Soldano Super Lead Overdrive Channel

The First Stage

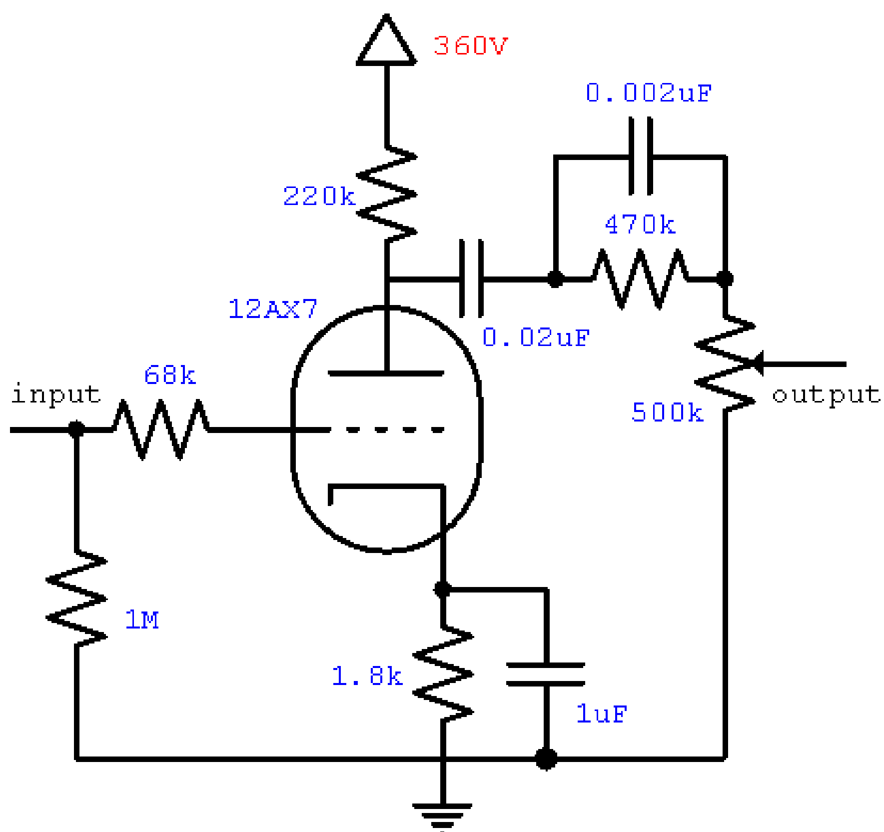
Classic Preamp Overdrive

The Soldano Super Lead Overdrive channel is renown for gain. In fact, input sensitivity for preamp overdrive, as we will demonstrate, is less than 1 millivolt with the volume control at maximum. This is more than an order of magnitude greater than classic amps like the Fender Bassman and its offspring.

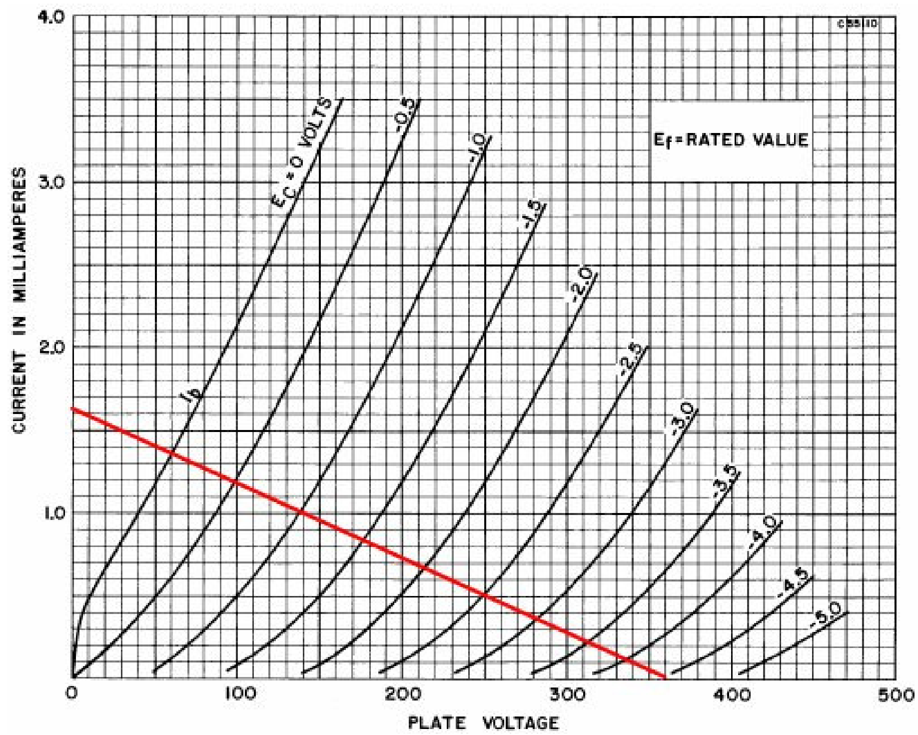
Soldano's master volume control is placed between a modded Fender Bassman Tone Stack and a 5F6-A phase inverter and power amp. Crank the potentiometer to maximum and the preamp drives the power amp into classic Class AB distortion. Turn it way down and the preamp creates its own second-to-third harmonic transition and sustain that can last well beyond the band's next smoke break. Somewhere between minimum and maximum, however, is a realm of pure magic that is unique to Soldano's carefully crafted design. Let's take a closer look.

DC Operating Conditions

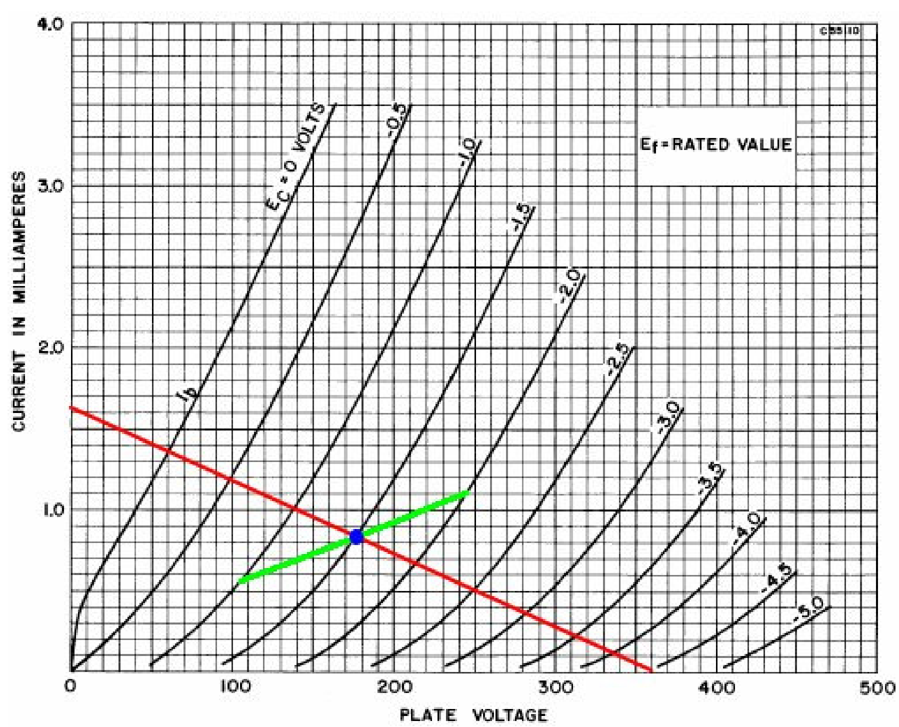
The first stage has a gamma network at the input and a bright boost circuit at the output.



The DC load line has one end at the DC plate supply voltage of 360 volts and the other at a plate current of (360) / (220k + 1.8k) = 1.6mA.

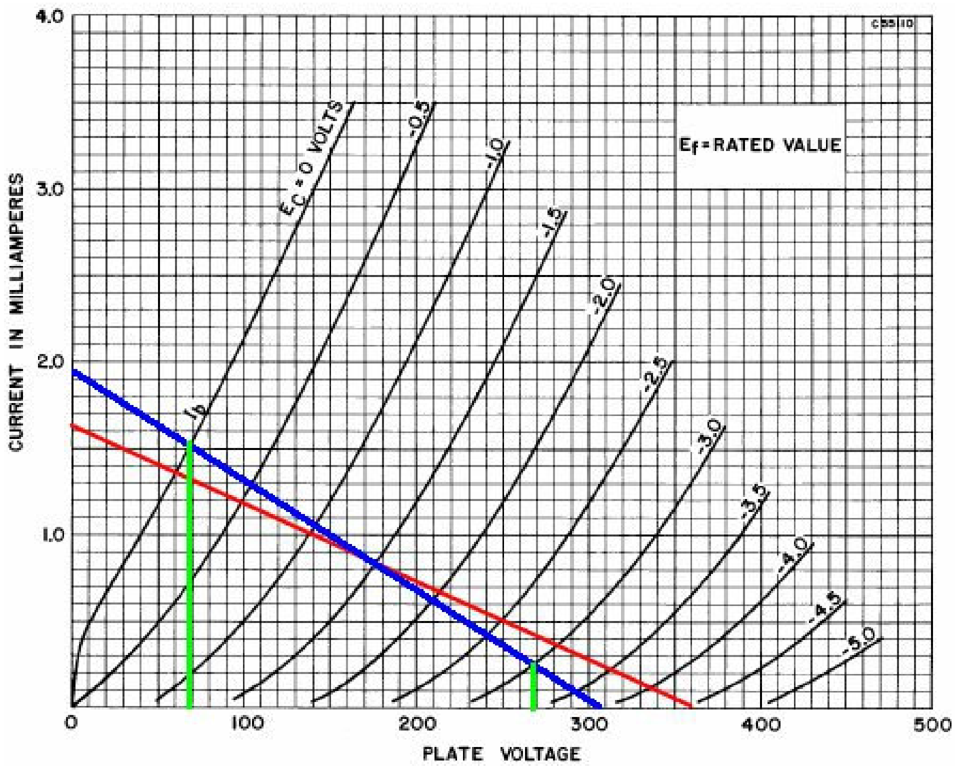


If the grid voltage is minus 1 volt then the plate current passing through the 1.8k cathode resistor is 1 / 1.8k = 0.56mA. For grid voltages of minus 1.5 and minus 2 volts, the plate current is 0.83mA and 1.1mA, respectively. These points create a grid line that puts the DC operating point at minus - 1.5 volts.



Headroom and Distortion

At high frequencies when the 470k resistor is shorted by the capacitor across it, the AC load becomes 220k in parallel with 500k for an effective impedance of 154k. In that case a drop in plate voltage from 175 volts (the DC value) to zero volts creates an increase in current of 175 / 154k = 1.1mA. The current thus rises from 0.83mA (the DC value) to 1.93mA, which forms the upper left end of the blue AC load line show here. (At lower frequencies the AC load line is closer to the DC load line.)



An input signal with an amplitude of 1.5 volts drives the plate voltage between 68 and 268 volts (the green lines). Large signal voltage gain is therefore (268-68) / 3 = 67.

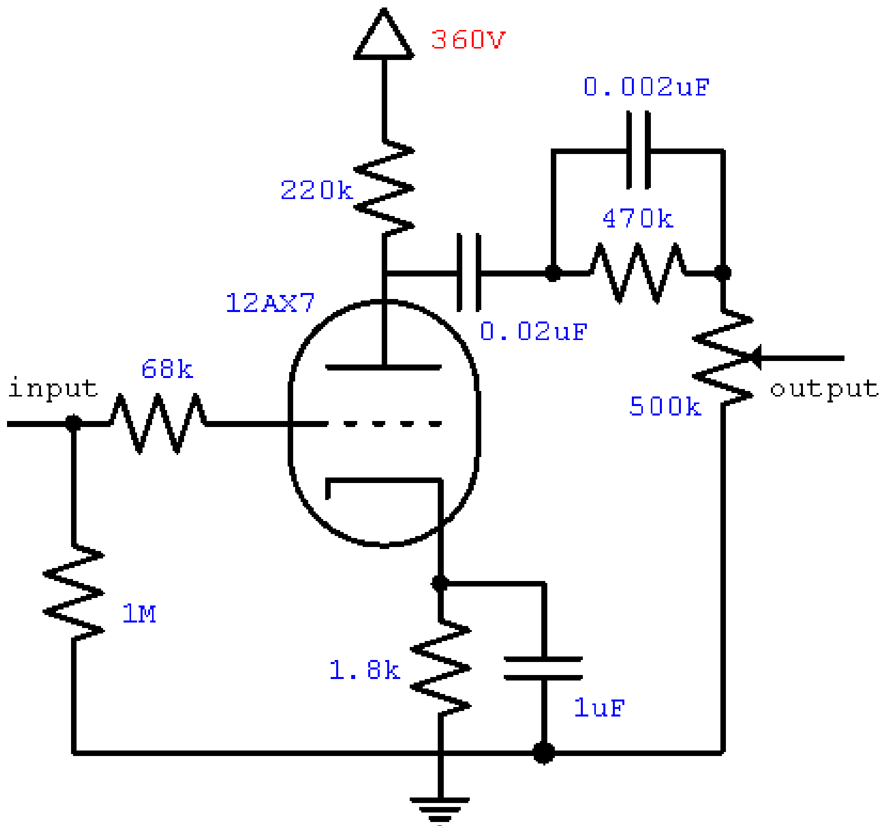
The gain at maximum swing is slightly less than the gain at low signal levels because of compression as the grid voltage approaches minus 3 volts. The grid lines are closer together so the plate voltage swings less. This compression creates second-harmonic distortion that increases as the signal amplitude approaches 1.5 volts. Beyond 1.5 volts the triode goes into saturation on positive swings of the input signal. Above 2.5 volts the grid swings to below minus 4 volts, forcing the tube into cutoff as well.

Distortion is thus characterized by steadily increasing second harmonic distortion as the signal amplitude approaches 1.5 volts, rapidly increasing second harmonic distortion as the amplitude increases from 1.5 to 2.5 volts, and severe third harmonic distortion at higher levels. Ultimately an input sinewave creates an output square wave when the input signal is high enough.

With a high-gain pickup, guitar volume set to maximum, and amp volume set low enough, this stage could conceivably be driven into overdrive while keeping subsequent stages clean. In typical operation, however, the triode operates well below its swing limits, creating substantial voltage gain and a modest amount of second harmonic distortion that is enhanced by the bright boost of the output circuit.

The Input Circuit

The overdrive channel's first stage uses a classic gamma network for the input circuit.



Assuming a voltage gain of 74 and a grid-to-plate capacitance of 1.7 picofarads this means the -3dB high-frequency cutoff is at 18kHz. There is unity gain for guitar frequencies so the input headroom at the jack is the same as at the grid: 1.5 volts. Radio frequencies are effectively suppressed.

Bright Boost

Small signal voltage gain increases from 51 at 82Hz to about 74 at 400Hz due to the relatively small, 1uF cathode bypass capacitor. At the top of this range the output impedance is 49k, equal to the plate load resistor in parallel with the plate resistance of a 12AX7 triode. With a load ranging from 500k to 970k, depending on frequency, this creates a loss of 1dB or less across the 0.02uF coupling capacitor.

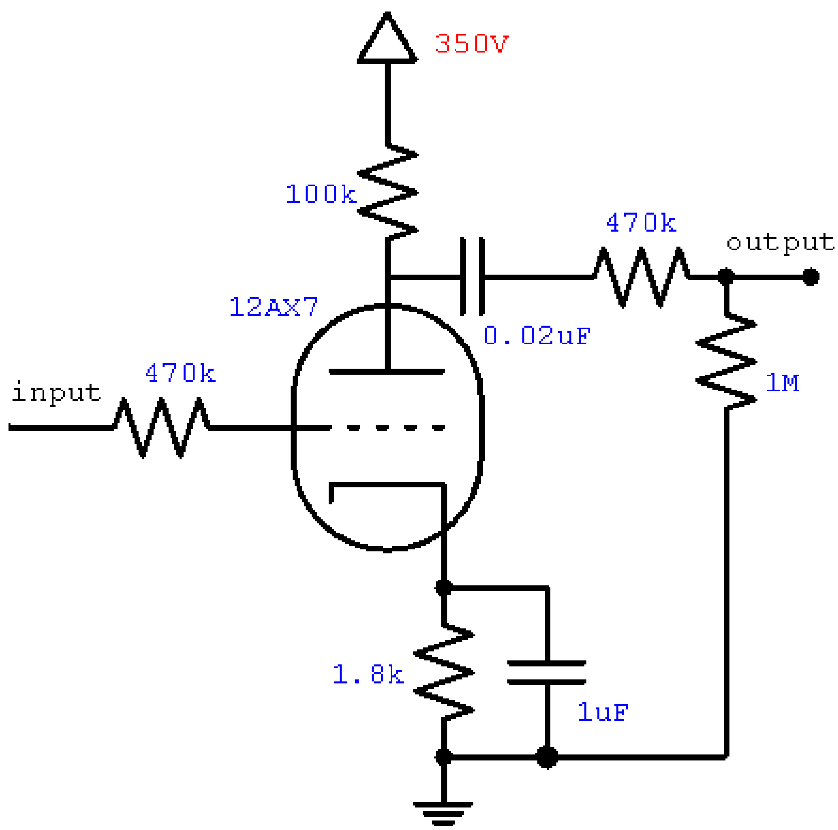
The 0.002uF capacitor in the output circuit provides bright boost at higher frequencies by shorting the 470k resistor across it. With the volume control at maximum the 12AX7 output is attenuated by almost 6dB at 82Hz but down by only 1dB at 1kHz. (This assumes the bright boost circuit is driven by a constant 49k output impedance, which is a reasonable approximation for treble frequencies in which the cathode is fully bypassed.)

Soldano's first stage certainly brightens up the signal.

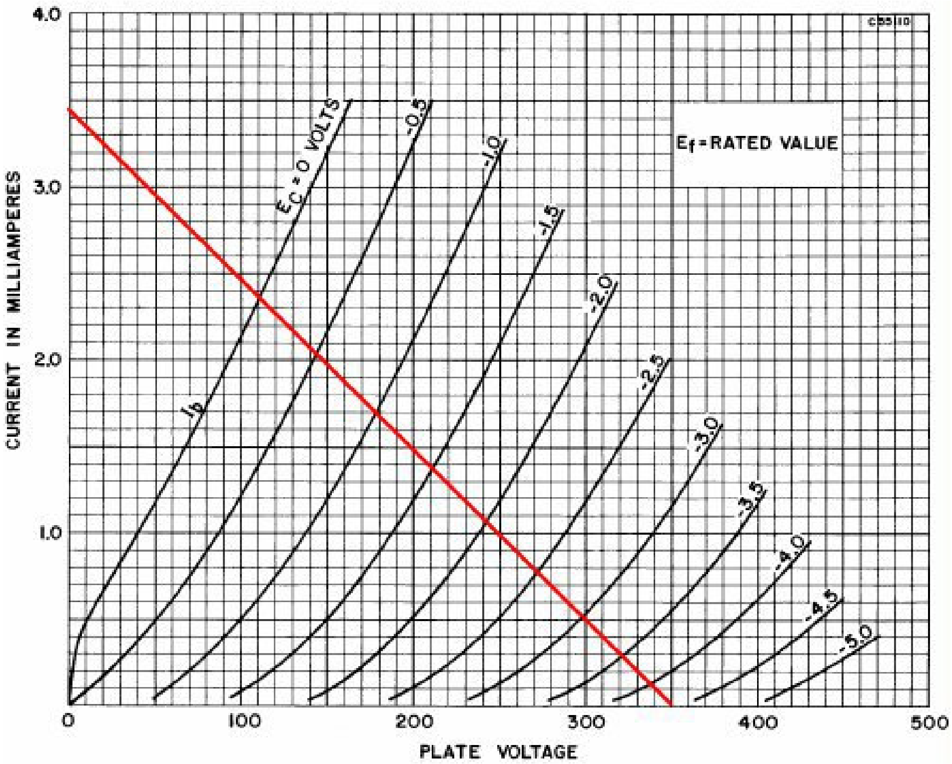
The Second Stage

DC Operating Conditions

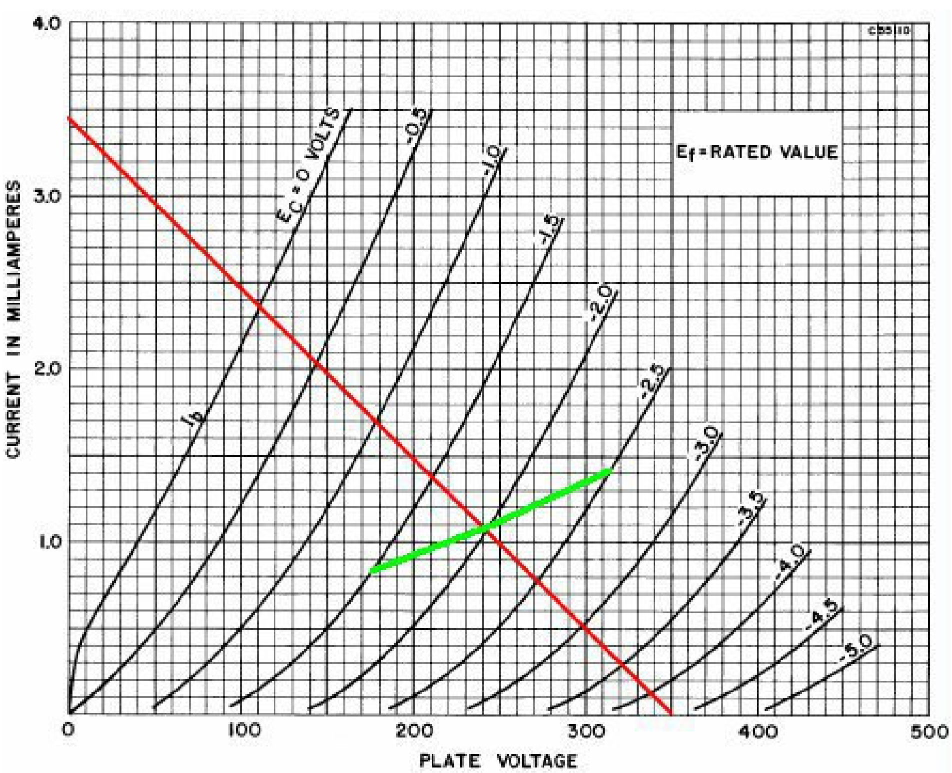
The second stage has a 12AX7 triode driven via a large grid-stopper.



The DC load line has one end at the DC plate supply voltage of 350 volts and the other at a plate current of (350) / (100k + 1.8k) = 3.4mA.

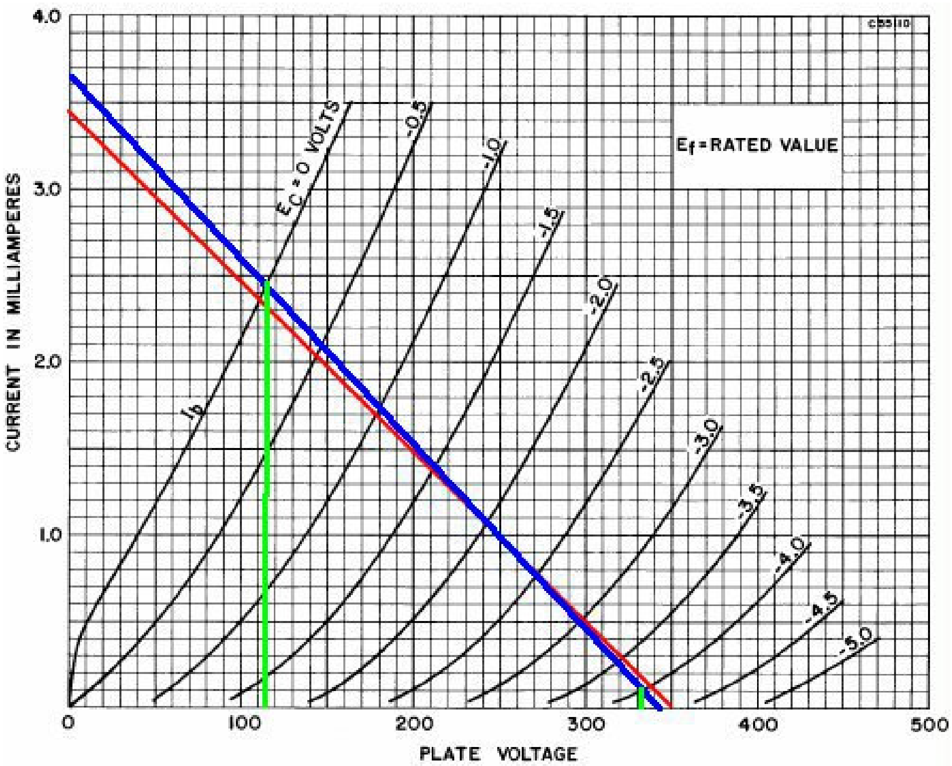


If the grid voltage is minus 1.5 volts then the plate current passing through the 1.8k cathode resistor is 1.5 / 1.8k = 0.83mA. For grid voltages of minus 2 and minus 2.5 volts, the plate current is 1.1mA and 1.4mA, respectively. The resulting grid line puts the DC operating point at minus 2 volts.



Headroom and Distortion

The effective plate load is 94k at high frequencies where the cathode is shorted and the plate is loaded by the 1.47M output circuit. In that case a drop in plate voltage from the DC operating value of 240 volts to zero volts creates an increase in current of 240 / 94k = 2.55mA. The current thus rises from 1.1mA (the DC value) to 3.65mA, which is the upper left end of the blue AC load line show here.



Notice that the AC load line is much closer to the DC load line in this stage compared to the first stage. This is because the latter has a 220k plate resistor that creates a greater output impedance. It also drives a 500k load, which demands more current than the 1.47M load in this stage.

A grid voltage swing from zero to minus 4 volts causes a plate voltage swing from 115 volts to 332 volts. The gain over this range is therefore (332-115) / 4 = 54.

Compared to the first stage the DC operating point is closer to the middle of the AC load line. A 4 volt grid voltage swing thus drives the tube into saturation and cutoff nearly simultaneously. Distortion is therefore characterized by increasing second harmonic distortion as the signal amplitude approaches 2 volts, then rapidly increasing third harmonic distortion as the signal level increases further. Ultimately a sinewave input signal becomes a square wave at maximum overdrive.

Input Sensitivity

At high frequencies the first stage has a gain of about 74 at its plate. With the volume control at maximum the first stage output circuit has a gain of about 0.5, creating a total first stage gain of

(0.5)(67) = 34. Thus the amplitude at the input jack needed to drive the second stage into overdrive is 2 / 34 = 59 millivolts. This is certainly achievable, even with low gain pickups. Stay tuned, however, because Soldano's legendary preamp gain doesn't stop here.

Frequency Response

Small signal voltage gain increases from 35 at 82Hz to about 55 at 400Hz due to the relatively small, 1uF cathode bypass capacitor. Maximum treble gain is 60. The 0.02uF coupling capacitor is effectively shorted at all guitar frequencies. The voltage divider formed by the 470k and 1M resistors at the output attenuates the signal by a factor of 0.68 (3.3dB).

Overdrive

The 470k resistor is in series with the first stage output impedance, which is well under 100k. From the perspective of the second stage, the effective first stage output impedance increases to about 500k, many times higher than in a typical 12AX7 voltage amplifier.

The high output impedance causes Miller capacitance in the second triode to have more of an effect, enough to significantly attenuate high frequency guitar signals. The grid stopper attenuation for a 4 kilohertz signal, for example, is 4dB to 6dB depending on the volume control setting. This response offsets the substantial treble boost created by the first stage.

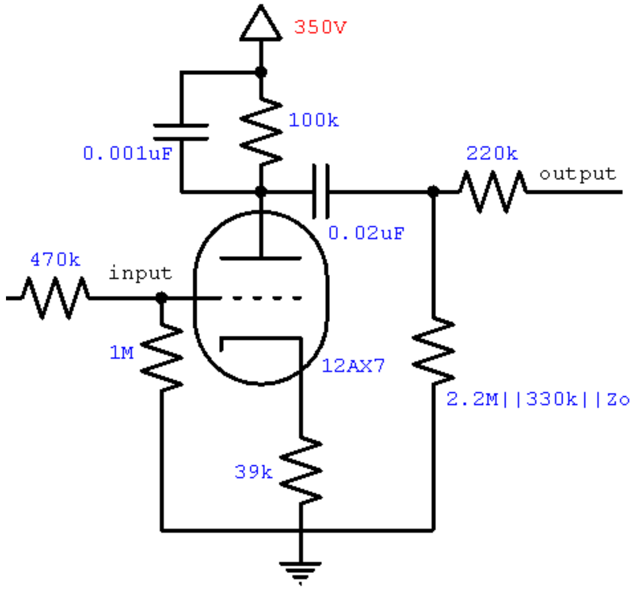
In overdrive the high output impedance becomes a distinct advantage. It ensures that the first stage cannot drive the second stage grid positive by any appreciable amount and is not bogged down by any grid current that flows. It always sees a load of at least 470k independent of the state of the second triode. This greatly reduces bias excursion that can lead to blocking distortion.

Large grid stoppers are often used in high-gain, master volume control preamps, but are absent in classic amps that rely on power amp distortion. In the Fender Bassman 5F6-A, for example, the power stage is overdriven long before the preamp stages. Preamp bias excursion is therefore not an issue. Bright boost to compensate for large grid stoppers is also unnecessary in a more traditional design.

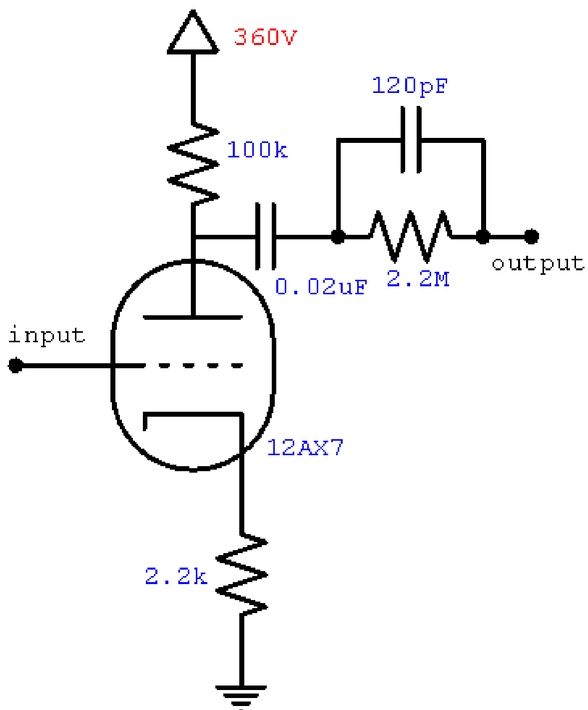
The Third Stage

DC Operating Conditions

The third stage has a 12AX7 triode sharing the same plate supply as the second stage.



The AC load consists of a 2.2M resistor in parallel with a 330k resistor and the output impedance $\mathbf{Z_o}$ of the normal channel's second stage. Here is what that stage looks like:

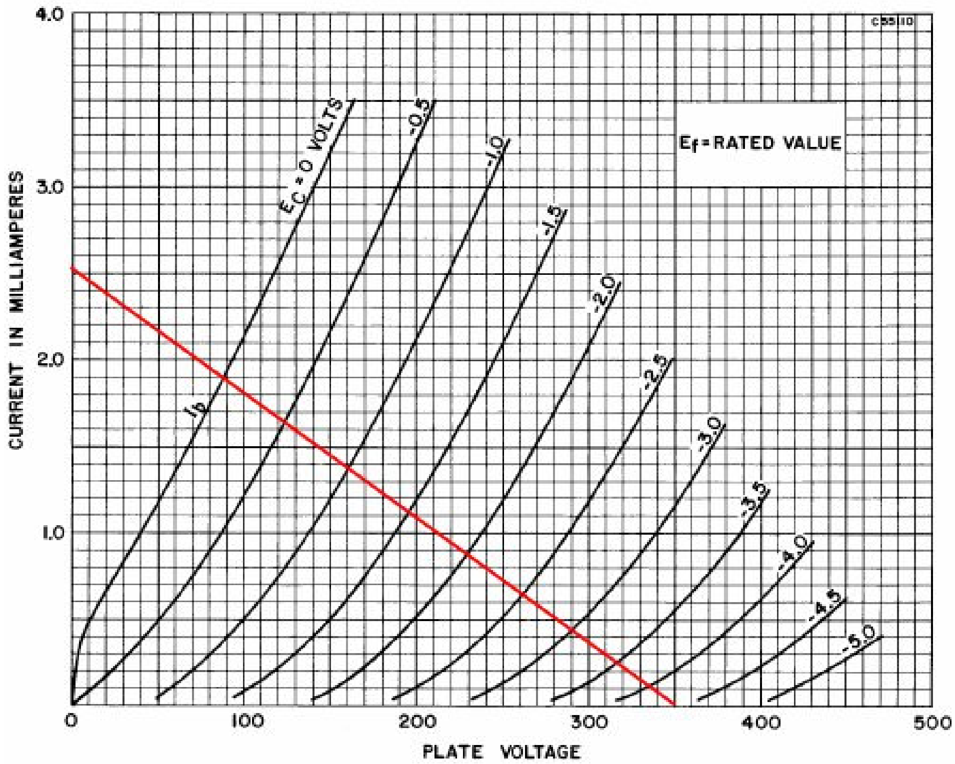


For audio frequencies its output impedance is 74k plus the impedance of 120pF in parallel with 2.2M. If we ignore the small capacitor, then the overdrive channel's load for midrange signals is equal to

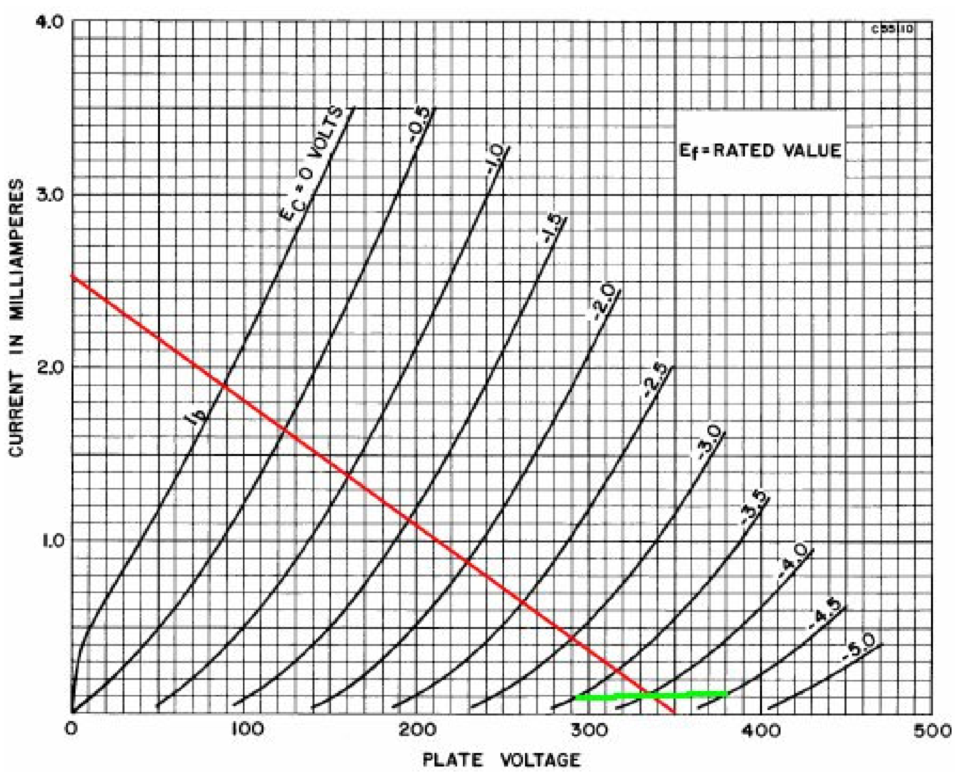
2.2M || 330k || (2.2M + 74k) = 255k

This is the value we will use as the effective output load when we plot the AC load line.

The DC load line has one end at the DC plate supply voltage of 350 volts and the other end at a plate current of (350) / (100k + 39k) = 2.5mA.



As the grid voltage varies from minus 3.5 to minus 4.5 volts the current passing through the 38k cathode resistor rises from 0.09mA to 1.1mA, as shown by the green grid line shown below.



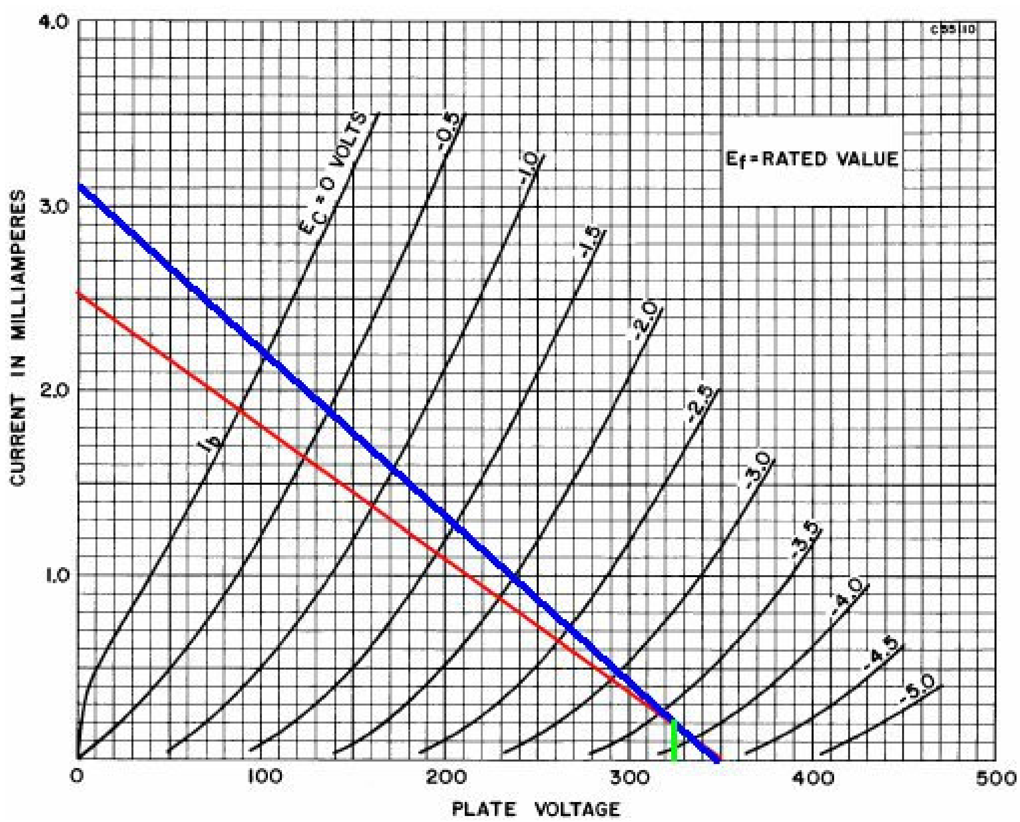
The triode is thus biased very close to cutoff at a grid voltage of about minus 4 volts. Such a situation may seem a bit perilous, but having a whopping 39k at the cathode creates substantial negative feedback to counteract changes in grid voltage due to the input signal. We'll take a look at why this stage is not as close to cutoff as it appears and then examine the distortion effects of operating in this region of the curves.

Headroom

This stage has a 0.001uF plate bypass capacitor to prevent high-frequency parasitic oscillation. It serves the same purpose, for example, as the 47pF capacitor between the plates of the Fender Bassman's long tailed pair. In this case, however, the value is much higher, creating significant treble attenuation.

At high treble frequencies the 0.001uF plate bypass capacitor acts as a short circuit and gain is zero. At bass frequencies the capacitor is open and there is an effective gain of about 1.8 (5dB), providing significant bass boost but not a lot of voltage gain compared to upstream stages. For audio signals the capacitor is in parallel with an output impedance of 98k and an effective load of 255k (as described earlier). This creates a -3dB treble cutoff frequency of 2.2kHz.

Potential gain is dramatically reduced by the large, unbypassed cathode resistor which creates substantial negative feedback. This makes the cathode "follow" the grid. (This is not a cathode follower, however, because the output is taken from the plate, not the cathode.) Thus the grid-to-cathode voltage, which is the value shown in the characteristic curves below, is much less than the grid-to-ground voltage, which represents the input signal.



For bass and midrange frequencies the plate circuit resistance is

39k + 100k||255k = 111k

This means that a drop in plate voltage from 335 volts (the DC value) to zero volts creates an increase in current of 335 / 111k = 3mA. The current thus rises from 0.1mA (the DC value) to 3.1mA, which forms the upper left end of the blue AC load line show here.

A grid voltage swing of about plus or minus 0.3 volts relative to the DC operating point of minus 4 volts is all that can be achieved without the tube going into cutoff. The corresponding plate current swing is plus or minus 0.1mA, which creates a voltage swing across the cathode resistor of plus or minus (0.1mA)(39k) = 3.9 volts. Thus the signal needed at the input is plus or minus 3.9 + 0.3 = 4.2 volts. There is thus more headroom in this stage than in previous stages, despite a DC operating point barely above cutoff.

Using 34 for the gain of the first stage, 60 for the gain of the second stage, and 0.68 for the gain of the second stage output circuit, the signal at the input jack required to overdrive the third stage is

4.2 / 34 / 60 / 0.68 = 3 millivolts

This is very easily achieved. Even with low-gain pickups, when the volume controls are at maximum it takes very little pick pressure to force the third stage well into overdrive. Under typical volume control settings this stage transitions into overdrive long before the previous stages.

Distortion and Overdrive

Operating this stage close to cutoff and far from saturation affects harmonic distortion and the dynamics of how rapidly the circuit transitions into overdrive. Because negative signal swings are flattened long before positive swings, the output signal shape is unsymmetrical, creating primarily second harmonic distortion. Placing the DC operating point closer to the center of the load line would cause both positive and negative swings to be flattened, creating mostly third harmonic distortion.

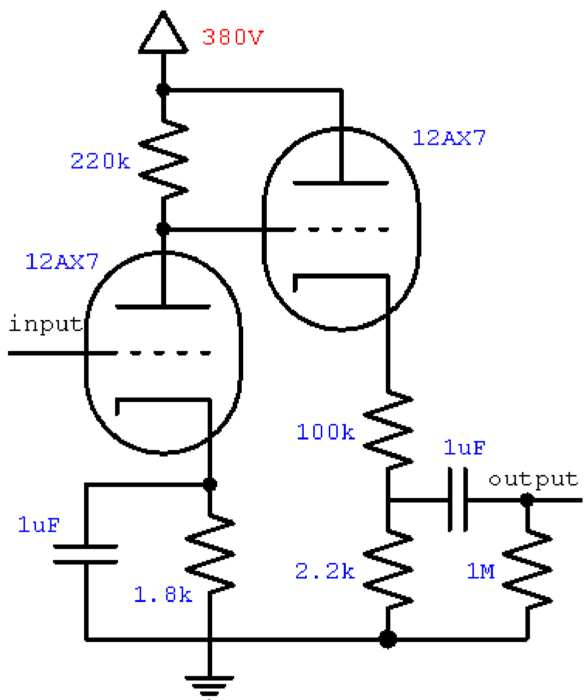
A DC operating point close to saturation also would create second harmonic distortion. The dynamics, however, would be quite different. Because of the driving circuit's high output impedance (made even higher by the 470k grid stopper) the flattening on positive signal swings is relatively sharp and well defined. The grid swings to zero volts in its most linear range and then immediately stops, refusing to go positive by any appreciably amount. At cutoff, on the other hand, the tube is operating in its least linear range. Parts of the tube go into cutoff before others, creating compression that reduces gain gradually until ultimately the plate current reaches zero. Soldano's third stage thus has a softer transition into overdrive.

We conclude that as the signal level increases, second harmonic distortion gradually increases, becoming more severe as the stage is overdriven. Input sensitivity is quite low compared to traditional designs, so overdrive is easily achieved. The Soldano SLO, however, doesn't end voltage boost here - there's more gain and overdrive to come

The Fourth Stage

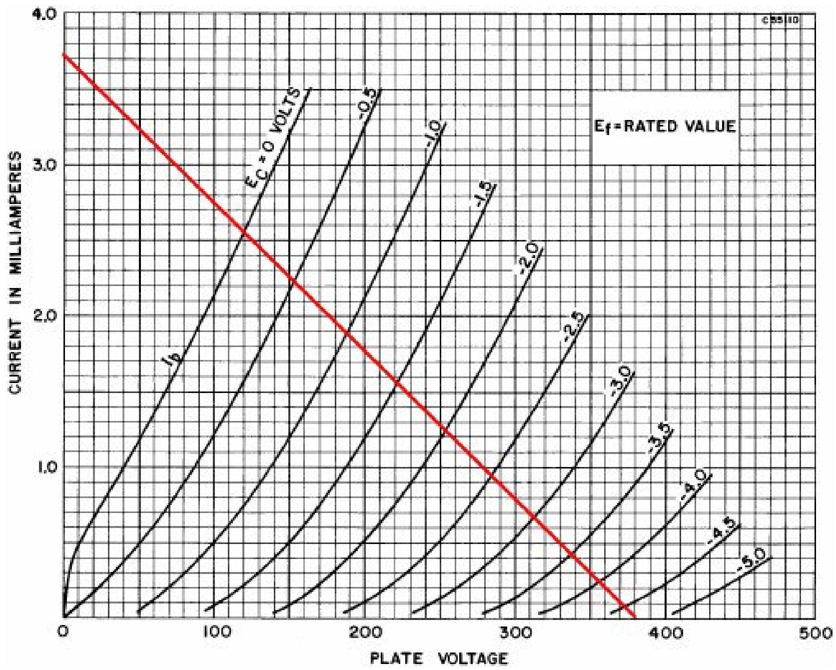
DC Operating Conditions

The fourth stage is a voltage amplifier DC coupled to a cathode follower. It is driven by a 220k grid stopper at the output of the previous stage. This serves the same purpose as the 470k resistor at the input to the second stage - it minimizes bias excursion to reduce the chance of blocking distortion. The smaller resistor value and higher voltage gain create 3.6dB attenuation at 4 kHz, so treble attenuation is a bit less than at the input to the second stage.



The voltage amplifier has the same configuration as Soldano's first stage. Small signal voltage gain increases from 51 at 82Hz to about 74 at 400Hz due to the relatively small, 1uF cathode bypass capacitor. The cathode follower has a gain of almost unity. Its output passes through a voltage divider with a "gain" 2.2k / (100k + 2.2k) = 0.02, representing 34dB of attenuation. There is hardly any loss at any audio frequency across the voltage divider formed by the 1uF capacitor and 1M grid resistor for the next stage. Net gain for both triodes is thus (51)(0.02) = 1 at 82Hz and (74)(0.02) = 1.5 at 400Hz.

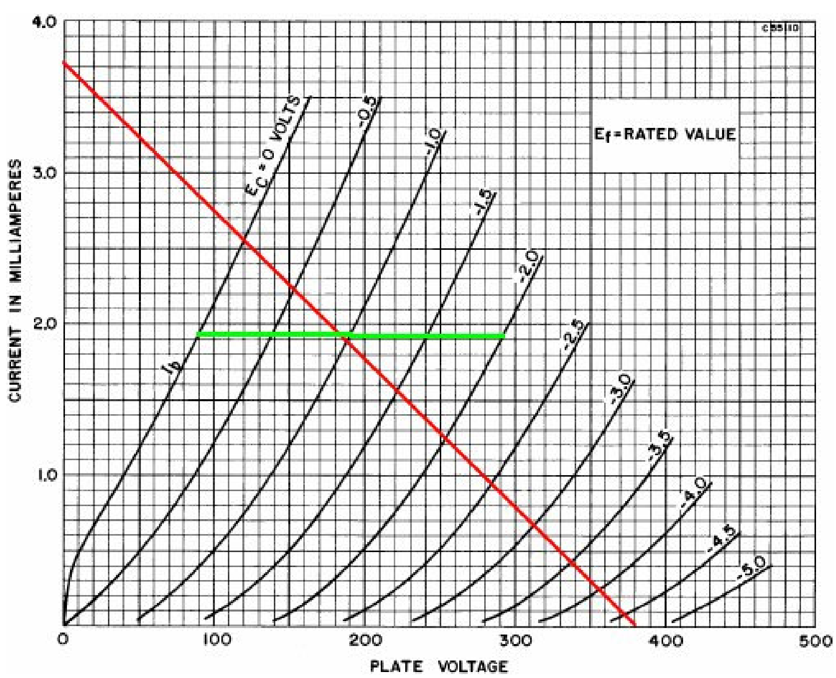
The DC load line for the cathode follower is marked by one end at the DC plate supply voltage of 380 volts and the other end at a plate current of (380) / (100k + 2.2k) = 3.7mA.



The grid voltage relative to ground is equal to 380 volts minus the voltage drop across the 220k plate resistor. From our analysis of the first stage the DC plate current is 0.83mA, so the voltage drop is

(220k)(0.83mA) = 183 volts

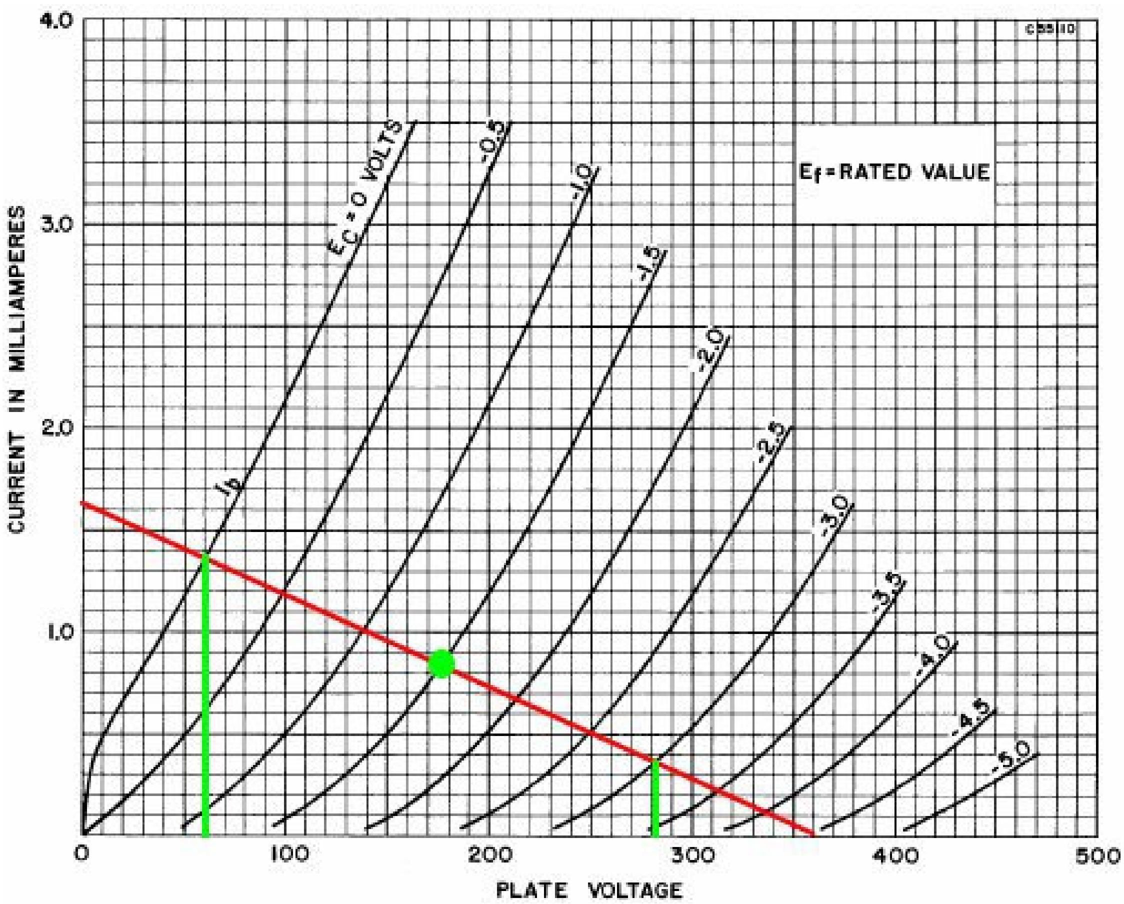
The grid-to-ground voltage is thus 380 - 183 = 197 volts. If the grid-to-cathode voltage is zero, then the current through the 100k + 2.2k tail resistance is 197 / 102k = 1.93mA. If, on the other hand, the grid voltage is minus 2 volts, then the current is 195 / 102k = 1.91mA. The DC operating point is at the intersection of a line representing these conditions (in green) and the DC load line.



Headroom

The voltage amplifier is directly coupled to a cathode follower with a very high input impedance and its 1.8k cathode resistor is fairly small, so the AC load line is nearly the same as the DC load line. Using the DC load line and DC operating point for the first stage we get a maximum plate voltage swing from 55 volts to 297 volts.

Large signal gain is (297 - 55) / 3 = 81.



Because of its inherent negative feedback, the cathode follower easily handles the voltage amplifier's maximum swing without going into overdrive. The cathode voltage "follows" the grid voltage so that the grid-to-cathode voltage changes very little.

Using 34 for the gain of the first stage, 60 for the gain of the second stage, 0.68 for the gain of the second stage output circuit, and 1.8 for the gain of the third stage, the signal amplitude at the amplifier input jack required to drive the fourth stage into overdrive (volume control set to maximum) is

1.5 / 34 / 60 / 0.68 / 1.8 = 600 microvolts

This is much lower than in traditional guitar amp designs, so it takes very little input signal to force this stage into overdrive.

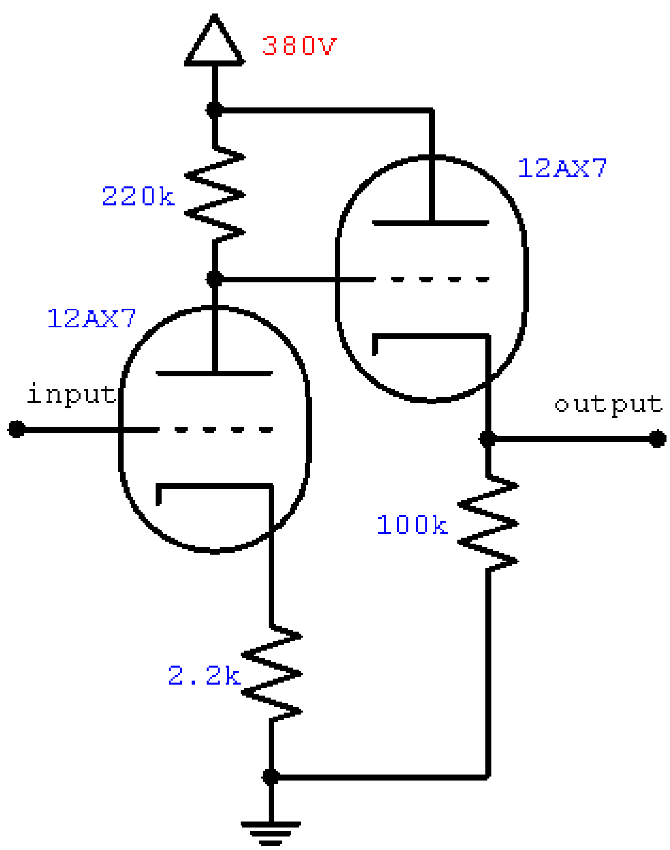
Distortion

The DC operating point is near the middle of the AC load line. A 1.5 volt grid voltage swing drives the tube into saturation. It takes about 2.5 volts to achieve cutoff. Distortion is therefore characterized by increasing second harmonic distortion as the signal amplitude approaches 1.5 volts, rapidly accelerating second harmonics as the signal amplitude increases further, and finally a transition to predominantly third harmonic distortion as the signal level increases beyond 2.5 volts.

The Fifth Stage

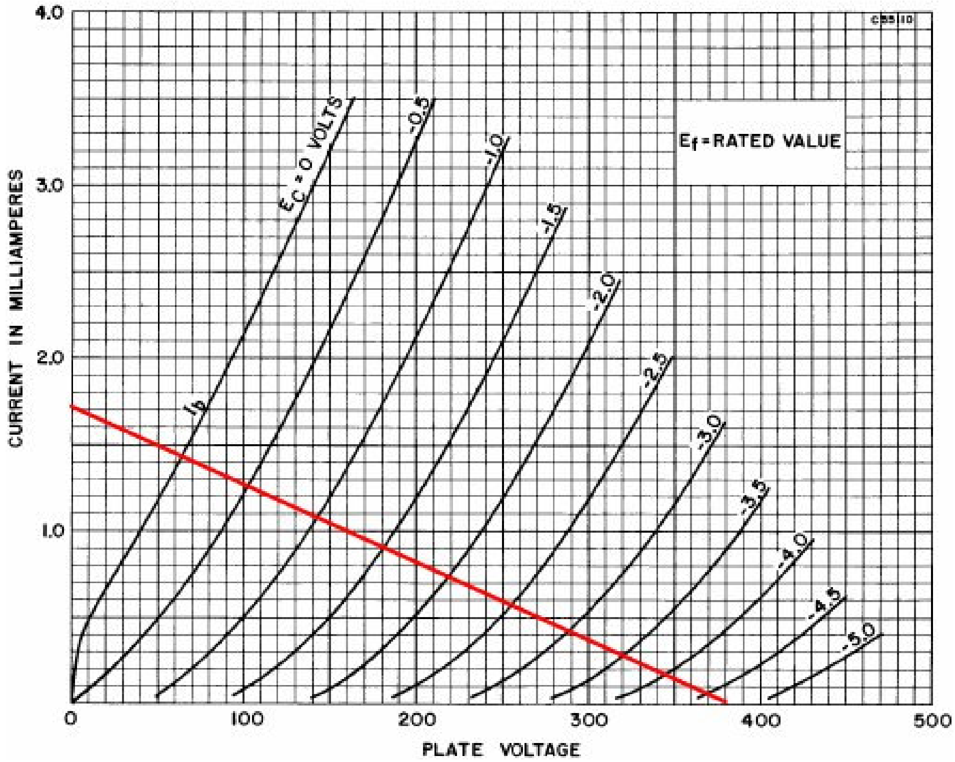
DC Operating Conditions

The fifth stage is almost identical to the fourth and similarly creates approximately unity gain. Both stages end with cathode followers that provide low-impedance outputs to drive relatively heavy loads. The fourth stage drives an optional effects loop and the fifth stage drives a [Fender Bassman 5F6-A tone stack] with modified parts values.

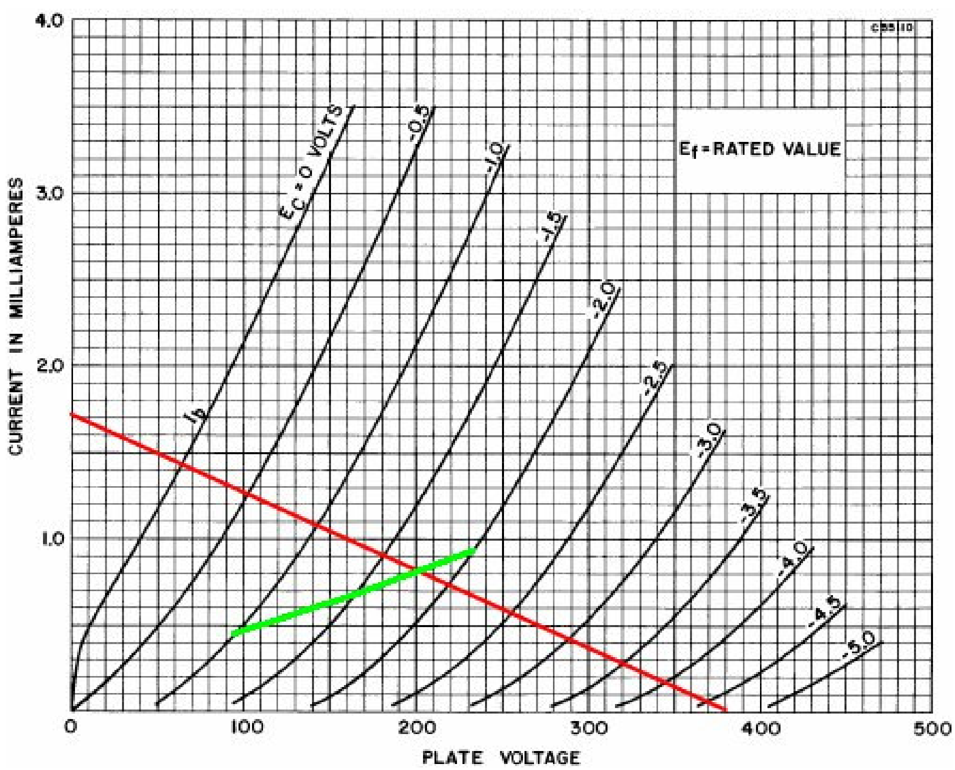


The voltage amplifier's DC load line has one end at the DC plate supply voltage of 380 volts and the other end at a plate current of

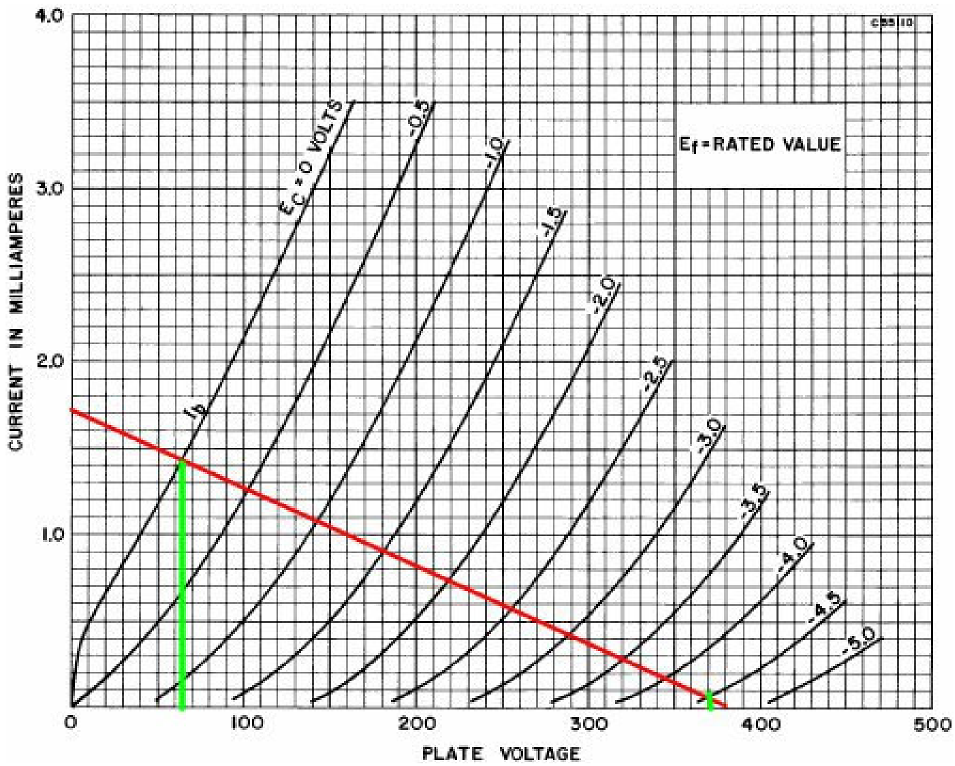
(380) / (220k + 2.2k) = 1.7mA



If the grid voltage is minus 1 volt then the plate current passing through the 1.8k cathode resistor is 1 / 2.2k = 0.45mA. For grid voltages of minus 1.5 and minus 2 volts, the plate current is 0.68mA and 0.91mA, respectively. These points create a grid line that puts the DC operating point at minus -1.75 volts.



Because the cathode follower has a very high input impedance, the AC load line is nearly identical. Based on the resulting DC operating point, a 1.75 volt grid voltage swing drives the tube into saturation. It takes about 2.75 volts to achieve cutoff.



Distortion

If the grid voltage rises from its DC value of minus 1.75 to a value of zero, then the plate current rises from 0.8mA to 1.43mA. The current through the 2.2k cathode resistor thus increases by 1.43mA - 0.8mA = 0.63mA. This raises the cathode voltage by (0.63mA)(2.2k) = 1.4 volts. It therefore takes an input signal amplitude, measured grid-to-ground, of 1.4 + 1.75 = 3.15 volts to overdrive this stage.

Using 34 for the gain of the first stage, 60 for the gain of the second stage, 0.68 for the gain of the second stage output circuit, 2.3 for the gain of the third stage, and 1.5 for the gain of the fourth stage, the signal amplitude at the amplifier input jack required to drive the fifth stage into overdrive (volume set to maximum) is

3.15 / 34 / 60 / 0.68 / 1.8 / 1.5 = 840 microvolts

This is 40 percent higher than our estimate for the fourth stage, so the fifth stage remains within its headroom limits even under severe overdrive conditions. The fourth stage, which is notably upstream of the optional effects loop, produces a clipped output that is within the headroom limits of the fifth stage, albeit not by a huge margin.

The voltage amplifier has a gain of 44, about half the gain that could be achieved with a large cathode bypass capacitor. The cathode follower has almost unity gain. Thus total stage gain is about 44, or 33dB, which more than compensates for the attenuation of the tone stack that follows.

Distortion is characterized by increasing second harmonic distortion as the signal amplitude, measured grid-to-cathode, approaches 1.75 volts, rapidly accelerating second harmonics as the signal amplitude increases further, then a transition to predominantly third harmonic distortion as the signal level increases beyond 2.75 volts. As noted, however, these limits are never reached unless the effects loop introduces significant gain.

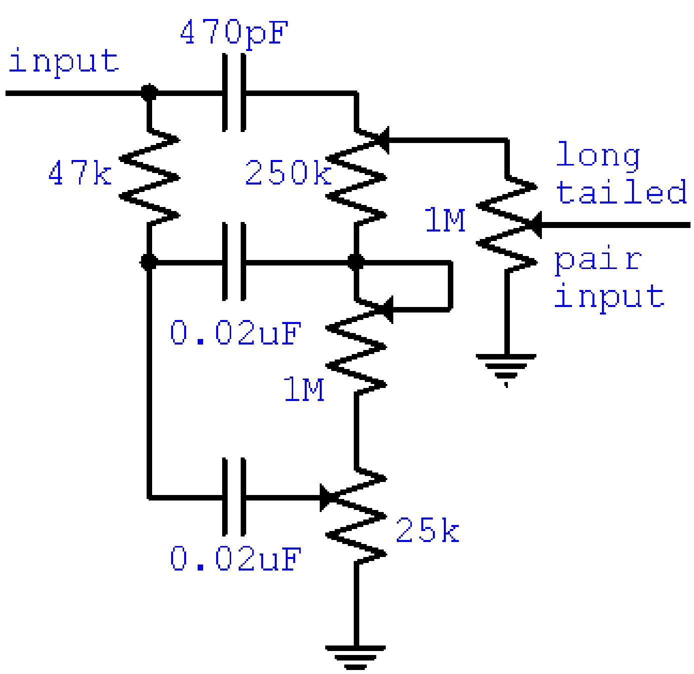
Lessons Learned

High-Gain Preamp Design

Based on our analysis of the SLO overdrive channel, let's see what conclusions we can draw concerning Soldano's strategy for high-gain preamp design.

1. Make the Master Volume Control Frequency Selective

The Soldano Super Lead Overdrive's tone stack and overdrive control are in series.



The controls work together to attenuate the preamp output, thereby making the distortion dynamics highly frequency selective. If the tone stack were located further upstream and separated from the overdrive control by one or two stages of voltage gain, the results would be quite different.

2. Place the Master Volume Control in Front of the Phase Inverter

Soldano's tone stack and overdrive control are placed between the last preamp stage and the phase inverter, so the phase inverter always has enough headroom to drive the power amp to full power and beyond. Except in extreme cases, overdrive is limited to the preamp or the power amp, not the phase inverter.

3. Place Preamp Clipping in Front of the Effects Loop

Soldano's effects loop follows the fourth stage, which has the overdrive channel's lowest input sensitivity. This ensures that signal clipping is upstream of the loop. Effects thus operate on the distorted signal, not the input to the distortion-producing stage. In the case of reverb, for example, the preamp creates reverberated distortion, not distorted reverberation.

4. Limit the Signal Passband

Three of Soldano's voltage amplifiers use relatively small cathode bypass capacitors. Partial bypassing creates negative feedback for low frequencies, thereby creating bass attenuation.

Unlike the Fender Bassman and other classic amps created before the era of extreme overdrive, Soldano's third stage includes a plate resistor bypass capacitor with a -3dB cutoff of only 2.2kHz. Any treble from the guitar pickups that manages to run the gauntlet of the upstream grid stopper suffers a substantial cut. The nature of overdrive, however, is harmonic distortion, and this amp creates bucket loads of its own high-frequency content. Soldano's design introduces harmonic distortion generated predominantly by the guitar's fundamental frequencies and low-order harmonics. High frequency content is created by overdriving the amplifier.

Solo guitar voice usually has a range of only 2 or 3 octaves. Limiting the passband reduces intermodulation distortion and a plethora of extraneous and undesirable harmonic artifacts that can pollute the mix.

5. Keep Input Impedances High

In traditional designs the power amp is the first stage in the signal chain to break into extreme distortion. Except under unusual circumstances it is the only stage to succumb to bias excursion, which contributes substantially to the distortion dynamics of Class AB. Without proper foresight, however, bias excursion can lead to highly undesirable effects like blocking distortion.

By incorporating a 4-knob master volume control, Soldano creates the opportunity to overdrive the preamp while allowing the power amp to run relatively clean. This shifts the potential for bias excursion to the overdriven preamp stage. To prevent blocking distortion, Soldano uses grid stoppers to ensure that the overdriven stage's input impedance remains high even when its grid tries to exceed zero volts. Only the first stage and the effects return, which are unlikely to be overdriven, have an input impedance of less than 220k.

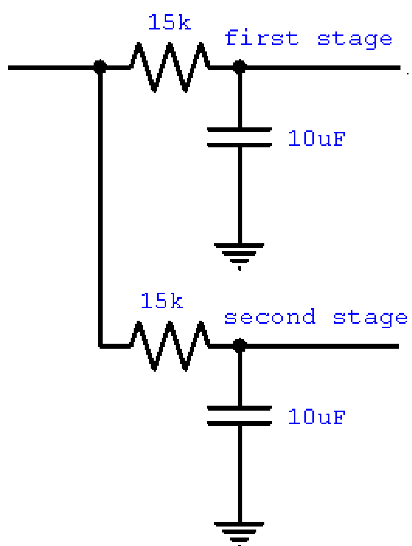
From the perspective of the grid to which the grid stopper is attached, the resistor adds substantially to the output impedance of the upstream stage. The high output impedance is incapable of providing the current necessary to drive the grid positive by any appreciable amount.

This makes the driven tube's transition from near linear operation to severe distortion relatively sharp.

Large grid stoppers also have a substantial impact on treble response, but in the context of treble-creating overdrive there is plenty of brightness in the final result.

6. Provide Adequate Low-Frequency Decoupling

Soldano's signal chain has an incredible 7 triodes upstream of the phase inverter. Nevertheless, no more than 2 inverting voltage amplifiers are driven by the same plate supply. This ensures adequate decoupling to prevent low-frequency feedback that can lead to motorboating. To keep voltages up, Soldano uses a parallel power supply filter for the first two stages.



7. Prevent Parasitic Oscillation

Wires and components have inherent inductance and capacitance that can lead to parasitic oscillation. This highly undesirable affect, which often occurs at radio frequencies, is caused by feedback from output circuits to input circuits. High-gain preamps are particularly susceptible.

Soldano's generous use of grid stopper resistors helps attenuate the outbreak of parasitic oscillation. The SLO's plate bypass capacitor in the third stage also chokes off high frequency signals, effectively isolating upstream stages from downstream stages for the span of frequencies over which oscillation can occur. It is worth emphasizing, however, that grid stoppers, plate bypass capacitors, and other proactive measures are effective only in the context of good circuit layout. Parts and wire placement are crucial in a high-gain preamp.