An Innovative 2-kW Linear Tube Amplifier

Can a tube full-legal-limit amplifier be small and light?

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This prototype was built for testing a new concept in linear amplifiers, which could be named AB/F class. It is not actually a new operating class, but has characteristics of the well known class AB and class F applied to the same amplifier. It is composed of a bunch of old and new technologies, resulting in a very small and light amplifier able to operate in AM, CW and SSB at legal limit power.

The idea was to get linear performance from a non-linear high efficiency amplifier. To achieve it I adopted an envelope elimination and restoration approach: The incoming signal is demodulated and the original envelope amplified by a high efficiency, high speed switching supply that modulates the feeding of output stage power.

The incoming RF signal is also applied to the tubes' control grids. At low power levels the grid polarization circuit keeps the amplifier at class AB. As the power gets higher, the tubes are driven into saturation and the output power is controlled by the rising voltage of the modulating power supply.

Why tubes and not semiconductors? Here are some reasons:

- Relative fragility of power FETs in high power RF circuits. Tubes are much more resistant to mistuning and unpredictable conditions that may occur during development.
- Possibility of applying this project to more powerful commercial amplifiers.
- Smaller variable capacitors at tuning output circuits, due to higher impedance levels.
- Tubes are fun! It's amazing to see four small TV tubes effortlessly pumping out RF over the legal limit. Old PL509 TV sweep tubes were built to operate as switches, so they perform very well in this saturated class, achieving high anode efficiency.

Refer to the block diagram of Figure 1.

(Continued on page 24.)

Address?

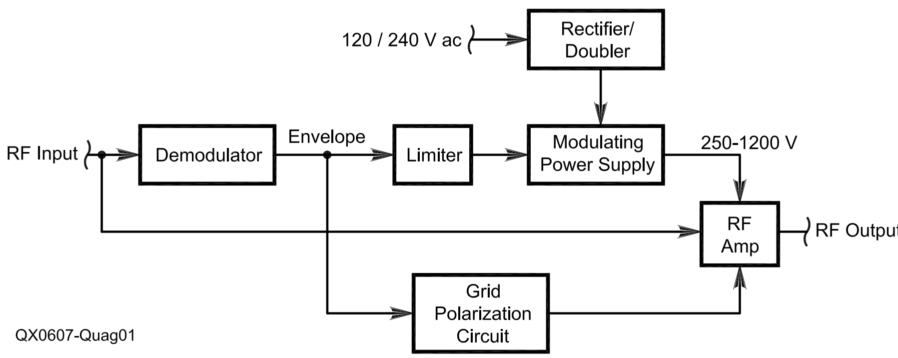


Figure 1 — Amplifier block diagram.

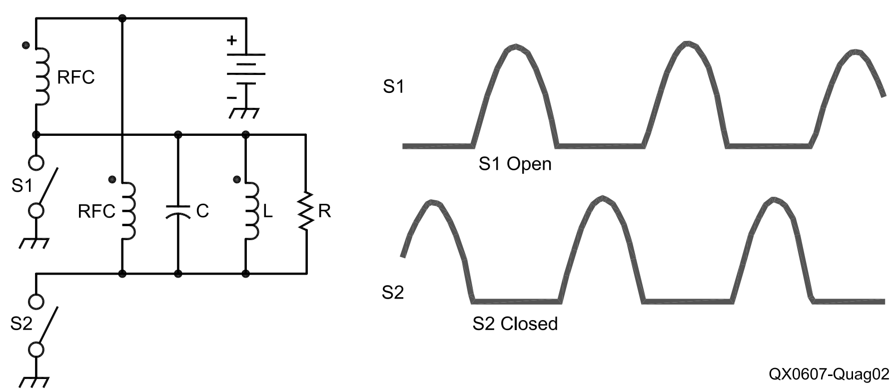


Figure 2 — Basic waveforms.

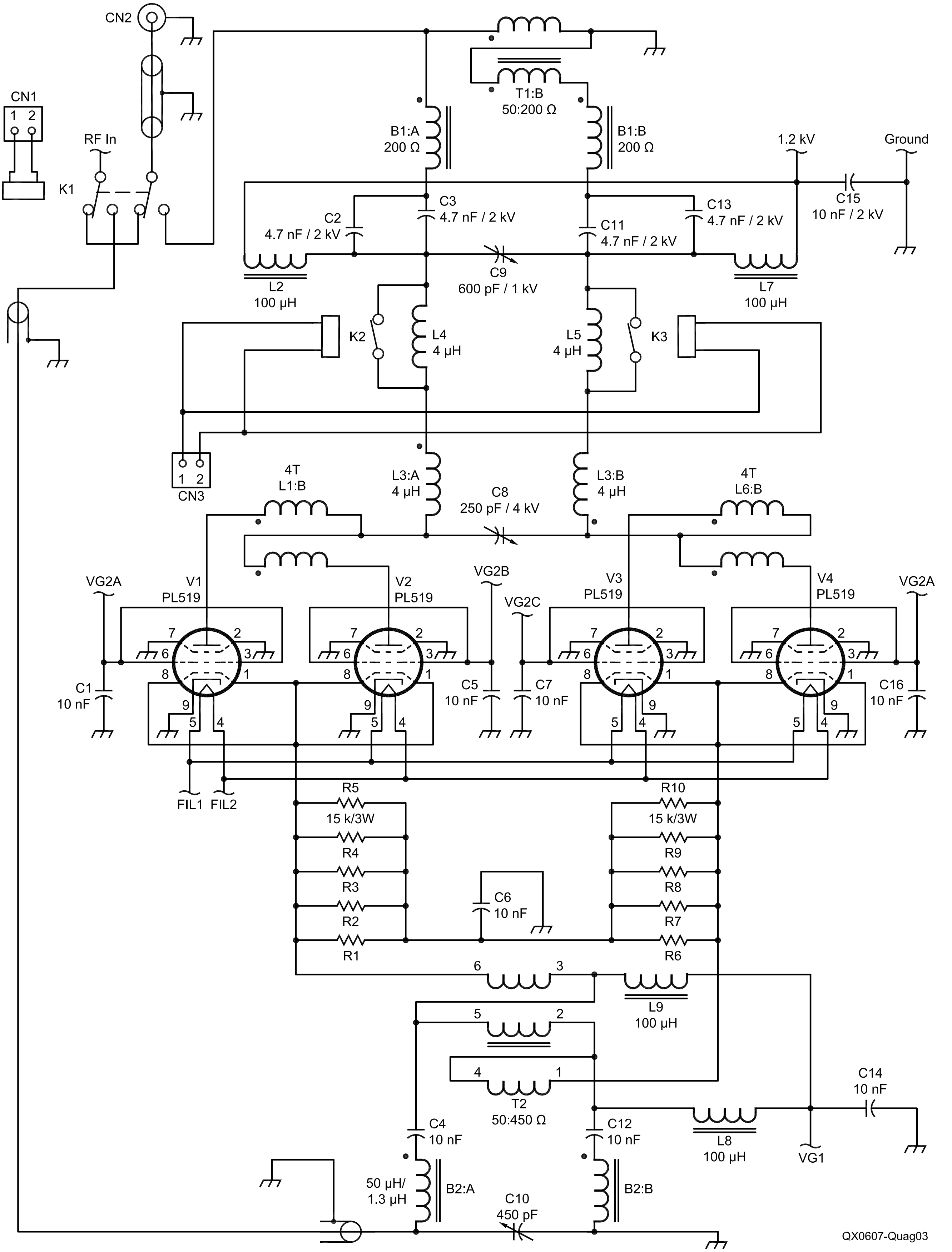


Figure 3 — RF amplifier schematic diagram.

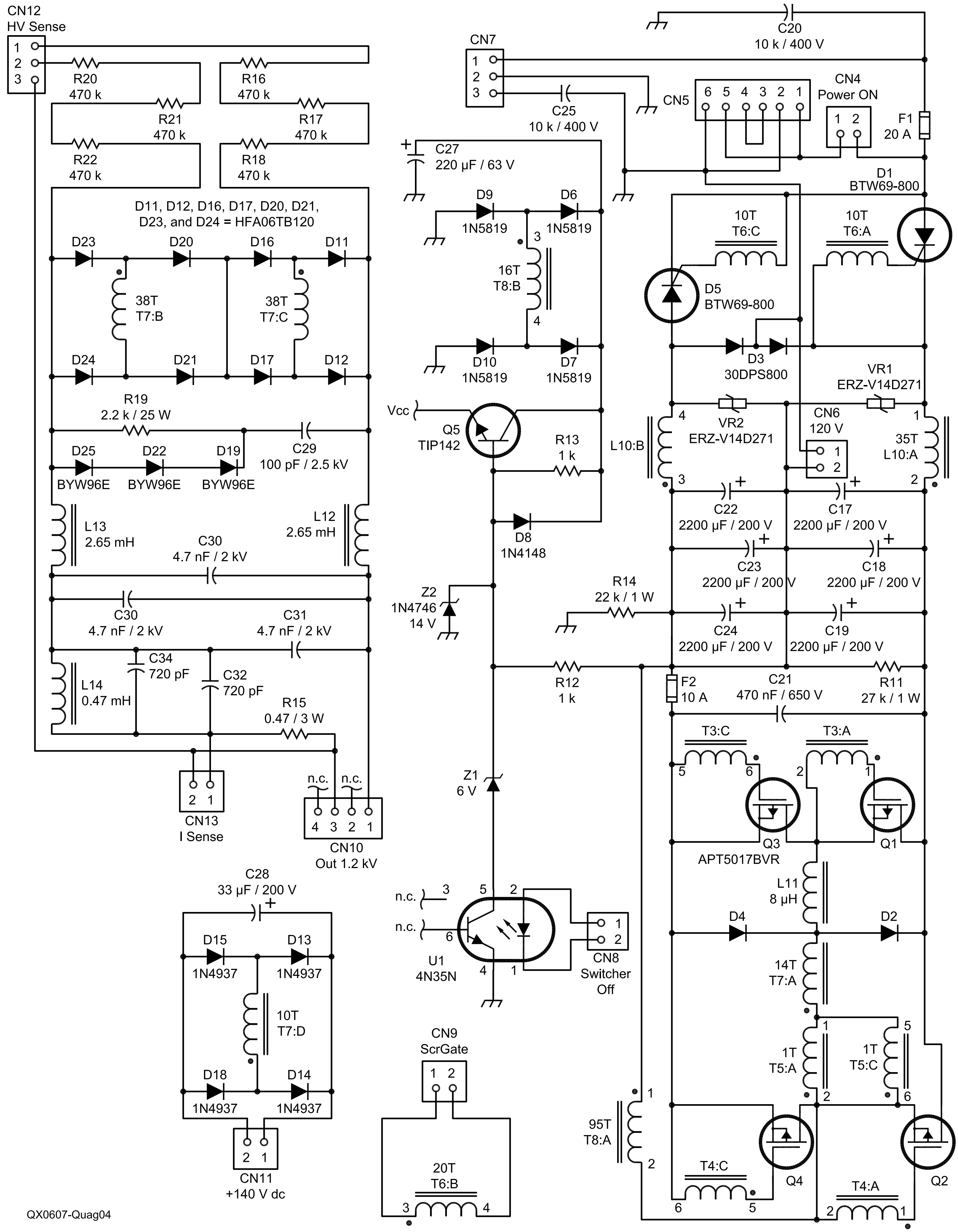


Figure 4 — Power supply schematic diagram.

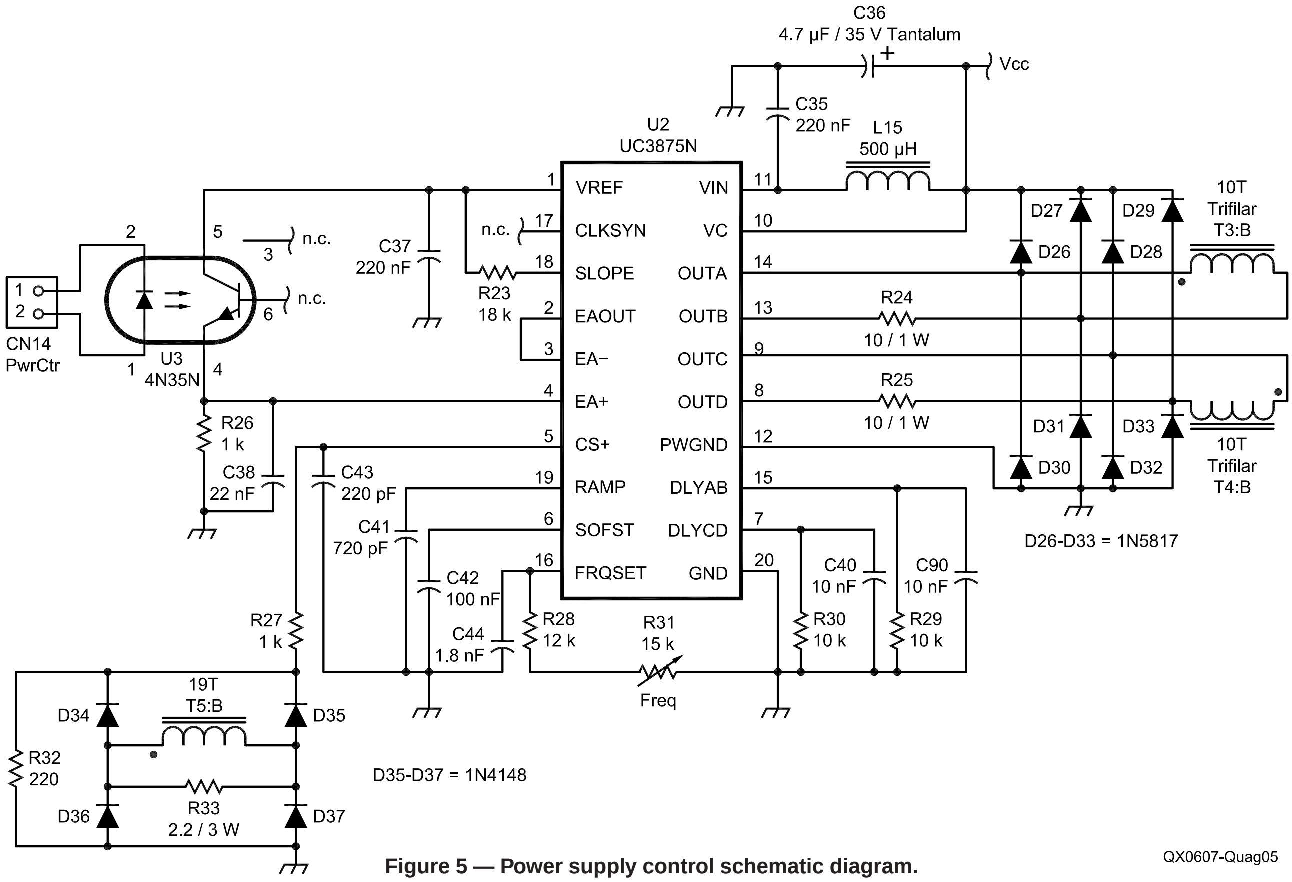


Figure 5 — Power supply control schematic diagram.

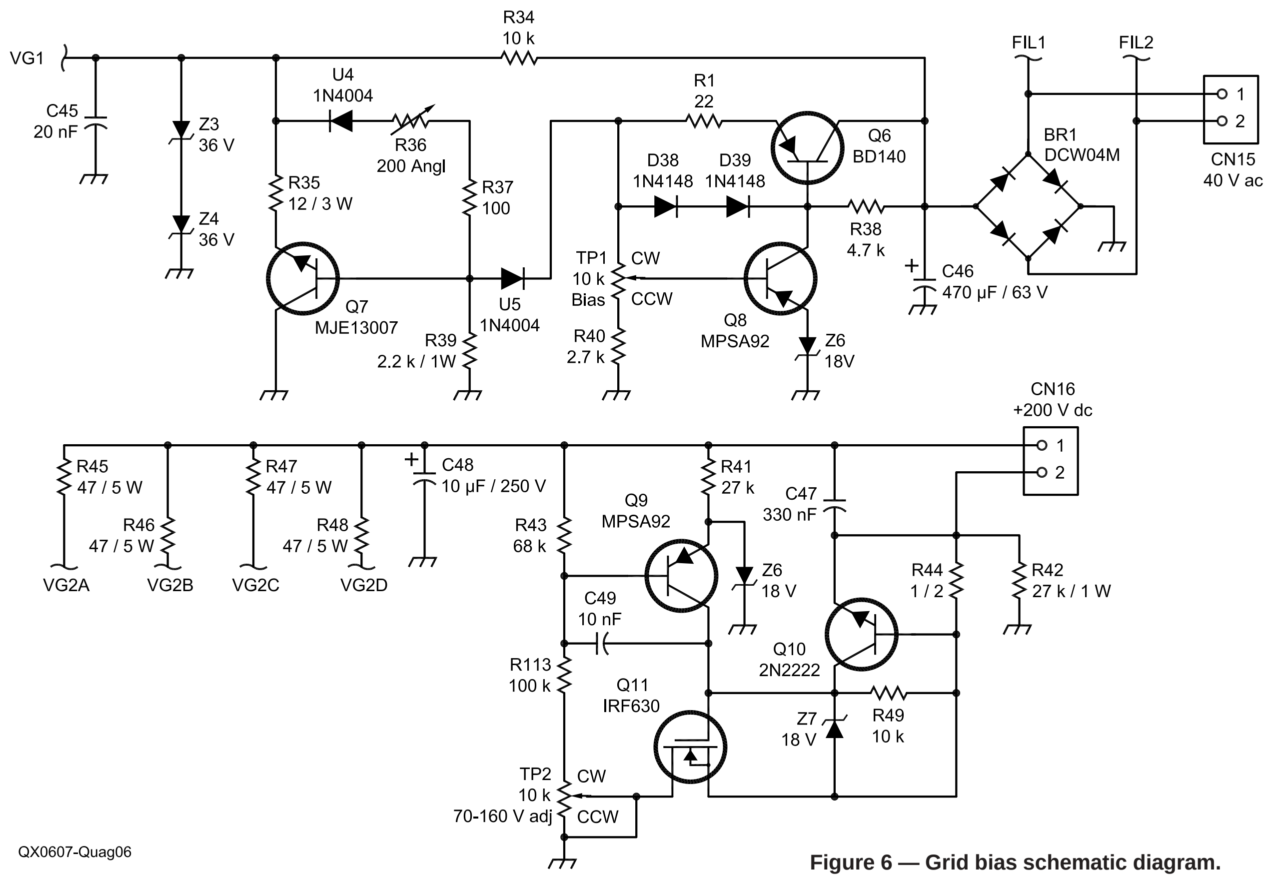


Figure 6 — Grid bias schematic diagram.

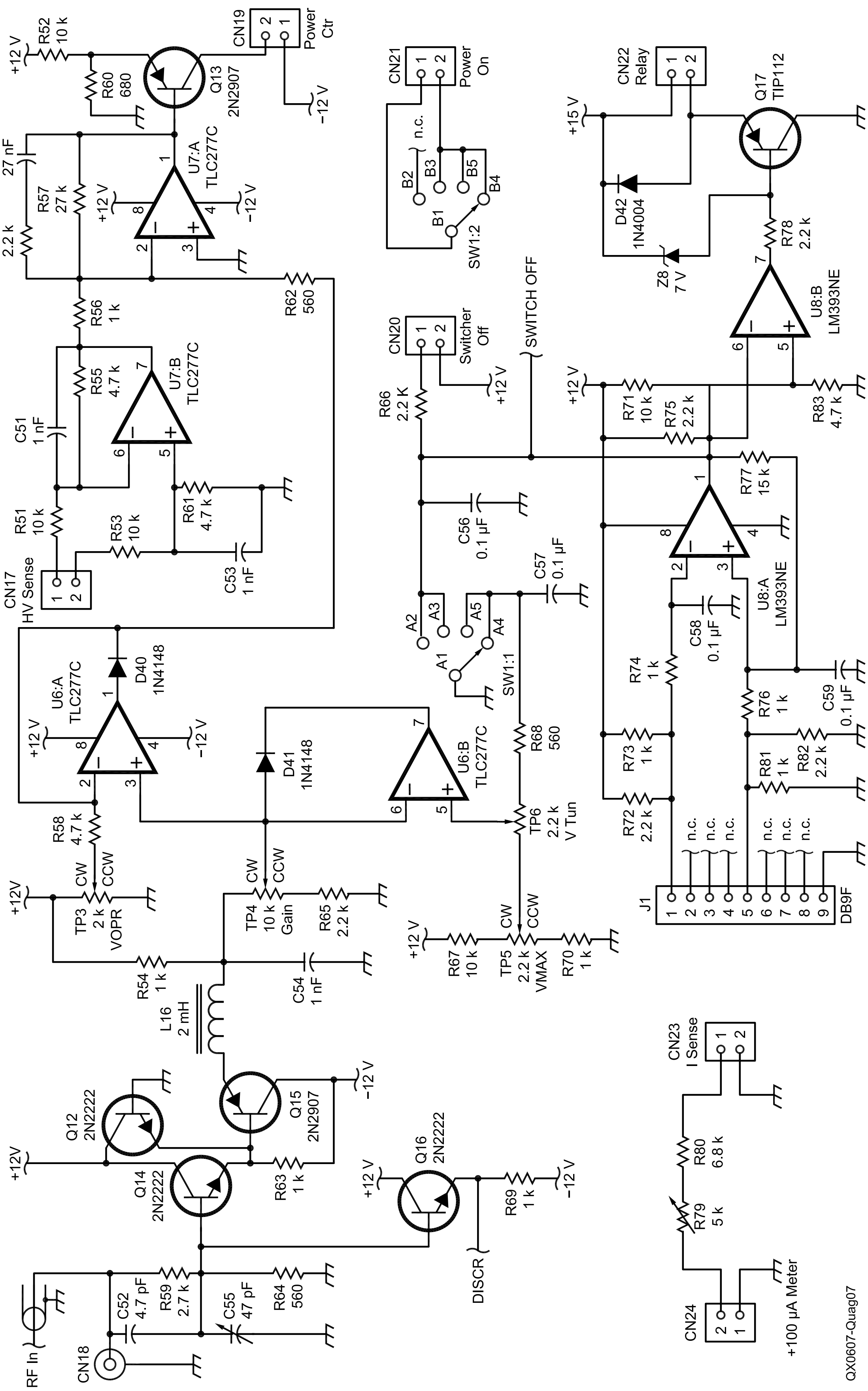


Figure 7 — Control schematic diagram.

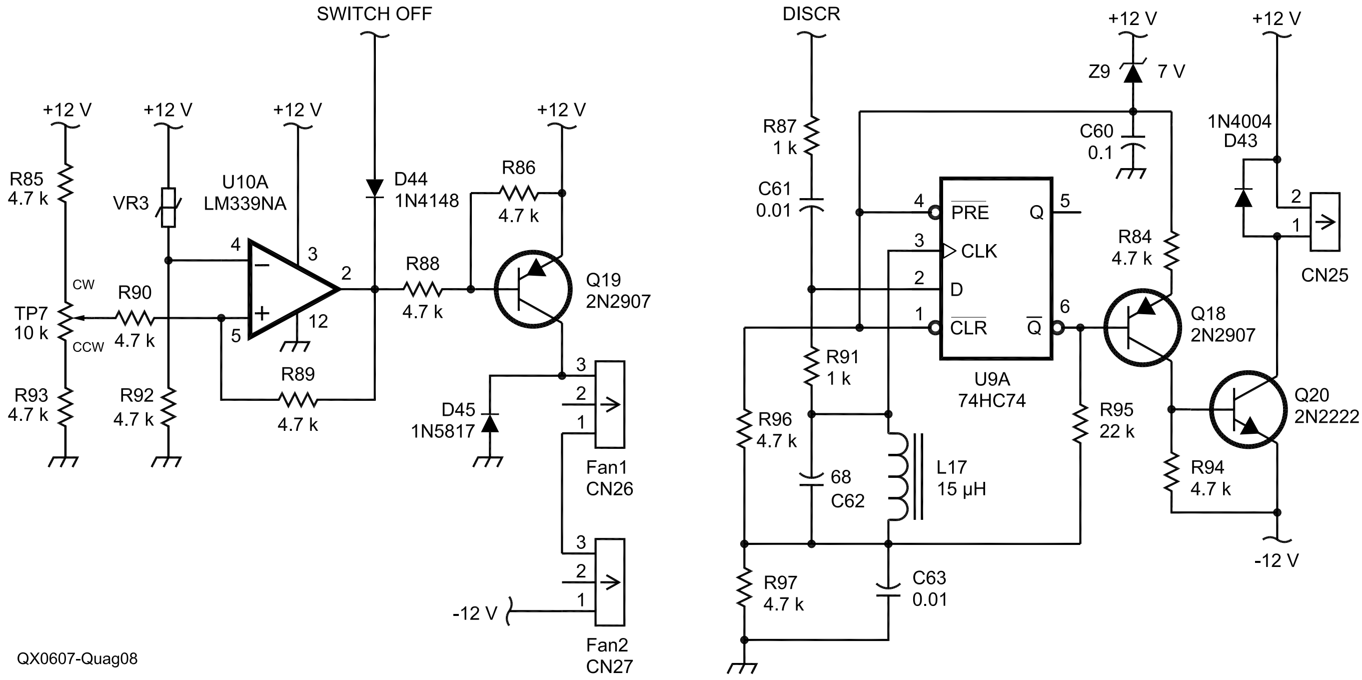
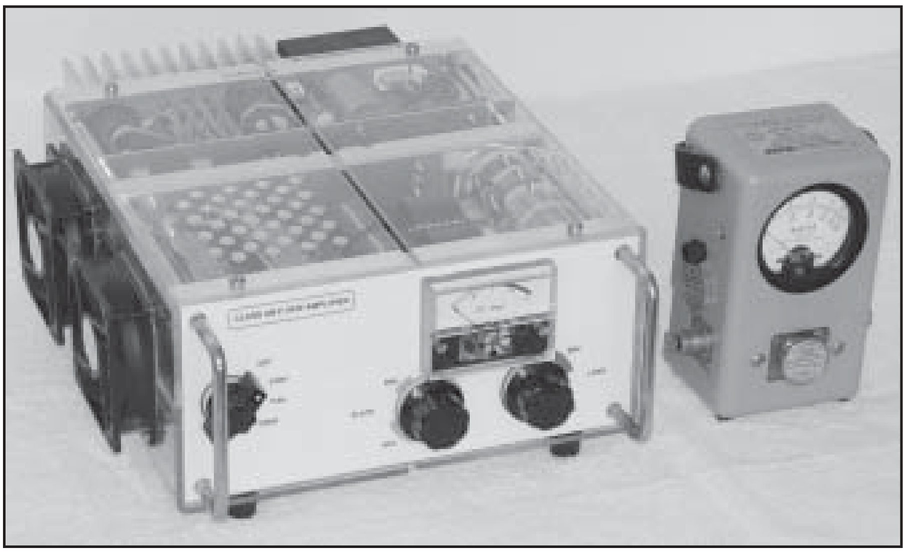


Figure 8 — Thermal protection schematic diagram.

(Continued from page 19.)

The amplifier is a harmonically controlled push-pull arrangement operating in a mode known as *inverse class F*. In the frequency domain, the symmetric resonant load presents an open circuit to odd harmonics, a short circuit to even harmonics and is resistive to the fundamental frequency.

Another way to explain how it works in the time domain is to consider the tubes as switches grounding alternatively the two sides of a resonant load consisting of a resistor, a capacitor and an inductor in parallel. Across each switch is a half sinusoid voltage pulse when opened, and zero volts when closed. The two halves combine at the load in a full sine wave. Two RF chokes feed dc power to the circuit. Note that the load must be isolated from ground.



You can see the small size by comparing the amplifier to a Bird model 43 wattmeter.

Basic Waveforms

Refer to the basic waveforms shown in Figure 2. Theoretically, this mode allows 100% efficiency, since there is no voltage and current simultaneous at the switches; but because of parasitic capacitances, resistive losses and minimum anode voltage, the actual plate efficiency runs around 85%.

To ensure correct coupling, a differential adjustable pi circuit lowers the impedance from 1800 Ω at the tube side to 200 Ω, and at the same time provides the resonance needed. A 200 Ω transmission line "unun" isolates the pi circuit from ground, and a 200 to 50 Ω balun also converts from differential to common mode.

Circuit Description

Refer to the schematic diagrams in Figures 3 through 9 during the following discussion. A side benefit of the push-pull output arrangement is that since there are virtually no even harmonics generated, a loaded Q of 5 is enough to filter out the 3rd and 5th harmonics, permitting smaller bobbins, capacitors and commutating relays than allowed by conventional unbalanced pi circuits.

A high frequency diplexer isolates the paralleled tubes against VHF oscillations. These oscillations actually occurred, making the internal tube plate connections glow red!

The incoming RF signal is detected by a discriminator circuit centered at 5.4 MHz that actuates two high-current relays, which short the bobbins, halving the pi inductance when operating on 40 m.

This configuration allows linear class-AB push-pull operation until the amplifier reaches roughly 100 W. From this level up the tubes start to saturate, and the current through the control grids forces the polarization level more negatively, out from class-AB. The amplifier changes smoothly from class-AB to class-F as the plate voltage rises following the input signal envelope.

The input circuit is a wideband balanced circuit, operating with no tuning from 3 to 8 MHz with reasonable SWR. The input transformer is a 1:9 transmission-line type loaded by an array of resistors paralleled to the control grids.

The Switching Power Supply

The power supply is an off-line, full-bridge, phase-controlled, quasi-resonant converter operating at 100 kHz, capable of 2500 W. Phase control means that each side of the bridge operates always with square waveforms, and the control circuit changes the relative phase between bridge sides from zero to 180°, varying the output voltage from zero to 1200 V.

The quasi-resonant approach was adopted not only to increase efficiency but also to reduce secondary ringing by slowing primary turn-on slope. Unlike conventional switchers, this one has broad response bandwidth, necessary to follow the audio envelope of the incoming reference signal. Stability compensation versus ripple attenuation limits the bandwidth to 8 kHz, enough to follow AM and SSB input signal envelopes.

The output filter is a 2^{nd}-order 15-kHz low-pass Chebyshev, followed by a 200-kHz series trap. The commutating ripple is attenuated 60 dB by this filter.

It is interesting to note that the small capacitors at the output and the fast current limiting gives a "soft" characteristic to this power supply: A sudden short circuit at full power only fires a small spark, very unlike a conventional high voltage supply of this size!

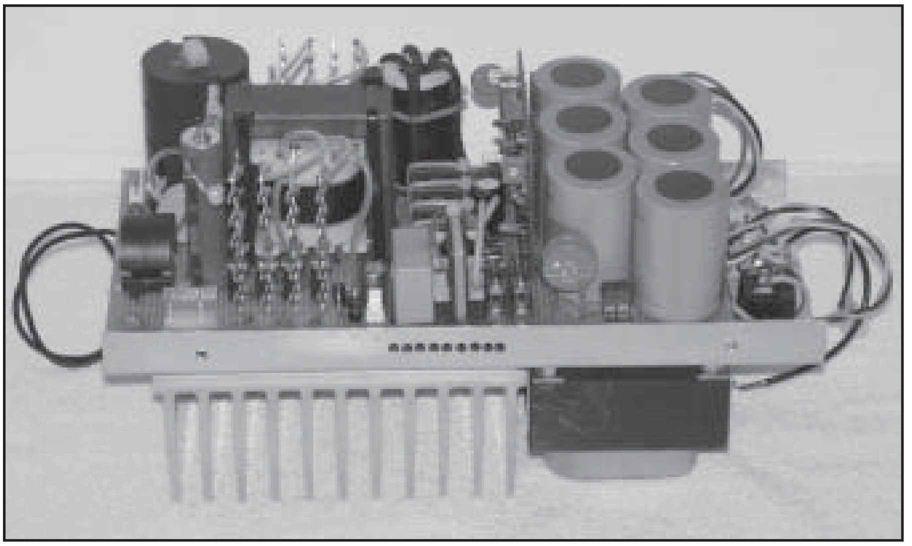
The 240 V ac power input is rectified by an SCR-diode bridge, provided there's a soft start circuit to limit inrush current and an input choke to improve the power factor. The SCRs also act as the main power relay. The input rectifier could work as a doubler to operate 120 V ac, if you set some jumpers and have heavy duty wiring in your shack.

I did not try to shield this big switcher for RFI: When not transmitting it is held totally off. This required a small 60 Hz transformer to supply tube heaters and control circuit power, but it is worth the space occupied — there's no receiving interference at all. And while transmitting? Well, if you can keep the TV sets working during your 2 kW chattering, interference from the switcher is no problem.

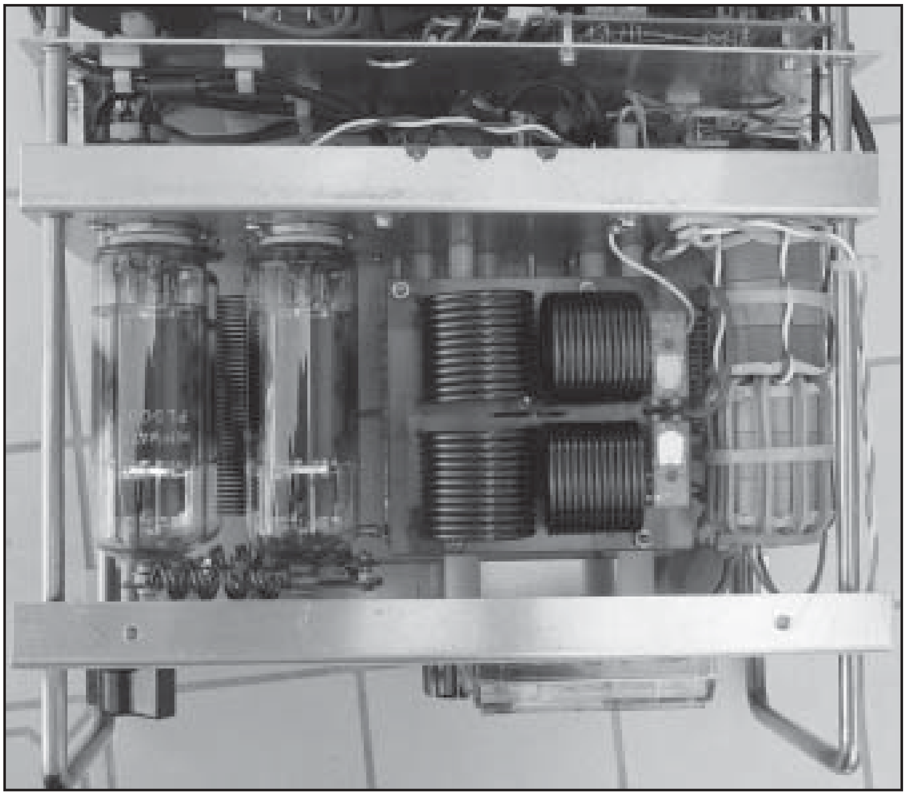
Demodulator, Limiter and Control Circuits

The input active differential RF detector performs better than simple diodes, presenting very good linearity. Following the RF filter, the limiting circuit keeps the power supply above 250 V, to allow the tubes to operate in class-AB at low power. It also limits the maximum voltage, to protect the amplifier if the main ac supply goes high. Without it, the instantaneous input power can reach 3 kW, meaning danger to tubes and capacitors.

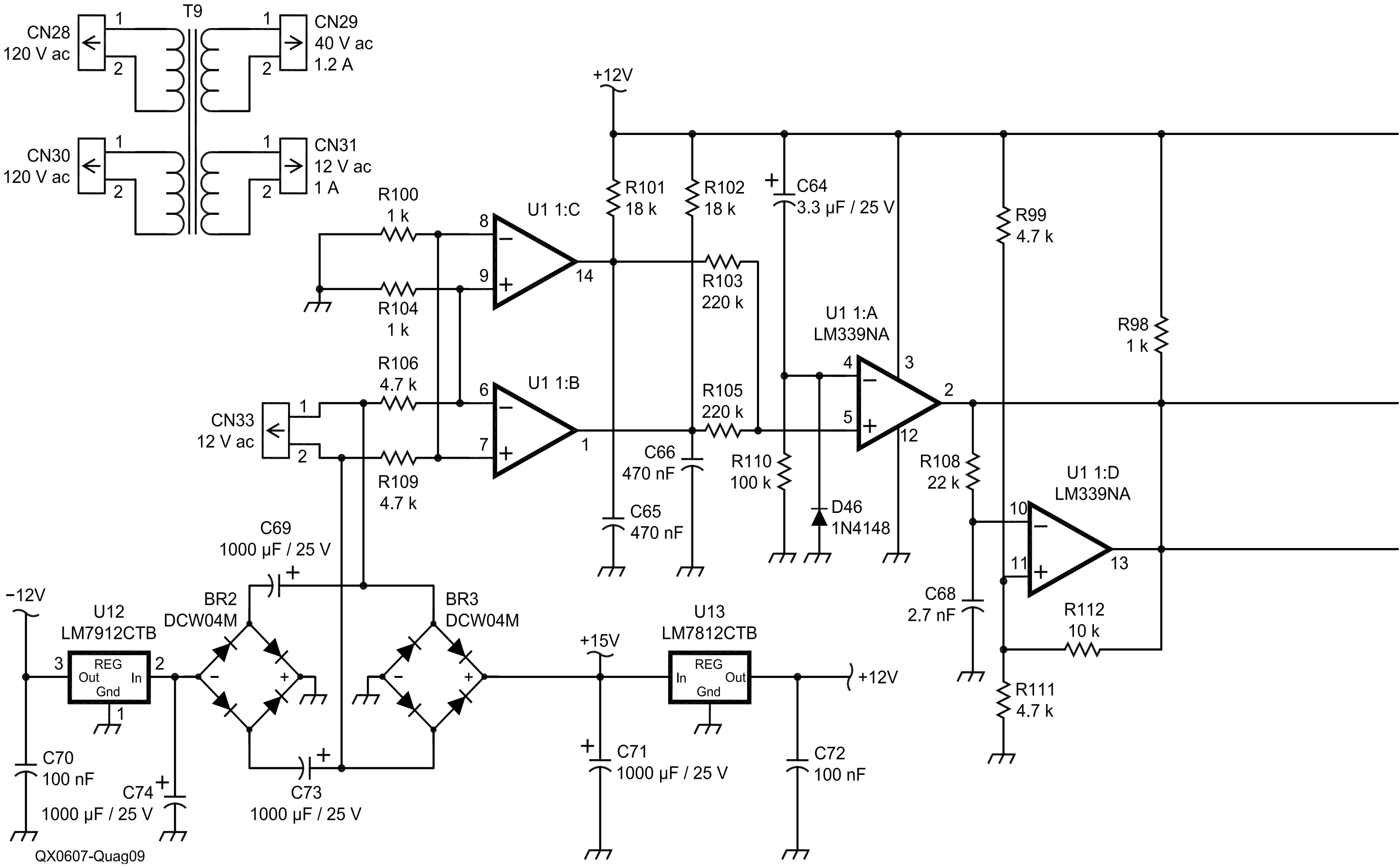
Another limiter function is to keep anode voltage below 500 V during tuning, also to protect components and to give a stable tuning reference current.



Amplifier with power supply removed.



The RF deck top view: tubes, output bobbins, relays and balun stacked to output transformer. The vertical "coil" between tubes is a spring to keep them in place.



The conditioned envelope input is compared to a voltage output sample, and the error signal is amplified, compensated and applied to the power supply phase control via an optocoupler. TR switching and sequencing is performed according to the MODE switch, whose positions are:

1 — Off.

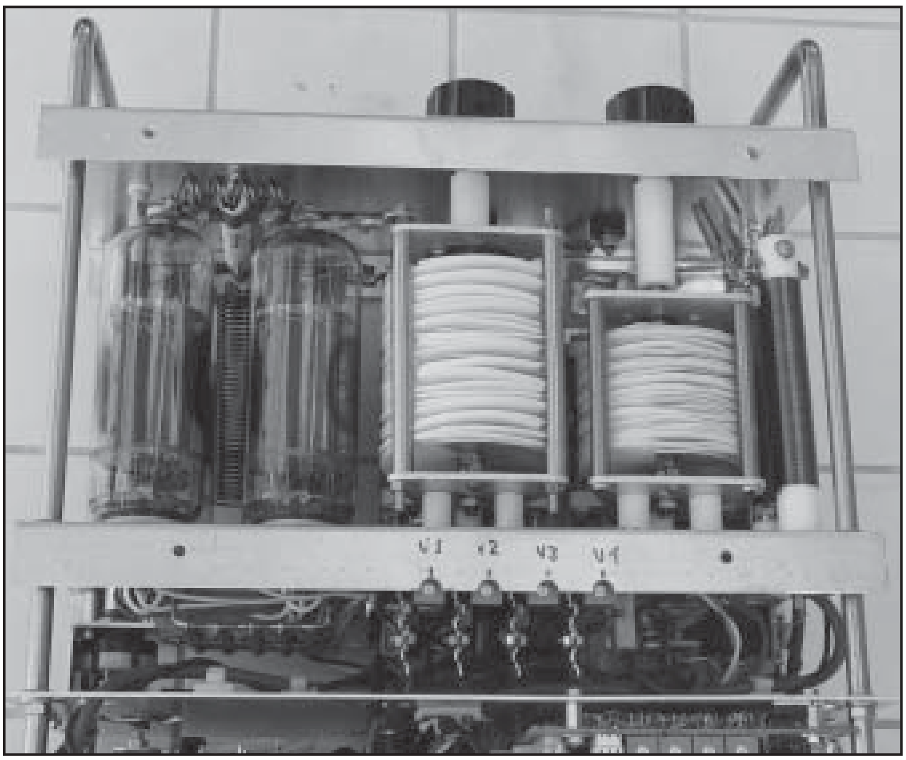
2 — Standby: Heaters and fans on, switching power supply off, RF input bypassed to output.

3 — Tuning: Anode voltage limited to 500 V, RF amplifier connected.

4 — Operating: Maximum power enabled, RF amplifier connected.

Tuning is performed by increasing drive power until saturation is reached (no further increase in plate current), at the same time setting a dip at 1.2 A adjusting alternately plate and load capacitors, as with any pi output amplifier.

The tuning procedure is the same for SSB, CW and AM. In AM the input carrier must be adjusted to read 1.2 A (approximately 500 W RF output). It must be done carefully because of the low power dissipation capabilities of the PL509. The efficiency drops quickly when it is out of tune, and if RF drive is applied care-



RF deck bottom view: tubes, variable capacitors and dc feed chokes.

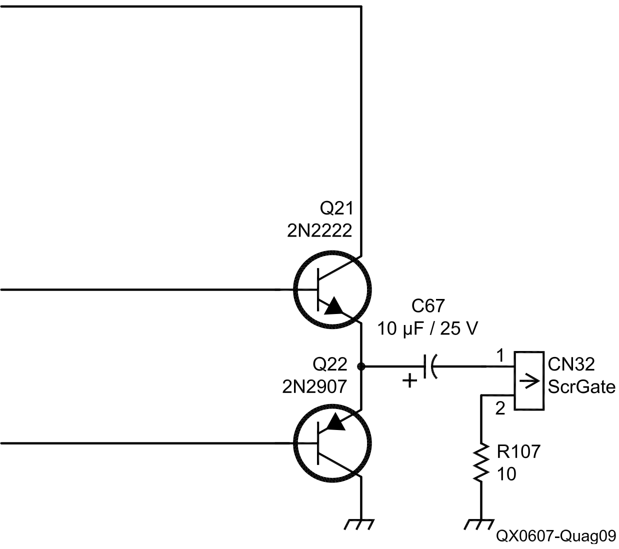


Figure 9 — Auxiliary supply and soft-start schematic diagram.

lessly the thermal protection circuit can be called on to save the tubes, turning power off.

Grid Polarization Circuits

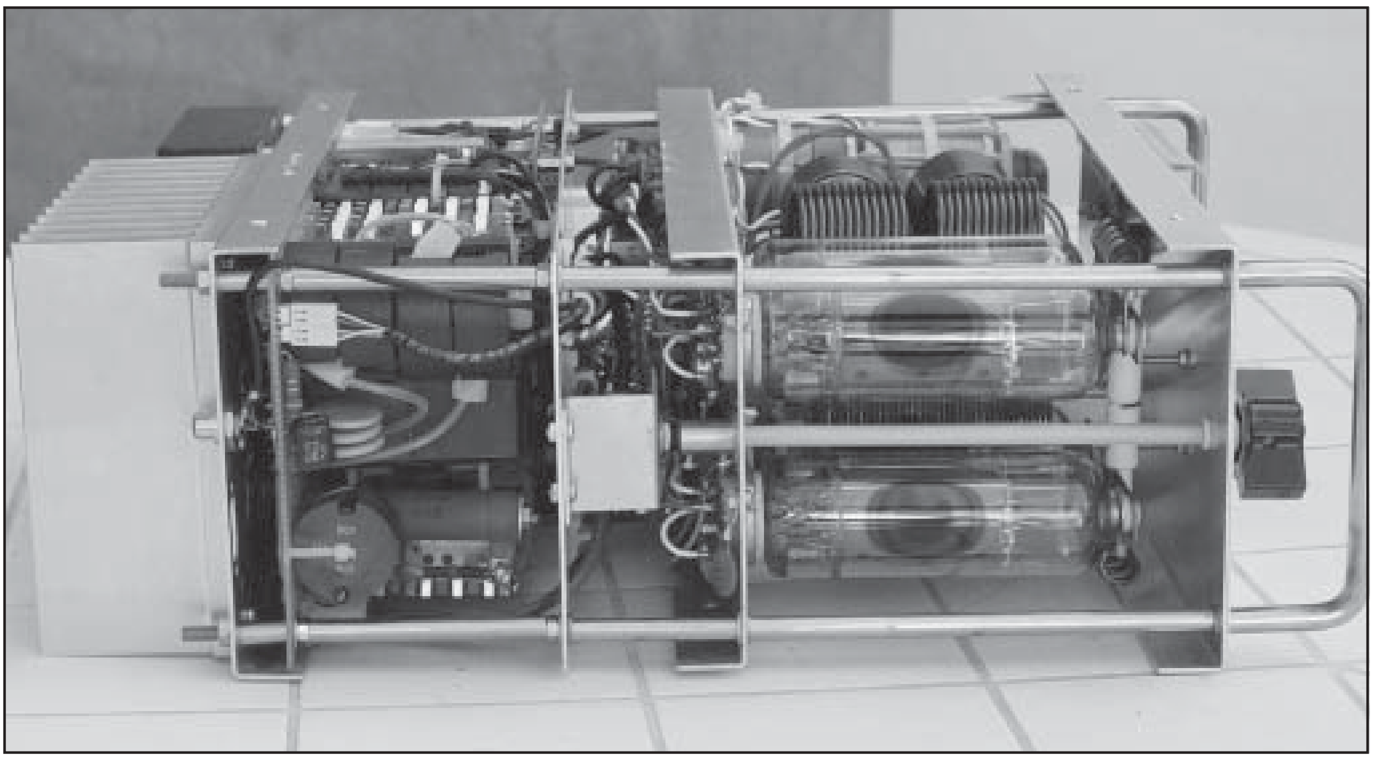
The switching supply provides unregulated 200 V dc to the screen grid series regulator. The circuit also applies negative bias to control grids, keeping the tube's quiescent current at 200 mA (class AB). When drive power reaches the point where the grids start to conduct, the bias becomes more negative due to rectification of input RF. When the tubes are in full saturation, the control grids conduct half of the RF cycle, and its voltage waveform is a negative half sinusoid, much like the plate waveform with inverse polarity.

Also like the output, these half sinusoids appear summed at the input transformer as a complete wave, so there is no input loading distortion even with broadband coupling.

Construction

The photos illustrate the construction of this project.

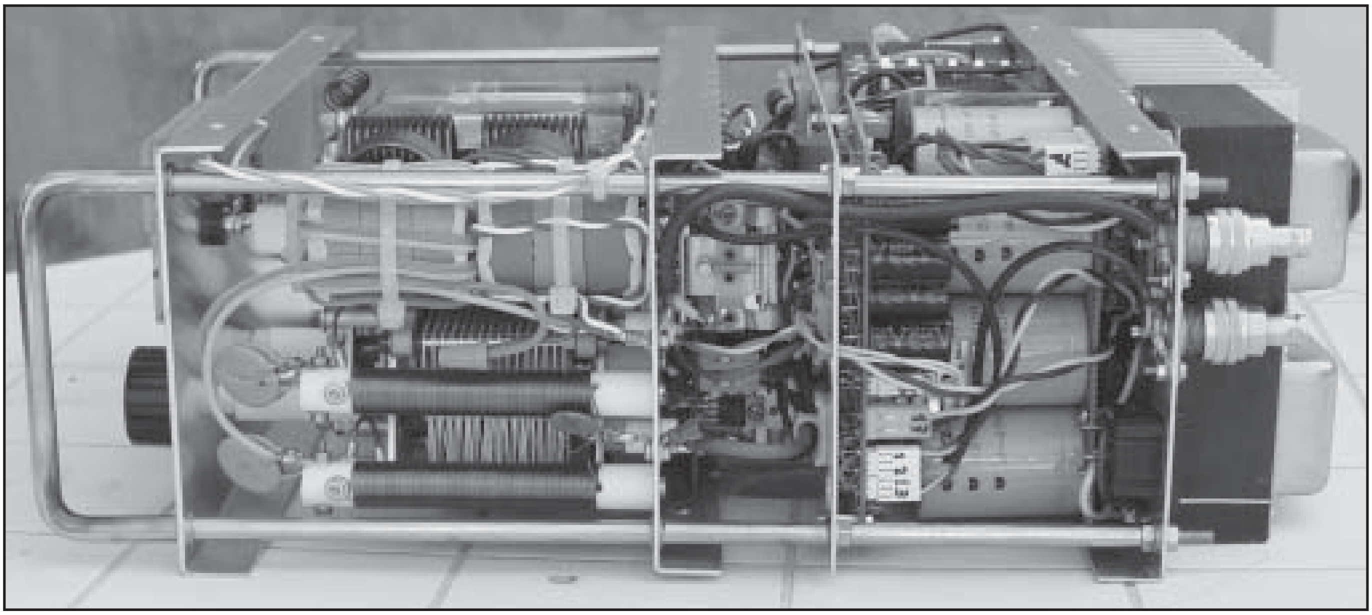
The whole amplifier is mounted over four aluminum decks held together by "inox" threaded bars inside inox tube separators. Four L-shaped acrylic sheets close the cabinet. This cover was made for demonstration purpose only, but as it looks good, it was kept. I am aware this is not a definitive solution, since there is a considerable RF field flowing across the operator and neighboring electronics. A cover made of identically shaped aluminum will be provided soon.



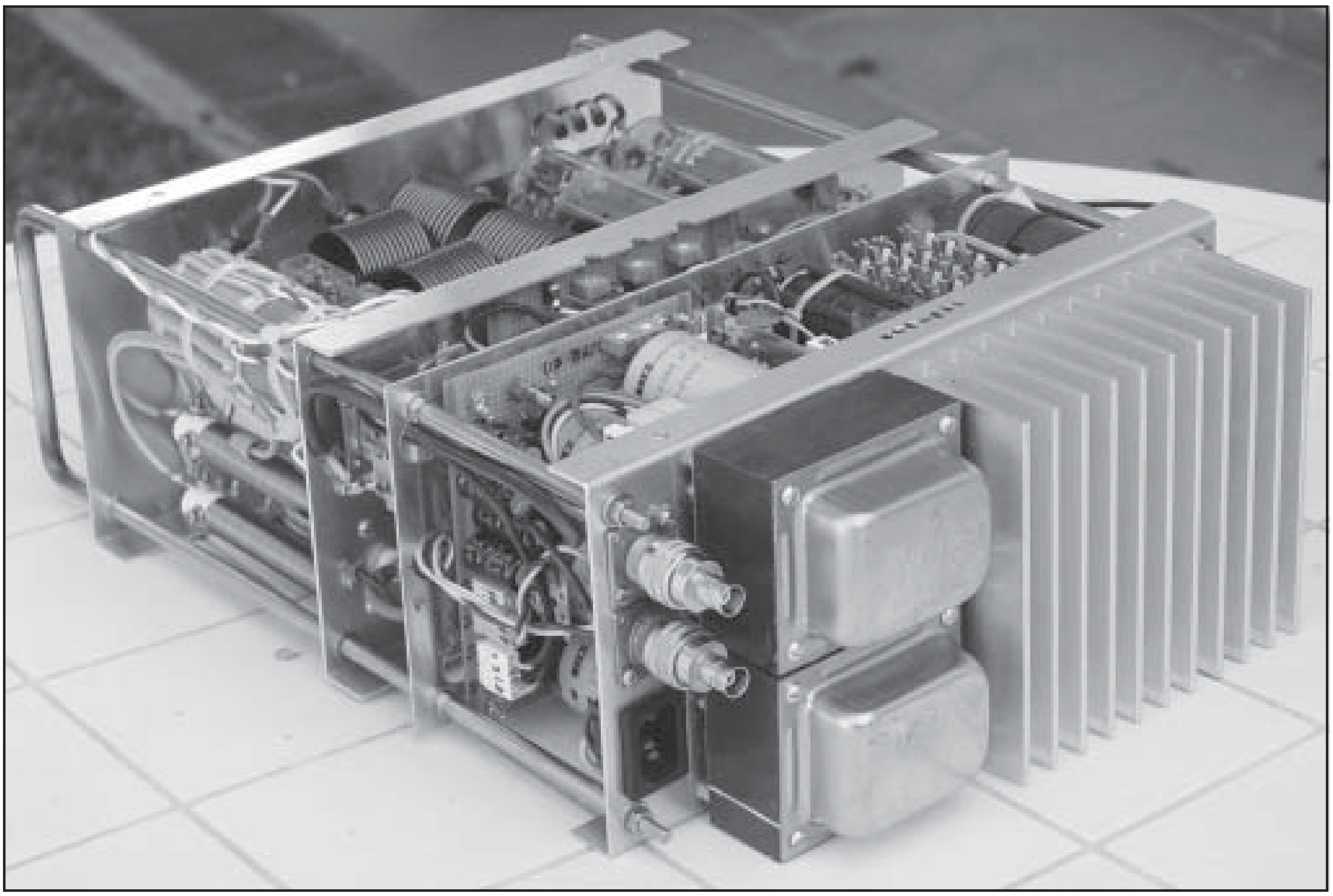
Left side view: power supply output transformer and filter, mode switch and tubes

To shrink the variable capacitors into the small space available, the aluminum plates were interleaved with Teflon discs. Because of Teflon's higher dielectric constant and electrical rigidity, it was possible to construct open capacitors similar to vacuum types regarding to size and isolation. But I am not sure if they will last long in an environment full of dust and humidity.

Two dc computer fans operating at half voltage (they are near inaudible at this power level) keep the amplifier cold even during long



Right side view: balun and transformer, dc chokes, RF commutating relay and input storage capacitors.



Back side: Auxiliary transformer, ac input filter choke, RF input/output connectors.

AM chats. When triggered by thermal overload, the protection circuit applies full voltage to the fans, shortening the shut-off period.

Only the critical circuit boards were made by printing (actually hand-painting and etching): The output bobbin board and power supply control/drive. Other boards were hand wired wire-wrap style but all joints were soldered.

The front panel meter is a no-barrel type to save RF deck space. All the switching supply power semiconductors are mounted over the aluminum heat sink located at the back side. The heater transformer is also mounted on the back, together with the rectifier input choke. They both are built with a silicon-iron core to reduce size and weight (see photo).

Specifications

Bandwidth: 3.5 to 3.8 MHz and 7.0 to 7.4 MHz

SWR output: 2.5:1 max.

SWR input: 1.5:1 max.

Output power

- SSB: 2000 W PEP
- CW: 1000 W, 50% duty cycle
- AM: 500 W carrier, 2000 W peak
- FM, RTTY: 500 W continuous

Power gain: 15 dB

Plate efficiency @ 1000 W: 83%

3rd-order IMD: –3 5 dB @ 2 kW PEP

Spurs and harmonics: – 60 dB

Dimensions: 30 × 13 × 45 cm

Weight: 8 kg

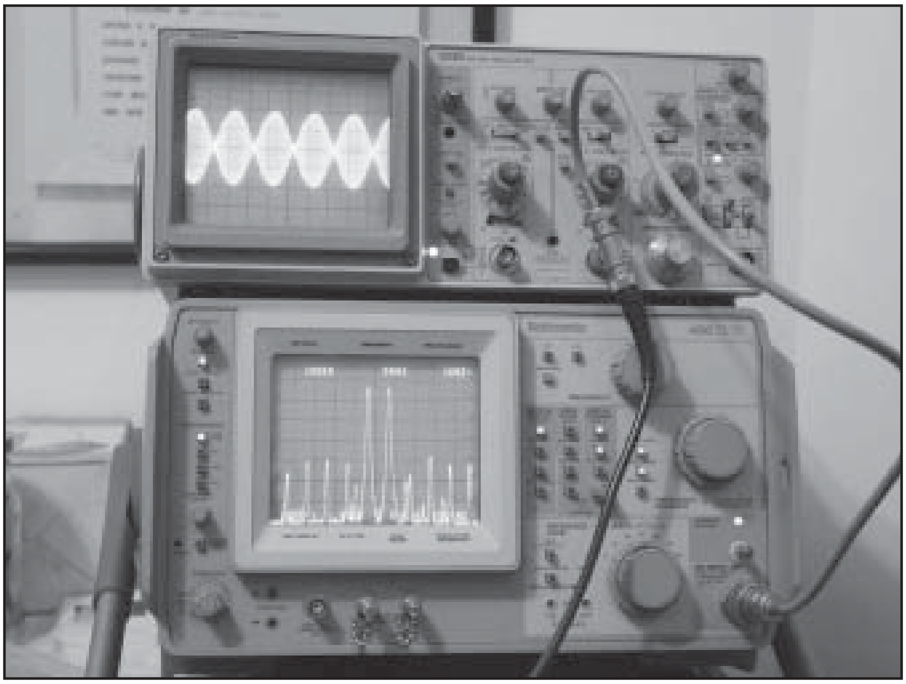
Conclusion

This prototype was a good platform to test some innovative concepts. I was surprised by its good linearity. As you can see in the oscilloscope photo, there is a visible discontinuity at crossover level, because of the limited frequency response of the switcher loop. It seems that this distortion only worsens high-order intermodulation products, making them a bit higher than measured with conventional amplifiers, but the third-order products are lower. Both are well below accepted standards in any case.

The amplifier has impressive performance, is very compact, unconditionally stable and easy to tune. There are some drawbacks on this project, however:

- It's not very easy to duplicate due to some hard to find parts as TV tubes, uncommon capacitors, old sockets, etc.
- High PL519 interelectrode capacitance precludes working at higher bands.
- The compact layout is somewhat clumsy and difficult to test and service.

But it could be a starting point to develop an all-HF-bands semiconductor version, microprocessor-controlled, with auto-tuning and other goodies. Another interesting project could use more powerful tubes, such as two 4CX400 tubes, which would develop a 2 kW output level continuously.



IMD at 1 kW output.

I've gotten good contacts on AM and SSB with it, and when I tell technically minded fellow hams what is inside the equipment they are hearing, they find it hard to believe: What? Plate modulated linear? Two kilowatts from TV tubes?

Saulo Quaggio holds a degree in Electrical Engineering from the University of Sao Paulo. He has been licensed as PY2KO since 1990. He has worked in several Brazilian government and commercial electronics/mechanical projects. He is dedicated to ragchewing and construction projects, and also enjoys scuba diving and flying ultralight aircraft. Saulo runs his own company (where he also works as a computer and hardware engineer) that specializes in automatic fare collection systems for public transportation.

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