Tesla Coil Frequently Asked Questions
Chapter 7: The Primary Coil
Part 1 of 5

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Overview

This chapter of the tesla coil FAQ (Frequently Asked Questions) deals with the primary coil. In a tesla coil, a high voltage power supply charges up the primary capacitor until a spark gap breaks down and shunts the energy stored in the capacitor into the primary coil, an inductor. This energy is then magnetically coupled to the secondary coil. Some time later (some tens of microseconds), the spark gap becomes non-conducting while the primary current is swinging through a zero crossing, and the charging cycle begins again. This energy exchange may occur several hundred times per second if the power supply is capable of recharging the capacitor fast enough. In the meantime, the energy deposited in the secondary coil system rings down, usually in the form of a spark discharge. During the primary system discharge, the high voltage charging power supply is essentially out of the circuit and we are left with a capacitor, an inductor and the closed switch (spark gap). The energy during the discharge cycle is exchanged back and forth between magnetic field in the primary coil and electric field stored in the capacitor. The rate of exchange of energy between the capacitor and inductor is a resonance phenomenon which follows the equation:

$$F = \frac{1}{2\pi\sqrt{L_p \times C_p}}$$

where: F is the resonant frequency, π is a constant (3.14159...), Lp is the inductance and Cp is the capacitance of the primary circuit. The resonant frequency of this inductor/capacitor pair must match the resonant frequency of the secondary circuit, which consists of a secondary coil (inductor) with inherent distributed capacitance plus a toroid or sphere on top (providing additional capacitance to the secondary circuit). Typical operating resonant frequencies are in the 50-500 kilohertz range, well below AM radio. BTW, the secondary coil resonant frequency formula is identical, except Cp is now the sum of the distributed capacitance of the coil plus the capacitance of the toroid or sphere on top, and the inductance of the secondary is substituted for Lp.

Safety

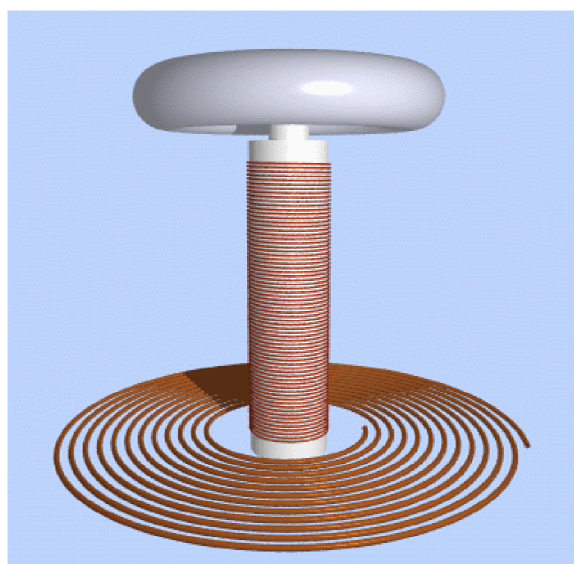
The primary circuit is often uninsulated, and raw 50-60 Hz A.C. at high voltages (5-20 kilovolts typically) is present whenever the unit is energized. This is absolutely lethal to humans and pets if contact is made. In addition, the primary capacitor can retain a lethal charge for many weeks after turning the unit off. Always turn off the coil AND unplug the power supply AND short out the capacitor before making any adjustments of the primary circuit. If you have no experience with high voltage equipment, do not build a tesla coil. These devices are inherently very dangerous and should only be constructed by individuals with high voltage experience. If you do have experience with high voltage equipment, read the tesla coil safety FAQ for additional safety tips before constructing your first coil. The author assumes no responsibility for your safety and provides this FAQ for educational and informational purposes only.

In addition to contact dangers, an arc from the secondary to the primary can couple raw high voltage A.C. to whatever else is in contact with the arc (possibly you). Do not touch secondary coil spark discharges under any circumstances. Some tesla coils use the Oudin coil geometry (invented by Nikola Tesla, popularized by Oudin), which feeds raw high voltage A.C. directly into the secondary coil, making all arcs from it potentially lethal. Be careful and keep the equipment out of the hands of children, pets and others who aren't familiar with the tesla coil. Several individuals have been killed by these devices, including a small child (with a nearby intoxicated parent) and an experienced longtime coiler.

Primary Coil Geometries

There are three common primary coil geometries: the flat spiral (Archimedian spiral), helical (solenoidal) and the saucer (inverted cone) coil. Each has advantages and disadvantages. In general, most of the inductance in the primary is in the outermost turns, since inductance is proportional to diameter. Inductance is also proportional to the number of turns squared, so a turn or two difference makes a relatively large change in inductance.

Most primaries contain between five and 25 turns, and are designed so that the innermost turn (or bottom turn of a helical coil) is always attached to the capacitor. The other connection to the primary is usually in the form of a movable tap, so the primary circuit can be tuned to the secondary circuit. The primary capacitance is usually not easily changed, although this may be possible with some capacitor configurations (e.g., salt water caps).



The flat spiral coil is perhaps the most common configuration, especially if the coil is to process more than a kilowatt of power or so. It is illustrated to the right. The innermost turn connects to the capacitor, and a tap is made from below the coil to form the inductance of the primary.

It is a good idea to construct the primary quite a bit bigger than you initially expect, since if power permits, you will find the need to use larger toroids on the secondary, which will lower the resonant frequency, requiring additional primary inductance. With the flat spiral configuration, expect to add enough turns for at least 25-30% more inductance than you think you need. You will be glad you did it later.

The wire that leads from the innermost turn to the outside is placed beneath the coil, usually an inch or so below the turns to prevent arcing. I usually cover this lead with polyethylene tubing for additional insulation, or place a piece of plastic as a shield.

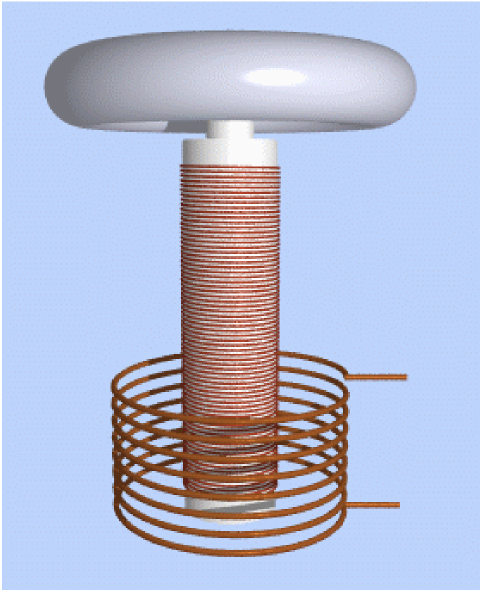
This coil is usually constructed of copper tubing or thick wire, but spirals of flat copper flashing work well, too. They can be wound closer together than copper tubing, still allowing enough space for tapping the primary for tuning purposes. There is a tendency for corona to occur with flashing if high primary voltages are employed (>15 kV).

The formula for estimating the inductance of a flat spiral coil is:

$$Lp = \frac{n^2 x\, a^2}{8a + 11w}$$

Where: n=number of turns, a=coil radius in inches, w=thickness of the spiral in inches ([outside diameter-inside diameter]/2). This formula will get you within 10% or so of the true value generally.

Another common configuration for primaries is the helical or solenoidal primary, depicted here to the right. This geometry is often used with vacuum tube coils. It is not so often used with disruptive (spark gap) tesla coils because of difficulties in obtaining the right coupling. It is easy to over couple with this configuration. However, in the Tesla magnifier configuration, tight coupling is important, and here it is often employed as the primary coil for the driver. The solenoidal primary is usually placed somewhat lower than a comparable flat spiral or saucer geometry primary. See the comments under coupling below. Again, the bottom lead attaches to the capacitor and the tap point is on a turn above the bottom turn somewhere. As the tap point is changed, the coupling changes more with this geometry more so than with the flat spiral coil.

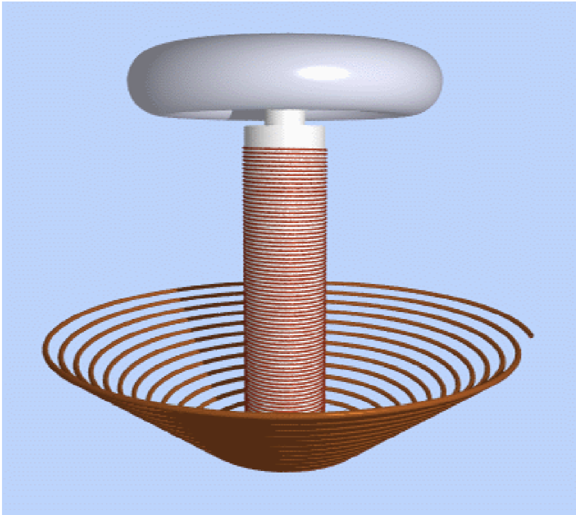


Wheeler's formula for estimating the inductance of a helical (solenoidal) coil is:

$$Lp = \frac{n^2 x\, a^2}{9a + 10l}$$

Where n=number of turns, a=coil radius in inches, l=height of the solenoid in inches. This formula will get you within 10% or so of the true value generally.

The third common coil geometry is the saucer or inverted cone geometry, shown here. The turns are placed on inclined planes so that each successive turn is higher than the other. Typical angles are 15-45 degrees, with 30 degrees often used (outer turn height equals one half the thickness of the turns on one side).



The coil is usually supported using a series of four to eight wedges which are cut out of acrylic or some other insulating material which is attached to a plywood base. In small coils, Styrofoam posterboard is often employed, with the turns held in place using a hot glue gun. The main advantage of this configuration is ease of tapping the turns from below, and an esthetically pleasing coil. It is not used a lot with high power coils since there is an increased risk of arcs between the secondary discharge and the top turn of the primary.

The coupling characteristics of this coil are similar to the flat spiral for angles of 30 degrees or less, so there is little to be gained with this configuration except appearance. (See coupling comments below.)

This geometry is useful with angles of 45-60 degrees for constructing magnifier primary/driver systems, which will not be covered here.

The formula for the saucer or inverted cone coil is an interpolation between the two previous formulas. A common approximation formula is the following:

$$Lp = \sqrt{(L_1 \sin(\Theta))^2 + (L_2 \cos(\Theta))^2}$$

where: L_1=formula for a helical coil above, L_2=formula for a flat spiral coil described earlier, w is the horizontal thickness of the coil, Θ is the tilt angle, and the other terms are as they would be used in the formulas stated above. Linear interpolation of the above formulas also works about the same. It will usually get you within 10% of the true inductance.

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Design Strategies

The idea is to build a primary which will have very low losses and the tightest possible coupling, consistent with not destroying the secondary due to racing sparks up and down the secondary. BTW, racing sparks along the secondary are an indication of EITHER coupling that is too tight OR having a coil out of tune. If you see this, stop immediately before you destroy the secondary. Move the primary several inches below the secondary to reduce the coupling and get things tuned up properly before raising the primary to increase the coupling. You need to sort out each problem independently.

When designing a primary coil, keep in mind the losses that are present. The maximum possible current in the primary coil system is the capacitor voltage when the spark gap closes divided by the total resistance of the primary circuit. The resistance consists of the resistance of the spark gap, usually 1-5 ohms, plus resistive losses in the wiring (hopefully small), dielectric losses in the capacitor, plus Zp, the surge impedance of the LC circuit:

$$Zp = \sqrt{Lp / Cp}$$

The surge impedance should be around 15-75 ohms typically, so that the losses in the spark gap and wiring do not dominate the losses in the primary. If your spark gap is a rotary with tungsten and you are using a pulse discharge capacitor with thick copper tubing, use the lower figure for Zp. If you are using salt water or other lossy capacitors, thin wiring, and/or a poor spark gap, use a higher value for Zp (perhaps 50-75 ohms). If you know the resonant frequency of your secondary system and have a fixed primary capacitor value (often the case), it constrains the surge impedance. Make sure this constraint leads to a reasonable Zp value if possible. Remember also that the primary power supply must have enough capability to quickly charge the capacitor, further constraining the design.

The total resistance plus surge impedance limits the maximum possible current flow in the primary circuit. For example, if Zp plus resistive losses equals 50 ohms and the spark gap closes when 5000 volts are applied, the maximum primary current will be 5000/50 = 100 amperes! That is why you want to construct your primary using thick wires or copper tubing with solid connections to each component.

Another aspect in primary circuit design to consider is off-axis inductance. Every foot of wire used to connect the spark gap, capacitors and primary produce about 1 uH of inductance. This inductance affects the resonant frequency but is not used to induce currents in the secondary. It is wasted energy, and is called off-axis inductance because it does not couple energy to the secondary. Keep leads short and try to lay out components with this in mind. Many builders construct a two level platform with the lower level for the power supply, spark gap and capacitor, and the upper level for the primary. This keeps lead lengths minimal.

Construction Hints and Tips

The primary coil inductance is generally between 20 uH (microhenries) and 120 uH, when using primary capacitors in the typical 5-25 nF range (.005 uF to .025 uF). This inductance value is quite small, and most inductance meters will fail miserably when measuring inductances below 1000 uH or so, especially if there is stray capacitance present (like some unused turns of the primary). You are better off just finding the resonance frequency of your LC pair than believing the reading on an inductance meter.

Avoid placing ferromagnetic objects close to the primary if possible. Use nylon screws to prevent distortion of the magnetic fields. It is common practice in large coil systems to place a loop of copper tubing located about one inch above and just outside the outermost turn of the primary to serve as a strike ring if the secondary chooses to draw an arc to the primary. This tubing should not form a complete loop. Leave a gap of about one inch so it does not act as a shorted turn, which would rob power from the primary. The strike guard is hooked to your RF ground to protect your primary components.

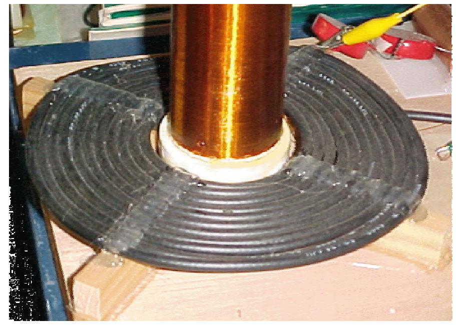
The primary coil needs to handle tens to hundreds of amperes of current, depending on its size. The current is at radio frequencies, so it travels on the outer surface of the conductor. Keep the surfaces clean and consider the use of hollow tubing, since the current is on the outside anyway. The primary coil is usually constructed of either copper tubing or flat copper flashing one to three inches tall. If you use copper tubing, purchase refrigeration tubing instead of copper tubing for plumbing. The refrigeration tubing is much more flexible and will bend without kinks, unlike the plumber's tubing. For small desktop coils I use either 8-12 AWG solid copper wire which is PVC coated, or enamel coated wire of the similar gauge for low voltage tube coils.

The innermost turn of the primary should be no closer than one to 2 inches away from the secondary. For a first coil, I suggest 1 ½ inches. This means that the primary coil inside dimension must be no smaller than 3 inches larger in diameter than the secondary coil diameter. If you build it closer, you will probably have problems with arcing between the primary and secondary. Remember, the bottom of the secondary coil gets connected to earth ground, which is a place high voltages like to find. Normally, the primary circuit is floating with respect to ground, having no connection (except perhaps the midpoint of an NST).

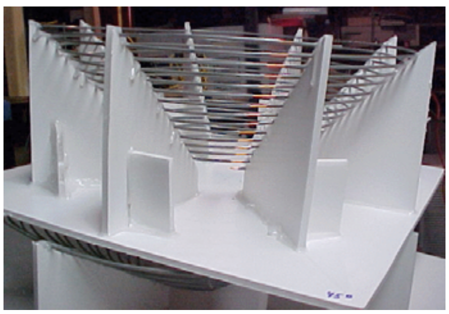
The spacing between turns should be sufficient to allow for placing a tap point on the coil. I use a minimum of ½ inch for 3/16 or 1/4 inch diameter tubing, and a spacing equal to the tubing diameter for larger tubing sizes. If you make it closer, it is likely that your tap point connection will short out turns, which causes a loss of energy. Larger spacing results in a large primary coil dimensions, which reduces coupling. The tap should have a large surface area but should be adjustable for tuning purposes. An alligator clip of appropriate size with curved copper contacts soldered to the clip is often used.

Alternatively, a band of copper flashing is wrapped around the tubing and held in place with a bolt and screw, which is also used to attach the heavy lead cable.

A series of photos with short descriptions is provided below to provide ideas and examples of typical primary construction. It is by no means complete.

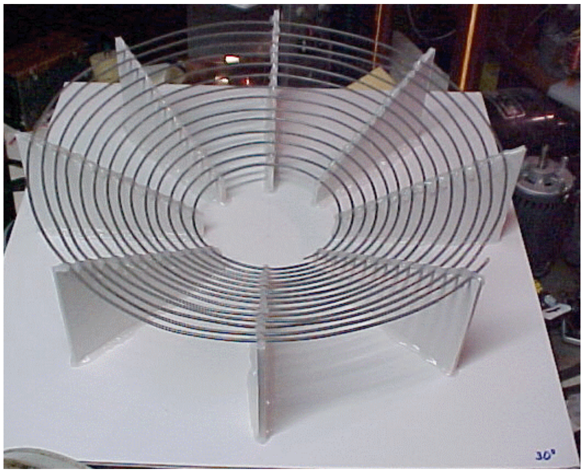


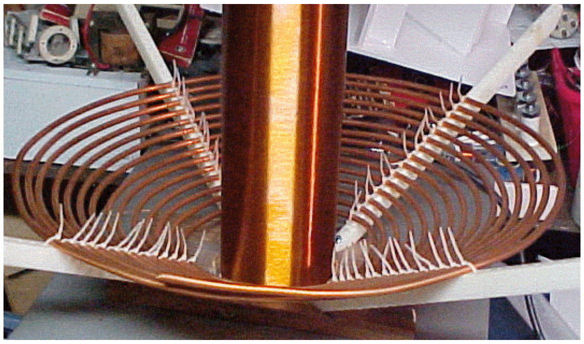
Coaxial cable is used in some small coils. The outer braid is the conductor. It is lossy and not recommended for large coils, but works okay for a small first coil. The coil to the right is 2" in diameter with 12 turns of coax mounted on some small strips of wood. The tap point uses a tack initially which is pushed through the coax to the braid. When the tap point is established, a portion of the jacket is stripped away so a solder connection can be made.



Here is a 45 degree saucer-shaped primary coil constructed from 16 AWG solid PVC coated wire on a foam board coil former. Foam board designed for posters and wires are assembled using a hot glue gun. It is a simple construction method for a small coil. Note how the PVC insulation has been stripped away from the wire in several places at each turn for tuning purposes.

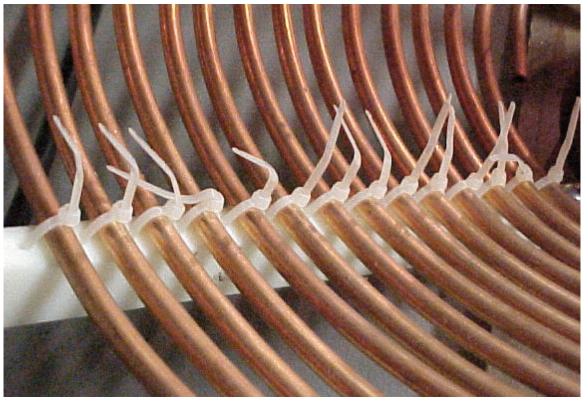
Here is another example of another inverted cone geometry primary coil, constructed in the same manner as the previous example (30 degrees angle this time). Eight support wedges are used to secure the wire in position. Some people use four the whole way and use four partial wedges to support the outer turns

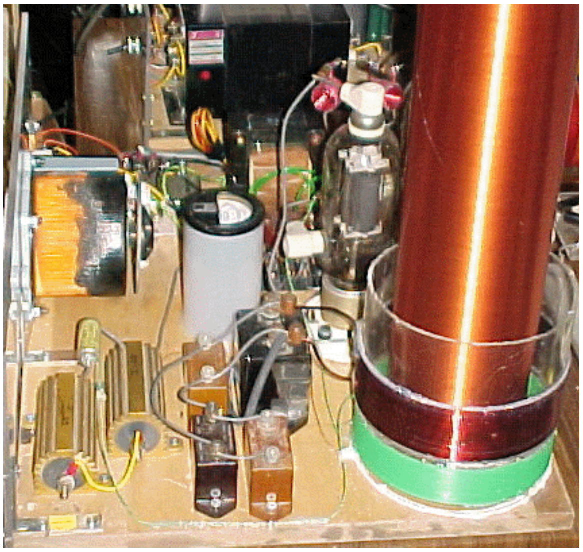




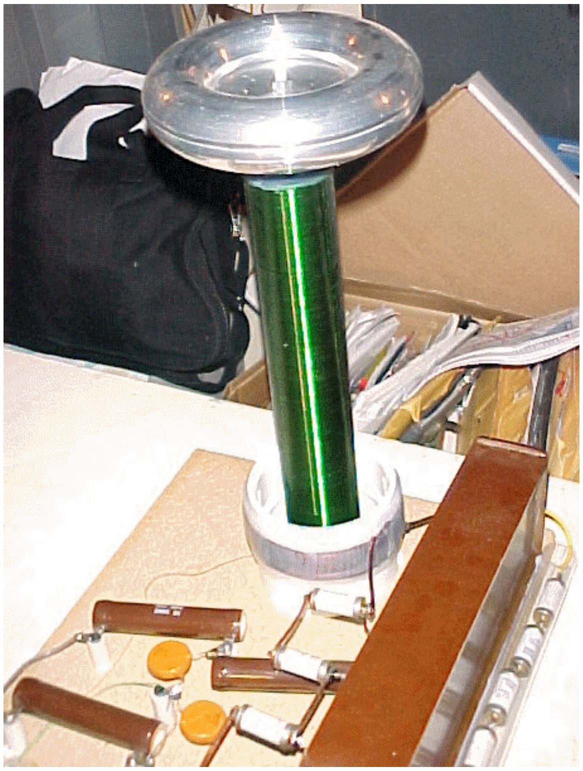
Here is an example of an inverted cone geometry using copper tubing and cable ties to hold the tubing in position. The ends of the cable ties are removed later to clean up the layout. This is for a 4.25" secondary in this example.

A detail of the cable ties is shown to the right. Holes are drilled down through the plastic to form a loop for the cable tie around each tube. The plastic support beams are bolted to a plywood base at the bottom.

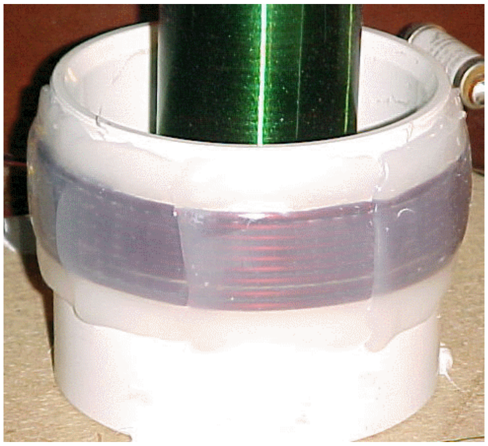


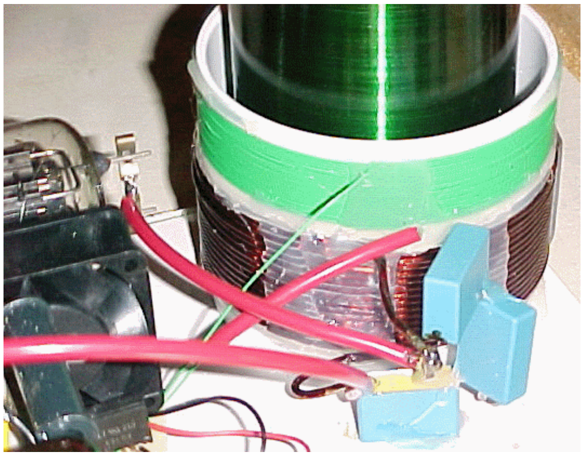


Here is an example of a solenoidal or helical geometry in a tube coil. The green coil is the grid coil in this example, wound with about 20 turns of 24 AWG PVC coated wire. The plate tank coil is 10 AWG enamel-coated wire. In this example, about 18 turns are required for this 4" secondary coil. The primary is wound on a 6" diameter form. The tank capacitor consists of four mica capacitors in parallel in this dual 810 triode tube coil. It puts out 12" sparks using a microwave transformer for the power supply.



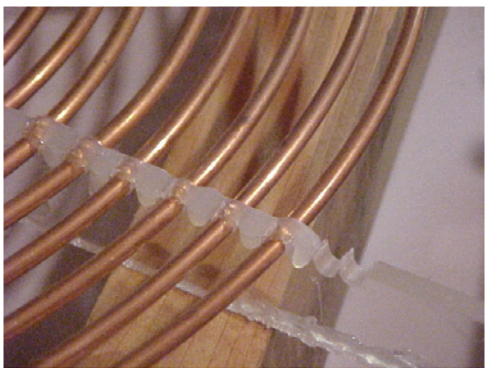
Here is an example of a small spark-gap disruptive tesla coil using a helical primary wound with 10 AWG enamel coated wire. The turns are held in place by a coating of hot glue. The primary is 3" in diameter and the secondary is a 2" by 11" coil wound with 28 AWG green enamel wire. This little coil puts out 11" sparks using a .005 uF primary capacitor with a 7.5 kV NST. The spark gap in this coil is a series arrangement of four 2500 volt Victoreen spark gaps. The are also used as for overvoltage protection of the capacitor, shown to the right of the capacitor. A detailed view of the windings is shown below. The coupling is about 0.15 for this coil.

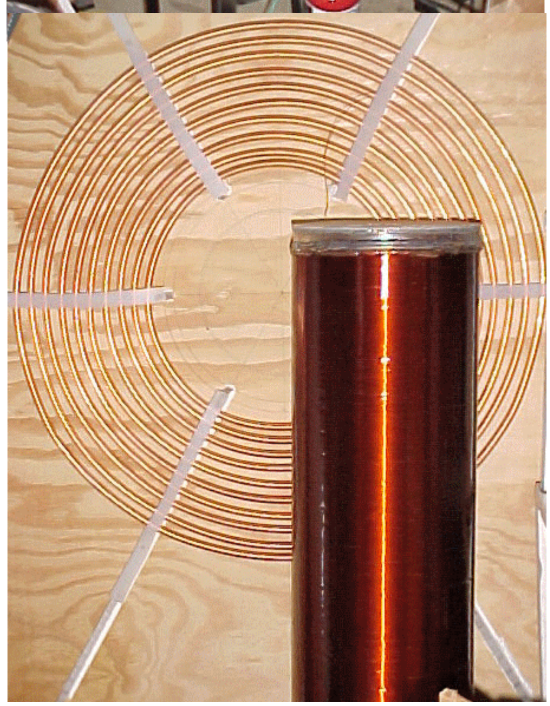




Another tube coil primary is shown here, this time with the grid winding above the primary winding. The primary tank circuit capacitor in this case consists of three of the .015 uF WIMA units in series. These capacitors are sometimes used in large parallel/series arrangements to form the primary capacitor (designated MMC, mini-multi capacitor). This is a small tube coil with a 3.5" diameter secondary using a single 829B beam power tube, producing 2.5" sparks. It is mainly used for demonstration purposes for illuminating gas-filled tubes. Again, hot glue and enamel wire are used in the construction. PVC coated 10 or 12 AWG wire is also excellent for this application. In this example, tuning was achieved by varying the capacitance rather than tapping the primary inductor.

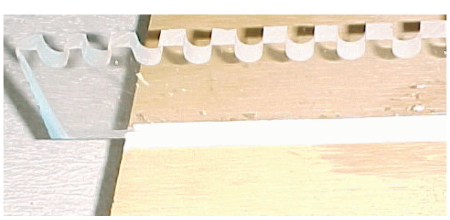
Here is a 4.25" diameter secondary fed by a flat spiral coil with an inner diameter of 8" and an outer diameter of 20", constructed of 3/16" refrigeration tubing. The tubing is layed in grooves cut in acrylic guides using a router. A detail view is provided below. The tubing is held in place with hot glue, which fills the interspaces. This primary was designed to operate with a 5" diameter secondary originally, so the spacing between the primary and secondary is a bit larger than seen in some coils. Nonetheless, sufficient coupling is easily obtained by raising the primary above the bottom turn of the secondary by about 3" using simple wood blocks.





The coil to the right is my large coil. The secondary is 8" by 26.5", wound with 22 AWG wire and coated with several coats of polyurethane. The primary is constructed of 50 feet of 3/8" refrigeration tubing placed in grooves cut in acrylic strips. A detail view of the acrylic former construction is shown below. The grooves were made using a router. The tubing is placed in the grooves and is held in place using some thin strips of polyethylene which are tack-glued in place.

If you don't have a router, clamp two rectangular pieces of acrylic together and use a drill press to drill holes along the seam where the two pieces meet. Place the tubing into the grooves starting in the inside, working your way out, and lock it in place using the top piece with some nylon screws as a clamp.



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Coupling

Coupling refers to the transfer of energy from the primary resonant LC circuit to the secondary resonant LC circuit. The exchange of energy depends on the mutual inductance between the primary and the secondary inductors. There is no simple formula for computing mutual inductance. The mutual inductance results presented in this section are through direct numerical integration of the equation describing the coupling between two inductors (Neumann formula), which can be accomplished without difficulty if sufficient computer horsepower is available. An approximation formula using a power series has been used by some folks, but it is prone to severe roundoff errors when tesla geometries are employed.

Mutual inductance M is one measure of the coupling. A more common calculation is to determine the coefficient of coupling K:

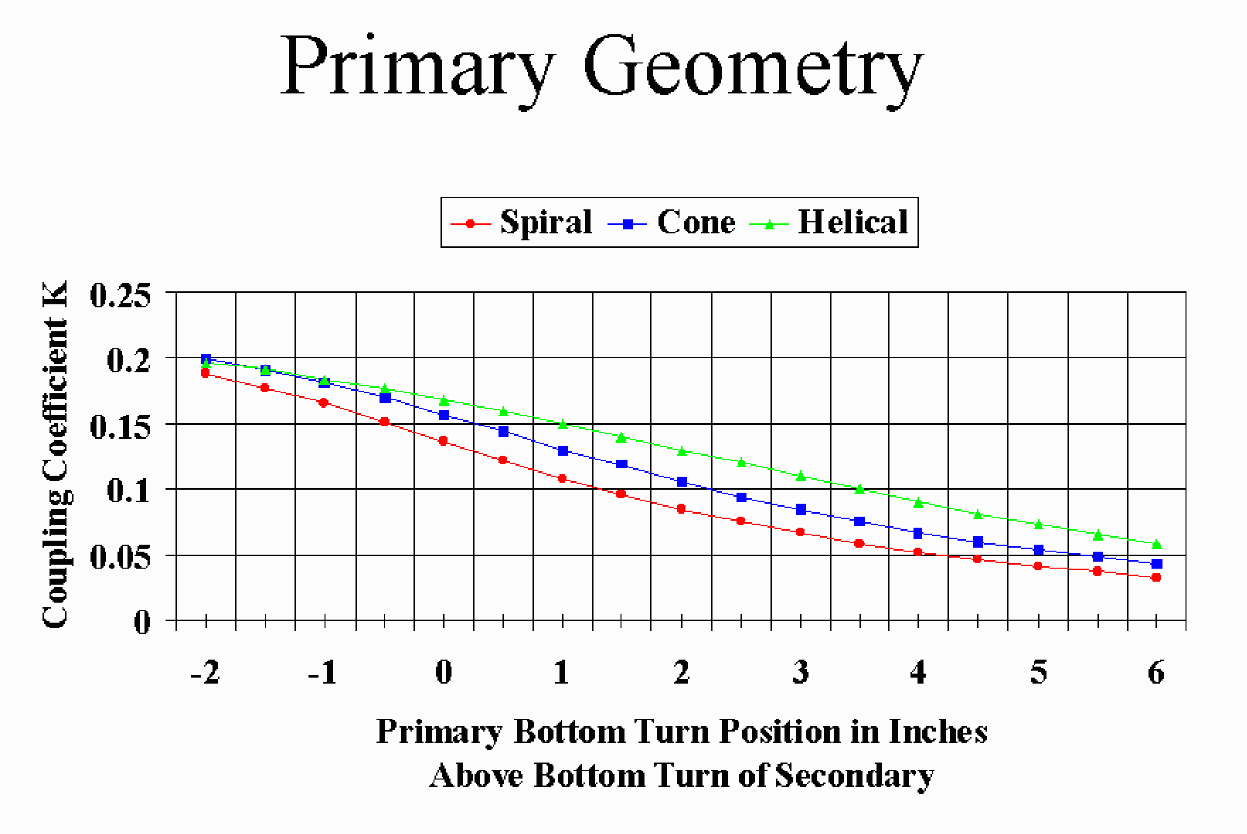
$$K = \frac{M}{\sqrt{Lp \cdot Ls}}$$

The coupling coefficient describes the fraction of inductance coupled between the two circuits. Typical K values are between 0.05 and 0.25 for conventional tesla coils. For magnifiers, we strive for K values of 0.3 and higher.

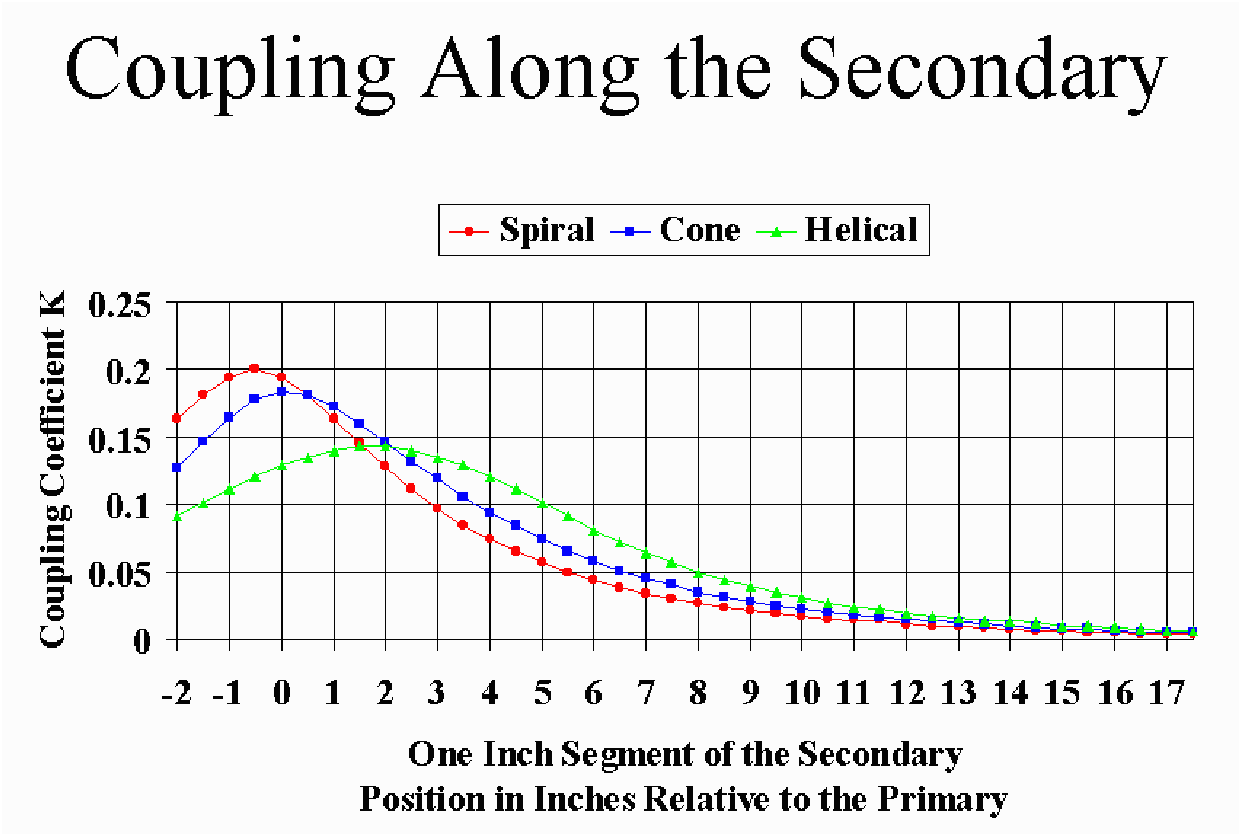
One can measure the mutual inductance between the primary and secondary of a tesla coil at any coil position or orientation using the following method: Place the tesla coil in the position you want to measure the coupling at. Remove the toroid from the secondary, the spark gap and the primary capacitor. Apply as much 50-60 Hz current to the secondary as it can handle. (Consult wire tables for maximum current ratings.) I usually use a 100 ohm resistor in series with the secondary, then connect it to a variac and measure the voltage on the resistor while adjusting the variac such that 1.00 amperes of current flows through the secondary (100 volts AC). Be aware of the inherent dangers of using raw AC! Call the secondary current "Is." Measure the open circuit voltage on the primary Vp using an AC voltmeter. The mutual inductance is equal to:
Vp / (Is *377) for 60 Hz, or VP/(Is * 314) for you 50 Hz folks.

Since coupling is awkward to calculate, little has been published regarding how the primary bathes the secondary. This is remedied here using examples of the three primary geometries. Consider a tesla coil with the following design criteria: The secondary is 4.25 inches in diameter (e.g., thin walled PVC pipe), 18.5 inches tall and is wound with 950 turns of 26 AWG enamel wire. The toroid and spark corona cloud on top is assumed to contribute 15 pF of capacitance to the secondary resonant circuit (about a 4 inch torus diameter with an outside diameter of 12 inches). This results in a secondary resonant frequency of about 235 kilohertz, since the distributed capacitance for a secondary this size is about 8 picofarads. Let us use a primary capacitance of 0.015 microfarads (15 nF). That leaves us with a required primary inductance of about 30.6 uH, yielding a surge impedance of about 45 ohms (within our target range). Let us now design three primary coils to yield about 31 uH inductance each and see how they couple to the secondary. First, we design the flat spiral. I choose an inside diameter of 6.25 inches (one inch away from the secondary). I plan to use 3/16 inch refrigeration tubing since it is easy to bend and since this is a small coil system which will handle no more than 1.5 kVA. For convenience of tapping the primary, I choose a turn-to-turn spacing of ½ inch. To obtain 31 uH, I need 10 turns. That's about 30 feet of tubing. I would purchase a 50-foot roll and wind additional turns in case I later add a larger toroid (likely if I increase the power a bit). For the saucer geometry, I use the same inside diameter, same number of turns, and use an angle of 30 degrees, yielding an outer turn height of 2.5 inches above the first turn. The inductance of this coil is slightly higher, about 35 uH so I would tap it at about nine and a half turns or so. Again, I would wind the primary with 50 feet of tubing to provide a reserve for adding a larger toroid later. Finally, I design the solenoidal geometry primary. I know from experience that the diameter will have to be quite a bit larger than the secondary. That is one of the common pitfalls of using a solenoidal primary coil. For consistency, I use 10 turns for this coil also with a turns spacing again of ½ inch. This yields a required diameter of 12 inches. Upon more detailed calculations, I find that I must use only nine turns to yield the required 31 uH of inductance. As a result, the coil is 4.5 inches tall. Again, in practice, I would use about 50 feet of wire, yielding perhaps 45-50 uH total inductance to allow for larger toroid sizes in the future.

We can examine the coupling between the primary and secondary for these three geometries by graphing the coefficient of coupling K as the relative position between the bottom turn of the primary and the bottom turn of the secondary are changed. This is shown at the top of the next page. For convenience, a value of zero indicates the bottom turns of both coils are in the same plane. A negative value indicates that the bottom turn of the secondary is below the bottom turn of the primary. A positive value means the secondary is above the primary bottom turn. If the desired coupling is 0.10 for this coil, we see that the solenoid is overcoupled until the secondary is raised about 3 1/2 inches above the bottom of the primary, even for this rather large diameter helical coil (12 inch versus 4 ½ inch secondary). Note how the inverted cone (saucer-shaped) coil couples more than the flat spiral, but less that the solenoid. The flat spiral primary couples at 10% when it positioned 1 1/4 inches below the bottom turn of the secondary. These curves show that any of these geometries will work with this secondary, but if a solenoidal primary is used, the diameter must be fairly large. All of the primaries require around 30 feet of tubing at resonance, with a few inches less for the solenoid.



The curves at the top of the next page illustrate how the turns of the primary couple to a small portion of the secondary. In this example, the secondary coil consists of a one inch length of the original 18.5 inch secondary. We can examine how the primary couples to this portion of the full-size secondary coil by graphing the coupling coefficient as this small portion of the coil is moved about the large primary. These results are shown above. Examining the flat spiral curve, we see that maximum coupling occurs at -0.5 inches, where the one inch secondary coil is centered about the plane of the flat spiral coil. The coupling falls off quickly with distance as the turns are moved away from the primary. Note how once we are about one primary coil radius above the primary coil (8 inches in this case), there is very little coupling between the primary and secondary. This is a desired result. We want to dump all the energy into the bottom of the secondary and then let the standing wave develop along the coil. The saucer coil couples to the secondary over a larger distance, but is again negligibly affecting the secondary after about one primary coil radius in distance. The solenoidal coil couples over a much longer distance, even with its rather large diameter compared to the secondary diameter. This can be advantageous if the secondary coil is very long, which is true for small coils (less than 3 inches diameter), where the length to diameter ratio may approach 6:1 or more. In the case of a magnifier, the primary is brought in as close as it can to force the coupling above 30% or so if possible.



The next logical question is how much coupling should we use? The voltage induced in the secondary is directly proportional to the mutual inductance M so one might think that maximizing M is desirable. However, another factor comes in to play. We have two coupled resonant circuits, and the exchange and interplay of energy between the two circuits can result in beat frequencies that can be very appreciable. This phenomenon is also called frequency splitting, and it is a natural phenomena associated with coupled resonant circuits. Frequency splitting occurs if the coefficient of coupling exceeds some critical value Kc, which may be between 0.15 and 0.25 for typical tesla coils. Generally, we operate conventional tesla coils with K values less than Kc. This means using K values between .05 and .15 for typical small coil systems. If we are clever and experienced, we may be able to raise this into the .15 to .25 range. Initially, one should use relatively loose coupling until everything is working well. Then raise the coupling by moving the primary closer to the secondary (raising the primary coil relative to the secondary coil). The beat frequencies can cause racing sparks along the secondary and can destroy the secondary in short order if left unchecked. Basically, the beat frequencies cause multiple voltage peaks along the secondary instead of just one voltage maximum at the toroid end of the secondary. Sparks can break out from any of these voltage maxima. A well-insulated secondary may allow slightly higher coupling to be employed.

There is a mathematical relationship between the coupling K and the time it takes for the energy to transfer from the primary to the secondary. Ideally, we would like all the energy in the primary to transfer to the secondary in the first half cycle of oscillation and then have the spark gap stop conducting when the first zero current crossing of the primary occurs. This would result in the least loss and the optimal energy transfer. Unfortunately, we cannot turn off the spark gap this quick, even with a rotary spark gap, and, in addition, the required coupling is above critical coupling, so the likelihood of racing sparks along the secondary is high. More often, we use looser coupling, which allows for the energy transfer to take several half cycles before the spark gap turns off. To put things in perspective, consider a resonant frequency of 200 kilohertz, which implies a period of 1/200,000 seconds, or five microseconds. We would have to turn off the spark in one half this time for a half cycle. This is not practical even with a rotary spark gap, so we let it ring down a few half cycles, accepting the dissipative losses in the system along the way.

There are so called magic K values: 0.6, 0.385, 0.28, 0.222, 0.18, 0.153, 0.134, etc. where the energy transfer can occur in 1, 2, 3, . . . half cycles. In practice, the spark gap will turn off when it wants to, and the quality factor Q of the two resonant circuits will dominate the choice of optimal coupling, since critical coupling depends on the operating quality factors of our dual resonant circuit system. The magic K values are based on lossless resonant circuits, which is not the case in an actual tesla coil system. In the overall scheme of things, it is more important to construct the coil system to have minimal losses and then empirically increase the coupling as high as you can. For maximum voltage rise, it is more important that the two resonant systems are tuned to the same frequency than the coupling. When constructing a magnifier, the choice of coupling coefficient becomes more important.

Tesla Coil Frequently Asked Questions
Chapter 7: The Primary Coil
Part 4 of 5

This document is provided for educational and informational purposes only. The author assumes no responsibility for the safety of individuals who pursue the actual construction of tesla coils and/or other related high voltage devices.

Frequently Asked Questions About Primaries

Here are some frequently asked questions about primaries which have appeared on the listserver over the past few years. I have edited the answers minimally, in the interest of demonstrating various viewpoints about primary coil construction. There is no "right" way, just many different methods that work. Keep this in mind as you plan your first coil or your "next best" coil.

Should I use a flat, conical or solenoidal primary coil geometry?

The choice depends on the size and type of the coil. All of them can and do work okay. Most folks use flat spirals for large coil systems (secondary diameter 8" and up) because of the risk of strikes from the secondary. The inverted cone offers improved coupling, especially useful with small coil systems of the 2-4 inch secondary diameter size. It works okay with 6" coils, too, but the likelihood of strikes increases. Solenoidal primaries can be used with any coil in theory, but you have to use a larger diameter than you might think to prevent over-coupling. Take a look at the coupling discussion which preceded this section. Solenoidal geometries are often used for the primaries of magnifiers, where tight coupling is desirable. Solenoidal primaries are also used a lot with small diameter secondaries (3 inches and less) and with vacuum tube tesla coils.

How do you guys keep your primaries looking so nice? All the pictures I have seen of primary's from copper tubing they are nice and flat and evenly spaced out. I tried running mine through hose for insulation, but this did not work well. (Boy is it tough to pull 40 feet of 1/4" copper through a 5/16 I.D. tube!) What about the spiral type primaries? They all look so esthetically pleasing.

Here is an excellent response to this question, courtesy of Father Tom McGahee. There are several ways to ensure that copper tubing primaries look nice. Here's one that is fairly easy: Let's assume we want to make a ten turn primary using 3/8" copper tubing and 3/8" spacing between turns. Let's further assume we want a starting diameter of 5" to allow a 3" coil and 1" around it before the primary starts so we can use a separate RF ground and keep primary and secondary insulated from one another.

That means that from the inside "side" of the copper tubing to the *next* inside "side" of the spiral will be 6/8". So for ten full turns it will be 60/8 of an inch *plus* the width of the tubing (since we measured from inside to inside . . .) for a total of 63/8 of an inch which is

7 7/8 inches. Allow an inch extra for the inside and an extra inch for the outside and you have 9 7/8 inches.

Cut three pieces of Lexan or Plexiglass or other GOOD insulating material to a size of 1+3/8+1 for a total height of 2 3/8 inch and a length of 9 7/8 inch. I prefer 1/2" thick Plexiglass or other plastic for maximum strength.

I make a drilling guide that is 2 3/8" by 9 7/8" out of thin cardboard or poster board like material. Draw a line lengthwise down the middle of this guide. Start at a point 1 3/16" in from one side, and put a mark there along the center line. Now, from that point mark off nine additional points, all 3/4" apart. You should now have ten points marked off altogether. From the centerline draw two parallel lines that are 1/2" away from the centerline (one above, one below the centerline). Mark off ten points along each of these two lines, the same as the markings for the centerline.

Using this cardboard guide, place it over one of the plexiglass pieces and use an awl to transfer the (30) marks to the plastic. Using the awl, lightly scribe or draw a line through the centerline markings to aid you in cutting later. Repeat for all three pieces of plastic. Now drill the outside holes with a 1/4" drill bit, and the inner centerline holes with a 3/8" bit. Repeat for all three pieces of plastic. Now, using the centerline we drew or scribed earlier, use a jigsaw or bandsaw to cut each of the three pieces in half lengthwise. You will now have Six identical plastic pieces. The side with the "C" shaped cuts is the top.

Locate the center of the "board" that you will be mounting the primary onto. Mark it. Draw a 3" diameter circle around this point. That represents the 3" secondary. Draw a set of six straight lines radiating from the center out to the edges of the "board." Number these radial lines 1 through 6. For line #1 make a mark 1" outward from the 3" diameter circle. Now, since the distance between the inside of one turn and the inside of the next is 3/4" and we have 6 pieces, then each next # radial will have the position of the previous plus 3/(4*6)", which comes out to be 3/24 which is 1/8". So #1 is 1" from the 3" diameter circle, #2 is 1 1/8" #3 is 1 2/8" #4 is 1 3/8" #5 is 1 4/8 #6 is 1 5/8. Mark each of these points along their respective radial lines. These points determine where the inside of each plastic primary support begins. Using whatever means you choose, mount all six primary supports, using the radial lines and guide points to determine how they align. Avoid any kind of fastening device or screw that is not either copper or plastic or other insulating material such as nylon. Various glues may be used. Once the supports have been mounted (and are determined to be very sturdy), then we can begin with the copper tubing. Clean it well, now, before it is coiled, because once it is mounted you won't be able to clean it easily. The inside of the primary is going to begin at radial #1. You have to determine whether you want to extend the copper tubing through the top plate, solder a wire to the tubing, or anchor the tubing to the support and connect power later via a copper bolt. If you are going to use the bolt approach, then use a hammer to flatten out the end of the copper tubing. Then drill or punch a hole that is 1/4" into the flat side and use a 1/4" copper bolt and copper nut to tighten the tubing down through the 1/4" hole just below the "C" on radial #1. If using any other method of electrical connection, then you can drill a 3/8" hole next to the side of the #1 radial so that the tubing can come up through the hole and then bend at a 90 degree angle so that it passes through the "C".

Now route the tubing to the "C" on the next radial. When it is in place, use a tie-wrap (all nylon or other plastic . . . NO METAL) to secure the tubing to the "C" mounting position.

The tie-wrap goes around the tubing and through the 1/4" hole. Be CONSISTENT in the way you run the tie-wraps. I suggest that at the beginning you NOT pull the tie wraps totally tight. Just make it snug for now, but don't cut off the tail of the tie wrap until we are all done. This allows us to jiggle the tubing a little to keep things smooth. Avoid making tight bends over short sections of tubing. It is better to make a wide bend and then keep narrowing it down by working on it with your fingers gently then to make a kink. Form about a foot of the tubing and then work it in so that it fits the "C" mount. As each one mounts, tie it down gently. The last turn can be secured in the same manner as the first, or by any other means that you find appropriate.

Once you have everything exactly the way you want it, you can pull all tie-wraps as tight as you can, and cut off the excess tail. Modify the method as desired.

Some people use "V" cuts instead of "C" cuts. Some people use insulating pegs placed into drilled holes. Some people just use a baseboard with holes for the tie wraps, and tie it down flush with the baseboard. The key is to have each radial section *offset* from the next by 1/6th the distance from the center of one winding to the center of the next. Personally I like a "C" holder because it matches the shape of the tubing the best and is very consistent. By the way, I like to make my secondary coils with MORE than 1" of unwound distance on the bottom. This is to compensate for the height of the primary coil so we don't get overcoupled. I also usually glue a Copper sheet to the bottom of my secondaries and run a 1/2" wide Tab of this same copper up the side so I have a place to solder the end of the secondary. I have a matching copper plate that is 2 inches in diameter glued to the baseboard, right in the middle of the 3" circle. This gives me a good RF ground connection, as the other side of the plate has a 2" wide copper strip connected to it and exiting through a slot at the center of the baseboard. This 2" wide copper strip leads to my external Good RF Ground Connector.

To prepare a secondary wire for soldering to the tab from the bottom grounding plate you can *gently* scrape the insulation off using a razor blade, or sand it off with a very fine sandpaper (Stroke only toward the cut end, not back and forth!). I don't know of any solvent that can be used to strip the insulation off. If using a thicker wire, such as a size #22, you can also carefully flatten the wire and then solder. If you have never done this kind of thing before, then FIRST EXPERIMENT USING WIRE SCRAPS. Only attempt the real thing once you are confident you can do it right. After soldering the wire I apply several coats of varnish to prevent the wire from getting snagged later.

I normally have the top of my coil done up in a similar fashion with a copper plate on the top. This allows you to set a toroid on it and get an instant good connection.

Hope this helps you with the construction details. Read them, try to understand them, and then modify as desired.

How do I proceed with tuning the primary? (I have a signal generator.)

If your signal generator can output a couple volts, it is really simple. Hook up a pair of LED's (light emitting diode) in parallel, connected anode to cathode (back-to-back). Attach one end of this pair to the output of the signal generator. First, let's find the resonant frequency of the secondary. Remove the secondary from the primary and place it on a nonmetallic bench or on top of an inverted 5 gallon pail (away from a concrete floor). Hook the opposite end of the LED pair to the bottom turn of your secondary. Hook the ground of your signal generator to your RF ground. Turn up the voltage to several volts (maximum is usually okay). Now sweep the frequency until the LED's lights up brightly. You should do this with your toroid on top, as you expect to operate it as a tesla coil. Start at a low frequency and increase it until the LED's first light up, since they will also light on harmonics of the fundamental frequency. You can use a computer program like WINTESLA or TESLAC to estimate the resonant frequency beforehand if you like so you don't end up on a harmonic. Write down the frequency. Now disconnect the secondary and remove it from the vicinity of your primary. Next, connect the primary coil in parallel with the primary capacitor. The ends of the capacitor connect to the two primary coil connections (inside or bottom turn and tap point). Connect the output and ground from your signal generator to the ends of the capacitor. At this point the capacitor is across the signal generator output AND the primary coil is across the signal generator output. The LED's will now be lit brightly until the point where resonance is achieved, at which point the light output will be reduced. Move the tap point around on the primary until the frequency reading matches the secondary resonant frequency you wrote down earlier. Make sure the secondary coil has been removed from the primary for this measurement. When finished, reconnect the primary circuit in the proper configuration, including reattaching the spark gap. You will probably have to increase the primary inductance somewhat in operation, since the corona on top acts like a capacitive topload, lowering the resonant frequency a bit. Note that this method is approximate due to loading down of the resonant circuit by the LED's and signal generator, but will generally get you within plus or minus one turn of the proper tap point. Then follow the tuning procedure in the next question.

How do I proceed with tuning the primary? (I do NOT have a signal generator.)

When you get the opportunity, borrow or purchase a signal generator at a hamfest, or make your own. You can start by running your coil geometry through the program WINTESLA or TESLAC to see what it says about your resonant frequencies and how many turns you need in the primary. Use that as a starting point. Then, you can tune things up using a 10-20 watt fluorescent bulb and a breakout point on your toroid. Set up your coil ready for firing. Place a pointed wire, screw or screwdriver on your toroid so it has a sharp protrusion on it. Tape it in place so it doesn't move while you are varying other parameters. Now raise up the secondary so it is well above the primary, about one secondary coil diameter above the top turn of the primary coil (no matter what the primary coil geometry). This insures that the coupling will be low. If you are way off on the tuning OR overcoupled, sparks can race up and down your secondary, destroying it. Loosening up the coupling removes coupling as a possible cause of the racing sparks. Now short out part of your spark gap or close it down so that when you apply about 10 volts AC to your high voltage transformer (using the variac you hopefully added to drive your high voltage transformer), the gap begins to fire. Connect one end of the fluorescent lamp to your RF ground with a long lead, and place the lamp about a foot from your coil. Now systematically move the tap point around on your primary coil until the bulb begins to light. Be extremely careful to TURN THE POWER OFF and short out the primary capacitor before you touch the primary coil tap lead. As you get closer to the tune point, begin to move the bulb further away from the coil, using it as a relative field strength meter. When you get close to the proper tune point, the breakout point on the toroid will begin to spark, and you can use the spark length to hone in on the proper tune point. When you get the tuning close you can also drop the coil down to increase the coupling a bit. If you get racing sparks, raise it up again. When you get close, open up the spark gap some and adjust for best performance with the breakout point still attached. When that is completed, remove the breakout point and re-adjust coupling, etc. for maximum performance. You will probably have to increase the primary coil inductance a bit at full power to take into account the added capacitance of the corona field caused by the sparks.

Why does nobody mention the importance of connecting wires in the primary tank circuit?

Thin wire has a high resistance at high frequencies. The resulting low Q primary gives considerably reduced efficiency. I've just reduced the length of my connections on my first coil primary tank by relocating my cap and have made the connections from copper tube. The improvement has been dramatic! For the highest efficiency all tank circuit wiring should be of the same size as your primary coil. If your primary is made of 1/4 inch copper tubing consider using that size conductors for all tank circuit wiring. The 60 HZ HV feeds are low current and need not be large conductors. Neon sign wiring is excellent for this purpose. It is designed to handle 30 kilovolts. The more power you run the more important this becomes.

What can I use as a coil form for a helical primary?

PVC pipe comes in a variety of diameters and is fairly inexpensive. You can also use PVC pipe couplers, especially for small coils. For larger coils, plastic pails, garbage cans and plastic barrels are available. Look on the bottom of the container for the plastic type. It often says PE, LDPE or HDPE if it is polyethylene, or PP for polypropylene which are excellent plastics for tesla coiling. Avoid black plastic products since the black is often graphite which is conductive or at least lossy. Sonotube can be used for very large solenoidal coils, as with magnifiers and large coil secondaries. It is somewhat lossy but has been used with considerable success.

How do you guys get such beautiful smooth coils out of copper tubing? I've bought a bunch of 1/4" soft copper tubing and I'm having a terrible time making it bend symmetrically.

First, purchase refrigeration tubing, not plumbers tubing which is much more difficult to bend. If you purchased a 50 roll of 1/4 inch tubing then the spiral starts out big, gets smaller toward the center of the roll and then expands back outward again. It is good to keep this is mind. It does not have to be pretty to be functional. Here is my method. Keep in mind my primaries are either flat or inverted cone (mostly inverted cone). Having a friend around for another set of hands helps.

Find the diameter of your smallest inside turn of your primary. I found a coffee can that was about THAT size. Place the coffee can on the floor and place the end of the copper tubing on the floor up against the coffee can. Using the coffee can as a guide make your first turn around the coffee can. This first turn is a little difficult as it is the start of the process. When you finally get that turn back around to itself then, while keeping the tubing flat on the floor the whole time, wind the next turns 'ON' the previous turn. This will not only make a continuous expanding outward wind but will allow you to bend (let’s use the word 'form' - I hate bend) the tubing around the previous turn and this keeps kinks from happening. The more you work with the soft copper the more it gets out of whack, so if you just keep winding the pipe out of the box onto the existing previous turns you are now just working with it once (the first time). Have a friend there to hold the previous turns down flat on the floor as to make the next turn easy. When you get to the center of the roll and the spiral in the box gets smaller, you will have to work a little bit to open that small spiral to fit on the spiral your are forming around the coffee can. When you get done, you have all of your pipe in a flat spiral on the floor wrapped around the coffee can and the innermost spiral is about the size of the inner most turn of your Tesla primary. Now comes the time to have to work with the copper tubing for the second time. As you place the tubing in the primary form, from the inside out, the adjustments you make to the tubing are to make the spiral just a little bigger to fit. When working with the tubing, it is MUCH easier to expand the diameter of a turn than it is to make a turn smaller. Just slowly work your way from the primary center outward. As your progressive expanding turns occur on your primary, so do they on the tubing, because you have already pre-formed the tubing when you wrapped it around the coffee can.

Do I need to cover the turns of the primary coil with insulation?

No. Do space the turns out about 1/4" apart or more if using copper tubing. The primary's construction should be that of space allowance between turns to avoid flashover. Keep it at least one inch away from the secondary and its RF ground connection.

My secondary is arcing to the primary. What should I do?

If you wound your primary so the inside turn is less than an inch from the secondary coil, it is a bit close. Try placing some plastic sheeting around the secondary base to reduce the flashovers. You could also be over coupled or not properly tuned. Try raising the secondary up one full secondary diameter above the bottom turn of the primary. This will result in loose coupling. If you still get flashovers, you are probably out of tune. Follow the procedure for tuning provided in an earlier question. If the problem was overcoupling, first raise the secondary until it is one secondary diameter above the top turn of the primary. Then slowly try lowering the secondary or raising the primary ½" at a time until maximum coupling is achieved (without flashovers).

Why is the tap point on my primary getting hot?

During the time the spark gap is firing, the circulating current in the primary can easily exceed 100 amperes in a well constructed tesla coil. Make sure your connections to the primary are solid. If using alligator clips, shape them to the contour of the tubing or solder on copper plates in that shape to lower the connection resistance. Ideally, you should build you own compression fitting primary tap. This is a tap that is designed so that it is primarily a PERMANENT TAP, but in a Temporary sort of way. A 'gator clip is temporary and makes a lousy permanent tap. Soldering and other such methods are permanent and you have to live with it. A compression fitting can be fabricated in many ingenious ways, but its main feature is that you can move it around, but once you are at the right place, you can tighten this sucker down and leave it there forever if you want. The down side is that it takes a bit longer to move it around. But it makes an EXCELLENT connection. I have seen small hose clamps used. Properly trimmed they aren't all that bad. These work best on larger diameter tubing. The compression fitting has SOME means to clamp the metal tightly around the primary coil. The metal that gets clamped should have some flexibility, but most importantly it should make an extremely tight connection with a good sized surface area. The material should be something that can take a certain amount of flexing without breaking. I have used copper strapping to good advantage. You can make your own from sheet copper, or actually buy pieces that are about 1/2 to 1" wide at building supply stores. You can also use wide flat braid as the flexible conductor part and use brass plates to do the compression part. The compression part consists of some means to pull the strap tightly around the copper tubing and secure it. I often use brass plates that I have drilled and tapped so that one plate has holes larger than the screws and the other has been tapped so that the screw can be secured by that plate. Also connected to this brass plate is the supply lead. It may be soldered or also compression clamped. Think surface area. Sometimes I attach more than one feed lead per clamp. That increases the surface area of the feed lead while keeping it relatively flexible. I normally have the flexible flat copper/brass or braid section soldered to the two aforementioned plates. Solder them well, as the solder is going to be providing physical strength to the assembly. Another method is to use another plate to clamp the flexible metal band to the master plate. If using braid, consider first rounding the edges of the plates that are where the braid passes by. Otherwise the sharp edges will bite through. However you decide to do it, get the spacings adjusted so that when the flexible piece is wrapped around the tubing and you tighten down the screw(s) the unit is firmly attached with a decent surface area.

Can I use wood for the primary coil form?

Yes, wood works okay. I usually use it for the base plate. I find that plastics are easier to machine for mounting tubing, but wood can be used as well. Ideally, it should be dried and coated with polyurethane to prevent moisture absorption.

Could someone explain what exactly coupling is?

You could fill a book answering that question. The time it takes for energy to transfer from the primary to the secondary depends on the coupling. Tight coupling means the energy transfer is rapid, before losses in the primary circuit cause significant energy absorption. However, tight coupling requires rapid turn-off of the spark gap in order to trap the energy in the secondary coil. Loose coupling gives you more time to transfer the energy, allowing for a poorer spark gap. Naturally, the longer the high currents circulate in the primary, the less energy is transferred to the secondary. Generally, you want the coupling to be as tight as possible so as to transfer as much energy to the secondary as possible. However, too much coupling will result in arcing between the primary and secondary and even insulation breakdown of the secondary from overvoltage. See the discussion on coupling presented earlier in this FAQ.

Does the primary coil make a difference when charging the capacitor?

Not really. The charging cycle occurs at 50-60 Hertz and at that frequency the reactance of the primary inductance is very small. As far as the high voltage supply is concerned, the primary coil is a chunk of wire.

*I was wondering though if the equation E=1/2 * C * V^2 would be valid for charging the capacitor at resonance? If so, I would know how much total energy the capacitor would have before the gap fired provided it had time to charge. Now I am just not sure how much of that energy would actually be used due to gap losses, RC discharge time constant, etc? Any estimates on this?*

The total amount of energy that's available in the TC primary circuit each time the gap fires will be ½ x Cp x Vg^2, where Vg is the gap firing voltage. This chunk of energy, termed the "bang size" represents the maximum available energy that could be transferred to the secondary whenever the gap fires. Once the gap fires, the tuned primary LC circuit begins oscillating, transferring energy to the tuned secondary LC circuit electromagnetically. The secondary tuned circuit thus gains energy at a rate that's governed by the degree of electromagnetic coupling (called K, the coefficient of coupling) between the two. Typical coils will have a K between 0.1 and 0.25. The sum of the energy in the primary and secondary will be limited to the initial bang size, since Tesla Coils do not violate Conservation of Energy.

However, while the gap is firing, tremendous energy is being dissipated as heat and light, so a fair portion of the original energy is being lost through the gap. In addition, resistive losses in the primary and secondary circuits and in the secondary's base path to the RF ground are also causing energy loss through I^2 x R heating. If there were no losses in a Tesla Coil, ALL the energy original "bang" energy would be transferred to the secondary over a few cycles. In the real world, losses in a well-designed Tesla Coil limit this to perhaps 80-85% of the energy making it to the secondary, with 50-65% being the norm for most typically constructed coils. That is why it is so important to keep resistive losses low in the primary circuit, including losses in the capacitor.

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I'm also having some problems constructing my primary. My original idea was to use about 14 turns of 1/4 inch copper tubing. Then I discovered that copper tubing has a particular aversion to being bent or shaped (especially into a spiral). What I ended up with was about 10 feet or expensive horribly mangled copper tubing. If anyone has any good ideas for primary materials that are easier to shape or better than copper tubing, please say so. Or if there are any ideas on how to better shape the copper tubing, I'd love to hear them.

Get a 25' or 50' spool of fresh refrigeration tubing from the hardware store. This stuff is wonderful since it is already rolled in a spiral. Shaping the tubing to form the secondary is fairly easy then. My form has 1/4" grooves cut in it. I was able to hold the tubing above the form and work it into the grooves as I worked around in circles. Worked really well. In another primary, I tried to drill holes which were cut in half and the tubing sandwiched between but this was much harder and the result was not as pretty as the grooved primary.

Also 10 feet will not give you many turns. Treat each turn as a separate circle and sum up the circumference of each. Even 50' burns up pretty fast. Think that I was able to get 15 turns starting with a 5.5" inner diameter. Since the tube is 1/4" in diameter and I used 1/4" spacing between turns and the circles are growing relative from their centers, the sum for the total circumference on my primary looks like: (5.5+6.5+7.5+8.5+ . . .) x Pi which gives a result in inches. I added as many progressively larger circles into the above sum until all the tubing was used up as full turns.

Make sure you buy soft refrigeration tubing and NOT the harder plumbing grade tubing. The soft tubing is not too difficult to shape or bend and comes in a nice spiral shape right out of the box. If you got plumbing grade tubing it will be next to impossible to shape it adequately.

The idea is to take advantage of the shape the tubing comes in rather than fight it into a different shape. You'll need to increase the distance between the innermost turn of the primary and the secondary to at least 1.5" to permit you to adjust the secondary up or down relative to the primary without getting arc-overs between them. A flashover at this point will often do significant damage to the secondary, and has been known to create shorted turns on the secondary due to welding between adjacent turns. This means your innermost primary diameter should be at least 3" in diameter larger than your secondary diameter. Keep at least 1/4" open space between turns.

I am making a spiral coil. Should I space out the notches on the support plastic so I have *a true spiral?*

Yes, you should. Here is some guidance on the subject. Say you have eight limbs. Say the coil spacing is 3/8". The limbs must be numbered 1-8 for simplicity. Divide the 3/8" by the number of limbs, which is eight. You will get 3/64". Keep the first limb exactly as it is in length. Limb #2, you will add 3/64" to its length. Limb #3 will be 3/64" longer than #2, #4 will be 3/64" longer than #3, . . . and so on. Soon, all of your limbs will be 3/64" longer than the one before it, 1-8. Now, measure all of your slot locations starting from the outside edge of each limb, so that each slot will have a 3/8" space between them, until you reach the inside edge of each limb. You will see once you start winding the coil itself, that the spiral will be clean from slot to slot, limb to limb. I will be drawing this out pretty soon for everyone who has problems determining how to arrange the slots to get that picture perfect coil every time. It sounds like a lot of work, but it is not really, and it does provide for a very easy to wind and very smooth, curving coil.

Also remember, that all primary coils should be "tapped". This means that only the inner end is hard wired to your electronics. The outer end of the coil is "floating", meaning that it is not hard wired to the circuit. Use a clip of your choice to connect to the coil anywhere along the spiral you wish, in order to tune it. The clip, of course, is hard wired into the circuit. I hope my words are understood and beneficial to all.

What is work hardening and how do I prevent it?

When you buy the copper tubing fresh in the box --- don't try to straighten it first. Carefully remove the coil from the box and make slow and careful bends gently as you fit it into your primary holders. Don't force it and try to slowly work at least 1 full turn ahead as you gently twist the entire coil into a tighter spiral as you slowly work outward. With this technique you should be able to slowly work up a copper tubing spiral in about 30-45 minutes for a single 6-10 turn primary.

Once you bend or straighten the tubing first it "work-hardens" and becomes completely unable to make smooth bends. If you have done this you will have to scrap it out and start with a new roll. Also, best to use K-soft copper. There is another type used for plumbing that work hardens much faster and is much harder to work with. Guess what --- the electrons won't know the difference!

Here are some more excellent comments from Father Tom regarding primary coils.

At its simplest level the primary of a Tesla coil is just a coil of wire that creates a magnetic field when you pump current through it. One of our basic goals as Coilers is to find ways to create repeating pulses of very high current in the Tesla primary. This will produce intense magnetic fields. If we can get these magnetic fields effectively coupled to the secondary and operating at the self-resonant frequency of the secondary, then we can throw some pretty big sparks. So the design of the primary coil is important.

So here are the challenges before us:

1) Make the primary capable of handling repetitive high currents.
2) Keep the time it takes for a pulse of high current to rise and fall as short as possible.
3) Make the primary a tuned resonant circuit.
4) Use the high level primary currents to create intense magnetic fields.

5) Shape the resulting magnetic field so that as much of the energy as possible is transferred to the secondary.
6) Minimize all sources of power loss.
7) Try to do all this and not implode your wallet.

Why do we want repetitive currents that rise and fall rapidly? One of the factors affecting the strength of a magnetic field around a wire carrying current is the current itself. Current is defined in terms of the number of electrons flowing through a conductor per second. If we store the electrons up (in a capacitor) over a fair period of time and then dump them all at once, as fast as we possibly can, then even though our average current flow may be small, we can still make the peak value very high! At the instant we dump all those electrons into the primary we can get really obscene peak values if we can keep the resistance of the primary really really low.

OK, so how do we go about making the primary resistance low? When dealing with high frequency circuits we want to maximize the surface area. With DC circuits we would want to increase the cross sectional area, but high frequencies flow mostly over the surface of conductors, instead of through them as DC would. This is great, because if we use a thin ribbon of copper that is fairly wide, it can readily carry lots of high frequency currents with only a fraction of the total material that a solid conductor would need.

Flat ribbons have these nasty sharp edges. We don't like sharp edges on RF conductors, because it promotes energy loss through corona discharge. So we come up with an almost perfect answer: a conductor with lots of surface area, little or no wasted cross sectional area, and as non pointy as you can get (and still be a long conductor). Behold hollow copper tubing! Meets all the criteria and is readily available to boot. Why copper tubing? Why not make it out of lead pipe or iron pipe? Because we also need the lowest possible DC resistance, and the metal should be non-ferromagnetic. If it was ferromagnetic, then when it produced a magnetic field, the magnetic field would want to stay close to the iron, because iron conducts magnetic flux quite well. But we want to get the magnetic field to couple with the secondary, not hoard it. If you used a ferromagnetic material, the energy loss due to eddy currents would be horrendous. Much of the energy would be expended in heating the pipe. This would be bad news, so we don't do that. We use copper. Copper is king when it comes to Tesla coils. Some people plate their copper primary with a coating of silver. This gives about a 4% increase in conductivity.

For smaller coils the 1/4 inch copper refrigerator tubing is often used. Many medium to large size Tesla coils employ 3/8 inch copper tubing. Really big coils use 1/2 inch and larger copper tubing. It is best if you can get a single piece to form the primary, but if not, then pieces can be soldered or brazed together. If you put a sleeve on the outside to make a splice, then you might have a corona problem later. An alternative is to stick a short section of thinner copper tubing partially inside both halves and then solder. Use fine sand paper to remove any spots that are bumpy and might cause corona problems. When bending copper tubing, you want to avoid having the inside of the bend crimp or buckle. One method is to make sure the inside bend is firmly pressing up against something and to only bend it a small amount at a time.

We'll cover the topic of the shape of the primary later in this article, but we need to mention inductive reactance now. Whenever you have a coil, it builds up a magnetic field when you pass current through it. Because of the adjacent turns in the coil, self-induction exists in the coil. That is the tendency of the coil to oppose changes in current flow. A pulse would normally cause a coil to have an increasing magnetic field. This magnetic field will produce a current in the adjacent windings that will tend to oppose increases in current. Then, when the magnetic field collapses, it will produce a current that will add to the decaying current such that it tends to prolong the current flow instead of letting it decay. This tendency to oppose changes in current (it's called inductive reactance) is a function of the inductance of the coil and the Effective Frequency of the applied Pulse. I say the effective frequency, because a pulse will always appear to a coil as if it had a Frequency higher than its repetition rate. A pure sine wave will have no pulses, and its frequency and repetition rate will be the same.

Oh Great! So we are supposed to keep the resistance of the primary coil as low as possible, and now we find that it's got this stupid inductive reactance thing that makes it act like a dumb resistor. Sheesh! Now what? How do you cancel out the effects of inductance? It's really fairly simple. You put the coil in series with a capacitor that has capacitive reactance that is equal to the coil's inductive reactance at the effective frequency of the pulse. This works because inductive reactance and capacitive reactance are 180 out of phase with one another.

For any given inductor/capacitor combination, there is ONE frequency where the two reactances are EQUAL in Reactance value and opposite in phase. This frequency is the resonant frequency. (It's the same frequency that we ultimately want to also equal the self-resonant frequency of the secondary coil.)

Hey, what if we use the same exact capacitor that we used for energy storage to act as this capacitive reactance thingie?? It happens to be exactly the idea that Tesla had. (You are getting SO smart!)

By the way, do you see how all the parts constantly interact? The Transformer and Capacitor are ALSO supposed to be matched for Maximum Efficiency, but at the frequency of the AC line, which is 50 or 60Hz in most cases.

Most of the really spectacular things that a Tesla coil can do occur only when the tuning of the primary circuit matches the tuning of the natural self-resonant frequency of the entire secondary circuit (That includes the toroid, if any is used).

Consider coupling to be the way the primary's magnetic field interacts with the secondary. If coupling is too loose, the coil is inefficient and wimpy. If coupling is too tight, then you may over-stress the primary and have voltage breakdown occurring along the secondary or between the primary and the secondary coil. In olden days there was much emphasis on tight coupling, because many coil builders erroneously thought that a Tesla coil worked mainly by transformer action. Not so. A Tesla coil is a transformer that is tuned to resonance. The resonance is just as important as the magnetic effects. Even more so if you are talking about a Tesla Magnifier!

The shape of the primary affects its inductance and its coupling to the secondary. The inductance affects the resonant frequency of the primary circuit, and the coupling affects the overall energy transfer from the primary circuit to the secondary circuit.

Many of the early Tesla coils used a rising helical primary that was closely coupled to the secondary. Flashover from secondary to primary was common with this design, and many a secondary coil was destroyed because of the sparks destroying the insulation.

When coupling is too close, the windings of the secondary get over-stressed and the secondary circuit can experience breakdown between windings, or sparking between the primary and the secondary. Some people try to compensate for this by cramming as much solid or liquid insulation as they can between the primary and the secondary. That works somewhat, but it has its limits and its limitations. Eventually almost any insulation can be broken down, even oil insulation.

The flat pancake coil and the saucer shaped primary are the most popular primaries among serious coilers, but there are specialty coils that still use the rising helical primary.

Spiral coils have less of an over-coupling problem. The usual arrangement is what is sometimes called an Archimedes or Archimedian Spiral (because the Greek mathematician Archimedes was the one who formulated its characteristics). In this kind of spiral the distance between adjacent turns is kept constant. If the spiral is kept flat, it is often referred to as a "pancake" coil. If the coil is not kept flat, but instead each turn of the spiral also includes a rise, then you have an inverted cone or saucer shaped primary.

The question usually comes up as to how far apart from the outside of the secondary should the primary begin. Most coilers have the first primary turn beginning at a distance of one to two inches from the outside of the secondary coil. This may be adjusted to a larger starting diameter, especially if the coil requires looser coupling. Coupling can be adjusted somewhat if the primary and secondary are made moveable with respect to one another. Some coilers arrange things so that the secondary may be raised and lowered. Others prefer to move the primary and leave the secondary fixed. Which method is used is more a matter of convenience and personal preference than anything else.

Keep in mind, however, that just because most people do something a particular way does not mean that that is the only way it can be done. Nor does it necessarily imply that it is always the best way that it can be done. For example, Malcolm Watts reports that he has made primary coils whose inside diameters have been less than that of his secondary coils, and he reports good results from this arrangement. One of his coils had as its primary a flat pancake spiral made of 3/8" copper tubing with the first turn having an inner diameter of about 5", and an outer diameter of about 20". The secondary diameter was about 17". He states: "I have noticed no substantial difference between performance of a helical primary and spiral primary of the same inductance, using same cap and transformer, and coupled to the secondary with the same k. I submit that the gap losses (reduced with higher values of k and/or higher primary surge impedance) determine system performance if all other components are of good quality and unchanged in value. I think Bert's SPICE simulations bear this out."

Why are flat spirals and saucer shaped primaries so popular? Because they work so well. Why do they work so well? Because each creates a magnetic field that is large and encompasses (ideally) the entire secondary. You can actually SEE the beautiful shape of this field if you operate a powerful Tesla coil in the dark. The corona discharge from the primary will engulf the entire secondary in a kind of inverted parabolic curve when the coupling and geometry are just right.

A Tesla coil is a 1/4 wave resonant device. When it is operating properly the base of the secondary has a low voltage and a high current, while the top of the secondary has a high voltage and a relatively low current. It may be useful if you think of it in terms of a standing wave: Imagine one cycle of a sine wave. It reaches its Peak value at 90 degrees.

That is a quarter of a full wave. If you get a Tesla coil to operate at resonance, you have a standing wave in which the top of the secondary is operating at this 90 degree point. It will therefore have maximum voltage at that point.

There is a simple experiment you can try with a child's jump rope that will illustrate standing waves. Have someone hold one end of the rope tightly in both hands, with their hands held tight against their stomach so that the rope at that end will be anchored fairly securely. You grab the other end of the rope tightly in one hand, and begin moving the rope up and down about one foot. Start off slowly, and then gradually increase the speed at which you are moving the rope. Keep the up and down distance you move as constant as you can. Every time your hand moves the rope up and down it will send a traveling wave down the rope. But you will reach one particular rate at which you will no longer see a wave traveling down the rope. Instead you will see that there is a point right at the center of the rope that appears to be standing relatively still. At a distance halfway from the center of the rope to where you are you will see that the rope is whipping up and down pretty good. That is the 1/4 wave point. That is where the greatest activity is. When a Tesla coil is operating at resonance, it is operating at its 1/4 wavelength. Notice that you can get the rope to have standing waves at higher frequencies. Struggle really hard with the rope and you might be able to get a standing wave with two nodes standing still, each about one third of the way down the rope. Notice that it requires a lot more work on your part to maintain a standing wave with two nodes, and that the amplitude of the wave is not as big as when you only had one node. In the same way, you can force a Tesla coil to operate at the wrong frequency, but it is not achieving full resonance. If a Tesla coil is improperly tuned the applied energy is wasted because returning waves cancel the original waves.

The key, then is to achieve this 1/4 wave resonant point. And you want to do it with efficiency. That's where all the little nitty gritty details come into play. The frequency we tune the primary circuit to should ideally match the natural self-resonant frequency of the secondary. Of course, in real life nothing is quite as simple as that. The secondary's natural self-resonant frequency varies (in real time!)

I have made the secondary height adjustable via scissors jack underneath. It has a range of 9 inches travel.

A metal jack? Might not be a good idea to have that amount of metal in the primary field. This will cause localized heating as well as distortion of the magnetic field. You can use pulleys to raise and lower a secondary or primary, or place the primary or secondary on blocks which are adjustable.

What are the formulas for primary coils? (Answer courtesy of Bert Hickman)

The helical and Archimedes formulas are from Wheeler, and the inverse conical is a hybrid closed-form that appropriately weights the vertical and horizontal components of Helical and Archimedes inductances.

All dimensions are in inches, and L is in microHenries. While the Archimedes calculation is a little "hairier" than the first two, it's relatively easy to calculate for any desired angle, especially if set up in a spreadsheet.

Case 1: Archimedes Spiral:

```
Let R = Ave Radius
    N = Number of Turns
    w = Width of Winding
```

```
    |   R    |      N Turns
o o o o o o o  |  o o o o o o o
|    W    |
```

L = R^2*N^2/(8*R+11*W)

Case 2: Helical Primary:

```
     | R |
 --  o       o
 |   o       o
     o       o
 L    o       o  N Turns
     o       o
 |   o       o
 --  o       o
```

L = R^2*N^2/(9*R+10*L) (Vertical Helix)

Case 3: Inverse Conical Primary:

```
                          /
 \                                  --  o
  /    o
   |    o   N turns           /    o
        o               Z  /    o
   h      o                 /    o   /
          o               /    o   /
   |       o             /    o   /  Angle = X
            o             \  o   /
```

```
--        o            o    ------------
                |
  |   w   |   R   |
                |
     |<--  W  -->|
```

Z = Coil Width (hypotenuse)
X = Angle of Cone
h = Z*sin(X) Effective vertical Height
w = Z*cos(X) Effective horizontal Width
W = R + w/2   Average horizontal Radius

L1 = W^2*N^2/(9*W+10*h) (Vertical Inductance Component)

L2 = W^2*N^2/(8*W+11*w) (Horizontal Inductance Component)

L = SQRT[(L1*Sin(X))^2 + (L2*cos(X))^2]

Here are some really good suggestions regarding primary taps by Father Tom.

Resistive losses from the primary TAP mechanism can be excessive. The losses are from several factors.

1) The currents are just obscenely high. But that's what we WANT, so we will NOT try to reduce *that* in any way :)

2) With extreme high RF currents you need a large surface area to get the current transferred. The stupid little teeth on even the best 'gator clips are pathetic for RF use. The points just intensify the problem.

So, get rid of the stinking teeth and increase the surface area. Grind the jaw structure so that a maximum surface area come in contact. Add a more robust surface area by soldering on copper pieces shaped so as to maximize surface contact (not too easy since the shape of the spiral changes from turn-to-turn). Easier for you solenoid guys, as the pitch and radius are constant in that form of primary. Use a MUSHY metallic material to make the contact. Think metallic Braid. Think of the outside metallic braid on coax cable. Yeah, I know that everyone tells us not to use braid. But they are talking about the main power runs, my friend! HERE is a place where the braid has a quality that overcomes its defect. The great MUSHINESS of the braid makes it ideal to create a larger surface area contact.

Try *this* with your existing clip lead setup: wrap two or three turns of braid **tightly** around the desired tap point. Let the clip lead sink its old 'gator teeth into the braid. Not perfect, but a definite improvement! (And ridiculously EASY to implement, for all you lazy bones coilers out there). How many wraps you can tolerate depends on the size of your 'gator, and the spacing between primary turns.

All right, so now that I have convinced you of the joys of braid, consider attaching the braid right to the inside of the jaws of the 'gator itself. You can file away the teeth and that will give you more room for the braid. Solder it only OUTSIDE the mouth of the 'gator clip. We want the stuff between the jaws to remain MUSHY. Be careful, as the braid LOVES to wick up solder. TIN the outside of the jaws and lightly tin the end of the braid. Heat up the jaw until the solder melts and then touch the tinned end of the braid into the solder on the jaw . Hold the braid in a needle nose pliers jaw, tightly and near the end. This will restrict the solder wicking by drawing away the heat. It will also prevent your fingers from having the permanent imprint of wire braid branded into them.

After soldering one end, wrap the braid along the inside of the jaw and solder the other end on the other side. What you want is a run of mushy flat braid across the inside of the jaw. Do both the top and bottom jaws.

An alternative to going across the width of the jaw is to run it down from the top of the nose of the jaw, loop it INSIDE the jaw, and around such that it then comes back out across the bottom of the bottom jaw. Soldered on the outside, of course.

There are MANY variations on the theme. Pick one. Make a mushy jawed 'gator clip. Amaze yourself. Impress the neighbors.

3) With really huge currents the TYPE of conductor becomes very important. Heavy duty solid COPPER is best. It is also one of the few metals that really solders well. So if you are going to modify a 'gator clip, I suggest beginning with a solid copper one if you can get one. Trying to solder aluminum 'gator clips is an exercise in frustration. Save your energy and your sanity. Buy copper 'gator clips.

Now, some of you are using those dumb little Radio Shack mini 'gator clip leads with all the cool little colored booties on them. Doomed to failure from the word go. Not enough surface area to conduct our obscene RF currents. These babies get hot enough for the solder to melt and the plastic booties begin to drip off. Forsake the wimpy mini gator clip and go for the Macho 'gator clip. Think Surface Area.

4) 'Gator clips are made from two sections. In a high current RF environment this is bad news, as the second section has only a few minor points of contact with the main section. This means a high RF resistance for half of the clip. This in turn means lots of heating WITHIN the 'gator clip itself. Solder coax braid from the wide top to the wide bottom. Keep it short and WIDE. Really industrious little coilers will find ways to do this work from the INSIDE as well as from the outside. Think Skin Effect.

5) And the final 'gator clip modification: Throw out the stinking gator clip. Build you own Compression Fitting Primary Tap. This is a tap that is designed so that it is primarily a PERMANENT TAP, but in a Temporary sort of way. A 'gator clip is temporary and makes a lousy permanent tap. Soldering and other such methods are permanent and you have to live with it.

A compression fitting can be fabricated in many ingenious ways, but its main feature is that you can move it around, but once you are at the right place, you can tighten this sucker down and leave it there forever if you want. The down side is that it takes a bit longer to move it around. But it makes an EXCELLENT connection.

I have seen small hose clamps used. Properly trimmed they aren't all that bad. These work best on larger diameter tubing.

The compression fitting has SOME means to clamp the metal tightly around the primary coil. The metal that gets clamped should have some flexibility, but most importantly it should make an extremely tight connection with a good sized surface area.

The material should be something that can take a certain amount of flexing without breaking. I have used copper strapping to good advantage. You can make your own from sheet copper, or actually buy pieces that are about 1/2 to 1" wide at building supply stores. You can also use wide flat braid as the flexible conductor part and use brass plates to do the compression part.

The compression part consists of some means to pull the strap tightly around the copper tubing and secure it. I often use brass plates that I have drilled and tapped so that one plate has holes larger than the screws and the other has been tapped so that the screw can be secured by that plate. Also connected to this brass plate is the supply lead. It may be soldered or also compression clamped. Think surface area. Sometimes I attach more than one feed lead per clamp. That increases the surface area of the feed lead while keeping it relatively flexible.

I normally have the flexible flat copper/brass or braid section soldered to the two abovementioned plates. Solder them well, as the solder is going to be providing physical strength to the assembly. Another method is to use another plate to clamp the flexible metal band to the master plate.

If using braid, consider first rounding the edges of the plates that are where the braid passes by. Otherwise the sharp edges will bite through.

However you decide to do it, get the spacings adjusted so that when the flexible piece is wrapped around the tubing and you tighten down the screw(s) the unit is firmly attached with a decent surface area.

Has anyone experimented with super cooling the primary / secondary?

Well. My thought is that it would unnecessarily complicate a relatively simple system with little to no gain. You aren't going to see any type of super conductivity and the amount of heat generated is so low as to make any type of cooling unnecessary.

The only component that generates any significant heat is the spark gap. Here some form of positive heat removal is beneficial. However just cooling the electrodes isn't enough. You need to remove the hot ions clogging up the space between electrodes. Forced air is the way to go. In fact a vacuum quench gap with airflow supplied with a strong vacuum cleaner motor gives nearly rotary gap performance without the complexity and with much less strain on components.

There *IS* some utility to super cooling the primary and also in the case of the secondary. In fact, Tesla even received a patent on the idea in connection with his Wardencliffe project. Specifically the super cooling reduces the resistance and therefore increases the Q of the circuit. For the average coiler the gain would be insignificant. But on the HUGE scale that Tesla was envisioning, it was a gain worth the pain.

I just read an article which showed the primary and secondary both connected to ground. Is this recommended?

This is inherently dangerous because it places 50-60 Hertz primary energy directly on the secondary. Never tie your secondary and primary together. If they are tied together and you happen to get hit by an arc, high voltage power from the supply will pass through your body. The results could be disastrous.

From a performance stand point a good low loss ground connection tied to the base of the secondary is very important for efficient operation. A Tesla secondary needs to work against ground. If you deny it a ground connection it will still try to work against the wiring in your system as ground. This will often work at low power levels. But this type of artificial ground will easily be overwhelmed. At best this will severely limit performance. At worst it could lead to unwanted arcing and destruction of components.

How about some talk about how the whole of a TC's resonant circuit actually works together as it relates to resonance. I guess I don't understand how there is a resonance set up between the primary HV circuit and the secondary. Or is the only resonance of components, that really matters, in the primary circuit, and the resulting inductance provided to the secondary just a unique way to use that resonance and not part of the resonant circuit at all?

OK, this is a very important and FUNDAMENTAL point: A Tesla coil is not "A TUNED CIRCUIT". It is TWO TUNED CIRCUITS. The Tesla coil only really "works" as a true Tesla coil when the resonant frequency of the primary circuit (Primary and Main Cap) are exactly tuned to the (current) resonant frequency of the entire secondary circuit (secondary, inter-turn capacitance, self-capacitance due to size and shape [Medhurst], and glorious Top Load capacitance). Hmmm. You are wondering why I said (current) resonant frequency. The Tesla coil's resonance is affected by things like the presence of your body in the same room. When the Tesla coil is operating it has an ion cloud around the secondary and the topload that CHANGE its actual operating frequency from that which you have so meticulously calculated using resonance formulae and Wheelers's and Medhurst's formulae. Fact is, until your coil is actually functioning, you don't know the EXACT operating frequency. That is why we have tappable primaries! After all our careful measuring and calculating, we still have to slide the old tap around to get "best spark".

My next primary will probably be copper tubing instead of #10 household wire, any suggestions for the tubing diameter? 1/4", 3/8", . . . ? Is there a problem with arcing between the primary turns since it is not insulated (if that makes a difference in the HV land)?

1/4 inch soft copper tubing will make an excellent primary coil and will handle a considerable amount of power. Several KVA. The space between turns need only be from 1/4 inch to 3/8 inch. There is not a problem of arcing between turns as the voltage difference between adjacent turns isn’t very great. 3/8 inch tubing is frequently used for secondaries in the 8-12 inch diameter size, and larger tubing sizes are employed with the really big secondaries.

I was wondering if our coil is being hindered by the fact that the primary is resting about 1/4 inch off the concrete floor, basically the ground plane.

Concrete floors usually have metal reinforcing bars or wire mesh which act as a ground plane. In addition, concrete retains moisture and is a part of the earth ground. Locate your coil at least 12-18" above a concrete floor. You will see a performance increase (and a slight change in tuning).

I want to use a solenoidal primary and place it inside the secondary coil so it looks really *cool. Can I do this?*

Sure. It will work fine if you keep in mind several points: First, the primary diameter is small so you will need quite a few more turns than if you placed it on the outside. Watch your coupling. Second, keep in mind how you will tap the primary to tune it (from an access point of view); and third, keep in mind the voltage stresses if you place a primary in close proximity to the secondary. You may need some additional insulation to prevent arcs.

Here is a quiz about coupling I posed a few years back. It offers a little more insight into coupling between the primary and secondary.

Here is a little food for thought. "K" is the term applied to the degree of magnetic coupling between the primary and secondary coils of a conventional tesla coil (or the primary and driver coil in the magnifier configuration). Typically, we aim for values between 0.1 and 0.25 or so for a conventional tesla coil, and 0.4 or higher for magnifier primary/driver coil systems. "M" is the amount of mutual inductance between the primary and secondary coil. We define:

K = M / SQUARE_ROOT [Lp x Ls]

where Lp is the primary inductance, Ls is the secondary inductance, M is the mutual inductance, and K is the coefficient of coupling between the two coils.

Consider the following scenarios:

Primary coil A:

flat pancake coil, 10 turns, inside diameter = 12", outside diameter=22"
Lp=56.6 uH

Primary coil B:

flat pancake coil, 5 turns, inside diameter = 12", outside diameter=22"
Lp=15.8 uH

Secondary coil #1:

solenoidal coil, 24" tall, 8" diameter, 888 turns #22 wire, Ls=45.8 mH

Secondary coil #2:

solenoidal coil, 24" tall, 8" diameter, 566 turns #18 wire, Ls=18.7 mH

Secondary coil #3:

solenoidal coil, 24" tall, 8" diameter, 288 turns #12 wire, Ls= 4.8 mH

where: uH is microhenries, mH is millihenries and dimensional units are in inches.

Assume the bottom turn of the secondary coil is aligned with the plane of the flat pancake primary coil for all cases. For primary coil A used with secondary coil #1, I experimentally measure K=0.23 with M=375.2 uH.

My question is this, what happens to K as we try the different combinations of primaries and secondaries above? Think about it. (BTW, I know what the answer is!)

Primary	Secondary	K
A	#1	0.23
B	#1	?
A	#2	?
B	#2	?
A	#3	?
B	#3	?

I posed a question about how K changes as the primary and secondary coils are modified, to which an individual responded:
>I do not have enough data to make a determination
>to fill in missing K values. Though you have
>stated M for the first setup, it is missing for
>all the others. I can not solve for K without
>the known value of the variable M.

While true, by knowing the geometry and the method by which M arises, one can predict the solution (as proven by an off-list response I have already received).

> You said assume the primary
>and secondary coils <are> aligned on a flat plane.
>If there is a way to calculate M from this
>geometry, I am not aware of it. IMO as soon as
>you change out 1 coil for another, the field
>interaction changes and M must be re-calculated
>prior to solving the coefficient of coupling.

Yes, M changes whenever either coil changes. Mathematically, M can be determined by computing the line integral of the paths of little dl line segments along both Ls and Lp. This is known as Neumann's formula, and can be found in physics texts. I have implemented this on a computer, and it works, although it is incredibly slow to compute. By thinking about the preceding sentences and the relationship between K, M, Lp and Ls, one can arrive at the correct answer without explicit knowledge of M.

>I've got my flame-proof suit on so have at it! Heheh

No flames. I had the same thoughts until I took a look at it through simulation and demonstration in the lab to prove the math was right! I'll post the answer on Tuesday or Wednesday.

And here is the answer:

Last week I posted a short quiz on the coupling coefficient K. Three different secondaries were considered, and two different primaries were employed. In each case, the primary inside and outside dimensions remain constant, only the number of turns changed. Similarly, the secondary diameter and height was held constant, and again only the number of turns changed (by varying the wire gauge).

Recall that the coupling coefficient K equals the mutual inductance M divided by the square root of the product of the primary and secondary inductances. The mutual inductance is the degree of inductive coupling between the primary and secondaries. Typical conventional tesla coils employ coupling between .05 and 0.20 or so, (perhaps a bit higher for you folks with fast rotary spark gaps).

Since K=M/sqrt(Lp x Ls), and only Np and Ns (the number of turns) were varied, what I was really asking was how does M depend on Np and Ns? It turns out that Lp is proportional to Np^2 for a flat pancake coil. The same is true for a solenoid so Ls is proportional to Ns^2. What is perhaps not obvious is the fact that M is proportional to Np times Ns for most coil geometries we use in a tesla coil (solenoid, flat pancake, inverted cone, for five turns or more in the primary). As a result, by keeping the same geometry and only varying the number of turns, K remains constant since as Lp and Ls vary, so too does M. In this case K=0.23 for all coil pairs.

Several folks arrived at this conclusion fairly quickly. John Couture pointed out that there is an approximation formula for M in Terman's "Radio Engineers' Handbook" for a solenoidal primary with solenoidal secondary (not quite applicable here). I warn the readers that this formula, as well as a series approximation published by Dwight, are prone to severe roundoff errors because several large numbers are subtracted from each other to arrive at a small value numerical solution. These formulas work best if you break up the coil into a series of small coils (mathematically) and then sum up the individual contributions. Neumann's formula, consisting of a double line integral, is the more appropriate formula, but requires numerical integration for arbitrary wire geometries. This was used in posing the quiz, along with experimental verification.

For the newbie, M is the inductive coupling between the primary and secondary coil. The voltage we induce in the secondary coil is directly proportional to M, so we may want to make it large. However, if the coupling is too tight we start to introduce a splitting of the frequencies observed in the secondary, due to the complex phase shift of the induced current. (The secondary current is 90 degrees out of phase with the primary current.) The degree of coupling at which this occurs is called critical coupling, and it depends on the losses in the primary and secondary. We usually try to operate coils near critical coupling. Once this frequency splitting starts, the secondary coil may start to break out with spark at locations along the secondary coil away from the top, which can cause the coil to self destruct. You can also get significant kickback into the primary circuit, potentially causing damage. Initially, use very loose coupling (secondary coil raised up 4-8 inches above the bottom turn of a flat or conical primary coil), and lower it in stages after you get your coil working well.

Several people also asked how to measure K. There are a variety of methods:

Method 1:

Set up your primary and secondary coils in the geometry you intend to use. Connect the two coils (primary and secondary) in series with each other and measure the inductance with an L meter. Call it La. Now reconnect the two coils in series, reversing the leads on the secondary coil. Measure it again to get Lb. M is then determined from the formula: M = absolute value of [La-Lb]/4. Be aware that the calculation involves the subtraction of two large numbers to obtain a small number since Lp is usually in uH and Ls is in mH (a factor of 1000).

Method 2:

Set up your coil in the geometry you intend to use. Connect up your inductance meter to the primary with the secondary in its proper position for normal operation. Disconnect all leads to the secondary (including ground). Measure the primary coil inductance with the secondary coil open circuited, and call it Lpso. Next, short circuit the secondary windings using a small piece of wire extending from the top of the secondary to the bottom. Again, measure the primary coil inductance, and call it Lpss. One can now compute the coupling coefficient k using the formula:

k = SQRT [1.0 - (Lpss / Lpso)]

where SQRT means take the square root.

Again, this method is sensitive to measurement errors because the two quantities are so different in value. In addition, the capacitive coupling between the coils can result in erroneous readings.

Method 3:

This method measures M instead of K. Place a small 1% precision resistor (50-100 ohms) in series with your primary coil, and apply 60 cycle A.C. Measure the A.C. voltage across the resistor, and calculate the primary current Ip from the expression Ip=V/R, where V is the applied A.C. voltage in the circuit. Measure the induced voltage developed across the secondary coil (Vs). Now compute M from the relationship Vs=w x M x Ip, where w is 2 times pi times the operating frequency (60 Hz). This measurement should be done at a low frequency, well below the resonance of the coil. Tesla used this method at Colorado Springs to measure M. It is the best method to measure coupling experimentally.

Method 4:

If you are using tight coupling (K > 0.2) you can use an oscilloscope to find the two resonance peaks due to frequency splitting. Tune the primary and secondary so their resonances match. Then drive the primary with a signal generator and monitor the signal of the secondary with the scope (using a probe with 1/2 meter of wire dangling several feet away from the coil). Vary the frequency around resonance (Fres), and you will see two peaks, one at frequency F1 below Fres, and another at frequency F2 above Fres. If Fres is the natural resonant frequency for both coils, then:

Fres=sqrt[2 / (1 / F1^2 + 1 / F2^2)]   (reality check)

and

K = 1 - 2 / [1 + (F2^2/F1^2)]

Acknowledgments

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FAQ Revision History
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Feedback

Please send comments, flames, criticisms, and constructive feedback to msr7@po.cwru.edu Let me know what is missing from the FAQ. Yes, I know this FAQ is too long - already been told that by several folks - sorry. If you simply have a newbie question, please post it on one of the fine tesla related listservers. I get far too much mail to answer at times and may not be able to get back to you in a timely manner.