Patrick Lindecker (F6CTE)
Maisons-Alfort (France)
22th of October 2025 - Revision C

Study of a Single Gas Tube AM Signal Generator

SUMMARY **Page**

1. Introduction

After the article "Study of a Single Diode Tube Receiver" (see reference [1]), which aimed to study a diode-type vacuum tube, it remained to propose an assembly highlighting another type of tube: the gas-filled tube or "gas tube." These tubes were widely used at the time when vacuum tubes reigned, particularly in stabilized power supplies. Apart from lighting ("neon tubes," etc.), these tubes are still used wherever a mains-powered indicator light is desired. A common application is the small neon tube fitted to certain screwdrivers designed to indicate whether a live wire has been touched.
Note that the color of the plasma depends on the gas used.

Currently, the only gas-filled tubes still widely distributed are the NE2 neon tubes and the entire family, as well as their equivalents. The following article will therefore be based on the NE2 neon tube, which is widely available and inexpensive, for example under the name “Standard orange neon bulb 6x22 mm” or equivalent..

Having previously proposed a longwave AM receiver, an assembly featuring a longwave AM transmitter seemed like the ideal subject. I therefore searched the available documentation for an AM "transmitter" principle using this type of tube and settled on the assembly proposed in the document referenced [2], on page 90. This diagram will therefore serve as my model.

As with the previous AM receiver, the goal is not to propose a directly feasible assembly (that would be of very little interest). This is an experiment, the aim being to study the operation of an assembly. I will rely on the simulation of a gas tube, developed by the author (reference [3]).

Before describing the AM signal generator ("transmitter" being too strong a term for this assembly) in §3, a description of the operation of gas tubes is provided in §2.

The instruments used by the author in this article are: voltmeter, ammeter, ohmmeter, inductance meter, capacitance meter, LF/HF generator up to 2 MHz, frequency meter, adjustable DC power supply (0 to 300 V), and 8-bit digital oscilloscope.

<u>Notations</u>
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 $x^{0.5}$.
- "≈" means "approximately".

2. Operation of a gas tube

2.1 General information and comparison with vacuum tubes

2.1.1 History

Electrical discharges in gases have been studied since the 18th century using electrostatic generators. Volta's invention of batteries in the early 19th century made it possible to produce continuous electrical discharges, which were studied by various physicists, including Davy, Faraday, and later by Crookes. At the end of the 19th century, Paschen studied the breakdown phenomena leading to electric arcs. At the beginning of the 20th century, Townsend explained the different regimes of low-pressure discharges, in particular, the cold glow discharge (whereas the electric arc is a high-current "thermal" discharge).

Furthermore, neon gas, which was discovered in 1898, was then the subject of experiments by Georges Claude, who invented neon lighting in 1910.

In the 20th century, studies were conducted on alternating current and high-frequency electrical discharges, high-pressure discharges (at atmospheric pressure or higher), and micro-discharges made possible by advances in miniaturization.

Discharge lamps are universally used for lighting. Different gases are used depending on the desired type of light.
But electrical discharges are also used in other areas such as thin-film material deposition or dust removal.

Gas tubes were also widely used in electronics: for rectification ("83" tubes) or stabilization ("VR 75/30" tubes, "VR 150-30" tubes, etc.).

Today, NE2 tubes or equivalents are still used for signaling or detecting mains voltage.

2.1.2 General information about gas tubes

On the following page, you will find two photos of NE2 neon gas tubes:

- The first tube is not powered: note that the two electrodes are identical.
- The other is in operation, with the plasma clearly visible around the electrode acting as the cathode.

This gas tube is a miniature tube filled primarily with neon, probably with a hint of argon (to trigger the discharge at a lower breakdown voltage). The exact composition is not specified. The pressure, which is also not specified, is probably between 1 and 10 Torr (1 Torr = 133 Pa or 1.33 mBar). According to my simulations, it would be closer to 2.6 Torr.

Inside the NE2 tube, there are two identical electrodes, 6 mm long and 0.5 mm in diameter. The electrode axes are separated by 1 mm. These dimensions will be used for the tube simulation.
Each of these electrodes can be either the cathode (connected to the - terminal) or the anode (connected to the + terminal). An electronic current can flow from the cathode to the anode during an electrical discharge.

General operating principle (see diagram below)
Initially, electrons are emitted by the unheated (called "cold") cathode and attracted to the anode. Indeed, as soon as the anode becomes positive, it generates an electric field between the cathode and the anode, which accelerates the electrons toward the anode by Coulomb attraction (the "+" attracts the "-").

> Note: electrons are produced spontaneously in the gas by cosmic radiation and natural radioactivity. However, the main source of electrons is linked to photons of light which can tear electrons from the cathode (which are then called "photoelectrons"). For this purpose, the latter is covered with a layer of barium or strontium oxide, metals for which the output work is not too high. For this reason, the establishment time of the discharge is longer in complete darkness (see reference [4] for more details).

If the gas pressure is sufficiently low (but not too low) and the voltage on the anode is higher than the so-called "breakdown" (or "disruption" or "ignition") voltage, the collisions between the accelerated electrons and the neon atoms create ion/electron pairs. These new electrons, in turn, create other pairs, and this in an exponential manner. This is then an "avalanche" type discharge. The (+) ions attracted by the (-) cathode, for their part, bombard the cathode and create, for a fraction of them, secondary electrons which act like the other electrons.

Once the discharge is triggered, it is limited only by the maximum current delivered by the power supply through a resistor (labeled "R" in the figure on the next page). The discharge is said to be "self-sustaining" because even if the electron source (mainly photoelectrons) were turned off, the discharge would not stop. The voltage across the gas tube stabilizes at the so-called "sustaining" voltage. To stop the discharge, the supply voltage must be lowered below the so-called "extinction" voltage.

For an NE2 tube, the typical (DC) supply voltages for breakdown and then extinction are approximately 70 V and 60 V, respectively. Under normal operating conditions (0.5 mA), the sustaining voltage across the NE2 gas tube is approximately 55 V.

Note that the breakdown and extinction voltages depend on the resistance R.
For example, experimentally, I measured (in DC) on one of the tubes in my stock (but not the one used for the assembly):

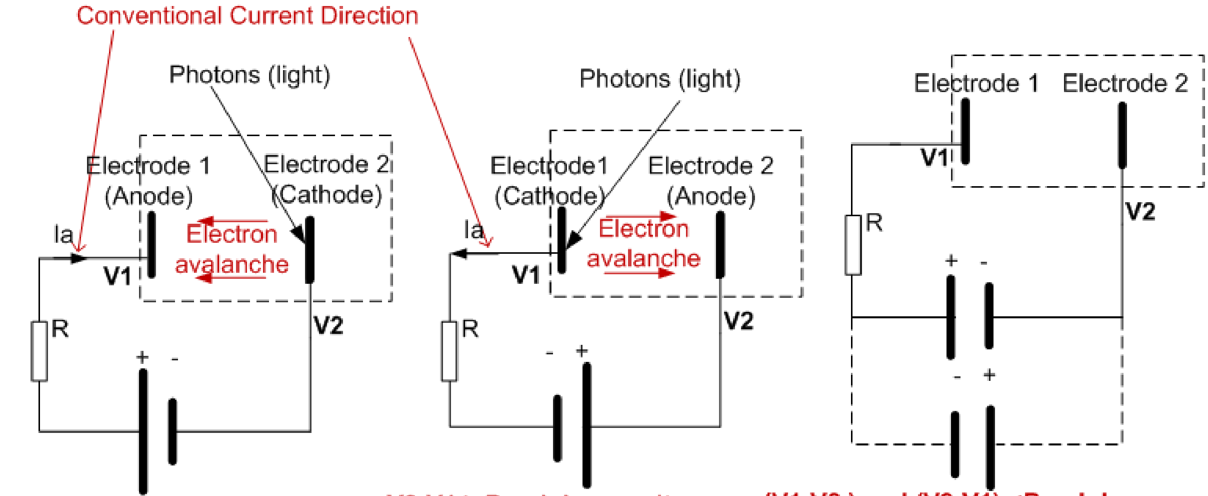
- with R=1 Mohm, Vbreakdown=70.7 V and Vextinction=67.2 V,
- with R=0.47 Mohm, Vbreakdown=69.5 V and Vextinction=62.3 V,
- with R=0.22 Mohm, Vbreakdown=69.3 V and Vextinction=59.2 V,
- with R=0.1 Mohm, Vbreakdown=69.2 V and Vextinction=57.5 V.

This variation of the two voltages is due to the particular evolution of the holding voltage of the NE2 tube as a function of the current (see §2.2.1). In AC mode, the breakdown and extinction voltages depend on R but also on the frequency (see reference [4] for more details).
In all cases, there is a certain dispersion of the breakdown and extinction voltages from one tube to another and from one discharge to the next.

These gas-filled tubes can be used, in discharge, in either DC or AC mode up to approximately 10 kHz.

The operating principle of the gas tube is illustrated in the following figure.
As mentioned previously, the resistor R is required and limits the current in the gas tube. R is calculated using the formula:
R (Ohm) = (Supply voltage (V) – Holding voltage (V)) / Current I (A)
Note that the holding voltage depends on the current.

Gas Tube Operation



V1-V2 ≥ Breakdown voltage (for an initial non-conducting state) or
V1-V2 ≥ Holding Voltage (for an initial conducting state):
an electron current ("electron avalanche") flows between the cathode and the anode

V2-V1 ≥ Breakdown voltage (for an initial non-conducting state) or
V2-V1 ≥ Holding voltage (for an initial conducting state):
an electron current ("electronic avalanche") flows between the cathode and the anode

(V1-V2) and (V2-V1) <Breakdown voltage (for an initial non-conducting state) or
(V1-V2) and (V2-V1) <Extinction voltage (for an initial "conducting" state):
no current flows between electrodes 1 and 2

The characteristics of the NE2 gas tube can be found in reference [4].

2.1.3 Differences and similarities with diode-type vacuum tubes

In a vacuum tube, the cathode is heated to between 900 and 1000°C by a tungsten filament, whereas in a gas tube, the cathode is not heated, so the gas tube is immediately usable.

In a gas tube, the electrodes are symmetrical and therefore interchangeable, which is not the case with vacuum tubes.

In both cases, there is an electron current, a phenomenon obtained:

- by the strong electron emission of the cathode heated to 950°C, for the vacuum tube,
- and by the electron avalanche in the discharge, for the gas tube.

If in both cases the flow of this electronic current can only be in one direction (the "diode" aspect being common to both), the vacuum diode can rectify very low voltages and currents at very high frequencies, which is not the case with gas tubes. Therefore, a vacuum tube could not be replaced by a gas tube in an HF rectification application.

2.2 Study of the operation of the NE2 gas tube from a physical perspective

First, for more details on electrical discharges, please refer to the documents in references [5] to [7]. For more details on the NE2 family of gas tubes, please refer to the documents in references [2] and [4].

2.2.1 Experimental study of the current-voltage curve of the NE2 gas tube

The electrical characteristics of a discharge are described by a DC current-voltage curve (taken across the gas tube). The range considered in the documents on the subject ranges from a minimum current of 10^{-20} A to a maximum current of 100 A, or even more.
Except in unstable phases, a given current flowing through the gas tube corresponds to a single voltage.

This current-voltage curve reveals three areas:

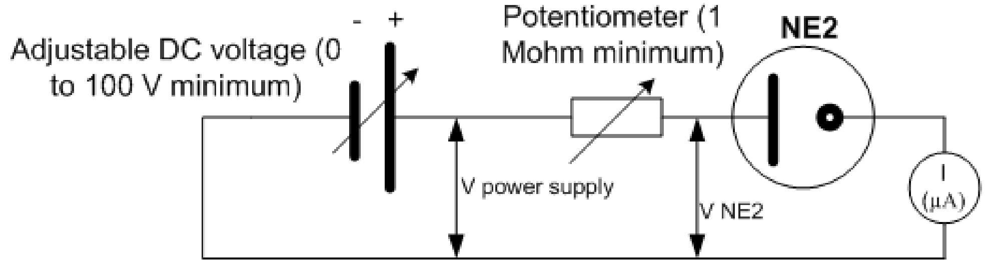
- The "dark discharge" between 10^{-20} A and 10^{-6} A. In the context of the NE2 tube's operation, this is of no interest to us. In any case, we can't measure such low currents with amateur equipment.

- The "glow discharge" between 10^{-6} A and 1 A. This is what interests us, but we can't exceed 2 mA with the NE2 tube.

- The "arc discharge" from 1 A, for information, as this does not apply to the NE2 tube.

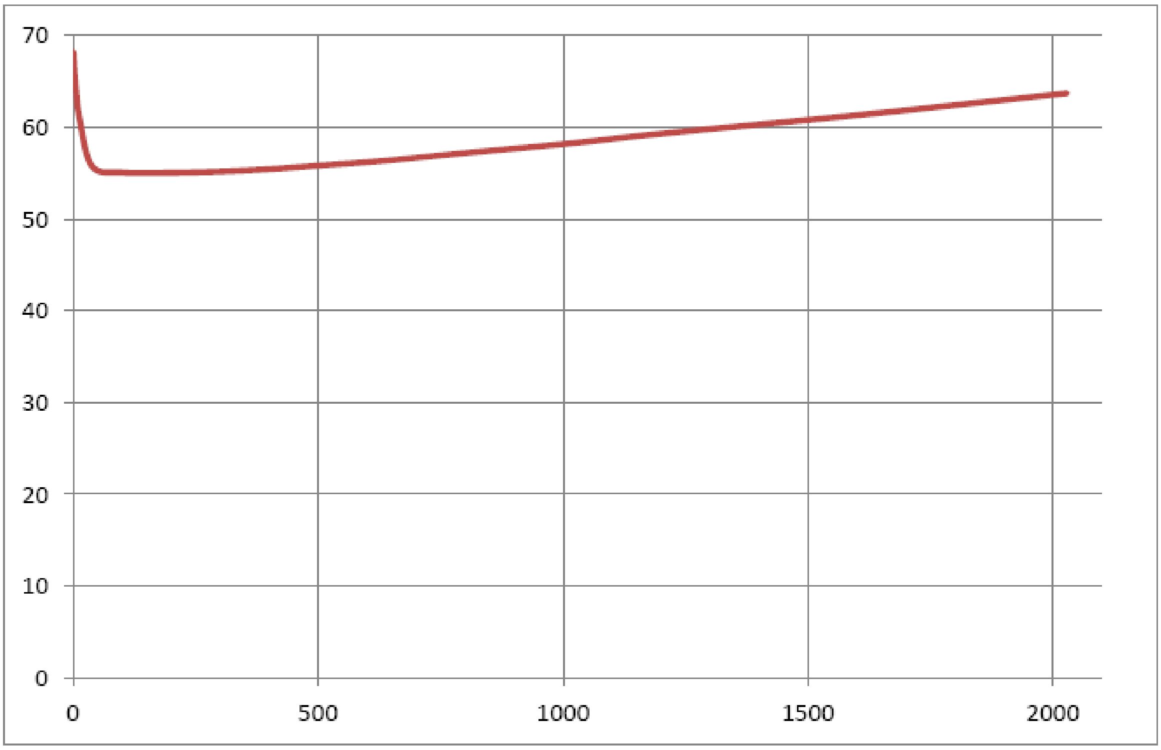
So, with an adjustable DC power supply and a potentiometer, we can establish a large number of voltage/current pairs. This is what was done with the following test bench.

The test bench for determining the current-voltage curve



The following figure shows the results in the form of a curve showing the current (in microA) as a function of the voltage (in V) across the NE2 tube ("sustaining voltage"), when the discharge is established.

Supply voltage (V)	Current through the NE2 tube (microA)	Voltage across tube NE2 (V)
68.2	0	68.2
100	5	64.3
100	13.4	60.7
100	38.6	55.7
100	100	55.04
100	200	55.01
100	304	55.15
100	406	55.43
100	500	55.79
100	609	56.21
100	697	56.64
100	809	57.22
100	1008	58.19
100	1204	59.3
100	1607	61.32
100	2029	63.66



Current through tube NE2 (abscissa) as a function of the voltage across tube NE2 (ordinate)

We see that the breakdown voltage is 68.2 V and that at 500 microA (the nominal current), the holding voltage is 55.79 V.

Note that, according to the curve:

- From 0 to 60 microA, the voltage decreases as the current increases. This is the so-called "subnormal" regime.
- Between 60 and 300 microA, the curve is relatively flat. This is the so-called "normal" regime.
- Above 300 microA, this is the so-called "abnormal" regime (increasing voltage). The nominal operating point (0.5 mA) is therefore at the beginning of the "abnormal" regime.

2.2.2 Estimating the gas pressure in the NE2 tube

The breakdown voltage depends on the gas pressure and on the inter-electrode distance (assumed to be flat and parallel), according to Paschen's law. It would be interesting (for informational purposes) to know the gas pressure in the NE2 tube and its nature as a function of the observed breakdown voltage.

However, the classic Paschen curve is not really applicable here because the exact nature of the gas is unknown, and the electrodes of the NE2 tube are not flat. However, we can get an idea of the breakdown voltage evolution as a function of pressure by using the simulation of this NE2 tube (created with the program in reference [3]).

To do this, we will assume one of two hypotheses about the nature of the gas:

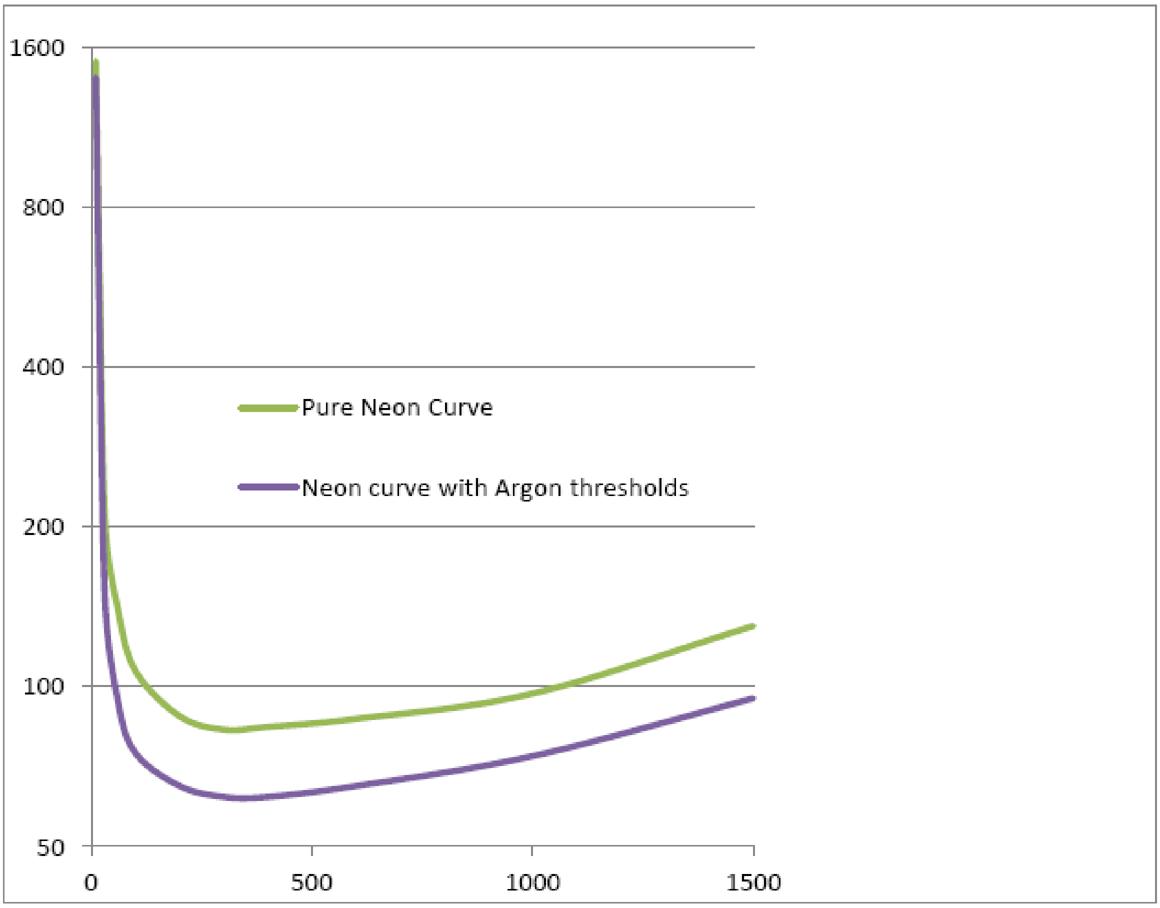
- One that the NE2 tube is filled with pure neon gas (" Ne ").
- The other that the neon gas contains a small amount of argon (" Ne* "), which we translate, for lack of more information, by replacing the excitation and ionization thresholds of neon with those of argon (which are lower, ionization is therefore easier).

Finally, the two pseudo-Paschen curves are shown on the next page.

Provided that the modeling error is not too large, the following conclusions can be drawn:

- Since the breakdown voltage has been experimentally observed to be 68 V, and that with pure neon alone, the minimum (simulated) breakdown voltage is 83 V, but 62 V using the argon thresholds, there is likely some argon in the neon.
- The minimum breakdown voltages are obtained at around 350 Pa (2.6 Torr). Logically, the manufacturer of the NE2 tube must have also targeted this pressure.

Gas pressure in tube NE2 (Pa)	Breakdown voltage for pure Neon gas (V)	Breakdown voltage for Neon gas with Argon thresholds (V)
10	1500	1400
30	210	150
60	140	94
100	107	75
200	88	65
300	83	62
400	84	62
600	87	65
1000	97	74
1500	130	95



Pseudo-Pashen curves obtained by simulation of an NE2 tube
Breakdown voltage (on the ordinate) as a function of pressure (on the abscissa)

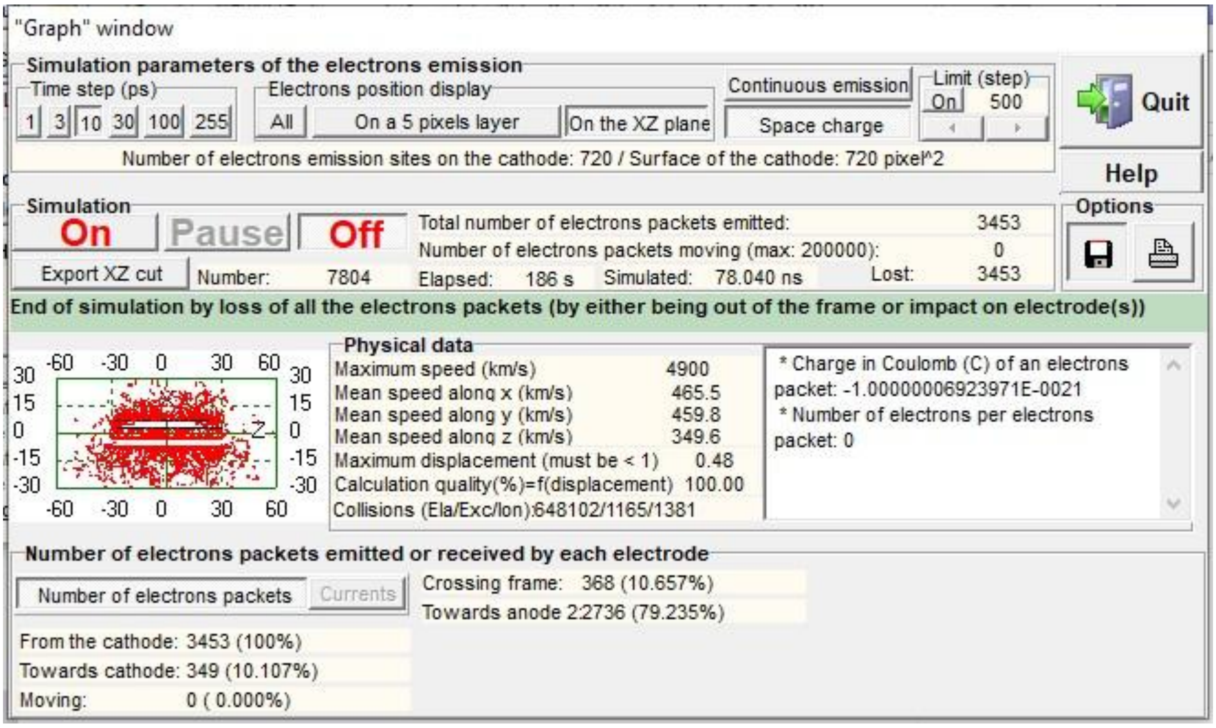
2.2.3 Electron trajectories

We cannot plot each 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.
In the case studied (voltage of 70 V, below the breakdown voltage), the cathode is at the bottom and the anode (at 70 V) at the top, in the screenshot below. The gas is neon at 300 Pa. We send a burst of electrons and observe their evolution. Below the breakdown voltage, the burst is not self-sustaining and the electrons are eventually all absorbed.

We note that 79% of the electrons go towards the anode, 10% return to the cathode, and 11% escape towards the tube glass. The vast majority of collisions are elastic. The average speeds of electrons are relatively low (a few tens of km/s).

For the screenshot below, we assumed a minimum current density (photoelectrons) of 1 µA/cm², for a cathode temperature of 5500°C (corresponding to the "temperature" of natural light). The anode voltage is set at 70 V, and the cathode voltage is 0 V. The cathode and anode are enlarged 10 times.

> Note: We consider that very locally, where the photon "falls," the cathode reaches the "temperature" corresponding to the photon's energy. This is not a generalized cathode temperature, but an equivalent temperature relative to the points struck by the photons.



2.3 Study of the NE2 gas tube from an electrical perspective

2.3.1 Modeling the gas tube

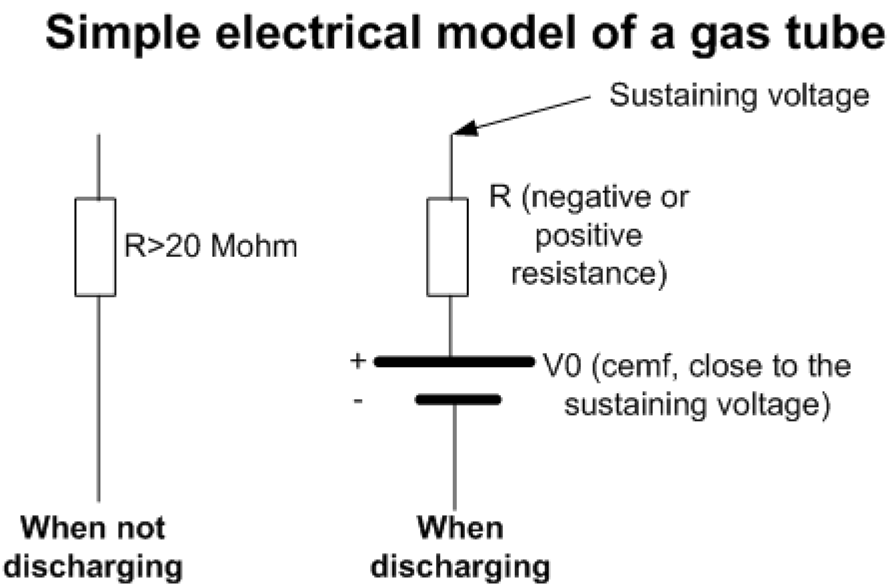
Before going any further, it is necessary to clarify the behavior of a gas tube during and outside of an electrical discharge:

- Outside of any electrical discharge, the NE2 tube exhibits a very high resistance between its terminals, greater than the resistance measurable by an ohmmeter, namely 20 Mohms.

- During an electrical discharge, the NE2 gas tube behaves like a resistor (R) followed by a cemf (back electromotive force) V0. In our case, at the nominal current (0.5 mA), we can easily determine that the resistance is approximately 3750 ohms and the cemf V0 of 54 V.
  Therefore, the holding voltage V_{NE2}, around the nominal point, is equal to:
  V_{NE2} (V) = 54 + 3750 x I (A),

- The characteristics R and cemf vary as a function of the current, with resistance R being, for example, negative in the descending part of the "Sustaining Voltage vs. Current" curve (see §2.2.1), then stable, then positive.

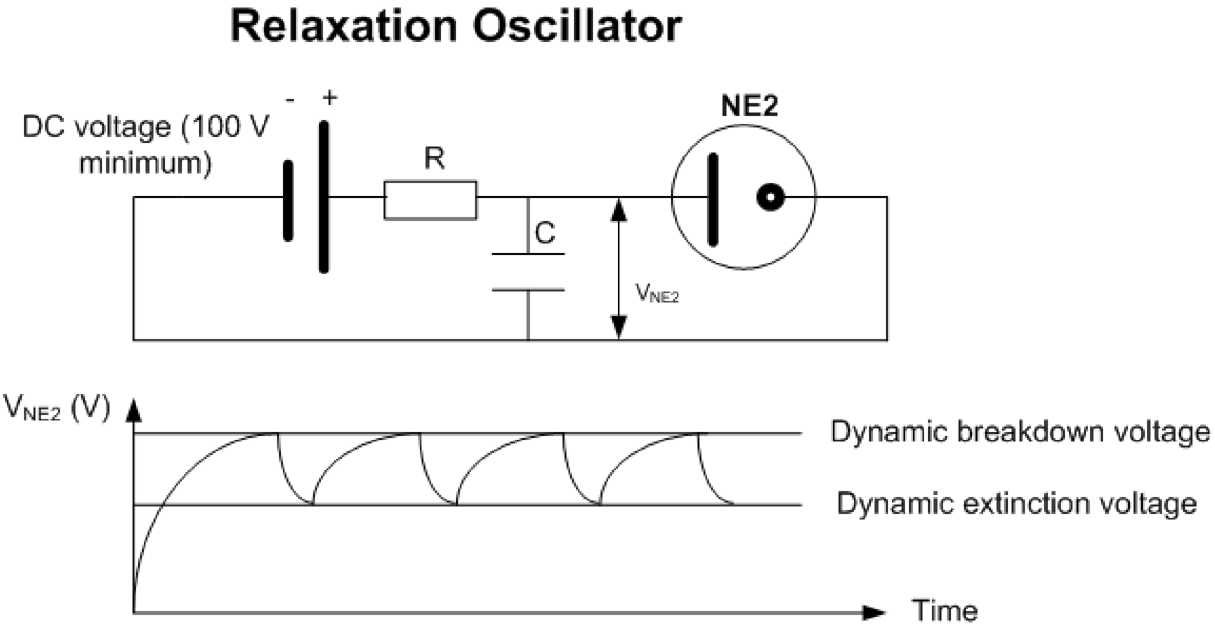
In summary, when not discharging, the gas tube is an insulator and when discharging, it is a conductor.



For more details on more comprehensive discharge models, see references [4] (page 7) and [7].

2.3.2 Using the gas tube as a relaxation oscillator

Using the voltage difference between the breakdown voltage and the extinction voltage, an oscillation (discharge/discharge extinction) can be triggered between these two voltages, according to the following diagram (for more details, see reference [2], starting on page 37).



The operation is simple. Starting with a zero voltage throughout the circuit (gas tube blocked), the DC supply voltage (above the breakdown voltage) is applied to the circuit.
Capacitor C will charge through resistor R. The voltage V_{NE2} across capacitor C will therefore increase to the breakdown voltage. At this point, the gas tube, which has become conductive, will rapidly discharge capacitor C to the extinction voltage, at which point the tube becomes insulating again. As a result, capacitor C no longer discharges but recharges through R to the breakdown voltage, and so on.

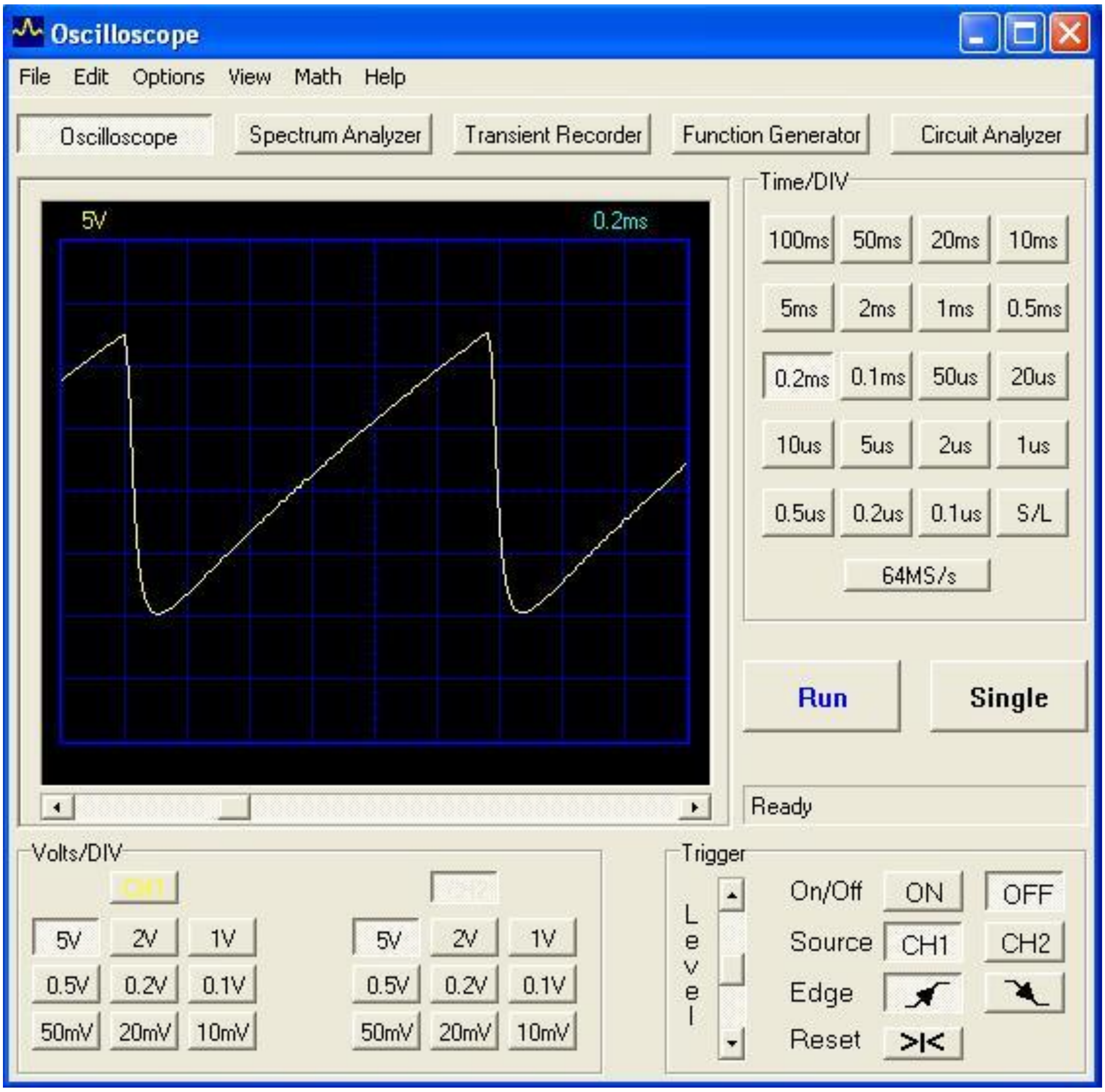
Reference [4] proposes on page 16 the following formula for calculating the oscillation frequency f: $f(Hz) = \frac{1}{R \times C \times \ln\left(\frac{\text{Usupply – dynamic extinction voltage}}{\text{Usupply – dynamic breakdown voltage}}\right)}$

With "Usupply" for the supply voltage and "ln" for the natural logarithm.
The dynamic values of the breakdown and extinction voltages (which depend on the frequency) are given by reference [4], using curves as a function of frequency. The following respective default values can be taken: 76 V and 52 V.

This formula is approximate. Experimentation is required to find the desired oscillation frequency.

For example, for Usupply = 299 V, R = 2.2 Mo, and C = 4.7 nF, the formula (using the default values) gives f = 946 Hz, and in practice, it's closer to 800 Hz.

Below is a screenshot of the periodic signal (voltage V_{NE2} across capacitor C) provided by the assembly, with values close to those given in the previous example.



3. The AM signal generator

3.1 Schematic diagram of the AM signal generator and photo

The schematic diagram of this AM generator is given below. It is inspired by the assembly proposed in the document referenced [2] on page 90.

> Note: for possible demonstration purposes (a more serious application not being possible, given the very low power output) or to ensure identification of the transmitted signal, a Morse code keyer can be added to modulate the AM transmission in CW.

The AM signal can be received on a standard AM radio (LW band) between 130 and 200 kHz (the bandwidth depends on the variable capacitor). The AM receiver must be very close to the assembly (less than 30 cm).

Note that the original intention of the author (William G. Miller) was for the assembly to serve as a 455 kHz generator for receiver alignment purposes, without contact.

AM Generator Diagram

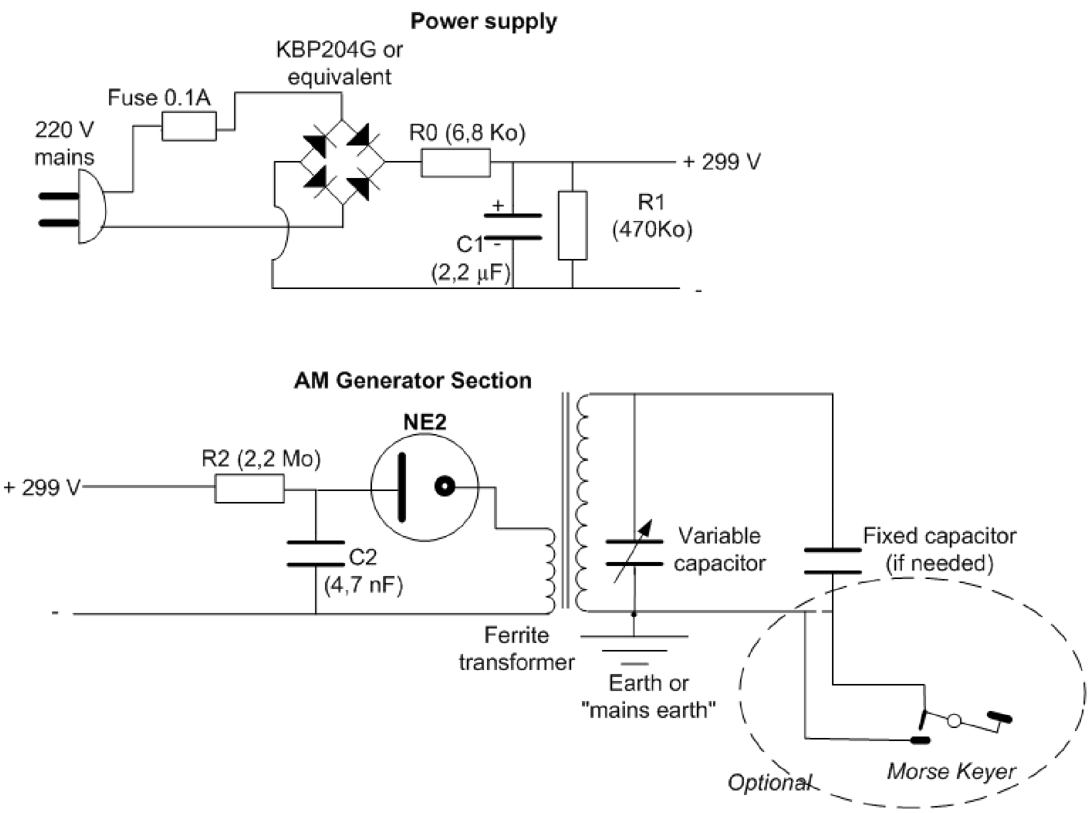
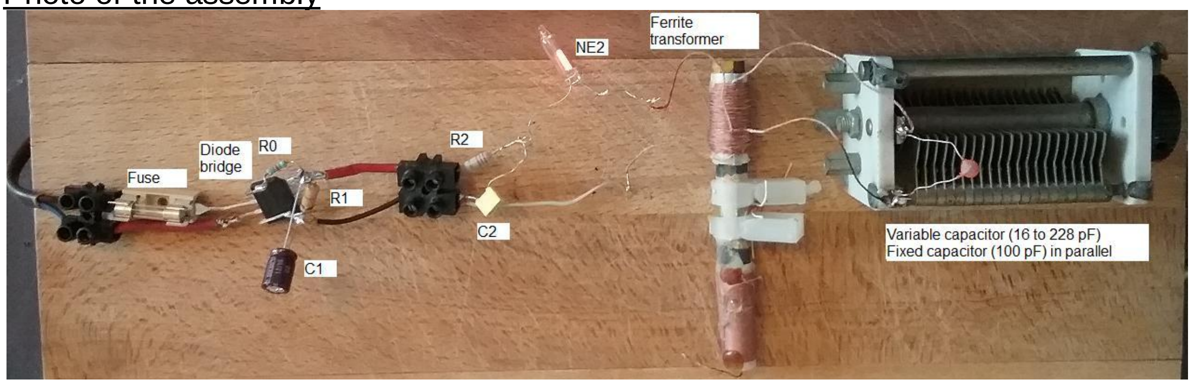


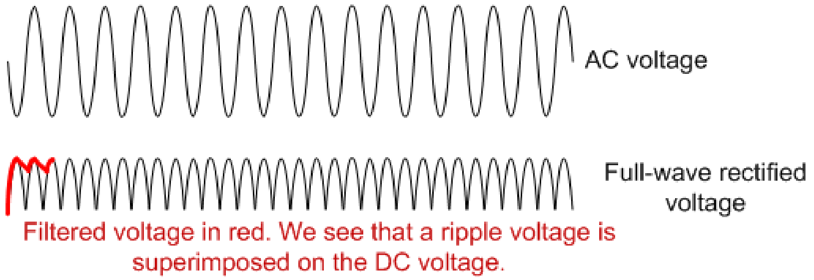
Photo of the assembly



3.2 Description and calculation of the power supply

The fuse limits the current to 0.1 A and will blow if the diode bridge shorts.
The latter transforms the alternating current into full-wave rectified current, which is filtered by capacitor C1.

Rectification of the signal received by the diode bridge and filtering



The no-load DC voltage Uc is very close to the peak AC voltage (Urms = 230 V), i.e. Uc = 230 V * √2 = 325 V. As a first assumption, we use this value. The actual value under load will be lower (we will find 299 V).
The maximum I_{NE2} current in mA passing through the NE2 gas tube is of the order of 1000 * (Uc - Usustaining) / R2, i.e. I_{NE2} = 1000 * (325 - 55) / 2.2E6 = 0.12 mA. The minimum I_{NE2} current is almost zero. The average current is therefore 0.06 mA.

Furthermore, a resistor (R1) must be placed in parallel with C1 to discharge it when the circuit is stopped. We initially choose 470 kΩ, which carries a continuous current of 325/470 = 0.69 mA. In total, the maximum current absorbed is therefore I_{max}=0.69+0.15=0.81 mA and the average current absorbed is 0.75 mA.

To calculate C1, the traditional formula for 50 Hz is: C = I_{abs}/(η.Uc) with η being the ripple factor in % (ratio between the peak-to-peak ripple voltage and the DC voltage).
We choose η = 1%, which will ensure a ripple voltage below 3 V, a sufficiently low value given the difference between the breakdown and extinction voltages (approximately 22 V).
We therefore find C1 = 0.81E-3/(1*325) = 2.5E-6 F, or a 2.2 µF capacitor capable of supporting 400 V.

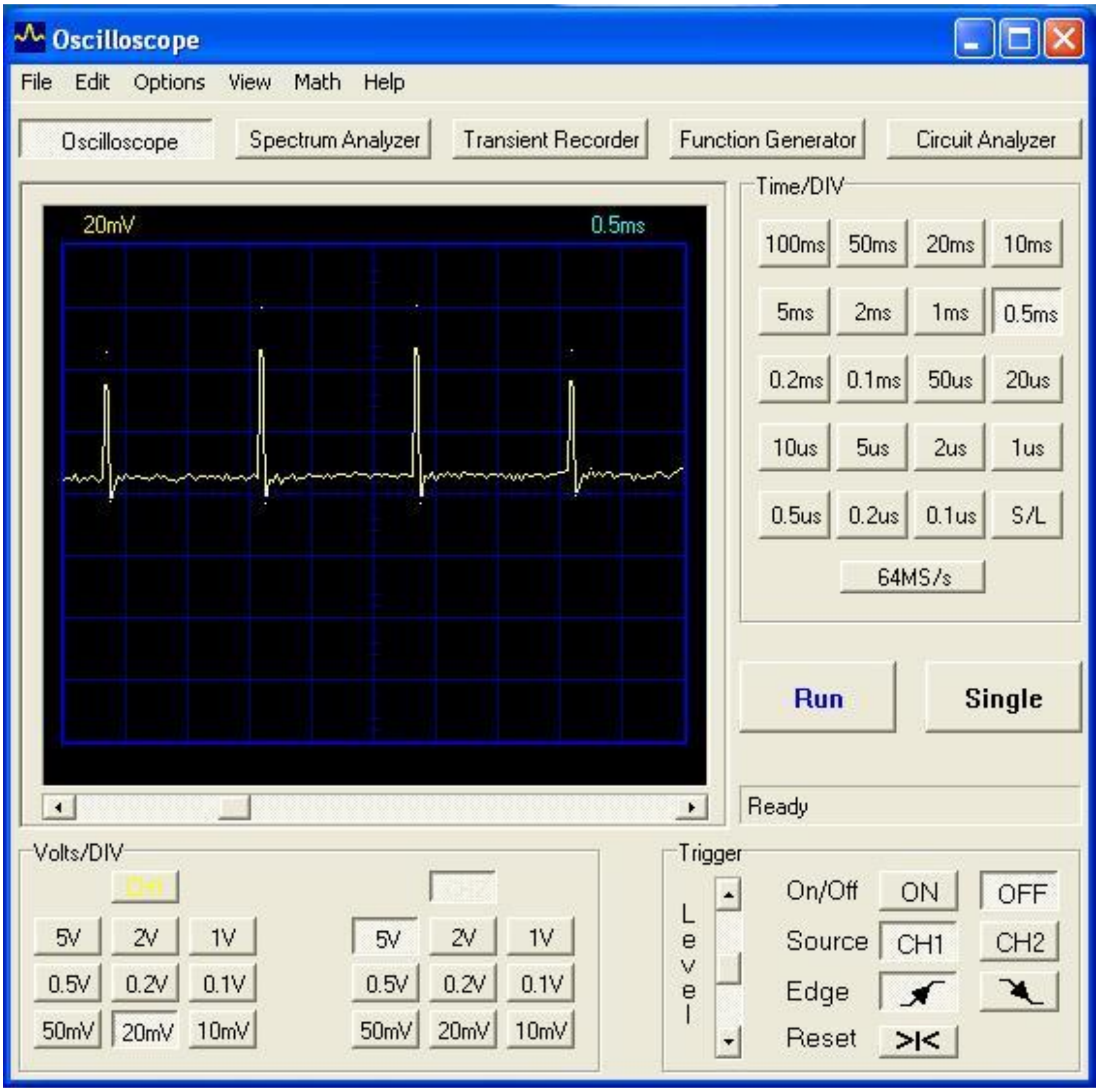
Once charged, the capacitor C1 will discharge into R1, at standstill, in less than t = 5 * R1 * C1 = 5.17 seconds, which is acceptable. The power dissipated by R1 is 325*0.75E-3 (P= UI) or 0.24 W, which does not impose any requirements on the resistance.

Resistor R0 prevents the capacitor from blowing the fuse, which is rated at I_{fuse} = 0.1 A, during its initial charge.
R0 is chosen so that the maximum charging current of C1 does not exceed half the fuse rating, i.e., R0 = Uc / (I_{fuse} / 2), or 6500 Ohms, or 6800 Ohms in practice. The voltage drop across R0 will be 6800 * 0.75E-3 = 5.1 V and the dissipated power will be 5.1 * 0.75E-3 = 3.8E-3 W, which is negligible.

Note: The measured RMS AC voltage is 237 V and the measured DC voltage is 299 V.

3.3 Description of the "AM signal generation" section

As indicated in §2.3.2, with R2 = 2.2 Mo and C2 = 4.7 nF, we obtain an oscillation frequency of 800 Hz.
Therefore, 800 times per second, the NE2 tube will alternately turn on and off.
The following screenshot shows the voltage across the primary inductance of the ferrite transformer.
The pulses correspond to the instants when the NE2 tube is conducting due to an electrical discharge. We find the period of 1.25 ms corresponding to the LF frequency of 800 Hz. The height of these pulses is independent of the HF and LF frequencies.



This pulsed current excites the tuned circuit on the secondary side of the transformer and causes a train of damped waves at the secondary's resonant frequency.
The (exponential) decay of the voltage produces an amplitude-modulated wave at the pulse frequency and therefore at the frequency of the R2/C2/NE2 relaxation oscillator (see §2.3.2). This is why an AM receiver produces a sound at this frequency. The signal produced is periodic but not sinusoidal and therefore not very pleasant.

The transformer is a "Long Wave/Short Wave" ferrite rod extracted from an old transistor radio. The windings from the "Long Wave" section are used. The primary winding is 183 µH and the secondary winding is 4.33 mH. The transformation ratio (unmeasured) should be slightly less than 5.

> Note: I tested the operation with the "Medium Wave" windings (120 µH primary and 397 µH secondary). The result is less satisfactory (weaker signal), but these windings are well suited to a potential "Medium Wave" AM signal generator.

The secondary winding, along with the variable capacitor and, if necessary, the fixed capacitor, forms a tuned circuit whose frequency f is given by the Thomson formula: f=1/(2.Pi.√(L.C)) (with L being the inductance, C being the capacitance, and f being the resonant frequency).

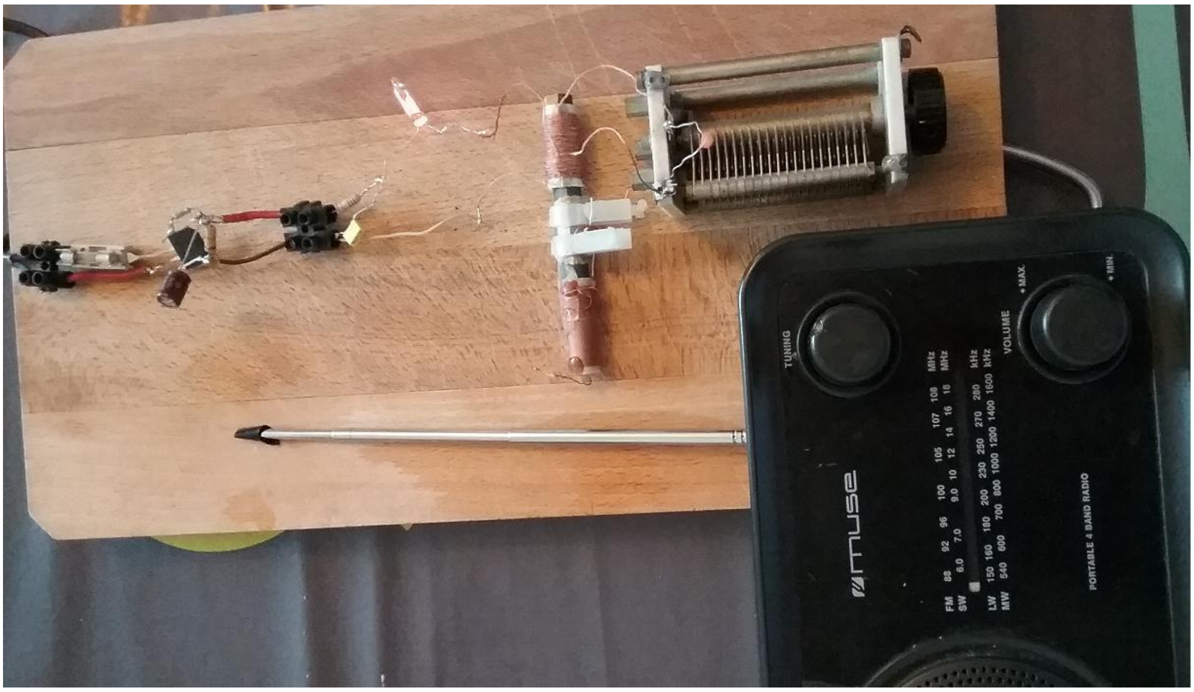
Depending on the target frequency, a fixed capacitor may be added to the variable capacitor. For example, I use a CV that allows for a variation between 16 and 228 pF. I added a 100 pF capacitor in parallel to obtain between 116 and 328 pF. I could just as easily have used a more standard variable CV between 22 and 492 pF, which would have provided a wider bandwidth.

> Note regarding the mounting direction of the HF transformer
> One might wonder whether it is better to have a step-up or step-down transformer for very short-distance transmission (less than 30 cm). Indeed, transmission can be achieved either by the electric field or by the magnetic field, as the decreases in transmitted power are very rapid.

- If the transformation ratio m is >1, Us will be greater than Up (Us≈Up.m). If m and therefore Us are very large, the electric field, which is proportional to Us, will be relatively strong.

- If the transformation ratio m is <1, Is will be greater than Ip (Is≈Ip/m). If m is small, Is will therefore be high and the magnetic field, which depends on Is, will be relatively strong.

I tested both possibilities with a standard transistor receiver (see photo below). The first solution (step-up transformer) is the best.



Since this is only a signal generator and not a transmitter, there is no need to add an antenna. The receiver simply needs to be placed near the tuned circuit (within 30 cm, as shown in the photo).

Appendix 1 provides some additional explanations on pulse operation.

4. Conclusion

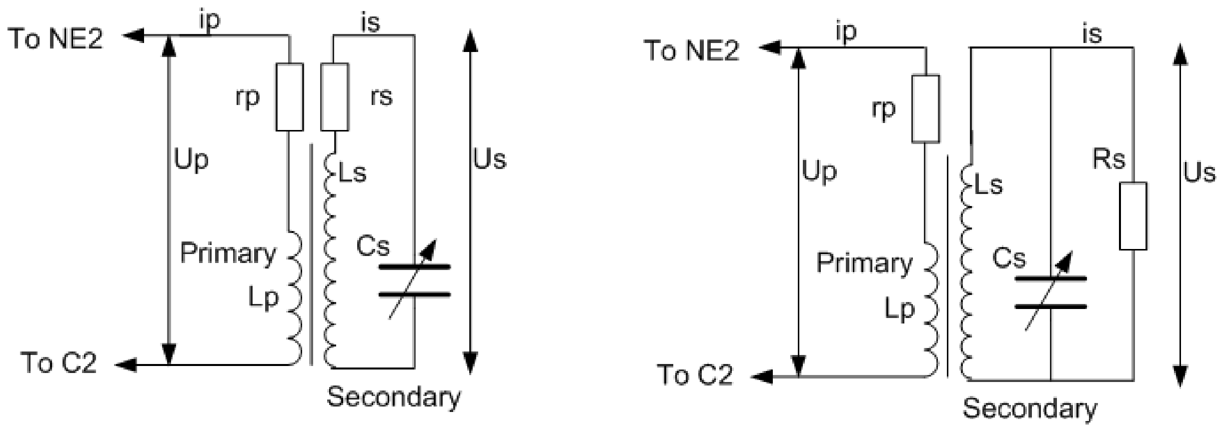
For educational purposes, this simple generator has provided us with a pretext for describing gas tubes and their use as an oscillator. Perhaps this assembly will give you other ideas.

APPENDIX 1

Additional explanations on pulse operation

Below is the electrical diagram of the HF transformer (untuned primary and tuned secondary). Regarding the secondary, the series resistance rs can be transformed into a parallel resistance Rs (such that $Rs \approx rs^*Q^2$, with Q being the quality factor). The two diagrams are equivalent (not strictly, but sufficiently so for our purposes). Furthermore, at resonance, the tank circuit formed by Ls and Cs has an impedance that tends towards infinity and therefore no longer has any influence. Therefore, only Rs remains at resonance.

Electrical diagram of the HF transformer



Equivalent diagrams (if Q large), with Rs=rs.Q2

The tuned circuit (Rs/Ls/Cs) is excited by the primary current pulses ip. This variation in ip causes, after each pulse, a train of damped oscillations.
Indeed, the variation in the primary current ip during the pulses is, as we saw in the screenshot in §3.3, very rapid. It follows that this pulse will generate, at the secondary level, through the mutual inductance M between the primary and secondary, an induced voltage Es with a wide spectrum.

For the duration of the pulse, by discretizing the current as a function of the frequency spectrum, we can write, for frequency fi:
$Es_{fi} = j.M.2.\pi.fi.Ip_{fi}$ with j.M. 2.π.fi the reactance of M and Ip_{fi} the primary current at frequency fi. The voltage Es_{fi} induced by each current element Ip_{fi} will supply the impedance Zs_{fi} of the secondary circuit (Ls//Cs//Rs). For each current element at a frequency fi, we can write: $Zs_{fi}.Is_{fi} + j.M.2.\pi.fi.Ip_{fi} = 0$, “0” because the circuit is closed on itself.

This equation only makes sense during the brief instant of the pulse. After the pulse, the secondary circuit is left to itself because there is no longer any induced current (ip=0). Based on the energy stored in the inductor and the capacitor Ws_{fi}, the tuned circuit will evolve autonomously. The lower the impedance Zs_{fi}, the faster the energy Ws_{fi} will be dissipated.
In fact, generally and simplified, we have $W=P.\Delta t$, with P being the power dissipated by R and Δt the time taken to dissipate the energy W. Now $P=U^2/R$. Hence

$W= (U^2*\Delta t)/R$, and therefore $\Delta t=(W*R)/U^2$. The lower the resistance R, the lower Δt. Ultimately, for very low R, there is a "short circuit."

From this, assuming that the secondary resonant frequency is "fs", it follows that off-resonance (fi<>fs), the voltage Esfi will be "short-circuited" by the low reactance of Zs_{fi} ($rs_{fi}+Ls_{fi}//Cs_{fi}$) as soon as Ip disappears. On the other hand, at resonance (fi=fs), the tank circuit formed by ($Cs_{fs}//Ls_{fs}$) having an infinite impedance, only Rs will remain, which will be very large.
Indeed, we know that $Rs \approx rs*Q^2$ with Q=Ls.w/rs, so $Rs= (Ls.w)^2/rs$.
The lower rs, the higher Rs. At resonance, there will therefore be no "short circuit" but a "relatively" slow decay of $Es_{fs} = Rs.Is_{fs}$.

To study the decay dynamics of this system, we must write its constitutive equation (from the "series" diagram), thus:
Us + Ls.d(is)/dt +rs.is + M d(ip)/dt = 0

> Recall that e = L.d(i)/dt is derived from Faraday's laws (e = dφ/dt) and self-induction (φ = L.i).

During the autonomous phase, the current ip is zero, so the equation transforms to:
Us + Ls.d(is)/dt +rs.is = 0

Furthermore: is=Cs.d(Us)/dt
It is recalled that Q=CV and i=dQ/dt.

The equation then becomes:
$Us + Ls.Cs.d^2(Us)/dt^2 + rs.Cs.d(Us)/dt=0$
Let's rearrange this second-order differential equation by dividing by (Ls.Cs):
$d^2(Us)/dt^2 + rs/Ls.d(Us)/dt+Us/(Ls.Cs)=0$

Without going into the solution of this type of differential equation (found in reference [8]), we must calculate the damping ratio ξ ("Ksi"). This is:
$\xi = (rs/Ls)/(2*\sqrt{(1/Ls.Cs)})=rs.\sqrt{(Cs)}/(2*\sqrt{(Ls)})$
The measurements of Ls and Cs are precise because they are measurable. However, we do not have access to the true value of rs. The only value rs is the ohmic measurement of Ls, i.e., 8.6 ohms. However, there is a skin effect that cannot be directly measured, and the presence of ferrite introduces losses (through hysteresis, for example), losses that are equivalent to a resistance in parallel with the tuned circuit. We must therefore determine rs experimentally. This is what we will do as explained in the following note.

> <u>Note regarding the experimental determination of rs</u>
> To obtain a realistic estimate of the value of rs at the HF frequency, the bandwidth (B) must be measured for a given resonant frequency (fres), using the method provided in reference [10]. The quality factor Q will then be determined using the formula $Q=B/f_{res}$.
> Since $Q=Ls.w_{res}/rs$ (with $w_{res} = f_{res}*2*\pi$), we deduce $rs= Ls.w_{res}/Q$.
> In my case, for a resonant frequency of 165.18 kHz, the bandwidth measured at -3 dB is 5.53 kHz. The quality factor Q is therefore 165.18/5.53=29.9. We deduce rs=Ls.w/Q=150 ohms (a value very different from the ohmic value).

We repeat the calculation of ξ = rs.√(Cs)/(2*√(Ls)) with Ls=4.33 mH, rs=150 ohms, and Cs such that the resonance is at 165.18 kHz. Applying Thomson's formula, we find Cs= $1/((2.\pi)2*L*f^2)$=214 E-12 F, or 214 pF. After calculation, we find ξ =0.017, so ξ<1.
For ξ<1, the regime is pseudo-periodic. The main term of the decay (the "decay rate"), starting from the initial voltage Us0 at the very beginning of the autonomous period, is exp(-t/T) with T=2.Ls/rs, or exp(-2.t.rs/Ls).

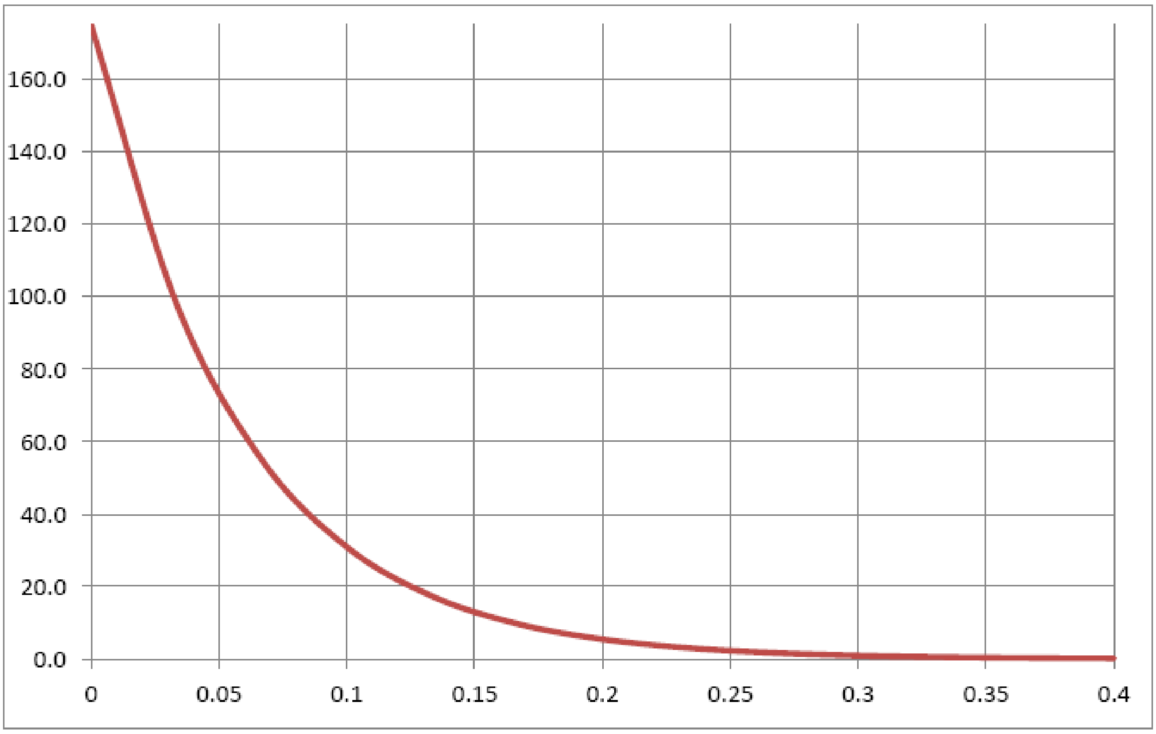
The meaning is clear: the greater the resistance rs of the inductor Ls, the faster the decay. Conversely, a zero resistance (by hypothesis) would result in a decay rate ξ=exp(0)=1, and therefore no decay. The tuned circuit would continue to oscillate ad infinitum.

In our case, T=2*Ls/rs=0.0577 ms

Below is the theoretical decay of the output voltage envelope normalized to U0=175 mV (value of the first peak observed on the secondary) for the case of the assembly (T=0.0577 ms).

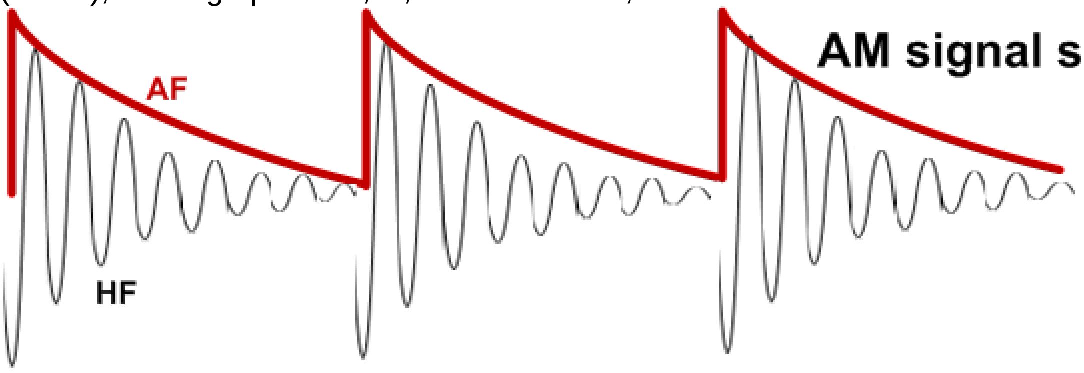
Note: experimentally, we note that the U0 value of 175 mV remains approximately constant when the HF frequency varies (in long waves).

t (ms)	U (mV)
0	175.0
0.0333	98.3
0.0666	55.2
0.1	30.9
0.1333	17.4
0.1666	9.8
0.2	5.5
0.2333	3.1
0.2666	1.7
0.3	1.0
0.3333	0.5
0.3666	0.3
0.4	0.2



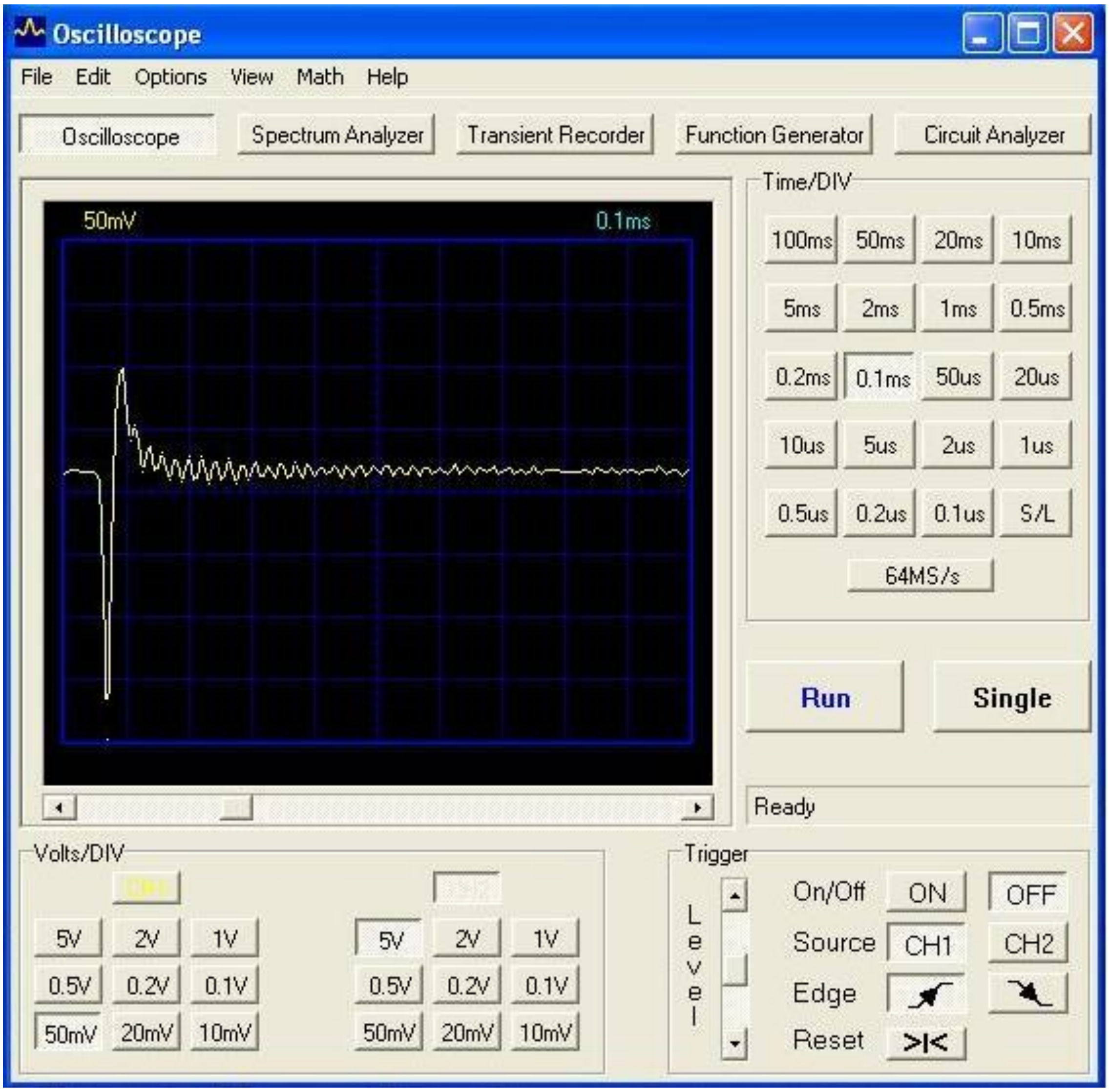
Decay of the alternating signal during 0.4 ms in steps of 1/3 ms

So, the shape of the AM signal will look like the following. The modulation envelope (in red), although periodic, is, as we can see, not sinusoidal.



Below is a screenshot of the voltage signal measured across the CV terminals. This roughly reflects the expected decay. Indeed, the first peak has an amplitude of 175 mV. The second peak, which follows the first at approximately 1/30th of a ms, has a voltage of approximately 83 mV. At 1/30th of a ms, the theoretical decay (see above) gives 98 mV, which is not far from 83 mV.

> Note 1: since the primary peak has an amplitude of approximately 40 mV, the transformation ratio of the HF transformer is approximately 4 (175/40).
>
> Note 2: the HF emission principle used here is not far removed from that of Tesla's spark gap. For more details on the latter device, see reference [9].



References

[1] « Study of a Single Diode Tube Receiver » Rev. C by the author (F6CTE):
http://f6cte.free.fr/Study_of_a_Single_Diode_Tube_Receiver.pdf

[2] « Using and Understanding MINIATURE NEON LAMPS » by William G. Miller (accessible sur Internet)

[3] « Multiplasma 1.2 » by the author (F6CTE):
http://f6cte.free.fr/MULTIPLASMA_1_2_setup.exe
For information because it is an old version not very accurate for the space charge, but sufficient here.

[4] « Glow lamp manual – Theory – Circuits – Ratings - 2nd edition » edited by General Electric Company (available on Internet)

[5] Thesis « Calcul de la courbe de Pashen et la tension de claquage pour les décharges à gaz rare » by GHALEB Fatiha (available on the Net)

[6] Thesis « Etude du transfert d'énergie entre un arc de court-circuit et son environnement : application to the « Arc tracking » by Hadi EL BAYDA (available on the Net)

[7] Thesis « Génération, modélisation et détection des défauts d'arc électrique : application aux systèmes embarqués aéronautiques » by Jonathan ANDREA (available on the Net)

[8] Damping – Wikipedia :
https://en.wikipedia.org/wiki/Damping

[9] Tesla coil - Wikipedia:
https://en.wikipedia.org/wiki/Tesla_coil

[10] « Fréquence de résonance – facteur de qualité » by F6CRP :
http://meteosat.pessac.free.fr/Cd_elect/perso.wanadoo.fr/f6crp/elec/ca/freqre.htm