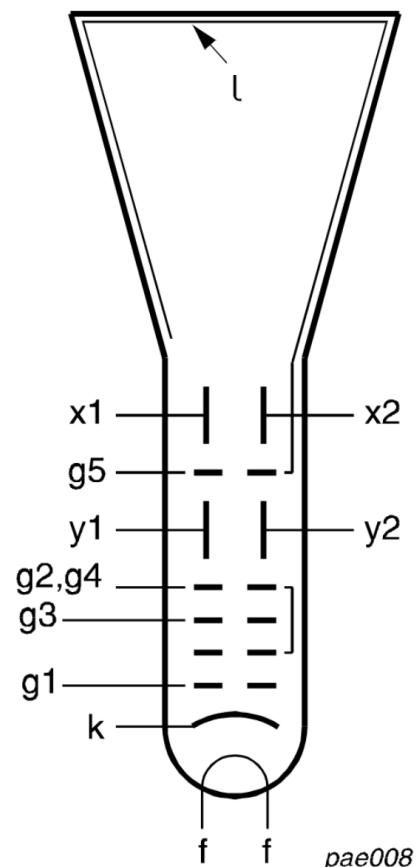
This section describes how the mechanisms described above are implemented in the CRT that was used in this project: the PDS/CRT Heerlen D14-363GY. Figure 2.4a shows an image of said CRT, fig. 2.4b shows a schematic depiction. The cathode is not visible, as it is fixed inside the Wehnelt cylinder (1), 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 $0.08c$. The electrostatic lenses are realized using three conducting rings (3), that are set to the same potential but have varying radii: Each consecutive ring has a smaller radius than the previous one. This section describes the CRT that is used in this project: PDS/CRT Heerlen D14-363GY. Figure 2.4a shows an image of said CRT and fig. 2.4b 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 hole in the anode (2), they gain their full kinetic energy over this short distance. The electrons that go through the hole and enter the electrostatic lens, have 2 keV and therefore move at a speed of approximately $0.08c$. The electrostatic lenses are realized using three conducting rings (3), that are set to the same potential but have varying radii: Each consecutive 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) 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). Its potential can be regulated separately (usually it's on the same potential as the anode)

It is connected to the aquadag coating inside the glass envelope and prevents charge up and image distortion. Finally the beam hits the phosphorous-coated screen which fluoresces on electron impact. It is connected to the aquadag coating inside the glass envelope and prevents charge building up, that could lead to image distortions. 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 [3]

Figure 2.4

2.2.1 The Cathode

As already mentioned, we are using a hot cathode, where electrons are excited 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 is 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 [4, chp 3.2.3]: As already mentioned, we are using a hot cathode, where electrons are thermally excited to leave the material. Compared to cold cathodes which work by field emission, this leads to a broader energy distribution. For electron microscopy, where a high resolution is the goal, this is 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 by thermal emission is described by [4, chp 3.2.3]:

$$I = A \cdot T^2 \cdot e^{-b/T} \quad (2.3)$$

Where b is proportional to 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” [4, chp 3.5.2.1] describes a typical oxide cathode as a coating of barium and strontium oxides on a structure made from nickel alloys. Nickel is chosen for its 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. The “Power Vacuum Tubes Handbook” [4, chp 3.5.2.1] describes a typical oxide cathode has a coating of barium and strontium oxides on a structure made from nickel alloys. Nickel is chosen for its strength and toughness, which it retains even at high temperatures. These cathodes are normally made by coating a case structure

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² suspended in a binder material and then baking the structure, causing the carbonates
³ to be reduced to oxides.

⁴ These metal oxide cathodes normally operate at 700 °C to 820 °C and are capable of
⁵ average emission densities of 100 mA cm^{-2} to 500 mA cm^{-2} . Still higher peak emissions
⁶ are possible for shorter periods of time; as already mentioned, one of the advantages of
⁷ this type of cathode is its high emission current capability compared to cathodes made
⁸ from other materials. Downsides to this cathode type are its greater susceptibility
⁹ to so-called oxygen poisoning and to ion bombardment. The literature therefore
¹⁰ recommends to avoid prolonged exposure to oxygen. Oxygen poisoning is the process
¹¹ in which oxygen adsorbs onto the cathode and increases its work function, effectively
¹² reducing the ability to emit electrons. Also the material from the oxide cathode
¹³ will evaporate during the tube's lifetime and will travel to other parts of the tube,
¹⁴ adsorbing to electron optics parts and turning them into additional emitters. The
¹⁵ literature (also from [4, chp 3.5.2.1]) therefore also advises against exceeding the design
¹⁶ value for the heater voltage, as this reduces the lifetime of the cathode significantly.
¹⁷ (However during the course of our project, we did drive the cathode with higher heater
¹⁸ voltages on various occasions in order to increase the available beam current.) These
¹⁹ metal oxide cathodes normally operate at 700 °C to 820 °C and are capable of average
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³⁰ therefore, also advises against exceeding the design value for the heater voltage, as this
³¹ reduces the lifetime of the cathode significantly. (However, during the course of our
³² project, we did drive the cathode with higher heater voltages on various occasions in
³³ order to increase the available beam current.)

with what result?

³⁴ 2.2.2 Cathode Layout

³⁵ Figure 2.5 shows how metal oxide cathodes for CRTs typically look; the depiction agrees
³⁶ very well with the layout of our cathode. On the image we see the cathode cylinder,
³⁷ which corresponds to the nickel support structure mentioned above. It is shaped into a

2 Cathodic Ray Tube Basics

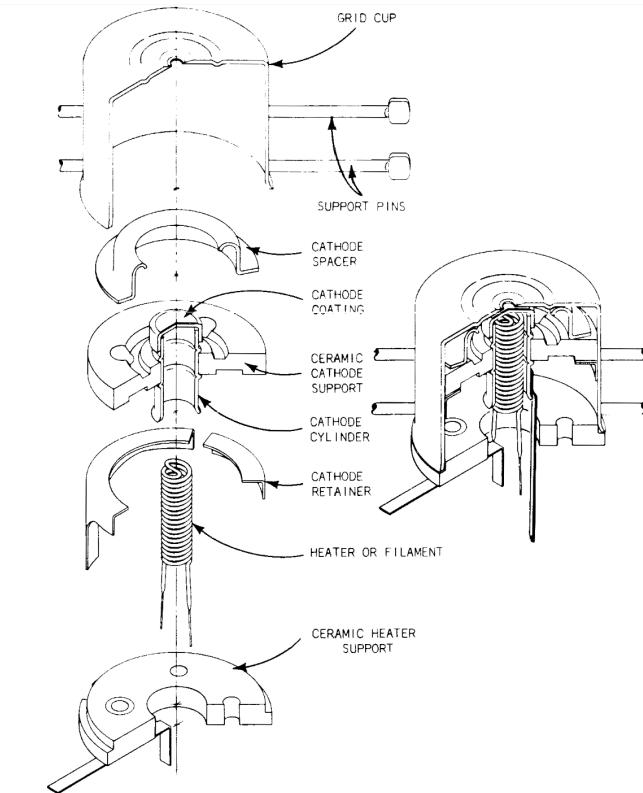


Figure 2.5: Schematic of the layout of a typical CRT-cathode from [5]

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 2.5 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, in which the heater filament (shaped into a 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.

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¹ **3 Cicero Word Generator**

² This chapter describes the installation and initial setup of Cicero Word Generator [6]
³ on a PC running Windows 10 with analog and digital cards from National Instruments
⁴ (NI). The code is freely available on GitHub [7]. This chapter contains only differences,
⁵ problems, and possible solutions encountered when Cicero was installed for the PC
⁶ ‘Fritz Fantom’ which will be used for the QuaK experiment. It is therefore advised to
⁷ use the technical and user manual [8] in conjunction.

⁸ **3.1 Installation of National Instruments drivers**

⁹ Before setting up the Cicero Word Generator, it is necessary to install the newest
¹⁰ .NET Framework [9] from Microsoft. Then NI drivers, NI-DAQmx (version 9.3),
¹¹ NI-VISA (newest version), and NI-4888.2 (newest version) should be downloaded from
¹² the National Instruments website [10] and installed. When installing the NI drivers it
¹³ is possible to get an ‘Runtime Error!’. In this case it is necessary to set the Regional
¹⁴ format settings of Windows 10 to ‘English (United States)’ [11].

¹⁵ **3.2 Installation of National Instruments Cards**

¹⁶ After installation of the necessary drivers, the physical cards can be inserted in the
¹⁷ PCIe slots on the motherboard. On ‘Fritz Fantom’ the digital card (NI PCIe-6537B)
¹⁸ was installed on PCIe bus 3 while the analog cards (NI PCIe-6738) were installed on
¹⁹ PCIe bus 4 and 5.

²⁰ **3.3 Configuring Atticus**

²¹ After installation of the NI cards, Atticus should be launched for the first time and
²² closed without changing any settings. After this, the NI-DAQmx drivers should be
²³ 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_Fantom’. **Dev1** to **Dev3** were set in the same ascending order as the physical installation on the motherboard.

3.3.1 Configure hardware timing / synchronization

For synchronization, a **Shared Sample Clock** was used with **Dev1** being the master card. The settings are summarized in table 3.1 and table 3.2. **Dev3** follows the same settings as **Dev2** except ‘SampleClockExternalSource’ was 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 3.1: Settings for **Dev1**.

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

Table 3.2: Settings for **Dev2**.

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

3.4 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’.

¹ **3.4.1 Saving of Settings and Sequences**

² The ‘SettingsData’ of the Server Atticus are saved in C:\Users\confetti\Documents
³ \Cicero_Atticus\Cicero\SettingsData while the ‘SequenceData’ of Cicero are saved in
⁴ C:\Users\confetti\Documents\Cicero_Atticus\Cicero\SequenceData.

⁵ **3.4.2 Sequence length limit**

⁶ The duration of a sequence is limited to $2^{32}/(16 * 32 * 350 \text{ kHz}) = 23.967 \text{ s}$ coming
⁷ from a 32-bit application, 16 bit per channel, 32 channels in a NI PCIe-6738 card, and
⁸ 350 kHz clock rate.

4 Electron beam setup

1

4.1 Charatarization of a working CRT

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HAMEG HM507 oscilloscopes [12] were used for testing purposes which contain a D14-363GY/123[3] CRT. Although it only has a bandwidth of 0 MHz to 50 MHz, which is not sufficient to reach the hyperfine splitting frequency of 461.7 MHz for ^{39}K [1] (or 254 MHz for ^{41}K), it was used nevertheless because of its simple construction and availability. The back pin arrangement is shown in fig. 4.1.

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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 a voltage divider of 100:1 and are summarized in table 4.1. It was not possible to measure pin g3 directly. Therefore a HVPS (section 4.2) was used to set a voltage and the beam diameter was observed. The best focus was achieved with the value written 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 are the mean of the minimum and maximum measured voltage. The deflection coefficient is summarized in table 4.2.

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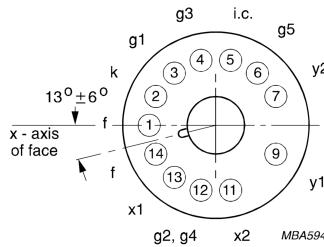


Figure 4.1: Pin arrangement, bottom view from [3]

Table 4.1: D14-363GY/123 CRT pin measurements

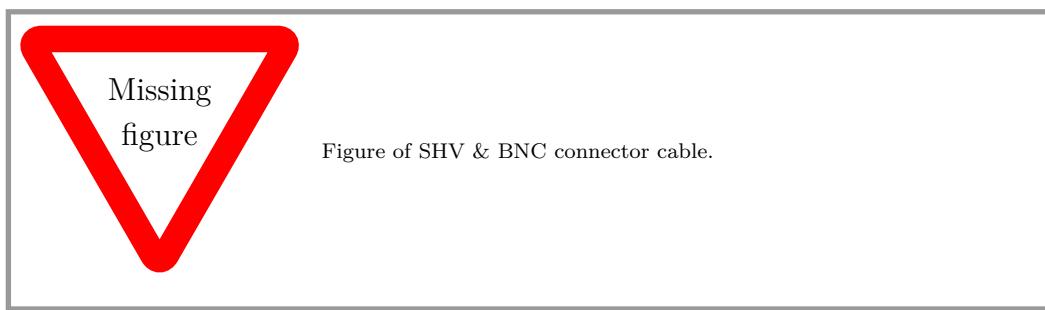
number	pin	voltage/V	current/ μA
1	f	-1.99×10^3	86.6×10^3
2	k	-2.00×10^3	-7.6
3	g1	-2.03×10^3	0
4	g3	-1.813×10^3	0
5	i.c.	71.7	0.1
6	g5	64.0	7.2
7	y2	78	-
9	y1	78	-
11	x2	96	-
12	g2, g4	71.0	0
13	x1	96	-
14	f	-1.97×10^3	-86.2×10^3

Table 4.2: D14-363GY/123 deflection coefficient from [3]

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

¹ 4.2 High Voltage Power Supply HVPS

² To produce high dc voltages to drive the CRT, four HCP 14-6500 power supplies [13]
³ were used. They were named ‘HVPS 1’ to ‘HVPS 4’ and can provide up to 2 mA at
⁴ ± 6.5 kV. To connect the output to the CRT pins, BNC cables were refitted with a save
⁵ high voltage (SHV) connector on one side while on the other end the BNC connector
⁶ was kept (fig. 4.2). A 6 kV probe was used to obtain the breakdown voltage, which is
⁷ around 3 kV caused by the coaxial cable which was not built do sustain high voltages.

**Figure 4.2:** Coaxial cable with SHV and BNC connector.

4.2.1 Ripple measurement

Each power supply was measured for its ripple with a set voltage of 2 kV. A 2.5 kV probe (attenuation ratio 100:1) 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. 4.3 with the values summarized in table 4.3. As can be seen, the ripple is very close to the noise level and can not really be distinguished.

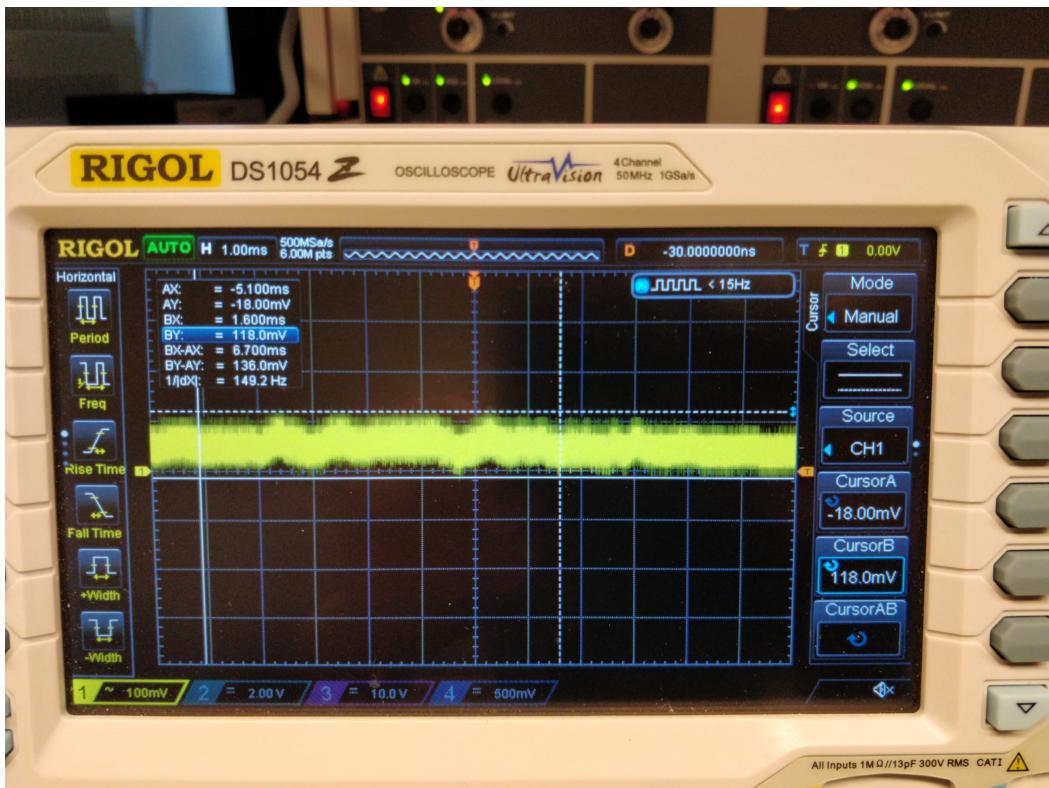


Figure 4.3: Measurement of HVPS ripple.

Table 4.3: HVPS ripple

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

¹ 4.3 CRT wiring

² A schematic of the supplied power is shown in fig. 4.4. The pin i.c. stands for internally
³ connected and is wired to pin g2, g4. A small ac or dc voltage is necessary to drive the
⁴ heater filament f. This part of the setup is explained in section 4.4.

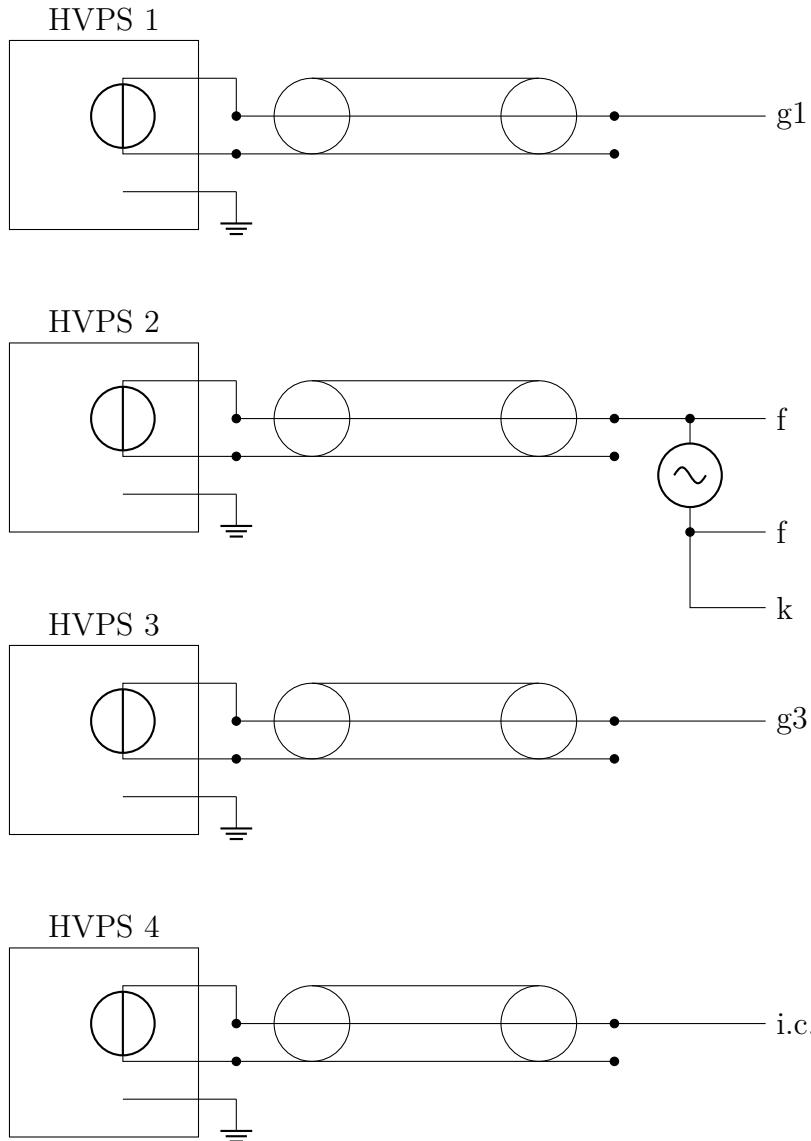
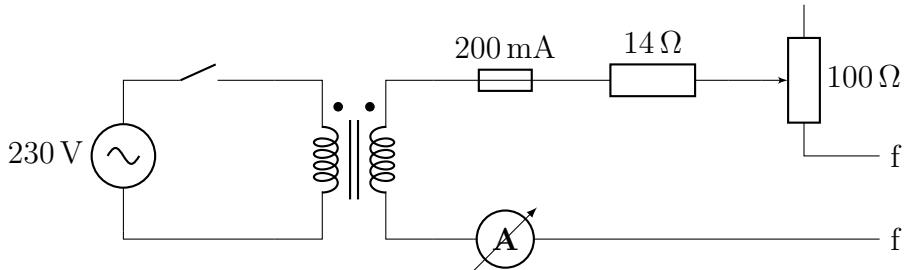


Figure 4.4: Schematics of supplying CRT pins with power.

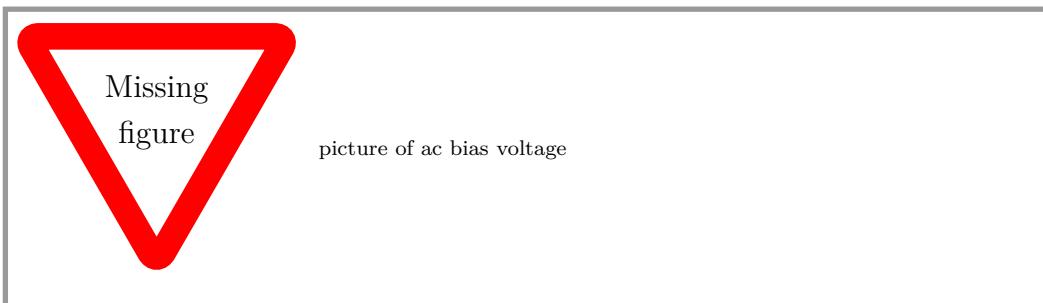
4.4 Heater

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 resistitance of approximately $15\ \Omega$, when the filament is hot, this value rises to $90\ \Omega$. The normal heater voltage for the D14-363GY/123 during operation is 6.0 V to 6.6 V according to [3]. Our ac-power supply (shown in figure 4.5) consists of an isolation transformer

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(a) Circuit diagram of filament power supply.



(b) Picture of built filament power supply.

Figure 4.5: AC power supply used to heat the filament with a -2 kV bias voltage.

check if really 14Ω or if it event exists

1 (from grid voltage to 12 V), its primary and secondary circuits are isolated up to 4 kV
 2 [14]. The power supply has two banana plug sockets to connect to the heater filament.
 3 It is connected to the transformer in series with a 100Ω potentiometer. Using the full
 4 resistance, there is a voltage of approximately 5.7 V applied to the heater filament,
 5 by lowering the resistance this value can goes up to nearly the full voltage of the
 6 transformer. The current running through the filament is measured with an integrated
 7 ampere meter [15], that measures currents up to two 2 A with mA accuracy.

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

5 CRT handling

1

5.1 Opening CRTs

2

In order to have a free electron beam in the experimental setup, to hit a cold ^{39}K , 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. 5.1) to reduce oxygen poisoning of the cathode.

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5.1.1 Rotary tool

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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.

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5.1.2 Wire cutting

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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 optic element mounts (fig. 5.2) 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.

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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 was first extensively tested on drinking glasses.

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5 CRT handling



Figure 5.1: Glovebox filled with nitrogen gas to open CRTs.

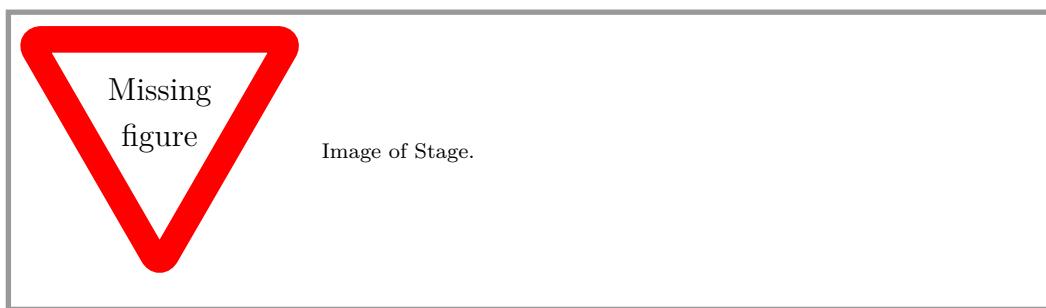


Figure 5.2: Stage to cut CRT with wire.

¹ 5.2 Oxygen poisoning

² As mentioned in chapter [2](#) it is paramount to avoid contact of the cathode with oxygen.
³ Therefore tests with a broken CRT were made to test on how well it can be isolated
⁴ from air.

⁵ The first experiment consisted of filling a drinking glass put upside-down with helium
⁶ and putting a lighter after a set amount of time. If the fire goes off, it means that
⁷ oxygen did not get inside. This was tested successfully from 0.5 min to 10 min.

⁸ Next, plastic wrap was put on top of the glass filled with nitrogen by a rubber band.
⁹ The glass was put with the open side up from 3 min to 10 min after which it was turned
¹⁰ upside down and the foil was removed. A lighter was put inside and the flame went
¹¹ out again.

¹² To improve the precision, a He leak tester was used. For the first two tests, one
¹³ plastic foil and one rubber band were used; for the third test three foils and two rubber
¹⁴ bands; and for the last test an aluminum foil was hot glued on the CRT to seal it. The
¹⁵ measurement locations are shown in fig. [5.3](#). For the glued seal, leakage was measured
¹⁶ on the whole circumference. In table [5.1](#) ‘glue avg’ denotes the average leak rate of this
¹⁷ measurement while ‘glue max’ describes the highest value. A seal with rubber band
¹⁸ and clear foil tend to higher leakage. Based on these measurements it is recommended
¹⁹ to use glued aluminum. But care needs to be taken in order ensure that the whole
²⁰ CRT is sealed since even a small leak can result in a rate around an order of magnitude
²¹ above the background.

5 CRT handling

Table 5.1: 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

5 CRT handling



(a) plastic foil



(b) rubber band



(c) glue



(d) aluminum

Figure 5.3: Measurement locations of He leakage.

6 Vacuum test chamber

1

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 6.2.

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explain more in detail what is the purpose of the chamber. The two iterations are not really important built this chapter rather about the function operation of chamber over time due to outgassing the pressure improved

6.1 First iteration

A 3D render of the chamber is shown in (fig. 6.1). Without a CRT installed, it was possible to reach a pressure of 6.8×10^{-7} mbar. With a CRT installed inside, the lowest achieved pressure was 2.0×10^{-6} mbar. It was not possible to reach a lower pressure due to outgassing.

6.1.1 Chamber Setup

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 (AlphagazTMN₂ purity $\geq 99.999\%$) when installing a new CRT to reduce oxygen poisoning and avoid water vapor getting into the chamber. 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 straight CF100 pipe of length 27 cm was installed at the top with a 5 port cluster flange, each being of type CF40.

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 80 Eco turbo pump was installed and on the left side a wobble stick was attached with a wire. A straight CF100 pipe was installed at the top with a 5 port cluster flange, each being of type CF40.

In the middle port, a Thyscont pressure gauge was installed. On the left, a 19 pin MIL 19 C 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

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water vapor getting into the chamber

explain in connection of the rendering; this makes it easier if necessary; can get more renderings

pure nitrogen name?

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26 AlphagazTM
27 N₂ purity
 $\geq 99.999\%$

water vapor getting into the chamber

length=27cm

Thyscont ex model is in note

6 Vacuum test chamber

1 to connect the x-, and y-plates, while the other connected to the wobble stick and
2 aluminum foil at the CRT screen. Further explanation will be given in chapter 8. The
3 last port was capped off by a blank flange.

4 In the middle port, a VSH pressure gauge was installed. On the left, a 19 pin
5 connector was installed to supply the necessary voltages to the CRT. Two flanges
6 were equipped with four BNC feedthroughs each. One of them was used to connect do
7 the x-, and y-plates, while the other connected to the wobble stick and aluminum foil
8 at the CRT screen. Further explanation will be given in chapter 8. The last port was
9 capped off by a blank flange.

10 For the inside wires, at first stranded copper cables were used. These were later
11 swapped for Kapton insulated BNC cables. The chamber was sealed by Viton rubber
12 gaskets which were changed to copper gaskets. For the inside wires, standard copper
13 cables were used. The chamber was sealed by rubber gaskets.

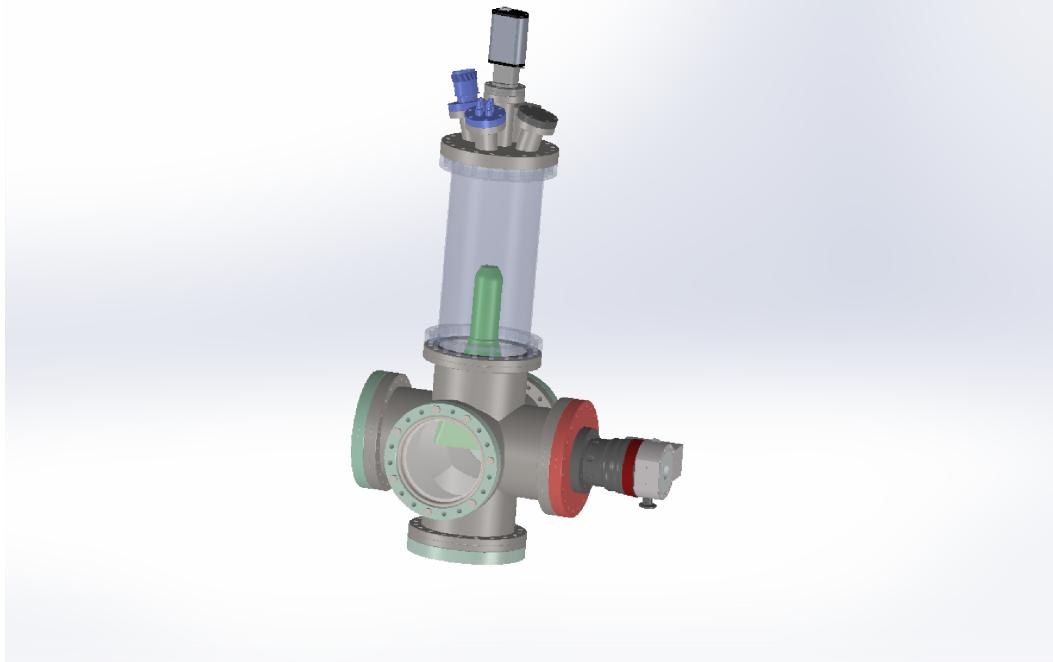


Figure 6.1: 3D rendering of test chamber.

Thyracont ex
model is in c
note

how many pins
model name? 1
Type C connec

MIL 19 C

F: but I'm talk
about first itera

we also used
Kapton insu
BNC cable

Viton, mayb
also describ
specification
these type of
seals

6.1.2 CRT mounting mechanism

Two M8 rods of length were screwed with a counter nut into the cluster flange. On each, a L shaped aluminum piece was installed between two nuts. These were then connected by a hose clamp, which was used to secure the CRT inside below the cluster flange (fig. 6.2).

Two M8 rods of length were drilled into the cluster flange. On each, a L shaped aluminum piece was installed between two nuts. These were then connected by a hose clamp, which was used to secure the CRT inside below the cluster flange (fig. 6.2).

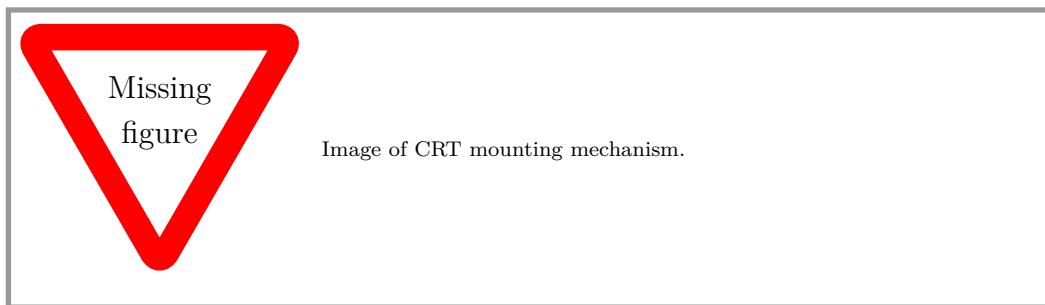


Figure 6.2: Image of CRT mounting mechanism.

6.1.3 Measurement of outgassing

6.1.4 Leak test

Before inserting a CRT for the first time, measurements were made in order to find out how well low pressure could be maintained inside the chamber. 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. 6.3.

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. 6.3.

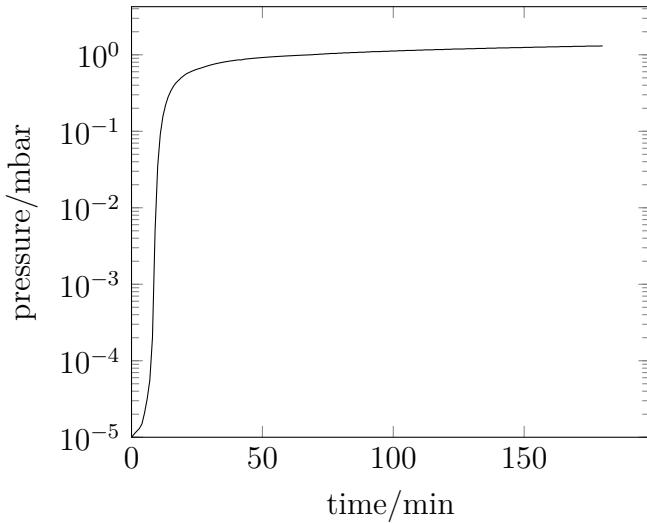


Figure 6.3: Time evolution of pressure inside the test chamber after turning off pump.

¹ 6.2 Second iteration

² At one point during experimentation, major changes were made to the chamber. Thanks
³ to these, it was possible to reach a pressure of 1.2×10^{-7} mbar.

⁴ 6.2.1 Changes

⁵ First, every rubber gasket was exchanged to a copper one for a better seal, except at the
⁶ cluster flange, since that spot will be opened and closed the most often. Each copper
⁷ stranded cable inside was switched to a coaxial one and the mantle was connected to
⁸ the chamber wall, which was set to ground. A Faraday cup was installed below the
⁹ wobble stick, to accurately measure the beam current (further details in section 8.2).
¹⁰ The aluminum foil was extended to cover all four sides of the screen.

¹¹ 6.2.2 Fastening

¹² When attaching flanges, it is important to start with a low torque and to fasten
¹³ opposite screws to prevent too much force on one side of the gasket. For M6 screws, the
¹⁴ torque was incrementally set to 6 N m, 10 N m, 15 N m and 20 N m and for M8 screws
¹⁵ 8 N m, 16 N m and 25 N m. After finishing every opposite screw pair at a set torque,
¹⁶ the procedure was repeated twice before going to a higher torque. This was done in
¹⁷ order guarantee a tight and even seal.

7 Deflection Electronics

1

7.1 Demands on the setup

2

For the QuaK experiment it is paramount to be able to deflect the beam precisely and with the right frequency. For the QuaK experiment it is paramount to be able to deflect the beam precisely at the right frequency. As previously mentioned, our deflection system simply consists of two pairs of parallel plates between which a voltage is applied. Controlling this voltage allows us to control the deflection of the beam. Various aspects are important here (illustrated in fig. 7.1):

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of a sufficient current

With a sufficient small enough bandwidth

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Optional: insert Foto of CRT's inflection plates fig:DeflectionSe

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16 what happens when there is no bias voltage
17 what is the purpose of it

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22 to achieve what

Offset: Although the deflection of the beam is controlled by the voltage between the plates, it is necessary to be able to set their mean potential as well. During normal operation this offset voltage is at 96 V for the x-direction and at 78 V for the y-direction.

Offset: Although the deflection of the beam is controlled by the voltage between the plates, it is necessary to be able to set their mean potential as well. During normal operation this offset voltage is at 96 V for the x-direction and at 78 V for the y-direction.

Amplitude: The deflection coefficients in the x and y planes are 19 V cm^{-1} and 11.5 V cm^{-1} respectively (see [3]). We therefore need to be able to supply approximately 70 V.

Amplitude: The deflection coefficients in the x and y planes are 19 V cm^{-1} and 11.5 V cm^{-1} respectively (see [3]). We therefore need to be able to supply approximately 70 V.

Frequency: The final goal is to be able to deflect the beam at the hyperfine splitting frequency of ^{39}K , which is 461.7 MHz. This is likely to prove impossible with this CRT-model, observations at the highest frequency we have tried so far will be discussed in section section 8.3.

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Waveform: Ultimately we want the cold atoms to experience a field that oscillates like a sine wave. As a first try it is therefore reasonable to apply a sinusoidal voltage.

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¹ **Lissajous curves:** Having the ability to control the deflection in both the x- and the
² y- axis, allows us to have our beam draw out Lissajous Curves (fig. 7.2). By
³ applying sine waves of equal frequency to both pairs of deflection plates and by
⁴ being able to control the phase between them we can have the beam oscillate on
⁵ a straight line or a circle. This allows us to generate either a linearly or circularly
⁶ polarized field.

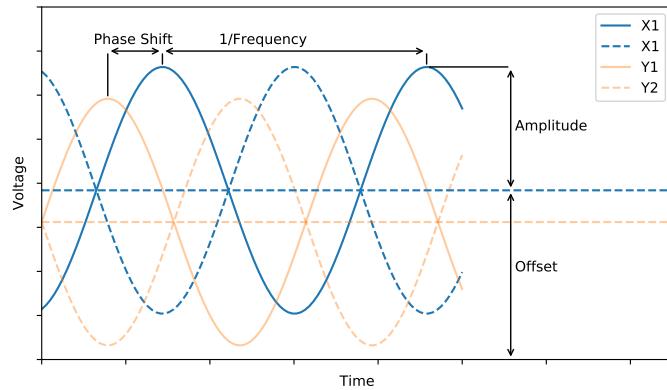


Figure 7.1

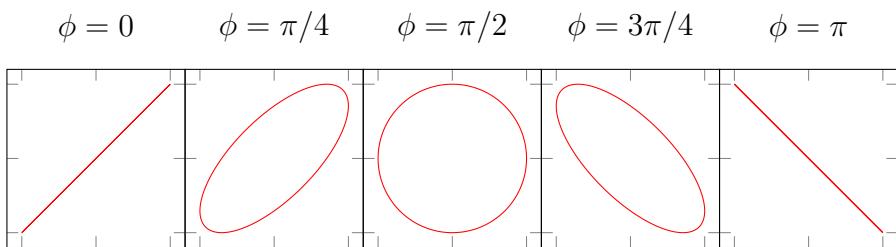


Figure 7.2: Lissajous Curves

⁷ 7.2 Implementation

⁸ A first setup with which we can try to obtain the desired voltages is depicted in
⁹ fig. 7.3. On the very left we have a signal generator that is capable of producing the
¹⁰ right frequency (461.7 MHz) this signal is then split up into an x-, and a y-branch.
¹¹ One of the two branches is connected to a phase shifter, which is able to delay the
¹² input signal by up to 200°, allowing us to set any desired phase shift between x-, and
¹³ y-deflection and to correct for inadvertent delays from the other electronics. Both the

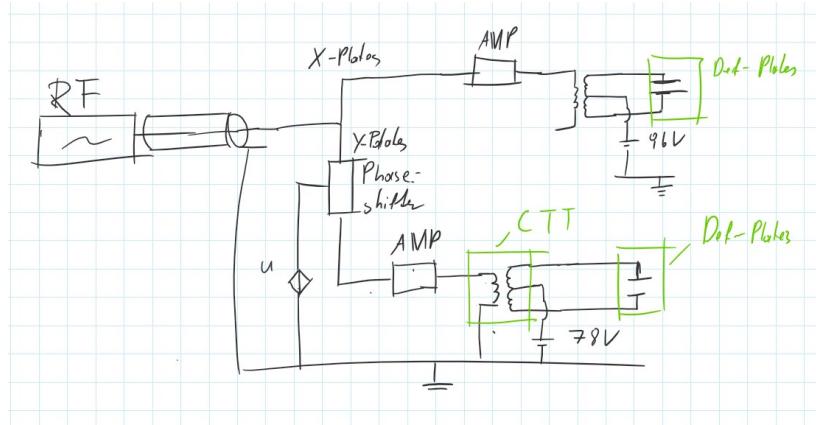


Figure 7.3: Deflection circuit

x-, and y-signal are then amplified using (amplifier) . In the final step, a center tapped transformer allows us to produce voltages for the plates X1 and X2 (or Y1 and Y2 respectively) with a phase shift of exactly 180° between them. By setting the center tap to the desired offset potential, we should get the voltage curves described above. To understand this setup in more detail, it is useful to examine its most important parts more closely:

Amplifier: Up to now we have used the XXX and the YYY amplifier, they amplify the signal by a fixed gain of (How much?) , inputs and outputs can simply be connected via BNC cables, the amplifier is powered by a linear power supply with a DC voltage of 24 V via two banana plugs in the front. Since we want to control the Lissajous curves shapes (as the deflection coefficients for the x- and y- plates differ), it is desirable to be able to adjust the amplifier gain in future versions of the setup.

Center Tapped Transformer: The center tapped transformer we use is the Mini-Circuits TC8-1G2+ ([16]), a transformer for frequencies between 2 MHz to 500 MHz, with an impedance ratio of 8. Figure 7.6 shows how the center tapped transformer is implemented. The in- and outputs, as well as the bias voltage can be connected via BNC cables. As usual, the shields of all these cables are connected to ground, furthermore they are connected to each other and to the housing. As a safety feature, both outputs X1 and X2 are directly connected to the bias through an arrangement of diodes: Two connections, each with a normal diode and a Zener diode facing in opposite directions. The breakthrough voltage of the Zener diode is 200 V, during normal operation the voltage on it stays below this value and none of the connections let any current through as one of the two diodes is always blocking it. However if one of the plates in the

Find out which amplifier

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which model?

8 which model?

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Check amplifier

specifications

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16 Optional: Go to lab and measure their performance with an Oszi.

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CRT accidentally comes in contact with high voltage, the connection with the appropriately oriented Zener diode opens up, preventing a voltage spike on the center tapped transformer and thereby protecting the electronics connected to its primary circuit. At the point of writing there are still some problems with the behavior of the center tapped transformer, the capacitance of the diodes introduces an undesired phase shift between the two signals. Figure 7.5a shows the circuit's behavior at 465 MHz without its diodes, here the signals are shifted by $120 \text{ ps} \doteq 20^\circ = 0.35 \text{ rad}$. Additionally, applying a bias voltage leads to differing amplitudes, as can be seen in fig. 7.5b.

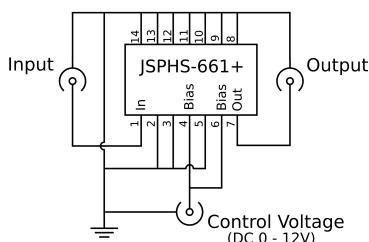
Phase Shifter: To control the phase shift between the x- and y-deflection plates, we use a Mini-Circuits [17] phase shifter. This part was put in a housing ([18]) on a separate PCB and can be connected via BNC cables. Figure 7.4a shows how the phase shifter is connected and fig. 7.4b shows the corresponding PCB layout. Note that again the shields of the BNC cables are connected among each other and to the housing. The JSPHS-661+ is designed for frequencies in the range 400 MHz to 600 MHz. By applying a DC voltage of 0 V to 12 V to the bias connector, it is possible to introduce a phase shift of up to 200° to the signal.

(figure)

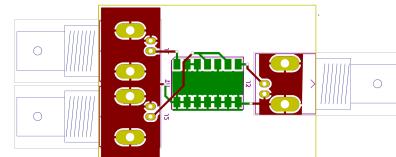
(Performance)

Insert fotos of
finished circuits in
the housings

Optional: Go
to the Lab, set
the whole thing
up and look at its
performance on the



(a)



(b)

Figure 7.4

picture place
ment and ca
tion is missin



(a) Signal of center tapped transformer without diodes, unbiased at 465 MHz

(b) Signal of center tapped transformer without diodes, biased at 465 MHz

Figure 7.5

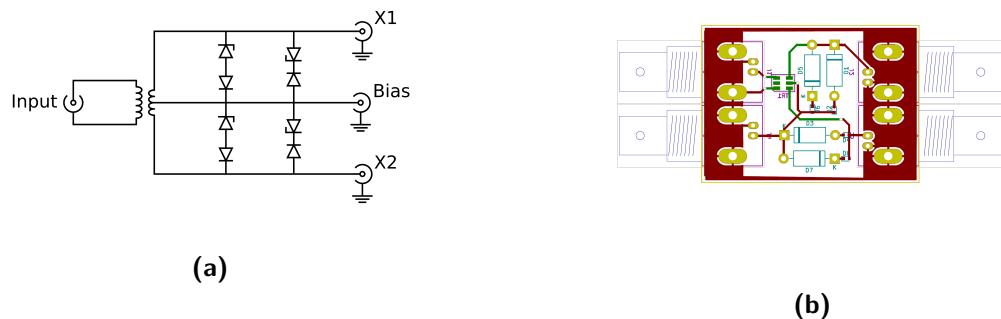


Figure 7.6

¹ 8 Beam Characterization

² 8.1 Aluminum foil

³ In fig. 8.1 the inside of the 6-way cross of the first iteration is shown. On one side
⁴ of the phosphor screen, aluminum foil was attached to simulate the aquadag coating
⁵ inside the cut CRT. The beam was deflected on the aluminum foil and the BNC output
⁶ was connected to ground through an ammeter to measure the beam current. As shown
⁷ in fig. 8.2 there is close to no difference in the filament voltage (and therefore heating
⁸ power) between an opened and sealed CRT while the beam current on the aluminum
⁹ foil varies widely. One possible reason could be that electrons scatter. Therefore, a
¹⁰ Faraday cup (see section 8.2) was used in the second iteration.

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skip: around
not all choose
the wire path
ground

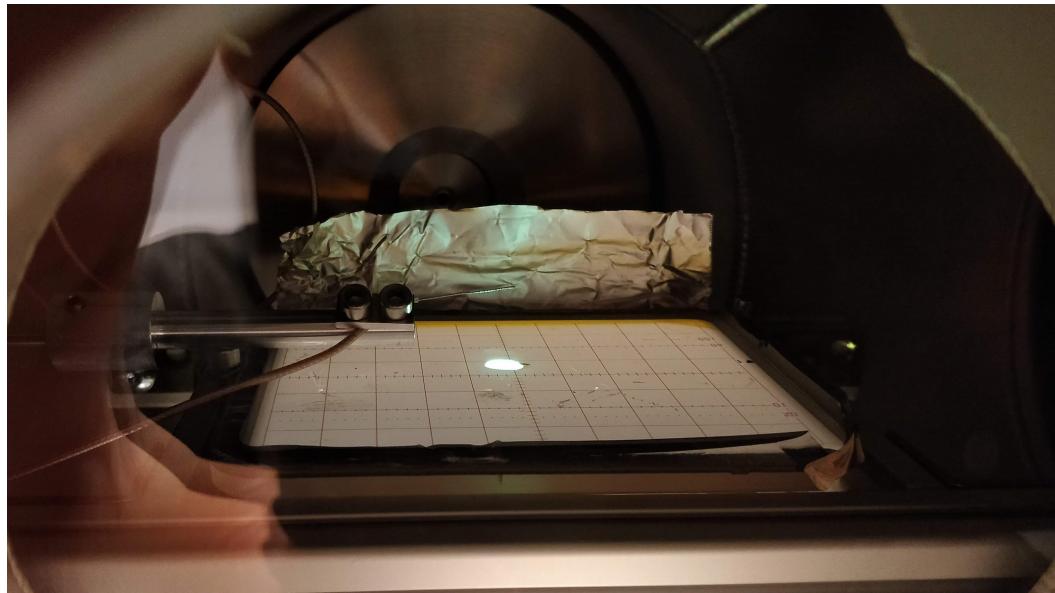


Figure 8.1: Front view of vacuum chamber (first iteration).

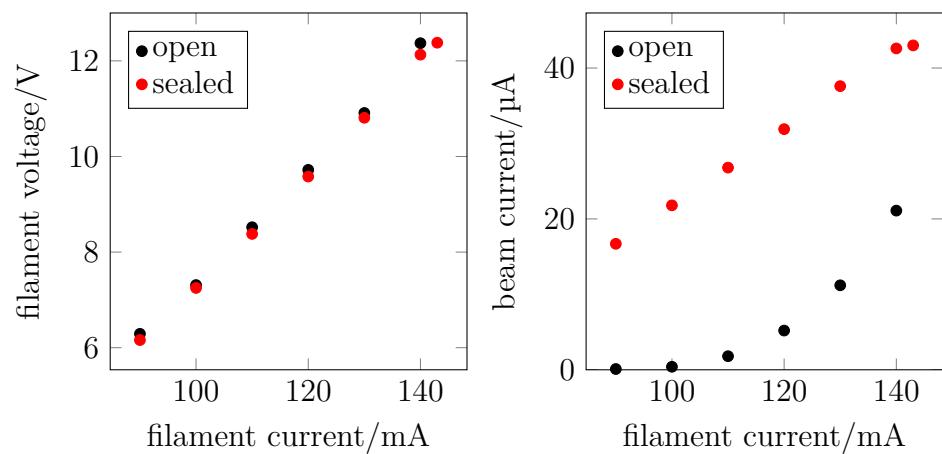


Figure 8.2: Difference in filament voltage and beam current between an open and sealed CRT.

¹ 8.2 Faraday cup

² In order to accurately measure the full beam current, a Faraday cup was built. A
³ schematic is shown in fig. 8.3. A copper tube was cut at an 45° angle on one side and
⁴ a Cu-sheet was soldered at the top and bottom. A small hole of around 5 mm was
⁵ drilled at the top and a coaxial cable was attached on the mantle which connects to
⁶ a BNC feed through at the top of the chamber. The small opening and angled floor
⁷ were added, in order to reduce electron loss through back scattering, as indicated by
⁸ blue arrows in fig. 8.3. At the top surface a phosphor coating was applied, in order to
⁹ make the beam visible. This made it easier to guide it into the opening hole.

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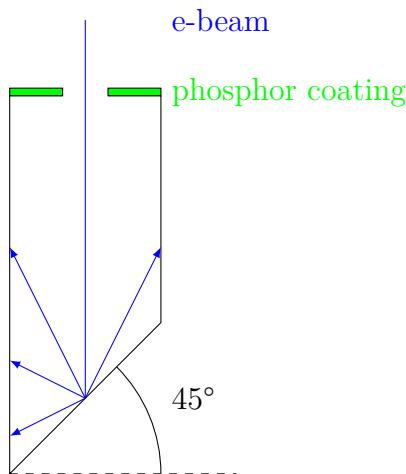


Figure 8.3: Schematics of Faraday cup.

¹⁸ With this improved setup, the beam current was measured again (fig. 8.4). It can
¹⁹ be seen, that a current of over $300 \mu\text{A}$ was achieved, which is more than the necessary
²⁰ amount for the experiment. However, through this measurement it became evident
²¹ that the current is not stable. A measurement on the next day under the same settings
²² resulted in a current between $50 \mu\text{A}$ to $120 \mu\text{A}$.

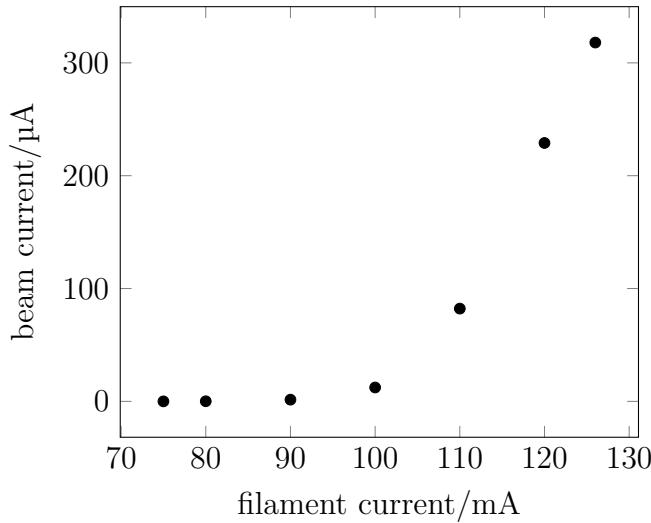


Figure 8.4: Beam current dependence on heater current.

8.3 Deflection frequency

This section describes a few observations, that were made when letting the electron beam interact with a short piece of wire, that is mounted to the wobble stick. Originally, we hoped to be able to measure the beam waist, using the knife edge method, i.e. observing the current transported by the beam, while slowly moving a razor blade through the beam path. However the beam is bent, when it passes closely to a conductive part. Whenever, we moved our wire close to the beam, the visible spot on the Phosphorous screen below was distorted. This will probably complicate the measurement of the beam waist in the future. When the wire is connected to an oscilloscope, one can see a sharp increase in voltage, when it is moved into the beam. This can be used to see whether our deflection plates work properly and to test how fast we are able to deflect the beam. If the beam oscillates back and forth on a straight line and crosses the wire on the midway point, we should see a spike in voltage on the wire, which repeats with twice the frequency of the beam. If the wire is not on the midway point, the periods between consecutive spikes should sum up to the period of the beam's oscillation (see fig. 8.5). At low frequencies we have indeed observed this behavior. As the frequency is increased, the magnitude of the signal decreases. This is easily explained by the fact that the remain time close to the wire is inversely proportional to the frequency and the amplitude of beams deflection. It was possible to see the spikes up to a frequency of 100 kHz, before they where obscured by noise and some other periodical, but so far unexplained artifacts. At high deflection frequencies, the wire may also pick up some signal form the capacitive charging and discharging of the deflection plates and the corresponding oscillating electromagnetic field. In order

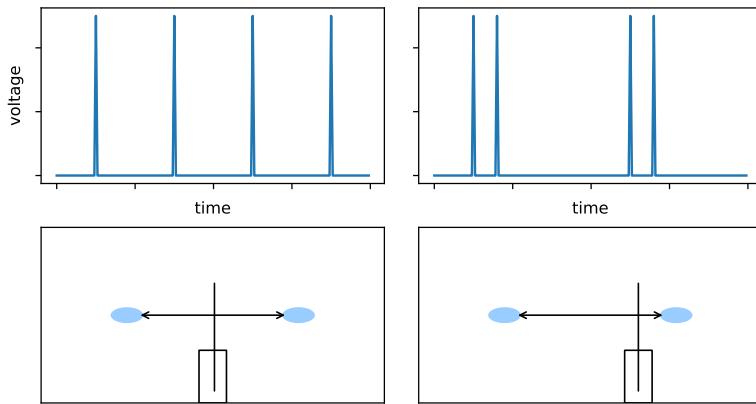


Figure 8.5

- ¹ to be able to see what happens at higher frequencies, a higher beam current and a
- ² smaller deflection amplitude would be beneficial. However, the most important factor
- ³ in order to understand what is happening, is a better focus and a better beam shape.

caption missi

9 Next Steps

To conclude this report, we will point out some of the next steps that need to be taken in order to advance the electron beam setup. To conclude this report, we will point out some of the next steps, that need to be taken in order to advance the electron beam setup.

Beam current stability: The most important challenge at this moment is the ability to produce a reproducible, stable, and sufficiently strong beam. In order to achieve this, more research on cathodes and their susceptibility to oxygen poisoning needs to be conducted. It may also prove useful to add another high voltage power supply to the setup in order to tune the filament potential independently from the Wehnelt cylinder.

Spot size characterisation: As previously mentioned, our original attempt was, to probe the electron beam's profile using a thin piece of wire on the wobble stick. However, we have observed that the beam got warped when passing close to conductive materials, therefore a different approach is needed.

Heating mechanism: As high currents will degrade the filament and cathode, it is desirable to be able to tune the heater current down to 0 mA continuously. Such a power supply needs to support a bias voltage of around -2 kV.

Lissajous Curves: Regarding the deflection electronics, the first issue that needs to be addressed is the fact that it is not possible to produce a clean sine wave when a bias voltage is applied to the center tapped transformer. Furthermore, it is recommended to implement the over voltage protection described previously with very low capacitance diodes.

Beam current stability: The most important challenge at this moment is the ability to generate a reproducible, stable, and sufficiently strong beam. In order to achieve this, more research on cathodes and their susceptibility to oxygen poisoning needs to be conducted. It may also prove useful to add another high voltage power supply to the setup, in order to tune the filament potential independently from the Wehnelt cylinder.

Spot size characterisation: As previously mentioned, our original attempt was, to

1 probe the electron beam's profile using a thin piece of wire on the wobble stick.
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3 conductive materials. Therefore, a different approach is needed.

4 **Heating mechanism:** As high currents will degrade the filament and cathode, it is
5 desirable to be able to tune the heater current down to 0 mA continuously. Such
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7 **Lissajous Curves:** Regarding the deflection electronics, the first issue that needs to be
8 addressed, is the fact that it is not possible to produce a clean sine wave, when
9 a bias voltage is applied to the center tapped transformer. Furthermore, it is
10 recommended to implement the over voltage protection described previously with
11 very low capacitance diodes. In the future, the setup should be able to produce
12 Lissajous curves at the ^{39}K hyperfine transition frequency of 461.7 MHz.

shortly referred
to the existing
one we built
how to change

Check whether
have explained
benchmarks for
beam (waist, c
rent, frequency)

Todo list

1

■	set date to English	A	2
■	also potassium 41, we might use this instead due to the smaller frequency	1	3
■	something is broken	1	4
■	use \person{}	1	5
■	this section is sometimes confusing and already deals with out CRT	2	6
■	you can probably explain it in your own words better	2	7
■	let e- come form cathode and not point source in mid air, cathode could be a bit smaller	2	9
■	explain why it has to be a sharp tip already here since it is shown in the picture	2	10
■	this is a strong statement I guess there are limitations to that, maybe a reference would be help full here	4	12
■	können die Maße stimmen?	5	13
■	maybe expplain here what this is	6	14
Figure:	Image of CRT	7	15
■	mention why it is important	8	16
■	in our ONEnote are some SEM pictures of the cathode	8	17
■	with what result?	9	18
Figure:	Figure of SHV & BNC connector cable.	15	19
Figure:	picture of ac bias voltage	19	20
■	check if really 14Ω or if it event exists	19	21
Figure:	Image of Stage.	22	22
■	explain more in detail what is the purpose of the chamber, the two iterations are not really important built this chapter rather about the function and operation of the chamber over time due to outgassing the pressure improved)	26	25

1	■ water vapor getting into the chamber	26
2	■ explain in connection of the rendering; this makes it easier, if necessary you 3 can get more renderings	26
4	■ pure nitrogen name?	26
5	■ Alphagaz TM 1 N ₂ purity ≥ 99.999 %	26
6	■ water vapor getting into the chamber	26
7	■ length=27cm	26
8	■ Thyracont exact model is in one note	26
9	■ Thyracont exact model is in one note	27
10	■ how many pins and model name? MIL Type C connector	27
11	■ MIL 19 C	27
12	■ F: but I'm talking about first iteration	27
13	■ we also used thin Kapton insulated BNC cable	27
14	■ Viton, maybe also describe the specification of these type of seals	27
15	■ rod length? check Solid works	28
16	■ rod length? check Solid works	28
17	■ screwed / with a counter nut	28
18	Figure: Image of CRT mounting mechanism.	28
19	■ in general make better section titles	28
20	■ this is not so much of a leak but mainly outgassing / how was the pressure 21 measured?	28
22	■ of a sufficient current	30
23	■ with a sufficient small enough bandwidth	30
24	■ Optional: insert Foto of CRT's deflection plates - fig:DeflectionSetup	30
25	■ what happens when there is no bias voltage, what is the purpose of it	30
26	■ to achieve what	30
27	■ Find out which amplifier	32
28	■ which model?	32
29	■ which model?	32

9 Next Steps

■ Check amplifier specifications	32	1
■ Optional: Go to the lab and measure their performance with an Oszi.	32	2
■ Insert fotos of finished circuits in housings	33	3
■ Optional: Go back to the Lab, set up the whole thing and look at its performance on the oszi	33	4
■ picture placement and caption is missing	33	6
■ skip: around and not all choose the wire path to ground	35	7
■ caption missing	39	8
■ shortly reference to the existing one we built and how to change it	41	9
■ Check whether we have explained the benchmarks for the beam (waist, current, frequency)	41	10
		11

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