Miniature Tesla Coil Teaching Lab

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The Tesla coil is one of the most famous and popularly recognizable high voltage devices. Utilizing the fame of recognizability of the Tesla coil in a "Build Your Own" laboratory exercise is a great way to create a successful and highly interesting learning activity. Classical Tesla coils utilize a spark gap as the primary switch,[1] whereas modern Tesla coils use solid state components instead[2] such as the transistor for the Tesla coil described here. Building a miniature Tesla coil is also a convenient teaching tool for the instruction of electric fields, electromagnetic induction, and transistors. The equipment needed is readily available and affordable while the resulting "mini" Tesla coil is robust and entertaining. In addition, the concepts needed to give a basic description are readily available to students finishing a typical algebra-based physics course.

Building a miniature Tesla coil

The supplies needed can best be described in three categories, structural components, circuit elements, and assembly expendables. The structural components are a wooden baseboard, a hollow tube for the secondary tower, a ping-pong ball for the dome, and a breadboard to connect the circuit elements. Sections of PVC pipe are excellent for the tower, but a rolled piece of paper works just as well. Self-adhesive mini breadboards are very inexpensive and for this lab were further cut in half. The circuit elements are a 9-V battery and connector, a 22-kΩ resistor (the exact value isn't important), a TIP31C transistor, an LED, magnet wire for the secondary coil, and thicker wire for the primary coil. Assembly further requires aluminum foil to wrap the dome, wire cutters/strippers, tape, and hot glue. All of the components are available on Amazon and a detailed supplies list is included as an appendix.

Building a miniature Tesla coil like that shown in Fig. 1 from scratch can easily be accomplished in a three-hour laboratory session. The most time-consuming part is winding the secondary coil, with the limiting factor often being the number of spools of magnet wire available. I will typically give a brief tutorial on coil winding (turn, don't wrap!)[3] and have students begin winding their secondary coils while explaining the rest of the circuit. There are two concepts required to understand the miniature Tesla coil circuit shown on the left in Fig. 2, the transistor and induction (aka Lenz's law). Typically introductory students have not encountered transistors before, so explaining the function of a bipolar NPN transistor utilizing the "kitchen faucet" analogy[4] is a good place to start. When the transistor is "open," current begins to flow through the primary coil, which induces a potential in the secondary coil. The induced potential then "closes" the transistor, which stops the current flowing through the primary coil. As the current through the primary coil decreases the induced potential in the secondary coil is reversed, which "reopens" the

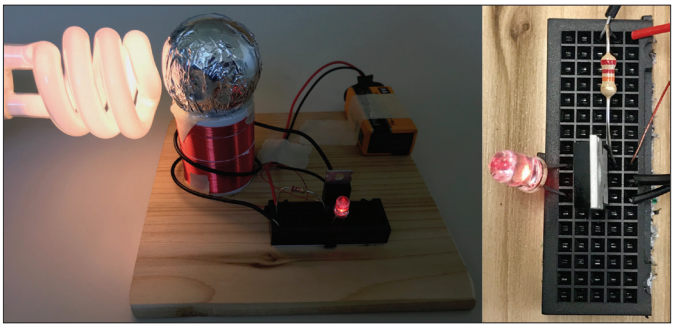

Fig. 1. The miniature Tesla coil as made in the "Build Your Own" Tesla coil lab using a 1.5-in tall PVC pipe as the secondary tower. This coil also functions without the LED, but the CFL doesn't glow as bright. Detailed image of the circuit on right.

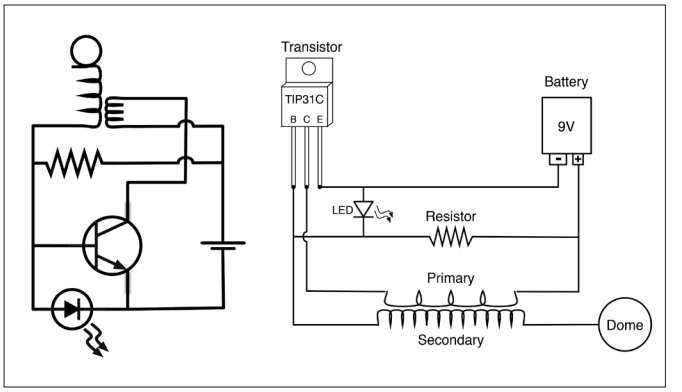

Fig. 2. Left: The circuit diagram for a miniature Tesla coil. The LED isn't strictly necessary but greatly improves the reliability of the circuit, especially with low price transistors. Right: An example of the circuit cartoon given to students. A note given with the cartoon reads: "The handedness of the two coils is important! If the two coils are wound parallel then the top of the primary coil is connected to the transistor collector. If the two coils are wound opposite then the bottom of the primary is connected to the transistor collector."

transistor. Thus, the interaction between the primary and secondary coil is what lowers the base voltage of the transistor, and Lenz's law can be used to explain where the voltage oscillations come from. Measurements of the mini Tesla coil demonstrate that the oscillation frequency is the transition frequency of the transistor (3 MHz for the TIP31C), further supporting that induction/Lenz's law is creating the oscillations.

After explaining transistors, Lenz's law, and walking through the entire oscillating circuit, I will give students a handout "cartoon" for them to use as a guide for constructing their Tesla coils. An example of such a cartoon is shown on the right in Fig. 2. Building the circuit itself takes very little time as all of the pieces can be directly plugged into the breadboard. The last thing I provide is the wire for the primary coil. The handedness of the primary is very important and is dictated by the handedness of the secondary; a primary coil connected backwards renders the circuit nonfunctional and

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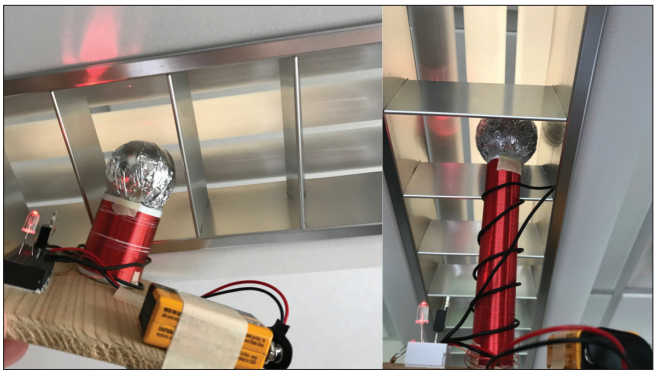

Fig. 3. Miniature Tesla coils lighting up the fluorescent bulbs in the author's office.

can damage the transistor.

A simple rule of thumb is to wrap the primary parallel to the secondary with a turn ratio of roughly 1:100; the exact ratio isn't important. The circuit design shown in Fig. 2 assumes the coils are wound parallel, though anti-parallel winding is easily accommodated by reversing the connections to the primary. A quick note on transistor choice. I originally used a 2N2222A transistor for this lab as it creates a more powerful and reliable Tesla coil, never bothering to include the LED. However, the 2N2222A readily overheats and will melt if the primary coil is connected backwards. Because of the overheating issue, I now use a TIP31C transistor. The TIP31C has had zero heat issues but is only intermittently successful, with the variation seemingly dictated by the manufacturer of the device. Including the LED has improved the performance and reliability of the circuit and removed the dependence on transistor manufacturer. The LED functions to protect the transistor during the negative polarization of the base. When the current through the primary is increasing, causing a negative potential at the base, current is diverted through the LED such that the potential difference between the base and emitter never exceeds 2 V. This prevents a Zener breakdown in the transistor, which causes the circuit to fail and is the most likely source of the manufacturer variability. I highly encourage including the LED to aid reliability and to function as a status indicator for a functioning unit.

A quick note on lab safety. As noted above, incorrectly connecting the primary coil can cause the transistor to overheat and melt. However, this does not pose a fire hazard as after the transistor fails the circuit is broken and current stops flowing. The worst that has been experienced is a very unpleasant odor similar to that of burnt rubber. In addition, while Tesla coils are known for their impressive streamers, the potential produced by the miniature Tesla coil presented here is insufficient to do so. A finger can be safely placed on the dome of the miniature Tesla coil during operation. In fact, placing a finger on the Tesla coil grounds the dome and can function as a "Morse code"-type demonstration.

Electric field demonstrations

The electric field from the mini Tesla coil can be readily detected by illuminating fluorescent lights bulbs or LEDs held near the dome. Most of the plasma globe demonstrations

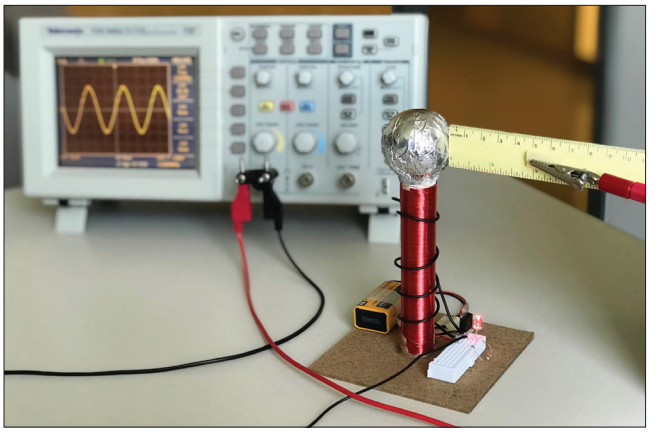

Fig. 4. A demonstration of measuring the voltage at a distance of 50 mm from the dome. The 4.25-in secondary tower for this Tesla coil is a single piece of printer paper folded in half and rolled around a highlighter (the highlighter was removed *after* wrapping the coil).

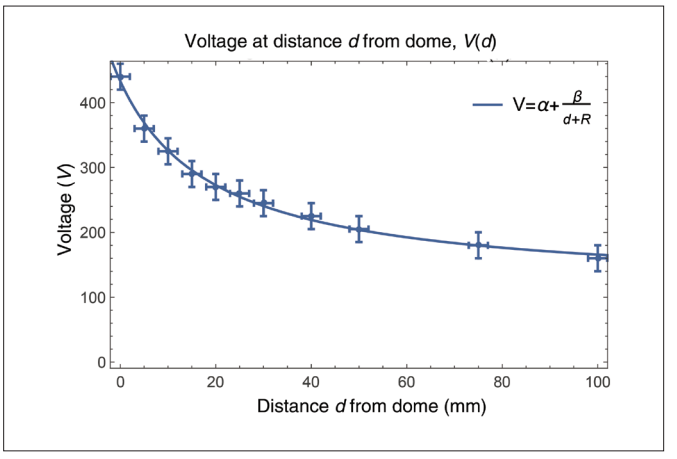

Fig. 5. The voltage as a function of distance *d* from the dome nicely fit by a curve of the expected *V*~1/*r* form, where *r* = *d* + *R*. The fit is a curve of $V = \alpha + \frac{\beta}{d+R}$, where α = 112 V, β = 6.42 V·m, and *R* = 20 mm.

James Lincoln wrote about[5] can be reproduced by the students at home with Tesla coils powered by a 9-V battery they built themselves. In lab, students were instructed to demonstrate their coils before leaving by illuminating either a handheld compact fluorescent bulb as demonstrated in Fig. 1 or the fluorescent bulbs on the ceiling as demonstrated in Fig. 3.

Additionally, if operating without the LED, the resistor can be removed during operation as the current through the resistor is only needed to start the Tesla coil, not to maintain functionality.

Measuring the electric potential

The electric potential as a function of distance from the dome can be readily measured using an oscilloscope. The grounding cable from the oscilloscope is connected to the base of the secondary coil, and the positive probe is held at a specified distance *d* away from the dome as depicted in Fig. 4. It is important to make the measurements without being physically near the Tesla coil as the human body will greatly attenuate the potential. Here the probe was taped to a plastic ruler,

which was then taped to a cardboard box.

The measured data are nicely fit by a curve of the form

$$V = \alpha + \frac{\beta}{d+R},$$

where α and β are fitting parameters, d is the distance from the dome, and R is the dome radius as shown in Fig. 5. This experiment nicely demonstrates the importance of including the dome radius as otherwise the fit will not work. The values of α and β depend heavily on how the coil is constructed and the voltage of the battery.

Acknowledgments

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References

1. J. B. Kelley and L. Dunbar, "The Tesla coil," *Am. J. Phys.* **20**, 32–35 (Jan. 1952).
2. D. G. Bruns, "A solid-state low-voltage Tesla coil demonstrator," *Am. J. Phys*. **60**, 797–803 (Sept. 1992).
3. Wrapping the wire around the core introduces twist, which will eventually cause a kink in the wire. Turning the core and allowing the spindle to rotate prevents this.
4. A description of the transistor water valve analogy can be found at https://learn.sparkfun.com/tutorials/transistors/extending-the-water-analogy.
5. J. Lincoln, "Plasma globe revisited," *Phys. Teach*. **56**, 62–63 (Jan. 2018).

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Supply List for Miniature Tesla Coil Lab

Structural components

- **Baseboards:** A piece of wood or plastic, roughly 4 in by 4 in.
- **Tubes:** A PVC pipe or rolled piece of paper, roughly 1 in in diameter and 4 in tall.
- **Ping-pong balls:** A typical inexpensive ping-pong ball.
- **Breadboard:** Self-adhesive miniature breadboards for Arduino projects (for example, the "Phantom YoYo," which was used here) are readily available on Amazon. These breadboards are plastic with no metal connections down the middle and can thus be easily further cut in half using a bandsaw or hacksaw.

Circuit elements

- **9-V batteries:** Available in bulk most anywhere.
- **9-V battery connectors:** Readily available on Amazon. Those without braided wires are easier to connect to the breadboards.
- **TIP31C transistors:** Available in bulk on Amazon or Jameco.
- **22-Ω k resistors:** Available in bulk on Amazon.
- **LEDs:** Typical 2 V 20 mA, color doesn't matter. Available in bulk on Amazon.
- **Magnet wire:** Thin enameled copper wire for electromagnetic coils; 28 AWG is typical but the diameter isn't critical. Available on Amazon.
- **Loop wire:** Flexible insulated wire for primary coil; 22 AWG is typical but the diameter isn't critical. Available on Amazon.