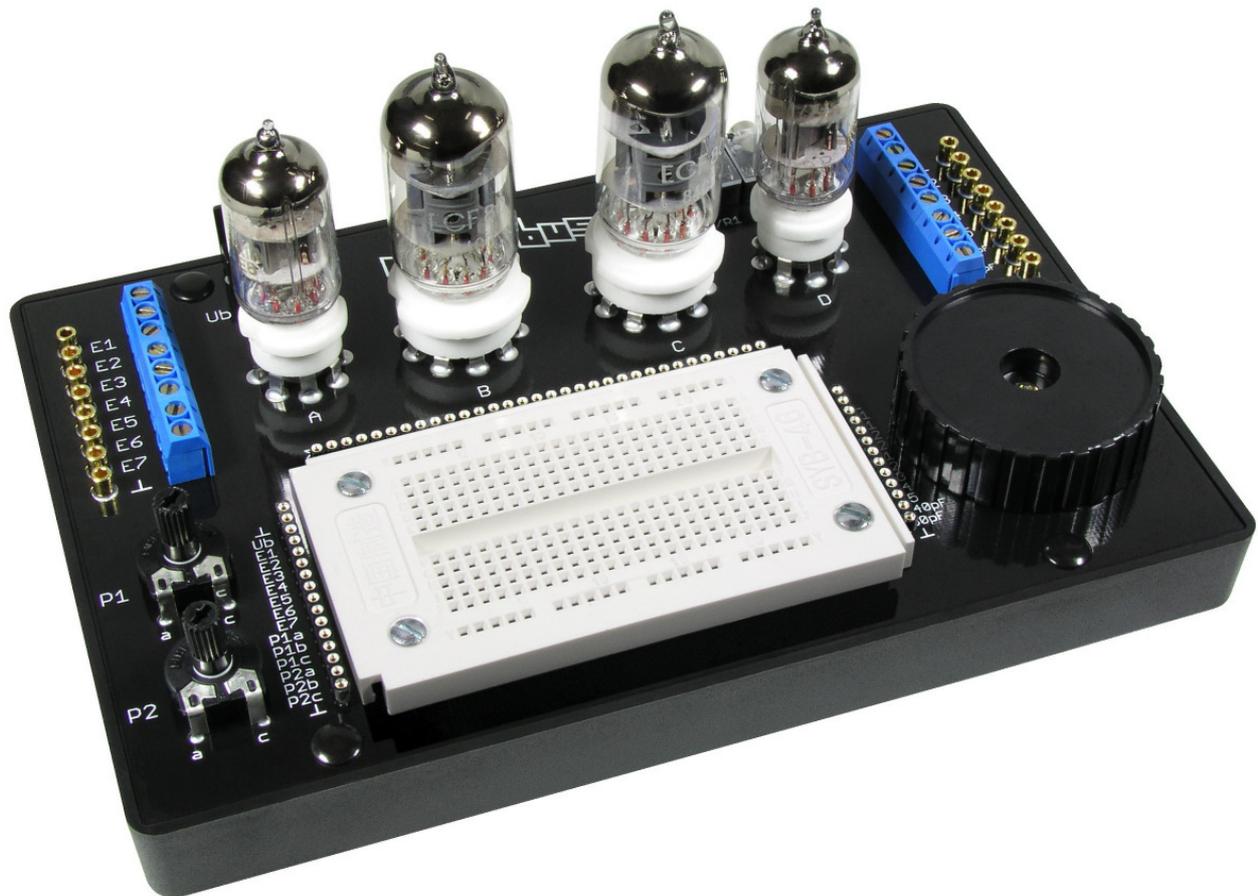# Experimental Kit Vacuum Tube Technology

RT100

Provided courtesy of the Electrical Engineering Department, Stanford University
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Professor of Electrical Engineering

Handbook by Burkhard Kainka (Germany)
Translation by Dr. Stephan Hengstler, Stanford University

Preface

The engagement with electron tubes is more than just a nostalgic hobby. It offers a thorough study of the fundamentals of electronics and therefore has its justified place in the Physics curriculum and the scientific education. In addition there are applications, in which tubes have not been displaced by semiconductors, in particular in audio technology and transmit power amplifiers.

It absolutely makes sense to study the fundamentals of vacuum tube technology through hands-on experimentation. The experimental kit eases the initial study of vacuum tube technology. Without detours it delves right into the experiments. The assembly of a circuit takes only a few minutes because wiring and components can be readily plugged in.

This tutorial introduces exemplary experiments, during which many areas are covered ranging from low-frequency amplifier, oscillators, and radio circuits to test transmitters. In general, only low and non-hazardous voltages are worked with. The system should only be used up to a maximum of 60 V for safety reasons.

We wish a lot of fun and success during the experimentation with tubes!


Your AK MODUL-BUS Team

Contents

1 Introduction

Experimentation with tubes often necessitates elaborate assembly with chassis and solder lugs or with special printed circuit boards. Moreover it most of the time requires a dual power supply for the heater (filament) operating voltage and the anode voltage. Assembly is simplified with the Experimental Kit Vacuum Tube Technology because sockets and the most important additional components are already present on the prototype board. The suggested experiments make do with small anode voltages such that solely a 12 V power supply mostly suffices for the heater operating voltage and at the same time for the anode voltage. However, this does not result in the power and amplification maximally achievable with the tubes, but it is sufficient for simple experiments and the study of the basic principles.

## 1.1   Material in the Experimental Kit

The core of the kit consists of a board with tube sockets and a breadboard for small components and the actual wiring. A soldering iron is not required since all connections are pluggable. This also simplifies modification of existing experiments. The board is mounted onto a plastic frame with rubber feet such that everything rests firmly and safely on the workbench.

On the board are several connections for external accessibility. A barrel connector serves as the connection for a power supply. Two stereo jack plugs serve as the in- and outputs for low-frequency signals and for connection of a headset. Gold-plated 2-mm jacks and screw terminals can be utilized for arbitrary additional connections. Furthermore, there are two potentiometers of 10 kΩ and one dual variable capacitor of 80 pF and 160 pF available. This way high-frequency experiments can be carried out without significant effort. All photographs in this tutorial were taken with the prototype board having green solder mask to achieve good contrast. The production version however uses black solder mask.
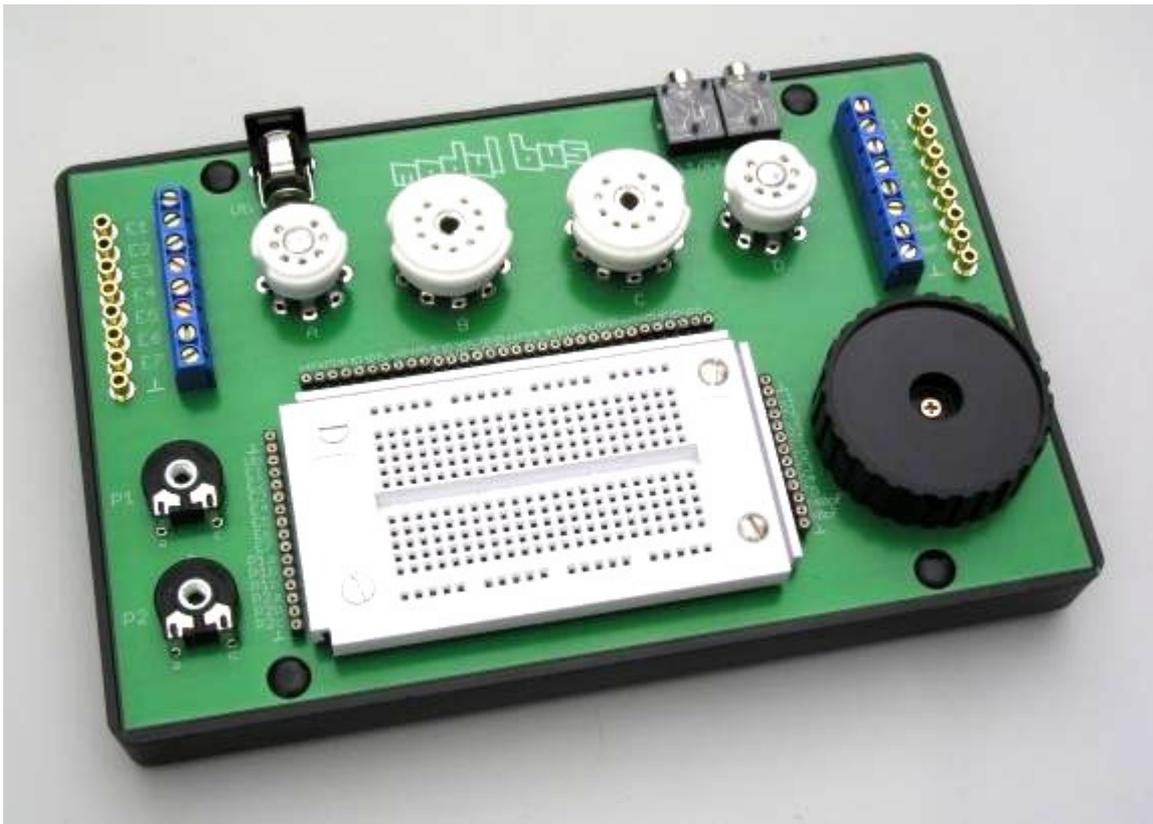
Caution, the kit shall only be operated with maximum voltages of 60 V! Electrical safety is not guaranteed at higher voltages since there is no protective insulation and one may touch conductive areas. Moreover, the insulation on the printed circuit board is not dimensioned for higher voltages since reduced gaps exist partly between traces.

The kit contains two tubes each of type ECF80 and EF95 (or the identical types 6SH1P or 5654, respectively). The EF95 is a high-frequency pentode with a seven-pole miniature socket. Internally the connections cathode, grid 3 and shielding are connected.
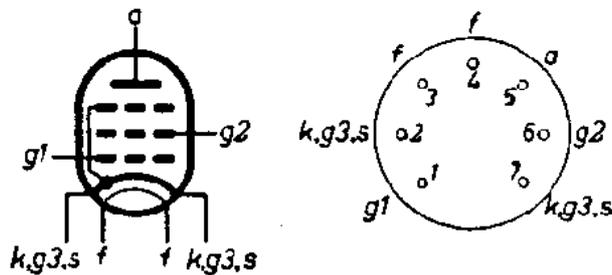
Connections of EF95

The ECF80 is a high-frequency combination tube with a triode and a pentode with separate cathodes. For the pentode, there also is an internal connection between cathode, grid 3 and shielding.
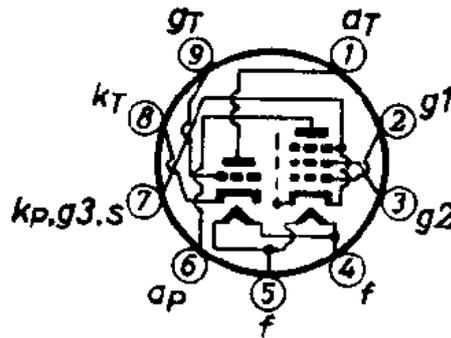
Socket schematic diagram of the ECF80

When all four tubes are mounted, a total of six tube systems are available for the assembly of complex circuits. In addition, the kit contains the following components:

14 Resistors:
2 resistors 75 Ω
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

4 Meter jumper wire

As a power supply for the experimental kit, we recommend a stabilized wall power supply like the NT 500S for example with voltage adjustment up to 12 V and load carrying capacity of 500 mA. It supplies a ripple–free voltage, which is important for many of the suggested experiments.

A stabilized wall power supply

Furthermore, several experiments require a digital multimeter to verify the functionality of the circuits in more detail. The descriptions of the experiments list measurement readings, which should be checked in some experiments.

An oscilloscope and additional tools are not a mandatory requisite for successful use of the kit but they enrich the experience. Measurement results are often shown in the form of oscillograms, which aid in illustrating the experimental results.

1.2   Functioning of a Tube

Whoever nowadays engages in electronics, knows the functioning of transistors while the mode of operation of a tube is oftentimes less familiar. We therefore compare a tube with a transistor with respect to basic functioning. The simple form of an amplifier tube is the triode with the three terminals cathode (= negative pole), anode (= positive pole) and control grid. These terminals are comparable to the terminals of an NPN transistor emitter (negative pole), collector (positive pole) and base as the control electrode. However, the tube can operate only when the cathode is heated up to approx. 800 to 1000 degrees centigrade. The heating element serves this purpose which is like a filament in an incandescent lamp typically made from tungsten. The hot cathode contains a layer of material with low electron bonding force such that the electrons can exit into the vacuum at these temperatures. The electrons in turn are attracted to the positive anode such that a current starts flowing.
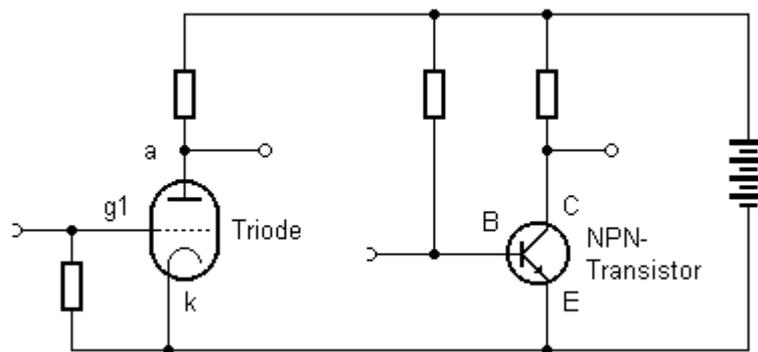
Comparison tube and transistor

Both devices control the current. In the transistor, a small base current controls the greater collector current. In the tube, the voltage at the control grid controls the anode current. In both cases a higher control voltage results in a higher current through the load circuit and hence to a higher voltage drop across the load resistance and accordingly to a smaller voltage at the output electrode, anode and collector, respectively. An amplifier with a triode or with a transistor normally rotates the phase of the amplified voltage by 180 degrees. One difference is however that the transistor requires a positive bias voltage whereas the tube is mostly operated with a negative grid bias voltage. The voltage automatically occurs at the grid resistance because free electrons from the cathode charge the grid negatively.
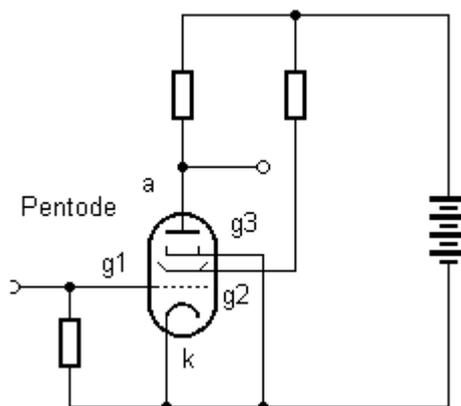
The pentode

There are two additional grids in a pentode. The screen grid (g2) is charged positively and insulates the control grid from the effect of changes in voltage at the anode. The voltage at the screen grid impacts like the control grid the anode current and the amplification of the tube. The suppressor grid (g3) is typically connected to the cathode and its purpose is to drive electrons, which emit from the anode (secondary electrons), back to it.

In the comparison of transistor and tube it stands out that the tube requires considerably more energy for the same function due to the necessary heating power. Energy-saving circuits are nowadays thus equipped with transistors. Advantages of the tube are high input impedances and good high-frequency characteristics, which for example lead to astoundingly good radio circuits. In hi-fi applications, the tube is said to have a softer sound because especially when overdriving less sharp transitions into saturation occur.

2 Heating and Current Supply

Tube circuits generally operate off of two supply voltages, the heating voltage and the anode voltage. But for simple experiments it is more convenient when for instance only a single stabilized 12 V wall power supply is needed. This voltage heats two tubes, connected in series, at a time and suffices in many experiments also as anode voltage. The current supply occurs though the barrel connector at the back of the experimental kit. The outer contact is connected to the ground plane; the inner contact is routed to Ub.

2.1 Heating of the EF95

The deployed tubes are intended for parallel heating with a heater voltage of 6.3 V. This voltage derives for historical reasons from the utilization of lead acid batteries, which have a nominal voltage of 2.1 V per cell. Other tubes exist that are intended for serial heating, for example the P-designated tubes with a total heater current of 0.3 A and the U-designated tubes with 0.1 A. Actually, tubes intended for parallel heating should not be heated in series because an exactly identical heating performance cannot be guaranteed and because the tubes could heat up at different rates. But nothing in simple experiments argues against heating in series as long as tubes of the same type are used.
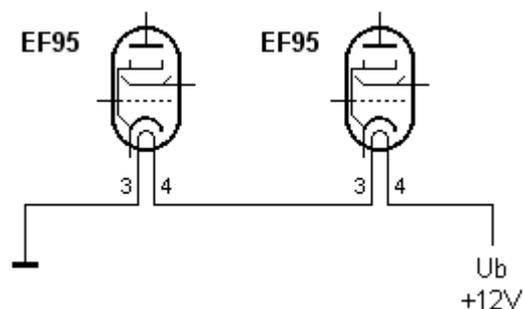
Tube heaters connected in series

The filaments of the two EF95s are—as for almost all tubes with 7-pole miniature sockets—on pin 3 and 4. The circuit diagram shows the wiring of the heating circuit. The upper contact bank of the breadboard is connected to Ub and obtains +12 V from a wall power supply. The heaters of tubes A and D are connected in series to 12 V such that each tube obtains a voltage of 6 V.
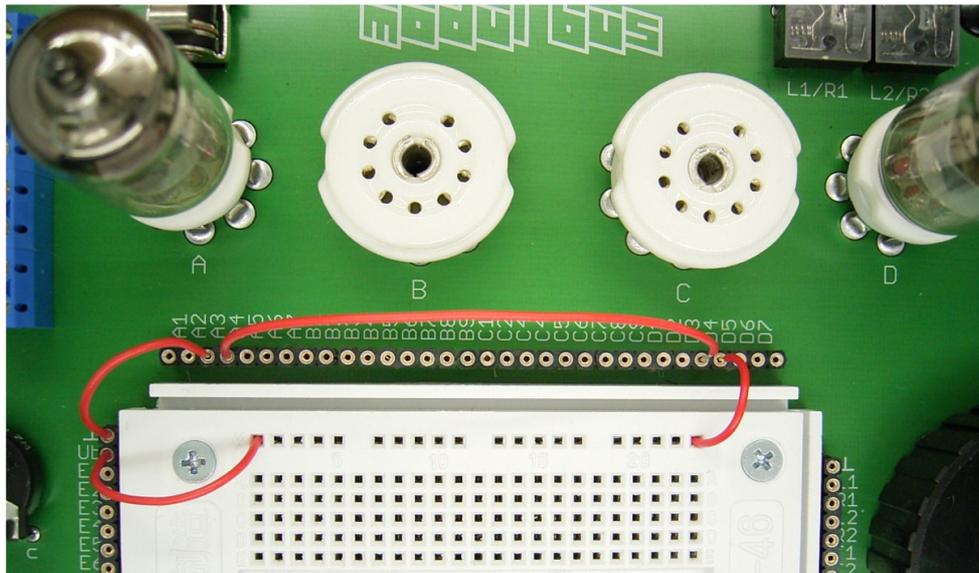
Wiring of the tubes' heaters

It takes a few seconds after applying the operating voltage before the glowing of the cathodes can be seen. Pay attention every time during turn on whether both tubes are properly glowing. Faults in the wiring or the current supply can be readily detected. When a tube heater is for example inadvertently connected to too high of a voltage, one may catch this by too bright of a glow and can turn off quickly.

Under normal heating with 6 V per tube, both cathodes should be glowing equally bright. The tubes become tangibly warm after a few minutes but not yet uncomfortably hot. You can find out through a measurement whether the filaments in their warm state in fact have exactly the same resistance value.
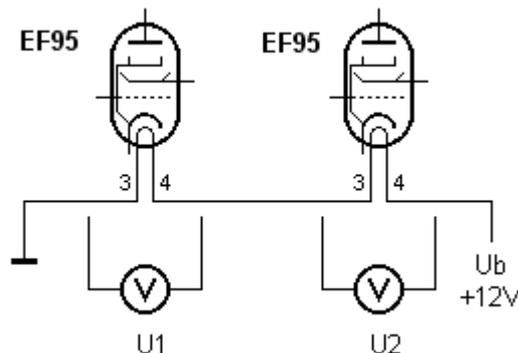

Measurement of the heating voltages

The following voltages were measured in a test experiment: 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 differing heating voltage is still tolerable. The nominal voltage of these electron tubes is 6.3 V in which a tolerance of +/- 10% is not yet problematic.

2.2 Heating of the ECF80

The ECF80 is nominally heated with 6.3 V and 430 mA. Series heating is possible with a stabilized 12 V wall power supply whereby a 500 mA power supply already gets relatively warm. However, the case of heating a single tube with 6 V is less advantageous since more heat loss occurs in the power supply. Even if a circuit only requires one tube, both tubes should therefore be heated simultaneously.
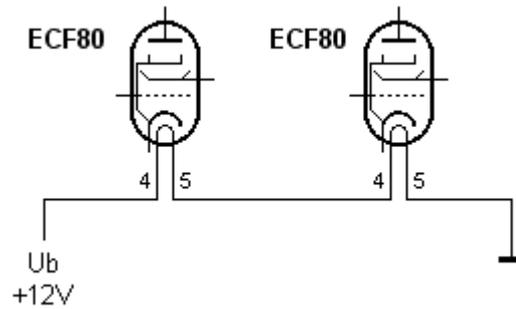
Heater terminals of the ECF80

Most tubes with the 9-pole Noval socket are heated through pins 4 and 5. The photo below shows a wiring possibility in the actual assembly.
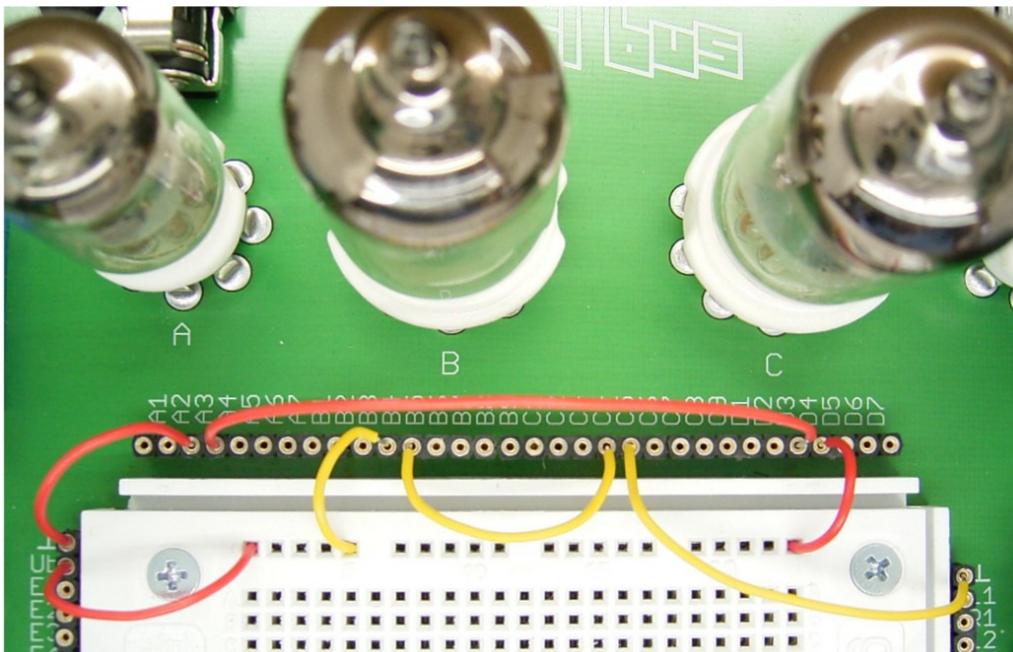

Wiring of all four heaters

We also measured the individual heater voltages for the ECF80 (6.0 V and 6.2 V). The voltage division is arbitrary and dependent upon the tolerances during production. The measurements indicate that the tubes can be heated in series in basic experiments although technically they are intended for heating in parallel.

With all for tubes combined the heating current amounts to 430 mA for the ECF80s plus 175 mA for the EF95s. With a total current just over 600 mA, a basic stabilized wall power supply rated at a nominal current of 500 mA reaches its limits. Experiments of short duration are nevertheless feasible.
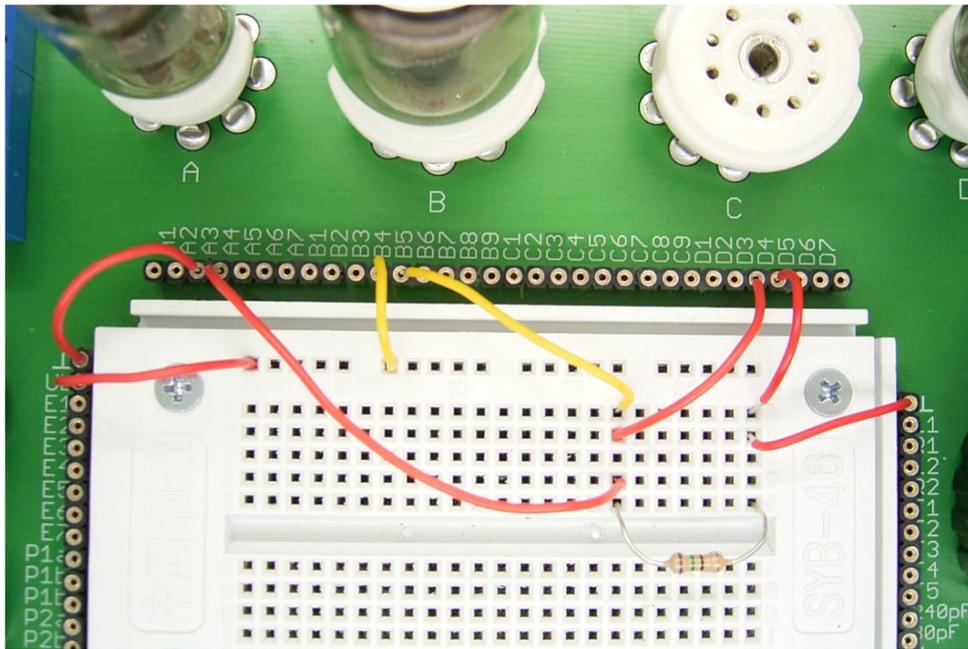
2.3 Three Tubes with One Heating Voltage

In case three tubes need to be operated at once in an experiment, one can resort to the following circuit. Here, two EF95s are in parallel and together draw a current of 2*175 mA=350 mA. An additional resistor of 75 Ω carries at 6 V an additional current of 80 mA so that the parallel circuit draws just the heater current of an ECF80 with 430 mA.
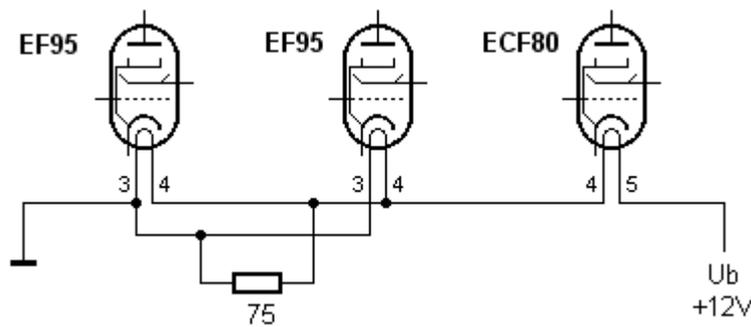
Composite series/parallel heating

The two EF95s initially glow somewhat brighter during heating-up, thus get somewhat more than 6 V. The reason is that a filament in its cold condition is of lower resistance, the additional load resistor in contrast is unchanging. The correct current division then exists not until the heated condition. After a few seconds the correct heater voltage of about 6 V adjusts itself at every tube. The resistor incidentally dissipates a power loss of 480 mW and thereby becomes quite hot.

Three tubes with one heating voltage

The alternative to heating in series would be the parallel heating. However, this would require a beefier power supply with 6 V or better yet 6.3 V or an adjustable power supply capable of stabilization with higher load rating up to approx. 2 A. A second voltage supply is then necessary for the anode voltage.

2.4   Wiring of the Tube Terminals

For the following circuits all tube terminals with exception of the pins for the filaments shall be brought onto the breadboard via short wires. The wiring to the breadboard has to be carried out only once and alleviates the setup of the subsequent experiments. The cathode terminal of the EF95 exists twice but is connected to the breadboard only once. Altogether the wire connections add up to the following:

| 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 B, 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 A, EF95
D1	20	g1
D2	21	k, g3 ,s
D3		f
D4		f
D5	22	a
D6	23	g2
D7		k, g3 ,s
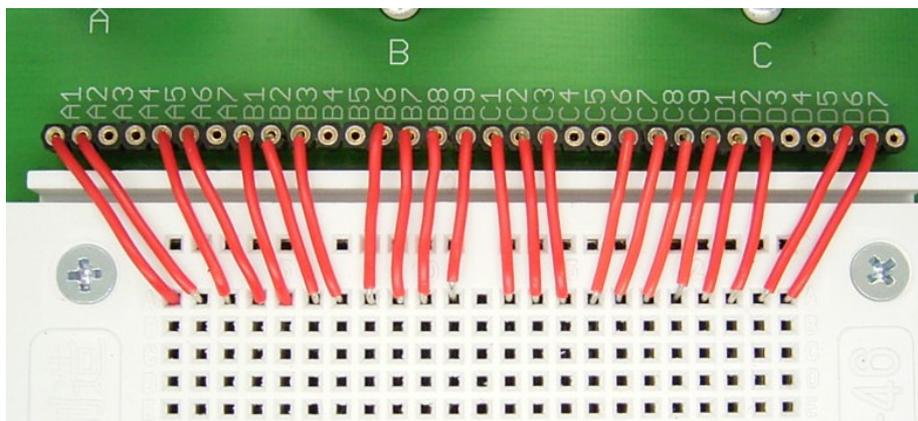
Connection of the tube terminals with the breadboard

These wire connections can be maintained for the most experiments in this tutorial. Therefore one can rely on always the same connections and has less effort in assignment of the connections.

The heater terminals are wired independently, and they are only connected when a tube will actually be used. Generally, two identical tubes at a time are heated in series to yield a voltage of 12 V.

3 Low-Frequency Preamplifier

The basic principle of a tube amplifier can be easily demonstrated with a low-frequency preamplifier. A synthesizer and an oscilloscope are useful in the following experiments. However, one can also deploy a preamplifier between a sound source, like a pick-up head of a record player for instance, and a final amplifier and observe the increased sound volume.

## 3.1 One-Stage Low-Frequency Preamplifier

The initial experiment utilizes only one tube EF95. But the second tube will already be heated in conjunction so that a voltage of 12 V can be used. The second tube forms merely the series resistor so to speak for the heater of the amplifier tube.
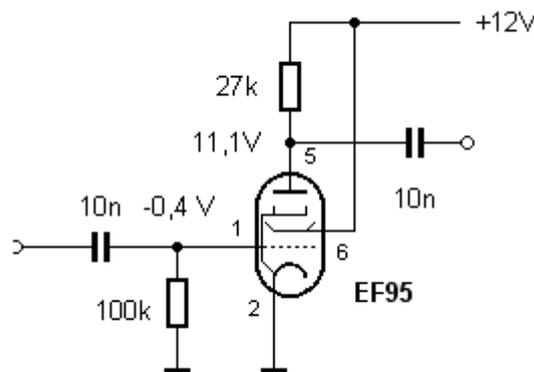
Low-frequency stage with the EF95

A low-frequency amplifier with one tube is comparable 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. The grid however requires a negative bias voltage in difference to the base of a transistor. The grid resistance thus is at ground potential. The warm-up current of the grid leads to a voltage drop across the grid resistance and hence to a negative bias voltage of the grid. The pentode though has yet two more grids than the

triode. The screen grid (g2) must be connected to the supply voltage. The suppressor grid (g3) is already internally connected to the cathode.
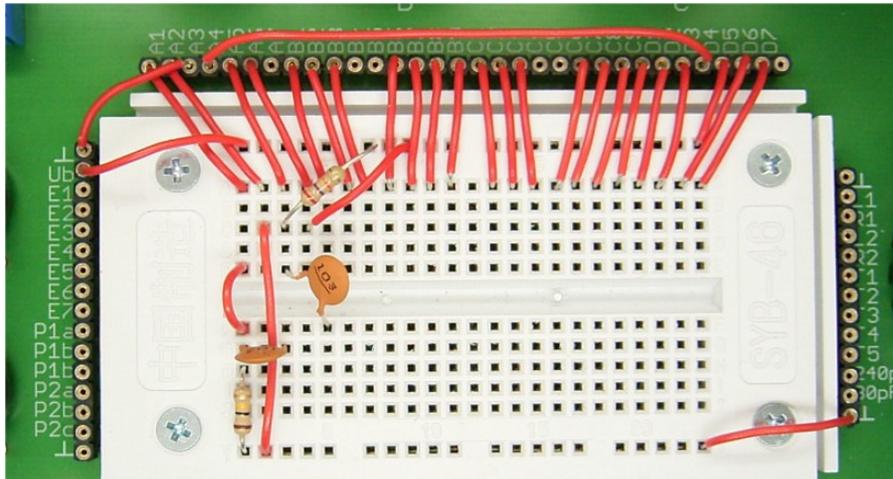

Assembly of the amplifier stage

The photo shows the assembly of the circuit on the breadboard. The left tube in socket A is used here. Input and output can be connected at will to terminals E1 through E7 as well as to the stereo jack plugs. External connections are not shown here in the interest of a better clear view.

After a brief heating-up period the voltages at the tube may be measured with a voltmeter. The grid reads -0.4 V; hence the grid carries a current of 4 µA. The voltage at the anode resistance of 27 kΩ is 12 V – 11.1 V = 0.9 V. This results in an anode current of 33 µA.

Now a signal voltage for example from a sine wave generator shall be applied to the input. The grid voltage modulates the anode current. Then the amplified output voltage can be seen as the voltage drop across the anode resistance.
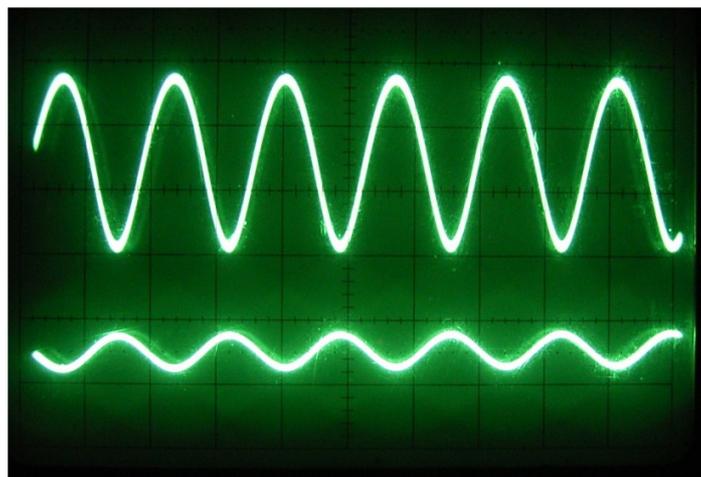
Input voltage (bottom) and output voltage (top)

The oscillogram shows that the amplifier stage inverts the phase. A higher grid voltage means more anode current, a larger voltage drop across the anode resistance and hence a lower anode voltage. The magnitude of the input and output voltage indicates a voltage amplification gain of approx. V = 5. This results in a tube transadmittance of about S = 0.185 mA/V because the voltage gain is the product of transadmittance and anode resistance (V = S * Ra). The transadmittance depends over a wide range on the bias point of the tube. When more anode current and more transadmittance are needed, the grid voltage has to be increased.
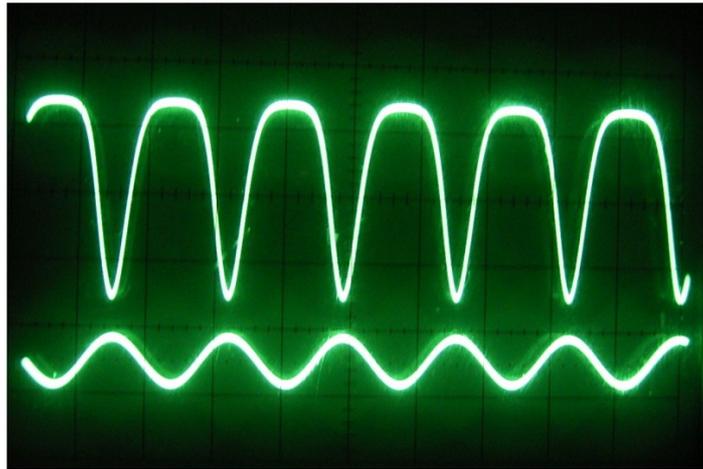

Signal waveform during overdrive

Noticeable distortions occur when overdriving the amplifier stage. The specific characteristic of tube distortions in contrast to distortions in most semiconductor amplifiers lies in that the clipping kicks in relatively smoothly.

Supplemental experiments:
Reduce the anode resistor to 10 kΩ and repeat all measurements. Then use a smaller grid resistance of 27 kΩ or 10 kΩ and therefore shift the bias point toward more anode current. Find the optimal resistor value that attains the highest voltage gain.

3.2   Two-Stage Low-Frequency Amplifier

Two stages can be connected in succession to increase the gain. The second low-frequency stage matches the configuration of the first one. A coupling capacitor exists between the two stages.
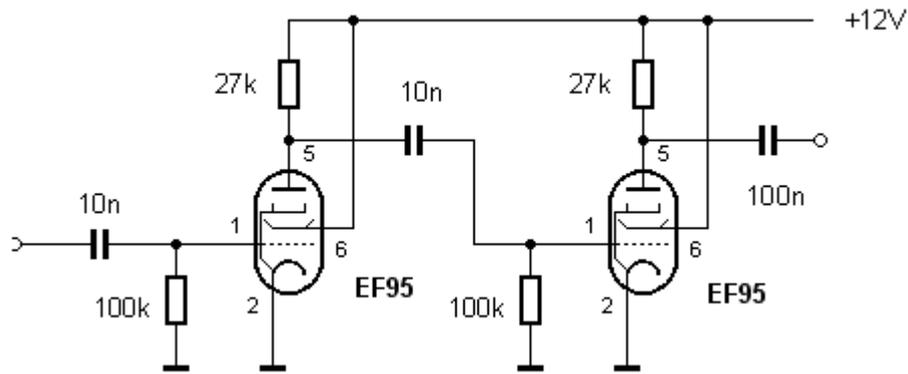
The two-stage amplifier

This time the assembly also uses tube D. The photograph of the assembly clearly shows the signal connection from the output of the left tube to the input of the right tube.
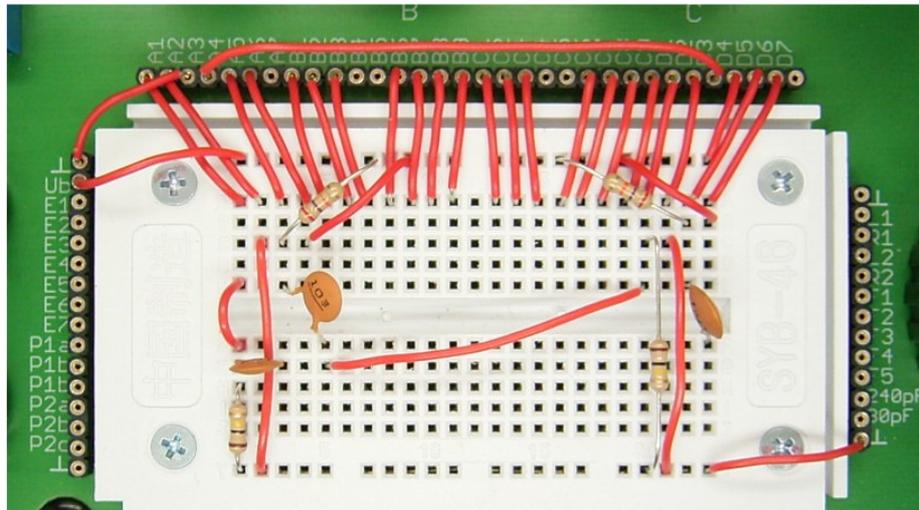
Wiring with two stages

One can now expect a gain of approx. V = 25. Actually, the two-channel oscillogram indicates a gain of about 25. Moreover, it reveals that the phase inversion has been compensated for by the second stage. Hence, input and output voltages are now in phase.
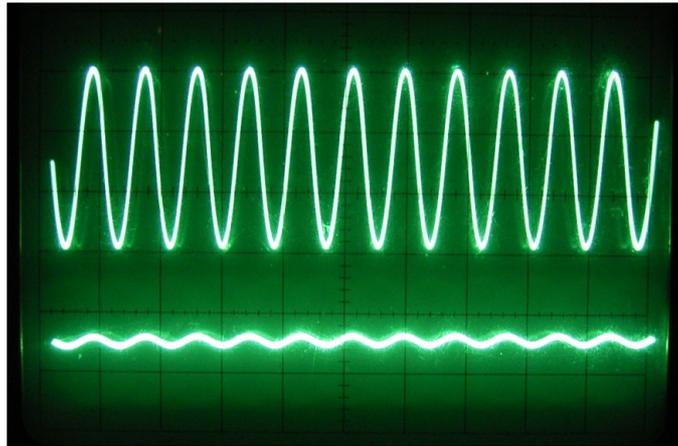
Input signal and output signal

Supplemental experiments:
Increase the total gain through application of a higher anode voltage of for example 24 V or 40 V. Deploy the two-stage amplifier as a sensitive microphone amplifier.

3.3 A Synthesizer

Since the phase difference between input and output of a two-stage amplifier is null, oscillations can be readily generated. All that is needed for this purpose is feedback from the output to the input.
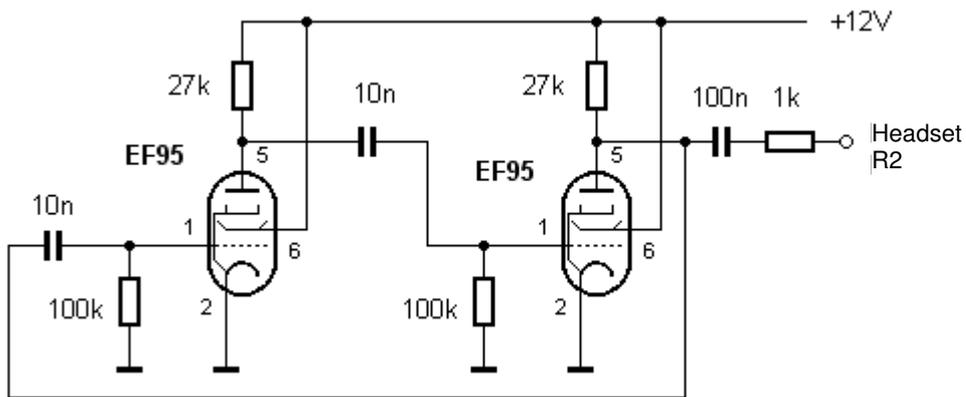
The synthesizer

The circuit has an output with a coupling capacitor and an additional resistor of 1 kΩ so that a low-impedance headset cannot reduce the gain to the point where oscillation would cease. Here the headset connection R2 is used. A headset can be plugged into the stereo jack 2. The tone should then be audible on the left channel.

Synthesizer with headset output

The oscilloscope shows a low-frequency signal of 800 Hz. The circuit is suitable for a Morse practice generator, for instance, in which a Morse key is placed in the input lead to the headset.

Output signal of the synthesizer

Supplemental experiments:
Change the resistors and capacitors in order to alter the pitch. Connect 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   Headset Amplifier

Headset amplifiers are an appealing application for tubes with low anode voltage as little output power is needed and the unique tube sound can be attained with little effort.

4.1   Stereo Headset Amplifier

A headset amplifier with tubes has a very unique sound. One problem sometimes is the small anode current and the small output power with low-impedance headsets. But the anode current may be increased through a positive grid bias voltage. Here we connected a grid resistor of 47 kΩ to +12 V. This produces an anode current of 2 mA with the EF95 at an operating voltage of 12 V. With a high-impedance headset of 600 Ohm (for example Sennheiser HD414), good volume and very good sound is attained. The PC sound card for instance serves as low-frequency source.
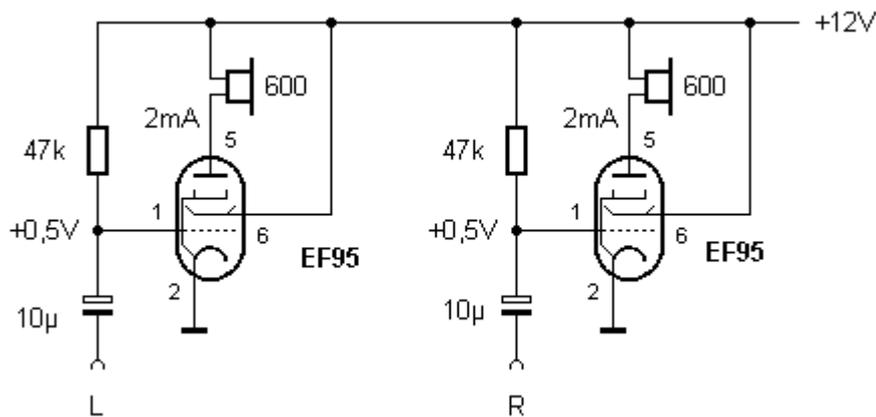
A stereo headset amplifier

In this case, the headset is directly placed in the anode path, i.e., the common connection of both channels is at the operating voltage +12 V. Therefore, none of the stereo jacks can be used here since they are grounded. The headset can be connected through the screw terminals for example. The input on the other hand can be attached via a stereo cable and a stereo jack.

Supplemental experiments:
Investigate the impact of different grid resistors between 10 kΩ and 1 MΩ on volume and sound of the circuit.

4.2   Triode Circuit

Experiments with smaller grid resistances show that more grid current increases the anode current of the EF95 only marginally but causes significant distortions. One possible reason is the adverse current distribution between suppressor grid and anode.
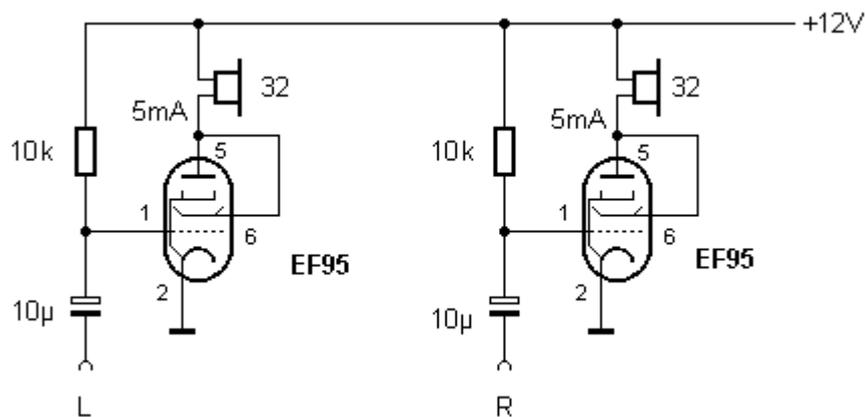
Triode circuit

Both electrodes were therefore connected in a second experiment so that the tubes operate as triodes. In fact, currents of 5 mA can be achieved now with grid resistors of 10 kΩ. The triode amplifier is extremely loud with high-impedance headsets. But a low-impedance type of only 32 Ohm already demonstrated outstanding results. However, a type with decent efficiency should be deployed.

The amplifier delivers indeed an entirely unique sound, which has been subjectively perceived as very pleasant. Generally tubes are known for their "warm" sound. There are several reasons for this:

   * The headset is hardly energized due to the high internal impedance of the tube.
   * The slightly curved characteristic of the tube alters the sound.
   * When overdriving the tube transitions into saturation very smoothly.

Supplemental experiment:
Measure the input voltage and output voltage of the amplifier with an oscilloscope and determine the transadmittance at the given bias point.

4.3   RC-Coupling

For the most part, one would like to avoid a DC current contribution through the headset since it may cause additional distortions and it induces crackling when connecting the headset. In this case, coupling through an output transformer or a capacitor offers the solution. RC-coupling is especially easy and suffices for lower-power headset amplifiers.

Here we deploy the triode system of the ECF80 as headset amplifier. The tube already provides sufficiently high current and good transadmittance without positive bias voltage. High-impedance as well as low-impedance headsets can be connected to the output.
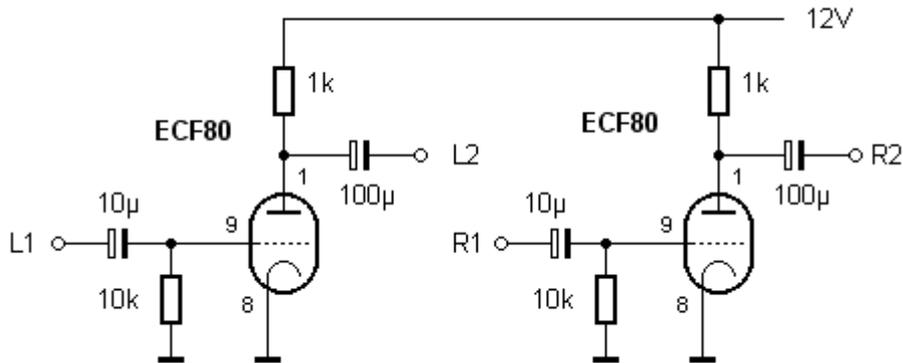
Headset amplifier with two ECF80s

Supplemental experiments:
Determine the anode current through measurement of the voltage drop across the anode resistor. Increase the anode current through a positive grid bias voltage by connecting the grid resistor to the anode voltage of +12 V instead of ground.

4.4   Preamplifier

A higher voltage gain is achieved with an additional preamplifier. Here we utilize the pentode system of the ECF80 as preamplifier. This way, a relatively high-impedance input can be realized. The amplifier in this form is suitable, e.g., for a headset amplifier of a record player with high-impedance crystal system.
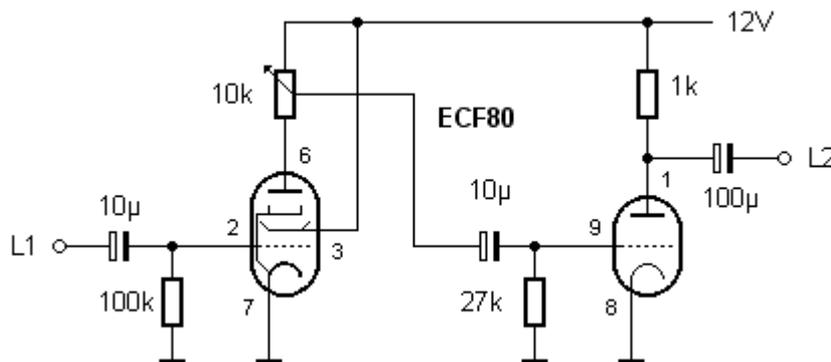
One channel with pentode preamplifier

In addition, we built in a volume control. The potentiometer serves at the same time as the anode resistor. The circuit diagram only shows the left channel of the amplifier.

Supplemental experiment:
Measure the total amplification of the two-stage amplifier.

4.5   Hybrid-Amplifier

Frequently it makes sense to combine tubes and transistors in one circuit. Tubes have generally very high impedance. Just with a low-impedance headset, the output power achievable is not high. One possible solution is the use of an output transformer. But it is easier and cheaper to deploy a transistor.
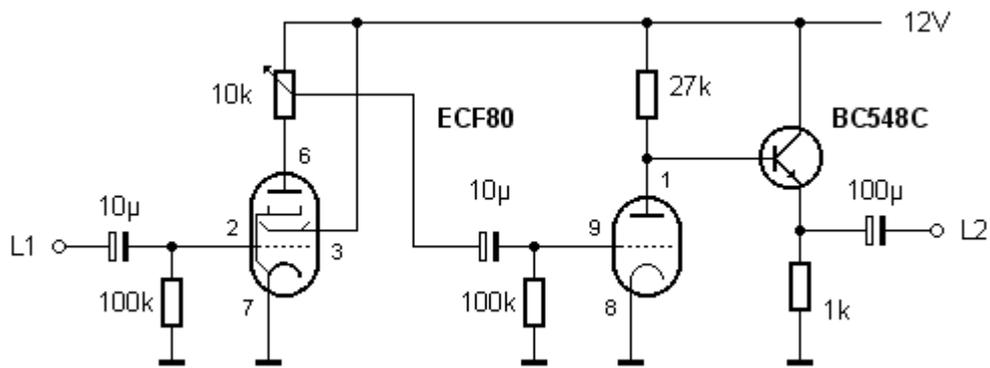
Tube amplifier with subsequent emitter follower

The circuit diagram shows a tube amplifier successively connected to an emitter follower with an NPN transistor BC548C. The circuit drives even low-impedance headsets at high volume. But the tubes primarily define the sound.


Supplemental experiment:
Determine the maximum output power at a load resistance of 32 Ω.

5 Radio Circuits

The first tube radios used the relatively simple audion circuit. The tube takes care of the demodulation and at the same time the amplification of the radio-frequency signal. Carefully designed audion receivers can attain the receive power of substantially more expensive receivers and oftentimes feature a particularly pleasant sound.

5.1 Shortwave Audion with the EF95

The core of an audion receiver is the resonator with coil and rotary capacitor. The frequency range can be changed over a wide range through the specification of the coil. Especially simple and manageable are coils for the shortwave range. The coil can be made from jumper wire as a self-supporting coil. For this purpose, one coils two times 8 windings around an AA battery in the same direction of winding and joins the mutual center ends to a center tapping. The wire ends are supposed to be twisted around the coil such that a mechanically stable winding results.
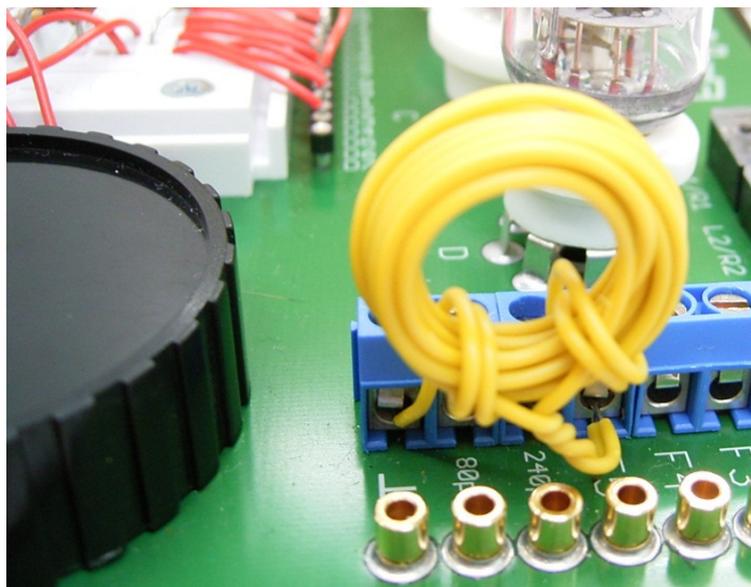
The shortwave coil

The coil is directly connected to the screw terminals leading to the rotary capacitor. The outer contacts are placed at the rotary capacitor half with 160 pF. The center tapping is placed at terminal F5. To prevent losses, the connection between coil and rotary capacitor must be of low resistance so that connections on the breadboard in the resonant circuit should be avoided.
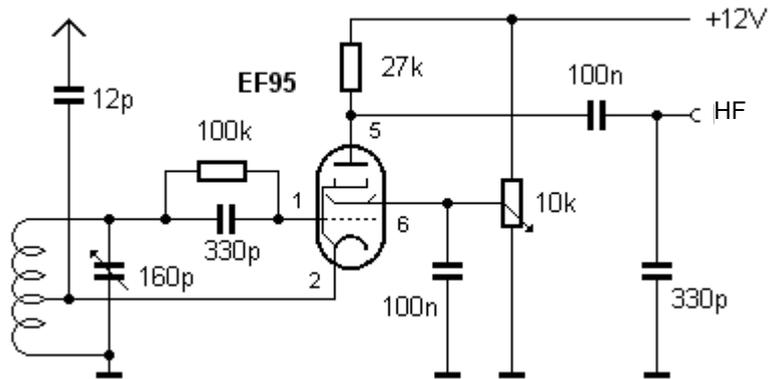
The audion with one pentode

The circuit diagram shows the basic circuit of an audion with feedback. The amplified radio-frequency signal is fed back into the resonant circuit via the cathode to compensate for losses. Through the de-attenuation the resonant circuit attains a small bandwidth and a high signal voltage. The suppressor grid voltage and hence the gain of the tube can be varied with the potentiometer. The audion is tuned right up to the point before self-oscillations set in.

The antenna has to be coupled very loosely with a small coupling capacitor. A too direct of coupling can attenuate the resonant circuit so strongly such that the tube does not reach sufficient gain for the build-up of self-oscillations.
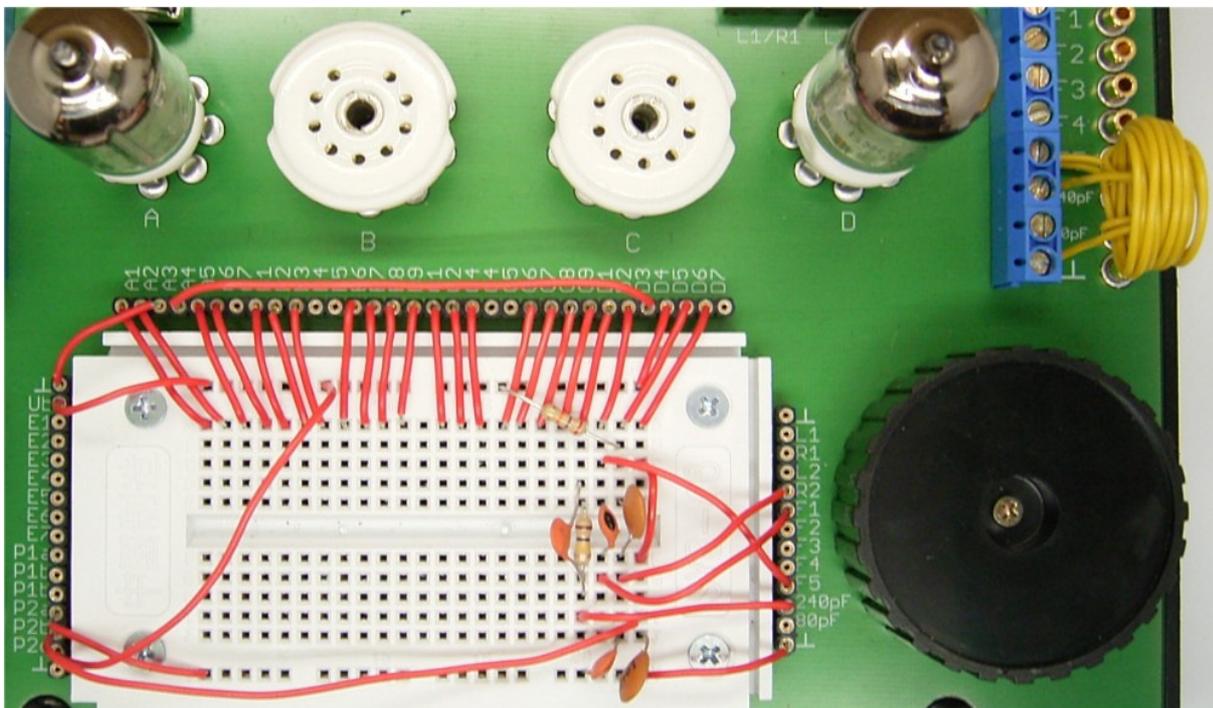

Assembly of the audion

The low-frequency output is connected to one of the stereo jacks. A low-frequency amplifier or even a high-impedance headset can be connected here. The signal voltage is however still small, the reception therefore low volume.

Supplemental experiment:
Investigate the effect of direct antenna coupling under varying antenna length. Also test a short vertical whip antenna directly at the top end of the resonant circuit.

5.2 Audion with Low-Frequency Stage

Up to now, two tube heaters were always connected in series in the experiments with the EF95, that is, two tubes were loaded even when only one was used. Thus, it seems obvious to utilize the second tube as low-frequency amplifier for the audion.
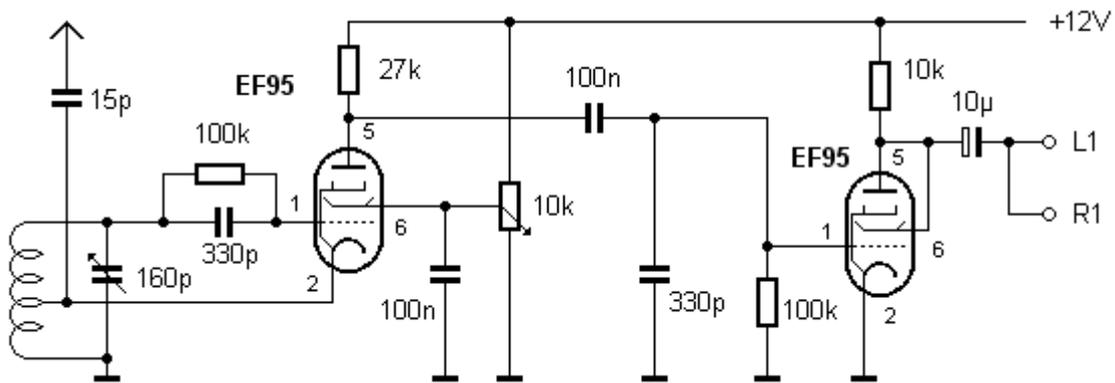
Audion with low-frequency stage

The low-frequency tube operates in triode configuration with RC coupling to the headset or an attached low-frequency amplifier. The volume is sufficient with a high-impedance headset; a 32-Ohm headset with good efficiency can be directly operated as well.

The matching of the low-frequency stage must be improved for higher volume. A low-impedance headset should be connected with an output transformer. Suitable is for example a small power transformer 230 V / 12 V. The ratio of turns equals approx. 10 : 1, the impedance ratio thus 100 : 1. Connecting both headset speakers in parallel yields an impedance of 16 Ω. The tube thus operates onto an external resistance of 1.6 kΩ. The better matching to the high-impedance internal resistance of the tube results in an improved output power.
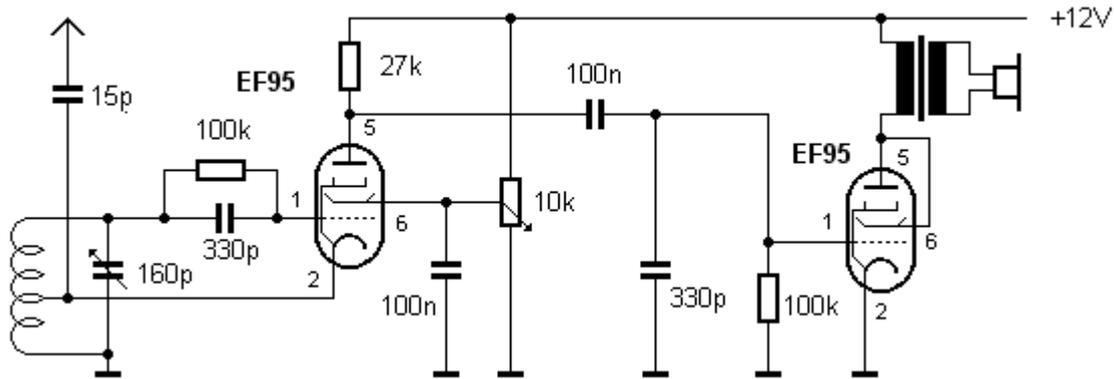
Matching with an output transformer

Supplemental experiment:
Use an output transformer with multiple taps. Suitable for instance is a power transformer of a wall power supply with selectable output voltages between 3 V and 12 V. Find the best matching for maximum volume. Also try a loudspeaker at the output. Operation of a speaker at low volume should already be possible with an advantageous matching provided that the speaker has good efficiency.

5.3   Shortwave Audion with the ECF80

A high-volume audion can be built with only one tube ECF80 even without an output transformer because the triode already delivers sufficient output power even at small voltages.
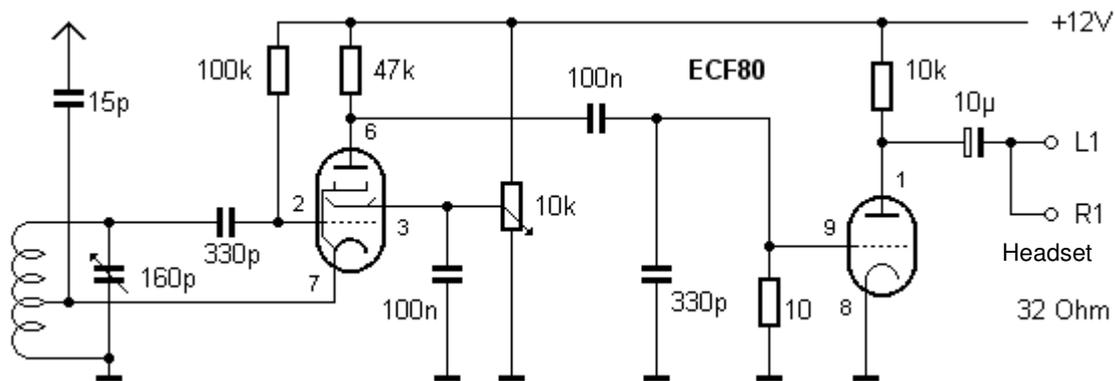
Two-stage receiver with one ECF80

The pentode system of the ECF80 requires a positive grid bias voltage at the low operating voltage of 12 V to achieve sufficient high-frequency gain for an oscillation onset of the audion stage. The characteristics of this audion differ substantially from the version with the EF95. The onset of the feedback is relatively harsh since the tube hardly adjusts down with increasing high-frequency input voltage. That means that one can set a higher gain and overall achieve a higher volume than with the EF95. One disadvantage though is

the harsh onset of the feedback, which forces the operator to adjust the feedback potentiometer considerably below the oscillation onset. Despite this weakness, the circuit is excellently suited for high-volume reception of distant shortwave broadcast stations.

Supplemental experiment:
Equip the receiver with a volume control. Try out the operation of a speaker through an output transformer.

6 High-Frequency Oscillators

A high-frequency oscillator consists of a signal amplifier and a resonator with distinct resonance frequency. This can either be an oscillating circuit or a quartz crystal. Oscillators are deployed in the design of receivers and for measurement purposes.

6.1 ECO Oscillator

The basic circuit of a free-running oscillator was already utilized for the audion. Here, a high-frequency oscillator for test purposes shall be built. The ECO (Electron Coupled Oscillator) circuit features good decoupling of the oscillating circuit from the high-frequency output. Therefore, the output feedback is small that could negatively affect stability.
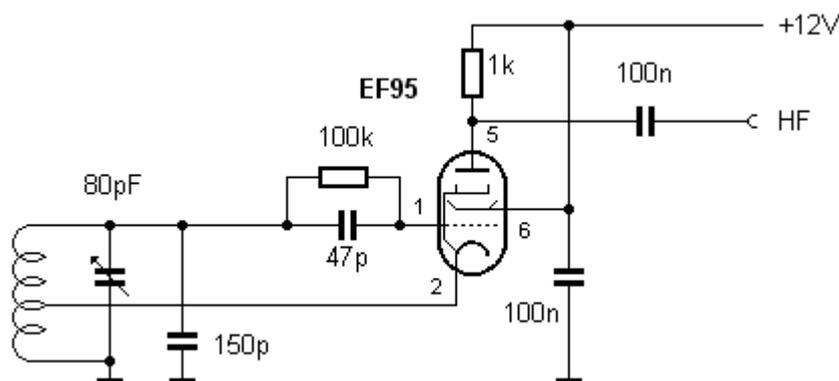
The ECO oscillator

The circuit realizes band-spreading via the parallel capacitor of 150 pF and the smaller part of the dual rotary capacitor with 80 pF. The oscillating circuit capacity can be varied between 150 pF and 230 pF at a ratio of 1 : 1.5. The variation in frequency corresponds to the square root of the capacity ratio and equals approx. 1 : 1.24. The absolute value of the

frequency depends on the inductance of the coil. With the audion coil introduced above, the range 7 MHz to 8.7 MHz can be tuned in for example.

The high-frequency output of the test oscillator can be connected with any receiver input and be used for adjustment tasks for instance.

Supplemental experiment:
Determine the frequency range through comparison with an available shortwave radio and draw up a frequency scale.

6.2 Quartz Oscillator

A quartz crystal behaves like an oscillating circuit with extremely little attenuation. A quartz oscillator is therefore especially stable and precise. In this experiment, we use the triode system of the ECF80 to build a 6 MHz oscillator. The rotary capacitor serves for fine tuning and allows for frequency adjustment of one to two kilohertz.
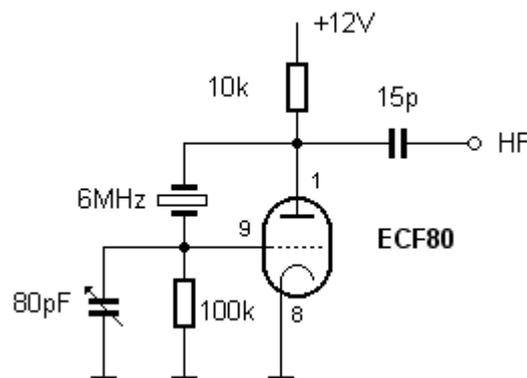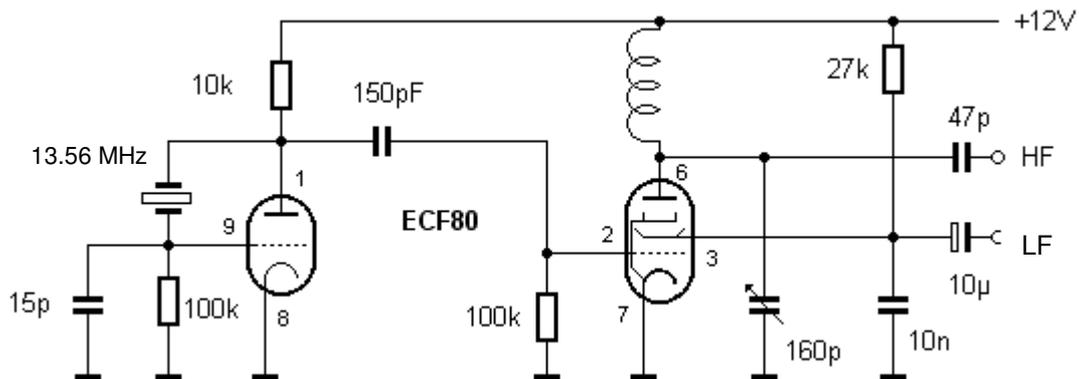

A quartz oscillator

Investigate the signal of the oscillator with a shortwave radio. At weak coupling, an interference with the AM radio station at 6005 kHz is heard. Adjustment of the rotary capacitor changes the interference whistling.

Supplemental experiment:
Check the sensitivity of the oscillator with respect to hand capacitances. Test how strongly or weakly the frequency reacts to approaching it by hand.

6.3 Amplitude Modulation

The frequency 13.56 MHz has been cleared for experimental and scientific purposes and is used here for a small AM transmitter. The required accuracy is only achievable with a quartz crystal.

A shortwave AM transmitter with one ECF80

The circuit matches largely a traditional radio station transmitter. The quartz oscillator drives the transmitter output stage with a pentode. An isolated oscillating circuit lies in the anode sub-circuit. The output amplitude is modulated by changing the screen grid voltage. The low-frequency input needs a modulating voltage of several volts.

Connect an approx. two meter long wire antenna to the high-frequency output. Scan for the 13.56 MHz signal on a shortwave radio. Then adjust the rotary capacitor to maximum signal strength. Once a low-frequency signal is applied to the modulation input, it can be heard in the radio. Investigate the range of the transmitter. Avoid sustained broadcast since regular radio broadcast operation is not permitted even at this frequency.

Supplemental experiment:
Use the circuit to build a DRM transmitter. For this purpose, feed it with the output signal of a PC soundcard and generate a DRM baseband signal with the software DREAM in transmit mode. The circuit can now be used for testing any DRM receivers.

6.4   AM Medium Wave Transmitter

This medium wave transmitter utilizes a free-running oscillator with a ferrite antenna from an old radio. Two EF95s were deployed here. One tube serves as free-running oscillator, the other as modulation amplifier.
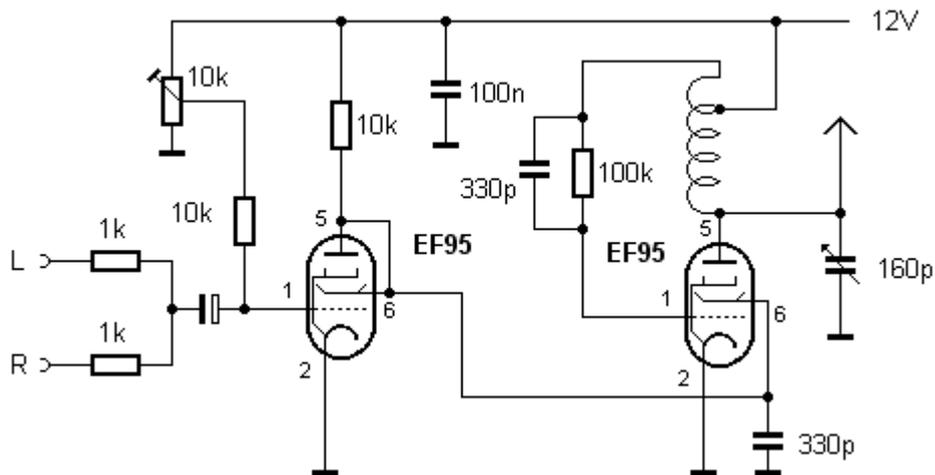
A freely tunable medium wave transmitter

The free-running oscillator is modulated via the screen grid. The upstream modulation amplifier operates in triode configuration in order to achieve a sufficiently high modulation amplitude with low distortion despite the small anode voltage. The bias point is set to minimal distortions with a variable capacitor. The response curves of both stages curve in opposite direction due to the phase shift of the modulation amplifier. At optimal adjustment, the arising distortions cancel each other to a large extent so that a large modulation amplitude range results up to a modulation factor of about 50%. The input is attached to a stereo jack, which can be connected to, for example, a PC soundcard as modulation source. Both channels are added up to a mono signal because medium wave radio unfortunately only transmits one channel.
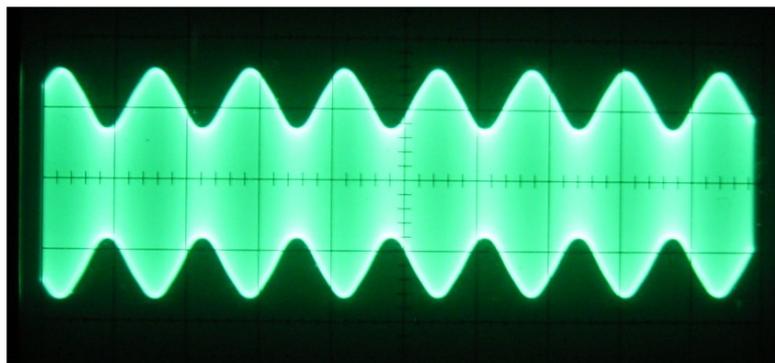
The amplitude-modulated high-frequency signal

Here, the coil in the oscillating circuit wraps around a ferrite rod and can, at the same time, serve as an antenna also when brought into proximity of a radio with ferrite antenna. Alternatively, a wire antenna can be attached as well although this increases the risk of one's favorite playlist to be heard in the neighborhood.
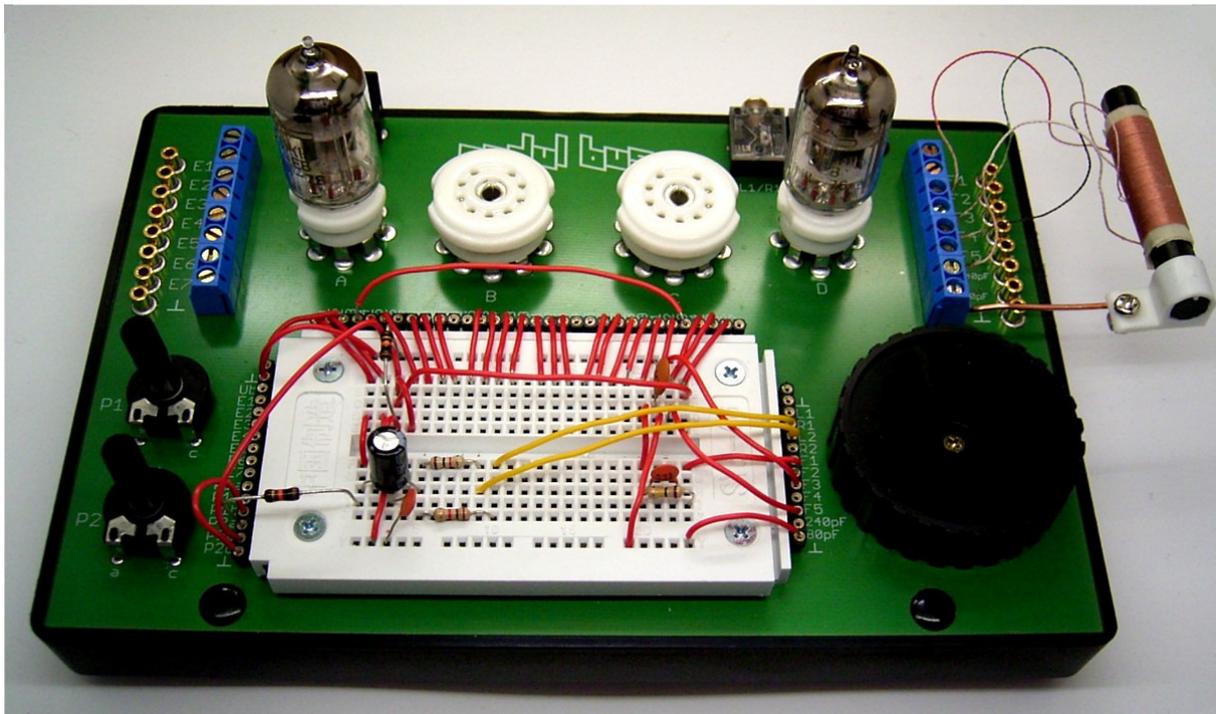
Assembly of the medium wave AM transmitter

7 Digital Broadcast DRM

The new digital broadcast below 30 MHz is called Digital Radio Mondiale (DRM). DRM combines VHF-like broadcast quality with the wider coverage at long wave, medium wave, and shortwave. Only a few commercial DRM receivers exist so far although many stations are already live. A PC software decoder like DREAM for example can be used. A receiver down-converts the DRM signal onto an intermediate frequency of 12 kHz for instance, which is then fed into the PC soundcard. DREAM converts the signal to the audio stream and plays the decoded signal back through the soundcard. The critical requirement for the receiver used is absolute frequency stability, which is achieved the easiest with a quartz oscillator.

## 7.1 RTL2 Direct-Conversion Mixer with the EF95

This hybrid DRM receiver utilizes an EF95 as mixer and an NPN transistor as oscillator. The circuit is configured for DRM RTL 2 at 5990 kHz. In this case, we can use a standard quartz crystal with 6 MHz, which provides the required stability.
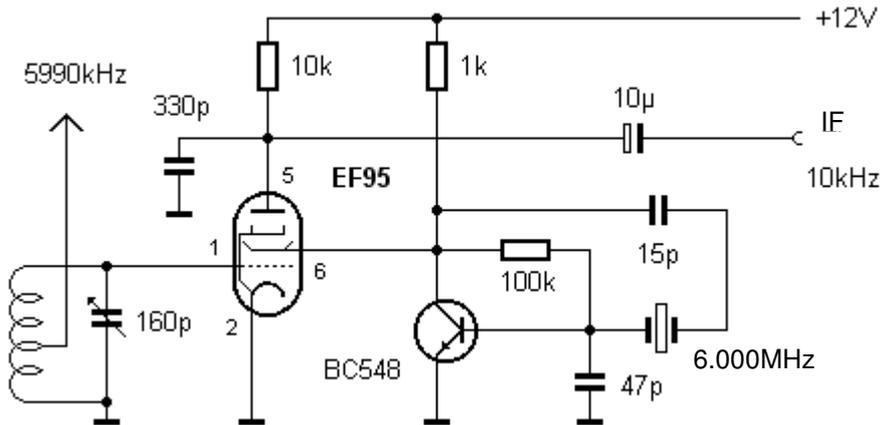
The DRM direct-conversion mixer

Thanks to the high sensitivity of the PC soundcard, the receiver does not need a large gain. The input oscillating circuit may be coupled to the antenna relatively strongly. The rotary capacitor is tuned to maximum signal amplitude.

The signal spectrum of the receiver can be displayed in the Evaluation dialog window of DREAM. A 10 kHz-wide band shows with numerous data carriers.
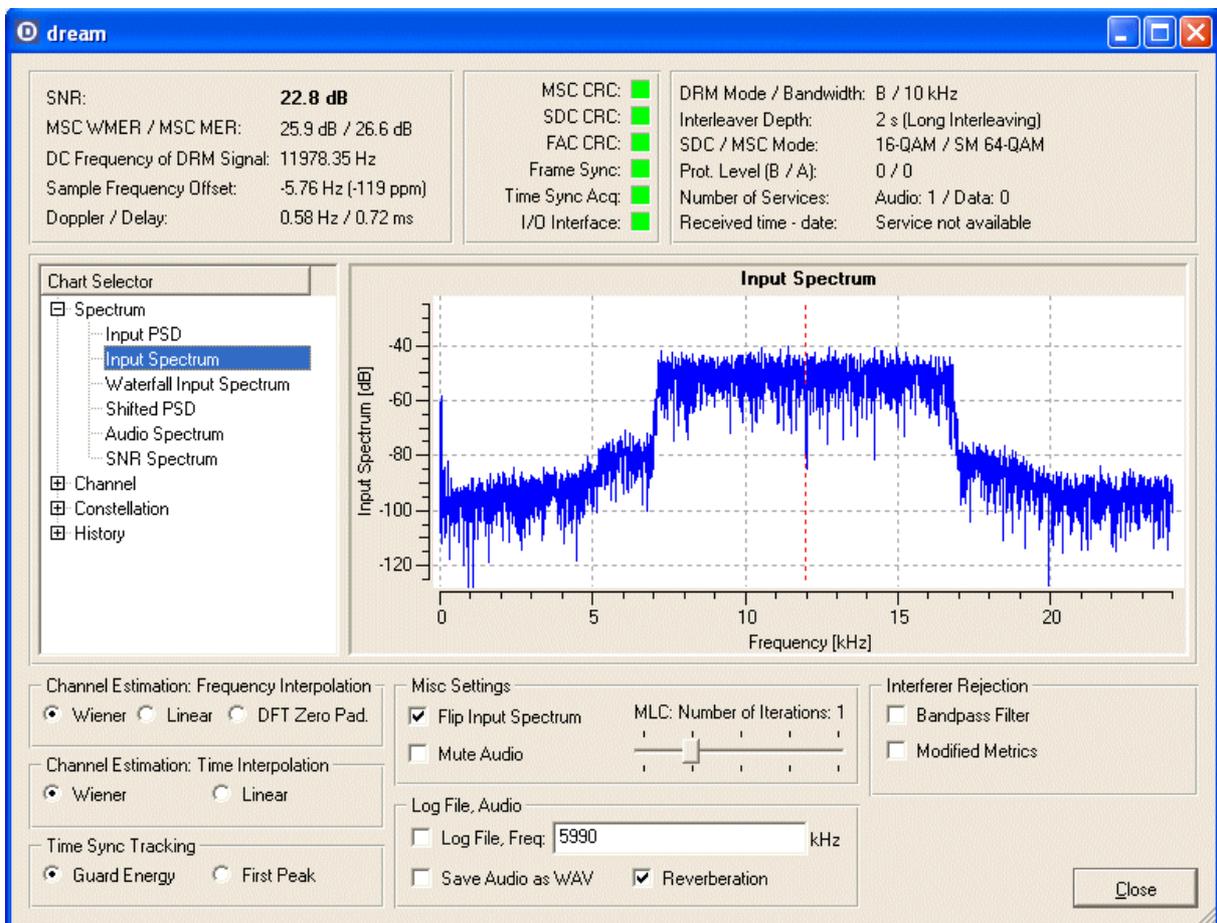

The spectrum of a DRM station

Since the simple receiver uses an oscillator frequency above the receiving frequency, the signal spectrum becomes inverted. Therefore, the control box "Flip Input Spectrum" in DREAM must be activated. At sufficiently high signal strength, DREAM decodes the data stream so that the DRM station can be heard through the PC speakers.

Supplemental experiment:
Replace the transistor oscillator with an equivalent tube circuit. Attempt to deploy an ECF80 as mixer and oscillator.
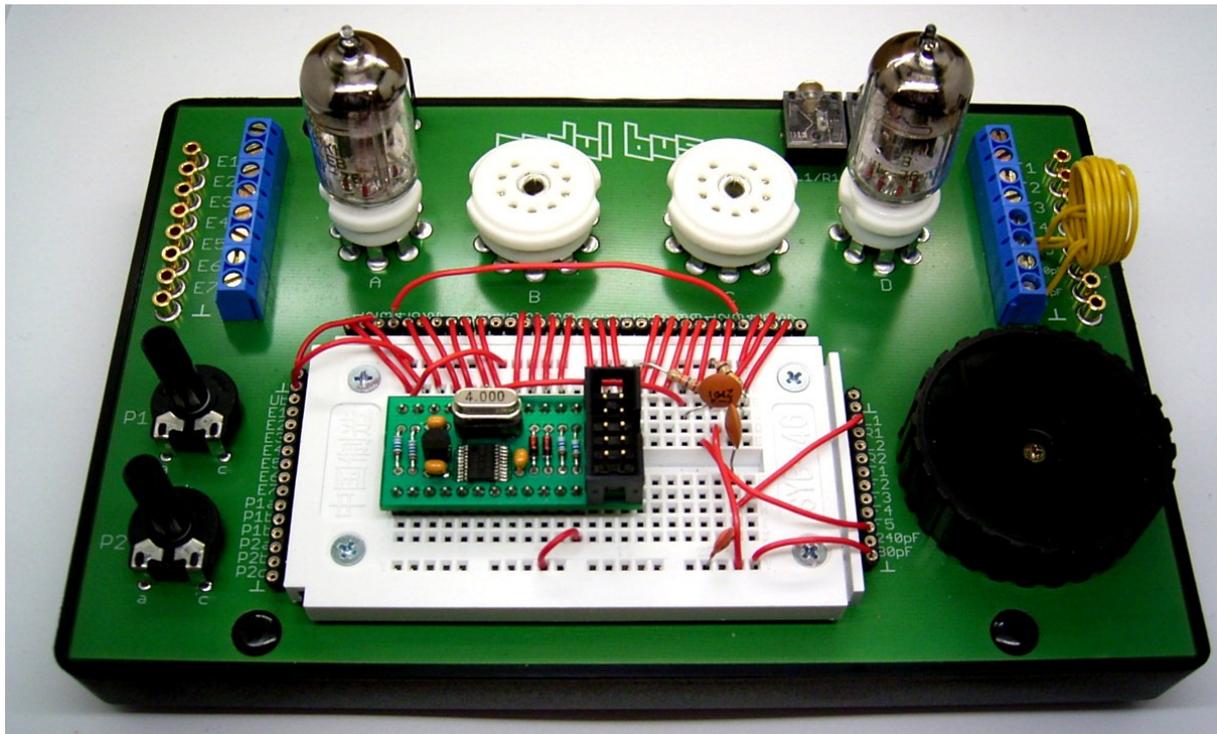
7.2   DRM with Programmable Quartz Oscillator

A DRM receiver places particular requirements on the stability of the mixer oscillator. A quartz oscillator thus has an advantage over a free-running oscillator. However, this generally limits reception to only a single frequency. Yet this experiment employs a programmable quartz oscillator of the Elektor magazine, which can be adjusted across the range 1 MHz to 100 MHz. The oscillator can be obtained fully assembled from AK MODUL-BUS and fits directly onto the breadboard.
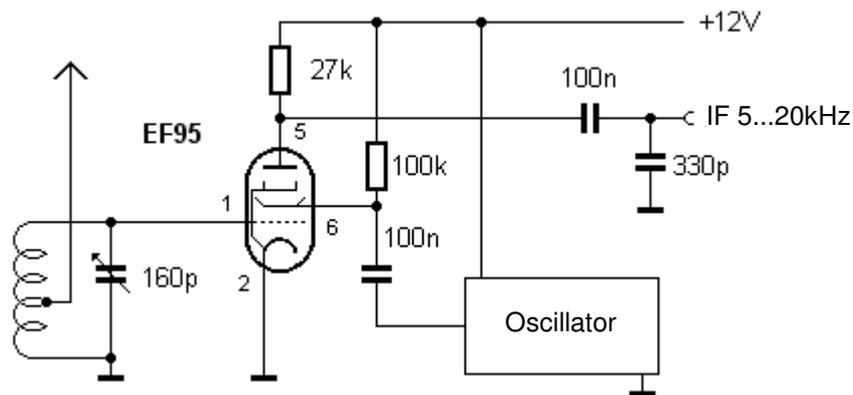
Direct-conversion mixer with programmable quartz oscillator

The circuit diagram shows a mixer stage with one tube. The input features an oscillating circuit matched to the receiving frequency. The oscillator signal with an amplitude of 3.3 Vss is applied to the screen grid and modulates the transadmittance of the tube, which makes this a simple multiplicative mixer. Typically, the PC is given an intermediate frequency of 12 kHz such that the oscillator should resonate 12 kHz below the receiving frequency. Other frequencies however are possible with the decoder software DREAM so that, for example, 10 kHz or 15 kHz can be chosen, too.

Assembly of the tunable DRM receiver

The programmable quartz oscillator has a 3.3 V voltage regulator onboard and thus may be operated with any voltage between 5 V and 12 V. The output delivers a square-wave high-frequency voltage with 3.3 Vss no matter what.
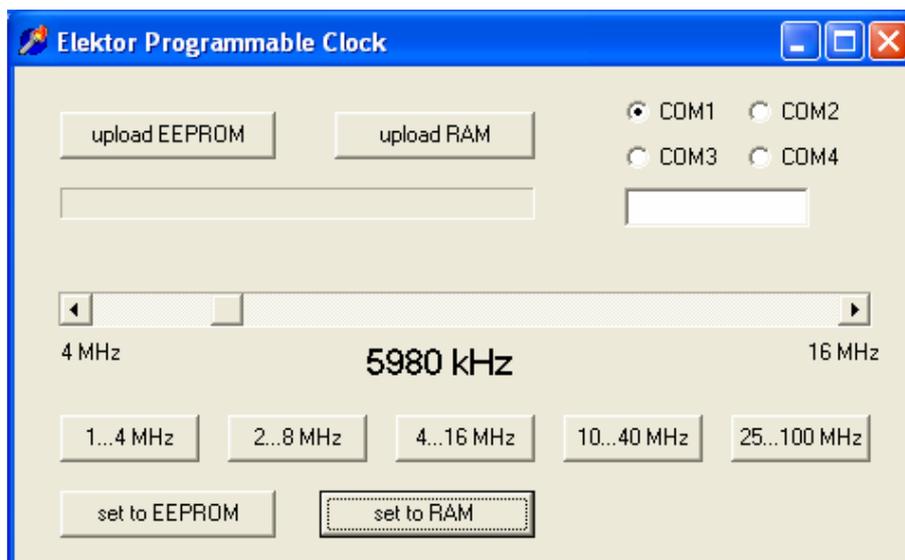

The Software for Tuning

Setting of the programmable quartz oscillator happens through a small Windows program and the serial interface of the PC. To receive RTL DRM-2 at 5990 kHz for instance, one sets the oscillator frequency to 5980 kHz resulting in an intermediate frequency of 10 kHz. The settings are saved to the RAM of the oscillator and hence take effect immediately.

Transferring the setting to the EEPROM of the system causes a nonvolatile configuration, which is activated during the next power-on without the help of a PC. The module thus behaves on one hand like a normal quartz oscillator and on the other hand like a tunable oscillator. Exchanging the quartz crystal of 10 MHz on the module for one with 4 MHz, causes the lower frequency limit to shift down to 400 kHz.

Station identification in DREAM

The DRM software DREAM decodes the IF signal with the PC. At adequately noise-free reception, the audio signal as well as the station identification can be received. Some stations broadcast text messages or images at the same time. The dialog window Evaluation shows the signal spectrum and contains further information like the signal-to-noise ratio for example.
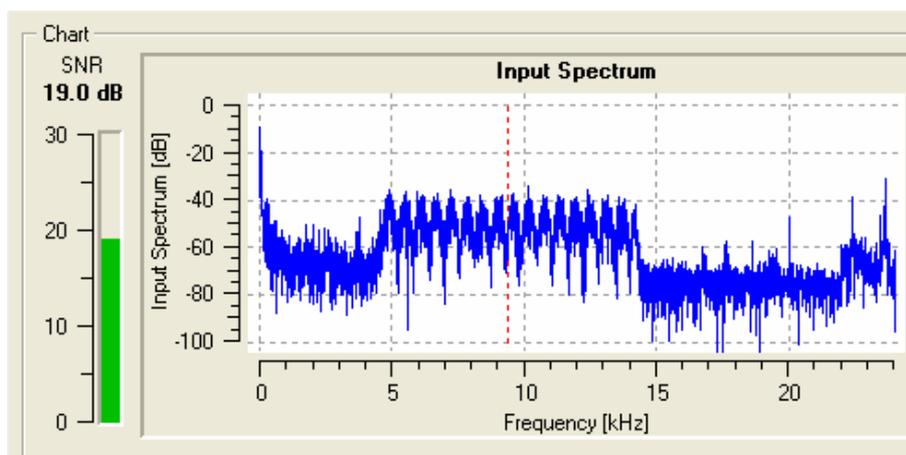
DRM signal with signal-to-noise ratio of 19 dB

With this direct-conversion mixer, we were able to receive almost all available DRM stations in the 49 meter band and numerous additional stations in the shortwave range. The reception performance however does not reach that of a superhet. Mainly the not

suppressed mirror image reception leads to increased interference. In particular cases, interferences can be faded out by adjusting to an advantageous oscillator frequency above the receiving frequency and setting DREAM to inverted spectrum. In other cases, one tunes the oscillator exactly to the carrier of an adjacent interfering station, whose spectrum then only reaches up to 5 kHz.

Supplemental experiment:
Extend the reception range to medium wave. Use a ferrite antenna or a frame antenna for the input circuit.

8 Tube Specifications and Bias Points

The tube experiments presented here operate at low voltages; mostly at 12 V. However, the tubes were originally intended for higher voltages such that the manufacturer specifications and recommended bias points and circuits are not directly applicable. Therefore, we have to investigate for each tube under which conditions and with which specifications it can be operated at a voltage of 12 V. In this section, appropriate measurements shall be carried out. In [1], a measurement method was introduced for the determination of the grid current, the anode current and the transadmittance of a tube, which is applied here as well.

8.1 Manufacturer Specifications

The tubes used here were originally developed for application with higher anode voltages. The following tables list the typical bias points. Both tubes were designed for high-frequency applications. In our case, we intend to deploy the tubes at lower anode voltages of 12 V. One look at the manufacturer specifications reveals the differences. Most tubes were built for anode voltages of 250 V. The tubes used here have always managed with smaller voltages.

The EF95 was especially designed for mobile applications at lower heating power and relatively small anode voltage.

EF95	Heating	Limiting Values	Operating Values
for high-frequency ampl.,	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 deployed in VHF mixer stages of television receivers. It is a multi-tube with one triode and one pentode. The triode exhibits already a relatively large anode current of 14 mA at only 100 V and hence one expects relatively much even at low voltages.

| ECF80, Triode	Heating	Limiting Values	Operating Values
for VHF mixer	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 is roughly comparable to the EF95 in its specifications, which measurements at only 12 V also will demonstrate.

| ECF80, Pentode	Heating	Limiting Values	Operating Values
for VHF mixer	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   Bias Points at 12 V

In [1], a method has been devised to analyze the characteristics of a tube at low voltages. The bias point at a time is established through different grid resistors. The negative grid bias voltage arises thereby through the initial grid current.

The following circuit was chosen for comparative measurements of different tubes. All tubes shall be tested at an operating voltage of 12 V and with an anode resistor of 1 kΩ. The grid resistance is varied across a wide range in order to arrive at differing grid bias voltages and bias points. Measurement of the voltage drop across the anode resistor yields the anode current at each bias point.
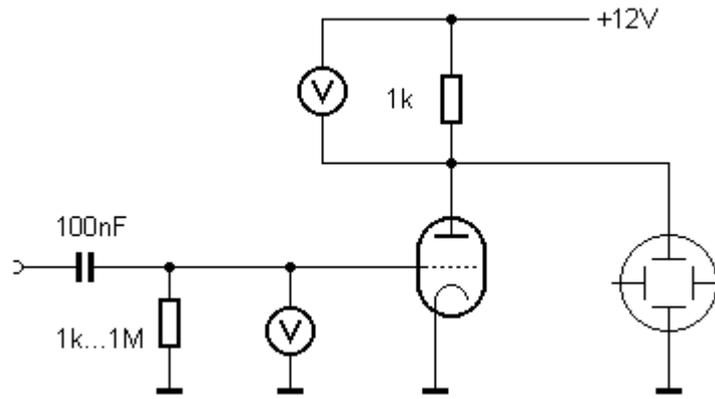
Measurement of a triode
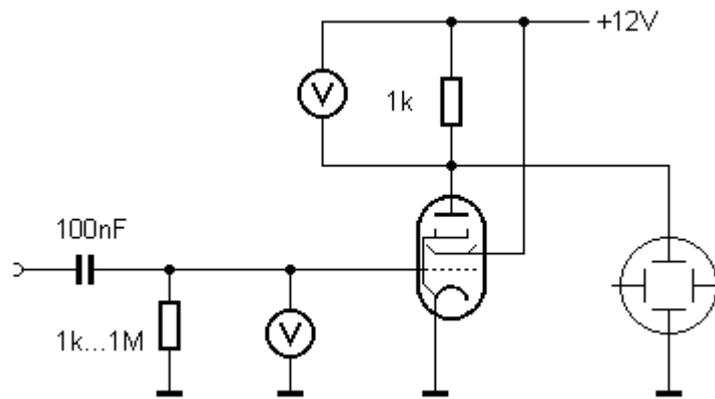
The test circuit for a pentode

If, in addition, we also want to measure the transadmittance of the tube at each bias point, a synthesizer and an oscilloscope are needed. The circuit is then driven by a 10 kHz signal with 10 mV. The oscilloscope measures the output voltage. The transadmittance at each bias point can then be determined from the gain. Unity voltage gain translates to a transadmittance of 1 mA/V due to the anode resistor of 1 kΩ.

This circuit requires several points of measurement and connections for a synthesizer and an oscilloscope. For this purpose, it proves of value that the experimental kit comes with the lateral terminals E1 to E7, which can be connected to with short wires. The actual circuit needs only two resistors and one capacitor. The following picture shows the assembly for the left EF95. The grid voltage can be measured between ground and the test jack E6. The voltage drop across the anode resistor can be measured between E1 and E4. An input signal voltage can be applied to E7.
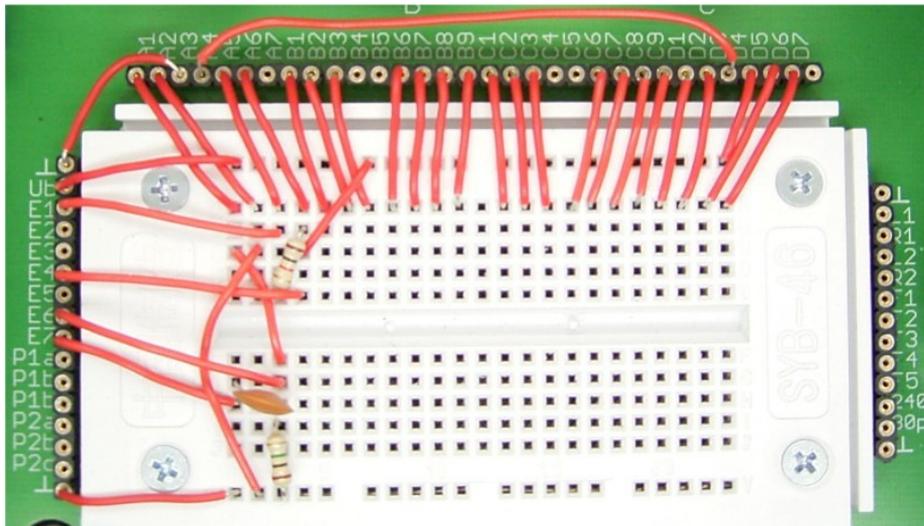
Wiring of the measurement assembly

The measurements are carried out with different grid resistors. The photo shows the circuit with a grid resistor of 1 MΩ. Alternatively, the resistor on the plugboard could be removed and a resistance decade connected externally between ground and E6.

## 8.3   Specifications of the EF95

The following table shows the results for the tube EF95. The transadmittance was determined with 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 indicate that the tube builds up a high negative grid bias voltage at high grid resistances and then attains only small anode currents. In some applications, it thus may become necessary to tie the grid resistor not to ground but rather to the positive operating voltage.

8.4   Specifications of the Triode in the ECF80

The test circuit can be reused for the ECF80 with relatively little effort since the EF95 has already been characterized successfully. First we will test the triode. Connect grid 1 and anode of both tubes. The heating of the EF95 is turned off, the one of the ECF80 turned on. Although the first tube is still part of the circuit, only the triode is in operation now.
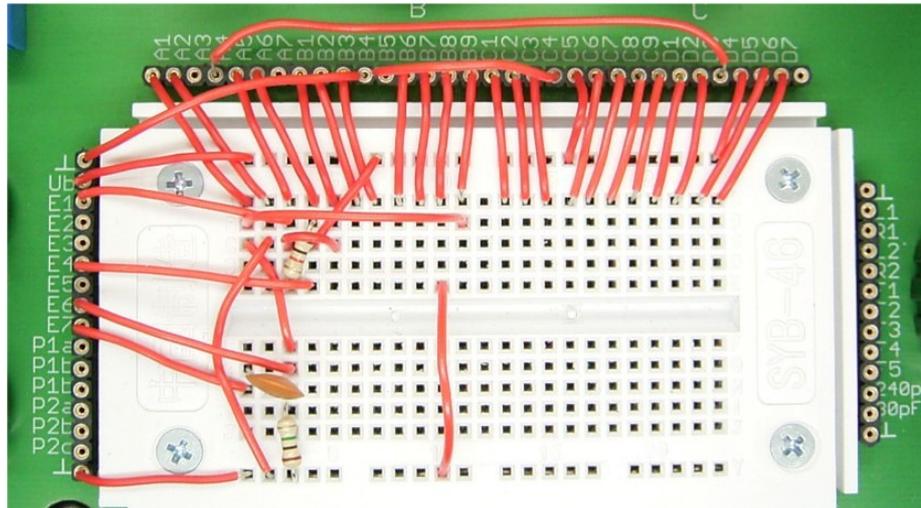
Measurements of the triode of an ECF80

The following table shows the measured values at an operating voltage of 12 V. The tube achieves surprisingly high anode current and transadmittance at this low voltage. Therefore, it is suitable for example for low-frequency output stages and for driving low-impedance headsets.

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 Specifications of the Pentode in the ECF80

During the characterization of the pentode in the ECF80, one should not forget to tie grid 2 to +12 V. A pentode generally shuts off almost completely when no screen grid voltage is applied.
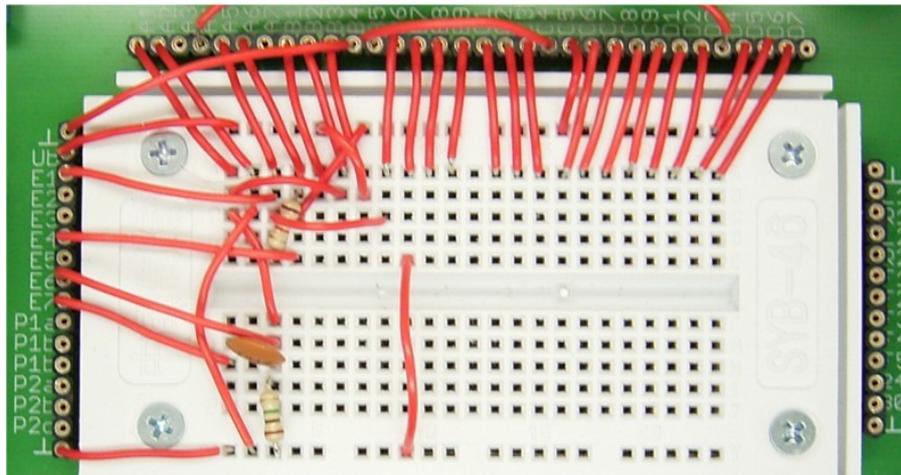
Measurement of the pentode of the ECF80

The following table shows the measured values for the pentode system 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 actual values of a tube depend heavily on its previous history. An entirely new tube often shows a higher current after a certain duration of operation. Some tubes are therefore heated for several hours during production and burnt in with high anode current. The ECF80 is a tube for consumer electronics, for which simulated aging was not performed for cost reasons. Thus an increasing anode current is noticed at the beginning.

You can perform simulated aging yourself in which care should be taken in exposing both ECF80s to the same conditions. One feasible procedure consists in tying the control grids of the pentode through resistors of 75 Ω to +12 V. This causes a large grid and cathode current to flow, which improves the emission of the cathode. The grid current should be turned off after every minute to redetermine the properties of the tube.

A more gentle variation of aging utilizes a grid resistor of 1 kΩ to +12 V. The tube can remain turned on for several hours without suffering any damage. In addition, you can apply a 10% to 20% raised heating voltage.

Appendix

References

[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
[4] G. Haas, High-End mit Röhren, Elektor 2005
[5] W. Frohn, Audio-Röhrenverstärker von 0,3 bis 10 Watt, Franzis 2005