A Linear Amplifier for 80, 40 and 20 Metres

With the trial period for lifting allowed power levels in Australia from 400 watts PEP to 1 kilowatt PEP commencing in March 2012, I felt it was probably worth publishing broad details of a linear amplifier I have been working on, including some of the reasoning behind the design. Please note that this is not a construction article, but simply something to start minds working along the path to designing and building ones own linear. Parts for these beasts are not that readily available, and the junk box of each builder will probably have unique and expensive parts which can be used, and around which a particular design will evolve.

Warnings

Linear amplifiers with these sort of output powers are thoroughly dangerous animals, whether based around tubes or semiconductors. 1000 watts of rf (630V p-p into 50 ohms) no matter how it is generated, will do a great job of killing you, and finding or creating weak points in your antenna system. Tube amplifiers add the perils of high dc voltages to the list of dangers, and there is no such thing as a small mistake with these amplifiers. They are LETHAL, and you should not attempt construction of an amplifier (or even open a commercial unit) unless you are thoroughly competent to do so. Transmission lines to antennas and antenna tuning units etc should be regarded with similar caution. Finally also remember that the intense fields these powers produce around antennas should be regarded with considerable conservatism and suspicion.

General Concepts

I have built a number of linear amplifiers in the past, and generally these are not simple structures. The complexity normally starts in the power supply, and this is particularly so if the active device in the linear is a power tetrode or pentode. For tubes such as the 4CX1000 and 4CX1500, a highly regulated screen supply is necessary in order to create an amplifier with good intermodulation performance. This screen supply must hold the screen voltage constant within a few tens of millivolts whether the screen grid is sinking current , or later in the tube life, sourcing current . Such a supply is complex and expensive, and produces plenty of waste heat.

In these amplifiers, protection circuitry must be provided in case the plate supply fails, leaving the screen to absorb large amounts of current. Without protection, the screen grid will rapidly melt through over dissipation, destroying a very expensive tube in seconds.

Use of a triode overcomes these problems, massively simplifying both the power supply and control circuits. The price of course is a dramatic drop in the tube power gain, leading to an increase in the drive power required from the exciter. These days this is not much of a problem, as the common transceiver typically provides 100 watts of rf output. To produce 1KW thus requires the builder to find a triode with a power gain of just 10db and this is not difficult.

The question of overall cost raises its head too, and one of the major items is the main power transformer. I ended up winding my own to keep costs down but this is way beyond the scope of this article. If one is aiming for an amplifier with an output power of 1000 watts, then with the tube running in class AB for reasonable linearity, the overall efficiency will probably be around say 55%, meaning that the power supply will draw about 1.8 kilowatts. However, this is only true for FM or the unrealistic situation of continuous single tone testing at full power. If the linear is going to be used for SSB speech, then even with considerable amounts of speech compression, the average total power draw is unlikely to exceed 500 watts. This simple fact allows massive amounts of weight and cost to be saved. In the amplifier design following, the power supply is rated at 1050 watts continuous which at around 50% duty cycle allows continuous single tone and FM operation for quite long overs. This makes it a very heavy duty design, and many commercial 1000 watt units on the amateur market have supplies rated at only 500 to 600 watts continuous.

A comment on how a high power linear should be used is probably in order here too. First, it is rarely necessary to use a linear at all, as 100 watts and a good aerial system generally deliver the goods. The only normal exceptions to this rule typically occur when one is trying to control a national or international net, or when trying to make oneself heard on an ultra noisy band or during a large dog pile in a competition. Next, it is wise to run large amplifiers conservatively so that distortion and intermodulation products are minimised. A 1 kilowatt unit run at a 400 watt level is very neighbor friendly, and the difference in received signal strength between 400 watts and 1 kilowatt as shown on an S meter is minimal. The writer regards those who use linears simply to demonstrate that “mine is bigger than yours” as complete idiots, unworthy of a ham ticket.

The Published Design

After a lot of back and forth, I finally settled on the GI7BT triode as the basis of the design. These are a microwave triode offering around 14 db of gain and are available very cheaply on the ‘net. A brand new set of four can probably be obtained for around $100, providing 2 tubes for the amplifier and 2 spares. Sockets for these tubes can be very simply fabricated from scraps of fibreglass pcb and fingerstock (see photo and addendum), or alternatively the real thing can be obtained on Ebay. A couple of these tubes carefully used will give at least 850 watts on HF.

Russian military authorities of this era were very conscious of the need to use general purpose parts, which in turn, greatly simplified field service of military gear. The GI7BT is an excellent example of this philosophy with its primary application in tank borne radar. The T in the type number indicates the super rugged version of this tube developed for this brutal application. A less rugged but still very tough version is sold under the type number GI7B on the ‘net. In its radar use as a pulse tube, 12KV is applied to the anode. When used in linear applications, the manufacturers recommend anode voltages of not more than 2400 volts dc. Unlike most common rf power triodes, there is thus a tremendous safety margin built in against internal tube flashovers. The fifty watt series resistor normally included in the anode voltage supply line to limit current during flashovers can probably be quite safely omitted, which is another simplification and cost saving. Nonetheless, a sacrificial resistor of 0.47ohm 5watt rating has been included in the negative high voltage return line to provide some protection in this most unlikely event.

Yet another simplification has been the omission of ALC circuitry. A much better solution is to operate the amplifier and exciter intelligently in conjunction with a modulation monitor so that any overdrive is immediately visible and can be avoided. ALC does not necessarily prevent improper operation or the excessive production of spurious outputs.

Running through the power supply system first, at switch on power is supplied instantly to the blower and tube filaments. Without air, the tubes will rapidly overheat, but no protection system has been provided because the design is based on the KISS principle. Put simply, the operator has a pair of ears and a brain, and all common microwave blowers use shaded pole ac motors which are incredibly reliable. It is very easy to bury a linear design in an overly complex microprocessor based control system, which will probably do something stupid in the middle of the QSO which is getting you your 200th country.

Immediately power is applied, a 90 second delay starts which prevents high voltage being applied to the tubes before they have reached proper operating temperature. This prevents cathode material being ripped from the cold tube cathodes, completely ruining them. In the control circuitry, a 220uF capacitor charges towards the 12 volt rail via a series combination of 220 and 270K resistors, and when the voltage across this capacitor reaches about 7.3 volts (after 90 seconds), the collector voltage of the second BC548 in the Darlington pair moves down from 12 volts turning on the BC557 and operating relay A. Relay contact A1 closes, applying 240 volts to primary of the high voltage transformer via two 82 ohm resistors. This limits the surge current that can flow in the transformer secondary while the main 54uF filter capacitor is charging up, giving a “soft start”. When relay A operates, the full 12 volts appears across its winding and this voltage is then applied to the base of the second Darlington pair via another time delay circuit. It takes about 6-7 volts to cause a typical 12 volt relay to work, and so the base of the second Darlington pair of BC548s must reach about 7-8 volts before relay B will operate. This takes around 1 second due to the 10K and 47uF capacitor, at which point relay B operates closing the contact B1 and applying the full 240 volt directly to the primary of the high voltage transformer. Note that the high voltage can be switched on and off with S2, any time after the filaments have reached operating temperature, and that a “soft start” will always occur. If S2 is left closed during start up, the filaments will warm up but no anode voltage will be generated until the operator chooses.

The rest of the power supply circuitry is quite simple. A 33 volt 50 watt zener diode sets the grid cathode bias of the tubes, ensuring that the cathode potential is 33 volts below ground and setting the no signal standing current through the tubes to about 40- 50 ma (the zener voltage may need to be slightly lowered to get this standing current, but 33 volts is a good place to start). With the STANDBY switch open and the 15K resistor which it normally shorts now in circuit, additional negative bias is then developed totally cutting the tubes off (about 1 mA of standing current). All metering is done at potentials very close to ground, meaning that you can fall against the front of the linear and break a meter face without the risk of electrocution.
The voltage used to indicate anode current is derived across the 0.47 ohm 5 watt resistor in the negative supply line from the bridge through the zener diode to the tube cathodes. As pointed out previously, this resistor is sacrificial in the event of a tube flashover, as is the 100 ohm resistor in series with the meter, if the meter happens to be switched to monitor anode current. The voltage indicating anode voltage is derived across the bottom 33K resistor in a chain of 20 such resistors. It is vital that this many resistors appear in such a chain. If manufacturers specifications are consulted, the maximum dc voltage which should appear across a typical 1 watt resistor is limited to 250 volts. This produces intense electric fields along the length of the resistor which with time will actually cause the resistive material in the element to shift towards one end of the resistor, causing it to go open circuit. Another very substantial danger is the possibility of flashovers occurring between adjacent turns in the spiraling in the resistor element if too much voltage is applied. Once this occurs, extra stresses are applied to all the other resistors in the series chain, which in turn, can lead to catastrophic breakdown of all resistors. For these reasons in this design the voltage across each 33K is limited to around 120 volts dc. Finally, the grid current flowing during normal class AB2 operation (150mA max.) is monitored using the voltage developed across the 1 ohm 5watt resistor in parallel with M2.

Turning now to the rf section of the amplifier, the first section worthy of comment is the pi input filters. Because the tubes are operating in class AB, for about half of each cycle they will be off, causing a cathode input impedance of infinity during this time. For the other half of the cycle the tubes will be on, conducting varying amounts of anode current as the half cycle progresses, and causing the input impedance at the cathode to vary wildly. Some energy storage system is consequently necessary to even out these hugely varying demands for energy from the exciter. Modern semiconductor rigs will not tolerate this form of abuse which shows up as high swr, and will simply shut down to protect themselves.

The perfect energy storage system is of course a tuned circuit which can store up energy when the tubes are off and deliver it back when the tubes demand current (the flywheel effect). The pi section low pass filters fill this role and are designed to have an operating Q of between 1.5 and 2.5. This low Q provides a nice flat input response across each band while at the same time providing just enough flywheel effect to nicely smooth out the variable energy demands of the tubes and present the exciter with an swr of less than 1.2. Trying to calculate the average input resistance over the cycle from the limited tube characteristics available proved very difficult indeed, but the calculations did get me into the ballpark. After some empirical optimization, the average input resistance at full power over the cycle turns out to be 110 ohms. Note that the capacitors used in the filters are all silver micas. While the temperature characteristics of these capacitors are very good, these are not terrific components to use when high rf voltages and currents are around. I have had some very bad experiences with silver, which like the resistive film previously mentioned in the paragraph on 1 watt resistors, tends to wander about in the presence of high level currents and fields. For this reason, each capacitor used in the filters is fabricated from two silver micas of about equal value in parallel so that rf current flow in each capacitor is minimised. Finally the coils for the filters were made up from a few turns of 1.6mm copper wire wound around those wonderful little ferrite rods which master scroungers can obtain from inside the steel filament enclosure of dead microwave magnetrons. These little bits of low loss ferrite (5mm dia. 20mm long) can be slid into each coil until a very low swr is reached across each band and then locked into position with a dob of paint.

The position of the filters turns out to be vitally important too. Big pulses of anode current flow through the capacitors on the output side of the filter in use. If the filters are physically located far away from the cathodes which they drive, then the series inductance introduced in the connection between filter and cathodes can badly reduce the drive available at higher frequencies dropping the power output. This is the reason that the output capacitors of the 20 metre filter are located right at the tube cathodes. This underhand dodge allows the filter pcb to be located outside the tube enclosure and be connected to the cathodes using a short length of coaxial cable without loss of output.

The last part of the circuit is the tank section. The switching here could have been dramatically simplified if I had been able to source a 400pF variable capacitor with 2mm or more plate spacing. But I had the 250pF unit, so it got used. The tank coil is the first thing to comment on. After some careful calculations using the tube plate characteristics downloaded from the 'net, I settled on a plate load resistance of 1950 ohms, which turned out (amazingly) to be spot on. Normal design practice is to design the tank system for an operating Q of about 12, but this has no bearing on the unloaded Q required for each tank coil. In fact there is no such thing as an unloaded Q which is too high for these coils. The lower the loss the better, and the acid test is that at full power, the coils do not get hot. Having previously fabricated coils from 6 mm diameter copper tube, there had to be a better way. At 80 metres and these power levels, efficient coils can be made from bare copper wire 1.8mm diameter (available as single core 2.5mm square millimetre mains earth wire at your local hardware store), and as the frequency moves up, heavier copper conductors will be needed to minimise skin effect losses.

As I have a lathe, the solution to this was to cut a double start thread of 4 TPI (my lathe is Imperial) with a semi circular thread cross section on a piece of 60mm diameter plastic sewer pipe so that both strands of copper would lie side by side and just touch. This approach allows parts of the coil to be made up from a single conductor, two conductors, or three conductors by stacking to form a triangular shape. It works very nicely, and is very much easier to wind and solder than a piece of 6mm diameter tube AND the material is readily available in the length you want. The entire tank coil comprises 19 turns. I settled finally for 14 turns of two wire conductor and 5 turns of three wire conductor. The entire coil of 19 turns is used for 80 metres, with taps at 5 turns for 20 metres (the 3 wire section) , and 11 turns for 40 metres. In fact it would have been better to just make the entire coil up as a three wire animal.

Setting up the tank system was a snap when an aerial analyser was used. First all power was turned off and the analyser was connected to the amplifier output. With the tubes in their sockets so all stray capacitances were present and correct, a physical resistance of 1950 ohms (with short leads) was connected between the plates and ground. It was then just a matter of adjusting plate tuning and loading capacitors and the coil tap at the centre and ends of each band until a pure 50 ohm resistance was seen on the analyser. Of course, calculations had to be done so that approximately the right amount of capacitance and inductance was there initially, but the whole process for optimising the tank circuits for three bands took just 20 minutes and very closely confirmed the calculations.

The last item is the rf plate choke. K.R. Sturleys old but magnificent book “Handbook of Radio Receiver Design” Book 1 has a section in it which allows the resonant frequencies of single layer rf chokes to be accurately estimated and this was used to select 100uH as the value. The choke was wound using 153 turns of 0.5 mm dia. copper wire on a Delrin rod former 20 mm dia. with the winding ending up 86mm long.

That ‘s it. Proceed very carefully if you are going to build something at home. You have been warned. It is your life and your responsibility and there are simply no excuses. Use the very best safe working practices so you are alive and can brag to your mates about what you did ….

Addendum

Making your Tube Sockets

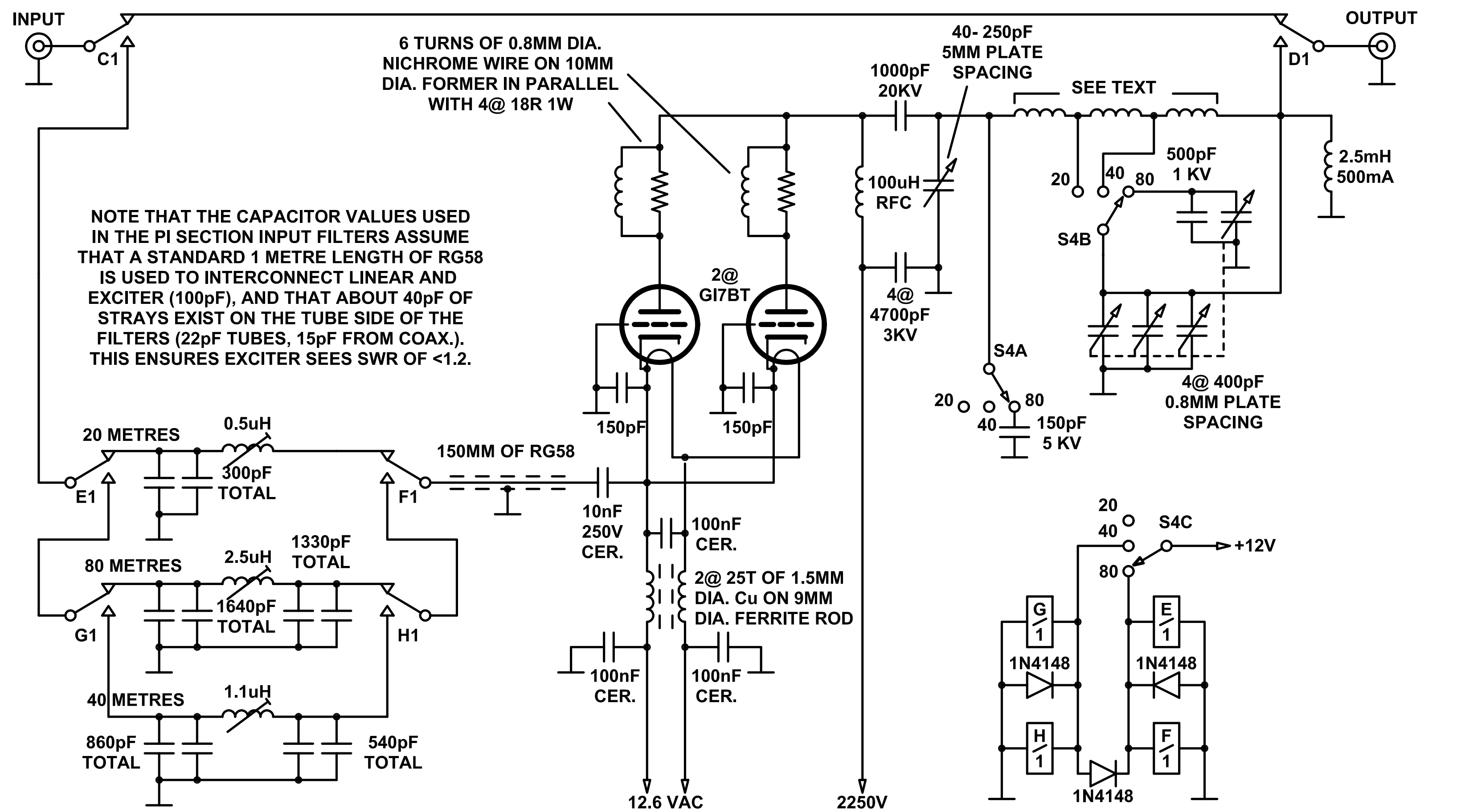
The tube sockets are fabricated from two small pieces of 1.6mm FR4 fibreglass printed circuit board, and U shaped phosphor bronze finger stock (see picture). Upper and lower pcbs are separated by six 16mm long tubular spacers. This assembly is mounted below an aluminium chassis, and the tube grids are grounded securely by making the copper side of the upper printed circuit board face upwards to contact the chassis. To allow easy mounting of the silver mica capacitors between filament and ground, and easy connection to the filament choke, the copper on the lower pcb faces downwards and is broken into two parts by removing a ring of copper. The outer part of this pcb is grounded via the 16mm long metal spacers while the inner parts are insulated and support the finger stock which connects to one side of the filament.

Forced air cooling of the tubes is achieved by passing air between the 2 pcbs and out through the holes in the upper grid pcb. There should be clear area of at least 10mm around the perimeter of the pcb assembly to allow free air flow through it. Chimneys for the tubes can be easily fabricated from high melting point plastic film. Mylar or Teflon film is ideal.

Fabrication starts with cutting out two pcbs 152 x 76 mm, which are then stuck together with double sided adhesive tape. The copper on both boards faces outwards. The centres of the 8 holes to be drilled are marked out and centre punched, and the 6@3mm holes for the spacers are then drilled. Next the 2 guide holes for the centre spigot of the fly cutter are drilled. The boards are then separated, and the insulating ring in the filament pcb is then cut in the copper using the fly cutter.

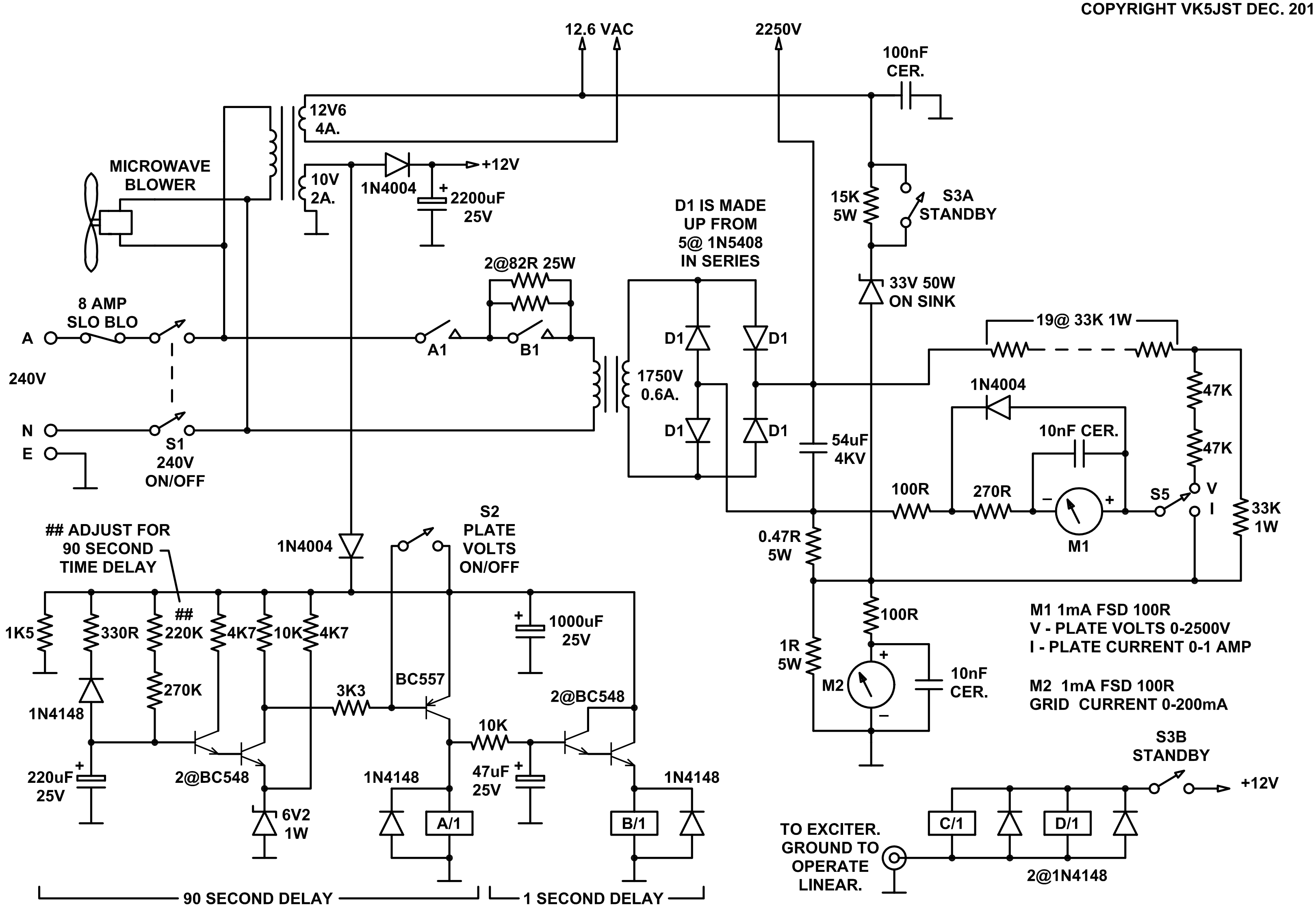
The hole diameters for the finger stock in both boards are not given because available finger stock varies widely. My finger stock had an uncompressed thickness of 3 mm, and a compressed thickness of 2 mm. Finger width was 3mm and finger spacing 4mm. As the diameter of the tube grid and cathode cylinders are 36 and 18mm respectively, this made the diameters of the grid and filament finger stock holes 40 and 22 mm in my case. But you will have to measure up your finger stock and adjust these diameters accordingly. After you have done this, use the fly cutter to form both sets of holes. Debur, clean up, and solder the finger stock to the printed circuit boards.

This completes all fabrication, apart from giving both boards a good clean to remove all flux, and spraying the copper sides of both pcbs with a good solder through printed circuit lacquer. Protect the inner parts of the finger stock with tape when you do this.



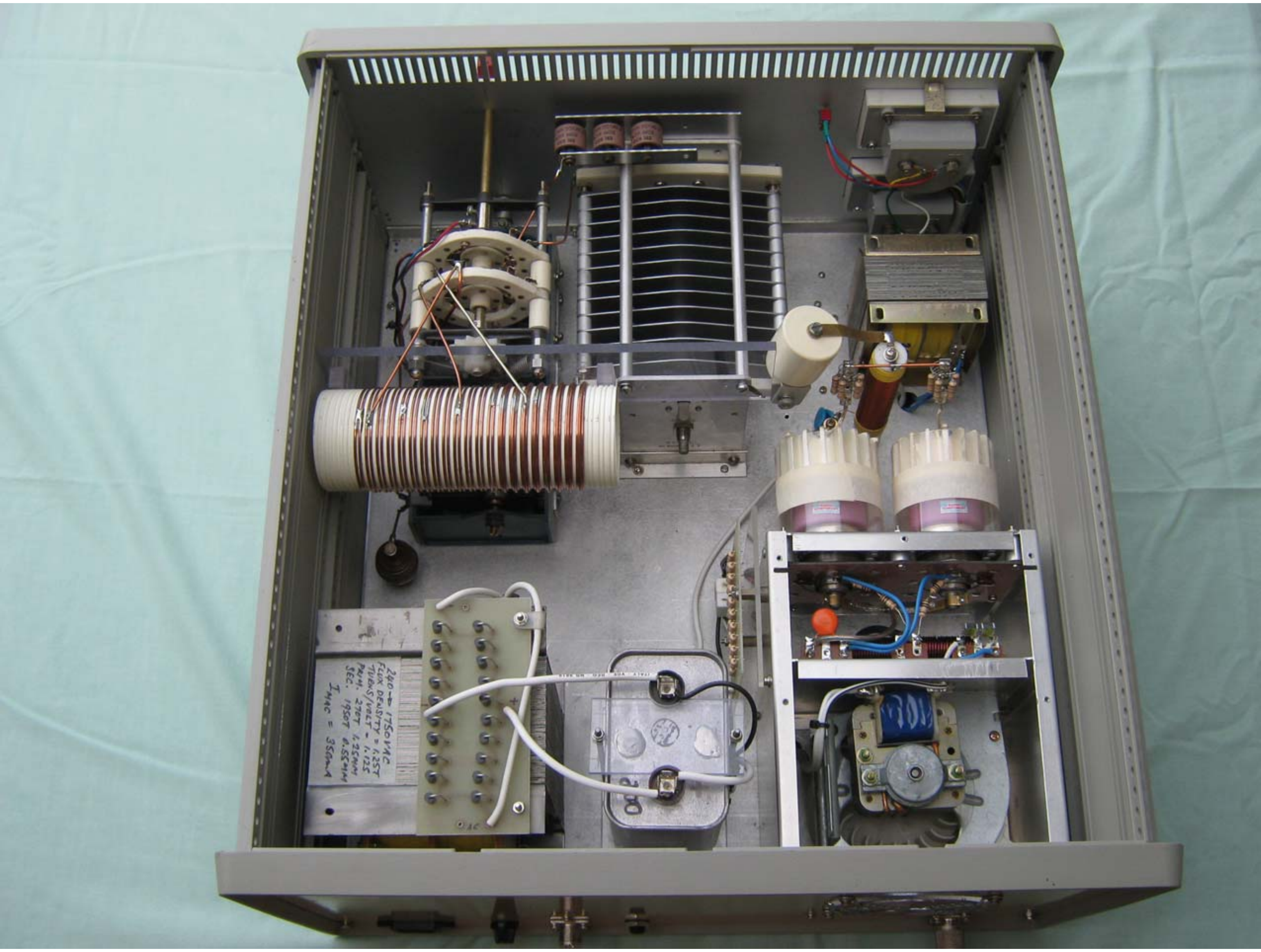
WHERE NOT OTHERWISE SPECIFIED, ALL CAPACITORS ARE 600 VOLT SILVER MICAS.

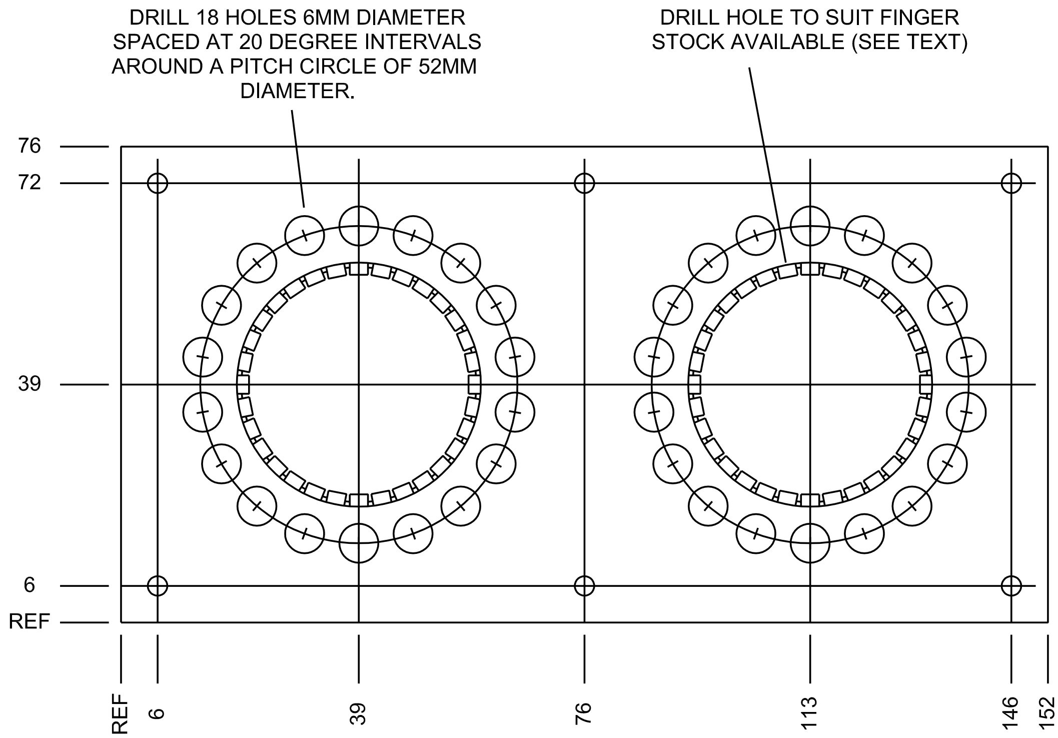
20/40/80 METRE LINEAR AMPLIFIER PART 1- RF SECTION



20/40/80 METRE LINEAR AMPLIFIER PART 2- POWER SUPPLY AND CONTROL CIRCUITS

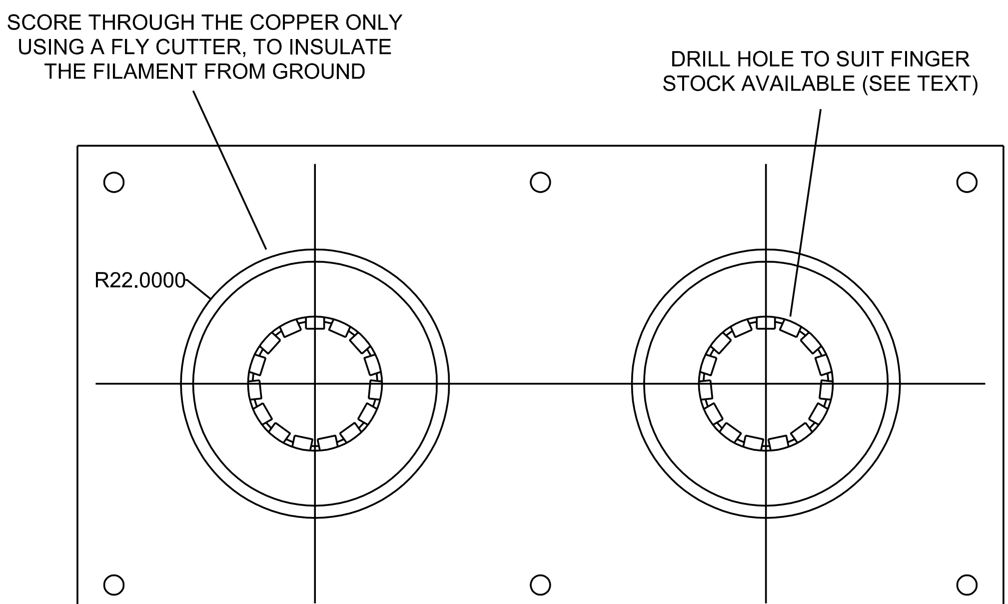

VK5JST 800W LINEAR HF LINEAR AMPLIFIER
VOLTS
mA
PLATE
mA
GRID
80 40 20
STANDBY
ON
OFF
PLATE SUPPLY
OFF
240V


240 → 1750VAC
FLUX DENSITY = 1.25T
TURNS/VOLT = 1.125
PRIM. 270T 1.25MM
SEC. 1950T 0.55MM
I MAC = 350mA



GRID PCB DETAILS

NOTE COPPER SIDE FACES
UPWARDS TOWARD PLATE COOLER



FILAMENT PCB DETAILS

NOTE COPPER SIDE FACES DOWNWARDS

SOCKET DETAILS FOR 2 GI-7BT TUBES

MATERIAL - 1.6MM THICK SINGLE SIDED FR4 FIBREGLASS PCB

NOTES
1. ALL UNMARKED HOLES ARE 3MM DIAMETER
2. STICK BOTH BOARDS TOGETHER WITH DOUBLE SIDED ADHESIVE TAPE, AND DRILL ALL HOLES SIMILTANEOUSLY TO ENSURE PERFECT MATCHING
3. ALL MAJOR HOLES FOR MOUNTING GRID AND FILAMENT FINGER STOCK ARE FORMED WITH A FLY CUTTER