Tesla Coil

A guide written by Henry Love and Julian Thomassie

1 Tesla Coil

What is a Tesla coil?

A Tesla coil is a large, high voltage, air-core transformer. The total voltage gain is produced by two coupled inductor-capacitor (LC) circuits tuned to the same resonant frequency that drive each other in synchronized cycles. Tesla coils act as an exciting introduction to the world of high voltage alternating current (AC) systems. They demonstrate wireless power transfer and produce visually stunning electrical arcs. Unlike high voltage direct current (DC) systems such as a Van de Graaff generator, the arcs produced by a Tesla coil appear as continuous persisting streams rather than single sparks.

How does a Tesla coil work?

Tesla coils work by initially converting the standard 120V of a household wall outlet to a few thousand volts using a high voltage transformer. The second, much larger, voltage gain is produced by the resonant LC circuits, which exchange energy via a pair of coils (primary and secondary). The primary coil is a large copper tube wound into a flat spiral at the base of the secondary coil. The secondary coil is a long strand of 22-24 gauge copper magnet wire wound in a tight helix around a hollow plastic tube. The primary and secondary coils have no direct electrical connection; all of the energy is exchanged via electromagnetic induction (Faraday's Law).

What produces the first voltage gain?

In this particular Tesla coil, a neon sign transformer (NST) provides the first voltage gain. This transformer charges a bank of capacitors, that when full, discharge across a spark gap allowing current to flow into the primary coil. It is essential that the NST does not have a ground fault interrupt circuit because this safety mechanism would cause the transformer to shut down upon the firing of the spark gap.

What produces the second voltage gain?

The second voltage gain is produced by a series of steps. The main spark gap fires many times per second within the radio frequency (RF) range of 3 kHz to 300 GHz. This causes the primary circuit to oscillate. The oscillating current in the primary coil generates an electromagnetic pulse. This pulse travels up the secondary coil and induces a voltage in the wire, causing an electric charge to build on the topload; the topload is usually a sphere or toroid made of aluminum. As the energy of the secondary coil builds, the amplitude of the toroid's voltage rapidly increases and the air around the toroid begins to experience dielectric breakdown. Dielectric breakdown is the formation of electrically conducting regions in an insulating material exposed to a strong electric field. This process causes the formation of a corona discharge, which is a discharge caused by the ionization of a substance surrounding a conductor. In other words, the topload discharges its excess charge into the air, producing light, sound, and heat. The discharge can be directed off the toroid by introducing a sharp protrusion such as a nail on the surface of the toroid, causing the charge to concentrate at the point of the nail and flow off in the the direction of the nail. The primary and secondary LC circuits oscillate at the same resonant frequency in a synergistic relationship. The resonance allows the voltage on the topload to build to much higher level than it would in a typical transformer having the same ratio of turns between the primary and secondary coils. This entire process comprises the secondary voltage gain.

2 Materials

Here are the recommended materials to run a Tesla coil:

1) Grounding screen (for indoor operation)
2) Tesla coil base, including built-in ground rod
3) Secondary coil
4) Topload
5) Control box
6) 4 extension cords (Minimum of 2 required)
7) 2 IEC power cables
8) 2 plug wall outlet

3 Setup

This guide will bring you through setup in this order:

1) Grounding
   a) Rod ground (outdoors)
   b) Counterpoise ground using a screen (indoors)
2) Plugging in/connecting all wires
3) Setting the spark gaps
   a) Terry filter spark gap
   b) Main spark gap
   c) MMC spark gap
4) Installing secondary coil and toroid
5) Tuning the Tesla coil

3.1 Grounding

While running the Tesla coil, it is imperative that proper grounding is in place. Grounding techniques differ depending on whether the coil is being run outdoors or indoors, but there are always two grounds. Whether outdoors or indoors, parts of the circuit are connected to earth ground via a wall outlet. There is a separate ground for RF; this will be referred to as RF ground. Two grounds are needed because injecting radio frequency into the wall outlet can interfere with other electronic devices plugged into the wall.

3.1.1 Rod ground (outdoors)

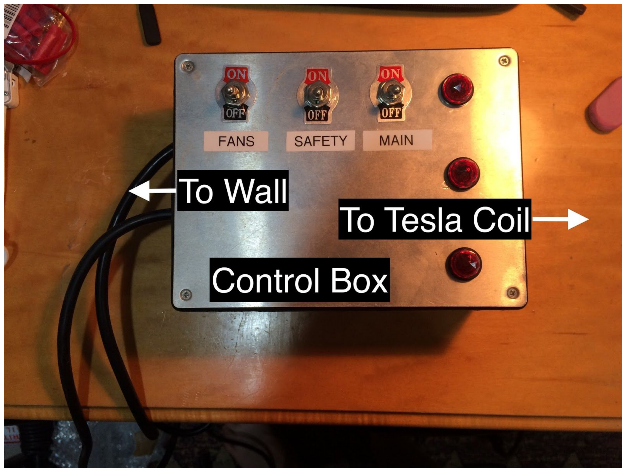
To operate the Tesla coil outdoors, the large copper grounding rod provided with the coil is the safest method for grounding, but is only viable in locations with reasonably deep soil. The rod should be thrust as deep into the ground as possible, and connected to the Tesla coil RF ground using the attached high voltage wire. For good measure, you may pour water around the rod to ensure a good connection to ground -- this should be done if the soil is dry. This method provides a direct connection between the RF ground and the earth, and is thus a true ground. The Tesla coil may sustain damage if an arc strikes the ground rod directly. To mitigate this risk, place the ground rod outside the approximate range of the arcs (about 2.5 meters), and orient the breakout point away from the ground rod. While operating, take caution not to stand close to the ground rod or the coil itself.

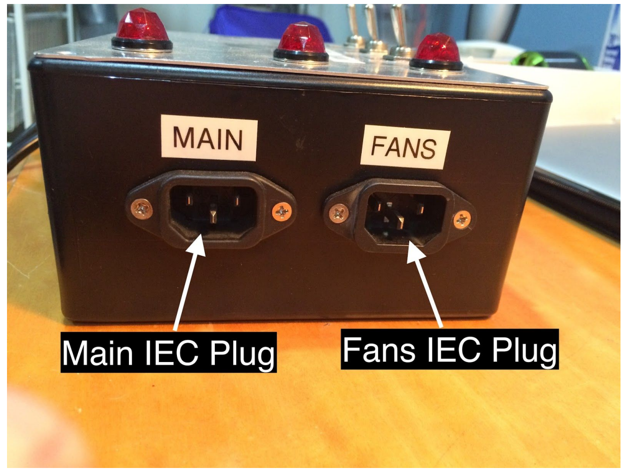
3.1.2 Counterpoise ground using a screen (indoors)

To operate the Tesla coil indoors, one may use a counterpoise ground. This may consist of a sheet of conductive screen or chicken wire positioned beneath the Tesla coil. The radius of the screen should be approximately the height of the secondary coil + topload. Place the metal screen flat on the ground and tape or weight it down if necessary. Place the Tesla coil on the center of the metal screen. Tape the copper ground rod onto the screen horizontally, such that the contact area between the rod and screen is maximized. **NOTE: Tesla coil arcs produce ozone due to the dielectric breakdown of air, therefore, consider limiting the duration of use indoors, especially in poorly ventilated areas.**

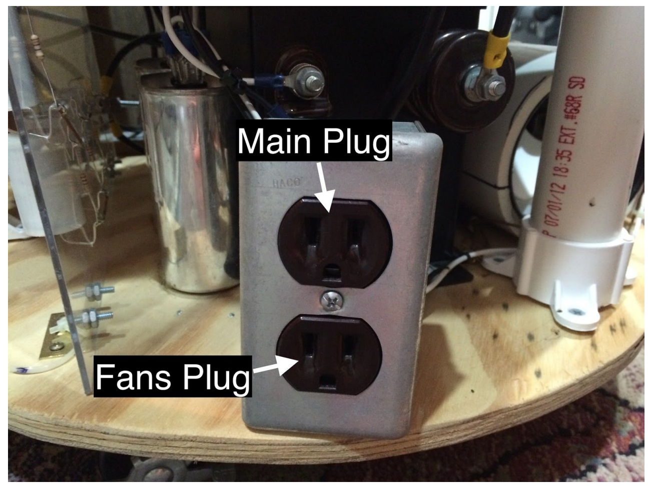
3.2 Plugging in/connecting all wires

After the Tesla coil is properly grounded, you may lock the wheels on the base of the coil to prevent movement of the base. Next, make sure all the switches of the control box are positioned in the “OFF” position. Make sure the secondary coil and topload of the Tesla coil are removed. Connect the control box to the Tesla coil using the two IEC power cords and two more extension cords. Finally, plug the two control box cables into the wall (you may need extension cords for this -- use sturdy cables *with grounds*). **NOTE: the output plugs on the control box that go to the Tesla coil are male. This is a design flaw -- touching the prongs while the control box is plugged into the wall may cause electrocution if the switches are on. NEVER TURN ON THE SWITCHES OF THE CONTROL BOX IF IT IS PLUGGED INTO THE WALL, BUT NOT SIMULTANEOUSLY PLUGGED INTO THE COIL.**



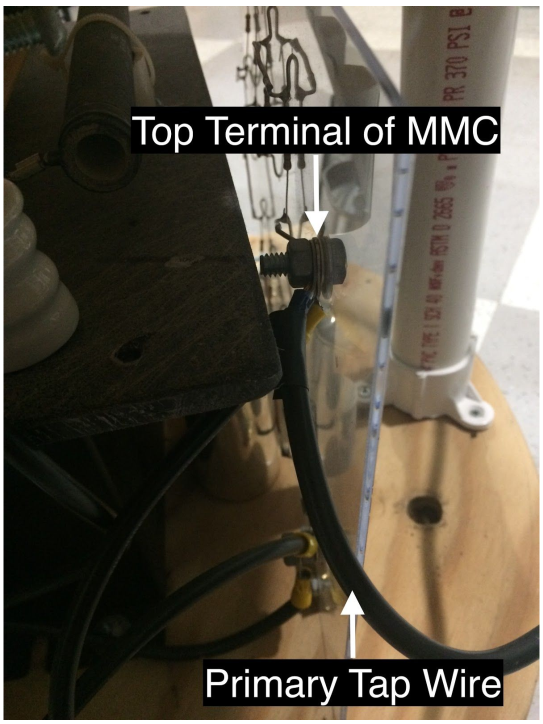


Once everything is plugged in, ensure that the fans plug is indeed connected to the fans jack on the control box and that the main plug is connected the jack on the control box labeled “MAIN”. **NOTE: Reversing these plugs can result in damage to the Tesla coil. Never run the coil without the fans on.**



3.3 Setting the spark gaps

This is the most time consuming process of the setup. NEVER AT ANY POINT should the switches be turned on while making any adjustments. To check the spark gap distance, back away from the device, and then turn on the switches one by one, starting with “FANS”, then “SAFETY”, then “MAIN”. Before continuing adjustments, turn ALL of the switches off again. IF THE FANS DO NOT TURN ON WHEN THE FIRST SWITCH IS POSITIONED TO THE ON STATE, IMMEDIATELY SHUT OFF THE DEVICE and go back to section 3.2 to check the wiring.



Disconnect the multiple mini capacitor (MMC) bank from the rest of the circuit. This can be done by finding the primary tap clip, and tracing it back to where it connects to the MMC. Unscrew the bolt, and remove this wire. Once this is completed, separate the electrodes in the main spark gap to create the largest possible gap; you can do this without a screwdriver by swiveling them. **NOTE: It is unsafe to be around the Tesla coil while the main spark gap is sparking. It shouldn’t spark with the MMC disconnected, but this is an important safety measure to keep in mind.**

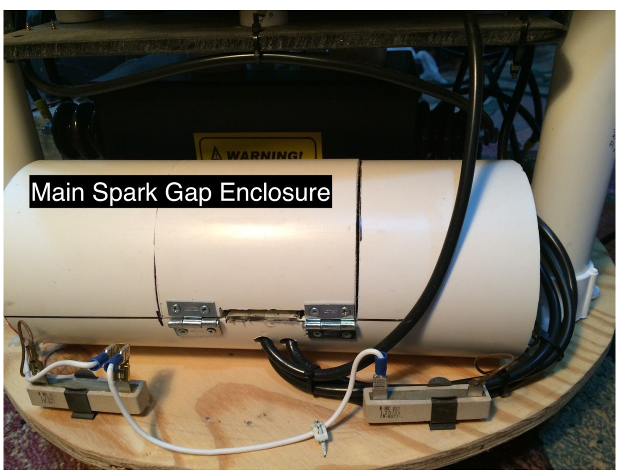
There are a two different types of spark gaps in the circuit: safety/protection and main. There are two safety/protection spark gaps and one main spark gap. Safety/protection spark gaps are characterized by brass balls and are wired across the MMC and Terry filter. The main, or primary, spark gap is enclosed in a PVC pipe, consists of two tungsten electrodes, and is essential to the operation of the Tesla coil.

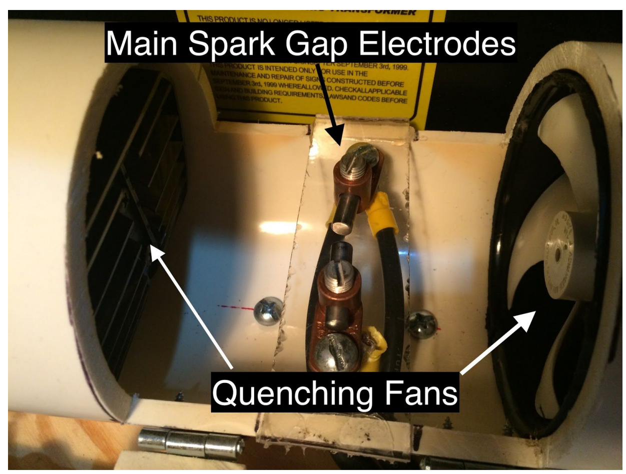
When setting the spark gaps, keep in mind that **EVEN THOUGH THE TESLA COIL IS OFF, THE CAPACITORS MAY STILL BE CHARGED. Always work with one hand in the pocket to avoid passing current through your heart!**

3.3.1 Terry filter spark gap

The Terry filter spark gap is a safety/protection spark gap that protects the NST from high voltage transients. This spark gap consists of three brass balls, with the center ball being connected to RF ground. To set this spark gap, make a small gap (~0.5 cm) between each ball, BUT ENSURE NO BALLS ARE TOUCHING! NOTE: The distance between the balls may be coarsely adjusted using the bolts and nuts that position the balls, or more finely adjusted by using the threads in the brass balls. The fine adjust is typically the only adjustment needed. Apply power to the Tesla coil by turning on all three switches on the control box (following the order stated above) and the gap should spark. Incrementally increase the distance between the balls until the sparking stops for both balls. At this point the gap is set.

3.3.2 Main spark gap





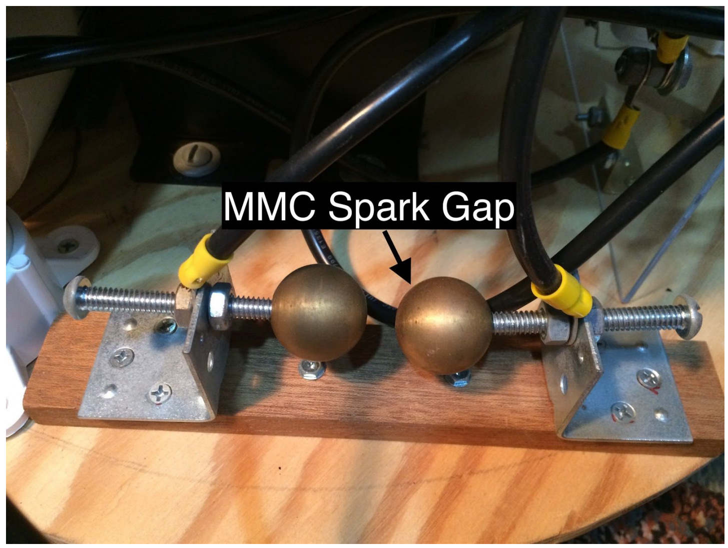
NOTE: THE SPARK FROM THIS SPARK GAP EMITS UV AND HIGH INTENSITY LIGHT AND THUS SHOULD NOT BE LOOKED AT DIRECTLY. ALWAYS OPERATE WITH THE ENCLOSURE LID CLOSED.

To set this spark gap, position the tungsten electrodes as far back in the copper lugs as possible and face the electrodes directly at each other; this is a tried-and-tested gap distance for this particular Tesla coil. A larger gap can be made by angling the tungsten electrodes away from each other, using the pan head screws that attach the copper lugs to the acrylic sheet as pivots. Making this gap wider will allow the MMC to charge to a higher voltage, increasing overall spark length, but a gap too big will prevent this spark gap from firing, and will probably trip the protection spark gaps. Therefore, it is advisable to set this gap to the tried-and-tested configuration described above.

When the gap is set to the proper position, reattach the primary tap clip, connecting the clip end to the primary coil and the other end to the top terminal of the MMC from where it was removed when setting the Terry filter spark gap.

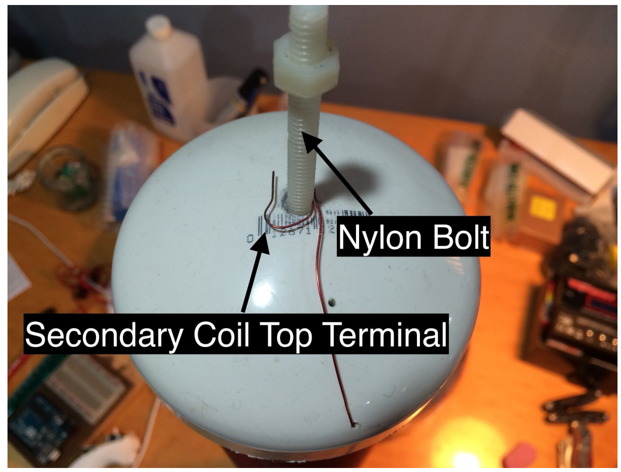
3.3.3 MMC spark gap

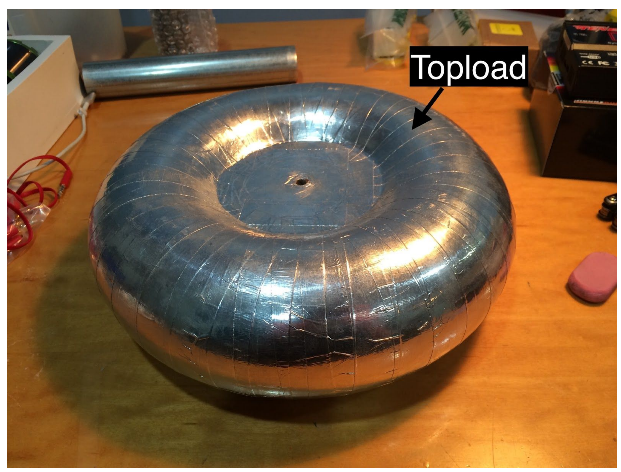
The MMC spark gap is another safety/protective spark gap and protects the MMC from an overvoltage event. The gap shown in the picture should be sufficient. This gap will be slightly larger than the main spark gap when the coil is in operation to ensure that if the main spark gap fails, this safety/protection gap fires and protects the MMC from accumulating too much charge. Monitor this gap while the coil is operating to ensure that it is not consistently firing. If it is, increase the distance between the balls slightly.



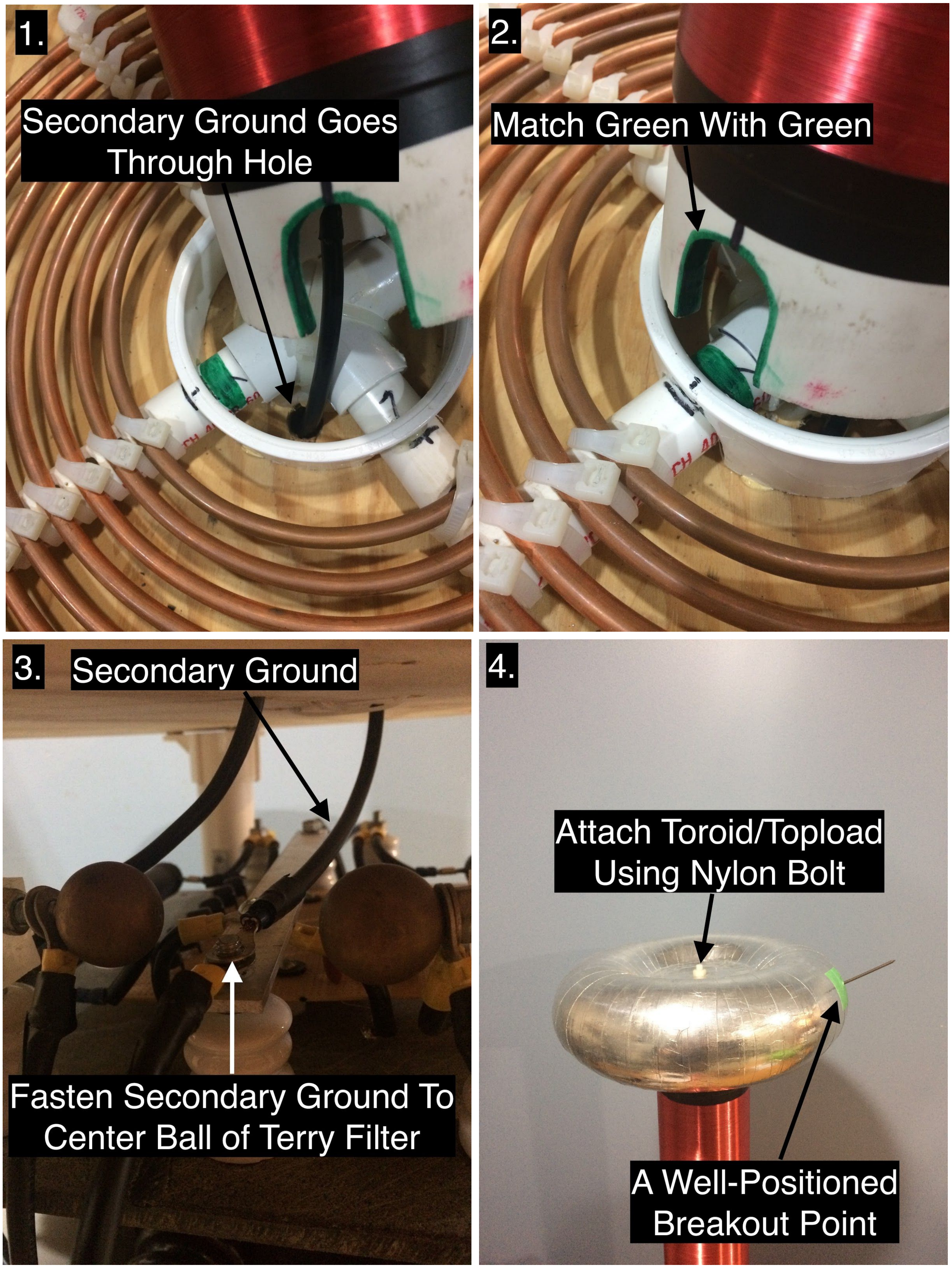
3.4 Installing the secondary coil and toroid

When the spark gaps are set, the Tesla coil is almost ready to run! **NOTE: Do not touch the secondary wire!** Salts on your hands can induce racing sparks and the wire may become loose if handled too much. Always handle the secondary coil where there is bare PVC. The nylon bolt is also fragile, so do not use this to prop up the secondary coil in any scenario.

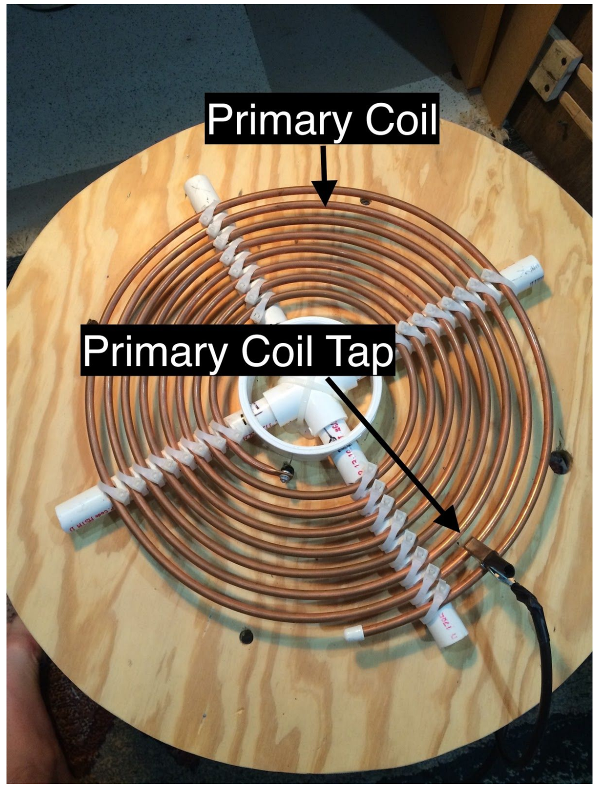




Insert the secondary coil into the base, feeding the secondary coil ground wire through the hole in the plywood (see following pictures) and seating the secondary coil firmly in the flange inside the primary coil. This is a tight fit, so be careful not to tear up the flange from the plywood when removing the secondary coil after use, and try to keep wiggling to a minimum. Unscrew the center ball of the Terry filter spark gap and ground the bottom of the secondary coil by threading the contact onto the bolt and screwing the center ball back onto the Terry filter. The secondary coil is now installed. Unscrew the nylon bolt on top of the secondary coil and place the toroid on top of the secondary coil, replacing the nut after the toroid is seated. Tape the wire (masking tape is sufficient) coming from the top of the secondary coil to the toroid, making electrical contact between this wire and the toroid. The secondary coil and toroid are now installed. For this particular Tesla coil, sparks rarely form without a breakout point, therefore, tape an object to the toroid, such as a paperclip or nail, to act as a breakout point. A breakout point is a sharp metal tip that coerces an arc to form.



3.5 Tuning the Tesla coil



The last step before running the Tesla coil is to tune the primary circuit such that maximum spark length is achieved. If the primary circuit is not tuned properly, sparks may not form. The primary coil should be tapped/clipped in at approximately 6.6 turns. Start with this, turn on the Tesla coil (all three switches, in the order stated above) and then adjust the tap point in either direction along the length of the coil based on observable spark length, making any adjustment with the Tesla coil OFF (all three switches). Make sure the clip doesn't accidentally make contact with the adjacent inside turn of the primary coil; this would be equivalent to tapping at 5.6 turns, even though the clip is physically clipped to 6.6 turns, and sparks will not form in this scenario. **NOTE: MAKE SURE ALL ELECTRONICS (PHONES, COMPUTERS, ETC.) ARE SEVERAL FEET AWAY FROM THE TESLA COIL BEFORE TURNING ON. THIS INCLUDES HANGING ELECTRICAL OUTLETS COMMONLY FOUND HANGING FROM THE CEILING IN SCIENCE CLASSROOMS.**

4 Running the Tesla coil

ONE SHOULD NEVER TOUCH THE ARCS OF THE TESLA COIL. ELECTROCUTION MAY ENSUE!

Now that the Tesla coil is operational, have fun! A grounded pole can be used to attract arcs and make the arcs appear brighter. NOTE: This acts as a virtual short and can put strain on some of the electronics, so this should be done only sparingly.

Things to watch out for:

- Constant arc grounding will shorten the lifetime of the Tesla coil, but is OK for a short duration.
- It is normal for the protection spark gaps to fire occasionally, though they shouldn't be firing constantly. If they are, go back to section 3.3 and reset the spark gaps.

- Racing sparks are sparks that traverse vertically up the secondary coil. These can damage the secondary coil and may also exist on the interior of the secondary coil. When cleaning up and disassembling the Tesla coil, inspect the secondary coil to see if there is damage to the secondary coil.
- Always operate the switches on the control box from left to right. That is, always turn on the FANS switch first, then SAFETY, the MAIN. **NOTE: NEVER operate the switches in a different order when turning on the Telsa coil. The main Tesla coil circuit will shut off if any switch is set to the OFF position, but for formal shut off, reverse the aforementioned order (MAIN first, the SAFETY, then FANS).**
- An arc event to the primary coil is not good. Try to prevent this from happening by keeping any grounded objects away from the primary coil such that the arcs are directed away from the location of the primary coil. In addition, make sure all breakout points on the toroid are pointed with a slight upward angle, that is, pointed away from the primary coil.

4.1 Simple experiments

Simple experiments can be performed such as holding/placing a compact fluorescent bulb in the vicinity of the coil and watching it turn on without any wires! A metallic propeller can be used to demonstrate the principle of corona propulsion. Can you think of others?

5 Disassembly and storage

Ensure that all switches are OFF and then unplug everything. Remove the topload, and then the secondary coil, being sure to detach the secondary coil ground from RF ground. Be gentle when removing the secondary coil as the flange that holds it steady is connected to the plywood solely by hot glue. Make sure the secondary coil ground wire does not snag on anything when being fed through the hole in the plywood. Place the topload and secondary coil in a safe location. The base can be wheeled to a closet or other location to be stored. The ground rod can be stored with the base in the drilled hole labeled “GROUND ROD”.

6 Safety Reminders and Technical Information

The plasma arcs of the Tesla coil produce ozone. Always operate in a well ventilated area and keep the runs short.

The control box contains an RF filter to prevent RF injection into the mains/wall outlets. Do not shake the control box as this heavy filter may come loose. In addition, do not hold the control box by the wires that feed into the box, as they may pull out.

The high voltage transformer used in this device is a 9kV neon sign transformer (NST) WITHOUT built in ground fault interrupt (GFI). Since large arcs are discharged to ground during operation, a Tesla coil will not operate with a transformer that contains GFI. **This means the coil will not shut off if there is a short circuit.**

Because of the way the switches are wired, it is not possible to turn on the Tesla coil without the fans or safety switch on. HOWEVER, THIS IS ONLY THE CASE IF THE DEVICE IS PLUGGED IN CORRECTLY TO BEGIN WITH. Always double check the wiring before turning on the Tesla coil.

Abbreviations:
MMC = Multiple Mini Capacitor
RF = Radio Frequency
NST = Neon Sign Transformer
GFI = Ground Fault Interrupt
LC = Inductor-Capacitor
AC = Alternating Current
DC = Direct Current

For the curious, here are the specifications of the Tesla coil:

Power Supply	
NST Input Voltage	120 V
NST Input Frequency	60 Hz
NST Output Voltage	9000 V
NST Output Current	60 mA
NST VA	540 VA
NST Impedance	150000 Ω
NST Watts	554 Watts
Primary Capacitor	
Primary Coil Resonant Capacitance	17.7 nF
Primary Coil Capacitance	16.7 nF
Secondary Coil	
Secondary Coil Form Diameter	3.5 in
Secondary Coil Wire Winding Height	19.4375 in
Magnet Wire AWG	24 AWG
Secondary Coil Turns	857 turns
Secondary Coil Capacitance	7.4 pF
Secondary Coil Height-Width Ratio	5.6 : 1
Secondary Coil Wire Length	785 ft
Secondary Coil Inductance	10.7 mH
Toroid	
Major Diameter	10 in

Minor Diameter	3 in
Toroid Capacitance	11.1 pF
Primary Coil	
Required Primary Inductance	11.9 μH
Tapped at	6.6 turns
Resonant Frequency	358 kHz