RESTORING THE EARLY PET COMPUTER 9" VDU.

LOPT (line output transformer) Testing & Analysis - EARLY PET VDU's.

(H. Holden. May, 2022)

Background:

This article is primarily about restoring the VDU to excellent working order. Some modifications are offered to improve the performance of the VDU and also to protect it from damage if it received abnormal H drive pulses from the computer board.

Early PETs (or CBM computers) used a 9 inch white Phosphor (P4) CRT, the 9VALP4. This was a CRT used in an early portable Zenith TV set. The later models moved to a green (P39) phosphor CRT, the MW24-302-GH which is an industrial VDU display type. The MW24-302-W, a white phosphor version can also be used in lieu of the 9VALP4.

Looking at the pcb assemblies for the 9 inch VDU's used in the 2001 PET computers, there are essentially two types:

The early version of the VDU board were devoid of two components typically found in most TV and computer VDU's. These were the horizontal width (H width) control coil and the magnetically saturable linearity coil. Due to this factor the horizontal scan linearity in these early versions is fairly poor. However there is a remedy to significantly improve it, which does not require a magnetic saturable reactor coil.

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1) General description of the PET VDU and some basic VDU theory:

The design is of a magnetically deflected electrostatically focussed rectangular CRT which is about 9 inches diagonal and runs a final anode voltage (EHT) of 10kV. This is a satisfactory value to have high screen energy and good beam brightness for a raster scan image on a 9" CRT, even in bright room lighting.

The arrangement is for the VDU to accept three separate signals, which are TTL logic level. These are the H (Horizontal) and V (Vertical) scan drive signals and the Video signal. This is unlike many other VDU's which accept a composite video signal and separate out the syncs and video internally.

The CRT scan circuits are greatly simplified compared to most VDU's because there are no local H or V scan oscillators.

The H & V scan "drive" signals emanate directly from the PET computer motherboard. The V scan frequency on my PET 2001 (which was acquired from a UK seller) is 60Hz and the H scan frequency measured 15,630 Hz or close to that on my PET.

The video signal (logic level) is on or off and the "video amplifier" which drives the CRT gun (at its cathode) is a binary switch, rapidly turning on the beam, or cutting it off. Therefore the VDU has no "Contrast" control. No shades of grey are possible with this video amplifier. A brightness control is present in the CRT's grid circuit, so as to adjust the screen brightness.

In my particular VDU, even with the brightness control at minimum setting (Full - 30V applied to the CRT grid circuit) the brightness was too high. This value is suited to cutting off the beam current in the 9VALP4 CRT, but not in the MW24-302-GH (in my VDU), this CRT requires in the region of -45 to -50V for full beam cut-off.

Some later versions of the PCB, with a variant of the flyback transformer (LOPT= line output transformer) could generate this higher negative voltage value. However, in my PET, the LOPT (rectifier for the grid circuit, was designed to produce -30V. Commodore seems to have "mixed and matched" CRT types and the LOPT's on the VDU boards. The fix for this problem, if it turns up in any other PET VDU's like mine, with this combination of parts, is in the modifications section of this article.

2) Pros & Cons of a VDU without its own scan oscillators – Risks to the HOT & LOPT:

One could argue that not having local scan oscillators in the design results in no oscillators to go out of lock. Many fewer parts, for example, no H & V hold controls and less resistors, capacitors & transistors.

However, there is the potential for VDU damage if the H drive signal from the computer becomes too abnormal.

Generally, if a DC supply is switched across an inductor L, the current rises in the usual inverted exponential format and settles out after a time at V/R, where V is the applied voltage and R is the DC resistance of the inductor. However, in the very early phases of this current profile (which is where H scan stages in VDU's operate) the rate of rise of current is fairly linear. The initial rate of rise of current with time is V/L which has units of Amps per second. This is found by differentiating the usual equation for the inductor's current profile. Also, the units can be checked because inductance, mostly talked about in Henries, has units of Volts.Seconds per Amp.

The simple reason for the hazard is that when the HOT (horizontal output transistor) switches the total inductance of the Yoke and LOPT together (about 91uH) across the 12V power supply, the HOT's collector current starts to rise at the *frightening rate* of V/L Amps per second.

12v/91.4uH = 131,291 Amps per second. However, the HOT is only conducting for about ½ the active scan time, or around 27uS. Therefore, at the end of scan on the right size of the scanning raster, the HOT's collector current has risen to around 131868 x 27uS = 3.55A, which is a typical sort of value, or a little less, as the peak HOT collector current a 9" VDU. In practice it is a little lower around 3A due to the inductor's resistances. The Yoke's H coil peak current is in the range of 2.7A.

Clearly, if the H drive frequency dropped, for example halved and the HOT was switched on for too long, the peak currents would double and in addition the stored magnetic energy at the end of scan would quadruple, because the stored energy is proportional to the square of the current. The peak HOT collector voltage would also double along with the EHT doubling. Some factors, such as yoke & LOPT winding resistances would limit this doubling. However the flyback voltages, derived from the stored magnetic energy in the LOPT's core could climb high enough to destroy the HOT and or damage the LOPT, or EHT rectifier inside it.

The energy stored in the magnetic components (Yoke and LOPT) has peaked at the end of scan, on the R hand side of the raster. At the point, the drive to the HOT actively forces it out of conduction. The magnetic fields (Yoke & LOPT) start to collapse and the inductance forms a resonant circuit with the total tuning capacity.

This "tuning capacity" takes the form of the self capacitance of the LOPT windings and H Yoke coils and HOT collector capacitance and the "lumped added tuning capacitance" of a larger value. In the case of the PET VDU, this lumped tuning capacitor is a 0.047uF designated C25 and a 0.001uF in parallel C24. The lumped value normally dwarfs the self capacitance in value, on the primary of the transformer.

After flyback starts and after ¼ cycle of oscillation of it, the system is halfway through flyback where the CRT beam would be in about the centre of the screen. At this point the yoke's current is zero and all the magnetic field energy (ignoring small losses) has now been transferred to the electric field of the capacitances. Also at this point the voltages on the LOPT terminals are peaking. Typically in a 9" VDU the HOT's collector voltage will have peak to a value in the order of 80 to 130V depending on the design.

The very high EHT voltage, in the order of 10kV for the PET VDU, comes from a secondary coil (called an Overwind coil on the LOPT) . The Overwind output is peak rectified for the CRT's final anode supply. It became customary to build this EHT rectifier into the LOPT body to help with issues of insulation.

As the oscillation progresses past ¼ of a cycle and by half a cycle later, the energy has been transferred back from the capacitances to the magnetic field of the inductances. Now the magnetic field is reversed in polarity, so after flyback the beam is now on the left side of the screen.

At the point the voltage on the HOT collector and ERD (energy recovery diode or damper diode) is zero and attempts to fall below zero (ground or common) the diode then conducts, clamping the voltage to near zero. This damps out what would have been the second half cycle of the flyback oscillation and results in a near linear decay of the Yoke's current to scan the left side of the raster. It is the current via the ERD which scans the left side of the raster toward the centre. The HOT is switched on again, a little prior to the beam reaching the centre, to let the H yoke coil current seamlessly start building up again to scan the right side of the raster. And so the cycle repeats.

One saving grace helping to protect the HOT & LOPT:

There is one saving grace or protection from abnormal drive signals to the HOT in a direct drive system without scan oscillators. This is because of the way the HOT's driver circuit, with a transformer is designed. This is not often mentioned and sometimes the schematics are incorrect when they show the polarity of the driver transformer's windings. The drive current to the primary of the driver transformer, via the collector circuit of the driver transistor, is such that the active drive switches the HOT off, not on. The HOT is switched on when the driver transistor switches off. The energy for this process is the stored magnetic field in the driver transformer's core. This increases if the driver transistor was turned on longer than normal though but there is a limit to the amount that can be stored due to magnetic core saturation of the small driver transformer.

Ideally then, the driver transformer is not too big, a case of smaller being better than bigger. Still, this feature won't always save the HOT if the drive signal to it is too long per cycle and sustained for too many cycles. Or if the HOT is high frequency over clocked, which puts it into an intermediate state of conduction and excessive current flows via the power supply and LOPT primary.

On the other hand, in general VDU & TV circuits which possess their own scan oscillators, these run at close to the correct operating frequency and duty cycle, even if presented with noise rather than stable sync pulses. This provides significant protection for the HOT and LOPT.

In the PET, the HOT is easily protected by adding a 120V 5W zener diode (1N5380B) either across the HOT's C-E terminals or adding it across the ERD. This is mentioned in the modifications section.

There are many aspects to the restoration of the VDU's pcb. I have divided this article into sections. The theory behind the suggested modifications is found in those sections.

Obviously not everybody might want to make the modifications suggested here and keep the unit entirely original. However these modifications have been designed in a manner where each change is fully reversible leaving no damage to the VDU, so it can be quickly returned to its original state if anybody wishes.

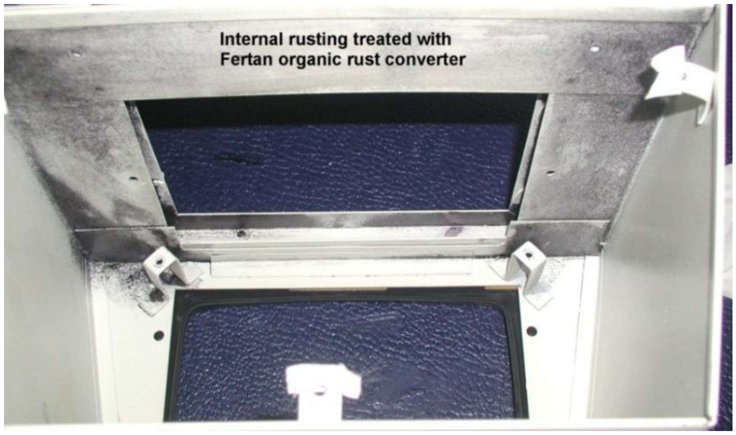
3) VDU housing restoration:

The enclosure of my original VDU looked very good, on the outside, with the paint in very good condition. However, when I took the back off the unit I noticed a red-brown powder on the EHT cap and fine pit marks in the metal, in places where the inside of the cabinet had not been properly spray painted and just had only what amounted to a light over spray.

I quickly determined this was surface rust and so was the fine red dust which had been electrostatically attracted to the CRT's EHT cap. This was confirmed on a taste test that the deposits on the EHT cap were microscopic rust crystals. Rust has a very characteristic unpleasant flavour much like the haemoglobin in blood. It became evident again, where the anti-rust treatment was applied, which turns rust crystals a dark blue.

To treat rust I use Fertan organic rust converter. This is a pale yellow liquid which is convenient to brush on. It reacts aggressively with the rust and turns it into a dark blue harmless organic compound. It will also expose rust on a surface, by changing its color to blue, if it is there. Many bare or plated steel surfaces might appear macroscopically free of rust, until Fertan is applied “seeks it out” and it becomes obvious in places that there were some rust crystals present.

A photo shows where the rust crystals have reacted with the Fertan:



The unaffected areas were masked and the affected areas spray painted. Because this was on the inside of the case, I simply used some stock white Duplicolor spray that was close enough. The purpose being to protect the metal from future rusting.

The picture above shows the completed rust repair. I'm not sure how many other PET VDU's would have this problem. It may have been unique to mine due to the poor internal spray painting. Some VDU's may require a complete repaint. In all cases if any rusting is detected it should be treated with Fertan and not just painted over, or the rust will return.

Of note: The temporary thick fibreglass tape around the metal mounting tabs for the rear case cover was placed there before the CRT was removed from the cabinet. It is very important handling a CRT to not let any sharp metal edges touch or scratch the glass. It can be advisable to remove the Yoke first as there is not much clearance removing the CRT. (see notes below about removing & re-fitting the Yoke)

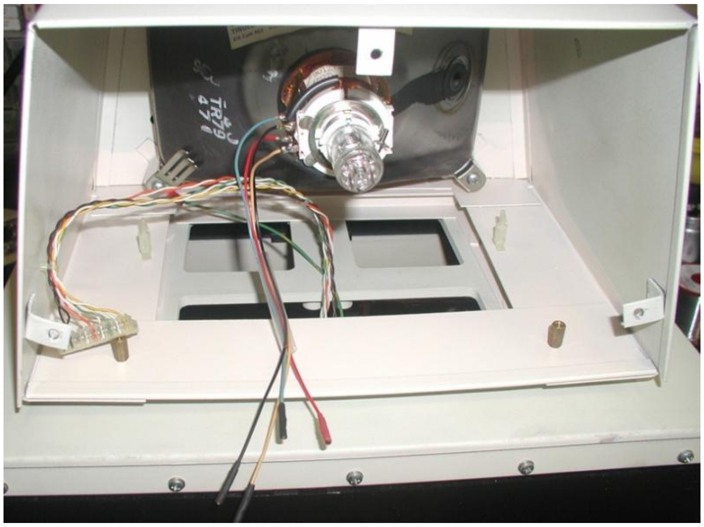
Initially I removed the VDU pcb prior to removing the VDU body from the PET case. The VDU pcb is easy to remove, first the two rear mounting screws are removed. Leave the unit for 24 hrs so the charge on the CRT bulb has dissipated, remove the anode cap. It is a reach to get at the two nylon mounting clips near the front of the pcb. I simply used a small piece of aluminium tubing around 4.5mm ID, to slip over them, which compressed the retaining projection and allowed them to release the pcb.

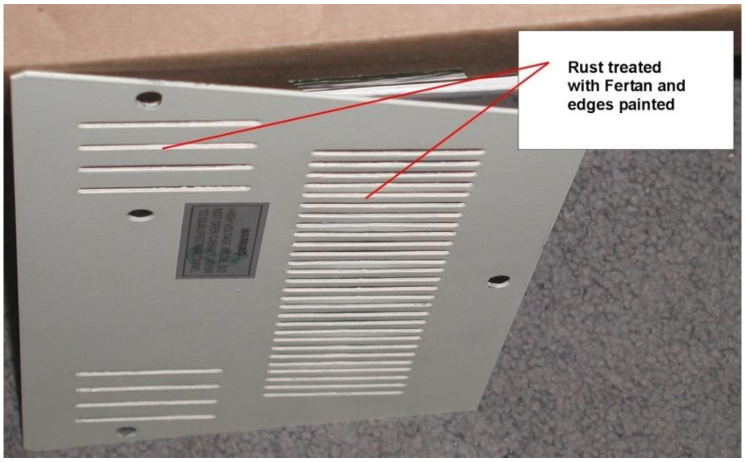
On the other hand if the whole VDU unit is removed from the case, with the pcb still there, it is easy to get at the bottom of the plastic mounting clips and remove them there, leaving them still attached to the pcb.

To aid removal of the pcb for testing and experimentation, I fitted single push fit connections to the Yoke's flying wires. These are gold plated 0.9mm diameter pins & sockets available from Jaycar electronics.

Previously the wires were soldered to the pcb & the yoke, which would mean needing to unsolder them each time I removed the pcb, unless I removed the yoke at the same time which is inconvenient. If you do this be cautious with any connectors, if added to the yoke's H scan coils, because the peak H scan current there is surprisingly high in the order of 2.7 Amps and an average current of around 1A. The vertical scan current is significantly lower for the V scan yoke coils and it is not an issue there.

The rear plate also had rust on all the edges where the metal has been punched and there was inadequate paint:

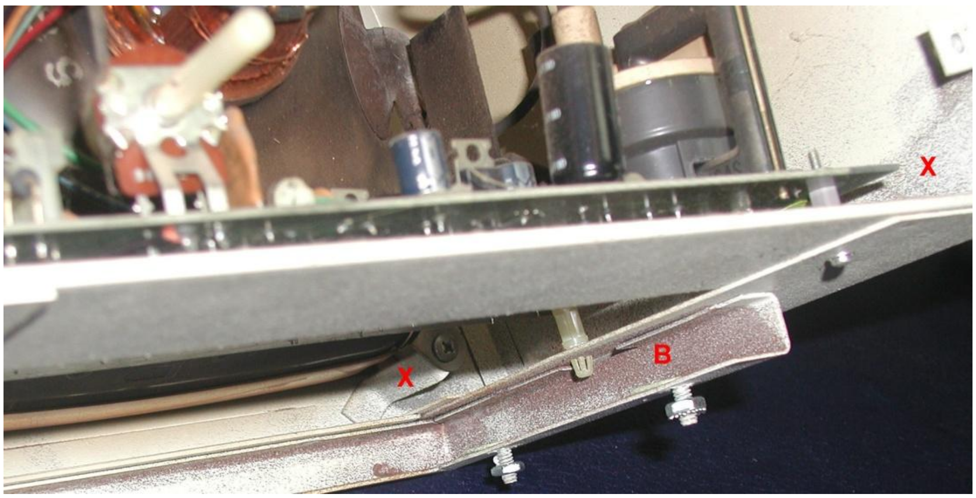


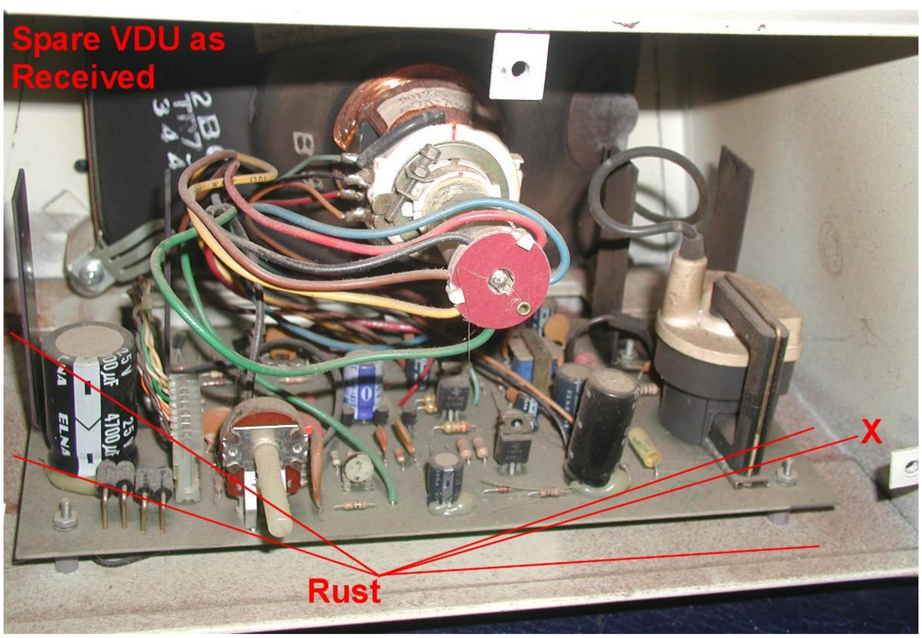


4) A second VDU Housing restoration:

A seller on ebay had parted out a PET and was selling the VDU on its own. So I bought it with view to performing an identical restoration as my first one. The cabinet was in much poorer order though and suffered from identical rust problems as the first, but much more severe.

In general, the problem is with the paint. Due to its textured thicker nature and the fact that the cabinet insides only got a cursory spray and the spay gun was not angled to get the spray around the CRT's mounting brackets and into corners. The metal was exposed in a myriad of small areas or pits in the paint. Obvious surface rust in the area marked B, but the pits are equally as sinister, marked X. When it comes to rust there is more there, always, than meets the eye.





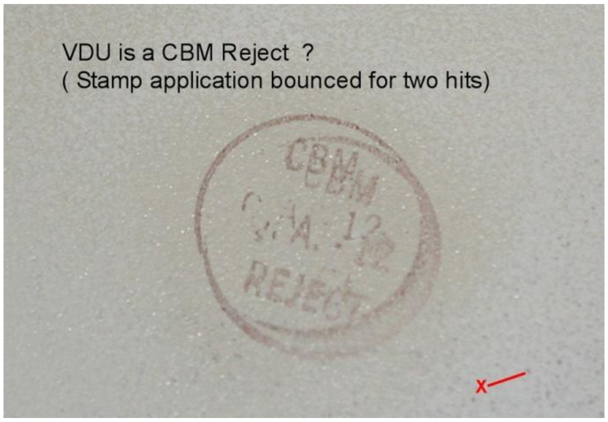
Again, as with the first VDU, some of the brown rust crystals had been attracted to and stuck to the EHT cap.

The Organic rust converter, Fertan, is like a forensic rust detector. If it is applied to rust free steel it remains a pale yellow-brown color, or applied to plastics or paint. Any microscopic rust at all it turns a blue black. After cleaning off the surface scale and applying it to the PET VDU case (including the painted areas inside & out) showed where the rust was, and it is much more extensive than it looked.

When the Fertan was applied to the paint, both inside and outside of the cabinet it unmasked multiple points of rusting in the pores of the paint. Even the outside the paint layer on this VDU did not provide perfect rust protection.

Therefore, before re-painting one of these VDU's it is important to deactivate all the rust crystals by applying Fertan everywhere, even over the paint. When it is dry (it is water based) a soft moist cloth can be used to wipe of the excess before preparing the surface for painting.

There was a stamp on the inner wall of this VDU saying it was a Commodore Reject ! Imagine that , buying your new computer and finding this stamp in it. There was nothing in this VDU that would have made it a reject, that I could find, the paint would have looked ok when it was made. It certainly won't be a reject when I have finished with it. X shows a typical rust pit area.



5) Removing & re-fitting the CRT's Yoke:

Be very careful. The neck of the CRT has a soft tape applied and the clamp around the plastic tabs on the yoke body sink a little into that tape. Over the years the tape hardens and the plastic tabs get very stuck to it.

It pays to unscrew the yoke clamp and remove it completely. Then with a plastic tool (don't put a metallic tool anywhere near the glass) gently free each of the 4 plastic tabs from the tape, just enough to get them to separate, don't bend them away from the surface too far. After that, gently manipulate the yoke to free it and remove it.

To re-fit the yoke, clean the old tape residue off the CRT's neck. Don't scrape the neck glass with anything metallic, only plastic or a fingernail is ok. Some WD-40 will help dissolve the glue residue and remove that residue with contact cleaner. Then apply 1 layer of fresh tape, Scotch 27 fibreglass works well as the yoke's plastic tabs under the clamp sink into it just a little with minimal force.

When the yoke is re-fitted, it will need to be rotated to get the raster level. Also there are two rotatory magnet rings on the yoke that can be used to centre the raster. When the clamp on the yoke is tightened up again, only screw it up with enough force, finder tight plus a 30 to 45 degree turn, to prevent yoke rotation with a mild force from the hand. There is no need to over-tighten it.

6) Replacement Electrolytic Capacitors.

It is generally better to prepare by acquiring these parts prior to starting the job.

I tend to replace the electrolytic capacitors in most apparatus if it is over 40 or more years old. Although, some of the older ones were well made and still after this time can appear reasonable on testing. In these cases, it could be counter productive to relace them, if a new poor quality capacitor was used in their place.

Most of the original capacitors fitted to my PET VDU were high quality Nichicon types, explaining why most were still reasonable on testing.

As technology has moved on, capacitors have become much smaller in volume. Often, for the same physical sized part with a particular uF rating, it is possible to select a step or two up in voltage, but more importantly a step or two up in temperature rating.

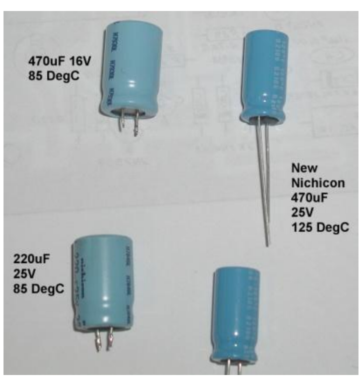
In the case of electrolytics, for the same uF rating, the ESR increases as the voltage rating increases, so, on the whole, it is better to stick to the same voltage rating or only one to three steps higher. For example a 10uF 16V capacitor has about half the ESR of a 10uF 160V capacitor.

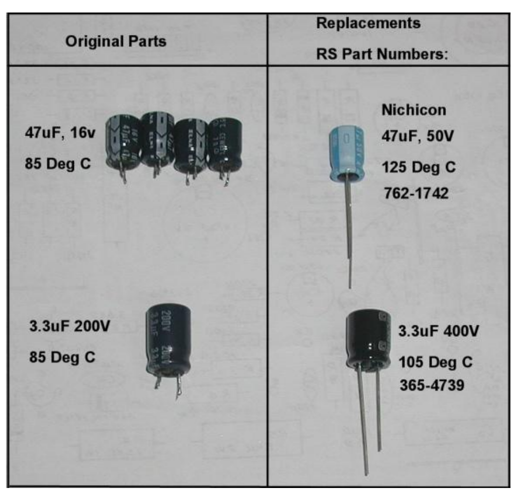
A modern 125 Deg C part is often no bigger than an 85 Deg C part of yesteryear.

To acquire a modern capacitor of the same lead pitch, it is necessary to go up in voltage rating. It is important that the lead pitch matches the pcb holes, ideally. This way the capacitor's rubber base can sit flush against the pcb. Then any forces on the capacitor body, if it is bumped, cannot encourage the pcb's pads to separate from the surface.

I have come to prefer Nichicon brand in the 125 Deg C rating, so I use these in most cases as replacements.

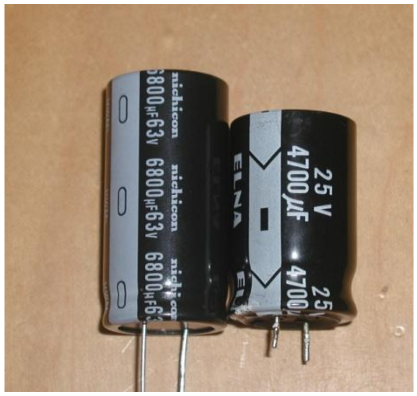
Capacitors C15 and C23, were both 470uF in some versions of the board and C23 being a 220uF in other versions. As C23 is the main power filter for the LOPT, it is better as a 470uF.





Capacitor C22 was a 3.3uF 200V in early boards and a 47uF 50v in later boards. This capacitor is up for discussion in section 1, about the Turn Off Spot problem. In my VDU I replaced it with a 220uF 63V 105 degC type.

The main power supply filter capacitor, prior to the regulator C1 is a 4700uF 25V type. In my VDU, to acquire a capacitor of the same lead pitch to fit snugly on the pcb, I replaced it with a 6800uF 63V type, RS part 739-5386.The photo below shows the new part is a little taller, but there is plenty of room for that.



There is one final capacitor of note; that is C28:

Generally C28 should not be replaced, unless it is for the modification suggested in section 11 0nwards. It is a special type and is likely a Paper in Oil or film type (unlikely a bipolar electrolytic). It is in a high current circuit in series with the yoke where the peak current at the end and beginning of scan exceeds 2.7A. This capacitor requires an extremely low ESR in the order of 0.15 Ohms.

(Electrolytic caps of around this uF value and voltage value have an ESR an order of magnitude higher).

I would have to cut the original 10uF capacitor open to be sure of its construction. It has near zero leakage, not detectable at >40 Meg ohm, highly uncharacteristic for any electrolytic capacitor. In any case, the suitable replacement can be a Film type, preferably the sort used for high current roles such as those with welded leads to foil, pulse grade, or motor run types.

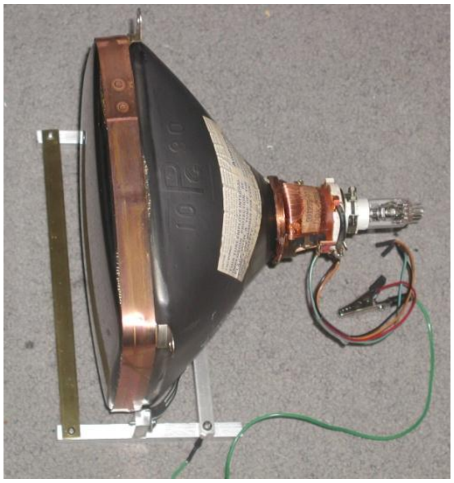
C28 is not just for DC isolation of the Yoke, it is known as the “S correction capacitor”. It alters the shape of the current drive to the Yoke’s H coils and its exact value affects the linearity of the scan. This is discussed in detail in section 11, with a suggested replacement.

C9 was originally a 1uF 25V electrolytic capacitor. Over the years I have learnt that low uF value electrolytic capacitors are better replaced with a modern film capacitor as they will never likely lose capacitance or suffer physical or electrical leakage issues. Therefore C9 was replaced with a 1uF 63V MKT type in my VDU.

None of the other electrolytic capacitors could have been replaced with a film type, except perhaps for C27, the 3.3uF 200V capacitor which filters the supply for the video output stage. But a film capacitor here would have been awkwardly physically large as a replacement.

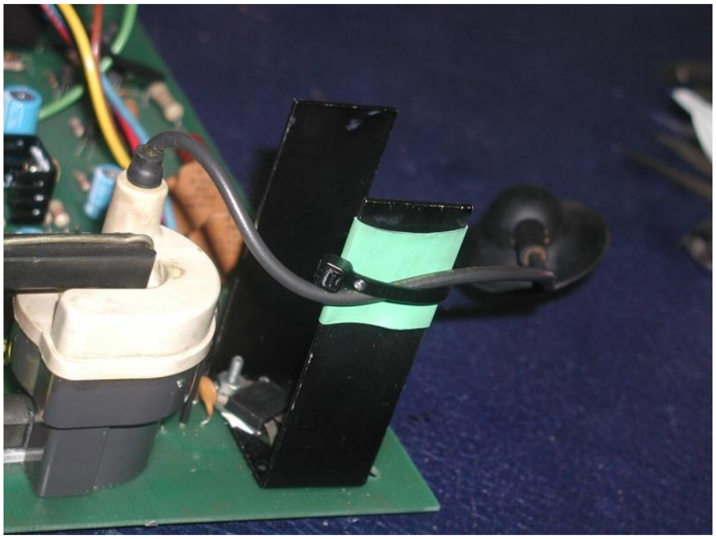
7) General handling instructions while working on the pcb & CRT:

The access to the PCB in the PET is poor with the CRT inside the VDU housing. To work on it effectively in some, but not all cases, requires removing the CRT from the housing. It then requires a CRT stand. I simply machined one out of some 3/8" square aluminium bar & some Brass I had on hand. If you do make a stand make sure it is sturdy, that it won't bend and the CRT tip over.



Since a number of capacitors are being replaced and the board will be manipulated, flipping it over and over again, I would caution to add some strain relied for the EHT wire from the LOPT. If this is flexed multiple times, it is possible it could fracture at the entry to the LOPT. So the first thing I did was strap it to the heat fin of the HOT. The EHT wire insulation is rated to handle >10kV, but if you are uncomfortable leaving it there later, simply cut the cable tie after the VDU's pcb is re-installed in the case.

(As can be seen in the photo, a small amount of the red-brown rust powder is still visible on the EHT cap where the cable enters , I have to do a better job cleaning that off later)



8) Charge on the CRT bulb:

The internal and external conductive layer on the glass forming the “plates” of a capacitor . The glass is the dielectric. It is a charged capacitor, of about 500pF, charged to 10kV and it remains charged immediately after turn off. The only way to contact the internal coating is go under the anode cap and touch the anode button, immediately after the set is turned off. The charge dissipates on its own and the charge is isolated from the CRT’s base pins, so if you don’t immediately go under the anode cap after turn off, there is no possible contact with it. The amount of charge energy stored in the PET’s CRT bulb’s 500pF capacitance at 10kV is a mere 25mJ and is harmless to a person’s health. This is the equivalent energy of a single spark in a car’s Kettering ignition system or lawnmower spark plug. But it could give a person a fright, if they were not expecting it.

Experimenting with my PET 9” VDU, I could reach under the anode cap with my finger 1 hour after the VDU was switch off and there is no detectable shock or residual charge on that test, that I could feel. The charge dissipated because of the non-zero reverse leakage of the Silicon EHT rectifier. So if you wait until the following day it is certain to be fine to remove the anode cap without discharging the CRT. If a CRT is to be discharged, it is better done with an EHT probe which contains a very high value resistor, generally > 100 Meg Ohms to limit the peak discharge current to a low value. Do not do it with a direct short.

9) Brightness control – modification.

I found when I first got my PET that the VDU’s brightness control potentiometer was ineffective at reducing the brightness of the CRT display to a satisfactory low level.

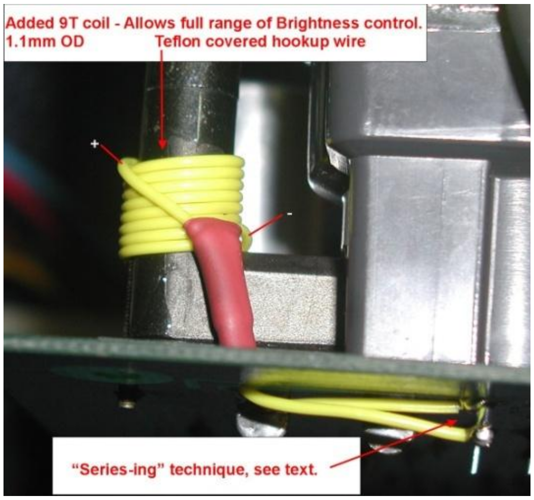
The tests showed that the LOPT was only producing around -30V to the brightness control potentiometer. And this matched the schematic. This may well have been satisfactory for the 9VALP4 CRT, but an experiment demonstrated that to cut off the beam, on the CRT in my VDU (a M24-302-GH) it required around 45 to 50V. Examination of a PET VDU schematic version that used the MW24-302-GH CRT indicated the voltage was -46V. So it appeared that my CRT, got teamed up with the earlier pcb and this was not ideal in this respect.

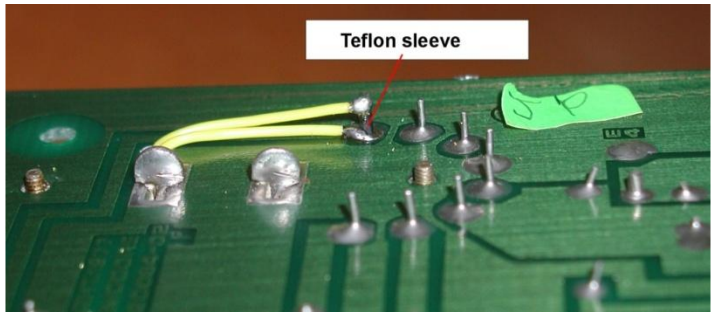
I found that the simple solution to this problem was to wrap 9 turns of wire around the LOPT’s core and place this in series with pin 8 of the LOPT.

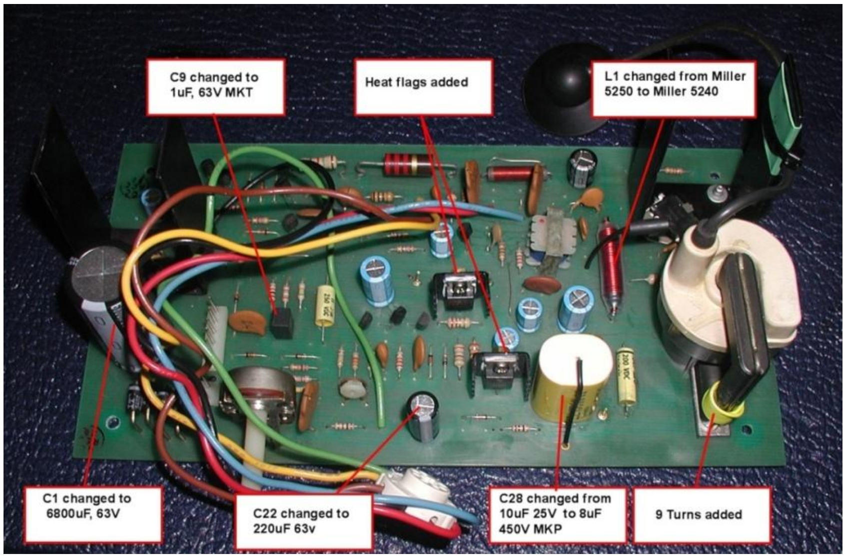
To achieve the modification without too much change, the solder around pin 8 of the LOPT was removed with solder wick. The transformer pin itself is about 0.75mm in diameter. However the pcb hole is just under 1.5 mm diameter. So I slipped a small piece of Teflon insulation (taken from some small calibre hook-up wire) over the pin and through the pcb hole. Then the added winding could be soldered to the pin and the pcb pad nearby, so as to place the added 9 turns in series.

It is important that the winding phasing is correct so the voltages add. It required one small hole (2.5mm dia) added to the pcb to allow the wires to pass through. This modification increased the available negative supply voltage to the brightness control to -50V, which allows the CRT brightness to be turned down for the MW24-303GH CRT so that the beam is just cutting off.

Generally the main reason the high negative grid voltage is required to cut the CRT beam off, is that the video output stage acts like a switch in this VDU, taking the CRT cathode to zero volts to illuminate the phosphor.







The board photo above shows some other changes I made to my PET VDU along the way.

Heat flags have been added to the vertical scan output transistors, which helps their junctions run at a lower temperature. Some of the early PET boards used heat flags on these transistors, some didn't. Commodore must have thought the need for them was marginal. But it is a good idea to have them.

The purpose of L1, a 100uH choke Miller number 5250, was a component sometimes found in TV set designs. It was to help filter transients, at the line frequency rate, off the 12V power rail feeding the LOPT. The reason being that these line rate transients can cause interlace problems in TV sets with synchronized vertical oscillators. Even then this part though is "optional" and many VDU designs don't bother with it at all, or had lower values such as 10uH. In a set with no vertical scan oscillator, there is no problem at all shorting it out (replacing it with a link). The original Miller part had a small voltage drop and slightly reducing the scan width. So in my VDU I simply replaced it with a lower inductance higher current part, the Miller 40uH 3A rated part 5240, to help keep the pcb looking original. In most cases its fine just to leave the original Miller part there.

The pcb holes where the energy recovery rectifier (ERD) rectifier CR17 is fitted have acquired 1.5mm diameter brass eyelets and 0.9mm connector pins (from Jaycar electronics). I fit these eyelets to the pcb where it might be likely that the component has to be soldered/unsoldered a few times for experimentation, it prevents damage to the pcb. They also receive the 0.9mm diameter connector pins very well. It is not strictly necessary, but I have a large range of these in different sizes for pcb repairs.

One of the modifications involved experimentally adding a different ERD in parallel with the existing one which is CR17, a 1N4935.The original diode is still left in place but moved to the rear of the pcb. As will be shown, I set it up so I could run the VDU with or without the added additional Germanium ERD, which simply plugs across the connections of the existing one to significantly improve the H scan linearity.

The other changed parts are explained in the various sections which relate to them.

10) Turn Off Spot Elimination.

I had been observed by PET owners that some seconds after turn-off (and immediately at turn off in some cases) a bright spot would appear in the centre of the screen. This comes about because at turn off, the CRT has the EHT voltage still present due to the charge on the CRT's bulb and the CRT's cathode is still emitting electrons.

Most CRT cathodes have cooled down by 20 to 40 seconds after turn off and the electron emission vanishes. But in some CRT's with a large heater cathode assembly, some electron emission can still occur up to 60 seconds after turn off.

Early in this process immediately after turn off, the raster scan has collapsed, leaving all of the beam energy concentrated in a small spot near the screen centre. Over time this can de-sensitize the phosphor in that location, or "burn" it.

In the PET VDU, the raster scan collapses very quickly at turn off because it does not have independent scan oscillators and the H & V drive signals from the computer disappear fairly quickly on power down.

(As an aside: It is interesting that the turn off spot, sometimes seen on a TV screen, made it into popular culture. In one Episode of the TV series The Young Ones, somebody asked, after they turned off the TV: "what does that spot in the middle of the screen mean?" Neil replied: "It means something really heavy, it means there is no more TV")

The normal method to suppress the spot is to make sure, at and after turn-off, that the CRT's grid remains negative with respect to the cathode, for long enough that the electrons emitted from the cathode are repelled by the grid and to not make it to the CRT's faceplate (Anode). It can be done with a number of circuits. They nearly all involve storing charge in a capacitor to achieve the result.

Commodore realized there was a problem and replaced C22 (a 3.3uF) capacitor in the CRT's negative grid bias circuit to 47uF. This capacitor, after turn off, discharges into the 100k brightness control, so the time constant there (for the capacitor to lose 63% of its charge and terminal voltage) is about 4.7 seconds. This change worked well to suppress the early phase of the turn of spot, however, many CRT's can keep emitting electrons in good numbers longer than this, so at a time after this the spot appeared and then faded away again after about 15 to 40 seconds.

The actual timing would depend very much on the CRT, its condition and type. In my PET, which uses the MW24-302GH CRT the solution was to simply fit a 220uF capacitor, 63V rated, for C22. Experiments showed that 150uF was adequate but in the end I used a 220uF to be 100% sure the problem was eliminated. It could be, that in an extreme case, a 330uF capacitor is required.

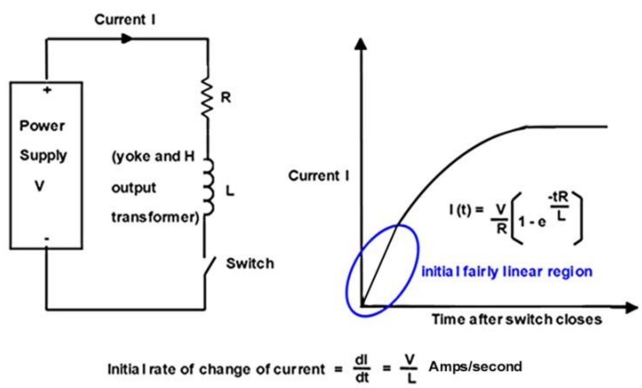
There was another method to do it that also worked, suggested on a Youtube video from Adrian's Digital Basement. This involved modifying the video amplifier by adding a zener diode-resistor to help keep the cathode more positive after turn off. However in my opinion it is better to simply increase the value of C22 to 220uF when the VDU is in the process of being re-capped.

11) Horizontal Scan Linearity improvement & protecting the HOT .

There were good reasons why the later versions of these VDU's, like most computer VDU's, moved to having a Width control coil and a Magnetic Linearity coil. The issues of Horizontal linearity defects are moderately involved so I have decided to explain it in steps with examples of TV sets from History.

In the case of a transistorized Horizontal output stage, the HOT acts as a saturated switch. The yoke and LOPT primary are both effectively switched across the power supply terminals, in this case 12V. The current in both of these inductors rises in the usual inverted exponential manner. However, the initial part of this rise, over a brief time is fairly linear, often just starting to taper off a little toward the end of scan on the R side of the raster.

As noted earlier the current rises at a rate of V/L Amps per second initially and starts to taper off in rate with time. Considering the Yoke alone, when the HOT is conducting the current will rise at a rate of 12v/ 117uH = 102564 Amps/Second. The HOT is only conducting current for the R side of the active scan time, which is about 27uS, so the yoke current in the H coils, will have risen to 2.77A, or a little less as circuit resistance slows the rate a little as time passes.



As noted previously, after this, the HOT is cut off, flyback occurs and after flyback the damped current in the ERD, scans the left side of the raster after that.

(An aside: Clearing up some terminology confusion; Prior to WW2, diodes, & resistors were use to damp ringing effects during flyback and at the start of the scan. The process was energy wasting and because it damped the flyback pulse too, this could not then be stepped up to generate EHT. So in these early TV sets they had quite dangerous line powered transformer supplies with large filter caps because of the 60Hz ripple. These could source enough current to kill people, unlike many modern flyback supplies, generating EHT in small VDU's, that cannot source the required > 10 to 30 mA to do that. The invention of the efficiency diode, or energy recovery diode ERD, which first appeared post WW2, to any commercial success, was in RCA's 1946 TV set, the 621TS. In this design *neither the output device (tube or later a transistor)or the diode(ERD) are conducting during flyback.* The magnetic energy at the end of scan time on the right side, after half a cycle of flyback oscillation, is re- used via the ERD current to scan the L side of the raster. It is a very efficient

system. The ERD current can also be used to charge a capacitor to increase the voltage available to the LOPT. The increase is called the B+ Boost Voltage. And it makes EHT generation from the flyback pulse possible. Yet, the terminology got very muddled in the books and the term Damper Diode, Efficiency Diode, Energy Recovery Diode and Booster Diode and even sometimes Flywheel Diode were used synonymously in the post war period. In this article I will refer to it as the Energy Recovery Diode or ERD as this is essentially what the diode does, it recovers the Yoke's magnetic energy from the right hand side of the scan, so as to scan the left hand side).

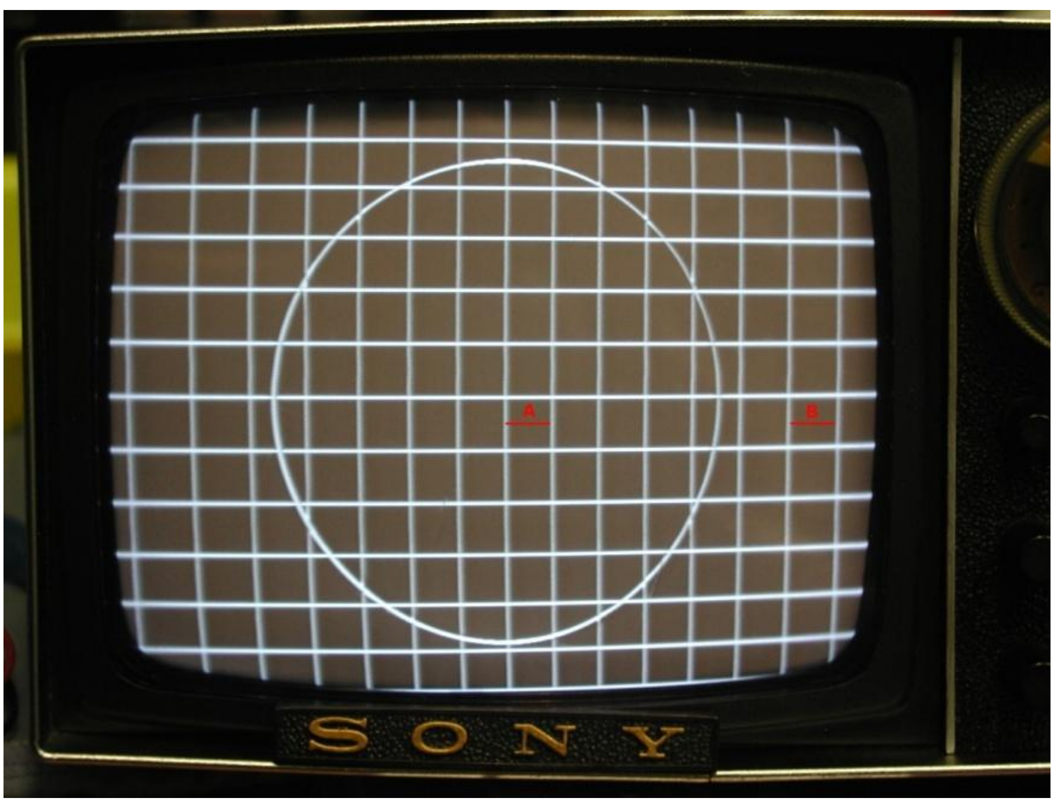
If the rise in Yoke current in the H scanning coils, as it often is, is not perfectly linear towards the R side of the scan and its rate of change with time tapers off to a lower value. This is actually helpful, because it compensates, to some degree at least, for the Yoke's sensitivity issue. The Yoke is more sensitive with increasing angles of deflection. However, this fall in the rate of change of current with time is not usually enough on its own to compensate the Yoke sensitivity issue. It requires some assistance to slow the rate of change of current a little more towards the right hand side (and the left too). This is where the yoke coupling capacitor or "S" correction capacitor comes into the equation.

When the beam is travelling faster across the faceplate with time, this corresponds to a higher rate of change (or slope) of H yoke current with time and stretching of the plotted image or data pixels. When the beam is slower, the data elements along a line, if they were arriving at uniform intervals, are relatively compressed or squashed together, corresponding to a lower rate of change of current with time. So from here on the terms "stretched" and "compressed" will be used to describe the linearity errors.

Ignoring the Left side of the raster scan for a moment:

There is an intrinsic problem with the H scan linearity. The reason is that the yoke's apparent sensitivity increases with increasing deflection angle. Therefore, even if a perfect sawtooth current wave was applied to the H yoke coils, from the screen centre to the right hand side, the beam will be travelling faster near the right hand side and the image will be horizontally stretched there.

It is quite instructive initially to look at the H scan linearity on a transistorized TV set which is devoid of both a linearity coil and an S correction capacitor. A good example is the early transistor TV, the Sony TV-503. It creates a perfect graph of the problems:



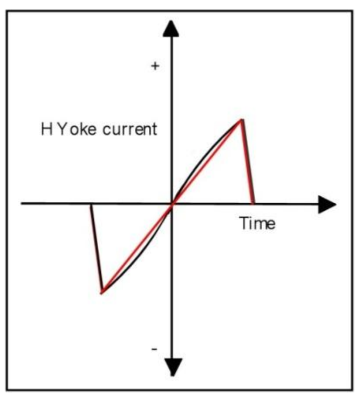
Again, initially, ignore for now the left hand side with the very stretched linearity, this will be explained later as it is more complex.

As can be seen above, looking at the spacing between the vertical lines on the test pattern (which indicate the H scan linearity) the linearity becomes stretched toward the right at B, compared to the centre area at A where they appear more compressed. The small taper off in the rate of rise of current with time, in the H yoke coils, due to their resistance, is not enough on its own to correct for the Yoke sensitivity issue with increasing angles of deflection.(Increasing the yoke's DC resistance though is not a solution as it further degrades the L side linearity).

When a capacitor of the correct value, is placed in series with the yoke, it can be chosen in value to effectively superimpose a shallow "S shaped" wave on the overall yoke current.

This has the effect of reducing the rate of change of current with time on both the left and right hand sides of the raster, compressing the linearity there, and stretching it near the centre of the raster. Generally the capacitor is chosen to have an approximate resonant frequency with the yoke of about 5kHz. Its value determines the amount of "S correction". The actual waveform that appears across the capacitor's two terminals though, is an interesting parabolic shaped wave (not S shaped) and this relates to the mathematics of integrating a sawtooth wave.

This is shown diagrammatically below, where the Red line would indicate a perfect sawtooth current wave and the black line the effect of the S correction capacitor on the Horizontal yoke coil's current waveform.

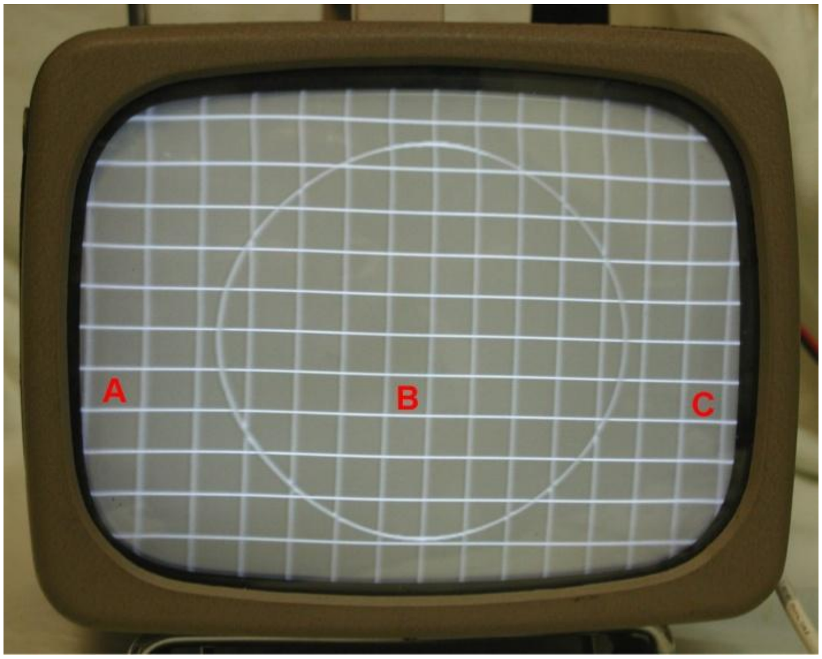


The rate of change of current with time has increased in the mid horizontal scan area, near the screen centre and decreased on either side, on the left and right side of the scan.

One additional useful feature is that because the S correction capacitor blocks DC, the yoke's circuit connection can be returned to ground, not the 12V supply.

Now we move to a TV example with the S correction capacitor present, but still no magnetic linearity coil.

A good example of this is the early Sanyo set, model 8P-2 below from 1962. Again ignoring the left sided stretch in area A, and concentrating on the central area, this time labelled B and right sided scan linearity in area C. This is also the sort of horizontal linearity one might expect from the early PET VDU, which has the S correction capacitor (assuming correct value) but no magnetic linearity coil:



As can be seen, on the Sanyo set above there is a near perfect relative horizontal linearity match from the centre screen area B to the right hand side area at C, so the S correction capacitor appears perfect in value, it is 7uF in this particular 12V operated TV set.

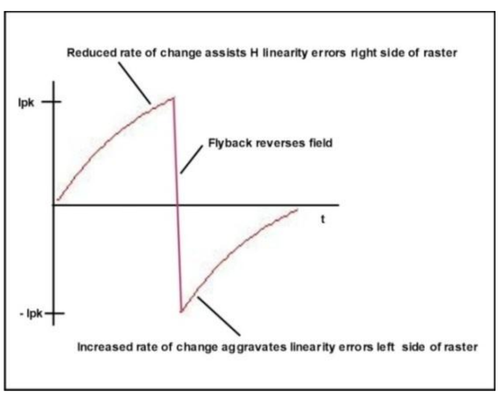
Now, what about the left sided linearity, why is it still stretched, despite having the S correction capacitor which so elegantly fixed up the relative central and right sided linearity disparity ?

This is another problem that is intrinsic to the design of transistorized magnetic deflection and why magnetic linearity coils (to create an opposite non linearity) were introduced into most TV sets and VDU's by the 1970's.

It relates to two reasons. The main reason is the reversal of the Yoke's magnetic field, after flyback. The stored magnetic energy is then used to scan the L side of the raster, via the ERD current. But rather than it being an inverted exponential build up, it is an inverted exponential decay process.

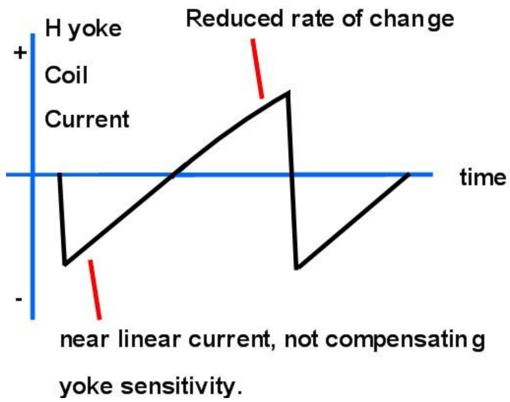
As is usual, the process is again an inverted exponential process. But this time its highest rate of change of current with time starts at the left side of the scan and decreases toward the centre of the screen. This is exactly opposite to the right side of the scan which has its highest rate of change of current with time near the centre of the screen and tapers off a little towards the extreme right hand side.

This is shown, exaggerated to make the point in the following diagram.

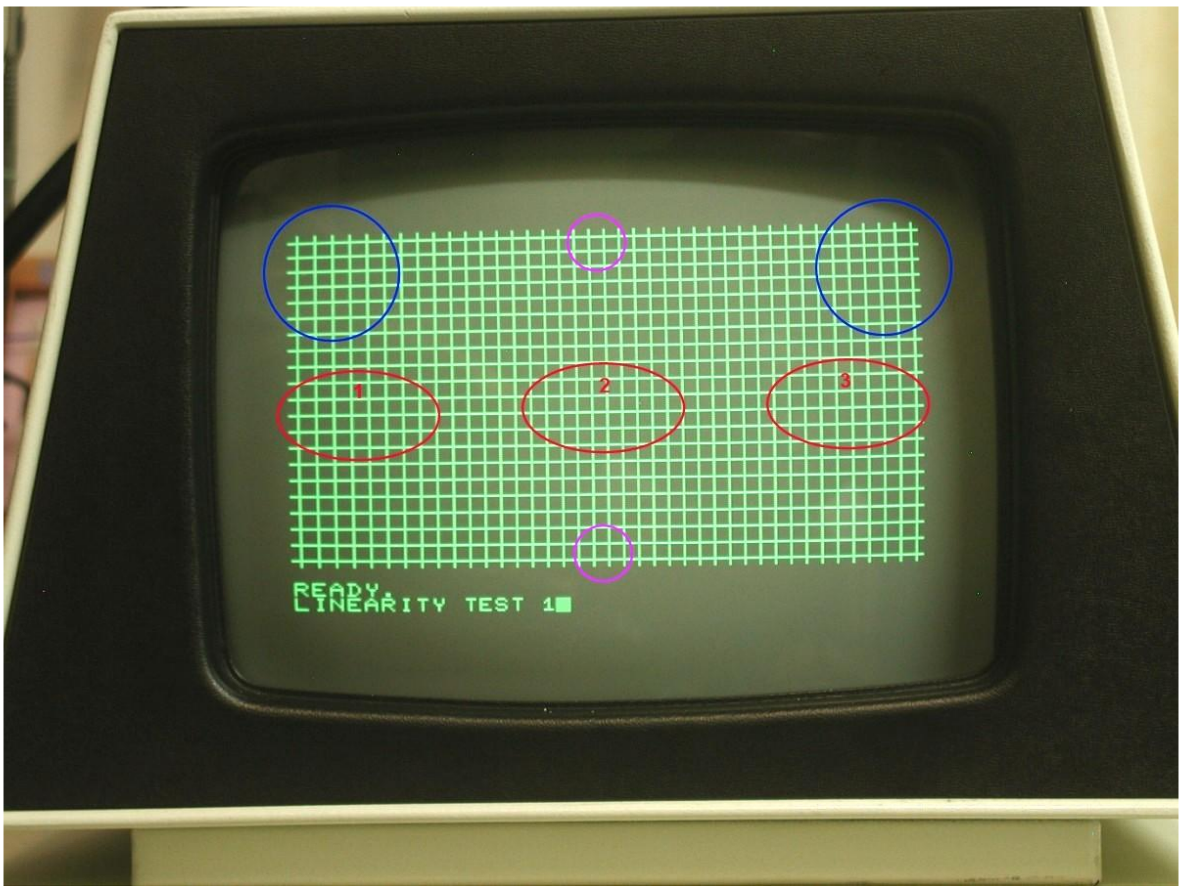


Some of the higher rate of change of current with time at the start of the scan on the left side is improved with S correction, but it is not enough at the point where the S correction is correct for the centre of the scan and right hand side of the scan at the same time.

Therefore, inspection of the current wave in the H yoke coils in nearly all TV sets & VDU's, that just have the S correction capacitor and no magnetic linearity coil show an H yoke current waveform very similar to this:



So, what do we see when we look at the H scan linearity on the early PET VDU ? It is exactly as expected for the case of S correction without linearity coil: This is shown below.



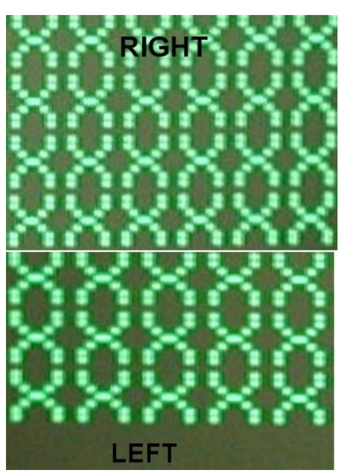
Firstly, the S correction capacitor value is not a perfect value because (looking in the central area 2 in the red ellipses) there is mild compression compared to the area 3. The capacitor's 10uF value is just a tad large in value.

It turns out, for correct S correction in my PET VDU at least, the value of the 10uF S correction capacitor is better to be 8uF or 8.2uF. This stretches the cental linearity a little and as a useful side effect, increases the overall width a little, which is fortunate.

There are some other scan defects such as mild barrel distortion on the blue areas due to the yoke geometry and some compression of the vertical linearity at the top compared to bottom, pink areas, these issues are not addressed in this article.

With the 8uF in place in the PET VDU, instead of the original 10uF and this time plotting X's to compare their widths, the central and right side linearity is now a near perfect match and the "S" correction spot on:

The relative left sided defect (stretch) is quite significant. Cutting out the right and left hand sides of the above image and pasting them into one photo without any scaling:



As noted, the stretched left sided linearity is intrinsic to a design devoid of a magnetic linearity coil.

Why not just add a magnetic linearity coil and fix the left sided stretch? The answer is, in the PET VDU the width of the scan is marginal and there is no width control to compensate for losses. For the Magnetic Linearity coil to work it has to result in some loss of width because of its overall inductance. The width could be increased by increasing the 12V supply a little however this will increase the EHT. There is an unused Tap on the LOPT primary pin 4 which could help a little.

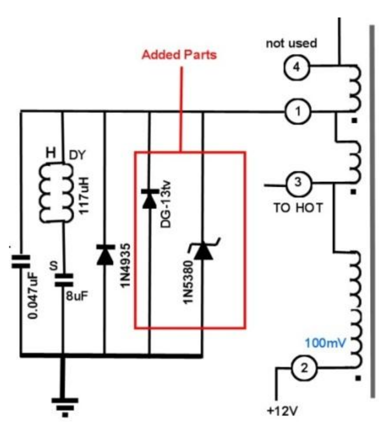
The second aggravating factor, for the stretched scan on the left, can be addressed to improve the problem, without having to add a linearity coil. It is the dynamic resistance and forward voltage drop of the original ERD, which compared to a saturated silicon HOT C-E junction; both these parameters are significantly higher.

Any circuit resistance of the Yoke for example, aggravates the linearity, compressing it on the right and stretching it further on the left. The manufacturers of Yoke coils, for 12V operated transistor sets, often run the H coils in parallel and they are often Quadra-filar wound to help keep the DC resistances low, but wire thin enough to physically form into a yoke, usually under 0.5 Ohms DC resistance. This is also why a very low ESR "S" correction capacitor is required, with an ESR only in the order of 0.15 Ohms. And if it wasn't low it would also overheat because, even in a 9" VDU, the peak yoke current can approach 3 Amps.

(As an aside: In the original research on energy recovery horizontal scanning systems for TV's, done at RCA labs in the 1940's, by Otto Schade, he recognised the degrading effects that resistance had in an L-R circuit, with a voltage switched across it, when attempting to create a linear sawtooth current ramp. His solution was to make the output tube behave as though it had a negative resistance, cancelling out the circuit resistance of the yoke, by providing the output tube with the appropriate drive voltage. It was very clever, but it is not appropriate to a transistor TV where the HOT acts as a saturated switch and its drive voltage profile has no effect on the H scan linearity)

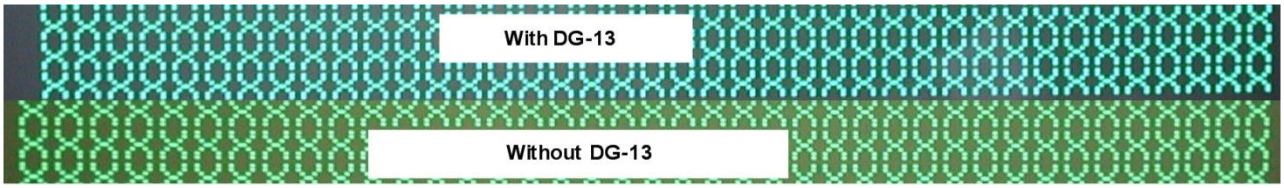
It turns out, that a significant proportion of the left sided Linearity Defect (stretch) in the PET can be improved by using a different ERD with an extremely low forward voltage drop and a very low forward dynamic resistance compared to the original Silicon1N4935 ERD used by Commodore. I discovered these rectifiers back in the 1970's. They are not a common part and are an obsolete Germanium types. But all is not lost:

There are 3 suitable types, all still available on ebay: the 1N4785 RCA, the AY102 (Philips) and the DG-13tv (Sanyo), made exactly for the application of H energy recovery scanning. The DG-14tv works too, but these are rarer now. The only awkward part is that they are in a TO-3 case. However, I created a simple reversible modification so they can be fitted to the PET VDU on a sub- board. The diagram below shows the added two parts:



The added 1N5380B 120V zener diode, is nothing to do with a linearity modification, it protects the HOT when the VDU is driven by a drive signal from the computer which is abnormal.

The added DG-13tv diode significantly improves the L sided scan linearity:

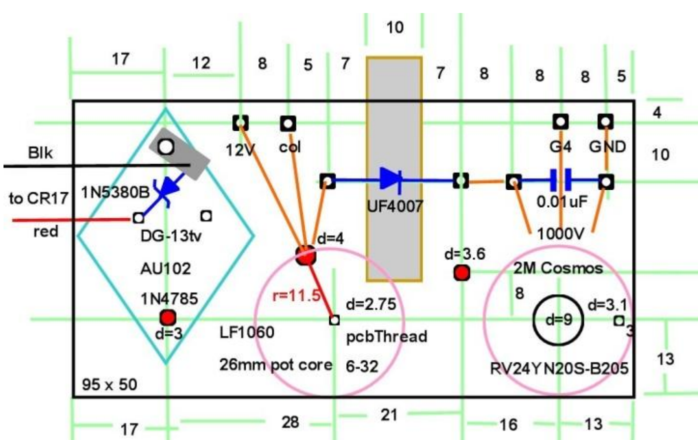


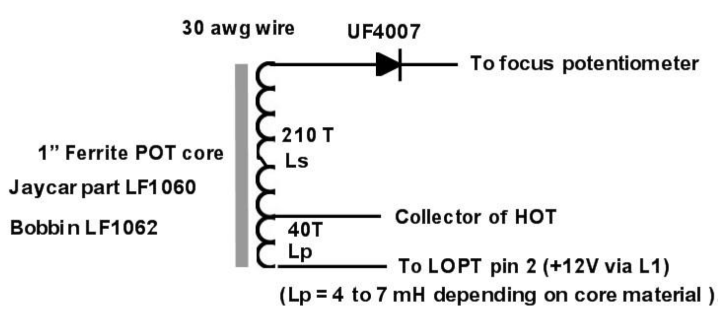
The additional parts are mounted on a pcb which is also a convenient place to mount a pot core transformer to generate a high focus voltage and a focus control potentiometer.

CRT FOCUS:

The CRT in the PET ideally would have had a focus control. The manufacturers gave two options to connect the focus electrode G4 with a jumper, either to ground or to the +85V supply. The MW24-302GH (or MW24-302W) gun though requires a focus voltage in the region of 300V to pass through a focus knee. On one of these CRT's, it required around 400V for corner focus and around 220V for perfect centre focus. The compromise is a voltage between those two values around 300v for better average focus, but of course you cannot set that if you don't have a control.

It is a simple matter to transform up the HOT's collector voltage up to around 540V with a small pot core auto transformer. It has a 40 turn primary and a 210 turn secondary as shown in the diagram below. This is peak rectified by a UF4007 diode and feeds a 0.01uF 1000v rated filter capacitor and a 2Meg focus potentiometer:

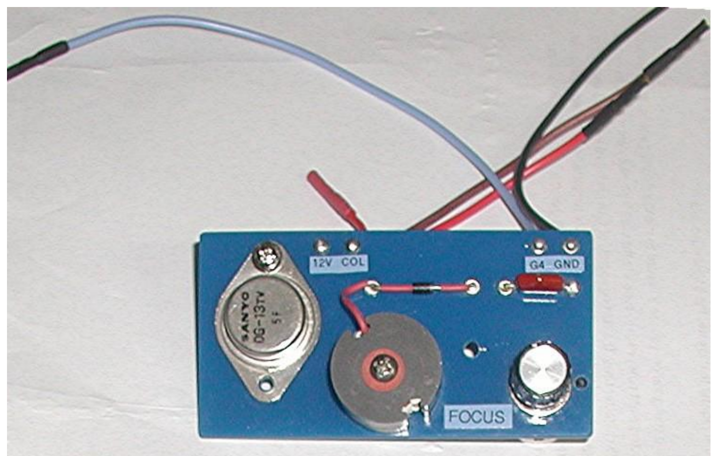




Two mounting posts, both 55mm long are used to mount the pcb. The one which passes the pcb hole where the original screw was needs a ¼ inch long 6-32 thread projection to pass into the threaded6- 32 stand off the pcb sits on. Both these posts can be metal, I used one phenolic one as I had it on hand and the metal one I used has 3mm threads.

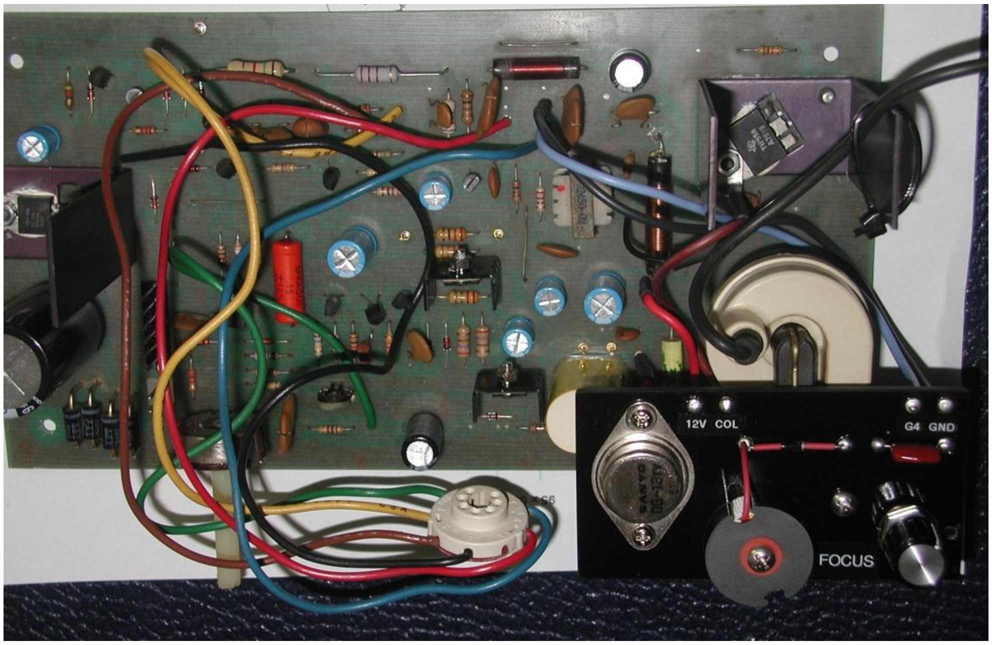
HOT & LOPT Protection:

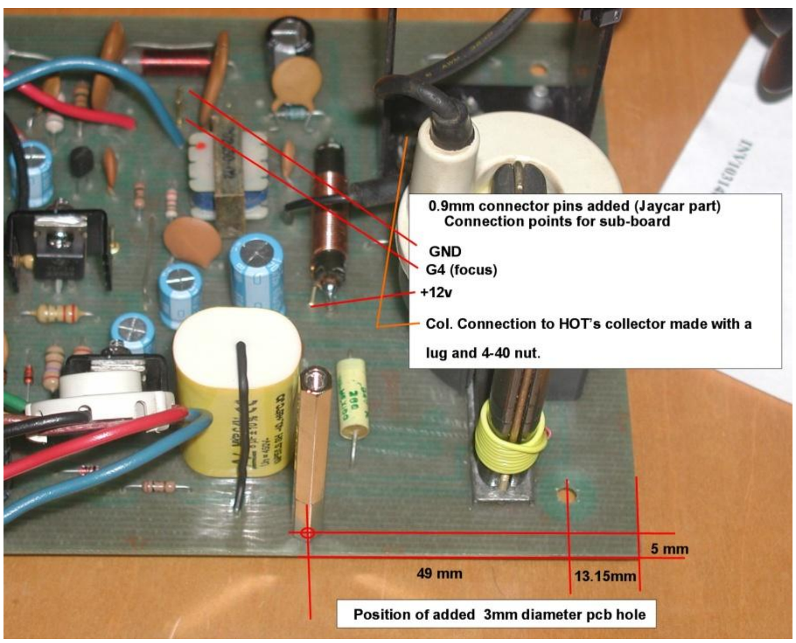
The peak voltage across the ERD is close to 110V in use, the 120V zener is not conducting. If the horizontal drive frequency drops though more energy is stored in the yoke & LOPT per cycle and the peak voltage could potentially near double, so the 120V Zener diode clamps it off to a safe value, protecting both the HOT, the LOPT and the EHT rectifier inside the LOPT body. The photo below shows the board assembly. I simply made it on a 1/8" fibreglass plate with 2.3 mm diameter silver plated brass eyelets, but a standard pcb would be just fine. I made one for each of my VDU's:



The spacers can both be metal, because the body of the DG13tv (or other rectifier types cited) is connected to ground. No insulators are required for the TO-3 cased diode. The TO-3 diode barely warms up in use, certainly less to than the original small 1N4935 glass diode it is shunting. Because the forward voltage drop of the DG-13 diode is so low, even though the 1N4935 is still there, it does not conduct any current.

The 6-32 nut shown in the lower right corner is there temporarily, when the pcb is being worked on outside the VDU cabinet. In use there is no nut there because that 55mm tall spacer simply screws into the threaded 6-32 stand off in the VDU case.





Overall result with Focus & Linearity mods in place shown above. The overall H scan linearity is quite good with just a very small trace of remaining left sided stretch (thanks to the Germanium ERD). The centre and corner CRT beam focus is good.

12) In Circuit Testing of the PET LOPT.

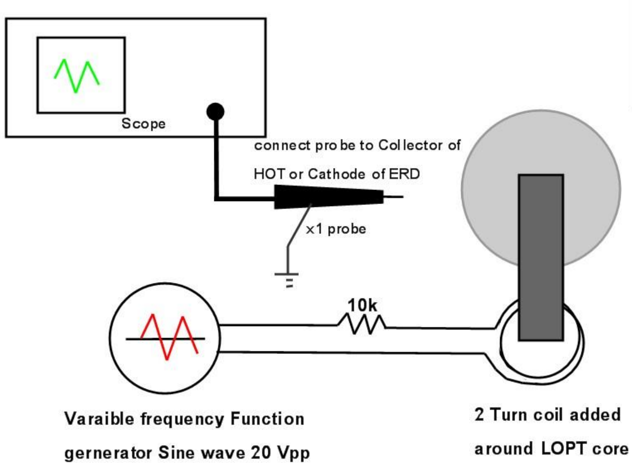
In the same way capacitors can be tested in circuit for ESR with low applied voltages, so that the semiconductors around them do not conduct, the same can be done to test a LOPT in circuit.

One interesting thing is that the complexity of the LOPT makes it dead easy to test, even while it is in circuit. The reason is that the LOPT is primarily two coupled resonant circuits on the same magnetic core. The coupling coefficient is in the range of 0.5 to 0.97 (depending on the LOPT design and intended harmonics, typically 3rd & sometimes 5th). It is the fact that the coupling is not perfect between the two tuned circuits which creates the two resonant frequencies, one low and one high. (A lot more about this is explained in the LOPT theory section for those interested)

The two tuned circuits are the primary of the LOPT, tuned by the external tuning capacitor and the other being the high voltage coil (called the Overwind) tuned by its own self winding capacitance.

It is easy to check these two resonant frequencies simply by loosely coupling a generator to a two turn coil added around the LOPT core without removing or disconnecting anything in the VDU. (Obviously it is done with the VDU not powered). So it can be done just by taking the back off the VDU to gain access:

IN CIRCUIT RESONANCE TESTING OF PET LOPT .



Probe connected to cathode of ERD:

Yoke Connected	Level Vpp	Frequency
F (low) peak	80mV	56.2 kHz
F (High) dip	≤2 mV	146kHz

Yoke Disconnected	Level Vpp	Frequency
F (Low) peak	250mV	28.1 kHz
F (high) peak	4mV	134 kHz

If there is anything wrong, shorted turns on the LOPT on any winding, a shorted EHT rectifier or a shorted HOT or ERD or tuning capacitor or shorted S correction capacitor, the resonances in the table above will be abnormal or absent. The test can be performed with the H yoke coils disconnected. This down shifts the two resonant frequencies. If the EHT rectifier is shorted, then removing the anode connection from the CRT will return the tests to normal. Likewise if the HOT or ERD or tuning capacitor/s are shorted out the resonances will be abolished, and disconnecting the ERD, HOT collector or replacing the tuning capacitors would return the tests to normal.

More sophisticated and detailed testing on the properties of the LOPT can be performed if it is removed from a set for analysis, but it is not in fact necessary for fault finding.

13) Advanced LOPT Theory & Substitute LOPTS.

A LOPT is a moderately complicated transformer. One reason is, unlike most transformers, designed for the efficient transfer of power and a high coupling coefficient (k value close to 1) the LOPT is not designed like this at all.

This is because the LOPT operates in three different modes. One mode is where the core is energized from the power supply and HOT's collector current during scan time. This process scans the right hand side of the raster and stores energy in the LOPT's magnetic field.

Another mode is where the LOPT's core magnetic energy has a controlled release to scan the left side of the raster. These two modes the LOPT primary is under very heavy damping as it effectively has a fixed voltage applied to it.

The third mode is where the LOPT's magnetic field collapses in a half cycle of un-damped oscillation, to both result in the CRT's beam flying back from the right side of the raster to the left in an "un-damped ringing mode" and the associated generation of a high voltage pulse from this half cycle of ringing, to supply the CRT's EHT. Typically this is around 10kV for a 9" CRT and the base of the flyback pulse around 10uS wide.

The parameters to characterize the LOPT are the following:

1) Primary inductance Lp.

2) Primary leakage inductance Lip.

3) Secondary inductance (The EHT overwind inductance) Ls

4) Secondary leakage inductance Lis.

5) The coupling coefficient k, between the primary and the Overwind.

6) The Overwind's self capacitance Cs.

7) The turns numbers on each winding and the Turn's ratios, including auxiliary windings.

8) The two resonant frequencies which result from imperfect magnetic coupling (K< 1) with two tuned circuits on the same core. (Rare exact solution provided by Page & Adams, Principles of Electricity. Chapman-Hall 1930).

9) The winding's DC resistance, for the primary and auxiliary windings are very low, generally less than 0.5 Ohms. The Overwind's DC resistance is generally in the region of 1000 Ohms, insignificant as the CRT's EHT current is very low. So the DC resistances of commercial LOPT's generally do not need to be considered in the analysis. Possibly, in fault finding, if they go open circuit.

The LOPT has two resonant circuits on the same core that are imperfectly magnetically coupled . The coupling factor k is generally in the order of 0.5 to 0.97 for a typical LOPT .

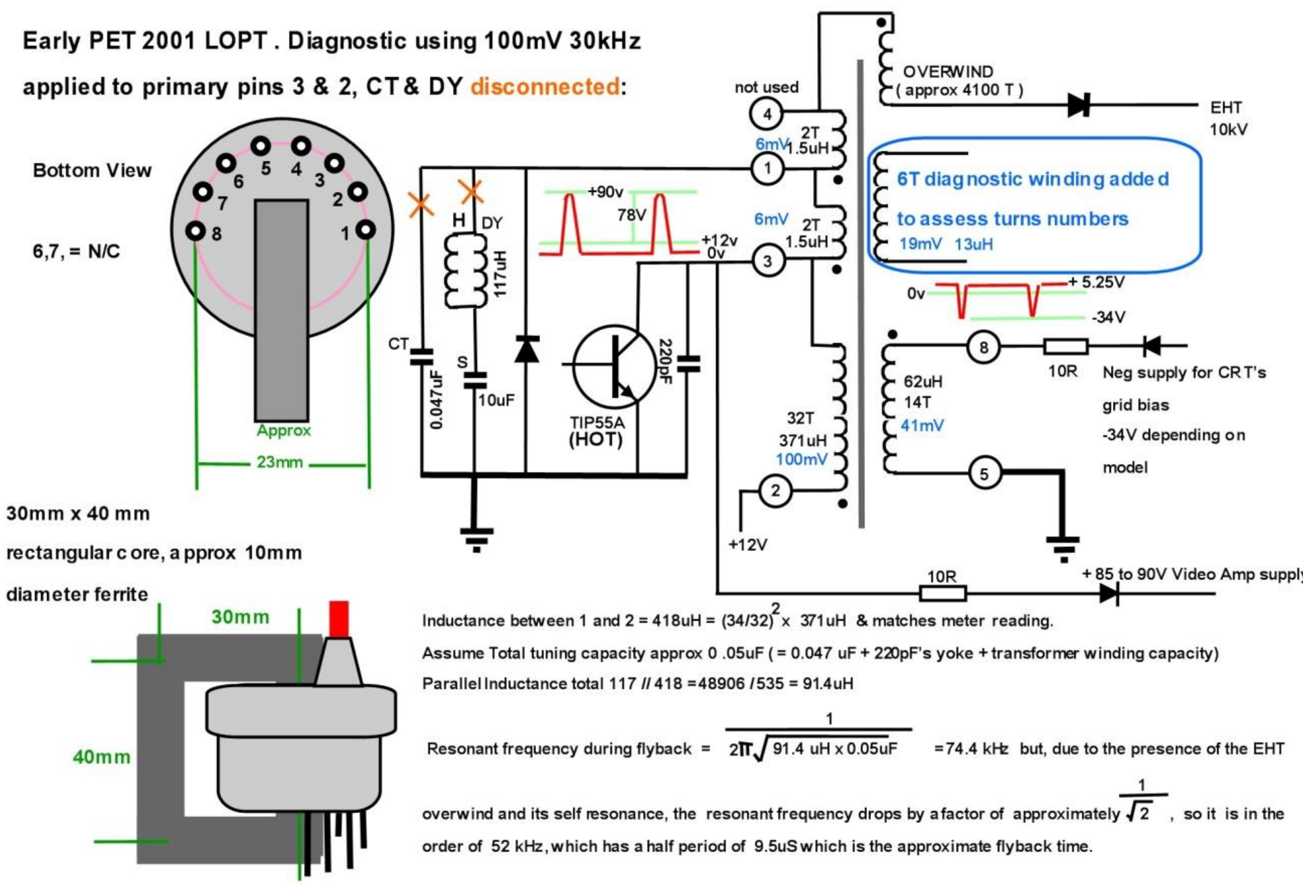
One of the resonant circuits is the high voltage overwind coil. It is tuned by its self capacitance. The EHT rectifier essentially isolates the CRT's bulb capacitance from the overwind and the EHT rectifier is coupled in only briefly on peaks. The capacitance of the EHT rectifier is very low.

The other tuned circuit is the LOPT primary winding, which is tuned by the tuning capacitor (0.047uF and a parallel 0.001uF and some self winding capacitances in the PET).

When the yoke inductance is paralleled with the primary winding, it up-shifts the value of both resonant frequencies of the LOPT.

Note: The primary winding is best considered as the one where the yoke & ERD connect, rather than the tap nearby where the HOT's collector connects. The small tap usually of 2 or 3 turns is not absolutely necessary and some LOPT's do dot have it and the HOT's collector connects directly to the cathode of the ERD & Yoke circuit. The tap is useful to improve the performance of the ERD as it switches on after flyback a little sooner than the HOT's collector voltage falling below ground, which also helps protect the HOT. The tap effectively also gains some scan width.

In the case of the PET LOPT, the primary inductance is in the order of 418uH and is down shifted to about 91uH due to the inductance of the yoke.



Inductance between 1 and 2 = 418uH = $(34/32)^2 \times 371$uH & matches meter reading.

Assume Total tuning capacity approx 0 .05uF (= 0.047 uF + 220pF's yoke + transformer winding capacity)

Parallel Inductance total 117 // 418 =48906 / 535 = 91.4uH

Resonant frequency during flyback = $\frac{1}{2\pi\sqrt{91.4\ \text{uH} \times 0.05\text{uF}}}$ =74.4 kHz but, due to the presence of the EHT overwind and its self resonance, the resonant frequency drops by a factor of approximately $\frac{1}{\sqrt{2}}$, so it is in the order of 52 kHz, which has a half period of 9.5uS which is the approximate flyback time.

The effect of the two resonant frequency circuits W1 and W2 on the one core, imperfectly coupled, is to create two resonant frequencies. (W = 2 π f where f is frequency).

One is shifted downward from the lower frequency, the other shifted upwards. The formula for the two frequencies which result is (from Page & Adams) very difficult to find this formula elsewhere, it is part of their master class in analytical calculus:

$$\left.\begin{aligned} \omega_0' &= \sqrt{\frac{(\omega_1^2 + \omega_2^2) - \sqrt{(\omega_1^2 + \omega_2^2)^2 - 4(1 - k^2)\omega_1^2\omega_2^2}}{2(1 - k^2)}}, \\ \omega_0'' &= \sqrt{\frac{(\omega_1^2 + \omega_2^2) + \sqrt{(\omega_1^2 + \omega_2^2)^2 - 4(1 - k^2)\omega_1^2\omega_2^2}}{2(1 - k^2)}}, \end{aligned}\right\} (125\text{-}7)$$

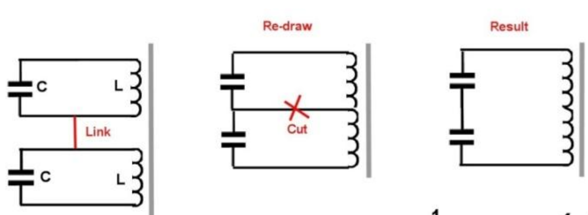
Luckily, if the two resonant circuits have the same resonant frequency, or close, if they were on the core on their own, Wo (or close enough as they are for the PET LOPT as it turns out), the solution reduces to equation 1 & 2 which are also available in Terman's Radio Engineers Handbook:

$$\omega_0' = \frac{Wo}{\sqrt{1 + k}}, \qquad \text{Equ, 1}$$

$$\omega_0'' = \frac{Wo}{\sqrt{1 - k}}. \qquad \text{Equ, 2}$$

As can be seen from the above, if the coupling coefficient was 1 and the two circuits perfectly coupled magnetically, the high frequency resonance Wo" of equation 2 would vanish and the resonant frequency would simply be $1/\sqrt{2}$) of the frequency of each single resonant circuit on its own.

Let us see if this makes intuitive sense. Consider two resonant circuits on the one core:



$$f = \frac{1}{2\pi\sqrt{\left(\frac{C}{2}\right)(4L)}} = \left(\frac{1}{\sqrt{2}}\right)\frac{1}{2\pi\sqrt{LC}}$$

A link is added, zero current flows in that link, the circuit re-drawn , a link is cut (because there is zero current in the link) and a new circuit results. Because the turn's numbers of the inductance have now doubled and the fact that inductance is proportional to the square of the number of turns, the inductance has increased by a factor of 4. The total capacitance value has halved as they are in series. Therefore, the resonant frequency, on account of having the two identical tuned circuits on the same core has dropped by a factor of $1/\sqrt{2}$), or by a factor of 0.7071, compared to what it would be if there were just the one resonant circuit on the core agreeing with equation 1.

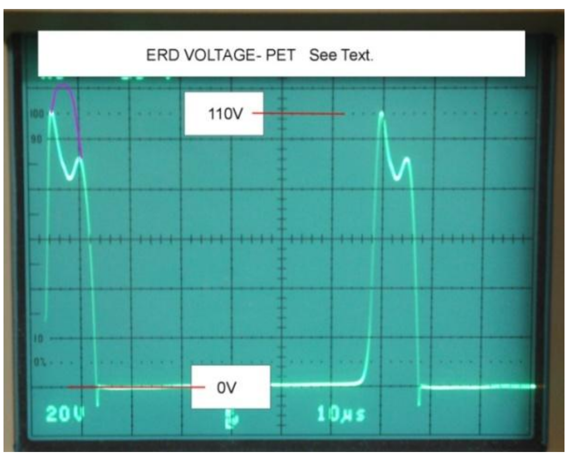
Also one could imagine a bifilar winding on the same core, each tuned by the same value capacitance, hence the capacitance is effectively doubled if each of the windings had a separate capacitor, again leading to the conclusion that resonant frequency is down shifted by a factor of $1/\sqrt{2}$.

This result above only has meaning when the coupling coefficient k, is 1. When it is not, and it is any value less than unity, another resonant frequency appears much higher in frequency, due to the leakage inductance between the two windings. his frequency is shown by (equation 2).

Also, it is obvious from equation 1 and 2, that as the two coupled circuits move further apart, and k drops to near zero, each of the tuned circuits returns to its natural resonant frequency.

Therefore we expect that with two tuned circuits on the same magnetic core, there will be two resonant frequencies, one high and one lower and this is the basis of the in circuit test for the PET LOPT shown in section 12.

Also of we look at the HOT's collector voltage, or the voltage across the ERD, we also see these two frequencies:



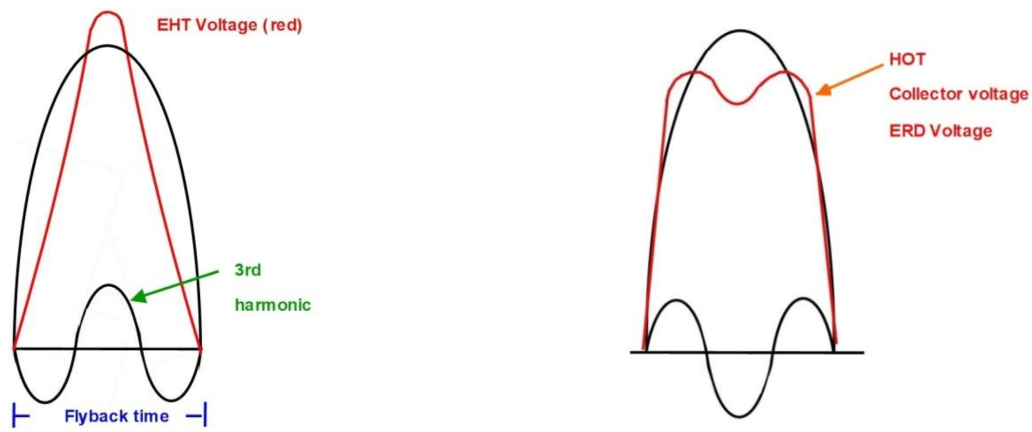
The Flyback pulse's base represents half the period of the low frequency resonance and the dimple in the top of the pulse represents the high frequency resonance. (The purple line drawn on the recording would be the shape if there was no high frequency resonance superimposed)

This resonance is the cause of the dimple in the peak voltage on the ERD and HOT's collector. This value is **intentional** and is known in LOPT design as **3rd Harmonic Tuning.** It is not a perfect symmetrical dip in the centre of the waveform so the high frequency resonance for the PET LOPT was just a little low, but it is basically close to 3rd harmonic tuning.

This high frequency resonance (for many LOPT's not all) is generally planned to be the 3^{rd} harmonic of twice the period of the flyback time, or the low frequency resonance for many monochrome VDU's.

Since the low frequency resonance for a typical VDU is 50kHz (to have a flyback time in the order of 10us or half a cycle), the 3^{rd} harmonic is in the order of 150kHz. The polarity of the voltages added by the leakage inductance (k less than 1) and this resonance is such that it results in a dip in the peak collector (or ERD voltage) on the primary circuit, as shown in the recording above, but a positive peak in the output of the overwind (EHT voltage). These effects are shown below, the flyback voltage in black would be a perfect half sinusoid, if there were no high frequency harmonics involved (k=1). The flyback time is half a cycle of 50kHz:

3^{rd} Harmonic Tuning:



It was stated in the early RCA Transistor manual, technical series SC-12, pg 67, 1966, that:

"This technique, which is referred to as "third-harmonic tuning" yields a voltage ratio of secondary - to – primary peak voltage of approximately 1.7 times the value expected in a perfect transformer".

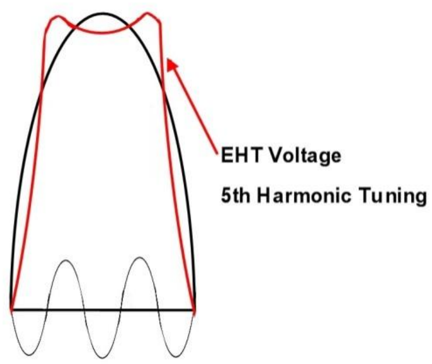
Meaning that the voltage produced on the EHT overwind output was much higher than what the primary to secondary (overwind) turn's ratios would have predicted for a simple transformer with a k close to 1.

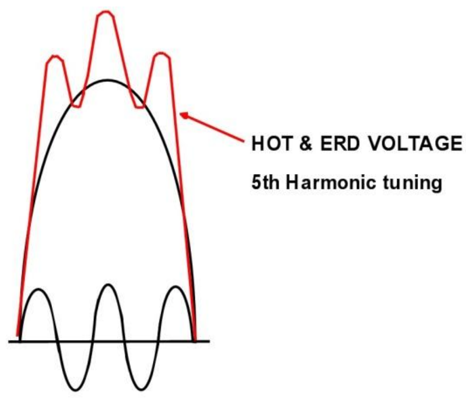
As the k value increases (with tighter coupling between the primary and the overwind) the high frequency resonance value increases. If it is increased to x 5 the fundamental value of the primary tuned resonance, it is called 5^{th} harmonic tuning. This tuning was more common in color VDU's than monochrome ones, however, the Classic Apple Mac LOPT (or at least the current replacement part from Dalbani Corp) has 5^{th} harmonic tuning.

In this case, the reverse happens. The peak of the EHT output voltage from the overwind is flattened down, while the peak voltage on the collector of the HOT (and ERD) is peaked up. This is shown in the diagrams below:

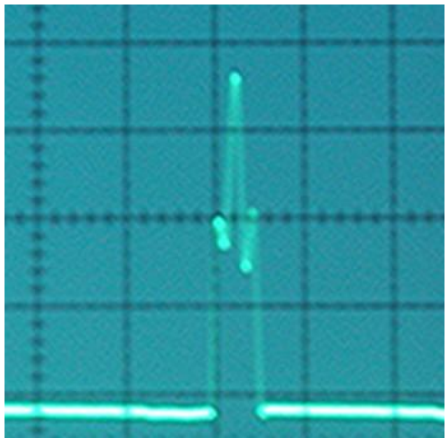
5^{th} Harmonic Tuning:

(As noted the Classic Apple Mac uses a LOPT with 5^{th} harmonic tuning)





A recording of the HOT voltage (LOPT primary) from a different VDU which has 5^{th} harmonic tuning, as an example, is shown below. This VDU is a Conrac (American made) Mil Spec aviation grade 14 inch monochrome radar VDU. Conrac went for 5^{th} harmonic tuning to help lower the output resistance of the EHT supply for superior performance. Though the company would never have published data on this, even the service manual is not available, being a military special order product, circa 1980.



Therefore it is quite easy to tell looking at the collector waveform on the HOT in a particular VDU, if the LOPT was designed for either 3^{rd} or 5^{th} harmonic tuning.

It has been said that because the EHT peak is flatter in 5^{th} harmonic tuning that more energy can be taken from the EHT because it creates a lower source resistance and better voltage regulation than if the EHT was very peaked as it is in 3^{rd} harmonic tuning. On the other hand, with lower peak collector voltages in 3rd harmonic tuning it is safer for the HOT and the turn's ratio of the overwind to primary does not have to be as high, because of the peaked up overwind output voltage with 3rd harmonic tuning.

Generally for most transformers a "k" value of less than one implies leakage inductance which is always counter productive in cases where power is being transferred through a transformer throughout the operating cycle.

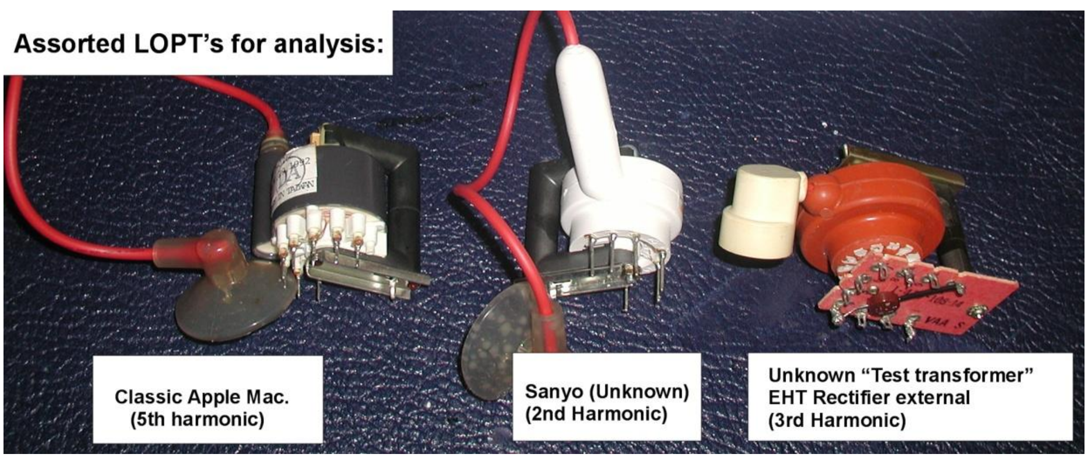
Powers is not transferred through the LOPT continuously. Instead energy is being stored in it in part of the operating cycle (half of active scan time from the centre to the right side of the CRT), oscillated in a resonant circuit for half a cycle (the flyback time) so as to reverse the magnetic field polarity and return the CRT beam to the left side to start the scan. Then after that the magnetic field energy used to provide a damped current to scan the left side of the raster.

One minor implication of the above is that if you are going to extract any energy, from the LOPT, say to run auxiliary circuits, you then have a choice whether to extract that during the resonant flyback time, or during scan time. Any significant energy taken on the flyback peak runs the risk of damping the free resonance and lowering the EHT voltage.

On the other hand, if the energy is taken during scan time, it can be regarded as taken when the LOPT is operating in "transformer mode" and more energy can be extracted with this method. But, the wave shape for the LOPT's transformed voltages is such that the transformed voltage, during scan time is only 10% of the peak to peak voltage on auxiliary (secondary windings), but the resonance voltage is 90% of the peak to peak voltage. Rectifying a flyback peak is good for a high voltage low current supply, such as powering a CRT anode, grid circuit or focus circuit, while rectifying the scan time voltage is better to say power a video output stage that is more hungry for power. Though, there are no hard and fast rules here.

How to physically measure LOPT parameters:

This is a photo of some similar LOPT's I have subjected to testing:



It greatly simplifies the analysis of a LOPT when the EHT rectifier is not built into its body. However, when it is there are ways around the problem. One tested transformer had 2nd harmonic thing.

The “Test transformer” shown on the right (in the photo above) with the red-orange colored overwind does not have an internal EHT rectifier, so it is possible to directly connect to the overwind coil.

(Of note if you have a LOPT with no built in EHT rectifier, for a CRT in the 9 inch range with an EHT of around 10kV, a suitable and readily available rectifier is the BY176)

Seldom is any specific information provided on LOPT’s by a manufacturer. They are “proprietary devices” and in many cases made for the particular VDU model.

The analysis of a LOPT is better done with a signal generator and a scope rather than with inductance meters. This is because the meter test frequencies might be unknown and due to the coupling between the two resonant circuits, with or without the primary tuning capacitance, it is better to far down tune the resonance with a large value capacitance on the primary and perform a resonance test at a relatively low frequency compared to the resonant frequency of the overwind.

The techniques shown here were developed over some years of working with LOPT’s. The scope and generator setups have been shown diagrammatically, so there is no confusion about how these tests are performed.

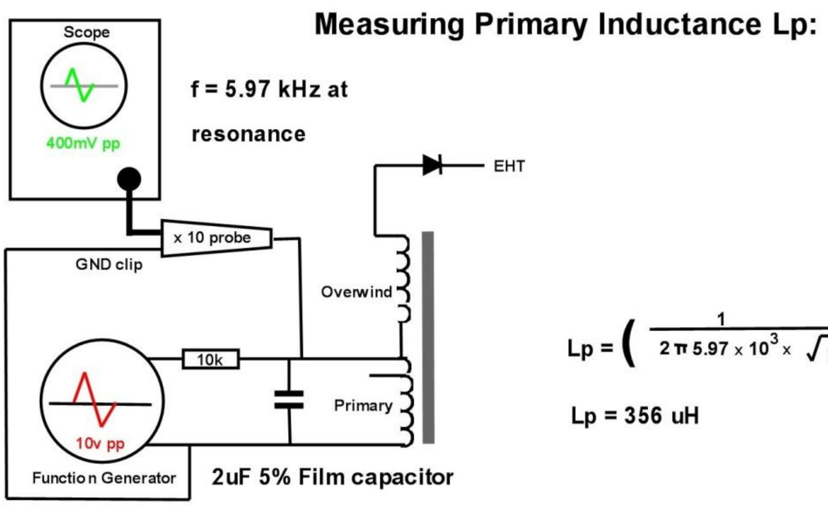
If it is not done correctly, including the way the generator & the scope are coupled, the loading effects from the signal generator’s output resistance, or the effects of the scope probe’s loading, will confound the recordings and give false results.

Since, the imperfect magnetic coupling between the LOPT primary and overwind coils, described by the coupling coefficient k (and it is the k value which determines the LOPT’s high frequency resonance 3rd harmonic tuning or 5th harmonic tuning) it is worth explaining how a LOPT can be physically measured, in practice. This way, the coupling coefficient k and the LOPT resonant frequencies can be calculated.

A spare generic “TEST” LOPT shown above was used for the examples below, because this LOPT has the overwind output available directly without an EHT rectifier being incorporated into the transformer.

Also, these measurements and calculations are with the LOPT on its own, not with the inductance of the Yoke coils applied to its primary, the effect of this is explained later and also how to get around the fact that many LOPT’s have the EHT rectifier built into them.

Primary inductance Lp:



$$Lp = \left(\frac{1}{2\pi \, 5.97 \times 10^{3} \times \sqrt{2 \times 10^{-6}}} \right)^2$$

Lp = 356 uH

The trick to an accurate assessment of the primary winding inductance Lp, is to down tune the primary resonance well below the Overwind's self resonant frequency with a large value capacitor (2uF) and to loosely couple in the signal generator.

A signal generator and Oscilloscope is used to find the primary's resonant frequency with the 2uF capacitor. The equation above is used to determine the primary inductance Lp.

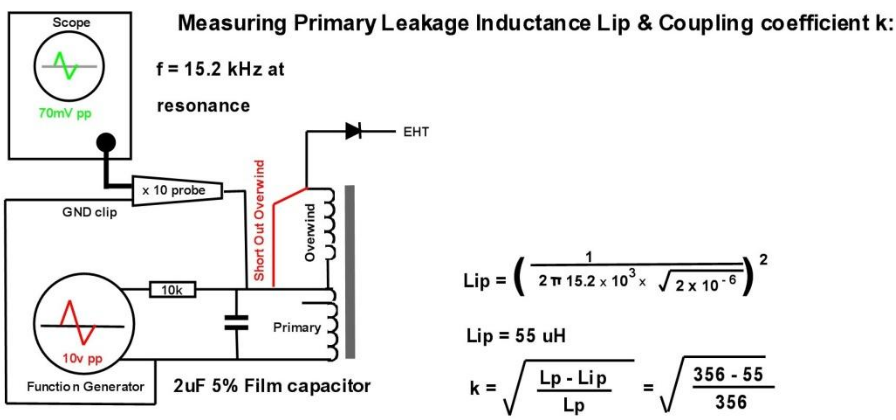
For the test transformer in this example, the primary inductance was found to be 356 uH.

The primary leakage inductance is measured by shorting out the Overwind (EHT winding). This can only be done properly if it is a type of LOPT that does not have the EHT rectifier embedded it .

When the overwind is shorted out, all the turns of it which are magnetically linked to the primary, act to neutralize the primary's main inductance, all that is left is an inductance (leakage inductance) which manifests itself in series with the primary.

From this information it is very easy to calculate the coupling coefficient k. The leakage inductance, all referred to the primary is 55uH and the k value is therefore 0.92:

Primary Leakage inductance and coupling coefficient k :



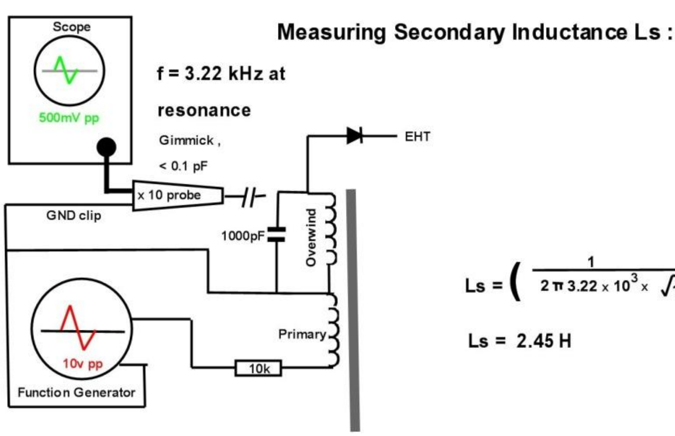
$$Lip = \left(\frac{1}{2\pi\, 15.2 \times 10^{3} \times \sqrt{2 \times 10^{-6}}} \right)^{2}$$

$$Lip = 55\ uH$$

$$k = \sqrt{\frac{Lp - Lip}{Lp}} = \sqrt{\frac{356 - 55}{356}}$$

$$k = 0.92$$

The secondary (Overwind inductance) is measured as follows:



$$Ls = \left(\frac{1}{2\pi\, 3.22 \times 10^{3} \times \sqrt{1000 \times 10^{-12}}} \right)^{2}$$

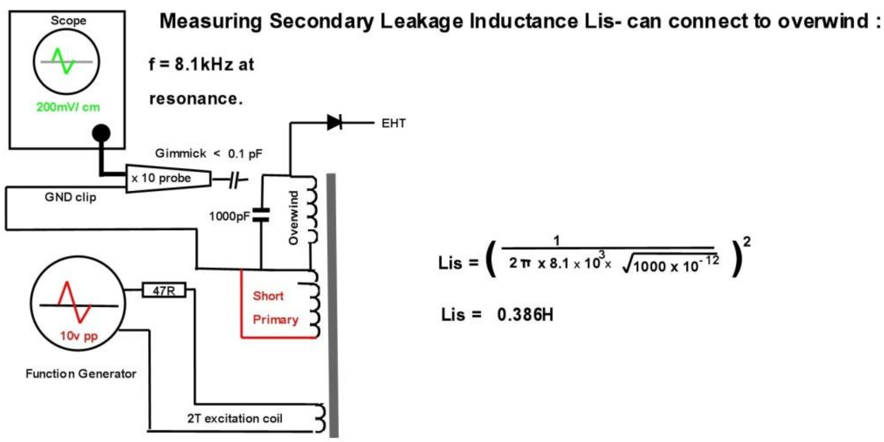
$$Ls = 2.45\ H$$

The scope probe is merely placed near the overwind output wire to create a small "gimmick" coupling capcitor. Generally, the Overwind's self capacitance is around 7 to 8 pF. This is swamped by adding a 1000pF capacitor to down tune the resonant frequency to the range of 3.2kHz. In the example transformer tested, the Overwind's inductance is calculated at 2.45 Henries.

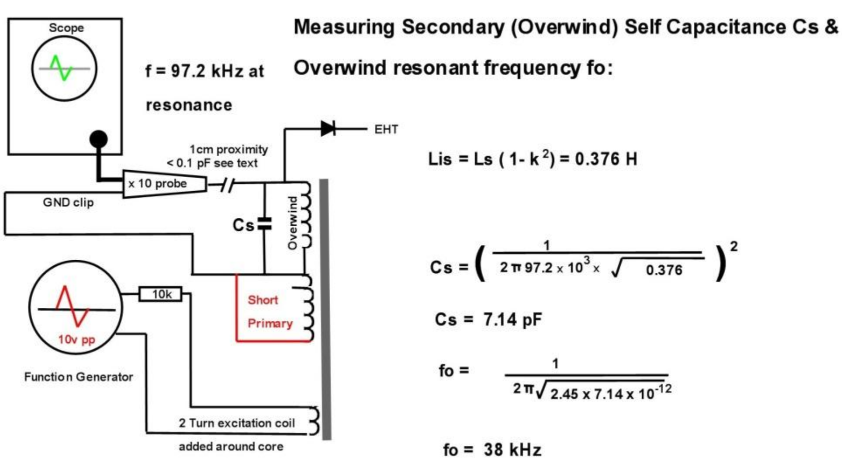
Overwind's leakage inductance Lis:

In the same way that all of the leakage inductance between the primary and the secondary can be referred to the primary side (appearing in series with the primary winding), the primary can be shorted out instead, then all of the leakage inductance appears in series with the secondary.

But, it is not the same value as the primary leakage inductance and is 0.368 Henries. For this the probe tip on the scope is just placed near the overwind coil body to create a fraction of a pF coupling capacitor and the resonant frequency peak observed:



Once the secondary leakage inductance is known it becomes possible to calculate the Overwind coil's self capacitance. The reason is that this capacitance resonates with the secondary's leakage inductance, when the primary is shorted:



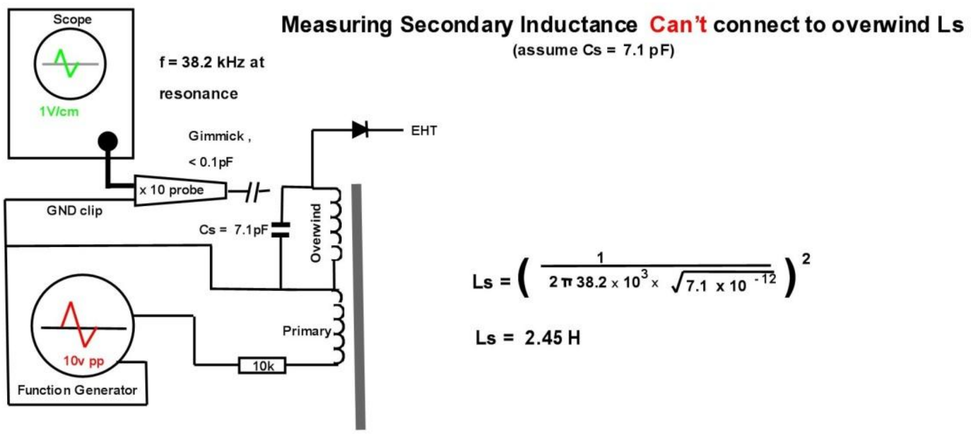
Note: The Primary inductance = 356 uH and typical Tuning capacitor total approx 0.05uF (see text) the Primary self resonance fp = 37.7kHz, almost identical.

See text for the effect of two tuned curcuits on the same core with nearly identical self resonant frequencies and a specific k value.

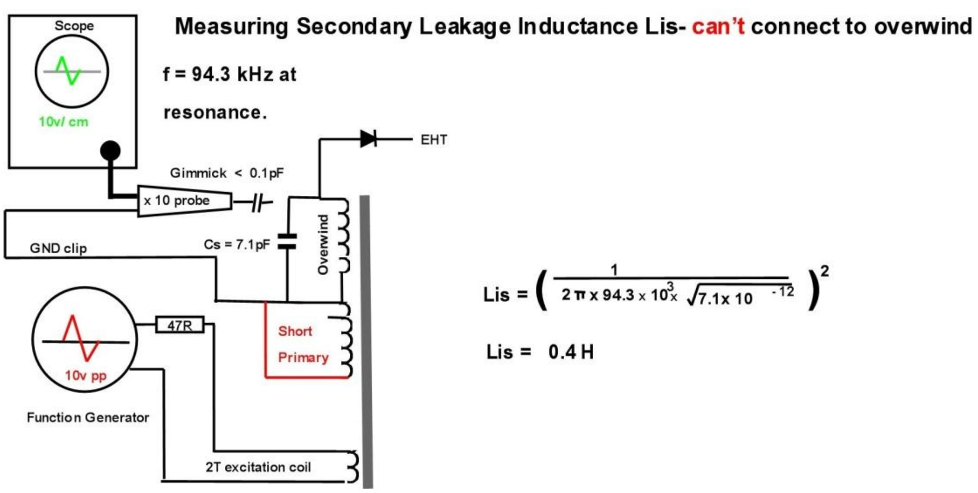
The self capacitance of the Overwind is in the order of 7pF to 8pF.

In practice of course, many LOPT's have the EHT diode built into the body of the LOPT, so that the EHT wire from the LOPT can lead directly to the EHT connection on the CRT bulb, without having to pass through an external rectifier assembly. So this raises the question of how to establish the parameters of a particular transformer, when you cannot add additional capacity to the overwind coil connection (as done with the 1000pF capacitor in the examples above), or indeed how to determine the Lip because it is not possible to directly short out the EHT overwind coil.

In this case one can make an assumption about the approximate self capacitance value of the LOPT's overwind coil, the value of which is similar for TV's and VDU's with a similar sized CRT:



Likewise the secondary leakage inductance (and hence the k value) can be estimated if the self capacitance of the Overwind is estimated to be in the region of 7pF:



In the case where the EHT rectifier is present in the assembly, it is not possible to short the overwind out to determine Lip. However Lip can be calculated from Lp and the coupling coeficient k , calculated from the two above figures for Ls & Lis when a connection directly to the overwind cannot be made:

$$k = \sqrt{\frac{Ls - Lis}{Ls}} = \sqrt{\frac{2.45 - 0.4}{2.45}} = 0.91 \qquad Lip = Lp\,(1 - k^2) = 0.179 \times Lp = 0.1719 \times 356\ \text{uH} = 61\ \text{uH}$$

Measuring turns numbers and turn's ratios:

This can be done without having to unwind the LOPT. Simply a small number of turns is added (wound around the LOPT core) near the main windings, 5 to 10 turns is suitable. Then a diagnostic voltage is applied to the primary winding, 100 to 200mV pp applied directly from the generator at 30kHz. The voltage across each winding is then measured with the scope and the voltage ratios predict the turn's ratios. If the measurement are basically correct, then the square root of the inductance ratios of the windings, should match up with the turn's ratios.

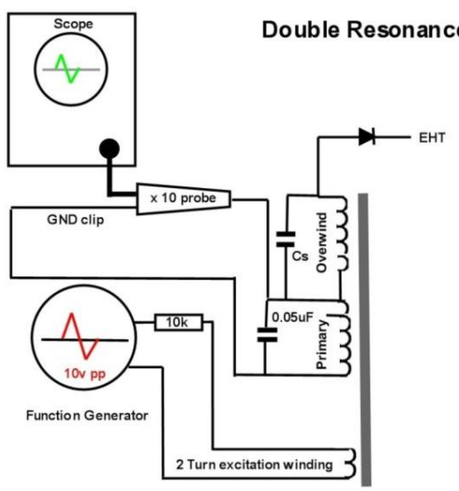
Bringing it all together:

One way to bring all the essential LOPT data relating to the LOPT's two resonant frequencies is to perform a dual resonance test. The data can be used from this test, in conjunction with the calculated tuned primary resonant frequency, to calculate the k value for the specific transformer.

Dual resonance on the TEST LOPT:

Since Equations 1 and Equation 2 predict two resonant frequencies on a LOPT, with two tuned circuits (when their resonant frequencies on their own are roughly equal), it is easy to measure them with a simple test and also calculate the k value this way too:

Double Resonance Test With Primary Tuning capacitor:



k = 0.92

two peaks occur:

f_{low} = 28.3kHz and f_{high} = 136.7 kHz (measured)

Predicted value from Page & Adams Equations:

$$f_{low} = \frac{38\text{kHz}}{\sqrt{1 + k}} = 27.4\text{ kHz}$$

$$f_{high} = \frac{38\text{ kHz}}{\sqrt{1 - k}} = 134\text{ kHz}$$

NOTE: When the 117uH Yoke inductance is paralled with the primary, the two resonant frequencies up-shift to 53.2 kHz and 146.6 kHz, the higher frequency being close to the Third Harmonic. This is "3rd Harmonic tuning", see text. 1/2 the 53.2 kHz period, is the "Flyback Time" = 9.4 uS.

As noted above, testing the tuned LOPT, on its own, without the parallel inductance of the H yoke coils the two frequencies calculated are 27.4 KHz and 134 KHz, close to what is actually measured on the dual resonance test. However, as noted, both of these frequencies up-shift to 50kHz and close to 150kHz (the third harmonic) respectively when the Yoke inductance is connected to the primary (as it is in use).

The k value is easy to calculate from the way it down tunes the primary self resonant frequency. Or it can be calculated from the dual resonance test alone, that is of course, if the natural resonant frequency of the tuned primary is close to that of the secondary (overwind) self resonance. This happens to be the case for the PET LOPT and the Test transformer, both of these are third harmonic tuned types.

Equation 1 and equation 2 can be combined to eliminate Wo and formatted as follows:

Using Dual Resonance test result to calculate k

$$k = \frac{\left[\frac{Fhigh}{Flow}\right]^2 - 1}{\left[\frac{Fhigh}{Flow}\right]^2 + 1}$$

As an example using the result of the dual resonance test on the TEST transformer of 136.7 and 28.3 kHz respectively, from the above equation the k = 0.92. The resonances and k values are very similar for the PET LOPT and the TEST transformer.

The data shows therefore shows that theTest transformer and the PET LOPT are very close.

The test transformer, to substitute in for the PET LOPT would require an EHT rectifier added into its output connection (as it is not internal) and its auxiliary windings would also require some adjustments by adding extra turns around the core and placing those in series, in phase or anti-phase to attain the correct voltage for the CRT bias. Unfortunately, the Test transformer shown here is not an available part, and I don’t know what model set it originated from.

If it is the case though, that the tuned primary frequency and the Overwind’s self resonance were not similar values, the simplicity of equation 1 and equation 2 cannot be applied and the more elaborate equation provided by Page and Adams must be applied.

For example, this is the case for the LOPT from the Apple Mac. If the result from the twin resonance test is used to calculate a k value and that k value is then used to calculate Wo. And then then the theoretical primary resonance is calculated from the primary inductance test (that derives Lp) and the tuning capacitor value (normally used with that LOPT) and that doesn’t closely match Wo, then it is obvious that the tuned primary resonance and the overwind’s self resonance are not a close match.

Selecting and using replacement LOPT:

Obviously from the above, it would ideal to find a substitute LOPT where:

1) The dual resonance test frequencies matched as closely as possible.

2) The primary inductance values matched as close as possible (though some adjustment of the primary tuning capacitor can help here which affects the EHT and flyback time)

3) The transformers turn's ratios and auxiliary windings were similar, but these can be corrected by adding auxiliary turns in series aiding or opposing Phase.

4) The resultant EHT running from the same power supply voltage was similar.

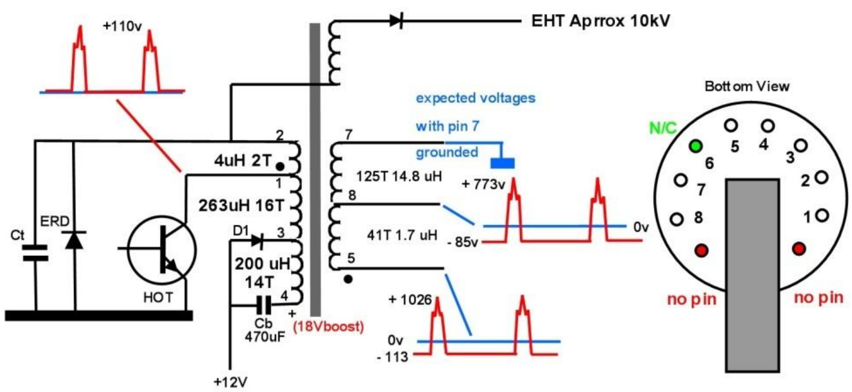
5) The replacement LOPT was intended to be used in a similar sized VDU and with a yoke with H coils of a similar inductance.

6) The replacement LOPT should ideally use the same harmonic tuning.

The above is an ideal world unlikely to be realised.

However, that does not mean that another substitute LOPT type, with disparate parameters, if readily available would not work, even one such as the Apple Mac type with a much higher k values and 5th harmonic tuning. These are currently available from Dalbani Corp. These types also have an auxiliary winding to create an 18V boost voltage and inject the 12V supply to the primary via a diode. The turn's ratios and the inductances were measured in the ways described above and the voltages deduced from those and some data that was on the original Apple Mac schematic. There are suggestions of how it could be used in the PET.

Apple Mac LOPT 157-026C (replacement for Apple part HR42031)- Made in Taiwan.
Currently available from Dalbani Corporation, on Ebay.



Data suggests for use in PET:

Make adapter pcb.

Introduce +12V directly to pin 3. Leave pin 4 not connected...see text about using D1 and Cb, or not.

ground pin 7 and acquire -85V in "transformer mode" via UF4007 rectifier for grid brightness control from pin 8 see text.

Pin 5 not connected.

If EHT too high (>11kV), move HOT collector connection to pin 2 and leave pin 1 N/C. Also increase the original PET tuning capcitor Ct, from 0.047 uF to 0.056uF.

The +773 could be rectified with a UF4007 to provide the CRT's foucs voltage with a 2M Focus potentiometer.

The main thing to be sure of is that the flyback period was about correct, this can be adjusted by the tuning capacitor value Ct. Also that the final EHT was close to correct. Ct can be used (increased) to lower the EHT and lengthen the flyback or the converse.

It would have to be found by experiment, if it was permissible not to use pin 4 and simply introduce the +12V at pin 3. If there was not enough scan width, the diode D1 (an MR854) and the 470uF capacitor Cb, would have to be added to the adapter board which interfaced it into the PET VDU.

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