english translation by Gerhard Oed (thank you very much to him)

Working characteristic curves

1. static and dynamic characteristic curves

a) static characteristic curves

For the static characteristic curve the tube is viewed without considering any connecting circuitry outside. To one of the electrodes a variable voltage is connected. All other electrodes are connected to fixed voltages (without series resistors). Depending on what voltage is made variable one can measure Ug1, Ua or Ug2 characteristic curves.

Static characteristic curves are optimal for matching tubes or to compare the tube data to the manufacturers data.

b) dynamic characteristic curves

These are also known as **working characteristic curves.**

With dynamic characteristic curves the behavior of the tube is determined using a given circuitry (that means with load resistance(s)). The difference compared to the static characteristic curves is that changes of one parameter (e.g. Ug1) also change other parameters and are not fixed.
Example: Triode using resistive coupling: At the load resistor a voltage drop occurs that depends on the tube's current. Reducing Ug1 will increase the anode current. This will increase the voltage drop across the load resistor and the anode voltage will decrease. The characteristic curve is influenced by several parameters. With Pentodes there is an additional influence by the screen grid.

Dynamic characteristic curves are suitable to find proper working areas for the tube within a give circuit, to calculate the expected distortion factor etc.

2. Determining dynamic characteristic curves

There are several possibilities to do that:

a) Solution using drawings
This is the classic approach that is described in several tube books (Barkhausen, Kammerloher, et.al.).

A static set of characteristic curves (with Ua as variable) is recorded. Following this a resistor line according to the load resistance is also drawn (right part of the drawing) Then the values are transferred to the left side using a diagram that depends on Ug1 and the working characteristic curve is achieved (here done for a triode, but works also for pentodes).

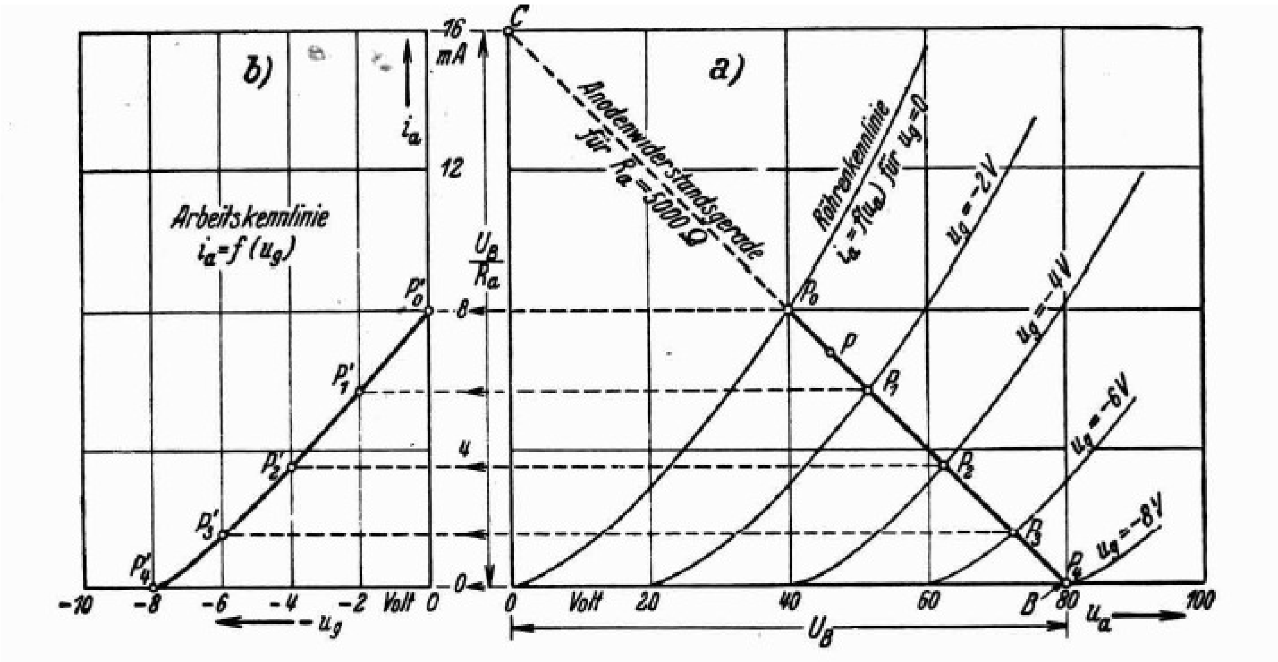


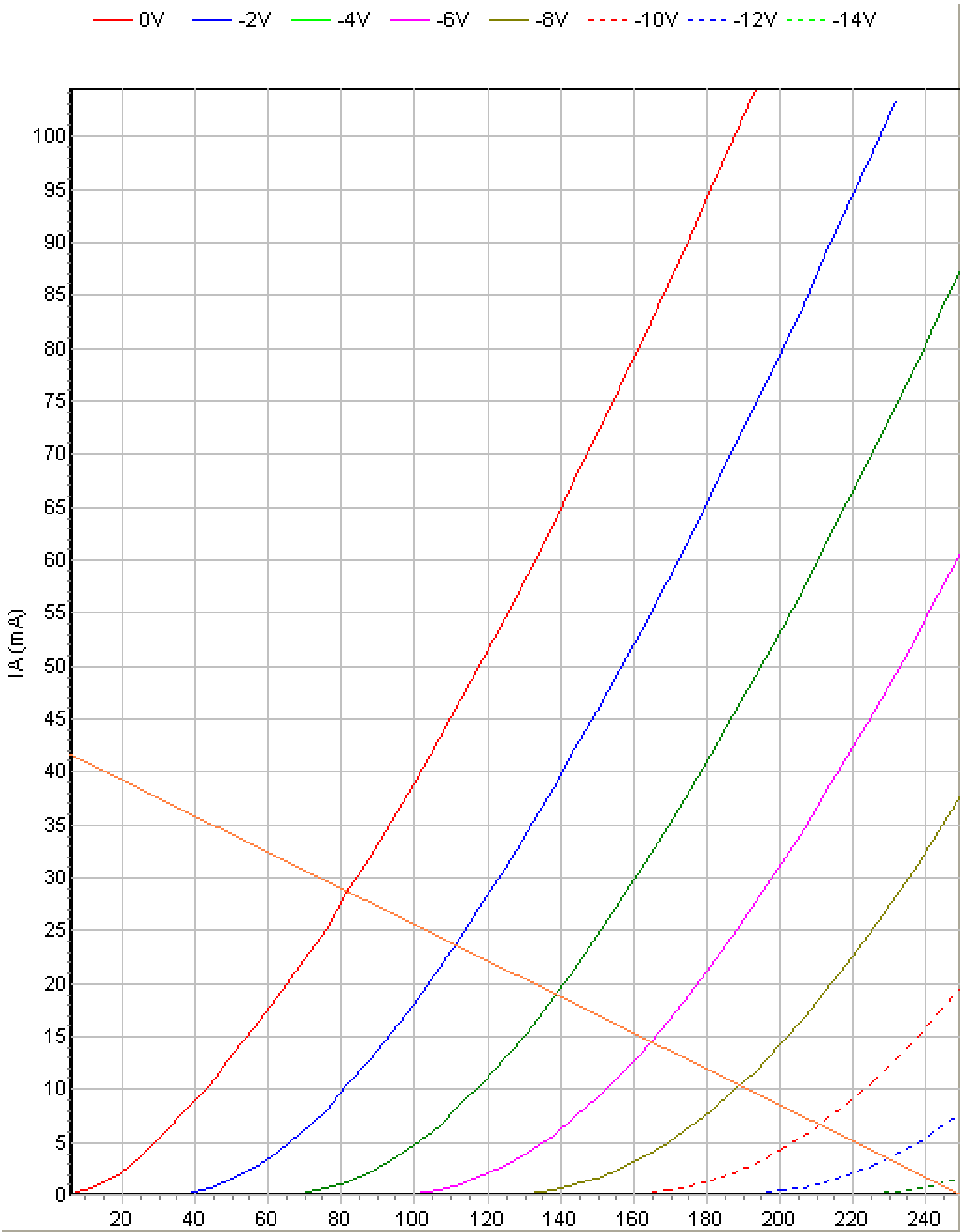
Abb. 185. Konstruktion der Anodenwiderstandsgeraden und der Arbeitskennlinie $i_a = f(u_g)$.

From the working characteristic curve the optimal control area for low distortion factor, optimal match and the needed grid AC voltage can be derived. The drawings above show the case when resistive coupling is used (Ua = 80V).

If the resistor is replaced with an output transformer things change. Assuming an ideal transformer (ohmic resistance = 0 ohms) there is no voltage drop at the load if the tube is not modulated. In the idle state the tube gets the full supply voltage. When modulated the anode supply will swing around the supply voltage. The solution using drawings is also possible in this case and is explained in the cited books above.

Advantage of this method (using drawings): descriptive and comprehensible. Disadvantages: Requires recording of many characteristic curves. Due to drawing inaccuracy there is a source for distortions. The few points available can only show the output characteristic curve in a very rough raster. If there are more complex circuits (e.g. an additional resistor in series with the screen grid or a so called *"Ultralinear" circuit – in this case the screen grid is connected to a tap of the output transformer) those methods will not yield a solution.

Here is an example:



An EL84 used as triode, set of characteristic curves Ua at given constant Ug1. The resistive line for Ra = 5400 ohms is drawn in orangecolor. (static characteristic curves recorded with RoeTest – The derivative of the working characteristic curve has to be added manually).

b) mathematical Solution

I do not know if it is possible to calculate the working characteristic curve from the set of static characteristic curves or the measuring (sample) points; this is beyond my mathematical skills. Anyway this will be very complex. Considering more factors (e.g. additional screen grid with own circuit) the complexity will be overwhelming, perhaps impossible to solve.
I mention this approach only for the sake of completeness.

c) Working characteristic curve using approximation

It is also possible to record a working characteristic curve without using any series resistor.

First a point of the characteristic curve Ug1 is measured that leads to a certain amount of current. Now assuming a defined output resistance Ra there will be a voltage drop (Ia x Ra) across the resistor. Then we reduce Ua in the measuring dvice and get a new value for Ia. We continue this approximation process until an equilibrium is reached. This is done for all measure points of Ug1 and we will so get the working characteristic curve.

Advantages: no series resistance needed
Disadvantages:

- very complex – only useful when using an automated solution
- inaccuracies due to limited resolution of the measurement device
- limitless when analyzing complex circuits (screen grid!)

d) Working characteristic curve by Simulation
Keyword: Spice. These simulation program can be used to generate much more complicated circuits. The problem here is the modeling of the tubes. There are only a few types of tubes for which more or less exact models do exist.

Advantages:
rapid circuit design
Disadvantages:
some deviations from the real values

My opinion: Use it if you like it. I for myself are more the practical type and try to construct ***real*** circuits.

e) Solution using measurements

This is my preferred approach. Therefore I will discuss this possibility a little bit further. What is more suggesting itself than simply use a tube, connect it to components and then measure the characteristic curve ?
Some considerations are necessary for that. When recording characteristic curves we operate solely with DC. For this reason we cannot use transformers but only load resistors when measuring.

<u>Resistive coupling:</u>
When there is a resistor used as load for the tube (resistive coupling) one only needs to insert the desired load resistance into the anode connection wire. Then this holds: Ub of measuring device = Ub of the real circuit.

<u>Transformer coupling:</u>
When there is an inductive load (output transformer) the items mentioned in case a) apply. Instead of the transformer an ohmic resistor (representing the AC resistance of the transformer) is put in series with the measurement equipment. The supply voltage of the measuring equipment must be risen to accommodate the swing at the anode (which is about one half of the modulation control value). The level of control (modulation) is not known in the beginning therefore several tries may be required using different supply voltages. It has to be taken into account that the real conditions can differ from the results of this method due to unknown phase shift due to the inductive

load. For a coarse estimation this method will suffice (using the drawing method will yield no better results).

Advantages: Simple to perform

-using only a single characteristic curve recording already gives you a working characteristic curve (f(Ug1)).

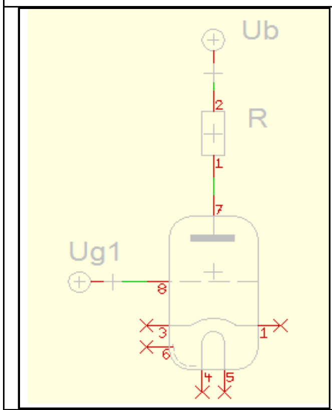
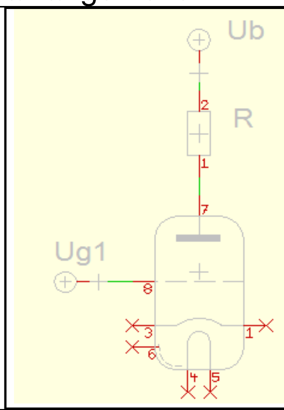
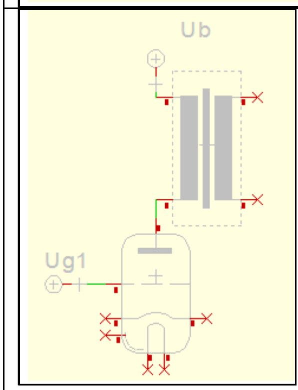
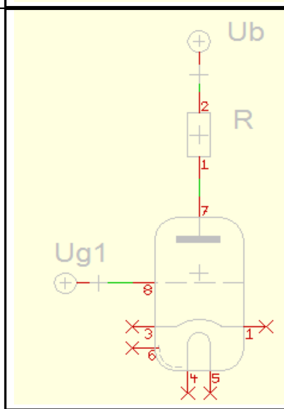
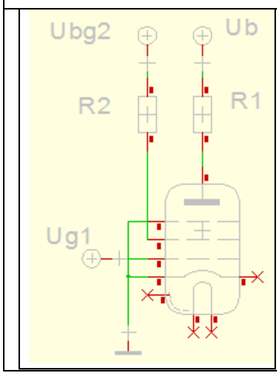
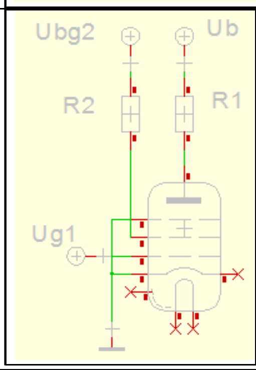
-applying a sufficient number of sample (measuring) points will lead to a very exact characteristic curve

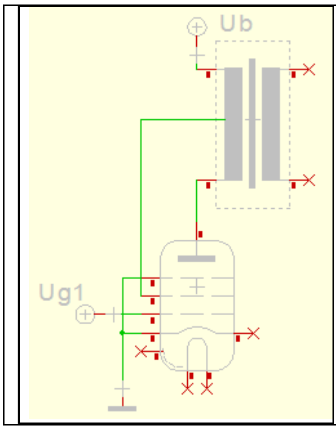
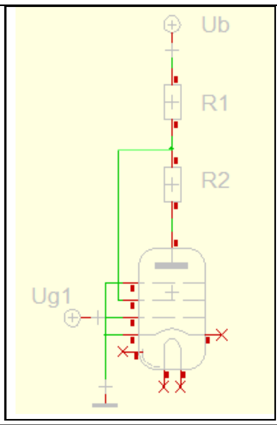
- even for complex circuits recording of the characteristic curve is possible (additional screen grid components)

Disadvantages:

- must insert selected resistor manually into the connections to the tube
- some considerations are required with complex circuits or output transformers

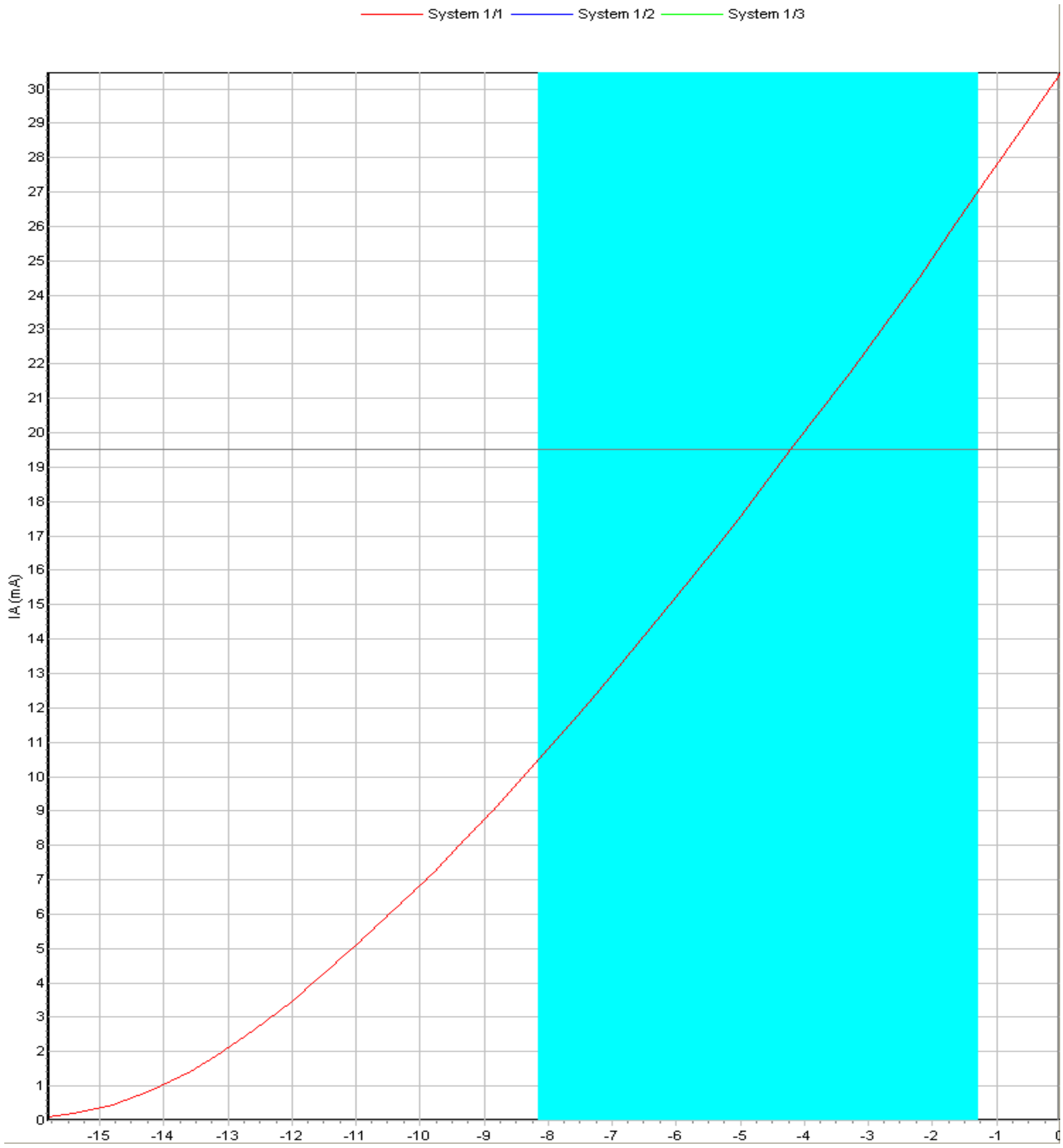
Some examples for measuring arrangements:

Real Circuit	Circuit of measuring arrangement	Notes
		Triode using resistor coupling R Measuring device = R real circuit Ub Measuring device = Ub real circuit
		Triode using output transformer R Measuring device = primary AC resistance of transformer (= secondary load * transfer ratio²) Ub Measuring device = Ub real circuit +1/2 Modulation
		Pentode using resistive coupling R1, R2 Measuring device = R1, R2 real circuit Ub Measuring device = Ub Measuring device Ubg2 Measuring device = Ubg2

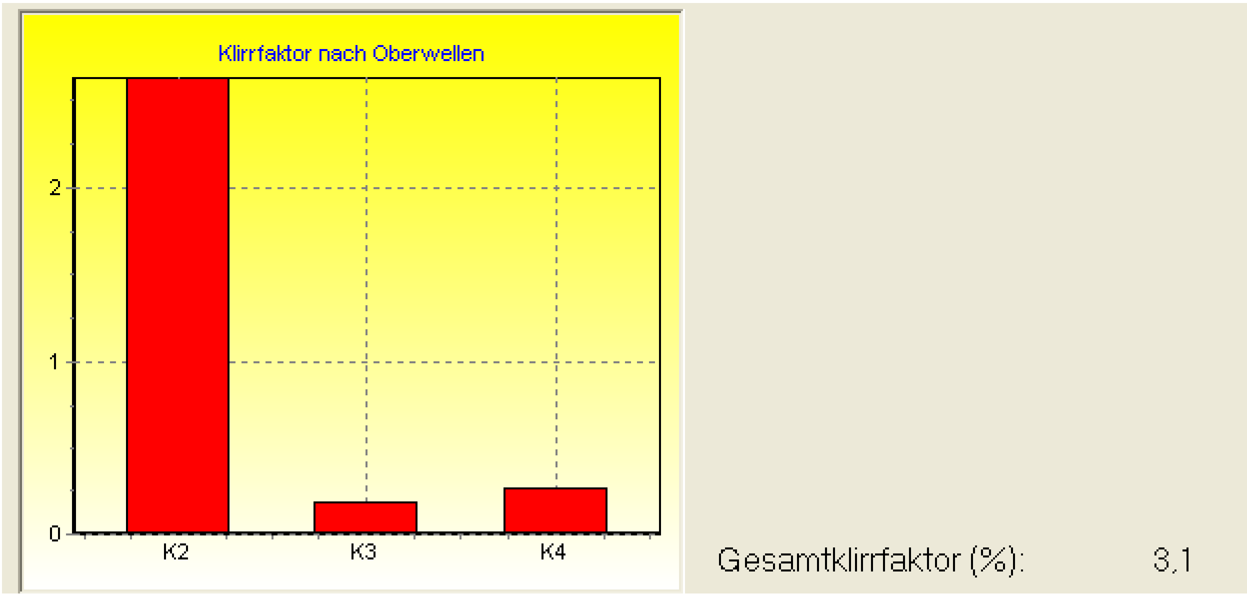
		Pentode using transformer coupling in 'Ultraliniear' circuit R1+R2 = primary AC resistance of the transformer. Ratio R1:R2 according to tap at the transformer Ub Measuring device = Ub real circuit+1/2 Modulation

More Possibilities can be created...

Next an Example:

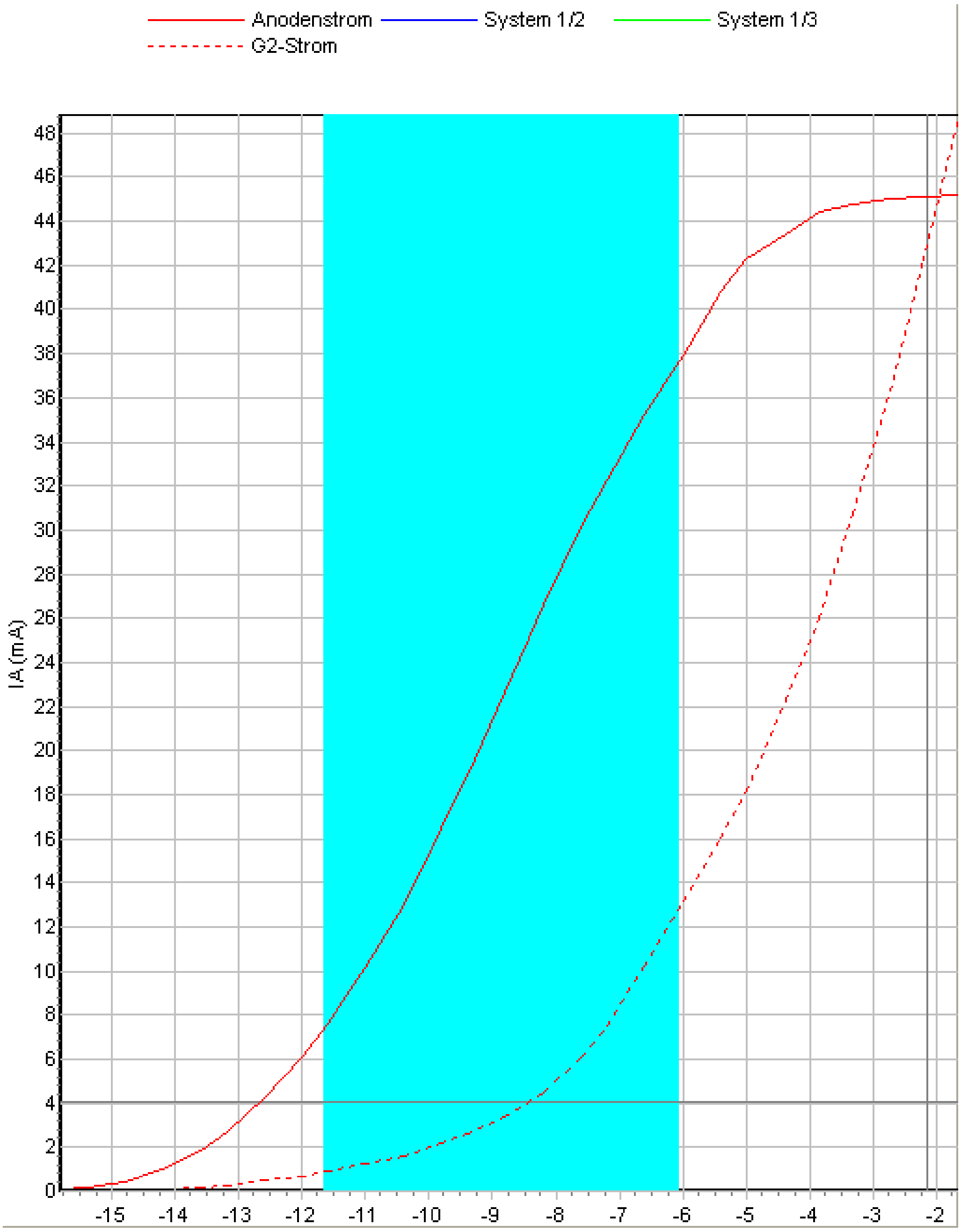


real measurement of working characteristic curve for EL84 working as a triode, Ra = 5400 ohms (resistor coupling – a resistor of 5400 ohms is inserted into the anode- / G2-connection).



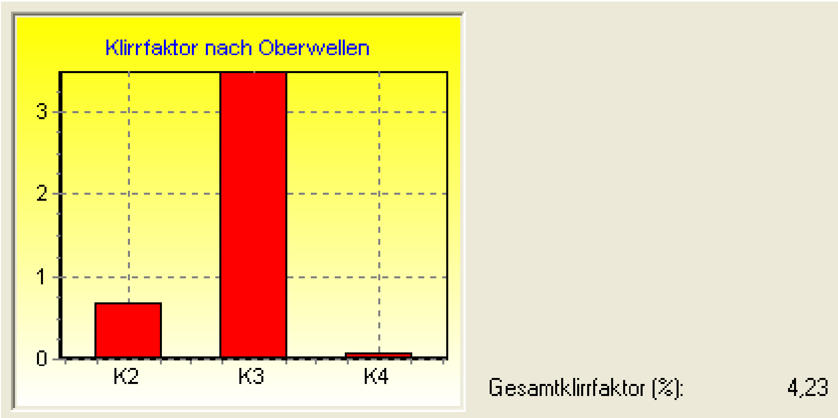
Total harmonic distortions – derived from above shown working characteristic curve (RoeTest). Especially K2 is present (the so derived harmonic distortion factor will always be Ia little bit larger than the real world distortion factor, as the measured characteristic curve has a finite amount of measure points and there is a small bend at each measuring point).

another example - Pentode:



EL84 used as Pentode. Ra=5400 ohms, Ub=250V (resistor of 5400 Ohm in series with Anode), Ug2=250V (fixed)

EL84 with working region and the resulting harmonic distortions:



as expected: higher anode current at same load compared to the triode circuit, but harmonic distortion factor K3 is higher.

Literature:

- Lehrbuch der Elektronenröhren, Barkhausen, Band 1, S.Hirzel Verlag Leipzig (Ausgabe 1965)
- Elektronenröhren und Verstärker, J. Kammerloher, C.F. WINTER'SCHE VERLAGSHANDLUNGIFÜSSEN, (7. Auflage 1958)
- Inside the vakuum tube, John F. Rider, John F. Rider Publisher Inc. (1945)