Wimshurst machine

Invented by British inventor James Wimshurst in the early 1880's. I built my version during one of the lockdowns in 2020. As always, this device generates extremely high voltages, so be careful. I got zapped several times, even though I always discharge the spark gap. When the inner foils have been discharged with respect to one another, there may still be a potential difference between the outer and inner foil on either capacitor. It hurts.

The Wimshurst machine is an electrostatic generator. It works by collecting opposite charges in two capacitors ('Leyden jars').

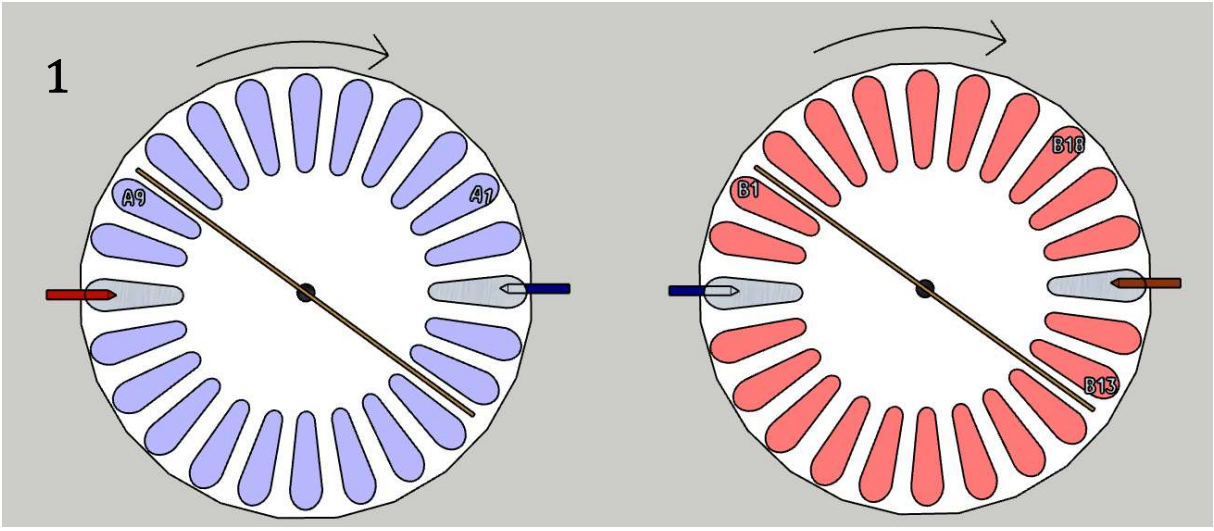
Parts:

- two discs made of an insulating material. I used LP vinyl records for this particular device.
- adjacent metal 'sectors'. I cut those out of aluminium tape and stuck them on the discs, evenly spaced. There are 24 of them per disc.
- neutralizer bars. A bit of a misnomer if you ask me: charge transfer bars would be more accurate. I made these from solid brass round stock (D4mm) and soldered pieces of stranded wire at the ends to serve as brushes. I used silicone insulated test lead wire, because the strands are very thin and the silicone is flexible enough to push the stripped tip of strands lightly against the discs.
- collectors: I made these from 2.5mm^2 copper wire. Bent into a U-shape and the ends ground to sharp tips.
- the capacitors: made of a length of PVC pipe, 50mm outer diameter and 2mm wall thickness. The inner and outer surfaces are covered with aluminium foil. The inner foil is tricky to apply evenly.
- the spark gap: two metal balls, one larger than the other. Drilled a hole in them, tapped a 4mm screw thread, so as to screw them on another piece of 4mm brass round stock on which I tapped threads as well. These connect to the inner foil of the capacitors.
- the discs are attached to small pulleys, mounted on a fixed axis. The pulleys move freely and are driven by a belt, in turn driven by larger pulleys attached to a freely spinning axis. The lower axis is turned by hand. One belt is twisted, so the discs move in opposite directions. In order to maximize friction I put a thin piece of anti-slip tape on the tread of the pulleys.
- the rubber belts are made of instrument cable sheath. I cut off a piece, removed the wires inside and used a hot air station to melt the ends together. I didn't expect it to hold up for long at first, but apparently it did.

It's not easy to explain in writing how this device works. There are good animated explanations on YouTube that make it easier to visualize.

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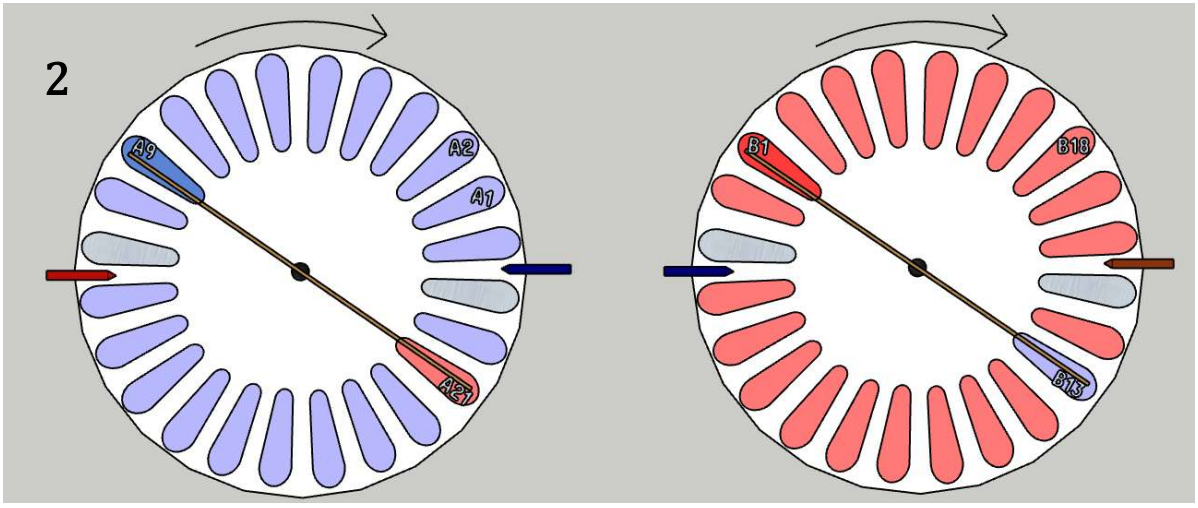
The two discs are sitting on the same axis, close to one another, and facing opposite sides, back-to-back as it were. In the following explanation the discs are represented as



both going clockwise, but you must imagine them sitting back-to-back, so as seen from the A-side alone, disc A is rotating clockwise, disc B is rotating counterclockwise.

Initially, on each disc there is a slight charge imbalance. They are slightly charged positively or negatively. It doesn't really matter. Let's call the sectors on one disc A-sectors and the sectors on the other disc B-sectors. There are 24 sectors on each disc, so we can refer to them as A1 to A24 and B1 to B24.

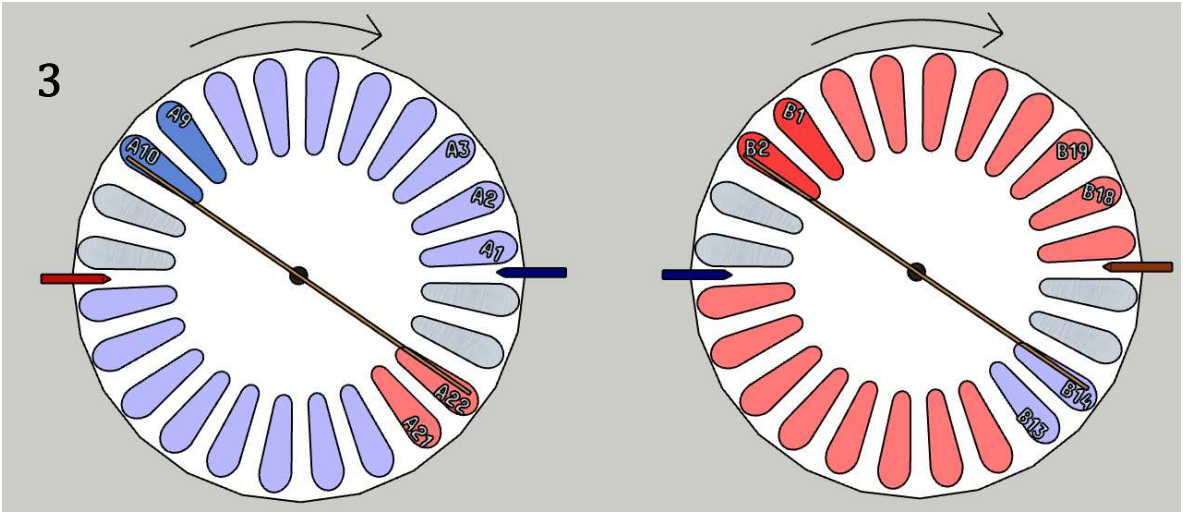
Let's say initially (1) sector A1 and B1 are both stationary and sitting opposite each other. As sector A1 is initially slightly charged, sector B1 experiences a force caused by the electric field emitted by A1. Let's assume A1 is negatively charged, then this negative electric field will repel electrons in sector B1 towards the outer layer of the metal. Nothing happens at this point yet since nothing is moving.



Now (2) suppose the discs turn a couple of degrees so the copper brush on the B neutralizer bar connects B1 electrically to B13, at the opposite edge of the B disc. The electric field from A2 will exert a force on the electrons in B1 and 'push' the electrons

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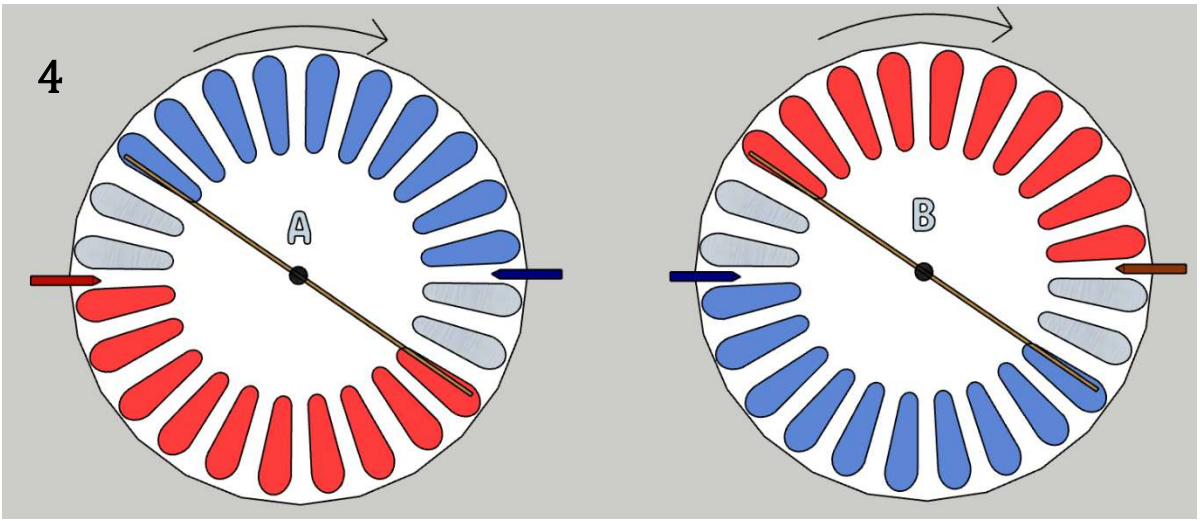
through the neutralizer bar to B13. As the disc turns just a little further, contact is broken and B13 remains negatively charged due to the excess electrons. B1 remains positively charged because some of its electrons were 'pushed' out to B13. B1 is *more* positively charged than before. A similar thing happens on the A-disc. As A9 is now electrically connected to A21, while experiencing a force from B18, attracting more electrons onto



A9 and pulling them away from A21, A9 becomes *more* negatively charged, and A21 is positively charged.

As the discs rotate further (3), the same thing happens to B2 and B14, and A10 and A22. What ends up happening (4) is that the top half of disc A and the bottom half of disc B become strongly negatively charged and the other halves are strongly positively charged.

At each side of the rotating discs there is a 'collector'. On one side all the sectors passing through one collector are positively charged, on the other side all sectors passing through the other collector are negatively charged. When the electric field is strong enough and the heavily charged sectors pass close to the collectors, they repel like charges, which then are collected in a charge bucket or capacitor. The collector is a U-shaped metal rod with needle-sharp ends. The sharp ends ensure that the electric field strength is very high at that point (the electric field lines are very close to each other). So let's say the negatively charged sectors on A and B pass the collector. The negative



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electric fields from both sectors at collector height will repel the electrons from each other towards the tips of the collector. The electrons are pushed into the capacitors, leaving the collector tip positively charged. Since it is a sharp point, the electric field is very strong there and more electrons are attracted from the air and the passing sectors. The sectors are robbed of many excess electrons. The same thing but inverted happens on the other side. The result is that one capacitor is being charged negatively and the other positively. If you turn the machine in a completely dark room and let your eyes adjust to the dark for a moment, you can clearly see the electron stream in and out of the collectors in the form of a blue haze.

The outer aluminium foils of the capacitors are connected together, so they are at the same potential. The inner foils are separated from the outer foils by a piece of PVC pipe, around 2mm thick. This functions as the dielectric of the capacitors. They must be able to withstand very high potential differences. Each capacitor has a measured capacitance of around 350pf. As charge builds up on the capacitors, the potential difference rises quickly. The maximum spark gap I could achieve is about 3.5cm, corresponding to a roughly estimated 100,000 volts, but that depends on humidity, the shape of the spheres, etc.

The charge on a capacitor is defined as

$$Q = CV$$

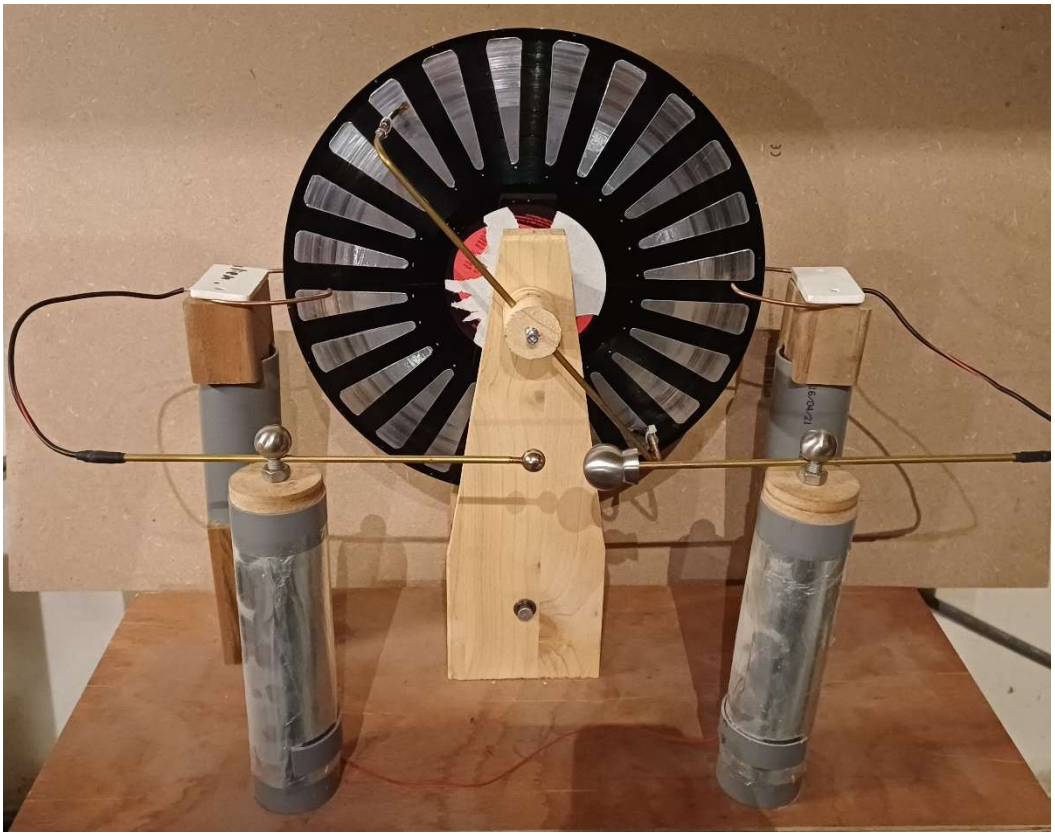
Capacitance of these Leyden jars is measured to be $350 \cdot 10^{-1}\ farad$. The potential difference between the foils of one capacitor at the point in time where arcing occurs can be estimated as half the potential difference across the spark gap, i.e. 50000 volts.

Then

$$Q = 350 \cdot 10^{-12} \cdot 50000 = 17.5\mu C$$

The charge of one electron is $-1.602 \cdot 10^{-19}C$. So the number of surplus electrons on one foil would be $109 \cdot 10^{12}$, or a million times 109 million surplus charges. There's no real point in this calculation, other than to marvel at the staggering magnitude of that number and how fast that all happens. It takes only a few seconds of turning to get a big spark.

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In order to get big sparks you need to minimize **losses**. Any sharp tips or edges on the connecting components (rods, bolts, nuts, threads, etc.) will create points with a strong electric field and discharge into the air (corona discharge). You lose energy.

Polarity. The small ball should be the positive terminal of the spark gap. A smaller surface area creates a stronger electric field. If the small ball is negative, i.e. has suplus electrons, the electrons will have a tendency to 'escape' into the air, a phenomenon called corona discharge. It can be observed as very thin bluish branches emanating from the small ball's surface. It is audible as a hissing sound. In order to control the polarity, you can rub a plastic bar (like PVC pipe) on your sweater or shirt to make it negatively charged. Make sure the spark gap is neutralized first by shorting the terminals. Then start the machine while holding the charged plastic bar close to one of the discs, where the neutralizer bar contacts the sectors, and start turning. If it doesn't work, do the same, but now on the opposite side. Once the machine is 'primed', it should hold the same polarity for a while. When left untouched for a longer period, the machine's polarity may be reversed again and you need to do the trick with the charged PVC again.

Energy. If we assume that a potential difference of 100kV is achieved, then the energy released at discharge is

$$E = \frac{1}{2}CV^2 = 1.75J$$

That is actually quite a lot. For reference: if a load is connected between two terminals at a mains voltage of 230Vrms, and that load draws 7.6mA for one second, that amount of energy equals 1.75 Joules. These amounts of energy can be lethal, so we need to take every precaution to avoid being shocked. Worst case is through the chest, e.g. by touching both poles with your hands when the capacitors are charged. Never touch the two poles with both hands. Always discharge the spark gap multiple times in a row with a 'discharge wand', which is just a piece of wire with two bare ends, attached to a plastic or wooden handle.

Dielectric absorption. A little devil. I have been zapped because of this phenomenon. Because there is such a strong electric field between the inner and outer foil, the molecules in the PVC (the dielectric) form dipoles: the electrons lean away from whichever foil is negative and form little dipoles, even though the charges cannot move as in a conductor. The dipoles align with the field direction. That is work done by the electric field. When the field suddenly collapses (the spark), it takes time for many dipoles to return to their previous quiescent state. So at the moment the field strength snaps to zero, the dielectric remains partly polarized. The molecular dipoles are sluggish to return to their quiescent positions, and as they do so slowly, they themselves now cause an electric field between the two foils. You can observe that notably in electrolytic capacitors. Immediately after discharge you can see the voltage climb back up on a DMM. It's like it remembers the previous state and attempts to go back (this is termed hysteresis). PVC suffers from rather high dielectric memory, and even if you discharge

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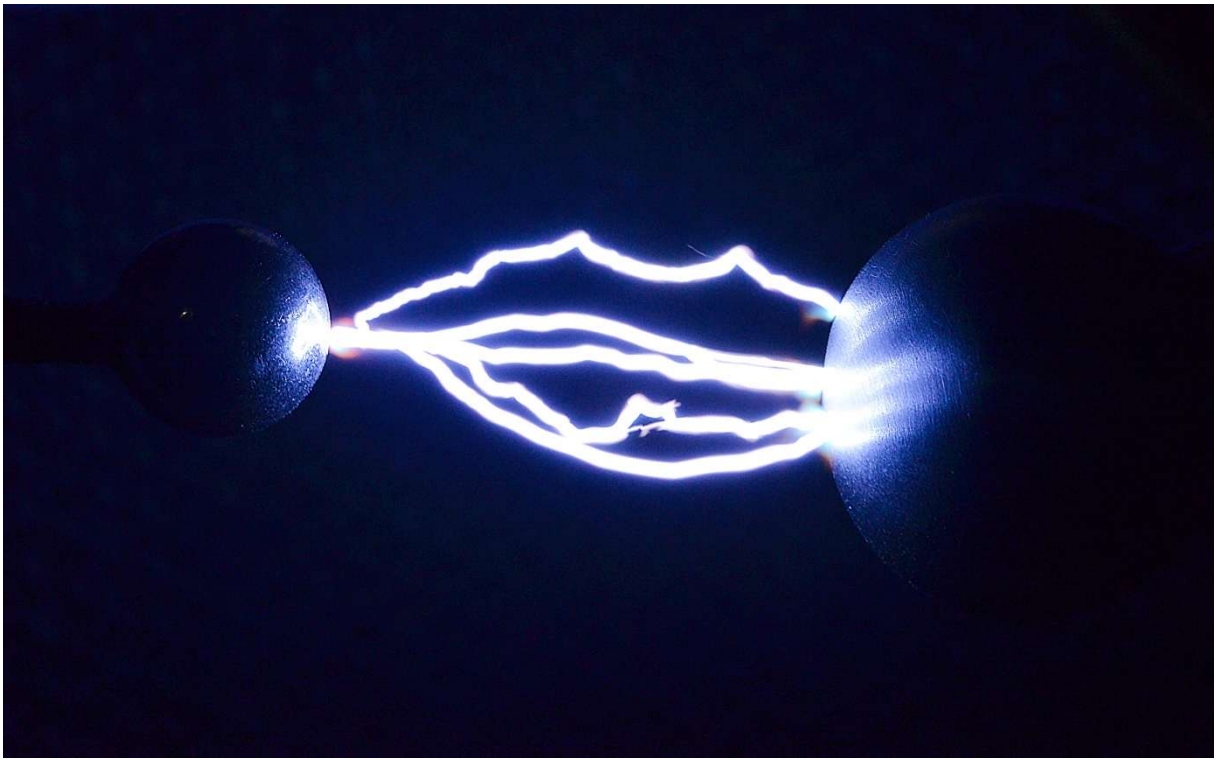
the capacitors with a discharge wand, the voltage will climb up again the next few seconds or minutes. Maybe even towards 15% of the previous voltage. Enough to give you a painful jab. For this reason I always leave the discharge wand hanging on the electrodes.

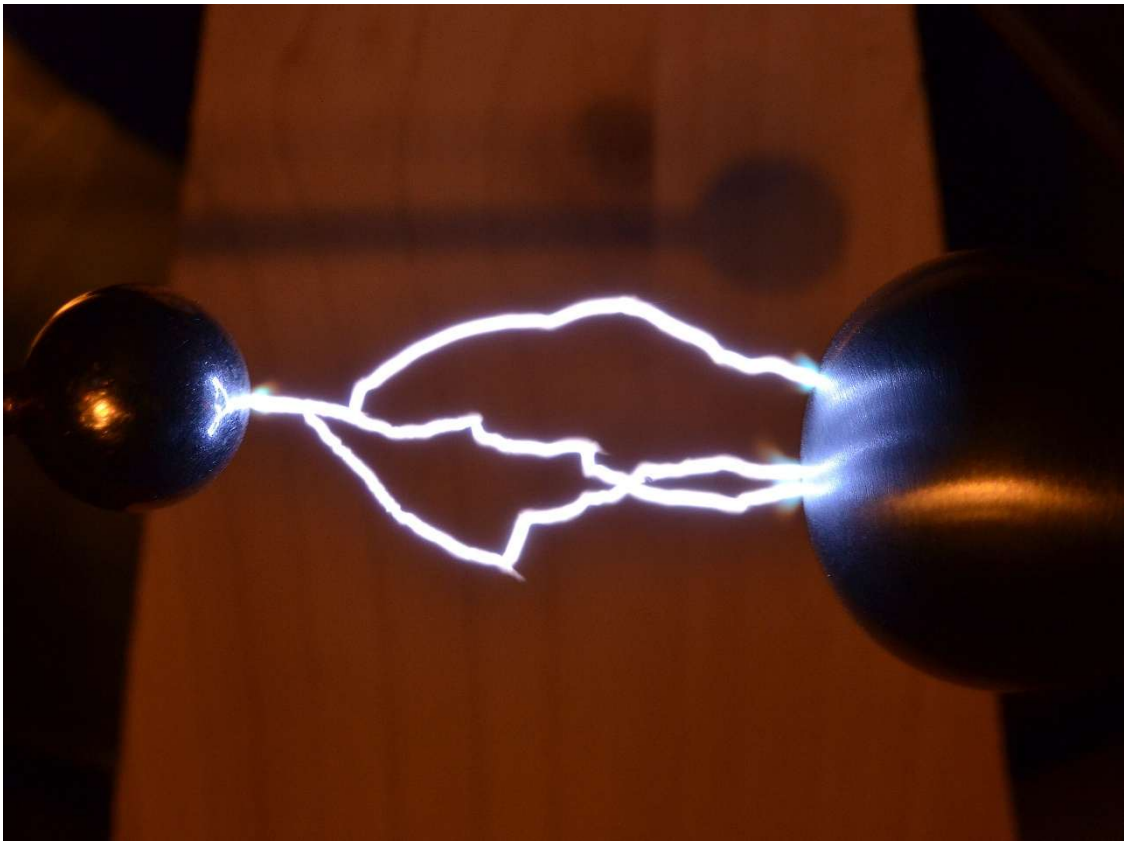
Dielectric strength of PVC. The PVC has a wall thickness of 2mm. The type I use here is something I had lying around and is to be used for cold water drainage. A little search on the web revealed that the dielectric strength of this type is likely 544V/mil (where 1 mil is 0.0254mm), which means that the maximum potential difference this pvc can withstand is around 42kV. With spark gaps of 3.5cm I am actually exceeding this maximum. Better alternatives would be polycarbonate, glass, acrylic, etc. but these materials are more expensive, more difficult to work with, or less likely to be found in general applications around the house. I should keep the spark gap below 3cm to avoid damage to the PVC. Once it is punctured by an arc, the capacitor is no more.

Dielectric constant of PVC. This determines how much energy you can store in the electric field between two foils with a given surface area at a given potential difference. A larger dielectric constant gives you more capacitance for the same surface area. PVC has a dielectric constant of 3 or 4. Not so much, but ok. Since I can generate intense blue sparks of 3cm easily, there is enough energy storage. A material like glass has a higher dielectric constant, but that would mean I would have bigger 'buckets' to fill with charges.

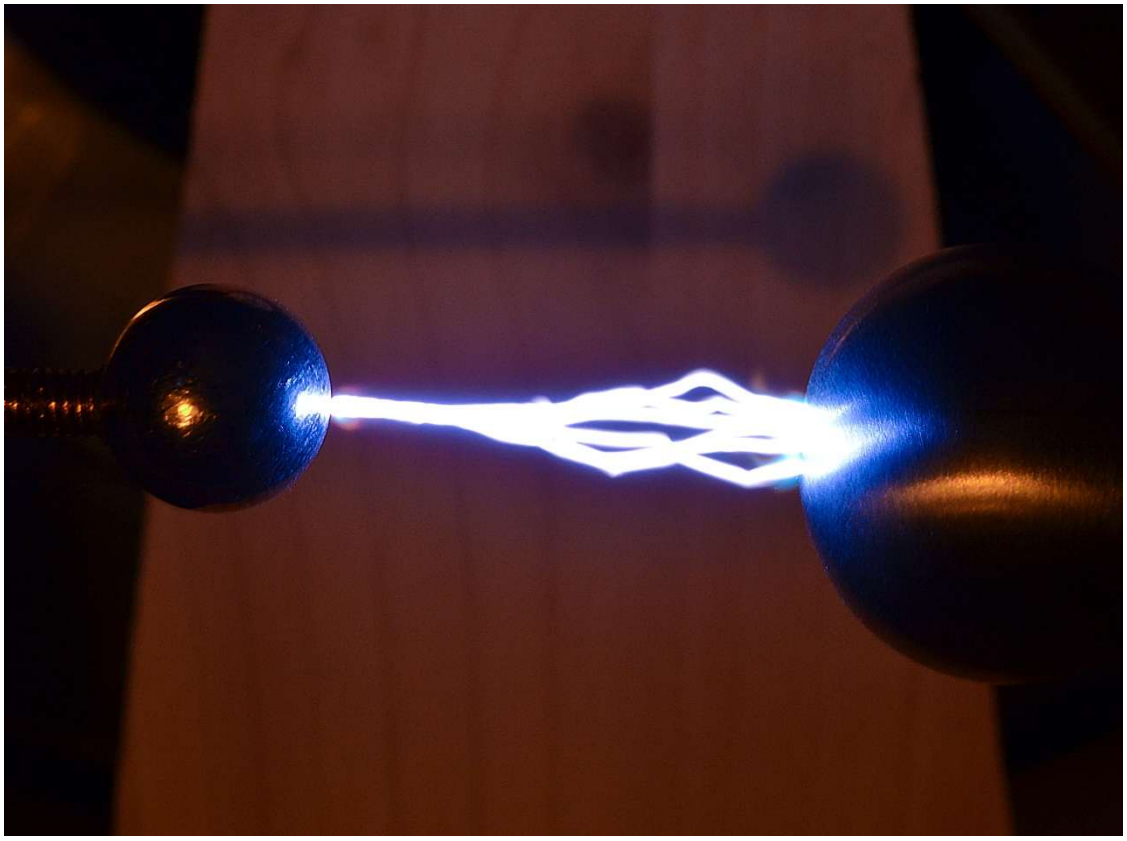
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