DCTriode

EC86 image courtesy of The Valve Museum http://www.r-type.org/index.htm

User Manual

Version 2.1 – September 2023. Add SE triode pentode power stages.

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Table of contents

1 Safety reminder

Playing with vacuum tubes is very dangerous and can be lethal because of the high voltages required to operate them !

Wear gloves, never handle a chassis when powered up, do not put your hand under a chassis, never put both hands under chassis, do not wear metallic jewels on finger, wrist, neck, be very careful when moving grips of voltmeter or oscilloscope !

Remember that electrolytic capacitors can hold a high voltage even long after power shutdown.

Above roughly 50V, high voltages start to inject significant current into your body. Be very very careful with the 200 to 500V !

This version has required a substantial design and documentation effort, mainly because of the new feature “frequency response”, which necessitated a global design approach compatible with the largest number of circuits. Less work for maximum output.

When I had setup the web site 2 years ago, I wrote that “luckily, the small number of circuits variants allows this approach by simple building-blocks, when compared to a pure Spice approach”. However, with now more than 30 circuits, and with pentodes, I see this way of calculating circuits has approached its practical limit, despite the fact that many solvers share same or similar routines and methods.

You will of course detect some bugs; in particular, the grid data summarising sequential simulations is not always populated by the right data.

The loadline graphs are just displaying the pure DC loadline, I have to add the AC loadline.

Also the stray capacitance unit per pin may be not always correct, depending on circuits.

This user manual is also imperfect. I had not time enough to present the new sections (AC models, frequency response models) completely exhaustive. Some Thévenin / Norton models may not correspond exactly to what is used in DCTriode. You will forgive me, after all, this is freeware!

2 Purpose of DCTriode

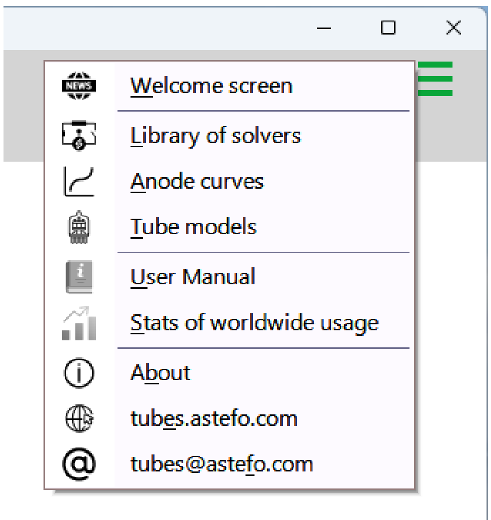
DCTriode is a freeware library of simple pre-designed circuits consisting in 1 triode or more DC-coupled triodes, or 1 pentode. Each circuit has a fixed structure, which values and types are defined by yourself :

- power supply voltage, between 20 and 800V ;
- tube type among the ready-to-use modelised versions or your own tube models ;
- resistor values ;
- bias voltage, if any like differential stages ;
- load current, for voltage regulators ;
- AC load on output, necessary to calculate voltage gain when possible.

Once parametrised, you launch the simulation and get results, consisting in :

- a list of voltages nodes, currents, Vak, Vgk, dissipated powers
- dynamic gain and impedances (when calculable...)
- a graph of stacked voltages across resistances and tubes
- a graph displaying the operating point within an Ia-Va space, plus the loadline if relevant
- successive simulation results are stored in a grid of rows and columns, that can be copied and pasted in a calcsheet.

3 How to use it



Use the « hamburger » menu icon at top right corner of main window. It provides you with main features :

- welcome screen, where are found some news and generic information
- access the library of solvers
- display operating curves and characteristics of the modelised tubes
- display and edit triode models
- display stats
- display this PDF user manual

4 Navigate into library of circuits solvers

4.1 Visual interface

The library is a list of circuits displaying all circuits or only a functional selection. There are 2 ways to display it :

- « gallery » mode : scrolling boxes with icons
- « tree » mode : a tree-view with labels only, more compact, also listing your custom configurations

Both views can be laid out either horizontally (top of window) or vertically (left side) by clicking the button with arrow.

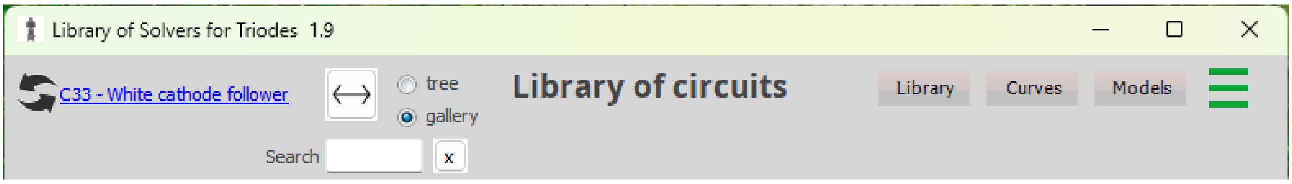


Figure 1: setting layout of library

4.2 Gallery mode

Move the mouse over a diagram to display an explanatory text in the bottom of window.

Click the diagram to open the corresponding solver window. You may open as many solver windows of different or same circuits as wished. See §5 for using a solver.

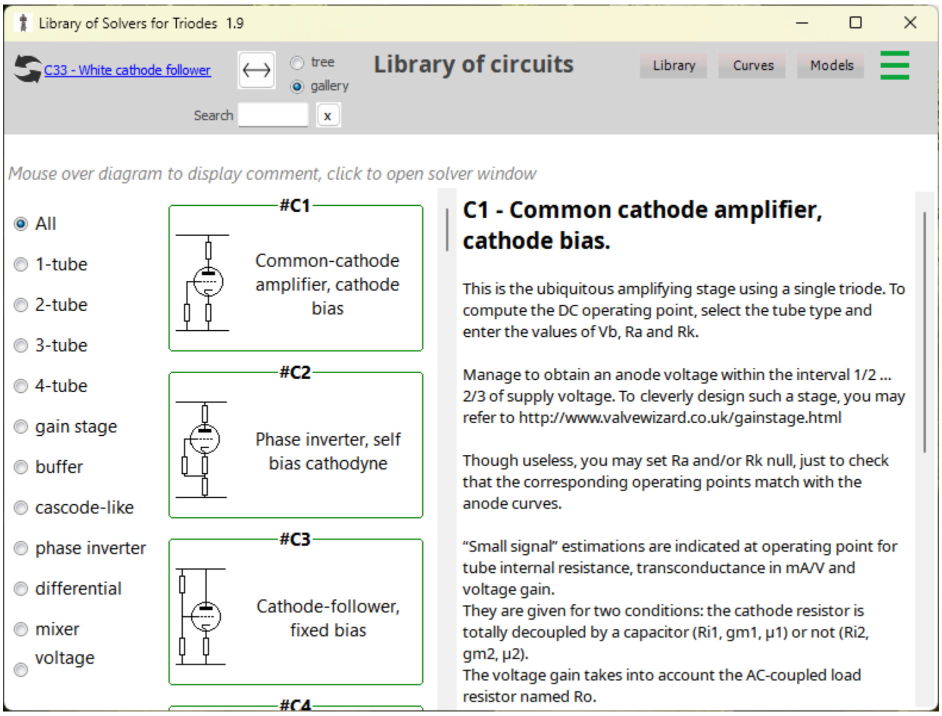


Figure 2: library of circuits displayed in "gallery mode"

4.3 Tree mode

Click a category node to expand or fold it.

Click a circuit name to display the explanatory comment.

Double-click it to open the solver window.

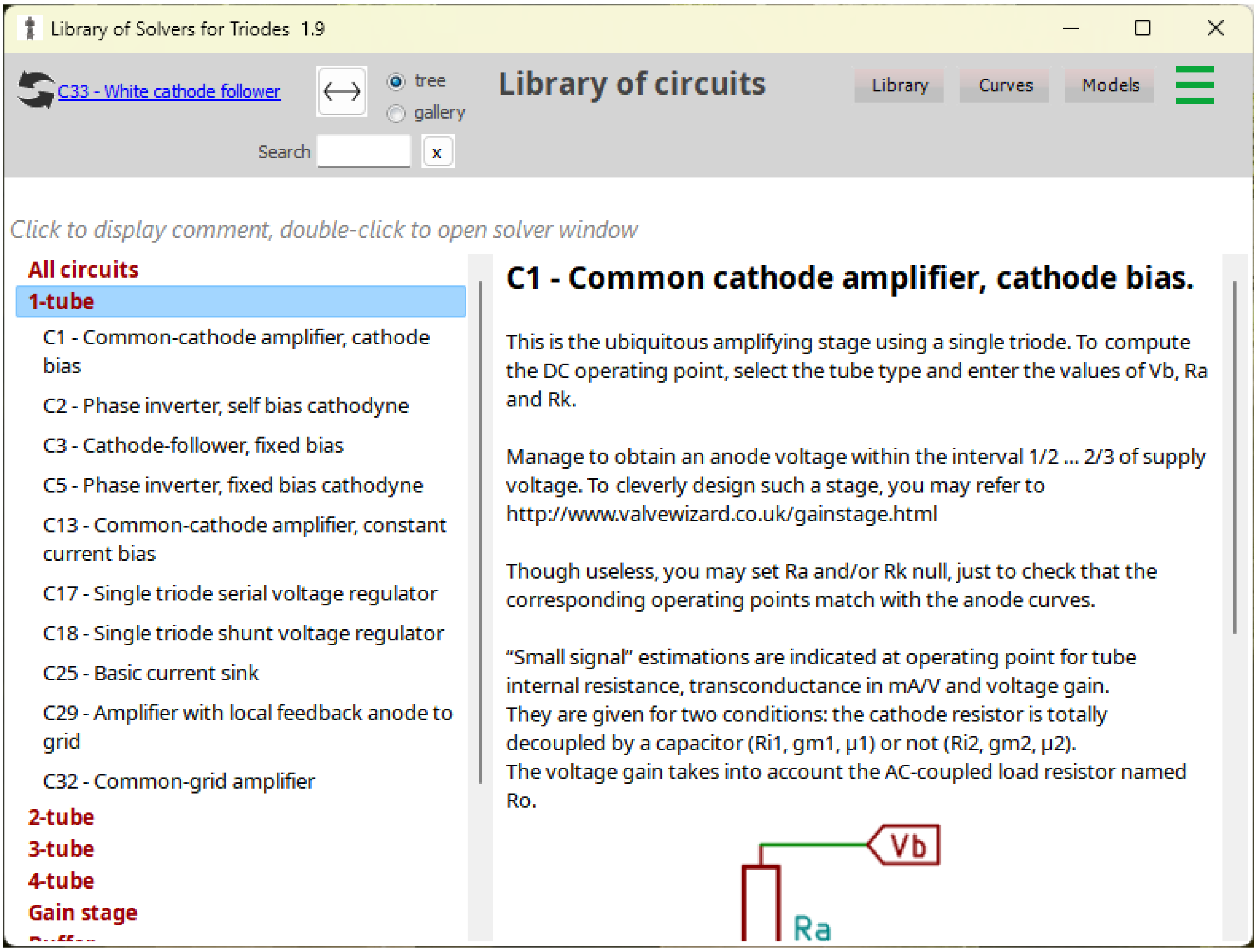
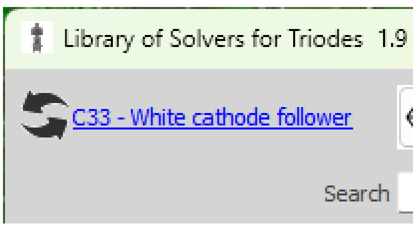


Figure 3: library of circuits displayed in "tree mode"

In both modes can you retrieve circuits by typing some string of characters, which are to be found in circuit's titles, or digits to retrieve them by their number.. Not that useful – as there are a small number of circuits – but it's here anyway.



At top left of window, you may recall the last simulated solver.

4.4 Available circuits

Below is the list of available circuits and a short status.

Convergence and tolerance : indicates if the DC solver is stable enough and converges easily even for conditions far from normal expectations. Tolerances for convergence are in most solvers ±1µA on currents or ±1mV on voltages.

Unsatisfactory convergence should be fixed in future release of software...

Circuit #	Name	DC convergence	AC data	Frequency response
1.	Common-cathode amplifier, cathode bias	Satisfactory	Gain, Zout	yes
2.	Phase inverter, self bias cathodyne	Satisfactory	Gain	yes
3.	Cathode follower, fixed bias	Satisfactory	Gain, Zout	yes
4.	Common-cathode amplifier and DC-coupled cathode follower	Satisfactory	Gain, Zout	yes
5.	Phase inverter, fixed bias cathodyne	Satisfactory	Gain	yes
6.	Cascode, classical with anode output	Satisfactory	Gain, Zout	yes
7.	Differential phase inverter, cathode bias	Medium	Gain	yes
8.	SRPP	Satisfactory	Gain, Zout	yes
9.	Common-cathode amplifier with direct coupling	Satisfactory	Gain, Zout	yes
10.	Differential phase inverter, constant current bias	Medium	Gain	yes
11.	Dual triode mixer, balanced	Satisfactory	Gain, Zout	yes
12.	Dual triode mixer, asymmetrical	Satisfactory	Gain, Zout	
13.	Common-cathode amplifier, constant current bias	Satisfactory	Gain, Zout	
14.	Common-cathode amplifier with DC level shifting	Satisfactory	Gain, Zout	yes

Circuit #	Name	DC convergence	AC data	Frequency response
15.	Differential phase inverter, long-tailed pair, cathode bias	Satisfactory	Gain	yes
16.	Two-triode serial voltage regulator	Satisfactory	Zout	N/A
17.	Single-triode serial voltage regulator	Satisfactory	Zout	N/A
18.	Single-triode shunt voltage regulator	Satisfactory	Zout	N/A
19.	3-triode common cathode amplifier with HV filters	Satisfactory	Gain, Zout	
20.	2-triode common cathode amplifier with HV filters	Satisfactory	Gain, Zout	yes
21.	Double-cascode after « Aikido Tubecad »	Satisfactory	Gain, Zout	yes
22.	Fixed bias cascode	Satisfactory	Gain, Zout	yes
23.	Push-pull amplifier with DC feedback (after Tubecad)	Satisfactory	N/A	
24.	SRPP headphone amplifier (after Tubecad)	Satisfactory	N/A	
25.	Basic current sink	Satisfactory	Zo	N/A
26.	Constant-Current-Draw-Amplifier after Tubecad	Satisfactory	N/A	
27.	Janus cascode shunt regulator after Tubecad	Satisfactory	N/A	N/A
28.	Totem pole split load phase splitter after Tubecad	Satisfactory	N/A	
29.	Common-cathode amplifier with local feedback anode to grid	Satisfactory	Gain, Zin, Zout	
30.	Mu-follower	Satisfactory	Gain, Zout	
31.	SRPP+	Satisfactory	Gain	

Circuit #	Name	DC convergence	AC data	Frequency response
32.	Common-grid amplifier	Satisfactory	Gain, Zin, Zout	yes
33.	White cathode follower	Satisfactory	Gain, Zout	
34.	Half-mu stage	Satisfactory	Gain, Zout	yes
35.	Cathode-follower with current sink	Satisfactory	Gain, Zout	yes
36.	Pentode gain stage	Acceptable	Gain	yes
37.	Single-ended power triode	Satisfactory	Power	
38.	Single-ended power pentode	Satisfactory	Power	

4.5 A word on cascode topologies

The author found out that there is, among the many documents available on the Web, some confusion about the various cascode topologies of circuits. His understanding is as follows :

- the generic term « cascode » refers to a circuit where two tubes are connected in series ;
- the actual cascode circuit – be it for audio or UHF – consists in a « lower » common-cathode triode, and an « upper » common-grid triode ; the output is taken on the anode of upper triode ;
- all other topologies (SRPP variants, mu-follower, white-cathode follower, half-mu follower, totem-poles, cathode-follower with current sink, etc.), still connected in series on DC point of view, generally operate with common-cathode lower tube and common-anode upper tube, both playing active and opposite roles, the output being « somewhere » on the path from lower anode to upper cathode ;
- the pure SRPP, if output tied to an infinite load (to obtain only a voltage gain) is no longer an SRPP but a common-cathode amplifier loaded by a tube with more or less constant Vgk.

In many circuits, the upper tube is frequently and erroneously considered as a current source or a cathode-follower. However, there are circuits which are driven by the grid of upper tube, a situation where the tube behaviour is effectively close to cathode-follower.

As a summary :

Tableau 4.1 : main « cascode-like » circuit topologies used in DCTriode. 1 : lower tube, 2 : upper tube

Topology	Operation	Input	Output
Fundamental cascode C6	Common-cathode, loaded by a common-grid, itself loaded by an anode resistor	G1	A2
Fundamental SRPP C8	Only 2 cathode resistors ; common-cathode loaded by a common anode	G1	K2
SRPP+ C31	Fundamental SRPP, with cathode 2 resistor split in 2 parts to optimise upper tube bias	G1	Tapping point on Rk2
Mu-follower C30		G1	
Half-mu stage C34		G1	A1
White-cathode follower C33	Full AC negative feedback from anode upper to grid lower	G2	A1 = K2
Cathode-follower with current sink C35	Buffer	G2	A1~K2

5 Playing with circuit solvers

All circuit solvers are built upon a same window structure, displaying several sections :

- top of screen : the « Solve » button (default button, type Enter), plus some auxiliary buttons
- left : an « interactive » electrical diagram, where to specify tube model(s), supply voltage, values of resistors, input voltage, output current (depending on circuits) and where will be displayed some voltage and current results
- a tabsheet containing the graph of « stacked voltages » and DC textual results
- a tabsheet where is displayed the « loadline » graph
- a tabsheet listing the AC small signal results (if any)
- a tabsheet containing a grid storing successive simulation results.

The auxiliary buttons are :

- « Solve », which launches the simulation (or hit ENTER key)
- « Options » to setup a few cosmetics effect for the interactive schematics
- « Tools » to access some practical tools (right now only one).

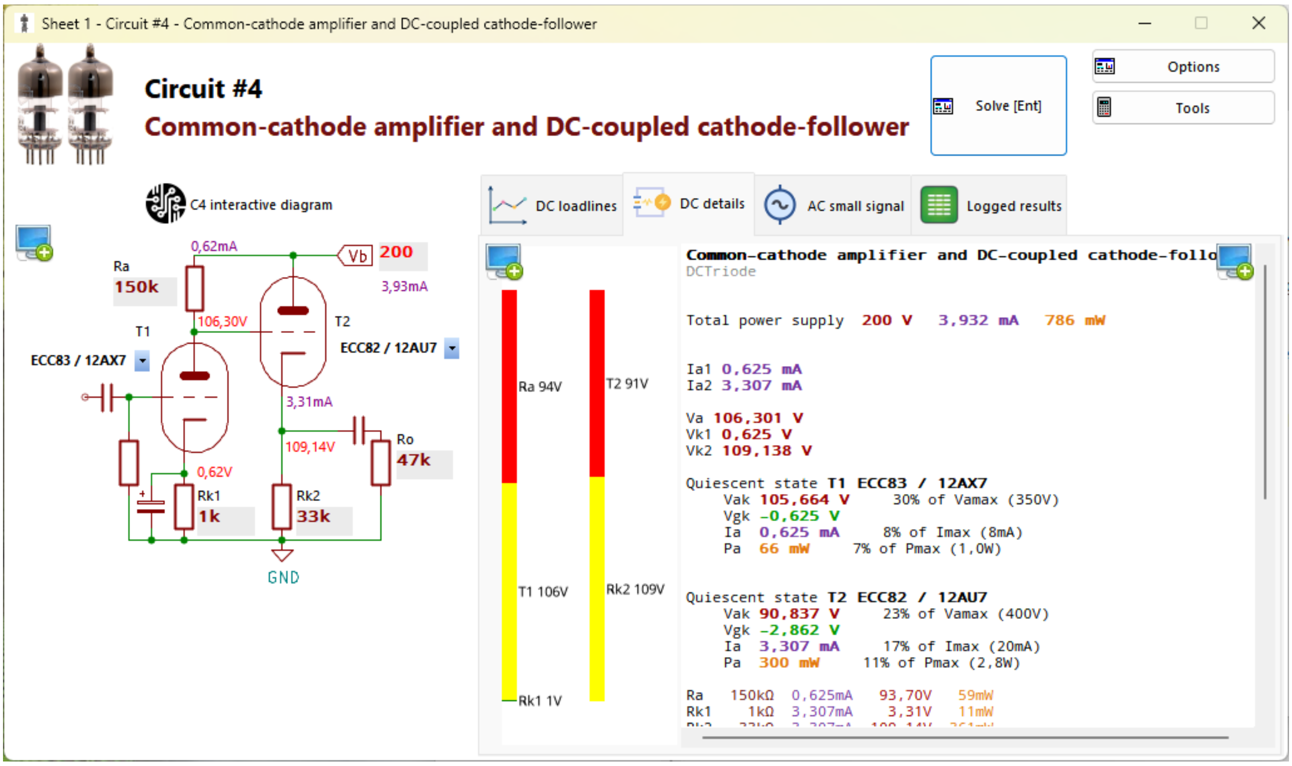


Figure 4: window of circuit "C4" solver once simulated

5.1 Parameterise a circuit

Select the tube type. Depending on tubes count, you may specify either a single tube type or 2 different types. A single choice is natural for differential stages, mixers and cascodes.

Regarding resistors, you parameterise only those having an effect on operating points, i.e. cathode and anode resistors, bridge resistors involved in grid biasing or in DC-coupling, and those impacting bandwidth. Grid leak resistors (pull down resistors) and grid stoppers supposedly have no influence on the operating point, so you cannot assign them a value ; they may even not be represented.

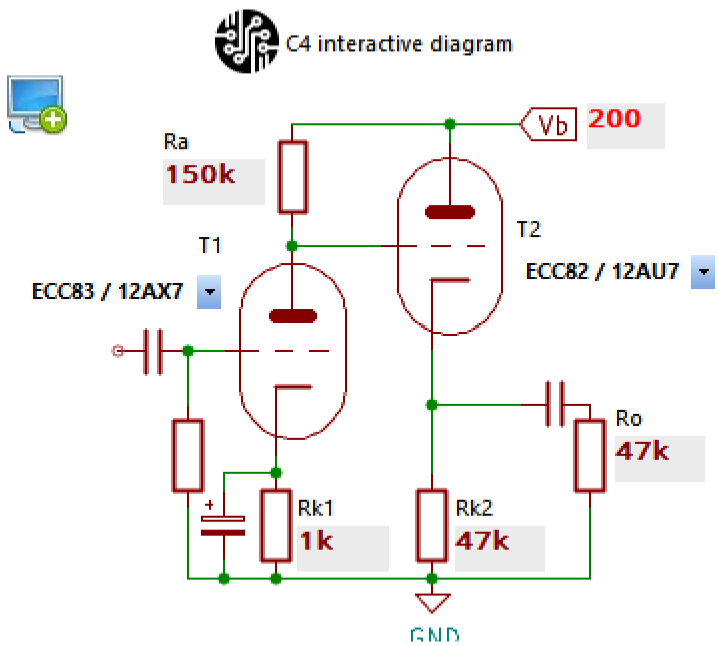


Figure 5: interactive diagram of circuit #4, viewed before simulation

Supply voltage : you may enter any positive number comprised between 0 and 500.

Resistors : enter any positive number, possibly with a decimal separator or a multiplier. Valid multipliers are :

- p : pico 10^{-12}
- n : nano 10^{-9}
- µ : micro 10^{-6}
- m : milli 10^{-3}
- k : kilo 10^{3}
- M : mega 10^{6}

Probably will you use only m, k and M … But do NOT mix multipliers and decimal separator !

Constant current : a few circuits require a constant current source. Specify its current in ampere ; you may use « m » or « µ » as multipliers for respectively mA and µA, rather than decimal numbers.

Bias voltages : some circuits require a common grid bias voltage and/or an offset voltage between grids. Depending on the circuits, those voltages may be positive or negative. Grid offset can always be positive or negative. Do not put too much offset on those stages requiring a differential input as it will diverge…

For those voltages, multipliers like « m » are valid too.

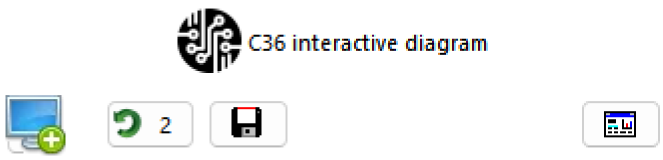
5.2 Cosmetics options for electrical schematics

Click button « Options » to access the few parameters altering the visual aspect of input controls for tube type, resistor, voltage or current.

5.3 Save and reload circuit configurations

You may store a circuit configuration – tube types, components values (resistors), imposed voltages, currents – and reload it later. You may store as many configurations per circuit as wished.

Save a circuit configuration by clicking the small button with a floppy disk icon. You'll be prompted for a name and an optional comment.



For instance, the number 2 in the button indicates there are 2 stored configurations that can be reloaded.

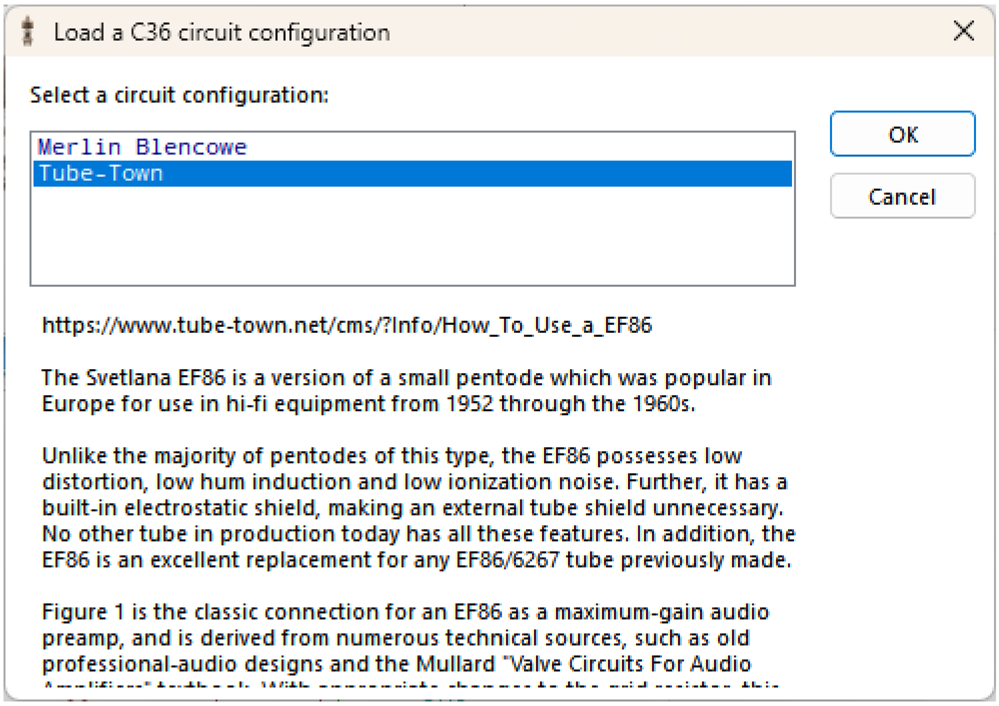


Figure 6: retrieving a recorded configuration for circuit #36

Select here a configuration, which associated comment is visible once you clicked.

Double-click or press OK to open the circuit with that configuration.

This saved configuration can be retrieved later (from the same circuit solver window) by clicking the small button with kind of reload icon.

You may then type a name if this is a new configuration.

If you are updating the configuration, let the name unchanged (just update the comment).

Changing the name will create a new configuration.

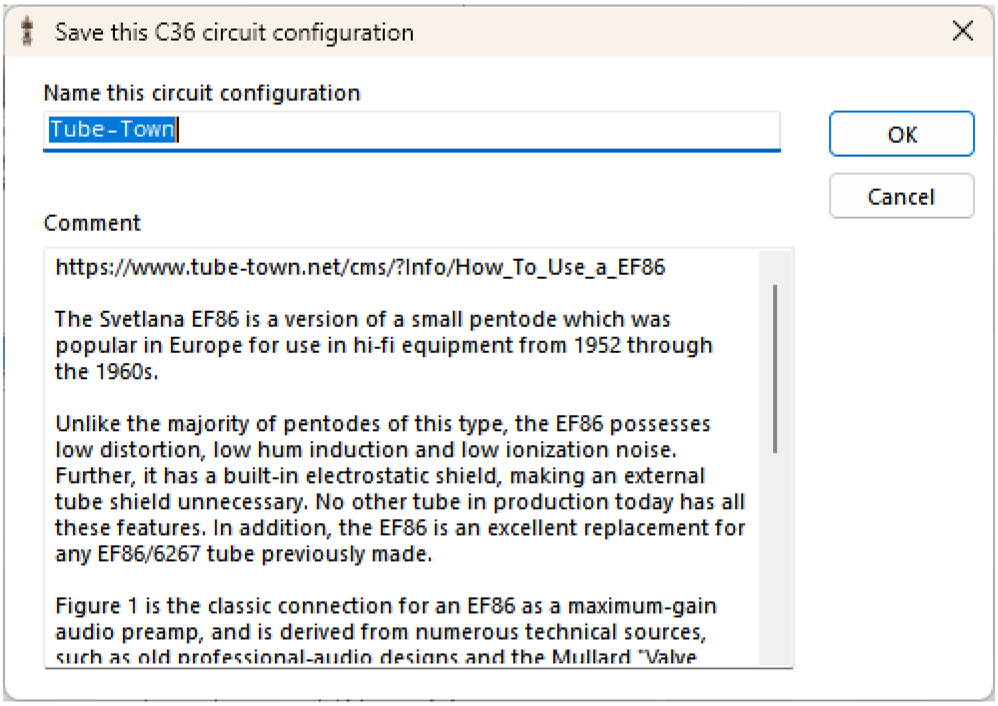
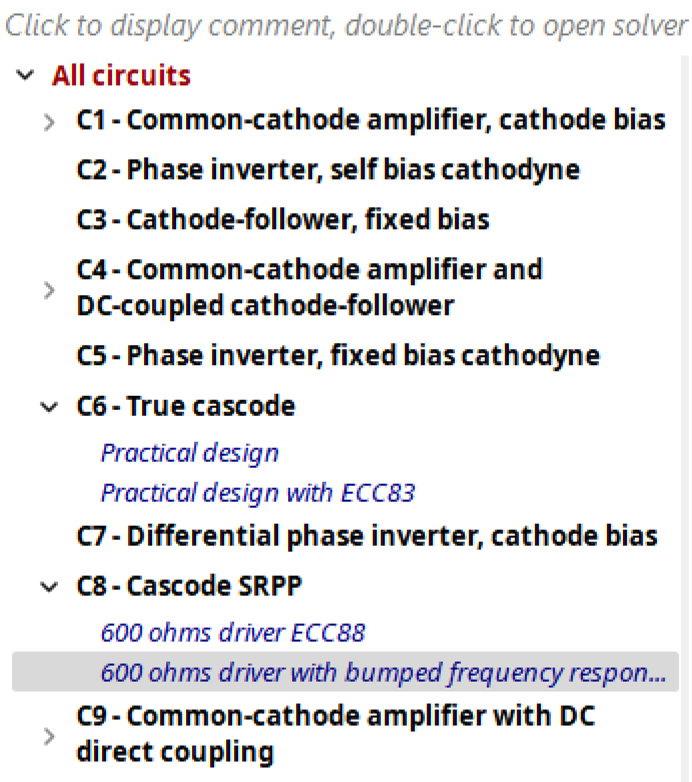


Figure 7: storing a parameters configuration for circuit #36

Alternatively, you may reload a configuration directly from the circuit library, when in « tree »mode ; just expand a generic circuit node to display your custom configurations, and double-click onto one of them.

You may delete a configuration from here, by right-clicking on it ; a menu will pop up for confirmation.



5.4 Get calculated DC data on schematics

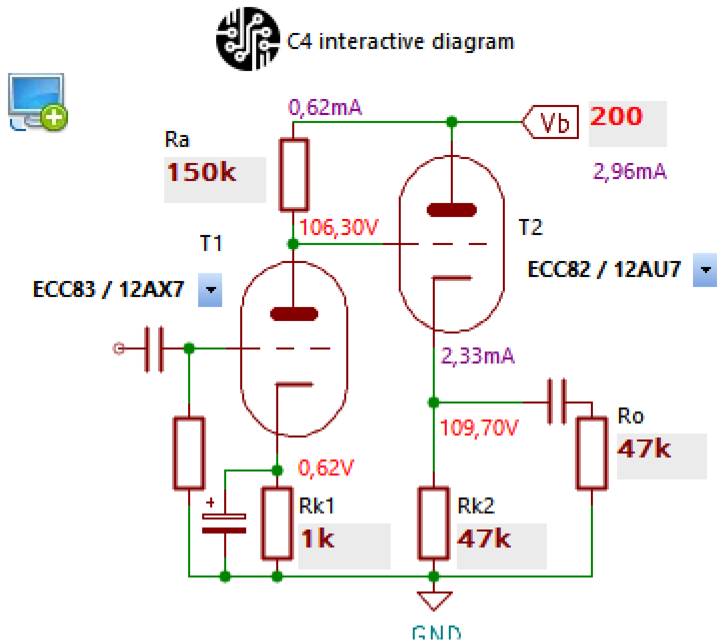


Figure 8: interactive schematics of circuit #4 after simulation

On the electrical schematics are displayed voltages and currents calculated by the solver, easing interpretation of circuit behaviour.

Voltages are coloured in red, currents in purple.

5.5 Get DC simulation results

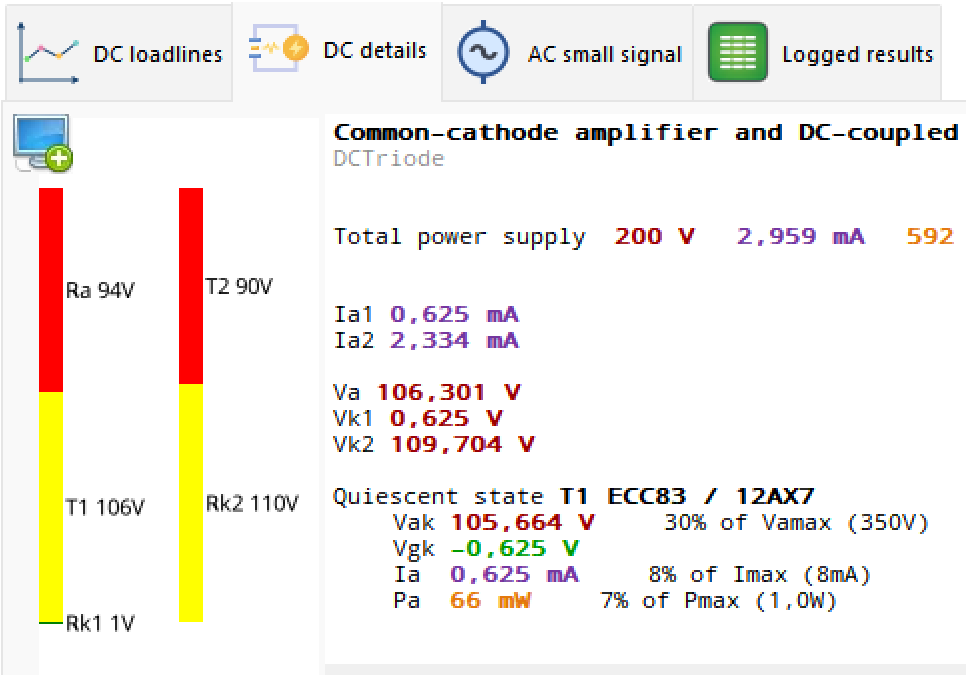


Figure 9: tabsheet of DC results

This tabsheet contains calculated voltages, currents and dissipated powers.

Whilst textual results are self-explanatory, « stacked voltages » may require some indication of what they attempt to figure out : the operating voltages of a single triode with an anode and a cathode resistor will be piled up as 3 segments which lengths are proportional to voltages ; e.g. 1V for voltage across the cathode resistor, 106V for the tube Vak, and 94V across the anode resistor. It instantaneously provides you with a view of the overall operating conditions of a tube.

The sum of voltages of each stack is equal to the supply voltage, here 200V.

5.6 Get AC loadline graph

The loadline graph plots, when relevant (i.e. when functional resistors define precisely the maximum current), the tube operating point on its loadline, and helps figure out how « hot » or « cold » is the bias, with anode curve @ Vgk null, with SOA limits (max cathode current, max anode voltage, max anode power dissipation). These graphs are easily interpretable when a triode behaviour is limited by only anode and cathode resistors.

Colours used in the graph :

- red : SOA limits
- blue : loadline and operating point
- maroon : Ia(Va) @ Vgk = 0V

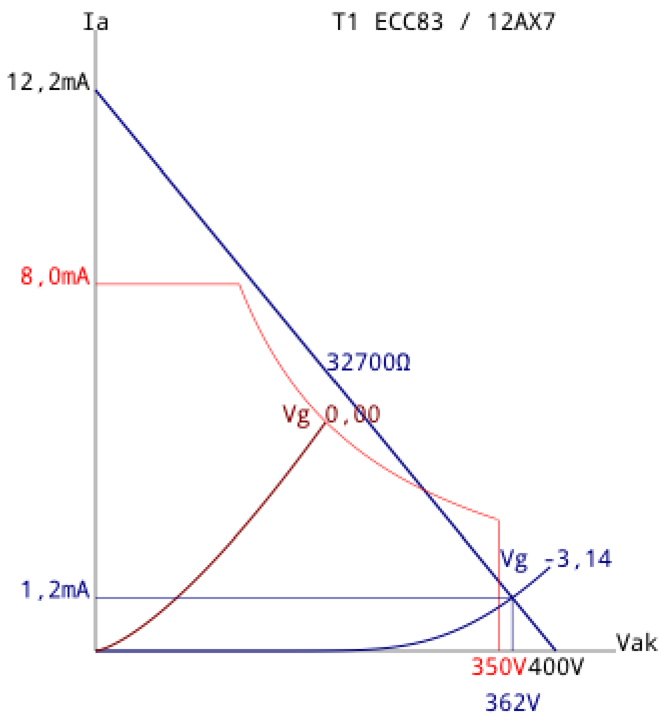
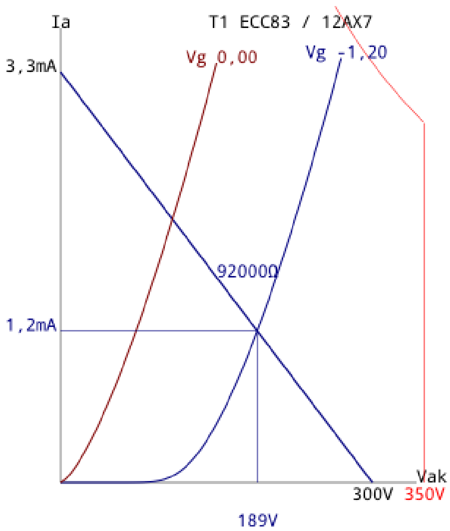


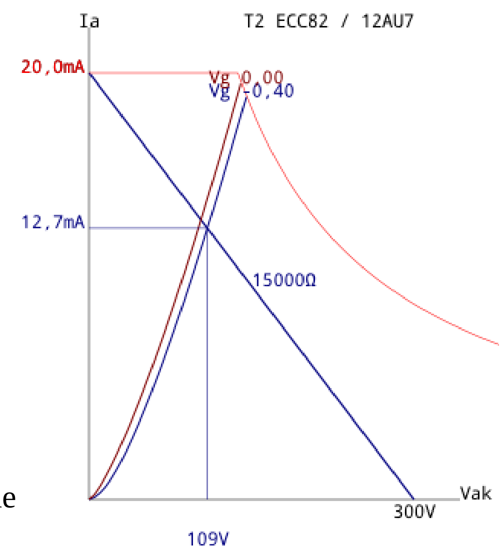
Figure 10: a loadline out of SOA

This example shows a badly biased basic amplifier : too high Vb (400V), too low anode resistor (30k) for a low current device ECC83 ; you see that the quiescent DC operating point is outside the SOA.

Pictures below show circuit « C4 » gain stage and a DC-coupled cathode follower under 300V. The T1 ECC83 amplifier is correctly biased, whilst T2 ECC82 follower is quite « hot » with a low 15k resistor..



For the circuits



Where the loadline either has no sense or cannot be easily calculated, it is simply not drawn, and the current upper limit of the graph is the maximum current (as stated in its SOA constants).

5.7 Get AC small-signal results

Most solvers provides you with some calculations of small signal voltage gain and output impedances.

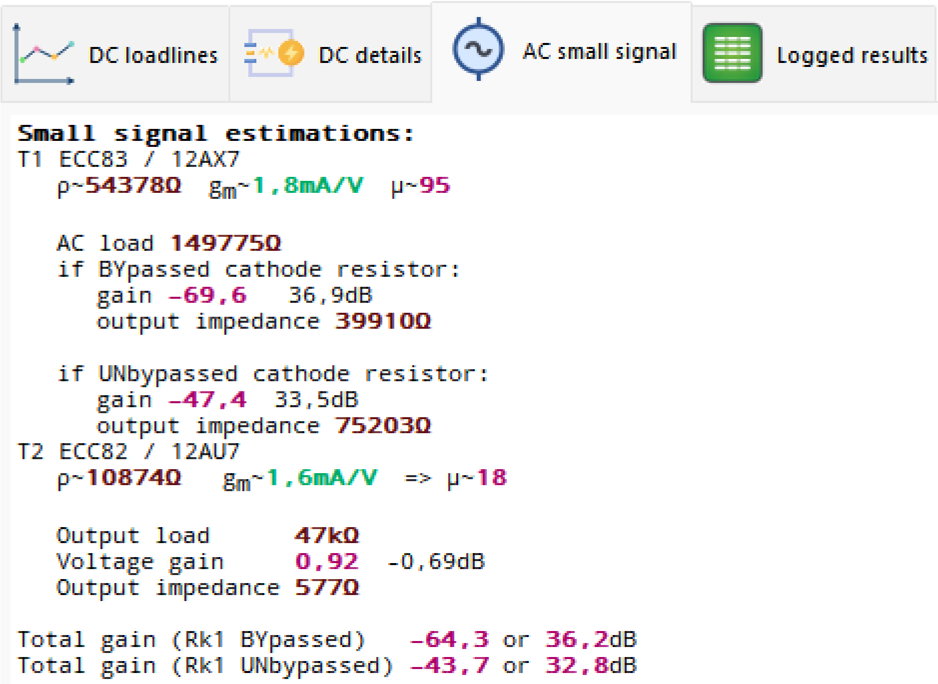


Figure 11: tabsheet of AC small-signal results

5.8 Get bandwidth estimate

This tabsheet contains the Bode plot of gain vs frequency. Below is the plot for circuit #4, five curves are visible :

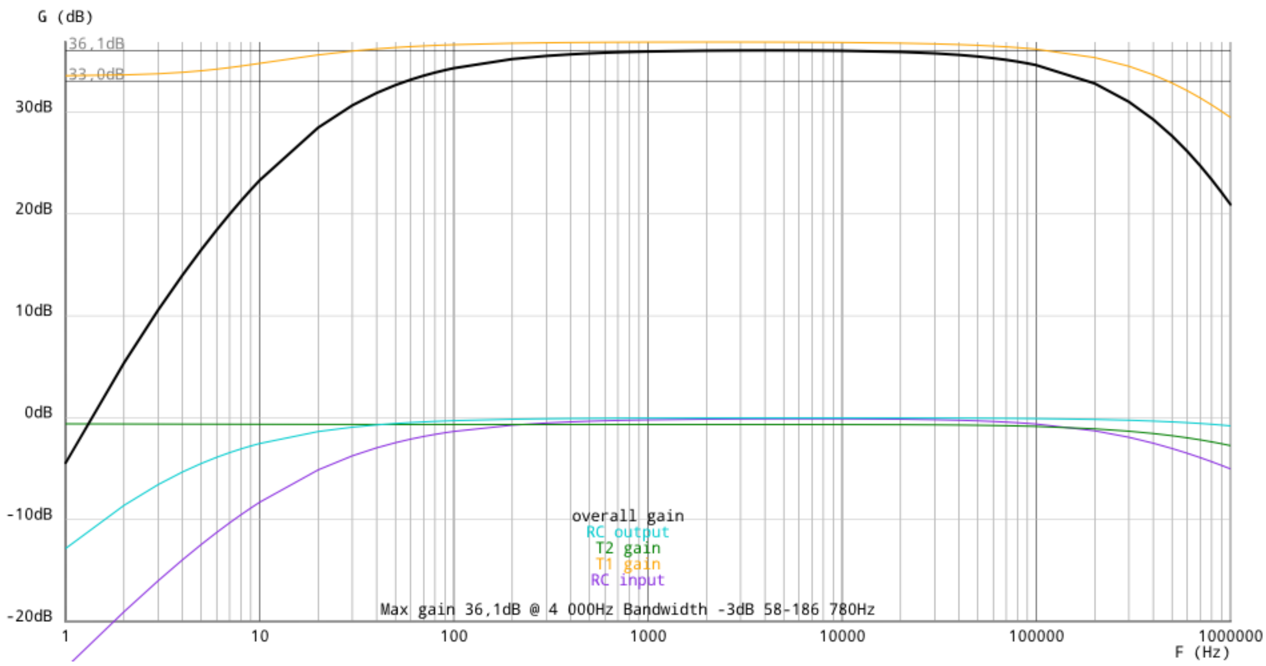


Illustration 5.1: Bode plot of C4 circuit frequency response from 1Hz to 1Mhz

- the voltage transfer of the input RC network (see § 12.1), always lower or equal to 1
- the common-cathode tube T1 gain (see § 12.5),
- the cathode-follower tube T2 gain, lower than 1,
- the voltage transfer to output RC load (see § 12.2)
- and the resulting overall voltage gain : 36.1dB max, the -3dB bandwidth being approximately 58 to 186kHz.

The bandwidth is indicated when an overall gain makes sense, i.e. when all quadripoles have a unique output.

The frequency at which peaks the overall gain (when it exists) is approximative [1].

The low and high limits (-3dB below the max gain) are reasonably credible for most circuits and configurations but are sometimes totally wrong [2]. Meanwhile can you reasonably trust the graph.

1 Specially when the response is wide and flat, and definitely when feedback is simulated, a fine tolerance trade-off has to be found for the Newton-Raphson algorithm to find the point where the derivative is null.

2 Also depending of the slopes of gain, the algorithm (successive approximations or Newton-Raphson) should use a variable tolerance criterion… Not done for now.

5.8.1 Options to calculate and display the frequency response

A set of options alters the way gains are computed and plot is displayed. Click the banner to access them :

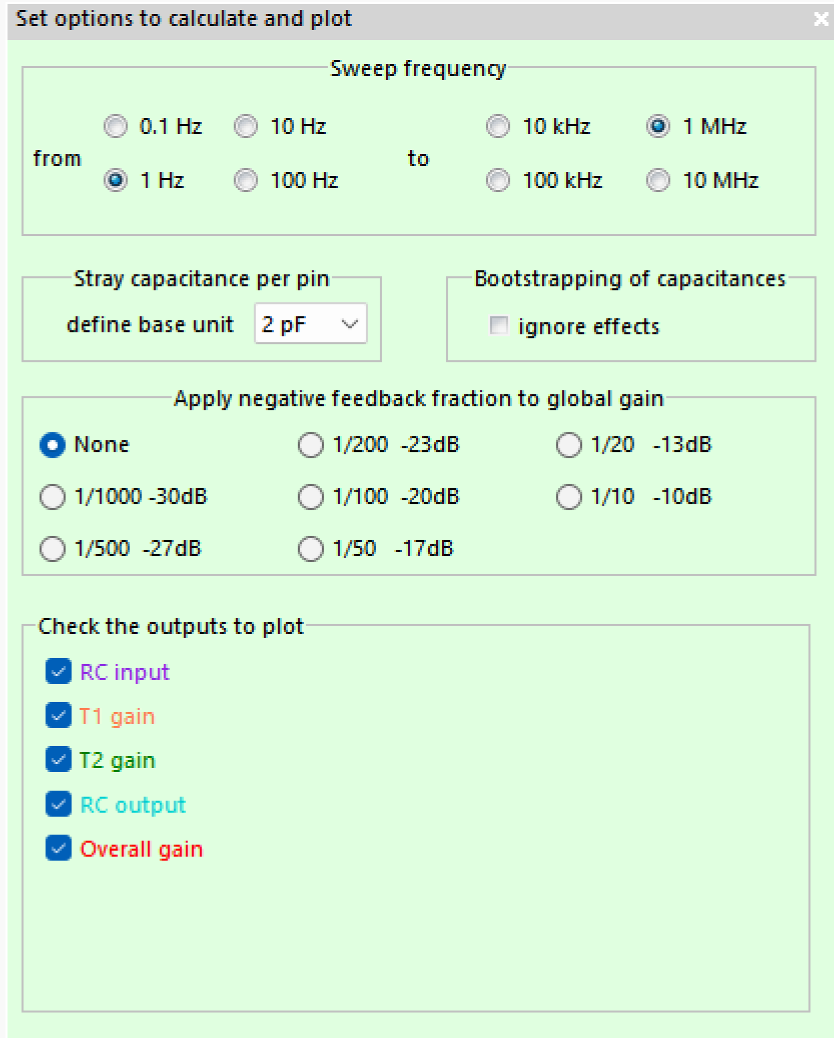


Illustration 5.2: Options to calculate frequency response and displaying it

- Set frequency interval : can be set from 0.1, 1 or 10Hz to 100kHz or 10MHz.
- Select a stray capacitance unit, from 1 to 5pF, see below.
- Checkbox « ignore capacitance bootstrapping » : if you check it, the solver plotter will not take into account the grid-cathode Miller effect (as well as the reduction of Cgk on cathode-follower, even though this will have very little impact on the frequency response).
- Feedback : you may apply a feedback fraction (ratio of output voltage injected into first gain stage) ; it will flatten frequency response. Values range from 1/1000 to 1/10.
- Several checkboxes, all checked by default ; when checked, corresponding outputs will be plotted. Uncheck those you do not want to see plotted.

5.8.2 Taking into account stray capacitance

Because of the high impedances of tube setups, parasitic capacitances play an actual role in frequency response of audio vacuum tube amplifiers ; just consider the RC circuit of 470kΩ and 20pF, leading to the specific frequency $1/2\pi RC \sim 17$kHz.

You may define stray capacitances on significant nodes : grid and anode of tube, inside some critical RC filters. It may have influence on the grid if there is a high grid stopper resistor ; it may have influence on the anode load if the anode resistor is high, or in case of a DC coupling.

What you choose here is the capacitance unit, which is used to set the stray capacitance per node, multiplying it by the count of connected pins to this node.

For instance, let us say you selected 2pF as unit ; for an anode grid, connected to a grid stopper RC low-pass filter, 3 pins are connected to this node : 1 grid, 1 resistor and 1 capacitor ; so the stray capacitance on this node is set to 6pF ; the solver will also take into account Cgk and the Miller effect (depending on the gain of tube).

5.8.3 Miller effect

How does the software simulate Miller effect ? When the above described checkbox « ignore effects » is unchecked (by default), the Cga parasitic capacitance of the triode is seen on the grid with a higher value $bootstrapped\, C_{ga} = C_{ga}(A+1)$ with A being the module of intrinsic gain between anode and grid. This pseudo capacitance is then taken into account into the device input impedance.

You may see its effect on the frequency response in the Bode diagram, and on the « Zin » presented by the triode-quadripole. The effect is particularly visible in the circuits where the triode is driven through a grid stopper low-pass filter. On circuit where the grid is driven without such an attenuating resistor, you will see that input impedance is lowered, even though the frequency response does not seem altered, this is because the input is supposedly driven by a null or very low impedance, able to maintain voltage on a capacitor whatever the frequency is.

5.8.4 Applying negative feedback

The calculation is basic : for every point of frequency, the overall gain obtained is modulated as follows :

$$Af = \frac{A}{1+k.A}$$

k being the feedback fraction (of output signal) being injected into the first gain stage, A being the module of open loop gain.

The result is of course theoretical : it does not care about the way signal is reinjected, about its phase, and phase shifts do not exist for it !

5.8.5 Displaying gain and input impedance of quadripoles

See gain and Zin @ frequency

75	Type	Frequ.	Gain x	Gain dB	Zin
RC input	RC-in	1kHz	0,98	-0,2dB	609,9 kΩ
T1	Cat-com	1kHz	55,62	34,9dB	1,8 MΩ
RC output	RC-out	1kHz	1,00	0,0dB	708,3 kΩ
RC input	RC-in	1Hz	0,06	-24,6dB	16,9 MΩ
T1	Cat-com	1Hz	28,01	28,9dB	4680,1 MΩ
RC output	RC-out	1Hz	0,26	-11,7dB	3,8 MΩ
RC input	RC-in	10Hz	0,39	-8,3dB	2,6 MΩ
T1	Cat-com	10Hz	32,83	30,3dB	409,9 MΩ
RC output	RC-out	10Hz	0,78	-2,2dB	1,3 MΩ
RC input	RC-in	100Hz	0,86	-1,3dB	1,1 MΩ
T1	Cat-com	100Hz	51,69	34,3dB	27,6 MΩ
RC output	RC-out	100Hz	0,97	-0,2dB	1,0 MΩ
RC input	RC-in	1kHz	0,98	-0,2dB	700,2 kΩ
T1	Cat-com	1kHz	55,83	34,9dB	2,6 MΩ
RC output	RC-out	1kHz	1,00	0,0dB	825,5 kΩ
RC input	RC-in	10kHz	0,99	-0,1dB	188,5 kΩ
T1	Cat-com	10kHz	47,02	33,4dB	300,2 kΩ
RC output	RC-out	10kHz	1,00	0,0dB	143,5 kΩ

Illustration 5.3: Gain and input impedance of quadripoles

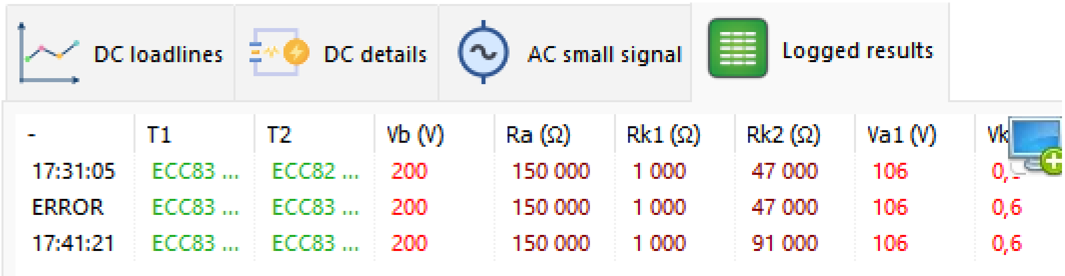
Click the banner « See gain and Zin @ frequency » to display the gain and input impedance of all quadripoles involved in frequency response computing. Blocks are listed from input to output for a set of 6 frequencies, the first being the one at which the overall gain is maximum.

Gain is expressed by its module and in decibel. The last column Zin is the impedance presented by the block to the preceding one (or the input impedance for the « RC input » passive block).

5.9 Successive results are stored for spreadsheet

The last tabsheet displays a table where are stored most values (circuit parameters, voltages, currents, powers), simulation after simulation.

You may copy those result with the « Copy to clipboard » button, and paste them into a spreadsheet.



-	T1	T2	Vb (V)	Ra (Ω)	Rk1 (Ω)	Rk2 (Ω)	Va1 (V)	Vk
17:31:05	ECC83 ...	ECC82 ...	200	150 000	1 000	47 000	106	0,[illegible]
ERROR	ECC83 ...	ECC83 ...	200	150 000	1 000	47 000	106	0,6
17:41:21	ECC83 ...	ECC83 ...	200	150 000	1 000	91 000	106	0,6

Figure 12: tabsheet of tabulated data (DC and AC) to be copied and pasted into a spreadsheet

The first column contains « ERROR » in case the simulation did not converge.

5.10 Single-ended power stages

DCTriode version 2.1 deals with SE stage, made of triode or pentode/tetrode, which can be parallelised. Two circuits (C37, C38) contains 1 to 4 tubes in parallel, an audio output transformer, voltages sources for grid bias (C37, C38) and screen bias (C38 only), a cathode resistor.

The cathode resistor and the transformer primary ohmic resistance (if not null) are used to compute the DC steady state of the tube(s). The cathode resistor is supposed to have no influence on the AC operation, as shorted by a very large capacitor.

5.10.1 Parameters

You parametrise the circuits as follows:

- supply voltage; e.g. 300V
- fixed grid bias voltage; it can be set to zero if you use a bias cathode resistor; otherwise, you enter a negative number; e.g. -35V
- fixed screen grid voltage (if any); e.g. 200V
- cathode resistor (can be null); e.g. 100Ω
- output transformer: primary impedance (e.g. 3500Ω, power yield (max 100%), primary ohmic resistance (can be null), e.g. 100Ω
- and of course, tube type, number of parallel tubes (1 to 4)

Output consists in:

- quiescent current(s) and voltages, power drain
- graph of dynamic loadline
- graph showing output power on the load, average supply current, power yield, vs grid input swing volt by volt
- display of output waveform, as a function of grid swing from zero to ±Vgbias

Like for all other DCTriode circuits, output results reflect your set of input parameters but do not suggest any optimisation paths. For power stages, it is up to you to tune your circuit by observing loadline changes, power output and waveform. Of course, outputs are based on the ia(va,vg) points calculated by the Norman Koren modelling, used in simplified equations.

Waveforms and power levels are computed for an interval of grid input swing ranging from 0 (i.e. vg = Vgbias) to maximum swing (vg null = Vgbias +swing max) or |Vgbias| (very negative vg = 2xVgbias).

5.10.2 How is it computed?

Again, DCTriode is not a black-box with obscure or hidden methods and formulas; understanding the way it computes results will certainly help you seize its fundamental limitations and biases.

Once the DC quiescent state is computed, DCTriode performs iterative calculations and draws 2 graphs:

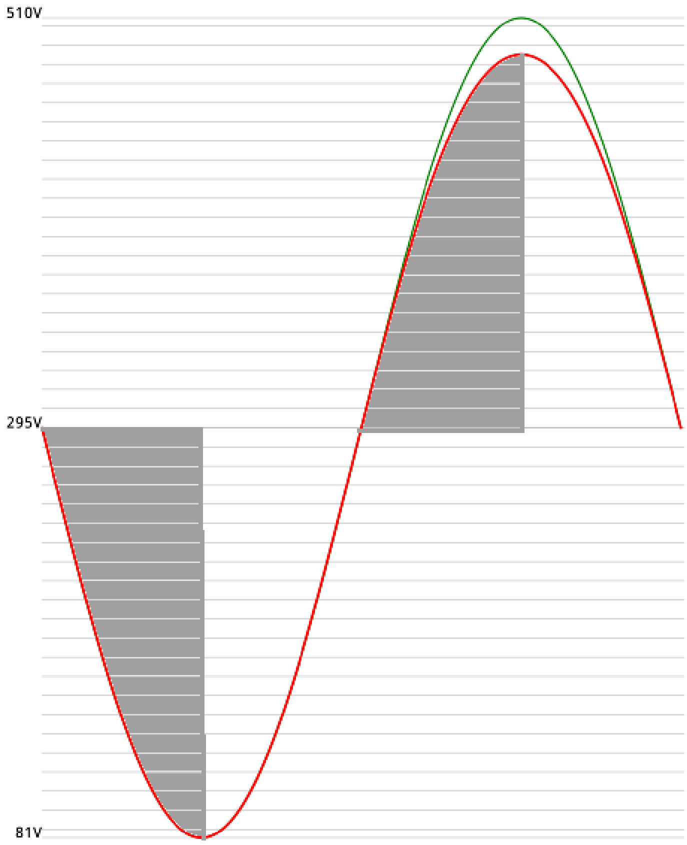
- draws the AC loadline, taking into account only the transformer impedance at primary;
- simulates the effect of sine inputs peaking from ±1V to ±Vgbias by 1V steps, using Norman Koren's equations for triode or tetrode/pentode; it allows to draw the output waveform on anode (current or voltage) for all those input voltages; for every cycle, 100 points are calculated (a lower number does not change significantly the power integration, but degrades graphs visual quality).

For each step of input drive, DCTriode computes:

- the average output power delivered to the load, equal to the AC power delivered to transformer primary multiplied by the transformer yield; it is computed by integrating the waveform as small surfaces;
- the average anode current;
- the electrical power yield, equal to the power available on transformer secondary divided by the total supply power (average anode current plus screen grid current if any).

Of course, those calculations are simple and just deliver estimations; distortion factor and levels of harmonics are not taken into account, simply because I cannot calculate them from the waveforms! However, the waveforms provide you with a basic but visual estimation of distortion.

The maximum power indicated in the graph is calculated for the maximum swing and corresponds for sure to a strong distortion.



Actually, the program computes only two half-waves of each phase (displayed here in gray), supposing that half-waves of same polarity are totally symmetrical (which might not be the case in real world).

The output power is calculable by adding absolute values:

P = 2.P1 + 2.P2, with Z being the transformer impedance:

$$P1 = \int_0^{\frac{pi}{2}} \frac{dv^2}{Z} dt$$

and

$$P2 = \int_{pi}^{\frac{3pi}{2}} \frac{dv^2}{Z} dt$$

If *vao* and *iao* are the quiescent anode voltage and current, DCTriode sums all surfaces $S = |(va - vao)(ia - iao)|$ and divides this sum by the total number of “sampled” points: P = S /2n

An effect is not taken into account: the increase of average current caused by increasing swing alters the bias voltage if a cathode resistor is present. If the decoupling capacitor is large enough, it translates in a more negative grid-cathode voltage, hence changing the average bias conditions. This effect on actual bias is not taken into account by DCTriode.

Note that this effect is caused by the non linearity of the tubes: for a plus or minus Vgk variation of same module, the current variation is larger for the positive Vgk variation, because the transconductance generally increases with current.

Transformer primary ohmic resistance and cathode resistor are taken into account for calculating the DC operating point, but are NOT for calculating output power; the cathode resistor is then considered as perfectly bypassed by a capacitor.

You may of course question this method and prefer another one. Nevertheless, have a look at the next table showing the power indicated in Western Electric 300B datasheet of 1939, onto which are added in green the data (Ia and Pout) obtained with DCTriode using the NK model of 300B. It shows that DCTriode delivers a non-stupid estimation (Ia equal or slightly above, Pout slightly inferior, in most cases):

TABLE

	Plate Voltage Volts	Grid Bias Volts	Plate Current Milliamperes		Load Resistance Ohms	Power Output Watts	
Recommended Operating Conditions	200	— 42	30	35	2000	3.0	4.2
	200	— 39	40	43	2500	2.6	4.3
	200	— 37	50	52	2500	2.5	4.2
	250	— 55	30	40	2000	4.9	3.5
	250	— 55	30	30	4500	3.2	2.8
	250	— 52	40	43	3000	4.0	3.5
	250	— 50	50	53	2500	4.4	3.8
	250	— 48	60	63	2000	4.7	4.1
	250	— 48	60	61	2700	4.1	3.7
	250	— 45	80	80	1500	5.0	4.4
	300	— 65	40	49	2500	6.7	6.4
	300	— 63	50	58	2000	7.2	6.8
	300	— 63	50	53	3000	6.1	6.5
	300	— 61	60	63	2400	6.6	6.8
	300	— 61	60	60	3400	5.6	6.4
	300	— 58	80	80	1700	7.5	7.3
	350	— 76	50	53	3600	7.8	6.6
	350	— 76	50	50	5000	6.2	5.8
	350	— 74	60	69	2000	10.2	8.2
	350	— 74	60	62	3000	8.3	7.4
	350	— 74	60	60	4000	7.0	6.6
	350	— 71	80	79	2200	9.6	8.6
	400	— 91	40	44	5000	8.4	7.5
	400	— 89	50	58	3000	11.5	8.5
	400	— 89	50	53	4000	9.4	8.1
	400	— 87	60	62	3500	10.5	8.5
	400	— 87	60	59	5000	8.3	7.9
	400	— 84	80	80	2500	12.5	9.3
Maximum Operating Conditions	450	—104	40	44	6000	9.5	8.1
	450	—102	50	52	5000	10.7	9.3
	450	—102	50	50	6500	9.0	8.2
	450	—100	60	63	4000	12.5	10.7
	450	—100	60	59	5500	10.1	9.3
	450	— 97	80	89	2000	17.8	14.2
	450	— 97	80	79	3000	14.6	12.7
	450	— 97	80	74	4500	11.5	10.6

Right table indicates in green the no-signal, full-signal currents and power output obtained by DCTriode for a single 5881 in class A1 against the figures of Tung-Sol datasheet. Not bad at all, isnt'it?

TYPICAL OPERATING CONDITIONS AND CHARACTERISTICS

CLASS A_1 AMPLIFIER – SINGLE TUBE

PLATE VOLTAGE	250		300		350		VOLTS
GRID #2 VOLTAGE	250		200		250		VOLTS
GRID #1 VOLTAGE	−14		−12.5		−18		VOLTS
PEAK AF SIGNAL VOLTAGE	14		12.5		18		VOLTS
TRANSCONDUCTANCE	6 100		5 300		5 200		µMHOS
PLATE RESISTANCE	30 000		35 000		48 000		OHMS
ZERO–SIGNAL PLATE CURRENT	75	75	48	46	53	50	MA.
ZERO–SIGNAL GRID #2 CURRENT	4.3		2.5		2.5		MA.
MAXIMUM SIGNAL PLATE CURRENT	80	80	55	51	65	60	MA.
MAXIMUM SIGNAL GRID #2 CURRENT	7.6		4.7		8.5		MA.
LOAD RESISTANCE	2 500		4 500		4 200		OHMS
POWER OUTPUT	6.7	7.0	6.5	6.9	11.3	11.2	WATTS
TOTAL HARMONIC DISTORTION	10		11		13		PERCENT

Right table is similar but relates to 6550 Tung-Sol datasheet:

TYPICAL OPERATING CONDITIONS

CLASS A1 AUDIO AMPLIFIER – SINGLE TUBE

PLATE VOLTAGE, DC	250		400		VOLTS
GRID 2 VOLTAGE, DC	250		225		VOLTS
GRID 1 VOLTAGE, DC	−14		−16.5		VOLTS
PEAK SIGNAL VOLTAGE	14		16.5		VOLTS
ZERO-SIGNAL PLATE CURRENT, DC	140	144	87	84	MA.
MAX. - SIGNAL PLATE CURRENT, DC	150	150	105	99	MA.
ZERO-SIGNAL GRID 2 CURRENT, DC	12		4		MA.
MAX. - SIGNAL GRID 2 CURRENT, DC	22		14		MA.
LOAD RESISTANCE	1500		3000		OHMS
TOTAL HARMONIC DISTORTION, APPROX.	7		13.5		PERCENT
MAX. - SIGNAL POWER OUTPUT	12.5	12.4	20	20.1	WATTS

Under certain conditions, you may see a power yield superior to 50%, when the theoretical maximum for class A single ended amplifier is 50%; in those cases, you probably biased the tube too cold (Vgk too negative), making it operate closer to class B even C rather than class A!

5.10.3 Output waveforms

The graph displays the shapes of anode voltage or current or both over a cycle. Reflecting the input voltage, a thin pure sine wave is added as a reference to what the output signal would be if the amplifier was perfect.

Next graphs show the anode voltage of a 6550 biased at Va=400V and Vgk=-16,5V; first image corresponds to the maximum grid swing. Horizontal lines are 50V or 10mA spaced.

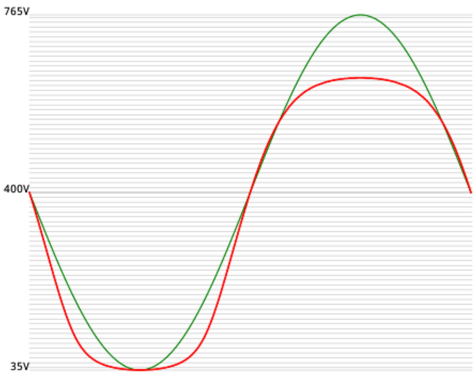
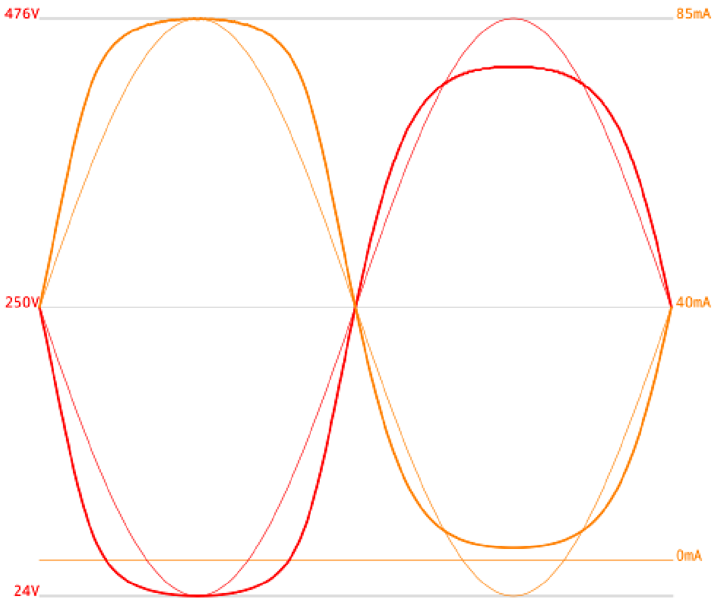


Illustration 5.4: anode waveform for a 16V grid swing

Illustration 5.5: anode waveform for a 5V grid swing

Both ia va curves are available on a single graph:

It corresponds to an EL84 biased under Vb=250V, Vgk=-7V and Ia=40mA, with a ±7V peak grid input.



5.10.4 AC loadline

This graph draws the AC loadline of the amplifier. In orange is pictured the loadline, in light blue is the DC operating point; in dark red is the anode current at Vgk null; in blue is the anode current at Vgbias.

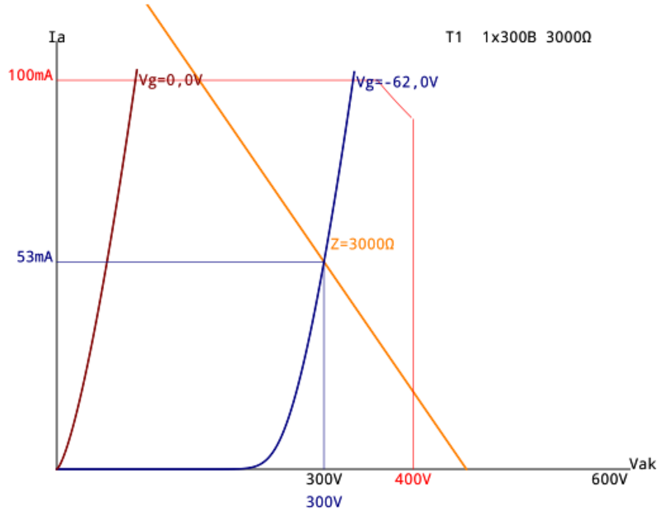


Illustration 5.6: Triode AC loadline: 1x300B under 300V bias -62V, with 3000Ω load

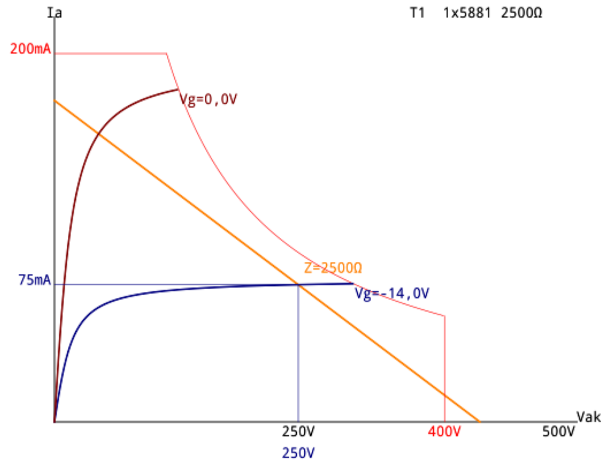


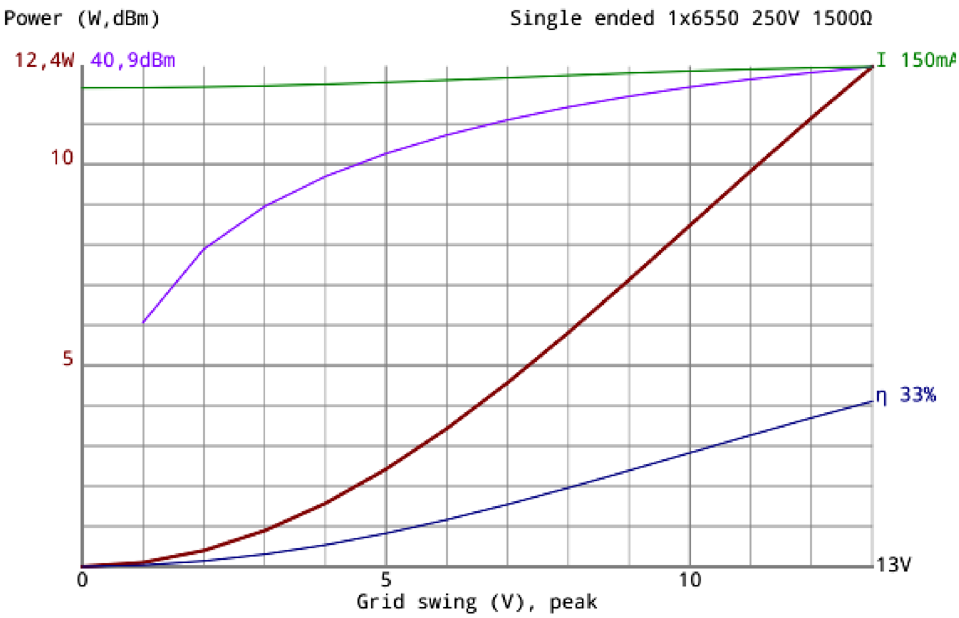
Illustration 5.7: Pentode 5881 AC loadine, under 250V, -14V bias, with 2500Ω load

As a reminder, the SOA red limits are:

- the maximum anode (~cathode) current ; it is not always easy to figure out what the actual value may be;
- the hyperbolic section delimited by the anode power: it is effectively important that the DC operating point remains inside this boundary;
- the maximum anode-cathode voltage: not so important, because this data is not always well documented in the datasheet (sometimes it is an absolute max rating, sometimes a DC operating value). Anyway, the anode voltage can go quite high, theoretically twice the supply voltage depending on the bias conditions, but it is generally not an issue.

5.10.5 Output power, average current, power yield

This graph displays the output power (red curve in W and purple curve in dBm), the anode current (mA) and the power yield as a function of the input grid swing.

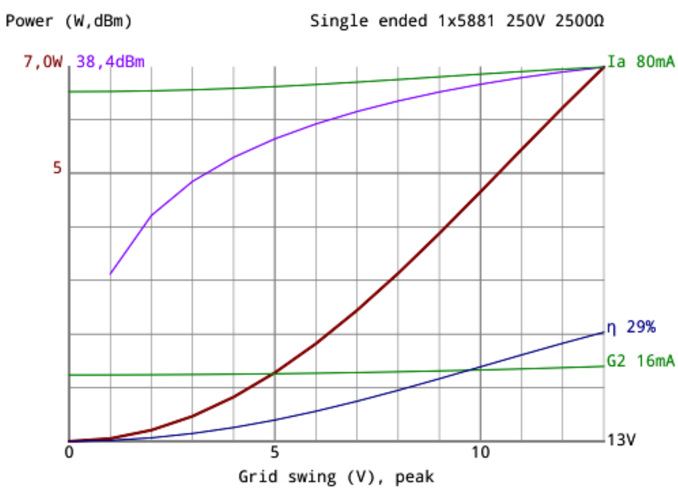


The max grid swing is oftentimes rounded to the preceding volt; e.g. if the bias voltage is -14V, the peak voltage grid will be ±13V.

The yield scale is 0 to 100%.

The current scale is determined by the max average anode current.

For tetrodes / pentodes, the average screen current is displayed. This graph displays Pout, Ia, Ig2, yield, their maximum values being obtained for 13V swing: 7,0W, 80 and 16mA, 29%.



6 Drawing anode curves

The window contains 3 tabsheets, labelled « Anode curves », « gm, ρ, µ », « All calculated points ».

Select a tube reference to display its anode curves, with either Vgk (grid curves) or Vak (mutual characteristics) as parameter.

6.1 Draw curves Ia (Va, Vg)

This is the first tabsheet « Anode curves ». Click in the graph to display specific operating point : data will appear in a green container if the clicked point lays within the SOA (Safe Operating Area), in a red container if outside SOA.

A button copies the graphic image to the clipboard.

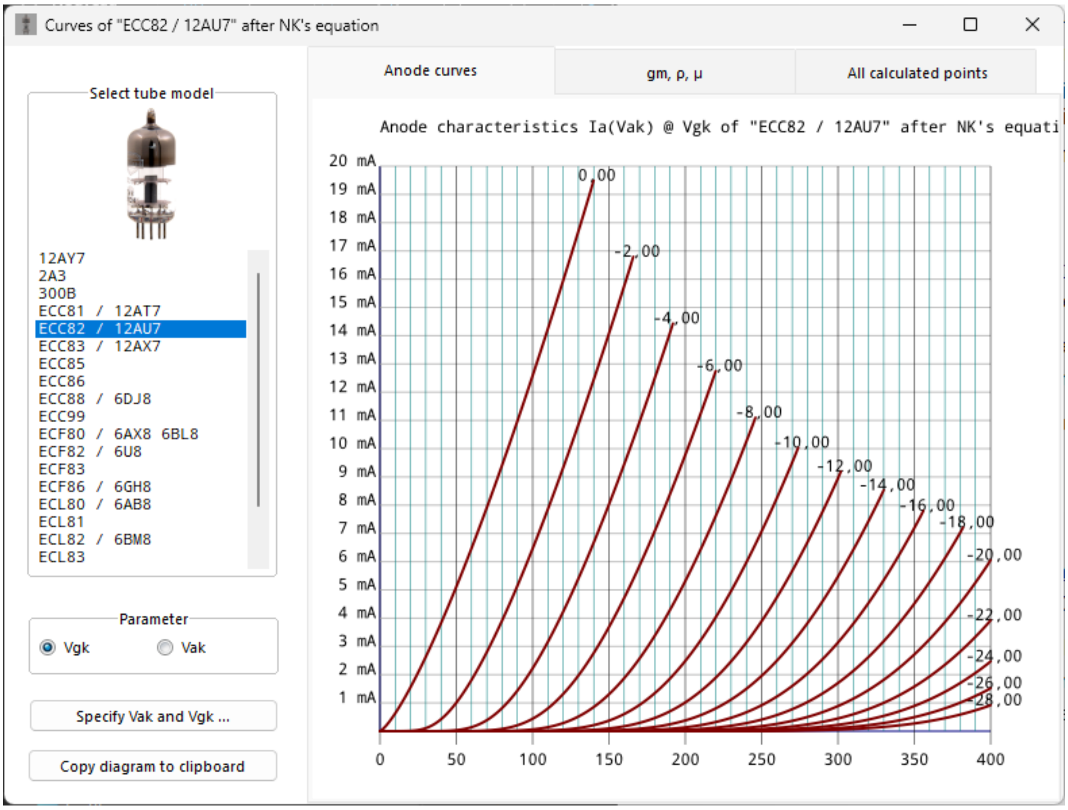


Figure 13: Ia(Vak) with Vg as parameter

A button « Specify Vak and Vgk » allows you to enter any couple of Vak/Vgk values and get the corresponding anode current as well as anode power (mW) and estimations of internal resistance (Ω), of transconductance (mA/V) and amplification factor µ.

Vgk must be entered with a minus sign, as a real number.

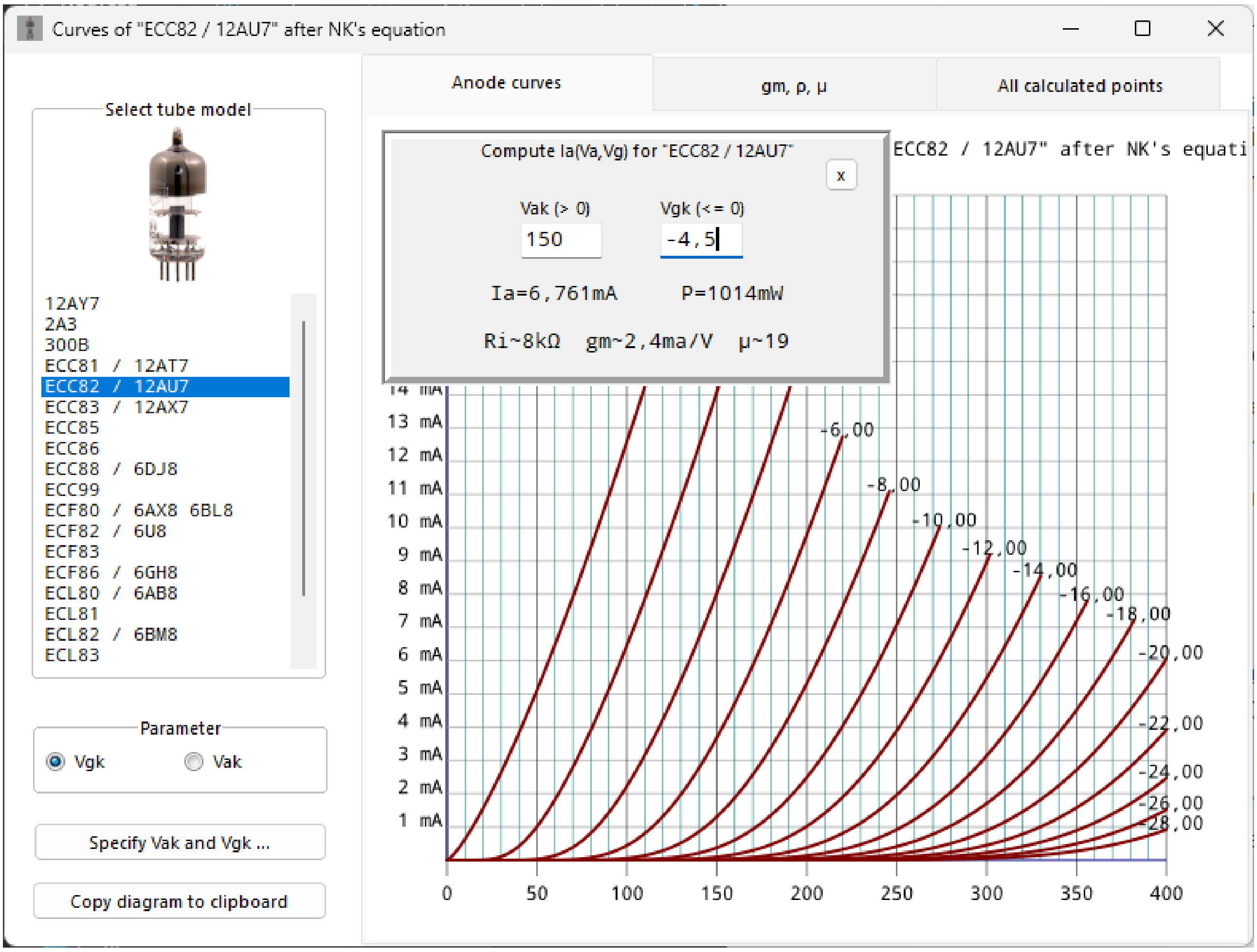


Figure 14: displaying a specific operating point

All above data is computed after Norman Koren’s equation.

Internal resistance is computed by sweeping Vak of ±1V at constant Vgk. Transconductance is computed by offsetting Vgk of -10mV at constant Vak.

For all graphs, the X,Y scales are computed after SOA limits, i.e. maximum anodic current and maximum anodic voltage, and a reasonable interval of Vgk.

Both the drawing of anode curves and the edition of tube model parameters are floating windows, enabling you to easily tune parameters and see their impact.

For pentodes only, a textbox appears for you to enter a reasonable screen-cathode voltage, which remains constant while Vak and Vgk are modulated.

By clicking into a « valid » area of the graph, you get the local operating point, with a green background (as shown below) when the point is within the SOA, or red when outside SOA :

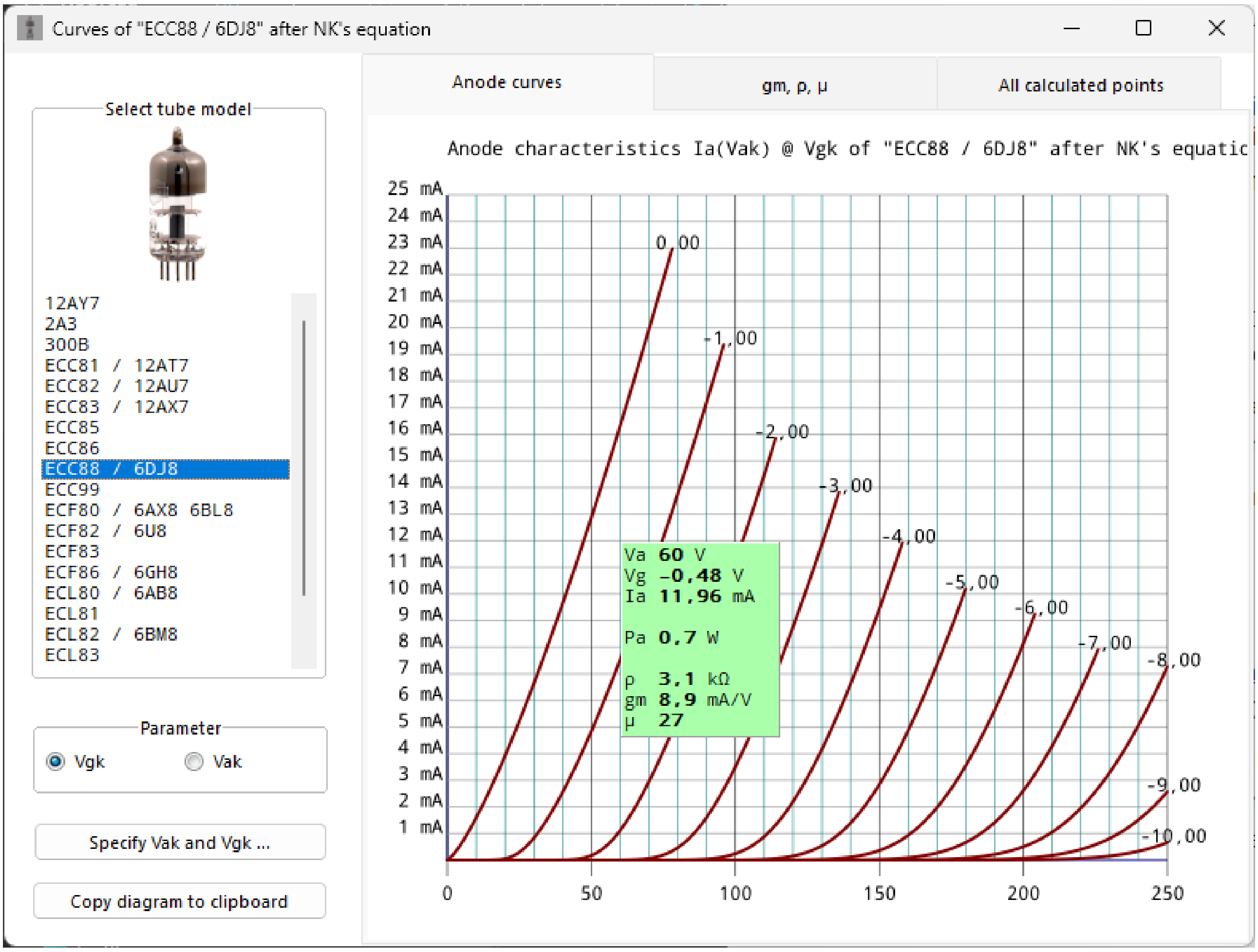


Figure 15: click into the curves area to display the specific operating point characteristics

6.2 Draw transconductance, internal resistor, amplification factor

The second tabsheet contains a graph displaying :

- the transconductance g_m in mA/V, on purple left vertical axis
- the internal resistance in kΩ, on green right vertical axis
- the amplification factor, $\mu = Ri \cdot g_m$; the μ fixed scale is 0 (bottom) to 100 for triodes or 1E4 for pentodes (top), no legend being drawn.

Those sets of 3 curves are computed for 3 anode voltages : 100, 200 and 300V.

Curves are truncated when anode current cannot be sustained at a certain V_{ak}.

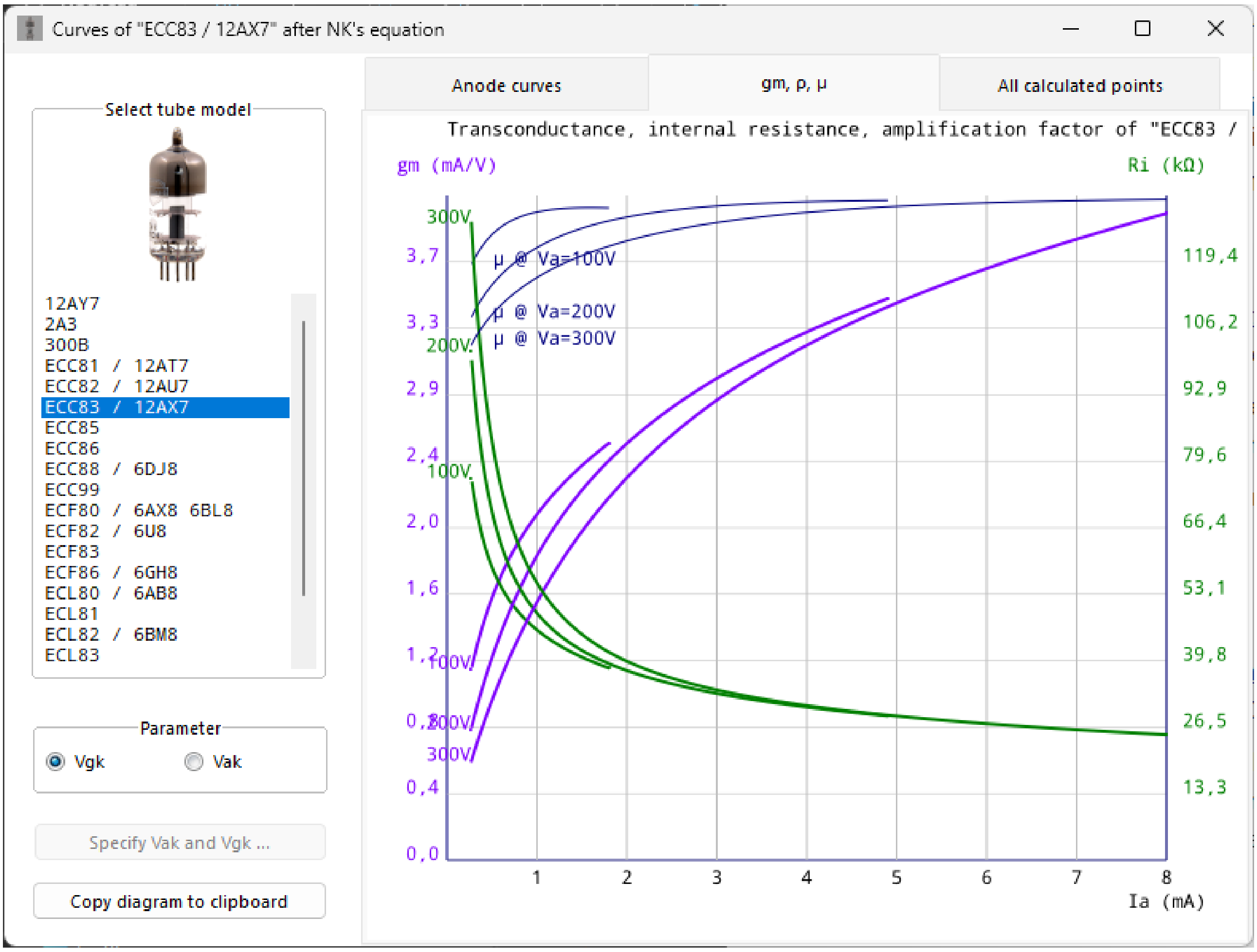


Figure 16: displaying transconductance, internal resistance and amplification factor for 3 anode voltages, and current from 0 to Imax

6.3 Get full data set for spreadsheet

The third tabsheet contains a list of all values used to draw the curve. It can be copied to clipboard and then pasted into a spreadsheet.

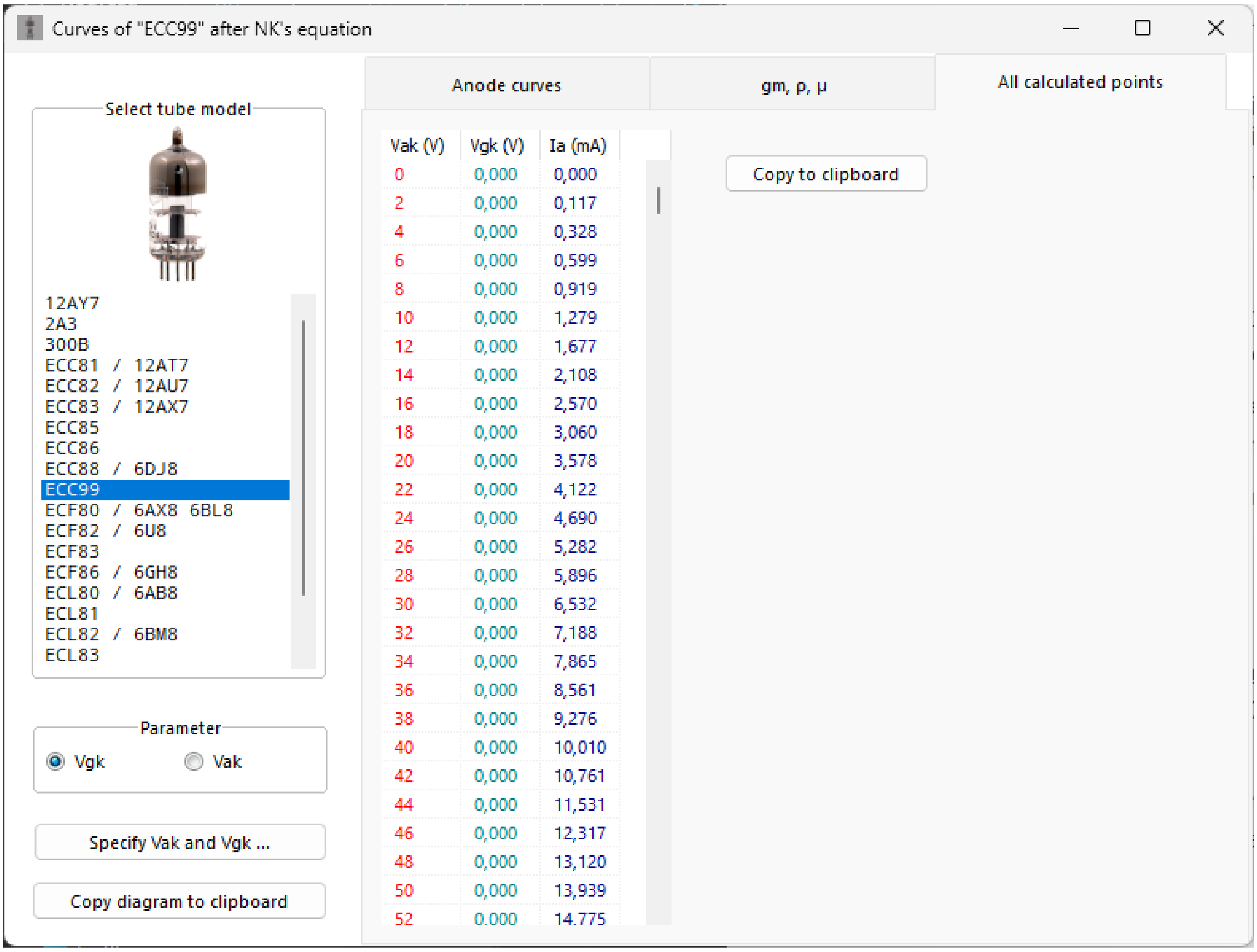


Figure 17: full data set used to display anode curves

7 Editing tube models

You may edit existing models or create yours, providing of course that you understand the role of the 5 key parameters for triodes Kp, Kvb, Kg1, µ, X, plus Kg2 for pentodes.

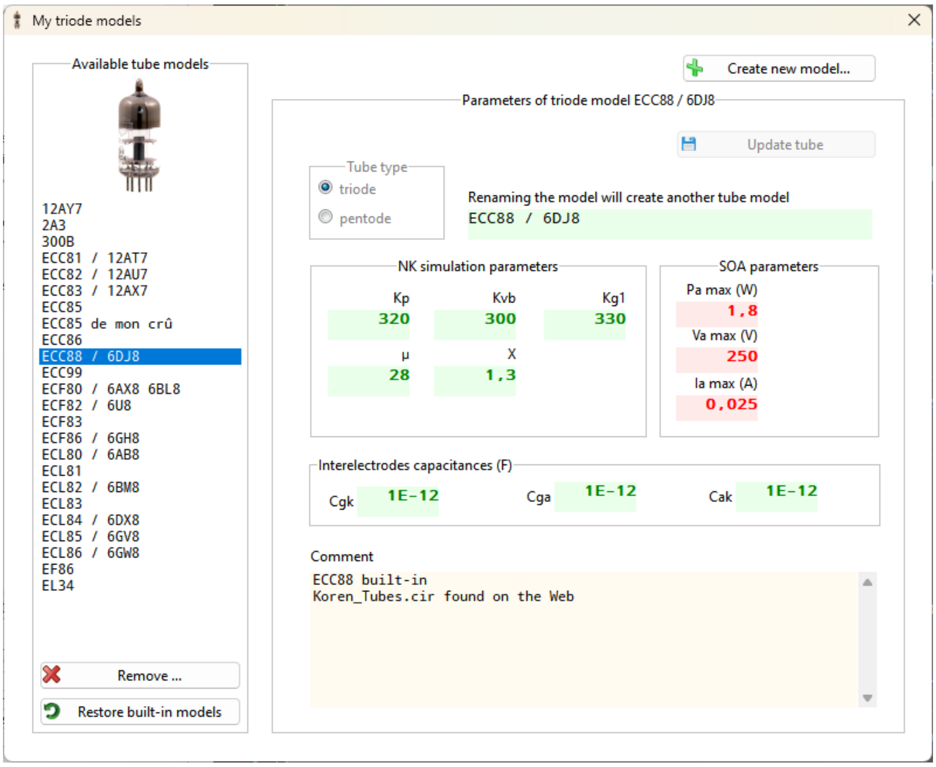


Figure 18: editing ECC88 triode

The left list selects an existing model and displays its parameters.

The « Create new model... » button prepares a blank parameters set, that you may record with « Update parameters » button.

When modifying an existing model, use the « Update parameters » button to record changes. You may rename the model.

The comment textbox may content whatever text you want.

In case you have erased or renamed any of the original models that came with the software when just installed, you may restore those missing with the button « Restore built-in models ».

The « NK simulation parameters » are those used by the solvers to play with Norman Koren's equation as well as for displaying anode curves.

The inter electrodes capacitances are limited to Cgk, Cga and Cak.

The « SOA parameters » (Safe Operating Area) define the maximum values under which the tube can supposedly be safely operated : max anode power (in watt), max anode current (in ampere), max anode voltage (in volt). They are useless in regard of solvers operations, but they are used to limit the display of anode curves. So do not put null or too small values otherwise anode curves will be truncated.

Both the drawing of anode curves and the edition of tube model parameters are floating windows, enabling you to easily tune parameters and immediately see their impact.

As soon you create or rename or delete a tube, the lists of tubes of all open solver windows and the list of tube of anode curves are updated.

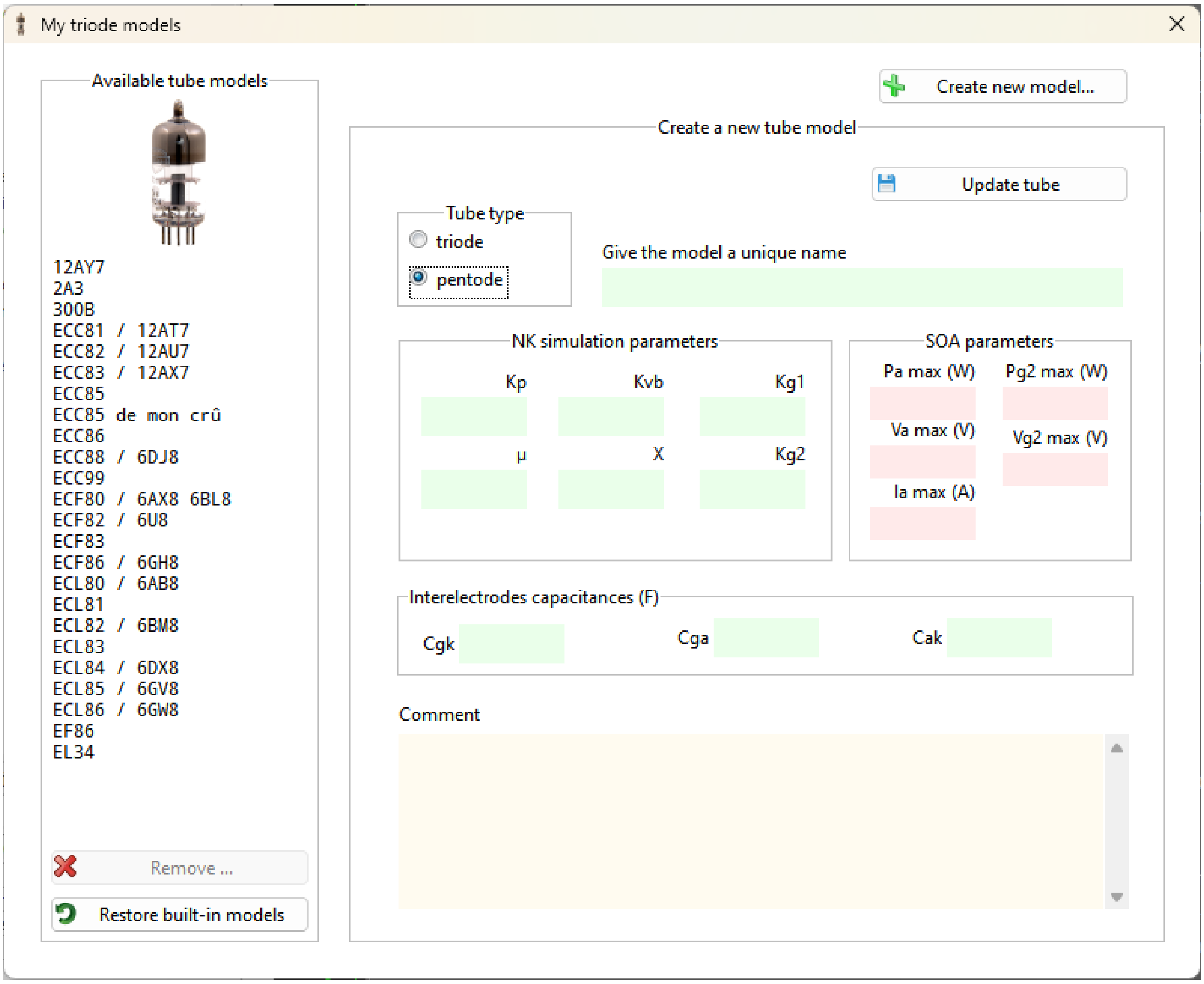
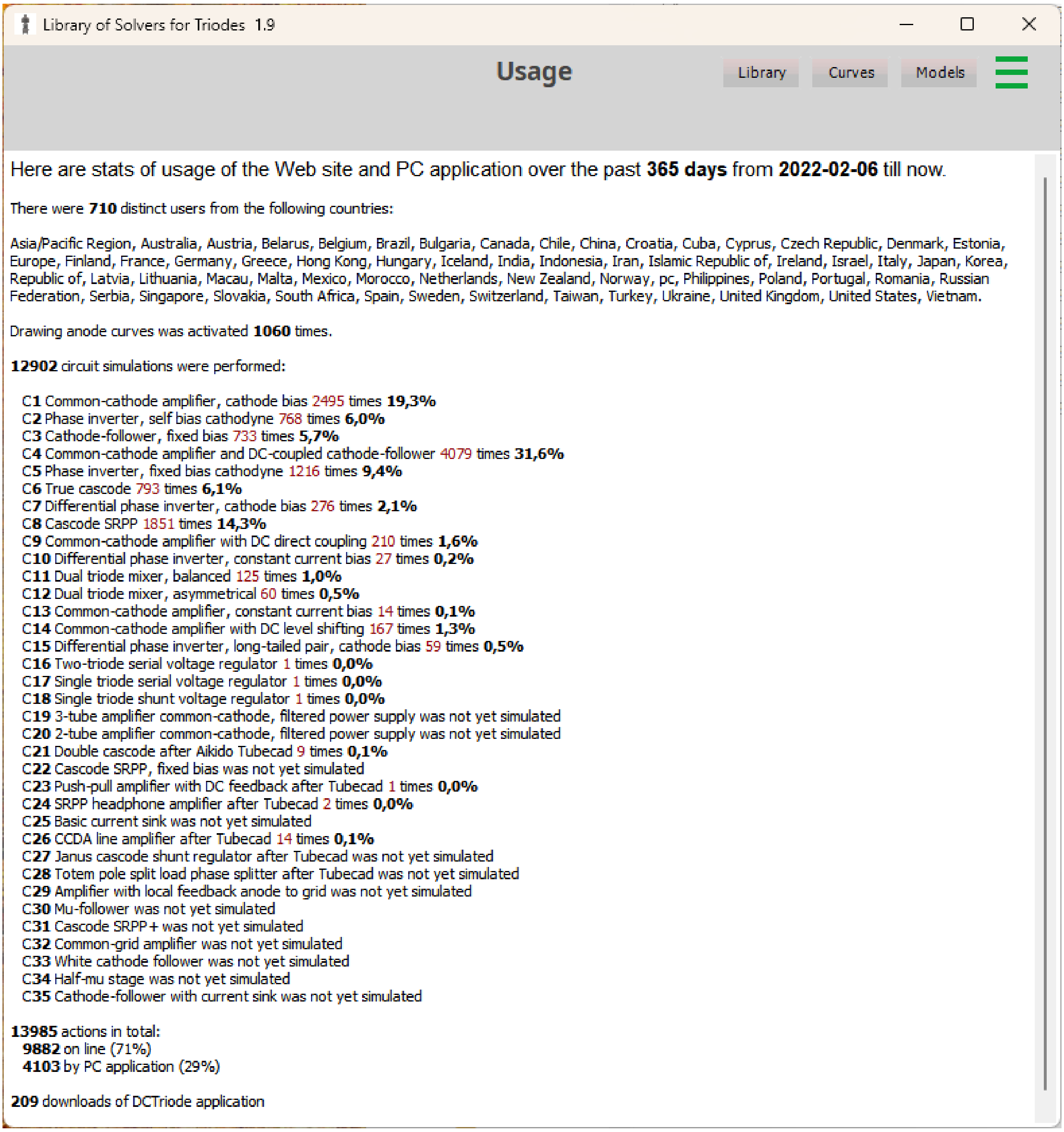


Figure 19: ready to create a new pentode model

8 Discover usage stats

This screen is just for fun : it is an attempt to measure how successful are the web site and the PC application :



Above figures are estimations only :

- the « activation » count of solvers per circuit (incremented whenever someone launches a simulation) can be lower than actual figures if people use the PC app without an active Internet connection ;
- the count of « distinct users » is based upon the Internet address of users and is just an indication : meanwhile it is unlikely that the search engines robots trigger simulations ;
- the « countries » are too only an indication as users may use VPNs to hide their IP details ;
- the count of PC app downloads is overestimated because of search engines hits.

DC Triode communicates with the tubes.astefo.com server only to build up this statistical data and to display potentially new information :

- when you launch it : it fetches from server the text of the « information » screen (causing the latency to appear) ;
- when you display a set of anode curves : it sends that a tube drawing was performed (it does not send tube model name or any other data) ;
- when you click « Solve » in any solver window : it sends the circuit number (nothing else, no values) ;
- when you display the « usage stats » screen : it asks server for the global stats for the rolling period of time.

Your IP is then associated by the server with tube drawing number and circuit number to distinguish users. The country is automatically retrieved from your IP, as do all servers worldwide.

That's all it does. Shutting down your Internet connection will not prevent the software to simulate your circuits, it will just stop your contribution to those stats.

9 Information screen

It displays generic text and some information, for instance to alert you on the availability of an updated version. This text is fetched from the tubes.astefo.com server.

10 Norman Koren’s equations

All solvers of DCTriode rely on the « new equations » defined by Norman L. Koren around 2000, see http://www.normankoren.com/Audio/Tubemodspice_article.html

All solvers use the parameters he indicates for the triodes 6DG8 (ECC88), 12AU7 (ECC82) and 12AX7 (ECC83). For other tubes, I took parameters from Spice models found on the Web, many coming too from Norman Koren (in a Spice file named Koren_Tubes.cir).

For your reference, the triode equation, valid for Vgk ≤ 0, is :

$$E1=(Vak/Kp)*\ln(1+\exp(Kp*(1/\mu+Vgk/\sqrt{(Kvb+Vak^2)})))$$
$$Ia=(1+sgn(E1))*(E1^{Ex})/Kg1$$

For pentodes, the set of equations is :

$$E1=(Vg2/Kp)*\ln(1+\exp(Kp*(1/\mu+Vgk/Vg2)))$$
$$Ia=(1+sgn(E1))*(E1^{Ex}/Kg1)*\arctan(Vak/Kvb)$$

and the screen grid current :

$$Ig2=\frac{\left(Vgk+\frac{Vg2}{\mu}\right)^{3/2}}{Kg2}\ if\ Vgk+Vg2/\mu\geq 0$$

The next tables contains sets of parameters from Norman Koren plus some SOA data (maximum values of Vak, Ia, Pa) extracted from data-sheets found on the web ; these latter data is more informative than actual specifications as it depends on manufacturers ; they are used by DCTriode to automatically compute the scales of the anode currents graphs.

The « built-in » sets of parameters used by DCTriode are :

Tube	Type	Koren’s intrinsic parameters					SOA		
		Kp	µ	Kvb	Ex	Kg1	Pa max (W)	Ia max (mA)	Va max (V)
ECC81	triode	282	71	1	1.03	168	2.5	15	300
ECC82	triode	84	21.5	300	1.3	1180	2.75	20	400
ECC83	triode	600	100	300	1.4	1060	1	8	350
ECC85	triode	224.4	69.5	2689.3	1.481	551.4	2.5	15	300
ECC86[3]	triode	48.11	29.91	210.6	1.596	294.6	0.6	20	30
ECC88[4]	triode	320	28	300	1.3	330	1.8	25	250

3 Philips data book 1959

ECC99[5]	triode	170	23.6	224.7	1.484	437.25	5	50	400
ECL80[6]	triode	45.50	29.30	300	1.332	1443.9	1.0	8	200
ECL81[7]	triode	369.30	66.31	2.5	1.390	1400.2	1.0	8	250
ECL82[8]	triode	500.37	71.97	0.7	1.480	1481.3	1.0	15	300
ECL83[9]	triode	305.21	119.15	1.8	1.321	732.5	3.5	15	250
ECL84[10]	triode	343.45	87.85	300	1.507	473.2	1.0	12	250
ECL85[11]	triode	247.12	56.54	3.0	1.608	719.6	0.5	15	300
ECL86[12]	triode	1098.83	109.92	0.5	1.425	1754.6	0.5	4	300
ECF80[13]	triode	72.36	22.63	578.3	1.318	624.8	1.5	14	250
ECF82[14]	triode	106.38	49.87	300.0	1.255	323.2	2.8	15 ?	300
ECF83[15]	triode	69.30	11.83	300.0	1.052	521.1			
ECF86[16]	triode	79.68	16.08	300.0	1.162	601.4	1.5	15	125
EF86[17]	pentode	222.06	34.09	4.7	1.35	2648.1	1	6	300

EF86: kg2=4627; Pscreen max=0.2W; Vscreen max=200V

If it does not make great sense to use power triodes with the library of small-signal of DCTriode, but the following data of power tubes are used to display graphs and play with voltage regulators and power stages :

Tube	Koren's intrinsic parameters						SOA		
	Kp	μ	Kvb	Ex	Kg1	Kg2	Pa max (W)	Ia max (mA)	Va max (V)
300B	65	3.95	300	1.4	1550		36	100	400
2A3	60	4.2	300	1.4	1500		15	200	300
EL34[18]	47.01	14.18	3.6	1.175	282.3	1147	25	150	800
EL84[19]	111.04	21.29	17.9	1.24	401.7	4500	12	65	550

4 Koren_Tubes.cir found on the Web
5 https://www.diyaudio.com/community/threads/jj-tesla-ecc99-spice-model.45287/page-2
6 Triode section, Philips Data book 1951 aka 6AB8
7 Triode section, universal vademecum (1960)
8 Triode section, Philips Data Book 17-02-1956 aka 6BM8
9 Triode section, universal vademecum (1960)
10 Triode section, Philips Data Book Sept 1968 aka 6DX8
11 Triode section, Philips Data Book Jan 1960 aka 6GV8
12 Triode section, Philips Data Book Jan 1970 aka 6GW8
13 Triode section, Philips data sheet aka 6AX8 6BL8
14 Triode section, WF data sheet aka 6U8
15 Triode section, Universal Vademecum (1960)
16 Triode section, Mazda Belvu Data Book aka 6HG8
17 Koren_Tubes.cir
18 Koren_Tubes.cir
19 Koren_Tubes.cir

KT66[20]	34.89	11.68	22.3	1.197	510.9	4500	25	200	500
KT88[21]	26.48	12.38	36.5	1.246	340.4	4500	42	230	800
6V6[22]	41.16	10.70	12.7	1.310	1672	4500	14	115	350
5881[23]	53.86	8.35	14.4	1.484	2507.1	4500	23	200	400
6550[24]	39.55	8.61	20.5	1.435	1066.6	4500	42	190	660

All above tubes are natively included in the program and can be restored at any time, should you have modified their parameters or renamed them.

20 Koren_Tubes.cir
21 Koren_Tubes.cir
22 6V6-GTA Koren_Tubes.cir
23 Koren_Tubes.cir
24 Koren_Tubes.cir

11 Small signal formulas

Some of the solvers indicate estimations of voltage gain and output impedance. Below are the formulas used to calculate them.

In all formulas :

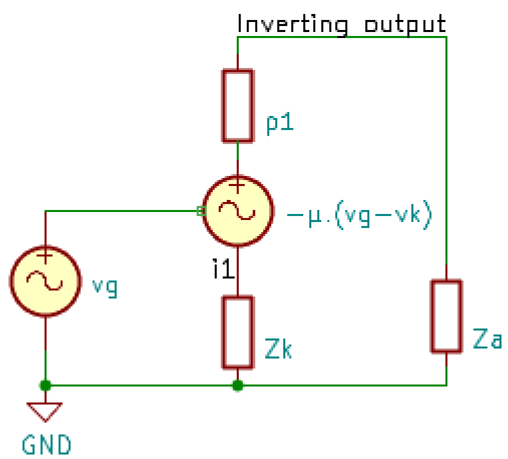
- ρ = triode internal resistor (at operating point)
- g_m = transconductance of triode (at operating point)
- μ = amplification factor of triode (at operating point), i.e. = ρ . g_m
- Ra = anode resistor ; Ro = dynamic load ; Za = output load impedance (e.g. Ra || Ro)

11.1 Common-cathode stage

Ra : anode resistor

Za : anode total output load (Ra || AC load)

Rk : cathode bias resistor



If Rk bypassed :

Gain $A=-\mu\frac{Za}{Za+\rho}$

Output impedance $Zo=\frac{Ra.\rho}{Ra+\rho}$

If Rk Unbypassed :

Gain $A=-\mu\frac{Za}{Za+\rho+Rk(\mu+1)}$

Output impedance $Zo=\frac{Ra[\rho+Rk(\mu+1)]}{Ra+\rho+Rk(\mu+1)}$

11.2 Common-cathode stage with local feedback

After The Valve Wizard http://www.valvewizard.co.uk/localfeedback.html

Rf = resistor between anode and grid ; Rg = resistor from input to grid

Ra = anode resistor ; Rao = supplemental AC load resistor on anode

Ao = gain without feedback, with bypassed Rk, obtained by $A=-\mu\frac{Za}{Za+\rho}$ with Za = Ra || Rao

Zoa = Ra || Rao || Rf

gain with applied feedback : $Avf = \frac{Zoa + Ao.Rf}{Rg + Rf + Zoa - Ao.Rg}$

Output impedance : $\frac{\rho(Rg+Rf)}{Rg+Rf+\rho(\mu+1)}$

Input impedance : $\frac{\rho(Rg+Rf)+Za(\rho+Rg(\mu+1)+Rf)}{\rho+Za(\mu+1)}$

11.3 Cathode follower

Rk : cathode bias resistor

Gain $A = \frac{\mu Rk}{\rho + Rk(\mu+1)}$

Output impedance $Zo = \frac{1}{\frac{1}{Rk}+\frac{1}{\rho}+gm}$ resulting in $Zo = \frac{\rho.Rk}{\rho + Rk(\mu+1)}$

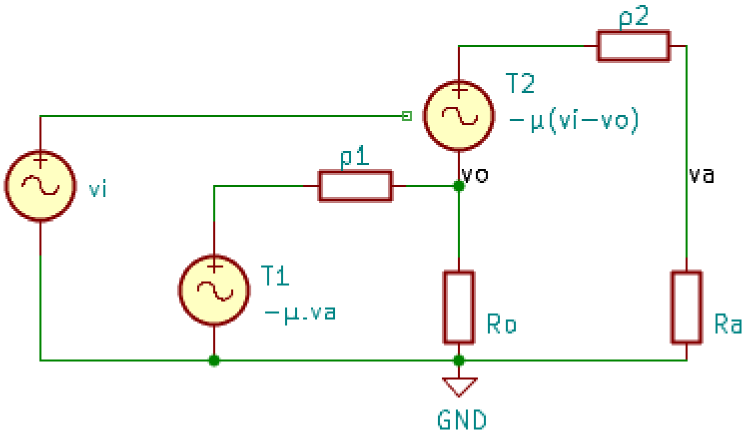
11.4 White-cathode follower

The following formulas are taken from https://www.tubecad.com/october99/page4.html

Gain : $A = \frac{\mu(\mu 1+\rho/Ra)}{(\mu^2+\mu+1)+(\mu+2)\rho/Ra}$ (issue : it does not take into account the load ! So unused)

Output impedance : $Zo = \frac{1}{\frac{1+\mu}{\rho+Ra}+\frac{1+\mu(\mu+1)/(1+\rho/Ra)}{(\mu+1)Rk+\rho}}$ (used in DCTriode)

For the gain, the author devised an equivalent Thévenin model (without guarantee because the maths is a bit boring…) :



Setting Ra = Ra || Rg (even though Ra is practically always far smaller than Rg),

with $D = Ro(1+\mu_2).\frac{\mu_1.Ra+Ro}{\rho_1+Ro}+Ra+\rho_2+Ro(1+\mu_2)$

the gain $Av = \mu_2\frac{Ro}{D}[1+\frac{\mu_1.Ra+Ro}{\rho_1+Ro}]$ of course always < 1

For information, the gain on the anode of upper tube is :

$$Ava = \frac{-Ra.\mu_2}{D}$$

11.5 Cascode gain stage

ρ1, µ1 : lower triode ; cathode is bypassed

ρ2, µ2 : upper triode

Ra : upper triode anode resistor

Voltage gain : $A = -\mu_1\frac{Ra(1+\mu_2)}{Ra+\rho_1+\rho_2(1+\mu_2)}$

Output impedance : $1/Zo = 1/Ra + 1/\rho_2+\rho_1(1+\mu_2)$

Formulas from https://keith-snook.info/calculators/triode-cascode-amplifier.html

Ra1: anode load due to upper triode : $Ra_1 = \frac{Ra+\rho_2}{1+\mu_2}$

Voltage gain at anode lower triode : $A1 = \frac{\mu_1.Ra_1}{Ra_1+\rho_1+Rk(1+\mu_1)}$

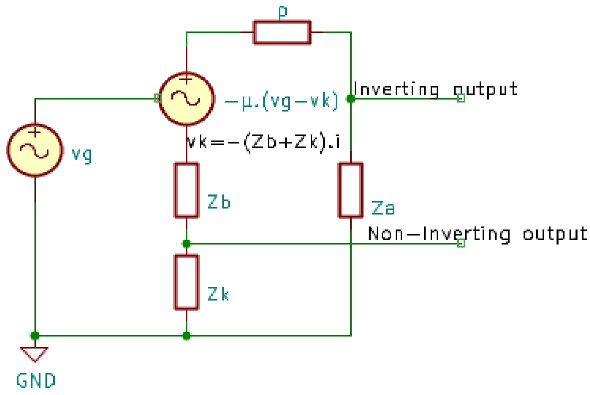
Voltage gain at anode upper triode : $A2 = A1\frac{Ra(1+\mu_2)}{Ra+\rho_2}$

11.6 Cathodyne phase inverter

Zk = Rk || external load

Za = Ra || external load

Zb = Rk || Ck (self bias if any)



Gain on anode : $Aa = -\mu \frac{Za}{Za + \rho + (Zb + Zk)(\mu + 1)}$

Gain on cathode : $Ak = \mu \frac{Zk}{Za + \rho + (Zb + Zk)(\mu + 1)}$

11.7 SRPP

Correct analysis and formulas related to this circuit are rare !

Voltage gain : $Abyp = -\mu_1 \frac{\rho_2 . Ro}{\rho_1 \rho_2 + Ro(\rho_1 + \rho_2)}$

which simplifies (if Rk1=Rk2 and identical tubes, hence both tubes under same conditions) to : $Abyp = -\mu \frac{Ro}{\rho + 2\,Ro}$

If Ro → ∞ then Abyp → -μ /2

Reference : The Optimised SRPP Amp (Part 1) by Merlin Blencowe, From Audio Xpress, May 2010, pp.13-19

The formulas below are for the « optimised » SRPP with an anode resistor. They suppose that Rk1=Rk2 and that Rk1 is bypassed (by a capacitor).

Considering :

Ro = dynamic load on cathode T2

Rk = Rk1 = Rk2

Ra = possible resistor in T2 anode, optimised as Ra=Rk

Gain with Rk1 bypassed : $Abyp = -\mu_1 \frac{Ro(\rho_2 + Ra + Rk . \mu_2)}{(\rho_1 + Rk)(\rho_2 + Ra) + Ro(\rho_1 + \rho_2 + Ra + Rk\,2(\mu_2 + 1))}$

which simplifies (if Ra=Rk2=Rk1) to : $Abyp = -\mu \frac{Ro(\rho + Rk(\mu + 1))}{(\rho + Rk)^2 + Ro(2\rho + Rk(\mu + 1))}$

Output impedance : $Zobyp=\frac{(\rho_2+Ra)(\rho_1+Rk)}{\rho_1+\rho_2+Ra+Rk(1+\mu_2)}$

which again simplifies to : $Zobyp=\frac{(\rho+Rk)^2}{2\rho+Rk(\mu+2)}$

Reference : The Optimised SRPP Amp (Part 2) by Merlin Blencowe, From Audio Xpress, June 2010, pp.18-21

The formulas below are for the « optimised » SRPP with an anode resistor. They suppose that Rk1 is Unbypassed.

Voltage gain :

$$Aunbyp=-\mu_1\frac{Ro(\rho_2+Ra+\mu_2.Rk2)}{[\rho_1+Rk2+Rk1(1+\mu_1)](\rho_2+Ra)+Ro[\rho 1+\rho_2+Ra+Rk1(1+\mu_1)+Rk2(1+\mu_2)]}$$

which simplifies if Rk1=Rk2 and identical tubes to :

$$Aunbyp=-\mu\frac{Ro[\rho+Rk(\mu+2)]}{[\rho+Rk(\mu+2)](\rho+2Rk)+Ro[2\rho+2Rk(\mu+2)]}$$

Output impedance : $Zounbyp=\frac{(\rho+2Rk)[\rho+Rk(\mu+2)]}{2\rho+2Rk(\mu+2)}$

11.8 Half-mu stage

Reference : The Optimised SRPP Amp (Part 2) by Merlin Blencowe, From Audio Xpress, June 2010, pp.18-21

The output is taken on the lower tube anode. The load is supposed to be infinite...

Load on the lower triode : $Rl=\rho+Rk2(\mu+1)$

The formulas below are for the « normal » SRPP without anode resistor.

Gain with both resistors bypassed : $Abyp=-\mu_1\frac{\rho_2}{\rho_1+\rho_2}$

Gain with both resistors unbypassed : $Aunbyp=-\mu_1\frac{\rho_2+Rk2(1+\mu_2)}{\rho_1+Rk1(1+\mu_1)+\rho_2+Rk2(1+\mu_2)}$ where 1 indicates lower triode and 2 indicates upper triode.

With identical triodes and Rk1=Rk2, above equation simplifies to $A=\frac{-\mu}{2}$

Output impedance with bypassed resistors : $Zobyp=\frac{\rho}{2}$

Output impedance with unbypassed resistors : $Zounbyp=\frac{\rho+Rk(1+\mu)}{2}$

11.9 SRPP+

Reference : The Optimised SRPP Amp (Part 2) by Merlin Blencowe, From Audio Xpress, June 2010, pp.18-21

The formulas used by the solvers are those of Merlin Blencowe's paper :

Formulas for gain by Tubecad in https://www.tubecad.com/2009/10/blog0173.htm

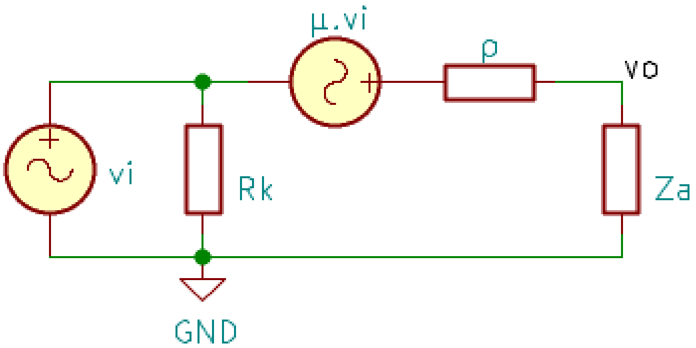
Voltage gain if Rk bypassed : $\frac{\mu(2Ro+R2)}{2Ro+R2+\rho}$

Voltage gain if Rk unbypassed : $\frac{\mu(2Ro+R2)}{2Ro+R2+\rho+(\mu+1)Rk}$

The solver uses the average values of ρ and μ of both tubes, as both operate under very similar conditions.

11.10 Common-grid stage

Thévenin's equivalent model :



Rk = bias resistance

Za = anode load

Input impedance : $Zin=\frac{Rk(\rho+Za)}{\rho+Za+Rk(\mu+1)}$

Voltage gain : $A=(\mu+1)\frac{Za}{Za+\rho}$

If we consider that a decoupling capacitor Ck is inserted between actual input and cathode, formulas for dynamic Zin and A become :

decoupling capacitor reactance $Xc=\frac{1}{Ck.\omega}$

input impedance « into » cathode $Zk=\frac{Za+\rho}{\mu+1}$

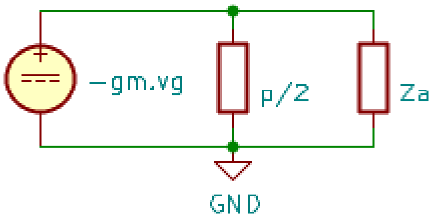
input impedance $Zin = Xc + \frac{Rk(\rho + Za)}{\rho + Za + Rk(\mu + 1)}$

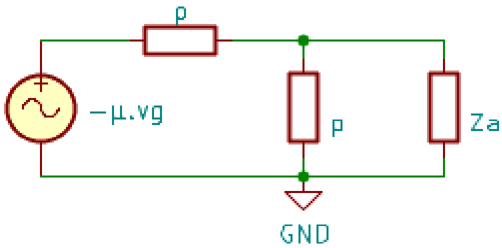
and voltage gain from input capacitance to anode $A = (\mu + 1)\frac{Za.Zk}{(\rho + Za)(Xc + Zk)}$

11.11 Dual-triode mixer, symmetrical

Calculated after Norton / Thévenin models.

With bypassed cathode resistor :



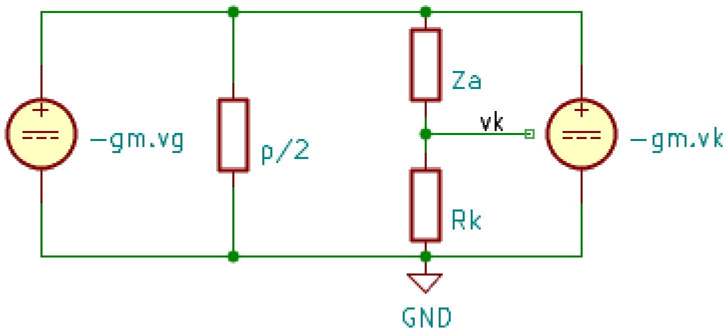


Gain : $Av = gm \dfrac{Za\,.\,\rho}{\rho + 2\,Za}$ or $\mu \dfrac{Ra}{\rho + 2\,Ra}$

Output impedance : $Zo = \dfrac{Ra\,.\,\rho}{2\,Ra + \rho}$

With unbypassed cathode resistor :

the author devised the following Norton model ; output voltage is taken on Za (the voltage reference is shifted to both cathodes to ease calculation) :



Gain : $A = -\mu \dfrac{Za}{2\,Za + \rho + \mu Rk}$

Output impedance : $Zo = \dfrac{Ra(\rho/2 + Rk(\mu+1))}{Ra + \rho/2 + Rk(\mu+1)}$ this formula is the one for the single triode common-cathode stage with unbypassed Rk with internal resistance halved (µ unchanged as gm doubles).

11.12 Dual triode mixer, asymmetrical

Both cathode resistors bypassed ;

Gain on T1 anode : $A\,1 = -\mu 1 \dfrac{Za\,.\,\rho 1}{\rho 1\,.\,\rho 2 + Za(\rho 1 + \rho 2)}$

Gain on T2 anode : $A\,2 = -\mu 2 \dfrac{Za\,.\,\rho 2}{\rho 1\,.\,\rho 2 + Za(\rho 1 + \rho 2)}$

11.13 Long-tailed-pair phase inverter

After Merlin Blencowe's « Designing Tube Preamps for Guitar and Bass ».

Differential gain if identical anode loads : $Adiff=-\mu\frac{Za}{\rho+Za}$

Gain on non-inverting output : $Aninv=\mu\frac{Za}{(Za+\rho)(2+\frac{Za+\rho}{Rk(\mu+1)})}$

Gain on inverting output : $Ainv=Aninv(1+\frac{Za+\rho}{Rk(\mu+1)})$

Differential gain if different anode loads : Ainv+Aninv

In case of different anode impedances (different resistors and/or different external AC load), refer to the formulas of § 11.14 which were specially elaborated for that.

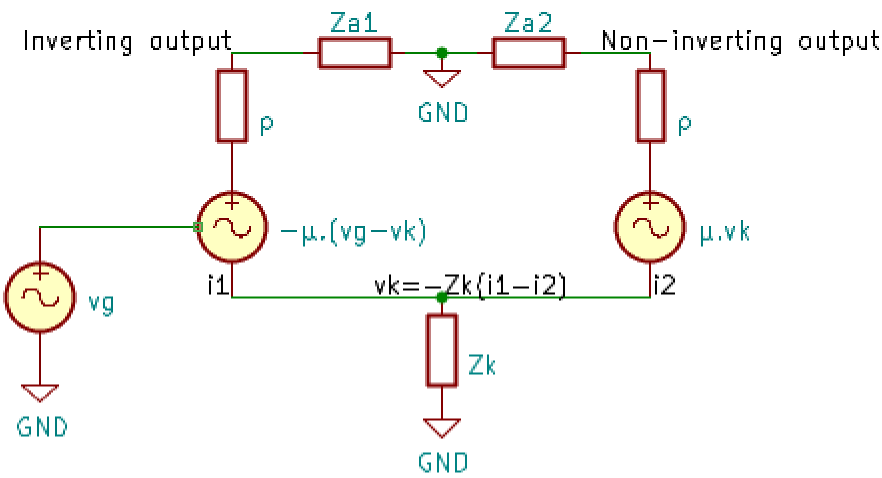
11.14 Differential phase shifter

Gain formulas given here were obtained by the author after the following equivalent Thévenin model :

Identical anode resistors (Ra1 = Ra2) :

In case DC and AC anode load are identical for both tubes, then both triodes are identically biased, hence exhibit same µ and ρ.

Za = AC anode loads (same anode resistors, same AC loads)



Zk = AC impedance of the current source (normally quite high if source is BJT, JFET, MOSFET)

To simplify :

α = µ + 1

Rs = Za +ρ +α.Zk

Inverting gain : $Ai=-\mu\frac{Za.Rs}{Rs^2-(\alpha Zk)^2}$ simplified to $Ai=-\mu\frac{Za.(Za+\rho+\mu Zk)}{(Za+\rho+\mu Zk)^2-(\mu Zk)^2}$

Non-inverting gain : $An=\mu\dfrac{\alpha.Za.Zk}{Rs^2-(\alpha Zk)^2}$

Different anode resistors (Ra1 <> Ra2) :

In case the anode resistors are different (a practice to minimise the gain difference of inverting and non-inverting outputs), then each tube is calculated with its own values of internal resistance ρ, μ and AC load :

With $\alpha_1 = \mu_1 + 1$ and $\alpha_2 = \mu_2 + 1$

Inverting gain : $Ainv=-\mu_1\dfrac{Za_1(Za_2+\rho_2+\alpha_2 Zk)}{(Za_1+\rho_1+\alpha_1 Zk)(Za_2+\rho_2+\alpha_2 Zk)-\alpha_1\alpha_2 Zk^2}$

Non-inverting gain : $Aninv=\dfrac{\mu_2\alpha_2 Zk\, Za_2}{(Za_1+\rho_1+\alpha_1 Zk)(Za_2+\rho_2+\alpha_2 Zk)-\alpha_1\alpha_2 Zk^2}$

Differential gain = |Ainv| +Aninv

11.15 Cathode-follower with current sink

The gain was devised using 2 equivalent Thévenin models : one for the upper cathode-follower, one for the lower current sink, so that the lower tube can be replaced by its equivalent resistance Z_t

Rk_1 = cathode resistor or current sink

R_2 = cathode resistor of upper triode

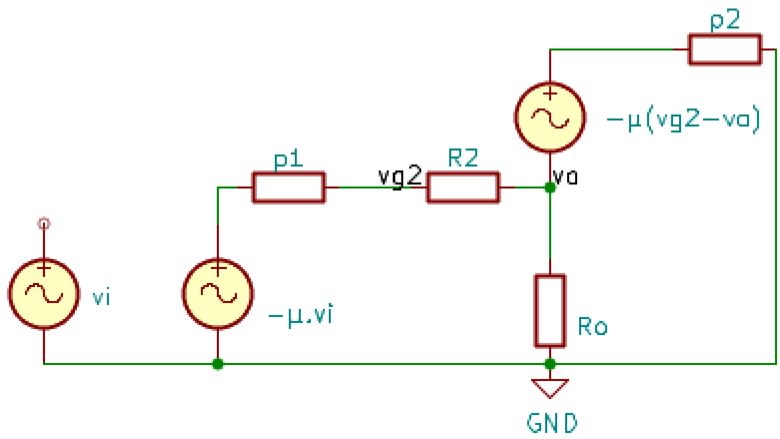
Ro = external load

Impedance of lower tube : $Z_t=\rho_1+Rk_1(1+\mu_1)$

Voltage gain : $Av=\dfrac{\mu_2 Z_t Ro}{(Z_t+Ro)\rho_2+(1+\mu_2)[Z_t Ro+R_2(Z_t+Ro)]}$ always < 1

11.16 Fixed bias cascode SRPP

I devised the following Thévenin equivalent model for circuit 22 :

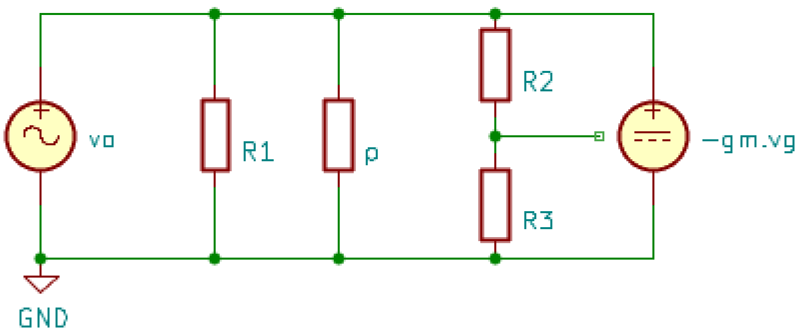


With $B=\rho+R2+Ro-\frac{Ro(Ro+Ro.\mu_2)}{\rho_2+Ro}$

the gain is $Av=-\mu_1[1-\frac{\rho_1+Ro}{B}]$ which is continuous from Ro null to infinite, but gives a gain slightly higher than the SRPP formulas by Blencowe, for instance 28 instead of 21…

11.17 Single triode shunt voltage regulator

This simple equivalent circuit is used to estimate the internal impedance of circuit #18.



The voltage generator « vo » connected at output forces a current and « sees » the internal impedance of C15, named Z :

$$Z=\frac{Ro}{1+k.Ro.g_m}$$

where $\frac{1}{Ro}=\frac{1}{R1}+\frac{1}{R2+R3}+\frac{1}{\rho}$ and $k=\frac{R3}{R2+R3}$

Of course, this is theoretical : the power supply impedance is not null (meaning R1 greater), it does not take into account filtering capacitors, it supposes that the reference voltage is constant.

12 How is obtained frequency response

You may want to figure out how is computed the frequency response because you do not trust black-boxes and you are right, this chapter is for you! For a limited number of circuits, bandwidth is calculated, based on the following assumptions :

- it does not take into account the limited output current capabilities of stages and associated slew-rates ;
- parasitic capacitance Cga is used to simulate Miller effect (increasing the Cgk capacitance by A+1);
- resistance bootstrapping (increase by 1/(1-A)) is used for cathode follower stages ;
- parasitic capacitances Cgk and Cak are tied to ground ;
- stray capacitances are added to all nodes : a unit of stray capacitance is chosen by you (1 to 5pF), and stray capacitance is added to significant nodes, the rule being Cstray = Cunit x number of attached pins.

For instance, if the stray capacitance is set to 2pF, then :

- stray capacitance on a grid driven by a RC grid stopper filter will be 6pF because of the 3 connected pins (R, C, grid) ;
- same result for an anode connected to its load resistor and its coupling capacitor ;
- an unbypassed cathode resistor will add a 4pF stray capacitance, because of the 2 pins, cathode and resistor.

This rule is of course totally arbitrary …

Frequency response is calculated by modelling the circuit with a few basic quadripoles, either passive (to drive tubes by grid or cathode, connect them from anode to grid, load tubes) or active (tubes mounted as common-cathode, common-anode, common-grid, active load, cathode-follower, cathodyne).

The cathodyne phase splitter is actually a pseudo-quadripole because of its 2 outputs.

Whenever a circuit can be modelised by true quadripoles (1 input – 1 output), the overall gain is calculated and its bandwidth is accessible. Additionally, a negative feedback can be simulated.

As soon as a block has 2 outputs, the overall gain does not make sense [25], as well as bandwidth. Meanwhile, frequency responses of individual blocks are always accessible.

For differential stage, the overall gain is actually the differential gain, i.e. |Ainv|+Aninv. It is not yet implemented in the software (it breaks the homogeneity by adding a special case).

25 Well it could be replaced by the differential gain, valid for cathodyne and differential stages; this is not implemented in the current DCTriode version.

For each quadripole, a « transfer » function is available, which calculates the gain of the device after 2 mains parameters :

- the frequency
- the output load, which is the input load of the driven device

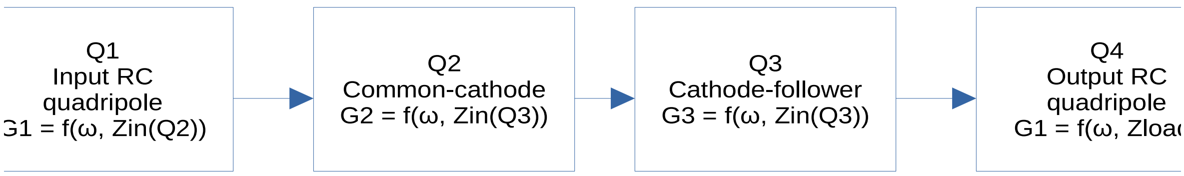
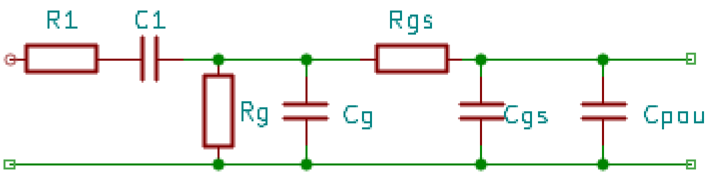


Illustration 12.1 : quadripoles modelling circuit C4

The next sections describe the used quadripoles and indicates their transfer functions.

12.1 RC input



It consists in RC cells : a high-pass cell (R1 resistance of source in series with C1 blocking capacitor ; a pull-down resistor (Rg grid resistor) in parallel with Cg ; a low-pass cell (Rgs grid stopper, Cgs capacitance).

Cpin is the stray capacitance on input valued at 1 stray unit.

Cpou is the stray capacitance at output, 2 units.

For this quadripole, the gain is calculated after :

impedance of cell R1C1 $Z1=\sqrt{R1^2+\frac{1}{C1^2\omega^2}}$

impedance of cell R2C2 $Z2=\frac{R2}{\sqrt{1+R2^2C2^2\omega^2}}$

impedance of cell R3C3 $Z3=\sqrt{R3^2+\frac{1}{C3^2\omega^2}}$

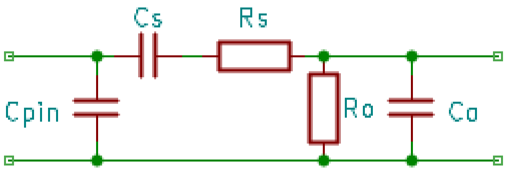
reactance of C3 $X3=\frac{1}{C3.\omega}$

and the gain $A=\frac{X3.Z2}{Z1(Z2+Z3)+Z2.Z3}$

12.2 RC output

This RC network is loading a tube anode or cathode output ; it does not include the DC anode or cathode resistor which is part of the preceding tube quadripole.

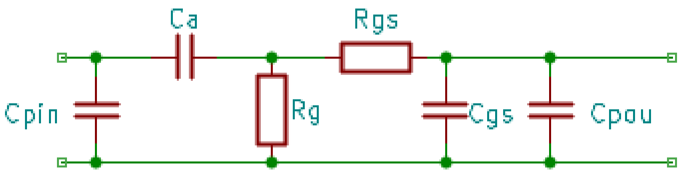
Cs is the DC blocking capacitor. Rs is an optional series resistor (possibly used if driven by a cathode-follower) ; Ro and Co are the output load.



Cpin = 1 unit of stray capacitance, Cpou = 2 units.

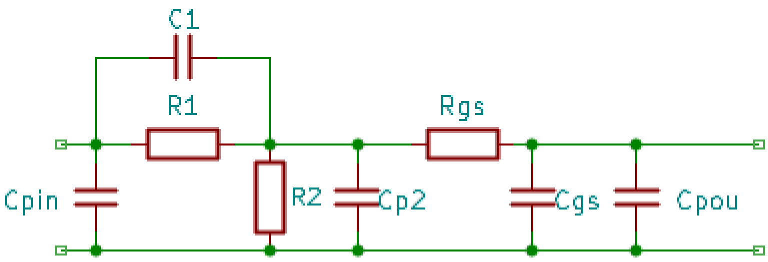
12.3 RC inter-stage

This is the circuitry linking an anode to a grid, and blocking the DC. Ca is the anode blocking capacitor, Rg is the grid pull-down, Rgs and Cgs are the grid-stopper. Cpin is the stray capacitance on input = 1 stray unit. Cpou is the stray capacitance at output = 2 units.

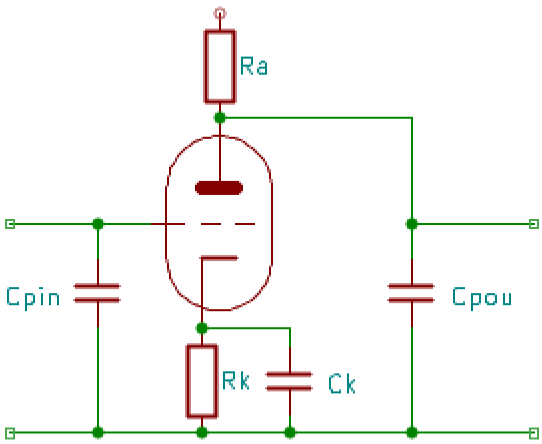


12.4 RC level shifter

This quadripole is used in circuit #14, connecting T1 anode to T2 grid. R1 and R2 constitutes the DC level shifter. C1 bypasses R1 to cancel the loss of the level shifter, and to compensate the parasitic impedance made of capacitance C2 and grid stopper Rgs Cgs, plus the Miller effect appearing on the output (connected to T2 grid). Cpin is the stray capacitance on input = 2 units. Cpou is the stray capacitance at output = 2 units.



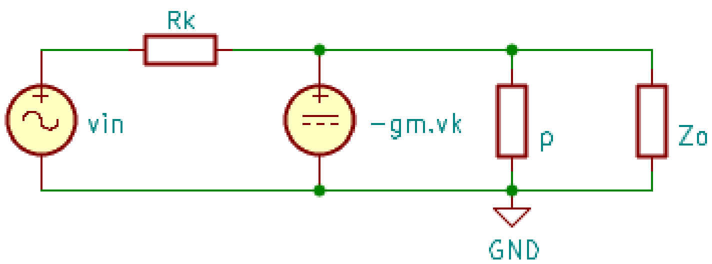
12.5 Tube common-cathode



A simple stage consisting in the tube with its anode resistor and cathode RC, equal to a voltage generator of gain A. Cpin is the input capacitance, made of Cgk and the « Miller » equivalent capacitance (A+1).Cga, plus 1 stray capacitance unit for 1 pin.

Cpou is the output stray capacitance, 2 units.

12.6 Tube common-anode



This model is used for the upper tube of SRPP circuit, mounted as common-anode.

Without anode resistor, the other components being Rk, Z=Zo || ρ, the formulas used to get dynamic gains are :

$$A=\frac{Z+gm.Rk.Z}{Rk+Z+gm.Rk.Z}$$ always lower then 1

and the input impedance Zin (presented to the lower tube of SRPP is $Zin=\frac{Rk}{1-A}$

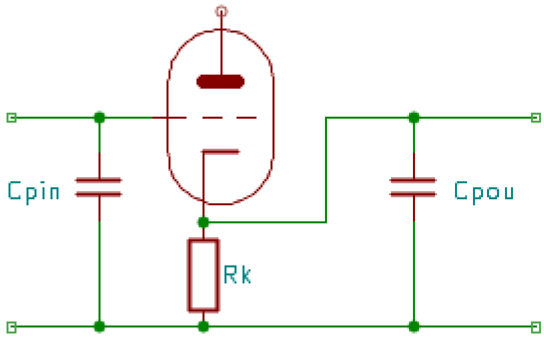
Of course, in such stage, Rk is not null, otherwise the tube would have no gain at all ; however, above formula can be replaced by the following one :

$$Zin=Rk+\frac{\rho.Zo}{\rho+Zo}[1+gm.Rk]$$ with Zo= output load.

12.7 Tube cathode-follower

Cpin is the sum of 1 stray capacitance unit, Cga, and bootstrapped (or not) Cgk.

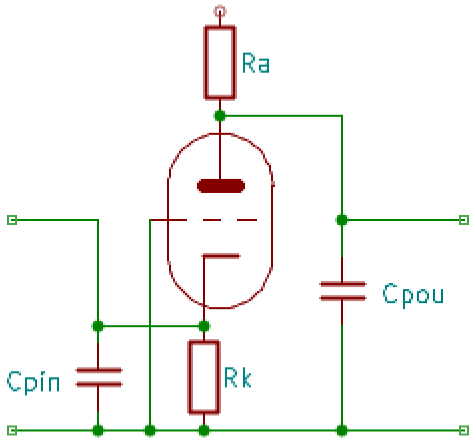
Cpou is 2 units of stray capacitance.



12.8 Tube grid-common

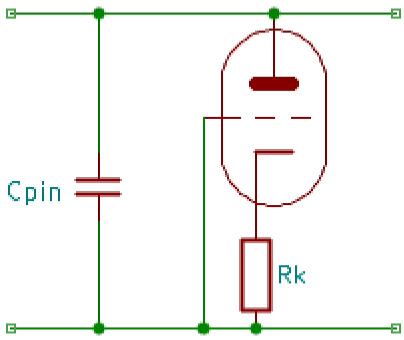
Ra is the anode load, Rk is the bias resistor.

Cpin and Cpou are 2 units of stray capacitance.



12.9 Tube pulldown or pullup (active load)

This quadripole is used in circuit like C34, C35 where it acts as an active load, pulling voltage up or down.



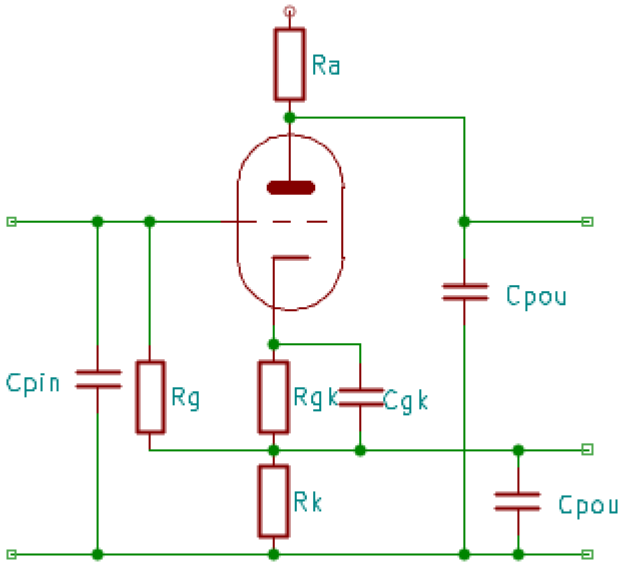
In both cases, input and output are a single pin, and the gain is always set to unity. Only does its impedance change a bit with frequency because of Cga and Cak.

Input capacitance is also the output capacitance, and is valued at Cga +Gkk +2 units of stray capacitance (logically, should be one for pullup as only is the anode involved).

As a pull-up, its input-output is connected to grid and foot of cathode resistor. As a pull-down, it is only the anode.

Its intrinsic impedance is Cpin || ρ+Rk(μ+1). Meanwhile, the impedance it presents to the preceding quadripole is own impedance || input impedance of the next quadripole ; effectively, the 3 quadripoles are connected.

12.10 Pseudo-quadripole tube cathodyne



This circuit is not exactly a quadripole as it presents 1 input and 2 outputs. However, it is integrated in the chain of quadripoles used to compute frequency response, coupled to 1 passive input cell (consisting in a single capacitor) and 2 output cells.

If self-biased, all components have realistic values ; if biased by an external voltage on grid, Rg is infinite, Rgk and Cgk are null.

When self-biased, the input Rg on grid is bootstrapped by the gain on cathode (Rg seen as Rg (1-A)).

DCTriode calculates the modules of gains on anode and cathode with the following formulas :

$Aa = \mu . Za / D$ and $Ak = \mu . Zk / D$ where

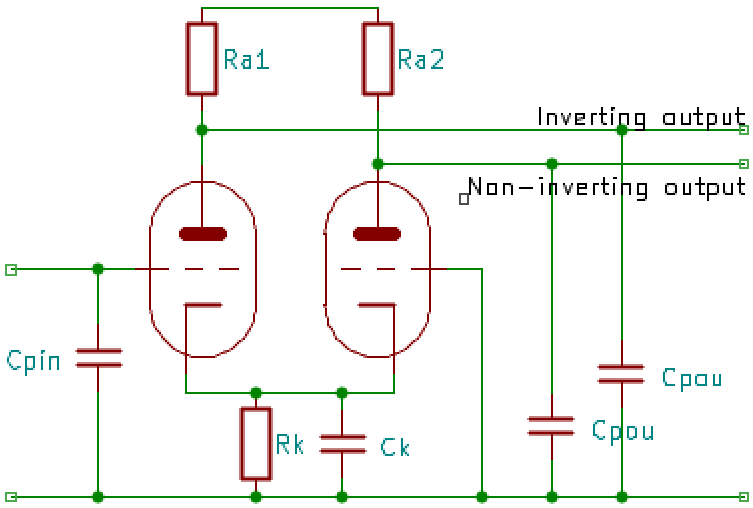
- Za is the total AC anode load (internal resistance, Ra, external load impedance)
- Zk is the impedance Rk in parallel to external load
- Zgk = Rgk || Cgk
- and the denominator $D = Za + \rho + \mu(Zgk + Zk)$

Note that, if Zk is inferior to Za, the anode gain may be a bit superior to 1.0 (a normal situation), whilst the cathode gain is always lower than 1, whatever the conditions are.

Rg is integrated into the quadripole (and is not part of a passive input RC) to take into account its bootstrapping. The effect is visible at low frequencies, before the parasitic capacitances takes precedence.

12.11 Pseudo-quadripole differential stage

This circuit is not exactly a quadripole as it presents 1 input and 2 outputs. However, it can be integrated in the chain of quadripoles used to compute frequency response, coupled to 1 passive input cell (consisting in a single high-pass RC filter) and 2 output cells.



Ra1, Ra2 and Rk are defining the operating conditions ; coupled to parasitic capacitances, including Miller effect (on first tube), they define the high poles of frequency response.

In case the device is biased by a current source, Rk is the AC impedance of this current source.

DCTriode uses the following formulas to compute gains :

Za = Ra || output load || Cpou

Zk = Rk || Ck

With $\alpha_1 = \mu_1 + 1$ and $\alpha_2 = \mu_2 + 1$

Inverting gain : $$Ainv = -\mu_1 . \frac{Za_1 (Za_2 + \rho_2 + \alpha_2 Zk)}{(Za_1 + \rho_1 + \alpha_1 Zk)(Za_2 + \rho_2 + \alpha_2 Zk) - \alpha_1 \alpha_2 Zk^2}$$

Non-inverting gain : $$Aninv = \frac{\mu_2 \alpha_2 Zk\, Za_2}{(Za_1 + \rho_1 + \alpha_1 Zk)(Za_2 + \rho_2 + \alpha_2 Zk) - \alpha_1 \alpha_2 Zk^2}$$

Differential gain = |Ainv| +Aninv

Miller effect is calculated by adding a capacitance (1 +A_{inv}) C_{ga} to the input parasitic Cpin.

12.12 Pseudo-quadripole mixer symetrical

Frequency response of this circuit is done by using a single input and its output.

13 Convergence of solvers

Solvers are basically successive approximations loops, started with initial current and voltage conditions obtained by theoretical load lines or expected currents and voltages ; they perform successive approximations on anode currents (sometimes on cathode voltages) and consider that the job is done when absolute difference between 2 successively computed values is lower than a certain tolerance (1-5µA, a few mV in most solvers).

Once this is done, the solver checks that obtained data is realistic by performing all or part of the following tests :

- compare triode operating point to Norman Koren result, at ±10µA
- compare Vb to sums of voltages across resistors and tubes (with a ±1V tolerance)
- check all Vgk are < 0
- check count of iterations is not too high (in solvers which are not certain to converge by construction ; maximum 1000 iterations)
- check that tubes operating points are on the load line, at ±20µA (when it makes sense, i.e. when maximum cathode current is imposed by resistors)

In case any of above test fails, this is notified in the text results, as well as in the table of successive simulations.

14 Credits

EC86 picture from The Valve Museum http://www.r-type.org/exhib/aaa1000.htm used in DCTriode

John Broskie on https://www.tubecad.com for the many clever and well documented circuits, several of them being DC-coupled, which were useful inputs for DCTriode.

Merlin Blencowe on http://www.valvewizard.co.uk/ for his clear descriptions and calculations of many circuits.

Norman Koren, for his work on tube modelling and simulation years ago, yet not superseded by any other studies.