10.5.8 The bias-current in the power stage (bias-setting)

The bias-current in the power stage is the current that runs through a power tube when it is "in idle"-state. "In idle" means that all supply voltages are present (in contrast to the "standby"-state) but no input signal is fed to the circuit (volume = 0). In some circuits, the bias-current sets itself automatically (cathode-resistor, Chapters 10.5.2 and 10.5.2), in others it can be adjusted within certain limits by a potentiometer (bias pot). For such an adjustment, instructions are required: what is the optimum setting, and how (and what) do we measure?

What is measured? The bias, of course! *"If the mains voltage drops from 230 V to 220 V (translator's remark: or from 110V to 105 V, if your are in the corresponding part of the world), the bias changes by a few milliamps, and the sound does change"*. Of course: the bias! Adjusting that just right, the sound will be right! The bias; that's apparently the idle-current in the power stage. But which one – the cathode- or the plate-current? This is where it already gets tricky (and slippery) for most experts. Recommendation 1: *you measure the bias by disconnecting the plate from the output transformer and putting an ampere-meter in between.* This expert clearly targets your plate-current. And if, while you're measuring away, suddenly Jimi H. appears and invites for a jam: then the insulation was inadequate. Because **plate-voltages can be – SERIOUSLY! – absolutely DEADLY!** Measurements of this kind are not something the layperson can do; real expert knowledge is required. Recommendation 2: *You measure the bias by connecting an ampere-meter in parallel to the primary winding of the output transformer.* Our second expert also targets the plate-current and sees a measurement error (due to the copper resistance) of 5 – 10% as unproblematic. These primary windings are not of that high an impedance, possibly as low as 30 Ω. For an orientation measurement, this is good enough, though. Recommendation 3: *You insert (solder) a 1-Ω-resistor into the cathode-connection of every power tube and you measure the voltage drop across it.* Ooops – now we've jumped to the cathode-current, i.e. the sum of the plate- and the screen-grid-current. For a plate-current of 35 mA, the screen-grid-current may well be 5 mA with the result that the cathode-current is 40 mA. If we think of a 5%-change in the mains voltage as substantial, we should not include a 14%-error in our current measurements. Most serious datasheets specify the **plate-current** in the operating point; measurements at the cathode resistor would give us the **cathode-current**. That in fact is no problem if the screen grid (g_2) is operated with a grid-resistor in series (e.g. 470 Ω): in this case the screen-grid-current can easily be calculated from the voltage drop across this resistor. Still: CAUTION! This measurement, too, can have a deadly conclusion … the same danger that always exists when doing measurement on the opened-up amplifier. Do observe all regulations!

Instead of recommendations relating to the plate- or cathode-current in idle state, we also find hints towards an optimal setting of the bias-voltage at the grid: *adjust to -42 V at the grid (g1) of the power tube.* Indeed, this also is a workable approach: measure – using a volt-meter with high input impedance – the voltage between grid and cathode with no drive signal present: the more negative this value, the smaller the plate current, i.e. at -50 V there is less current through the tube than at -40 V. The actual current value is, however, not revealed this way.

So, what **is** the correct voltage or the correct current? Answers fill many thousand pages on the Internet; it's a science in itself. Correction: it's a playground for self-proclaimed experts, not a science as such. Searching for Ohm's law, you will consistently find $U = RI$. Looking for rules to set the bias, results are contradictory. One advice might be to use an oscilloscope and "*turn up the bias until the kinks in the curves disappear*". Plausible, that one: the spelling is correct – must be a studied person. But the next entry calls exactly this method: "*couldn't be further from the truth*". Is it even more plausible because the guy has 1532 postings?

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Well then, let us add version 1001 to the 1000 existing ones. First, however, and as always, we need to suffer through some basics. In **push-pull** power stages (and only those are discussed here, anyway), the audio signal is first dissected into two parts that are amplified separately and then re-joined. The separation- and re-joining processes are error-prone, and it is here that the bias-current adjustment helps out. Changing the bias-current may improve the sound – or make it worse if you don't do it right. If the bias-current is set too low (cold biasing), distortion of the not-so-nice kind appears. At the same time the power-stage has an expander-effect: a lightly plucked string will be reproduced too softly, and with a stronger attack the amp suddenly roars. For the bias-current set high (hot biasing), the sound is good (if there are no other issues). So, should we set the bias-current as high as possible? No, don't – that will reduce the power-tube lifespan (which anyway is relatively short) even further, and could possibly destroy the power supply if it is under-sized. This would be the main effects.

In the details, 2nd-order-effects show up, as well. For small bias-currents, the filter-capacitors in the power supply get charged to a higher voltage, which might give the preamplifier- and intermediate-amplifier-stages a different operational behavior. We should not expect big effects from this but it should be mentioned for completeness sake. A small effect could also manifest itself in terms of the impulse-power i.e. the power measured at the onset of a tone. If the filter caps are charged to a higher voltage, the impulse power, too, will be a little higher. It is, however, not purposeful to reduce the bias-current just because of such effects – the distortion connected to the readjustment is normally not acceptable. If we do not start with the details but stick with the main effects, we have a simple rule: **low bias-current = distortion**, **high bias-current = premature death of the tubes**.

But then, we also find: high bias = distortion, low bias = tube-death. How can that be? Simple, actually: the experts, in particularly the self-proclaimed ones, writing (rather: allowed to write?) their columns in the guitar-magazines do have very different educations[♣]. The term bias is not always meant to refer to the actual bias-current but may be used as for the bias-voltage fed to the grid of the power tubes in idle. This is where a mix-up may well happen, and even a double mix-up at that, because for the negative bias-voltage, it is easy to confuse the magnitude of the given number and the actual value (with a "-"-sign). A lower (more negative: e.g. -50 V instead of -40 V) bias-voltage leads to smaller bias-current (and vice-versa), but this means that the larger absolute number (50 vs. 40) corresponds to the smaller bias current (and vice versa). All this is now connected to the one term "bias" in many not-so-professional publications. What does an author seek to express when he/she writes "turn up the bias"? Should it be more bias current (idle-current) i.e. plate-current (or even cathode-current!) when no input signal is present? Or more voltage fed to the grid via the bias pot? If the latter: more voltage in absolute numbers (i.e. go to from 40 V to 50 V, both voltages being negative), or higher voltage in terms of physics (i.e. go from -50 V to -40 V)? It's all rather complicated, and one person implies *this* while the other understands *that* – but only because (and if) unclear terminology is used. Therefore, let's talk about idle-current, or bias-current, or grid-bias-voltage or even bias-voltage (with a clear "-"-sign, and watching the polarity of our meter); but let's avoid "bias" without further specifics. That term is simply not precise enough.

[♣] The corresponding scale (no lower boundary) includes the rating „has not a single clue whatsoever, at all".

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In the following, the term “**bias-current**“ is used to designate the plate-current flowing in *one* power tube when no input signal is present. Alternative terms for “bias-current” would be "quiescent plate-current" or "idle current". We will use the term “**bias-voltage**” to indicate the DC-voltage fed to the control-grid of the power tubes when no input signal is present. It is always a negative voltage. An alternative term for “bias-voltage” would be “grid-bias-voltage”. This terminology will lead to e.g. the precise statement: “At a bias-voltage of -50 V, a bias-current of 38 mA flows.” Only one possible pitfall remains: it needs to be clear that the bias-voltage is the voltage measured from grid to cathode. In case the cathode is connected to ground via a resistor (and possibly a capacitor in parallel), the grid/cathode voltage is not the same as the grid/ground-voltage. When taking a measurement, this is important. In the following, “bias-voltage” always indicates the grid/cathode-voltage.

Cold Biasing indicates that the bias-current is set to a relatively low value – corresponding to the “very negative” bias-voltage. In line with what has been said above, it is a bit problematic to use the terminology “small bias-voltage” because not everyone may understand that -50 V is smaller than -40 V. For a thermometer, the situation would be clear: -20 C° (or F°) is colder than -10 C° (or F°), and so -20 C° (or F°) is the colder/lower/smaller temperature. Despite a clear separation into topological and metrical scales, the Internet community has found its own interval scaling, and we may read the terminology “turning up the grid voltage” as a readjustment from -40 V to -50 V. Whether the voltage or the magnitude of the voltage is increased – it does make a difference. **Hot Biasing** is the other extreme: high bias-current, and a “less negative” bias-voltage. In other words, to safely avoid all doubts: the smaller the magnitude (i.e. the numeric value) of the (negative) bias-voltage, the hotter the tube is run. 10 mA/-60V is cold, 80 mA/-40 V is hot – just as an example! Because we will see in the following that these numbers are circuit-specific; one circuit’s “cold biasing” may well be the other circuit’s “relatively hot”.

In **Fig. 10.5.21** we see both the characteristics of the individual tubes (dashed) and the overall characteristic generated by superposition. The center picture shows a “cold operating point” i.e. “**cold biasing**”. With little change in the drive level (the voltage indicated on the abscissa), neither of the tubes feels animated towards much activity – both still are in blocking mode and the overall current remains small. Only for larger input voltages, the tubes start to move into the respective (alternating) conducting state and the current increases. The result is a saddle-shaped crossover-distortion. In the left-hand picture, the situation is different: the bias-currents in the operating point are higher, the overall (summed) characteristic retains its incline over a broad range and only curves clearly at the overdrive-limit.

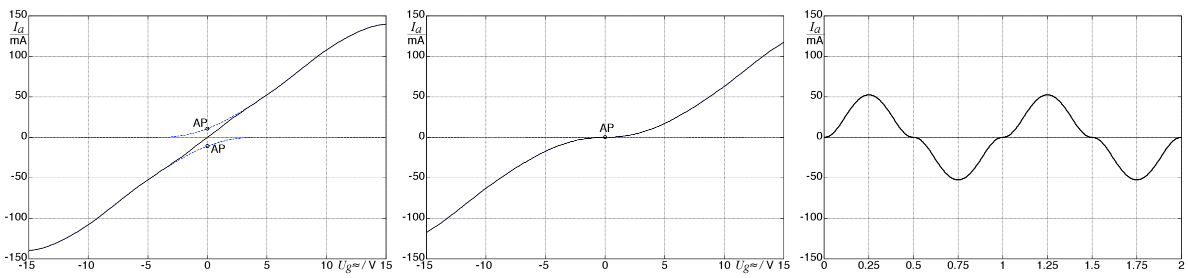

Fig. 10.5.21: Characteristics for two different settings of the bias-current. On the right, the distortion relating to the characteristic in the center picture is shown (“crossover-distortion”).

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The cold biasing shown in the center picture has two effects: undesirable non-linear distortion, and an expansion just as unwanted. In contrast to a compressor, an expander increases its gain with increasing signal level – not a stylistic device many guitarists welcome. Corresponding measurement data are shown in **Fig. 10.5.22**: in a Super-Reverb, the bias-current (I_a) of the power stage was varied between 10 mA and 53 mA. With a bias-current set to 10 mA, the output level increases by 27 dB as the input level rises by 10 dB – this is already a noticeable expansion. The right-hand picture shows the corresponding 3rd-order distortion level – again there are clear differences.

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Fig. 10.5.22: Fender Super-Reverb (2x 6L6-GC), bias-voltage varied between –65V and –40V.
Left: output signal level vs. input signal level; right: distortion level vs. input signal level. **NFB disabled**.

In order to document the effects of the bias-current on the forward branch, the measurements for Fig. 10.5.22 were done with the negative feedback loop left open. With active NFB (**Fig. 10.5.23**) we see similar curves with a minimally weaker expansion and slightly lower distortion. For the "hot" operating modes the difference in the distortion is clearly visible; for the operation with low bias-current we need to consider that for equal input levels, the output levels differ considerably, after all.

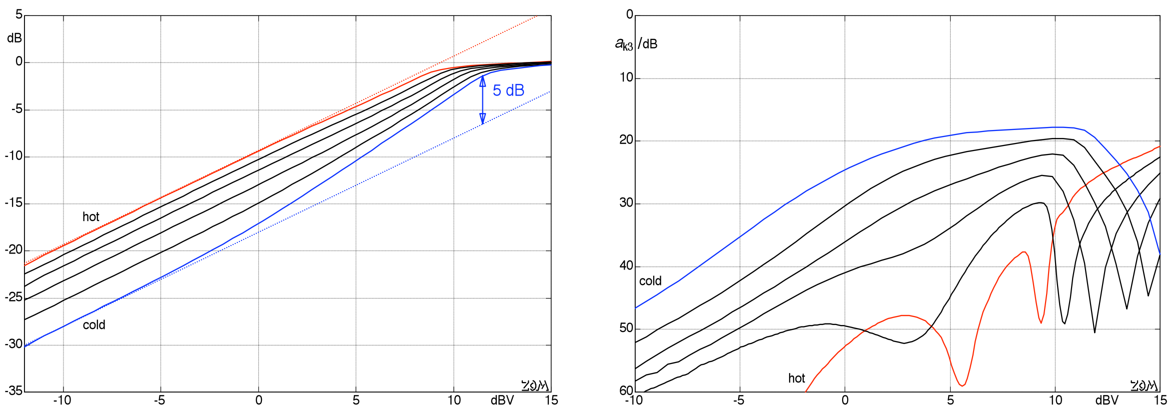

Fig. 10.5.23: Fender Super-Reverb (2x 6L6-GC), bias-voltage varied between –65V and –40V.
Left: output signal level vs. input signal level; right: distortion level vs. input signal level. **NFB enabled**.

Usually, the Super-Reverb will not be operated with a bias-current as small as shown via the blue curves. A larger bias-current (about 35 – 45 mA) would be normal. However, the bias-current should not be much larger, either, because the plate-loading would then possibly enter the critical range (see Fig. 10.5.26).

Variations of the bias-current in the power stage will change distortion, gain and dynamics, and also alter the internal impedance. We have already seen in Chapter 10.5.7 that the internal impedance of a tube is not constant but depends on the operating point. The internal impedance transformed by the output transformer therefore depends on the OP, too. With a high internal impedance of the power stage, the loudspeaker experiences less dampening, and resonances influence the transmission behavior more strongly. Moreover, since the speaker impedance rises towards high frequencies (Chapter 11), the high internal impedance results in a treble boost. **Fig. 10.5.24** shows measurement results for a Super-Reverb.

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Fig. 10.5.24: Super-Reverb. Left: magnitude of the output impedance; right: transfer-function of the power stage. NFB active; amplifier loaded with loudspeakers (4x Jensen 4xPR-10). Different bias-currents.

Operating the amplifier with a small bias-current (cold biasing, I_a = 15 mA), the internal impedance of the amplifier (with active negative feedback) amounts to 30 Ω – this is relatively high compared to the load impedance. The resonance peak and the treble boost are more pronounced than for the “hot biasing” shown in red (I_a = 50 mA).

A different picture emerges for the Marshall power amplifier which features stronger negative feedback. The output is of significantly lower impedance, and the loudspeaker impedance maps onto the output voltage to a much lower extent (**Fig. 10.5.25**). For usual settings of the bias-current, the 16-Ω output of the JTM-45 is lower in impedance compared to the Super-Reverb by a *factor of five*! However, it would be wrong to conclude that the Marshall could/should be operated with a loudspeaker of smaller impedance (or the Fender with a loudspeaker of higher impedance): the optimum load-resistance is not directly derived from the internal impedance but from the limit data of the tubes.

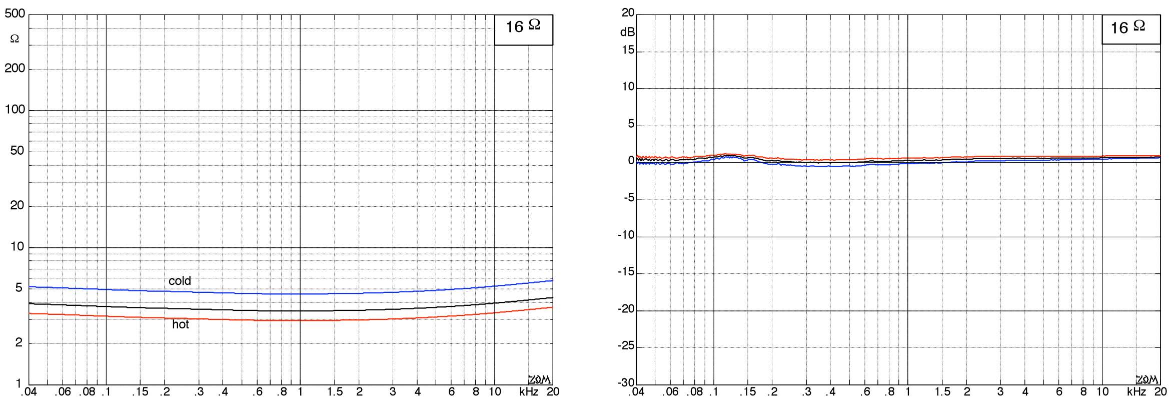

Fig. 10.5.25: JTM-45. Left: magnitude of the output impedance; right: transfer-function of the power stage. NFB active; amplifier loaded with loudspeaker (Marshall 1960-AX). Different bias-currents.

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The above pictures show that the transmission characteristics (and therefore also the sound) of a power stage depend on the setting of the bias-current. The latter also influences the **power dissipation**, and the following is dedicated to this issue. The less negative the bias-voltage is, the larger is the plate-current and the larger the power dissipation at the plate. We frequently read that the power dissipation at the plate (without input signal) should be 70% of the maximum permissible power dissipation. As an example: for the 6L6-GC, specified at 30 W, this would be 21 W (e.g. 47 mA at 450 V). It is not purposeful to search for the origin of the 70%-rule – that would be much too speculative. More conducive is to build an example explaining the strain that the tubes experience. **Fig. 10.5.26** shows three load lines of the 6L6-GC drawn into the output characteristic. For the upper line, we assume a bias–current of 47 mA, and for the lower line one of 33 mA. We calculate (for a plate-voltage of 450 V) a power dissipation in idle of 21 W (70%), and 15 W (50%), respectively. Although the dissipations in idle differ by as much as 40% ($21 = 1.4 \cdot 15$), the maximum power for R_a = 1.3 kΩ varies by only 7%. Only changing the load-impedance from 1.3 kΩ to 1 kΩ brings larger differences in the strain on the plate. What about the mean values of these curves? They depend on the individual drive levels. The worst-case would be a square-shaped plate-current of an amplitude of 200 mA (1.3 kΩ); the determined instantaneous power would have to be halved because each power tube conducts only for one half-wave. For R_a = 1.3 kΩ, the maximum allowable power dissipation at the plate is not reached – it is, however, already slightly surpassed for R_a = 1.0 kΩ.

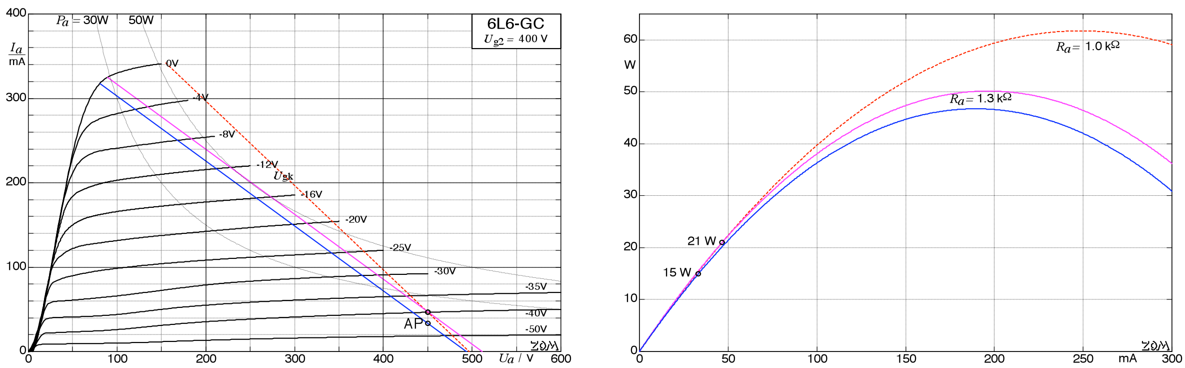

Fig. 10.5.26: Output characteristic of the 6L6-GC. AP = operating point without input signal.
Right: power dissipation at the plate dependent on the plate-current. Load impedance = 1.3 kΩ / 1.0 kΩ.

In conclusion: regarding the strain on the plate, the load-impedance is much more important than adjusting the bias-current to the second decimal. If the load impedance becomes too small, the plate will be overloaded. Of course, the type of drive- (or overdrive-) signal plays a role, as well – as does the voltage at the screen-grid … and as does the plate-voltage. Most everything that can change does change. Therefore there is no harm in calculating a load line once in a while – but only if we do not seek to adhere slavishly to the results. In Fig. 10.5.26, the operating point was assumed for 450 V. However, with the presence of a drive signal, the voltage delivered by the power supply does not remain constant but may easily change by as much as 50 V depending on the load… the strain on the plate will change correspondingly. Also, the load line will deviate even much more from the normally assumed straight line. No **loudspeaker** has a constant and purely ohmic impedance (Chapter 11). Rather, the loudspeaker impedance is complex (voltage and current are phase-shifted re. each other), and its magnitude can easily vary by a factor of 10 depending on frequency. Calculations using straight load lines are highly idealized models – nothing more but also nothing less. Reality is very different, in any case.

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In reality, a guitar amplifier is neither driven by sine-tones nor is it loaded with a purely ohmic resistance. Neither its supply voltage nor the voltage at the screen-grid are constant. **Fig. 10.5.27** shows a first step in the direction of reality: these output characteristics were not determined on the test-bench but from a real guitar amplifier.

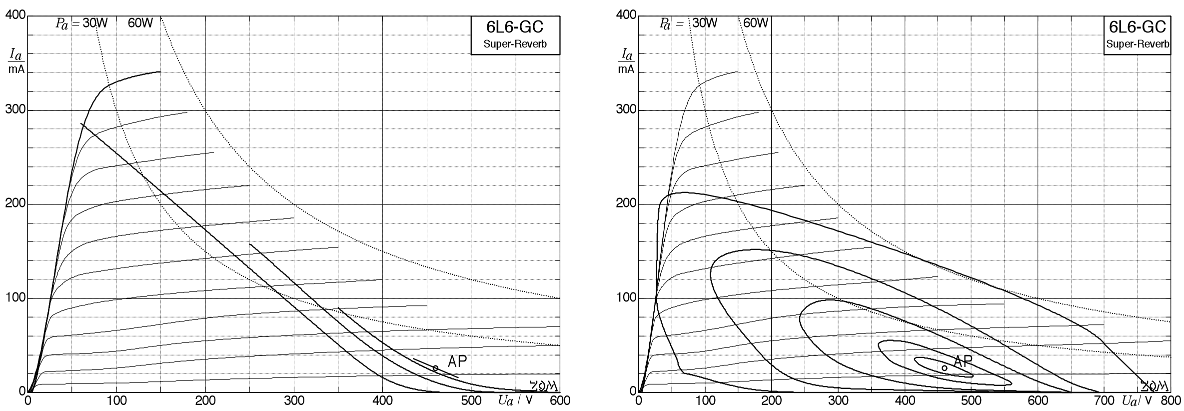

Fig. 10.5.27: Output characteristic; Super-Reverb with purely ohmic load (left), and with complex load (right).

For the measurements shown on the left, the amplifier was loaded with a purely ohmic 8–Ω–resistor. Small drive levels yield a small, straight line through the operating point. This line grows as the drive level increases, bends and shifts to the left. Consequently, even an ohmic load does not generally warrant assuming a straight line passing through the operating point. This is because on one hand the supply voltage drops, and the other hand the coupling capacitors are polarized due to the current flowing through the grids (Chapter 10.4). The curves on the right are for a complex loudspeaker-load (f = 3 kHz). For small input levels we see ellipses encompassing the operating point; large drive levels result in sharply bent curves that extend into the range of 30 W – which has been specified as limit. Since that value needs to be seen as short-term power average, this transgression does not generally indicate a thermal overload of the tubes (Chapter 10.5.9).

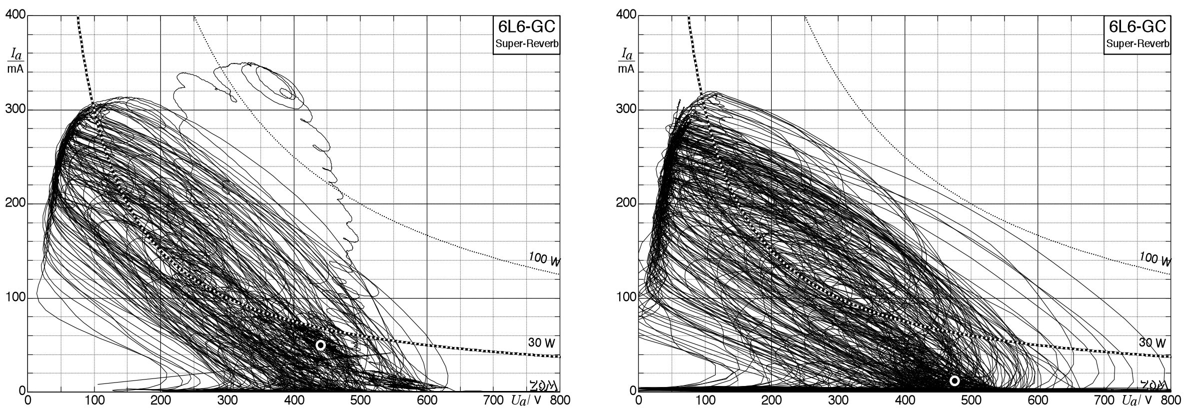

Fig. 10.5.28: Output characteristic, Super-Reverb with loudspeaker load using guitar tones (Stratocaster).

Even closer to reality are the curves depicted in **Fig. 10.5.28**: with a loudspeaker as load, the Super-Reverb was played with a guitar – and no sign of any straight load line at all remains! Rather, there is a myriad of highly different loops that only with great difficulty allow for any conclusion regarding the setting of the bias-current (white circle). Therefore, the load line is unsuitable to establish any connection between bias-current and power dissipation in the tubes – to do this, true measurements of the power dissipation are necessary.

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In order to measure the power dissipation at the plate, the plate-voltage and the plate-current need to be recorded. Just multiplying the RMS-value of the plate-voltage with the RMS-value of the plate-current is not sufficient because that way we would merely determine the *apparent power* [20]! So: anybody connecting a volt-meter to the plate, and an ampere-meter serially into plate-connection, will indeed measure U_a and I_a, but the product of these values will only give information about the strain on the tube in a DC-situation. With an input signal present, however, AC results – and here we need to distinguish between effective power, reactive power and apparent power. It is the **effective power** (the product of plate-voltage and plate-current averaged over time) that heats up the plate. It is important to understand that it makes a difference whether the multiplication comes first (ahead of the averaging – correct for the present considerations) or averaging comes first (ahead of the multiplication – incorrect in the present case). Fig. 10.5.28 has impressively shown that for this 6L6-GC, the short-term dissipation at the plate exceeds 100 W – more than three times the value specified as a maximum. A tube needs to be able to take such a short-term overload if it is to be successfully deployed in a guitar amplifier. As we switch on the plate-current, the temperature of the plate begins to rise – thermal energy is supplied. At the same time, **thermal energy** is dissipated via radiation, and after some time a steady equilibrium, i.e. a constant plate temperature, is reached. If this temperature is too high (with the plate glowing brightly), the tube dies. If we do not wait until the equilibrium is in place, the temperature remains below the steady final value. Compare this to a car: stepping on the accelerator for only 2 seconds will not give you maximum speed. For a tube, though, 2 seconds would already be relatively long – in any case the typical short-term overload situations in a guitar amplifier will be of lesser durations.

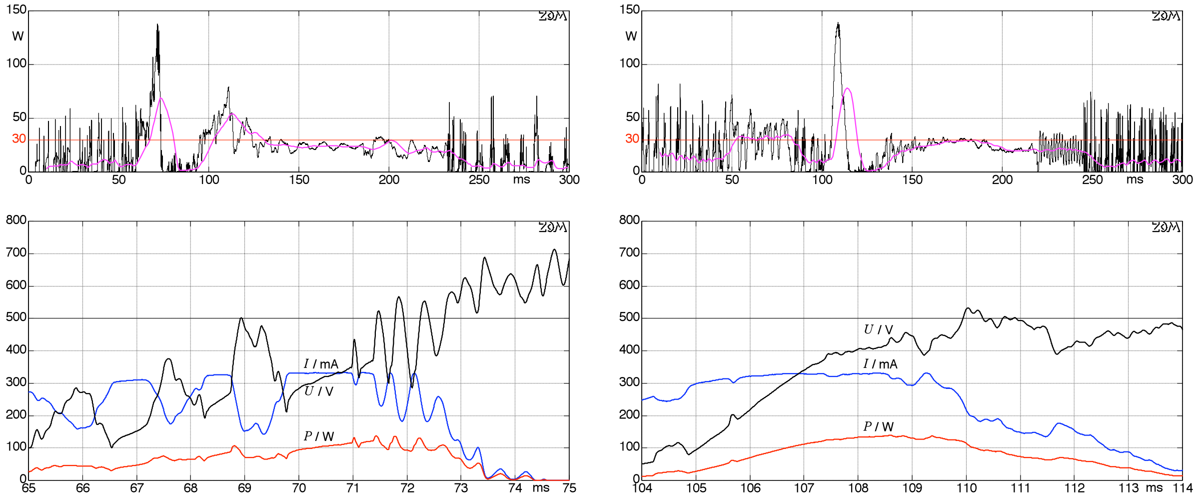

Fig. 10.5.29: Instantaneous power dissipation at the plate (black), sliding 10-ms-average (magenta).
The lower section shows excerpts from the progress of the plate-voltage, -current, and -power-dissipation.

Fig. 10.5.29 shows two examples for a loudspeaker-loaded Super-Reverb. The instantaneous values of the plate dissipation (sampled at 48 kHz) reach about 140 W. Averaging over 10 ms still gives values significantly in excess of the specified 30-W-limit. The lower line in the figure indicates that this strain happens in a frequency range unusually low for guitar tones: interpreting 10 ms as half a period, we get 50 Hz. This is not connected to the mains frequency but results from effects of overdrive-related recharging processes in phase-inverter (Chapter 10.4) and power stage. Since such short-term overloads can happen repeatedly, it is purposeful not to set the bias-current too high so that little effective power is fed to the tube in between such high-power phases. The question now remaining is: how high is a bias-current set “not too high?

So, at last: what is the correct setting of the bias-current (the "**bias setting♣**")? Unfortunately, there is no formula that will generally hold – the circuits, tubes, loudspeakers, and ways of playing that can occur are too diverse. Nevertheless here are some basic recommendations:

For **group 1** including laypersons i.e. persons without any education in electronics: whoever is not clearly aware of the reasons why in a 40W-amp voltages of over 800 V may occur, and who does not know how to protect him-/herself against the corresponding deadly dangers, must not open up an amplifier. Studying the manual of a multi-meter must not be understood as an education in electronics, and the same holds for confident handling of a screwdriver. Not everybody who removes an amp chassis from a cabinet instantly keels over dead – but this fact must not lead to the conclusion that this will never happen. If we are not allowed to open an amp, we can merely resort to measurements using a socket-adapter. The latter should be certified and re-checked regularly according to local regulations because it is subject of the same high voltages. Equipped this way, we now (more or less incorrectly) consider ourselves part of group 2.

Group 2 includes appropriately trained persons (e.g. certified electricians) who have simple measurement devices at their disposal. They should be in the position to adjust the bias-current without being in danger, should be able to recognize whether a power stage operates in true class-A mode (BIG exception), and then be able to find – using an oscilloscope – the middle of the load line. For an amplifier working in class-AB mode, the only helpful approach is a mixture of listening-tests and simple measurements of the power consumption in idle: if the amp already sounds good at 50% of the allowable plate-dissipation (e.g. 450 V, 33 mA for the 6L6-GC), you should just let it be. If your hearing (or the musician looking over your shoulder) demands more, you can run the thing a bit hotter – but at 70% most practitioners will raise an admonitory finger although there is no theoretical foundation for this limit. In any case, the power tubes need to be looked at in the dark to check whether, during any phase of extensive and multifaceted testing, grids and/or plate are visibly glowing. That this testing is not to be done with just a sine-generator and simple load-resistor should be – in view of the above – crystal clear by now.

Group 3 includes persons belonging to group 2 who have special instrumentation equipment in their arsenal, for example a current clamp that can measure with a resolution of 10 mA or better, and in the frequency range of 0 – 10 kHz. Seriously: 0 Hz – because the DC-components need to be measured, as well, and thus a frequency limit of 1 Hz is useless. Suitable would be e.g. the Tektronix AM305B/A6302, with the offset continuously monitored. Given such a current-measuring device and a high-voltage test-probe for the voltage measurement, you can then capture the factors determining the plate dissipation, digitize them in the calibrated front-end, store them in the computer and derive the actual, true loading of the tube. Once you've gotten that far, inevitably the question will arise whether today's tube manufacturers will actually still adhere to the tube data from the 1950s, and will warrant e.g. 800 hour MTBF for their products. The other immediate question is whether indeed every tube-wholesaler who allegedly cooperates in the development of "his" special tubes will expend such an effort.

In the case that "no" is the answer to these questions, we quickly move to become members of **group 0**. Here we join all those who have noticed that old Marshalls or Fenders did not even have any means to adjust the bias-current – but still did their job admirably. And so we change the tubes, if need be, and that's it.

♣ too much of a bias never is a good thing – that seems to hold for all aspects in life.

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