A Solid-State 6T5 Replacement

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v1.1 September 2022

History

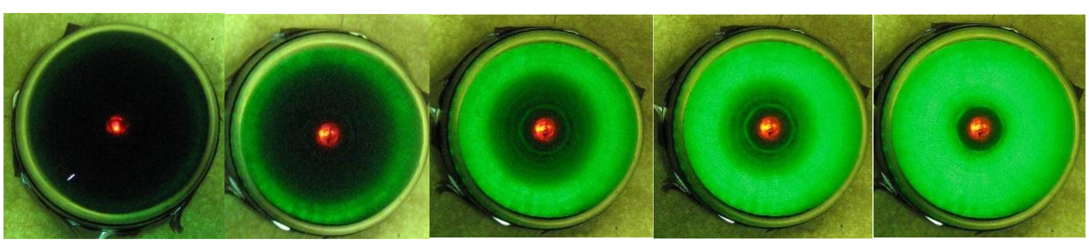
In 2021, I crated a solid-state version of the 6E5/6U5 tuning eye tube. Tuning eyes are getting rare (though they are certainly still available), and I wanted an eye tube that would plug into a vintage radio without modification, in the same form-factor as the original tube, that I could keep on for prolonged periods. The result was the SS6E5 project http://www.rabjohn.ca/gord/ss6e5/ . When word got out, I had several requests for a solid state 6T5 tuning eye. The 6T5 was used in Zenith radios, and is very difficult and expensive to get, much more difficult than the 6U5. In fact, I have never seen one. Furthermore, if you have one, you probably don't want to power it up very often.

The 6E5/6U5 has the familiar "fan" pattern, where the width of the fan shaped shadow depends on voltage. The 6T5 is more like a dilating pupil: At low grid voltage (not tuned to a station), only a narrow ring of green is visible. As the grid voltage becomes more negative (as a strong station is tuned in), the inner radius of the light ring of light decreases.

Above: a 6T5 in action, from https://www.sm5cbw.se/tubes/htm/6t5.htm

The 6E5/6U5 replacement I designed before can't do anything like that. An entirely different LED board is needed. LEDs must be wrapped around in concentric rings. A new control board is required as well. This document describes these boards.

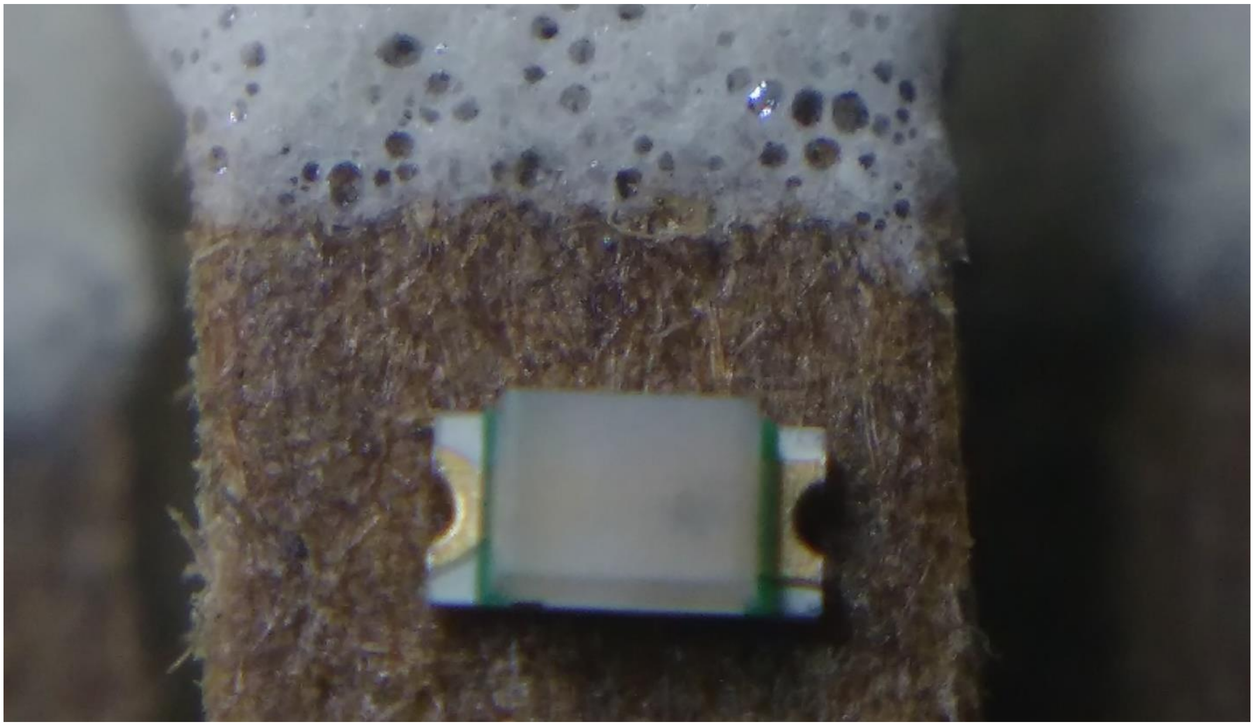
The solid-state replacement looks like this:



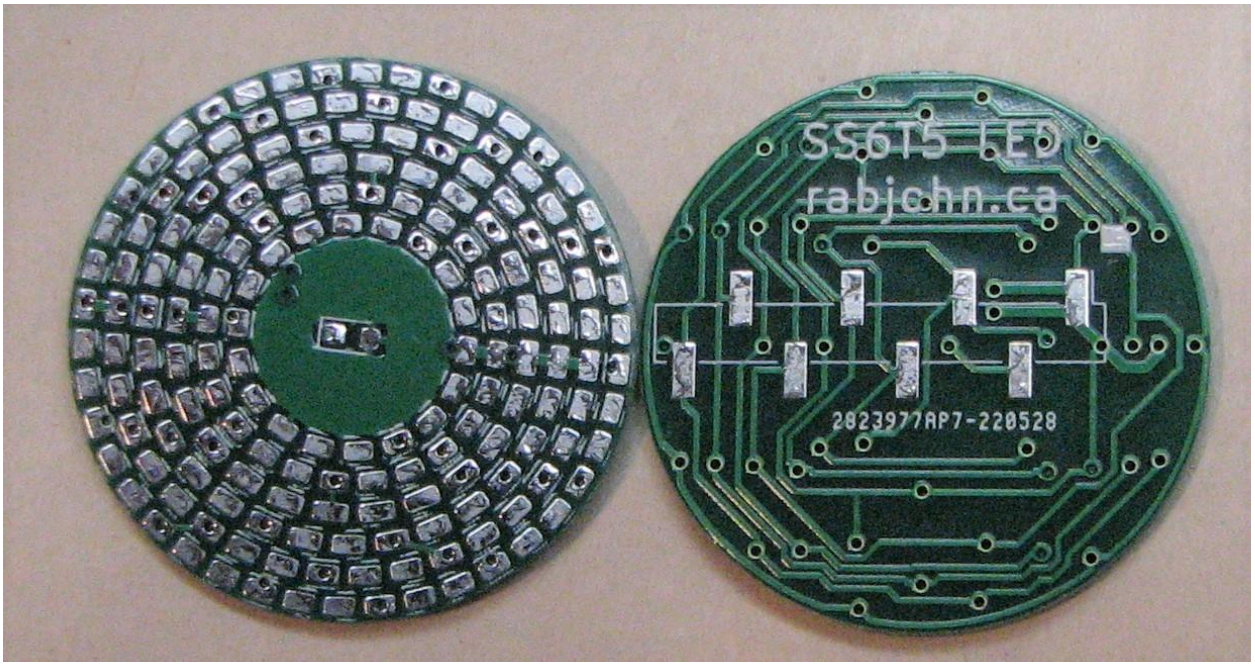
The LED Board

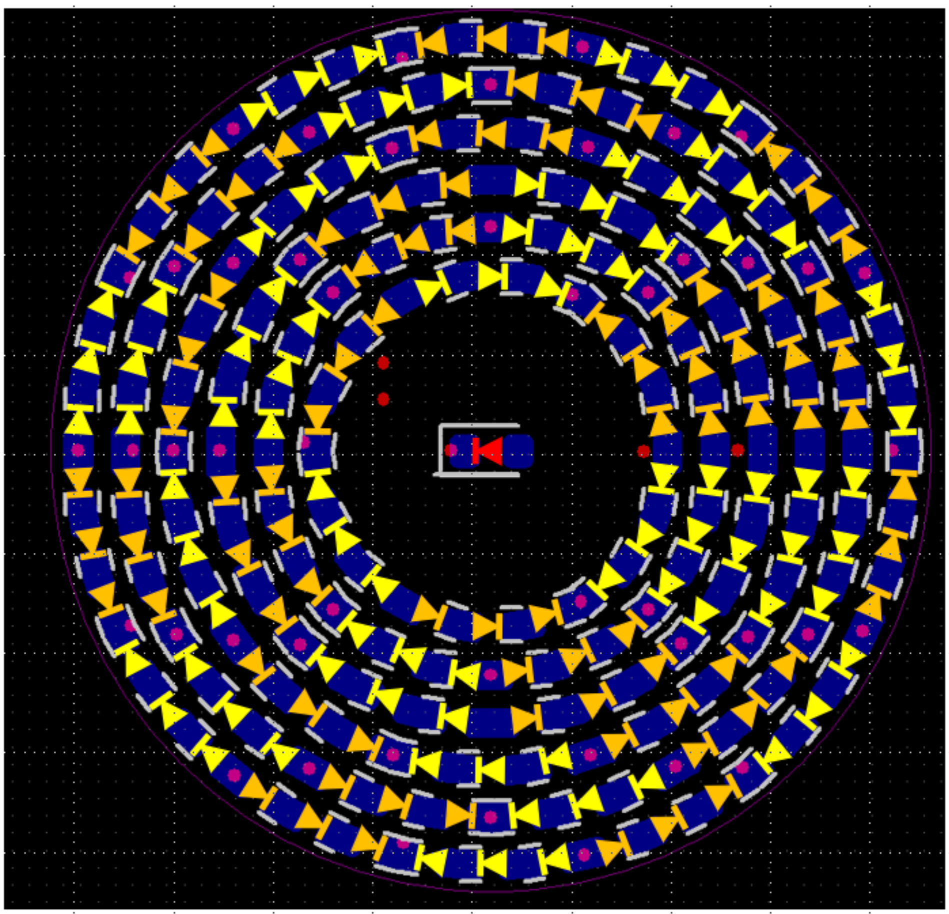
I wanted the rings to be completely uniform; no obvious start or stop. This can be done (assuming you can place vias in solder pads, which is not always allowed, but I had little choice) if you use LEDs placed end-to-end in repeated patterns. I found that I could place up to about 44 0603 size LEDs end-to-end in a circle on a 26mm diameter (that's the largest I could fit into a 6U5 tube) circuit board. Options I considered were, for example, two 22 diode stacks in the outer ring, but this would require too much voltage for the LM391x driver IC, and high voltage drive circuitry would be required. Or, I considered 6 stacks of 7 diodes on the outside ring, 6 stacks of 6 on the next ring, and so on. Less voltage would be required, but a doubler or quadrupler would be required to generate it; at least the LM391x IC could probably handle this sort of voltage directly. I ended up settling on 42 diodes in the outer ring, 14 stacks of 3 diodes. 3 diodes in series work off of a 6V filament supply.

The outermost ring uses 14 sets of 3 LEDs, 42 in total. The next ring uses 12 sets of 3 LEDs, 36 in total. The third ring in uses 30 LEDs. The 4th and 5th ring use 24 LEDs. Finally, the 6th ring uses 18 LEDs. Since each ring uses groups of 3 LEDs in series, the bar graph IC can drive them directly, and use the 6.3V heater supply. The 6T5 has an exposed cathode that glows red. This design includes an orange LED in the middle to emulate the heated cathode. I looked at various LEDs in the red-to-orange spectrum, and settled on the orange Rohm SML-D12D8WT86. Since I do not have an authentic 6T5 to compare to, I urge you to try different LEDs in this location to find the one that looks best. So, in total, there are 174 green LEDs, plus one red/orange one. The only practical way to build this is with a custom circuit board, which I designed on “KiCad”, a free PC-based tool. The boards were fabricated at JCLPCB https://jlcpcb.com/ . I intend to make the boards and the Gerber files available to anyone who wants them.



Green LED on the head of a match.



The bare 6T5 LED Board

6T5 LED board, with placement and polarity of LEDs shown.

The green LED I selected was the Rohm SML-D12P8WT86, which is a green AlGaInP diffused LED with a dominant wavelength of 560nm, a 0603 outline, and a height of 0.55mm. There are other green LEDs from other manufacturers, but these Rohm LEDs seem to be more efficient than others. There are other green LEDs based on InGaN that offer a shorter dominant wavelength around 527nm (the Avago/Broadcom HSMQ-C191 for example). The problem is that these LEDs have a forward voltage of over 3V, which means that only a stack of 2 (not 3) can be supported from a 6.3V filament supply. And, I fear that they may look too "blue". The Rohm 0.55mm thick LED that I used is not as "diffused" as I was hoping; the LED chip location is still very visible, but I need an external diffuser anyway. So, I think my LED choice was not too far off, and under 10 cents each in quantity (Digi-key or Mouser), they were also one of the cheapest options.

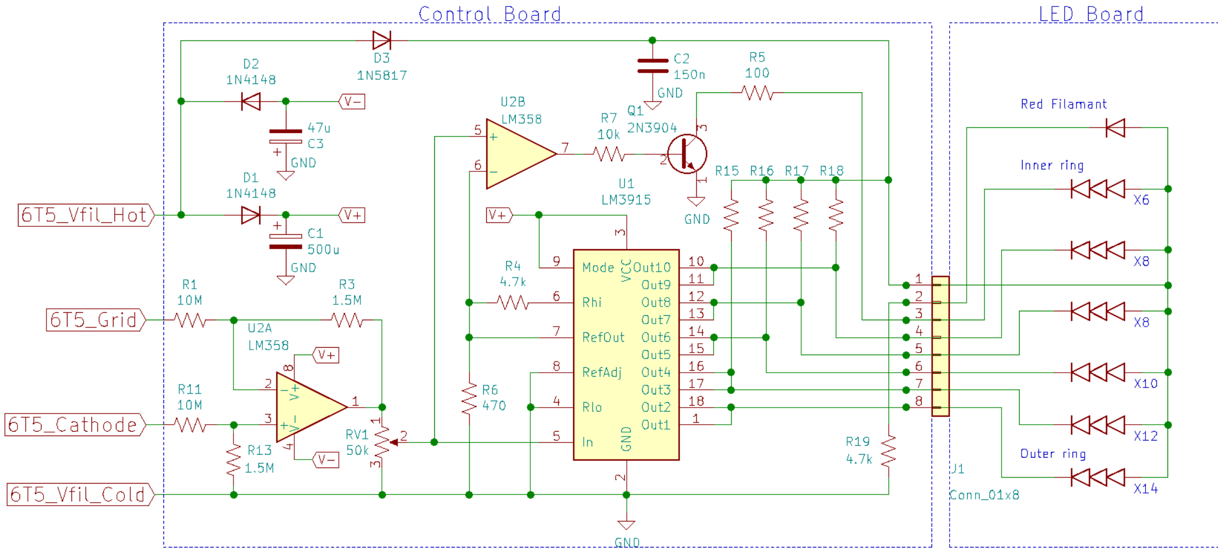
The Electronics

The green LEDS are driven by the LM3914/LM3915/LM3916 series of bar-graph ICs. These ICs have all the circuitry needed to drive a 10-segment bar-graph display (I'll talk about the 11th segment later). The differences between them are: the 3914 is a linear display (10 steps, 10% per step), the 3915 is logarithmic (10 steps, 3dB per step), and the 3916 is quite similar to a 3914, but with "VU meter" scale (where the upper 5 segments are 1dB per step for indicating clipping, but the lower 5 segments are farther apart and not evenly spaced). I am not sure how the 6T5 behaves; whether it is closer to linear or to log. There is a video comparing the two on the project web site. I used a LM3915 because it gives better sensitivity at low voltages (low signal levels), but you can use any of the three with simple resistor changes. All of these are easily available in 18-pin DIPs as old stock. So, use whatever you can get; any of these are viable options, and they have the same pin-out. I purchased mine from Maddison Électronique in Montréal.

There is nothing unusual about the driver circuit, which I show below. It is very similar to the 6E5/6U5 circuitry. Since I only require 6 outputs, I paired the 10 outputs on the LM3915 to make 5, and used the "11th" signal (see below) for the innermost (6th) ring. I was concerned that the inner rings might be too bright (the same current for fewer diodes), so I added the provision to shunt current away from the LEDs with R15-R18. However, I found it unnecessary to use these. Unlike the 6E5/6U5 design, I use rectified AC (filament voltage) directly on the LEDs. This is because the resistors R15-R18 would impose a negative voltage to the LM3915 if I used unrectified AC. In order to translate the 0 to -22V 6T5 grid voltage to a 0 to 1.28V (RefOut) signal for the LM3915, I used a simple op-amp circuit. A potentiometer RV1 makes the sensitivity adjustable. It has an input impedance of 10M (larger precision resistors are harder to find; you can ratio the resistors R1, R3, R11, R13 up if you want higher input impedance), which should be high enough for most applications.

Since I needed an op-amp and the most common op-amps come in pairs, what should I do with the remaining op-amp? I used the extra op-amp to add an 11th signal, used for the inner-most ring. This ring brightness is set by R5, and the threshold is set by R4.

The brightness of the outer 5 rings depends on the current pulled from RefOut, pin 7 (which, in this design, is configured to its default voltage of 1.28V). R6 sets this current, and therefore the brightness of all but the inner ring. There are different resistors in the LM391x ladders that drive the comparators. So, R4 (the 11th resistor on the voltage divider) must be decreased to about 1K if a LM3914 is used.



The default assembly of the board makes the input fully differential, so it can be used in equipment where the cathode is not tied to one side of the filament. There are several ways to populate the board: With or without the sensitivity adjustment, and in differential or single-ended (cathode connected to one side of the filament) operation. I expect the most popular configuration will be fully differential with sensitivity adjustment. The only disadvantage of the fully differential circuit is that it takes more parts, and some resistors need to be matched in order to optimize common mode rejection (R1=R11 and R3=R13. To save trouble, I just use 1% resistors for these 4 parts). If your application has one side of the filament connected to the cathode (so you do not need common mode rejection), then you can eliminate D2, C3, R11, R13 (replace R13 and C3 with shorts), and matched (or 1%) resistors are not required. If you do not need adjustable sensitivity, eliminate RV1 (and connect terminal 1 to 2), and use 680K for R3 and R13.

There are a few situations where this circuit cannot directly substitute for a real tube:
- If DC is applied to the filament, beware that the op-amp will not have a negative supply, so the circuit must be configured without common mode rejection.
- If AC or RF or other odd signals are applied to the grid, and the host circuit is relying on the diode action of the 6T5 grid, the results will be unpredictable. You may be able to add a diode to emulate the grid-to-cathode diode of the 6T5.
- If this circuit is used in a series string filament circuit, it will receive excessive voltage and be damaged. If this is required, 6V Zener diodes (in series back-to-back) must be placed across the filament.
- The common mode voltage (heater to cathode voltage) must be less than about 40V (R3=1.5M) or 90V (R3=680k).

Below I list is a full bill of materials. Note that I specify a 10-pin male connector for the LED board. Only 8 pins are required, but standard 8-pin connectors have a foot-print that is the mirror image of what is needed on this board. So, you must buy either a 9- or 10-pin connector and cut off the unused pins.

Designation	Value	Size	Comment
R1	10M (match R11)	¼ w	Sets input impedance and gain
R3	1.5M (match R13)	¼ w	Sets gain
RV1	50k	¼ w	Sets gain
R11	10M (match R1)	¼ w	Sets input impedance and gain
R13	1.5M (match R3)	¼ w	Sets gain
R4 (LM3914 version)	1k	¼ w	Sets inner ring threshold
R4 (LM3915 version)	4.7k	¼ w	Sets inner ring threshold
R5	100	¼ w	Sets brightness of inner ring
R6	470	¼ w	Sets brightness of other rings
R7	10k	¼ w	Sets Q1 base current. Not critical
R19	4.7k	¼ w	Sets brightness of red LED
R15-R18	See text	¼ w	Not required.
Q1	2N3904	TO92	Any old NPN
U1	LM3914…5…6	18 DIP	See text
U2	LM358	8 DIP	
C1	500uF	≥ 10V	Filter Cap
C2	0.15uF	≥ 10V	High frequency decoupling as per DS
C3	47uF	≥ 10V	Filter Cap. Needs to be small.
D1, D2	1N4003		Any old rectifier diode
D3	1N5817		Schottky rectifier
J1	Sullins PPPC081LGBN-RC	Thru-hole	8 Position Header Connector, female, Through Hole, Right Angle, 0.100"
J2	Harwin M20-8771042	SMT	10 Position Header Connector, male, Surface Mount, 0.100" (2.54mm)
LED (Qty 174)	Rohm SML-D12P8WT86	0603	Green diffused surface-mount LED
LED	Rohm SML-D12D8WT86	0603	Orange LED. Emulates the lit filament. Red OK, too.

Assembly

There are 4 steps to the assembly:
-The LED board (takes patience)
-The driver board (easy)
-The LED diffuser (be creative!)
-Final assembly (make it as beautiful as you like)

There are 2 boards as shown in the schematic. The boards connect to each-other with an 8-pin connector. The LED driver board is straight-forward, it uses thru-hole technology. I recommend populating RV1 at the very end, maybe even after you test it; RV1 blocks access to several parts, which would make rework difficult.

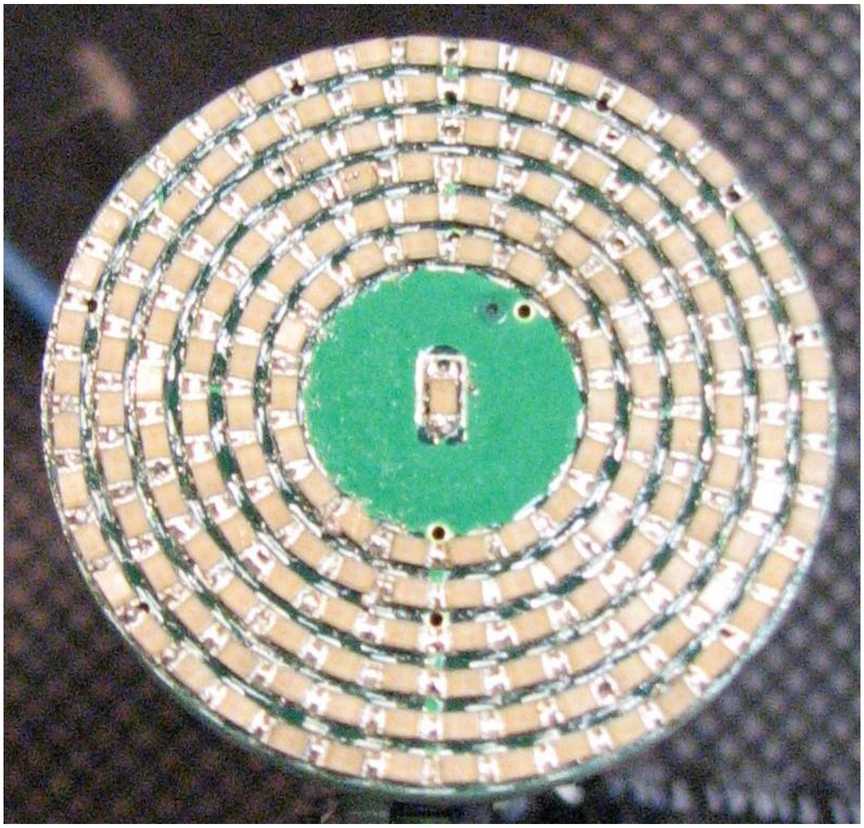
The LED board, however, uses surface-mount components and is quite dense. Assembling this takes a steady hand and patience but is not particularly difficult.

To assemble the LED board, lead-tin solder paste (not lead-free) is the best way to go. I know people who would succeed with wire solder, but solder paste is so much easier. Install the LEDs before the connectors on the back.

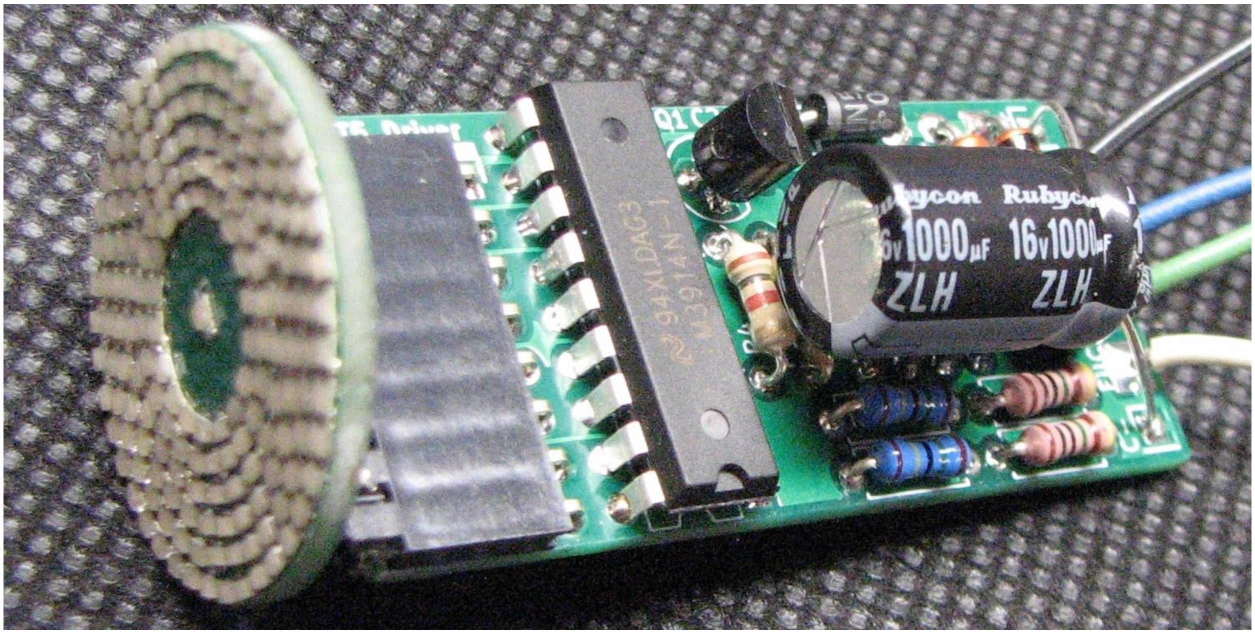
Please see the 6T5 board assembly instructions on http://www.rabjohn.ca/gord/ss6e5/ for detailed instructions and suggestions.

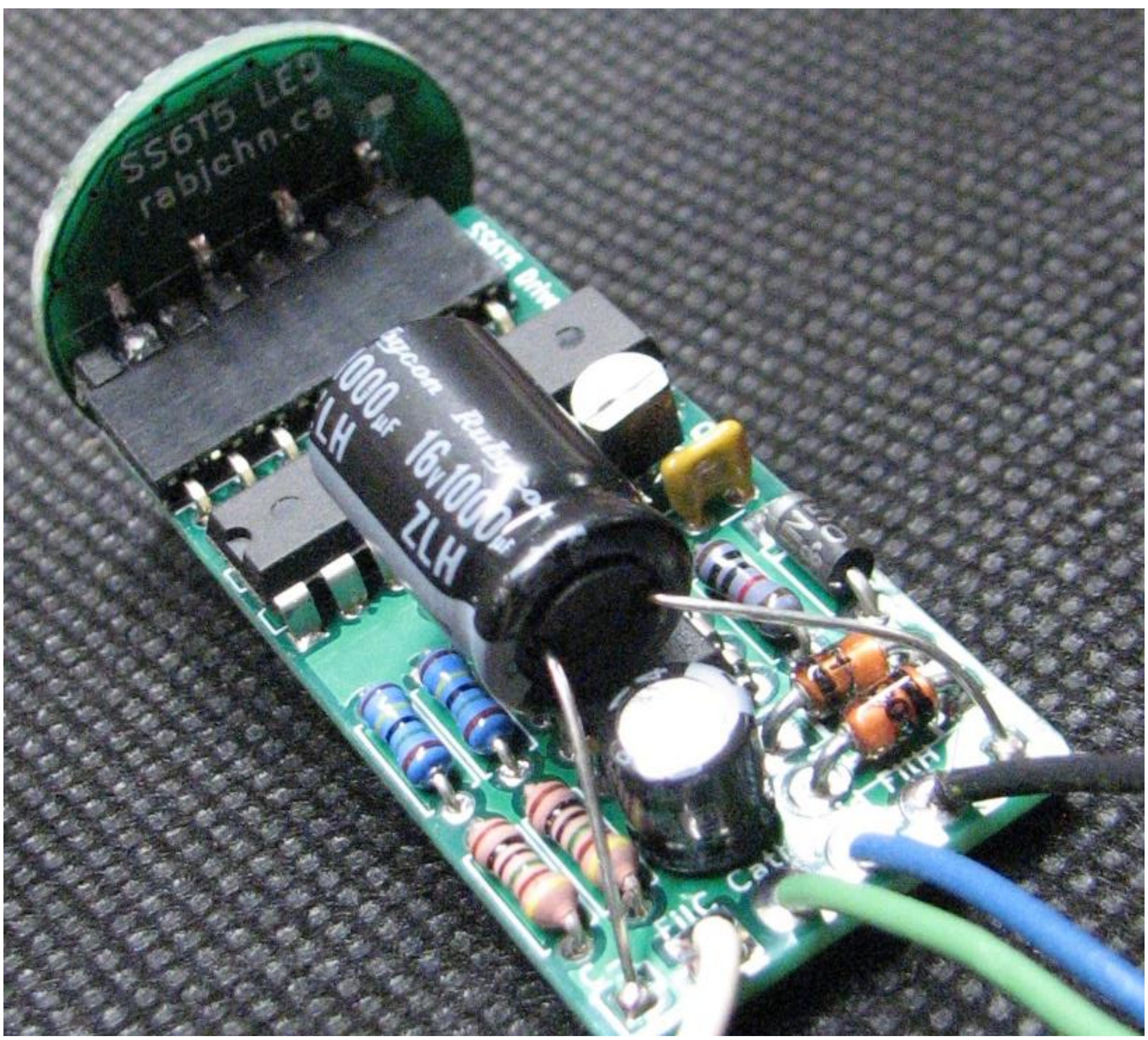
Once the board cools, test all the LEDs (each ring) by applying (for example) 9V to them thru a 470ohm resistor. If any rework is needed, now is the time to do it, as the board is much more difficult to handle after the connector is soldered to the back. A hand assembled board may not look very uniform, but that does not matter, the joint under the device is what is important.

The front of the LED board populated with 175 LEDs is shown below.



The two boards, assembled, connected with the 8-pin header connector are shown below. This board happens to use the LM3914 driver IC.

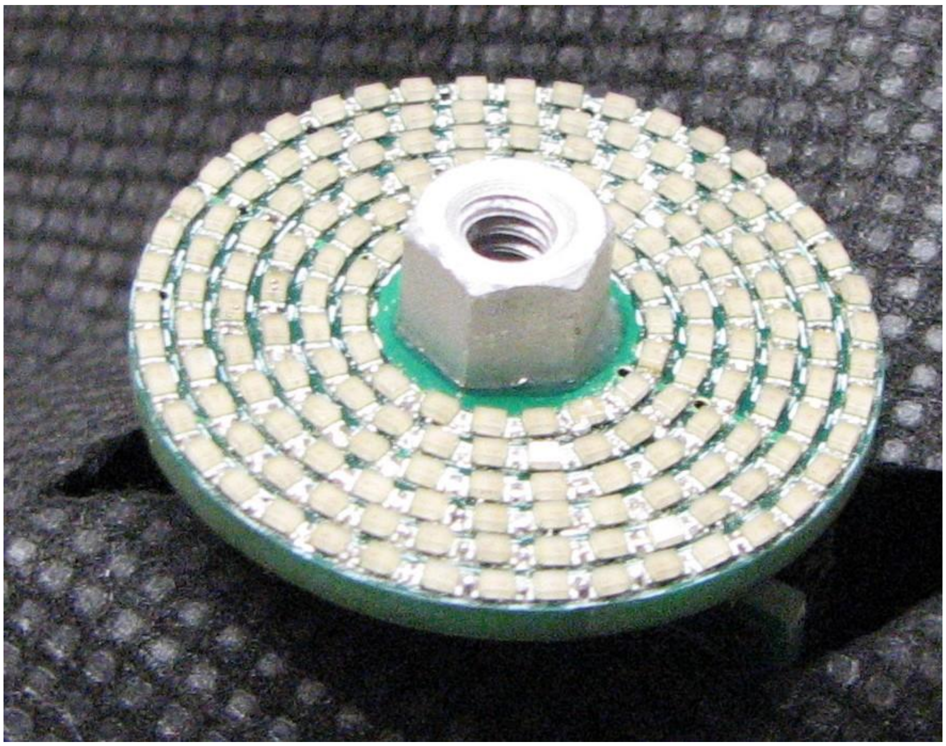

Rubycon
16v1000µF
ZLH


SS6T5 LED
rabjchn.ca
Rubycon
16v1000µF
ZLH

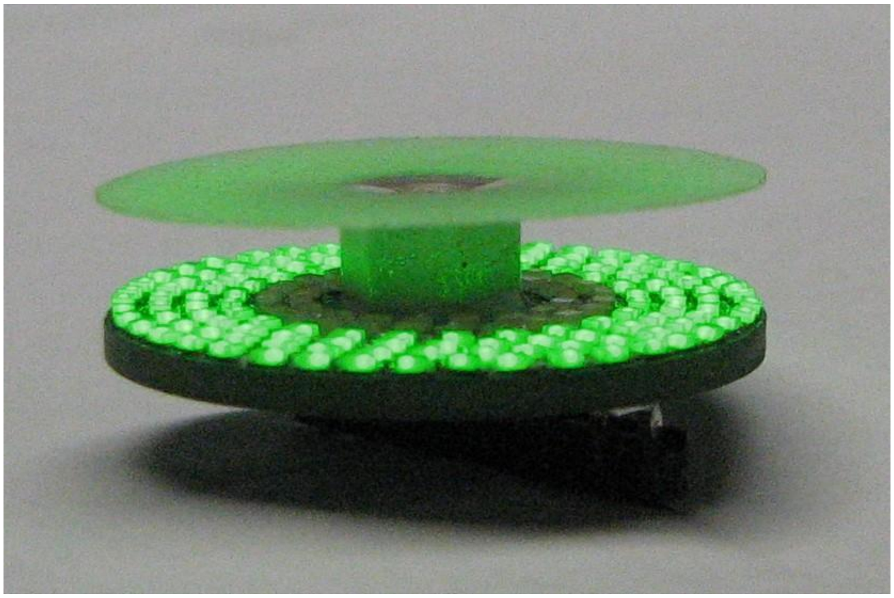
The project benefits from a light diffuser to smooth out the pixilation caused by the array of LEDs. I have not yet found a perfect solution. I find that a piece of clear plastic (cut into a 26mm circle, from a container that fruit comes in) roughened up with sandpaper does a fair job. For the 6T5, I find that aggressive radial scratches tend to smear the light circularly, and that's what you want. You also want *a little* smear radially, and I do this by lightly sanding in a circular direction on the other side of the plastic (I placed it on an arbor in a drill and sand a circular pattern into the plastic with 100 grit sandpaper). The distance between the diffuser and the LEDs is important, you will want to play with it as it depends on the roughness. The possibilities are endless: sandpaper grit, depth of sanding, plastic used, placement, colour of plastic… I even tried paraffin wax (described in the 6E5/6U5 write up). To mount the diffuser, I epoxied a short length of 6-32 aluminum spacer or quarter inch copper tubing (length determined experimentally) over the orange LED (the orange is seen through the spacer's hole). Then I epoxied the plastic diffuser onto the spacer.

The diffuser, scratched up.

The assembly can be mounted in a cardboard tube for protection. But better still, the whole assembly can be placed into the glass envelope of a dud eye tube. (please, not a 6T5, they are too rare, even dead) I cut the glass from an appropriate tube (6E5/6U5 of course, and you get the correct socket too, or a 6AX4 or tall 6SN7 (I seem to have lots of these). Pick one without getter marks on the end) close to the base with a hot nichrome wire. I wrap a wire scrounged from a rheostat around the circumference of the tube where I want it to break, then pass current through the wire until it glows red. This stresses the glass and causes it to snap amazingly cleanly. I have also tried to use a Dremel tool but results were very inconsistent. I clean out the 6-pin socket, place the electronics into the socket and slide the glass envelope over the electronics. The grid goes to pin 3 of the 6T5 base, cathode to pin 5, FilC to pin 6, and FilH to pin 1. (Pin 5 and 6 are usually tied together to ground at the socket) Pins 2 and 4 are not used. Heat-shrink tubing holds it all together, but note that the glass envelope is not as rugged as an intact tube, so be gentle when shrinking the heat-shrink tubing.



The aluminum spacer epoxied in the middle of the LED board



The diffuser mounted on the LED board

Conclusion

The eye replacement will be very reliable, it should last practically forever as long as it is not abused. You can confidently power it up 24-7 and it will last for years. All the components run cool and run well below their maximum ratings. The weakest components are probably the electrolytic capacitors, so use the highest quality that fit. And, maybe replace them every 30 years!

I have some bare boards available which I will sell for approximately $5 per set. The most expensive parts are the LEDs, which will cost a total of under $20 from Digi-key or Mouser (depending on quantity), and the connectors. The LM3915 is a few dollars from Maddison, and there are multiple sources for it on Amazon.

Solid-state 6T5 (left) next to a 6U5 (right).