# Theory and construction of a plasma tweeter

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# Abstract

The seemingly futuristic, however approximately 120 year old technology of sound generation through plasma is investigated. A short introduction into the history and commercial products is given, followed by the transducer theory of a Tesla coil in combination with the ionization procedures and the thermo-acoustic sound generation through the amplitude modulation of a constantly generated plasma. Important items being discussed in order to understand the functionality of a plasma speaker are the degree of ionization, thermodynamic equilibrium and Saha equation. A brief overview of differences between different plasmas is given and the plasma present at the speaker of this project is classified. The advantages of a plasma speaker such as an omnidirectionality, a high frequency range and a fast transient response with their causes are discussed just like the disadvantage of the generated ozone. Lastly, the project finishes with the description of the built plasma speaker by shining a light on both circuitry and coil construction.

Die futuristisch scheinende, jedoch bereits ca. 120 Jahre alte Technologie der Schallerzeugung mittels eines Plasmas wird untersucht. Es gibt eine kurze Einleitung in die Geschichte sowie die kommerziellen Produkte, gefolgt von der Wandlungstheorie eines Tesla-Transformators in Kombination mit den Ionisationsprozessen und der thermo-akustischen Schallerzeugung durch die Amplitudenmodulation eines konstant generierten Plasmas. Zu den wichtigen, dabei behandelten Themen gehören Ionisationsgrad, thermodynamisches Gleichgewicht und die Saha-Gleichung, um die Funktionalität eines Plasma-Lautsprechers besser verstehen zu können. Es folgt ein Überblick über die Unterschiede diverser Plasmen und das Plasma des für dieses Projekt gebauten Lautsprechers wird anhand dieser Merkmale eingeordnet. Außerdem werden die Vorteile wie z.B. die Omnidirektionalität, der hohe Frequenzumfang und das schnelle Einschwingverhalten sowie deren Ursache beschrieben. Das Gleiche gilt für den Nachteil der Ozon-Entstehung. Zuletzt wird der für dieses Projekt gebaute Plasma-Lautsprecher erläutert, indem ein Blick sowohl auf den Schaltkreis als auch auf die Konstruktion der Primär- und Sekundärspule gerichtet wird.

# Contents

# 1. Introduction

A plasma tweeter is an acoustic transducer making use of ionized air, also called plasma. Plasma is also known as the fourth aggregate state in which the electrons are more agile than in gaseous state. Plasma can be caused by high temperatures, a strong electric field or through chemical reactions. There are different forms of plasma with varying temperatures, plasma densities and types of discharges.

The first type of plasma tweeter can be dated back to William Duddell with his singing arc at the end of the $19^{th}$ century. Since then different companies like DuKane, Telefunken or Magnat have built plasma speakers based on Duddells concept which was extended and improved by french physicist Siegfried Klein. Today, mainly two german manufacturers build plasma speakers, Lansche Audio and Acapella Audio Arts.
The plasma tweeter being built for this work creates a strong electric field of approximately $150kV$ to ionize the surrounding air which creates a coronal discharge of about $5cm$ length; also called plasma flame. The creation of this plasma flame can be modulated with a specific signal, for example an audio signal.
By modulating the electric field and therefore the degree of ionization, a changing amount of electrons collide with the surrounding air molecules and transfer part of their energy to them, in effect creating a sound wave.
Advantages of the plasma tweeter are mainly caused by the non existing membrane which means that only the electrons themselves need to be moved. This results in omnidirectionality of the speaker, a high frequency range with an even response and a very fast transient response. The main disadvantage of the plasma tweeter is the creation of ozone, which however is possible to overcome with one of a few techniques.
The plasma tweeter for this work makes use of a Class-E switching topology operating at a (carrier) frequency of $4MHz$. This frequency is amplitude modulated with the audio signal to create audible sounds.

# 2. Background and related work

Following, a short introduction will be given as to why this subject was chosen and how it can be used if further investigated.
Additionally, a brief overview on previously written articles and books on the subject are stated.

## 2.1. Background

After understanding the principles of a plasma loudspeaker and having built one, the next step will be to measure the acoustical properties of the previously built plasma speaker such as

- maximum sound pressure level
- noise floor and signal to noise ratio
- directivity/polar pattern
- total harmonic distortion (THD)

Furthermore, it would be interesting to measure the plasma flame's temperature and its ozone emissions.

With all these measurements a fundamental and objective basis could be built to describe the plasma tweeter and its properties which is essential for prospective scientific works.

One of these would be combining the plasma tweeter with a conventional woofer to build a broadband omnidirectional speaker on condition that a directivity measurement of the plasma speaker would prove its omnidirectionality. In that case such two-way speaker could be used for room classification measurements like room reverberation time or sound pressure level.

## 2.2. Previously conducted works on the subject

Both the books "Introduction to Plasma Physics" by R. Goldston and P. Rutherford and "Plasmaphysik - Phänomene, Grundlagen und Anwendungen" by U. Stroth give basic insights into plasma physics. While they deal with many physical and mathematical fundamentals exceeding the focus of this work, they are helpful in understanding important properties like the definition of a plasma or the degree of ionization.
"Electrical Breakdown and Discharges in Gases" and "Gaseous Electronics. Volume 1" deal with the interaction of electronics in gaseous surroundings and "Theoretical Acoustics" is an essential source for anything acoustics related. In the case of this work, chapter 12 called "Plasma Acoustics" was used for specific information on the principles of thermo-acoustic sound generation and its characteristics.

When talking about previously conducted scientific papers, the following are of interest:

- Lafleur, Matese and Spross: Acoustic refraction by a spark discharge in air
- Fitaire and Sinitean: Acoustic wave excitation in a flame
- Bastien: Acoustics and gas discharges - applications to loudspeakers
- Bayle, Bayle and Forn: Blast wave propagation in glow to spark transition in air
- Der Plasmalautsprecher als Lehrversuch
- Sutton, Moore, Sharp and Braitwaite: Looking into a plasma loudspeaker
- Eichwald, Jugroot, Bayle and Yousfi: Modeling neutral dynamics in pulsed helium short-gap spark discharges
- Mazzola and Molen: Modeling of a dc glow plasma loudspeaker
- Bequin, Castor, Herzog and Montembault: Modelling Plasma Loudspeakers
- Babcock, Baker and Cattaneo: Musical Flames
- Bayle, Bayle and Forn: Neutral heating in glow to spark transition in air and nitrogen
- Daschewski, Boehm, Prager, Kreutzbruck and Harrer: Physics of thermo-acoustic sound generation
- Fitaire and Mantei: Some experimental results on acoustic wave propagation in plasma
- Nature vol. 63 (1900): Some Experiments on the Direct-Current Arc
- Daschewski: Thermophony in Real Gases

# 3. History of plasma tweeters

## 3.1. William Du Bois Duddell and the singing arc

Although plasma tweeter technology has a futuristic feel or sound to it, the first comparable generation of sounds was already introduced in 1899 by the English electrical engineer William Du Bois Duddell (1872-1912)[1].
Although the incandescent electric light bulb had been invented by the time, carbon arc lamps were still fairly common for various types of uses e.g. to light up streets or any other situation where a bright light was needed which could not yet be generated by the incandescent bulb.
Carbon arc lamps consist of two touching carbon rods acting as electrodes. When they are connected to a power source they detach from another and a bright light is created by the high current through the generated carbon vapor [2].
When conducting experiments with the carbon arc lamp to reduce its own noise, Duddell found out that rapidly changing the supply current would produce audible sound waves. Later, he added an inductor-capacitor resonant circuit to the resistance of the arc itself in order to minimize the noise being generated by the arc lamp. By doing so, he had constructed a tune-able oscillator which he was then able to play after appending a keyboard controlling the supply current to the circuit [3].

## 3.2. Ionophone / Ionovac

Between 1946 and 1951 the french physicist Siegfried Klein worked on the first compact and loud enough speaker working on the principles of ionization. By creating an anode composed of a platinum rod inside a quartz cylinder which was coated in a mixture of platinum, phosphate, graphite and iridium, Klein managed to build an ion source that would not need as much power as previous models. The exterior shield of the construction was acting as the anode. This can be seen in figure 3.1.

Operating at $400kHz$ and with voltages of up to $12kV$ the quartz cylinder in Klein's Ionophone reached temperatures of up to 1000°C creating a strong electric field of ions and electrons in the gaseous surrounding between the electrodes. By modulating the high operating frequency with lower, audible frequencies, first the change of the electric field and therefor the temperature

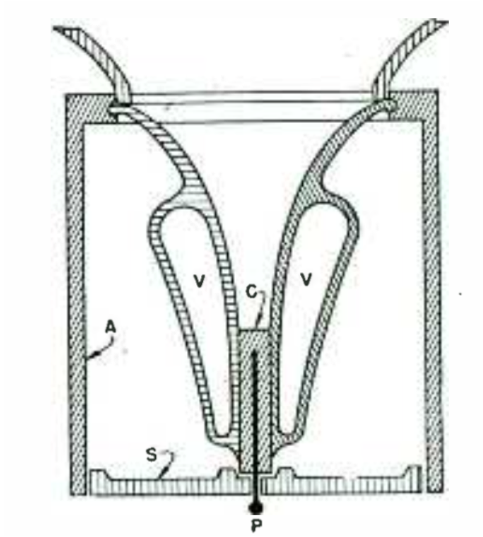



Figure 3.1.: Cross section of Siegfried Klein's Ionophone; explanation: **P**-platinum wire, **C**-quartz cylinder, **V**-vacuum space in the horn walls, **A**-outer shield [4]. **S** is not declared in original, however would be an insulating shield between platinum wire and outer shield

was modulated in result generating audible sounds [4].
This concept was later patented and licensed to different manufacturers all over the world. After some smaller changes to the device, it was e.g. sold as the "Ionophon Lautsprecher" by Telefunken or as the "Ionovac" by DuKane and later on Electro-Voice [5].

## 3.3. Commercial products

In 1956/1957, the first commercial plasma speaker, the "Ionovac Model T-3500", was announced by DuKane in various magazine articles and advertisements [6]. Its release was the beginning of only a handful of plasma speakers being introduced until today. There are especially two to three manufacturers worth mentioning, Magnat, Lansche Audio and Acapella Audio Arts.

### 3.3.1. Magnat

In 1978, Reiner Haas, CEO of Magnat, participated in the Consumer Electric Show (CES) in Chicago when for the first time he saw and heard a plasma tweeter by Siegfried Klein himself. He was fascinated enough to instantly purchase world licenses to build such speakers. After years of research and development, with Klein as project manager, Magnat released their first plasma tweeter, the Magnat MP-01.

As a second, more advanced version of the MP-01, just a few years later, Magnat introduced the MP-02. At a price of 2000,- DM a piece, it delivered a frequency range of $4.5kHz$-$150kHz$ with a sound pressure level of $95dB$ @ $1m$ [7][8]. As no information could be found on the supplied power, even in Magnat's own catalogue from 1983, one can act on the assumption that it was fed with $1W$ as it is a standard measurement power. Magnat also stated that their MP-02 speaker was the first plasma tweeter that was built in such a way that it radiates omni-directionally [9].

a) Magnat MP-01 [10]


b) Magnat MP-02 as part of a four-way speaker with visible plasma flame [11]

Figure 3.2.: Magnat's commercial plasma loudspeakers

### 3.3.2. Lansche Audio & Acapella Audio Arts

Two manufacturers that still produce plasma tweeters today are Lansche Audio and Acapella Audio Arts. Both German companies, they have their unique approaches to the construction of the plasma tweeter, although similarities can be observed. Both, the Lansche Audio Corona tweeter and the Acapella Ion TW 1S look similar to the first designs by Siegfried Klein making use of exponential horns for impedance matching.

The Lansche Audio Corona tweeter offers a frequency range from $1.5kHz$ to $150kHz \pm 3dB$ and a sound pressure level of $110dB$ [12]. For the maximum SPL no information on provided power or measurement distance could be found. One can assume that it was measured at a distance of 1m with a power of $1W$. Since it is not obtainable as a single unit but only as the built-in tweeter of high fidelity speakers, no price for a single unit could be researched.

a) Lansche Audio Corona [12]

b) Acapella Audio Arts Ion TW 1S [13]

Figure 3.3.: Both products nowadays are only obtainable as built-in tweeters in multi-way speakers

The Acapella Audio Arts Ion TW 1S used to be purchasable as a stand-alone unit (see figure 3.3b) but today is only built into speakers such as the "Campagnile 2" or the "Triolon Excalibur" and provides a frequency range from $5kHz$ up to $50kHz$ with a maximum sound pressure level of $110dB$ @ $1m/1W$ [13], [14]. In 2001, the price for a single unit was listed at 5000,-DM [15]. Today, the units can only be bought second-hand and reach prices of more than 12.000,-€.

## 3.4. Summary

It can be seen that although the technology might seem futuristic, it is actually already more than 100 years old. Introduced by William D.B. Duddell and steadily developed further, nowadays there are different highly sophisticated versions of plasma speakers available.
Additionally to the above shown commercial products, there are numerous Do-It-Yourself versions available ranging from small builds to big and advanced constructions. Most of these DIY-projects however do not have two built-in electrodes to generate a plasma between them but use the ground surrounding the speaker as a second electrode. The speaker being built for this work is one of these.

# 4. Audio transducing theory

In chapter 6.1 a deeper look into the circuit board design will be taken discussing the specific build for this work as there are several different approaches for the schematics. However, the transformer itself with its primary and secondary windings is always part of a plasma tweeter. Therefor, this chapter will approach the actual coils and the method of creating audible sound waves.

## 4.1. Tesla coil functionality

The basis for any plasma speaker are the primary and secondary windings of a transformer which, together with specific capacitors, build up the so called Tesla transformer or Tesla coil. The ultimate goal is to maximize the output voltage of the Tesla coil in order to get the biggest possible plasma or, in other words, to ionize as many molecules as possible (see section 4.2). Even without the capacitances, the voltage is stepped up by determining the amount of windings on both primary and secondary coils and as a consequence the ratio of turns.

$$\frac{N_{L_1}}{N_{L_2}} = \frac{U_{L_1}}{U_{L_2}} \tag{4.1}$$

As is visible from equation 4.1, the ratio of wire turns directly defines the amount of voltage increase.

Since this increase is not enough for the generation of a plasma, the aforementioned capacitances are added to the circuit, of which the conceptual idea is shown in figure 4.2. There are two different inductance-capacitance-resonance (LC resonance) circuits, namely the primary and the secondary one. The primary LC resonance circuit in this example is composed of the capacitance from capacitors $C_{10/11}$ and $C_{12}$ and the primary coil $L_1$. The secondary resonance circuit is made of the secondary coil $L_2$, the stray capacitances between the individual secondary coil windings and the capacitance between the electrode $E_1$ and the ground $C_{gap}$. The contributions of the separate capacitances are represented in figure 4.1.

The trick is that although the values of all components differ, both resonance circuits have the same resonance frequency $f_{res}$ which can be calculated by the following equation if the parts' values are known.

$$f_{res} = \frac{1}{2\pi\sqrt{LC}} \tag{4.2}$$

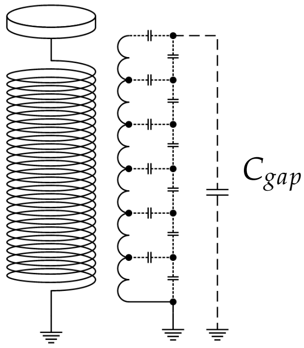



Figure 4.1.: Equivalent circuit showing different stray capacitances of the secondary coil of a Tesla transformer [16]

Consequently, the type of transformer being built is called resonant transformer or oscillation transformer. By making use of this type of transformer, the voltage across $L_2$ is particularly increased because the design performs with minimal resistive energy losses, or, in other words a high Q-factor. The resonance frequency of the secondary side is much harder to tune because it is quite elaborate to calculate the stray capacitances between the individual coil windings and the capacitance $C_{gap}$. Also the inductance $L_2$ can only be calculated as ideal; however the actual value will very likely differ from the calculated one. While that holds true for the primary coil, the primary capacitances can be specified.

The designer of the circuit predetermined the resonance frequency and chose component values accordingly, however, in case a problem arises, additional capacitors can be added to the primary side which is of essential importance to match resonance frequencies of both sides.

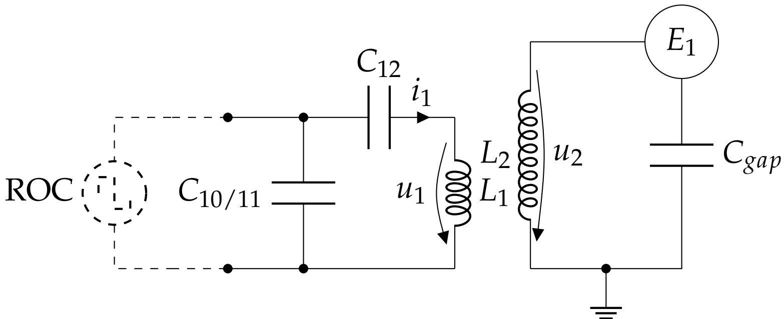



Figure 4.2.: Conceptual sketch of the Tesla transformer with its primary and secondary LC resonance circuits; ROC = rest of circuit

### Mutual inductance M

Another factor that needs to be mentioned is the mutual inductance $M$ of the two windings. Mutual inductance is the inductance caused in one electrical loop by a magnetic field which was itself caused by another electrical loop. In other words applied to the given circuit, the current through $L_1$ induces a magnetic field around it. This magnetic field itself induces a current in coil $L_2$.
The amount of magnetic field passing both primary and secondary winding is described by the coupling coefficient. It ranges from 0 to 1 and the higher it is, the more of a magnetic field passed through the secondary.
While in a general transformer, the used iron core causes a high coupling coefficient (normally $0,9$ to $1,0$; the transformer is called tightly coupled), this is unwanted in a Tesla coil. Therefor, the primary and secondary coils are placed further apart and *without* an iron core between them. This effects the wanted low coupling coefficient of $0,1$ to $0,6$; a loose magnetic coupling [17].
As the mutual inductance is purposely kept low in a Tesla coil, no further attention will be paid to it.

## 4.2. Ionization of air

The separation of at least one electron from an atom or molecule is called *ionization*. In general, ionization can be caused by high temperatures, a strong electric field or through chemical reactions. In the example of a plasma speaker, it is caused by the strong electric field between two electrodes. While most commercially available products make use of two hardware electrodes (see chapter 3), the tweeter being built for this project simply uses the ground as the second electrode in a fairly large distance, as it has been shown in section 4.1.

The air, especially surrounding the first electrode is functioning as the supply for gases to be ionized which are mainly oxygen and nitrogen, however miniscule amounts of argon and other trace elements are also ionized. The minimum energy needed to ionize gases is called the ionization energy or ionization potential and is measured in $\frac{eV}{atom}$ or $\frac{eV}{molecule}$. The unit $eV$ is called *electronVolt* and is "equal to the energy gained by an electron [...] when the electrical potential at the electron increases by one volt" [18].

Table 4.1 highlights the ionization potentials $W_{ion}$ for the three most common gases in the earthly atmosphere - nitrogen, oxygen and argon. The numbered index of the columns represents the count of the electrons split from their atoms or molecules. As an example: An energy of $13.618eV$ is sufficient to part the first electron of an oxygen molecule, for the second electron to be separated from the molecule, $35.121eV$ of energy are necessary, and so on [19].

| | $\mathbf{W_{ion,1}}$ | $\mathbf{W_{ion,2}}$ | $\mathbf{W_{ion,3}}$ | $\mathbf{W_{ion,4}}$ | $\mathbf{W_{ion,5}}$ | $\mathbf{W_{ion,6}}$ | $\mathbf{W_{ion,7}}$ | $\mathbf{W_{ion,8}}$ |
|---|---|---|---|---|---|---|---|---|
| $N_2$ | 14,534 | 29,601 | 47,449 | 77,474 | 97,890 | 552,072 | 667,046 | |
| $O_2$ | 13,618 | 35,121 | 54,936 | 77,414 | 113,899 | 138,120 | 739,29 | 871,410 |
| Ar | 15,760 | 27,630 | 40,740 | 59,810 | 75,020 | 91,009 | 124,323 | 143,460 |

Table 4.1.: Ionization energies $W_{ion}$ in [eV] for nitrogen ($N_2$), oxygen ($O_2$) and argon ($Ar$) rounded to three decimal places [19]

This splitting of electrons and their passage through ionized air is what can be observed as plasma, the electricity conducting fourth aggregate phase.
When the electrons pass through their surrounding space, they can collide with other molecules and cause them to loose electrons, too [20]. This chain reaction is called electron avalanche or avalanche ionization. The higher the voltage of the electric field causing the plasma, the more extensive the discharges will be which results in a greater plasma flame and provides a potentially louder sound later on.
While in space due to the vacuum the plasma is long-lasting, on earth, caused by the atmospheric pressure, the atoms or molecules will recombine with their split electrons [21]. Therefore, a continuous generation of plasma is an essential requirement for the operationability of a plasma speaker.

### 4.2.1. Classification of the plasma

Since there are several different types of plasma with a great many properties, the most important ones are mentioned following together with the classification of the plasma observed in the build for this work.

#### Type of discharge

The plasma can be present in the form of either arc or corona discharges.
The difference between these two is that an arc discharge (what is generally acknowledged as an electric arc) is per definition a discharge between two electrodes while a corona discharge is the discharge from a single electrode into a former non-conducting medium such as air. It is therefore also called one-electrode discharge [22], [23]. So it becomes clear that in the build for this work the plasma is present in the form of corona discharges.
An important value that needs to be addressed when talking about corona discharges is the *critical disruptive voltage* which, under normal conditions in air, is equal to the dielectric strength of air and is approximately $30\frac{kV}{cm}$; however, its exact value shifts with varying shapes and sizes of electrodes [24], [25]. This number can be interpreted as follows: In order to reach a

length of the coronal discharge of 1cm, the electric field between the two electrodes needs a minimum voltage of approximately $30kV$.

However, it is not the minimum voltage necessary for corona discharges to occur. According to Hurley et al., a minimum voltage of 2-6$kV$ is required to initiate corona discharges with a dependency on the size of the electrode. The finer it is, the lower the voltage needed [26].

### Plasma density and degree of ionization

When determining how strong the present plasma is, there are two intertwined terms that need to be addressed; electron density $n_e$ and ion density $n_i$, both in $1/m^3$. The present plasma has a state of quasi-neutrality in which the electron and ion density are almost the same [27].

$$n_i \approx n_e \tag{4.3}$$

Since gases can be ionized varyingly strong, the ion density can be used to calculate the degree of ionization $\alpha$:

$$\alpha = \frac{n_i}{n_i + n_n} \tag{4.4}$$

with $n_n$ being the neutral density in $1/m^3$. As it can be seen from equation 4.4, the degree of ionization is the ratio of ionized particles and total particles and can be expressed in percentages.
A fully ionized plasma with a degree of ionization of almost 1 (100%) only occurs in space during e.g. solar winds or solar fusion or on earth during artificially induced fusions, e.g. nuclear explosions [28].
However,

> "a gas achieves an electrical conductivity of about half its possible maximum at about 0.1% ionization and has a conductivity nearly equal to that of a full ionized gas at about 1% ionization." [29]

Therefore, the plasma observed when working with plasma tweeters is always a partially ionized plasma, also called weakly ionized gas.
In German literature, another term can be found for partially ionized gases: "low-temperature plasma" (Niedertemperaturplasma) refers to a gas with a low degree of ionization where boundary conditions such as spatial limits have a major influence on the plasma and does not necessarily refer to the temperature of the plasma [30].
The energy needed to sustain the ionization is drawn from the electric field induced by the electrode and after some time reaches an equilibrium. This means that the amount of energy which is lost to the surrounding air is equal to the amount of energy transferred to the electrons by the electric field [31]. How the electrons loose energy is covered in section 4.3.2.

**Temperature of the plasma / type of generation**

As Béquin et al. [32] have presented, plasma loudspeakers can be partitioned into two groups depending on the type of sound generation. On the one hand there are hot-plasma loudspeakers which use heat as a source for sound waves and on the other hand there are cold-plasma loudspeakers where the main acoustic source is a coulombic force source. The latter are also called ionic wind speakers or electrostatic fluid accelerator (EFA) speakers and work with a high DC voltage between two differently curved electrodes. Ions are moving from an emitting to a collecting electrode and on their way collide with air molecules creating a directed gas flow called "ionic wind" [33].

However, most plasma loudspeaker constructions such as the ionophone can be labelled as hot-plasma loudspeakers. In this type of speaker, an almost isotropic (not depending on direction) heat source changes the temperature and therefore the volume of the surrounding air resulting in pressure changes audible to the human ear.

## 4.3. Thermo-acoustic sound generation

The formation of the plasma through ionization of atmospheric gases was described in the previous section. Following the principles of sound generation are clarified.
As it has been described in section 4.2.1, the type of tweeter built for this paper is a hot-plasma loudspeaker. The corresponding manner of how the audible sound waves are generated is called "thermo-acoustic sound generation".

### 4.3.1. Thermodynamic equilibrium

As previously shown, a consistent generation of plasma is a requirement for the plasma tweeter to work. In this project, this is achieved by generating a very high AC voltage of approximately $150kV$ on the secondary winding side with a frequency of $\approx 4MHz$. At this point, with no audio being played, a thermodynamic equilibrium (German: "Thermodynamisches Gleichgewicht") is reached which means that the plasma flame and directly surrounding air thereof have the same consistent temperature. The calculation of the equilibrium temperature $T_{eq}$ is however too complicated for this paper and could therefore be determined by measurement.
Instead, one can take a look at the Saha ionization equation which puts the degree of ionization of a weakly ionized plasma in thermodynamic equilibrium in relation to the temperature, density and ionization energies

of the atoms. While the exact equation would go beyond the scope of this project, the simplified version which was derived from a reaction balance of ionization- and recombination processes and stated by Stroth can be discussed:

$$\frac{n_i}{n_n} \approx 3 \cdot 10^{27} \frac{T^{3/2}}{n_i} \cdot e^{\left[-\frac{W_{ion}}{T}\right]} \tag{4.5}$$

with $n_i$ being the amount of ions in $1/m^3$, $n_n$ the neutral density in $1/m^3$, $T$ the temperature of the gas in eV and $W_{ion}$ the ionization energy of a neutral atom in eV [34].
In equation 4.5, the ions are single positively charged, meaning only one electron was removed. One can see that the degree of ionization rises if the temperature (or thermal energy of the particles) becomes comparable to the ionization energy of such atoms or molecules.
Stroth shows the simplicity of the equation with low degrees of ionization at hand with the following example: At room temperature (corresponds to $0,026eV$) and a pressure of $1bar$ (concentration of the gas $n_{tot} \approx 2,6 \cdot 10^{25} m^{-3}$) the degree of ionization for hydrogen (with $W_{ion} = 13,56eV$) is only about $10^{-120}$.
The relation between the temperature in Kelvin and electronvolt is expressed in the following equation:

$$\frac{1eV}{k_B} = \frac{1,602176634 \cdot 10^{-19} J/eV}{1,380649 \cdot 10^{-23} J/K} = 11.604,51812 K/eV \tag{4.6}$$

This means, that with the help of the Boltzmann constant $k_B$ and the expression of electronvolt in its energy counterpart, a clear conversion can be stated.

### 4.3.2. Modulation of plasma

The formation process of audible sound waves can be characterized as a closed thermodynamic system with a finite volume $V$ in which energy is transported but no mass. The mean value of the pressure of the sound wave is directly connected to the mean value of the internal energy density of the volume $p \equiv U/V$. Making use of the first law of thermodynamics, the internal energy change of a system

$$\Delta U = \Delta Q + \Delta W \tag{4.7}$$

is calculated by summing up the energy which is gained as heat $\Delta Q$ with the work acted on it $\Delta W$. While it is important to note that the latter is of negative value which can be observed when rewritten as $\Delta W = -p \cdot \Delta V$, it is not of essence for a plasma speaker as there is no membrane or other mass to move to produce audible sound waves which means that $\Delta W = 0$. Therefore, the heat that is produced by a thermo-acoustic transducer is equal to the internal energy change

$$\Delta U = \Delta Q \tag{4.8}$$

and further is the change in pressure directly proportional to the change in internal energy density and, more importantly, the temperature change [35].

$$\Delta p = \frac{\Delta U}{V} = \frac{\Delta Q}{V} \tag{4.9}$$

This phenomenon can also be described as follows: When the voltage on the secondary winding increases, the gas surrounding the electrode gets more ionized, in other words, the corona discharge or plasma flame is greater. Subsequently, the temperature rises which leads to a higher mobility of the ions which start to interact with the surrounding, non-ionized air. During this interaction in the form of elastic collisions they transfer a part of their energy to these non-ionized air molecules which as a result get compressed. An audible sound wave is generated. Once the voltage goes back to its static value, the chain of events gets reversed.
That the amount of thermal energy $Q$ is in direct relation to the amount of electrical power can be seen from the following equation

$$Q = \int_0^{t_{th}} P_{el}(t)dt \tag{4.10}$$

or simplified with mean (RMS) values

$$Q = P_{el,eff} \cdot t_{th} = \frac{P_{el,eff}}{f_{th}} \tag{4.11}$$

with $P_{el}$, $P_{el,eff}$, $t_{th}$ and $f_{th}$ being the electric power fed into the system, its RMS value, the heating period and the heating frequency, respectively [36].

## 4.4. Summary

One can see that the functionality of a plasma speaker is dependent on many different factors including but not limited to the tuning of the resonance frequency of the coils to achieve maximum power output, the surrounding gas and conditions and the types of electrodes.
The plasma tweeter built for this project will discharge a coronal plasma flame after a voltage between $2kV$ and $6kV$ is reached. The plasma itself will be a weakly ionized one with a high temperature. Having achieved the thermodynamic equilibrium, the temperature of the plasma is modulated by the audio input and therefore generates sound by free electrons of the plasma interacting with the surrounding air.

# 5. Advantages and disadvantages of a plasma speaker

## 5.1. Advantages

The major difference between a plasma speaker as a transducer and conventional speakers is that no actual physical membrane or other mass needs to be moved in order to produce audible sound waves. For the sake of completeness, it is important to note that the mass of the moved electrons in the plasma needs to be accounted for and therefore the sound generation process is not completely massless. However, since one electron has a mass of only $\approx 9.1 \cdot 10^{-31} kg$ the transducer is almost massless [37].
This results in a couple of advantages which will shortly be discussed as follows.

### 5.1.1. Omnidirectionality

In conventional loudspeakers the physical membrane dictates some sort of directivity in higher frequencies because as the wavelength becomes smaller relative to the membrane, phase cancellation takes place. This is caused by the overlapping audio coming from different parts of the membrane and becomes stronger when moving off axis [38].
A plasma speaker does not have that problem as there is no considerable moving "area" against which the wavelength could become small. As described in section 4.3, the sound waves are generated by changing the temperature of the plasma resulting in electrons colliding with the surrounding air. As this happens in all directions, the plasma speaker radiates omnidirectionally on the condition, of course, that the plasma flame is in the open like in the Magnat MP-02 and not connected to an exponential horn like in modern products.

### 5.1.2. Frequency range and response

A limiting factor on traditional speakers is the maximum frequency they can accurately reproduce. Depending on the material, they surpass the standard of $20kHz$, for example the tweeter made from beryllium by Focal which

reproduces up to $40kHz$ [39]. Ribbon tweeters have the possibility to reach even higher frequencies.
However, additionally to the flaw of a directed sound, they all have resonance frequencies resulting from the mass-spring systems they are made of, rendering it near impossible to achieve a flat frequency response.
A plasma tweeter combines very high cut-off frequencies of at least $50kHz$ to $150kHz$ (like the Lansche Corona plasma speaker) with a very flat frequency response (see subsection 3.3.2).

### 5.1.3. Transient response

As the mass required to be moved in a plasma transducer is so incredibly small, it can be accelerated almost instantaneously resulting in an unbeatable response when reproducing transients [40].
Even taking into account the inertia of the enclosing air, a cubic centimeter of air weighs around $1.29mg$ which is around 15 times less than the calotte of a titanium tweeter [7].

## 5.2. Disadvantages

As Bastien already wrote in 1987, hot-plasma loudspeakers produce levels of ozone $(O_3)$ due to the energy of the ionization process itself [41]. When the air surrounding the electrode is ionized, ultra-violet light is emitted which has enough energy to turn atmospheric oxygen into ozone. It oxidizes everything it is getting into contact with and is hazardous in higher doses although even smaller doses are felt as unpleasant [7].
The safety issues coming with the production of ozone were counteracted in different ways by different manufacturers. The basket enclosing the electrode of Magnat's MP-01 and MP-02 was fitted with differently braided meshes to keep the temperature of the surrounding air high enough to accelerate the decomposition of the ozone. The Hill Plasmatronic Type 1 speaker was fitted with a helium tank which constantly supplied helium to the tweeter unit which decreased ozone production drastically. However, after every approximately 300 hours of listening the helium tank had to be refilled [42].
Modern manufacturer Lansche Audio makes use of yet another technology. For the first few minutes after powering up the Corona tweeter, a ceramic catalyst prevents ozone from emerging. After two minutes, when the inside of the combustion chamber has reached its final temperature of more than $350°C$, no ozone can develop as a result of the high temperature [43].

# 6. Construction of the plasma tweeter

The basis for the plasma tweeter constructed for this work is the "Class-E Plasma Speaker Kit" by Eastern Voltage Research. The operating frequency is around $4MHz$ and the frequency response is said to be $100Hz$ to $40kHz$ although the manufacturer does not state the testing conditions and maximum deviation.
By default, the design incorporates a class E switching topology, controls for output power, modulation depth and audio input levels and a 10-step LED VU meter [44].
The design was expanded with a 7-segment display for voltage display and a switchable fan.

According to the manufacturer, this specific plasma tweeter produces arcs of approximately 2 inches length (about $5cm$). Taking the critical disruptive voltage of $30\frac{kV}{cm}$ into account, the voltage across the secondary coil would amount to

$$V_2 = 30\frac{kV}{cm} \cdot 5cm = 150kV \tag{6.1}$$

The plasma speaker makes use of two separate power connections and two separate power supplies, one for the control circuit and one for the generation of the plasma flame. On the one hand this makes testing and configuring of the speaker easier and on the other hand it ensures that no special power transformer with several outputs needs to be bought/used.

## 6.1. Schematics and circuit board design

In order to construct the Tesla tweeter the schematics were bought from `easternvoltageresearch.com`. They were then transcribed to a digital format using a student license for Autodesk EAGLE (see figures 6.1-6.4). For simplicity reasons all schematics were divided into two printed circuit boards (short: PCB); a main PCB containing the power supply unit(s), the audio driving stage and the Class-E power stage and a control PCB containing different control LEDs, the 10-step LED VU meter and the 7-segment voltage meter together with a switch to turn on a fan which is useful to keep

the circuitry from running too hot.
When the planning process for the printed circuit boards was finished, five pieces of each were ordered from `jlcpcb.com`. Following, the components were soldered onto them, starting with small components like resistors and diodes and finished with bigger components like transformer $T_{41}$ or capacitor $C_{45}$ (see figure 6.14).

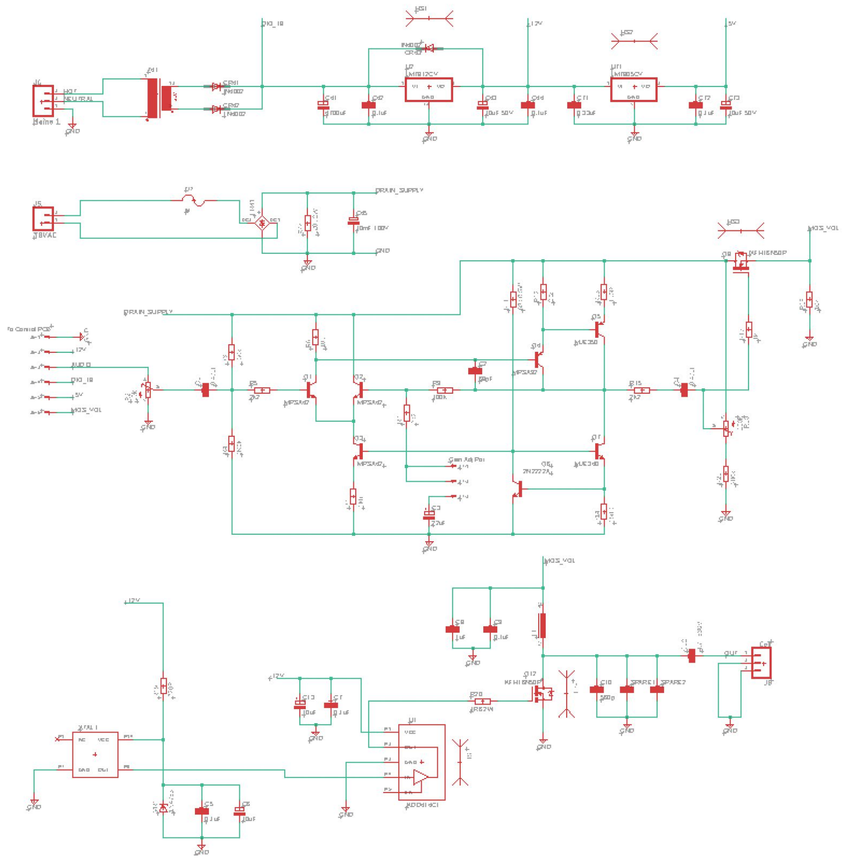


Figure 6.1.: Schematics of the main PCB

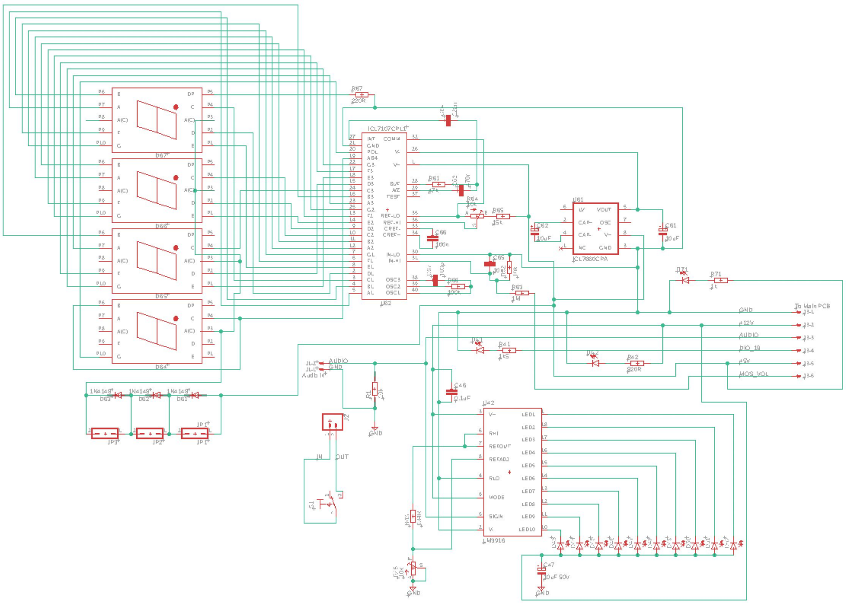


Figure 6.2.: Schematics of the control PCB

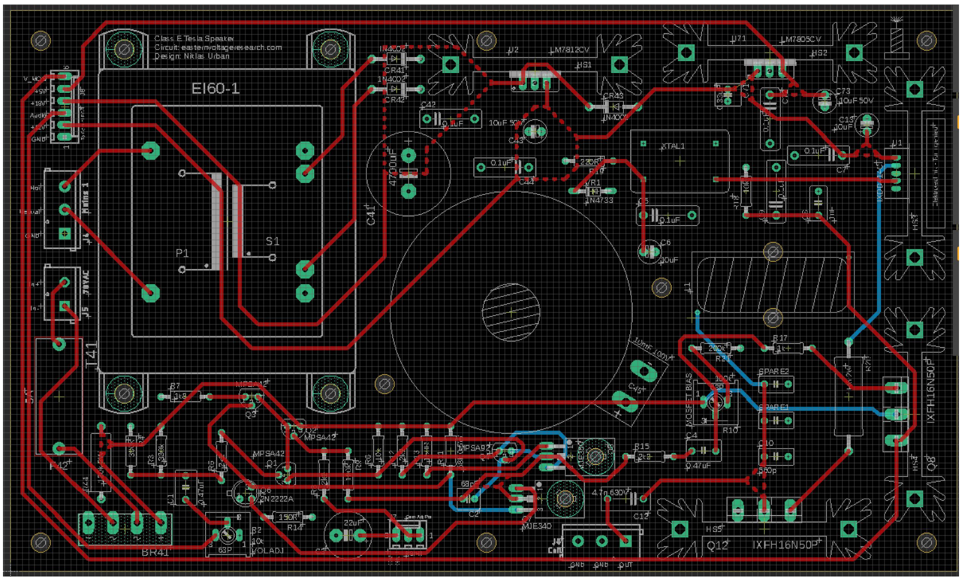



Figure 6.3.: PCB Design of the main PCB

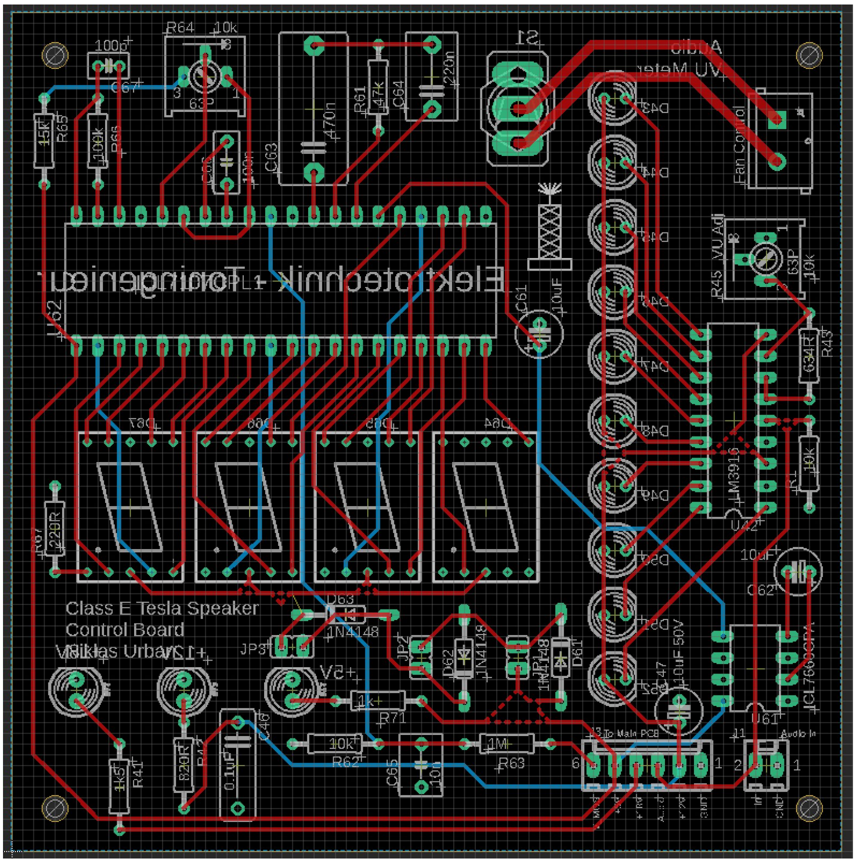



Figure 6.4.: PCB Design of the control PCB

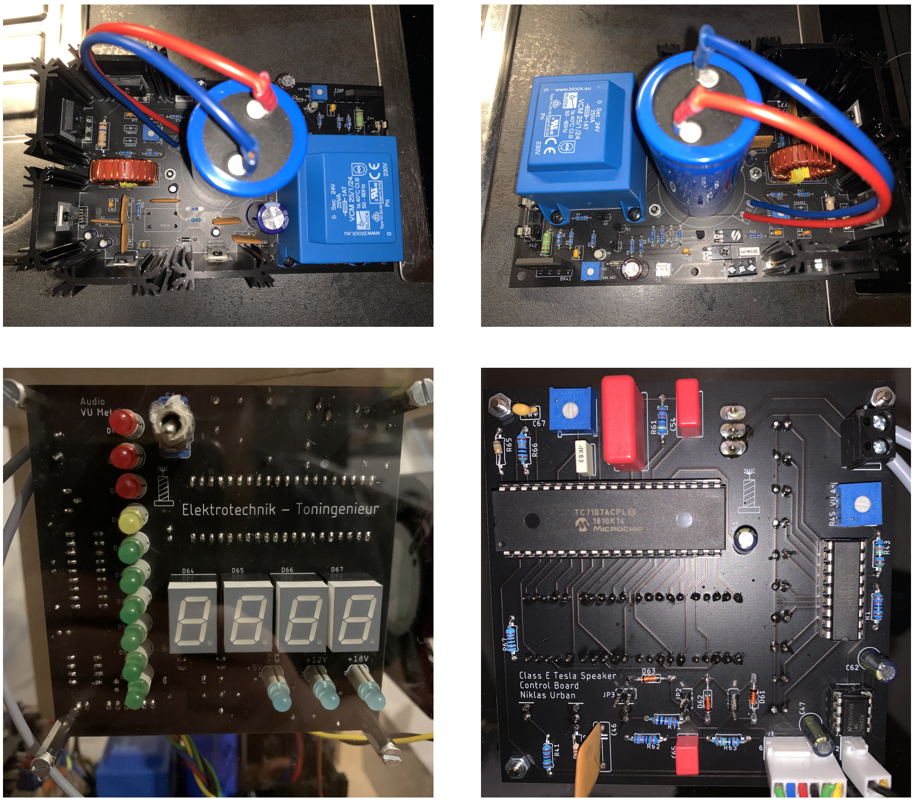



Figure 6.5.: Images of both soldered main PCB (top) and control PCB (bottom)

Scans of the original schematics are to be found in appendix A. Following, the individual parts of the schematics are explained.

### 6.1.1. Low voltage power supply

The low voltage power supply part is used to obtain different voltages. First, transformer $T_{41}$ is used to transform mains voltage of $230V_{ac}$ to about $24V_{ac}$ and diodes $CR_{41}$ and $CR_{42}$ rectify that voltage. Diode $D_{41}$ is an indicator for that voltage.
$U_2$ is a voltage regulator of type LM7812 and generates a voltage of $+12V$. The capacitors $C_{41}$ through $C_{44}$ are used for two main reasons. On the one hand they filter out any unwanted AC signal. On the other hand the ones at the voltage regulator's input protect it from self-oscillating which would end in an overheating and destruction of the voltage regulators.
Diode $CR_{43}$ has the purpose of protecting the subsequent circuit in such a way that should, for any reason, the voltage of its output rise above its input voltage it would destroy the voltage regulator. In that case the following circuit could be destroyed as it would experience a voltage exceeding the rated one.

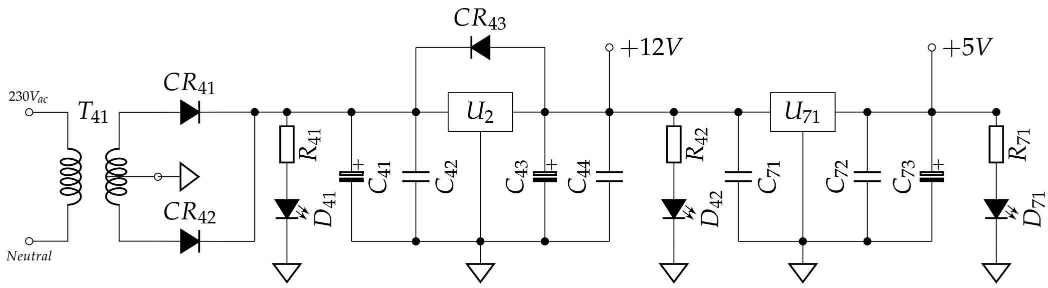



Figure 6.6.: Low voltage power supply schematics

LED $D_{42}$ indicates a present and working $+12V$ voltage. Afterwards the same circuitry obtains a $+5V$ level used for the 7-segment voltage meter by making use of a LM7805 voltage regulator.
Note: There is no diode shown from output to input of $U_{71}$ as it was initially forgotten. The actual build will incorporate such a diode (1N4002) soldered point-to-point.

### 6.1.2. High voltage power supply

The drain supply voltage for MOSFET $Q_8$ which is one of the main components of the Class-E power stage, is provided by a separate mains voltage input which is transformed to $70V$ by transformer $T_{42}$ with a maximum current rating of $4A$. Afterwards, the voltage is rectified by the full wave bridge rectifier $BR_{41}$ and $C_{45}$ acts as a DC filter capacitor removing some leftover AC ripple.
During negative half cycles, Resistor $R_{44}$ acts as a load resistor for the ripple capacitor to discharge itself.

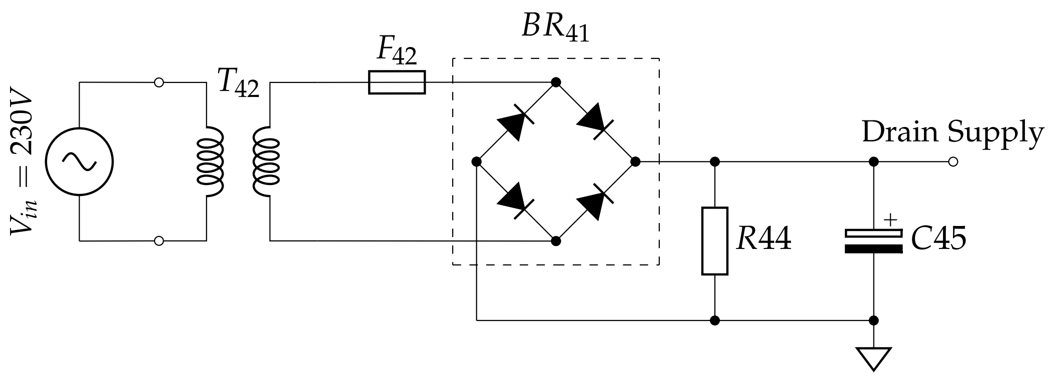



Figure 6.7.: High voltage power supply schematics

The rectified voltage under ideal circumstances can be calculated with

$$V_{dc} = \sqrt{2} \cdot V_{ac,eff}. \tag{6.2}$$

However, this is assuming no load and requires a clean sine wave as input signal. In such conditions, figure 6.8 displays the relationship between clean sine wave, rectified voltage and voltage after a ripple capacitor.

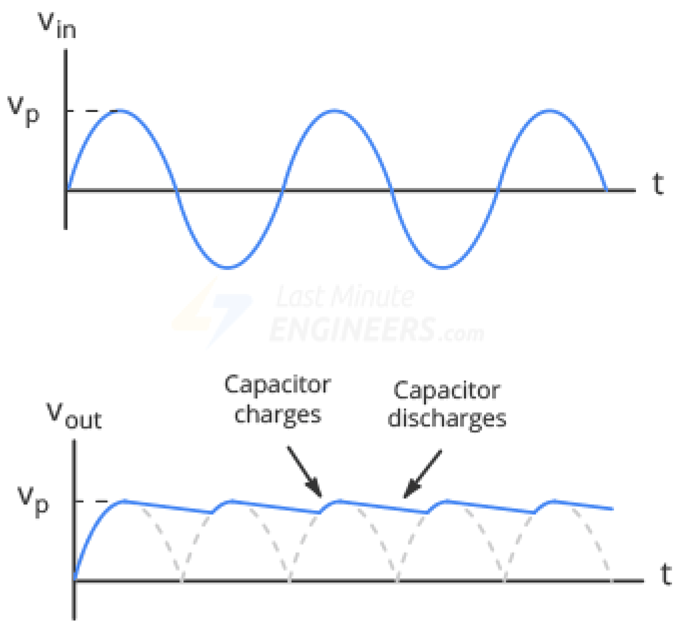



Figure 6.8.: Top: Input sine wave; Bottom-Dotted Line: Rectified sine wave; Bottom-Full Line: Rectified sine wave with ripple capacitor [45]

### 6.1.3. Audio drive stage

The audio drive stage, also called high side AM modulation stage, is comprised of many different components mainly serving one purpose, namely to act on the analog audio input at line level in such a way that it is amplified enough to modulate the carrier signal of the Tesla coil.
The audio signal input level can be adjusted with potentiometer $R_2$. Afterwards, the signal is amplified by transistors $Q_1$ through $Q_7$ and the connected resistors to create a high enough voltage to be able to modulate MOSFET $Q_8$. Therefore this circuit is a preamplifier circuit. $Q_8$ previously needs to be biased to about $80 - 85\%$ of the drain voltage to obtain operating point.
Potentiometer $R_{16}$ is used to adjust the output level of the preamplifier circuit.

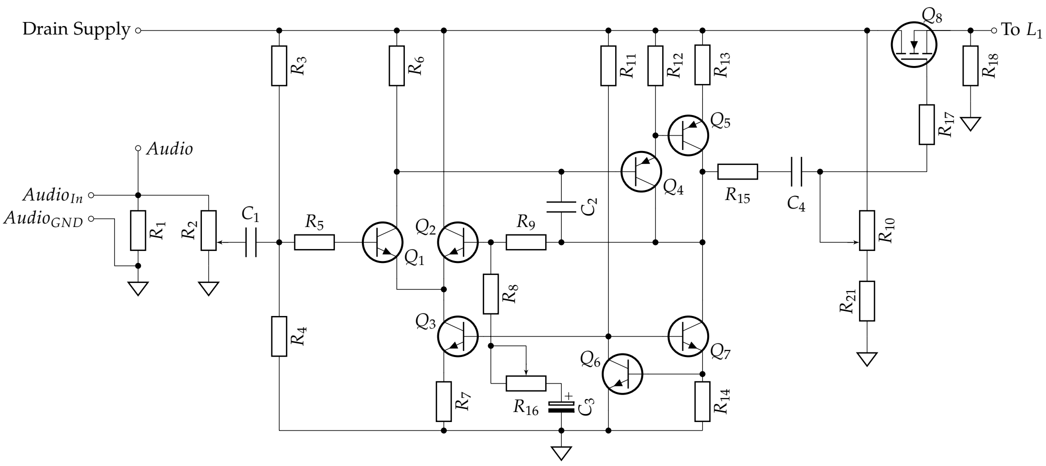



Figure 6.9.: High Side AM Modulation schematics

The whole stage is a linear modulating circuit, more precisely an amplitude modulation circuit, with transistor $Q_8$ as the linear pass element. A linear modulation means that the mathematical function between useful signal and transmission signal is a linear function. As the amplitude modulation represents a multiplication in the time domain, it is a linear modulation.

### 6.1.4. Class-E 4MHz power stage

The first component of the power stage is quartz oscillator $XTAL_1$ with a frequency of $4MHz$ creating a square wave signal acting as the carrier signal. Afterwards, the carrier signal drives the gate driver $U_1$. A gate driver is a specific type of amplifier required to drive powerful MOSFET gates which have a very high input capacitance and resistance. In this case it is a IXDD414CI, a high current, high frequency gate driver meaning it will provide currents of up to $14A$ "with voltage rise and fall times of less than $30ns$" [46]. In other words, it can operate at frequencies of more than 10MHz. The output signal of $U_1$ has a voltage of $+12V$ which is required to power the switching MOSFET $Q_{12}$. As it has been said in section 4.1, capacitors $C_{10}/C_{11}$ and $C_{12}$ are important to tune the resonance frequency of the primary resonance circuit. Per default, $C_{11}$ is not connected and just an empty space which can be used for an additional capacitor should it be necessary.

Central component of the Class E switching stage is the switch itself. In this build it is composed of MOSFET $Q_{12}$. The primary resonance circuit also acts as a load network to the switch which creates a sinusoidal output signal driving the actual load and which minimizes switching losses.
Inductor $L_1$ which is connected to MOSFET $Q_8$ of the audio driving stage acts as a constant current source since it is connected in series to the output

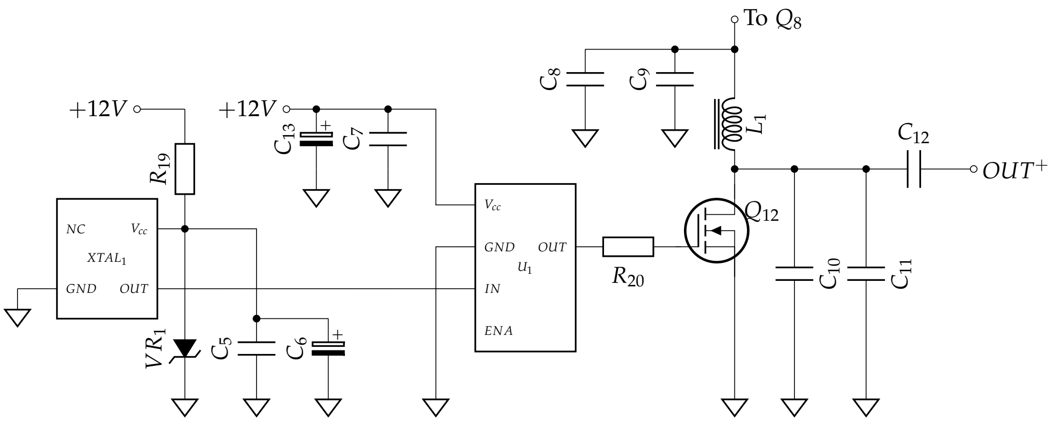



Figure 6.10.: Class E 4MHz power stage schematics

voltage of $Q_8$. The inductor smoothes the direct current and blocks high frequency signals. This effects a virtually constant current once the attack time has passed (no information could be found on how long this attack time is).
According to Class-E switching theory the input at the gate of MOSFET $Q_{12}$ has no useful influence on the output signal. Therefore, the modulating audio signal is connected to the MOSFET's drain. The relation between AM signal and output of the transistor can be described as almost linear [47].

### 6.1.5. 10-step LED VU meter

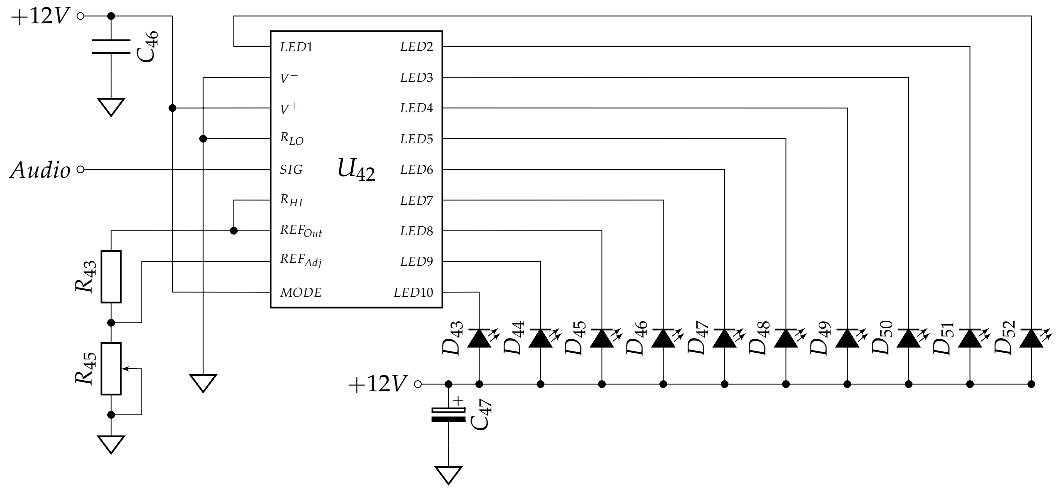



Figure 6.11.: VU meter schematics

The 10-step LED VU meter is used to visualize the level of the audio signal. Its main component, together with the LEDs themselves, is the LED display driver $U_{42}$ which is the integrated circuit LM3916. It is powered by the $+12V$ voltage line which is also connected to the pin called MODE. This sets the drivers operational mode to "Bar Graph Display" as opposed to Dot Display [48]. The voltage divider composed of $R_{43}$ and $R_{45}$ is used to set the threshold of the display.

### 6.1.6. 7-segment voltage meter

The 7-segment voltage meter is not part of the original schematics and was added to illustrate the current voltage of the output of MOSFET $Q_8$. However, this input can be manually changed, if necessary.
IC $U_{61}$ is a voltage converter called LMC7660IN to achieve a $-5V$ voltage line needed by the 3.5 digit A/D converter ICL7107 (U62) which is used to drive the four 7-segment LED displays. The connected capacitors and resistors are needed to set, among others, operating points. An exact explanation is not required for the understanding of this project and therefore left out.
Jumper pins $JP1$ through $JP3$ are used to define the displays brightness.

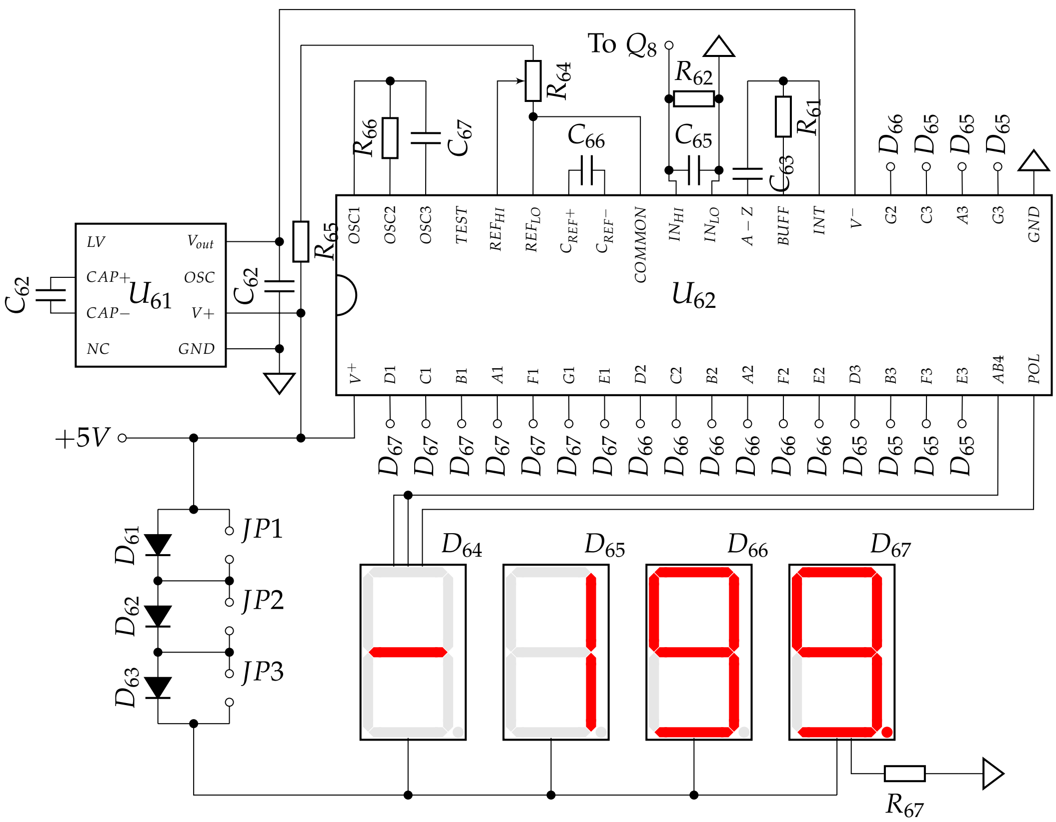



Figure 6.12.: 7 segment schematics

## 6.2. Coil and housing construction

In order to construct both primary and secondary coils, the coil forms were 3D printed. The primary coil form with a diameter of 3,1 inches ($7,874cm$) and the secondary coil form with a diameter of 2,3 inches ($5,842cm$). Both were designed with the free student edition of Fusion360 and both are fitted with four small legs with holes in order to screw them onto the top of the housing. The primary coil is composed of five turns with 14AWG ($2,08mm^2$) wire and the secondary coil is composed of enough turns of 22AWG ($0,324mm^2$) wire to get a width of 3⁵/8 inches ($9,2075cm$). At the top of the secondary coil, the electrode is constructed by extending the wire above the coil for 4 inches ($10,16cm$).

The housing was constructed by using $18mm$ multiplex wood for both base and top plates, $2x2cm$ square bars in the corners and $2mm$ acrylic glass for the sides to make it possible to look into the housing.

## 6.3. Configuration

Only the most important aspects of the configuration are described below as the full document is available for free on `easternvoltageresearch.com`. Before the configuration can start, the different DC voltage lines on the PCBs need to be checked. If they are correct, the output voltage of MOSFET $Q_8$ has to be configured to approximately $100V$ by disconnecting drain choke $L_1$ and adjusting trimmer $R_{10}$ until the voltage at Pin 3 of $Q_8$ reads the wanted value.

Afterwards, the electrode on top of the secondary winding needs to be prepared. This is done by first taking about 8 inches ($20,23cm$) of wire, straightening it above the coil and checking if coronal discharges are visible when both power cables are plugged in. Then, first in 0,25 inch ($0,632cm$) and then in 0,1 inch ($0,254cm$) increments the wire is shortened until the maximum coronal discharge of approximately $5cm$ is reached. At last, the end of the wire is made into a loop with about $2,5cm$ diameter.

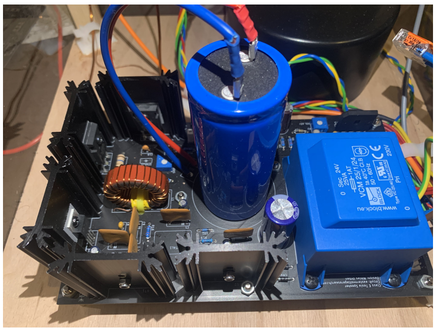
When the electrode is properly set up, the output voltage of MOSFET $Q_8$ is again changed and lowered to $85V$ the same way it was previously set to $100V$.

The next step is to adjust the trimmers $R_2$, $R_{45}$ and $R_{16}$ to specific positions by measuring the resistance across specific test points. With an audio input, $R_{45}$ can then be used to adjust the 10-step LED VU meter and $R_{16}$ to control the volume of the output music.

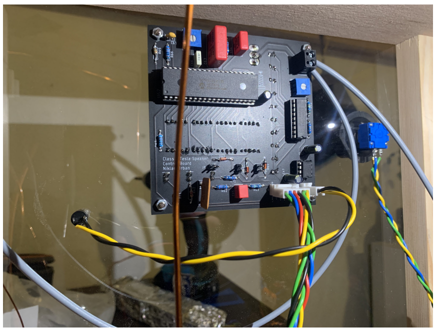
## 6.4. Photos

Following, more pictures of the completed unit are shown. Only the top of the electrode is not just yet configured in the figure 6.16a.

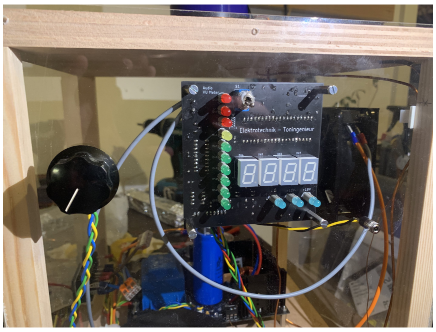
Figure 6.13.: Inside of the housing box with Main PCB and transformer $T_{42}$ on the floor plate, the fan to the left, power inputs to the right and the control PCB, volume knob and audio input on the backside



a) Main PCB top view with transformer $T_{41}$ (right) capacitor $C_{45}$ (middle)



b) Control PCB from inside the speaker with visible self-wound cable connections



c) Control PCB from the outside with visible 10-step LED meter, 7-segment meter, volume control knob (left) and Audio TS input (right)

Figure 6.14.: Images of both soldered main PCB and control PCB

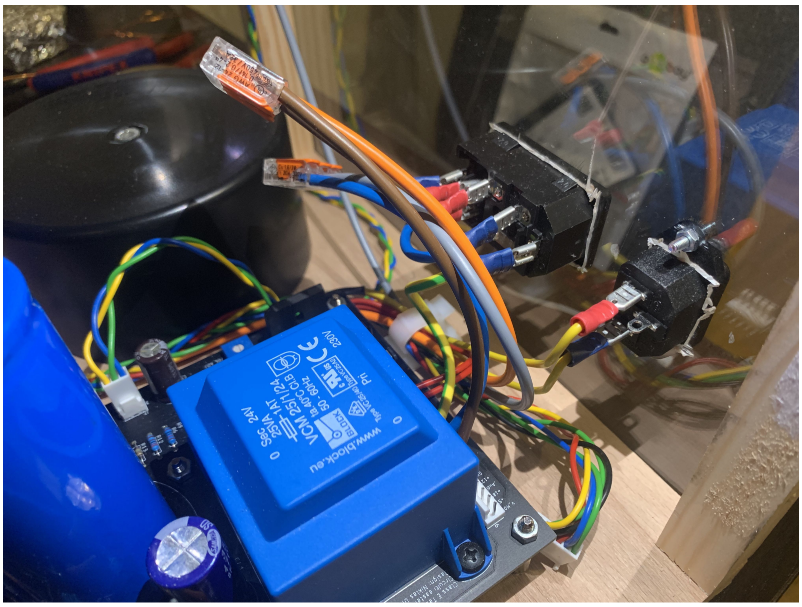
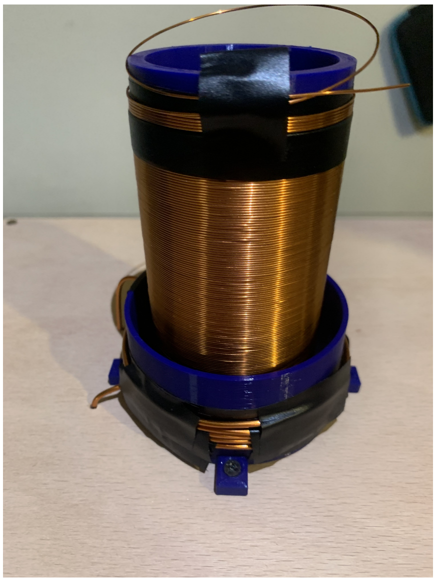
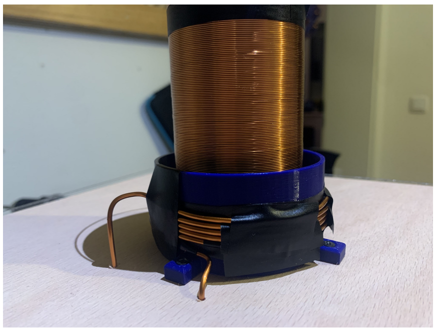


Figure 6.15.: Both IEC power connectors for low and high voltage circuitry



a) Overview of the windings on their 3D-printed coil forms



b) The connecting ends of both windings were fitted through the top plate of the housing box

Figure 6.16.: Primary and secondary windings

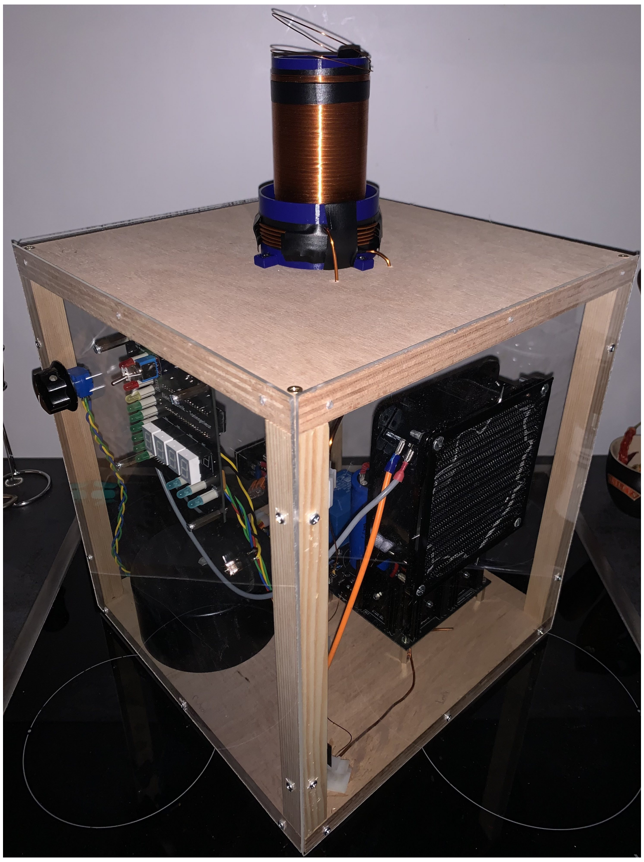


Figure 6.17.: Image of the whole speaker (without configured electrode)

# 7. Conclusion and future work

Overall it can be said that a plasma tweeter represents an interesting possibility to build omni-directional speakers with an unbeatable transient response because of the missing membrane at a relatively low cost (for this project approximately 300,- €).
While the seemingly futuristic approach behind the functionality of the tweeter can be hard to understand at first, it was possible to clarify its working principles. Namely, a strong electric field between an electrode and the ground ionizes the air around the electrode which becomes visible as coronal discharges, also called plasma flames. In this so called weakly ionized plasma, electrons and air component ions move at high rates and interact with the surrounding non-ionized air particles. During elastic impulses they transfer part of their energy to those. When the electric field is amplitude modulated with an audio signal, these impulses become audible.
The class-E plasma speaker by Eastern Voltage Research is a fitting project to get into the world of plasma tweeters as it is simple to construct and comes with a comprehensive manual and troubleshooting guide.

## Future work

In order to understand the plasma tweeter even better and either confirm or disprove the theories, the following measurements are planned for a future project:

- **Temperature of the plasma:** As the term "temperature" was always confusing since it also indicates the state of the plasma, the actual temperature as in heat is supposed to be measured. A possible approach would be the use of a thermal imaging camera
- **Ozone levels:** Since no reliable information could be found on the amount of ozone being generated by the plasma tweeter, an interesting measurement would be of the ozone levels at different distances from the speaker with the help of a ozone meter.
- **Sound pressure level:** One of the most important specifications of any speaker is the generated sound pressure level at $1m$ distance with a supplied power of $1W$. A measurement like that would indicate the possible use cases for such speaker.
- **Directivity:** One of the theories behind the plasma speaker is the isotropic sound propagation. This would need to be checked additionally with the review if the polar pattern is perfectly omni-directional or has small directivities.
- **Distortion and noise:** A measurement for the "total harmonic distortion and noise (THD+N)" is supposed to give information on use cases of the speaker for measurement applications.

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# A. Original schematics

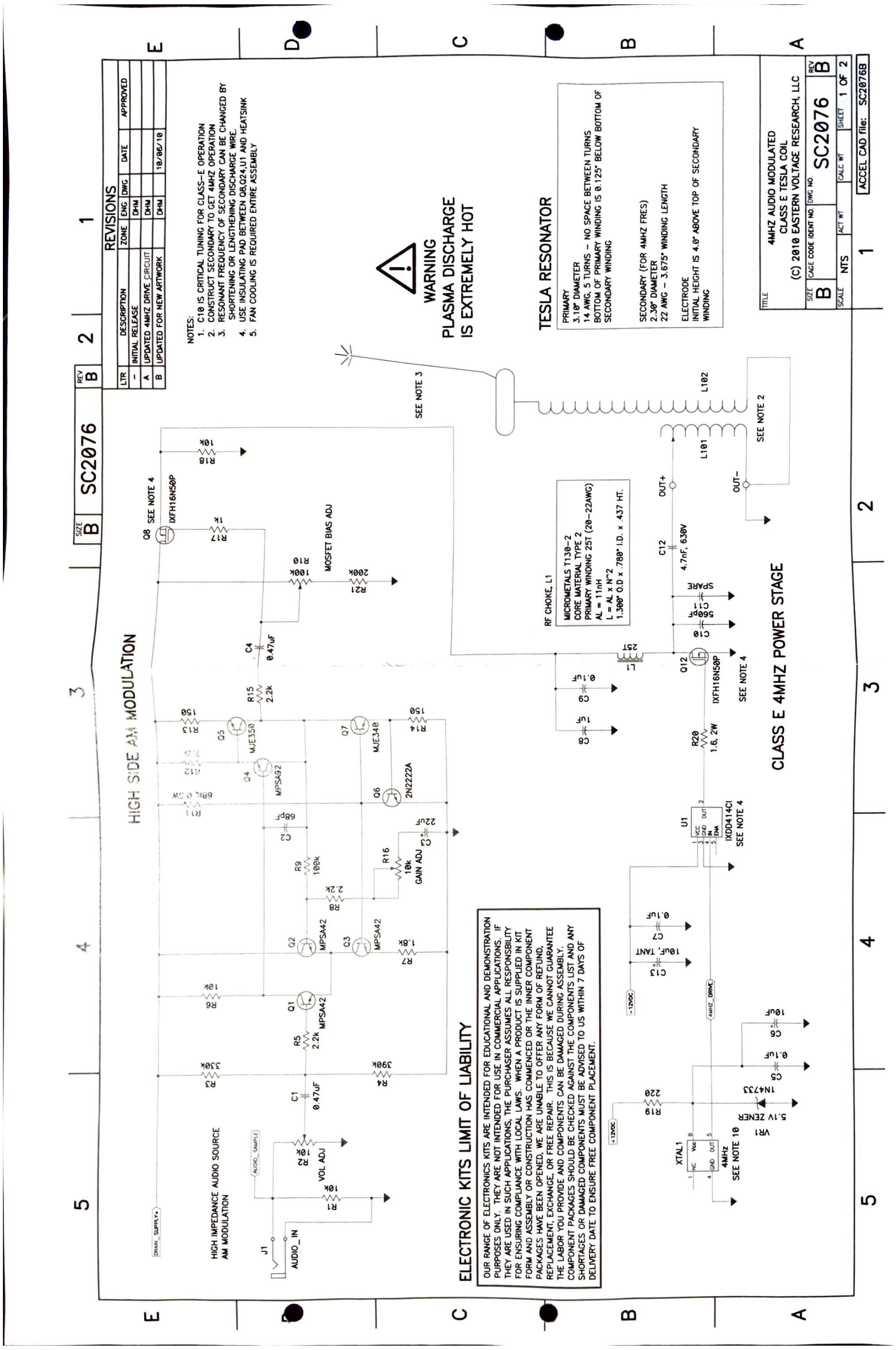

Figure A.1.: Schematics for AM modulation and 4MHz power stage by Eastern Voltage Research

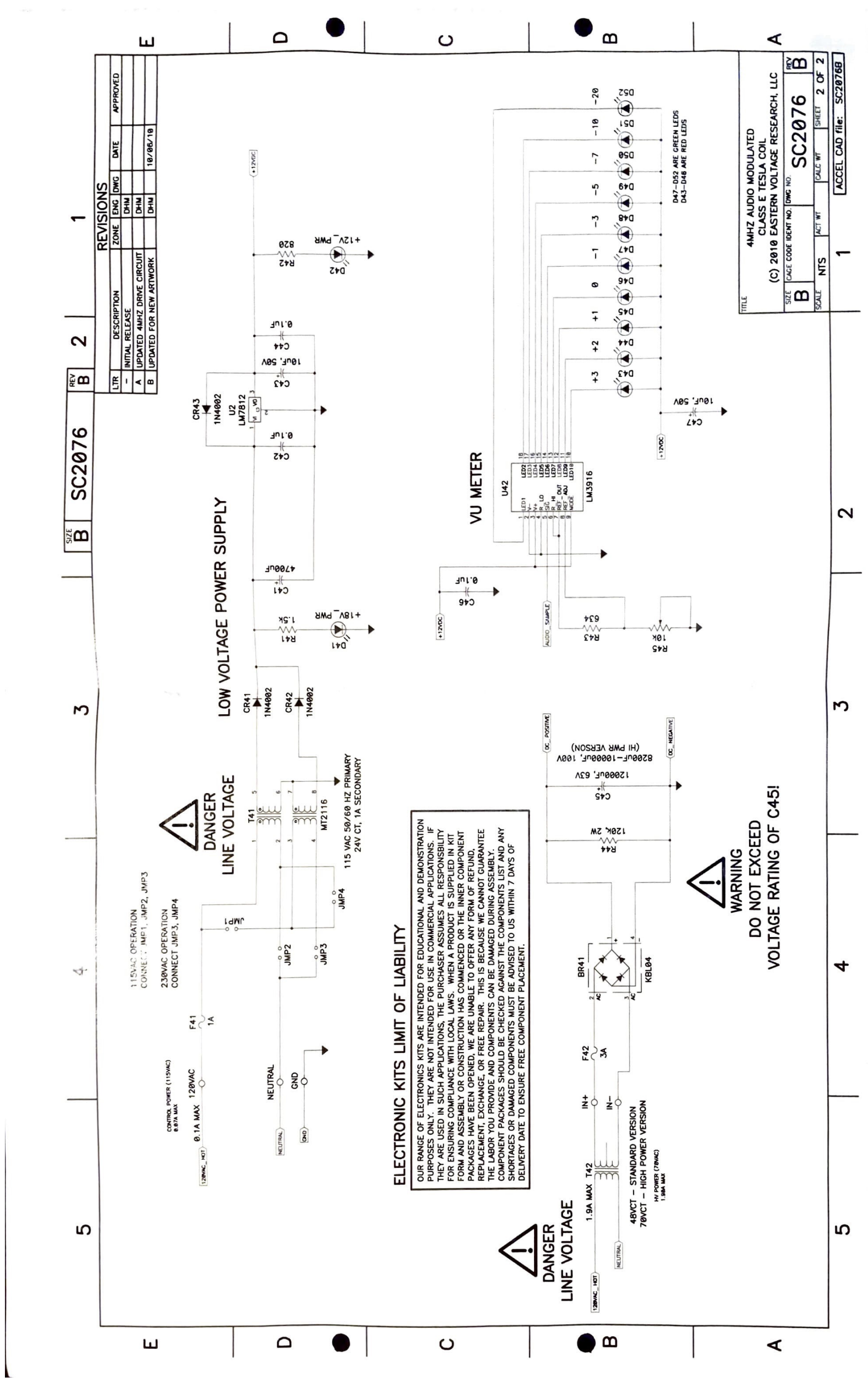


Figure A.2.: Schematics for power supply (low and high voltage) and the VU meter by Eastern Voltage Research

# B. Parts list

| Parts No. | Value | Type | Comment |
|---|---|---|---|
| | | **Resistors** | |
| R1 | $10k\Omega$ | Resistor | |
| R2 | $10k\Omega$ | Trimmer | Input Volume Adjustment |
| R3 | $330k\Omega$ | Resistor | |
| R4 | $390k\Omega$ | Resistor | |
| R5 | $2.2k\Omega$ | Resistor | |
| R6 | $10k\Omega$ | Resistor | |
| R7 | $1.8k\Omega$ | Resistor | |
| R8 | $2.2k\Omega$ | Resistor | |
| R9 | $100k\Omega$ | Resistor | |
| R10 | $100k\Omega$ | Trimmer | MOSFET Q8 Bias Adjustment |
| R11 | $68k\Omega$ | Resistor | 0.5W |
| R12 | $2.2k\Omega$ | Resistor | |
| R13 | $150\Omega$ | Resistor | |
| R14 | $150\Omega$ | Resistor | |
| R15 | $2.2k\Omega$ | Resistor | |
| R16 | $10k\Omega$ | Potentiometer | Gain Adjustment |
| R17 | $1k\Omega$ | Resistor | |
| R18 | $10k\Omega$ | Resistor | |
| R19 | $220\Omega$ | Resistor | |
| R20 | $1.6\Omega$ | Resistor | 2W |
| R21 | $200k\Omega$ | Resistor | |
| R41 | $1.5k\Omega$ | Resistor | |
| R42 | $820\Omega$ | Resistor | |
| R43 | $634\Omega$ | Resistor | |
| R44 | $120k\Omega$ | Resistor | 2W |
| R45 | $10k\Omega$ | Trimmer | VU Meter Adjustment |
| R61 | $47k\Omega$ | Resistor | |
| R62 | $10k\Omega$ | Resistor | |
| R63 | $1M\Omega$ | Resistor | |
| R64 | $10k\Omega$ | Trimmer | |
| R65 | $15k\Omega$ | Resistor | |
| R66 | $100k\Omega$ | Resistor | |
| R67 | $220\Omega$ | Resistor | |
| R71 | $1k\Omega$ | Resistor | |

| Parts No. | Value | Type | Comment |
|---|---|---|---|
| **Capacitors** | | | |
| C1 | $0.47\mu F$ | Ceramic | |
| C2 | $68pF$ | Ceramic | |
| C3 | $22\mu F$ | Electrolytic | |
| C4 | $0.47\mu F$ | Ceramic | |
| C5 | $0.1\mu F$ | Ceramic | |
| C6 | $10\mu F$ | Electrolytic | 50V |
| C7 | $0.1\mu F$ | Ceramic | |
| C8 | $1\mu F$ | Ceramic | |
| C9 | $0.1\mu F$ | Ceramic | |
| C10 | $560pF$ | Ceramic | 200-500V |
| C11 | | | Spare |
| C12 | $4.7nF$ | Poly Film | 630V |
| C13 | $10\mu F$ | Electrolytic | 50V, Low ESR |
| C41 | $4700\mu F$ | Electrolytic | |
| C42 | $0.1\mu F$ | Ceramic | |
| C43 | $10\mu F$ | Electrolytic | 50V |
| C44 | $0.1\mu F$ | Ceramic | |
| C45 | $10000\mu F$ | Electrolytic | 100V |
| C46 | $0.1\mu F$ | Ceramic | |
| C47 | $10\mu F$ | Electrolytic | 50V |
| C61 | $10\mu F$ | Electrolytic | 50V |
| C62 | $10\mu F$ | Electrolytic | 50V |
| C63 | $470nF$ | Poly Film | |
| C64 | $220nF$ | Poly Film | |
| C65 | $10nF$ | Poly Film | 2W |
| C66 | $100nF$ | Poly Film | VU Meter Adjustment |
| C67 | $100pF$ | Ceramic | |
| C71 | $0.33\mu F$ | Ceramic | |
| C72 | $0.1\mu F$ | Ceramic | |
| C73 | $10\mu F$ | Electrolytic | 50V |
| **Semiconductors** | | | |
| CR41 | $1N4002$ | Diode | |
| CR42 | $1N4002$ | Diode | |
| CR43 | $1N4002$ | Diode | |
| BR41 | $KBL04$ | Bridge Rectifier | |
| D41 | Blue | LED | +18V_PWR |
| D42 | Blue | LED | +12V_PWR |
| D43 | Red | LED | +3dB |
| D44 | Red | LED | +2dB |
| D45 | Red | LED | +1dB |

| Parts No. | Value | Type | Comment |
|---|---|---|---|
| D46 | Yellow | LED | 0dB |
| D47 | Green | LED | -1dB |
| D48 | Green | LED | -3dB |
| D49 | Green | LED | -5dB |
| D50 | Green | LED | -7dB |
| D51 | Green | LED | -10dB |
| D52 | Green | LED | -20dB |
| D61 | $1N4148$ | Diode | |
| D62 | $1N4148$ | Diode | |
| D63 | $1N4148$ | Diode | |
| D64 | 7 Segment Display | LED | 1000's. |
| D65 | 7 Segment Display | LED | 100's |
| D66 | 7 Segment Display | LED | 10's |
| D67 | 7 Segment Display | LED | 1's |
| D71 | Blue | LED | +5V_PWR |
| VR1 | $1N4733$ | Zener Diode | |
| Q1 | $MPSA42$ | NPN Transistor | |
| Q2 | $MPSA42$ | NPN Transistor | |
| Q3 | $MPSA42$ | NPN Transistor | |
| Q4 | $MPSA92$ | PNP Transistor | |
| Q5 | $MJE350$ | PNP Transistor | |
| Q6 | $2N2222A$ | NPN Transistor | |
| Q7 | $MJE340$ | NPN Transistor | |
| Q8 | $IXFH16N50P$ | N-Channel MOSFET | |
| Q12 | $IXFH16N50P$ | N-Channel MOSFET | |
| **Integrated Circuits** | | | |
| U1 | IXDD414CI | MOSFET Driver | alternative: IXDD614CI |
| U2 | LM7812 | Voltage Regulator | +12V Generation |
| U42 | LM3916 | Display Driver | LED Bar Graph Driver |
| U61 | LMC 7660 IN | Voltage Converter | -5V Generation |
| U62 | ICL 7107 | $3\frac{1}{2}$ Digit A/D Converter | 7-segment Driver |
| U71 | LM7805 | Voltage Regulator | +5V Generation |
| XTAL1 | | Quartz Oscillator | 4MHz |
| **Miscellaneous** | | | |
| L1 | | RF Choke | Core material type 2[1] |
| T41 | | Power Transformer | 24V CT, 1A; PCB mounted |
| T42 | | Power Transformer | 70V CT, 2A min. 5A max. |
| F41 | 1A | Fuse | Fast Blow |
| F42 | 5A | Fuse | Fast Blow |

Table B.1.: List of all electronic parts used. [1]Used core: Micrometals T130-2