Building a QRP arc transmitter

The arc radio transmitters had a very short life. Appearing at the beginning of the 20th century as replacements for spark transmitters, they were quickly supplanted by triode transmitters, so much so that by 1925, there were practically none in service. We are not far to celebrate the centenary aniversary of their disappearance, why not revive this technology and build an arc transmitter? As we will see, this requires very few resources, especially if we consider a low-power transmitter

Historical Background

The electric arc was not initially discovered to emit radio waves in the way we understand them today. Shortly after the Italian Alessandro Volta discovered the electric battery in 1800, it wasn't until 1811 that the Englishman Humphry Davy discovered that one could emit light by bringing two carbon rods connected to a stack of Voltaic cells into contact. This property was widely utilized during the latter half of the 19th century for public lighting. However, until 1867 and the publication of the theoretical work by James Clerk Maxwell, it was not known that radio waves could exist. It took until 1887 and the experiments of H. Hertz to demonstrate the existence of these waves. (Figure 0)

A bit of history

- 1864 Maxwell publishes his equations predicting the possibility of electromagnetic waves capable of propagating at the speed of light in matter or in a vacuum.
- 1886 Hertz experimentally demonstrates these radio waves with a spark transmitter.
- 1895 Marconi achieves the first radio connection over 1.5 miles using a spark transmitter.
- 1903 Poulsen register for a patent and develops the arc transmitter, gradually replacing spark transmitters
- 1907 Lee De Forest invents the triode.
- 1919 First commercial radio station with a triode transmitter.
- 1921 First unilateral transatlantic radio connection by an amateur radio operator between Connecticut and Scotland on 1820 kHz using a triode transmitter.
- 1923 First bilateral transatlantic connection between Connecticut and France between 1MO and 8AB on the 110-meter band using a triode transmitter.
- 1925 End of arc transmitters, replaced by triode transmitters or equivalents.

Figure 0

Then everything happened very quickly. The Italian engineer Marconi extrapolated Hertz's spark transmitter to achieve the first connection in 1895, covering barely more than 2 km. Soon, the limitations of spark transmitters became apparent, and among the possible techniques, one emerged: the arc transmitter, for which the main contributor was the Danish inventor Waldemar Poulsen, who patented the principle in 1903.

They rapidly replaced the spark transmitters. However, they also faced obsolescence, being replaced by triode transmitters, whose patent was filed in 1907 by the American Lee De Forest.

One of the last arc transmitters to operate in France was located in the Bordeaux region, in the town of Marcheprime (Figure 1). Built in 1917 by the Americans, it transmitted at 17 kHz to ensure connections between France and the USA. The arc transmitter had a power supply of 1000 kW and utilized Poulsen technology. In 1923, this arc transmitter was replaced by an alternator, which was later replaced by a tube transmitter, allowing for a cleaner emission and better efficiency.

The genesis of arc transmitter

If we refer to patent literature, one of its merits being open access and self-verified by patent offices managing them, the first person to patent an alternating current generator was Elihu Thomson in 1893

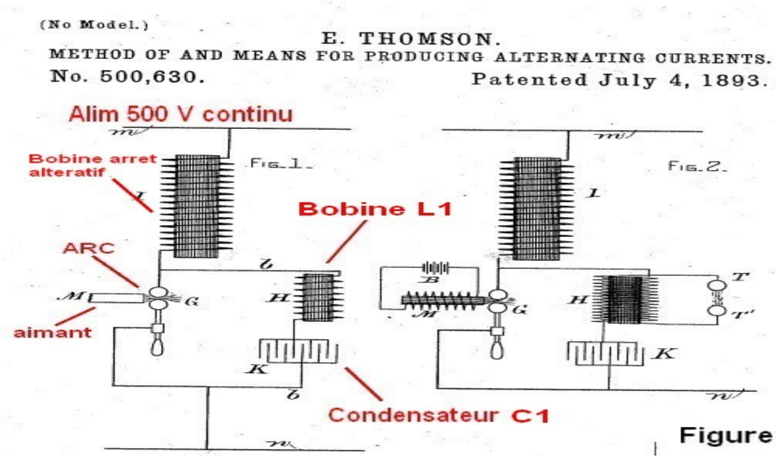


Figure 2

The stated objective was to obtain, from a direct current, an alternating current whose frequency could be adjusted based on a coil and a capacitor (US Patent No. 500,630 dated July 4, 1893). To achieve this, an arc powered by direct current was in parallel with a coil L1, itself in series with a capacitor C1 (see Figure 2). The frequency of the alternating current corresponded to the resonance frequency of the L1/C1 circuit. The presence of a magnetic field at the arc level was noted, its function being to stabilize the arc. The generated alternating current was recovered by inductive coupling on the coil L1. The frequency of the alternating current did not exceed 50 kilocycles per second (Figure 2).

Another contributor to arc transmitter technology is the Englishman William Duddell. Tasked with studying the stability of arcs used for public lighting in Great Britain, he obtained a patent in 1900 without truly making a significant contribution to the technology. The main claim was to use this device to generate musical sounds, essentially the first 'synthesizer' in history (GB Patent No. 21,629 dated November 25, 1900).

The essential contributor to the technology is undoubtedly the Danish inventor Waldemar Poulsen, who patented his invention and its application in the field of radio wave generation in 1903 (US Patent 789,449, Figure 3). His contribution to the evolution of the technique lies in operating the arc not in the air but in a controlled composition atmosphere, improving the efficiency of converting direct current into alternating current. The claimed gas was hydrogen or substances capable of producing it through decomposition. Subsequently, hydrogen was quickly replaced by a more manageable substance: ethyl alcohol.

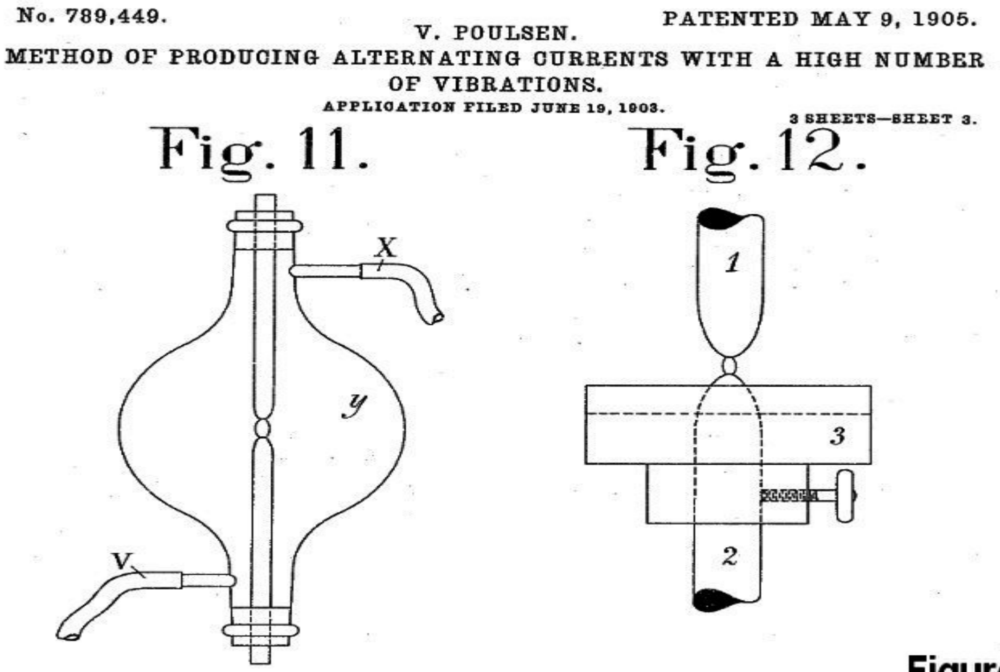
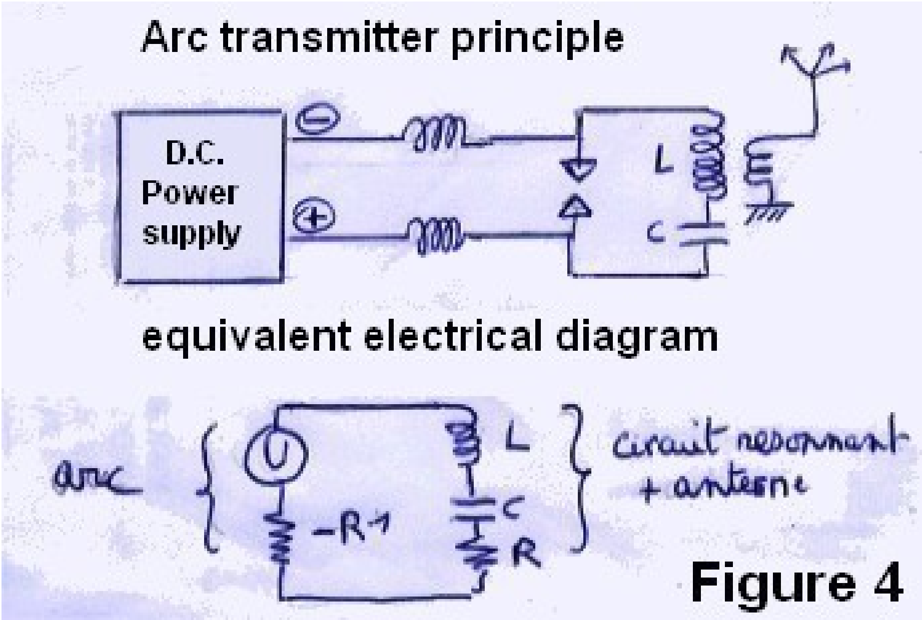


Figure 3

Interestingly, Poulsen was far from being the first to operate the electric arc in hydrogen. As early as the mid-19th century, numerous chemists had utilized the possibilities offered by the electric arc to conduct chemical reactions that were otherwise impossible. For instance, the French scientist Marcellin Berthelot had published in 1860 the synthesis of acetylene using a setup similar to Poulsen's, where hydrogen reacted with the carbon from the arc electrodes. The major difference was that the chemist Berthelot did not include an L/C circuit in parallel with the arc. It's also fair to acknowledge that in 1860, the existence of electric radio waves was not yet known.

How an arc transmitter works

The transmitter consists of an arc in parallel with a series oscillating circuit, as shown in Figure 4. The operation is made possible because the arc exhibits negative resistance, meaning that for certain operating points, when the voltage increases, the current decreases. It's easy to measure this negative resistance, as we'll see later on. If this negative resistance compensates for the positive equivalent resistance of the oscillating circuit and associated circuits (antenna, etc.), the L/C circuit will start oscillating at a frequency determined by the inductance L and the capacitor C.



The negative resistance of the arc depends on several parameters: the nature of the species present in the plasma generated by the arc is the most important parameter. These species are dependent on the gas in which the arc operates and also on the nature of the electrodes between which the arc occurs. This negative resistance also depends on the operating point of the arc and the frequency at which it operates.

The real setup of the Poulsen arc transmitter was a bit more complicated than the schematic shown in figure 4 (see figure 5). The arc's anode was made of graphite while the cathode was made of copper with a cooling system to prevent melting. The arc was enclosed in a sealed chamber with continuous injection of a specific product, often ethyl alcohol. Of course, it was necessary to evacuate the products generated by this introduction. Additionally, a magnetic field was applied to stabilize the arc's operation. A mechanical system was also necessary to compensate for the wear of the graphite cathode.

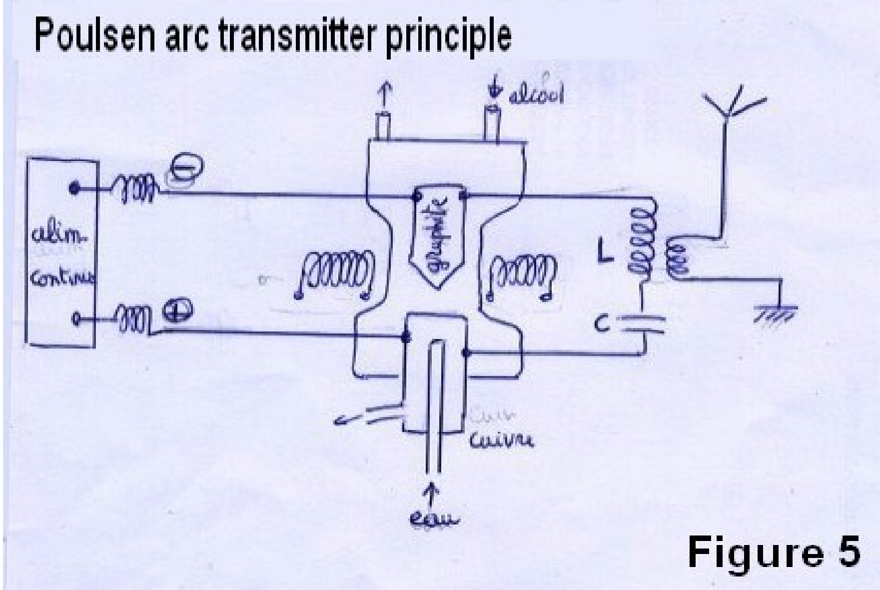


Figure 5

The Oscar Kilo arc transmitter

Rather than using an arc working in an atmosphere of alcohol vapor as was done in the early 20th century, we've shifted towards a much simpler way taking advantage of what we can get easily to day by hacking xenon bulbs that have been popular in automotive lighting for many years. Nowadays, one can easily find online lighting kits for around twenty euros. For this amount, you receive two xenon bulbs (H1 model) and two power supplies (see figure 5 bis). In the following, we'll explore how to use these components to create a radio arc transmitter.

Figure 5 bis

Xenon tubes appeared in 1952, marketed by the German company Osram and subsequently by many others (see figure 6). They have excellent luminous efficiency, and a high level of luminous power can be easily achieved.

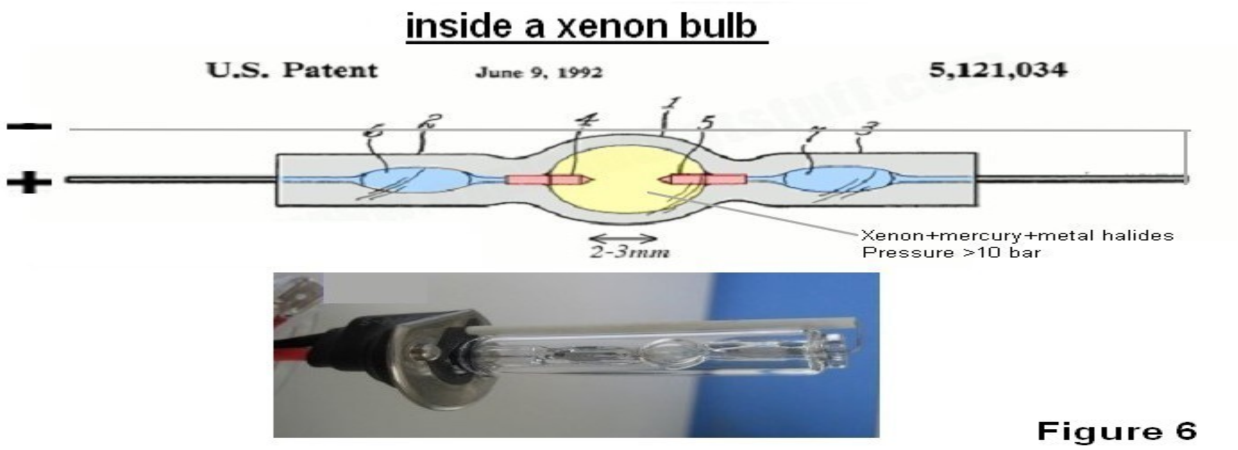


Figure 6

A xenon bulb used in automotive lighting (H1 model) is composed of a fused silica tube with two tungsten electrodes separated by approximately 3 millimeters.

The filling gas of the bulb is primarily composed of pressurized xenon, a chemically relatively inert gas to which various additives (traces of mercury, different metal chlorides, etc.) are added to improve efficiency, operation, and the whiteness of the emitted light.

The tube is powered by a direct current generator. In stable operation, the voltage settles in the range of approximately 50-150 volts (for an H1 bulb). To start the lamp (initiate the arc), it's necessary to send a few pulses between 10 and 20 kilovolts.

To use this tube as a radio transmitter and to control its operation, different components need to be added (see figure 7).

Xenon transmitter :electrical schematic

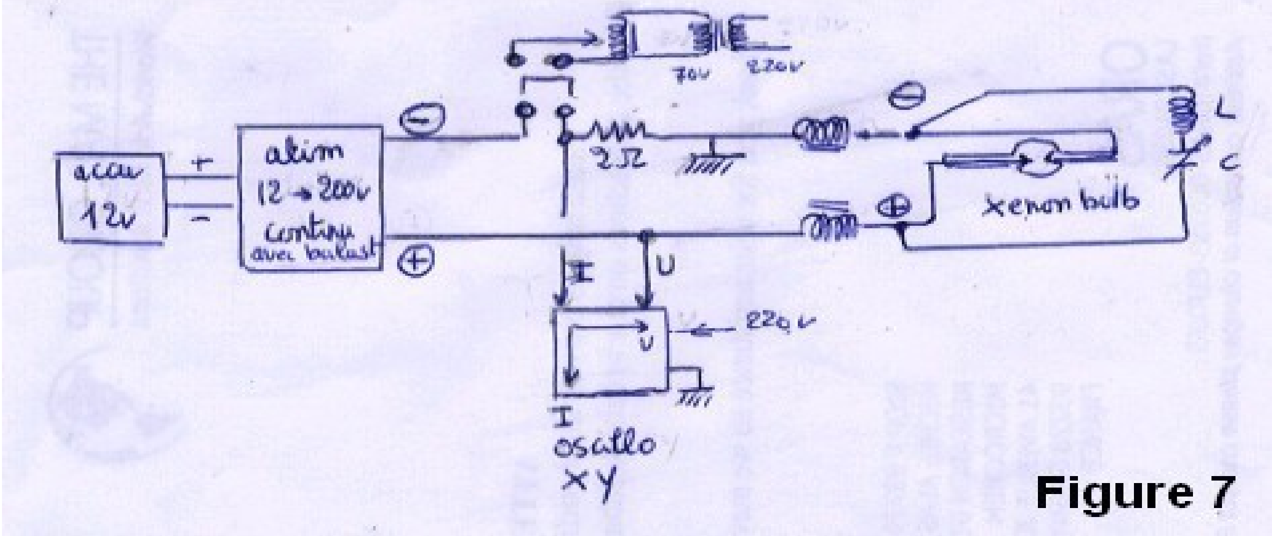


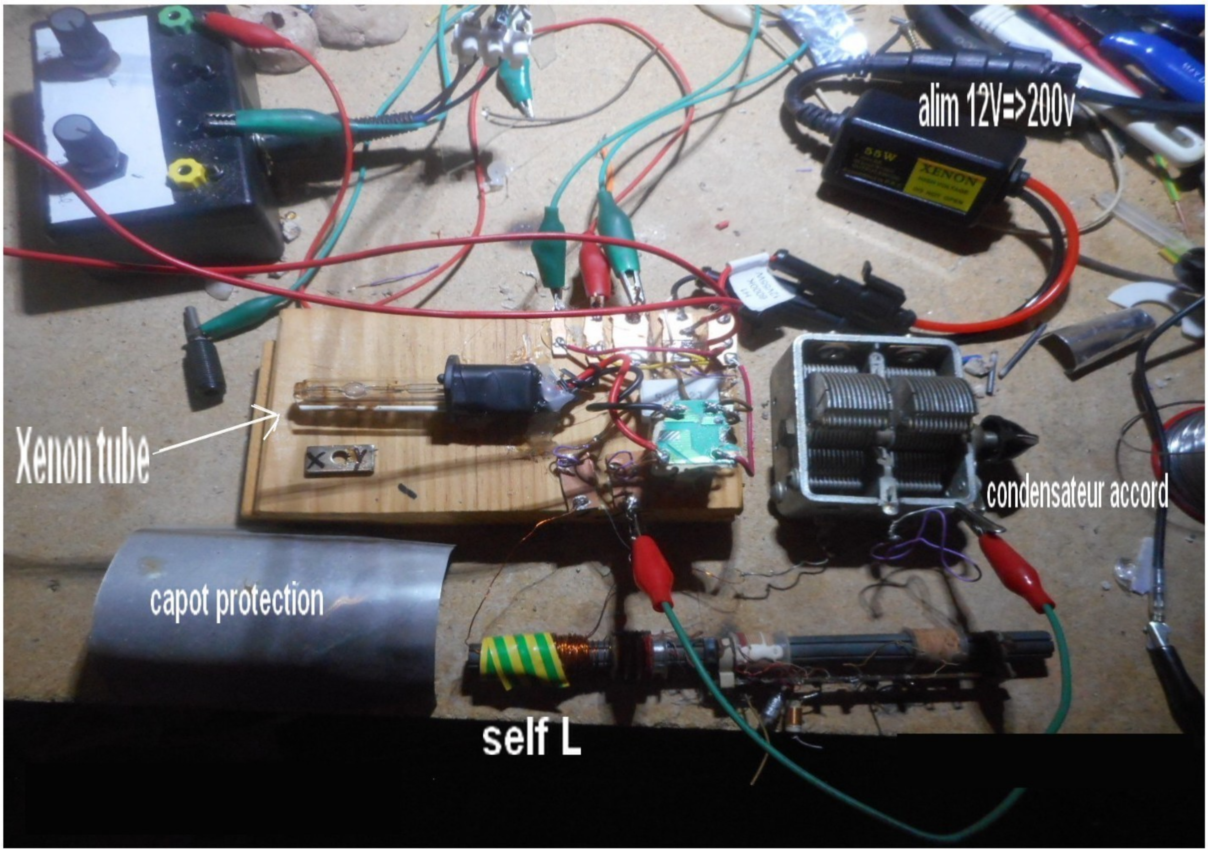
Figure 7

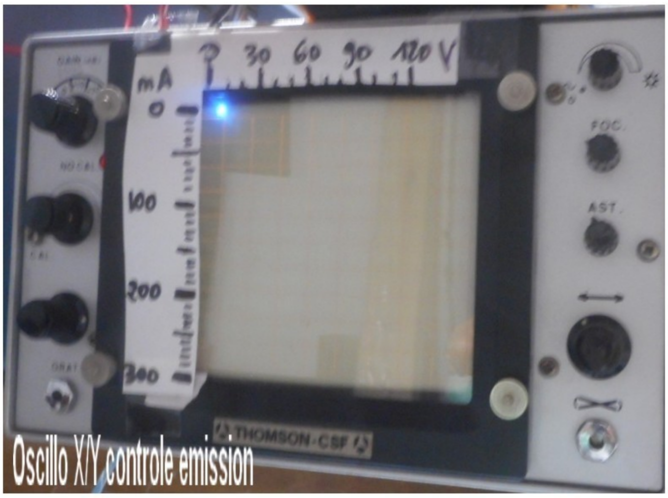
We start with a 12-volt accumulator connected to the power block retrieved from the H1 lighting kit. In series with the negative power line, we insert a variable autotransformer capable of sending a maximum AC voltage of 70 volts (50 Hz frequency). This system is not necessary for operation, but it allows simple measurement of the negative resistance of the xenon tube.

To visualize the operation of the xenon tube, we connect an X/Y oscilloscope. Horizontally, we apply the xenon tube's supply voltage, while vertically, we measure the current supplying the tube. This current is measured by the voltage drop across a 2-ohm resistor in series with the power line. Prior calibration of the system with known DC voltages and currents is necessary (scale of 0-120 volts for voltages, scale of 0-300 milliamps for current). While not essential, this oscilloscope provides a better knowledge of the arc's operation.

The xenon tube is connected to the setup via two choke coils, so as to block the generated alternating current. The coil L consists of a copper wire winding (200 turns) on a feroxcube rod, salvaged from an old radio, in series with a variable capacitor C . The entire assembly (L/C) resonates between 150 and 250 kHz depending on the value of the variable capacitor.

To check the operation of the xenon transmitter, a simple broadcast receiver easily available and tuned to the AM band with an S-meter connected at the detection level is used to get an idea of the signal strength. Additionally, a mini spectrum analyzer (SPECTRUM ANALYZER) is used to have an idea of the spectral purity of the signal generated . An overview of the entire setup can be seen in figure 8.





Xenon transmitter : experimental set up

Figure 8

Oscar Kilo Xenon transmitter at work

Starting the transmitter is particularly simple. First, the xenon tube must be started by disconnecting one branch of the oscillating circuit. During the tube's startup, the power supply unit sends a series of high-voltage pulses to initiate the xenon tube, which would otherwise be short-circuited by the variable capacitor unable to withstand such voltages.

Once the tube is lit, we connect the previously adjusted oscillating circuit, set around 180 kHz, similar to the radio receiver. As soon as the circuit is connected, a strong noisy carrier signal is audible on the receiver.

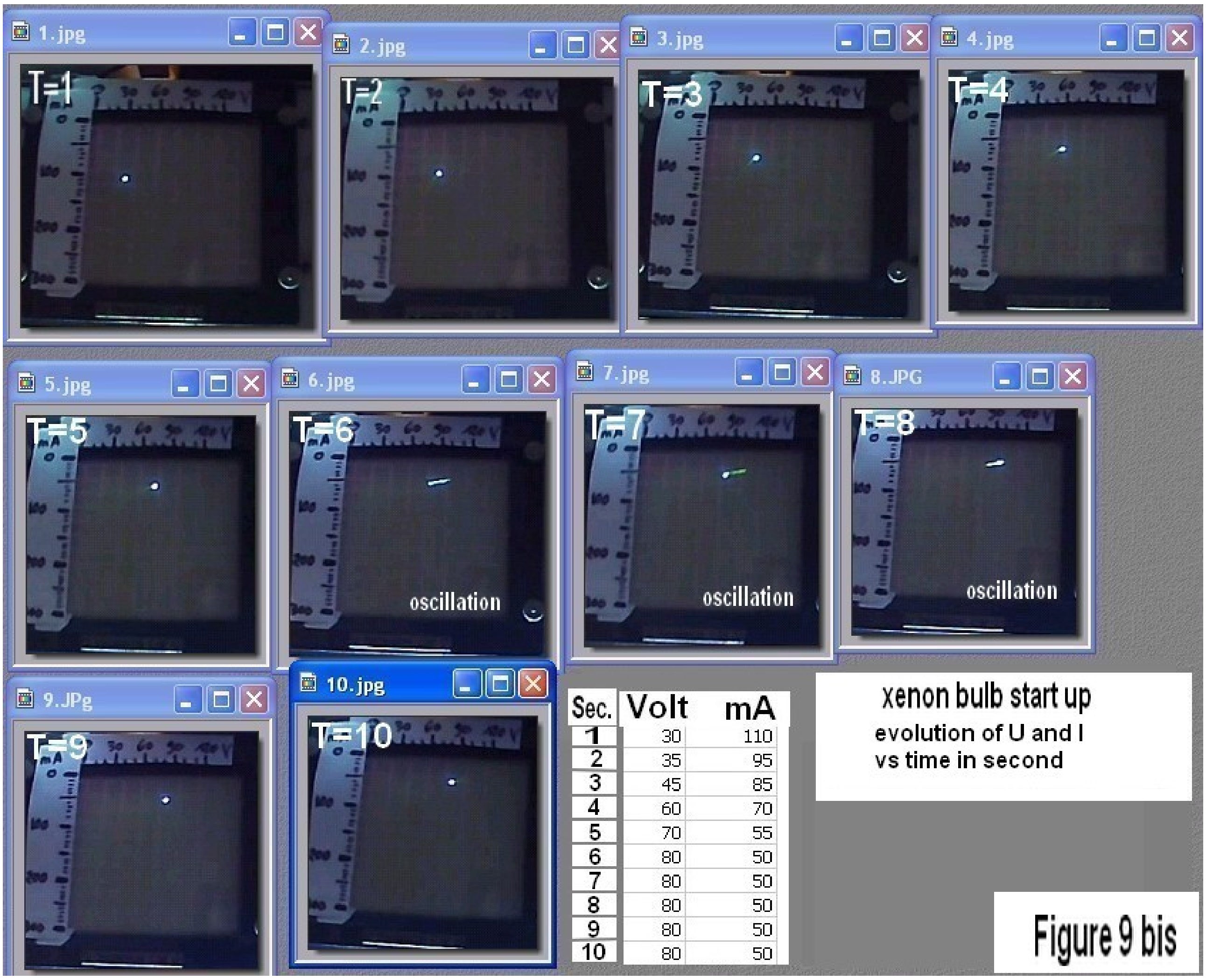
If the value of the variable capacitor is modified , the frequency observed on the receiver shifts accordingly . By connecting the spectrum analyzer (set between 50 and 500 kHz), one observes a carrier occupying a relatively wide spectrum (see figure 9), with the superimposition of the frequency of the "chopper" oscillating at 122 kHz. (This "chopper" generates the high voltage required for the tube.)

Figure 9

The operation of the tube is altered depending on whether a fixed or variable magnetic field is applied, created by a fixed neodymium magnet or an electromagnet powered by direct or alternating current. The position of the magnetic field (axial or radial in relation to the tube) has an impact on its operation.

We can also modify the operating mode by inserting a variable resistor in the power line. This allows us to decrease the power and more conveniently observe the state of the plasma inside the xenon tube through an absorbing screen like tinted glass or an equivalent material. This observation helps in tracking its evolution, especially when external magnetic fields are applied. Another way to alter the operating point is by cooling the tube using any suitable method.

As it can be verified during the start-up of the xenon tube, when its temperature rises from 20°C to a temperature not precisely measured but higher than 600°C (indicated by the cherry-red color of the tube upon arc cessation), the operating point varies significantly. Semi-quantitative data can be obtained by recording the electrical state of the arc as it appears on the X/Y oscilloscope at a rate of 25 frames per second (see figure bis). By replaying the video and sampling the state every second, it becomes evident that the operating point is shifting widely : at the arc's start, the operating point is at 30 volts/110 mA, while after 10 seconds, once thermal equilibrium is reached, the same operating point is at 80 volts/50 mA.

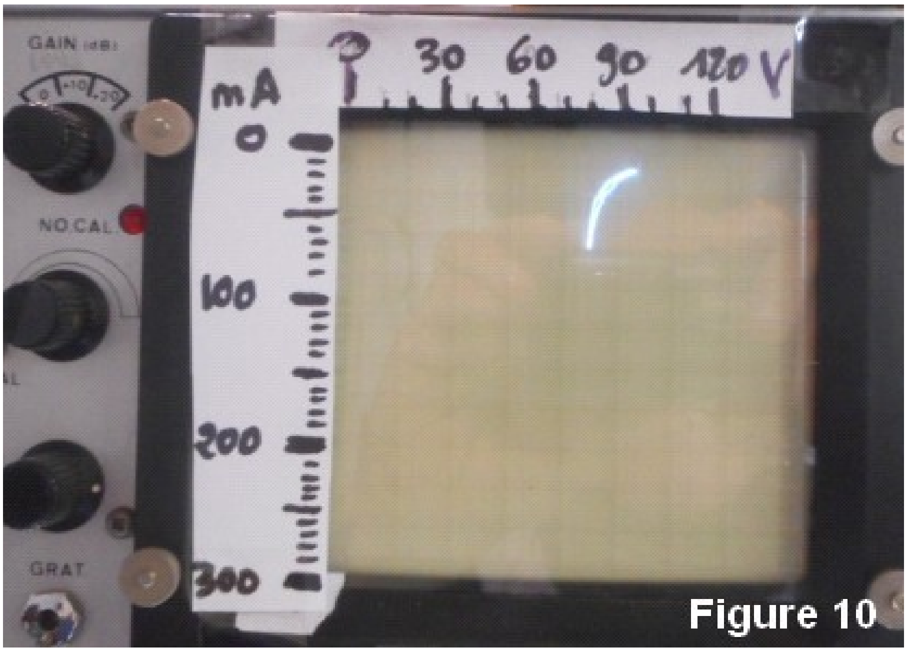


Sec.	Volt	mA
1	30	110
2	35	95
3	45	85
4	60	70
5	70	55
6	80	50
7	80	50
8	80	50
9	80	50
10	80	50

Figure 9 bis

In terms of frequency performance, the setup oscillates smoothly at 180 kHz without any issues. No attempts have been made for frequencies lower than this. It's possible to increase the frequency up to 250 kHz by decreasing the value of the capacitor in series with the coil. However, the setup fails to oscillate beyond 250 kHz.

The negative resistance of the xenon tube can be measured during operation. To do it we have to modulate the continuous voltage supplying the xenon tube with an alternating voltage and observe the evolution of the operating point on the X/Y oscilloscope. As seen, the negative resistance is not constant and depends on the operating point (see figure 10).



This resitance is equal to the slope of the curve U=F(i) .Its calculation is not complicated .By collectig the values on the scope screen we get the following values :

U= 95v   I=20 mA   U=80 v   I=40 mA   U=75 v   I=70 mA

frome there it comes ::

Between 95 and 80 volt d(U)= 95-80=15 volt   d(I)=20-40 =-20 mA ==> R=d(u)/d (I)=-750 ohm
Between 80 et 75 volt d(U)= 80-75=5 volt   d(I)=40-70 = 30 mA ==> R=d(U)/d(I)=-166 ohm

As we can see, there is room for experimentation with the xenon arc emitter, its main advantage over the Poulsen arc transmitter being the reliability of its operation.

The setup as described can be directly adapted to make some experiment on a very small scale with Poulsen arc technology transmitter , as we will see.

Experiments with a QRP Poulsen arc transmitter

The assembly diagram remains unchanged. The xenon tube is simply replaced by an homemade micro spark emitter.

Two types of spark gaps have been used : uncooled spark gaps and a cooled spark gap. The former are very convenient for conducting experiments with an arc where the nature of electrodes can be easily changed, thereby observing the impact on the assembly's operation mode. Electrodes made of various metals can be used, but the issue is that the operating time is brief (a few seconds) due to the melting or destruction of the metal in the arc, which reaches temperatures in the thousands of degrees range .

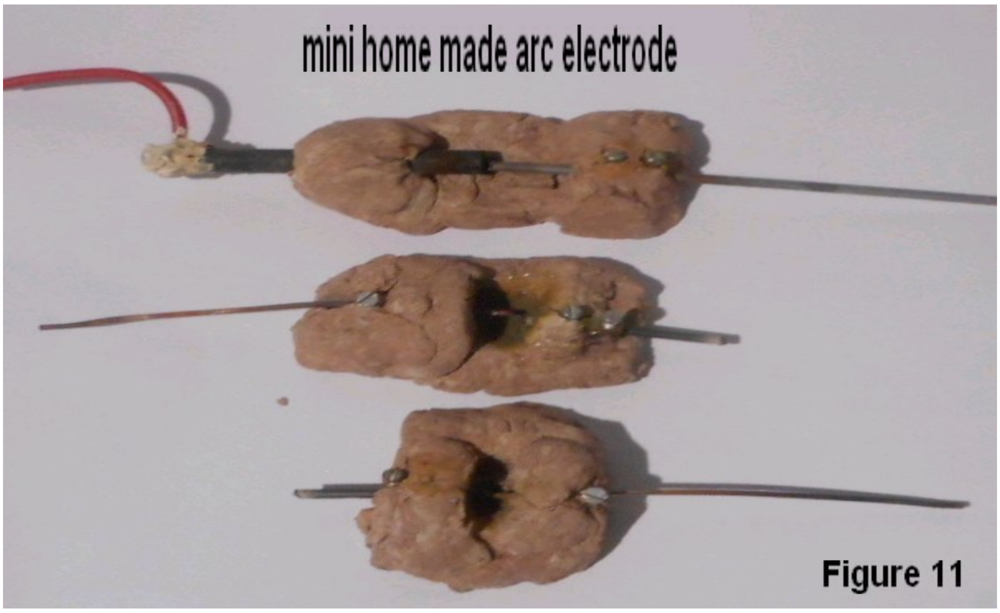


Figure 11

The mini uncooled spark gaps are contained within a shell made of clay, a material that is very easy to shape and has excellent temperature resistance (melting point above 1200°C). The electrodes to be tested are inserted into brass terminals themselves embedded in the clay. It is not necessary to fire the clay; simple air drying at room temperature for 2 or 3 days is sufficient to obtain the desired mechanical rigidity with pratically no electric conductivity (Figure 11)

The testing of these mini spark gaps was conducted with an oscillating circuit set at approximately 150 kHz, with emission detection on a receiver tuned to the same frequency and placed nearby. As mentioned earlier, the test is brief and lasts only a few seconds. This allows for the testing of various electrode materials. All tests are conducted in the air.

graphite/graphite : NO oscillation
graphite/copper : Oscillation

graphite/stainless steel : Oscillation
graphite/zinc : Oscillaton
copper /copper : Oscillation

Curiously, if both electrodes are made of graphite, no oscillation is observed, whereas with other materials, this is always the case.

The assembly of a cooled spark gap allows for longer-lasting operation. The cathode is made of graphite, and the anode is a brass tip inserted into a 12 mm diameter copper tube filled with water (see Figure 12). The entire setup is held in place within a dry clay casing. With such an assembly, tests can run from 1 to 2 minutes until the arc stops naturally due to the consumption of the graphite electrode, which is just a simple pencil lead. This setup enables exploration of several operating modes. The absence of a magnetic field at the arc level makes it unstable, as observed in the continuous current/voltage curve displayed on the X/Y oscilloscope

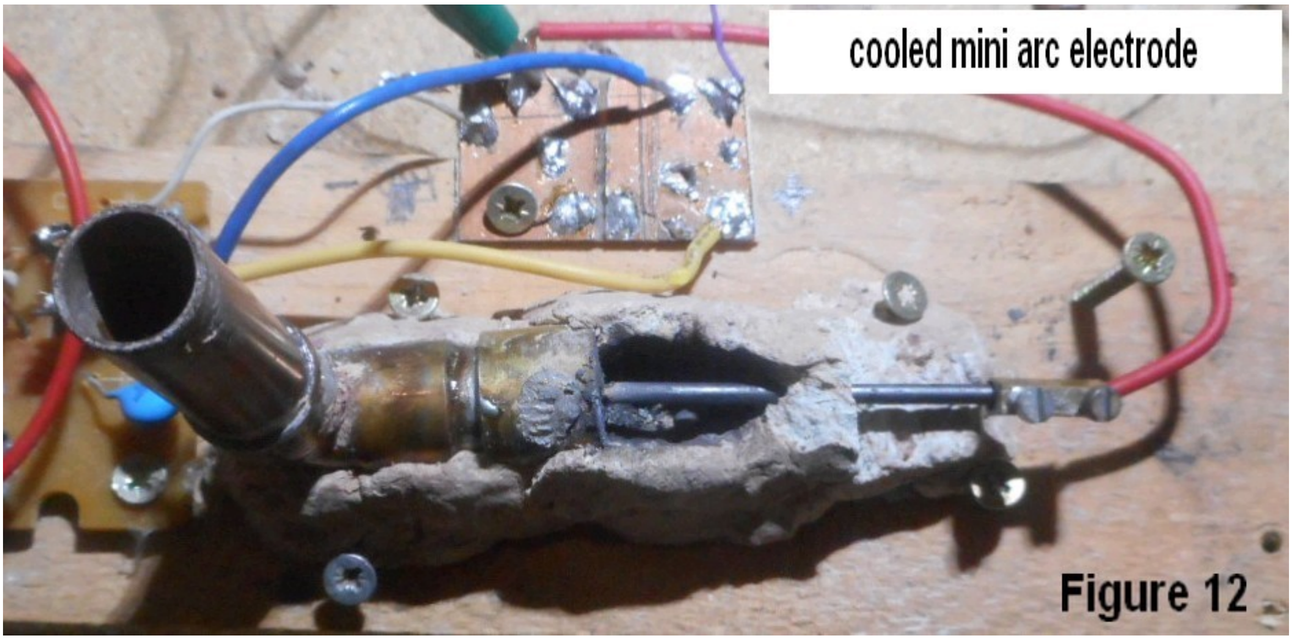
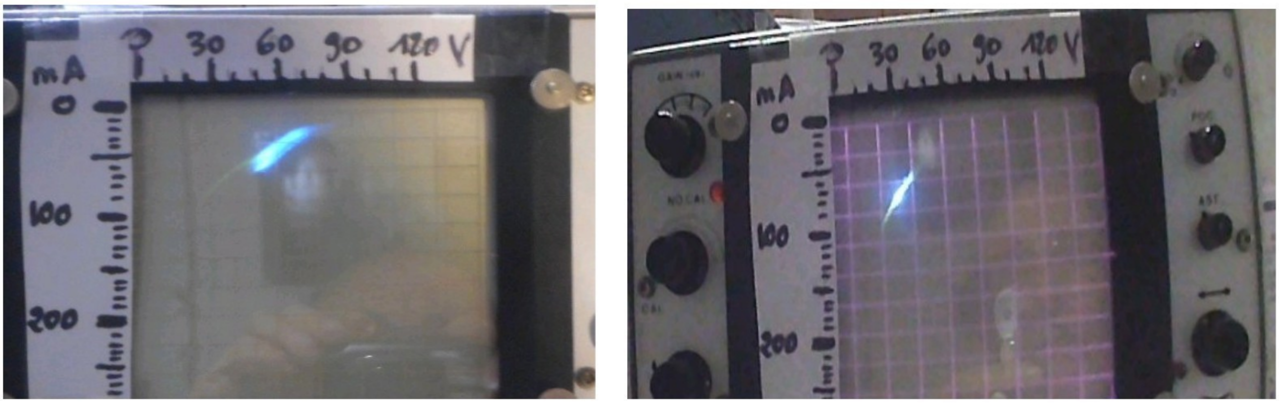


Figure 12

With this setup, by modifying the oscillating circuit in parallel on the arc, we can observe oscillation up to 1 MHz but not beyond that with the graphite/brass combination

Curiously, the operating point of the arc varies depending on the oscillation frequency (see Figure 13)

Frequency : 850 Khz   Frequency : 150 Khz



Graphite/Brass arc transmitter
working conditions vs frequency

Figure 13

In both cases, instead of having a fixed operating point resulting in a point on the X/Y display (as seen with the xenon arc), we observe a relatively straight trace attributable to arc instability

By making a video recording at 25 frames per second of what appears on the X/Y oscilloscope, and reviewing it frame by frame, it can be seen that this segment evolves very rapidly and erratically. To solve at least part of this issue, it would be necessary to stabilize the arc using an external magnetic field (as Poulsen and others did), which has not been attempted

Operating at 850 kHz, the average operating point is 60 volts / 40 mA, whereas it is at 30 volts / 75 mA at 150 kHz. Analyzing the operating point allows for measuring the arc negative resistance, similar to what was done for the xenon arc transmitter. This way, a negative resistance of approximately 666 ohms can be measured for the oscillation at 150 kHz

Many more experiments could be envisioned on this Poulsen arc transmitter. However, while it allows for higher frequency operation compared to the xenon arc transmitter, to make it safely working is very challenging . It provides numerous experimental options. For instance, altering the nature of the electrodes and their doping with various elements, as well as adjusting the atmosphere in which the arc operates, could reveal their impact on working frequency and conversion efficiency

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