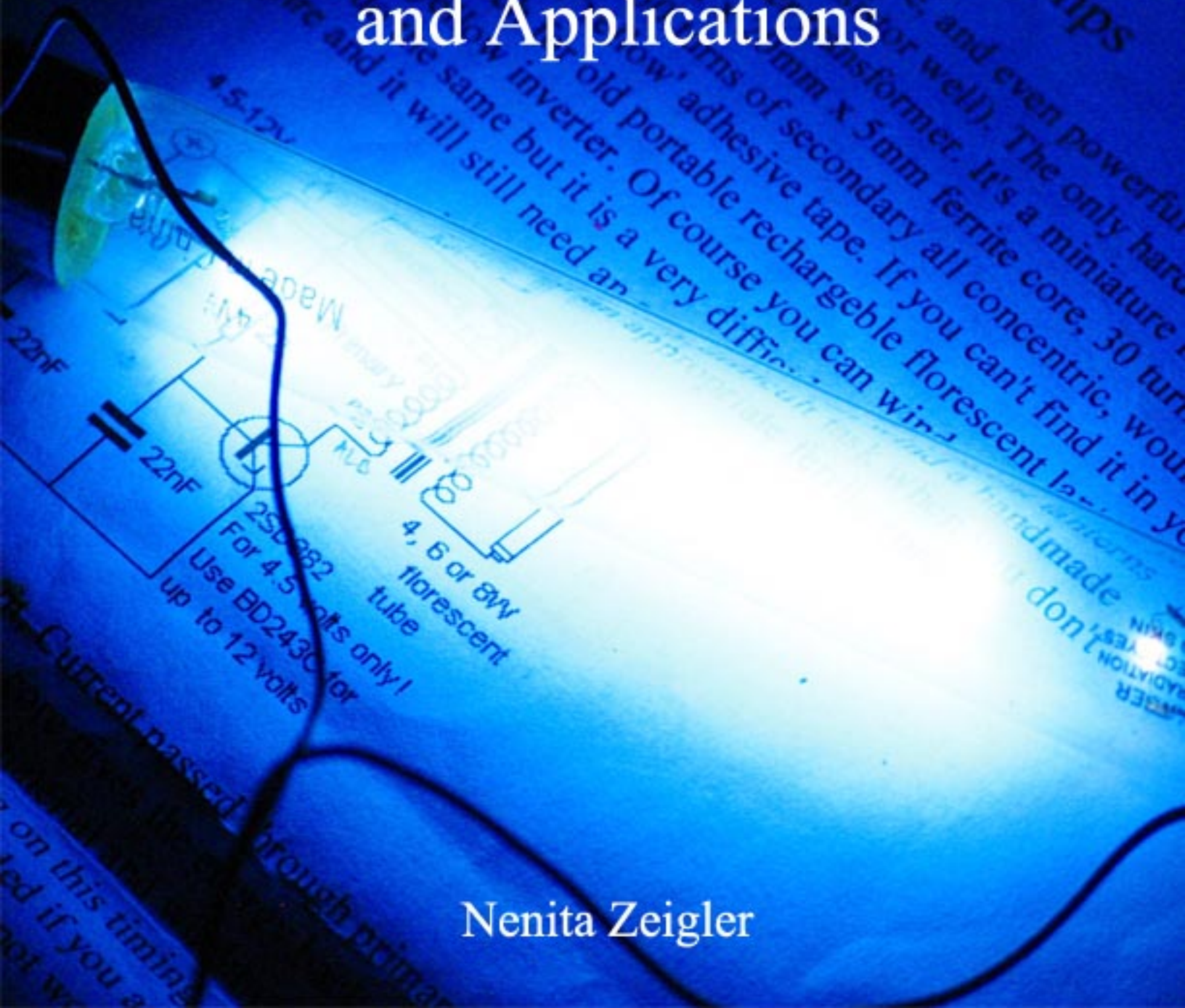


# Electromagnetic Coils and Applications



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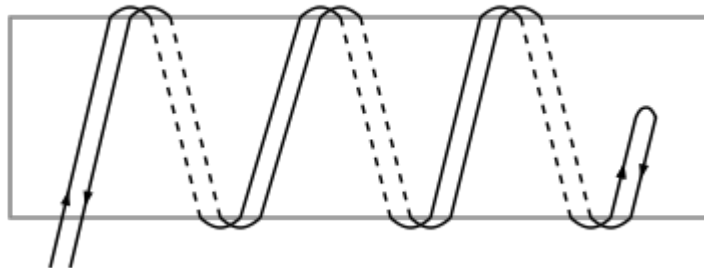
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## Chapter 1

# Bifilar Coil and Basket Winding

## Bifilar Coil

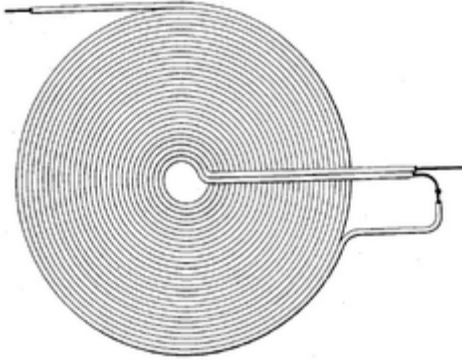


Non-inductive bifilar winding

A **bifilar coil** is an electromagnetic coil that contains two closely spaced, parallel windings. In engineering, the word *bifilar* describes wire which is made of two filaments or strands. It is commonly used to denote special types of winding wire for transformers. Wire can be purchased in bifilar form, usually as different colored enameled wire bonded together. For three strands, the term **trifilar coil** is used.

## **Description and applications**

### **Bifilar coil configurations**



Nikola Tesla's flat bifilar coil.

1. parallel-wound, series connected
2. parallel-wound, parallel connected
3. counter-wound (series)
4. counter-wound (parallel)

Some bifilar coils have adjacent coils in which the convolutions are arranged so that the potential difference is magnified (i.e., the current flows in same parallel direction). Others are wound so that the current flows in opposite directions. The magnetic field created by one winding is therefore equal and opposite to that created by the other, resulting in a net magnetic field of zero (i.e., neutralizing any negative effects in the coil). In electrical terms, this means that the self-inductance of the coil is zero.

The bifilar coil (more often called the *bifilar winding*) is used in modern electrical engineering as a means of constructing wire-wound resistors with negligible parasitic self-inductance.

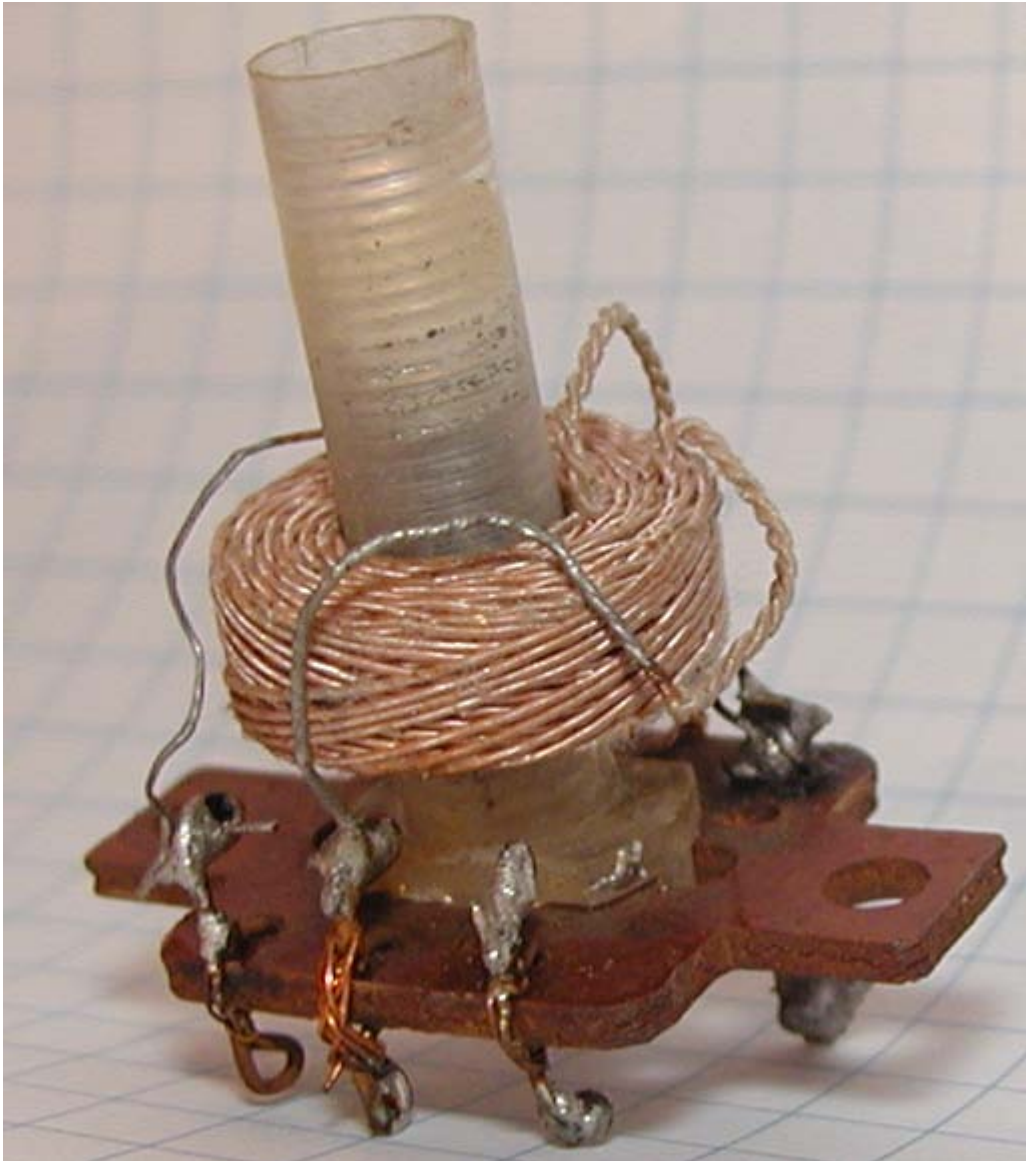
A different type of bifilar coil is used in some relay windings and transformers used for a switched-mode power supply to suppress back-emf. In this case, the two wire coils are closely spaced and wound in parallel but are electrically isolated from each other. The primary coil is driven to operate the relay, and the secondary coil is short-circuited inside the case. When the current through the primary is interrupted, as happens when the relay is switched off, most of the magnetic energy is intercepted by the secondary coil which converts it to heat in its internal resistance. This is only one of several methods of absorbing the energy from the primary coil before it can damage the device (usually a vulnerable semiconductor) that drives the relay. The main disadvantage of this method is that it greatly increases the switching time of the relay.

When used in a switching transformer, one winding of the bifilar coil is used as a means of removing the energy stored in the stray magnetic flux which fails to link the *primary coil* to the *secondary coil* of the transformer. Because of their proximity, the wires of the bifilar coil both "see" the same stray magnetic flux. One wire is clamped to ground usually by a diode so that when the other "primary" wire of the bifilar coil no longer has a voltage applied across it by the switching transistor, the stray magnetic flux generates a current in the clamping coil with the primary side voltage appearing across it, causing an equal voltage to appear across the primary winding. If this clamping coil was not used, the stray magnetic flux would attempt to force a current to flow through the primary wire. Since the primary wire is switched off and the switching transistor is in a high resistance state, the high voltage which would appear on the semiconductor switching transistor would exceed its electrical breakdown or even damage it.

## ***History***

An early example of the bifilar coil can be seen in Nikola Tesla's United States patent 512,340 of 1894. Tesla explains that in some applications (which he does not specify) the self-inductance of a conventional coil is undesired and has to be neutralised by adding external capacitors. The bifilar coil in this configuration has increased self-capacitance, thereby saving the cost of the capacitors. It is notable that this is *not* the kind of bifilar winding used in non-inductive wirewound resistors where the windings are wired anti-series to null out self-inductance.

## Basket Winding



Basket winding made with a Litz wire

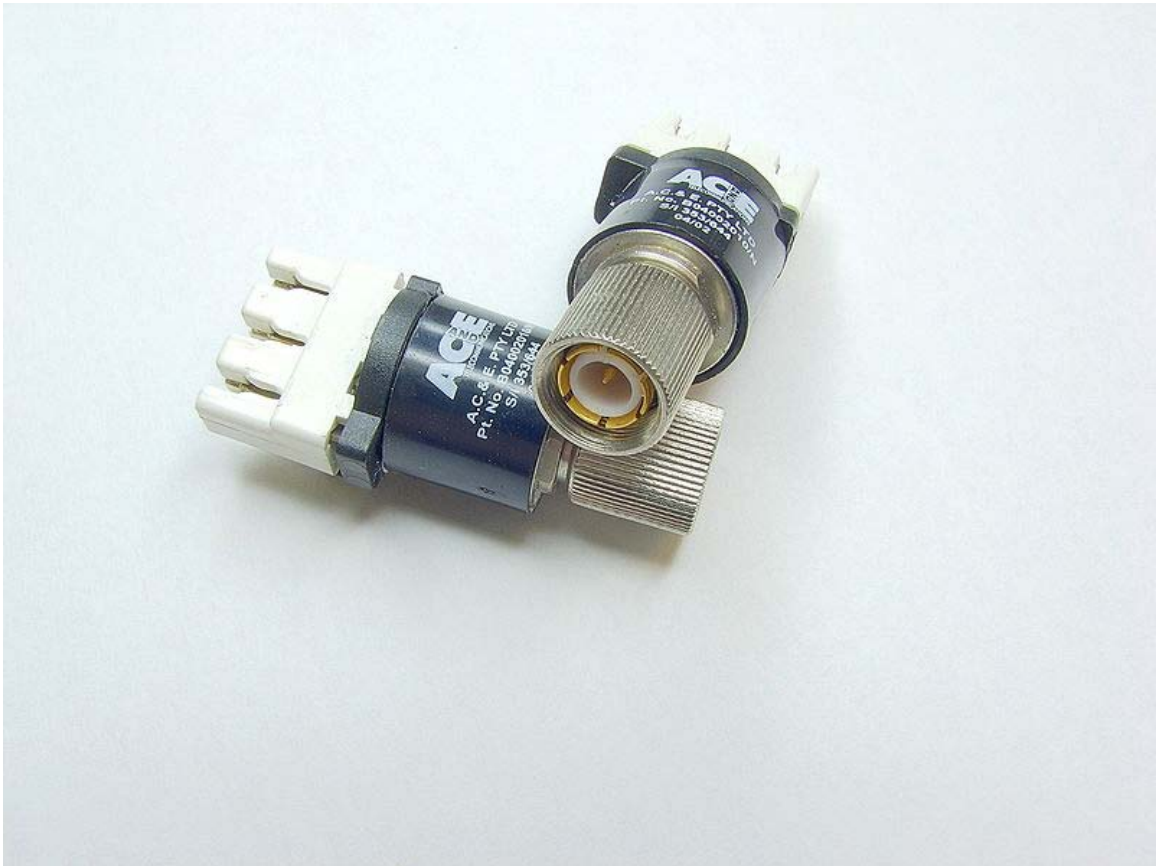
**Basket winding** is an electromagnetic coil wound in a special way, such that the wires in neighbouring layers cross each other at an angle as close to 90 degrees as possible. Such a winding results in low parasitic capacitance as compared with a regular winding with the same number of turns. However, the physical dimensions are greater which leads to higher leakage inductance.

Basket windings are used for high frequency coils, and are wound with a Litz wire, or a wire isolated with cotton or silk. The type of isolation is important also from mechanical

point of view during the winding, because a common enamelled magnet wire would not provide sufficient surface friction to hold the subsequent turns at the large angle.

## Chapter 2

# Balun



Pair of AC&E 120 Ohm twisted pair (Krone IDC) to 75 Ohm coaxial cable balun transformers. Actual length is about 3cm.

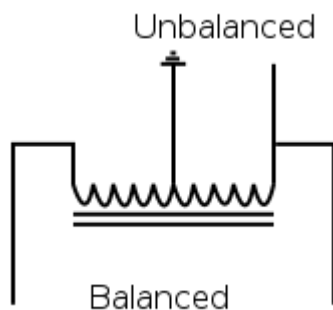


2 balun matching transformers

A **balun**, is a type of electrical transformer that can convert electrical signals that are balanced about ground (differential) to signals that are unbalanced (single-ended) and vice versa. They are also often used to connect lines of differing impedance. The origin of the word balun is **bal**(ance) + **un**(balance).

Baluns can take many forms and their presence is not always obvious. They always use electromagnetic coupling for their operation.

### ***Types of balun***

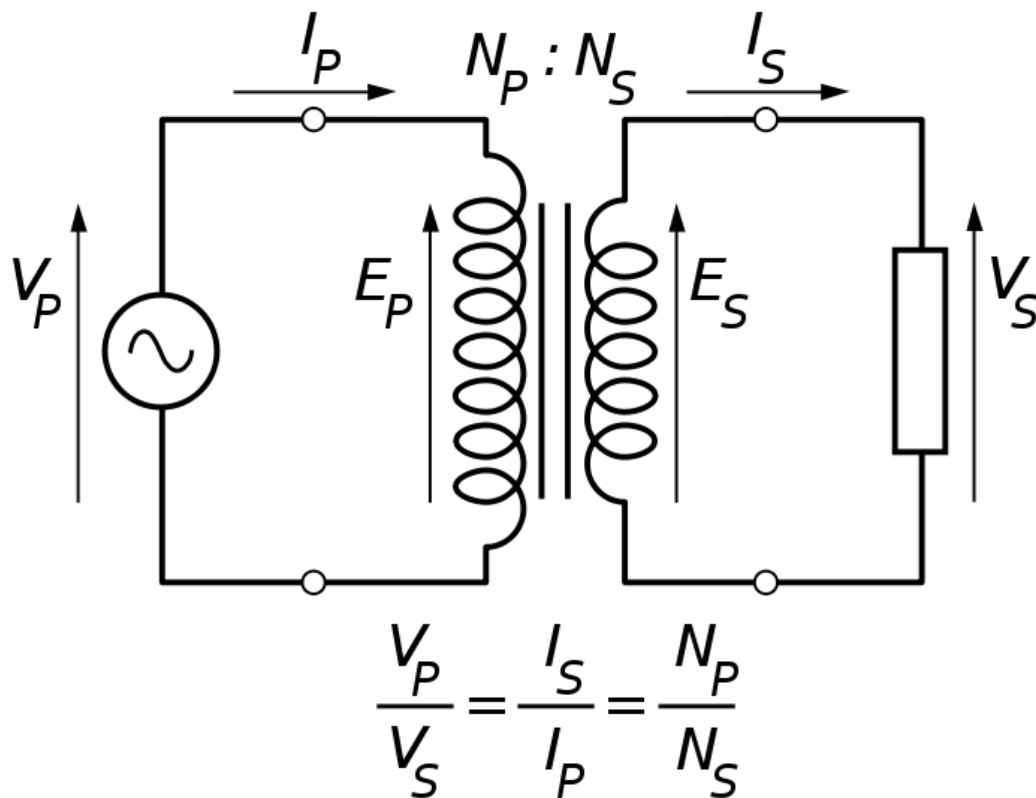


Autotransformer 4:1 wideband balun using two windings on a ferrite rod.

## Autotransformer type

In an autotransformer, two coils on a ferrite rod can be used as a balun by winding the individual strands of enameled wire comprising the coil very tightly together. This winding can take one of two forms: either the two windings must be wound such that the two form a single layer where each turn is touching each of the adjacent turns of the other winding; or the two wires are twisted together before being wound into the coil.

The two windings are joined to become a single coil. The end of one of the windings on one side of the coil is connected to the end of the other winding on the other side of the coil. This point then becomes the ground for the unbalanced circuit. One of the remaining ends is connected to the ungrounded side of the unbalanced circuit, and one side of the balanced circuit. Finally, the other side of the balanced circuit is connected to the remaining end.



Isolated transformer

## Classical transformer type

Isolated transformers have a real impedance at a resonance frequency where self-inductance and self-capacitance for each individual winding cancel themselves out.

## Transmission-line transformer type

Baluns can be considered as simple forms of transmission line transformers.

A more complex (and subtle) type results when the transformer type (magnetic coupling) is combined with the transmission line type (electro-magnetic coupling). This is where whole transmission lines are used as windings, resulting in devices capable of very wideband operation. This whole class known generally as "Transmission Line Transformers" spawn their own huge variety. Very commonly, they use small ferrite cores in toroidal or "binocular" shapes. Something as simple as 10 turns of coaxial cable coiled up on a diameter about the size of a dinner plate makes an extremely effective choke balun for frequencies from about 10 MHz to beyond 30 MHz. The magnetic material may be "air", but it is a transmission line transformer.



Homemade 1:1 balun using a toroidal core and coaxial cable. This simple RF choke works as a balun by preventing signals passing along the outside of the braid. Such a device can be used to cure television interference by acting as a braid-breaker.

The Guanella transmission line transformer is often combined with a balun to act as an impedance matching transformer. Putting balancing aside a 1:4 transformer of this type consists of a 75 Ohm transmission line divided in parallel into two 150 Ohm cables, which are then combined in series for 300 Ohm. It is implemented as a specific wiring around the ferrite core of the balun.

## Delay line type

A large class of baluns uses connected transmission lines of specific lengths, with no obvious "transformer" part. These are usually built for (narrow) frequency ranges where the lengths involved are some multiple of a quarter wavelength of the intended frequency in the transmission line medium. A common application is in making a coaxial

connection to a balanced antenna, and designs include many types involving coaxial loops and variously connected "stubs".

One easy way to make a balun is a one-half wavelength ( $\lambda/2$ ) length of coaxial cable. The inner core of the cable is linked at each end to one of the balanced connections for a feeder or dipole. One of these terminals should be connected to the inner core of the coaxial feeder. All three braids should be connected together. This then forms a 4:1 balun which works at only one frequency.

Another narrow band design is to use a  $\lambda/4$  length of metal pipe. The coaxial cable is placed inside the pipe; at one end the braid is wired to the pipe while at the other end no connection is made to the pipe. The balanced end of this balun is at the end where the pipe is wired to the braid. The  $\lambda/4$  conductor acts as a transformer converting the infinite impedance at the unconnected end into a zero impedance at the end connected to the braid. Hence any current entering the balun through the connection, which goes to the braid at the end with the connection to the pipe, will flow into the pipe. This balun design is not good for low frequencies because of the long length of pipe that will be needed. An easy way to make such a balun is to paint the outside of the coax with conductive paint, then to connect this paint to the braid.

### ***Balun alternatives***

An RF choke can be used in place of a balun. If a coil is made using coaxial cable near to the feed point of a balanced antenna then the RF current that flows on the outer surface of the coaxial cable can be attenuated. One way of doing this would be to wrap a lossy material, such as ferrite around the coaxial cable;

### ***Applications***

A balun's function is generally to achieve compatibility between systems, and as such, finds extensive application in modern communications, particularly in realising frequency conversion mixers to make cellular phone and data transmission networks possible. They are also used to convert an E1 carrier signal from coaxial cable to UTP CAT-5 cable.

## Radio and television



A 75-to-300 ohm balun built into the antenna plug.

In television, amateur radio, and other antenna installations and connections, baluns convert between 300 ohm ribbon cable or 450 ohm ladder line (balanced) and 75  $\Omega$  coaxial cable (unbalanced) or to directly connect a balanced antenna to (unbalanced) coax. To avoid EMC problems it is a good idea to connect a centre fed dipole antenna to coaxial cable via a balun. Match 300  $\Omega$  twin-lead cable to 75  $\Omega$  coaxial cable

In electronic communications, baluns convert Twinax cables to Category 5 cables, and back, or they convert between coaxial cable and ladder line.

In measuring the impedance or radiation pattern of a balanced antenna using a coaxial cable, it is important to place a balun between the cable and the antenna feed. Unbalanced currents that may otherwise flow on the cable will make the measured antenna impedance sensitive to the configuration of the feed cable, and the radiation pattern of small antennas may be distorted by radiation from the cable.

Baluns are present in radars, transmitters, satellites, in every telephone network, and probably in most wireless network modem/routers used in homes. It can be combined with transimpedance amplifiers to compose high-voltage amplifiers out of low-voltage components.

## Video

While not as high as most RF applications, baseband video still uses frequencies up to several megahertz. Since this bandwidth is now well within range of modern twisted-pair cables, they are now being used to send video which would otherwise run over coaxial cable. Many better security cameras now have both a balanced UTP output and an unbalanced coaxial one via an internal balun, though any camera can be used with an external balun. A balun is also used on the video recorder end to convert back from the 100-ohm balanced to 75-ohm unbalanced. A balun of this type has a BNC connector with

two screw terminals. VGA/DVI baluns are baluns with electronic circuitry used to connect VGA/DVI sources (laptop, DVD, etc.) to VGA/DVI display devices over long runs of CAT-5/CAT-6 cable. Runs over 130 m (400 ft) may lose quality due to attenuation and variations in the arrival time of each signal. A skew control and special low skew or skew free cable is used for runs over 130 m (400 ft).

## Audio



Three audio baluns (transformers).

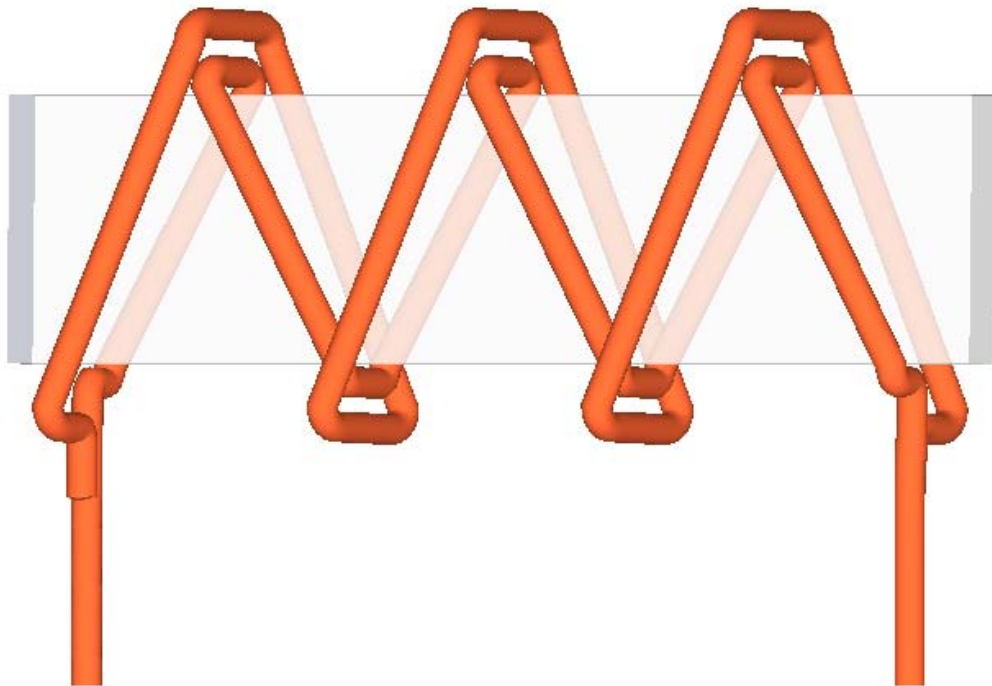
In audio applications, baluns convert between high impedance unbalanced and low impedance balanced lines.

Except for the connections, the three devices in the image are electrically identical, but only the leftmost two can be used as baluns. The device on the left would normally be

used to connect a high impedance source, such as a guitar, into a balanced microphone input, serving as a passive DI unit. The one in the centre is for connecting a low impedance balanced source, such as a microphone, into a guitar amplifier. The one at the right is not a balun, as it provides only impedance matching.

In power line communications, baluns are used in coupling signals onto a power line.

## Ayrton-Perry Winding



Ayrton-Perry winding

**Ayrton-Perry winding** is a type of bifilar winding pattern used in winding wire on forms to make electronic components. Its advantage is that the resulting coil of wire has low values of parasitic inductance and parasitic capacitance. Ayrton-Perry windings of resistance wire are used to make wirewound RF resistors that are used at high frequencies, where inductance and capacitance are unwanted.

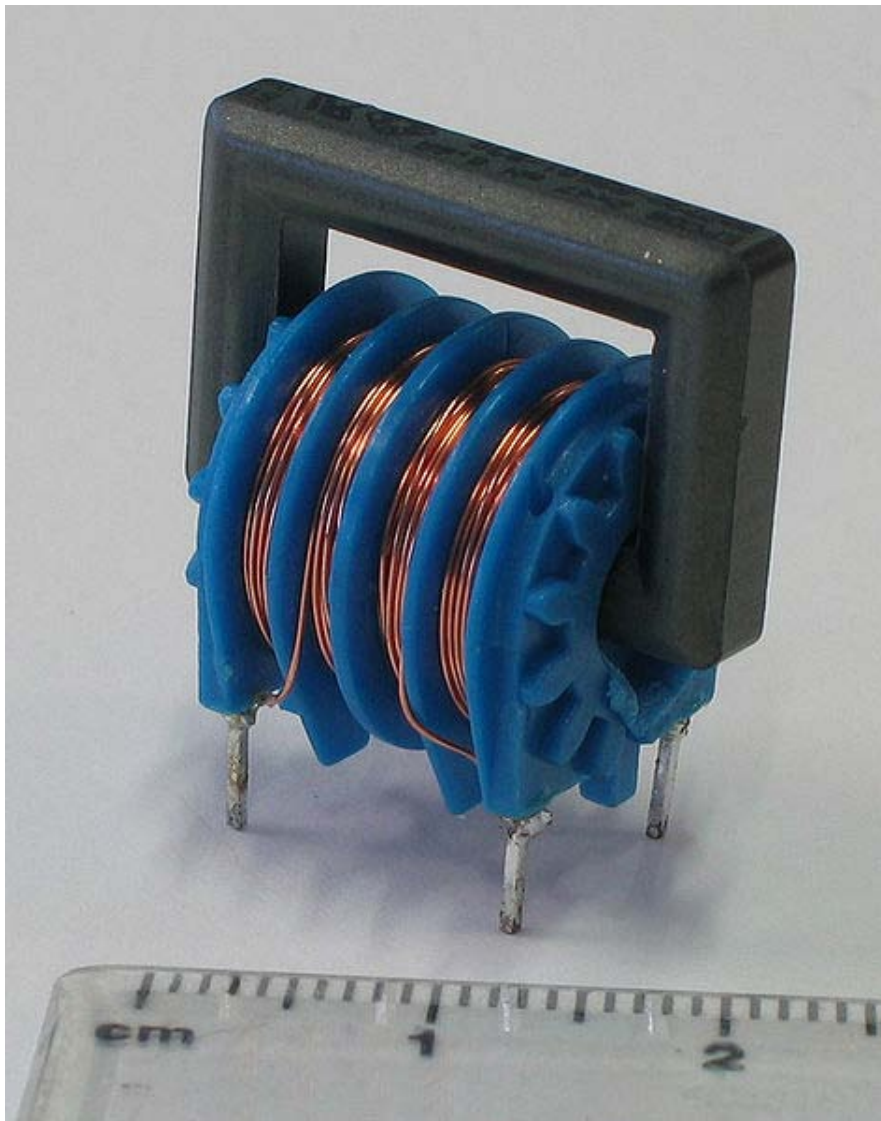
The winding is made of two separate wires wound in opposing directions along an insulating form and connected in parallel at the ends. Since there are the same number of turns of wire in either direction, the magnetic fields of the two wires cancel each other out, so the coil has little inductance. And since adjacent turns of the two wires are at approximately the same voltage, there is little parasitic capacitance between the turns.

One disadvantage is that because the two lengths of resistive wire are connected in parallel, four times the length of wire (twice the length for each coil) is needed to make a given resistance than if a single coil was used.

## Chapter 3

# Choke (Electronics) and Helmholtz Coil

## Choke (Electronics)



A choke, with two 47mH windings and rated to handle 0.6A

A **choke** is an inductor designed to block (have a high reactance to) higher frequencies in an electrical circuit while passing signals of much lower frequency or direct current.

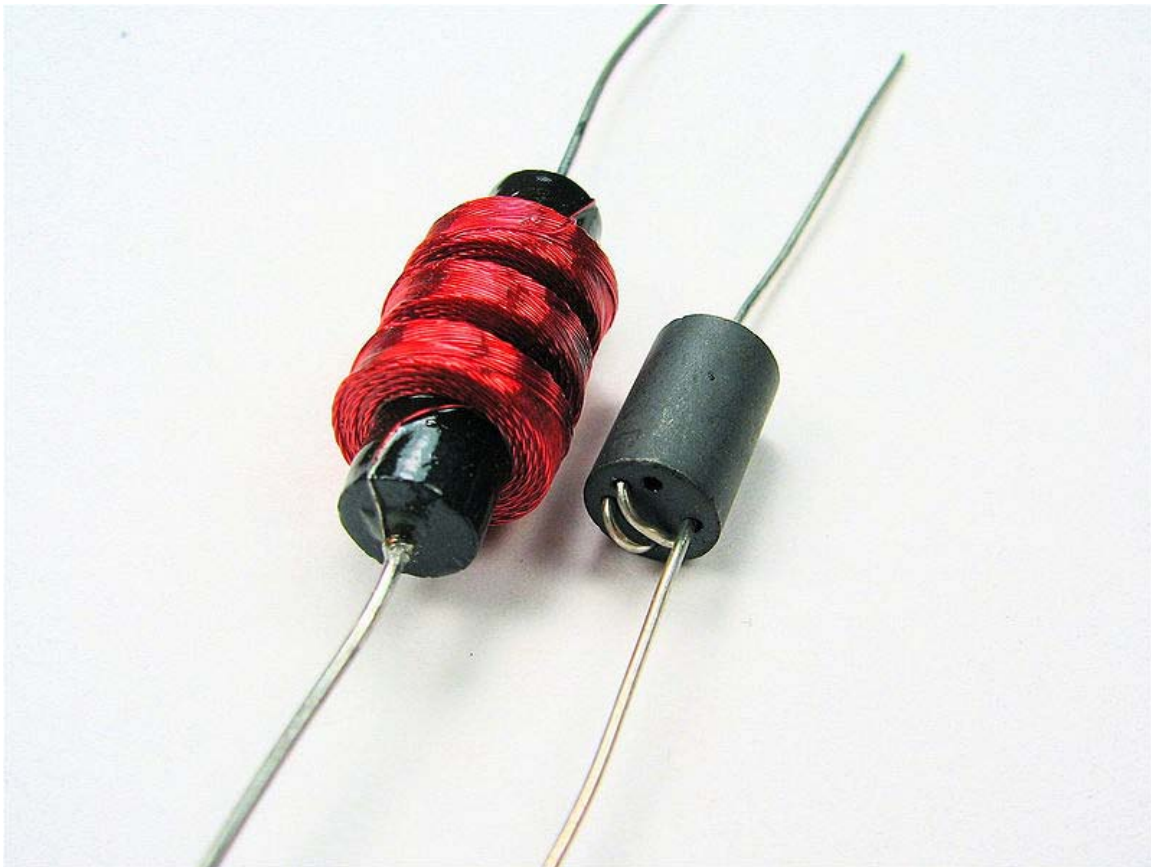
### ***Description***

Choke coils are inductances that isolate AC frequency currents from certain areas of a radio circuit. Chokes depend upon the property of self-inductance for their operation. They can be used to block alternating current while passing direct current (contrast with capacitor).

### **Common-mode choke**

Common-mode choke coils are useful in a wide range of prevention of electromagnetic interference (EMI) and radio frequency interference (RFI) from power supply lines and for prevention of malfunctioning of electronic equipment. They pass differential currents (equal but opposite), while blocking common-mode currents.

### ***Types and construction***



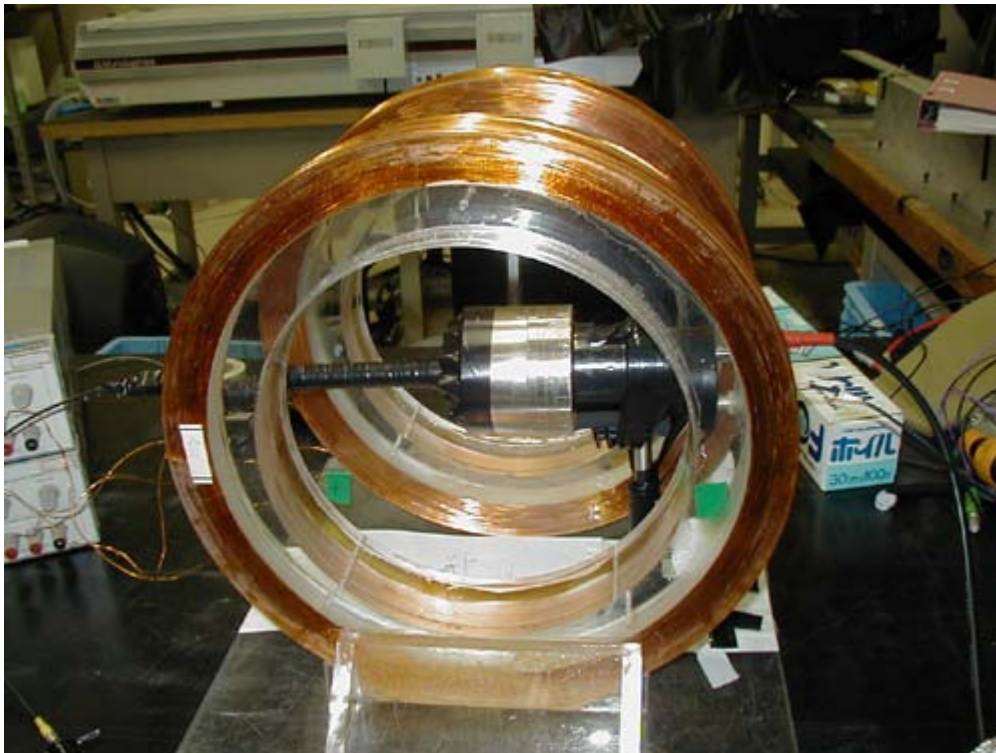
An MF or HF radio choke for tenths of an Ampere and several hundred Volts, and a ferrite bead VHF choke for several Amperes and tens of Volts.

Chokes used in radio circuits are divided into two classes – those designed to be used with audio frequencies, and the others to be used with radio frequencies. Audio frequency coils, usually called A.F. chokes, can have ferromagnetic iron cores to increase their inductance. Chokes for higher frequencies often have iron powder or ferrite cores. Chokes for even higher frequencies have non-magnetic cores and low inductance simulating the effects of an air-core.

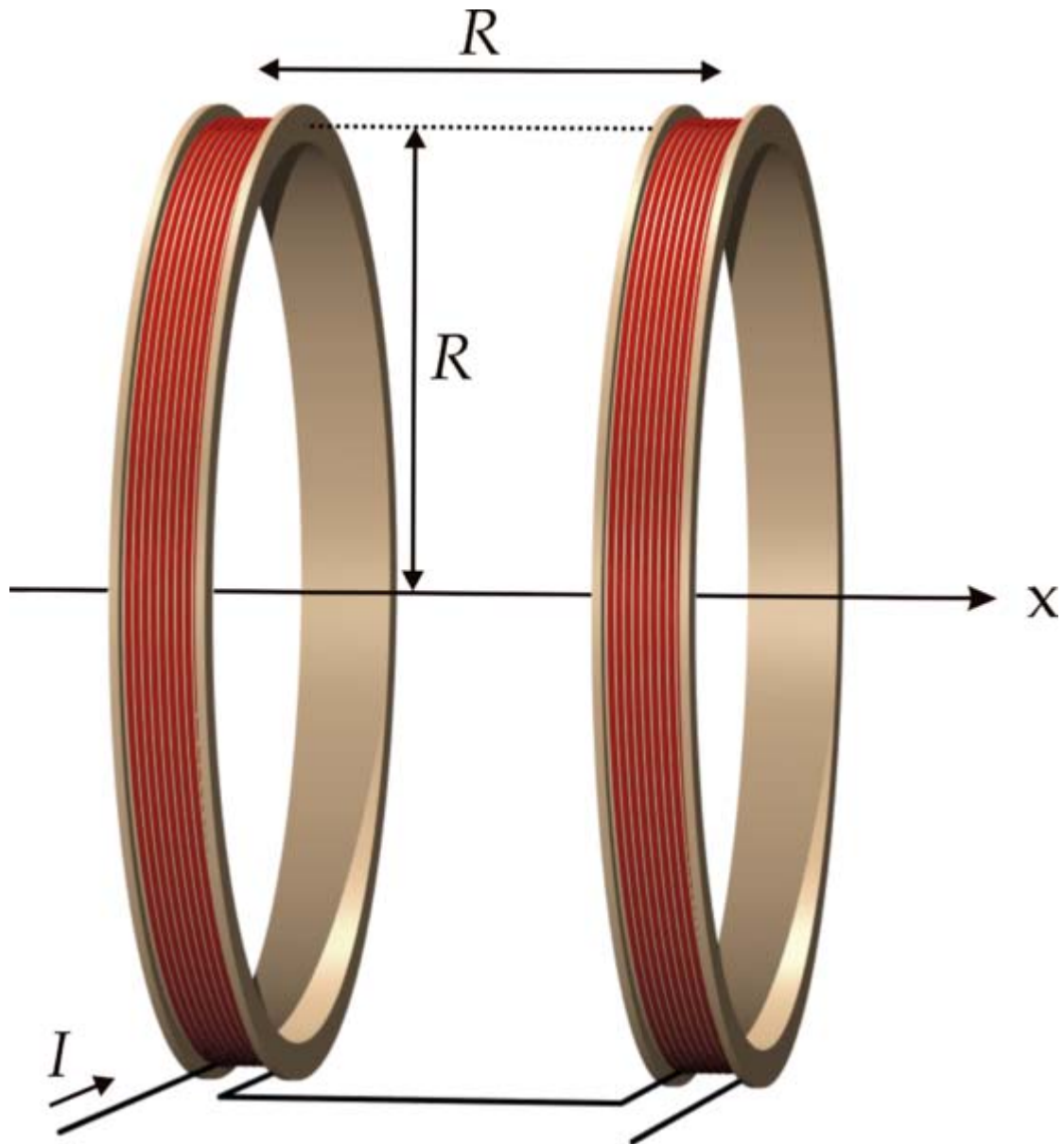
### ***Solid-state chokes***

Solid-state chokes (SSC) can manage higher currents than traditional chokes. They can help reduce the high frequency buzzing noises that occur when running under high electrical currents.

## **Helmholtz Coil**



A Helmholtz coil



Helmholtz coil schematic drawing

A **Helmholtz coil** is a device for producing a region of nearly uniform magnetic field. It is named in honor of the German physicist Hermann von Helmholtz.

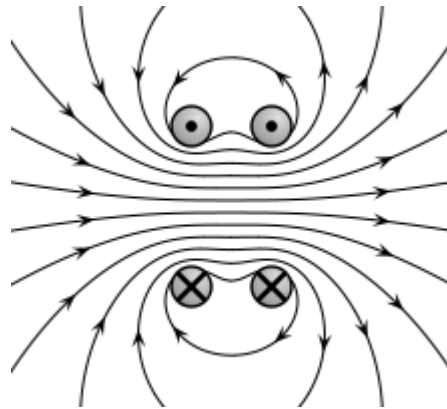
### **Description**

A Helmholtz pair consists of two identical circular magnetic coils that are placed symmetrically one on each side of the experimental area along a common axis, and separated by a distance  $h$  equal to the radius  $R$  of the coil. Each coil carries an equal electrical current flowing in the same direction.

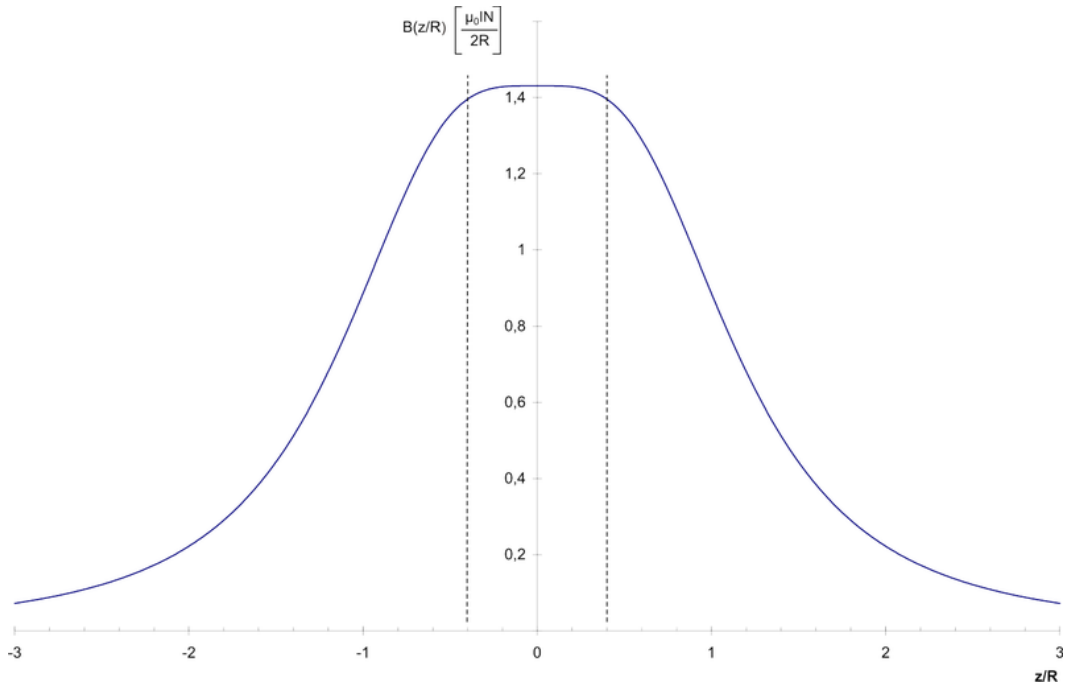
Setting  $h = R$ , which is what defines a Helmholtz pair, minimizes the nonuniformity of the field at the center of the coils, in the sense of setting  $d^2B / dx^2 = 0$  (meaning that the first nonzero derivative is  $d^4B / dx^4$  as explained below), but leaves about 6% variation in field strength between the center and the planes of the coils. A slightly larger value of  $h$  reduces the difference in field between the center and the planes of the coils, at the expense of worsening the field's uniformity in the region near the center, as measured by  $d^2B / dx^2$ .

In some applications, a Helmholtz coil is used to cancel out Earth's magnetic field, producing a region with a magnetic field intensity much closer to zero.

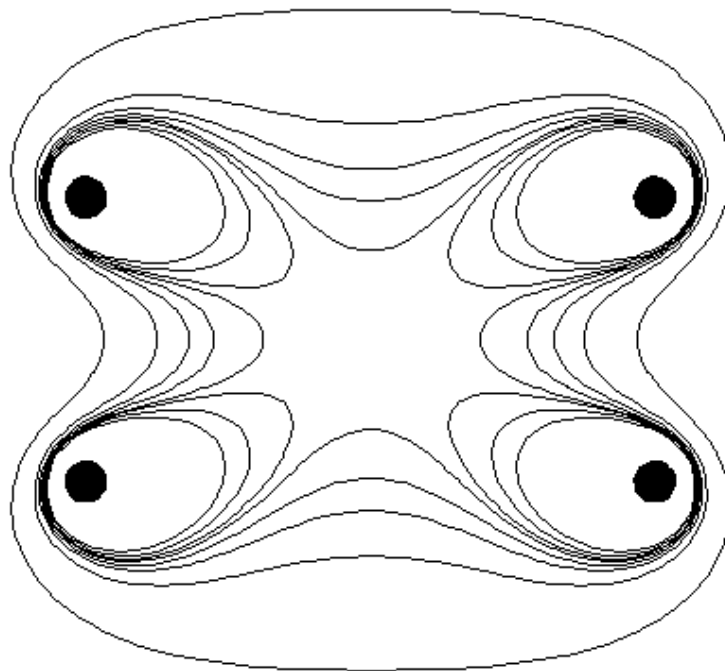
### **Mathematics**



Magnetic field lines in a plane bisecting the current loops. Note the field is approximately uniform in between the coil pair. (In this picture the coils are placed one beside the other: the axis is horizontal)



Magnetic field induction along the axis crossing the center of coils;  $z = 0$  is the point in the middle of distance between coils.



Contours showing the magnitude of the magnetic field near the coil pair. Inside the central 'octopus' the field is within 1% of its central value  $B_0$ . The five contours are for field magnitudes of  $0.5B_0$ ,  $0.8B_0$ ,  $0.9B_0$ ,  $0.95B_0$ , and  $0.99B_0$ .

The calculation of the exact magnetic field at any point in space has mathematical complexities and involves the study of Bessel functions. Things are simpler along the axis of the coil-pair, and it is convenient to think about the Taylor series expansion of the field strength as a function of  $x$ , the distance from the central point of the coil-pair along the axis. By symmetry the odd order terms in the expansion are zero. By separating the coils so that charge  $x = 0$  is an inflection point for each coil separately we can guarantee that the order  $x^2$  term is also zero, and hence the leading non-uniform term is of order  $x^4$ . One can easily show that the inflection point for a simple coil is  $R/2$  from the coil center along the axis; hence the location of each coil at  $x = \pm R/2$

A simple calculation gives the correct value of the field at the center point. If the radius is  $R$ , the number of turns in each coil is  $n$  and the current flowing through the coils is  $I$ , then the magnetic flux density,  $B$  at the midpoint between the coils will be given by

$$B = \left(\frac{4}{5}\right)^{3/2} \frac{\mu_0 n I}{R}$$

$\mu_0$  is the permeability of free space ( $1.26 \times 10^{-6} \text{ T} \cdot \text{m/A}$ ), and  $R$  is in meters.

### Derivation

Start with the formula for the on-axis field due to a single wire loop (which is itself derived from the Biot-Savart law):

$$B = \frac{\mu_0 I R^2}{2(R^2 + x^2)^{3/2}}$$

Where:

$\mu_0$  = the permeability constant =

$$4\pi \times 10^{-7} \text{ T} \cdot \text{m/A} = 1.26 \times 10^{-6} \text{ T} \cdot \text{m/A}$$

$I$  = coil current, in amperes

$R$  = coil radius, in meters

$x$  = coil distance, on axis, to point, in meters

However the coil consists of a number of wire loops, the total current in the coil is given by

$nI$  = total current

Where:

$n$  = number of wire loops in one coil

Adding this to the formula:

$$B = \frac{\mu_0 n I R^2}{2(R^2 + x^2)^{3/2}}$$

In a Helmholtz coil, a point halfway between the two loops has an x value equal to R/2, so let's perform that substitution:

$$B = \frac{\mu_0 n I R^2}{2(R^2 + (R/2)^2)^{3/2}}$$

There are also two coils instead of one, so let's multiply the formula by 2, then simplify the formula:

$$B = \frac{2\mu_0 n I R^2}{2(R^2 + (R/2)^2)^{3/2}}$$
$$B = \left(\frac{4}{5}\right)^{3/2} \frac{\mu_0 n I}{R}$$

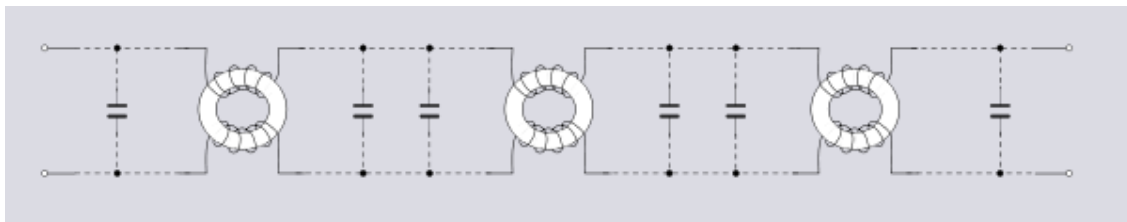
## Chapter 4

# Loading Coil

In electronics, a **loading coil** or **load coil** is a coil (inductor) that does not provide coupling to any other circuit, but is inserted in a circuit to increase its inductance. The need was discovered by Oliver Heaviside in studying the disappointing slow speed of the Transatlantic telegraph cable. He concluded additional inductance was required to prevent amplitude and time delay distortion of the transmitted signal. The mathematical condition for distortionless transmission is known as the Heaviside condition. Previous telegraph lines were overland or shorter, hence had less delay and the need for extra inductance was not so great. Submarine communications cables are particularly subject to the problem, but early 20th century ones using balanced pairs were often continuously loaded by iron tape rather than discretely by load coils.

Loading coils are archaically known as **Pupin coils** after Mihajlo Pupin (especially when used for the Heaviside condition), and the process of inserting them is sometimes called *pupinization*.

### **Applications**



Schematic of a balanced loaded line. The capacitors are shown connected with dotted lines to indicate that the capacitance is actually distributed along the line rather than the discrete elements shown. The windings of the loading coil are wound such that the magnetic flux induced in the core is in the same direction for both windings.

## **Voice circuits**

A common application of loading coils is to improve the voice-frequency amplitude response characteristics of the twisted balanced pairs in a telephone cable.

Loading coils inserted periodically in series with a pair of wires reduce the attenuation at the higher voice frequencies up to the cutoff frequency of the low-pass filter formed by the inductance of the coils (plus the distributed inductance of the wires) and the distributed capacitance between the wires. Above the cutoff frequency, attenuation increases rapidly. The shorter the interval between the coils, the higher the cut-off frequency.

It should be emphasised that the cutoff effect is an artifact of using lumped inductors. With loading methods using continuous distributed inductance there is no cutoff.

Without loading coils, the line response is dominated by the resistance and capacitance of the line with the attenuation gently increasing with frequency. With loading coils of exactly the right inductance, neither capacitance nor inductance dominate: the response is flat, waveforms are undistorted and the characteristic impedance is resistive up to the cutoff frequency. The coincidental formation of an audio frequency filter is also beneficial in that noise is reduced.

## **DSL**

When loading coils are in place, signal attenuation remains low for signals within the passband of the transmission line but increases rapidly for frequencies above the audio cutoff frequency. Thus, if the pair is subsequently reused to support applications that require higher frequencies (such as analog or digital carrier systems or DSL), any loading coils that were present on the line must be removed or replaced with one which is transparent to DSL. Using coils with parallel capacitors will form a filter with the topology of an m-derived filter and a band of frequencies above the cut-off will also be passed.

If they are not removed, as when the subscriber is an extended distance (e.g. over 4 miles) from the Central Office, DSL can not be supported. This sometimes happens in dense, growing areas (subject to frequent national numbering scheme repartitioning) such as Southern California in the late 1990s and early 21st century.

## **Carrier systems**

American early and middle 20th Century telephone cables had load coils at intervals of a mile (1.61 km), usually in coil cases holding many. The coils must be removed to pass high frequencies, but the coil cases provided convenient places for repeaters for digital T-carrier systems, which could carry 1.5 Mbit/s across that distance. Due to narrower streets and higher cost of copper, European cables had thinner wires and needed closer intervals. Intervals of a kilometer allowed European systems to carry 2 Mbit/s.

## Radio antennae

A (mobile) radio antenna, shorter than a quarter wavelength for practical reasons, presents capacitive reactance to a transmission line. This can be canceled by inserting an equal and opposite (inductive) reactance in series, by means of a loading coil typically at the base or center of the antenna. Consequently the antenna presents a resistance (desirable) to the transmission line.

### **Campbell equation**

The Campbell equation is a relationship due to George Ashley Campbell for predicting the propagation constant of a loaded line. It is stated as;

$$\cosh(\gamma'd) = \cosh(\gamma d) + \frac{Z}{2Z_0} \sinh(\gamma d)$$

where,

$\gamma$  is the propagation constant of the unloaded line

$\gamma'$  is the propagation constant of the loaded line

$d$  is the interval between coils on the loaded line

$Z$  is the impedance of a loading coil and

$Z_0$  is the characteristic impedance of the unloaded line.

A more engineer friendly rule of thumb is that the approximate requirement for spacing loading coils is ten coils per wavelength of the maximum frequency being transmitted. This approximation can be arrived at by treating the loaded line as a constant k filter and applying image filter theory to it. From basic image filter theory the angular cutoff frequency and the characteristic impedance of a low-pass constant k filter are given by;

$$\omega_c = \frac{1}{\sqrt{L_{\frac{1}{2}} C_{\frac{1}{2}}}} \quad \text{and,} \quad Z_0 = \sqrt{\frac{L_{\frac{1}{2}}}{C_{\frac{1}{2}}}}$$

where  $L_{\frac{1}{2}}$  and  $C_{\frac{1}{2}}$  are the half section element values.

From these basic equations the necessary loading coil inductance and coil spacing can be found;

$$L = \frac{Z_0}{\omega_c} \quad \text{and,} \quad d = \frac{2}{\omega_c Z_0 C}$$

where C is the capacitance per unit length of the line.

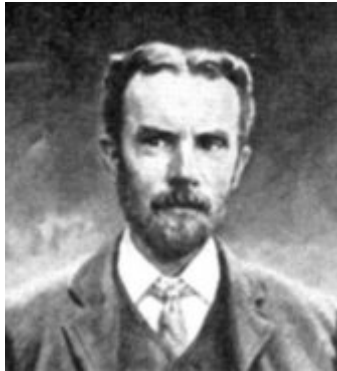
Expressing this in terms of number of coils per cutoff wavelength yields;

$$\frac{\lambda_c}{d} = \pi v Z_0 C$$

where  $v$  is the velocity of propagation of the cable in question.

## **History**

### **Oliver Heaviside**



Oliver Heaviside

The origin of the loading coil can be found in the work of Oliver Heaviside on the theory of transmission lines. Heaviside (1881) represented the line as a network of infinitesimally small circuit elements. By applying his operational calculus to the analysis of this network he discovered (1887) what has become known as the Heaviside condition. This is the condition that must be fulfilled in order for a transmission down a line to be free from distortion. The Heaviside condition is that the line series impedance,  $Z$ , must be proportional to the line shunt admittance,  $Y$ , at all frequencies. In terms of the primary line coefficients this is the condition;

$$\frac{R}{G} = \frac{L}{C}$$

where;

$R$  is the series resistance of the line per unit length

$L$  is the series self-inductance of the line per unit length

$G$  is the shunt leakage conductance of the line insulator per unit length

$C$  is the shunt capacitance between the line conductors per unit length

Heaviside was aware that this condition was not met in the practical telegraph cables in use in his day. In general, a real cable would have,

$$\frac{R}{G} \gg \frac{L}{C}$$

This is mainly due to the low value of leakage through the cable insulator, which is even more pronounced in modern cables which have better insulators than in Heaviside's day. In order to meet the condition, the choices are therefore to try and increase  $G$  or  $L$  or to decrease  $R$  or  $C$ . Decreasing  $R$  requires larger conductors. Copper was already in use in telegraph cables and this is the very best conductor available short of using silver. Decreasing  $R$  means using more copper and a more expensive cable. Decreasing  $C$  would also mean a larger cable (although not necessarily more copper). Increasing  $G$  is highly undesirable, while it would reduce distortion, it would at the same time increase the signal loss. Heaviside considered, but rejected, this possibility which left him with the strategy of increasing  $L$  as the way to reduce distortion.

Heaviside immediately (1887) proposed several methods of increasing the inductance, including spacing the conductors further apart and loading the insulator with iron dust. Finally, Heaviside made the proposal (1893) to use discrete inductors at intervals along the line. However, he never succeeded in persuading the British GPO to take up the idea. Brittain attributes this to Heaviside's failure to provide engineering details on the size and spacing of the coils for particular cable parameters. Heaviside's eccentric character and setting himself apart from the establishment may also have played a part in their ignoring of him.

## **John Stone**

John S. Stone worked for the American Telephone & Telegraph Company (AT&T) and was the first to attempt to apply Heaviside's ideas to real telecommunications. Stone's idea (1896) was to use a bimetallic iron-copper cable which he had patented. This cable of Stone's would increase the line inductance due to the iron content and had the potential to meet the Heaviside condition. However, Stone left the company in 1899 and the idea was never implemented.

## **George Campbell**

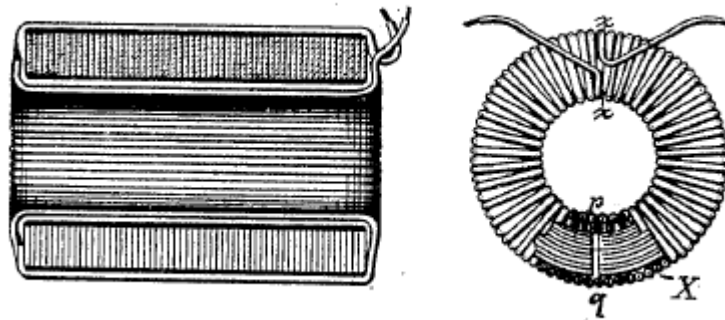
George Campbell was another AT&T engineer working for them in their Boston facility. Campbell was tasked with continuing the investigation into Stone's bimetallic cable, but soon abandoned this in favour of the loading coils idea. This was an independent discovery, Campbell being aware of Heaviside's work in discovering the Heaviside condition, but apparently not aware of Heaviside's suggestion of using loading coils to force a line to meet it. The motivation for the change of direction was Campbell's limited budget.

Campbell was struggling to set up a practical demonstration over a real telephone route with the budget he had been allocated. After considering that his artificial line simulators used lumped components rather than the distributed quantities found in a real line, he wondered if he could not insert the inductance with lumped components instead of using Stone's distributed line. When his calculations showed that the manholes on telephone routes were sufficiently close together to be able to insert the loading coils without the expense of either having to dig up the route or lay in new cables he changed to this new

plan. The very first demonstration of loading coils on a telephone cable was on a 46-mile length of the so-called Pittsburgh cable (the test was actually in Boston, the cable had previously been used for testing in Pittsburgh) on September 6, 1899 carried out by Campbell himself and his assistant. The first telephone cable using loaded lines put into public service was between Jamaica Plain and West Newton in Boston on May 18, 1900.

Campbell's work on loading coils provided the theoretical basis for his subsequent work on filters which proved to be so important for frequency-division multiplexing. The cut-off phenomena of loading coils, an undesirable side-effect, can be exploited to produce a desirable filter frequency response.

## Michael Pupin



Pupin's design of loading coil

Michael Pupin, inventor and Serbian immigrant to the USA, also played a part in the story of loading coils. Pupin filed a rival patent to the one of Campbell's. This patent of Pupin's dates from 1899. There is an earlier patent (1894, filed December 1893) which is sometimes cited as Pupin's loading coil patent but is, in fact, something different. The confusion is easy to understand, Pupin himself claims that he first thought of the idea of loading coils while climbing a mountain in 1894, although there is nothing from him published at that time.

Pupin's 1894 patent "loads" the line with capacitors rather than inductors, a scheme that has been criticised as being theoretically flawed and never put into practice. To add to the confusion, one variant of the capacitor scheme proposed by Pupin does indeed have coils. However, these are not intended to compensate the line in any way. They are there merely to restore DC continuity to the line so that it may be tested with regular equipment. Pupin states that the inductance is to be so large that it will block all AC signals above 50 Hz. Consequently, only the capacitor is adding any significant impedance to the line and "the coils will not exercise any material influence on the results before noted".

## **Legal battle**

Heaviside never patented his idea; indeed, he took no commercial advantage of any of his work. Despite the legal disputes surrounding this invention, it is unquestionable that Campbell was the first to actually construct a telephone circuit using loading coils. There also can be little doubt that Heaviside was the first to publish and many would dispute Pupin's priority.

AT&T fought a legal battle with Pupin over his claim. Pupin was first to patent but Campbell had already conducted practical demonstrations before Pupin had even filed his patent (December 1899). Campbell's delay in filing was due to the slow internal machinations of AT&T.

However, AT&T foolishly deleted from Campbell's proposed patent application all the tables and graphs detailing the exact value of inductance that would be required before the patent was submitted. Since Pupin's patent contained a (less accurate) formula, AT&T was open to claims of incomplete disclosure. Fearing that there was a risk that the battle would end with the invention being declared unpatentable due to Heaviside's prior publication, they decided to desist from the challenge and buy an option on Pupin's patent for a yearly fee so that AT&T would control both patents. By January 1901 Pupin had been paid \$200,000 and by 1917, when the AT&T monopoly ended and payments ceased, he had received a total of \$455,000.

## **Benefit to AT&T**

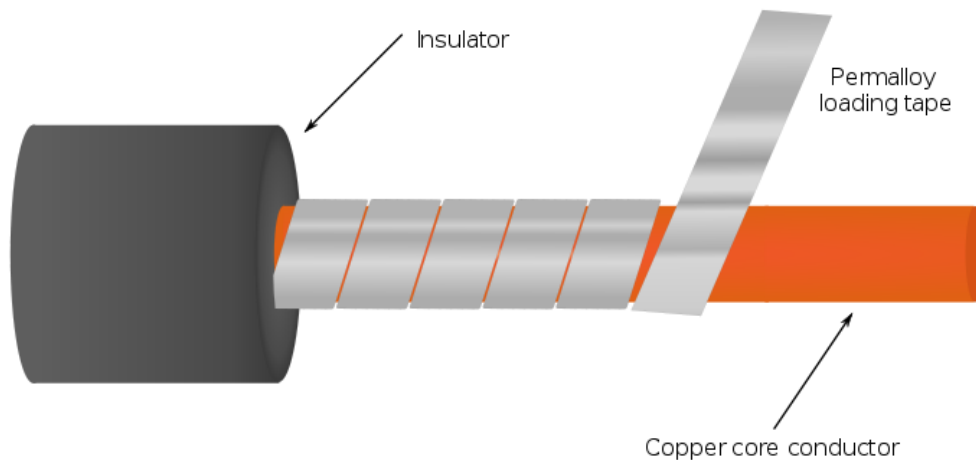
The invention was of enormous value to AT&T. Telephone cables could now be used to twice the distance previously possible, or alternatively, a cable of half the previous quality (and cost) could be used over the same distance. When considering whether to allow Campbell to go ahead with the demonstration, their engineers had estimated that they stood to save \$700,000 in new installation costs in New York and New Jersey alone. It has been estimated that AT&T saved \$100 million in the first quarter of the 20th century. Heaviside, who began it all, came away with nothing. He was offered a token payment but would not accept, wanting the credit for his work. He remarked ironically that if his prior publication had been admitted it would "interfere . . . with the flow of dollars in the proper direction . . .".

## **Krarup cable**

Loading coils were not without their problems. For submarine cables where they were of most benefit, they were difficult to lay. The cable needed to be heavier and both this and the discontinuities in the profile where the coils occurred caused stresses in the cable during laying. Without great care, the cable might part and would be enormously expensive, possibly impossible, to fix. A second problem was that the material science of the time had difficulties sealing the joint between coil and cable against ingress of seawater. When this occurred, of course, the cable was ruined.

A Danish engineer, Carl Emil Krarup, invented a form of continuously loaded cable which solved these problems and the cable is named for him. Krarup cable has iron wires continuously wound around the central copper conductor with adjacent turns in contact with each other. This cable was the first use of continuous loading on any telecommunication cable. In 1902 Krarup both wrote his paper on this subject and saw the installation of the first cable between Helsingør (Denmark) and Helsingborg (Sweden).

### Permalloy cable

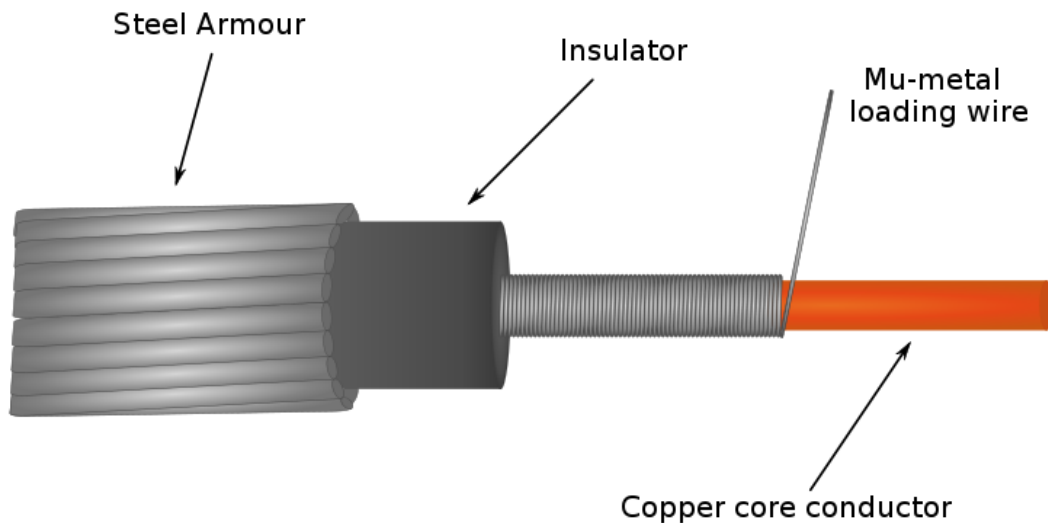


Permalloy cable construction

Even though Krarup cable added inductance to the line, it did not add enough to meet the Heaviside condition. AT&T searched for a better material with higher magnetic permeability. In 1914 Gustav Elmen discovered permalloy, a magnetic nickel-iron annealed alloy. Oliver E. Buckley, along with his colleagues at Bell Labs, H. D. Arnold and Elmen, c.1915 proposed a method of constructing submarine cable using permalloy tape wrapped around the copper conductors. This construction greatly improved the performance of the cable.

The cable was tested in a trial in Bermuda in 1923. The first permalloy cable to be put into service was between New York and Horta (Azores) in September 1924.

## Mu-metal cable



Mu-metal cable construction

Mu-metal has similar magnetic properties to permalloy but the addition of copper to the alloy increases the ductility and allows the metal to be drawn into wire. Mu-metal cable is easier to construct than permalloy cable, the mu-metal being wound around the core copper conductor in much the same way as the iron wire in Krarup cable. A further advantage with mu-metal cable is that the construction lends itself to a variable loading profile whereby the loading is tapered towards the ends.

Mu-metal was invented (1923) by The Telegraph Construction and Maintenance Company Ltd., London, who made the cable, initially, for the Western Union Telegraph Co. Western Union were in competition with AT&T and the Western Electric Company who were using permalloy (the patent for permalloy was held by Western Electric).

### Current practice

Loaded cable is no longer a useful technology for submarine communication cables, having first been superseded by co-axial cable using electrically powered in-line repeaters and then by fibre-optic cable. Manufacture of loaded cable declined in the 1930s and was then superseded by other technologies post-war. Loading coils can still be found in some telephone landlines today but new installations would use more modern technology.

## Chapter 5

# Low Tension Coil and Ignition Coil

## Low Tension Coil

A **low tension coil** is an electrical device used to create a spark across the points of an ignitor on early 1900s gasoline engines, generally flywheel engines, hit and miss engines, and other engines of that era. In modern electronic terms, a low tension coil is simply a large inductor, an electrical device that stores energy for brief periods. The term "low tension" was the terminology of the day used to differentiate it from the term "high tension", and generally meant "low voltage" (tension) as opposed to "high voltage" (tension). High tension coils produce high voltages, generally meant to produce a spark across a spark plug.

## ***Construction***



A typical low tension coil (reproduction) used in the ignition system of an ignitor fired engine

A low tension coil consists of an iron core that has wire wrapped around it. The size of the iron core, the number of turns of wire, and the size of the wire determine the electrical properties of the coil. Terminals are provided to connect the coil into the ignition circuit. The wood ends are provided for mechanical stability, to provide for the terminal placement and to hold the wire on the coil over time. A cloth or tape covering is provided to protect the windings.

## ***Use***

A low tension coil for engine ignition is used in conjunction with a battery and an ignitor. The ignitor is no more than a set of contacts that reside inside the combustion chamber of the engine. A series circuit is made between the three components: battery connects to coil, second terminal on the coil connects to the ignitor, second terminal on the ignitor (usually connected electrically and mechanically to the engine itself) connects to the second terminal of the battery.

## ***Theory of Operation***

An inductor attempts to maintain a constant current flow through it. If the current in the circuit in which the inductor is connected goes down for some reason, the voltage developed across the inductor will go up in an attempt to try to maintain the constant current. When used with an ignitor ignition system in an engine, there is current flow

when the ignitor contacts are closed. When the ignitor contacts are opened by the mechanical parts of the engine, current flow is interrupted. Because the low tension coil wants to maintain that current flow, the voltage across the coil rapidly goes up (usually to several hundred volts). When the voltage rises high enough, the voltage will jump the still very small gap of the ignitor contacts and create a spark which ignites the fuel mixture in the engine. Since there is a finite amount of energy stored in the coil, as soon as the spark jumps the gap the voltage across the coil collapses. As soon as the engine rotates and the ignitor contacts again close, current starts to flow through the coil and it again stores energy for the next cycle. A good description and moving gif of a low tension coil in operation can be found on [Harrys Old Engines Ignition Page](#)

## Ignition Coil



Bosch ignition coil.



Dual ignition coils (top of picture) on a Saab 92.

An **ignition coil** (also called a **spark coil**) is an induction coil in an automobile's ignition system which transforms the battery's 12 volts (6 volts in some older vehicles) to the thousands of volts (20 to 30 thousand volts or more) needed to spark the spark plugs. Some coils have an internal resistor to reduce the voltage and some rely on a resistor wire or an external resistor to reduce the voltage from the cars 12 volt wiring flowing into the coil. The wire which goes from the ignition coil to the distributor and the wires which go from the distributor to each of the spark plugs are called spark plug wires or high tension leads.

This specific form of the autotransformer, together with the contact breaker and a capacitor (still referred to in automobile parlance by its old name of "condenser"),

converts low voltage from a battery into the high voltage required by spark plugs in an internal combustion engine.

### ***Basic principles***

When the contact breaker closes, it allows a current from the battery to build up in the primary winding of the ignition coil. (The current does not flow instantly because of the inductance of the coil.) Once the current has built up to its full level, the contact breaker opens. Since it has a capacitor connected across it, the primary winding and the capacitor form a tuned circuit, and as the stored energy oscillates between the inductor formed by the coil and the capacitor, the changing magnetic field in the core of the coil induces a much larger voltage in the secondary of the coil. More modern electronic ignition systems operate on exactly the same principle, but some rely on charging the capacitor to around 400 volts rather than charging the inductance of the coil.

### ***Use in cars***

In older vehicles a single (large) coil would serve all the spark plugs via the ignition distributor. Notable exceptions are the Saab 92, and the Wartburg 353 which have one ignition coil per cylinder.

### **Modern ignition systems**

In modern systems, the distributor is omitted and ignition is instead electronically controlled. Much smaller coils are used with one coil for each spark plug or one coil serving two spark plugs (for example two coils in a four-cylinder engine, or three coils in a six-cylinder engine). A large ignition coil puts out about 20 kV, and a small one such as from a lawn mower puts out about 15 kV. These coils may be remotely mounted or they may be placed on top of the spark plug (*coil-on-plug* or *Direct Ignition*). Where one coil serves two spark plugs (in two cylinders), it is through the "waste spark" system. In this arrangement the coil generates two sparks per cycle to both cylinders. The fuel in the cylinder that is nearing the end of its compression stroke is ignited, whereas the spark in its companion that is nearing the end of its exhaust stroke has no effect. The wasted spark system is more reliable than a single coil system with a distributor and cheaper than coil-on-plug.

Where coils are individually applied per cylinder, they may all be contained in a single molded block with multiple high-tension terminals. This is commonly called a coil-pack.

A bad coil pack may cause a slight or not so slight misfire, bad fuel economy, loss in power, and in some rare cases loss of braking performance and power steering problems.

### ***Tesla coil***

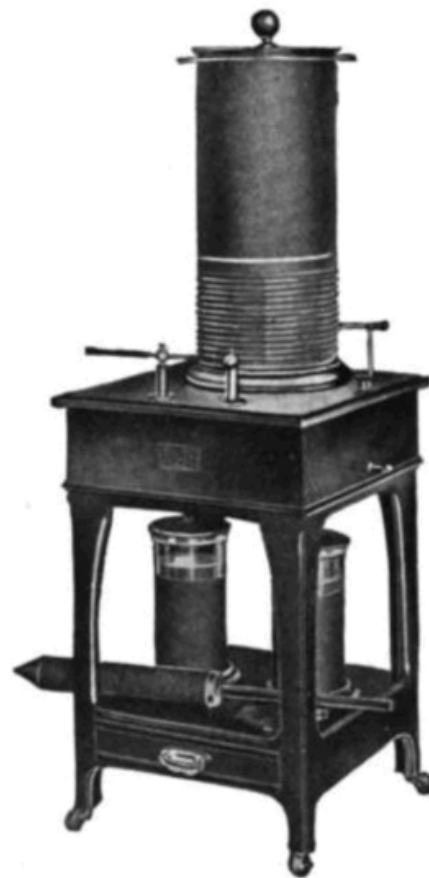
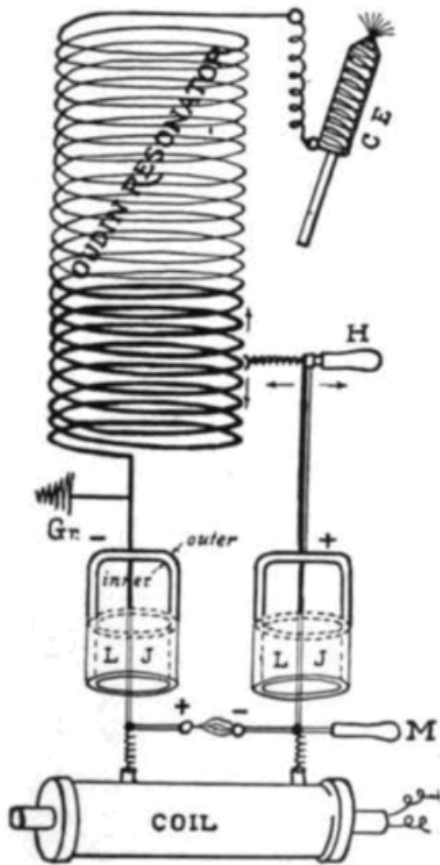
The disruptive discharge Tesla coil is an early predecessor of the "ignition coil" in the ignition system as was invented in 1891. Tesla also gained U.S. Patent 609,250,

*"Electrical Igniter for Gas Engines"*, on August 16, 1898. The principles of the modern ignition coil used today is based on this design. A. Atwater Kent, in 1921, patented the modern form of the ignition coil.

Chapter 6

# Oudin Coil, Polyphase Coil and Maxwell Coil

## Oudin Coil



Oudin coil used for medical 'electrotherapy', 1907.

An **Oudin coil**, also called an **Oudin oscillator** or **Oudin resonator**, is a disruptive discharge coil wired as a transformer designed to produce high voltage arcs and discharges, similar to a Tesla coil. It was invented by French physician Paul Marie Oudin and physicist Jacques d'Arsonval around 1899.

The device is a high frequency current generator which uses the principles of resonant electrical circuits. It produces an antinode of high potential. The high-voltage, self-regenerative resonant transformer has the bottom ends of the primary and secondary coils connected together and to ground.

*Oudin coils* generate high voltages at high frequency, but produce lower currents than other disruptive discharge coils (such as the later version of the Tesla coil). The Oudin coil is modified for greater safety.

## **Polyphase Coil**

**Polyphase coils** are electrical coils (phases) connected together in a polyphase system such as a generator or motor. In modern systems, the number of phases is usually three or a multiple of three. Each phase carries a sinusoidal alternating current whose phase is delayed relative to one of its neighbours and advanced relative to its other neighbour. The phase currents are separated in time evenly within each period of the alternating current. For example, in a three-phase system, the phases are separated from each other by one-third of the period.

### ***Coil construction***

Like all coils used in electrical machinery, polyphase coils (made from insulated conducting wire) are wound around ferromagnetic armatures with radial projections and maximum core-surface exposure to the magnetic field.

The windings are physically separated around the circumference of an electrical machine. The result of such an arrangement is a rotating magnetic field that is used to convert electrical power to rotary mechanical work, or vice versa.

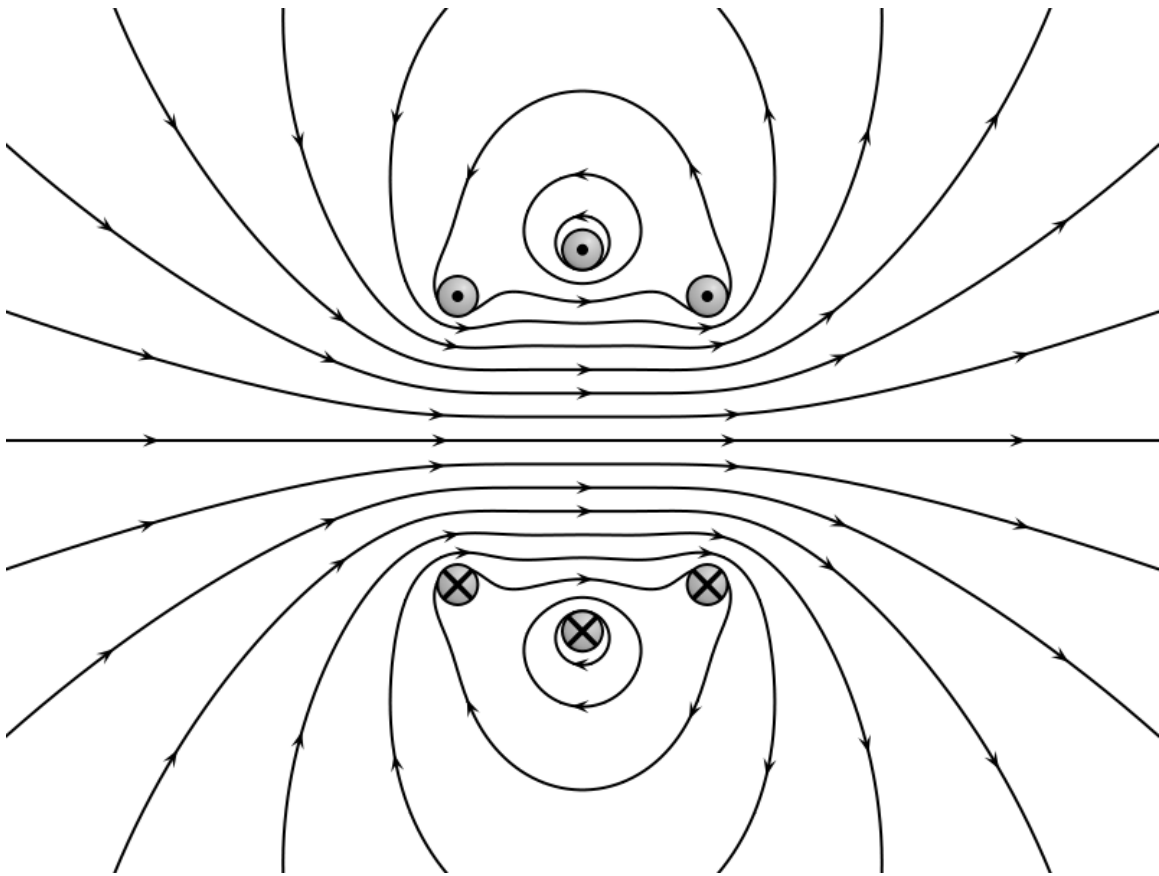
### ***Polyphase motors and generators***

Compared to single-phase motors and generators, polyphase motors are simpler, because they do not require external circuitry (using capacitors and inductors) to produce a starting torque. Polyphase machines can deliver constant power over each period of the alternating current, eliminating the pulsations found in a single-phase machine as the current passes through zero amplitude.

## ***History***

The use of polyphase coils in electrical power systems was pioneered by the engineers Nikola Tesla, Galileo Ferraris, and Michail Dolivo-Dobrovolsky.

## **Maxwell Coil**



Magnetic field around a Maxwell coil

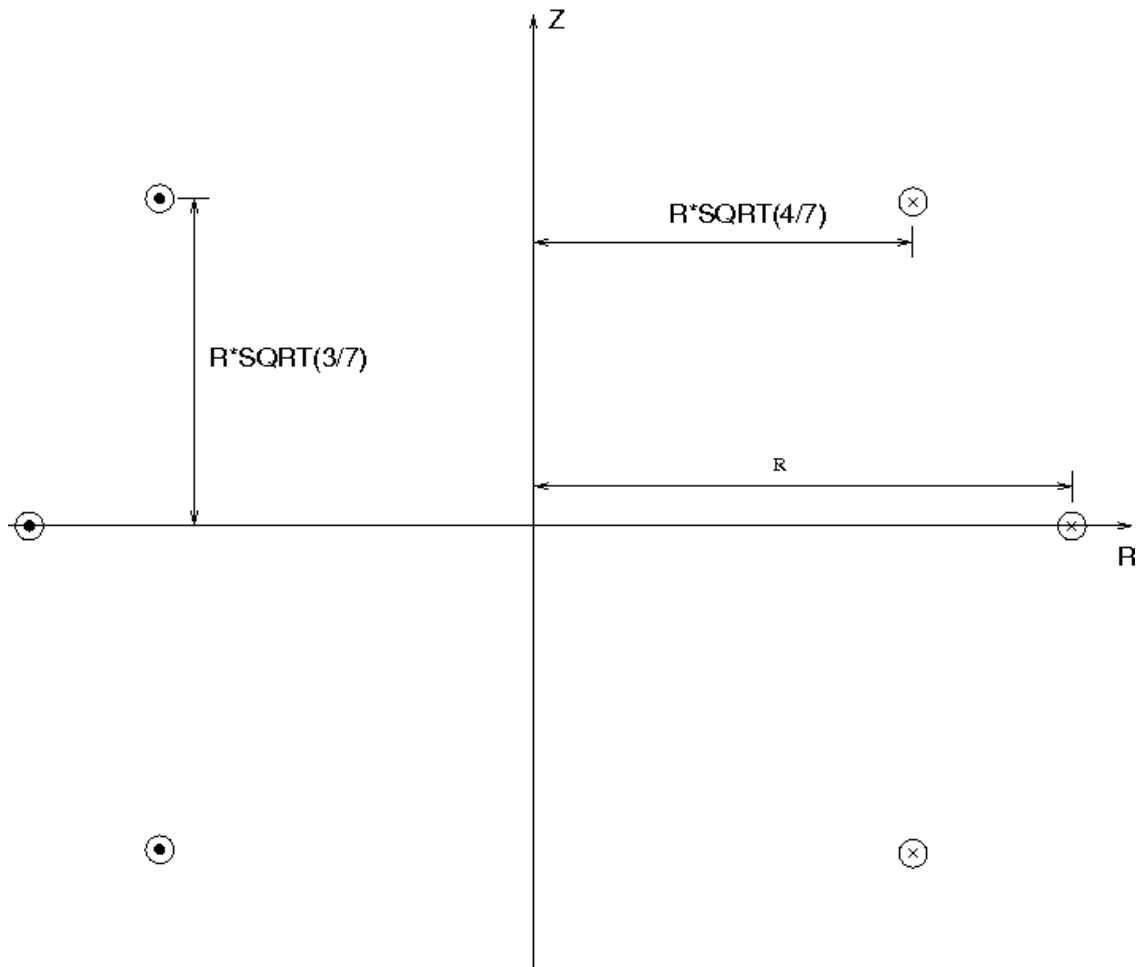
A **Maxwell coil** is a device for producing a large volume of almost constant (or constant-gradient) magnetic field.

## ***Description***

A constant-field Maxwell coil set consists of three coils oriented on the surface of a virtual sphere. According to Maxwell's original 1873 design each of the outer coils

should be of radius  $\sqrt{\frac{4}{7}}R$  and distance  $\sqrt{\frac{3}{7}}R$  from the plane of the central coil of radius  $\frac{49}{64}R$ .

The number of ampere-turns of each of the smaller coils should equal exactly  $\frac{49}{64}$  of the middle coil. This arrangement removes variations in magnetic field, up to its 6th-order derivative with respect to position, near the centre of the virtual sphere.



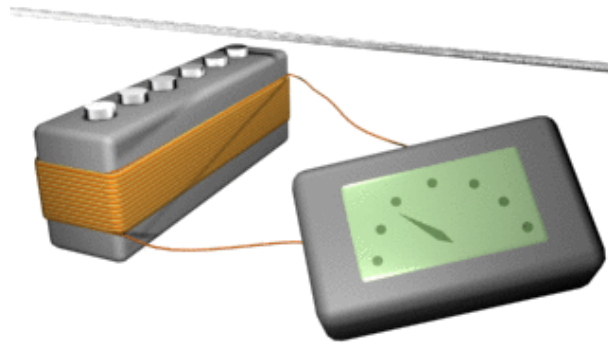
A gradient-field Maxwell coil is essentially the same geometry of the 3-coil configuration above, with the central coil removed to leave only the smaller two coils. If the current in one of the coils is reversed, a uniform-gradient magnetic field is produced near the centre of the two coils.

## Chapter 7

# Single Coil



This image shows three single coil pickups on a Stratocaster guitar. Left to right: bridge, middle and neck pickups.



String effect on a single coil (electric guitar). The coil is connected to a multimeter that indicates the voltage changes when the string moves. This signal is normally sent to the amplifier.

A **single coil pickup** is a type of magnetic transducer, or pickup, for the electric guitar and the electric bass. It electromagnetically converts the vibration of the strings to an electric signal. Single coil pickups are one of the two most popular designs, along with dual-coil or "humbucking" pickups.

### ***History***

### **Beauchamp**

Aug. 10, 1937.

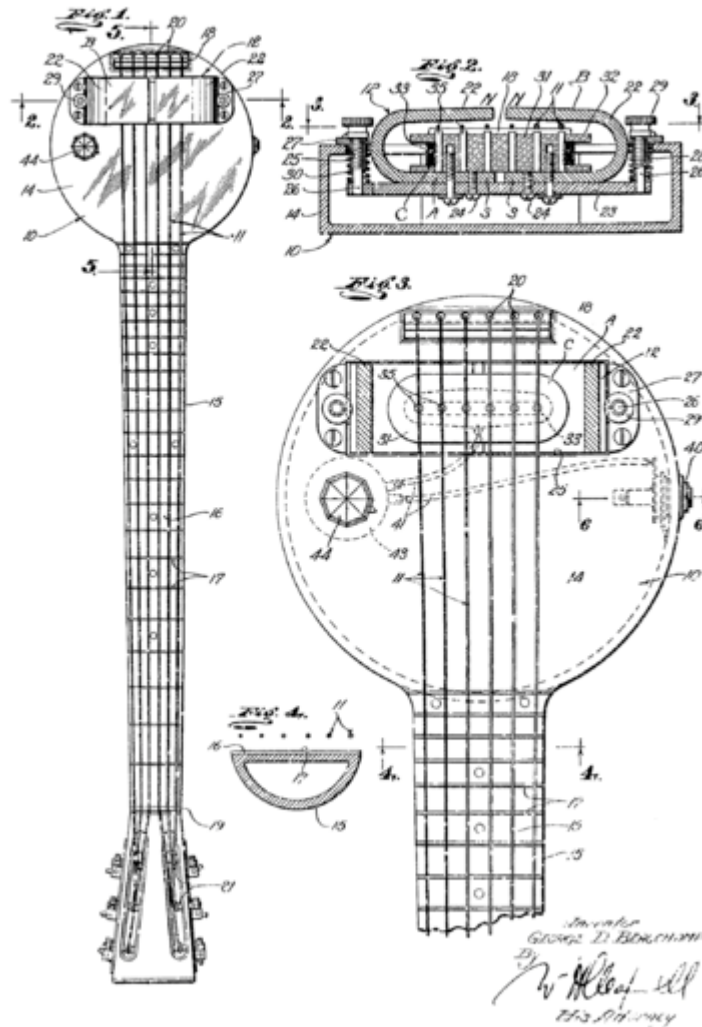
G. D. BEAUCHAMP

2,089,171

ELECTRICAL STRINGED MUSICAL INSTRUMENT

Filed June 2, 1934

3 Sheets-Sheet 1



Sketch of Rickenbacker "frying pan" lap steel guitar from 1934 patent application.

In the mid 1920s George Beauchamp, a Los Angeles, California guitarist, began experimentation with electric amplification of the guitar. Originally using a phonograph pickup assembly, Beauchamp began testing many different combinations of coils and magnets hoping to create the first electromagnetic guitar pickup. He wound his earliest coils using a motor out of a washing machine, later on switching to a sewing machine motor, and eventually using single coiled magnets.

Beauchamp was backed in his efforts by Adolph Rickenbacker, an engineer and wealthy owner of a successful tool and die business. Beauchamp eventually produced the first successful single coil pickup. The pickup consisted of two massive "U" shaped magnets and one coil and was known as the "horseshoe pickup". The two horseshoe-shaped

magnets surrounded the strings that passed over a single core plate (or blade) in the center of the coil.

Beauchamp outfitted the pickup in a custom built lap slide guitar. The production model based on this prototype became the Hawaiian Electro lap steel guitar, nicknamed the "Frying Pan" for its round, flat body.

In 1931 Beauchamp founded the Ro-Pat-In Company with Rickenbacker and his associates. Ro-Pat-In eventually became The Electro String Instrument Corporation and subsequently the Rickenbacker International Corporation. The company introduced its first "Electro-String Instruments" to the public in 1932.

## **Gibson**

The Gibson Guitar Corporation introduced the "bar pickup" in 1935 for its new line of Hawaiian lap steel guitars. The pickup's basic construction is that of a metal blade inserted through the coil as a shared pole piece for all the strings. A pair of large flat magnets were fastened below the coil assembly.

In 1936 Gibson introduced the ES-150, its first electric Spanish styled guitar. The ES-150 was outfitted with the bar pickup. Jazz guitar innovator, Charlie Christian, began playing an ES-150 in the late 1930s with the Benny Goodman Orchestra. This caused the popularity of the electrified guitar to soar. Due to Christian's close association with the ES-150 it began being referred to as the "Charlie Christian Model" and Gibson's now famous bar pickup as the "Charlie Christian pickup" or "CC unit".

## **Sound**

The sound of a single coil pickup can range from the strong, fat midrange sound of the Gibson P-90 to the bright and clear Fender Telecaster single-coil tone.

## **Common designs**

### **Gibson P-90**

The P-90 is a single-coil pickup designed by the Gibson Guitar Corporation. These pickups have a large, flat coil with adjustable steel screws as pole pieces, and a pair of flat alnico bar magnets lying under the coil bobbin. The adjustable pole pieces pick up the magnetism from the magnets. Moving the screw closer or further away from the magnet determines signal strength, thus tone as well. There are two variations of P-90 pickup that differ mainly by mounting options:



Gibson P-90 soap bar

- **Soap bar** casing has true rectangular shape and the mounting screws are contained within the coil perimeter, positioned between the pole pieces, between strings 2-3 and 4-5, thus creating irregular and somewhat unusual pattern. Occasionally, they are mistaken for pole pieces; thus, the P-90 is sometimes erroneously said to have eight pole pieces. The "soap bar" nickname most probably comes from its predominantly rectangular shape and proportions resembling a bar of soap, and the fact that the first P-90s on the original Gibson Les Paul Model of 1952 were white.



P90 dog ear

- **Dog ear** is a casing type with extensions at both sides of pickup that somewhat resemble dog's ears. These are extensions of the predominantly rectangular cover that encompass the outlying mounting screws. Dog-ear P-90 pickups were commonly mounted on Gibson's hollowbody guitars like the ES-330 and occasionally on solid body models like the Les Paul Junior. The same pickups were also available on Epiphone models (since Gibson was building Epiphone guitars in the 1950s) and the design is best remembered for its appearance on the hollow body Epiphone Casino of the mid to late 1960s.

The sound of a P-90 is somewhat brighter and more transparent than Gibson's later humbucker pickup, and every bit as crisp and snappy as Fender's single-coil pickups despite its high output and big sound.

Despite its tonal qualities the P-90 fell out of favor with Gibson in the early 1950s as a consequence of guitar players complaining about the amount of hum (noise) it put out. Gibson employee Seth Lover solved the hum problem by designing a hum-canceling pickup known as a humbucker, it was supposed to sound like a P-90 but in fact has quite a different sound. It nevertheless became Gibson's mainstay pickup from that point on. The P-90 likely did not become as popular for that reason, although many guitarists still prefer the tone of the P-90.

The hum problem proved extremely difficult to solve and despite numerous attempts by Gibson with their P-100, and the larger aftermarket pickup manufacturers with their stacked and sidewinders noiseless designs, hum-canceling P-90 pickups lost most of their favored tonal characteristics and generally did not gain acceptance among guitar players.

## Telecaster design



Two pickups on a Telecaster

The Fender Telecaster features two single coils. The neck pickup produces a mellower sound, while the bridge pickup produces an extremely twangy, sharp tone with exaggerated treble response, because the bridge pickup is mounted on a steel plate. These design elements allow musicians to emulate steel guitar sounds, making it particularly appropriate for country music.

Pickups are selected with a three-position switch, and two wiring schemes exist:

- **Vintage:** 1) neck pickup with treble cutoff for a bassier sound; 2) neck pickup only; 3) bridge pickup only.
- **Modern:** 1) neck pickup only, with no treble cutoff; 2) neck and bridge; 3) bridge pickup only.

The Fender Esquire has a variation to the Vintage wiring scheme by using the scheme on a single pickup. This gives a treble cutoff in the first position, normal in the middle position, and a tone control cutoff in the third position.

## Stratocaster design



Stratocaster pickups, viewed along the neck profile. Note that the poles are of different heights.

The traditional Stratocaster design guitar features three single coils. The guitarist can control which pickup or combination of pickups are selected with a lever switch. The pickup positions are usually referred to as the bridge, middle and neck pickups based on their proximity to those parts of the instrument.

Pickup position, number of coil winds, type of magnet wire, magnets and other factors shape the sound. A given pickup in the neck position will give louder, mellower and warmer sound, while an identical pickup in the bridge position will have lower output and produce a brighter, sharper sound. The reason the neck pickup has the most output is that the string's vibration has a higher amplitude at the neck position, being near the middle of the string length. Some manufacturers overwind the bridge pickup for more output to compensate for this difference.

The magnet poles have different heights. This is called a **magnet stagger** and is done to compensate for the different outputs of the string for two reasons. The first reason is that the fretboard has a radius (also called *camber*) of between 7 and 12 inches usually. Naturally the strings will follow the radius of the fretboard and so must the top surface of

the magnets, generally speaking. The second reason is that some strings have naturally higher output, the plain or non-wound G-string being the most significant and this calls for the corresponding magnet to be further compensated, resulting in an apparent odd looking stagger. Fender Strat pickups generally follow the traditional design and have the G string's magnet pole piece as tall as the D-string's, but this causes the G-string of modern string sets to be excessively loud and dominate all the other strings. This comes about because Stratocaster pickups were designed in the 1950s when string sets came with a wound G-string, but modern rock and blues players found it difficult to stretch or bend wound G-strings across the fretboard because of their inherently higher tension. In the 1970s, string manufacturers responded and introduced the now standard non-wound G-string which has lower tension and can be stretched more easily, but which produces much higher output. In order for the G-string to have the same output the corresponding magnet pole should have the greatest gap between the string and the magnet pole piece, thus different strings have magnets with differently compensated heights.

The first Stratocasters had a three-way pickup selector switch, selecting either the neck, middle or bridge pickup. Innovative guitarists found they could get an interesting sound by carefully positioning the selector switch lever between detented positions, where any two adjacent pickups would be on simultaneously. Some players wedged a plectrum between the pickguard and the selector switch to lock it in these positions. Later on, Fender introduced the now standard five-way selector switch, which uses additional detents between the original three positions to allow the combinations of any two adjacent pickups.

Modern Stratocasters have five-position pickup selector switch. Positions 1, 3 and 5 activate only one pickup (bridge, middle or neck respectively), while positions 2 and 4 activate a combination of two pickups (bridge and middle, or middle and neck, respectively). Some pickup sets have a reverse wound and reverse polarity middle pickup that when in combination with the normal bridge or neck pickups will cancel electromagnetic interference (noise/hum) which single coil pickups suffer badly from. The sonic effect of positions 2 and 4 is sometimes referred to as a "quack" or "notch positions", and some guitar notation includes directions to use these pickup combinations. One example is "Sultans of Swing" by Dire Straits which is played in position 2 (bridge and middle).

### ***Noise problems***

Fender Stratocaster and Telecaster pickups, being of the single-coil type, output a type of noise known as mains hum or 50Hz / 60Hz hum. Mains hum has its origin in wiring of a building and electrical apparatus/appliances such as transformers, electric motors and lighting. Hum is undesirable because it pollutes the musical notes being played on the instrument with its own sound of fixed unchanging frequency or pitch (usually 50 or 60 hertz) which is discordant with the musical sounds. To address this undesirable situation various attempts to eliminate mains hum signal from Fender single-coil pickups were made dating back to the early 1970s. DiMarzio, Seymour Duncan and EMG manufactured what are commonly known as stacked single coils which canceled mains

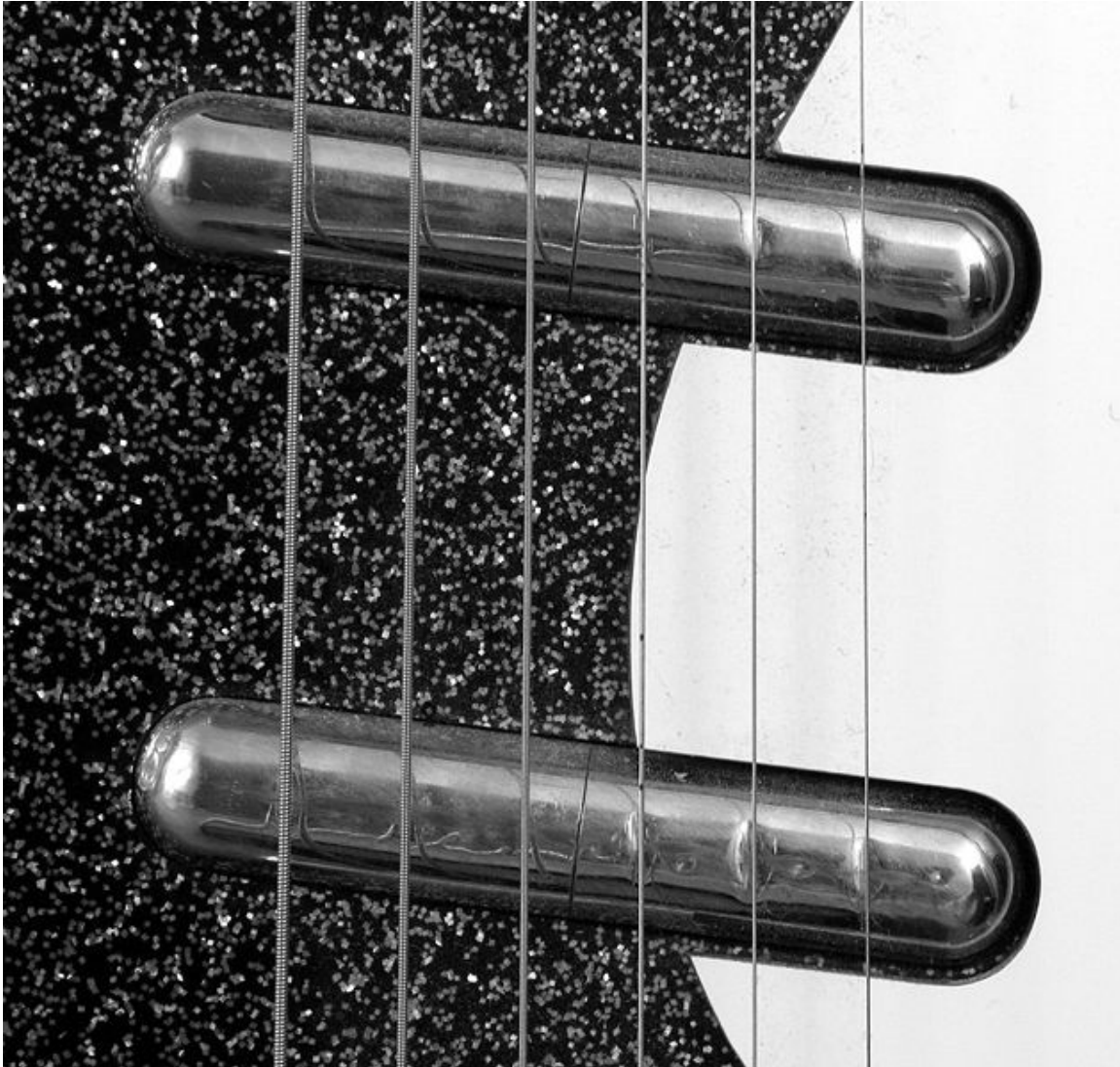
hum. Unfortunately these stacks also canceled string signal and had a detrimental effect on sound quality. EMG used active circuitry within the pickup to compensate for the losses caused by stacked coils by boosting and reshaping the damaged sound but this required an on-board battery with its attendant problems. The resultant sound was not authentic Fender trade mark sound but EMG pickups became popular for their own sound.

Actodyne General manufactured a low-noise design of single-coil pickup known as Lace Sensors, Don Lace being the inventor. The Lace Sensor pickup had a rubberized particle magnet and used ferrous shielding to reduce hum. Being the best at the time, Fender installed Lace Sensors on the Strat Plus model for many years as a solution to the mains hum problem. However the Lace Sensor was a stopgap solution because the sound was not authentic Fender trademark sound. Fender purists wanted the genuine sound of the original Fender pickups with Alnico rod magnets and Fender eventually discontinued Lace Sensors as their mainstay solution to mains hum circa 1998. Lace Sensors continue to be used by many guitar players regardless.

The search for an acceptable solution to mains hum gained new impetus around 1995 as guitar players became increasingly intolerant of degraded stacked single-coil sound. Fender was researching new techniques to solve the loss of tone around that time and eventually came out with their Vintage Noiseless design circa 1998.

## ***Notable single-coil pickups***

There are several well-known single-coil pickups that have a distinctive sound:



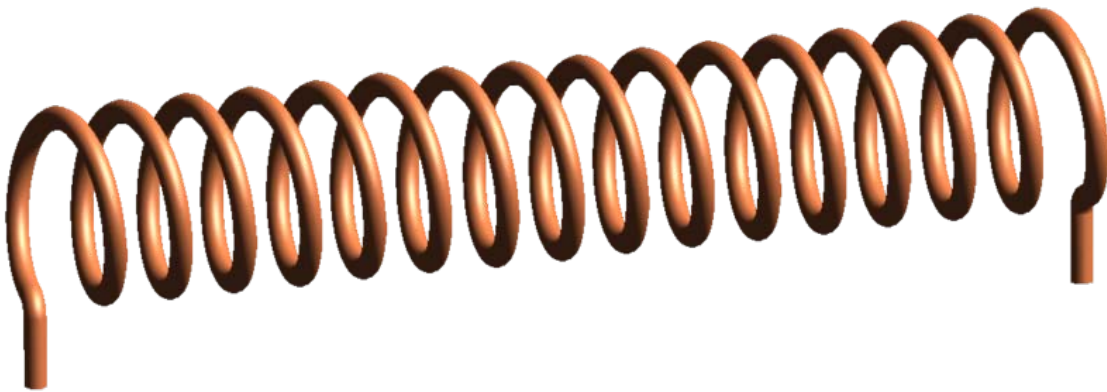
"Lipstick"-style single coil pickups on a Danelectro guitar

- Rickenbacker pickups (including the original 1930s "horseshoe" pickup as used in lap steel and solidbody upright basses, and later 6 string electric guitars, pedal steels, and electric bass guitars; also the "Toaster" and "Hi-Gain")
- Gibson bar pickup (1935) — later called the Charlie Christian pickup (1938)
- Gibson P-90 (1946)
- Fender Telecaster, Stratocaster, Jazzmaster, Jaguar, and other pickups
- Danelectro Lipstick
- Gretsch pickups (including the "HiLoTron")

- DeArmond pickups (found on various 50s and 60s guitars by various manufacturers including Gretsch, Guild, Epiphone, Martin, Kustom, Harmony, Regal, Premier, and others, but produced by the Rowe - DeArmond company of Toledo, Ohio; the trade name is now owned by Fender; single coil models including the 200 aka Dynasonic, 2K, and 2000, "mustache", various "gold foil" types, and many clip on, rail, or screw mount pickups designed for acoustic guitars and other instruments). The Fender "Tele-Sonic" featured large DeArmond single coils.
- Valco single coil pickups by Ralph Keller (1954) can be found in Airline, Supro, National, English Electronics, and a few Gretsch models of guitar from the 50's, 60's, and 70's. The majority of these pickups maintain the physical appearance of a larger, humbucking pickup. Early variations on the over-strings horseshoe pickup can be found on a number of similarly branded lapsteel guitars.
- Epiphone "New York" pickups
- Lace Sensor pickups (1987)

## Chapter 8

# Solenoid



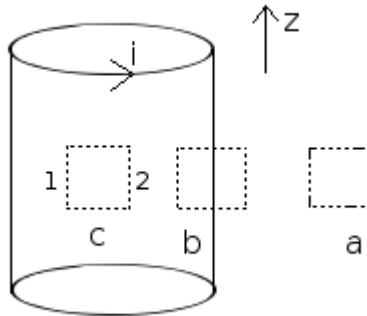
Solenoid

A **solenoid** is a coil wound into a tightly packed helix. In physics, the term **solenoid** refers to a long, thin loop of wire, often wrapped around a metallic core, which produces a magnetic field when an electric current is passed through it. Solenoids are important because they can create controlled magnetic fields and can be used as electromagnets. The term *solenoid* refers specifically to a magnet designed to produce a uniform magnetic field in a volume of space (where some experiment might be carried out).

In engineering, the term **solenoid** may also refer to a variety of transducer devices that convert energy into linear motion. The term is also often used to refer to a solenoid valve, which is an integrated device containing an electromechanical solenoid which actuates either a pneumatic or hydraulic valve, or a solenoid switch, which is a specific type of relay that internally uses an electromechanical solenoid to operate an electrical switch; for example, an automobile starter solenoid, or a linear solenoid, which is an electromechanical solenoid.

## ***Magnetic field of a solenoid***

### **Inside**



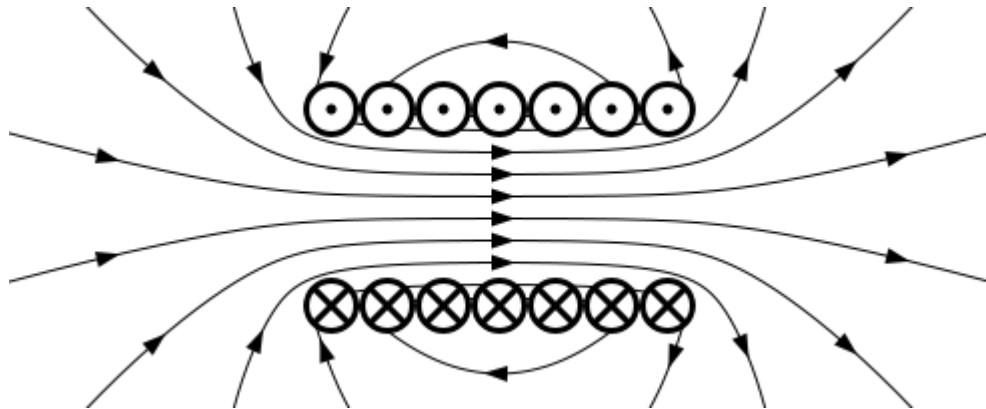
A solenoid with 3 Ampèrian loops: *a*, *b* and *c*.

In short: the magnetic field inside an infinitely long solenoid is homogeneous and its strength does not depend on the distance from the axis.

This is a derivation of the magnetic flux density around a solenoid that is long enough so that fringe effects can be ignored. In the diagram to the right, we immediately know that the flux density vector points in the positive  $z$  direction inside the solenoid, and in the negative  $z$  direction outside the solenoid. We see this by applying the right hand grip rule for the field around a wire. If we wrap our right hand around a wire with the thumb pointing in the direction of the current, the curl of the fingers shows how the field behaves. Since we are dealing with a long solenoid, all of the components of the magnetic field not pointing upwards cancel out by symmetry. Outside, a similar cancellation occurs, and the field is only pointing downwards.

Now consider the imaginary loop *c* that is located inside the solenoid. By Ampère's law, we know that the line integral of  $\mathbf{B}$  (the magnetic flux density vector) around this loop is zero, since it encloses no electrical currents (it can be also assumed that the circuital electric field passing through the loop is constant under such conditions: a constant or constantly changing current through the solenoid). We have shown above that the field is pointing upwards inside the solenoid, so the horizontal portions of loop *c* doesn't contribute anything to the integral. Thus the integral of the up side 1 is equal to the integral of the down side 2. Since we can arbitrarily change the dimensions of the loop and get the same result, the only physical explanation is that the integrands are actually equal, that is, the magnetic field inside the solenoid is radially uniform. Note, though, that nothing prohibits it from varying longitudinally, which in fact it does.

## Outside



Magnetic field created by a solenoid (cross-sectional view) described using field lines.

A similar argument can be applied to the loop *a* to conclude that the field outside the solenoid is radially uniform or constant. This last result, which holds strictly true only near the centre of the solenoid where the field lines are parallel to its length, is important inasmuch as it shows that the flux density outside is practically zero since the radii of the field outside the solenoid will tend to infinity.

An intuitive argument can also be used to show that the flux density outside the solenoid is actually zero. Magnetic field lines only exist as loops, they cannot diverge from or converge to a point like electric field lines can. The magnetic field lines follow the longitudinal path of the solenoid inside, so they must go in the opposite direction outside of the solenoid so that the lines can form a loop. However, the volume outside the solenoid is much greater than the volume inside, so the density of magnetic field lines outside is greatly reduced. Now recall that the field outside is constant. In order for the total number of field lines to be conserved, the field outside must go to zero as the solenoid gets longer.

## Quantitative description

Now we can consider the imaginary loop *b*. Take the line integral of  $\mathbf{B}$  around the loop, with the length of the loop *l*. The horizontal components vanish, and the field outside is practically zero, so Ampère's Law gives us:

$$Bl = \mu_0 Ni$$

where  $\mu_0$  is the magnetic constant, *N* the number of turns, *i* the current. From this we get:

$$B = \mu_0 \frac{Ni}{l}.$$

This equation is for a solenoid with no core. The inclusion of a ferromagnetic core, such as iron, increases the magnitude of the magnetic flux density in the solenoid. This is expressed by the formula

$$B = \mu_0 \mu_r \frac{Ni}{l} = \mu \frac{Ni}{l}$$

where  $\mu_r$  is the relative permeability and  $\mu$  ( $\mu_0 \mu_r$ ) the permeability of the material that the core is made of.

### **Inductance of a solenoid**

As shown above, the magnetic flux density  $B$  within the coil is practically constant and is given by

$$B = \mu_0 \frac{Ni}{l}$$

where  $\mu_0$  is the magnetic constant,  $N$  the number of turns,  $i$  the current and  $l$  the length of the coil. Ignoring end effects, the total magnetic flux through the coil is obtained by multiplying the flux density  $B$  by the cross-section area  $A$ :

$$\Phi = \mu_0 \frac{NiA}{l},$$

When this is combined with the definition of inductance,

$$L = \frac{N\Phi}{i}$$

it follows that the inductance of a solenoid is given by:

$$L = \mu_0 \frac{N^2 A}{l}.$$

A table of inductance for short solenoids of various diameter to length ratios has been calculated by Dellinger, Whittmore, and Ould.

This, and the inductance of more complicated shapes, can be derived from Maxwell's equations. For rigid air-core coils, inductance is a function of coil geometry and number of turns, and is independent of current.

Similar analysis applies to a solenoid with a magnetic core, but only if the length of the coil is much greater than the product of the relative permeability of the magnetic core and the diameter. That limits the simple analysis to low-permeability cores, or extremely long

thin solenoids. The presence of a core can be taken into account in the above equations by replacing the magnetic constant  $\mu_0$  with  $\mu$  or  $\mu_0\mu_r$ , where  $\mu$  represents permeability and  $\mu_r$  relative permeability. Note that since the permeability of ferromagnetic materials changes with applied magnetic flux, the inductance of a coil with a ferromagnetic core will generally vary with current.

## Applications

### Electromechanical solenoids

**28. The Commercial Solenoid.**—The solenoid is used in practice for tripping circuit breakers (Par. 237), for operating contactors in automatic motor starters (Par. 219), for operating voltage regulating devices (Par. 207), for arc lamp feeds (Chap. XIII, Vol. II), for operating valves, and for numerous other purposes. In practically all instances a soft iron (or steel) plunger-

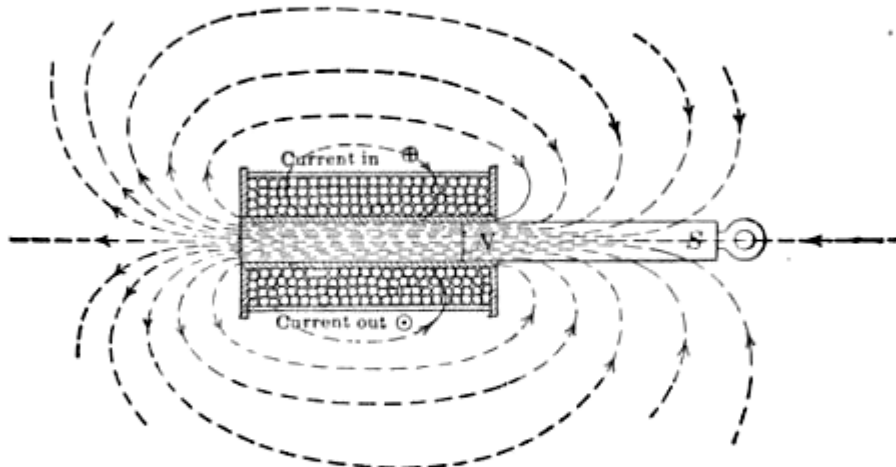


FIG. 30.—Simple solenoid and plunger.

er or armature is necessary to obtain the tractive pull required of the solenoid. The operation of a solenoid and plunger is indicated in Fig. 30. The flux due to the solenoid produces magnetic poles on the plunger. The pole nearer the plunger will be of such sign that it will be urged along the lines of force, (see Par. 11) and in such a direction as to be drawn within the solenoid.

A 1920 explanation of a commercial solenoid used as an electromechanical actuator

Electromechanical solenoids consist of an electromagnetically inductive coil, wound around a movable steel or iron slug (termed the armature). The coil is shaped such that the armature can be moved in and out of the center, altering the coil's inductance and thereby becoming an electromagnet. The armature is used to provide a mechanical force to some mechanism (such as controlling a pneumatic valve). Although typically weak over anything but very short distances, solenoids may be controlled directly by a controller circuit, and thus have very low reaction times.

The force applied to the armature is proportional to the change in inductance of the coil with respect to the change in position of the armature, and the current flowing through the coil. The force applied to the armature will always move the armature in a direction that increases the coil's inductance.

Electromechanical solenoids are commonly seen in electronic paintball markers, pinball machines, dot matrix printers and fuel injectors.

## **Rotary solenoid**

The rotary solenoid is an electromechanical device used to rotate a ratcheting mechanism when power is applied. These were used in the 1950s for rotary snap-switch automation in electromechanical controls. Repeated actuation of the rotary solenoid advances the snap-switch forward one position. Two rotary actuators on opposite ends of the rotary snap-switch shaft, can advance or reverse the switch position.

The rotary solenoid has a similar appearance to a linear solenoid, except that the core is mounted in the center of a large flat disk, with two or three inclined grooves cut into the underside of the disk. These grooves align with slots on the solenoid body, with ball bearings in the grooves.

When the solenoid is activated, the core is drawn into the coil, and the disk rotates on the ball bearings in the grooves as it moves towards the coil body. When power is removed, a spring on the disk rotates it back to its starting position, also pulling the core out of the coil.

The rotary solenoid was invented in 1944 by George H. Leland, of Dayton, Ohio, to provide a more reliable and shock/vibration tolerant release mechanism for air-dropped bombs. Previously used linear (axial) solenoids were prone to inadvertent releases. U.S. Patent number 2,496,880 describes the electromagnet and inclined raceways that are the basis of the invention. Leland's engineer, Earl W. Kerman, was instrumental in developing a compatible bomb release shackle that incorporated the rotary solenoid. Bomb shackles of this type are found in a B-29 aircraft fuselage on display at the National Museum of the USAF in Dayton, Ohio.

## **Rotary voice coil**

This is a rotational version of a solenoid. Typically the fixed magnet is on the outside, and the coil part moves in an arc controlled by the current flow through the coils. Rotary voice coils are widely employed in devices such as disk drives.

## **Pneumatic solenoid valves**

A pneumatic solenoid valve is a switch for routing air to any pneumatic device, usually an actuator, allowing a relatively small signal to control a large device. It is also the interface between electronic controllers and pneumatic systems.

## **Hydraulic solenoid valves**

Hydraulic solenoid valves are in general similar to pneumatic solenoid valves except that they control the flow of hydraulic fluid (oil), often at around 3000 psi (210 bar, 21 MPa, 21 MN/m<sup>2</sup>). Hydraulic machinery uses solenoids to control the flow of oil to rams or actuators to (for instance) bend sheets of titanium in aerospace manufacturing. Solenoid-controlled valves are often used in irrigation systems, where a relatively weak solenoid opens and closes a small pilot valve, which in turn activates the main valve by applying fluid pressure to a piston or diaphragm that is mechanically coupled to the main valve. Solenoids are also in everyday household items such as washing machines to control the flow and amount of water into the drum.

Transmission solenoids control fluid flow through an automatic transmission and are typically installed in the transmission valve body.

## **Automobile starter solenoid**

In a car or truck, the starter solenoid is part of an automobile starting system. The starter solenoid receives a large electric current from the car battery and a small electric current from the ignition switch. When the ignition switch is turned on (i.e. when the key is turned to start the car), the small electric current forces the starter solenoid to close a pair of heavy contacts, thus relaying the large electric current to the starter motor.

Starter solenoids can also be built into the starter itself, often visible on the outside of the starter. If a starter solenoid receives insufficient power from the battery, it will fail to start the motor, and may produce a rapid 'clicking' or 'clacking' sound. This can be caused by a low or dead battery, by corroded or loose connections in the cable, or by a broken or damaged positive (red) cable from the battery. Any of these will result in some power to the solenoid, but not enough to hold the heavy contacts closed, so the starter motor itself never spins, and the engine does not start.

## Chapter 9

# Tesla Coil

A **Tesla coil** is a type of resonant transformer circuit invented by Nikola Tesla around 1891. It is used to produce high voltage, low current, high frequency alternating current electricity, although Tesla coils produce higher current than the other source of high voltage discharges, electrostatic machines. Tesla experimented with a number of different configurations and they consist of two, or sometimes three, coupled resonant electric circuits. Tesla used these coils to conduct innovative experiments in electrical lighting, phosphorescence, x-ray generation, high frequency alternating current phenomena, electrotherapy, and the transmission of electrical energy without wires.

The early Tesla coil transformer design employs a medium- to high-voltage power source, one or more high voltage capacitor(s), and a spark gap to excite a multiple-layer primary inductor with periodic bursts of high frequency current. The multiple-layer Tesla coil transformer secondary is excited by resonant inductive coupling, the primary and secondary circuits both being *tuned* so they resonate at the same frequency (typically, between 25 kHz and 2 MHz). The later and higher-power coil design has a single-layer primary and secondary. These Tesla coils are often used by hobbyists and at venues such as science museums to produce long sparks.

Tesla coil circuits were used commercially in sparkgap radio transmitters for wireless telegraphy until the 1920s, and in electrotherapy and pseudomedical devices such as violet ray. Today their main use is entertainment and educational displays. Tesla coils are built by many high-voltage enthusiasts, research institutions, science museums and independent experimenters. Although electronic circuit controllers have been developed, Tesla's original spark gap design is less expensive and has proven extremely reliable.

## ***History***

### **Tesla's coil**

The "American Electrician" gives a description of an early Tesla coil wherein a glass battery jar, 15 x 20 cm (6 x 8 in) is wound with 60 to 80 turns of AWG No. 18 B & S magnet wire (0.823 mm<sup>2</sup>). Into this is slipped a primary consisting of eight to ten turns of AWG No. 6 B & S wire (13.3 mm<sup>2</sup>) and the whole combination immersed in a vessel containing linseed or mineral oil. (Norrie, pg. 34-35)

### ***Tesla Coil Theory***

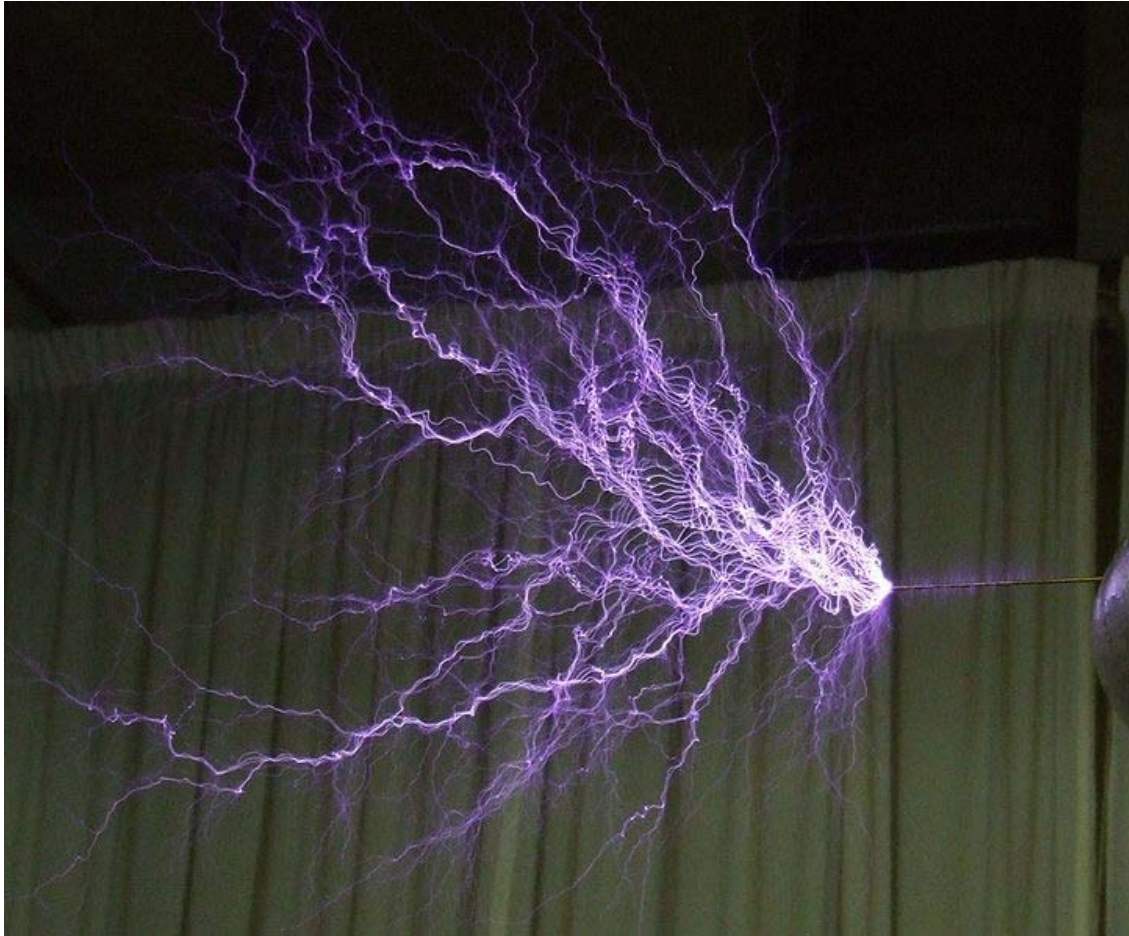
A Tesla coil transformer operates in a significantly different fashion than a conventional (i.e., iron core) transformer. In a conventional transformer, the windings are very tightly coupled, and voltage gain is determined by the ratio of the numbers of turns in the windings. This works well at normal voltages, however, at high voltages, the insulation between the two sets of windings is easily broken down, and this prevents iron cored transformers from running at extremely high voltages without damage.

With Tesla coils, unlike a conventional transformer, which may couple 97%+ of the magnetic fields between windings, a Tesla coil's windings are "loosely" coupled, with a large air gap, and thus the primary and secondary are typically sharing only 10–20% of their respective magnetic fields. Instead of a tight coupling, the coil transfers energy (via loose coupling) from one oscillating resonant circuit (the primary) to the other (the secondary) over a number of RF cycles.

As the primary energy transfers to the secondary, the secondary's output voltage increases until all of the available primary energy has been transferred to the secondary (less losses). Even with significant spark gap losses, a well designed Tesla coil can transfer over 85% of the energy initially stored in the primary capacitor to the secondary circuit. Thus the voltage gain of a Tesla coil can be significantly greater than a conventional transformer, since the air gap has a very high insulation.

With the loose coupling the voltage gain is instead proportional to the square root of the ratio of secondary and primary inductances.

## ***Modern day Tesla coils***



Electric discharge showing the lightning-like plasma filaments from a *Tesla coil*.

Modern high voltage enthusiasts usually build Tesla coils that are similar to some of Tesla's "later" air core designs. These typically consist of a primary tank circuit, a series LC (inductance-capacitance) circuit composed of a high voltage capacitor, spark gap and primary coil, and the secondary LC circuit, a series resonant circuit consisting of the secondary coil plus a terminal capacitance or "top load." In Tesla's more advanced design, the secondary LC circuit is composed of an air-core transformer secondary coil placed in series with a helical resonator. The helical coil is then connected to the terminal capacitance. Most modern coils use only a single helical coil comprising both the secondary and primary resonator. The terminal capacitance actually forms one 'plate' of a capacitor, the other 'plate' being the Earth (or "ground"). The primary LC circuit is tuned so that it resonates at the same frequency as the secondary LC circuit. The primary and secondary coils are magnetically coupled, creating a dual-tuned resonant air-core transformer. Earlier oil insulated Tesla coils needed large and long insulators at their high-voltage terminals to prevent discharge in air. Later version Tesla coils spread their electric fields over large distances to prevent high electrical stresses in the first place, thereby allowing operation in free air.

Tesla's 1902 design for his advanced magnifying transmitter used a top terminal consisting of a metal frame in the shape of a toroid, covered with hemispherical plates (constituting a very large conducting surface). The top terminal has relatively small capacitance, charged to as high a voltage as practicable. The outer surface of the elevated conductor is where the electrical charge chiefly accumulates. It has a large radius of curvature, or is composed of separate elements which, irrespective of their own radii of curvature, are arranged close to each other so that the outside ideal surface enveloping them has a large radius. This design allowed the terminal to support very high voltages without generating corona or sparks. Tesla, during his patent application process, described a variety of resonator terminals at the top of this later coil. Most Modern Tesla coils use simple toroids, typically fabricated from spun metal or flexible aluminum ducting, to control the high electrical field near the top of the secondary and to direct spark outward and away from the primary and secondary windings.

As pointed out above, more advanced Tesla coil transmitters involve a more tightly coupled air core resonance transformer network or "master oscillator" the output of which is then fed another resonator, sometimes called the "extra coil." The principle is that energy accumulates in the extra coil and the role of transformer secondary is played by the separate master oscillator secondary; the roles are not shared by a single secondary. In some modern three-coil Magnifying transmitter systems the extra coil is placed some distance from the transformer. Direct magnetic coupling to the upper secondary is not desirable, since the third coil is designed to be driven by injecting RF current directly into the bottom end.

This particular Tesla coil configuration consists of a secondary coil in close inductive relation with a primary, and one end of which is connected to a ground-plate, while its other end is led through a separate self-induction coil (whose connection should always be made at, or near, the geometrical center of that coil's circular aspect, in order to secure a symmetrical distribution of the current), and of a metallic cylinder carrying the current to the terminal. The primary coil may be excited by any desired source of high frequency current. The important requirement is that the primary and secondary sides must be tuned to the same resonant frequency to allow efficient transfer of energy between the primary and secondary resonant circuits. The conductor of the shaft to the terminal (topload) is in the form of a cylinder with smooth surface of a radius much larger than that of the spherical metal plates, and widens out at the bottom into a hood (which is slotted to avoid loss by eddy currents). The secondary coil is wound on a drum of insulating material, with its turns close together. When the effect of the small radius of curvature of the wire itself is overcome, the lower secondary coil behaves as a conductor of large radius of curvature, corresponding to that of the drum. The top of the extra coil may be extended up to the terminal U.S. Patent 1,119,732 and the bottom should be somewhat below the uppermost turn of the primary coil. This lessens the tendency of the charge to break out from the wire connecting both and to pass along the support.

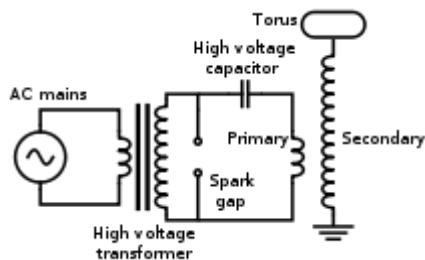
A sword-like discharge characteristic of a Vacuum Tube Tesla Coil. This particular coil was constructed by Xellers of the instructables community.

Modern day transistor or vacuum tube Tesla coils do not use a primary spark gap. Instead, the transistor(s) or vacuum tube(s) provide the switching or amplifying function necessary to generate RF power for the primary circuit. Solid-state Tesla coils use the lowest primary operating voltage, typically between 155 to 800 volts, and drive the primary winding using either a single, half-bridge, or full-bridge arrangement of bipolar transistors, MOSFETs or IGBTs to switch the primary current. Vacuum tube coils typically operate with plate voltages between 1500 and 6000 volts, while most spark gap coils operate with primary voltages of 6,000 to 25,000 volts. The primary winding of a traditional transistor Tesla coil is wound around only the bottom portion of the secondary (sometimes called the resonator). This helps to illustrate operation of the secondary as a pumped resonator. The primary *induces* alternating voltage into the bottommost portion of the secondary, providing regular "pushes" (similar to provided properly timed pushes to a playground swing). Additional energy is transferred from the primary to the secondary inductance and toload capacitance during each "push", and secondary output voltage builds (called *ring-up*). An electronic feedback circuit is usually used to adaptively synchronize the primary oscillator to the growing resonance in the secondary, and this is the only tuning consideration beyond the initial choice of a reasonable toload.

In a *dual resonant solid-state Tesla coil (DRSSTC)*, the electronic switching of the solid-state Tesla coil is combined with the resonant primary circuit of a spark-gap Tesla coil. The resonant primary circuit is formed by connecting a capacitor in series with the primary winding of the coil, so that the combination forms a series tank circuit with a resonant frequency near that of the secondary circuit. Because of the additional resonant circuit, one manual and one adaptive tuning adjustment are necessary. Also, an interrupter is usually used to reduce the duty cycle of the switching bridge, in order to improve peak power capabilities; similarly, IGBTs are more popular in this application than bipolar transistors or MOSFETs, due to their superior power handling characteristics. Performance of a DRSSTC can be comparable to a medium power spark gap Tesla coil, and efficiency (as measured by spark length versus input power) can be significantly greater than a spark gap Tesla coil operating at the same input power.

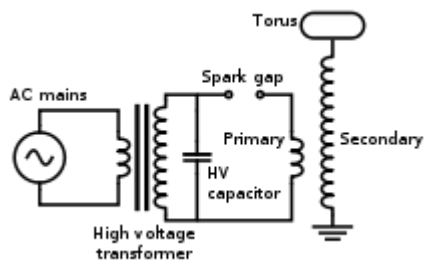
## Applications

### Transmission



Typical Tesla Coil Schematic

This example circuit is designed to be driven by alternating currents. Here the spark gap shorts the high frequency across the first transformer. An inductance, not shown, protects the transformer. This design is favoured when a relatively fragile Neon Sign Transformer (NST) is used.



### **Alternate Tesla Coil Configuration**

This circuit also driven by alternating currents. However, here the AC supply transformer must be capable of withstanding high voltages at high frequencies.

### **High voltage production**

A large Tesla coil of more modern design often operates at very high peak power levels, up to many megawatts (millions of watts). It should therefore be adjusted and operated carefully, not only for efficiency and economy, but also for safety. If, due to improper tuning, the maximum voltage point occurs below the terminal, along the secondary coil, a discharge (spark) may break out and damage or destroy the coil wire, supports, or nearby objects.

Tesla experimented with these, and many other, circuit configurations. The Tesla coil primary winding, spark gap and tank capacitor are connected in series. In each circuit, the AC supply transformer charges the tank capacitor until its voltage is sufficient to break down the spark gap. The gap suddenly fires, allowing the charged tank capacitor to discharge into the primary winding. Once the gap fires, the electrical behavior of either circuit is identical. Experiments have shown that neither circuit offers any marked performance advantage over the other.

However, in the typical circuit (above), the spark gap's short circuiting action prevents high frequency oscillations from 'backing up' into the supply transformer. In the alternate circuit, high amplitude high frequency oscillations that appear across the capacitor also are applied to the supply transformer's winding. This can induce corona discharges

between turns that weaken and eventually destroy the transformer's insulation. Experienced Tesla coil builders almost exclusively use the top circuit, often augmenting it with low pass filters (resistor and capacitor (RC) networks) between the supply transformer and spark gap to help protect the supply transformer. This is especially important when using transformers with fragile high voltage windings, such as Neon-sign transformers (NSTs). Regardless of which configuration is used, the HV transformer must be of a type that self-limits its secondary current by means of internal leakage inductance. A normal (low leakage inductance) high voltage transformer must use an external limiter (sometimes called a ballast) to limit current. NSTs are designed to have high leakage inductance to limit their short circuit current to a safe level.

### **Tuning precautions**

The primary coil's resonant frequency should be tuned to that of the secondary, using low-power oscillations, then increasing the power until the apparatus has been brought under control. While tuning, a small projection (called a "breakout bump") is often added to the top terminal in order to stimulate corona and spark discharges (sometimes called streamers) into the surrounding air. Tuning can then be adjusted so as to achieve the longest streamers at a given power level, corresponding to a frequency match between the primary and secondary coil. Capacitive 'loading' by the streamers tends to lower the resonant frequency of a Tesla coil operating under full power. For a variety of technical reasons, toroids provide one of the most effective shapes for the top terminals of Tesla coils.

## Air discharges



A small, later-type "*Tesla coil*" in operation. The output is giving 17-inch sparks. The diameter of the secondary is three inches. The power source is a 10000 V, 60 Hz current limited supply.

While generating discharges, electrical energy from the secondary and toroid is transferred to the surrounding air as electrical charge, heat, light, and sound. The electric currents that flow through these discharges are actually due to the rapid shifting of quantities of charge from one place (the top terminal) to other places (nearby regions of air). The process is similar to charging or discharging a capacitor. The current that arises from shifting charges within a capacitor is called a displacement current. Tesla coil discharges are formed as a result of displacement currents as pulses of electrical charge are rapidly transferred between the high voltage toroid and nearby regions within the air (called space charge regions). Although the space charge regions around the toroid are invisible, they play a profound role in the appearance and location of Tesla coil discharges.

When the spark gap fires, the charged capacitor discharges into the primary winding, causing the primary circuit to oscillate. The oscillating primary current creates a magnetic

field that couples to the secondary winding, transferring energy into the secondary side of the transformer and causing it to oscillate with the toroid capacitance. The energy transfer occurs over a number of cycles, and most of the energy that was originally in the primary side is transferred into the secondary side. The greater the magnetic coupling between windings, the shorter the time required to complete the energy transfer. As energy builds within the oscillating secondary circuit, the amplitude of the toroid's RF voltage rapidly increases, and the air surrounding the toroid begins to undergo dielectric breakdown, forming a corona discharge.

As the secondary coil's energy (and output voltage) continue to increase, larger pulses of displacement current further ionize and heat the air at the point of initial breakdown. This forms a very conductive "root" of hotter plasma, called a leader, that projects outward from the toroid. The plasma within the leader is considerably hotter than a corona discharge, and is considerably more conductive. In fact, it has properties that are similar to an electric arc. The leader tapers and branches into thousands of thinner, cooler, hairlike discharges (called streamers). The streamers look like a bluish 'haze' at the ends of the more luminous leaders, and it is the streamers that actually transfer charge between the leaders and toroid to nearby space charge regions. The displacement currents from countless streamers all feed into the leader, helping to keep it hot and electrically conductive.

The primary break rate of sparking Tesla coils is slow compared to the resonant frequency of the resonator-topload assembly. When the switch closes, energy is transferred from the primary LC circuit to the resonator where the voltage rings up over a short period of time up culminating in the electrical discharge. In a spark gap Tesla coil the primary-to-secondary energy transfer process happens repetitively at typical pulsing rates of 50–500 times per second, and previously formed leader channels don't get a chance to fully cool down between pulses. So, on successive pulses, newer discharges can build upon the hot pathways left by their predecessors. This causes incremental growth of the leader from one pulse to the next, lengthening the entire discharge on each successive pulse. Repetitive pulsing causes the discharges to grow until the average energy that's available from the Tesla coil during each pulse balances the average energy being lost in the discharges (mostly as heat). At this point, dynamic equilibrium is reached, and the discharges have reached their maximum length for the Tesla coil's output power level. The unique combination of a rising high voltage Radio Frequency envelope and repetitive pulsing seem to be ideally suited to creating long, branching discharges that are considerably longer than would be otherwise expected by output voltage considerations alone. High voltage discharges create filamentary multi-branched discharges which are purplish blue in colour. High energy discharges create thicker discharges with fewer branches, are pale and luminous, almost white, and are much longer than low energy discharges, because of increased ionisation. There will be a strong smell of ozone and nitrogen oxides in the area. The important factors for maximum discharge length appear to be voltage, energy, and still air of low to moderate humidity. However, even more than 100 years later after the first use of Tesla coils, there are many aspects of Tesla coil discharges and the energy transfer process that are still not completely understood.

## Wireless transmission and reception

The Tesla coil can also be used for wireless transmission. In addition to the positioning of the elevated terminal well above the top turn of the helical resonator, another difference from the sparking Tesla coil is the primary break rate. The optimized Tesla coil transmitter is a continuous wave oscillator with a break rate equaling the operating frequency. The combination of a helical resonator with an elevated terminal is also used for wireless reception. The Tesla coil receiver is intended for receiving the non-radiating electromagnetic field energy produced by the Tesla coil transmitter. The Tesla coil receiver is also adaptable for exploiting the ubiquitous vertical voltage gradient in the Earth's atmosphere. Tesla built and used various devices for detecting electromagnetic field energy. His early wireless apparatus operated on the basis of Hertzian waves or ordinary radio waves, electromagnetic waves that propagate in space without involvement of a conducting guiding surface. During his work at Colorado Springs, Tesla believed he had established electrical resonance of the entire Earth using the Tesla coil transmitter at his "Experimental Station."

Tesla stated one of the requirements of the World Wireless System was the construction of resonant receivers. The related concepts and methods are part of his wireless transmission system (US1119732 — Apparatus for Transmitting Electrical Energy — 1902 January 18). Tesla made a proposal that there needed to be many more than thirty transmission-reception stations worldwide. In one form of receiving circuit the two input terminals are connected each to a mechanical pulse-width modulation device adapted to reverse polarity at predetermined intervals of time and charge a capacitor. This form of Tesla system receiver has means for commutating the current impulses in the charging circuit so as to render them suitable for charging the storage device, a device for closing the receiving-circuit, and means for causing the receiver to be operated by the energy accumulated.



Tesla coil in one experiment of many conducted in Colorado Springs. This is a grounded tuned coil in resonance with a nearby transmitter; Light is glowing near the bottom.

A Tesla coil used as a receiver is referred to as a *Tesla receiving transformer*. The Tesla coil receiver acts as a step-down transformer with high current output. The parameters of a Tesla coil transmitter are identically applicable to it being a receiver (*e.g.*, an antenna circuit), due to reciprocity. Impedance, generally though, is not applied in an obvious way; for electrical impedance, the impedance at the load (*e.g.*, where the power is consumed) is most critical and, for a Tesla coil receiver, this is at the point of utilization (such as at an induction motor) rather than at the receiving node. Complex impedance of an antenna is related to the electrical length of the antenna at the wavelength in use. Commonly, impedance is adjusted at the load with a tuner or a matching networks composed of inductors and capacitors.

A Tesla coil can receive electromagnetic impulses from atmospheric electricity and radiant energy, besides normal wireless transmissions. Radiant energy throws off with great velocity minute particles which are strongly electrified and other rays falling on the insulated-conductor connected to a condenser (*i.e.*, a capacitor) can cause the condenser to indefinitely charge electrically. The helical resonator can be "shock excited" due to radiant energy disturbances not only at the fundamental wave at one-quarter wave-length but also is excited at its harmonics. Hertzian methods can be used to excite the Tesla coil

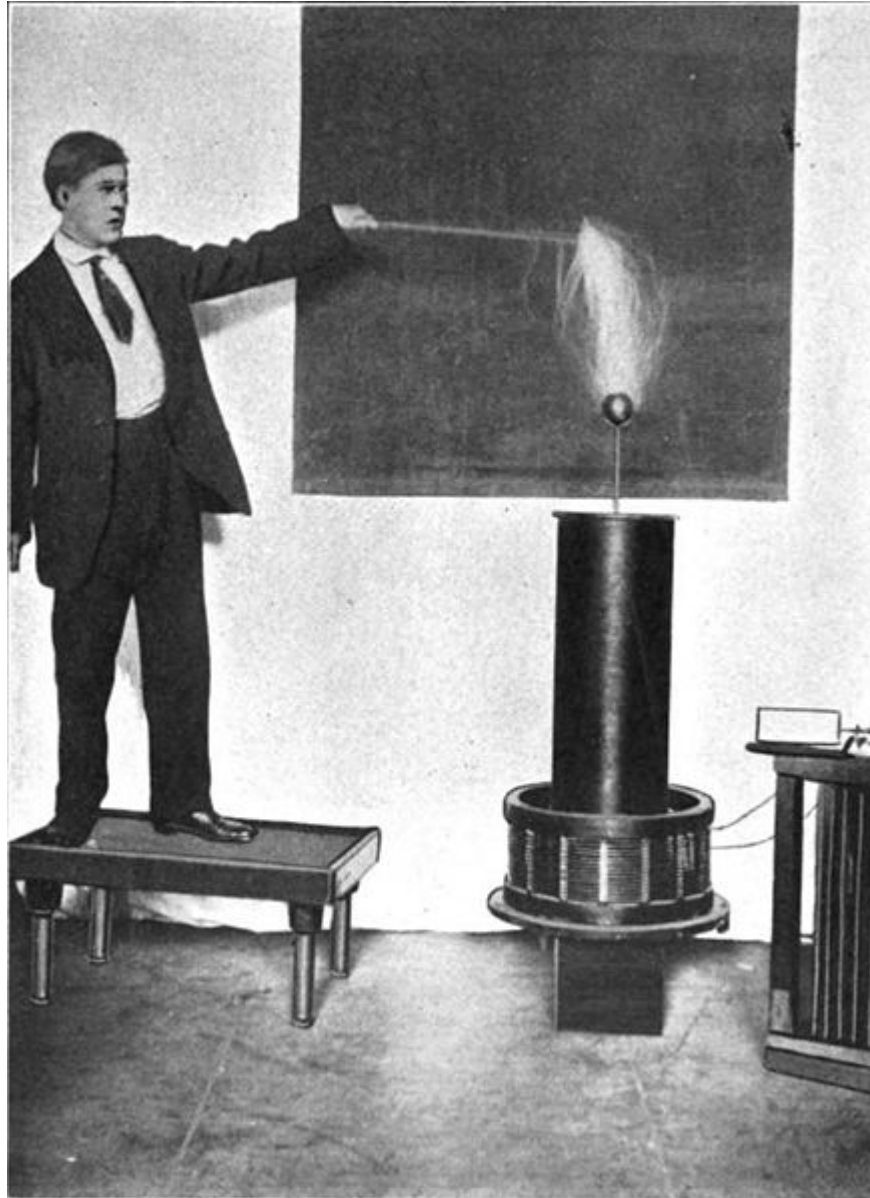
receiver with limitations that result in great disadvantages for utilization, though. The methods of ground conduction and the various induction methods can also be used to excite the Tesla coil receiver, but are again at a disadvantages for utilization. The charging-circuit can be adapted to be energized by the action of various other disturbances and effects at a distance. Arbitrary and intermittent oscillations that are propagated via conduction to the receiving resonator will charge the receiver's capacitor and utilize the potential energy to greater effect. Various radiations can be used to charge and discharge conductors, with the radiations considered electromagnetic vibrations of various wavelengths and ionizing potential. The Tesla receiver utilizes the effects or disturbances to charge a storage device with energy from an external source (natural or man-made) and controls the charging of said device by the actions of the effects or disturbances (during succeeding intervals of time determined by means of such effects and disturbances corresponding in succession and duration of the effects and disturbances). The stored energy can also be used to operate the receiving device. The accumulated energy can, for example, operate a transformer by discharging through a primary circuit at predetermined times which, from the secondary currents, operate the receiving device.

While Tesla coils can be used for these purposes, much of the public and media attention is directed away from transmission-reception applications of the Tesla coil since electrical spark discharges are fascinating to many people. Regardless of this fact, Tesla did suggest that this variation of the Tesla coil could utilize the phantom loop effect to form a circuit to induct energy from the Earth's magnetic field and other radiant energy sources (including, but not limited to, electrostatics). With regard to Tesla's statements on the harnessing of natural phenomena to obtain electric power, he stated:

Ere many generations pass, our machinery will be driven by a power obtainable at any point of the universe. — "Experiments with Alternate Currents of High Potential and High Frequency" (February 1892)

Tesla stated that the output power from these devices, attained from Hertzian methods of charging, was low, but alternative charging means are available. Tesla receivers, operated correctly, act as a step-down transformer with high current output. There are, to date, no commercial power generation entities or businesses that have utilized this technology to full effect. The power levels achieved by Tesla coil receivers have, thus far, been a fraction of the output power of the transmitters.

## ***High frequency electrical safety***



Student conducting Tesla coil streamers through his body, 1909

### **The 'skin effect'**

The dangers of contact with high frequency electrical current are sometimes perceived as being less than at lower frequencies, because the subject usually doesn't feel pain or a 'shock'. This is often erroneously attributed to skin effect, a phenomenon that tends to inhibit alternating current from flowing inside conducting media. It was thought that in the body, Tesla currents travelled close to the skin surface, making them safer than lower

frequency electric currents. In fact, in the early 1900s a major use of Tesla coils was to apply high frequency current directly to the body in electrotherapy.

Although skin effect limits Tesla currents to the outer fraction of an inch in metal conductors, the 'skin depth' of human flesh at typical Tesla coil frequencies is still of the order of 60 inches (150 cm) or more. This means that high frequency currents will still preferentially flow through deeper, better conducting, portions of an experimenter's body such as the circulatory and nervous systems. The reason for the lack of pain is that a human being's nervous system does not sense the flow of potentially dangerous electrical currents above 15–20 kHz; essentially, in order for nerves to be activated, a significant number of ions must cross their membrane before the current (and hence voltage) reverses. Since the body no longer provides a warning 'shock', novices may touch the output streamers of small Tesla coils without feeling painful shocks. However, there is anecdotal evidence among Tesla coil experimenters that temporary tissue damage may still occur and be observed as muscle pain, joint pain, or tingling for hours or even days afterwards. This is believed to be caused by the damaging effects of internal current flow, and is especially common with continuous wave (CW), solid state or vacuum tube type Tesla coils. Some transformers can provide alternating current with such high frequencies that the skin depth becomes small enough for the voltage to be safe. Skin depth is inversely proportional to the root of the frequency, putting these frequencies in the megahertz range.

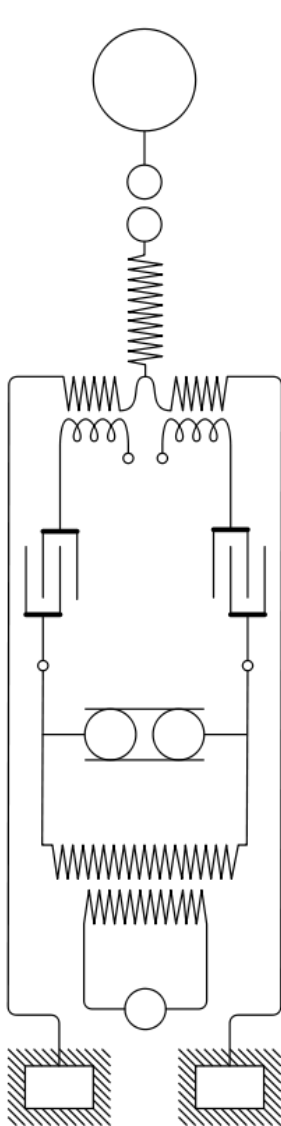
Large Tesla coils and magnifiers can deliver dangerous levels of high frequency current, and they can also develop significantly higher voltages (often 250,000–500,000 volts, or more). Because of the higher voltages, large systems can deliver higher energy, potentially lethal, repetitive high voltage capacitor discharges from their top terminals. Doubling the output voltage quadruples the electrostatic energy stored in a given top terminal capacitance. If an unwary experimenter accidentally places himself in path of the high voltage capacitor discharge to ground, the low current electric shock can cause involuntary spasms of major muscle groups and may induce life-threatening ventricular fibrillation and cardiac arrest. Even lower power vacuum tube or solid state Tesla coils can deliver RF currents that are capable of causing temporary internal tissue, nerve, or joint damage through Joule heating. In addition, an RF arc can carbonize flesh, causing a painful and dangerous bone-deep RF burn that may take months to heal. Because of these risks, knowledgeable experimenters avoid contact with streamers from all but the smallest systems. Professionals usually use other means of protection such as a Faraday cage or a chain mail suit to prevent dangerous currents from entering their body.

The most serious dangers associated with Tesla coil operation are associated with the primary circuit. It is the primary circuit that is capable of delivering a sufficient current at a significant voltage to stop the heart of a careless experimenter. Because these components are not the source of the trademark visual or auditory coil effects, they may easily be overlooked as the chief source of hazard. Should a high frequency arc strike the exposed primary coil while, at the same time, another arc has also been allowed to strike to a person, the ionized gas of the two arcs forms a circuit that may conduct lethal, low-frequency current from the primary into the person.

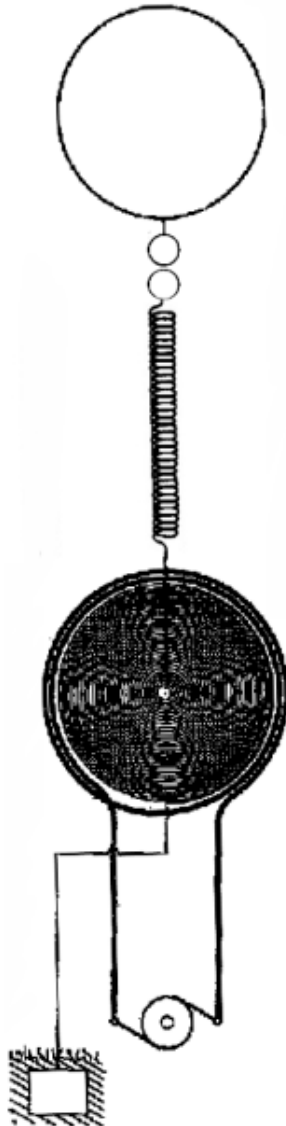
Further, great care should be taken when working on the primary section of a coil even when it has been disconnected from its power source for some time. The tank capacitors can remain charged for days with enough energy to deliver a fatal shock. Proper designs should always include 'bleeder resistors' to bleed off stored charge from the capacitors. In addition, a safety shorting operation should be performed on each capacitor before any internal work is performed.

### ***Instances and devices***

## **Magnifier Configurations**



Classically driven configuration.



Later-type driven configuration. Pancake may be horizontal; lead to resonator is kept clear of it.

Tesla's Colorado Springs laboratory possessed one of the largest Tesla coils ever built, known as the "Magnifying Transmitter". The Magnifying Transmitter is somewhat different from classic 2-coil Tesla coils. A Magnifier uses a 2-coil 'driver' to excite the base of a third coil ('resonator') that is located some distance from the driver. The operating principles of both systems are similar. The world's largest currently existing 2-coil Tesla coil is a 130,000-watt unit, part of a 38-foot-tall (12 m) sculpture. It is owned by Alan Gibbs and currently resides in a private sculpture park at Kakanui Point near Auckland, New Zealand.

The Tesla coil is an early predecessor (along with the induction coil) of a more modern device called a flyback transformer, which provides the voltage needed to power the cathode ray tube used in some televisions and computer monitors. The disruptive discharge coil remains in common use as the *ignition coil* or *spark coil* in the ignition system of an internal combustion engine. These two devices do not use resonance to accumulate energy, however, which is the distinguishing feature of a Tesla coil. They do use inductive "kick", the forced, abrupt decay of the magnetic field, such that a voltage is provided by the coil at its primary terminals that is much greater than the voltage that was applied to establish the magnetic field, and it is this higher voltage that is then multiplied by the transformer turns ratio. Thus, they do store energy, and a Tesla resonator stores energy. A modern, low power variant of the Tesla coil is also used to power plasma globe sculptures and similar devices.

Scientists working with a glass vacuum line (e.g. chemists working with volatile substances in the gas phase, inside a system of glass tubes, taps and bulbs) test for the presence of tiny pin-holes in the apparatus (especially a newly blown piece of glassware) using a Tesla coil. When the system is evacuated and the discharging end of the coil moved over the glass, the discharge travels through any pin-hole immediately below it and thus illuminates the hole, indicating points that need to be annealed or re-blown before they can be used in an experiment.

## Chapter 10

# Voice Coil

A **voice coil** (consisting of a former, collar and winding) is the coil of wire attached to the apex of a loudspeaker cone. It provides the motive force to the cone by the reaction of a magnetic field to the current passing through it. The term is also used for similar actuators, commonly used as the positioning actuator in the disk read-and-write head of computer hard disk drives.

### ***Operation***

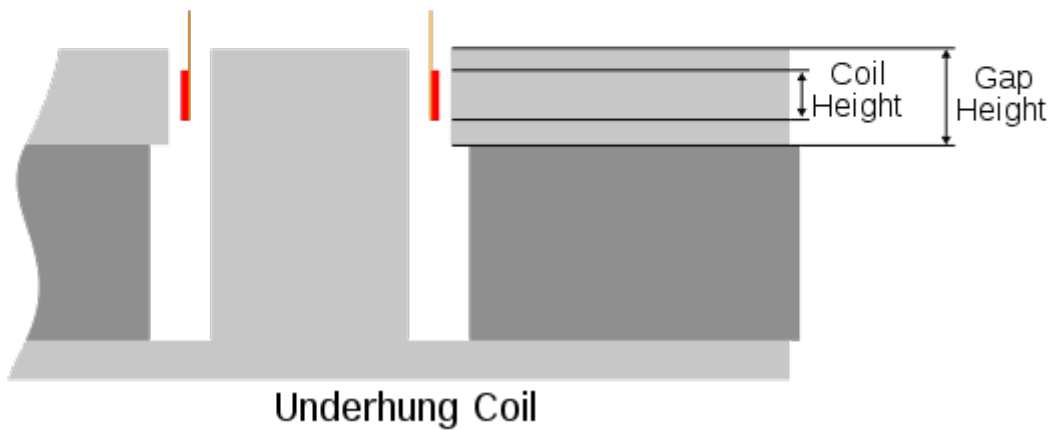
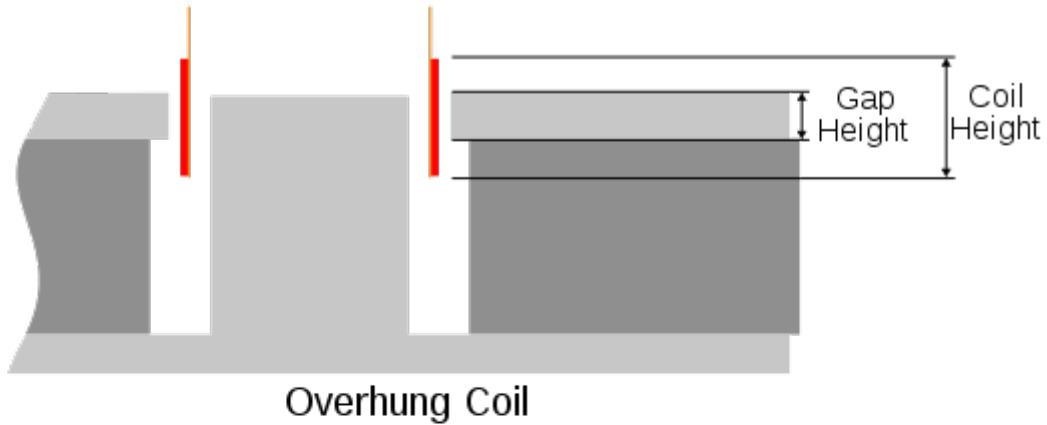
By driving a current through the voice coil, a magnetic field is produced. This magnetic field causes the voice coil to react to the magnetic field from a permanent magnet fixed to the speaker's frame, thereby moving the cone of the speaker. By applying an audio waveform to the voice coil, the cone will reproduce the sound pressure waves, corresponding to the original input signal.

### ***Design considerations***

Because the moving parts of the speaker must be of low mass (to accurately reproduce high-frequency sounds), voice coils are usually made as light weight as possible, making them delicate. Passing too much power through the coil can cause it to overheat. Voice coils wound with flattened wire, called *ribbon-wire*, provide a higher packing density in the magnetic gap than coils with round wire. Some coils are made with surface-sealed bobbin and collar materials so they may be immersed in a ferrofluid which assists in cooling the coil, by conducting heat away from the coil and into the magnet structure. Excessive input power at low frequencies can cause the coil to move beyond its normal limits, causing knocking and distortion.

Power handling is related to the thermal tolerance of the wire insulation, adhesive, and bobbin material, and may be influenced by the coil's position within the magnetic gap. The majority of loudspeakers use 'overhung' voice coils, with windings that are taller than

the height of the magnetic gap. In this topology, a portion of the coil remains within the gap at all times. The power handling is limited by the amount of heat that can be tolerated, and the amount that can be removed from the voice coil. Some magnet designs include aluminium heat-sink rings above and below the magnet gap, to improve conduction cooling, significantly improving power handling. If all other conditions remain constant, the area of the voice coil windings is proportional to the power handling of the coil. Thus a 100 mm diameter voice coil, with a 12 mm winding height has similar power handling to a 50 mm diameter voice coil with a 24 mm winding height.



#### Overhung & underhung voice coils.

In 'underhung' voice coil designs (see below), the coil is shorter than the magnetic gap, a topology that provides consistent electromotive force over a limited range of motion, known as  $X_{max}$ . If the coil is overdriven it may leave the gap, generating significant distortion and losing the heat-sinking benefit of the steel, heating rapidly.

Many hi-fi, and almost all professional low frequency loudspeakers (woofers) include vents in the magnet system to provide forced-air cooling of the voice coil. The pumping

action of the cone and dustcap draws in and expels cool air. This method of cooling relies upon cone motion, so is ineffective at midrange or treble frequencies, although venting of midranges and tweeters does provide some acoustic advantages.

In the earliest loudspeakers, voice coils were wound onto paper bobbins, which was appropriate for modest power levels. As more powerful amplifiers became available, alloy 1145 aluminium foil was widely substituted for paper bobbins, and the voice coils survived increased power. Typical modern hi-fi loudspeaker voice coils employ materials which can withstand operating temperatures up to 150°C, or even 180°C. For professional loudspeakers, advanced thermoset composite materials are available to improve voice coil survival under severe simultaneous thermal (<300°C) and mechanical stresses.

Aluminium was widely used in the speaker industry due to its low cost, ease of bonding, and structural strength. When higher power amplifiers emerged, especially in professional sound, the limitations of aluminium were exposed. It rather efficiently but inconveniently transfers heat from the voice coil into the adhesive bonds of the loudspeaker, thermally degrading or even burning them. Motion of the aluminium bobbin in the magnetic gap creates eddy-currents within the material, which further increase the temperature, hindering long-term survival. In 1955 DuPont developed Kapton, a polyimide plastic film which did not suffer from aluminium's deficiencies, so Kapton, and later Kaneka Apical were widely adopted for voice coils. As successful as these dark brown plastic films were for most hi-fi voice coils, they also had some less attractive properties, principally their cost, and an unfortunate tendency to soften when hot. Hisco P450, developed in 1992 to address the softening issue in professional speakers, is a thermoset composite of thin glassfibre cloth, impregnated with polyimide resin, combining the best characteristics of polyimide with the temperature resistance and stiffness of glassfibre. It withstands brutal physical stresses and operating temperatures up to 300°C, while its stiffness helps maintain the speaker's 'cold' frequency response.

The actual wire employed in voice coil winding is almost always copper, with an electrical insulation coating, and in some cases, an adhesive overcoat. Copper wire provides an easily manufactured, general purpose voice coil, at a reasonable cost. Where maximum sensitivity or extended high frequency response is required from a loudspeaker, aluminium wire may be substituted, to reduce the moving mass of the coil. While rather delicate in a manufacturing environment, aluminium wire has about one third of the mass of the equivalent gauge of copper wire, and has about two thirds of the electrical conductivity. Copper-clad aluminium wire is occasionally used, allowing easier winding, along with a useful reduction in coil mass compared to copper.

One manufacturer uses anodized aluminium flat wire, which is effectively insulated against shorting between turns of the coil, so is not subject to dielectric breakdown as is the case with the enamel coatings on other voice coil wire. This creates lightweight, low-inductance voice coils, ideally suited to use in small, extended range speakers. The principal power limitation on such coils is the thermal softening point of the adhesives that bonds the wire to the bobbin, or the bobbin to the spider and coil.

Voice coils can be used for applications other than loudspeakers, where time force linearity and long strokes are needed. Some environments like vacuum or space require specific attention during conception, in order to evacuate coil losses. Several specific methods can be used to facilitate thermal drain.

### ***Overhung & underhung coils***

The image above shows two ways in which the voice coil is immersed in the magnetic field. The most common method is the *overhung* design where the height of the voice coil is greater than the magnetic gap's height. The *underhung* design which is used mostly in high-end speakers has the coil's height smaller than the gap's. The differences, advantages and disadvantages of both methods are given in the table below.

#### **Overhung coil**

- Coil height is greater than the gap's height.
- This method keeps the number of windings within the magnetic field (or flux) constant over the coil's normal excursion range.
- Higher coil mass, sensitivity medium to high.‡
- Soft non-linearity as the coil exceeds limits.

#### **Underhung coil**

- Gap's height is greater than the coil's height.
- This method keeps the magnetic flux that the coil experiences, constant over the coil's normal excursion range.
- Low coil mass, sensitivity low to medium.‡
- Hard non-linearity as the coil exceeds limits.

Both topologies attempt the same goal: linear force acting on the coil, for a driver that reproduces the applied signal faithfully.

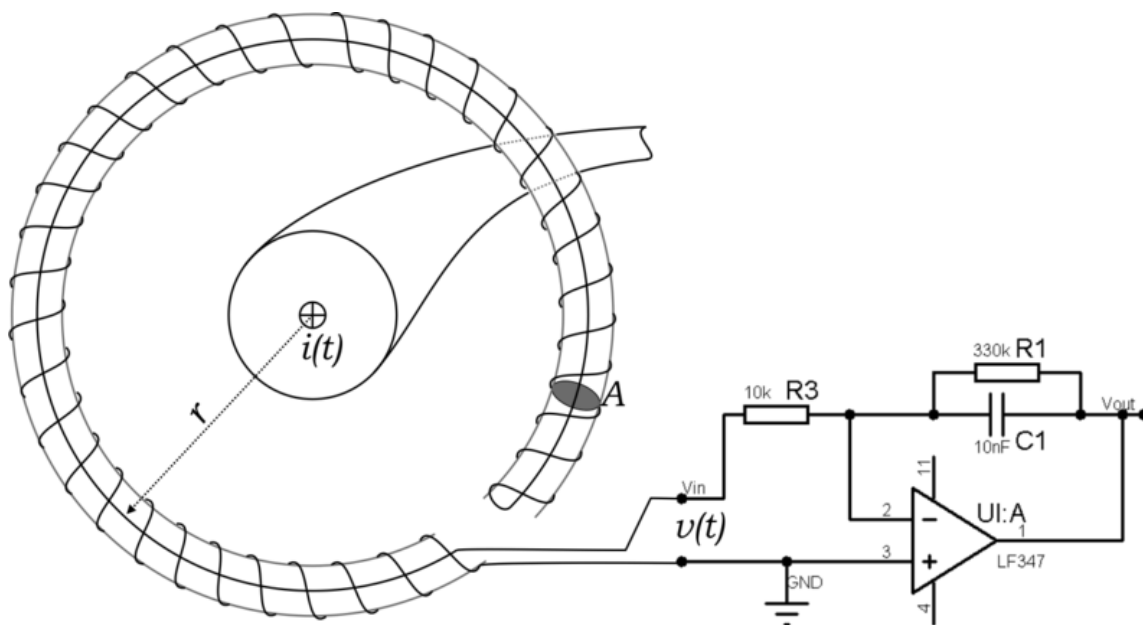
### ***Other uses for the term***

The term *voice coil* has been generalized and refers to any galvanometer-like mechanism that uses a solenoid to move an object back-and-forth within a magnetic field. In particular, it is commonly used to refer to the coil of wire that moves the read-write heads in a moving-head disk drive. In this application, a very lightweight coil of wires is mounted within a very strong magnetic field produced by rare earth permanent magnets. The voice coil is the motor part of the servo system that positions the heads: an electric control signal drives the voice coil and the resulting force quickly and accurately positions the heads.

## Chapter 11

# Rogowski Coil and Singing Tesla Coil

## Rogowski Coil



A Rogowski coil is a toroid of wire used to measure an alternating current  $i(t)$  through a cable encircled by the toroid. The above picture shows a coil encircling a current-carrying cable, with its output terminals  $v(t)$  connected to an integrator circuit, in order to obtain a voltage  $V_{out}(t)$  proportional to  $i(t)$ .

A **Rogowski coil**, named after Walter Rogowski, is an electrical device for measuring alternating current (AC) or high speed current pulses. It consists of a helical coil of wire with the lead from one end returning through the centre of the coil to the other end, so that both terminals are at the same end of the coil. The whole assembly is then wrapped

around the straight conductor whose current is to be measured. Since the voltage that is induced in the coil is proportional to the rate of change (derivative) of current in the straight conductor, the output of the Rogowski coil is usually connected to an electrical (or electronic) integrator circuit in order to provide an output signal that is proportional to the current.

This type of coil has many advantages over other types of current transformers, the most notable being that it is not a closed loop, because the second terminal is passed back through the center of the toroid core (commonly a plastic or rubber tube) and connected along the first terminal. This allows the coil to be open-ended and flexible, allowing it to be wrapped around a live conductor without disturbing it.

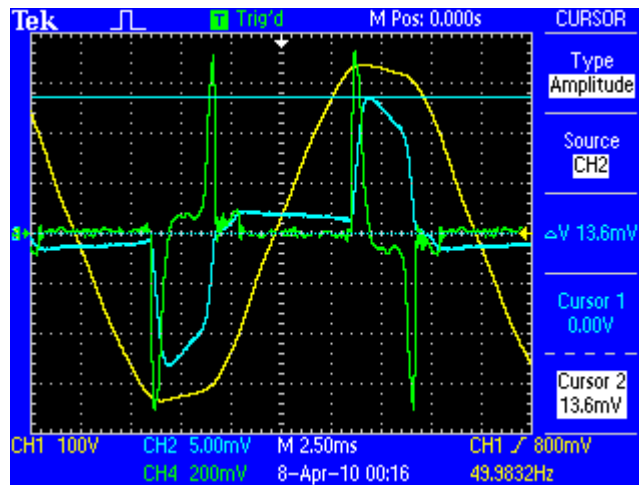
Furthermore, since a Rogowski coil has an air core rather than an iron core, it has a low inductance and can respond to fast-changing currents. Also, because it has no iron core to saturate, it is highly linear even when subjected to large currents, such as those used in electric power transmission, welding, or pulsed power applications. A correctly formed Rogowski coil, with equally spaced windings, is largely immune to electromagnetic interference.

A good set of traditional and more recent designs of Rogowski coils can be found in the US patent n° 6313623. In this patent there is a mention to an added purpose of the second wire returning through the center of the toroid, claiming that it helps reject interference from electrical fields present in the environment.

A device similar to the Rogowski coil was described by A.P. Chattock of Bristol University, ("On a magnetic potentiometer", *Philosophical Magazine and Journal of Science*, vol. XXIV, no. 5th Series, pp. 94–96, Jul-Dec 1887). Chattock used it to measure magnetic fields rather than currents. The definitive description was given by Walter Rogowski and W. Steinhaus in "Die Messung der magnetischen Spannung", *Archiv für Elektrotechnik*, 1912, 1, Pt.4, pp. 141–150.

More recently, low-cost current sensors based on the principle of a Rogowski coil have been developed. These sensors share the principles of a Rogowski coil, measuring the rate of change of current using a transformer with no magnetic core. The difference from the traditional Rogowski coil is that the sensor can be manufactured using a planar coil rather than a toroidal coil. In order to reject the influence of conductors outside the sensor's measurement region, these planar Rogowski current sensors use a concentric coil geometry instead of a toroidal geometry to limit the response to external fields. The main advantage of the planar Rogowski current sensor is that the coil winding precision that is a requirement for accuracy can be achieved using low-cost printed circuit board manufacturing.

## Formulae



Example waveform of R.C. output for switched-mode load. As explained above the output waveform - CH4 (green) - represents derivation of current waveform - CH2 (Blue). CH1 (Yellow) is 230V AC Mains waveform

The voltage produced by a Rogowski coil is

$$V = \frac{-AN\mu_0}{l} \frac{dI}{dt},$$

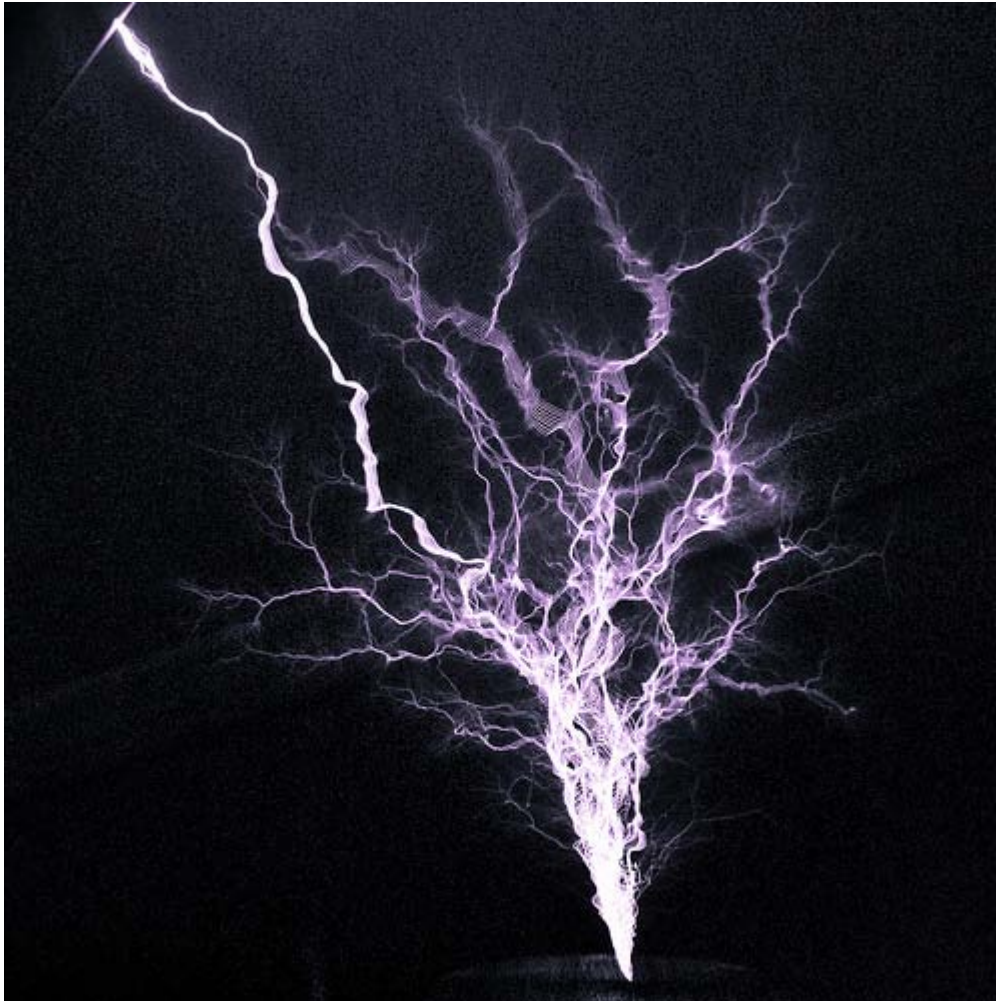
where  $A = \pi a^2$  is the area of one of the small loops,  $N$  is the number of turns, and  $l = 2\pi R$

is the length of the winding.  $\frac{dI}{dt}$  is the rate of change of the current threading the loop. This formula assumes the turns are evenly spaced and that these turns are small relative to the radius of the coil itself. At high frequencies, the Rogowski coil's inductance will decrease its output. The inductance of a toroid is

$$L = \mu_0 N^2 (R - \sqrt{R^2 - a^2})$$

$\mu_0 = 4\pi \times 10^{-7}$  is the magnetic constant,  $R$  is the major radius of the toroid, and  $a$  is its minor radius.

## Singing Tesla Coil



ArcAttack's singing Tesla coil at SXSW, March 14, 2007

The **singing Tesla coil** is a form of plasma speaker. It is a variation of a solid state Tesla coil that has been modified to produce musical tones by modulating its spark output. The resulting pitch is a low fidelity square wave like sound reminiscent of an analog synthesizer.

The term, "singing Tesla coil" was coined by David Nunez, the coordinator of the Austin, TX chapter of Dorkbot, while describing a musical Tesla coil presentation by Joe DiPrima and Oliver Greaves during DorkBot's 2007 SXSW event. The term was then made popular by a CNET article describing the event. Though they had been doing public performances with the technology since March of 2006. Shortly after that, DiPrima named their performance group "ArcAttack" and became the first musical group to ever use this technology in live performance.

While early versions of musical Tesla coils generally used Zero crossing threshold detector as a method of producing music through their spark output, Scott Coppersmith was the first person to design a complete MIDI based Tesla coil system.

Now, MIDI is the most common method of music production. It works by means of a microcontroller that is programmed to interpret MIDI data, and output a corresponding Pulse-width modulation (PWM) signal. This PWM signal is coupled to the Tesla coil through a fiber optic cable, and controls when the Tesla coil turns on and off.

Steve Ward demonstrated a singing Tesla coil at the DucKon 16, science fiction convention on June 9, 2007, at which time it was suggested to him to nickname the device, the "Zeusaphone". It is a play on the name of the Sousaphone, giving homage instead to Zeus, Greek god of lightning.