Building the HVPS—High Voltage Power Supply

Introduction

Voltages higher than the LVPS provides—kilovolts—are needed in later experiments to get strong electric fields and to generate microwaves. The *high-voltage power supply* makes such experiments possible. You will have voltages from $100V$ to $1000V$ available to you, at a safe current of less than a milliampere.

The HVPS is built on the empty space of the LVPS board and is powered by it. Some experiments in this course will need both the HVPS and another device, an amplifier, which will be built on the board of a second LVPS. You and your partner will have the necessary pair of LVPS's between you; if you are working alone, you will eventually need two LVPS's.

Background

To get adjustable high voltage, we will convert the adjustable dc from the LVPS into adjustable ac at a frequency of about , by means of an LC oscillator. Then, a step-up transformer will be used to get high voltage ac, which can be turned into dc with a half-wave voltage-doubler rectifier. Here is the block diagram:
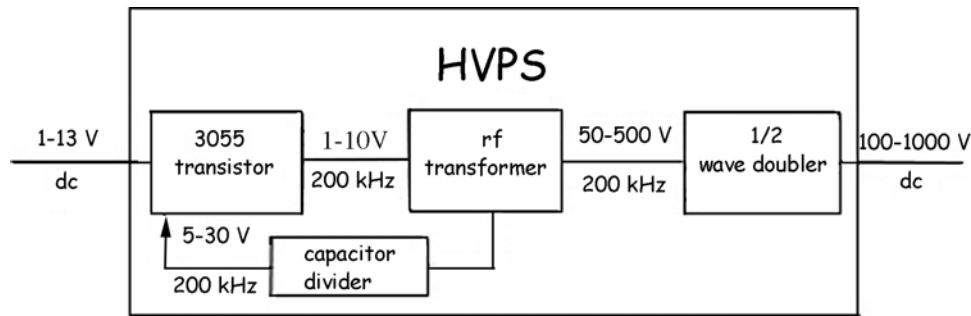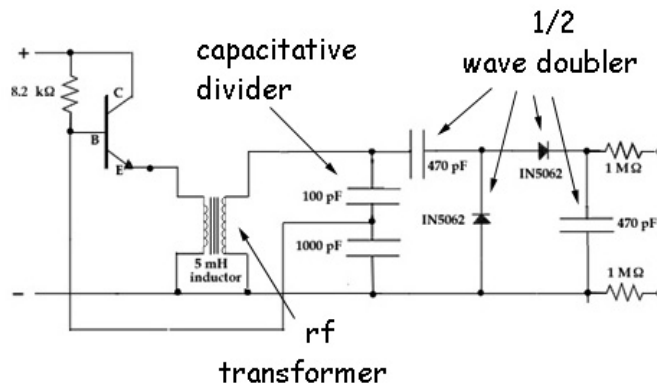

Figure 1: HVPS block diagram

Figure 2: HVPS circuit diagram

The oscillator is powered by the 2N3055 transistor. The main feature of a transistor is that a small current from base to emitter results in a large current from collector to emitter (larger by a factor of order 100).

Then the emitter current flows through an six turn primary winding on a transformer made by using the windings of a 5 millihenry inductor as the secondary, as shown below. The transformer is a device that converts an ac voltage across the primary coil winding into a different ac voltage across the secondary coil winding. This is accomplished by using two closely spaced coils of different number of turns, one is called the primary, and the other, the secondary. The primary coil has a number of turns denoted by N_P, and the secondary coil has N_s number of turns. Then the voltage across the primary, V_P, is related to the voltage across the secondary, V_S, according to

$$\frac{V_P}{N_P} = \frac{V_S}{N_S}.$$

The secondary has about 300 turns, so the secondary voltage is about 50 times the primary voltage.
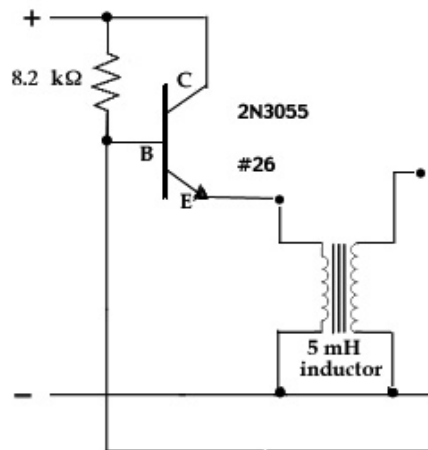

Figure 3: LC oscillator

The secondary winding of the transformer is part of a parallel LC circuit with a resonant frequency

$$f = \frac{1}{2\pi} \frac{1}{\sqrt{LC}}$$

The inductance is $5\,mH$ and the equivalent capacitance is $91\,pF$, so the resonant frequency is

$$f = \frac{1}{2\pi} \frac{1}{\sqrt{LC}} = \frac{1}{2\pi} \frac{1}{\sqrt{(5\times10^{-3}H)(9.1\times10^{-11}F)}} = 2.4\times10^{5}\,Hz.$$
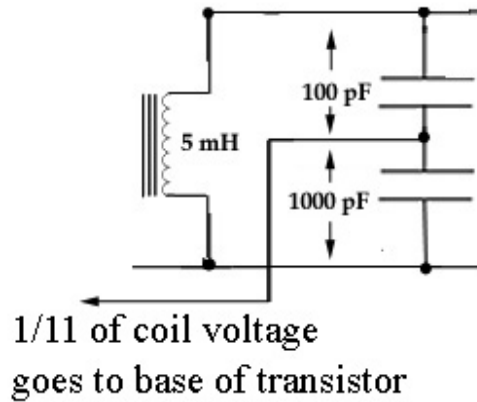
Figure 4: capacitor voltage divider

The two capacitors shown above make a voltage divider, such that 1/11 of the total voltage across the coil appears across the $1000\,pF$ (.001 microfarad) capacitor. This voltage is fed back to the base of the 2N3055. If the transformer windings are properly connected, an increasing current through the transistor will produce an emf in the secondary of the resonant circuit which, when part of it is fed back to the base of the transistor, has the correct polarity to cause yet more current to flow in the 2N3055. This is <u>positive</u> feedback, rather than the negative feedback utilized in the LVPS regulator.

The positive feedback tries to make the transistor current go to infinity, which, of course, is not possible. The voltage across the primary coil does increase to almost the positive power supply voltage, at which point it must stop increasing, and the voltage induced in the transformer secondary goes through zero and changes sign. Then the positive feedback makes the current through the transistor plunge in the opposite direction to zero. Thus, an alternating voltage almost equal to the LVPS voltage is produced at the primary, at the resonant frequency of the LC circuit of which the transformer is a part. This ac is stepped up to $1000\,V$ or more, peak-to-peak (maximum to minimum), by the transformer action.

The high voltage ac is rectified so as to produce an output dc voltage approximately equal to its peak-to-peak voltage, by using two high voltage diodes in a voltage doubler circuit:
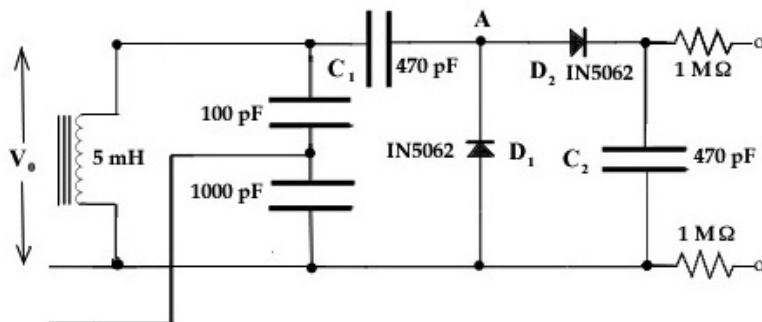

Figure 5: voltage doubler

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Here is how is how the voltage doubler works: if the sine wave voltage across the resonant circuit has a peak-to-peak value $2V_0$, then an alternating voltage of amplitude V_0 appears across the circuit composed of C_1 and D_1. Thus C_1 and D_1 act as a half-wave rectifier, which charges C_1 to V_0. As a result the sine wave voltage at point A causes the voltage at A to oscillate from 0 to $2V_0$. The second diode, acting as a half-wave rectifier, will then charge to a voltage approximately equal to $2V_0$. Hence the name 'doubler'.

Following the voltage doubler, there is a filter capacitor, C_2, and then each output lead is in series with a one megohm resistor. These are to isolate the supply from the long leads you may connect to it, and to reduce the intensity of the shock you can get by putting yourself across the output. The supply is safe, because the stored charge in the small filter capacitance is too small to be dangerous, and the steady output the supply can deliver is also too small to hurt you. However, if you touch it lightly you can feel the burn of the resulting spark.

HVPS Parts

- LVPS, already built
- resistor, $8.2\,k\Omega$ $1/2W$
- 2N3055T transistor, TO-220 type
- TO-220 white transistor socket
- clip on heat sink
- 2 - 1N5062 diodes, (max $800\,V$ peak inverse voltage, $750\,mA$ max forward current)
- ferrite core inductor ($5\,mH$), 3 segment
- $1\,ft$ - #26 insulated solid wire
- $1\,ft$ - #22 bare solid wire
- $1\,ft$ - #22 red insulated solid wire
- 2 - $1\,M\Omega$ resistors, $1/2W$
  ceramic disc capacitors:
- $100\,pF$, $1\,kV$, [$1\,pF = 1$ picofarad $= 10^{-12}\,F$.]
- $1000\,pF$, $500\,V$
- 2 - $470\,pF$, $1\,kV$
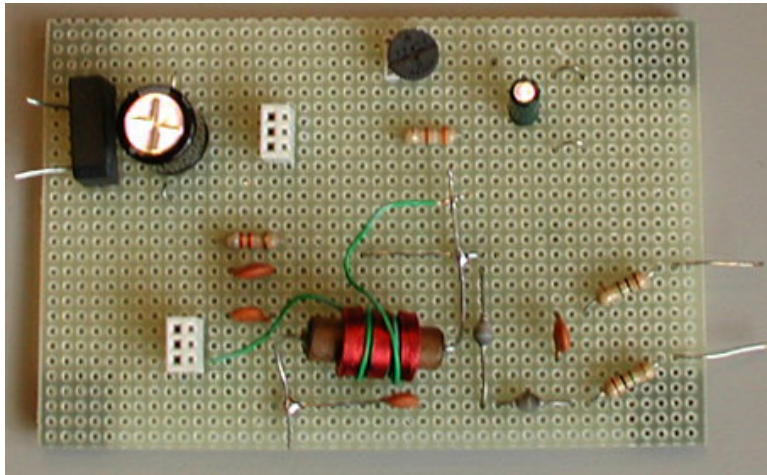
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Recognizing the Parts

Figure 6: Top view of HVPS

Transistor: The transistor package looks like the regulator of the LVPS, and since it also produces heat that must be led away, you should mount a heat sink on it. The transistor is an amplifier of current, and in conjunction with the transformer produces ac at a frequency of about $240\, kHz$.
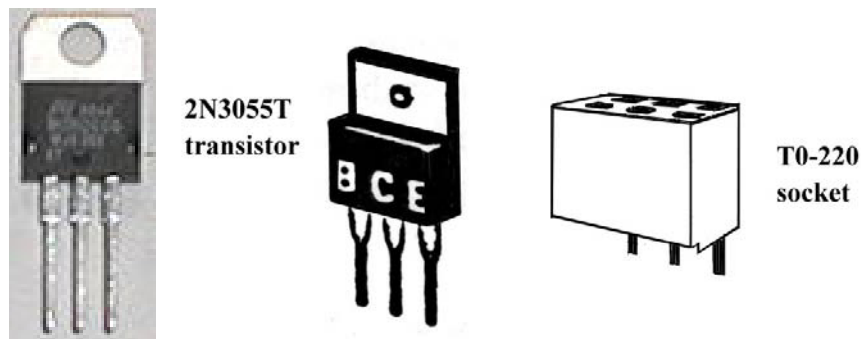

2N3055T transistor

B C E

T0-220 socket

Figure 7: 2N3055T Transistor

Inductor: Your inductor consists of three connected coils wound on a ferrite core (a magnetic sintered powder); the coils are about 45 feet in length, something under 500 turns of thin insulated wire. You will change the inductor into a "step-up" transformer converting low alternating voltage at relatively high current to high voltage at low current. (Your wall transformer, converting $120\,V$ ac to $12\,V$ ac, is a "step-down" transformer.)

Figure 8: Inductor

Capacitors: The differences in shape and rating between these capacitors and the ones in the LVPS strongly suggest that they are made of different materials. That is true: also, this type of capacitor is not polarized as to current direction: it doesn't matter which way around you place it. The physical size of capacitors is determined by their voltage rating capacitance and the materials used in their construction.
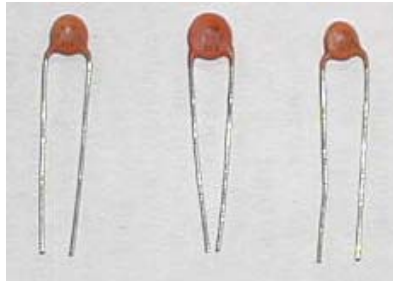

Figure 9: Ceramic Disk Capacitors

To tell which capacitor is which use the decoding system for disc capacitors. Numbers on the discs that don't end with a zero in the units place, for example numbers like 102, have a code meaning: the "2" means "put 2 zeros here". So, 102 = 1000, 101 = 100, and 471 = 470. In addition, numbers that are not decimal fractions should be read as picofarads (10^{-12} F), whereas decimal fractions, like .001 in the figure, mean microfarads (10^{-6} F). Thus .001 = .001 x 10^{-6} farads or 1000 picofarads. The capital letters following these numbers indicate tolerances. Some of the other coding tells the factory name, the country of origin or the manufacturer.

Diodes: The diodes pass current from the + anode, to the - cathode, the black end in the case of the 1N5062. (Placing the diode in the wrong direction can happen; so note carefully the black end).
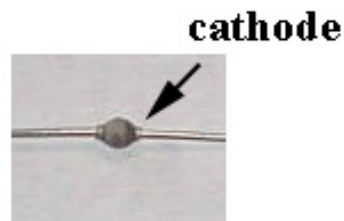

Figure 10: 1N5062 Diode

Construction Notes

Making the Transformer

To make the inductor into a transformer, you will need to wind six turns of the insulated #26 solid wire onto the core of the inductor to act as the primary coil. First cut the wire to $10 - 1/2$ inches and strip off the insulation from the two ends to expose the bare wire.

Notice that the windings already on the inductor are in three parts; wind three of your turns in each of the two gaps between. Wind in the same direction as the winding already there. Here's how; find the starting end of the inductor winding (see Figure 11), where the wire enters the coil at the inner core. Hold the inductor by that end and wind in a counterclockwise direction, three turns in the first gap and three in the second.

The wire already on the inductor is thin, fragile and exposed. Breaking these wires is a common source of trouble with HVPS construction. Don't wrap your turns so tightly as to break the wires already there.
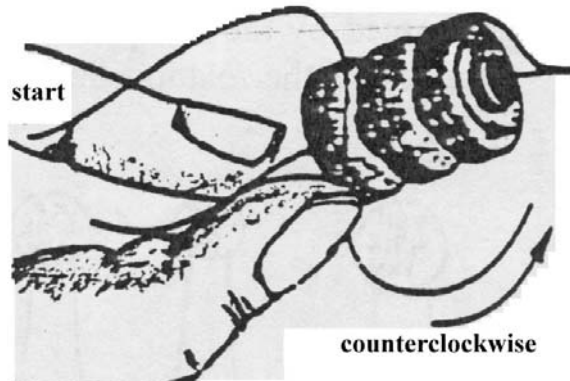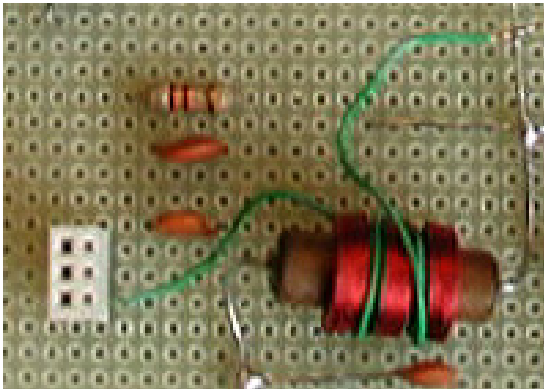

Figure 11: Winding the Transformer

You have now made a transformer. Check for electrical continuity in both coils to make sure no wire got broken. If it is unbroken, you will see about 10-50 ohms (depending on the make of the inductor) across the inductor's coil. The 6-turns you added, which become the "primary" of the transformer, have a small resistance (too small to measure). There should be no electrical connection between the two coils. You should certainly check for this if you run into any troubles.

Perfboard Diagram for the Top of the HVPS

The figure below shows the placement of HVPS parts on the top of the perfboard. Start with one of the boards on which you have already built a low-voltage power supply (LVPS). Follow the parts layout shown in the pictures and in the templates shown below.
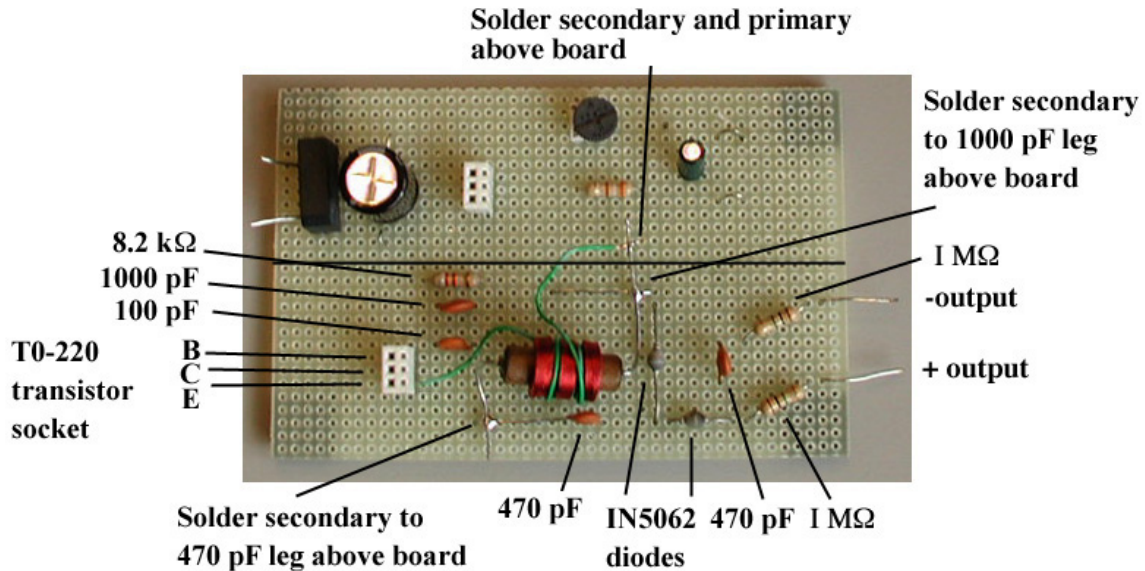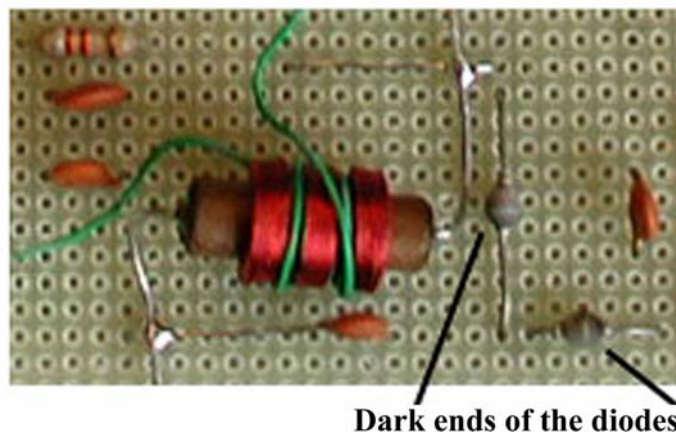
Figure 12: Parts lay out for the HVPS

Figure 13: Diode and inductor wiring

A common mistake is to wire the diodes the wrong way. In Figure 13 the wiring for the diodes is shown. Notice that one end of the diode is dark. Make sure that these ends point in the correct direction.

Another common mistake is to wrap the primary in the wrong direction with respect to the secondary wrappings of the ferrite core inductor. If the HVPS does not work correctly, you may want to rewrap the primary wire. You will need to unsolder the primary. Another way to correct this problem is to unsolder the wires that emerge from either end of the ferrite core inductor. Then flip the inductor and re-solder the ends so that it will now connect the other way. For this reason the ends of the secondary are soldered above the board. Once you are sure you have the wires the correct way you may want to solder the ends from the inductor underneath the board for more stability.

One leg of the 1000 *pF* capacitor first passes underneath the board then returns to the top side of the board where it soldered to the wire emerging from the end of the inductor. The other end of the inductor is soldered to the 470 *pF* capacitor.

Perfboard Diagram for the Bottom of the HVPS

The diagram below shows the wiring of HVPS parts on the bottom of the perfboard. The solid lines point to where the indicated components are soldered or go through the board. The positive and negative LVPS lines are marked.
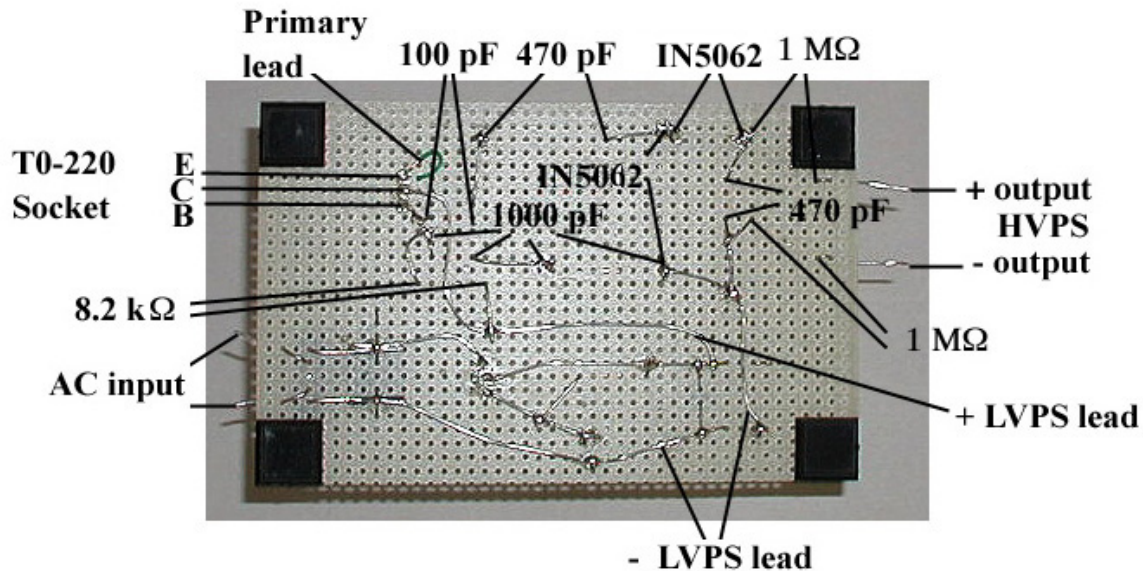

Figure 14: Bottom View

When you assemble your HVPS make sure that connections are convenient and that shorts are not likely to occur. Be sure to get the diodes the right way around, and remember to connect to the outputs of the LVPS. The HVPS ends up with two 1-megohm resistors to limit the current to completely safe values, less than 1 mA (milliampere).

Testing the HVPS

Here are some procedures to follow for your circuit tests.

Set your multimeter to the l K range and connect to the output leads. (**You must use the appropriate input to the meter, labeled +DC1000 V.**)
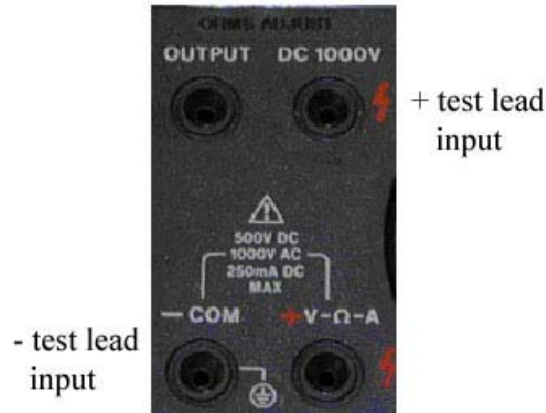
Figure 15: Test lead inputs to multimeter for 1 K range

Insert the 2N3055T transistor into the clip on heat sink. Insert the transistor into the transistor socket. The writing on the transistor should face the opposite direction from the inductor. Insert your LM317 regulator into the LVPS and also make sure it is facing the correct direction (towards the rectifier). Plug in the wall transformer. You should be able to adjust the HVPS output voltage to anywhere from $100V$ to over $1000V$ by turning the pot of the LVPS. You can expect several components to get hot after a while. The transistor will probably be the most noticeable one.

Because of the low power involved (about 1 watt), it is safe in this case to short the output with a clip lead. You'll probably see small sparks when you do so. You can also put your fingers across the output (not usually a good practice!) because the current is limited to less than $1mA$. If you do, you may feel a slight tingling sensation if you grasp firmly, or the burn of the spark if you hold it loosely.

Troubles?

If you get no output voltage:

1) Did you plug in your transistors?

2) Do you have a low-voltage input? Connect the multimeter on the 25V range to the LVPS output terminals; set the LVPS for $10V$ or so.

3) Feel the 3055 transistor. It should warm up after a minute. (A film of water placed on it would evaporate in a few seconds -- but wouldn't sizzle!)

    a) If the transistor's not hot, measure the voltage between each of its terminals and the minus terminal of the LVPS. The base could read $0.5V$ positive and the emitter will read zero if the circuit is not oscillating; if it is oscillating you may get hard-to-interpret readings even with only one meter lead connected. The collector reading should match the output of the LVPS. Other readings might suggest wrong wiring or a bad transistor.

b) If the 3055 is hot but the circuit is not oscillating, reverse the primary leads of the transformer you wound. This makes the feedback positive as needed for oscillation**.**

4) If you still see no high-voltage output, check the capacitative dividers for correct placement. (The $100 \, pF$ capacitor may be physically larger than the $1000 \, pF$.)   Could they be defective? Check the capacitors themselves: on the ohmmeter they should show infinite resistance.

5) If the capacitors are OK, see if there is $240 \, kHz$ on the secondary of the transformer. Apply maximum voltage from the LVPS to the HVPS and touch the "hot" top-side of the transformer secondary with a regular wooden or plastic "lead" pencil. You should see a small spark. If not, reverse the transformer leads one more time and try again.

Disconnect the first $470 \, pF$ capacitor. Now look again for $240 \, kHz$. If you don't see it, reverse the transformer leads one last time! If you still get no ac reading, the problem is too subtle for these techniques. (See an expert in the lab help sessions.)

6) If you do have ac, check the $470 \, pF$ for shorts. Also use the ohmmeter to check the diodes.

We tested several diodes and got these readings on the various ohmmeter ranges with the red lead (+) connected to the cathode: Rx1: 20Ω , Rx10: 180Ω, Rx1k: $9 \, k\Omega$. With the meter leads reversed we got ∞ on all ranges.

Now it has to work, unless it is a really tricky problem. Rebuilding with greater care to follow the drawing of the perfboard often clears matters up. Sometimes the only recourse is a persevering expert.

Try this

Bring a transistor radio close to your HVPS. Turn the radio on and place it inches from the coil. On almost any AM dial setting the radio will reproduce a strong buzz that will disappear if you unplug the power supply, or even turn the pot down. If you make a spark at the output, you should hear it broadcast sharply.

Testing the HVPS
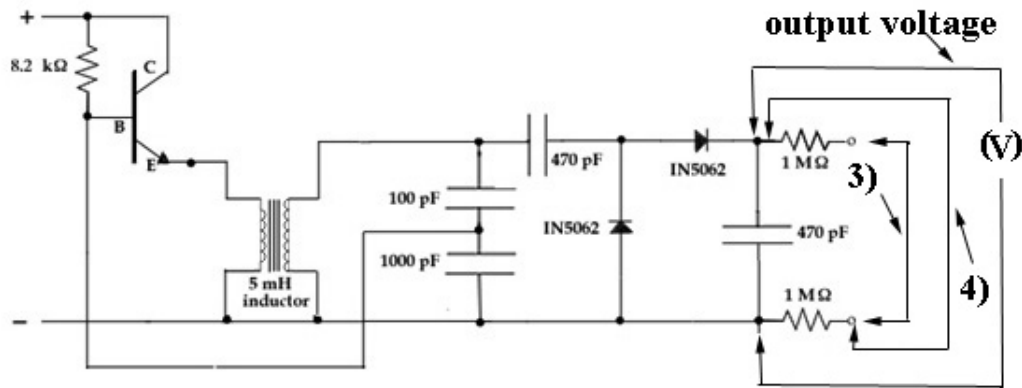
Measurements:

We will measure the voltage output of the HVPS with no-load and with the $1\,M\Omega$ resistors as loads. Adjust the pot on your LVPS so that the output voltage of the LVPS is between $1.5V$ and $12\,V$. Use one of your multimeters to monitor the output voltage of the LVPS throughout the following measurements. Set the other multimeter to the l K range and connect the leads not at the output of the HVPS but just before the $1\,M\Omega$ resistors. **(Use the appropriate input to the meter, labeled +DC1000 V.)**

1) Determine the range of output voltages for the HVPS.

Now make five measurements of your HVPS between $100V$ to $1000V$ with three loads, MMM only, the MMM and the two $1\,M\Omega$ resistors, and the MMM and one $1M\Omega$ resistor . For each setting of the pot:

2) For each setting of the pot, measure the output voltage of the HVPS with your MMM (note that the MMM is the only load).

3) Use a clip lead to connect the ends of the two $1\,M\Omega$ resistors together so as to put them in series across the output of the HVPS. For each setting of the pot, measure the new output load voltage of the HVPS.

4) Use a clip lead to put only one of the $1\,M\Omega$ resistors as a load across the output of the HVPS. For each setting of the pot, measure the new output voltage of the HVPS.

Record your results in the accompanying data table.

Data Table for HVPS Problem

V_{LVPS}	V_{HVPS} (no load) [V]	V_{HVPS} (2 MΩ load) [V]	V_{HVPS} (1 MΩ load) [V]	Current HVPS (2 MΩ load) [I]	Current HVPS (1 MΩ load) [I]

5) The multi-meter, on the 1K scale, acts like a resistor with resistance of $20,000\Omega/VDC$. This means that to find the resistance you multiple $20,000\Omega/VDC$ by the full scale voltage reading which is $1000V$. What is the resistance R_{MMM} of your multi-meter on the 1K scale?

6) Draw circuit diagrams of your HVPS, the multi-meter and the loads. Is your multi-meter in parallel or in series with the load?

7) Is the multi-meter is in parallel or in series with the load equivalent resistance R_{eq}? What is the equivalent resistance for loads of 2 MΩ and 1 MΩ loads?

8) Calculate the current output of your HVPS is given by

$$I = \frac{V_{output}}{R_{eq}}.$$

9) Calculate the current output of your HVPS for each setting of the LVPS pot for both the 2 MΩ load and 1 MΩ load. Record your results in the last two columns of the data table.