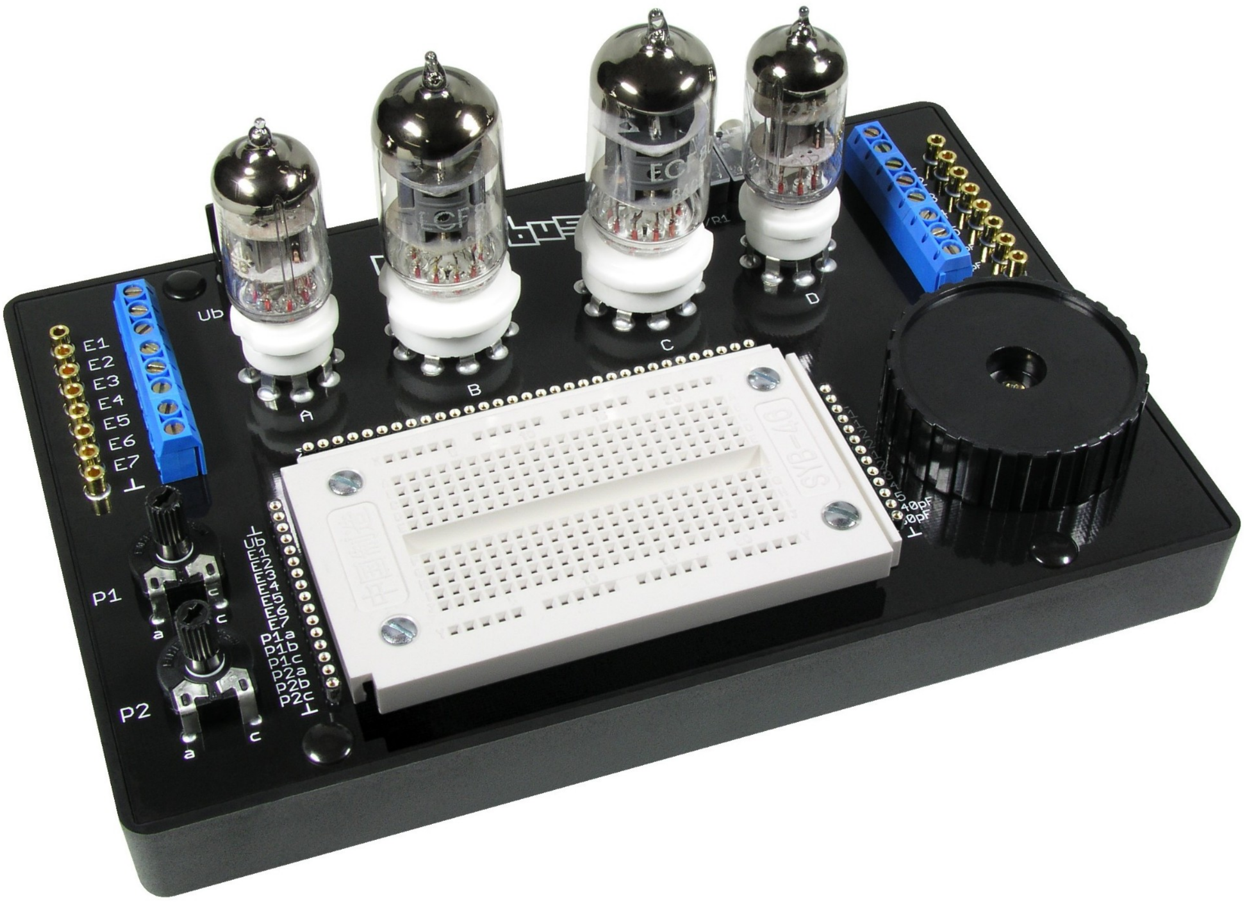
AK MODUL-BUS Computer GmbH

Tube Technology Experimentation Kit

RT100



Preface

Engaging with electron tubes is more than just a nostalgic hobby. It provides a thorough exploration of the fundamentals of electronics and thus has its rightful place in physics education and technical training. Furthermore, there are areas of application in which tubes have not been completely replaced by semiconductors, especially in audio technology and radio-transmitter power amplifiers.

Therefore it certainly makes sense to delve into the basics of tube technology through your own experiments. The experimentation system facilitates the entry into tube technology. Without detours you can proceed directly to the experiments. Setting up a circuit takes only a few minutes, as wiring and components are simply plugged together.

This guide presents exemplary experiments with tubes, covering many areas from audio amplifiers to oscillators, radio circuits, and test transmitters. Overall small and safe voltages (12 Volts) are used here. For safety reasons, the system should only be operated at a maximum of 60 V.

We wish you lots of fun and success experimenting with tubes!

Your AK Modul-Bus Team

Note 1: The text parts highlighted in blue and underlined are links to helpful products in our shop or to external sources. You can click on these directly if you are viewing the manual in a PDF viewer (such as Acrobat Reader).

Note 2: Due to tolerances, especially of the **EF95** tube, there may be issues with some experiments using the 12V anode voltage used here. The solution is to vary the grid leak resistor to smaller values. More details can be found in Chapters 8.2 to 8.4.
(In extreme cases with very low anode voltages, it may even be necessary to connect the grid resistor to the positive side instead of ground/cathode.)

Note 3: Some experiments require high-impedance headphones with an impedance of 600 Ω or even 2,000 Ω. These can now be found only with difficulty or at high cost in the professional studio or hi-fi segment. Alternatives include used headphones from platforms like eBay or using an audio-transformer with a minimum 1:10 transformation ratio, such as our TR110 or better the TR16K16W, with low-impedance modern headphones of 32 Ω. Further suggestions can be found in the text and a list of suitable high-impedance headphones the appendix.
In some cases, our piezo earpiece can also help, but it requires a parallel resistor of 1...10 kΩ in some circuits to function as an anode load (e.g. Experiment 4.1). Alternatively, instead of headphones you can use the line input of an audio amplifier or PC sound card, which usually have an uncritical input impedance of 10...100 kΩ.

Note 4: *(Vacuum) "Tube"* and (*Thermionic) "Valve"* are interchangeable as well as *"Anode"* and *"Plate"* as well as *"Heater"* and *"Filament"*

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1 Introduction

Experiments with tubes often require elaborate setups involving chassis, soldering terminals or specialized circuit boards. Additionally a dual power supply for filament voltage and anode voltage is usually needed. The Tube Technology Experimentation System simplifies this setup, as sockets and other essential components are already present on the board. The proposed experiments operate with low anode voltages, typically requiring only a 12V power supply for both filament voltage and anode voltage. While this approach might not give the maximum achievable power and amplification from the tubes, it is sufficient for basic experiments and understanding fundamental principles.
After having worked through this manual you are free to use also higher anode voltages up to 60 Volts, which are still safe concerning the board layout.

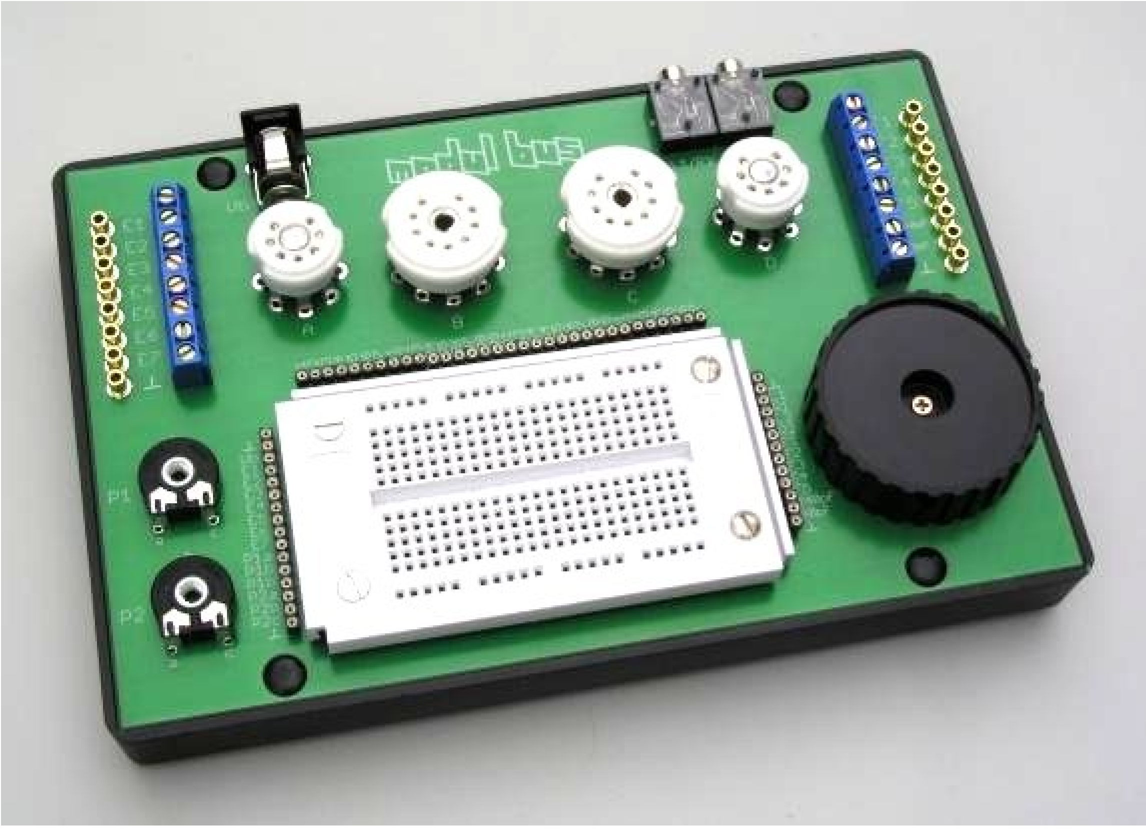
1.1 Material in the Experimentation System

The core of the system consists of a board with tube sockets and a plug-in board for small components and the actual wiring. A soldering iron is not necessary, as all connections can be plugged. This also facilitates the modification of existing experiments. The board is mounted on a plastic case with rubber feet, ensuring stability and security on the worktable.

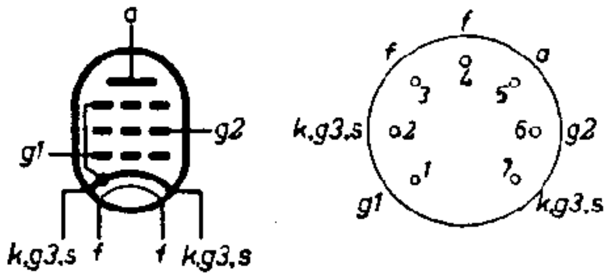
Several connectors for external connections are present on the board. On the one hand there are screw terminals along with 2mm banana jacks, for which we offer a complete cable, connector, and adapter system. A standard barrel jack (2.1/5.5mm) is used for connecting a power supply. Two stereo audio jacks serve as input and output for audio signals and headphones connections. Additionally, there are two potentiometers with 10 kΩ and a dual variable capacitor with 80 pF and 160 pF (or 2x265 pF). This enables radio frequency experiments to be conducted with ease. All photos in this manual were taken with the prototype green PCB to achieve good contrast. The final version, however, utilizes a black PCB.

Caution: The system should only be operated with maximum voltages up to 60 V! Electrical safety is not guaranteed at higher voltages, as there is a lack of protective insulation and the connectors, tube sockets etc. are open to touch. Additionally, the insulation on the board is not designed for higher voltages, as the PCB traces are often quite near to each other (small creeping distance).

When inserting or removing tubes from the sockets please proceed with great care. First ensure that the tube pins are straight to fit into the holes of the sockets. Tubes are inserted/removed by gently wiggling them into or out of the sockets. If a tube pin is bent to the point where it no longer fits into the socket hole during insertion, it can be very cautiously straightened at about half its length using small flat pliers. However, this process might cause microcracks in the tube, potentially leading to a loss of vacuum. A "lost" vacuum inside the tube is indicated by the absence of the "getter mirror." This is the reflective area at the top end of the tube. In leaky tubes, oxidation will immediately transform the getter mirror into a slightly milky translucent coating.

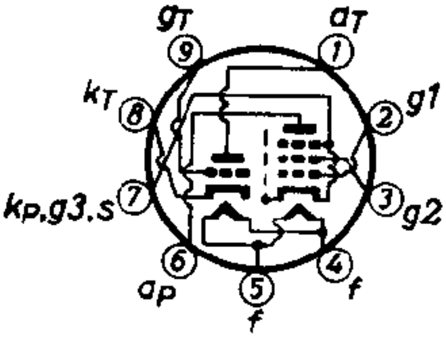


The set includes two tubes each of type ECF80 and EF95 (or the identical types 6BL8, 6SH1P and 6AK5,5654,6F32,6J1). The EF95 is an HF pentode with a seven-pin miniature socket. Internally the connections for cathode, grid 3, and shielding are connected.



Connection of the EF95 (seen from below!)

The ECF80 is a RF dual-system tube with a triode and a pentode, each having separate cathodes. In the pentode, there is also an internal connection between the cathode, grid 3, and shielding.



Socket diagram of the ECF80 (seen from below!)

When all four tubes are populated, you have a total of six tube systems available for constructing complex circuits.

In addition to the 4 tubes, the package includes the following components:

14 Resistors:
2 Resistors 75 Ω (additional: 1x 68Ω + 1x82Ω / 2 Watt-Resistor)
2 Resistors 1 kΩ
2 Resistors 10 kΩ
2 Resistors 27 kΩ
2 Resistors 47 kΩ
2 Resistors 100 kΩ
2 Resistors 1 MΩ

16 Capacitors:
2 Ceramic Capacitors 15 pF
2 Ceramic Capacitors 47 pF
2 Ceramic Capacitors 150 pF
2 Ceramic Capacitors 330 pF
2 Ceramic Capacitors 10 nF
2 Ceramic Capacitors 100 nF
2 Electrolytic Capacitors 10 µF
2 Electrolytic Capacitors 100 µF

2 Quartz Crystals:
1 Crystal 6.000 MHz
1 Crystal 13.56 MHz

2 NPN Transistors BC548C

4x 1 meter hookup wire

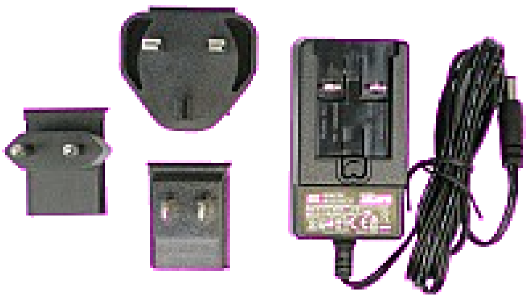
(optional: 1 Audio Transformer 1...16kΩ-4/8/16Ω or similar)
(optional: 1 Piezo Earpiece)
(optional: 1 Small Speaker 32 Ω or 64 Ω)
(optional: 1 MW antenna with coupling coil or secondary tap)

1.2 Power Supply

For powering the experimentation system, a stabilized wall-wart power supply, such as the NTS with adjustable voltages of 3...12 V and a minimum capacity of 600 mA, is recommended. When using all four tubes simultaneously, slightly more current capability is needed, and thus the 12V/1A fixed voltage power supply NTS12-1000INT is recommended, which also includes plug adapters for non-German power outlets.

However, both of the mentioned power supplies are switch-mode power supplies, which might introduce interference into the circuit during RF experiments and potentially affect reception. For interference-free RF experiments, an adjustable, linear regulated power supply is the preferred choice, such as the LABSUPPLY18-3A or (simple and cheap) a 12V battery or rechargeable battery pack.

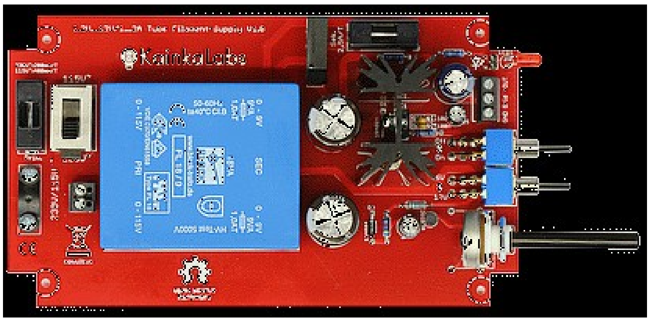
Wall-Wart Supply NTS
3-12V/600mA



12V fixed-Voltage Supply
12V/1A with plug adapters

The 0...18V/0...3A linear
regulated Lab-Supply

For advanced experiments we have also developed our own, linear-regulated, and thus completely RF-interference-free filament and anode voltage power supplies (12...60V / 60...120V / 140...240V):



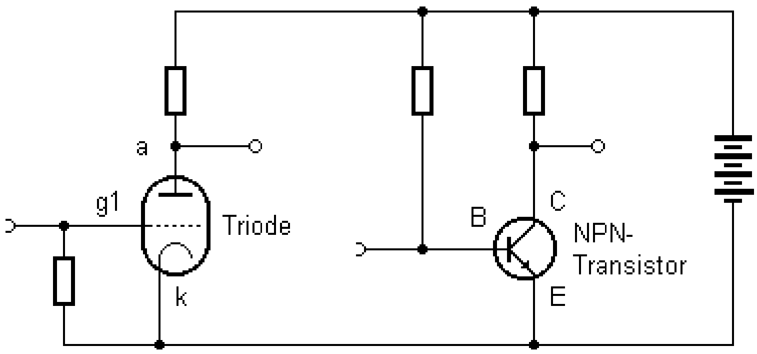
Filament-Supply 1,25...12V/2A

Anode-Voltage Supply 12...60V/50mA

Moreover, some experiments also require an additional simple **multimeter** if you intend to thoroughly validate the functionalities of the circuits and the tubes. The experiment descriptions provide measurement values that should be cross-verified in your own experiments.
An **oscilloscope** and further equipment are not obligatory for successful utilization of the system. Cheaper and in many cases better is the line-input of a PC/laptop in combination with an audio analyzer-software to visualize waverforms and make special measurements like the frequency response or harmonic distortions. For a list see the appendix. We recommend the semi-professional shareware software "audiotester".

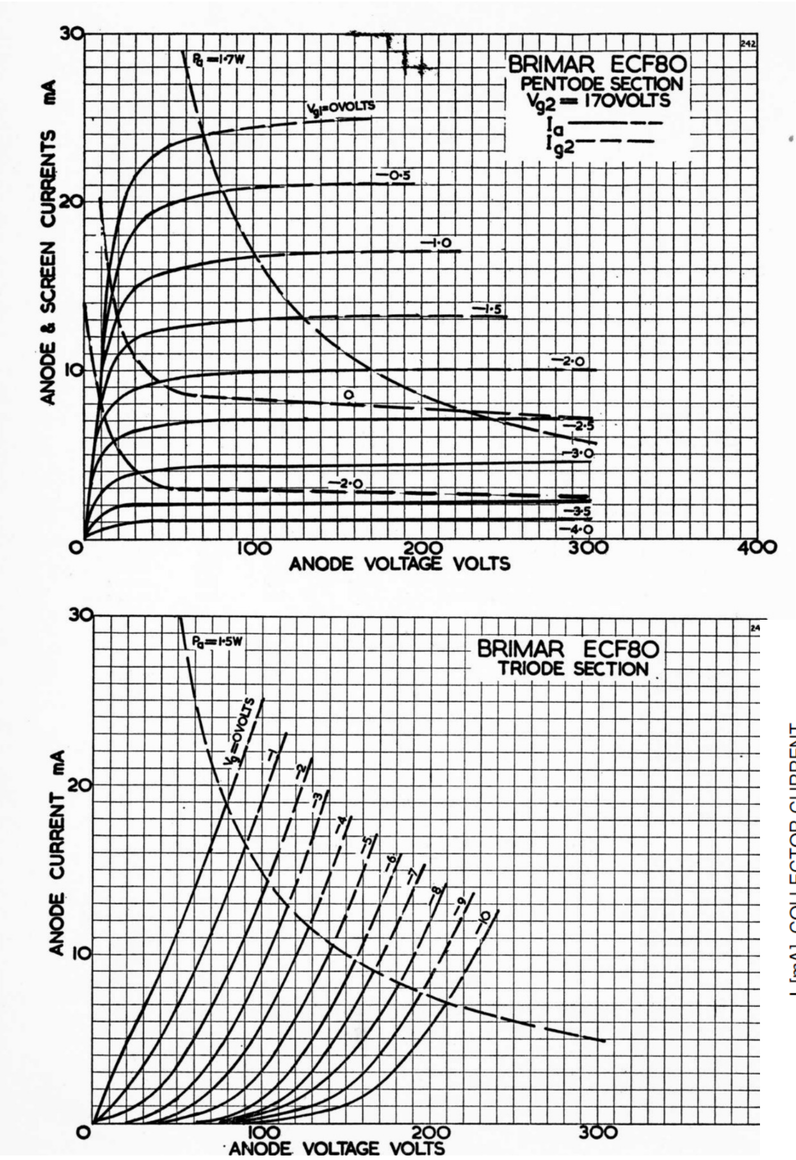
1.3 How A Tube Works

Those engaging with electronics today are often familiar with the function of (bipolar) transistors, while the operation of a vacuum tube might be less familiar. In order to understand the fundamental workings, a comparison can be drawn between a vacuum tube and a transistor. The basic form of an amplifying vacuum tube is the triode, which has three terminals: Cathode (negative electrode) *"k"*, Anode or Plate *"a"* (positive electrode) and Control Grid *"g"*. These terminals can be likened to the connections of an NPN transistor: Emitter (negative electrode), Collector (positive electrode) and Base as the control electrode. However the vacuum tube operates only when the cathode is heated to around 800° to 1000° Celsius. This heating is achieved using a filament, often made of tungsten, similar to the filament in an incandescent light bulb. The heated cathode contains a layer of material with low electron binding energy enabling electrons to escape into the vacuum at these elevated temperatures. The electrons are then attracted to the positively charged anode, resulting in the flow of current.

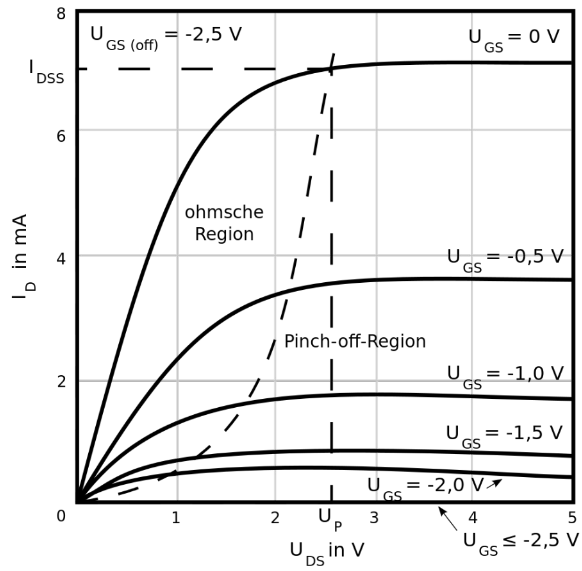


Comparison between a Tube (Triode) and an NPN Bipolar-Transistor

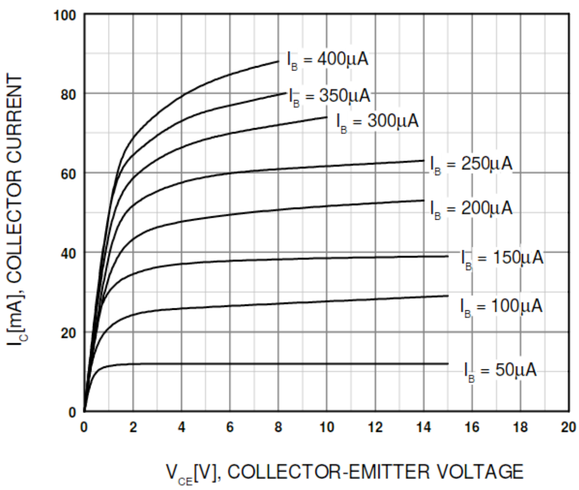
Both tube and bipolar transistor control a current. In the case of an NPN transistor a small base current controls a (larger) collector current. For the vacuum tube the voltage at the control grid controls the anode current. In both cases, a more positive control voltage leads to more current in the load circuit resulting in a larger voltage drop across the load resistor or a smaller voltage at the output electrode (anode or collector). Consequently, an amplifier with a triode or an NPN transistor typically reverses the phase of the amplified voltage by 180 degrees.
However, there is a difference in that an NPN bipolar transistor requires a positive bias, whereas the vacuum tube is usually operated with a negative grid bias. This negative voltage forms automatically across the grid resistor, as free electrons from the cathode negatively charge the grid.
When comparing a triode with an N-channel JFET transistor (Junction-Gate Field-Effect Transistor), their characteristics are almost identical since an N-channel JFET is also controlled with negative gate voltages. As a playful analogy, a triode is sometimes humorously referred to as a *"JFET with pilot-light"* :-)
You can familiarize yourself with the characteristics and characteristics of the used triodes and pentodes in Chapter 8, which may be helpful for understanding tube circuits before delving into Chapter 3 and starting the experiments.



Characteristic curves of a Pentode (top) and a Triode (bottom)



Characteristic curves of an N-channel JFET

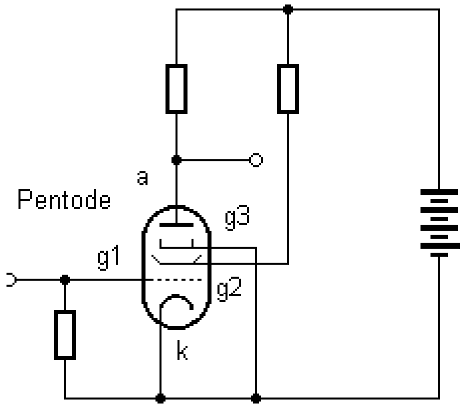


Characteristic Curves of a Bipolar NPN Trnasistor

Summary: The main difference between a vacuum tube (or a JFET transistor) and a bipolar transistor lies in how they control current. In the case of a vacuum tube, or a JFET transistor, a **negative** grid voltage controls the anode current in a high-impedance manner. On the other hand, in a bipolar transistor, a **positive** base current controls the collector current in a low-impedance manner.

Remember:

	Tube / N-Channel J-FET	**NPN Bipolar-Transistor**
Control Input:	grid/gate; high impedance	base; low impedance
Controlled by:	grid/gate-voltage	base current
Controlled Current:	anode current	collector current
Output Current at Maximum:	U_g = 0V	I_B = a few mA
Output Current Off	U_g = -3...-10V (dep. on type)	I_B =0 mA
Gain "Type"	voltage controlled current	current controlled current
Gain Factor	transconductance [mA/V]	B, beta or h_{fe} [mA/mA]



The Pentode

In the case of a pentode two additional grids come into play. The screen grid (g2) is positively charged and shields the control grid from the influence of the varying voltage of the anode. The voltage at the screen grid, much like the control grid, affects the anode current and the amplification of the tube. The suppressor grid (g3) is usually connected to the cathode and serves to redirect electrons that escape from the anode (secondary electrons) back to it.

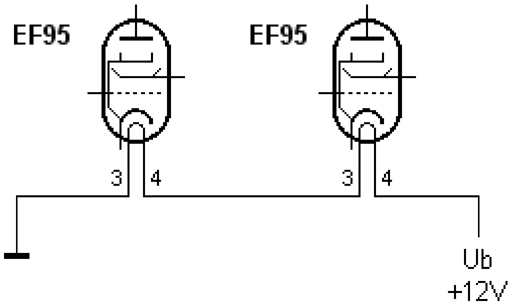
When comparing transistors and vacuum tubes it's notable that vacuum tubes require significantly more energy due to the necessary heating power for the same task. As a result, energy-efficient circuits are predominantly equipped with transistors today. The advantages of vacuum tubes include high input impedance and good radio-frequency properties, which contribute to remarkably sensitive radio circuits. In the realm of HiFi and stage-amplifiert vacuum tubes are associated with a softer sound, primarily because there is no hard "clipping" during overdrive and mostly even harmonics (k_2, k_4...) with triodes.

2 Tube Heaters and Power Supply

Tube circuits typically operate with two supply voltages: the filament (heater) voltage and the anode (plate) voltage. However for simple experiments it's more convenient to use just a single stabilized power supply with 12 V (ideally: 12.6 V). This voltage heats two tubes connected in series and is often sufficient as the anode voltage for many experiments. Power is supplied through the barrel connector at the back of the experimentation system. The outer contact is connected to the ground plane, while the inner contact is connected to "Ub".

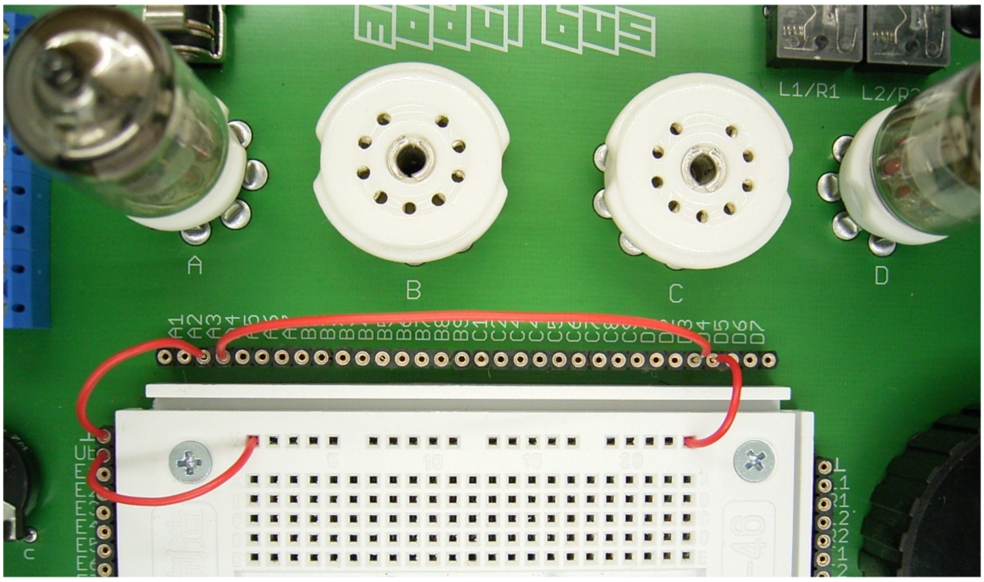
2.1 Heating the EF95

The utilized tubes are designed for parallel heating with a filament voltage of 6.3 V. Historically, this voltage is derived from the use of lead-acid batteries, which have a nominal voltage of 2.1 V per cell. There are other tubes intended for series heating, such as P-tubes with a shared filament current of 0.3 A and U-tubes with 0.1 A. Ideally tubes designed for parallel heating should not be heated in series, as uniform heating power cannot be guaranteed, and the tubes could heat up at different rates. However, for simple experiments, there's no issue with series heating, as long as tubes of the same type are used and they come from the same production run.



Series Connection of Tube Filaments

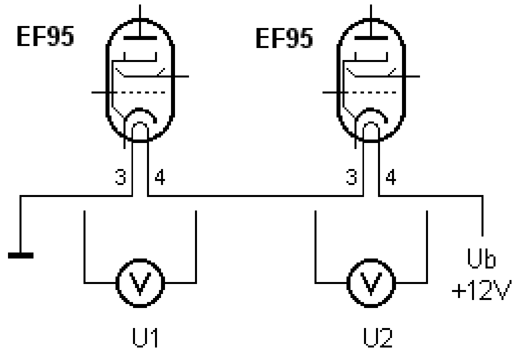
The filaments of both EF95 tubes are connected in a manner similar to almost all tubes with a 7-pin miniature socket, with pins 3 and 4 being used. The schematic above illustrates the wiring of the filament circuit. The upper row of contacts on the terminal board is connected to Ub and receives +12 V from a power supply. The filaments of tubes A and D are connected in series to 12 V, so that each tube receives a voltage of 6 V.



Wiring Scheme for 2 EF95-Filaments in Series

After applying the operating voltage it takes a few seconds until the glow of the cathodes becomes visible. When turning on always ensure that both tubes are glowing correctly. Errors in the wiring or power supply can be identified immediately. For instance, if a tube filament is accidentally exposed to a higher voltage, you'll notice it glowing excessively bright and you should promptly shut it off.

With standard heating of 6 V per tube, both cathodes should glow with equal intensity. After a few minutes, the tubes will become noticeably warm but not uncomfortably hot. To determine whether the filaments indeed have nearly identical resistance when warm, you can carry out a measurement.

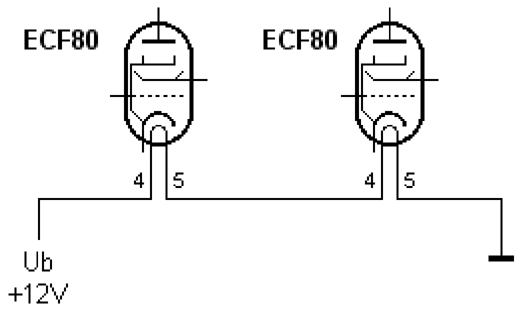


Measuring the Heater Voltages

In a trial setup, the following voltages were measured: Tube A: 5.8 V, Tube D: 6.5 V. The total voltage from the 12 V power supply was 12.3 V. The slightly uneven filament voltage is still within tolerable limits. The nominal voltage for these E-tubes is 6.3 V, with a tolerance of +/- 10% being acceptable. In this context, a slightly higher voltage is less detrimental than an undervoltage, as an undervoltage can affect the emission capability of the cathode.

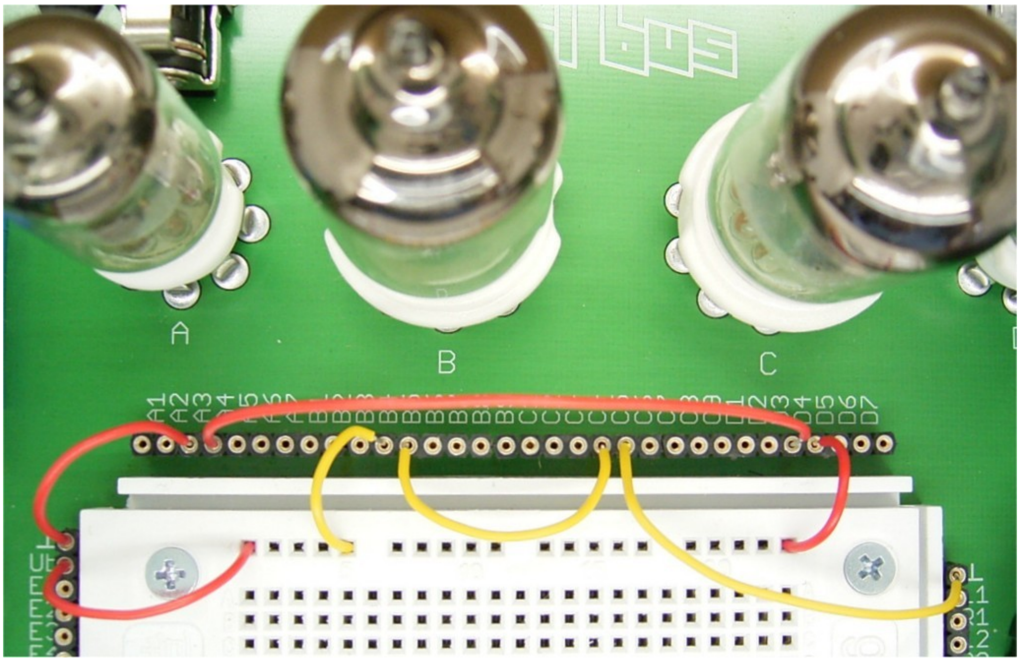
2.2 <u>Heating the ECF80</u>

The ECF80 is nominally heated with 6.3 V and 430 mA. Series heating with a stabilized 12V power supply is possible. However, the conditions are less favorable for heating a single tube with 6 V, as more heat loss occurs in the power supply. Even if only one tube is required in a circuit, it's advisable to heat both tubes in series together.



Heater Connections of the ECF80

Most tubes with the 9-pin Noval socket are heated at pins 4 and 5. The following photo illustrates a possible wiring configuration in an actual setup.



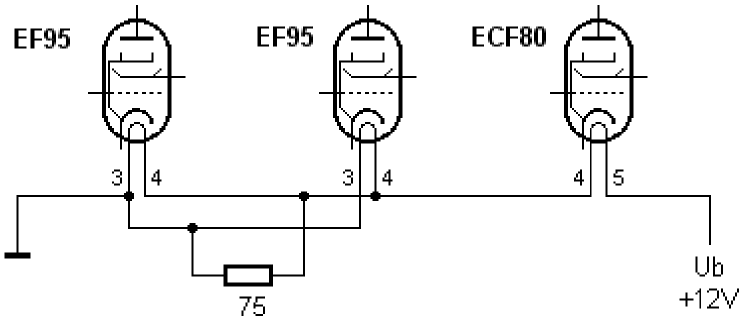
Wiring scheme for all four heaters

The individual filament voltages were also measured on the ECF80 (6.0 V and 6.2 V). The distribution is random and dependent on manufacturing tolerances. The measurements demonstrate that tubes originally designed for parallel heating can also be heated in series for simple experiments.

With all four tubes combined the filament current is 430 mA for the ECF80 plus 175 mA for the EF95, resulting in a total current slightly over 600 mA. Due to filament tolerances, the total current might be slightly higher. In such experiments, it's essential to verify that each tube has at least 5.8V as filament voltage.

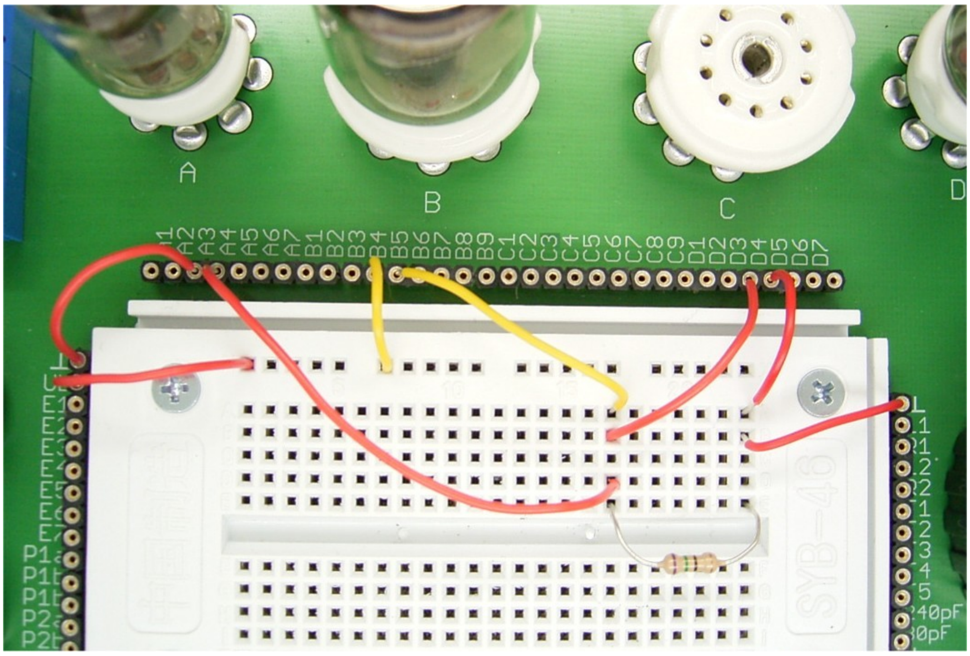
2.3 Heating Three Tubes with a Single Filament Voltage

If you intend to operate three tubes in an experiment, you can use the following circuit. Here two EF95 tubes are connected in parallel and together require a current of 2 * 175 mA = 350 mA. An additional 75 Ω resistor adds an extra current of 80 mA at 6 V, so that the parallel arrangement exactly matches the heater current of an ECF80 at 430 mA.
Also, measure whether at least 5.8V are applied to each heater in this setup and adjust the 75 Ω resistor if necessary. We supply an additional 68 Ω and 82 Ω / 2Watt power resistor that is suitable for this purpose.



Mixed Series/Parallel Filament Heating

During the first seconds of heating , the two EF95 tubes glow a bit more intensely, receiving slightly more than 6 V. This effect occurs because a cold filament has lower resistance, while the additional load resistor remains constant. The accurate current distribution is achieved only once the tubes are fully heated up. After a few seconds the correct heater voltage of about 6 V is established for each tube. By the way, the resistor dissipates 480 mW of power and becomes quite hot in the process.



Wiring Scheme for Three Tubes with a single Filament Voltage

The alternative to series heating is parallel heating. However, for this approach, a robust power supply with 6 V (or preferably 6.3 V) or an adjustable, stabilized power supply with a higher currrent capacity of around 2 A is necessary. A second voltage source will be required then for the anode voltage. On page 7, we have presented several power supplies from our range specifically designed for these purposes.

2.4 Wiring of Tube Connections

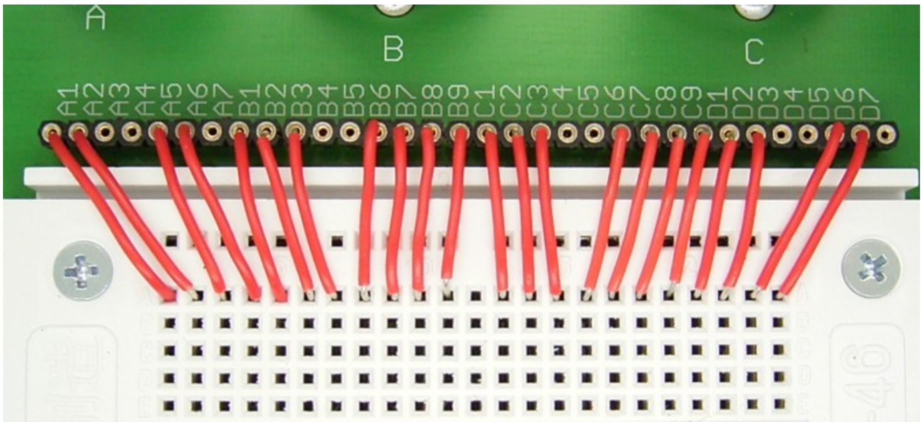
For the following circuits, all tube connections except for the pins for the filaments should be connected to the terminal board with short wires. The wiring to the terminal board only needs to be done once and makes the work easier for the subsequent experiments. The cathode connection of the EF95 is duplicated but only connected to the terminal board once. Overall, the following connections are obtained:
(*"f"* = Filament = Heater; *"k"* = Cathode; *"a"* = Anode; *"g1"*...*"g3"* = Grid 1...3; *"s"* = shield)

Socket-Pin	Board-Pin	Tube A, EF95
A1	1	g1
A2	2	k, g3 ,s
A3		f
A4		f
A5	3	a
A6	4	g2
A7		k, g3 ,s

Socket-Pin	Board-Pin	Tube B, ECF80
B1	5	Triode a
B2	6	Pentode, g1
B3	7	Pentode, g2
B4		f
B5		f
B6	8	Pentode, a
B7	9	Pentode, k, g3, s
B8	10	Triode, k
B9	11	Triode, g

Socket-Pin	Board-Pin	Tube C, ECF80
C1	13	Triode a
C2	14	Pentode, g1
C3	15	Pentode, g2
C4		f
C5		f
C6	16	Pentode, a
C7	17	Pentode, k, g3, s
C8	18	Triode, k
C9	19	Triode, g

Socket-Pin	Board-Pin	Tube D, EF95
D1	20	g1
D2	21	k, g3 ,s
D3		f
D4		f
D5	22	a
D6	23	g2
D7		k, g3 ,s



Connecting the Tube Terminals to the Plug Board

This wiring scheme can be maintained for most experiments in this manual. This way, you can become familiar with the consistent connections and have overall less effort in assigning the terminals.

The heater connections will be wired independently and connected only when a tube is actually being used. Normally two identical tubes are heated in series to achieve a heater voltage of 12 V.

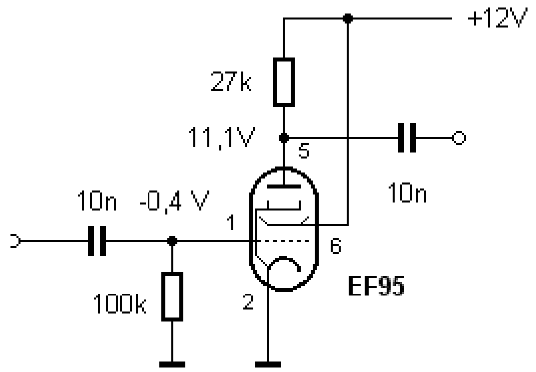
3 Audio Pre-Amplifier

The basic principle of a tube amplifier can be easily demonstrated by the use as an audio preamplifier. For the following experiments, a tone generator and an oscilloscope are useful tools. However, you can also connect this pre-amplifier between an audio source, such as a record player's pickup, a microphone etc. and a power amplifier or line-input of a PC to observe increased volume.

You can also directly connect high-impedance headphones (600Ω..2000Ω) to the output of the circuits. Information about the availability of high-impedance headphones can be found in the appendix.
Alternatively, low-impedance headphones (e.g., 32Ω) can be connected directly to the output using a suitable audio transformer (at least 1:10, preferably 1:30...1:100).

3.1 Single-Stage Audio Amplifier

In the first experiment only one EF95 tube is used. However, the second tube is also heated so that a supply-voltage of 12 V can be used. The second tube essentially acts as the filament resistor for the heater of the amplifier tube.

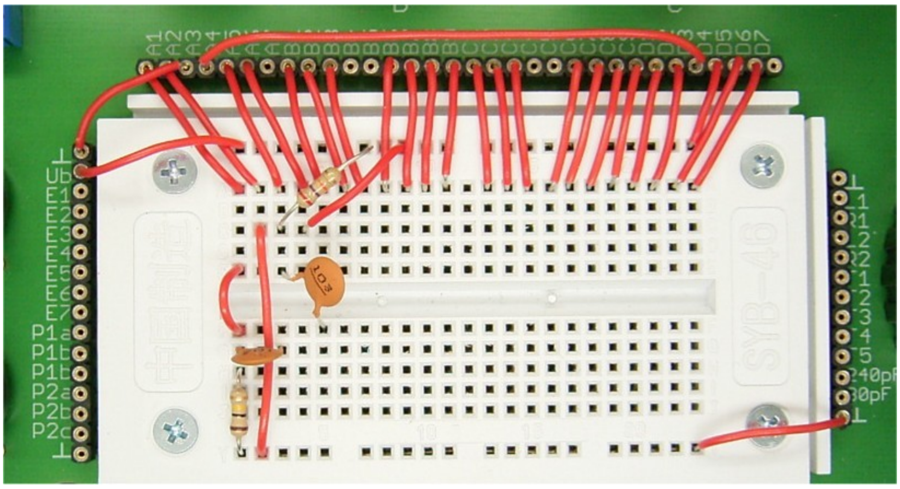


Audio Stage with EF95 Tube

An audio amplifier stage with a single tube can be compared to a transistor stage in common emitter configuration. The cathode corresponds to the emitter, the control grid to the base and the anode to the collector. However, unlike the base of a transistor the grid requires a negative bias voltage. Therefore the grid resistor is connected to ground. The grid bias current results in a voltage drop across the grid resistor, leading to a negative grid bias. In compsarison a pentode has two additional grids compared to the triode. The screen grid (g2) needs to be connected to the operating voltage. The suppressor grid (g3) is internally connected to the cathode.

The coupling capacitor of 10 nF at the input blocks DC voltages from the input signal from reaching the control grid g1 and allows the grid resistor to establish a bias voltage without feedback. The coupling capacitor from the anode to the output prevents the DC

component of the anode from reaching the output, ensuring that devices like headphones or speakers are not adversely affected.
This technique is also applied in all subsequent circuits.

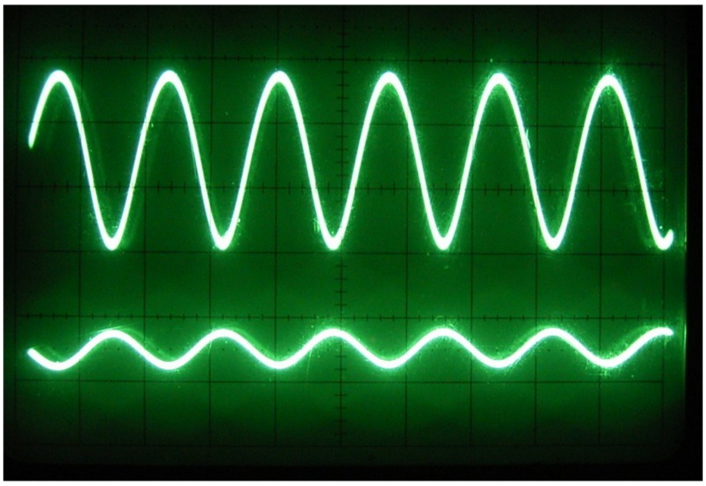


Wiring Scheme for the Amplifier Stage

The photo depicts the setup of the circuit on the plug board. In this arrangement, the left tube is used in socket A. Input and output connections can be made to the terminals E1 to E7 or to the headphones jacks as desired. The external connections are not shown here for the sake of clarity.

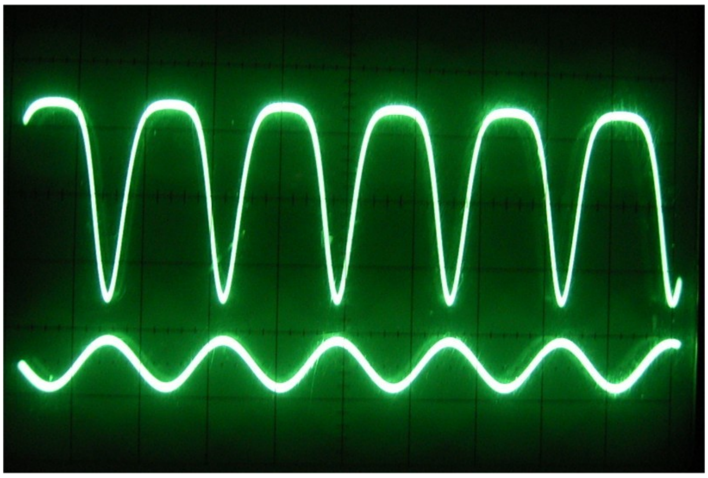
After a brief warm-up period, you can use a voltmeter to measure the voltages at the tube. At the grid, you will find -0.4 V, indicating a grid current of 4 µA. Across the anode resistor of 27 kΩ, there is a voltage of 12 V - 11.1 V = 0.9 V, resulting in an anode current of 33 µA.

Next, a signal voltage from a sine wave generator (or the line-output of a sound-card from a PC/laptop with an audio-analyzer software) is be applied to the input. The grid voltage modulates the anode current and the amplified output voltage can be observed as a voltage drop across the anode resistor.



Input voltage (bottom) and output voltage (top)

The oscillogram shows that the amplifier stage reverses the phase. A higher grid voltage means more anode current resulting in a larger voltage drop across the anode resistor, and thus a smaller anode voltage. The magnitude of the input and output voltages indicates a voltage gain of approximately V = 5. This results in a tube transconductance of approximately S = 0.185 mA/V, as the voltage gain is the product of the transconductance and the anode resistor (V = S * Ra). The transconductance is dependent on the operating point of the tube within wide limits. If you need more anode current and higher transconductance you need to make the grid voltage more positive.



Signal waveform when overdriving the tube

If you overdrive the amplifier stage noticeable distortions occur. The peculiarity of tube distortions, in contrast to the distortions in most semiconductor amplifiers, is that clipping sets in relatively softly.

<u>Additional experiments:</u>

- Reduce the anode resistor to 10 kΩ and repeat all measurements.
- Then, use a smaller grid resistor of 27 kΩ or 10 kΩ and shift the operating point towards higher anode current. Search for the optimal configuration with the highest voltage gain.
- Measure frequency response and harmonic distortions with an audio-analyzer program like "audiotester" (shareware).

3.2 Two-Stage Audio Amplifier

To increase the gain you can cascade two stages one after the other. The second audio amplifier stage is designed similarly to the first one. A coupling capacitor is placed between the two stages to prevent the DC component at the anode of the first tube from affecting the control grid (g1) of the second tube.
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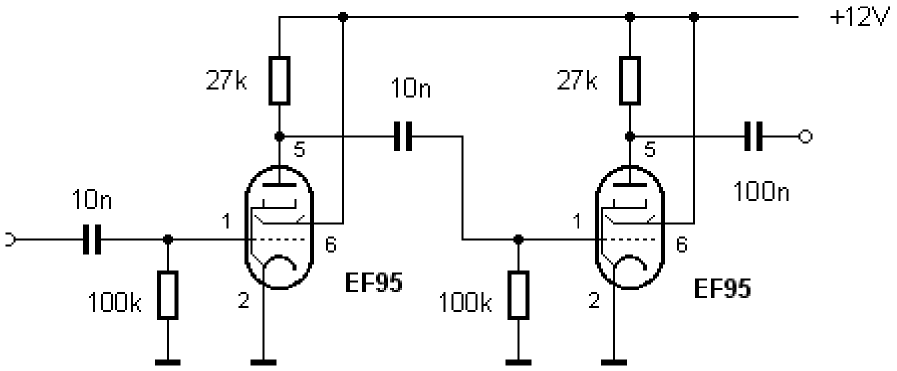
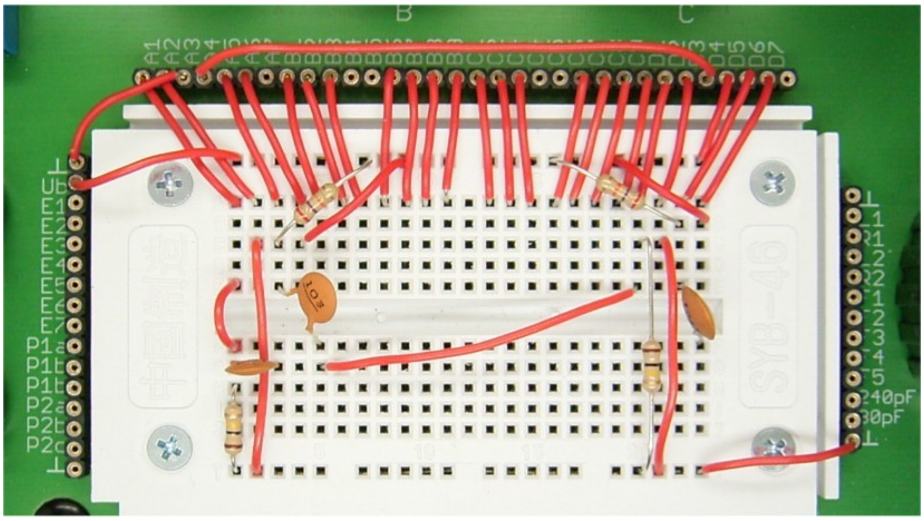


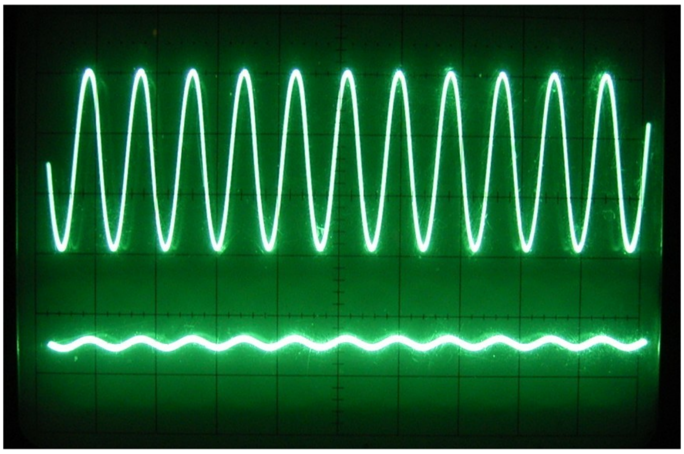
The two-stage audio amplifier

This time the setup also uses tube D. The photo clearly shows the signal connection from the output of the left tube to the input of the right tube.



Wiring Scheme with Two Stages

One can now expect a gain of around V = 25. The dual-channel oscillogram indeed does show a gain of approximately 25. Additionally it can be observed that the double phase inversions of the two stages cancel out each other. Therefore, the input and output voltages are now in phase.



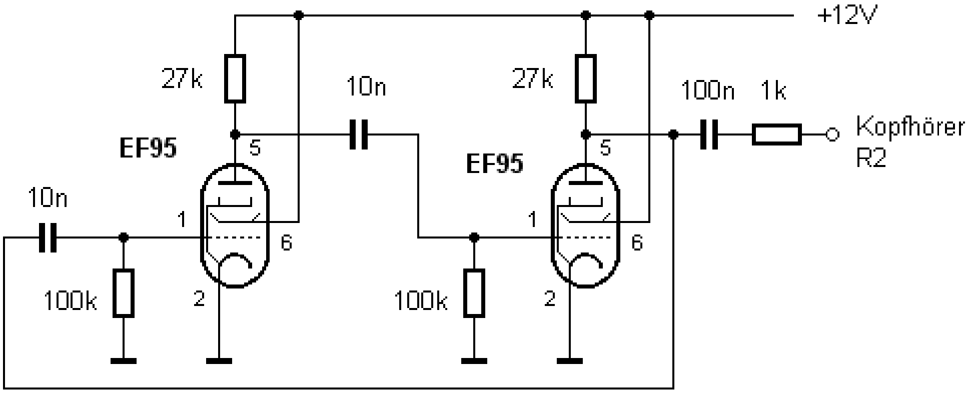
Input signal and output signal

Additional experiments:

- Increase the overall gain by using a higher anode voltage, e.g., 24V...60V.
- Use the two-stage amplifier as a sensitive microphone amplifier.
- Measure frequency response and harmonic distortions with an audio-analyzer program like "audiotester".

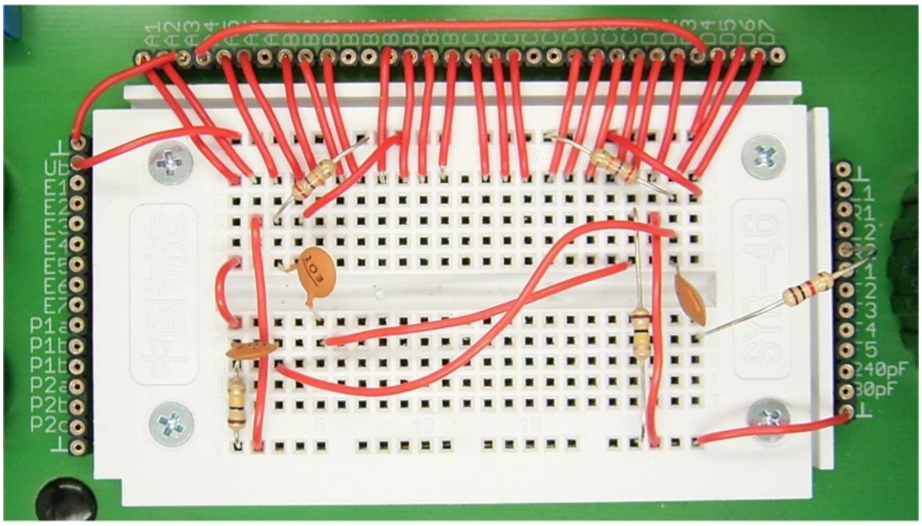
3.3 A Tone-Generator

Because in a two-stage amplifier the phase difference between the input and output of an amplifier is zero it is easy to generate oscillations. All you need for this is a feedback-connection from the output to the input.



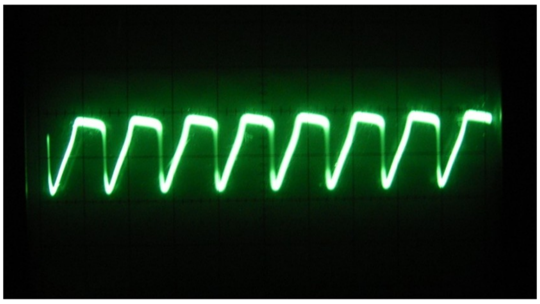
The Tone-Generator

The circuit features an output with a coupling capacitor and an additional resistor of 1 kΩ so that low-impedance headphones do not attenuate the amplification to the point where oscillations cease. In this case, the headphones connection R2 is used. Headphones can be connected to the stereo jack #2. The sound should then appear on the left side.



Tone-Generator with Headphones Output

With an oscilloscope (or audio-analyzer software) you can identify an audio signal with a frequency of around 800 Hz. This circuit is suitable for example as a Morse code practice generator, where a Morse key is inserted into the line leading to the headphones.



Output-Signal of the Tone-Generator

Additional Experiments:

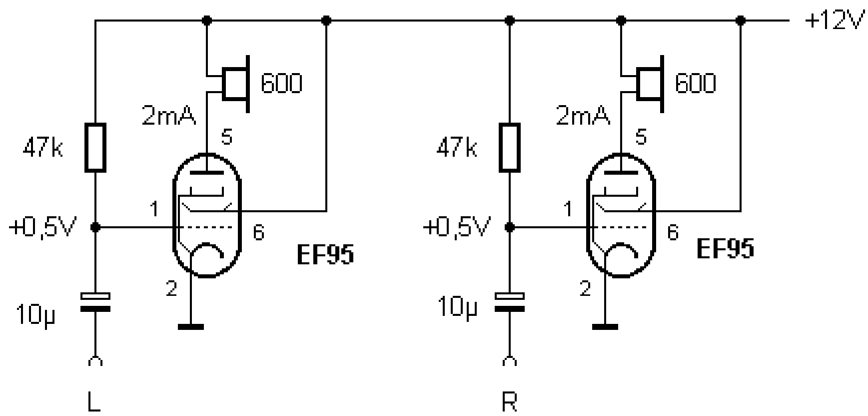
- Modify resistors and capacitors to change the tone frequency.
- Introduce a potentiometer for continuous frequency adjustment in series with the anode resistor of the left tube or in series with one of the coupling capacitors.

4 Headphone Amplifier

Headphone amplifiers are an attractive application for tubes at low anode voltage, as they require low output power and allow for obtaining the distinctive tube sound with minimal effort.

4.1 Stereo Headphone Amplifier

A headphone amplifier with tubes indeed imparts a unique and distinctive sound quality. One challenge often faced is the limited anode current and low output power to drive low-impedance headphones. However, it's possible to increase the anode current by applying a positive grid bias. In this setup, a grid resistor of 47 kΩ is connected to +12 V. With the EF95 tube, an anode current of 2 mA is achieved at a 12 V operating voltage. This configuration delivers good volume and excellent sound quality when paired with high-impedance headphones of around 600 ohms (such as the Sennheiser HD414; see appendix). The PC sound card, a smartphone or any line-output audio-source serves as a suitable audio source in this scenario.



A Stereo Headphone Amplifier

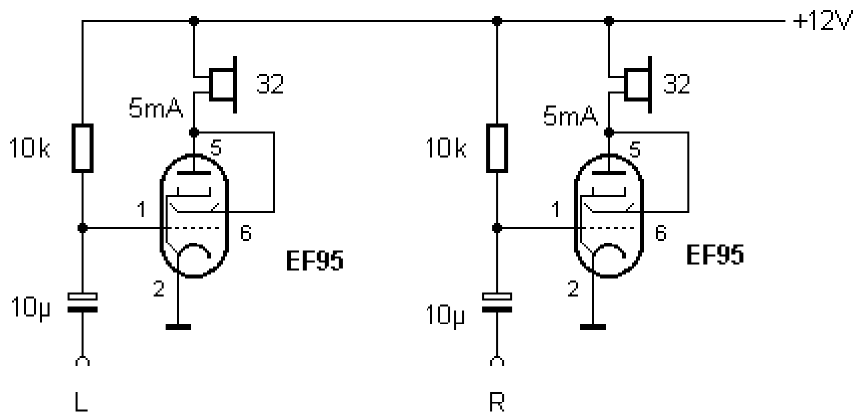
The headphones are connected directly to the anode of the tubes meaning the common terminal of both channels is connected to the operating voltage of +12V. Therefore, none of the stereo headphone jacks that are connected to ground can be used here. The headphones can be connected for example via the screw terminals. The input can be connected normally using a stereo cable and the other stereo jack.

Additional experiment:

- Investigate the influence of different grid resistors between 10 kΩ and 1 MΩ on the volume and sound quality of the circuit.
- Measure frequency response and harmonic distortions with an audio-analyzer program like "audiotester".

4.2 Triode Configuration

Experiments with smaller grid resistors show that increasing grid current only slightly increases the anode current of the EF95, but causes significant distortions. One possible cause is the unfavorable current distribution between the screen grid and the anode.



Triode Configuration

In a second experiment, the screen grid g_2 is connected to the anode allowing the tubes to operate as triodes! With grid resistors of 10 kΩ currents of 5 mA can now be achieved. The triode amplifier is extremely loud with high-impedance headphones. However, even a low-impedance type with only 32 ohms already showed excellent results. Nevertheless, a type with good efficiency should be used.

The amplifier does indeed produce a distinct sound that was subjectively found to be very pleasing. In general, tubes are said to have a "warm" sound. There are several reasons for this:

* The high internal resistance of the tube hardly dampens the headphones.
* The slightly curved characteristic curve of the triode alters the sound.
* The tube smoothly transitions into saturation when overdriven.

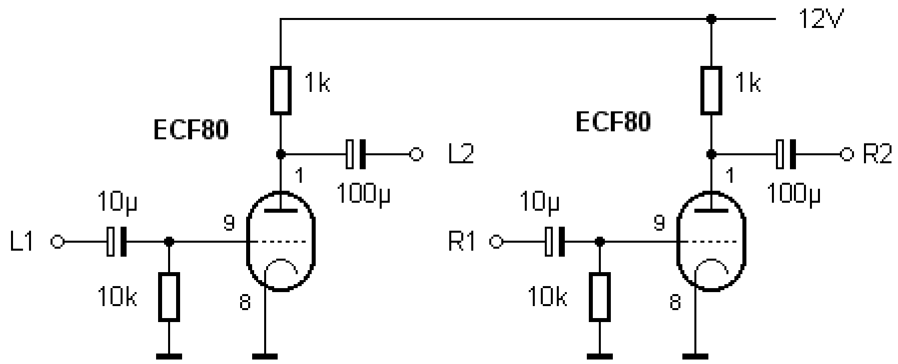
Additional Experiments:

- Use an oscilloscope to measure the input voltage and the output voltage of the amplifier and determine the tube's transconductance (slope of the characteristic curve) for the given operating point.
- Measure frequency response and harmonic distortions with an audio-analyzer program like "audiotester".

4.3 RC-Coupling

Most of the time you want to avoid a DC current through the headphones, as it could introduce additional distortions and create a pop when connecting the headphones. In such cases coupling through an output transformer or a capacitor is a suitable option. An output transformer like our 1:10 audio transformer TR110 or better the universal type TR16K16W can be used.
RC coupling is particularly simple and effective for low-power headphone amplifiers.

In this setup, the triode section of the ECF80 is used as a headphone amplifier. The tube already provides a sufficiently large current and good transconductance even without positive grid bias. Both high-impedance and low-impedance headphones can be connected to the output.



Headphone Amplifier with the Triode Section of two ECF80

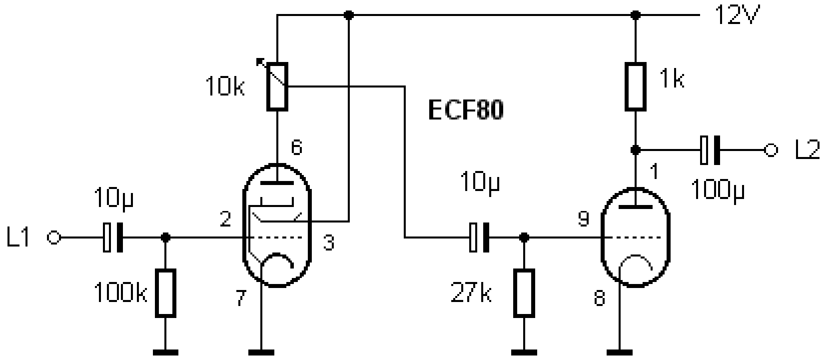
Additional experiments:

- Determine the anode current by measuring the voltage drop across the anode resistor. Increase the anode current by applying positive grid bias – connect the grid resistor to the anode voltage of +12 V instead of ground.
- Measure frequency response and harmonic distortions with an audio-analyzer program like "audiotester".

4.4 Pre-Amplifier

With an additional preamplifier stage, a greater voltage gain can be achieved. In this setup, the pentode section of the ECF80 is used as a preamplifier, allowing for a relatively high-impedance input. This configuration is suitable for instance as a headphone amplifier for a record player with a high-impedance crystal cartridge system.

However, modern magnet cartridges require an additional equalization of the pre-emphasis characteristic (which by the way is approximately achiepre-emphasisved by the characteristics of crystal systems). Without an equalization preamplifier bass frequencies are attenuated while treble frequencies are boosted unnaturally.



One Stereo Channel with Pentode Pre-Amplification.

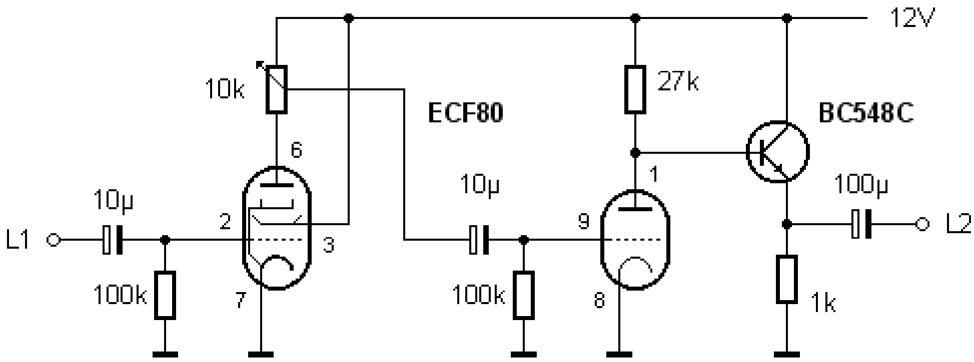
Additionally a volume control has been installed. The potentiometer also acts as the anode resistor. The circuit diagram depicts only the left channel of the amplifier.

Additional experiments:

- Measure the overall gain of the two-stage amplifier.
- Measure frequency response and harmonic distortions with an audio-analyzer program like "audiotester".

4.5 Hybrid Amplifier

Often it is beneficial to combine tubes and transistors in one circuit. Tubes generally have very high input impedance. Especially when using low-impedance headphones, the output power obtained is too low. One possible solution is to use an output transformer. However, a simpler and more cost-effective approach is to incorporate a transistor.



Röhrenverstärker mit nachfolgendem Emitterfolger

The circuit depicts a two-stage tube amplifier followed by an emitter follower using an NPN transistor BC548C. The circuit can drive low-impedance headphones with sufficient volume. However the sound quality is primarily influenced by the tubes.

Additional experiment:

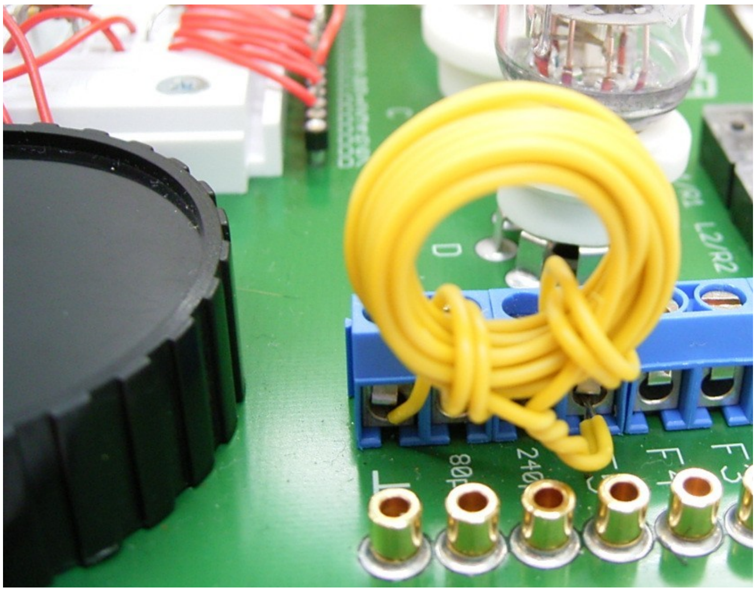
- Determine the maximum output power across a load resistor of 32 Ω.

5 Radio Circuits

Early tube radios utilized the relatively simple Audion[1] circuit ("Grid-Leak Detector" in English) . In this circuit, the tube serves both for demodulation and amplification of the RF signal. Carefully constructed Audion receivers can achieve reception capabilities comparable to more expensive receivers and often exhibit a particularly pleasant sound quality.

5.1 Shortwave-Audion with the EF95

The core of an Audion receiver is the tuned LC-circuit ("tank-circuit") composed of a coil and variable capacitor. The frequency range can be adjusted within wide limits by modifying the coil's specifications. Coils designed for the shortwave range are particularly simple and convenient. The coil can be created as a self-supporting air core coil using hookup wire. To achieve this, wind two sets of 8 turns in the same winding direction around an AA battery and connect the common point of the windings to create a tap. The wire ends should be wound around the coil in a way that ensures a mechanically stable winding.

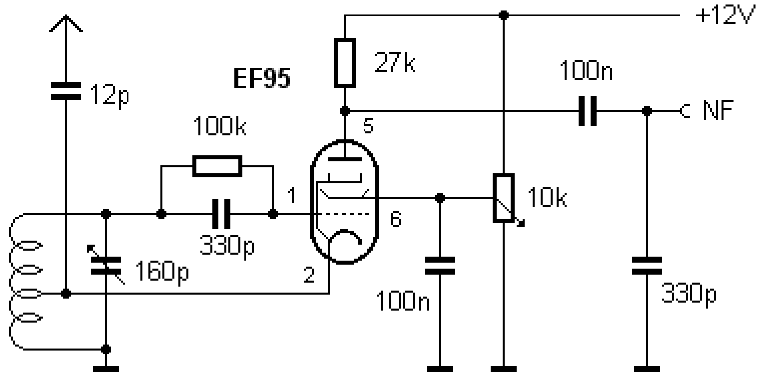


The Shortwave Coil

The coil is placed directly at the screw connection of the variable capacitor. The outer terminals are connected to the varaible capacitor with 160 pF (="C1"). The center tap is connected to the terminal "F5". To avoid losses, the connection between the coil and the

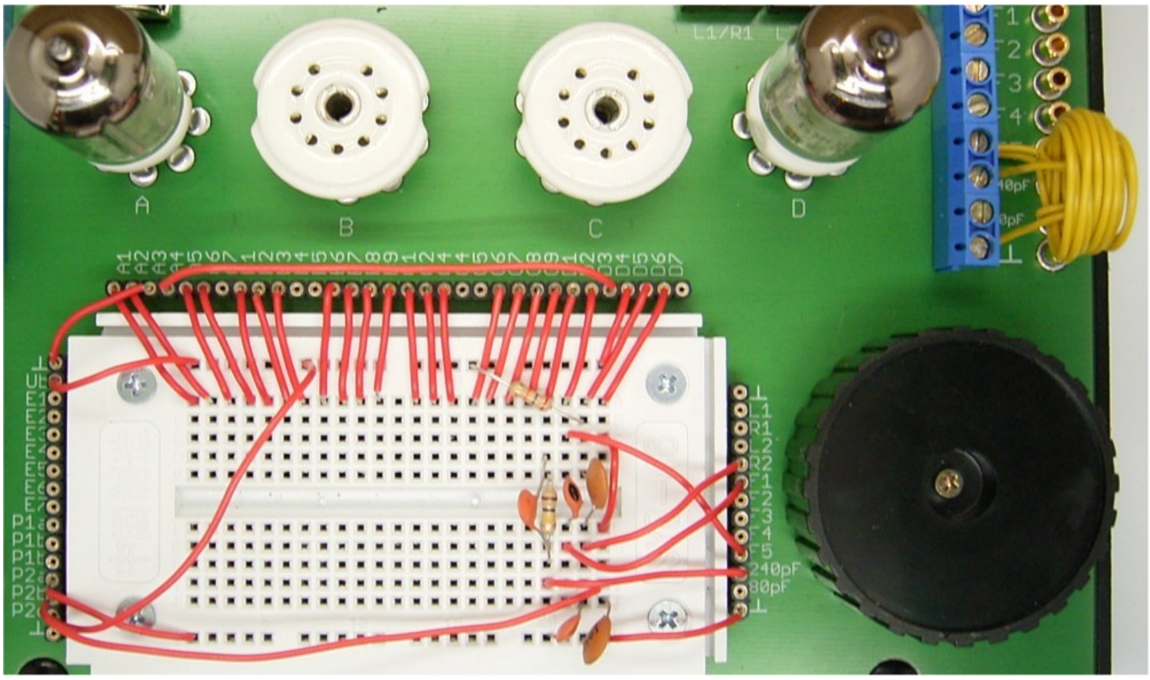
1 There are multiple definitions of the "Audion-Circuit". In German literature it is first of all used for a Tuned Radio Frequency Receiver with a tube or transistor which acts as amplifier and rectifier (demodulator) at the same time (= "Grid-Leak Detector"). Furthermore there is the "Rückkopplungs-Audion" (Feedback-Audion) in German, which is equivalent to the "Regenerative Circuit" in English. In English the word "Audion" is usually reserved for the original Lee DeForest vacuum tube.

variable capacitor must be low-impedance, so connectors on the plug board should be avoided in the LC circuit.



The Feedback-Audion Circuit with a Pentode

The schematic diagram shows the basic configuration of an Audion circuit with feedback. The amplified RF signal is fed back into the oscillating circuit through the cathode to compensate for losses. This feedback leads to a reduced bandwidth and increased signal voltage within the resonant circuit. The screen grid voltage and thus the amplification of the tube can be adjusted using the potentiometer. The Audion is adjusted with the potentiometer in such a way that the circuit operates just berfore self-oscillation sets in.
The antenna (e.g., a long rod-antenna or a long wire antenna with a minimum length of 6 meters) needs to be loosely coupled using a small coupling capacitor. Direct coupling can dampen the oscillating circuit to the extent that the tube doesn't achieve sufficient amplification for self-oscillation to occur.

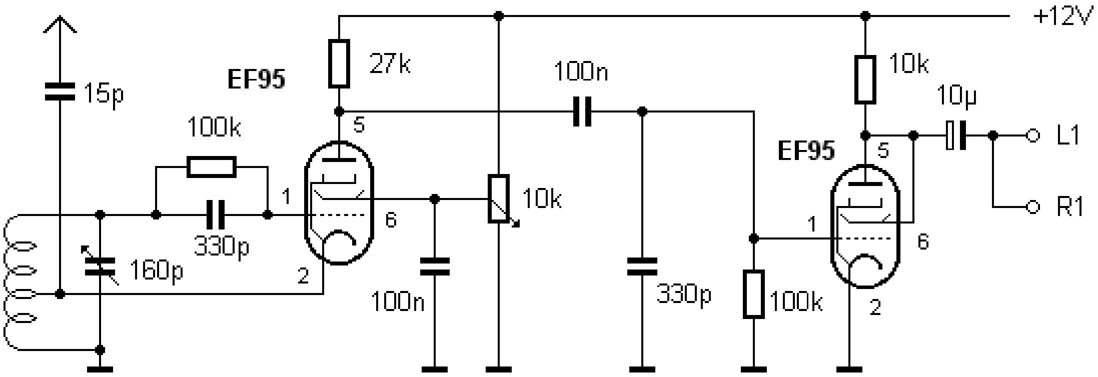


The audio output is connected to one of the stereo jacks. Here you can connect an audio amplifier or even a high-impedance headphone. However, the signal voltage is still low, so the reception will be very muted.

Additional Experiment:
Examine the effect of direct antenna coupling with varying antenna lengths.
Also test a short rod antenna directly at the upper end of the oscillating circuit.

5.2 SW-Audion with Audio Stage

In the previous experiments with the EF95, two tube filaments were always connected in series, meaning two tubes were installed even if only one was used. Given this, it's logical to utilize the second tube as an audio amplifier for the audion circuit.

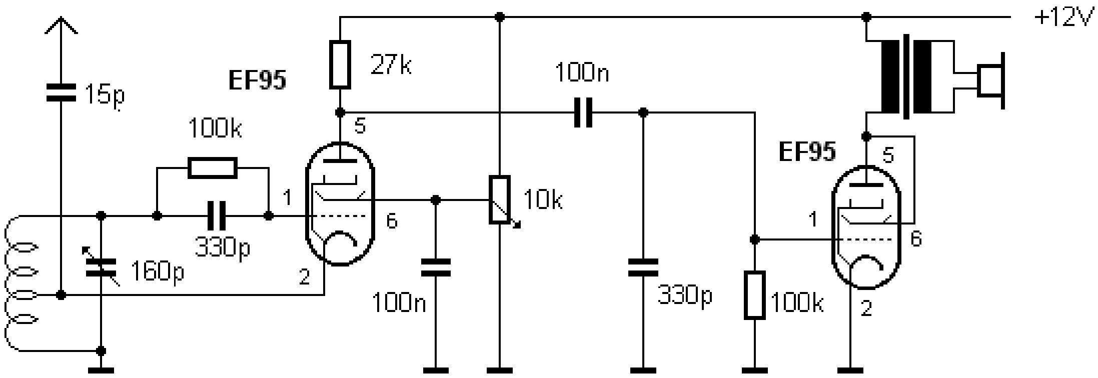


Audion with addtitional Audio Stage

The audio tube operates in triode mode with RC coupling for headphones or a connected audio amplifier. With high-impedance headphones, the volume is sufficient, and even 32-ohms headphones with good efficiency can be directly connected.

For more volume, the matching of the audio stage to the headphones or loudspeaker needs improvement. Low-impedance headphones should be connected using an output transformer. Our universal matching-transformer TR16K16W or the TR3k5_8W are good choices.

Another option is to use a small mains transformer, like a 230V/24V (or 120V/1V) transformer. The winding ratio is approximately 10:1, resulting in an impedance ratio of 100:1. When both headphone capsules of 32 ohms are connected in parallel, the impedance becomes 16 ohms. This setup makes the tube to work with an "apparently" (by the workings of the transformer) external load of 1.6 kΩ. The improved match to the high internal impedance of the tube leads to enhanced output power. But remember that power-transformers are designed only for 50/60 Hz transformation and not for the whole audio frequency-range. So don´t expect HiFi-quality sound experience :-)



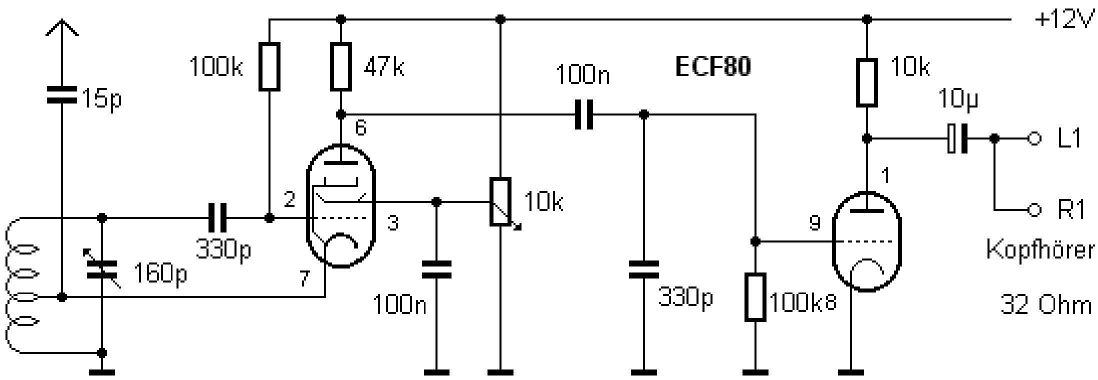
Impedance Matching with an Output Transformer

Additional Experiments:

- Use an audio-transformer with multiple taps like our TR16K16W and find the best match for maximum volume.
- Also, test a speaker connected to the output. With suitable matching even low-volume loudspeaker-operation should be possible, provided the speaker has good efficiency.

5.3 SW-Audion with the ECF80

A powerful audion amplifier can be constructed using just one ECF80 tube, even without an output transformer, as the triode section provides sufficient output power even at low voltages.



Zweistufiger Empfänger mit einer ECF80

The pentode section of the ECF80 requires a positive grid bias at the low operating voltage of 12 V to achieve sufficient RF amplification for oscillation in the audion stage. The characteristics of this audion setup are quite distinct from the version using an EF95. The start of feedback-oscillation sets in relative "hard", as the tube does not regulate the output significantly with increasing RF input voltage.

This means that you can achieve greater amplification and overall louder volume compared to the EF95 setup. However, a disadvantage is the abrupt start of feedback-oscillation, which forces the user to set the feedback potentiometer well below the oscillation threshold. Despite this drawback, the circuit is excellent for receiving distant shortwave radio stations at high volume.

Additional Experiments:

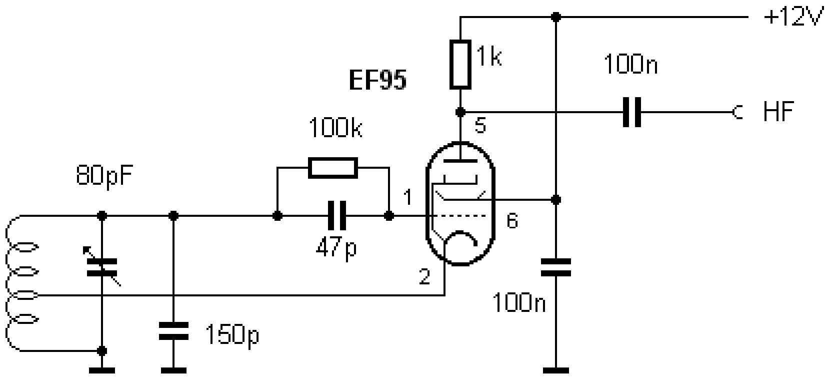
- Equip the receiver with a volume control.
- Try speaker operation using an output transformer.

6 HF-Oscillators

An RF-oscillator consists of a signal amplifier and a resonator with a well-defined resonant frequency. This resonator can be either a tuned circuit (like an LC-circuit) or a quartz crystal. Oscillators are used in the construction of receivers and for various measurement purposes.

6.1 ECO-Oscillator

The basic circuit of a free-running oscillator has already been used in the Audion circuit. Here now an RF-oscillator is to be built for testing purposes. The ECO circuit ("Electron Coupled Oscillator") provides good isolation of the resonant circuit from the RF-output. Therefore, there are only minimal feedback effects that could negatively affect stability.



The ECO-Oscillator

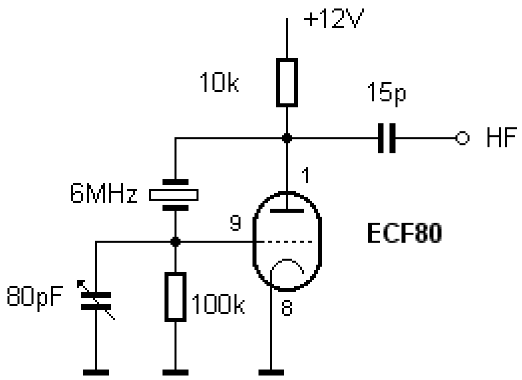
The circuit uses bandspread tuning with a parallel capacitor of 150 pF and the smaller section of the dual tuning capacitor with 80 pF ("C2"). The resonant circuit capacitance can be adjusted between 150 pF and 230 pF in a 1:1.5 ratio. The frequency variation corresponds to the square root of the capacitance ratio, approximately 1:1.24. The absolute frequency range is determined by the inductance of the coil. With the Audion coil presented earlier, a tuning range of 7 MHz to 8.7 MHz can be achieved.

The RF-output of the test oscillator can be connected to any receiver input and used for calibration purposes, among other applications.

Additional experiment:
Determine the frequency range by comparing it with an existing shortwave radio and create a frequency scale.

6.2 Quartz-Oscillator

A quartz crystal behaves like a resonant circuit with extremely low damping. Therefore, a quartz oscillator is particularly stable and precise. Here the triode system of the ECF80 is used to build a 6 MHz oscillator. The variable capacitor is used for fine-tuning and allows a frequency change of one to two kilohertz.



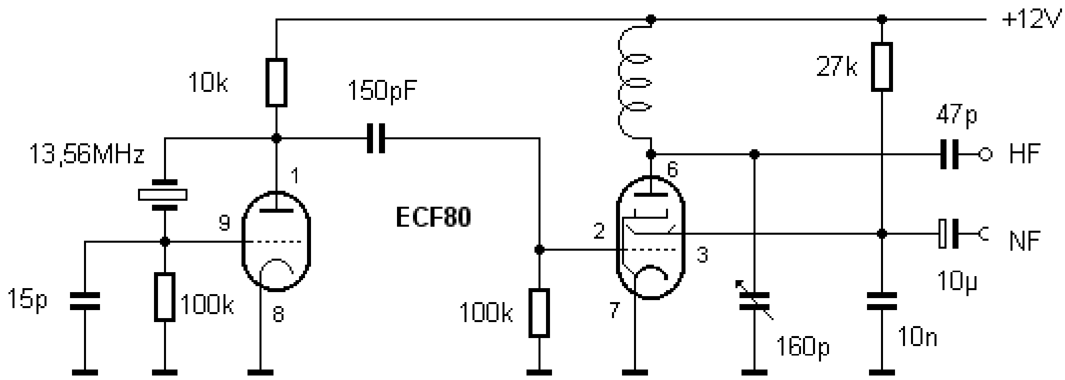
A Quartz-Oscillator

Examine the signal of the oscillator with a shortwave radio. With loose coupling, you may detect interference with the AM broadcast station at 6005 kHz. Tuning the variable capacitor will alter the interference whistle.

Additional experiment:
Check the oscillator's sensitivity to hand capacitance. Observe how much the frequency changes when you bring your hand closer or move it away.

6.3 Amplitude Modulation

The frequency 13.56 MHz is allocated for experimental and scientific purposes and is used here for a small AM transmitter. The required precision can only be achieved with a quartz crystal.



A Shortwave AM-Transmitter with an ECF80

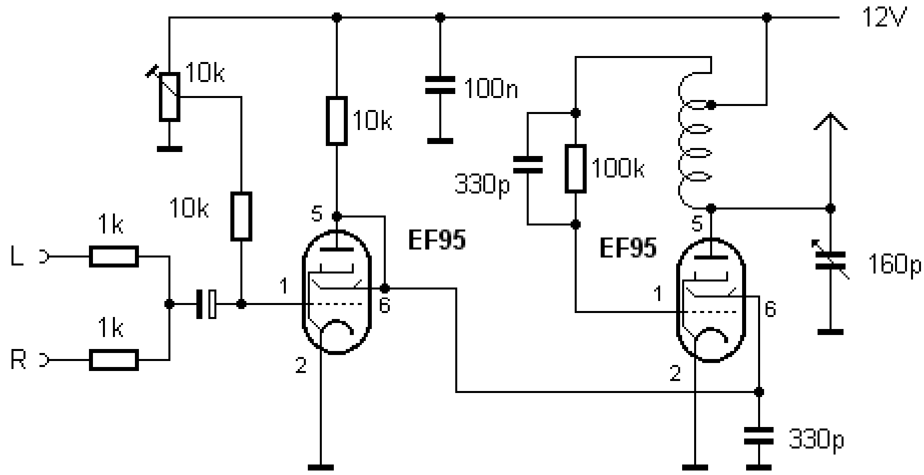
The circuit largely corresponds to a traditional broadcast transmitter. The quartz oscillator drives the transmission stage with a pentode. In the anode circuit, there is a tuned circuit where an antenna can be connected. By changing the screen grid voltage, the output amplitude is modulated. The Audio-input requires a modulation voltage of several volts.
The self-wound shortwave coil from Experiment 5.1 can be used as the coil at the anode.

Connect a wire antenna approximately two meters long to the HF output. Tune in to the 13.56 MHz signal on a shortwave radio. Then adjust the variable capacitor for maximum signal strength. Once an NF signal is applied to the modulation input, it will be heard on the radio. Examine the range of the transmitter. Avoid long transmissions, as full-fledged broadcasting is not allowed on this frequency either.

Additional experiment:
Use the circuit to set up a DRM (Digital Radio Mondiale) transmitter. Feed the output signal into the PC sound card and generate a DRM baseband signal using software like DREAM in transmission mode. The circuit can now be used to test various DRM receivers.

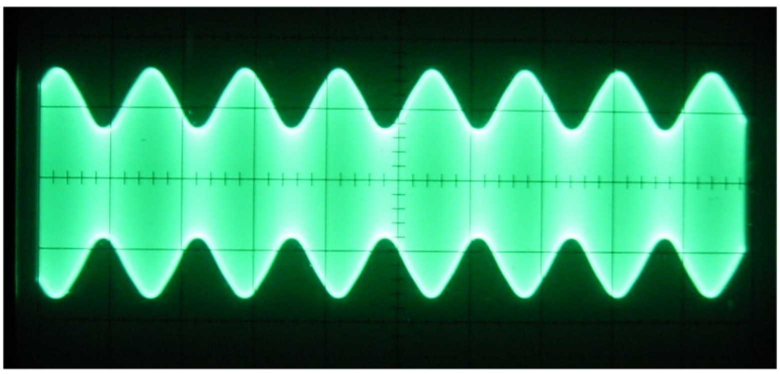
6.4 AM Medium-Wave Transmitter

This medium-wave transmitter uses a free-running oscillator with a ferrite antenna from an old radio. Ideally our small MW antenna with coupling winding can also be used for this purpose. Two EF95 tubes have been employed here. One tube serves as a free-running oscillator, while the other acts as a modulation amplifier.



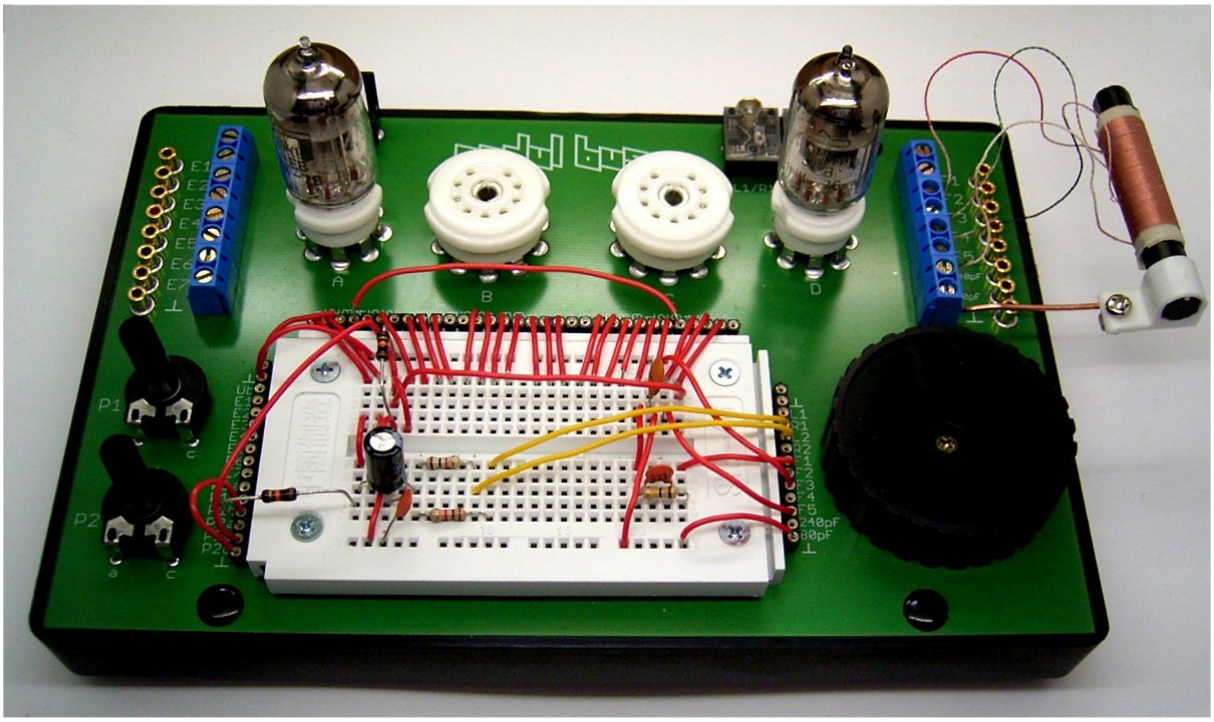
A freely tunable medium-wave transmitter

The free-running oscillator is modulated through the screen grid. The preceding modulation amplifier operates in triode mode to achieve a sufficiently large, low-distortion drive despite the low anode voltage. The operating point is set with a trimmer to minimize distortion. The characteristics of both stages are oppositely curved due to the phase shift of the modulation amplifier. With optimal settings, the resulting distortions largely cancel out, allowing for a large modulation range of up to approximately 50%. A stereo jack is used for the audio-input, where the PC sound card or another audio source with line-level can be connected. Both channels are summed to a mono signal because only one channel is transmitted on medium wave.



The Amplitude-modulated RF-Signal

The resonant circuit coil is wound on a ferrite rod here and can also serve as an antenna if you bring it close to a radio with a ferrite antenna. Alternatively, a wire antenna can be connected, but this increases the risk that your desired program can also be heard in the neighborhood :-)



The wiring of the medium-wave AM transmitter

7 Digital Radio DRM (Digital Radio Mondiale)

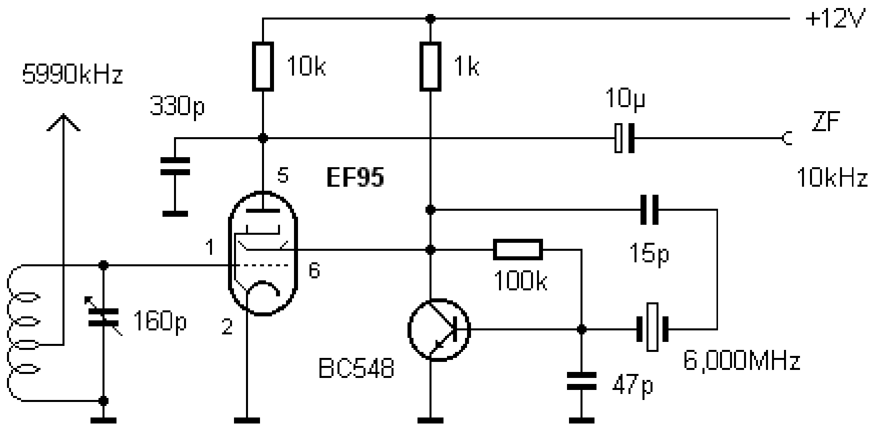
The attempt to digitalize Long-, Medium-, and Shortwave-broadcasting using DRM (Digital Radio Mondiale) aimed to combine FM-like audio quality with the extended reach of Longwave, Mediumwave, and Shortwave frequencies. Unfortunately, this initiative is considered to have practically failed as there are currently very few commercial DRM receivers available for purchase. Moreover, the number of DRM broadcasts has significantly decreased.

For a list of current DRM broadcasts (in Europe) it's best to refer to the German DRM Forum or the DRM Consortium. Consequently the circuits discussed here need to be adapted to the remaining receivable frequencies. Since the signals of the remaining DRM station in Germany/Europe are relatively weak, reception may only be possible with powerful antennas when using the receivers described here.

To receive DRM broadcasts, a software decoder in the PC, such as DREAM, is typically used. A receiver converts the DRM signal to an intermediate frequency, e.g. 12 kHz, which is then fed into the PC's sound card. DREAM decodes the signal into an audio stream and outputs the decoded signal through the sound card. The critical requirement for the receiver used is absolute frequency stability, which is easiest to achieve with a quartz oscillator.

7.1 RTL2-Direct Mixer with an EF95 [2]

This hybrid DRM receiver uses an EF95 as a mixer and an NPN transistor as an oscillator. The circuit is designed for DRM RTL 2 on 5990 kHz. You can use a standard 6 MHz quartz crystal to ensure the necessary stability.

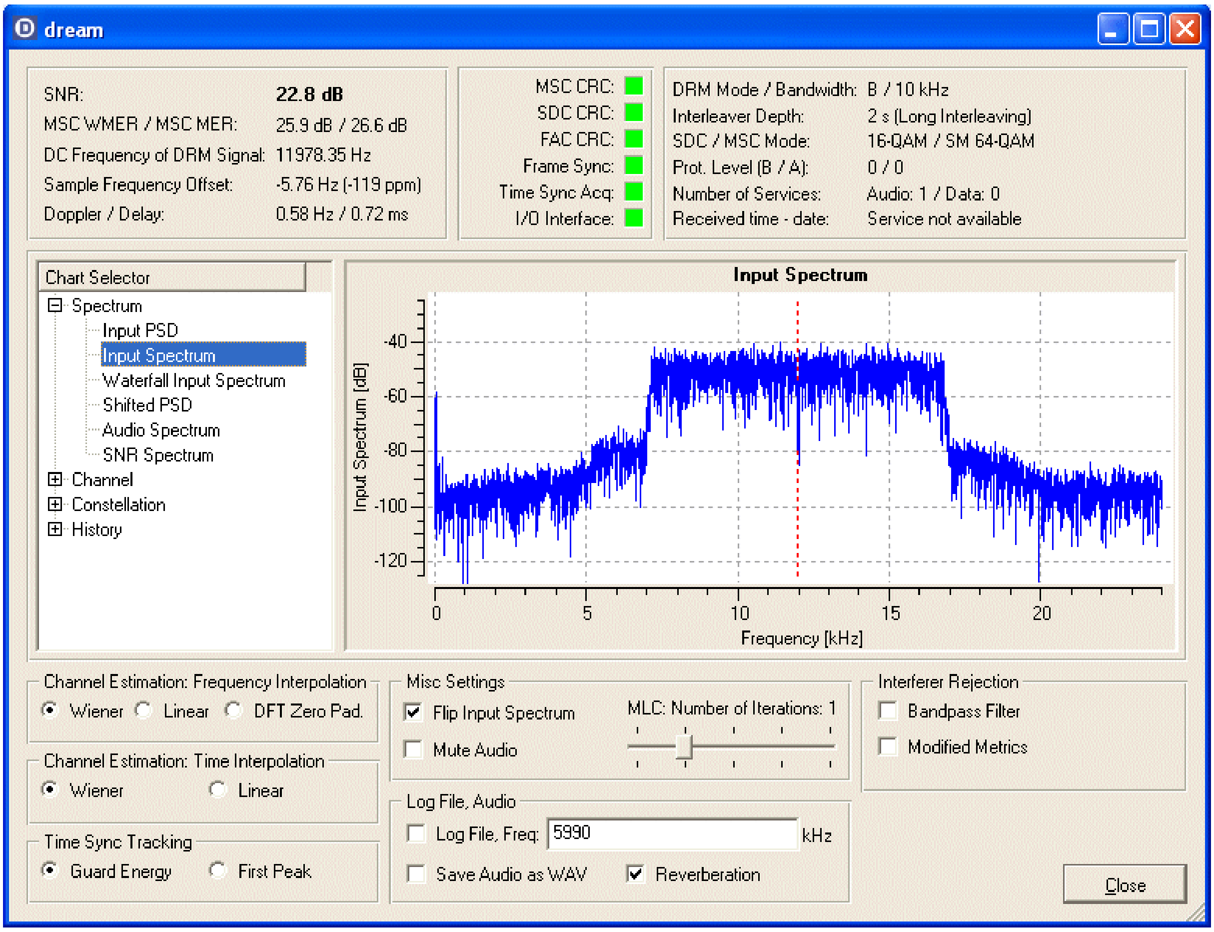


The DRM Direct Mixer

2 Since the RTL2 station on 5990 kHz has been shut down, you need to find a station from the table in the appendix that is still active and whose frequency can be matched with a quartz of the appropriate frequency (=transmit frequency +/- 10 kHz). A more versatile approach can be found in Experiment 7.2

Thanks to the high sensitivity of the PC sound card, the receiver does not require significant amplification. The input LC resonant circuit can be relatively strongly coupled to the antenna. The variable capacitor is tuned for maximum signal amplitude.

In the evaluation dialog in DREAM [3]the signal spectrum of the receiver can be displayed. You will see a 10 kHz wide band with numerous carriers.



The Spectrum of a DRM-Station

Since this simple receiver uses an oscillator frequency above the reception frequency, the signal spectrum is inverted. Therefore in DREAM the "Flip Input Spectrum" checkbox must be activated. With a sufficiently strong signal DREAM decodes the data stream allowing you to hear the DRM broadcast through your PC speakers.

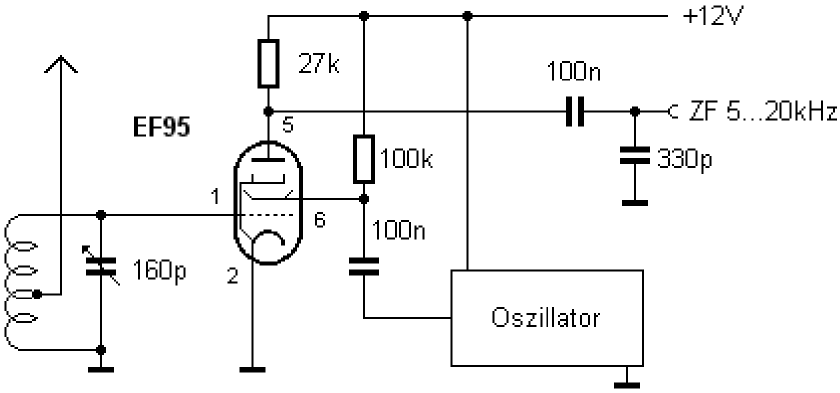
Additional Experiments:

- Replace the transistor oscillator with a suitable tube circuit.
- Try using an ECF80 as a mixer and oscillator.

3 Alternative DRM software-decorders can be found in the appendix

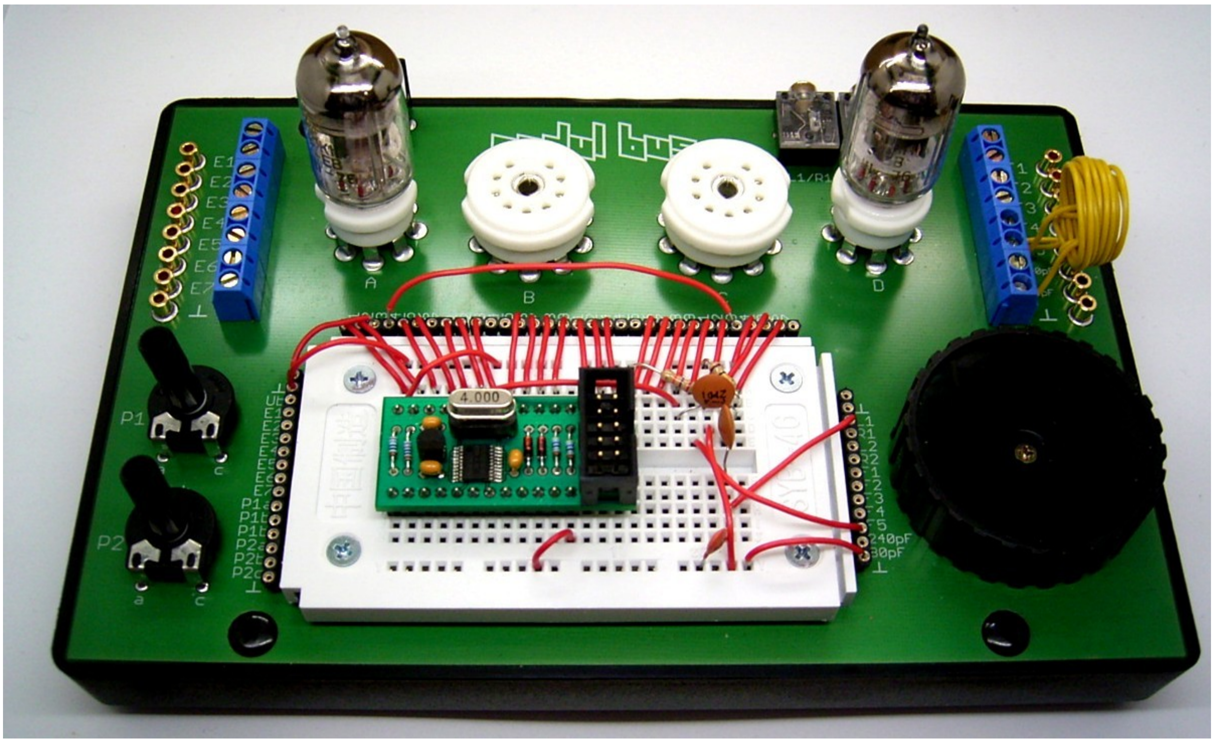
7.2 DRM with a programmable Quartz-Oscillator

A DRM receiver places special demands on the stability of the mixer oscillator. Therefore a quartz oscillator his preferred over a free-running oscillator. However in this case you typically have only one receiving frequency. Here, our programmable 3-channel RF generator or the PICS307 could be suitable options.



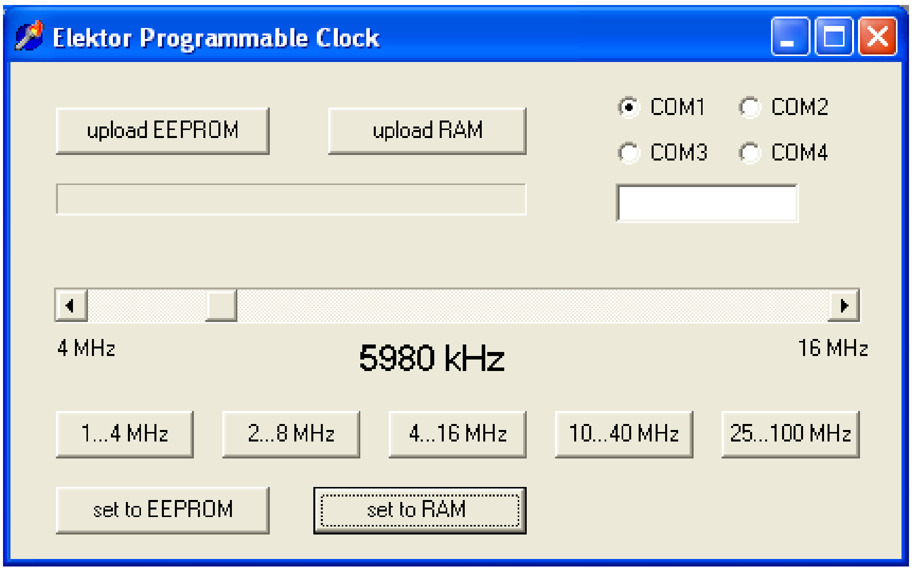
Direct Mixer with a programmable Quartz Oscillator

The circuit shows a mixer stage with a tube. At the input, there is a resonant circuit tuned to the reception frequency. The oscillator signal with an amplitude of 3.3 V_{pp} is applied to the screen grid and modulates the tube's transconductance, making it a simple multiplicative mixer. Usually, an intermediate frequency of 12 kHz is sent to the PC, so the oscillator should oscillate 12 kHz below the reception frequency. However, with decoding software like DREAM other frequencies are also possible, so you can choose for example 10 kHz or 15 kHz.



Wiring of the Tunable DRM Receiver

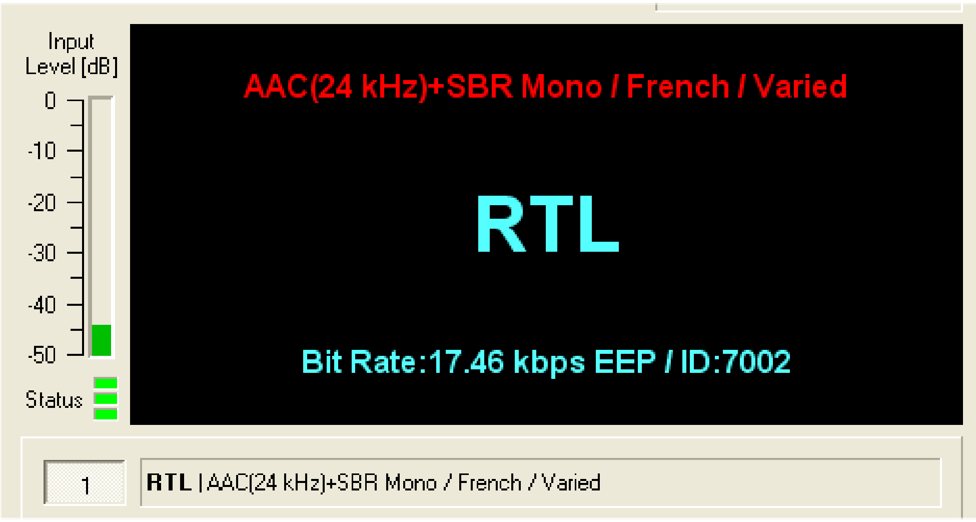
The programmable quartz oscillator[4] has a 3.3V voltage regulator onboard and can therefore be operated with any voltage between 5V and 12V. At the output, there is always a square-shaped RF-signal with $3.3V_{pp}$ amplitude.



The Tuning Software

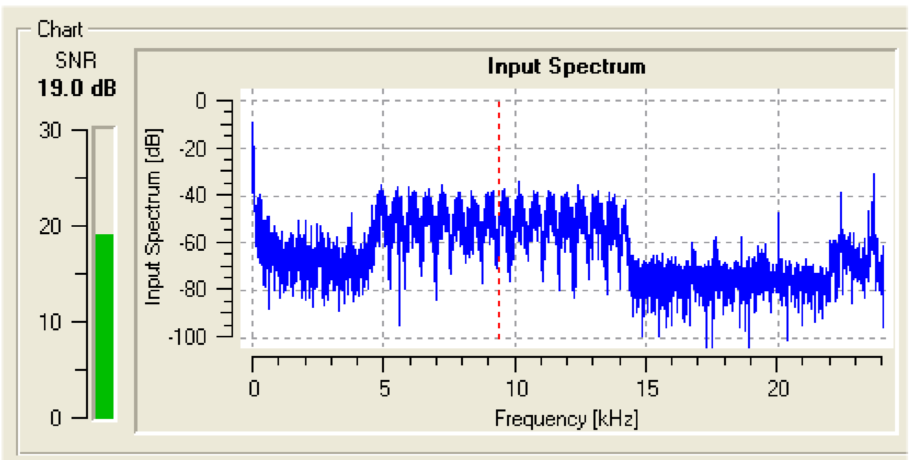
4 The programmable quartz oscillator shown here, as well as the Windows software, are from a discontinued type developed for Elektor-magazine. However, you can achieve the same results with the mentioned 3-channel RF generator or the PICS-307, which have their own Windows control programs available.

The programmable quartz oscillator is configured using a small Windows program and the PC's serial interface. For example, if you want to receive RTL DRM-2 at 5990 kHz you set the oscillator frequency to 5980 kHz, resulting in an IF of 10 kHz. The settings can be stored in the oscillator's RAM and take effect immediately. Transmitting the settings to the system's EEPROM creates a fixed programmed setting that activates without the need for PC intervention during the next startup. So, the module behaves both as a normal quartz oscillator and as a tunable oscillator. If you replace the 10 MHz quartz on the module with a 4 MHz quartz, you can shift the lower frequency limit down to 400 kHz.



Station Identification in DREAM

The IF-Signal is decoded in the PC using DRM software called DREAM. With sufficiently clear reception, you'll receive the audio signal along with station identification. Some stations also transmit text messages or images simultaneously. In the evaluation dialog you can observe the signal spectrum and access additional information such as the signal-to-noise ratio.



DRM signal with a signal-to-noise ratio of 19 dB

With this direct mixer almost all existing DRM stations in the 49-meter band and numerous other stations in the shortwave range could be received. However, the reception results do not match those of a superheterodyne receiver. Especially the unfiltered image reception leads to increased interference. In individual cases, interference can be eliminated by setting a favorable oscillator frequency above the reception frequency and setting DREAM to inverted spectrum. In other cases, the oscillator is tuned precisely to the carrier of a neighboring interfering station, whose spectrum then only extends up to 5 kHz.

Additional Experiment:

- Expand the reception range to medium wave. Use a ferrite antenna or a loop antenna for the input circuit.

8 Tube Data and Operating Points

The experiments presented here with vacuum tubes operate at low voltages, typically at 12 V. However these tubes were originally designed for much higher voltages, so the manufacturer's data and suggested operating points and circuits are not directly applicable. Therefore it is necessary to investigate for each tube under what conditions and with what parameters it can be operated at a voltage of 12 V. Here appropriate measurements will be conducted. In [1] a measurement method for determining the grid current, anode current, and transconductance of a tube is presented, which will also be used here.

8.1 Manufacturer Data

The tubes used here were originally designed for use with higher anode voltages. The following tables show the typical operating points. Both tubes were designed for high-frequency (RF) applications. Here the tubes are to be used with low anode voltages of 12 V. A look at the manufacturer's data reveals the differences. Most tubes were designed for anode voltages of 250 V. The tubes used here have always been used also with lower voltages.

The EF95 was especially designed for mobile applications with low heater power and relatively low anode voltage.

EF95	Heater	Limiting Values	Operating Point
for RF-Amplifiers	6,3 V/ 0,175 A	P_A = 1,5 W I_K = 14 mA	U_A = 120 V I_A = 7,5 mA U_G = -2 V S = 5 mA/V

The ECF80 was primarily used in VHF mixer stages of TV-receivers. It is a multi-purpose tube with a triode and a pentode. The triode exhibits a relatively large anode current of 14 mA even at just 100 V, which means it can still perform reasonably well at low voltages.

ECF80, Triode	Heater	Limiting Values	Operating Point
for VHF-mixers	6,3 V/ 0,430 A	P_A = 1,5 W I_K = 14 mA	U_A = 100 V I_A = 14 mA U_G = -2 V S = 5 mA/V

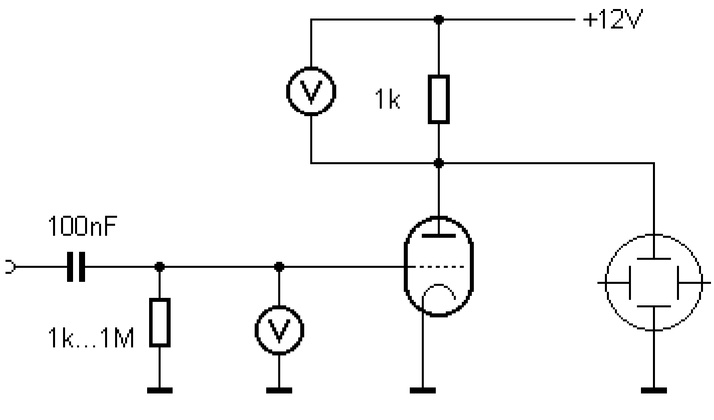
The pentode in the ECF80 is comparable to the EF95, which will also be evident in measurements at only 12 V.

ECF80, Pentode	Heater	Limiting Values	Operating Point
for VHF-mixers	6,3 V/ 0,430 A	P_A = 1,7 W I_K = 14 mA	U_A = 170 V I_A = 10 mA U_G = -2 V S = 6,2 mA/V

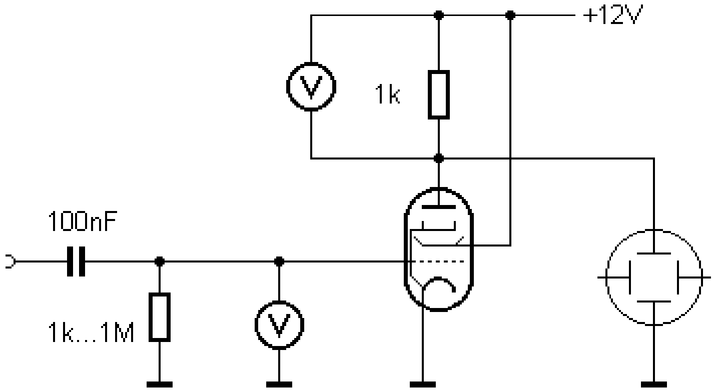
8.2 Operating Points at 12 V

In [1] a method was developed to investigate the characteristics of a vacuum tube at low voltages. The operating point is determined in each case by different grid resistors. The negative grid bias is generated by the grid starting current.

For comparative measurements on different tubes, the following circuit was chosen. All tubes are to be tested at an operating voltage of 12 V and with an anode resistor of 1 kΩ. The grid resistor is varied within wide limits to achieve different grid biases and operating points. The measurement of the voltage drop across the anode resistor provides the anode current at each operating point.



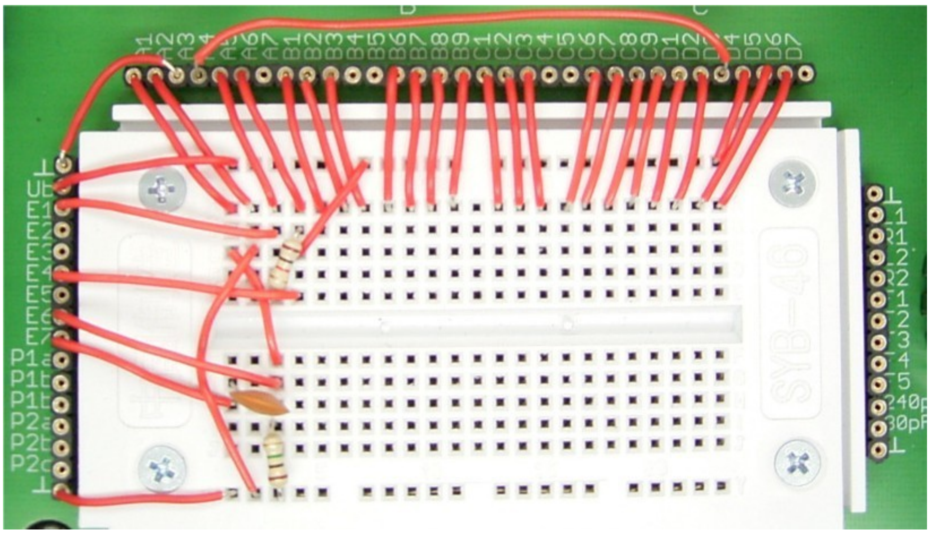
Measurement on a Triode



The Test Circuit for a Pentode

If you also want to measure the transconductance of the tube at each operating point, you will need a tone generator and an oscilloscope (or the already mentioned "audiotester" software with a PC soundcard). The circuit is then driven with a 10 kHz signal at 10 mV. The output voltage is measured on the oscilloscope. The transconductance at each operating point can be determined from the gain. A voltage gain of 1, due to the anode resistor of 1 kΩ, corresponds to a transconductance of 1 mA/V.

This circuit requires multiple measurement points and connections for a tone generator and an oscilloscope. Here it is convenient that the experimental system has side connectors E1 to E7 which can be connected with short wires. The actual circuit only requires two resistors and a capacitor. The following image shows the setup for the left EF95. The grid voltage can be measured between ground and measurement socket E6. The voltage drop across the anode resistor can be measured between E1 and E4. An input signal voltage can be applied to E7.



Wiring for the Test-Circuit

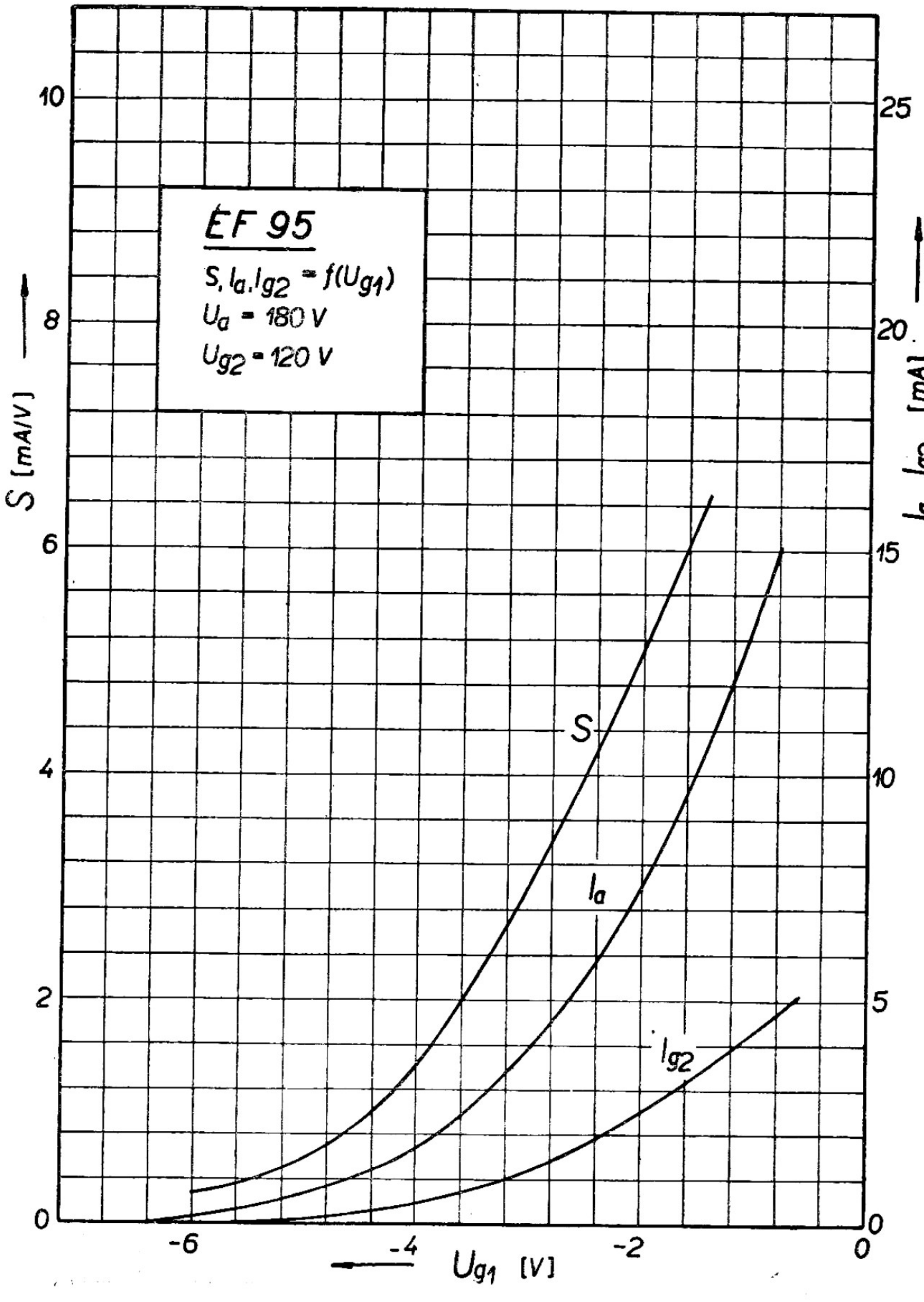
The measurements are carried out with various grid resistors. The photo shows the circuit with a grid resistor of 1 MΩ. Alternatively you could remove the resistor on the breadboard and externally connect a resistance decade box between ground and E6.

8.3 Data for the EF95

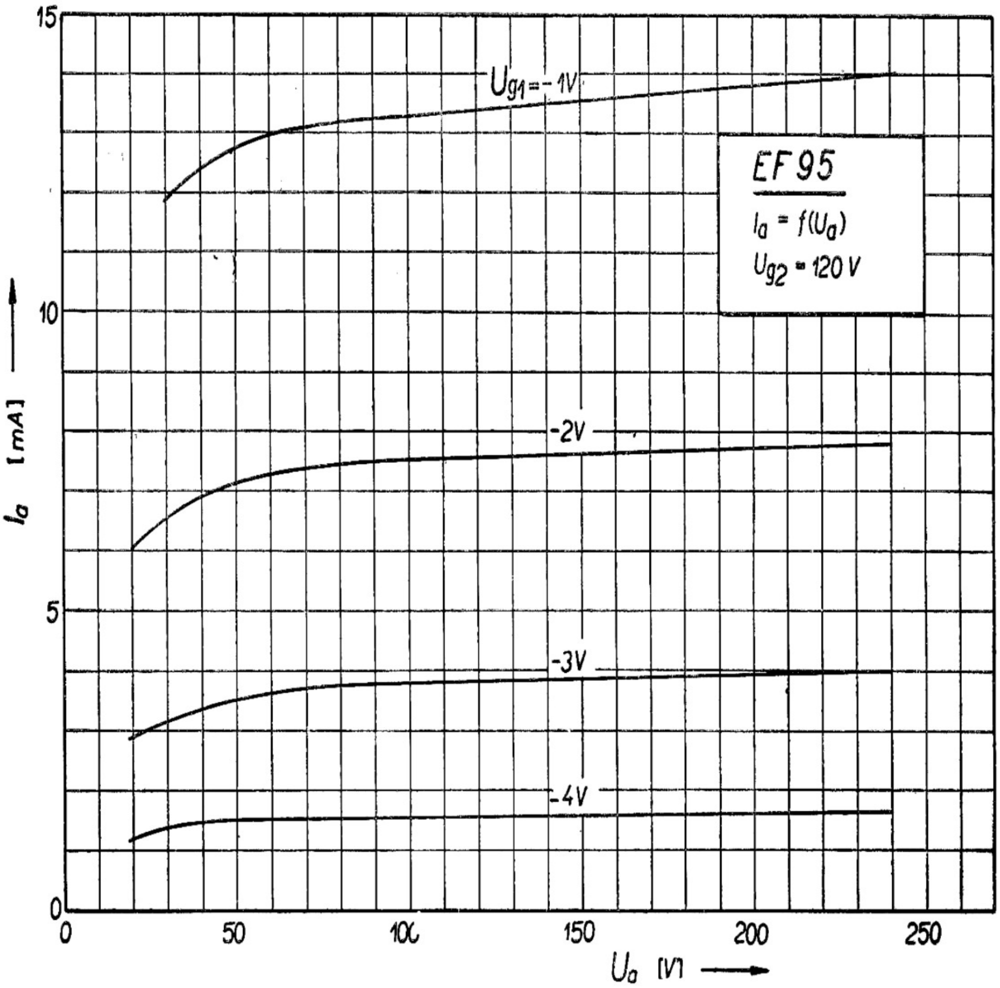
The following table shows the results for the EF95 tube. The transconductance (slope) was determined using the oscilloscope.

EF95	R_G	U_G	I_A	S
U_B=12V	0	0	0,24 mA	
	1 kΩ	-40 mV	0,20 mA	1,0 mA/V
	10 kΩ	-190 mV	0,09 mA	0,7 mA/V
	100 kΩ	-380 mV	0,03 mA	0,3 mA/V
	1 MΩ	-590 mV	0,01 mA	0,1 mA/V

The measurement results show that the tube builds up a high negative grid bias at large grid resistances and then only reaches small anode currents. In some applications, it may be necessary to connect the grid resistor not to ground but to the positive operating voltage.



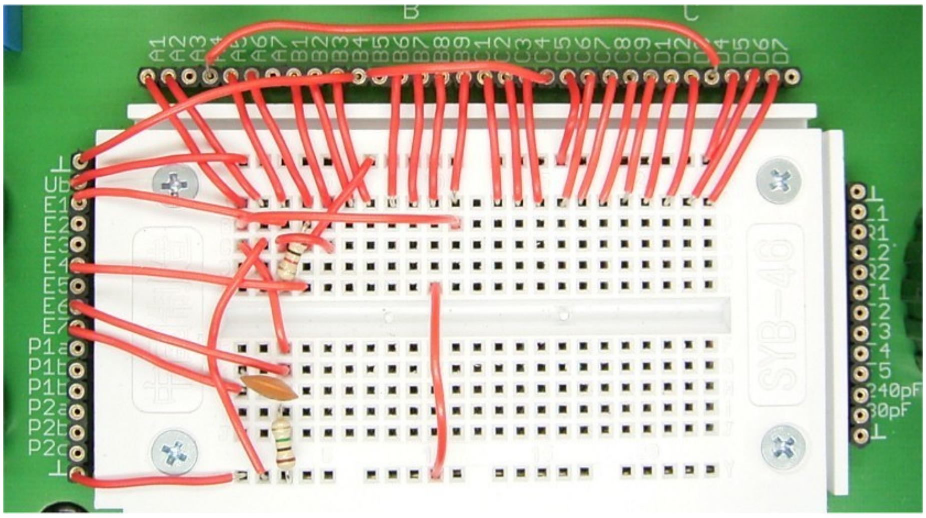
Characteristic Curves of the EF95 Pentode



Characteristic Curves of the EF95 Pentode

8.4 Data for the Triode in the ECF80

Since the EF95 has already been successfully measured, the measurement circuit for the ECF80 can be reused with relatively little effort. First, the triode will be examined. You connect grid 1 and anode on each both tube. The heater of the EF95 is turned off, and the ECF80's heater is turned on. Although the first tube is still in the circuit, only the triode is now active.



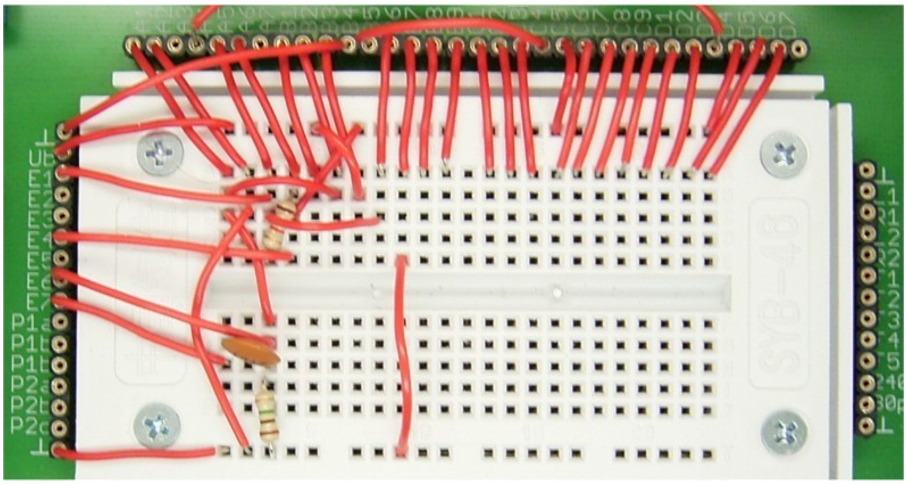
Wiring for Measurements of the Triode of an ECF80

The following table shows the measurements at an operating voltage of 12 V. The tube achieves a surprisingly high anode current and transconductance at this low voltage. Therefore, it is suitable for applications like audio "power" amplifiers and driving low-impedance headphones.

ECF80, Triode	R_G	U_G	I_A	S
U_B=12V	0 kΩ	0	1,68 mA	
	1 kΩ	- 48 mV	1,56 mA	2,5 mA/V
	10 kΩ	-175 mV	1,23 mA	2,4 mA/V
	100 kΩ	-350 mV	0,84 mA	2,0 mA/V
	1 MΩ	-550 mV	0,51 mA	1,4 mA/V

8.5 Daten for the Pentode in the ECF80

When examining the pentode section of the ECF80, it's important to remember to apply a +12V bias to grid 2. In general, a pentode will almost completely block electron flow if no screen grid voltage is applied.



Wiring for Measurements of the Pentode of an ECF80

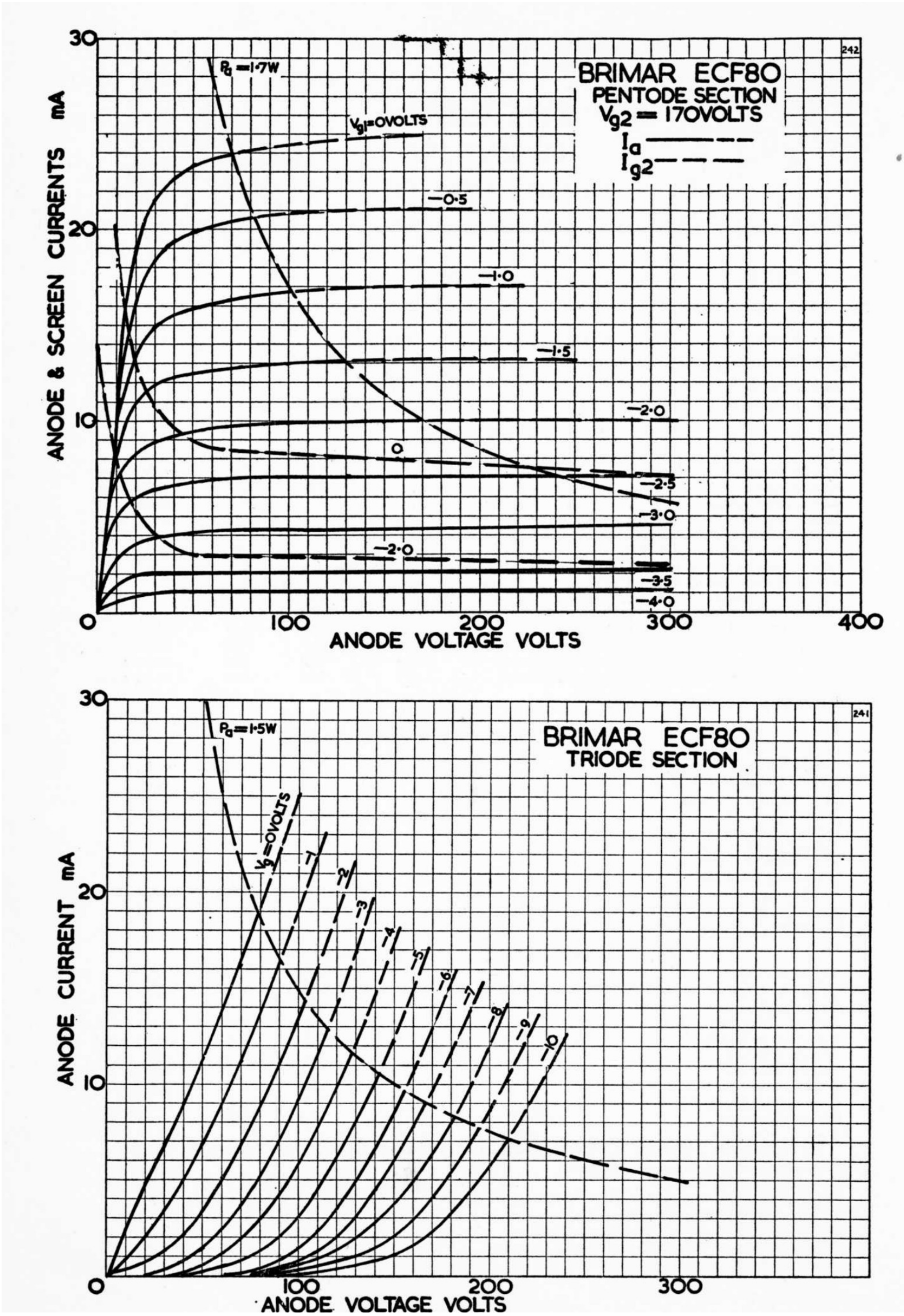
The following table shows the measurement values for the pentode section of the ECF80. The values are very similar to those of the EF95.

ECF80, Pentode	R_G	U_G	I_A	S
U_B=12V	0	0	0,22 mA	
	1 kΩ	- 35 mV	0,19 mA	1,0 mA/V
	10 kΩ	-160 mV	0,09 mA	0,7 mA/V
	100 kΩ	-330 mV	0,03 mA	0,3 mA/V
	1 MΩ	-500 mV	0,01 mA	0,1 mA/V

The characterisitc data of a tube can be significantly influenced by its history. A completely new tube often exhibits a higher current after a certain operating time. Some tubes are aged in the factory by being heated and subjected to high anode current for several hours. However, for cost reasons, artificial aging is not performed for tubes like the ECF80, which are intended for consumer electronics. Therefore at the beginning of the measurement one may observe an increasing anode current with time.

Artificial aging can be carried out manually, but it's important to ensure that both ECF80 tubes are subjected to the same conditions. One possible procedure involves applying a high voltage (+12 V) to the control grid of the pentode section through resistors of 75 Ω. This results in a substantial grid and cathode current, which can improve the emission of the cathode. The grid current should be turned off after one minute, and then the tube's characteristics can be re-evaluated.

A more gentle form of aging uses a grid resistor of 1 kΩ connected to +12 V. The tube can remain powered on for several hours without any harm. Additionally you can apply a slightly elevated heater voltage, typically 10% to 20% above the rated voltage, during this aging process.



Characteristic Curves of an ECF80 Pentode (top), Triode (bottom)

Appendix

Literature (partly available in our shop, partly only as PDF in the Elektor-Verlag, partly only available as second-hand):

[1] B. Kainka, Röhrenprojekte von 6 bis 60 V, Elektor 2003
[2] O. Diciol, Röhren-NF-Verstärker Praktikum, Franzis 2003
[3] J. Gittel, Jogis Röhrenbude, Franzis 2004 (auch *"Neues aus Jogis Röhrenbude"* und *"Neues aus Jogis Röhrenbude Teil 2"*)
[4] G. Haas, High-End mit Röhren, Elektor 2005
[5] W. Frohn, Audio-Röhrenverstärker von 0,3 bis 10 Watt, Franzis 2005
[6] K. Röbenack, Radiobasteln mit Elektronenröhren, Shaker-Verlag
[7] B. Kainka, Radiobau-Miniprojekte, Selbstverlag
[8] "Röhren"-Sonderheft 1...10, Elektor-Verlag
[9] M. van der Veen, High-End Röhrenverstärker, Elektor-Verlag

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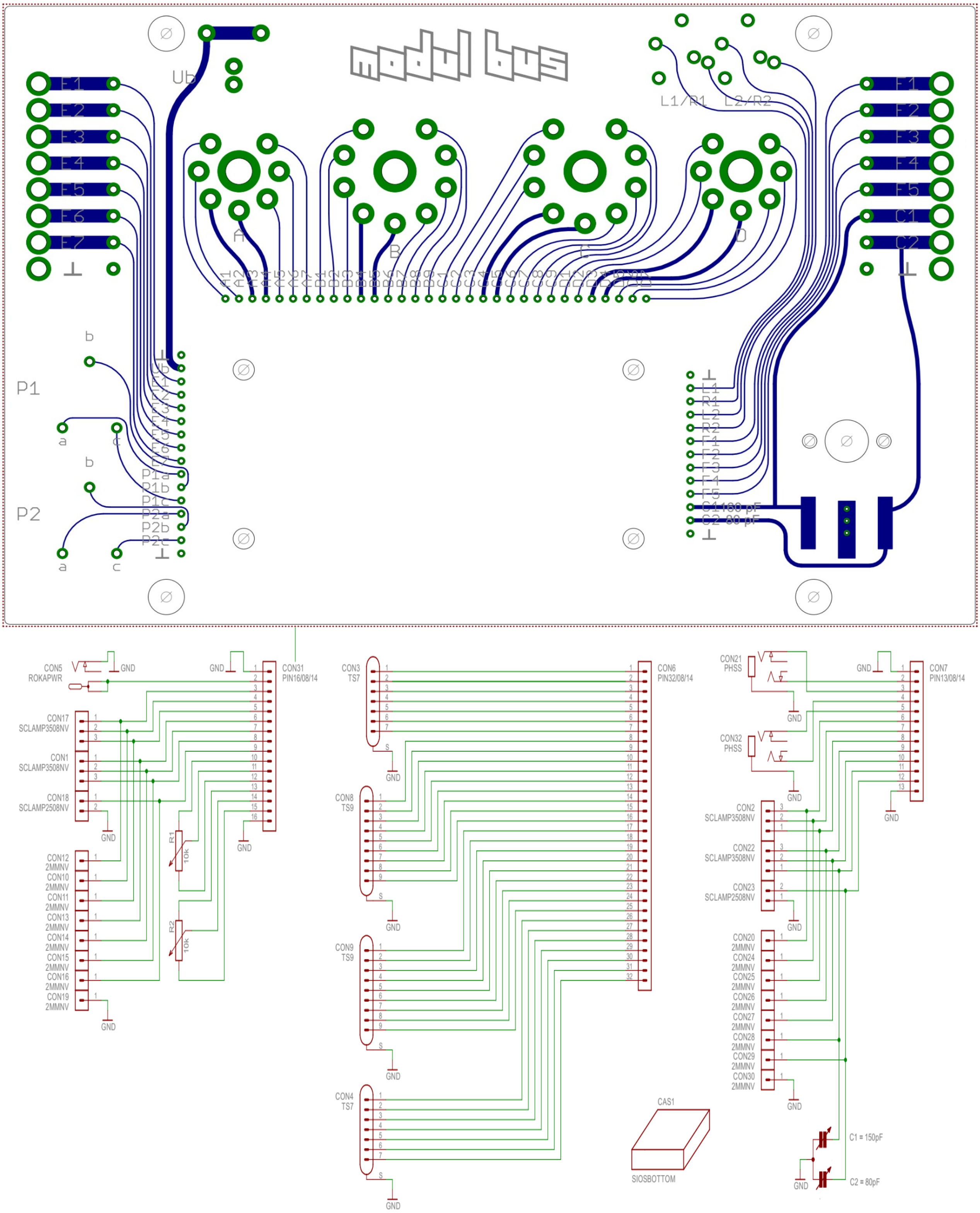
See also:
For further experiments with the RT100 see our "Electronics Experimental Server" ELEXS (in German):
http://www.elexs.de/rt100.htm
and here:
www.elexs.de
(for both links: always click "Weiter" at the bottom of the page for the next page)



PCB Layout with Wiring Diagram

Audio-Generator und Analyzer-Software:

(Freeware/Shareware; partially also available for Linux/iOS)

These programs allow you to directly use the line input and output of a PC or laptop (or a connected sound card) for generating test tones (sine, square, triangle, noise...) and analyzing audio signals (waveform, frequency response, distortion, spectrogram...).
Due to the low input and output voltages (typically max. 1VSS) used in the circuits here, the signal levels are often directly usable for input and output on a PC/laptop. If the levels are too high, a simple resistor divider can be used as an attenuator.
When connected directly to the anode output of a tube, however, a coupling capacitor of a few µF must be used to keep the harmful anode voltage away from the audio input.

If you know of any other recommended programs, please feel free to share them with us.

- Audio Tester (recommended)
- Virtual Analyser (recommended)
- Audacity
- Audio Measurement System
- Friture
- SFS/RTSPECT
- TrueRTA
- Oscilloscope
- Audiotool

High-impedance headphones:

Unfortunately headphones directly suitable for tube experiments with 2x600Ω or even 2x2000Ω are hardly available anymore. Current headphones are mostly built with very low impedances of 8...32Ω for use with smartphones etc. Only in the professional studio- or HiFi-sector you can still find headphones with 2x600Ω.
However you can sometimes find them on eBay or other used platforms, even though prices have risen significantly in recent years.
There's also a trick to double the impedance of headphones: You connect the two capsules in series by using the "L" and "R" terminals as connections. This way, you have the (mono) signal in both capsules simultaneously and put less load on the tube's anode output due to the doubled impedance. However this method doesn't work with the audio-jacks on the RT100, as the ground connections there are directly connected to the circuit ground. So, you either need to disconnect the ground connection of the headphone plug or you route the "L" and "R" connections through the external screw terminal connections or directly onto the breadboard.

Brand:	Type:	Impe-dance (nom.):	Impe-dance (meas.):	DC-Res. (meas.):	Type:	apprx. Price:	Availa-bility:
Audio-Technica	ATH-R70 X	2x 470Ω			open	350 €	new
AKG	K140	2x 600Ω			closed	ca. 30 €	used
AKG	K141 Monitor (not MK-II)	2x 600Ω			semi-open	ca. 50 €	used
AKG	K160	2x 600Ω			closed	ca. 30 €	used
AKG	K240 Monitor	2x 600Ω			semi-open	ca. 50 €	used
AKG	K241	2x 600Ω			semi-open	ca. 50 €	used
AKG	K260 Professional	2x 600Ω	635 Ω	615 Ω	semi-open	ca. 50 €	used
Beyerdynamic	DT-100/400-G	2x 400Ω			closed	120 €	new
Beyerdynamic	DT150	2x 250Ω			closed		new
Beyerdynamic	DT250	2x 250Ω			closed	140 €	new
Beyerdynamic	DT550 600Ω-Version!	2x 600Ω			semi-open	ca. 50 €	used
Beyerdynamic	DT770 Pro 250Ω-Version!	2x 250Ω			closed	130 €	new
Beyerdynamic	DT880 600Ω-Edition!	2x 600Ω			semi-open	300 €	new
Beyerdynamic	DT990 600Ω-Edition!	2x 600Ω			open	200 €	new
Beyerdynamic	DT770???	2x 250Ω			closed	500 €	new
Beyerdynamic	DT1990 Pro	2x 250Ω	2x 270 Ω		open	600 €	new
Beyerdynamic	T1	2x 600Ω			semi-	1.000 €	new

					open	
Beyerdynamic	T70	2x 250Ω			closed	270 € new
Beyerdynamic	T90	2x 250Ω	2x275 Ω		open	500 € new
German Maestro	GMP 8.3000 D Professional	2x 300Ω			closed	115 € new
German Maestro	GMP 400	2x 300Ω	2x276 Ω		closed	220 € new
German Maestro	GMP 450 Pro	2x 300Ω			closed	195 € new
Koss	Pro 4 AAT	2x 250Ω	2x252 Ω		closed	200 € new
Piezo-Earphone	27nF Capacity	1x6kΩ	6.000 Ω	infinite	Piezo	5 € new
Sennheiser	HD430	2x 600Ω			open	ca. 50 € used
Sennheiser	HD414-600Ω Version	2x 600Ω	2x635 Ω	2x630 Ω	semi-open	ca. 50 € used
Sennheiser	HD414-2kΩ Version	2x 2.000Ω			semi-open	ca. 50 € used
Sennheiser	HD424-600Ω Version	2x 600Ω	2x611 Ω	2x600 Ω	semi-open	ca. 50 € used
Sennheiser	HD424-2kΩ Version	2x 2.000Ω	2x2.2 kΩ	2x2 kΩ	semi-open	ca. 50 € used
Sennheiser	HD600	2x 300Ω	2x300 Ω		open	400 € new
Sennheiser	HD650	2x 300Ω			open	340 € new
Sennheiser	HD700	2x 300Ω	2x163 Ω		closed	700 € new
Sennheiser	HMD 26-II-600	2x 600Ω			closed	500 € new
TDK	ST 800	2x 200Ω	2x200 Ω		closed	130 € new
Telefunken	Teleset 4	2x 2.500Ω	2x2.900 Ω	2x2.500 Ω	closed	ca. 50 € used

Liste of DRM Software-Decodern (Stand 2023)

- http://drmradio.dk/Software-loesninger-en.htmhttp://drmradio.dk/Software-loesninger-en.htm
- https://www.drm.org/pc-based-receivers-and-software/

Active DRM-Stations in Europe (as of 2023)

TIME IN UTC	BROAD CASTER	FREQ in kHz	DAYS	LANG.	TARGET	TRANS-MITTING SITE	Power kW	Antenna beam degrees
0000-2400	Funklust	15785	Daily	German	Nuremberg area	Erlangen, Germany	0.2	Non Directional
0000-2400	University Station	26060	Irregular	Hungarian	Budapest	Budapest, Hungary	1	Non Directional
0100-0057	Radio France International	3965	Daily	French	France	France, Issoudun	1	Non Directional
0600-0700	BBC World Service	3955 + 5875	Daily	English	NW Europe	Woofferton, UK	100	114 + 78
0530-0600	Radio Romania International	11960	Daily	English	W. Europe	Romania, Galbeni	90	300
0600-0630	Radio Romania International	11620	Daily	German	W. Europe	Romania, Tiganesti	90	307
0500-0530	Radio Romania International	11740	Daily	French	W. Europe	Romania, Galbeni	90	285
0900-1500	Radio France International	6175 occasional tests	Daily	French	Europe + N. Africa	France, Issoudun	100 + 100	153 + 267
0945-1325	Radio Kuwait	15110	Irregular	Arabic	Europe	Kuwait, Sulaibiyah	200	310
1700-1800	Radio Romania International	13750	Daily	English	W. Europe	Romania, Tiganesti	90	307
1930-2030	All India Radio	9620	Daily	French	France	India, Bengaluru	100	300
1600-2100	Radio Kuwait	15540	Irregular	Urdu + English	W. Europe	Kuwait, Sulaibiyah	200	310
2000-	Radio	11975	Daily	French	W. Europe	Romania,	90	292

2030	Romania International					Tiganesti		
1800-1900	Radio Romania International	7245	Daily	German	W. Europe	Romania, Tiganesti	90	307
1800-1830	Radio Romania International	5910	Daily	Italian	Italy	Romania, Tiganesti	40	270
2000-2030	Radio Romania International	11975	Daily	French	W. Europe	Romania, Galbeni	90	285
2030-2100	Radio Romania International	11975	Daily	English	W. Europe	Romania, Galbeni	90	300
0430-0500	Radio Romania International	11800	Daily	Russian	Russia	Romania, Tiganesti	90	37
1500-1530	Radio Romania International	13660	Daily	Russian	Russia	Romania, Tiganesti	90	37
1700-2000	Radio Kuwait	13650	Irregular	Arabic	Middle East	Kuwait, Sulaibiyah	200	350
0700-0800	WINB	7330	Sunday	English	Europe	USA, Red Lion PA	50	62
0700-0900	WINB	9805	Mon-Fri	English	Europe	USA, Red Lion PA	50	62
0700-0730	WINB	13810	Saturday	English	Europe	USA, Red Lion PA	50	62
0730-0900	WINB	13740	Saturday	English	Europe	USA, Red Lion PA	50	62
0800-1000	WINB	9805	Sunday	English	Europe	USA, Red Lion PA	50	62
0900-1000	WINB	13740	Mon-Fri	English	Europe	USA, Red Lion PA	50	62
0900-1000	WINB	15750	Saturday	English	Europe	USA, Red Lion PA	50	62
1000-1400	WINB	15720	Mon-Fri	English	Europe	USA, Red Lion PA	50	62
1400-1500	WINB	15735	Mon-Fri	English	Europe	USA, Red Lion PA	50	62
1500-1700	WINB	15750	Mon-Fri	English	Europe	USA, Red Lion PA	50	62
2100-2200	Radio Romania International	13650	Daily	Spanish	Spain + S.America	Romania, Tiganesti	90	247