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20th of October 2025 -Revision C

Study of a Single Diode Tube Receiver

SUMMARY

1. Introduction

The author, although born after the invention of the transistor (1948), takes his first steps on tube circuits (see Reference [1]).
Wishing to rediscover tubes, I therefore set out to implement and re-examine the simplest of tubes, the diode, using what I had available in my drawers.

Since a circuit designed to rectify the current in a power supply wasn't very interesting, I opted for a longwave receiver with a single diode tube, the goal being to receive one of the broadcast stations heard in Paris during the day (in 2017), namely Europe 1 (183 kHz) or RTL (234 kHz). Note that other stations can be heard, but more faintly, such as the BBC (198 kHz) or RMC (216 kHz).

After researching the Internet and the available literature, and compiling all this information, I built a small AM receiver. The goal is not to propose a directly feasible setup (that would be of little interest).
This is an experiment, let's call it a "practical exercise", the goal being to study how a setup works. I will rely on the simulation of a diode-type vacuum tube, developed by the author (reference [7]).

Before describing the receiver in §3, some reminders on the physics of vacuum tubes are provided in §2.

The measuring instruments used by the author in the article are: inductance meter, capacitance meter, ohmmeter, standard universal controller, LF/HF generator up to 2 MHz, frequency meter, and variable DC voltage generator (1 to 30 V). The accuracy of this instrumentation is standard, therefore neither specified nor verified.

Notations
In the following text:

- The simple product is denoted " * " or " . " or is not denoted if there is no ambiguity.
- Powers of 10 are denoted Ex or 10^x (for example, 10^{-7} or E-7).
- The power of a variable is denoted ^ or with the exponent (x^2 or x^2, for example).
- The square root is denoted √(x) rather than x^0.5 or $x^{0.5}$
- “CV” is used for “Capacity variable”.

2. A review of how a diode vacuum tube works

2.1 General information and comparison of semiconductor diodes with vacuum diodes

2.1.1 General information about vacuum tubes

The vacuum tube was developed between the end of the 19th century and the beginning of the 20th century by inventors and physicists including Edison, Perrin, De Forest, Schottky and Fleming (inventor of the diode).

Below, on the left, is a photo of various tubes belonging to the author, and on the right, a close-up of the 25Z6GT diode, which will be used throughout this article.

The "single diode" type indirectly heated vacuum tube consists of two electrodes: the cathode and the anode, also called “plate." They are located inside a tube placed under a high vacuum to prevent collisions between electrons and atoms. Collisions with atoms would slow the electrons emitted by the cathode and create secondary ion/electron pairs. The ions attracted to the cathode can destroy its outer coating.

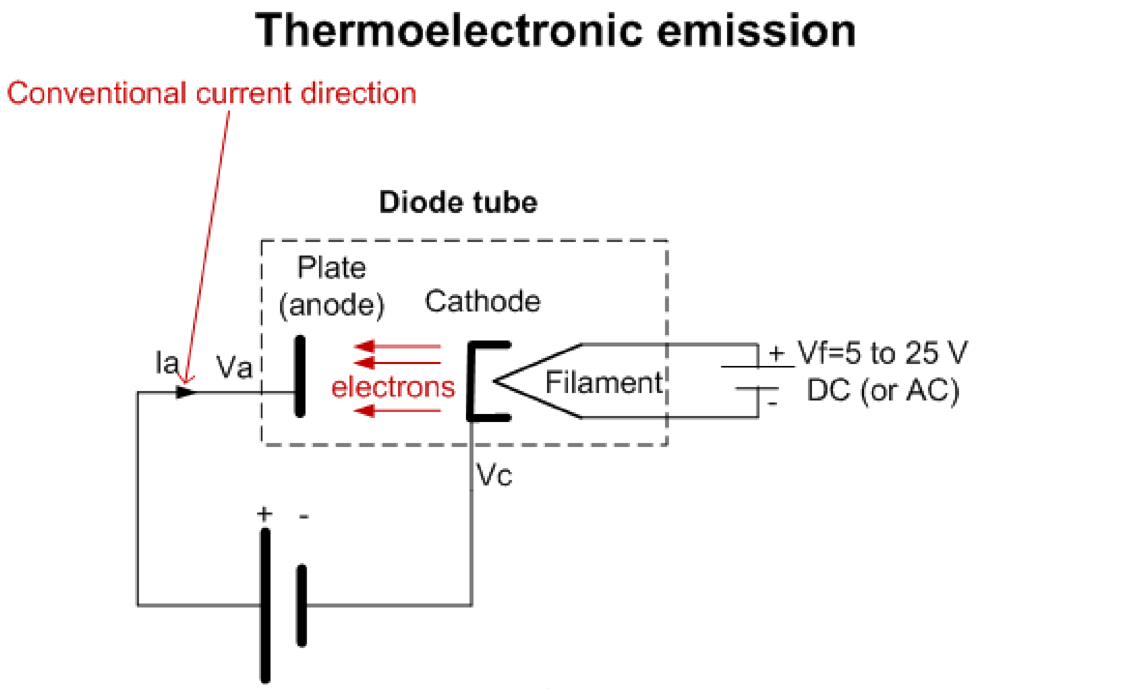
The cathode (a nickel alloy cylinder coated with a layer of barium or strontium oxide) is heated to between 900 and 1000°C by a tungsten filament. It takes approximately 30 seconds to heat the cathode, and stabilization is achieved after one minute.

The filament is electrically insulated but in thermal contact with the cathode through an intermediate cylinder made of refractory insulating material. The anode is a cylinder that closely surrounds the cathode but without contact.

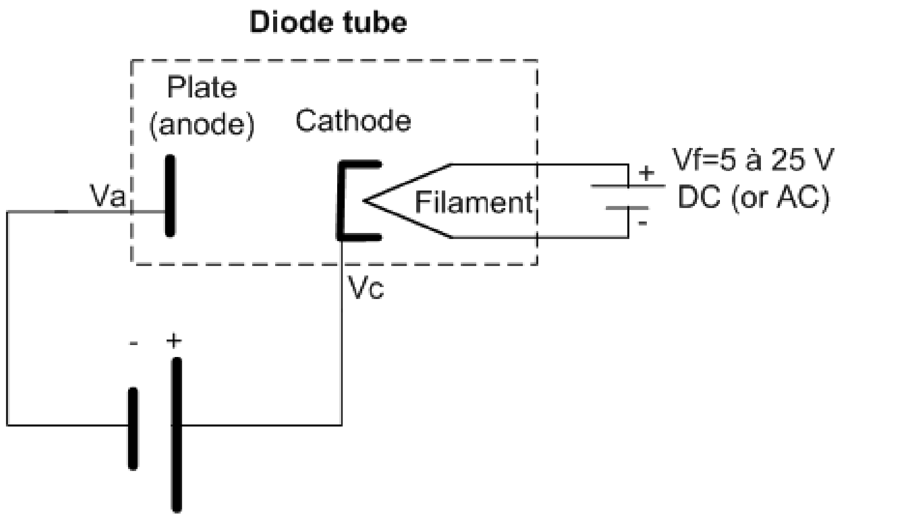
> Note that there are also, but less frequently, direct-heating tubes, where the filament acts as the cathode, the temperature being significantly higher (around 1600°C).

At this cathode temperature (900 to 1000°C), the thermal agitation and therefore the kinetic energy of the electrons (negatively charged particles orbiting the nucleus composed of protons and neutrons) is very high. Because of this energy, a certain number of electrons located on the outer layer of the cathode can be extracted. To do this, the electrons energy must exceed a certain "output work", so that the electrons can leave the cathode surface.
These electrons form a highly negatively charged electron cloud that generates an electric field that repels the newly extracted electrons (space charge, see §2.3.3) toward the cathode (the "-" repelling the "-"). In the absence of voltage at the anode, almost all of the electrons return to the cathode.
However, as soon as the anode becomes positive, it generates an electric field between the cathode and the anode that accelerates the electrons toward the anode by Coulomb attraction (the "+" attracting the "-"). Conversely, if the anode is negative, all the electrons are repelled toward the cathode and no current flows. Therefore, a current is only generated if the anode is positive. The diode is therefore a current rectifier.

This principle is illustrated below (for a planar diode).



Va > Vc: an electron current flows between the cathode and the anode



Va < Vc: no current flows between the cathode and the anode

For more details, the history of vacuum tubes and their operation, and in particular, that of the diode (known as the Fleming diode), are very well presented in the pages of F5ZV (reference [2]).

Hereafter, I will use the 25Z6GT double diode as an example for two good reasons:

- I had one left in my stockpile of tubes,
- They are still relatively inexpensive.

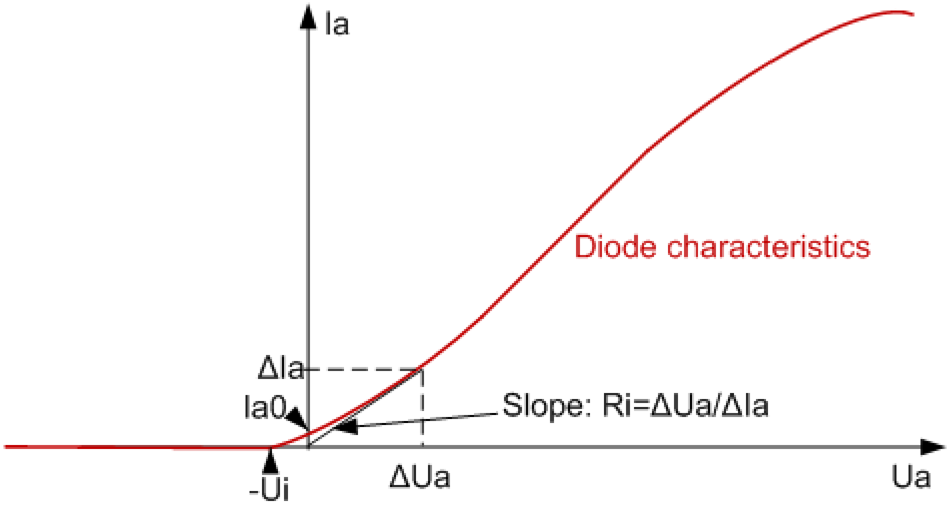
The specifications of this tube can be found in reference [3].
Note that the cathode is, at a glance, 1 mm in diameter and the anode 2 mm in diameter. The length of these cylinders is 25 mm. These dimensions will be used for the tube simulation.

2.1.2 Comparison of semiconductor diodes with vacuum diodes and their imperfections

It is known that silicon or germanium diodes are not ideal because the reverse resistance is not negligible (around 500 kOhm). Furthermore, they have a threshold before they become fully conductive (0.2 V for germanium and 0.6 V for silicon).

However, as can be seen on the following figure (Ia curve versus Ua), the diode tube is far from being a perfect rectifier.

Ia (I anode) versus Ua (U anode) curve – Vacuum diode imperfection (-Ui and Ia0) and internal resistance (Ri)



Indeed, even with a 0 V difference between the cathode and the anode, there is a non-zero current (Ia0), and to cancel this current, a negative voltage Ua (-Ui) of around -1 to -2 V must be generated.

> Note: we use this figure showing the tube's Ua/Ia characteristic (in red) to graphically determine the tube's internal resistance around Ua=0 V, therefore for the intended use (detection of an HF signal), ignoring -Ui and Ia0.

For example, the author measured this current (Ia0) for the 25Z6GT diode, for different voltages across the filament (and therefore different heating powers):

Uf (U filament in V)	Ia0 (I anode in µA)
7	0,08
8	0,4
9	1,2
10	6
13	47
15	260
20	950
25	1650

We see that the increase in Ia0 as a function of Uf is very rapid.
This behavior is explained by the fact that the higher the voltage across the filament, the greater the heating power and the higher the cathode temperature. However, the initial velocity of the electrons increases with the cathode temperature. Even if the space charge (see §2.3.3) brings most of the electrons back to the cathode, statistically, a certain number manage to pass through (due to their initial velocity) and strike the anode.

Given these results, we cannot say that a voltage Uf of 7 V would be better than one of 25 V, arguing that at 7 V the current Ia0 would be almost zero (and that we would tend towards a perfect diode). Indeed, at 7 V, thermionic emission is also very low, regardless of the potential difference between the anode and cathode. So it would rather be the ratio between this current Ia0 and the thermal saturation current which should be looked at.

Non-zero current Ia0 and voltage -Ui will cause some distortion due to imperfect detection, as well as limited sensitivity. By ear, for the receiver described below, we can see that a voltage of 13 to 14 V provides the best voice intelligibility. If the voltage is too high (>20 V), the sound seems muffled with hum, and if the voltage is too low (<7 V), we can hardly hear anything.

The essential difference between the two types of diode (semiconductor / tube) is that the current flowing through the semiconductor diode is taken from the current received from the antenna, whereas the current (Ia) flowing through the tube diode depends on the voltage across the anode Ua, the internal resistance of the diode (see previous figure), and therefore the heating power (related to the voltage across the filament) and not on the received current.

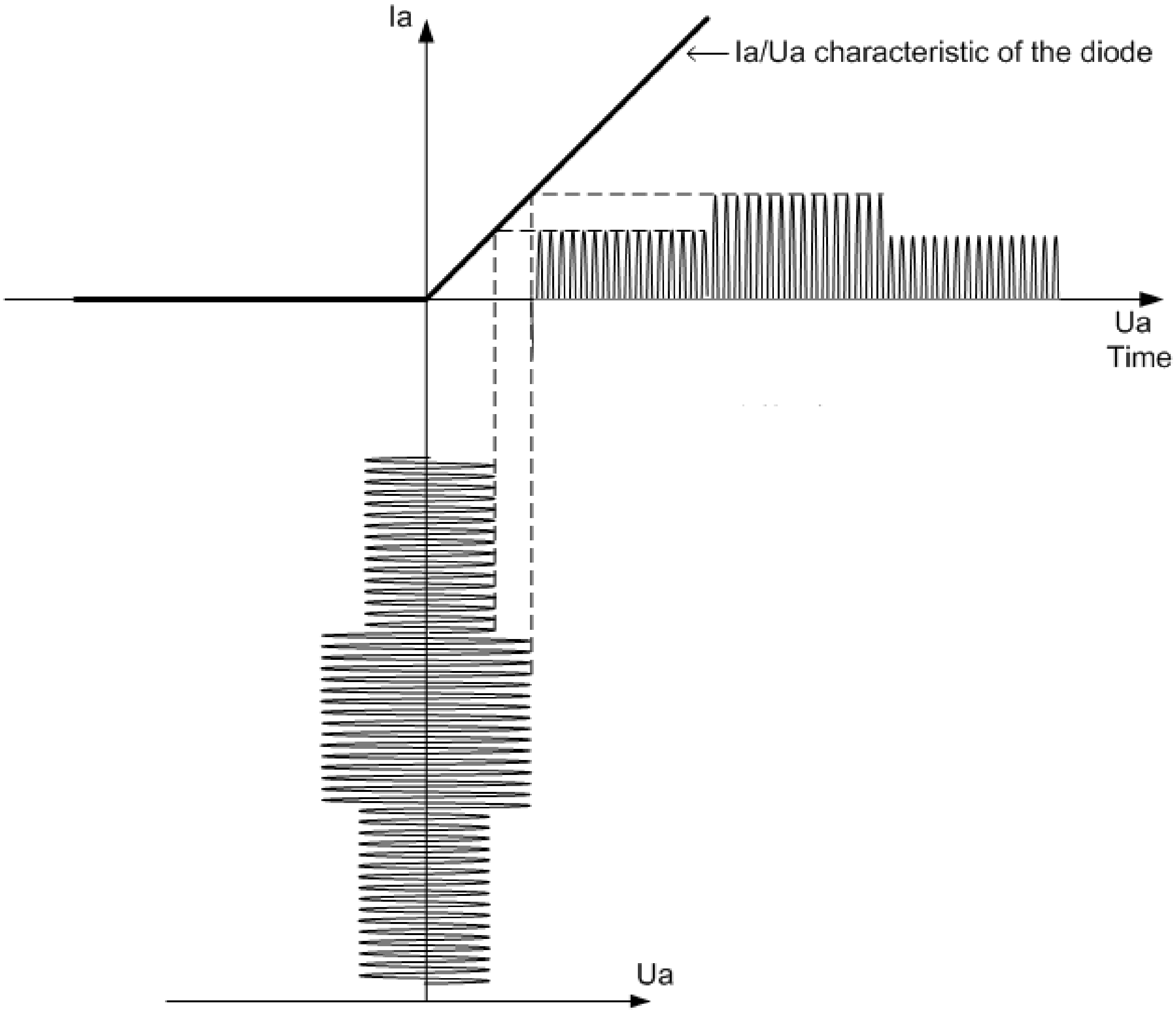
> Note: there must, however, necessarily be a certain displacement current to vary the voltage of the anode (the latter having a certain capacity), but we will not take this into account.

2.1.3 Signal rectification by the diode

Below is a diagram showing how the received signal is rectified. Here, the heating power, and therefore the filament voltage, is fixed. This determines the diode's plate (anode) characteristic (Ia as a function of Ua). Indeed, the greater the heating power, the greater the Ia current (the characteristic "rectifies").

Below, the Ia/Ua characteristic is assumed to be ideal (i.e. passing through the origin).

Rectification of the signal received by the diode



2.2 Filament and cathode study

A number of measurements (U filament / I filament) were made. From these, the heating power (P = U.I) and the filament resistance (R = U/I) can be directly deduced.

For information, the cathode temperature (which determines the initial velocity of the electrons) was estimated based on:

- An assumption: the nominal cathode temperature for a filament voltage of 25 V is 950°C (based on the cathode color).

- The variation in a metal's resistivity as a function of temperature (assumed to be linear).

- Heat dissipation by radiation (i.e. by applying Stephan's law: $P=K.(T^4 - Tambient^4)$, with Tambient=293°K), since there is no convection (the tube is devoid of atmosphere) and conduction through the metal parts is neglected. Qualitatively, the estimated temperature seems more likely according to this second law than according to the first (based on resistivity).

The results and curves illustrating this analysis are presented on the following page.

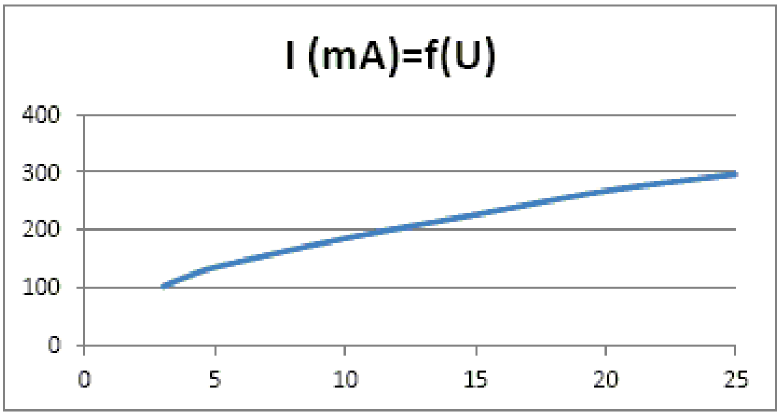
Study of cathode heating by filament

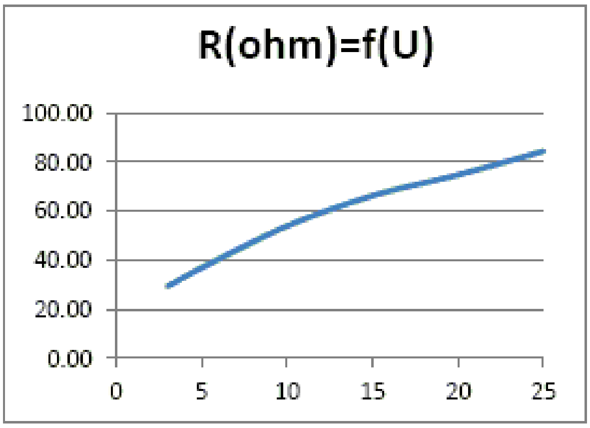
U filament (V)	I filament (mA)	P=U*I (mW)	R (ohm)	Estimated T on R (°C)	Estimated T on P (°C)
3	102	306	29.41	153	289
4	120	480	33.33	210	351
5	135	675	37.04	263	405
10	185	1850	54.05	510	594
15	226	3390	66.37	688	734
20	267	5340	74.91	812	855
25	296	7400	84.46	950	950

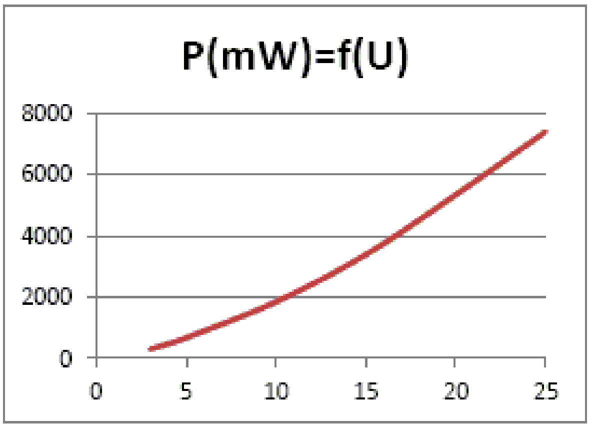
At 25 V the temperature of the cathode estimated on the basis of its color is 950°C or 1223°K

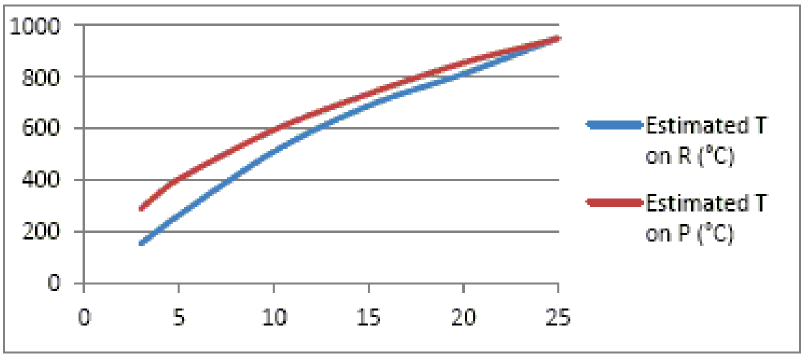
T (cathode) estimated on R (°C)=(1223/84.46)*R-273

T (cathode) estimated on P (°C)=(((P/7400*2.23E12)+7.39E9)^0.25)-273









2.3 Study of diode characteristics

2.3.1 Diode characteristic (Ia as a function of Ua)

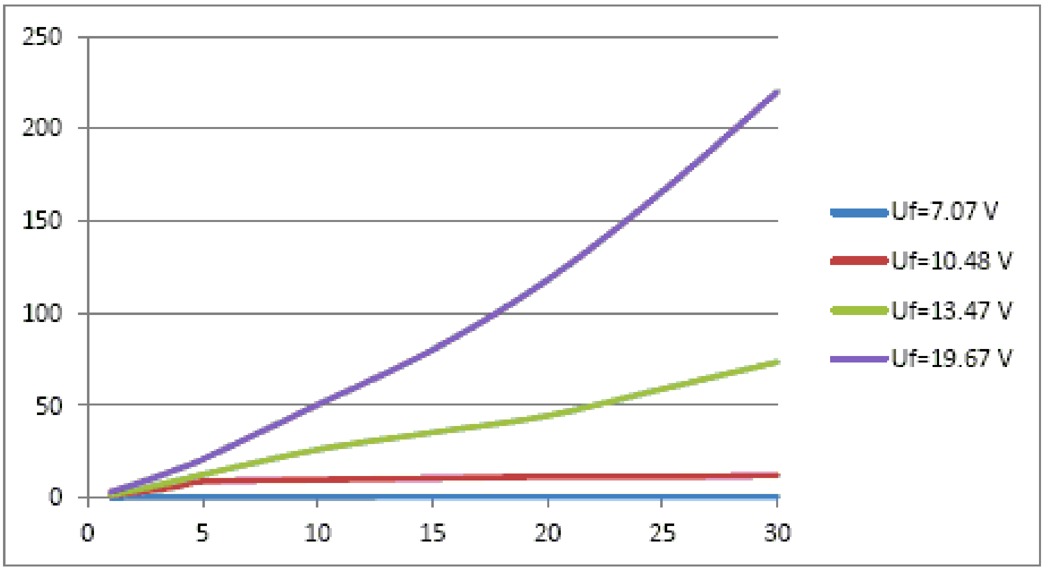
The diode characteristic (see §2.1.2) is very important. It allows us to determine the current flowing from the cathode to the anode as a function of the voltage across the anode, for a given filament voltage.
In fact, the controlled parameter is the cathode temperature. Indeed, without going into the equations, the electron energy is proportional to this temperature but also to the square of their velocity. Therefore, the (average) velocity of the electrons ejected by the cathode is proportional to the square root of the cathode temperature.

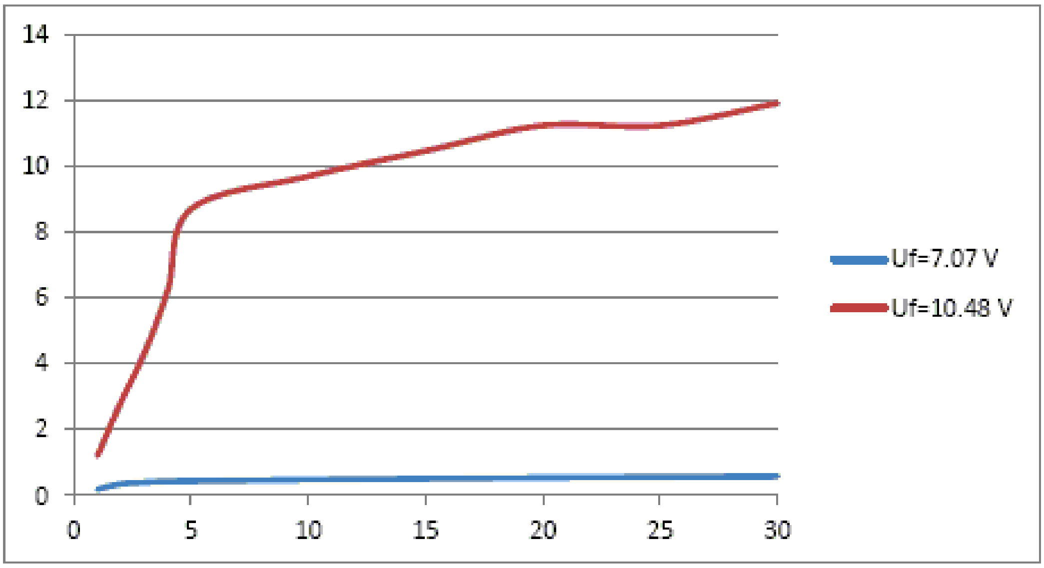
> Note: both the velocity and the direction of departure of the electrons are probabilistic (i.e. a function of statistical distribution laws). This implies that there is not a single velocity and a single direction, but an infinite number.

From the readings and curves shown on the next page, we see that the increase in current as a function of Uf is very rapid (1st figure).
This current follows the Dushmann-Richardson law, which shows that a small increase in cathode temperature corresponds to a large increase in the emitted current, for a constant voltage at the anode. This is indeed what we observe.

> Note 1: the normal supply voltage for the filament is 25 V for the 25Z6GT diode.
> Note 2: only one cathode/anode pair is involved here, not the two cathode/anode pairs connected in parallel, as for the receiver (see §3).

Ua (U anode) (V)	Uf=7.07 V Ia(mA)	Uf=10.48 V Ia(mA)	Uf=13.47 V Ia(mA)	Uf=19.67 V Ia(mA)
1	0.18	1.2	1.62	3.24
2	0.34	2.84	4.08	6.95
3	0.39	4.33	6.83	11.22
4	0.42	6.24	9.66	15.83
5	0.43	8.71	12.61	20.74
10	0.47	9.7	26.1	50.3
15	0.5	10.47	35.4	80.1
20	0.53	11.24	44.5	118
25	0.55	11.24	59	166
30	0.57	11.92	73.5	220





Current (Ia) cathode-> anode (0 to 220 mA) (ordinate) as a function of the volltage on the anode (Ua) between 0 and 30 V (abscissa) this for different supply voltages (Uf) of the filament

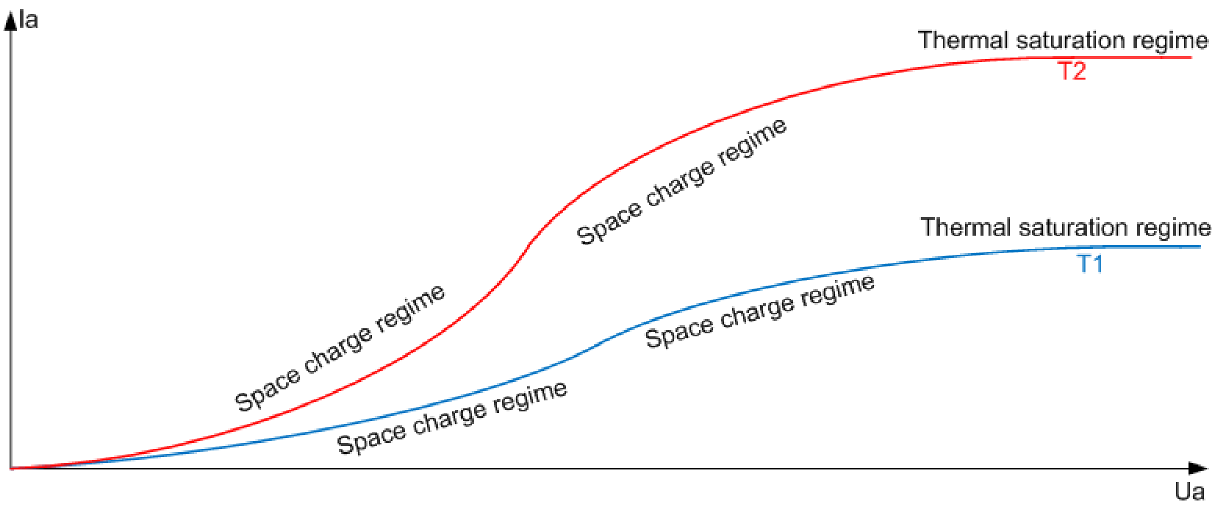
2.3.2 Thermal saturation

Moreover, we can see that the current depends on the anode voltage (assuming the cathode is at 0 V).
One might think, a priori, that all the electrons emitted by the cathode flow towards the anode. In this case, the current (electron flow rate) should not depend on the anode voltage. In fact, this is what happens when a certain anode voltage is exceeded (in normal operation, several hundred V). In this case, most of the emitted electrons reach the anode. This is called "thermal saturation".

> Note: in fact, the current continues to increase with the anode voltage, but only slightly. This is due to the fact that the electric field increases, which decreases the output work and therefore slightly increases the flow rate of emitted electrons (Schottky effect, see §2.3.5).

The figure below illustrates the phenomenon of thermal saturation (which should be avoided when using vacuum tubes).

Anode current (Ia) as a function of anode voltage (Ua), for two cathode temperatures (T1 and T2 with T2>T1) showing the space charge and thermal saturation regimes of the diode



This thermal saturation phenomenon is also clearly visible in the second figure on the previous page, starting at 3 V for Uf=7.07 V and 5 V for Uf=10.48 V.

Indeed, since the cathode temperatures are low and therefore the electron flow rate is low, saturation is quickly reached, without waiting for hundreds of V.

2.3.3 Space charge

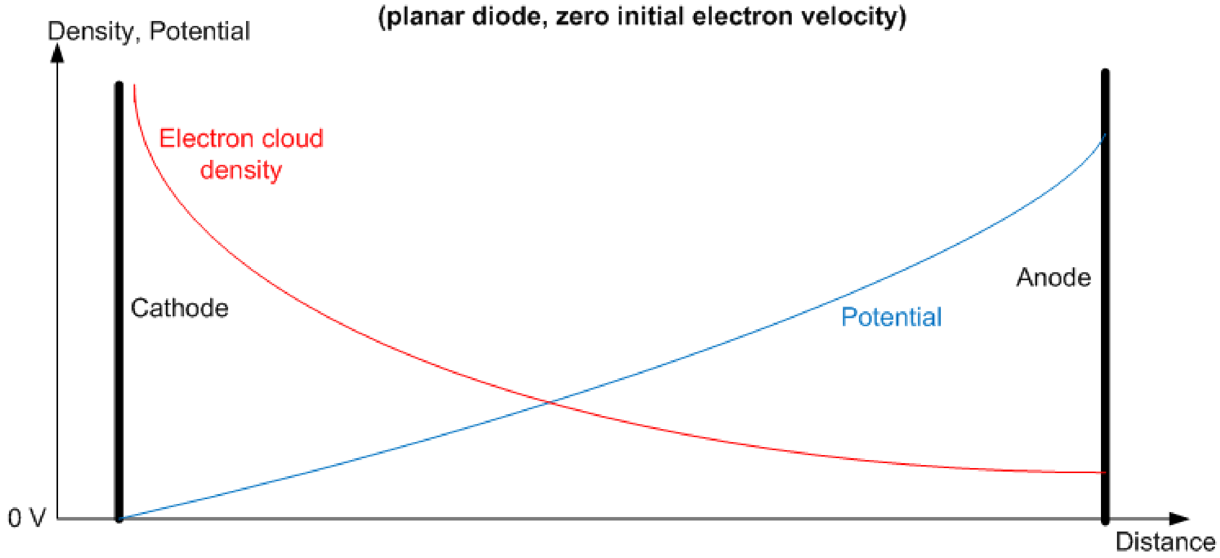
As mentioned previously, one might think that all the electrons emitted by the cathode flow toward the anode. In this case, the current (charge flow and therefore electron flow) should not depend on the anode voltage. However, we can see, for example, on the curve Ia=f(Ua) for Uf=19.67 V (see §2.3.1), that this is not the case. This is explained by the phenomenon of space charge.
The space charge consists of the electron cloud supplied with electrons by the cathode, a cloud located between the cathode and the anode. This cloud has a density (ρ) that increases near the cathode. Indeed, since the current density J=ρ.v (v: velocity) is constant, it follows that ρ is inversely proportional to the velocity.

Having a negative electric charge, this electron cloud decreases the local electric field (according to Poisson's law). Generally speaking, the stronger the current emitted by the cathode, the denser the electron cloud, the more it tends to limit the current flowing to the anode, until equilibrium is reached. Without going into the details of the calculations, we show, starting from a zero initial electron velocity and a zero field at the cathode, that the anode current is (roughly) proportional to the anode voltage to the power of 3/2 (Child-Langmuir law).

> Note: this formulation does not take into account whether or not the cathode can supply this current. As long as the cathode can supply this current, we are in a space charge regime (and what doesn't go to the anode returns to the cathode, see §2.3.4). If this is no longer the case, then we enter a thermal saturation regime.

Below we show the shape of the electron cloud density and potential.

Shape of the electron cloud density and potential, with a space charge (planar diode, zero initial electron velocity)



2.3.4 Taking into account the initial velocity of electrons

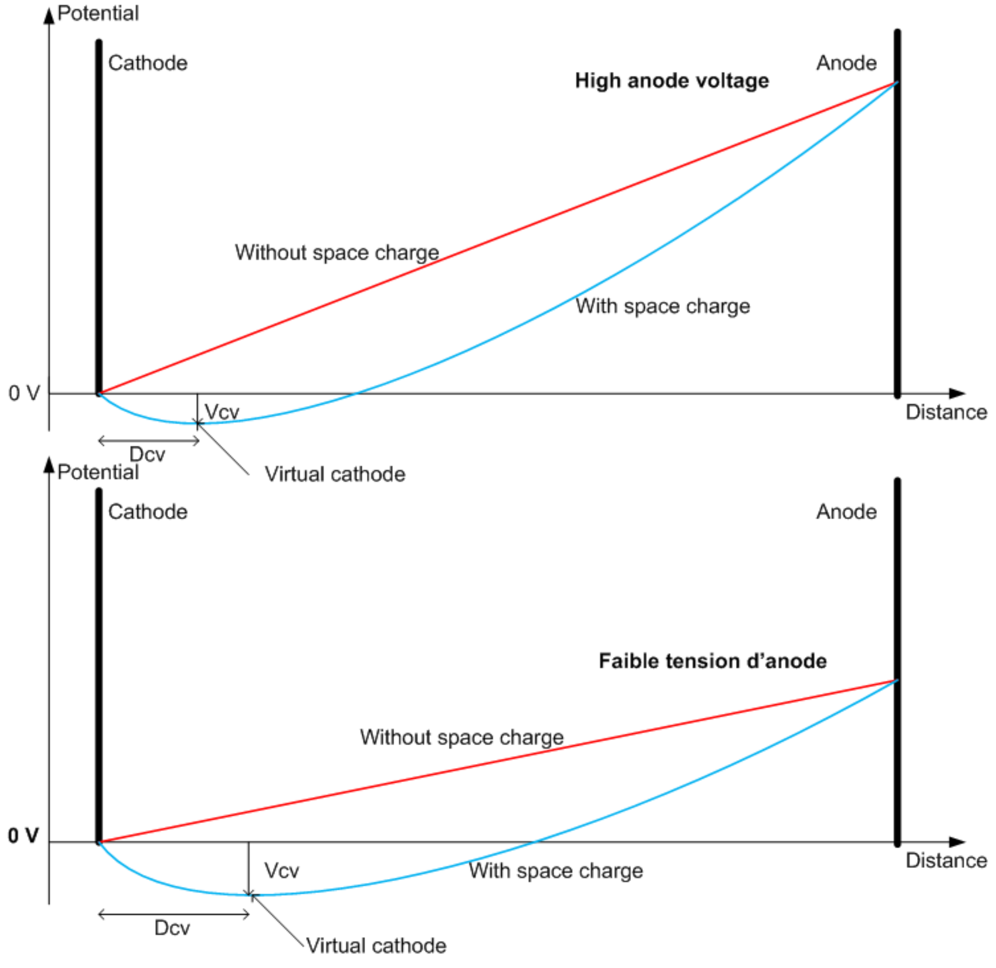
To be more precise about the space charge, the initial velocity of the electrons must be taken into account. Indeed, the flow rate of electrons going to the anode also depends on the velocity of the electrons leaving the cathode. As indicated above, the density of the electron cloud is very high near the cathode. This thin layer opposes the movement of electrons, sending some of the electrons back towards the cathode. Only the most energetic electrons can pass through this layer.

Below, the evolution of the potential between the cathode and the anode (for a planar diode) is shown at equilibrium, without space charge and then with space charge, taking into account a non-zero initial velocity (i.e. consistent with reality).
The minimum potential point forms a virtual cathode. If an electron, due to its initial speed, can reach the virtual cathode (negative potential), it is certain to reach the anode (the local potential then only increasing).

> Note that the potential difference between the anode and the virtual cathode is greater than that between the anode and the physical cathode.

We see that the lower the anode voltage, the greater the negative voltage Vcv of the virtual cathode. The same applies to the distance Dcv between the physical cathode and the virtual cathode.
Therefore, despite a non-zero initial velocity, the lower the anode voltage, the more difficult it is to reach the anode, which results in a decrease in current.

Taking into account the initial velocity of electrons - Distribution of the potential between cathode and anode, with and without space charge



2.3.5 Schottky effect

This effect is mentioned as a reminder because it only has an effect in the thermal saturation regime, slightly increasing the saturation current with the voltage at the anode. This phenomenon is due to the fact that at the cathode, the stronger the electric field, the lower the output work of the electrons, allowing more electrons to be extracted.

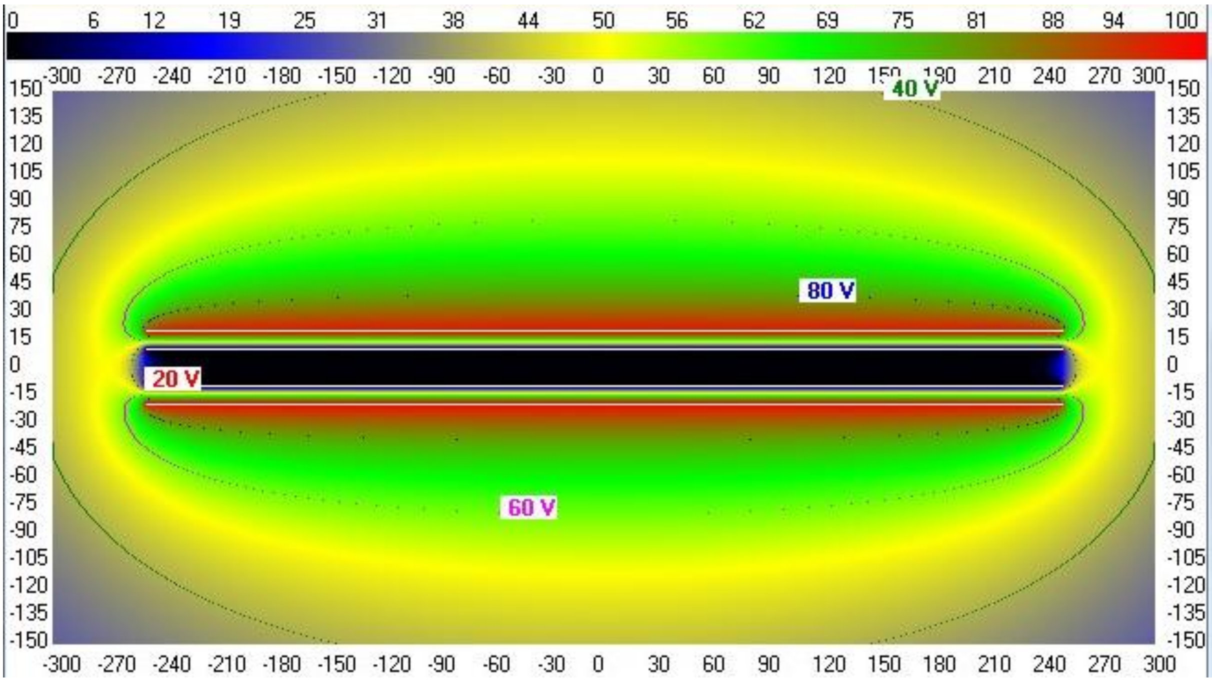
For more details on this topic (§2.3.1 to 2.3.5), see references [4] to [6].

2.3.6 Potential and electric field between cathode and anode

Considering the 25Z6GT diode, the anode (diameter of approximately 2 mm) surrounds the cathode (diameter of approximately 1 mm) over a distance of 25 mm. In the figures below (isopotentials then electric field), we see the cathode (interior white lines) and anode (exterior white lines) enlarged 20 times, with the graduations representing mm. The anode voltage is set at 100 V, that of the cathode is at 0 V.

<u>Isopotentials (V)</u>

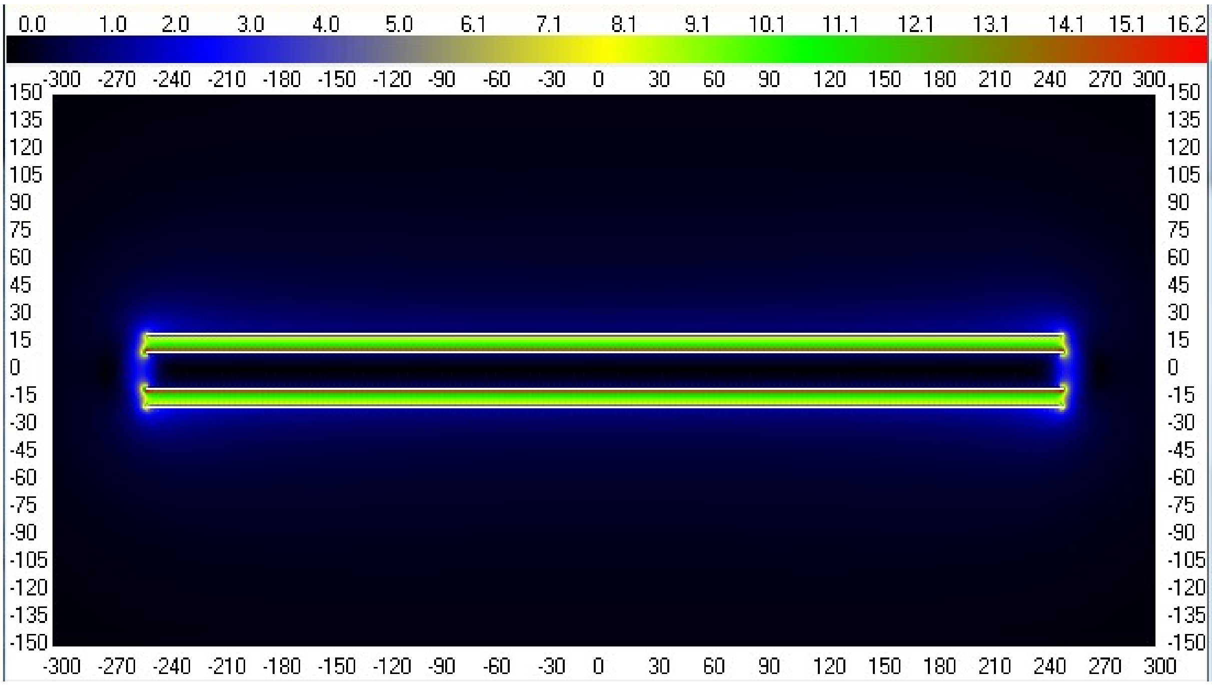
Between the electrodes, the variation in potential is regular (but non-linear) and always identical, while at the edges, the potential is much less regular. We can therefore predict that a greater or lesser fraction of the emitted electrons will be lost on the walls, via the edges.



Electric Field (V/mm)

Reminder: the electric field is a vector whose three components are each equal to the derivative of the potential with respect to x, y, or z. What is represented below is therefore the (scalar) modulus of the electric field.

We can observe that the electric field between the electrodes varies relatively little, although it cannot be constant because the variation in potential between electrodes is not linear. The average field between the cathode and anode is, in the example, approximately 10 V/mm. We can see so-called "spike" effects at the right and left edges.

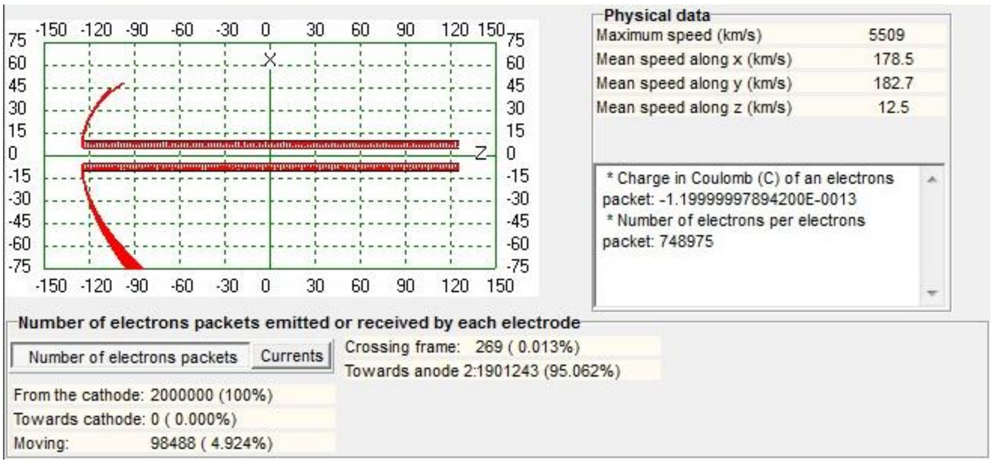


2.3.7 Electron trajectories

We cannot plot every trajectory because there are tens (or even hundreds) of thousands of them. However, we can get an idea of all the trajectories on a longitudinal section, taking into account the axisymmetry.
Specifically, we plot all the trajectories appearing within a 5 mm thickness, on either side of the central X/Z plane, i.e. between the X/Z plane with ordinate Y=-2.5 mm and the X/Z plane with ordinate Y=+2.5 mm.
For the screenshots below, we have assumed a current density of 100 mA/cm² for a cathode temperature of 900°C. The anode voltage is set at 100 V, and the cathode voltage is set at 0 V. The cathode and anode are enlarged 10 times.

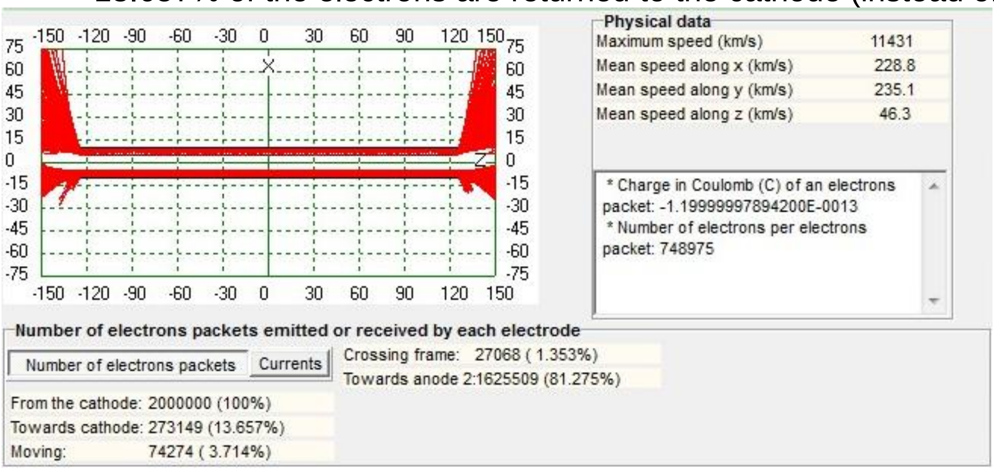
<u>Without taking space charge into account</u>
If electrons were solely dependent on the electrode potential, then electrons would simply flow from the cathode to the anode, as seen below. Indeed, we observe that:

- only 0.013% of the electrons escaped the anode, reaching the walls via the edges,
- no electrons returned to the cathode.



<u>Taking space charge into account</u>
Electrons are dependent on the electrode potential and the space charge constituted by the other emitted electrons, which are still moving. Compared to the previous image, we observe that:

- the number of electrons expelled towards the walls is much greater (1.353% instead of 0.013%)
- 13.657% of the electrons are returned to the cathode (instead of 0%).

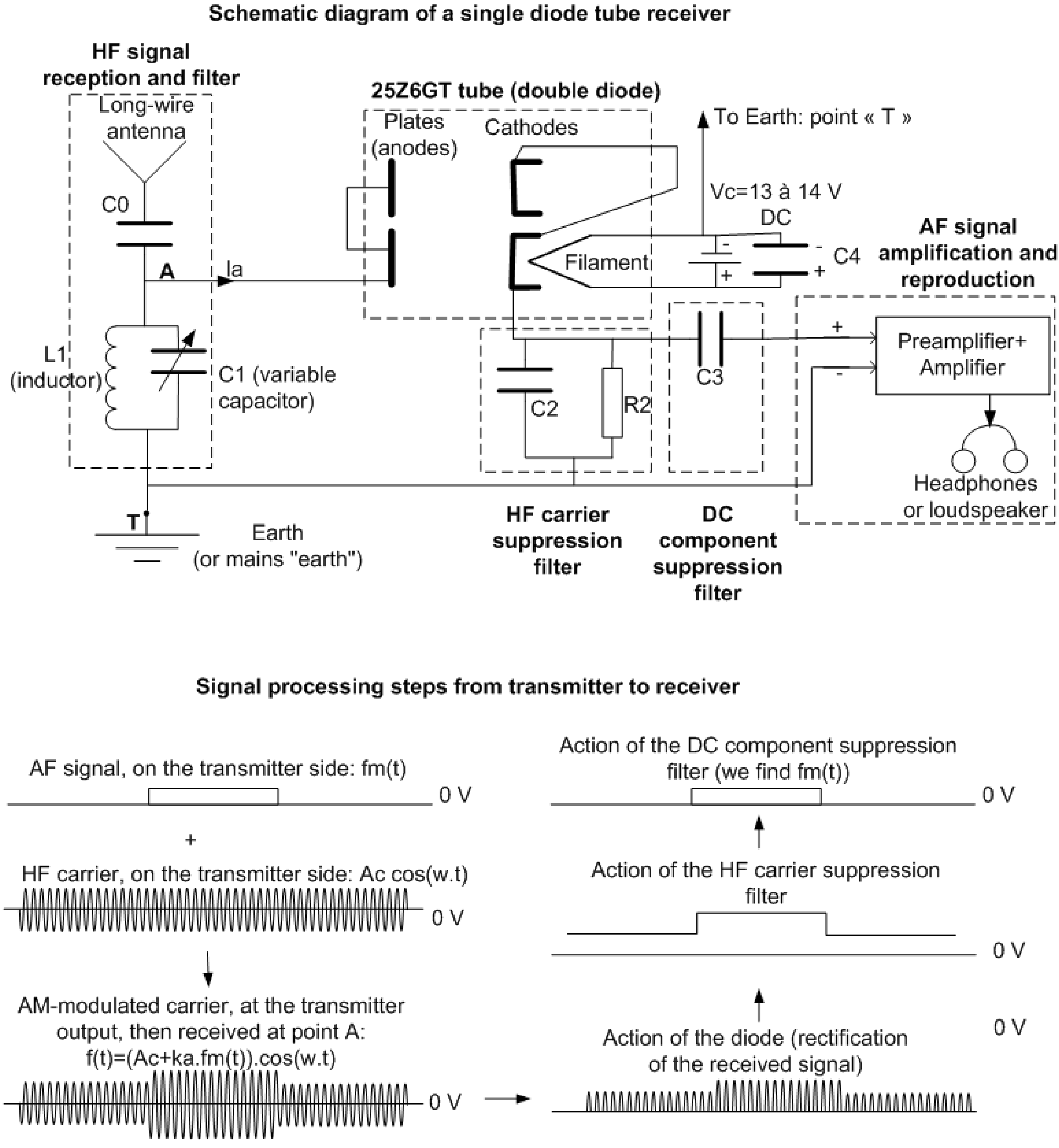


3. The Receiver

3.1 Description of the receiver

The schematic diagram of this first receiver is shown below.

Schematic diagram of a single diode tube receiver and signal processing from transmitter to receiver



<u>Pin numbers used on the 25Z6GT tube</u>
In this diagram, the two plates are connected together (pins 3 and 5) as are the two cathodes (pins 4 and 8). The filament pins are numbered 2 and 7.

The filament is powered between 13 and 14 V (non-critical; it can be reduced to 9 V). This voltage range provides good speech intelligibility (see §2.1.2). The power supply used is set to the "12V" position and provides 13 V, which is adequate. Electrolytic capacitor C4 cancels out residual 50 Hz hum. I used the largest capacitor I had on hand, a 2200 µF capacitor (non-critical value), capable of handling 25 V.

The AM (amplitude modulation) signal is received by the "long wire" antenna. In my case, the antenna consists of the 10 m of coaxial cable that connects the transceiver to my balcony antenna. I use braided wire, which seems to be slightly better than the coaxial core, as the sound level is higher.

If the "long wire" antenna is connected directly to the tuned circuit, it will be placed in parallel with it. However, it introduces a high capacitance (as well as a low inductance that can be ignored). If we measure the resonant frequencies of the tuned circuit, CV closed, with and without the antenna connected, we see that the long wire antenna introduces a capacitance of 420 pF (or 42 pF/m).

> Note: strictly speaking, this is not the only "parasitic" capacitance to be placed in parallel on the tuned circuit. The inductor and the wires, and probably, to a lesser extent, the tube and its circuit, add a small residual capacitance. I determined that the total should be about 16 pF.

Furthermore, we note that the antenna dampens the tuned circuit because the selectivity becomes poor.
The capacitor C0 in series with the antenna capacitance therefore allows it to be reduced. But if the value of C0 is too high, it serves no purpose; if it is too small, it blocks the signal. The value of C0 is therefore determined experimentally, aiming for the maximum power of the received signal (the RTL station in my case). For a "long wire" antenna of about 10 m, C0 = 82 pF gives the best result.

The 0 V of the circuit must be connected to ground, or even to the "mains ground" (to close the "Antenna" circuit). Without this connection, the sound quality is poor.

The signal is then filtered by the L1/C1 trap circuit, with an efficiency that depends on the circuit's quality factor (particularly that of L1 and the antenna).

The diode establishes a current that will depend primarily on the voltage at point A and the cathode's ability to diffuse electrons, a capacity that itself depends on the thermal power supplied by the filament.

> Note that the roles of the anodes and cathodes could be reversed, which should not change anything.

The rectified current Ia is filtered by C2/R2 to suppress the HF carrier (this is a low-pass filter), then capacitor C3 blocks the DC component. At the output of C3, the LF signal is recovered.

> Note: the return of current Ia to the anode is done via inductance L1 which behaves with respect to current Ia almost like a short circuit, the LF frequencies being much lower than the HF frequency.

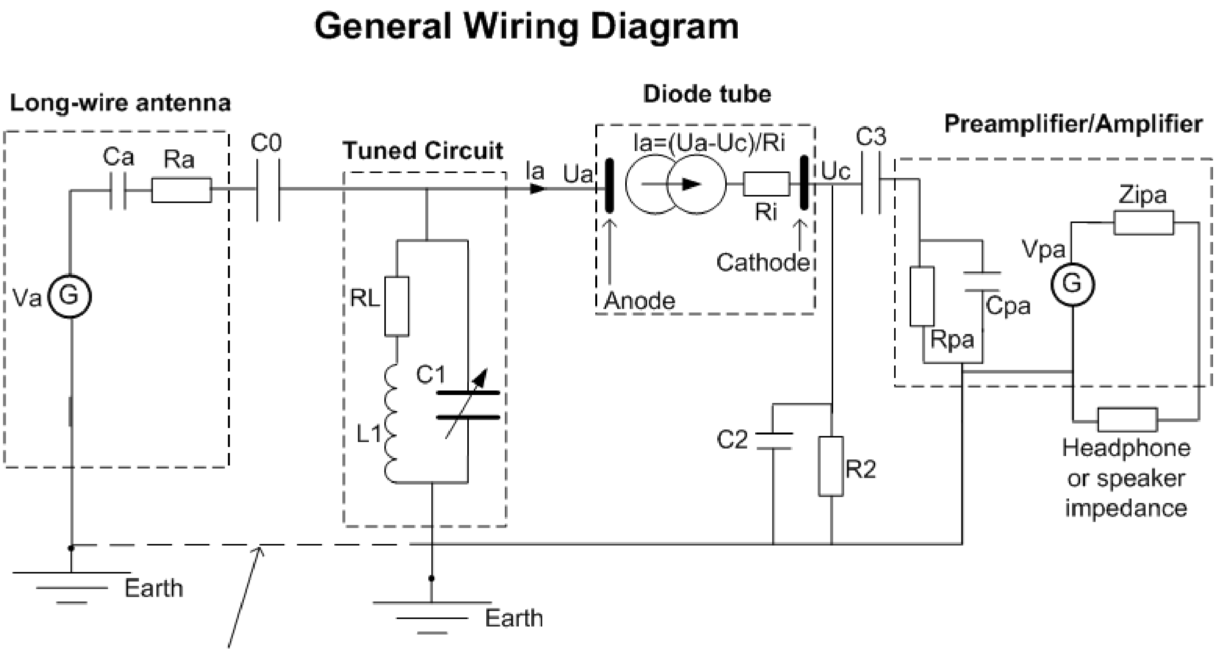
All that remains is to amplify the AF signal using the preamplifier/amplifier, hoping that the preamplifier's input impedance is as high as possible. Expect a value between 10 and 50 kOhm. Either headphones or a speaker will be connected to the amplifier output.

The previous diagram also shows the main signal processing steps:

- At the transmitter, the AF signal to be transmitted is assumed to be a square wave (a Morse code type signal). This signal modulates the AM carrier. The modulated carrier is amplified and transmitted to the transmitting antenna.
- At the receiver, the same modulated carrier is returned, but highly attenuated. It is rectified and then filtered to restore the original AF signal.

3.2 Electrical model of the receiver and selection of values

The general electrical model of the receiver is shown in the figure below.



Tuned Circuit

Selectivity is mainly provided by the L1/C1 tuned circuit.

- For L1: I had a 0.68 mH ferrite inductor available (for DCF77 reception), which I used. This is a little tight for the target frequencies (longwave), as it requires a large variable capacitance.
  An inductor around 2 mH would probably have been more suitable.

  Recall Thomson's formula: f=1/(2.Pi.√(L.C)) (where L is the inductance, C is the capacitance, and f is the target frequency). So, for a given frequency, if the inductance L is a little tight, the tuning capacitance C must be slightly larger.

- For C1: I had two variable CVs available:
  - the first from 69 to 171 pF,
  - the second CV is a double CV allowing a variation between 22 and 492 pF or 2x22=44 pF and 2x492 pF=984 pF (both CVs in parallel).

  The second CV is essential because it gives more adjustment latitude and allows RTL reception, with the two CVs in parallel.

  Note 1: you must take into account the different parasitic capacitances in parallel on C1 (see §3.1). Allow approximately 140 pF, which determines a reception bandwidth between 182 kHz (for L=0.68 mH and C=140+984 pF) and 450 kHz (C=140+44 pF). Only the bandwidth associated with RTL is fully received.

  Note 2: even if you add a capacity to the CVs to receive Europe 1, this station is poorly received. This is probably due to the position of the antenna.

RL is the series resistance of the inductor. It can only be measured DC (5 ohms for the 0.68 mH inductance). The quality factor at f=200 kHz would therefore be a priori equal to Q=L.2.Pi.f/RL=170. This would give a bandwidth of 200/170=1.2 kHz, which would also be too narrow. However, the RF resistance, due in particular to the skin effect, is greater than the DC resistance, which makes the bandwidth wider. If necessary, the tuned circuit could be damped more and thus increase the bandwidth by adding a resistor (100 kOhm, for example) in parallel with C1. To my ears, this didn't seem necessary to me.

C2/R2 Filter

Regarding the C2/R2 low-pass filter, which eliminates the HF carrier, while retaining the LF frequencies (100 to 3300 Hz):

- R2 must be high to recover the maximum LF voltage.
  Indeed, according to the electrical diagram on the previous page, we see that Ia=(Ua-Uc)/Ri (for the internal resistance of the tube Ri, refer to §2.1.2). If we neglect the input impedance of the preamplifier and the reactance of capacitor C2, to simplify the calculation, we can write that:
  Uc=R2*Ia=R2*(Ua-Uc)/Ri, from which Uc*Ri=R2*Ua-R2*Uc , or
  Uc*(Ri+R2)=R2*Ua
  This gives Uc=Ua * (R2/(R2+Ri)). We conclude that for Uc to be as large as possible, R2 must be large compared to Ri, but the value of Ri is between 300 and 5500 ohms (Ri=Ua/Ia) according to the results given in §2.3.1.
  We therefore need a resistance R2 much greater than 5500 ohms. We choose 470 kOhm, after experimenting with a 1 MOhm potentiometer.

- As a first approximation, C2 should be chosen to have a cutoff frequency Fc of 3300 Hz (maximum LF frequency). For this type of low-pass filter, we have Fc=1/(2*Pi*C*R) or C2=1/(2*Pi*Fc*R2) so C2=100 pF.
  Experimentally, once the circuit is fully assembled and the sound card preamplifier connected (via the PC's "microphone" jack), it turns out that this value is suitable. In fact, seen from the capacitance meter, the PC's microphone input has a capacitance of 258 pF. Moreover, if C2 is removed, the receiver continues to function correctly.

Filter C3
As for the coupling capacitor C3, which is designed to eliminate the DC component without blocking the lowest AF frequency (100 Hz), a value of 100 nF (non-critical) is suitable because it provides a reactance of 16 kOhm at 100 Hz, compatible with the preamplifier's input impedance.

> Note: since the PC's microphone input is capacitive, capacitor C3 is unnecessary. We keep it for the principle.

The AF signal is then transmitted to the sound card's microphone input.

Preamplifier/Amplifier
The preamplifier / amplifier is the one on the PC's sound card.
The maximum microphone gain is 30 dB, but a gain of 20 dB is sufficient.

> Note that the sound card, which digitizes the signal at 48 kHz, has, upstream of the analog-to-digital converter, an anti-aliasing filter that cuts frequencies above 24 kHz.

At the output of the sound card (digital-to-analog conversion stage), after configuring the mixing desk (the PC's mixer), you can connect either headphones or a speaker.

Of course, any external preamplifier/amplifier (for a turntable cell, for example) will do the trick.

3.3 Results obtained with this first receiver

The only station received within the receiver's bandwidth (182 to 450 kHz) is RTL. The sound quality is decent. The volume is rather low, but speech is perfectly intelligible. There remains a slight buzz. The level of this buzzing seems to depend on the filament supply voltage, although the reason is unclear. The sensitivity is not up to scratch...

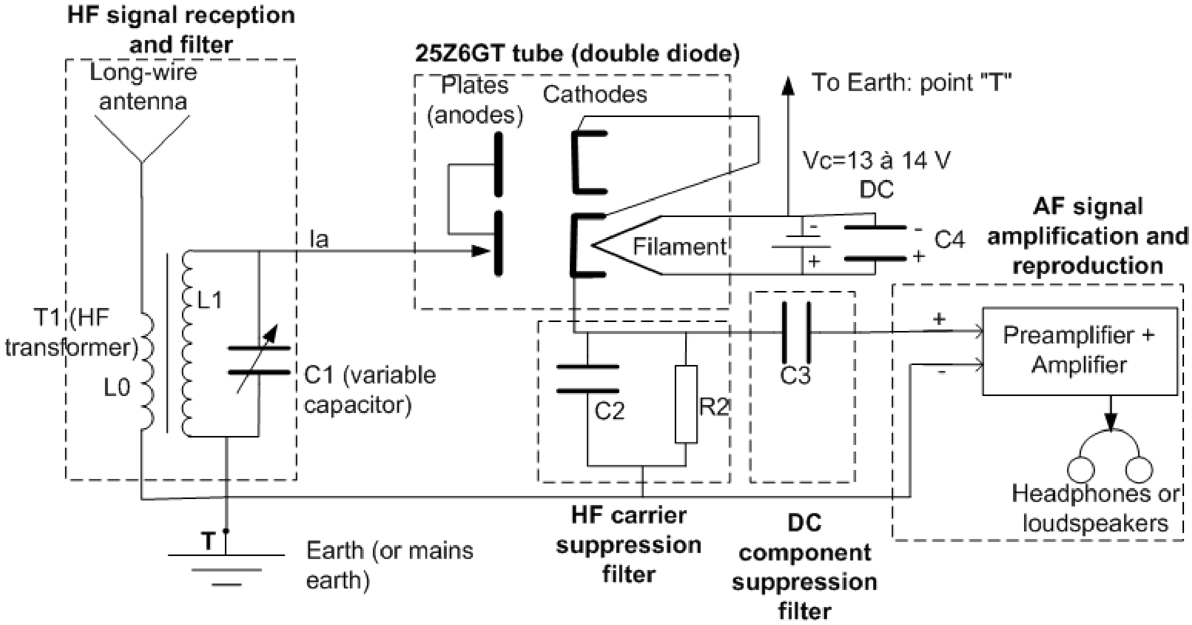
In this regard, don't forget to connect the "-" terminal of the receiver to ground, or even to the "mains ground." Without this connection, the sound quality is poor.

3.4 Improvements to this first receiver

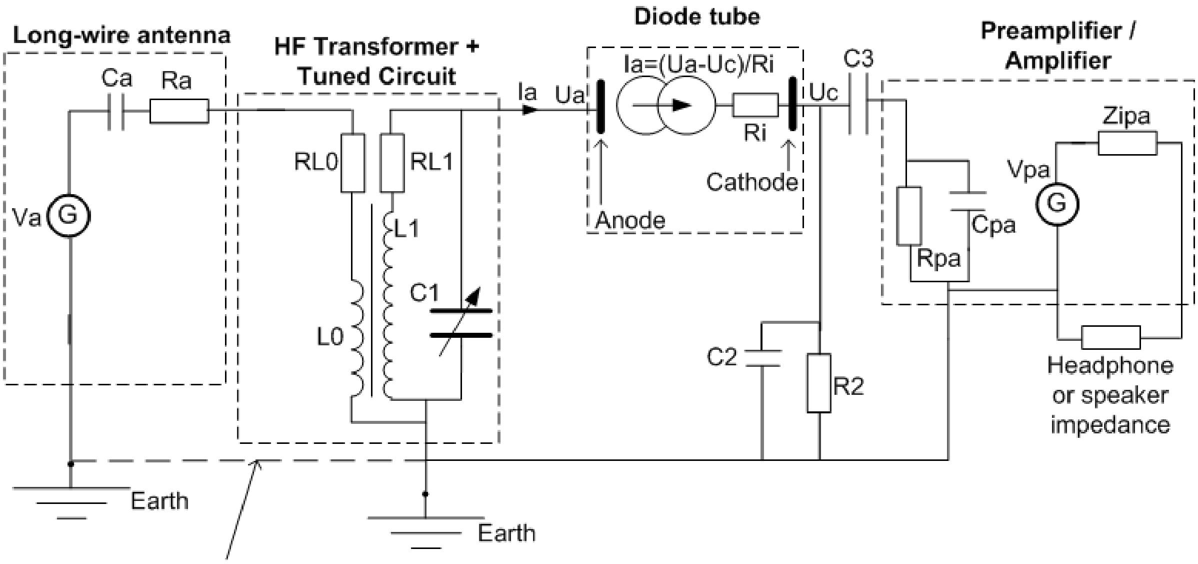
In the current circuit, there is no impedance matching between the antenna and the trap circuit. We simply reduce the antenna's capacitance with capacitor C0.
This circuit should be improved by matching the two impedances (antenna/receiver) using a step-up RF transformer.

On the next page, you will find the new schematic diagram followed by the electrical diagram of this second receiver.

Schematic diagram of the second receiver with a single diode tube



General electrical diagram



The dotted line represents the signal path through the Earth.

I have an old ferrite rod (which must have belonged to a transistor radio) on which is an RF transformer. The primary is 0.061 mH / 1 Ohm and the secondary is 5.64 mH / 21 Ohm. The no-load transformation ratio Nt, measured with a generator and a voltmeter, is approximately 12 (slightly variable with frequency).

> Note: this model of the RF transformer is simplified, but a more detailed model would be unnecessary here.

The primary (L0) will be directly powered by the antenna, and the secondary (L1) is the inductance of the trap circuit.

Using this transformer, we will greatly minimize the influence of the antenna's capacitance on the tuned circuit. Indeed, the antenna's capacitance Ca will be equal to $Ca/(Nt)^2$ at the secondary.
With Ca=420 pF (see §3.1), we find that Ca(at the secondary)=3 pF, a negligible value.

All that remains is to match the resistive portion of the primary to that of the secondary.

The resistive portion (Ra) of the antenna's impedance is not known. It is probably close to 0 ohms (see §3.2). RL0 (measured continuously) is equal to 1 ohm. Let's assume that at 234 kHz, the Ra+RL0 combination is 50 ohms (which is probably a significant overestimate).

On the secondary side, the impedance R (only resistive at resonance) of the tuned circuit when tuned to the RTL station (234 kHz), neglecting elements other than the tuned circuit, can be estimated as $R=(L.w)^2/RL1$. RL1 is 21 ohms continuously. Let's assume that at 234 kHz, RL1, due to the skin effect, eddy currents, and hysteresis in the ferrite, is twice as high (42 ohms). We will then find that R=1.64 MOhm. Here, R is the resistance equivalent to RL1 in parallel on the trap circuit.

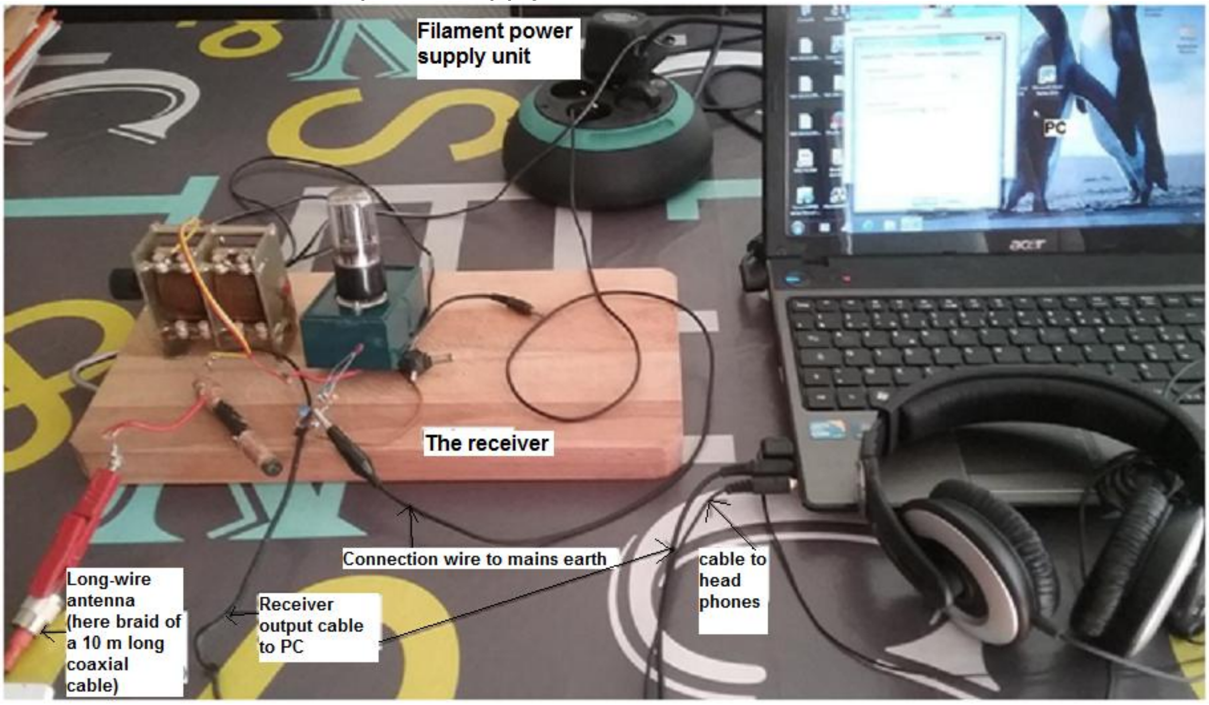
The impedance matching is performed if the resistance Ra+RL0 brought back to the secondary side, i.e. $(Ra+RL0)*(Nt)^2$, is equal to R.
Therefore, the ideal Nt is equal to $Nt=\sqrt{(R/(Ra+RL0))}=181$. The ideal Nt is therefore far from the real Nt of 12. There is therefore room for improvement by increasing this transformation ratio.

The measured bandwidth is between 92 and 284 kHz. The residual capacitance in parallel of the variable capacitor (22 to 492 pF) is therefore 34 pF.

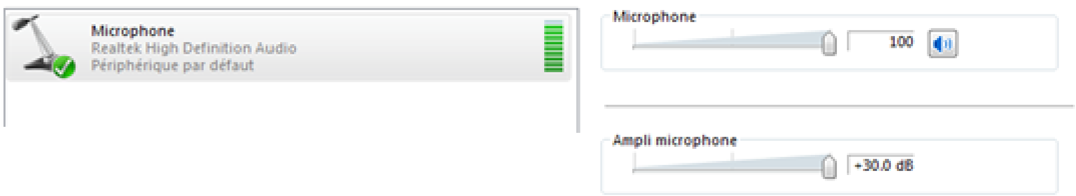
3.5 Results obtained with this second receiver
The only station received is RTL (Europe 1 is only heard). The sound quality is identical to that of the first receiver (there is still a slight buzzing noise) and the sensitivity is also poor. However, as expected, the received signal is much louder because the volume is significantly higher. As for the sound quality, it's not "High Fidelity," but speech is perfectly understandable.

3.6 Some photos of this second receiver

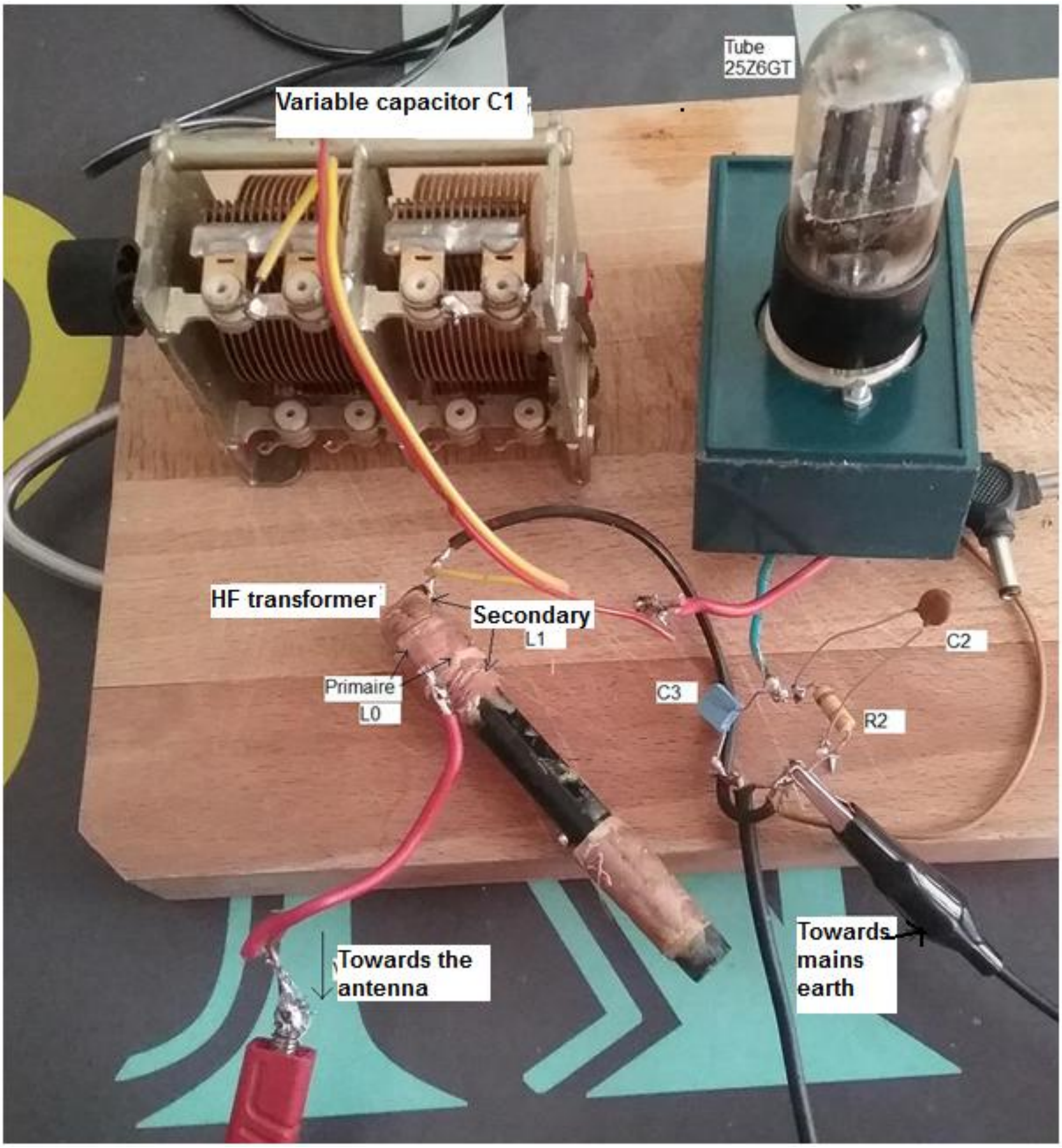
<u>Overview of the receiver, power supply, and PC</u>



<u>Excerpt from a copy of the PC screen showing the microphone input control panels.</u>



<u>Receiver view</u>



4. Conclusion

This small receiver demonstrates the use of a vacuum tube for detection. Even if the interest is purely educational, a glowing tube is more fun than a piece of semiconductor.

5. References

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[7] « Multiplasma 1.1 » by the author (F6CTE)
http://f6cte.free.fr/MULTIPLASMA_1_1_setup.exe
For information because it is an old version not very accurate for the space charge, but sufficient here.