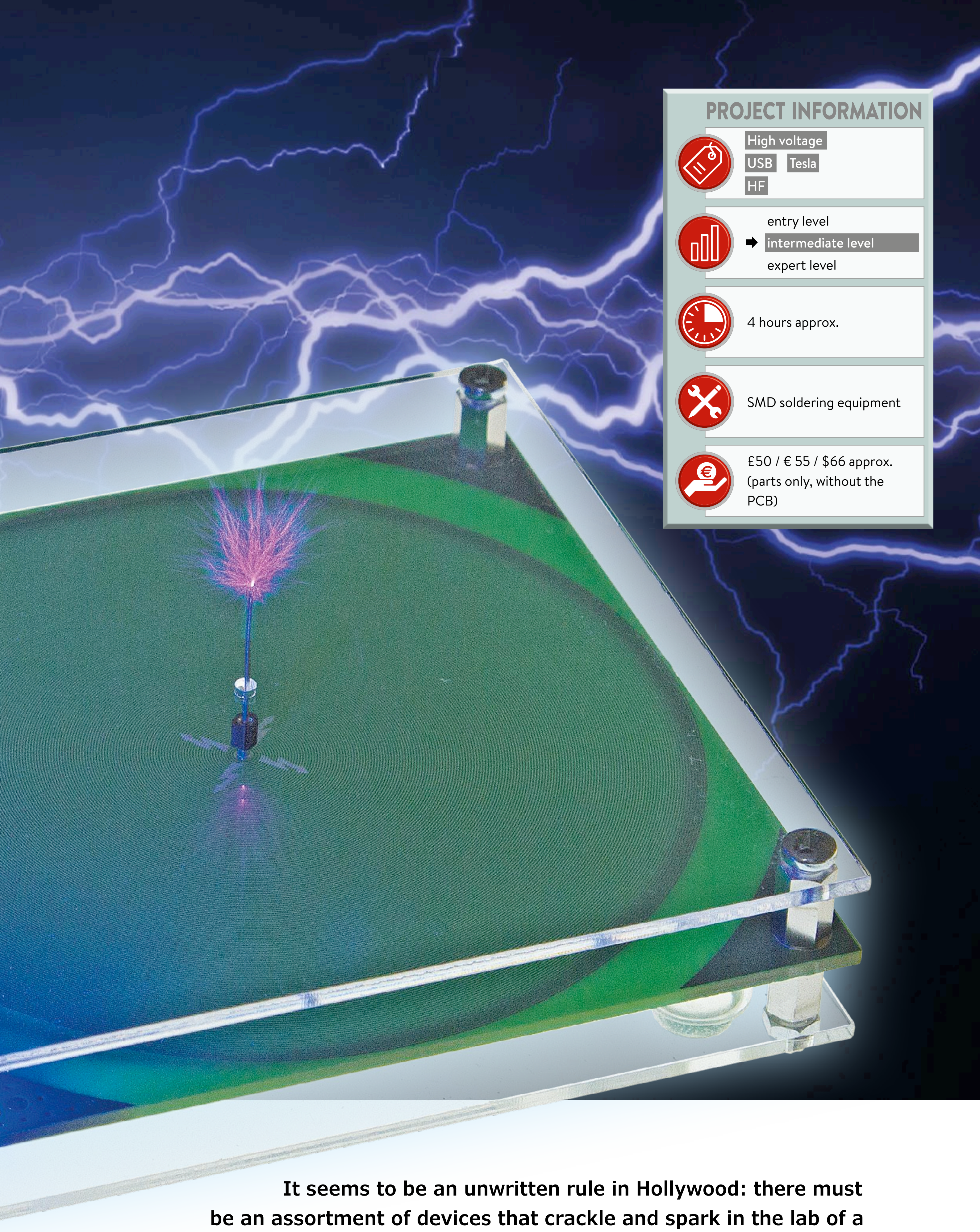
Spiral MicroTesla

sparks from a USB charger

By **Daniël Eindhoven** (The Netherlands)

Properties

- High voltage Tesla coil
- Uses printed PCB coils
- Powered by USB charger or adapter
- Safe sparks
- Complete DIY kit available



PROJECT INFORMATION

High voltage | USB | Tesla | HF

entry level
→ **intermediate level**
expert level

4 hours approx.

SMD soldering equipment

£50 / € 55 / $66 approx.
(parts only, without the PCB)

It seems to be an unwritten rule in Hollywood: there must be an assortment of devices that crackle and spark in the lab of a mad scientist. It doesn't matter that all those noises and flashes have no apparent purpose, as long as the effects look spectacular!

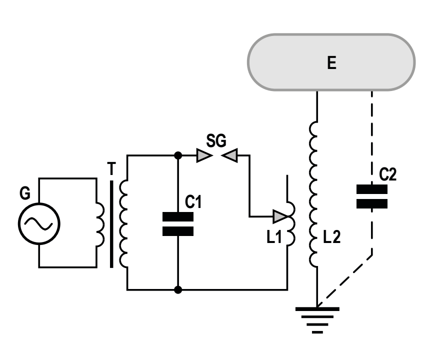


Figure 1. Basic circuit of the original Tesla coil.

To generate these spectacular sparks they used devices known as Tesla coils — named after the physicist and engineer Nikola Tesla (see inset). Most of the Tesla coils have in common that they're quite large and potentially dangerous. There is a lot of energy involved, which makes the chances of a serious shock and/or burns very possible. When we want to make a (relatively) safe Tesla coil we must therefore limit the amount of energy used. In contrast to what the free-energy advocates want us to believe, it is never possible to extract more energy from a system than what was first put into it.

Power supply via USB

The main advantage of the Tesla coil described in this article is that it is powered by a USB charger. This means that the supply voltage is only 5 volts. The maximum current consumption is in the region of 1 ampère. The maximum power consumed is therefore:

$P = U \times I = 5\text{ V} \times 1\text{ A} = 5\text{ W}$

which can't cause much damage. You can touch the sparks produced by our Tesla coil with your bare hands, despite the fact that the voltage has been increased to a staggering 30 kV. You would expect to feel a heavy shock, but because the current is so weak you will only notice a slight tingling at most. Nevertheless, we want to emphasize that Tesla coils aren't kids' toys! You can find many projects for Tesla coils on the Internet that are powered directly from the AC line. Please don't even think about building them: they can be absolutely deadly!

Theory behind the Tesla coil

The special transformer at the heart of the Tesla coil (L1 and L2 in the basic circuit of **Figure 1**) is called a resonant or oscillation transformer, which clearly operates in a different way to the normal transformers found in AC power supplies. A normal transformer has been designed to transfer energy from the primary winding to the secondary winding as efficiently as possible; an oscillation transformer also (temporarily) stores electrical energy. There is a capacitor in parallel with each winding, which effectively results in two tuned circuits. L1 consists of one or more turns of thick copper wire and it can be tuned; this coil is connected to capacitor C1 via a spark gap (SG). The secondary coil consists of a (very) large number of turns of thin copper wire, within the primary coil. Both coils are air-cored. There is no 'real' capacitor in parallel with the secondary, although there is a capacitance: capacitor C2, shown in dashes in the basic circuit, is the sum of the parasitic capacitances between the individual windings in the secondary and the capacitance between the end electrode (E) and Earth. Both circuits (L1-C1 and L2-C2) have been tuned to the same frequency.

The operation of the Tesla coil (shown in Figure 1 in its original configuration) can be explained (very briefly) as follows:

1. Capacitor C1 is charged up to a high voltage by the supply transformer (T).
2. When the voltage across the capacitor exceeds the breakdown voltage of the spark gap, a spark forms and the resistance across the SG is reduced to a very low value. This closes the primary circuit and a current flows from the capacitor through coil L1. This current oscillates backwards and forwards through L1 at the resonant frequency of the circuit.
3. This causes an oscillating current to be induced in the secondary winding (L2). The energy from the primary circuit is transferred to the secondary circuit during the course of several cycles. The total amount of energy (minus any losses) stays the same as the amount of energy initially stored in C1, so that the oscillating voltage in the primary circuit decreases, while the voltage in the secondary increases. The voltage at the end electrode of the secondary coil will be many times higher than the primary voltage. The very strong electric field at the end electrode ionizes the surrounding air, causing spectacular discharges.
4. The secondary current then generates a magnetic field that induces a voltage in the primary winding; the energy is transferred back to the primary again over a number of cycles. In this way the energy moves backwards and forwards at a high rate between the tuned circuits. The oscillating currents in the primary and secondary windings will gradually die out due to the losses that are always present.
5. When the current through the spark gap becomes too small to keep the air between its electrodes ionized, the spark disappears and the current flow in the primary circuit stops.
6. Capacitor C1 is then charged once more via transformer T and the whole process starts again.

The whole cycle takes place in a very short space of time — the oscillations die out within about a millisecond. Each spark across the spark gap produces a diminishing pulse train of a high-voltage sine wave at the end electrode of coil L2. This pulse train dies out well before the next one starts. The Tesla coil therefore produces a series of damped sine waves, rather than a continuous high-voltage sinewave.
Note that the end electrode of the secondary coil can either be a disc or torus, or have a needle-like shape. In the first two cases the Tesla coil looks a bit like a Van de Graaff generator, although the inner workings are completely different!
Regarding the spark gap: semiconductors were completely unknown when Nikola Tesla invented his coil, and mechanical switches were much too slow to be used in this circuit. The use of a spark gap was therefore a clever way to switch the current on and off very quickly.

Two types

There are many designs for the Tesla coil, although we can, broadly speaking, divide them into two groups. The first group consists of Tesla coils that follow the original design, in other words, with a spark gap. The acro-

nym SGTC (*Spark Gap Tesla Coil*) is used for these.
Fast, modern power semiconductors (thyristors, transistors, MOSFETs etc.) are an ideal replacement for the spark gap, without its disadvantages (noisy, gets warm, bad efficiency). These variants are known as SSTC (*Solid State Tesla Coil*).
It won't come as a surprise to the Elektor Magazine reader that we chose the semiconductor version for this project, although several colleagues in the lab have a distinct preference for 'noisy' circuits...

The circuit diagram

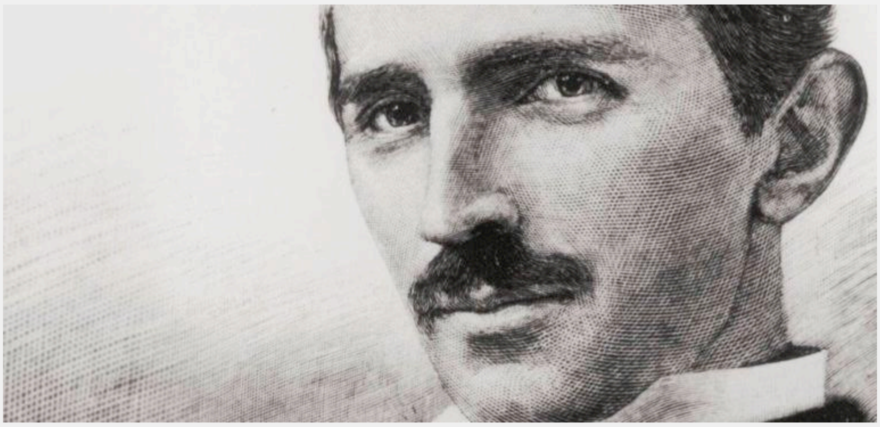
We have shown the circuit for the MicroTesla in **Figure 2**. This is, to be exact, a DRSSTC — *Dual Resonant Solid State Tesla Coil*. It's quite a mouthful, just to indicate that both the primary and secondary circuits use LC series-resonance in order to boost the voltage as much as possible.
The most important components of every Tesla coil are — you've guessed it — the primary and secondary windings. It's well known that electronics hobbyists have an intense dislike of coils if they cannot be bought ready-made. If you give the same instructions for making a coil to ten electronics hobbyists you'll probably end up with ten different coils... To avoid these kinds of problems, we implemented the primary and secondary coils as planar PCB coils. In other words, they've both been made using tracks on the PCB.
The primary coil consists of a single turn on the underside of the board; the secondary consists of 160 turns (in a spiral) on the topside of the board. This secondary coil has a total length of about 25 meters (75 feet).
As we mentioned earlier, the primary coil is not driven by a spark gap. Instead, four fast bipolar power transistors configured as an H-bridge (T4–T7 in the circuit) have been used. These in turn are driven by a couple of high power MOSFET drivers, IC2 and IC3.

Feedback loop

We will first concentrate on the driver circuit for the primary coil, since this is at the heart of the circuit. For optimum results, the resonance frequencies of the primary and secondary windings have to be identical (in our case that frequency was in the region of 4 MHz).
The H-bridge has to driven at exactly this frequency, but this creates a problem. If we were to use an oscillator with a fixed frequency, it would be very difficult to get its frequency just right. To start with, the inescapable component tolerances would immediately throw a spanner in the works.
It is much simpler (and better) to make use of feedback. When we consider that the current and voltage are in phase at resonance, the solution is easy to see: we're going to use the secondary voltage to switch the primary current.
Because only a relatively low current flows in the secondary circuit, we can use the voltage across a resistor (R28) as the switching signal, without the need to use a current transformer. Inverter IC4 inverts this voltage and turns it into a perfect square-wave (and hence a good switching signal). To prevent the voltage at the input to the inverter from rising too high, we've clamped the coil voltage with a two-stage clamp (D3 and D4).
The output signal of inverter IC4 (*PULSE* in the circuit diagram) is used to switch the H-bridge at exactly the

Nikola Tesla — a tragic genius

Nikola Tesla was born on 10 July 1856 in Smiljan (which is now in Croatia). He studied physics, engineering and philosophy at the universities in Graz and Prague. After having worked for some time in France and Germany, he emigrated to the United States in 1884, where he was naturalized as an American citizen in 1891.



In the United States, Tesla initially worked for Thomas Edison, although they fell out after a short period of time. Tesla was then supported by Edison's rival, George Westinghouse, and started his own company, where he either invented or improved upon the most important parts of our contemporary electricity network. Tesla obtained many patents for his inventions, but he wasn't a businessman, in contrast to Edison. He handed over lucrative patent rights to help Westinghouse, who became very wealthy (the Westinghouse Electric Company still exists, although it's now part of Toshiba). This ensured that they broke the monopoly of Edison's General Electric.
Around 1900 Tesla started experimenting with high-frequency alternating currents (one of the results was the Tesla coil) and wireless transfer of electrical energy. However, this turned out to become a (financial) fiasco.
The general public mainly remembers Tesla as an eccentric scientist and inventor. In the latter years of his life (which were mostly spent in New York) he lost contact with reality and he started looking at a 'death ray', anti-gravity, alien life forms and free energy from the 'aether'.
Tesla died in a hotel room in New York on 7 January 1943. However, he wasn't forgotten by his colleagues — they attended his funeral in great numbers.
The SI unit for magnetic flux density (the tesla, *T*) was named after him in his honor in 1960.

[Source: *Wikipedia*]

right time to ensure that the current keeps increasing in strength. This is known as a self-resonating circuit; a simulation of this process can be seen in **Figure 3**.

There is also another reason for choosing to use feedback: the secondary resonance frequency is not constant. Since the plasma channel where the spark appears has a certain capacitance, and because the circuit isn't really ideal due to the use of planar coils, the resonance frequency changes considerably during normal use. Feedback from the secondary circuit to the primary circuit therefore produces the best possible result.

For the same reason we've made the crossover point of the primary circuit much lower than the resonance frequency. It therefore takes several cycles before the resonance gets going.

Speed considerations

In order to achieve the best possible performance, the delay between the measurement of the secondary voltage and the switching of the primary current has to be as small as possible. This means that we need to use very fast components. For this reason we've chosen fast FZTx51-type transistors (T4–T7) for the switches (actually just emitter followers), and UCC2753x high-power MOSFET drivers (IC2, IC3) to control them.

Power supply considerations

The maximum supply voltage for the MOSFET drivers in the H-bridge (IC2, IC3) is 35 V; when we add a safety

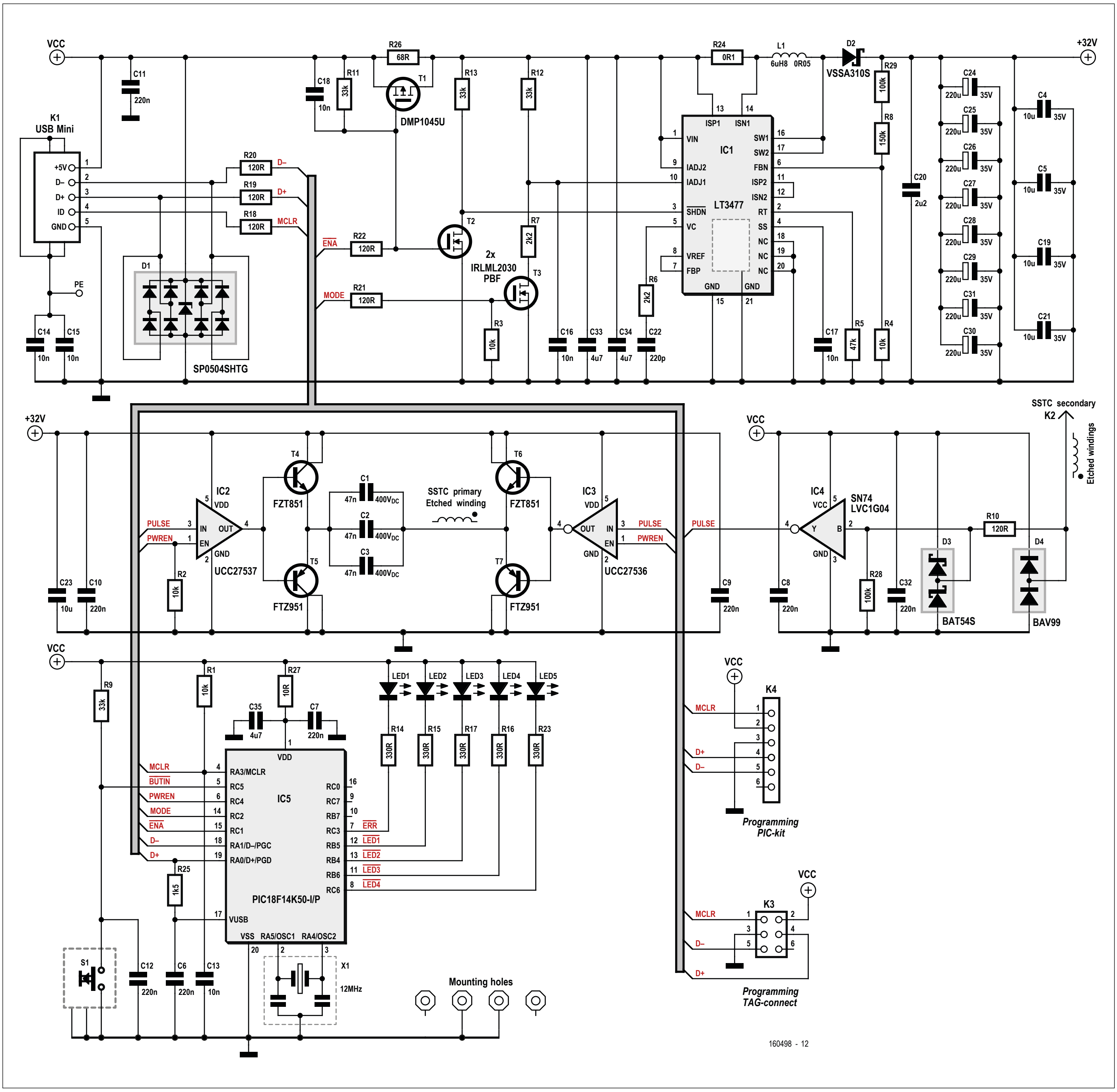


Figure 2. The complete circuit diagram for the Spiral MicroTesla.

margin of 3 V, the resulting supply voltage for the Tesla section becomes 32 V. This has to be derived from the 5 V USB voltage in some way. The first circuit that comes to mind is a DC/DC step-up converter, a circuit that has become a standard building block for the electronics hobbyist.
We decided to use an LT3477 made by Linear Technology, which has rail-to-rail current sense. This feature is perfect for the prevention of overloading the USB adapter or USB charger. The current limit is configured via the voltages on the Iadj pins. When T3 conducts, the input current is limited to a maximum of about 0.5 A (a voltage drop of 50 mV across R24). When the voltage at I_{adj1} is higher than 0.625 V (T3 blocks), the current is limited to a maximum of about 1 A (100 mV across R24). The *MODE*-signal is used to control T3.
The output voltage of the converter is heavily buffered using eight large electrolytic capacitors (C24–C31), with another five ceramic capacitors of 10 µF in 1210 packaging (C4, C5, C19, C21 and C23) connected in parallel. These capacitors ensure that we can obtain the large peak currents of 20 A (!) at the high switching frequencies required by this circuit. A precharge resistor of 68 Ω (R26) is used to keep the initial charging current at switch-on within a reasonable level (remember that we're dealing with a total capacitance of over 1800 µF). After one second this resistor is shorted by T1, which is driven by the */ENA* signal.

Duty cycle

It is quite a challenge for a designer to create a good Tesla coil. On the one hand, we want to have the largest and most spectacular sparks possible, on the other hand, the power consumption must remain fairly small. One good way to implement these seemingly contrasting requirements is to turn on the circuit for only very short periods of time — the power consumption and the duty cycle are directly proportional.
With a 5 V/1 A power supply we're scraping the bottom of the barrel with a duty cycle of 1.5%. If we choose to have the Tesla coil on continuously, the circuit would consume over 300 watts (!), which it wouldn't be able to cope with: the heat generated would be far too much.
The duty cycle of our Tesla coil can be varied via the software: stronger pulses less often (<10 Hz), or weaker pulses more often (>20 Hz). It is even possible to play some scales by varying the duty cycle (see later).
Virtually all of the power consumed is converted into heat, which has to be dissipated. The power stage uses up most of the power, which shouldn't come as a surprise. The printed circuit board needs to be designed so that all this heat can be dissipated and the components won't overheat. We've added a large copper area underneath the power components to aid with cooling. This is connected using thermal vias to the underside of the board, where more cooling copper has been added.
The infrared photo in **Figure 4** shows the MicroTesla after it has been in operation for two hours. A tempera-

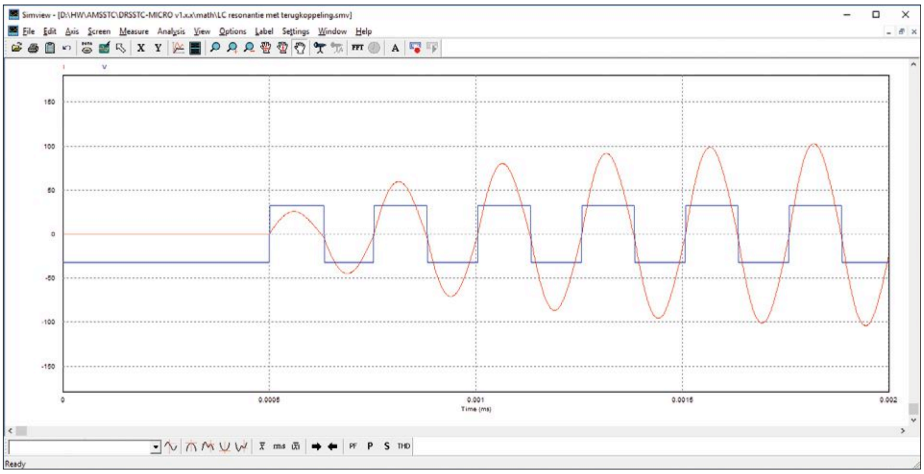


Figure 3. Simulation of the secondary voltage with feedback.

Lightning in the living room

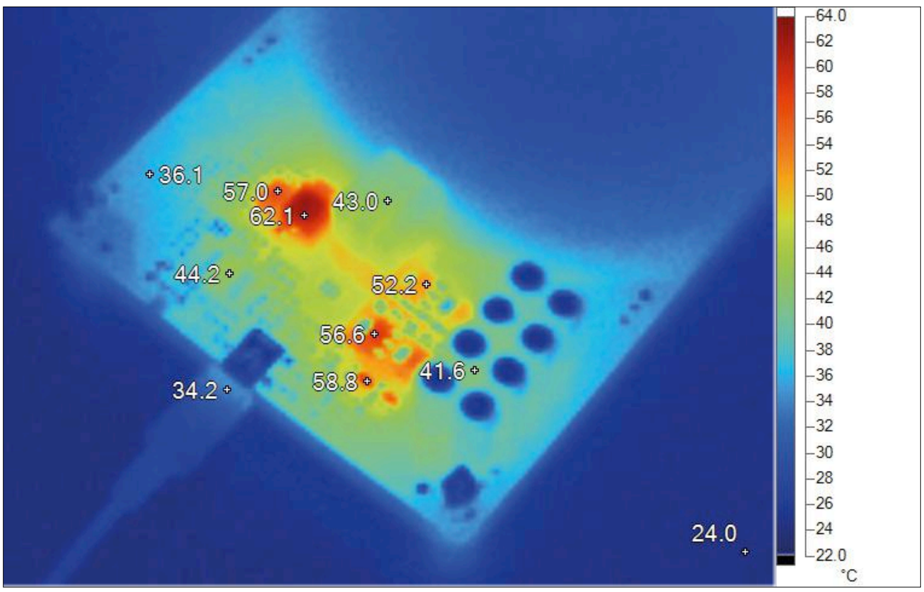


Figure 4. The temperature of the board increases during use, but stays within acceptable limits.

COMPONENT LIST

Resistors
Default: 1%, 0.125W, SMD 0805
R1,R2,R3,R4 = 10kΩ
R5 = 47kΩ
R6,R7 = 2.2kΩ
R8 = 150kΩ
R9, R11,R12,R13 = 33kΩ
R10,R18,R19,R20,R21,R22 = 120Ω
R14,R15,R16,R17,R23 = 330Ω
R24 = 0.1Ω, 250mW, 1%, SMD 1206
R25 = 1.5kΩ
R26 = 68Ω, 250mW, 5%, SMD 1206
R27 = 10Ω
R28,R29 = 100kΩ

Capacitors
C1,C2,C3 = 47nF, 400VDC, 5%, PP, 15mm pitch, 5mm width
C4,C5,C19,C21,C23 = 10µF, 35V, 10%, SMD 1210, X7R
C6,C7,C8,C9,C10,C11,C12,C32 = 220nF, 50V, 20%, SMD 0805, Y5V
C13,C14,C15,C16,C17,C18 = 10nF, 50V,10 %, SMD 0805, X7R
C20 = 2.2µF, 50V, 10%, SMD 0805, X5R
C22 = 220pF, 50V, 5%, SMD 0805, C0G/NP0
C24,C25,C26,C27,C28,C29,C30,C31 = 220µF, 35V, 20%, 8mm diam., 3.5mm pitch, EEUFC1V221L (Panasonic)
C33,C34,C35 = 4.7µF, 16V, 10%, SMD 0805, X7R

Inductor
L1 = 6.8µH, 3.04A, 0.0498Ω, SMD

Semiconductors
D1 = SP0504SHTG, SMD SOT-23-6
D2 = VSSA310S-M3/61T, 100V/3A, SMD SMA
D3 = BAT54S, SMD SOT-23
D4 = BAV99, SMD SOT-23
LED1 = red, low power, SMD, KPTL-3216EC (Kingbright)
LED2,LED3,LED4,LED5 = blue, low power, SMD, KPTL-3216QBC-D (Kingbright)
T1 = DMP1045U, SMD SOT-23
T2,T3 = IRLML2030TRPBF, SMD SOT-23

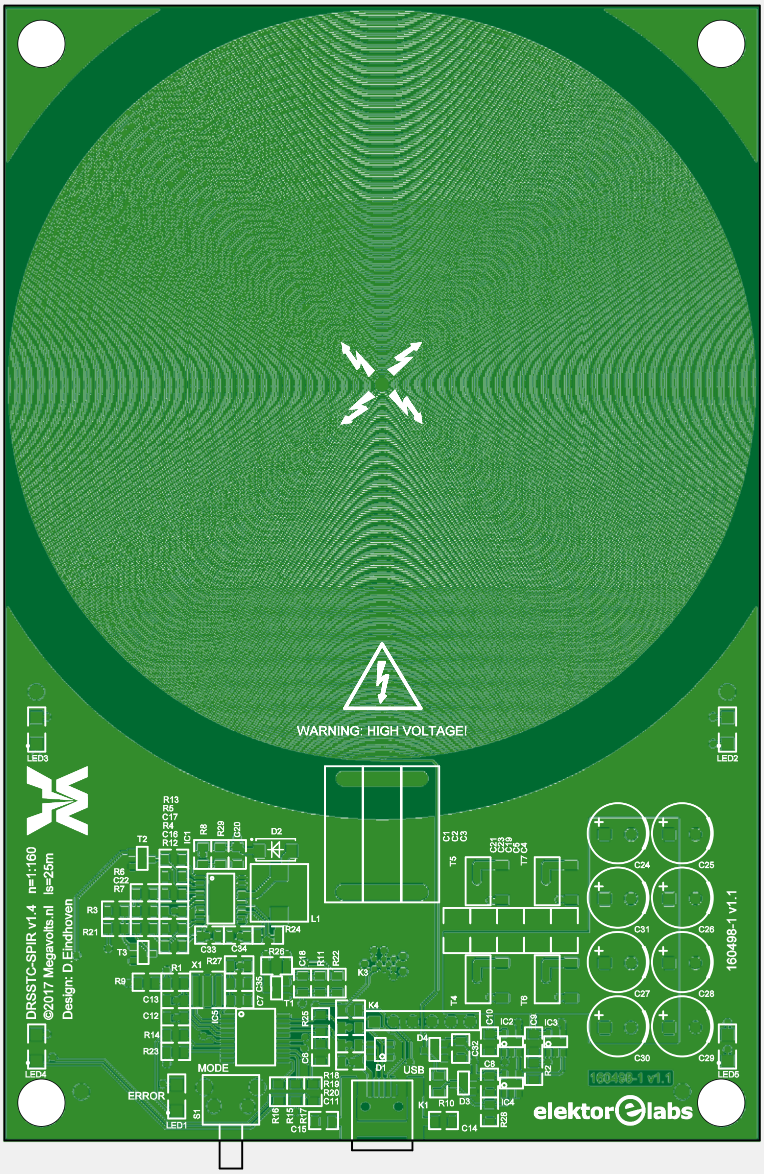


Figure 5. PCB and component layout.

T4,T6 = FZT851, SMD SOT-223
T5,T7 = FZT951, SMD SOT-223
IC1 = LT3477EFE#PBF, SMD, TSSOP-20
IC2 = UCC27537DBVT, SMD SOT-23-5
IC3 = UCC27536DBVT, SMD SOT-23-5
IC4 = SN74LVC1G04DBVR, SMD SOT-23-5
IC5 = PIC18F14K50-I/SS, SMD SSOP-20

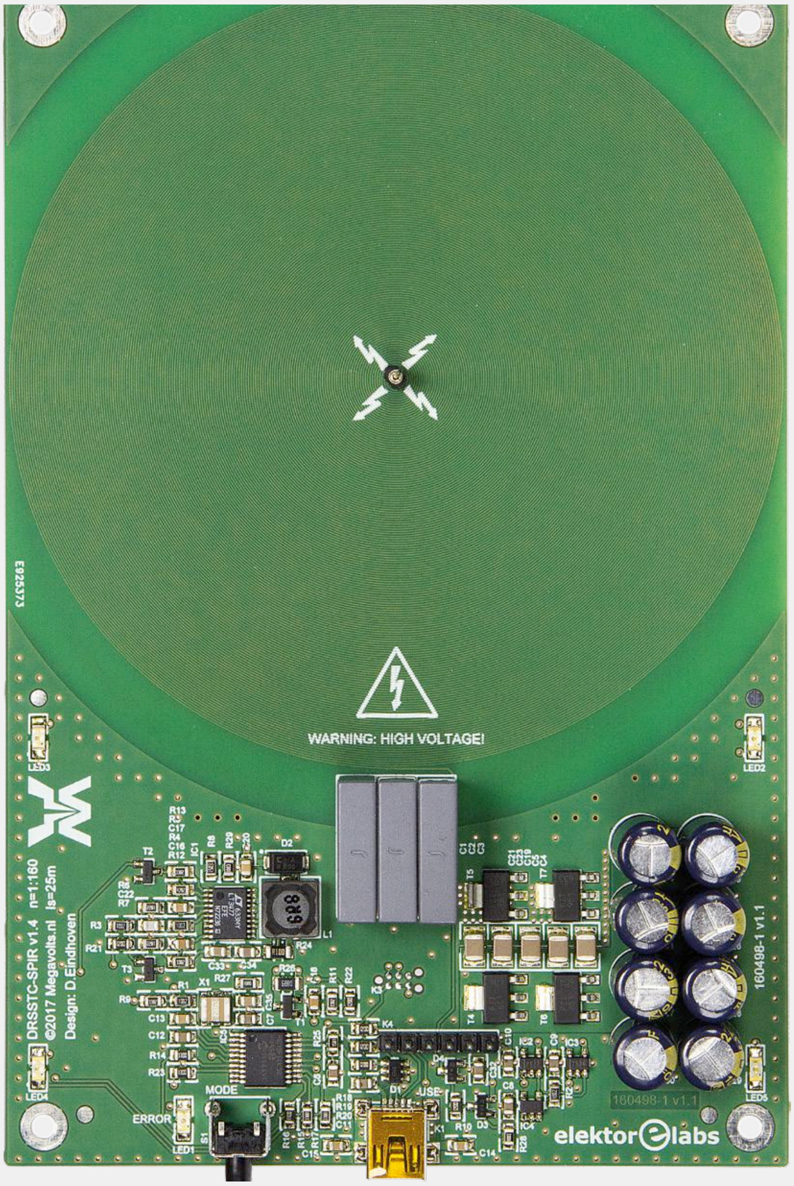
Miscellaneous
X1 = 12.0MHz resonator, 0.5%, 5pF with internal capacitors, AWSCR-12.00CV-T (Abracon)
K1 = USB-B mini-connector, horizontal PCB-mounting, SMD
K2 = turned-pin IC socket (only one contact

ture of 62.1 °C (which is 38 degrees above the ambient temperature of 24 °C) is perfectly acceptable for power electronics. The board settled at this temperature after about half an hour.

Firmware

A small PIC microcontroller (PIC18F14K50, IC5) takes care of all the control functions. It controls the precharge transistor, the setting for the current (500 mA or 1 A), and the duty cycle. We decided not to include USB communications in this version of the MicroTesla. The microcontroller also drives an Error LED (LED1). Since it only requires a bit of software and hardly any extra hardware, we've added four blue LEDs (LED2–LED5) to enhance the board's visual aspect. Switch S1 is used to select the required operating mode (see next paragraph).

The firmware can be downloaded from the project page [1], and programmed into the microcontroller via connector K4.



required)
K4 = 6-pin SIL pinheader, 0.1" pitch
S1 = pushbutton, horizontal,
SKHHLQA010 (Alps)

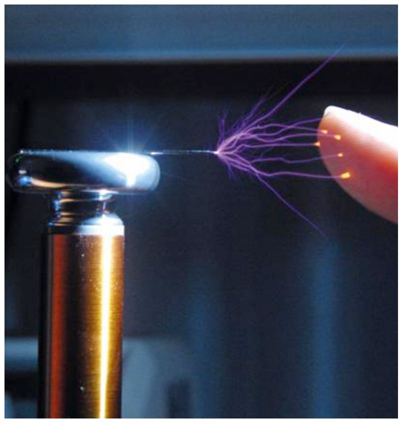
Mechanical components

8 spacers 15 mm
4 bolts M3 x 40 mm plus nuts
Acrylic sheet top, 100x150x2 mm
Acrylic sheet bottom, 100x150x2 mm

PCB 160498-1 v1.4

Sneak preview

The circuit for the Spiral MicroTesla can also be used as the basis for a 'traditional' Tesla coil with a vertical air-cored coil and a toroidal terminal — the ultimate high-voltage gadget. We hope to make this version available as a kit of parts in the near future.



A kit of parts for a 'real' Tesla coil will be made available in the near future.

Construction and operation

A double-sided PCB has been designed for our Tesla coil (or to give it its official name: Spiral MicroTesla), which is shown in **Figure 5**. You can try to etch this yourself, but we wouldn't recommend it — the smallest short between any of the windings in the secondary coil will make the circuit inoperative!

You can buy a ready-made board from the Elektor Store, which is guaranteed to work.

Most of the components are of the SMD variety, although this shouldn't be an insurmountable problem for an experienced hobbyist with a steady hand (and the right soldering equipment, of course).

There is good news for those of you who don't like to work with SMDs: a complete kit for the Spiral MicroTesla is also available, with a board that has all of the SMDs already mounted (you still have to solder a few through-hole components). You can't really go wrong then.

The end electrode is mounted using

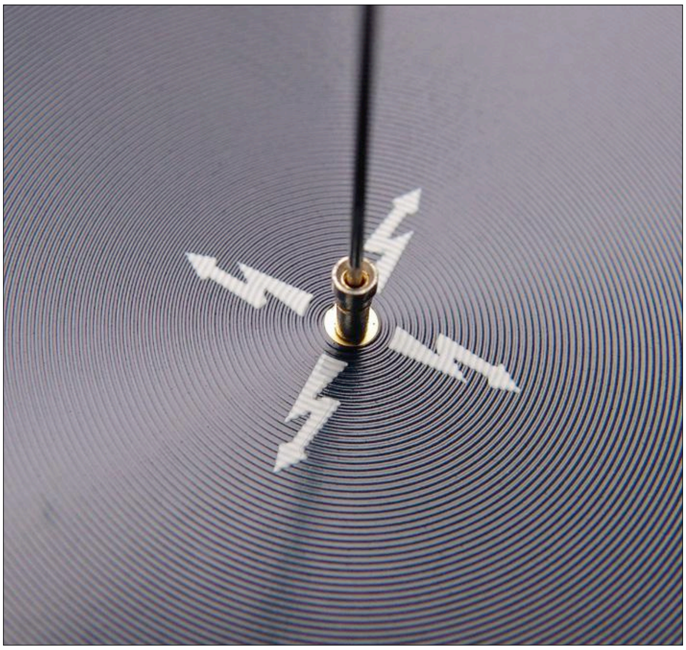


Figure 6. The end electrode is mounted in a sprung socket from an IC socket.

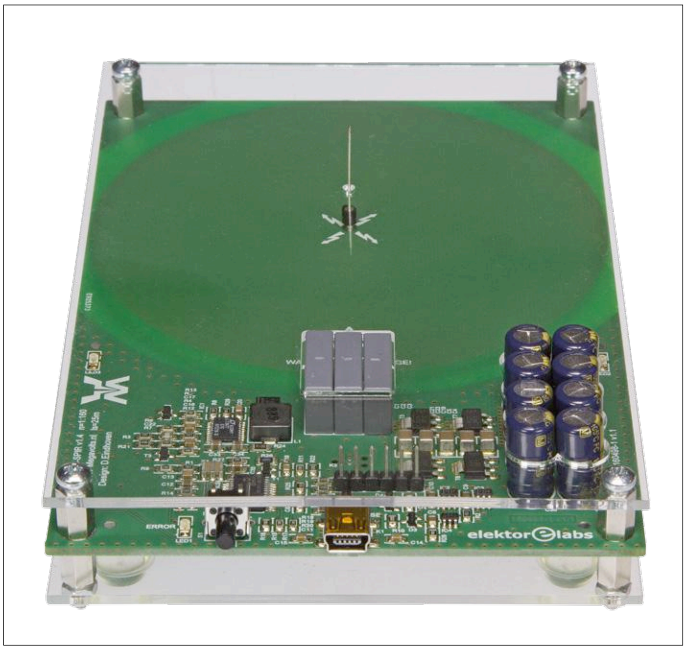


Figure 7. The MicroTesla board is mounted between two acrylic sheets (Perspex®) to prevent any parts from being touched.

About the author

Daniël Eindhoven (30) became fascinated by Tesla coils after playing the game Command & Conquer: Red Alert as a child. When he found out that you could make them yourself, there was no stopping him: Daniël has since built a large number of working devices of various designs and implementations. In 2010 he completed his studies in Electronic Engineering at the Haagse Hogeschool in Delft, The Netherlands. Since then he's been working as a hardware design engineer in power electronics. Daniël is interested in just about anything to do with technology. His website at www.megavolts.nl/en is certainly worth a visit.

a single sprung socket that has been carefully removed from an IC socket; the electrode is simply pushed into it (see **Figure 6**). Note that the board is mounted on spacers between two acrylic sheets to prevent any of the components from being touched. The end electrode sticks through a hole in the top acrylic sheet (as well as the large capacitors). **Figure 7** should give you a good idea what we have in mind. Note that these acrylic sheets are also included with the complete kit.
The Tesla coil is operated using a single push button (S1), which works as follows:

- A short press of S1 (less than 1 s) switches between the various operating modes:
  Turn on, 5-Hz pulses → 10-Hz pulses → 20-Hz pulses → musical scale → turn off.
- Press S1 for 1 s to return to the initial mode (5 Hz).
- Press S1 for 3 s to select the high-power (1 A) mode (red LED LED1 flashes); another 3 s press returns to the normal (0.5 A) mode.
- Press S1 for 8 s to turn off the blue LEDs (so that you can take impressive photos of the sparks in the dark).

Disclaimer

The use of the Spiral MicroTesla is completely at your own risk; neither the author nor the Editor nor the Publisher accepts any responsibility for any damage that may be caused by its use. You must connect the Spiral MicroTesla to a reliable USB charger or USB adapter, but you must never connect it to a USB port of a computer! Keep sensitive electronics away from the discharges! ◄

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Web Link

[1] www.elektormagazine.com/160498