Electrical Breakdown

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Electrical Breakdown

Electrical breakdown in an electric discharge showing the ribbon-like plasma filaments from a Tesla coil.

The term **electrical breakdown** or **electric breakdown** has several similar but distinctly different meanings. For example, the term can apply to the failure of an electric circuit. Alternatively, it may refer to a rapid reduction in the resistance of an electrical insulator that can lead to a spark jumping around or through the insulator. This may be a momentary event (as in an electrostatic discharge), or may lead to a continuous arc discharge if protective devices fail to interrupt the current in a high power circuit.

Electrical system failure

The most common meaning is related to automobiles and is the failure of an electric circuit or associated device resulting in a loss of vehicle function (a breakdown). Common problems include battery discharge, alternator failure, broken wires, blown fuses, etc.

Failure of electrical insulation

The second meaning of the term is more specifically a reference to the breakdown of the insulation of an electrical wire or other electrical component. Such breakdown usually results in a short circuit or a blown fuse. This occurs at the breakdown voltage. Actual insulation breakdown is more generally found in high-voltage applications, where it sometimes causes the opening of a protective circuit breaker. Electrical breakdown is often associated with the failure of solid or liquid insulating materials used inside high voltage transformers or capacitors in the electricity distribution grid. Electrical breakdown can also occur across the insulators that suspend overhead power lines, within underground power cables, or lines arcing to nearby branches of trees. Under sufficient electrical stress, electrical breakdown can occur within solids, liquids, gases or vacuum. However, the specific breakdown mechanisms are significantly different for each, particularly in different kinds of dielectric medium. All this leads to catastrophic failure of the instruments.

Disruptive devices

A **disruptive device** is a device that has a dielectric, whereupon being stressed beyond its dielectric strength, has an electrical breakdown. This results in the sudden transition of part of the dielectric material from an insulating state to a highly conductive state. This transition is characterized by the formation of an electric spark, and possibly an electric arc through the material. If this occurs within a solid dielectric, physical and chemical changes along the path of the discharge will cause permanent degradation and significant reduction in the material's dielectric strength. A spark gap is a type of disruptive discharge device that uses a gas or fluid dielectric between spaced electrodes. It may be used to discharge the primary capacitor of a resonance transformer into the primary inductor. Unlike solid dielectrics, liquid or gaseous dielectrics can usually recover their full dielectric strength once current flow (through the plasma in the gap) has been externally interrupted.

Mechanism

Electrical breakdown occurs within a gas (or mixture of gases, such as air) when the dielectric strength of the gas(es) is exceeded. Regions of high electrical stress can cause nearby gas to partially ionize and begin conducting. This is done deliberately in low pressure discharges such as in fluorescent lights or in an electrostatic precipitator.

Partial electrical breakdown of the air causes the "fresh air" smell of ozone during thunderstorms or around high-voltage equipment. Although air is normally an excellent insulator, when stressed by a sufficiently high voltage (an electric field strength of about 3×10^6 V/m), air can begin to break down, becoming partially conductive. If the voltage is sufficiently high, complete electrical breakdown of the air will culminate in an electrical spark or arc that bridges the entire gap. While the small sparks generated by static electricity may barely be audible, larger sparks are often accompanied by a loud snap or bang. Lightning is an example of an immense spark that can be many miles long. The color of the spark depends upon the gases that make up the gaseous media.
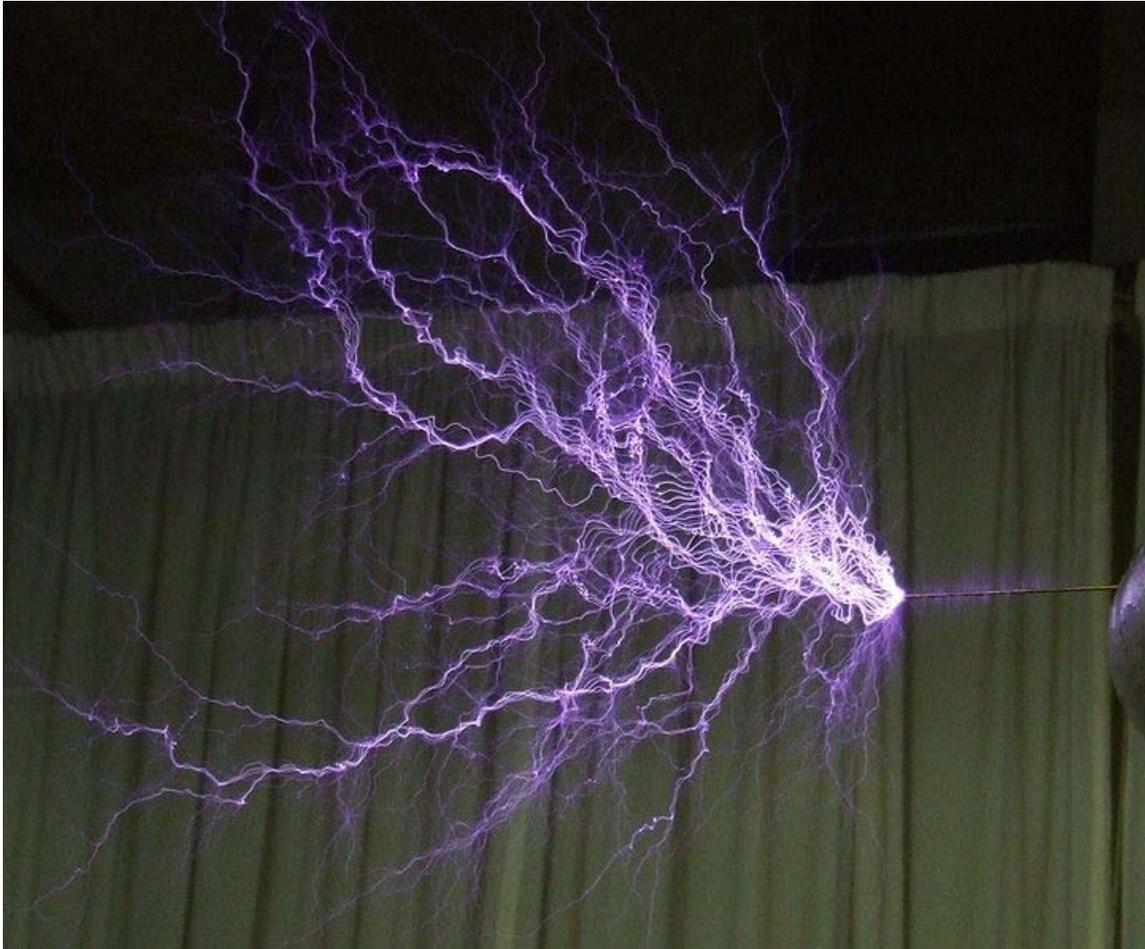
Electric discharge showing the lightning-like plasma filaments from a Tesla coil.

If a fuse or circuit breaker fails to interrupt the current through a spark in a power circuit, current may continue, forming a very hot electric arc. The color of an arc depends primarily upon the conductor materials (as they are vaporized and mix within the hot plasma in the arc). Although sparks and arcs are usually undesirable, they can be useful in everyday applications such as spark plugs for gasoline engines, electrical welding of metals, or for metal melting in an electric arc furnace.

Voltage-current relation
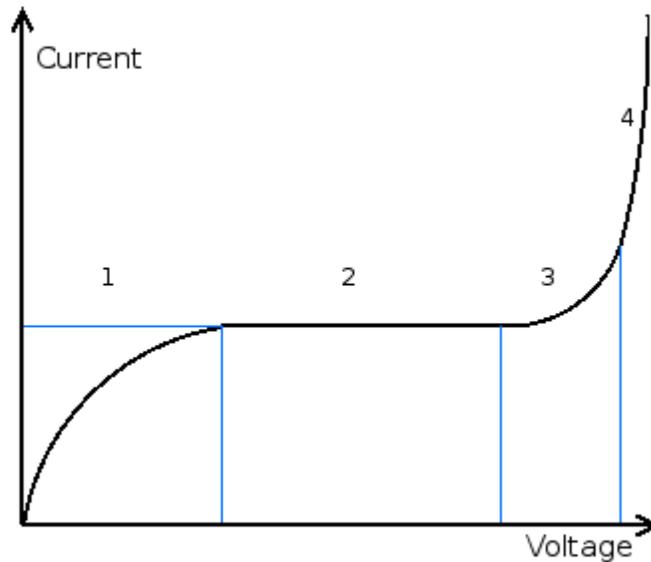
Voltage-current relation before breakdown

Before breakdown, there is a non-linear relation between voltage and current as shown in the figure. In region 1, there are free ions that can be accelerated by the field and induce a current. These will be saturated after a certain voltage and give a constant current, region 2. Region 3 and 4 are caused by ion avalanche as explained by the Townsend discharge mechanism.

Corona breakdown

Partial breakdown of the air occurs as a corona discharge on high voltage conductors at points with the highest electrical stress. As the dielectric strength of the material surrounding the conductor determines the maximum strength of the electric field the surrounding material can tolerate before becoming conductive, conductors that consist of sharp points, or balls with small radii, are more prone to causing dielectric breakdown. Corona is sometimes seen as a bluish glow around high voltage wires and heard as a sizzling sound along high voltage power lines. Corona also generates radio frequency noise that can also be heard as 'static' or buzzing on radio receivers. Corona can also occur naturally at high points (such as church spires, treetops, or ship masts) during thunderstorms as St. Elmo's Fire. Although corona discharge is usually undesirable, until recently it was essential in the operation of photocopiers (Xerography) and laser printers. Many modern copiers and laser printers now charge the photoconductor drum with an electrically conductive roller, reducing undesirable indoor ozone pollution. Additionally, lightning rods use corona discharge to create conductive paths in the air that point towards the rod, deflecting potentially-damaging lightning away from buildings and other structures.

Corona discharge ozone generators have been used for more than 30 years in the water purification process. Ozone is a toxic gas, even more potent than chlorine. In a typical drinking water treatment plant, the ozone gas is dissolved into the filtered water to kill bacteria and viruses. Ozone also removes the bad odours and taste from the water. The main advantage of ozone is that the overdose (residual) decomposes to gaseous oxygen well before the water reaches the consumer. This is in contrast with chlorine which stays in the water and can be tasted by the consumer.

Corona discharges are also used to modify the surface properties of many polymers. An example is the corona treatment of plastic materials which allows paint or ink to adhere properly.

Dielectric breakdown within a solid insulator can permanently change its appearance and properties.

Chapter-2

Corona Discharge

The corona discharge around a high-voltage coil

Corona discharge on a Wartenberg wheel

In electricity, a **corona discharge** is an electrical discharge brought on by the ionization of a fluid surrounding a conductor, which occurs when the potential gradient (the change in the strength of the electric field) exceeds a certain value, but conditions are insufficient to cause complete electrical breakdown or arcing.

Introduction

A corona is a process by which a current, perhaps sustained, develops from an electrode with a high potential in a neutral fluid, usually air, by ionizing that fluid so as to create a plasma around the electrode. The ions generated eventually pass charge to nearby areas of lower potential, or recombine to form neutral gas molecules.

When the potential gradient is large enough at a point in the fluid, the fluid at that point ionizes and it becomes conductive. If a charged object has a sharp point, the air around that point will be at a much higher gradient than elsewhere. Air near the electrode can become ionized (partially conductive), while regions more distant do not. When the air near the point becomes conductive, it has the effect of increasing the apparent size of the conductor. Since the new conductive region is less sharp, the ionization may not extend past this local region. Outside this region of ionization and conductivity, the charged particles slowly find their way to an oppositely charged object and are neutralized.

If the geometry and gradient are such that the ionized region continues to grow instead of stopping at a certain radius, a completely conductive path may be formed, resulting in a momentary spark, or a continuous arc.

Corona discharge usually involves two asymmetric electrodes; one highly curved (such as the tip of a needle, or a small diameter wire) and one of low curvature (such as a plate, or the ground). The high curvature ensures a high potential gradient around one electrode, for the generation of a plasma.

Coronas may be *positive* or *negative*. This is determined by the polarity of the voltage on the highly-curved electrode. If the curved electrode is positive with respect to the flat electrode we say we have a *positive corona*, if negative we say we have a *negative corona*. The physics of positive and negative coronas are strikingly different. This asymmetry is a result of the great difference in mass between electrons and positively charged ions, with only the electron having the ability to undergo a significant degree of ionising inelastic collision at common temperatures and pressures.

An important reason for considering coronas is the production of ozone around conductors undergoing corona processes. A negative corona generates much more ozone than the corresponding positive corona.

Applications of corona discharge

Corona discharge has a number of commercial and industrial applications.

- Drag reduction over a flat surface
- Removal of unwanted electric charges from the surface of aircraft in flight and thus avoiding the detrimental effect of uncontrolled electrical discharge pulses on the performance of avionic systems
- Manufacture of ozone
- Sanitization of pool water
- Scrubbing particles from air in air-conditioning systems
- Removal of unwanted volatile organics, such as chemical pesticides, solvents, or chemical weapons agents, from the atmosphere
- Improvement of wetability or 'surface tension energy' of polymer films to improve compatibility with adhesives or printing inks
- Photocopying

- Air ionisers
- Production of photons for Kirlian photography to expose photographic film
- EHD thrusters, Lifters, and other ionic wind devices
- Nitrogen laser
- Surface treatment for tissue culture (polystyrene)
- Ionization of a gaseous sample for subsequent analysis in a mass spectrometer or an ion mobility spectrometer
- Solid-state cooling components for computer chips

Coronas can be used to generate charged surfaces, which is an effect used in electrostatic copying (photocopying). They can also be used to remove particulate matter from air streams by first charging the air, and then passing the charged stream through a comb of alternating polarity, to deposit the charged particles onto oppositely charged plates.

The free-radicals and ions generated in corona reactions can be used to scrub the air of certain noxious products, through chemical reactions, and can be used to produce ozone.

Problems caused by corona discharges

Coronas can generate audible and radio-frequency noise, particularly near electric power transmission lines. They also represent a power loss, and their action on atmospheric particulates, along with associated ozone and NOx production, can also be disadvantageous to human health where power lines run through built-up areas. Therefore, power transmission equipment is designed to minimise the formation of corona discharge.

Corona discharge is generally undesirable in:

- Electric power transmission, where it causes:
  - Power loss
  - Audible noise
  - Electromagnetic interference
  - Purple glow
  - Ozone production
  - Insulation damage
- Inside electrical components such as transformers, capacitors, electric motors and generators. Corona progressively damages the insulation inside these devices, leading to premature equipment failure. One form of attack is ozone cracking of elastomer items like O-rings.
- Situations where high voltages are in use, but ozone production is to be minimised
- Static electricity discharge
- Lightning

Coronas can be suppressed by corona rings, toroidal devices that serve to spread the electric field over larger area and decrease the field gradient below the corona threshold.

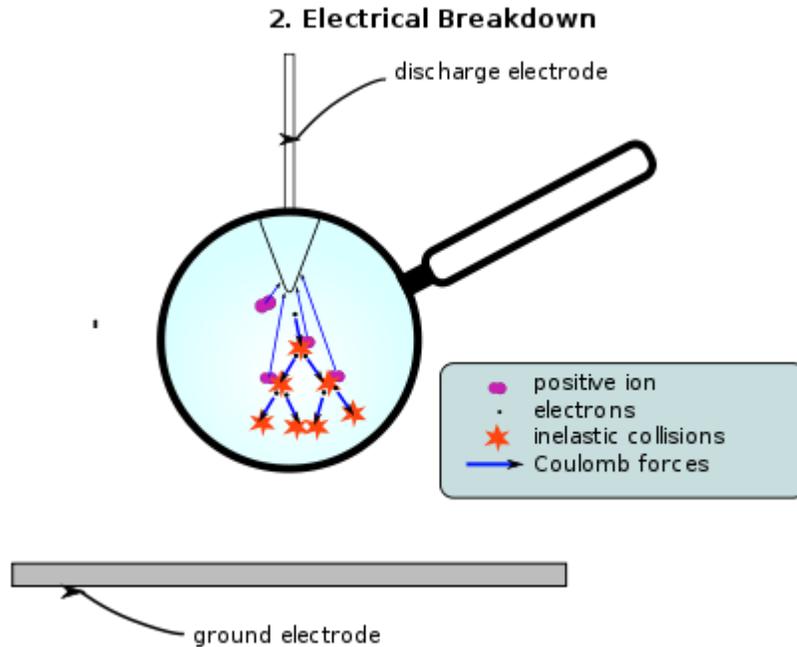## *Mechanism of corona discharge*

Corona discharge of both the positive and negative variety have certain mechanisms in common.

1. A neutral atom or molecule of the medium, in a region of strong electric field (such as the high potential gradient near the curved electrode) is ionized by an exogenous environmental event (for example, as the result of a photon interaction), to create a positive ion and a free electron.

1. Discharge initiation
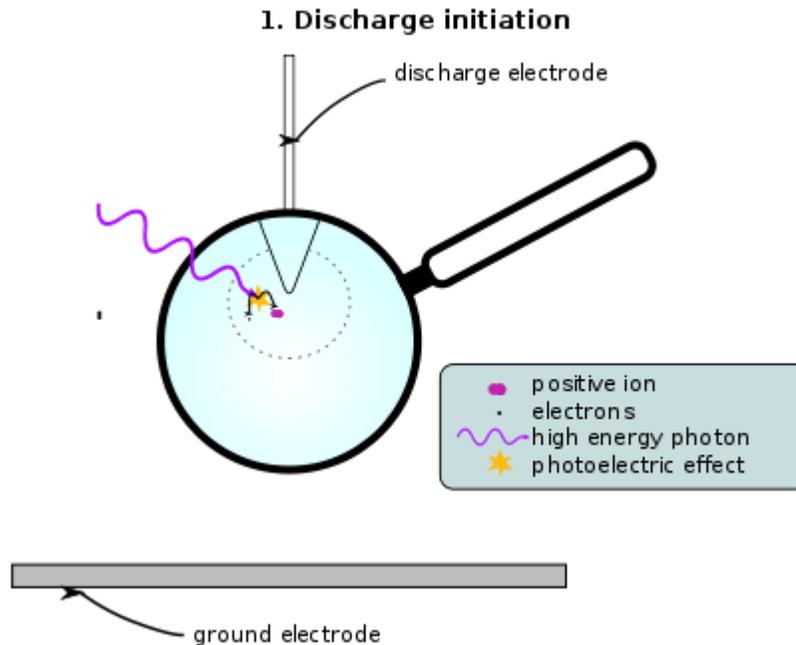
2. The electric field then operates on these charged particles, separating them, and preventing their recombination, and also accelerating them, imparting each of them with kinetic energy.
3. As a result of the energisation of the electrons (which have a much higher charge/mass ratio and so are accelerated to a higher velocity), further electron/positive-ion pairs may be created by collision with neutral atoms. These then undergo the same separating process creating an *electron avalanche*. Both

positive and negative coronas rely on electron avalanches.

2. Electrical Breakdown

discharge electrode

- **positive ion**
- **.** electrons
- **✱** inelastic collisions
- **→** Coulomb forces

ground electrode

4. In processes which differ between positive and negative coronas, the energy of these plasma processes is converted into further initial electron dissociations to seed further avalanches.
5. An ion species created in this series of avalanches (which differs between positive and negative coronas) is attracted to the uncurved electrode, completing the circuit, and sustaining the current flow.

3. Recombination and upkeep of the discharge

discharge electrods

negative

positive

- **positive ions**
- **negative ions**
- **.** electrons
- **★** photoelectric effect
- **✱** recombination/photon emissio
- · · · · · limit of the disruptive area
- · · · · · limit of the plasma area

ground electrode
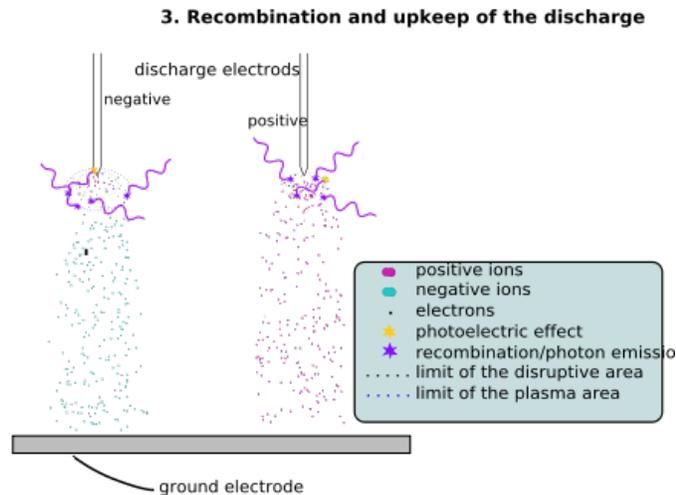
The onset voltage of corona or corona inception voltage (CIV) can be found with *Peek's law* (1929), formulated from empirical observations. Later papers derived more accurate formulas.

Electrical properties

The current carried by the corona is determined by integrating the current density over the surface of the conductor. The power loss is determined by multiplying the current by the voltage.

Positive coronas

Properties

A positive corona is manifested as a uniform plasma across the length of a conductor. It can often be seen glowing blue/white, though many of the emissions are in the ultraviolet. The uniformity of the plasma owes itself to the homogeneous source of secondary avalanche electrons described in the mechanism section, below. With the same geometry and voltages, it appears a little smaller than the corresponding negative corona, owing to the lack of a non-ionising plasma region between the inner and outer regions. There are many fewer free electrons in a positive corona, when compared to a negative corona, except very close to the curved electrode: perhaps a thousandth of the electron density, and a hundredth of the total number of electrons.

However, the electrons in a positive corona are concentrated close to the surface of the curved conductor, in a region of high-potential gradient (and therefore the electrons have a high energy), whereas in a negative corona many of the electrons are in the outer, lower-field areas. Therefore, if electrons are to be used in an application which requires a high activation energy, positive coronas may support a greater reaction constants than corresponding negative coronas; though the total number of electrons may be lower, the number of a very high energy electrons may be higher.

Coronas are efficient producers of ozone in air. A positive corona generates much less ozone than the corresponding negative corona, as the reactions which produce ozone are relatively low-energy. Therefore, the greater number of electrons of a negative corona leads to an increased production.

Beyond the plasma, in the *unipolar region*, the flow is of low-energy positive ions toward the flat electrode.

Mechanism

As with a negative corona, a positive corona is initiated by an exogenous ionisation event in a region of high potential gradient. The electrons resulting from the ionisation are attracted **toward** the curved electrode, and the positive ions repelled from it. By undergoing inelastic collisions closer and closer to the curved electrode, further molecules are ionized in an electron avalanche.

In a positive corona, secondary electrons, for further avalanches, are generated predominantly in the fluid itself, in the region outside the plasma or avalanche region.

They are created by ionization caused by the photons emitted from that plasma in the various de-excitation processes occurring within the plasma after electron collisions, the thermal energy liberated in those collisions creating photons which are radiated into the gas. The electrons resulting from the ionisation of a neutral gas molecule are then electrically attracted back toward the curved electrode, attracted *into* the plasma, and so begins the process of creating further avalanches inside the plasma.

As can be seen, the positive corona is divided into two regions, concentric around the sharp electrode. The inner region contains ionising electrons, and positive ions, acting as a plasma, the electrons avalanche in this region, creating many further ion/electron pairs. The outer region consists almost entirely of the slowly migrating massive positive ions, moving toward the uncurved electrode along with, close to the interface of this region, secondary electrons, liberated by photons leaving the plasma, being re-accelerated into the plasma. The inner region is known as the **plasma** region, the outer as the **unipolar** region.

Negative coronas

Properties

A negative corona is manifested in a non-uniform corona, varying according to the surface features and irregularities of the curved conductor. It often appears as tufts of corona at sharp edges, the number of tufts altering with the strength of the field. The form of negative coronas is a result of its source of secondary avalanche electrons. It appears a little larger than the corresponding positive corona, as electrons are allowed to drift out of the ionising region, and so the plasma continues some distance beyond it. The total number of electrons, and electron density is much greater than in the corresponding positive corona. However, they are of a predominantly lower energy, owing to being in a region of lower potential-gradient. Therefore, whilst for many reactions the increased electron density will increase the reaction rate, the lower energy of the electrons will mean that reactions which require a higher electron energy may take place at a lower rate.

Mechanism

Negative coronas are more complex than positive coronas in construction. As with positive coronas, the establishing of a corona begins with an exogenous ionization event generating a primary electron, followed by an electron avalanche.

Electrons ionized from the neutral gas are not useful in sustaining the negative corona process by generating secondary electrons for further avalanches, as the general movement of electrons in a negative corona is outward from the curved electrode. For negative corona, instead, the dominant process generating secondary electrons is the photoelectric effect, from the surface of the electrode itself. The work-function of the electrons (the energy required to liberate the electrons from the surface) is considerably lower than the ionization energy of air at standard temperatures and pressures, making it a more liberal source of secondary electrons under these conditions. Again, the source of

energy for the electron-liberation is a high-energy photon from an atom within the plasma body relaxing after excitation from an earlier collision. The use of ionized neutral gas as a source of ionization is further diminished in a negative corona by the high-concentration of positive ions clustering around the curved electrode.

Under other conditions, the collision of the positive species with the curved electrode can also cause electron liberation.

The difference, then, between positive and negative coronas, in the matter of the generation of secondary electron avalanches, is that in a positive corona they are generated by the gas surrounding the plasma region, the new secondary electrons travelling inward, whereas in a negative corona they are generated by the curved electrode itself, the new secondary electrons travelling outward.

A further feature of the structure of negative coronas is that as the electrons drift outwards, they encounter neutral molecules and, with electronegative molecules (such as oxygen and water vapor), combine to produce negative ions. These negative ions are then attracted to the positive uncurved electrode, completing the 'circuit'.

A negative corona can be divided into three radial areas, around the sharp electrode. In the inner area, high-energy electrons inelastically collide with neutral atoms and cause avalanches, whilst outer electrons (usually of a lower energy) combine with neutral atoms to produce negative ions. In the intermediate region, electrons combine to form negative ions, but typically have insufficient energy to cause avalanche ionization, but remain part of a plasma owing to the different polarities of the species present, and the ability to partake in characteristic plasma reactions. In the outer region, only a flow of negative ions and, to a lesser and radially-decreasing extent, free electrons toward the positive electrode takes place. The inner two regions are known as the corona *plasma*. The inner region is an *ionizing plasma*, the middle a *non-ionizing plasma*. The outer region is known as the *unipolar region*.

Chapter-3

Corona Ring and Breakdown Voltage

Corona ring

Corona rings on 380 kV line insulators

400 kV power lines with corona rings on insulators

This Cockcroft–Walton voltage multiplier was part of one of the early particle accelerators responsible for development of the atomic bomb. Built in 1937 by Philips of Eindhoven, it is now in the National Science Museum in London, England. Note the silver corona rings around the insulators.

A **corona ring**, also called **anti-corona ring**, is a toroid of (typically) conductive material located in the vicinity of a terminal of a high voltage device. It is electrically insulated. Stacks of more spaced rings are often used. The role of the corona ring is to distribute the electric field gradient and lower its maximum values below the corona threshold, preventing the corona discharge.

Corona rings are often seen on van de Graaf generators, electrical insulators, Cockcroft–Walton generators, particle accelerators, Lightning Arresters, high voltage bushing terminals, and other high voltage equipment.

Corona rings are typically installed on very high voltage power line insulators. Manufacturers suggest a corona ring on the line end of the insulator for above 230 kV and on both ends for above 500 kV. Corona rings prolong lifetime of insulator surfaces by suppressing the effects of corona discharge.

Corona rings may also be installed on the insulators of antennas of high-power radio transmitters. They however increase the capacitance of the insulators.

Corona discharge is a more serious problem in higher altitude locations, where the air is less dense.

Corona caps are caps with round edges; they are mounted on the ends of the insulators and play the same role as corona rings.

Breakdown voltage

High voltage dielectric breakdown within a block of plexiglas

The **breakdown voltage** of an insulator is the minimum voltage that causes a portion of an insulator to become electrically conductive.

The **breakdown voltage** of a diode is the minimum *reverse* voltage to make the diode conduct in reverse. Some devices (such as TRIACs) also have a *forward breakdown voltage*.

In Detail

Insulators

Breakdown voltage is a characteristic of an insulator that defines the maximum voltage difference that can be applied across the material before the insulator collapses and conducts. In solid insulating materials, this usually creates a weakened path within the material by creating permanent molecular or physical changes by the sudden current. Within rarefied gases found in certain types of lamps, **breakdown voltage** is also sometimes called the "striking voltage".

The breakdown voltage of a material is not a definite value because it is a form of failure and there is a statistical probability whether the material will fail at a given voltage. When a value is given it is usually the mean breakdown voltage of a large sample. Another term is also 'withstand voltage' where the probability of failure at a given voltage is so low it is considered, when designing insulation, that the material will not fail at this voltage.

Two different breakdown voltage measurements of a material are the AC and impulse breakdown voltages. The AC voltage is the line frequency of the mains (either 50 or 60 Hz depending on where you live). The impulse breakdown voltage is simulating lightning strikes, and usually uses a 1.2 microsecond rise for the wave to reach 90% amplitude then drops back down to 50% amplitude after 50 microseconds.

Two technical standards governing performing these tests are ASTM D1816 and ASTM D3300 published by ASTM.

Breakdown in vacuum

In standard conditions at atmospheric pressure, gas serves as an excellent insulator, requiring the application of a significant voltage before breaking down (e.g. lightning). In partial vacuum, this breakdown potential may decrease to an extent that two uninsulated surfaces with different potentials might induce the electrical breakdown of the surrounding gas. This has some useful applications in industry (e.g. the production of microprocessors) but in other situations may damage an apparatus, as breakdown is analogous to a short circuit.

The breakdown voltage in a partial vacuum is represented as :

$$V_b = \frac{Bpd}{\ln Apd - \ln(1 + \frac{1}{\gamma_{se}})}$$

where V_b is the breakdown potential in volts DC, A and B are constants that depend on the surrounding gas, p represents the pressure of the surrounding gas, d represents the distance in centimetres between the electrodes, and γ_{se} represents the Secondary Electron Emission Coefficient.

Diodes
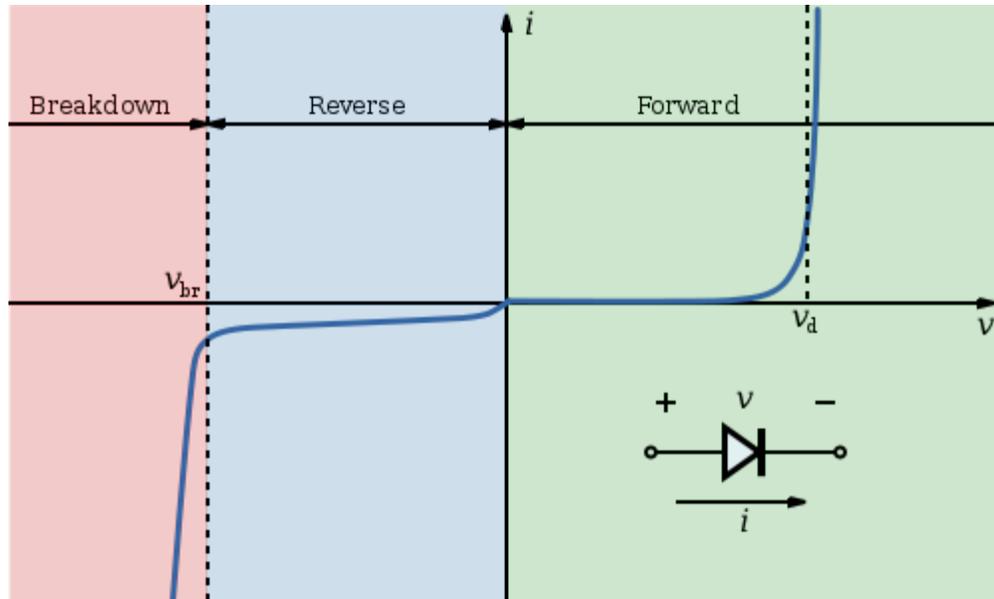
Diode I-V diagram

Breakdown voltage is a parameter of a diode that defines the largest reverse voltage that can be applied without causing an exponential increase in the current in the diode. As long as the current is limited, exceeding the breakdown voltage of a diode does no harm to the diode. In fact, Zener diodes are essentially just heavily doped normal diodes that exploit the breakdown voltage of a diode to provide regulation of voltage levels.

Electric Spark and Electrical Treeing

Electric spark
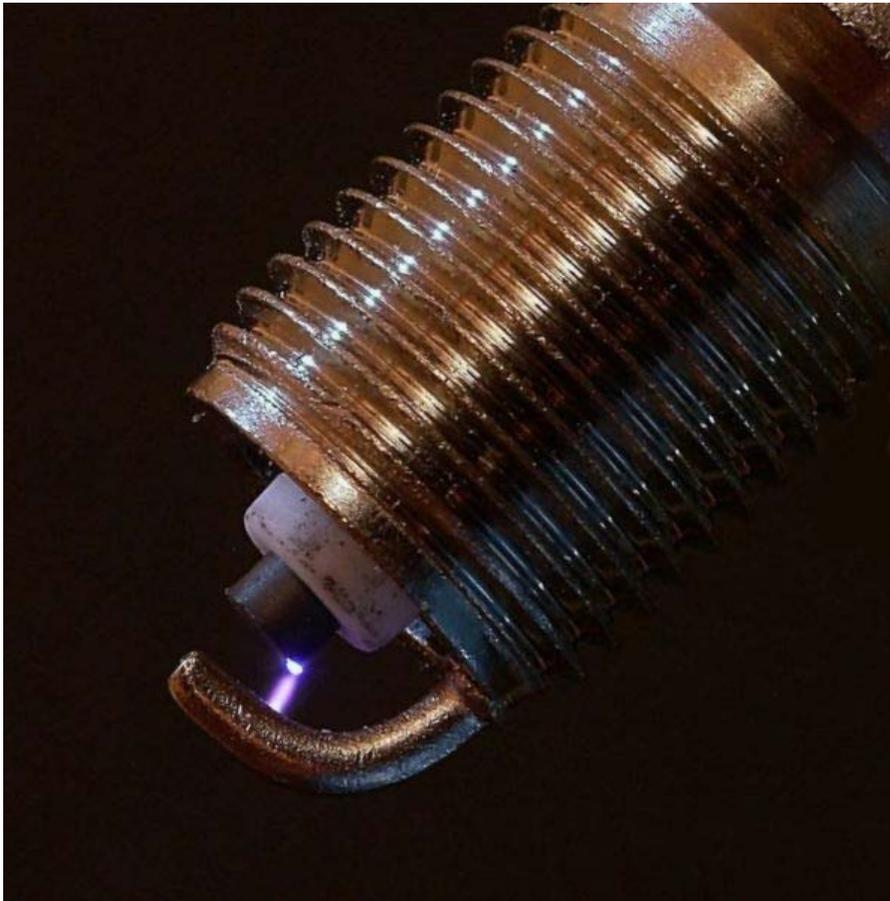
Spark plug electric discharge

An **electric spark** is a type of electrostatic discharge that occurs when a large electric field creates an ionized conductive channel in air producing a brief emission of light and sound. A spark is formed when the electric field strength exceeds the dielectric field

strength of air. This causes an increase in the number of free electrons and ions in the air, temporarily causing the air to become an electrical conductor through dielectric breakdown.

History

Around 600 BC, Greek philospher Thales of Miletus observed that amber could be electrified when rubbed with a cloth and attract other objects and produce sparks. In 1671, Leibniz discovered that sparks were associated with electrical phenomena. In 1708, Samuel Wall performed experiments with amber rubbed with cloth to produce sparks. In 1752, Thomas-François Dalibard and Benjamin Franklin independently demonstrated that lightning and electricity were equivalent. In Franklin's famous kite experiment, he successfully extracted sparks from a cloud during a thunderstorm

Ignition sources

Gas stove burner - the electric spark flame igniter is shown at the left.

Electric sparks are used in spark plugs in some internal combustion engines to ignite fuel and air mixtures. The electric discharge in a spark plug occurs between an insulated central electrode and a grounded terminal on the base of the plug. The voltage for the spark is provided by an ignition coil or magneto circuit that is connected to the spark plug with an insulated wire.

Flame igniters use electric sparks to initiate combustion in some furnaces and gas stoves in place of a pilot flame. Auto reignition is a safety feature that is used in some flame igniters that senses the electrical conductivity of the flame and uses this information to determine whether a burner flame is lit. This information is used to stop an ignition device from sparking after the flame is lit or restart the flame if it goes out.

Radio communications
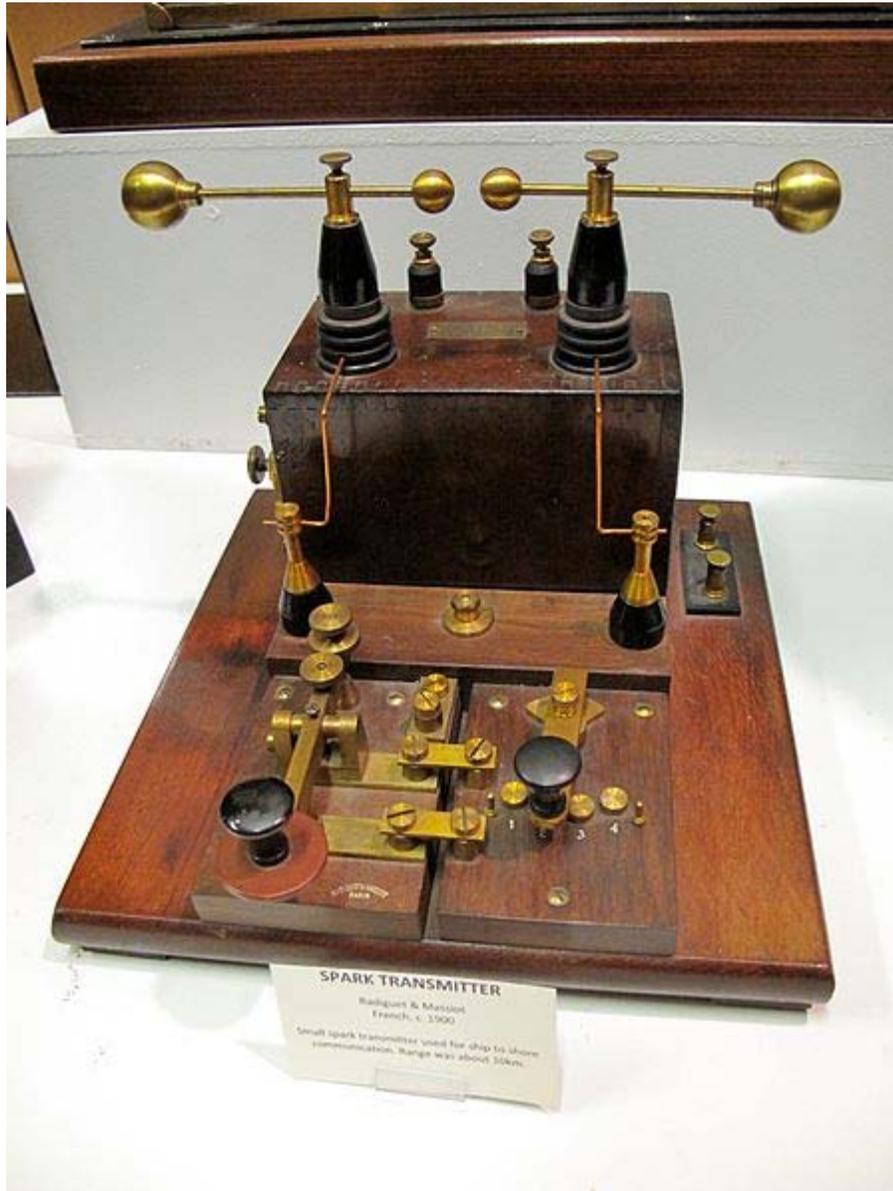
Spark transmitter used for ship to shore communication up to 10 km (c. 1900)."

A spark-gap transmitter uses an electric spark gap to generate radio frequency electromagnetic radiation that can be used as transmitters for wireless communication. Spark gap transmitters were widely used in the irst three decades of radio from 1887–

1916. They were later supplanted by vacuum tube systems and by 1940 were no longer used for communication. The wide use of spark-gap transmitters led to the nickname "sparks" for a ship's radio officer.

Metalworking

Electric sparks are used in different kinds of metalworking. Electric discharge machining (EDM) is sometimes called spark machining and uses a spark discharge to remove material from a workpiece. Electrical discharge machining is used for hard metals or those that are difficult to machine with traditional techniques.

Spark plasma sintering (SPS) is a sintering technique that uses a pulsed direct current that passes through an conductive powder in a graphite die. SPS is faster than conventional hot isostatic pressing, where the heat is provided by external heating elements.

Chemical analysis

The light that is produced by electric sparks can be collected and used for a type of spectroscopy called spark emission spectroscopy.

A high energy pulsed laser can be used to produce an electric spark. Laser induced breakdown spectroscopy (LIBS) is a type of atomic emission spectroscopy that uses a high pulse energy laser to excite atoms in a sample. LIBS has also been called laser spark spectroscopy (LSS).

Electrical treeing
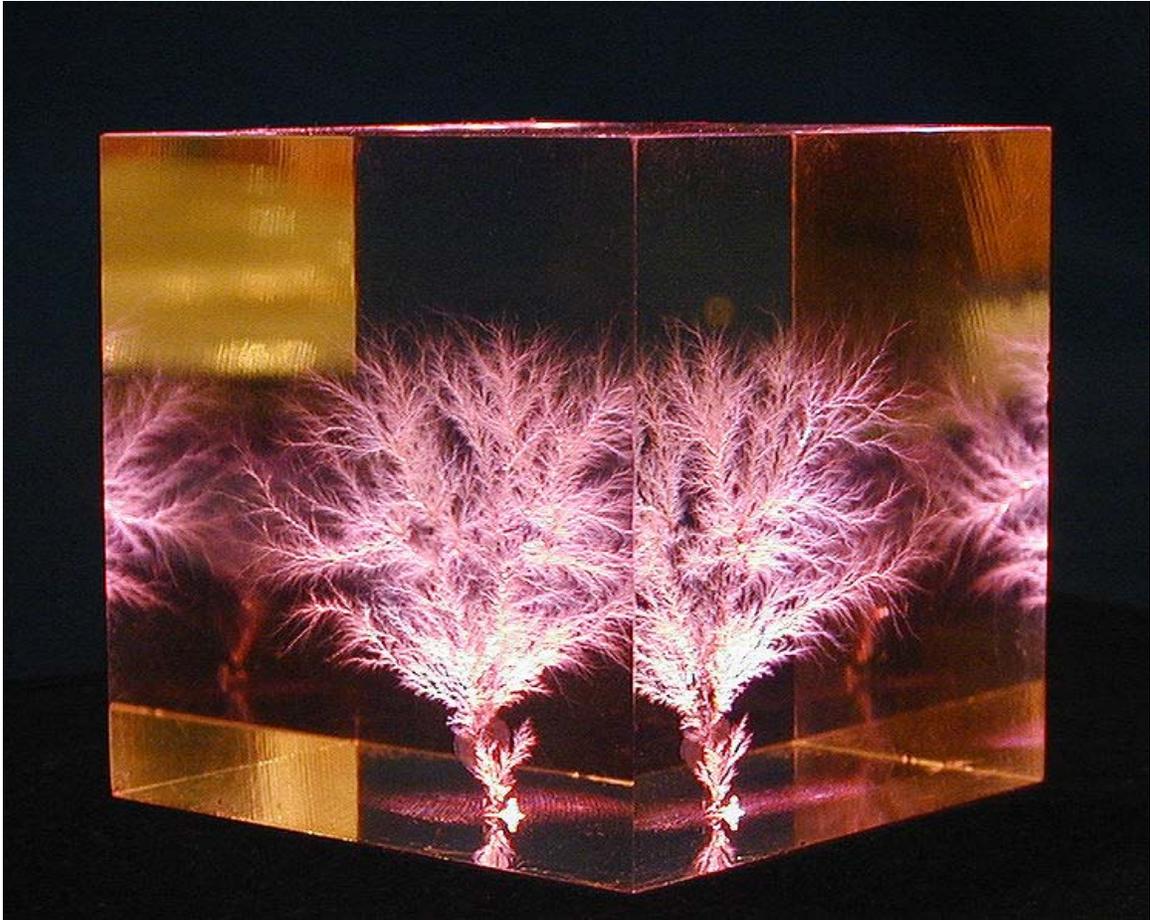
A 3D "Electrical Tree" (or Lichtenberg figure), imbedded within a 1.5" cube of Polymethyl Methacrylate (PMMA)

Within the field of electrical engineering, **treeing** is an electrical pre-breakdown phenomenon. It is a damaging process due to partial discharges and progresses through the stressed dielectric insulation, whose path resembles the form of a tree.

Occurrence and causes

Electrical treeing first occurs and propagates when a dry dielectric material is subjected to high and divergent electrical field stress over a long period of time. Electrical treeing is observed to originate at points where impurities, gas voids, mechanical defects, or conducting projections cause excessive electrical field stress within small regions of the dielectric. This can ionize gases within voids inside the bulk dielectric, creating small electrical discharges between the walls of the void. An impurity or defect may even result

in the partial breakdown of the solid dielectric itself. Ultraviolet light and ozone from these partial discharges (PD) then react with the nearby dielectric, decomposing and further degrading its insulating capability. Gases are often liberated as the dielectric degrades, creating new voids and cracks. These defects further weaken the dielectric strength of the material, enhance the electrical stress, and accelerate the PD process.

Over time, a partially conductive, branching 3D tree-like figure is formed within the dielectric. The tree can grow to the point that it eventually causes complete electrical failure of the dielectric. This has been a long-term failure mechanism for buried polymer-insulated high voltage power cables. In a similar fashion, 2D trees can occur along the surface of a highly stressed dielectric, or across a dielectric surface that has been contaminated by dust or mineral salts. Over time, these partially conductive trails can grow until they cause complete failure of the dielectric. Electrical tracking, sometimes called *dry banding*, is a typical failure mechanism for electrical power insulators that are subjected to salt spray contamination along coastlines. The branching 2D and 3D patterns are sometimes called Lichtenberg figures.

Technical occurrence

2D carbonized electrical trees (or tracking) across the surface of a polycarbonate plate that was part of a trigatron. These partially conducting paths ultimately led to premature breakdown and operational failure of the device

Electrical treeing or "Lichtenberg figures" also occur in high-voltage equipment just before breakdown. Following these Lichtenberg figures in the insulation during postmortem investigation of the broken down insulation can be most useful in finding the cause of breakdown. An experienced High-voltage engineer can see from the direction and the type of trees and their branches where the primary cause of the breakdown was situated and possibly find the cause. Broken-down transformers, High-voltage cables, bushings and other equipment can usefully be investigated in this way; the insulation is unrolled (in the case of paper insulation) or sliced in thin slices (in the case of solid insulations), the results are sketched and photographed and form a useful archive of the breakdown process.

Types of electrical trees

The electrical trees can be further categorized depending on the different tree patterns. They are dendrites, branch type, bush type, spikes, strings, bow-ties and vented trees. The two most commonly found tree types are bow-tie trees and vented trees.

Bow-tie trees
> Bow-tie trees are trees which start to grow from within the dielectric insulation and grow symmetrically outwards from the electrodes. As the trees start within the insulation, they have no free supply of air which will enable continuous support of partial discharges. Thus, these trees have discontinuous growth which is why the vented trees usually do not grow long enough to fully bridge the entire insulation between the electrodes, therefore causing no failure in the insulation.

Vented trees
> Vented trees are trees which initiate at an electrode insulation interface and grow towards the opposite electrode. Having access to free air is a very important factor for the growth of the vented trees. These trees are able to grow continuously until they are long enough to bridge the electrodes, therefore causing failure in the insulation.

Chapter-5

Induction Coil

An **induction coil** or "spark coil" (archaically known as a **Ruhmkorff coil** after Heinrich Ruhmkorff) is a type of disruptive discharge coil. It is a type of electrical transformer used to produce high-voltage pulses from a low-voltage direct current (DC) supply. To create the flux changes necessary to induce voltage in the secondary, the direct current in the primary is repeatedly interrupted by a vibrating mechanical contact called an *interrupter*. Developed beginning in 1836 by Nicholas Callan and others, the induction coil was the first type of transformer.

The term 'induction coil' is also used for a coil carrying high-frequency alternating current (AC), producing eddy currents to heat objects placed in the interior of the coil, in induction heating or zone melting equipment.
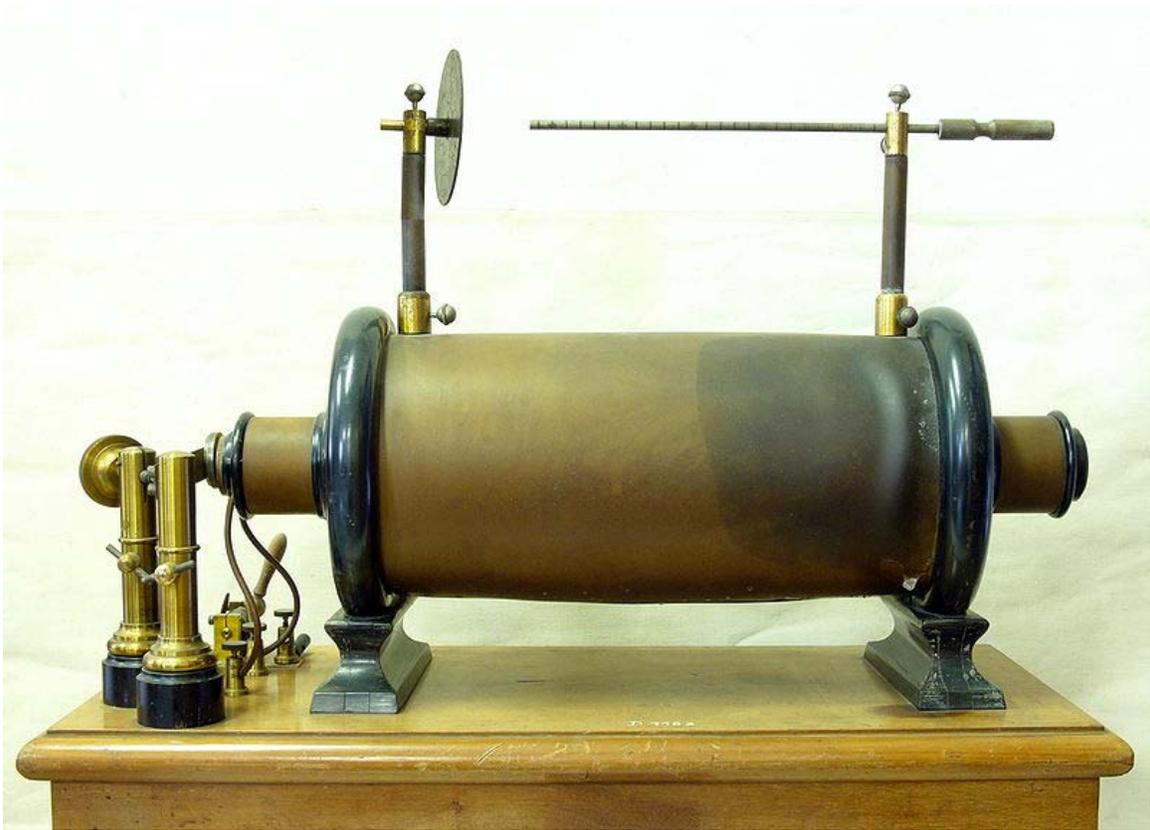
Antique induction coil used in schools, Bremerhaven, Germany

How it works
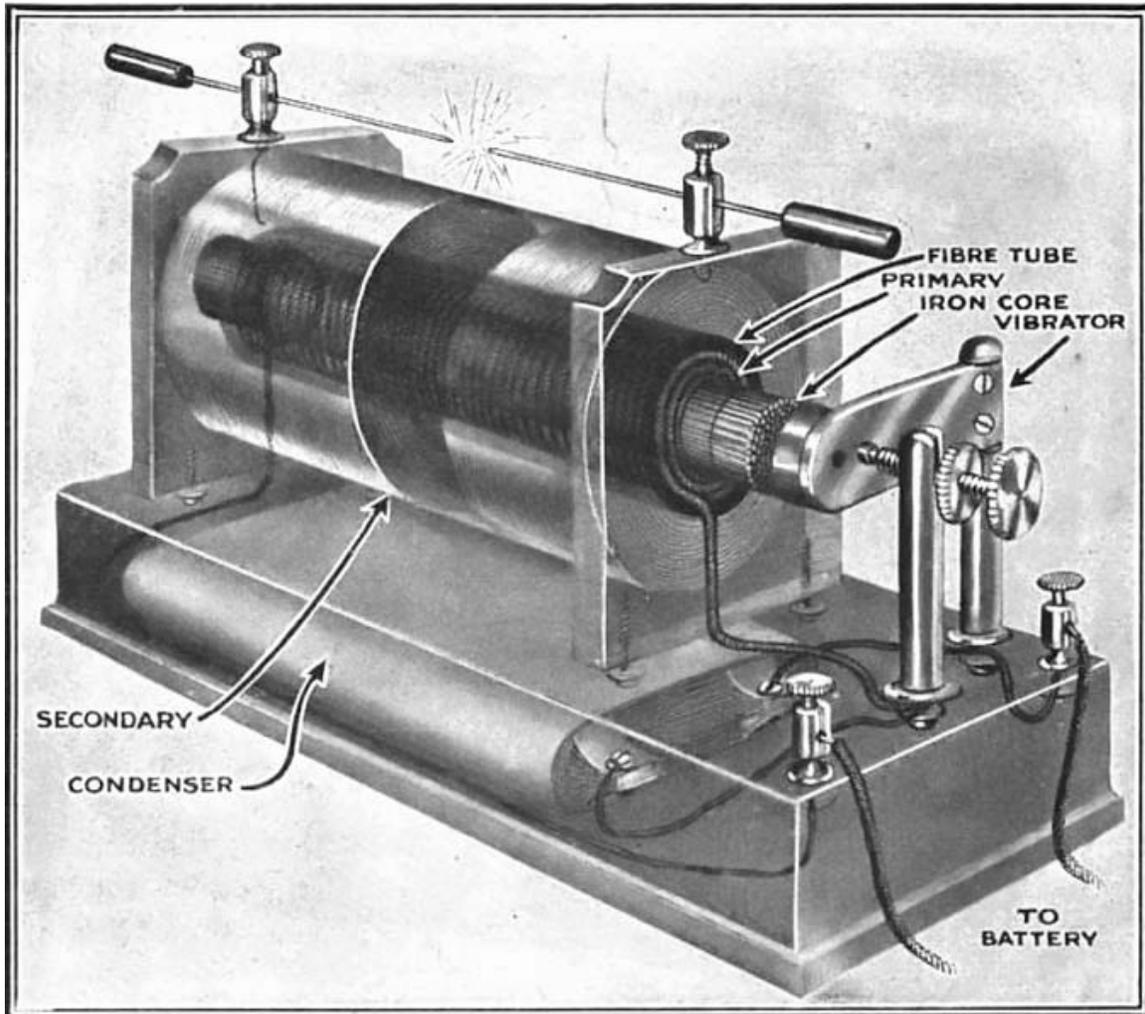
Induction coil showing construction, from 1920.

An induction coil consists of two coils of insulated copper wire wound around a common iron core. One coil, called the *primary winding*, is made from relatively few (tens or hundreds) turns of coarse wire. The other coil, the *secondary winding,* typically consists of many (thousands) turns of fine wire. An electric current is passed through the primary, creating a magnetic field. Because of the common core, most of the primary's magnetic field couples with the secondary winding. The primary behaves as an inductor, storing energy in the associated magnetic field. When the primary current is suddenly interrupted, the magnetic field rapidly collapses. This causes a high voltage pulse to be developed across the secondary terminals through electromagnetic induction. Because of the large number of turns in the secondary coil, the secondary voltage pulse is typically many thousands of volts. This voltage is often sufficient to cause an electric spark, to jump across an air gap separating the secondary's output terminals. For this reason, induction coils were called spark coils.

The size of induction coils was usually specified by the length of spark it could produce; an '8 inch' (20 cm) induction coil was one that could produce an 8 inch arc.

The interrupter

V_2

i_1

Time →

contacts:

open   closed   open   closed   open
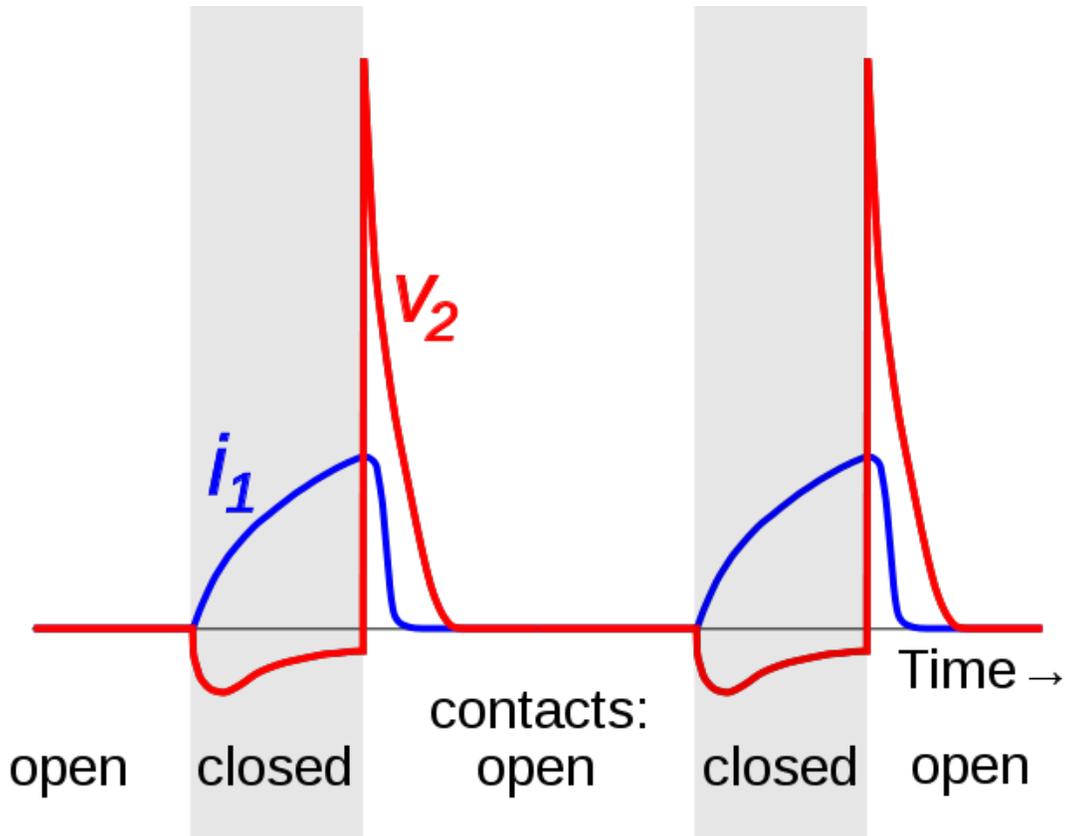
Waveforms in the induction coil, demonstrating how the interrupter works. The blue trace, i_1 is the current in the coil's primary winding. It is broken periodically by the vibrating contact of the interrupter. The changes in current create a changing magnetic flux in the coil which induces a high voltage in the secondary coil v_2 shown in red. Both the "make" and "break" of the current induce pulses of voltage in the secondary, but the current change is much more abrupt on "break", and this generates the high voltage produced by the coil.

To operate the coil continuously, the DC supply current must be broken repeatedly to create the magnetic field changes needed for induction. Induction coils use a magnetically activated vibrating arm called an *interrupter* or *break* to rapidly connect and break the current flowing into the primary coil. The interrupters on small coils were mounted on the end of the coil next to the iron core. The magnetic field created by the current flowing in the primary attracts the interrupter's iron armature attached to a spring, breaking a pair of contacts in the primary circuit. When the magnetic field then collapses, the spring closes the contacts again, and the cycle repeats.

Opposite potentials are induced in the secondary when the interrupter 'breaks' the circuit and 'closes' the circuit. However, the current change in the primary is much more abrupt when the interrupter 'breaks'. When the contacts close, the current builds up slowly in the primary because the supply voltage has a limited ability to force current through the coil's inductance. In contrast, when the interrupter contacts open, the current falls to zero suddenly. So the pulse of voltage induced in the secondary at 'break' is much larger than the pulse induced at 'close', it is the 'break' that generates the coil's high voltage output. A "snubber" capacitor is used across the contacts to quench the arc on the 'break', which causes much faster switching and higher voltages. So the output waveform of an induction coil is a series of alternating positive and negative pulses, but with one polarity much larger than the other.

Construction details

To prevent the high voltages generated in the coil from breaking down the thin insulation and arcing between the secondary wires, the secondary coil uses special construction so as to avoid having wires carrying large voltage differences lying next to each other. The secondary coil is wound in many thin flat pancake-shaped sections (called "pies"), connected in series. The primary coil is first wound on the iron core, and insulated from the secondary with a thick paper or rubber coating. Then each secondary subcoil is coated with an insulating layer like paraffin, connected to the coil next to it, and slid onto the iron core, insulated from adjoining coils with paper disks. The voltage developed in each subcoil isn't large enough to jump between the wires in the subcoil. Large voltages are only developed across many subcoils in series, which are too widely separated to arc over.

To prevent eddy currents, which flow perpendicular to the magnetic axis, and cause energy losses, the iron core is made of a bundle of parallel iron wires, individually coated with shellac to insulate them electrically. The ends of the primary coil often protruded several inches from either end of the secondary coil, to prevent arcs from the secondary to the primary or the core.

Mercury and electrolytic interrupters

Although modern induction coils all use the vibrating arm 'hammer' type interrupter described above, these had some disadvantages when powering the large induction coils used in spark-gap radio transmitters and x-ray machines around 1900. Therefore much research went into improving interrupters, and around the turn of the century improved designs came into use, and the hammer interrupters were only used on small coils Leon Foucault and others developed interrupters consisting of an oscillating needle dipping into and out of a container of mercury. The mercury was covered with a layer of spirits which extinguished the arc quickly, causing faster switching. In large coils these were often driven by a separate electromagnet or motor.

The largest coils used either an electrolytic or a mercury turbine "break". The Wehnelt or electrolytic interrupter consisted of a short platinum needle immersed in an electrolyte of

sulfuric acid, with the other side of the circuit connected to a lead plate electrode. When the primary current passed through it, gas bubbles formed on the needle which repeatedly broke the circuit. This resulted in a primary current broken randomly thousands of times a second, a higher rate than mechanical interrupters could achieve. Since each "break" produced a pulse of voltage from the coil, the more breaks per second the greater the power output. Mercury turbine interrupters had a centrifugal impeller which threw liquid mercury on metal contacts. The result again was a higher rate of "breaking" and higher power output.

History
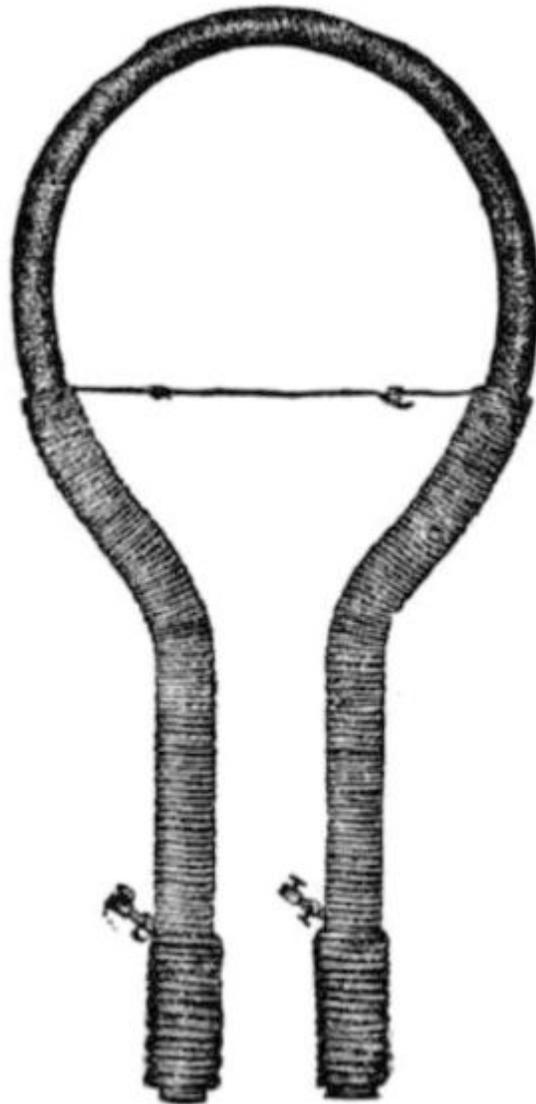
Callan's first induction coil.

Michael Faraday discovered the principle of induction, Faraday's induction law, in 1831 and did the first experiments with induction between coils of wire. The induction coil was invented by the Irish scientist and Catholic priest Nicholas Callan in 1836 at the St. Patrick's College, Maynooth and improved by William Sturgeon and Charles Grafton Page. The early coils had hand cranked interrupters, invented by Callan and Antoine Masson. The automatic 'hammer' interrupter was invented by C. E. Neef, P. Wagner, and J. W. M'Gauley. Hippolyte Fizeau introduced the use of the quenching capacitor. Heinrich Ruhmkorff generated higher voltages by greatly increasing the length of the secondary, in some coils using 5 or 6 miles (10 km) of wire. In the early 1850s, after examining an example of a Ruhmkorff coil, which produced a small spark of around *2 inches* (50 mm) when energized, American inventor Edward Samuel Ritchie perceived that it could be made more efficient and produce a stronger spark by redesigning and improving its secondary insulation. His own design divided the coil into sections, each properly insulated from each other. Ritchie's induction coil proved superior to other designs of the day, initially producing a spark of *10 inches* (25 cm) in length; later versions could produce an electrical bolt *24 inches* (60 cm) or longer in length. The full story of Page's invention of the induction coil in its modern guise is told in Robert Post, "Physics, Patents, and Politics: A Biography of Charles Grafton Page" (Science History Publications, 1976. In 1857, one of Ritchie's induction coils was exhibited in Dublin, Ireland at a conference of the British Association, and later at the University of Edinburgh in Scotland. Ruhmkorff himself purchased a Ritchie induction coil, utilizing its improvements in his own work.
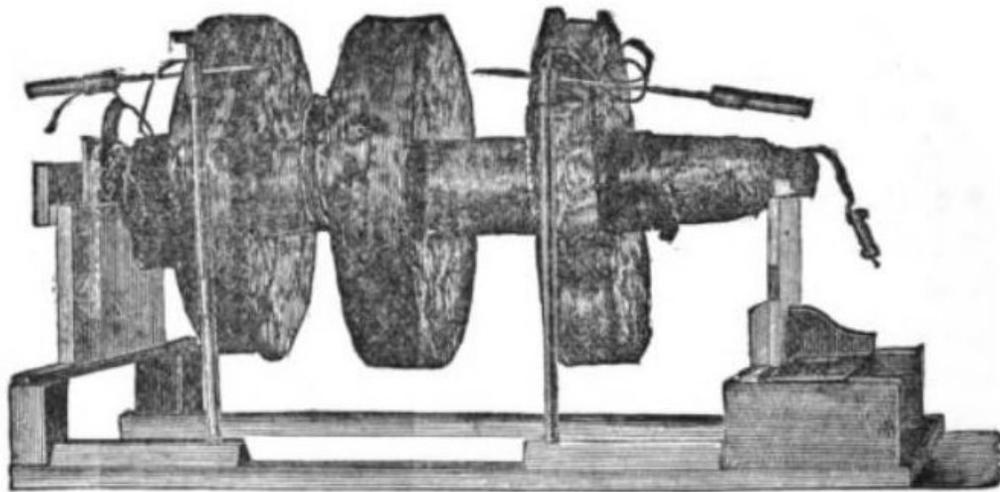
Callan's largest induction coil (Model of 1863), showing 'pancake' secondary construction. It was 42 inches (106 cm) long and could produce 15 inch (38 cm) sparks, corresponding to a potential of approximately 200,000 volts.

Induction coils were used to provide high voltage for early gas discharge and Crookes tubes and other high voltage research. They were also used to provide entertainment

(lighting Geissler tubes, for example) and to drive small "shocking coils", Tesla coils and violet ray devices used in quack medicine. They were used by Hertz to demonstrate the existence of electromagnetic waves, as predicted by James Maxwell and by Lodge and Marconi in the first research into radio waves. Their largest industrial use was probably in early wireless telegraphy spark-gap radio transmitters and to power early cold cathode x-ray tubes from the 1890s to the 1920s, after which they were supplanted in both these applications by AC transformers and vacuum tubes. However their largest use was as the ignition coil or spark coil in the ignition system of internal combustion engines, where they are still used, although the interrupter contacts are now replaced by solid state switches. A smaller version is used to trigger the flash tubes used in cameras and strobe lights.

Automobile ignition coil, the largest remaining use for induction coils

Wireless charging

Toyota's heavy duty division, Hino Motors, is testing a new kind of hybrid electric vehicle without a plug (hybrid outboard chargeable vehicle). The energy in the batteries doesn't come from a plug and a charging point, but it comes from a wireless charging system built into the road. A series of induction coils built into the road resonate energy at certain frequency, like radio waves. The bus is able to capture those waves and store the energy in its batteries.

Chapter-6

# Partial Discharge and Paschen's Law

Partial discharge

In electrical engineering, a **partial discharge** (PD) is a localised dielectric breakdown of a small portion of a solid or fluid electrical insulation system under high voltage stress, which does not bridge the space between two conductors. While a corona discharge is usually revealed by a relatively steady glow or brush discharge in air, partial discharges within solid insulation system are not visible.

PD can occur in a gaseous, liquid or solid insulating medium. It often starts within gas voids, such as voids in solid epoxy insulation or bubbles in transformer oil. Protracted partial discharge can erode solid insulation and eventually lead to breakdown of insulation.

Discharge mechanism

PD usually begins within voids, cracks, or inclusions within a solid dielectric, at conductor-dielectric interfaces within solid or liquid dielectrics, or in bubbles within liquid dielectrics. Since discharges are limited to only a portion of the insulation, the discharges only partially bridge the distance between electrodes. PD can also occur along the boundary between different insulating materials.
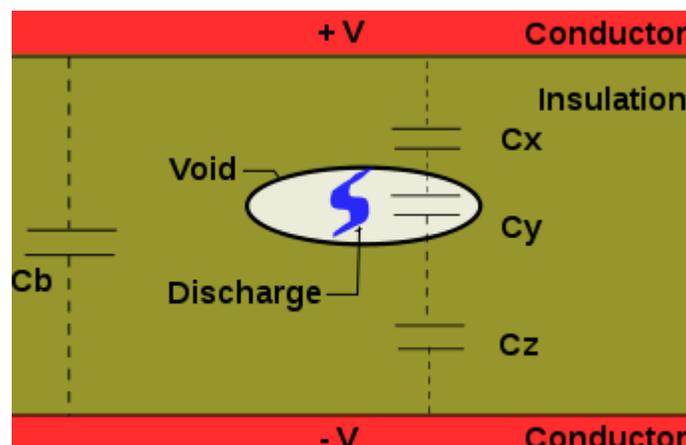
A partial discharge within solid insulation. When a spark jumps the gap within the gas-filled void, a small current flows in the conductors, attenuated by the voltage divider network Cx, Cy, Cz in parallel with the bulk capacitance Cb

Partial discharges within an insulating material are usually initiated within gas-filled voids within the dielectric. Because the dielectric constant of the void is considerably less than the surrounding dielectric, the electric field across the void is significantly higher than across an equivalent distance of dielectric. If the voltage stress across the void is increased above the corona inception voltage (CIV) for the gas within the void, then PD activity will start within the void.

PD can also occur along the surface of solid insulating materials if the surface tangential electric field is high enough to cause a breakdown along the insulator surface. This phenomenon commonly manifests itself on overhead line insulators, particularly on contaminated insulators during days of high humidity. Overhead line insulators use air as their insulation medium.

Partial discharge equivalent circuit

The equivalent circuit of a dielectric incorporating a cavity can be modeled as a capacitive voltage divider in parallel with another capacitor. The upper capacitor of the divider represents the parallel combination of the capacitances in series with the void and the lower capacitor represents the capacitance of the void. The parallel capacitor represents the remaining unvoided capacitance of the sample.

Partial discharge currents

When partial discharge is initiated, high frequency transient current pulses will appear and persist for nano-seconds to a micro-second, then disappear and reappear repeatedly. PD currents are difficult to measure because of their small magnitude and short duration. The event may be detected as a very small change in the current drawn by the sample under test. One method of measuring these currents is to put a small current-measuring resistor in series with the sample and then view the generated voltage on an oscilloscope via a matched coaxial cable.

When PD occurs, electromagnetic waves propagate away from the discharge site in all directions. Detection of the high-frequency pulses can identify the existence and location of partial discharge.

Discharge detection and measuring systems

A number of discharge detection schemes have been invented since the importance of PD was realised early in the last century. Partial discharge currents tend to be of short duration and have rise times in the nanosecond regime. On an oscilloscope, the

discharges look like randomly occurring 'spikes' or pulses. The usual way of quantifying partial discharge magnitude is in picocoulombs.

Calibration setup

The actual charge change that occurs due to a PD event is not directly measurable. *Apparent charge* is used instead. The apparent charge (q) of a PD event is the charge that, if injected between the terminals of the device under test, would change the voltage across the terminals by an amount equivalent to the PD event. This can be modeled by the equation:

$$q = C_b \Delta(V_c)$$

The apparent charge is not equal to the actual amount of changing charge at the PD site, but can be directly measured and calibrated. 'Apparent charge' is usually expressed in picocoulombs.

This is measured by calibrating the voltage of the spikes against the voltages obtained from a calibration unit discharged into the measuring instrument. The calibration unit is quite simple in operation and merely comprises a square wave generator in series with a capacitor connected across the sample. Usually these are triggered optically to enable calibration without entering a dangerous high no voltage area. Calibrators are usually disconnected during the discharge testing.

Laboratory methods

- Wideband PD detection circuits

In wideband detection, the impedance usually comprises a low Q parallel-resonant RLC circuit. This circuit tends to attenuate the exciting voltage (usually between 50 and 60 Hz) and to amplify the voltage generated due to the discharges.

- Tuned (narrow band) detection circuits
- Differential discharge bridge methods
- Acoustic and Ultrasonic methods

Field testing methods

The field testing of plant and equipment in service by the above methods, although it has been done, is not very convenient. Field testing for PD activity emphasizes basic indication of discharge activity over absolute accuracy of measurement. For example, *transient earth voltage* detectors sense the electromagnetic field at gaps in the metal enclosures of switchgear; by use of two or more sensors and measurement of the differences in reception time of an impulse, location of the impulses may be inferred.

## *Effects of partial discharge in insulation systems*

Once begun, PD causes progressive deterioration of insulating materials, ultimately leading to electrical breakdown. The effects of PD within high voltage cables and equipment can be very serious, ultimately leading to complete failure. The cumulative effect of partial discharges within solid dielectrics is the formation of numerous, branching partially conducting discharge channels, a process called treeing. Repetitive discharge events cause irreversible mechanical and chemical deterioration of the insulating material. Damage is caused by the energy dissipated by high energy electrons or ions, ultraviolet light from the discharges, ozone attacking the void walls, and cracking as the chemical breakdown processes liberate gases at high pressure. The chemical transformation of the dielectric also tends to increase the electrical conductivity of the dielectric material surrounding the voids. This increases the electrical stress in the (thus far) unaffected gap region, accelerating the breakdown process. A number of inorganic dielectrics, including glass, porcelain, and mica, are significantly more resistant to PD damage than organic and polymer dielectrics.

In paper-insulated high-voltage cables, partial discharges begin as small pinholes penetrating the paper windings that are adjacent to the electrical conductor or outer sheath. As PD activity progresses, the repetitive discharges eventually cause permanent chemical changes within the affected paper layers and impregnating dielectric fluid. Over time, partially conducting carbonized trees are formed. This places greater stress on the remaining insulation, leading to further growth of the damaged region, resistive heating along the tree, and further charring (sometimes called *tracking*). This eventually culminates in the complete dielectric failure of the cable and, typically, an electrical explosion.

PD dissipate energy, generally in the form of heat, but sometimes in as sound and light as well, like the hissing and dim glowing from the overhead line insulators. Heat energy dissipation may cause thermal degradation of the insulation, although the level is generally low. For high voltage equipment, the integrity of the insulation can be confirmed by monitoring the PD activities that occur through the equipment's life. To ensure supply reliability and long-term operational sustainability, PD in high-voltage electrical equipment should be monitored closely with early warning signals for inspection and maintenance.

PD can be prevented through careful design and material selection. In critical high voltage equipment, the integrity of the insulation is confirmed using PD detection equipment during the manufacturing stage as well as periodically through the equipment's useful life. PD prevention and detection are essential to ensure reliable, long-term operation of high voltage equipment used by electric power utilities.

Paschen's law
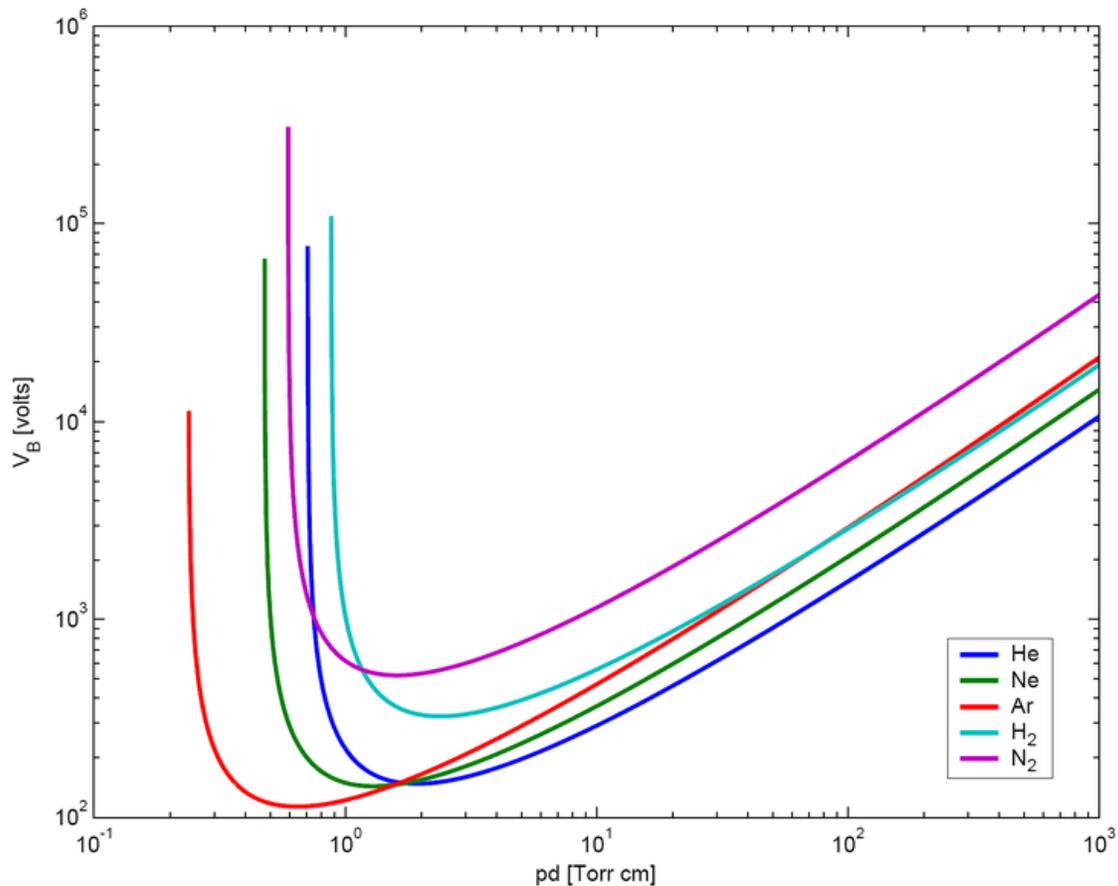
Paschen curves obtained for helium, neon, argon, hydrogen and nitrogen, using the expression for the breakdown voltage as a function of the parameters A,B that interpolate the first Townsend coefficient.

Paschen's Law, named after Friedrich Paschen, was first stated in 1889. He studied the breakdown voltage of parallel plates in a gas as a function of pressure and gap distance. The voltage necessary to arc across the gap decreased up to a point as the pressure was reduced. It then increased, gradually exceeding its original value. He also found that for normal pressure, that the voltage needed to cause an arc reduced with the gap size, but only up to a point. As the gap was reduced further, the required voltage began to rise and again exceeded its original value.

Paschen curve

Early vacuum experimenters found a rather surprising behavior. An arc would sometimes take place in a long irregular path rather than at the minimum distance between the electrodes. For example, at a pressure of 10^{-3} atmospheres, the distance for minimum

breakdown voltage is about 7.5 mm. The voltage required to arc that distance is 327 V and is greater for gaps above and below that point. For a 3.75 mm gap, the required voltage is 533 V, nearly twice as much. If 500 V were applied, it would not be sufficient to arc at the 2.85 mm distance, but would arc at a 7.5 mm distance.

Paschen found that breakdown voltage was described by the equation

$$V = \frac{a(pd)}{\ln(pd) + b}.$$

Where V is the breakdown voltage in volts, p is the pressure, d is the gap distance. The constants a and b depend upon the composition of the gas. For air at standard atmospheric pressure of 101 kPa, $a = 43.6 \times 10^6$ V/(atm·m) and $b = 12.8$, where p is the pressure in atmospheres and d is the gap distance in meters.

The graph of this equation is the Paschen curve. By differentiating it with respect to pd and setting the derivative to zero, the minimum voltage can be found. This yields

$$pd = e^{1-b}$$

and predicts the occurrence of a minimum breakdown voltage for $pd = 7.5 \times 10^{-6}$ m·atm. This is 327 V in air at standard atmospheric pressure at a distance of 7.5 µm. The composition of the gas determines both the minimum arc voltage and the distance at which it occurs. For argon, the minimum arc voltage is 137 V at a larger 12 µm. With sulfur dioxide, the minimum arc voltage is 457 V at only 4.4 µm.

For air at STP, the voltage needed to arc a 1 meter gap is about 3.4 MV. The intensity of the electric field for this gap is therefore 3.4 MV/m. The electric field needed to arc across the minimum voltage gap is much greater than that necessary to arc a gap of one meter. For a 7.5 µm gap the arc voltage is 327 V which is 43 MV/m. This is about 13 times greater than the field strength for the 1 meter gap. The phenomenon is well verified experimentally and is referred to as the Paschen minimum. The equation loses accuracy for gaps under about 10 µm in air at one atmosphere and incorrectly predicts an infinite arc voltage at a gap of about 2.7 micrometers.

Physical mechanism

The mean free path of a molecule in a gas is the average distance between its collision with other molecules. This is inversely proportional to the pressure of the gas. In air the mean free path of molecules is about 96 nm. Since electrons are much smaller, their average distance between colliding with molecules is about 5.64 times longer or about 0.5 µm. This is a substantial fraction of the 7.5 µm spacing between the electrodes for minimum arc voltage. If the electron is in an electric field of 43 MV/m, it will be accelerated and acquire 21.5 electron volts of energy in 0.5 µm of travel in the direction of the field. The first ionization energy needed to dislodge an electron from nitrogen is

about 15 eV. The accelerated electron will acquire more than enough energy to ionize a nitrogen atom. This liberated electron will in turn be accelerated which will lead to another collision. A chain reaction then leads to avalanche breakdown and an arc takes place from the cascade of released electrons.

More collisions will take place in the electron path between the electrodes in a higher pressure gas. When the pressure-gap product pd is high, an electron will collide with many different gas molecules as it travels from the cathode to the anode. Each of the collisions randomizes the electron direction, so the electron is not always being accelerated by the electric field -- sometimes it travels back towards the cathode and is decelerated by the field.

Collisions reduce the electron's energy and make it more difficult for it to ionize a molecule. Energy losses from a greater number of collisions require larger voltages for the electrons to accumulate sufficient energy to ionize many gas molecules. This is required to produce an avalanche breakdown.

On the left side of the Paschen minimum, the *pd* product is small. The electron mean free path can become long compared to the gap between the electrodes. In this case, the electrons might gain lots of energy, but have fewer ionizing collisions. A greater voltage is therefore required to assure ionization of enough gas molecules to start an avalanche.

Practically speaking, the breakdown voltage can be different from the Paschen curve prediction, for example when field emission from the cathode surface becomes important at very small electrode gaps.

Effects with different gases

Different gases will have different mean free paths for molecules and electrons. This is because different molecules have different diameters. Noble gases like helium and argon are monoatomic and tend to have smaller diameters. This gives them a greater mean free path length.

Ionization potentials differ between molecules as well as the speed that they recapture electrons after they have been knocked out of orbit. All three effects change the number of collisions needed to cause an exponential growth in free electrons. These free electrons are necessary to cause an arc.

Lichtenberg Figure and Arc Flash

Lichtenberg figure
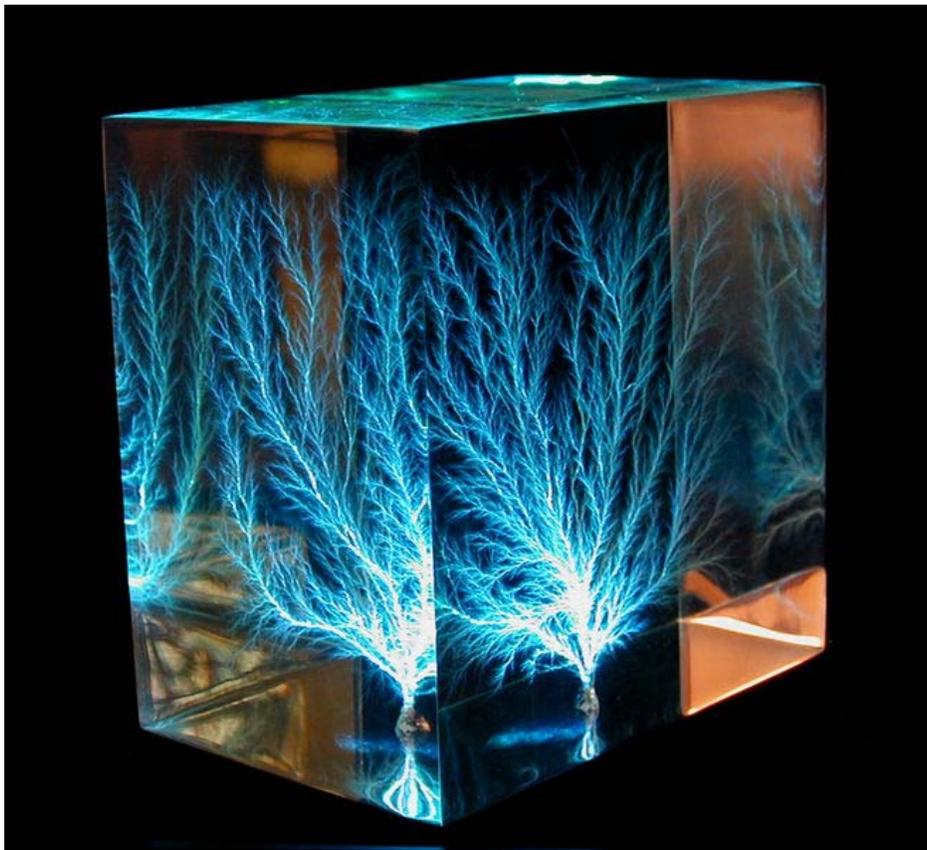
Modern "3D Lichtenberg Figures" or "Electrical treeing" in a block of clear acrylic. The fractal discharge pattern is believed to extend down to the molecular level. Actual size: 3" × 3" × 2" (76 mm × 76 mm × 51 mm)

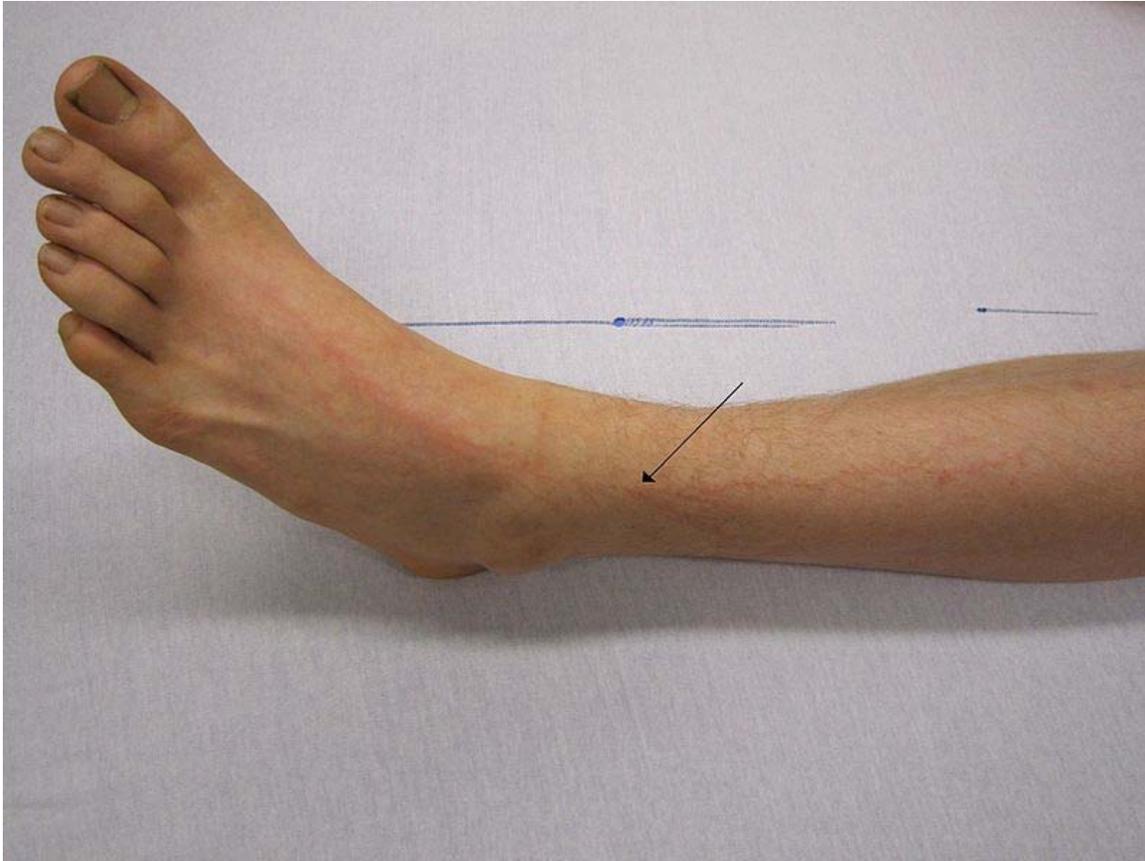A person who was affected by a nearby lightning strike. Note the slight branching redness traveling up his leg from the effects of the current.

Lichtenberg figures (Lichtenberg-Figuren, or "Lichtenberg Dust Figures") are branching electric discharges that sometimes appear on the surface or the interior of insulating materials. They are named after the German physicist Georg Christoph Lichtenberg, who originally discovered and studied them. When they were first discovered, it was thought that their characteristic shapes might help to reveal the nature of positive and negative electric "fluids". In 1777, Lichtenberg built a large electrophorus to generate high voltage static electricity through induction. After discharging a high voltage point to the surface of an insulator, he recorded the resulting radial patterns in fixed dust. By then pressing blank sheets of paper onto these patterns, Lichtenberg was able to transfer and record these images, thereby discovering the basic principle of modern Xerography. This discovery was also the forerunner of modern day plasma physics. Although Lichtenberg only studied 2-dimensional (2D) figures, modern high voltage researchers study 2D and 3D figures (electrical trees) on, and within, insulating materials. Lichtenberg figures are now known to be examples of fractals.

Formation

Two-dimensional (2D) Lichtenberg figures can be produced by placing a sharp-pointed needle perpendicular to the surface of a non-conducting plate, such as of resin, ebonite, or

glass. The point is positioned very near or contacting the plate. A source of high voltage, such as a Leyden jar (a type of capacitor) or a static electricity generator, is applied to the needle, typically through a spark gap. This creates a sudden, small electrical discharge to the surface of the plate. This deposits areas of charge onto the surface of the plate. These electrified areas are then tested by sprinkling a mixture of powdered flowers of sulfur and red lead (Pb_3O_4 or lead tetroxide) onto the plate.

During handling, powdered sulfur tends to acquire a slight negative charge, while red lead tends to acquire a slight positive charge. The negatively electrified sulfur is attracted to the positively electrified areas of the plate, while the positively electrified red lead is attracted to the negatively electrified areas. In addition to the distribution of colors thereby produced, there is also a marked difference in the form of the figure, according to the polarity of the electrical charge that was applied to the plate. If the charge areas were positive, a widely extending patch is seen on the plate, consisting of a dense nucleus, from which branches radiate in all directions. Negatively charged areas are considerably smaller and have a sharp circular or fan-like boundary entirely devoid of branches.

If the plate receives a mixture of positive and negative charges as, for example, from an induction coil, a mixed figure results, consisting of a large red central nucleus, corresponding to the negative charge, surrounded by yellow rays, corresponding to the positive charge. The difference between positive and negative figures seems to depend on the presence of air; for the difference tends to disappear when the experiment is conducted in vacuo. Riess explains it by the negative electrification of the plate caused by the friction of the water vapour, etc., driven along the surface by the explosion which accompanies the disruptive discharge at the point. This electrification would favor the spread of a positive, but hinder that of a negative discharge. Lichtenberg figures are fully described in his memoir *Super nova methodo motum ac naturam fluidi electrici investigandi* (Göttinger Novi Commentarii, Göttingen, 1777). It is now known that charges are transferred to the insulator's surface through small spark discharges that occur along the boundary between the gas and insulator surface. Once transferred to the insulator, these excess charges become temporarily stranded. The shapes of the resulting charge distributions reflect the shape of the spark discharges which, in turn, depend on the HV polarity and pressure of the gas. Using a higher applied voltage will generate larger diameter and more branched figures. It is now known that positive Lichtenberg figures have longer, branching structures because long sparks within air can more easily form and propagate from positively charged high voltage terminals.

Another type of 2D Lichtenberg Figure can be created when an insulating surface becomes contaminated with semiconducting material. When a high voltage is applied across the surface, leakage currents may cause localized heating and progressive degradation and charring of the underlying material. Over time, branching, tree-like carbonized patterns are formed upon the surface of the insulator called electrical trees. These may ultimately bridge the insulating space, leading to catastrophic failure of the insulating material.

Modern 3D Lichtenberg figures

Modern Lichtenberg Figures can also be created within solid insulating materials, such as acrylic (polymethyl methacrylate or PMMA) or glass by injecting them with a beam of high speed electrons from a linear electron beam accelerator (or Linac, a type of particle accelerator). Inside the Linac, electrons are focused and accelerated to form a beam of high speed particles. Electrons emerging from the accelerator have energies up to 25MeV and are moving an appreciable fraction (95 - 99+ percent) of the speed of light (relativistic velocities). If the electron beam is aimed towards an acrylic specimen, the electrons easily penetrate the surface of the acrylic, rapidly slowing down as they collide with molecules inside the plastic, finally coming to rest deep inside the specimen. Since acrylic is an excellent electrical insulator, these electrons become temporarily trapped within the specimen, forming a plane of excess negative charge. Under continued irradiation, the amount of trapped charge builds, until the effective voltage inside the specimen reaches millions of volts. Once the electrical stress exceeds the dielectric strength of the plastic, some portions suddenly become conductive in a process called dielectric breakdown.

During breakdown, branching tree or fern-like conductive channels rapidly form and propagate through the plastic, allowing the trapped charge to suddenly rush out in a miniature lightning-like flash and bang. Breakdown of a charged specimen may also be manually triggered by poking the plastic with a pointed conductive object to create a point of excessive voltage stress. During the discharge, the powerful electric sparks leave thousands of branching chains of fractures behind - creating a permanent Lichtenberg figure inside the specimen. Although the internal charge within the specimen is negative, the discharge is initiated from the positively charged exterior surfaces of the specimen, so that the resulting discharge creates a positive Lichtenberg figure. These beautiful objects are sometimes called **electron trees**, **beam trees**, or **lightning trees**. As the electrons rapidly decelerate inside the acrylic, they also generate powerful X-rays. The X-rays darken the acrylic by introducing defects (color centers) in a process called solarization. Solarization turns acrylic specimens an amber or brownish color, although older acrylic blends sometimes turn a lime green. The color usually fades over time, and gentle heating, combined with oxygen, accelerates the fading process.

Natural occurrences

Lichtenberg figures may also appear on the skin of lightning strike victims. These are reddish, fernlike patterns that may persist for hours or days. They are also a useful indicator for medical examiners when determining the cause of death. Lichtenberg figures appearing on people are sometimes called **lightning flowers**, and they are thought to be caused by the rupture of small capillaries under the skin due to the passage of the lightning current or the shock wave from the lightning discharge as it flashes over the skin. A lightning strike can also create a large Lichtenberg Figure in grass surrounding the point struck. These are sometimes found on golf courses or in grassy meadows. Fulgurites may also be created as sand and soil is fused into glassy tubes by the intense heat of the current.

Electrical treeing often occurs in high-voltage equipment prior to causing complete breakdown. Following these Lichtenberg figures within the insulation during post-mortem investigation of an insulation failure can be useful in finding the cause of breakdown. An experienced high-voltage engineer can see from the direction and the shape of trees and their branches where the primary cause of the breakdown was situated and possibly find the initial cause. Broken-down transformers, high-voltage cables, bushings and other equipment can usefully be investigated in this manner. The insulation is unrolled (in the case of paper insulation) or sliced in thin slices (in the case of solid insulating materials). The results are then sketched or photographed to create a record of the breakdown process.

Fractal similarities

The branching, self-similar patterns observed in Lichtenberg figures exhibit fractal properties. Lichtenberg figures often develop during the dielectric breakdown of solids, liquids, and even gases. Their appearance and growth appear to be related to a process called diffusion-limited aggregation or DLA. A useful macroscopic model that combines an electric field with DLA was developed by Niemeyer, Pietronero, and Weismann in 1984, and is known as the dielectric breakdown model (DBM). Although the electrical breakdown mechanisms of air and PMMA are considerably different, the branching discharges turn out to be related. So, it should not be surprising that the branching forms taken by natural lightning also have fractal characteristics.

Arc flash

An electric arc between two nails

An **arc flash** (or arc blast) is a type of electrical explosion that results from a low impedance connection to ground or another voltage phase in an electrical system.

Definition

An arc flash is an electrical breakdown of the resistance of air resulting in an electric arc which can occur where there is sufficient voltage in an electrical system and a path to ground or lower voltage. An arc flash with 1000 amperes or more can cause substantial damage, fire or injury. The massive energy released in the fault rapidly vaporizes the metal conductors involved, blasting molten metal and expanding plasma outward with extreme force. A typical arc flash incident can be inconsequential but could conceivably

easily produce a more severe explosion. The result of the violent event can cause destruction of equipment involved, fire, and injury not only to the worker but also to nearby people.

In addition to the explosive blast of such a fault, destruction also arises from the intense radiant heat produced by the arc. The metal plasma arc produces tremendous amounts of light energy from far infrared to ultraviolet. Surfaces of nearby people and objects absorb this energy and are instantly heated to vaporizing temperatures. The effects of this can be seen on adjacent walls and equipment - they are often ablated and eroded from the radiant effects.

Examples

In general, arc flash incidents which ignite clothing are highly improbable on systems operating at less than 208 volts phase to phase (120 V to ground) when fed by less than a 125 kVA transformer, as 120 volts does not provide sufficient energy to cause an arc flash hazard. Most 480 V electrical services have sufficient capacity to cause an arc flash hazard. Medium-voltage equipment (above 600 V) is higher energy and therefore a higher potential for an arc flash hazard.

As an example of the energy released in an arc flash incident, consider a single phase-to-phase fault on a 480 V system with 20,000 amps of fault current. The resulting power is 9.6 MW. If the fault lasts for 10 cycles at 60 Hz, the resulting energy would be 1.6 megajoules. For comparison, TNT releases 2175 J/g or more when detonated (a conventional value of 4,184 J/g is used for TNT equivalent). Thus, this fault energy is equivalent to 380 grams (approximately 0.8 pounds) of TNT. The character of an arc flash blast is quite different from a chemical explosion (more heat and light, less mechanical shock), but the resulting devastation is comparable. The rapidly expanding superheated vapor produced by the arc can cause serious injury or damage, and the intense UV, visible, and IR light produced by the arc can temporarily and sometimes even permanently blind or cause eye damage to people.

There are four different arc flash type events to be assessed when designing safety programs:

- Open Air Arc Flashes
- Ejected Arc Flashes
- Equipment Focused Arc Flashes (Arc-in-a-box)
- Tracking Arc Flashes

Protecting personnel

There are many methods of protecting personnel from arc flash hazards. This can include personnel wearing arc flash personal protective equipment (PPE) or modifying the design and configuration of electrical equipment. The best way to remove the hazards of an arc flash is to de-energize electrical equipment when interacting with it, however de-

energizing electrical equipment is in and of itself an arc flash hazard. In this case then one of the newest solutions is to allow the operator to stand far back from the electrical equipment by operating equipment remotely.

Arc flash protection equipment

With recent increased awareness of the dangers of arc flash, there have been many companies that offer arc flash personal protective equipment (PPE). The materials are tested for their arc rating. The arc rating is the maximum incident energy resistance demonstrated by a material prior to breakopen or at the onset of a second-degree skin burn. Arc rating is normally expressed in cal/cm^2 (or small calories of heat energy per square centimeter). The tests for determining arc rating is defined in ASTM F1506 *Standard Performance Specification for Flame Resistant Textile Materials for Wearing Apparel for Use by Electrical Workers Exposed to Momentary Electric Arc and Related Thermal Hazards*.

Selection of appropriate PPE, given a certain task to be performed, is normally handled in one of two possible ways. The first method is to consult a hazard category classification table, like that found in NFPA 70E. Table 130.7(C)(9)(a) lists a number of typical electrical tasks are various voltage levels and recommends the category of PPE that should be worn. For example when working on 600 V switchgear and performing a removal of bolted covers to expose bare, energized parts, the table recommends Category 3 Protective Clothing System. This Category 3 system corresponds to an ensemble of PPE that together offers protection up to 25 cal/cm^2 (105 J/cm^2 or 1.05 MJ/m^2). The minimum rating of PPE necessary for any category is the maximum available energy for that category. For example, a Category 3 arc-flash hazard requires PPE rated for no less than 25 cal/cm^2 (1.05 MJ/m^2).

The second method of selecting PPE is to perform an arc flash hazard calculation to determine the available incident arc energy. IEEE 1584 provides a guide to perform these calculations given that the bolted fault current, duration of faults, and other general equipment information is known. Once the incident energy is calculated the appropriate ensemble of PPE that offers protection greater than the energy available can be selected.

PPE provides protection after an arc flash incident has occurred and should be viewed as the last line of protection. Reducing the frequency and severity of incidents should be the first option and this can be achieved through a complete arc flash hazard assessment and through the application of technology such as high resistance grounding which has been proven to reduce the frequency and severity of incidents.

Reducing hazard by design

Three key factors determine the intensity of an arc flash on personnel. These factors are the quantity of fault current available in a system, the time fault until an arc flash is cleared, and the distance an individual is from an arc. Various design and equipment

configuration choices can be made to affect these factors and in turn reduce the arc flash hazard.

Fault current

Fault current can be limited by using current limiting devices such as grounding resistors or fuses. If the fault current is limited to 5 amperes or less, then many ground faults self-extinguish and do not propagate into phase-to-phase faults.

Arcing time

Arcing time can be reduced by temporarily setting upstream protective devices to lower setpoints during maintenance periods or by employing zone-selective interlocking protection (*ZSIP*).

Arcing time can significantly be reduced by protection based on detection of arc-flash light. Optical detection is often combined with overcurrent information. Light and current based protection can be set up with dedicated arc-flash protective relays or by using normal protective relays equipped with arc-flash option.

The most efficient means to reduce arcing time is to use an arc eliminator that will extinguish the arc within a few milliseconds.

Distance

The distance from an arc flash source within which an unprotected person has a 50% chance of receiving a second degree burn is referred to as the "flash protection boundary". Those conducting flash hazard analyses must consider this boundary, and then must determine what PPE should be worn within the flash protection boundary. Remote operators or robots can be used to perform activities that are high risk for arc flash incidents, such as inserting draw-out circuit breakers on a live electrical bus.

Research

Both the Institute of Electrical and Electronics Engineers (IEEE) and the National Fire Protection Association (NFPA) have joined forces on an initiative to fund and support research and testing to increase the understanding of arc flash. The results of this collaborative project will provide information that will be used to improve electrical safety standards, predict the hazards associated with arcing faults and accompanying arc blasts, and provide practical safeguards for employees in the workplace.

Loss prevention program

An *AFLP - Arc Flash Loss Prevention* program is designed to help businesses and organizations comply with Occupational Safety and Health Administration (OSHA) and

National Fire Protection Association (NFPA) requirements for protecting employees against arc flash injuries.

Chapter-8

Tesla Coil

Tesla coil

Tesla coil at Questacon - the National Science and Technology center in Canberra, Australia

Uses	Application in educational demonstrations, novelty lighting, as well as music
Inventor	Nikola Tesla
Related items	Electrical transformer, electromagnetic field

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 mm²). Into this is slipped a primary consisting of eight to ten turns of AWG No. 6 B & S wire (13.3 mm²) 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
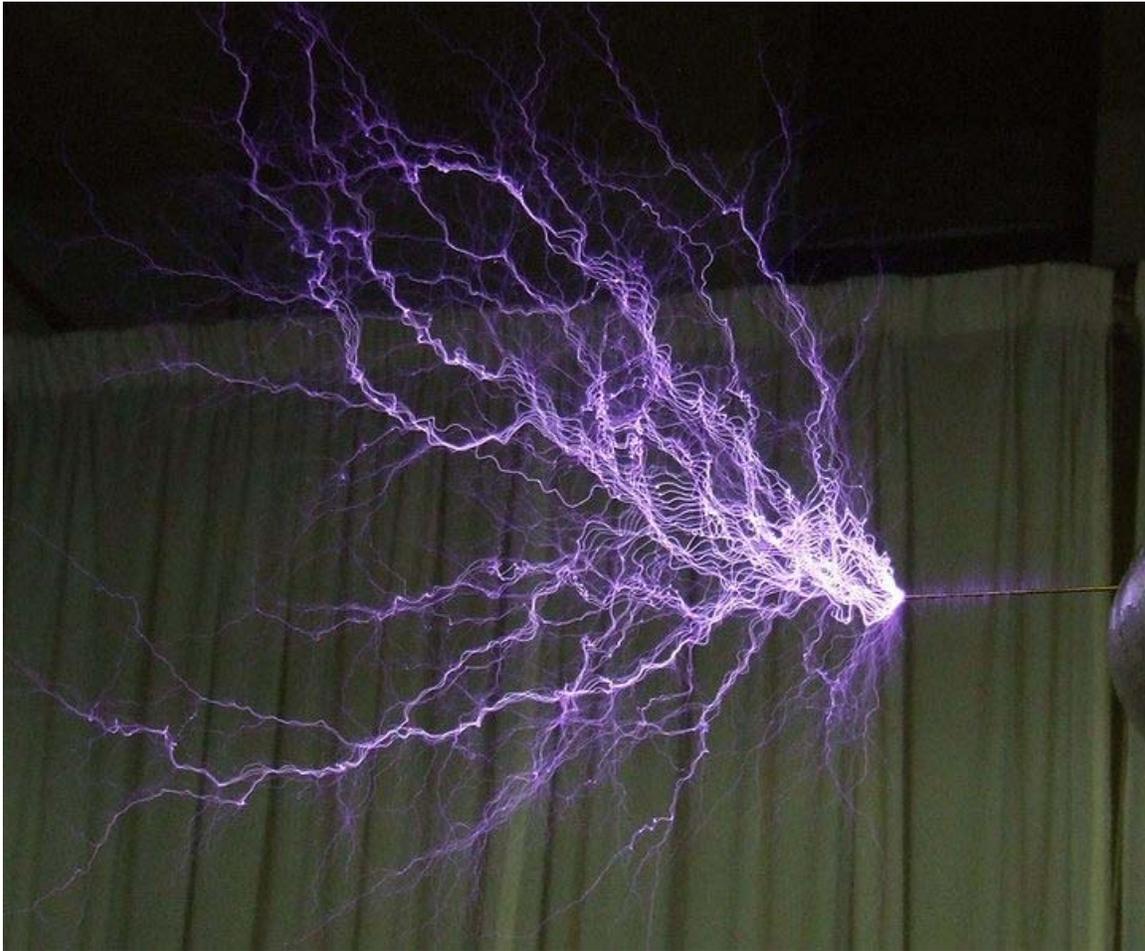
Electric discharge showing the lightning-like plasma filaments from a *Tesla coil*.

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 topload 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 topload.

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.
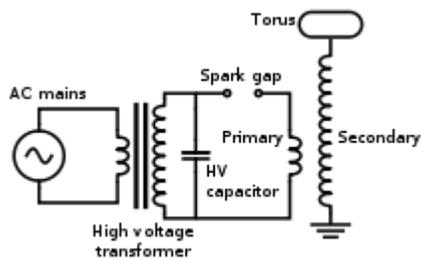
Applications

Transmission
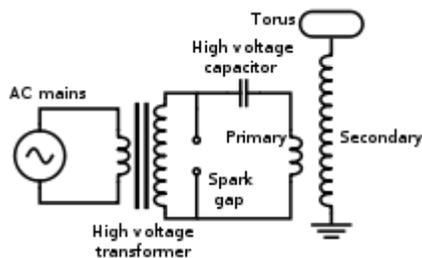
Typical Tesla Coil Schematic

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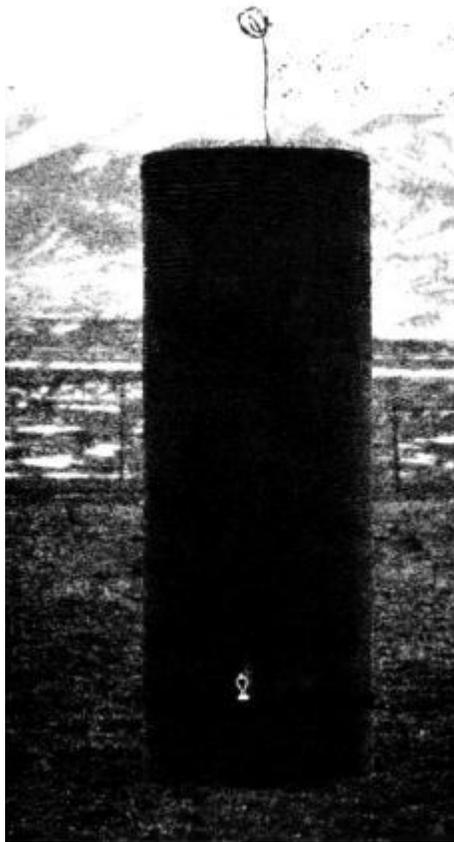
Tesla coil in one experiment of many conducted in Colorado Springs. This is a grounded tuned coil in resonance with a nearby transmitter; Light is glowing near the bottom.

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
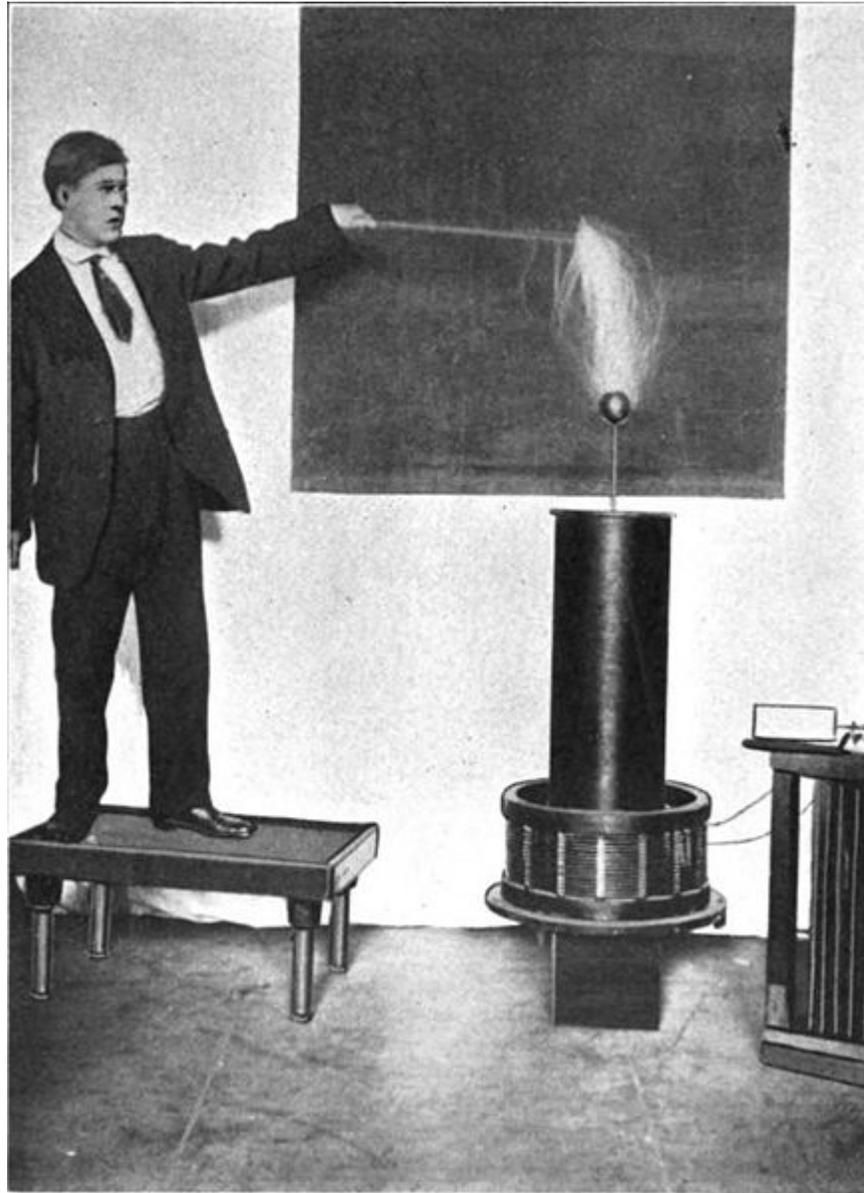
Student conducting Tesla coil streamers through his body, 1909

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
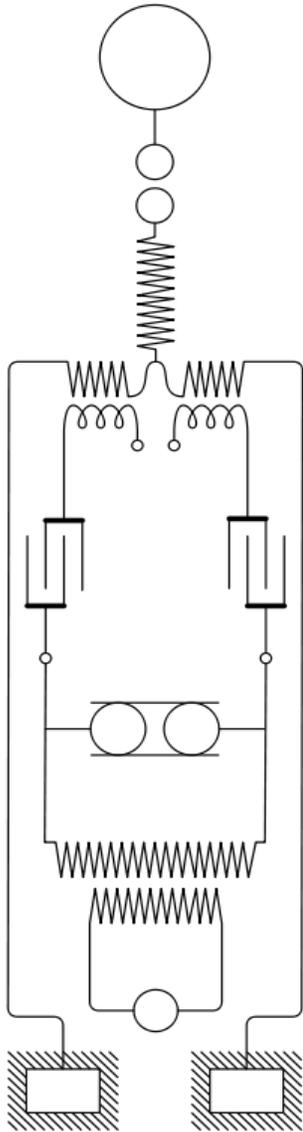
Classically driven configuration.

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-9

Gas-filled Tube

A **gas-filled tube**, also known as a **discharge tube**, is an arrangement of electrodes in a gas within an insulating, temperature-resistant envelope. Although the envelope is typically glass, power tubes often use ceramics, and military tubes often use glass-lined metal. Gas tubes are tubes whose electrical characteristics are substantially influenced by the pressure and composition of gas contained inside.

Gas-filled tubes exploit phenomena related to electric discharge in gases, operating by ionizing the gas with applied voltage to start electrical conduction. Both hot cathode and cold cathode type devices are encountered. Depending on application, either the glow from the gas or the electric arc or electric glow discharge may be the desired function.

Gases in use

Hydrogen

Hydrogen is used in tubes used for very fast switching, e.g. some thyratrons, dekatrons, and krytrons, where very steep edges are required. The build-up and recovery times of hydrogen are much shorter than in other gases. Hydrogen thyratrons are usually hot-cathode. Hydrogen (and deuterium) can be stored in the tube in the form of a metal hydride, heated with an auxiliary filament; releasing hydrogen by heating such storage element can be used to replenish cleaned-up gas, and even to adjust the pressure as needed for a thyratron operation at a given voltage.

Deuterium

Deuterium is used in ultraviolet lamps for ultraviolet spectroscopy, in neutron generator tubes, and in special tubes (e.g. crossatron). It has higher breakdown voltage than hydrogen. In fast switching tubes it is used instead of hydrogen where high voltage operation is required. For a comparison, the hydrogen-filled CX1140 thyratron has anode voltage rating of 25 kV, while the deuterium-filled and otherwise identical CX1159 has

33 kV. Also, at the same voltage the pressure of deuterium can be higher than of hydrogen, allowing higher rise rates of rise of current before it causes excessive anode dissipation. Significantly higher peak powers are achievable. Its recovery time is however about 40% slower than for hydrogen.

Noble gases
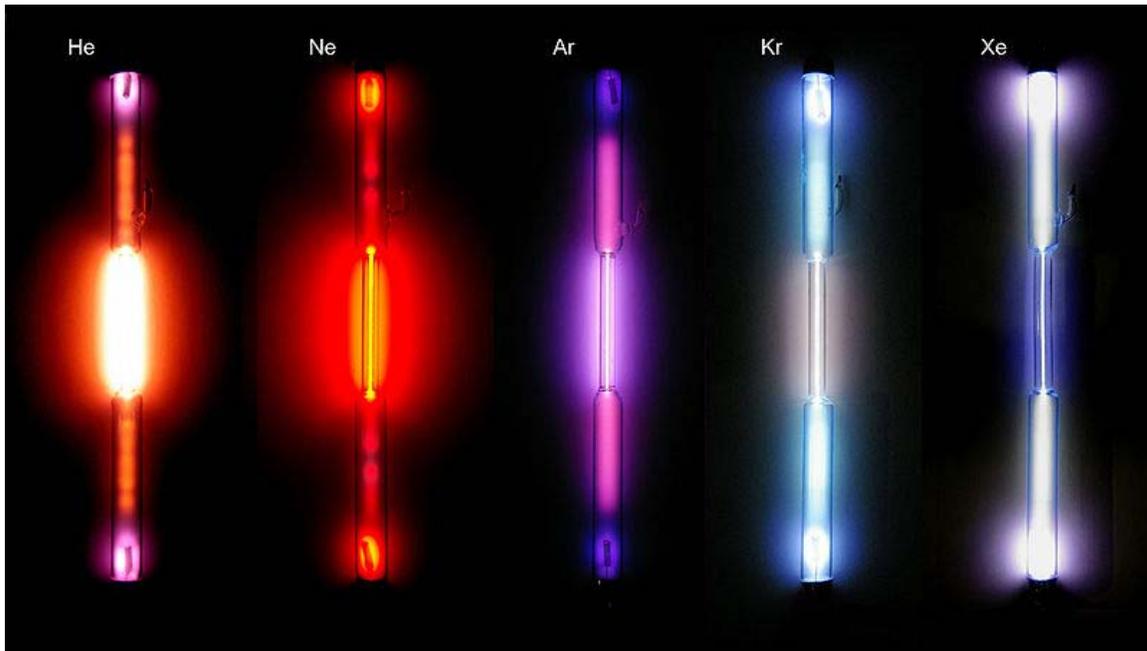
Noble gas discharge tubes; from left to right: helium, neon, argon, krypton, xenon

Noble gases are frequently used in tubes for many purposes, from lighting to switching. Pure noble gases are employed in switching tubes. Noble gas filled thyratrons have better electrical parameters than mercury-based ones. The electrodes undergo damage by high-velocity ions. The neutral atoms of the gas slow the ions down by collisions, and reduce the energy transferred to the electrodes by the ion impact. Gases with high molecular weight, e.g. xenon, protect the electrodes better than lighter ones, e.g. neon.

- Helium is used in helium-neon lasers and in some thyratrons rated for high currents and high voltages. Helium provides about as short deionization time as hydrogen, but can withstand lower voltage, so it is used much less often.
- Neon has low ignition voltage and is frequently used in low-voltage tubes. Discharge in neon emits relatively bright red light; neon-filled switching tubes therefore also act as indicators, shining red when switched on. This is exploited in the decatron tubes, which act as both counters and displays. Its red light is exploited in neon signage. Used in fluorescent tubes with high power and short length, e.g. industrial lighting tubes. Has higher voltage drop in comparison with argon and krypton. Its low atomic mass provides only a little protection to the electrodes against accelerated ions; additional screening wires or plates can be

used for prolonging the anode lifetime. In fluorescent tubes it is used in combination with mercury.

- Argon was the first gas used in fluorescent tubes and is still frequently used due to its low cost, high efficiency, and very low striking voltage. In fluorescent tubes it is used in combination with mercury. It was also used in early rectifier tubes; first thyratrons were derived from such argon-filled tubes.
- Krypton can be used in fluorescent lamps instead of argon; in that application it reduces the total energy losses on electrodes from about 15% to 7%. The voltage drop per lamp length is however lower than with argon, which can be compensated by smaller tube diameter. Krypton-filled lamps also require higher starting voltage; this can be alleviated by using e.g. 25%-75% argon-krypton mixture. In fluorescent tubes it is used in combination with mercury.
- Xenon in pure state has high breakdown voltage, making it useful in higher-voltage switching tubes. Xenon is also used as a component of gas mixtures when production of ultraviolet radiation is required, e.g. in plasma displays, usually to excite a phosphor. The wavelength produced is longer than with argon and krypton and penetrates the phosphors better. To lower the ionization voltage, neon-xenon or helium-xenon are used; above 350 torr, helium has lower breakdown voltage than neon and vice versa. At concentrations of 1% and less of xenon, the Penning effect becomes significant in such mixtures, as most of xenon ionization occurs by collision with excited atoms of the other noble gas; at more than few percents of xenon, the discharge ionizes xenon directly due to most energy of the electrons being spent on direct ionization of xenon.
- Penning mixtures are used where lower ionization voltage is required, e.g., in the neon lamps, Geiger-Muller tubes and other gas-filled particle detectors. A classical combination is about 98–99.5% of neon with 0.5–2% of argon, used in, e.g., neon bulbs and in monochrome plasma displays.

Elemental vapors (metals and nonmetals)

- Mercury vapors are used for applications with high current, e.g. lights, mercury arc valves, ignitrons. Mercury is used because of its high vapor pressure and low ionization potential. Mercury mixed with an inert gas is used where the energy losses in the tube have to be low and the tube lifetime should be long. In mercury-inert gas mixtures, the discharge is initially carried primarily by the inert gas; the released heat then serves to evaporate enough mercury to reach the desired vapor pressure. Low-voltage (hundreds volts) rectifiers use saturated mercury vapor in combination with a small amount of inert gas, allowing cold start of the tubes. High-voltage (kilovolts and more) rectifiers use pure mercury vapor at low pressure, requiring maintenance of maximum temperature of the tube. The liquid mercury serves as a reservoir of mercury, replenishing the vapors that are used up during the discharge. Unsaturated mercury vapor can be used, but as it can not be replenished, the lifetime of such tubes is lower. The strong dependence of vapor pressure on mercury temperature limits the environments the mercury-based tubes can operate in. In low-pressure mercury lamps, there is an optimum mercury pressure for the highest efficiency. Photons emitted by ionized mercury atoms can

be absorbed by nearby nonionized atoms and either reradiated or the atom is deexcited nonradiatively, too high mercury pressure therefore causes losses of light. Too low mercury pressure leads to too few atoms present to get ionized and radiate photons. The optimum temperature for low-pressure mercury lamps is at about 42 °C, when the saturated vapor pressure of mercury (present as a drop of about 1 mg of liquid mercury in the tube, as a reservoir compensating for losses by clean-up) reaches this optimum. In lamps intended for operation at higher ambient temperatures, and at a wider temperature range, mercury is present in the form of an amalgam with e.g. bismuth and indium; the vapor pressure above amalgam is lower than above liquid mercury. Mercury is used in fluorescent tubes as a source of visible and ultraviolet light for exciting the phosphor; in that application it is usually used together with argon, or in some cases with krypton or neon. Mercury ions deionize slowly, limiting the switching speed of mercury-filled thyratrons. Ion bombardment with mercury ions of even relatively low energies also gradually destroys oxide-coated cathodes.
- Sodium vapors are used in sodium-vapor lamps.
- Sulfur vapors are used in sulfur lamps.
- Vapors of many metals, alone or together with a noble gas, are used in many lasers.

Other gases
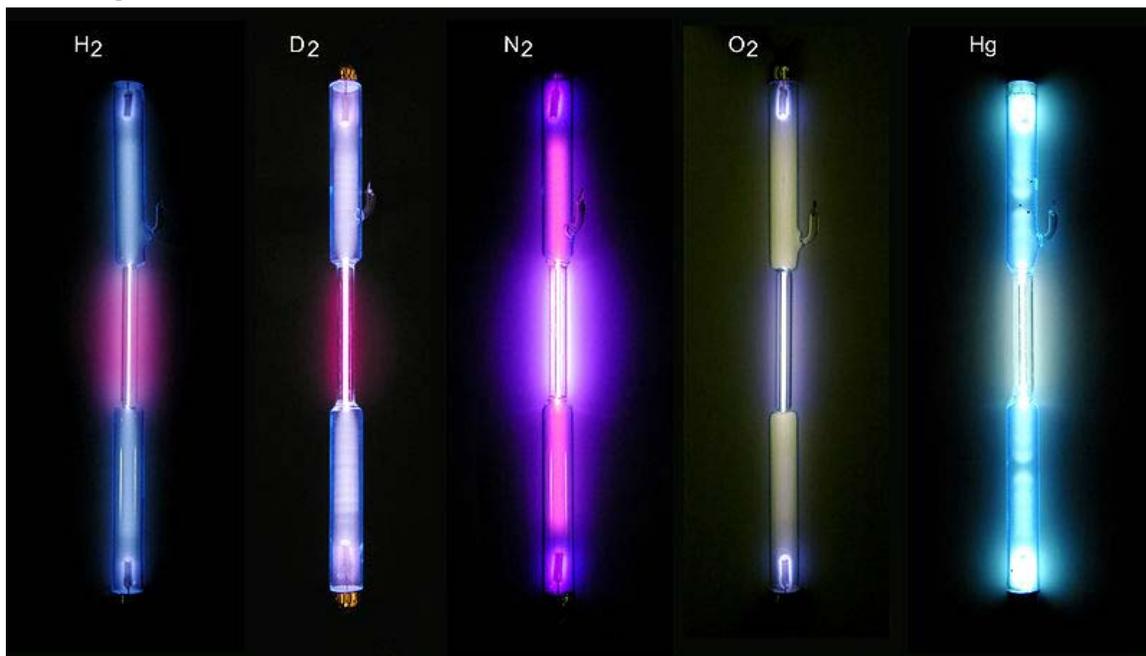
Other gases in discharge tubes; from left to right: hydrogen, deuterium, nitrogen, oxygen, mercury

- Air can be used in some low-demanding applications.
- Nitrogen at relatively high pressure tends to be used in surge arresters, due to its short build-up time, giving the tubes fast response time to voltage surges.

- Halogens and alcohol vapors absorb ultraviolet radiation and have high electron affinity. When added to inert gases, they quench the discharge; this is exploited in e.g. Geiger-Muller tubes.

Insulating gases

In special cases (e.g., high voltage switches), gases with good dielectric properties and very high breakdown voltages are needed. Highly electronegative elements, e.g., halogens, are favored as they rapidly recombine with the ions present in the discharge channel. One of the most popular choices is sulfur hexafluoride, used in special high-voltage applications. Other common options are dry pressurized nitrogen and halocarbons.

Gas-tube physics and technology

The gas pressure may range between 0.001 and 1000 torr; most commonly, pressures between 1-10 torr are used. The gas pressure influences the following factors:

- breakdown voltage (also called ignition voltage)
- current density
- operating voltage
- backfire voltage
- tube lifetime (lower pressure tubes tend to have shorter lifetimes due to using up of the gas)
- cathode sputtering, reduced at higher pressures

Above a certain value, the higher the gas pressure, the higher the ignition voltage. High-pressure lighting tubes can require a few kilovolts impulse for ignition when cold, when the gas pressure is low. After warming up, when the volatile compound used for light emission is vaporized and the pressure increases, reignition of the discharge requires either significantly higher voltage or reducing the internal pressure by cooling down the lamp. For example, many sodium vapor lamps cannot be re-lit immediately after being shut off; they must cool down before they can be lit up again.

The gas tends to be used up during the tube operation, by several phenomena collectively called **clean-up**. The gas atoms or molecules are adsorbed on the surfaces of the electrodes. In high voltage tubes, the accelerated ions can penetrate into the electrode materials. New surfaces, formed by sputtering of the electrodes and deposited on e.g. the inner surfaces of the tube, also readily adsorb gases. Non-inert gases can also chemically react with the tube components. Hydrogen may diffuse through some metals.

For removal of gas in vacuum tubes, getters are used. For resupplying gas for gas-filled tubes, **replenishers** are employed. Most commonly, replenishers are used with hydrogen; a filament made from a hydrogen-absorbing metal (e.g. zirconium or titanium) is present in the tube, and by controlling its temperature the ratio of absorbed and desorbed hydrogen is adjusted, resulting in controlling of the hydrogen pressure in the tube. The

metal filament acts as a hydrogen storage. This approach is used in e.g. hydrogen thyratrons or neutron tubes. Usage of saturated mercury vapor allows using a pool of liquid mercury as a large storage of material; the atoms lost by clean-up are automatically replenished by evaporation of more mercury. The pressure in the tube is however strongly dependent on the mercury temperature, which has to be controlled carefully.

The gas used dramatically influences the parameters of the tube. The breakdown voltage depends on the gas composition and electrode distance; the dependencies are described by Paschen's law.

Pure inert gases are used where the difference between the ignition voltage and the burning voltage has to be high, e.g. in switching tubes. Tubes for indication and stabilization, where the difference has to be lower, tend to be filled with Penning mixtures; the lower difference between ignition and burning voltages allows using lower power supply voltages and smaller series resistances.

Large rectifiers use saturated mercury vapor with a small amount of an inert gas. The inert gas supports the discharge when the tube is cold.

The mercury arc valve current-voltage characteristics are highly dependent on the temperature of the liquid mercury. The voltage drop in forward bias decreases from about 60 volts at 0 °C to somewhat above 10 volts at 50 °C and then stays constant; the reverse bias breakdown ("arc-back") voltage drops dramatically with temperature, from 36 kV at 60 °C to 12 kV at 80 °C to even less at higher temperatures. The operating range is therefore usually between 18–65 °C.

The gas in the tube has to be kept pure to maintain the desired properties; even small amount of impurities can dramatically change the tube values; presence of non-inert gases generally increases the breakdown and burning voltages. The presence of impurities can be observed by changes in the glow color of the gas. Air leaking into the tube makes the discharge look pale, milky, or reddish. Traces of mercury vapors glow bluish, obscuring the original gas color. Magnesium vapor colors the discharge green. To prevent outgassing of the tube components during operation, a bake-out is required before filling with gas and sealing. Thorough degassing is required for high-quality tubes; even as little as 10^{-8} torr of oxygen is sufficient for covering the electrodes with monomolecular oxide layer in few hours. Non-inert gases can be removed by suitable getters. for mercury-containing tubes, getters that do not form amalgams with mercury (e.g. zirconium, but not barium) have to be used. Cathode sputtering may be used intentionally for gettering non-inert gases; some reference tubes use molybdenum cathodes for this purpose.

Lighting and display gas-filled tubes

Fluorescent lighting, CFL lamps, mercury and sodium discharge lamps and HID lamps are all gas-filled tubes used for lighting.

Neon lamps and neon signage (most of which is not neon based these days) are also low-pressure gas-filled tubes.

Specialized historic low-pressure gas-filled tube devices include the Nixie tube (used to display numerals) and the Decatron (used to count or divide pulses, with display as a secondary function).

Xenon flash lamps are gas-filled tubes used in cameras and strobe lights to produce bright flashes of light.

The recently developed sulfur lamps are also gas-filled tubes when hot.

Gas-filled tubes in electronics

Some important examples include the thyratron, krytron, and ignitron tubes, which are used to switch high-voltage currents. A specialized type of gas-filled tube called a Gas Discharge Tube (GDT) is fabricated for use in surge protectors, to limit voltage surges in electrical and electronic circuits.

List of -tron tubes

- Mercury pool tubes
    - Excitron, a mercury pool tube
    - Gusetron or gausitron, a mercury arc pool tube
    - Ignitron, a mercury pool tube
    - Sendytron, a mercury pool tube
- Trignitron, a trade name for a mercury pool tube used in electric welders
- Capacitron, a mercury pool tube
- Corotron, a trade name for a gas-filled shunt regulator, usually contains small quantities of radioactive materials to set the regulated voltage
- Crossatron, a modulator tube
- Kathetron or cathetron, a hot cathode gas filled triode with grid outside of the tube
- Neotron, a pulse generator
- Permatron, a hot cathode rectifier with anode current controlled by magnetic field
- Phanotron, a rectifier
- Plomatron, a grid-controlled mercury-arc rectifier
- Pulsatron, a gas-filled triode with two cathodes
- Strobotron, a cold cathode tube designed for high current narrow pulses, used in high-speed photography
- Takktron, a cold cathode rectifier for low currents at high voltages
- Thyratron, a hot cathode switching tube
- Trigatron, a high-current switch similar to a spark gap
- Alphatron, a form of ionization tube for measuring vacuum
- Dekatron, a counting tube
- Plasmatron, a hot cathode tube with controlled anode current
- Tacitron, a low-noise thyratron with interruptible current flow

- Krytron, a fast cold-cathode switching tube

Chapter-10

Townsend Discharge and Electric Discharge in Gases

Townsend discharge
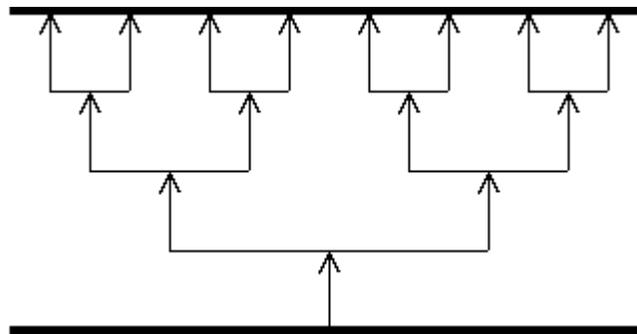
Avalanche effect between two electrodes

The **Townsend discharge** is a gas ionization process where an initially very small amount of free electrons, accelerated by a sufficiently strong electric field, give rise to electrical conduction through a gas by avalanche multiplication: when the number of free charges drops or the electric field weakens, the phenomena ceases. It is a process characterized by very low current densities: in common gas filled tubes, typical magnitude of currents flowing during this process range from about $10^{-18}A$ to about $10^{-5}A$, while applied voltages are *almost constant*. Subsequent transition to ionisation processes of dark discharge, glow discharge, and finally to arc discharge are driven by increasing current densities: in all these discharge regimes, the basic mechanism of conduction is avalanche breakdown. Townsend discharge is named after John Sealy Townsend, and is also commonly known by practitioners as a "Townsend avalanche".

Quantitative description of the phenomenon

The basic setup of the experiments investigating ionization discharges in gases consist of a planar parallel plate capacitor filled with a gas and a continuous current high voltage source connected between its terminals: the terminal at the lower voltage potential is named cathode while the other is named anode. Forcing the cathode to emit electrons (eg. by irradiating it with a X-ray source), Townsend found that the current *I* flowing into the capacitor depends on the electric field between the plates in such a way that gas ions seems to multiply as they moved between them. He observed currents varying over ten or more orders of magnitude while the applied voltage was virtually constant. The experimental data obtained from his experiments are described by the following formula

$$\frac{I}{I_0} = e^{\alpha_n d},$$

where

- *I* is the current flowing in the device,
- I_0 is the photoelectric current generated at the cathode surface,
- *e* is the Euler number
- α_n is the *first Townsend ionisation coefficient*, expressing the number of ion pairs generated per unit length (e.g. meter) by a negative ion (anion) moving from cathode to anode,
- *d* is the distance between the plates of the device.

The almost constant voltage between the plates is equal to the breakdown voltage needed to create a self-sustaining avalanche: it *decreases* when the current reaches the glow discharge regime. Subsequent experiments revealed that the current *I* rises faster than predicted by the above formula as the distance *d* increases: two different effects were considered in order to explain the physics of the phenomenon and to be able to do a precise quantitative calculation.

Gas ionisation caused by motion of positive ions

Townsend put forward the hypothesis that positive ions also produce ion pairs, introducing a coefficient α_p expressing the number of ion pairs generated per unit length by a positive ion (cation) moving from anode to cathode. The following formula was found

$$\frac{I}{I_0} = \frac{(\alpha_n - \alpha_p)e^{(\alpha_n - \alpha_p)d}}{\alpha_n - \alpha_p e^{(\alpha_n - \alpha_p)d}} \qquad \Longrightarrow \qquad \frac{I}{I_0} \simeq \frac{e^{\alpha_n d}}{1 - \alpha_p/\alpha_n e^{\alpha_n d}}$$

since $\alpha_p << \alpha_n$, in very good agreement with experiments.

The *first Townsend coefficient* (α), also known as *first Townsend avalanche coefficient* is a term used where secondary ionization occurs because the primary ionization electrons gain sufficient energy from the accelerating electric field, or from the original ionizing particle. The coefficient gives the number of secondary electrons produced by primary electron per unit path length.

Cathode emission caused by impact of ions

Townsend, Holst and Oosterhuis also put forward an alternative hypothesis, considering augmented emission of electrons by cathode caused by positive ions impact, introducing *Townsends second ionization coefficient* ε_i, the average number of electrons released from a surface by an incident positive ion, and working out the following formula:

$$\frac{I}{I_0} = \frac{e^{\alpha_n d}}{1 - \epsilon_i \left(e^{\alpha_n d} - 1\right)}.$$

These two formulas may be thought as describing limiting cases of the effective behavior of the process: note that they can be used to well describe the same experimental results. Other formulas describing, various intermediate behaviors, are found in the literature, particularly in reference 1 and citations therein.

Avalanche

A *Townsend avalanche* is a cascade reaction involving electrons in a region with a sufficiently high electric field. This reaction must also occur in a medium that can be ionized, such as air. The positive ion drifts towards the cathode, while the free electron drifts towards the anode of the particular device. It accelerates in the electric field, gaining sufficient energy such that it frees another electron upon collision with another atom/molecule of the medium. The two free electrons then travel together some distance before another collision occurs. The number of electrons travelling towards the anode is multiplied by a factor of two for each collision, so that after n collisions, there are 2^n free electrons.

Conditions

A Townsend discharge can be sustained over a limited range of gas pressure and electric field intensity. At higher pressures, discharges occur more rapidly than the calculated time for ions to traverse the gap between electrodes, and the streamer theory of spark discharge is applicable. In highly non-uniform electric fields, the corona discharge process is applicable. Discharges in vacuum require vaporization and ionization of electrode atoms. An arc can be initiated without a preliminary Townsend discharge; for example when electrodes touch and are then separated.

Applications

- Avalanche multiplication during Townsend discharge is naturally used in gas phototubes, to amplify the photoelectric charge generated by incident radiation (visible light or not) on the cathode: achievable current is typically 10~20 times greater respect to that generated by vacuum phototubes.
- The starting of Townsend discharge sets the upper limit to the blocking voltage a glow discharge gas filled tube can withstand : this limit is the Townsend discharge breakdown voltage also called **ignition voltage** of the tube.
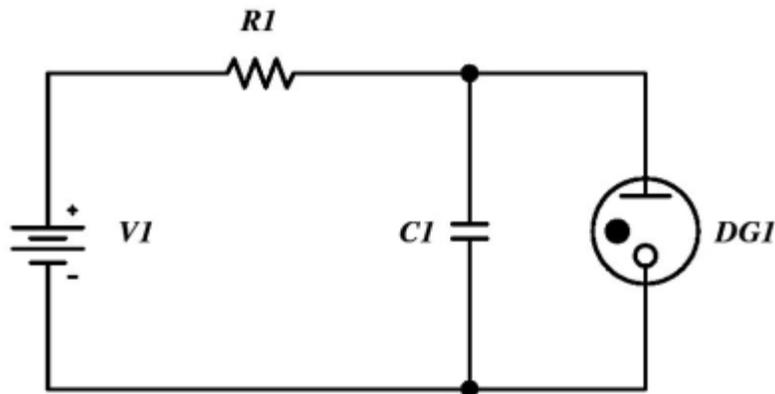
Neon lamp/cold-cathode gas diode relaxation oscillator

- The presence of Townsend discharge and glow discharge breakdown voltages shapes the $V_A - I_A$ characteristic of any gas diode or neon lamp in a way such that it has a negative differential resistance region of the S-type. This occurrence is typically used to generate electrical oscillations and waveforms, as in the relaxation oscillator whose schematic is shown in the picture on the right. The sawtooth shaped oscillation generated has frequency

$$f \cong \frac{1}{R_1 C_1 \ln \frac{V_1 - V_{\text{GLOW}}}{V_1 - V_{\text{TWN}}}},$$

where

- V_{GLOW} is the glow discharge breakdown voltage,
- V_{TWN} is the Townsend discharge breakdown voltage,
- C_1, R_1 and V_1 are respectively the capacitance, the resistance and the supply voltage of the circuit.

Since temperature and time stability of the characteristics of gas diodes and neon lamps is low, and also the statistical dispersion of breakdown voltages is high, the above formula can only give a qualitative indication of what the real frequency of oscillation is.

- Townsend avalanche discharges are exploited in devices such as Geiger counters and Proportional counters to detect and measure the energy of an ionizing radiation. Incoming radiation ionizes one of the atoms or molecules in the medium. When the electrons reach the anode, a current is induced, which is amplified further with electronics. This detects and measures some of the characteristics of the incident ionizing radiation.
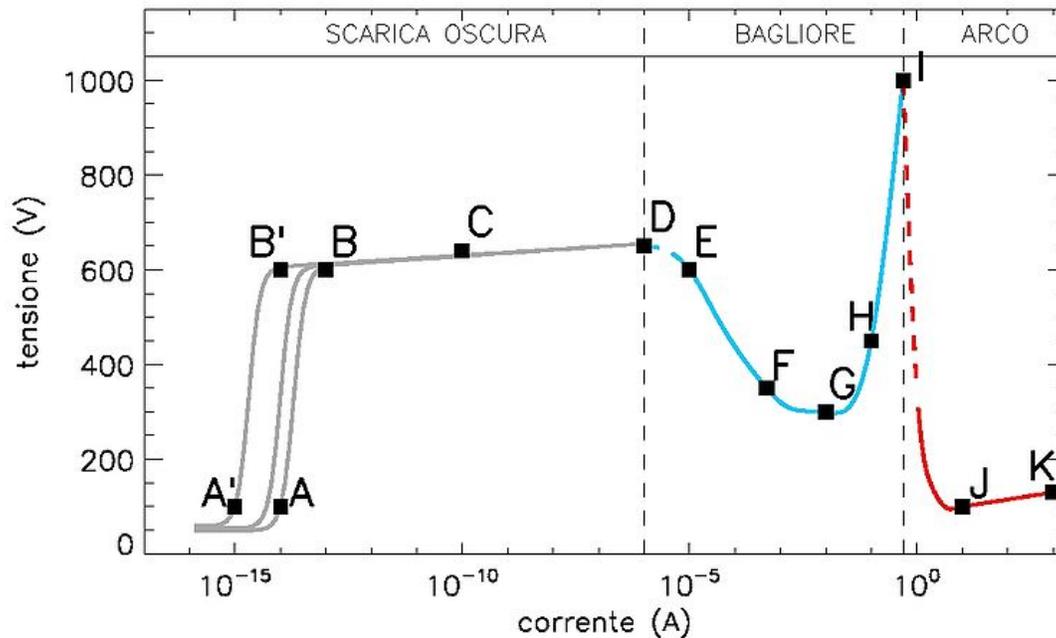
Electric discharge in gases

Electric discharge in gases occurs when electric current flows through a gaseous medium. Depending on several factors, the discharge may radiate visible light.

Discharge types
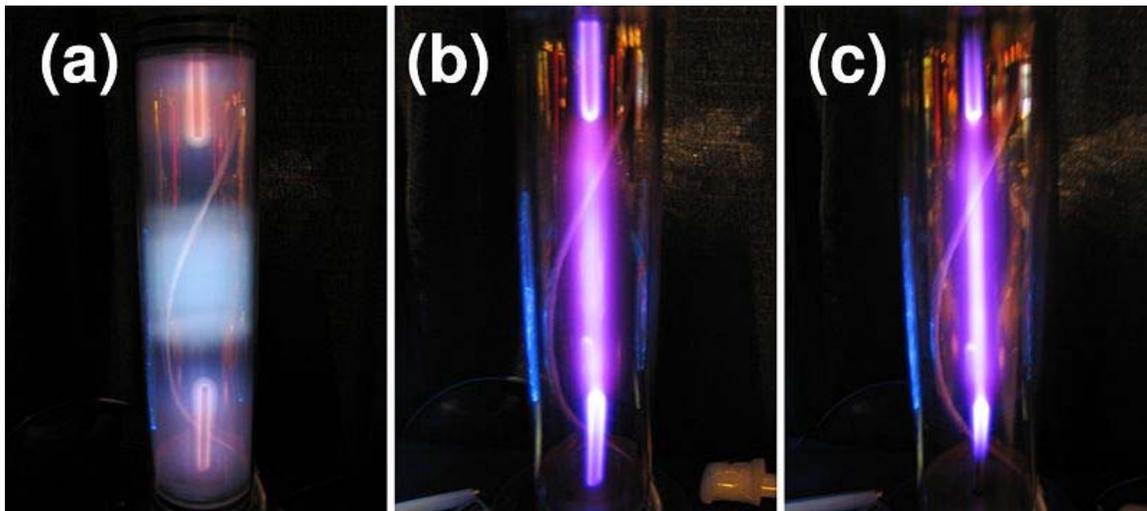
Transition from glow to arc discharge in argon, by increasing the gas pressure

Voltage-current characteristics of electrical discharge in neon at 1 torr, with two planar electrodes separated by 50 cm.
A: random pulses by cosmic radiation
B: saturation current
C: avalanche Townsend discharge
D: self-sustained Townsend discharge
E: unstable region: corona discharge
F: sub-normal glow discharge
G: normal glow discharge
H: abnormal glow discharge
I: unstable region: glow-arc transition
J: electric arc
K: electric arc
The A-D region is called a dark discharge; there is some ionization, but the current is below 10 microamperes and there is no significant amount of radiation produced.
The F-H region is a region of glow discharge; the plasma emits a faint glow that occupies almost all the volume of the tube; most of the light is emitted by excited neutral atoms.
The I-K region is a region of arc discharge; the plasma is concentrated in a narrow channel along the center of the tube; a great amount of radiation is produced.

In cold cathode tubes, the electric discharge in gas has three regions, with distinct current-voltage characteristics:

- **I**: Townsend discharge, below the breakdown voltage. At low voltages, the only current is that due to the generation of charge carriers in the gas by cosmic rays or other sources of ionizing radiation. As the applied voltage is increased, the free

electrons carrying the current gain enough energy to cause further ionization, causing an electron avalanche. In this regime, the current increases from femtoamperes to microamperes for very little further increase in voltage. The voltage-current characteristics begins tapering off near the breakdown voltage and the glow becomes visible.

- **II**: glow discharge, which occurs once the breakdown voltage is reached. The voltage across the electrodes suddenly drops and the current increases to milliampere range. At lower currents, the voltage across the tube is almost current-independent; this is used in glow discharge voltage stabilizers. At lower currents, the area of the electrodes covered by the glow discharge is proportional to the current. At higher currents the normal glow turns into abnormal glow, the voltage across the tube gradually increases, and the glow discharge covers more and more of the surface of the electrodes. Low-power switching (glow-discharge thyratrons), voltage stabilization, and lighting applications (e.g. Nixie tubes, decatrons, neon lamps) operate in this region.
- **III**: arc discharge, which occurs in the ampere range of the current; the voltage across the tube drops with increasing current. High-current switching tubes, e.g. triggered spark gap, ignitron, thyratron and krytron (and its vacuum tube derivate, sprytron, using vacuum arc), high-power mercury-arc valves and high-power light sources, e.g. mercury-vapor lamps and metal halide lamps, operate in this range.

Glow discharge is facilitated by electrons striking the gas atoms and ionizing them. For formation of glow discharge, the mean free path of the electrons has to be reasonably long but shorter than the distance between the electrodes; glow discharges therefore do not readily occur at both too low and too high gas pressures.

The breakdown voltage for the glow discharge depends nonlinearly on the product of gas pressure and electrode distance according to Paschen's law. For a certain pressure × distance value, there is a lowest breakdown voltage. The increase of strike voltage for shorter electrode distances is related to too long mean free path of the electrons in comparison with the electrode distance.

A small amount of a radioactive element may be added into the tube, either as a separate piece of material (e.g. nickel-63 in krytrons) or as addition to the alloy of the electrodes (e.g. thorium), to preionize the gas and increase the reliability of electrical breakdown and glow or arc discharge ignition. A gaseous radioactive isotope, e.g. krypton-85, can also be used. Ignition electrodes and keepalive discharge electrodes can also be employed.

The E / N ratio between E the electric field and N the concentration of neutral particles is often used, because the mean energy of electrons (and therefore many other properties of discharge) is a function of E / N. Increasing the electric intensity E by some factor q has the same consequences as lowering gas density N by factor q.

Chapter-11

Electrostatic Discharge

Electrostatic discharge (**ESD**) is the sudden and momentary electric current that flows between two objects at different electrical potentials. The term is usually used in the electronics and other industries to describe momentary unwanted currents that may cause damage to electronic equipment.

ESD is a serious issue in solid state electronics, such as integrated circuits. Integrated circuits are made from semiconductor materials such as silicon and insulating materials such as silicon dioxide. Either of these materials can suffer permanent damage when subjected to high voltages; as a result, there are now a number of antistatic devices that help prevent static build up.

Causes of ESD

One of the causes of ESD events is static electricity. Static electricity is often generated through tribocharging, the separation of electric charges that occurs when two materials are brought into contact and then separated. Examples of tribocharging include walking on a rug, rubbing plastic comb against dry hair, rubbing a balloon against a sweater, ascending from a fabric car seat, or removing some types of plastic packaging. In all these cases, the friction between two materials results in tribocharging, thus creating a difference of electrical potential that can lead to an ESD event.

Another cause of **ESD** damage is through electrostatic induction. This occurs when an electrically charged object is placed near a conductive object isolated from ground. The presence of the charged object creates an electrostatic field that causes electrical charges on the surface of the other object to redistribute. Even though the net electrostatic charge of the object has not changed, it now has regions of excess positive and negative charges. An ESD event may occur when the object comes into contact with a conductive path. For example, charged regions on the surfaces of styrofoam cups or plastic bags can induce potential on nearby ESD sensitive components via electrostatic induction and an ESD event may occur if the component is touched with a metallic tool.

Types of ESD

The most spectacular form of ESD is the **spark**, which occurs when a strong electric field creates an ionized conductive channel in air. This can cause minor discomfort to people, severe damage to electronic equipment, and fires and explosions if the air contains combustible gases or particles.

However, many ESD events occur without a visible or audible spark. A person carrying a relatively small electric charge may not feel a discharge that is sufficient to damage sensitive electronic components. Some devices may be damaged by discharges as small as 10 V. These invisible forms of ESD can cause device outright failures, or less obvious forms of degradation that may affect the long term reliability and performance of electronic devices. The degradation in some devices may not become evident until well into their service life.
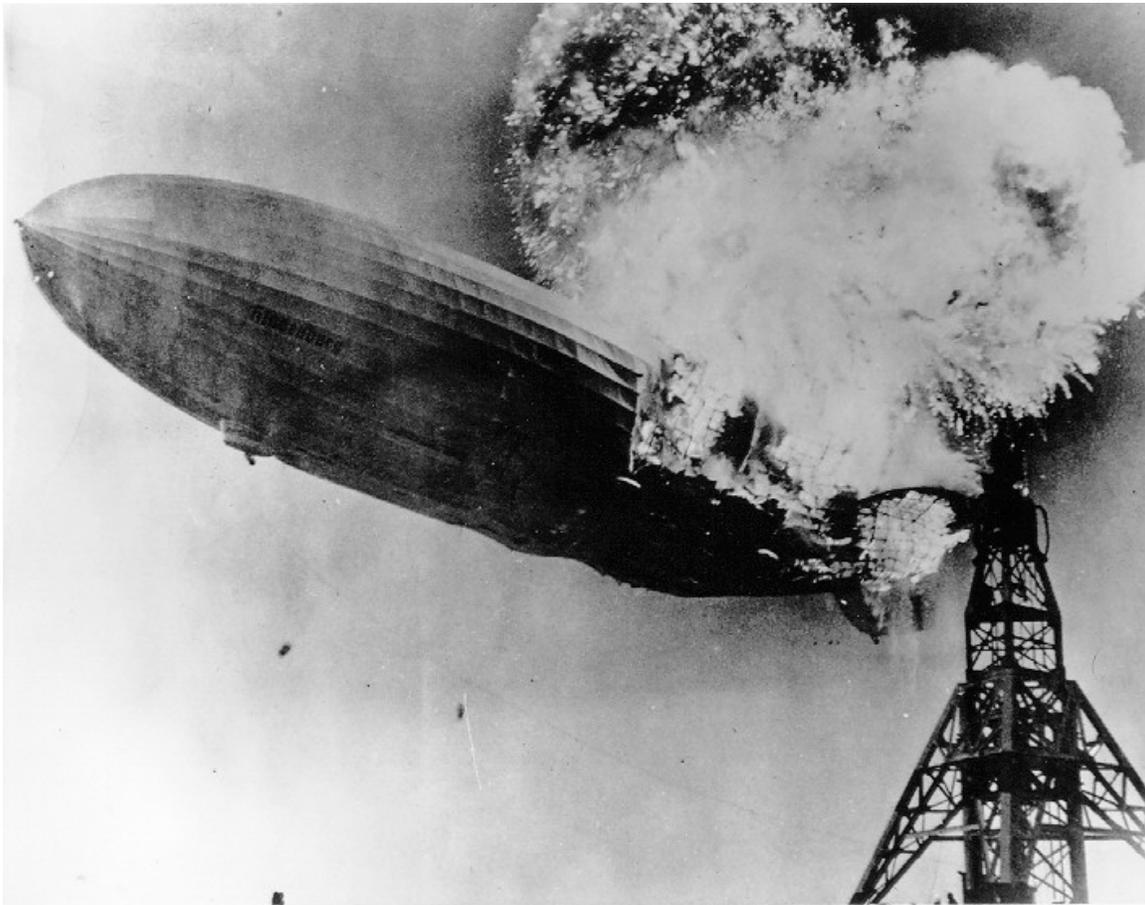
Sparks

A spark is triggered when the electric field strength exceeds approximately 4–30 kV/cm — the dielectric field strength of air. This may cause a very rapid increase in the number of free electrons and ions in the air, temporarily causing the air to abruptly become an electrical conductor in a process called dielectric breakdown.

Lightning over Rymań. Northern Poland.

Perhaps the best known example of a natural spark is a lightning strike. In this case the potential difference between a cloud and ground, or between two clouds, is typically hundreds of millions of volts. The resulting current that flows through the ionized air causes an explosive release of energy. On a much smaller scale, sparks can form in air during electrostatic discharges from charged objects that are charged to as little as 380 V (Paschen's law).

Earth's atmosphere consists of 21% oxygen (O_2) and 78% nitrogen (N_2). During an electrostatic discharge, the intervening atmosphere become electrically overstressed. The diatomic oxygen molecules are split, and then recombine to form ozone (O_3), which is unstable, or reacts with metals and organic matter. If the electrical stress is high enough, nitrogen oxides (NOx) can form. Both products are toxic to animals, and nitrogen oxides are essential for nitrogen fixation. Ozone attacks all organic matter by ozonolysis and is used in water purification.

The *Hindenburg*, moments after catching fire.

Sparks can cause serious explosions because of the high temperatures reached in a spark. Methane and coal dust explosions have been caused by electrostatic discharges. The Hindenburg disaster has been attributed to spark discharge igniting flammable panels tainted with thermite, which burned vigorously, violently, and extremely swiftly, which

ultimately led to the ignition of hydrogen gas held in or leaking from the airship at the time. The ship had just passed through a thunderstorm and therefore may have acquired a large charge. Discharge supposedly occurred when mooring ropes were dropped as it came in to land in New Jersey in 1937.

Corona discharge

A corona discharge occurs between a highly curved electrode, for example the tip of a needle or a small diameter wire, and an electrode of low curvature such as a flat plate. The high curvature produces a high potential gradient around one electrode.

Brush discharge

A brush discharge occurs between an electrode with a curvature between 5 mm and 50 mm and a voltage of about 500 kV/m. The resulting discharge paths have the shape of a brush.

Damage prevention in electronics

A portion of a static discharger on an aircraft. Note the two sharp 3/8" metal micropoints and the protective yellow plastic.

Prevention of ESD bases on Electrostatic Protective Area (EPA). EPA can be a small working station or a large manufacturing area. The main principle of an EPA is that there are no highly charging materials in the vicinity of ESD sensitive electronics, all conductive materials are grounded, workers are grounded, and charge build-up on ESD sensitive electronics is prevented. International standards are used to define typical EPA and can be found for example from International Electrotechnical Commission (IEC) or American National Standards Institute (ANSI).

ESD prevention within an EPA may include using appropriate ESD-safe packing material, the use of conductive filaments on garments worn by assembly workers, conducting wrist straps and foot-straps to prevent high voltages from accumulating on workers' bodies, anti-static mats or conductive flooring materials to conduct harmful electric charges away from the work area, and humidity control. Humid conditions prevent electrostatic charge generation because the thin layer of moisture that accumulates on most surfaces serves to dissipate electric charges.

Ion generators are sometimes used to inject ions into the ambient airstream. Ionization systems help to neutralize charged surface regions on insulative or dielectric materials. Insulating materials prone to triboelectric charging should be kept away from sensitive devices to prevent accidental charging of devices through induction. On aircraft, static dischargers are used on the trailing edges of wings and other surfaces.

Manufacturers and users of integrated circuits must take precautions to avoid ESD. ESD prevention can be part of the device itself and include special design techniques for device input and output pins. External protection components can also be used with circuit layout.

Due to dielectric nature of electronics component and assemblies, electrostatic charging can not be completely prevented during handling of devices. Most of ESD sensitive electronic assemblies and components are also so small that manufacturing and handling is made with automated equipment. ESD prevention activities are therefore important with those processes where component is touching on equipment surfaces. In addition, it is important to prevent ESD when electrostatic discharge sensitive component is connected with other conductive parts of the product itself. An efficient way to prevent ESD is to use materials that are not too conductive but will slowly conduct static charges away. These materials are called static dissipative and have resistivity values in the range of 10^5 to 10^{11} ohm-meters. Materials in automated manufacturing which will touch on conductive areas of ESD sensitive electronic should be made of dissipative material, and the dissipative material must be grounded.

Simulation and testing for electronic devices
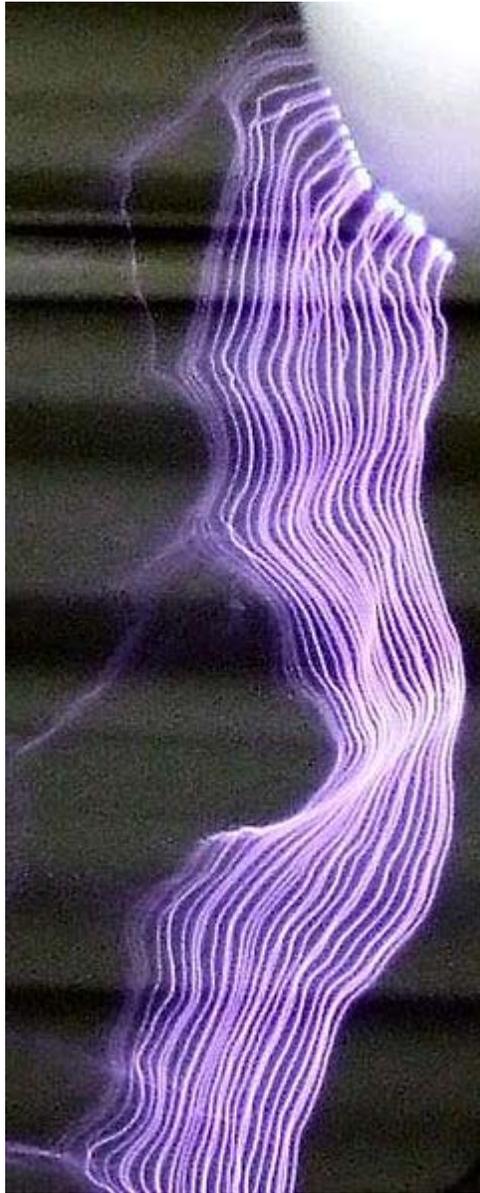
Electric discharge showing the ribbon-like plasma filaments from multiple discharges from a Tesla coil.

For testing the susceptibility of electronic devices to ESD from human contact, an ESD Simulator with a special output circuit, called the human body model (HBM) is often used. This consists of a capacitor in series with a resistor. The capacitor is charged to a specified high voltage from an external source, and then suddenly discharged through the resistor into an electrical terminal of the device under test. One of the most widely used models is defined in the JEDEC 22-A114-B standard, which specifies a 100 picofarad capacitor and a 1500 ohm resistor. Other similar standards are MIL-STD-883 Method 3015, and the ESD Association's ESD STM5.1. For comportment to European Union standards for Information Technology Equipment, the IEC-61000-4-2 test specification is

used. Guidelines and requirements are given for test cell geometries, generator specifications, test levels, discharge rate and waveform, types and points of discharge on the "victim" product, and functional criteria for gauging product survivability.

A Charged Device Model (CDM) test is used to define the ESD a device can withstand when the device itself has an electrostatic charge and discharges due to metal contact. This discharge type is the most common type of ESD in electronic devices and causes most of the ESD damages in their manufacturing. CDM discharge depends mainly on parasitic parameters of the discharge and is strongly depending on size and type of component package. One of the most widely used CDM simulation test models is defined by the JEDEC.

Other standardized ESD test circuits include the following:

- Machine model (MM)
- Transmission line pulse (TLP)

Chapter-12

Electric Glow Discharge

An **electric glow discharge** is a plasma formed by the passage of current at 100 V to several kV through a gas at low pressure, such as argon or another noble gas. It is found in products such as neon lamps and plasma-screen televisions, and is used in plasma physics and analytical chemistry.

Electric glow from a krypton gas discharge

Basic operating mechanism
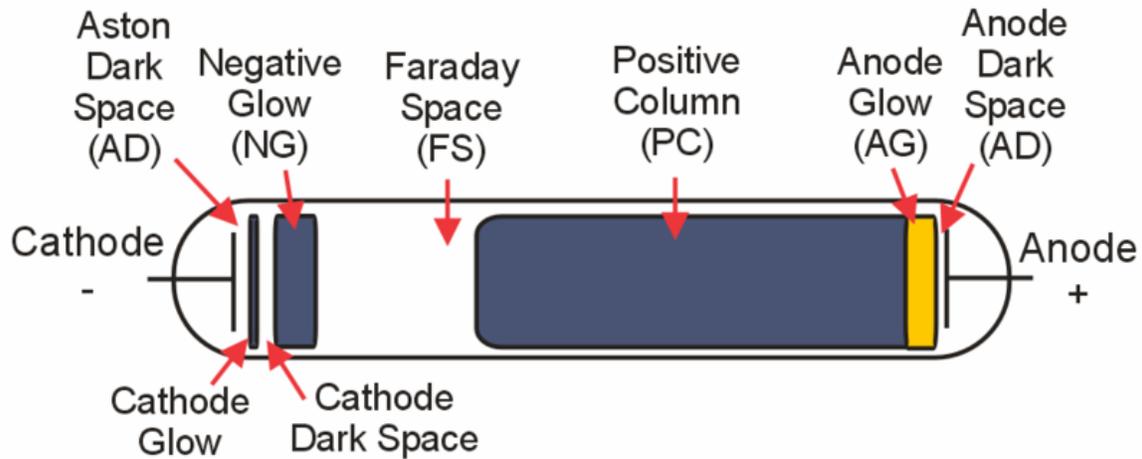
An electric glow discharge tube featuring its most important characteristics: (a) An anode and cathode at each end (b) Aston Dark Space(c) Cathode glow (d) Cathode dark space (also called Crookes dark space, or Hittorf dark space) (e) Negative glow (f) Faraday space (g) Positive column (h) Anode glow (i) Anode dark space.

This system was first made by William Crookes. The simplest type of glow discharge is a direct-current glow discharge. In its simplest form, it consists of two electrodes in a cell held at low pressure (0.1–10 torr; about $1/10000^{th}$ to $1/100^{th}$ of atmospheric pressure). The cell is typically filled with neon, but other gases can also be used. An electric potential of several hundred volts is applied between the two electrodes. A small fraction of the population of atoms within the cell is initially ionized through random processes (thermal collisions between atoms or with alpha particles, for example). The ions (which are positively charged) are driven towards the cathode by the electric potential, and the electrons are driven towards the anode by the same potential. The initial population of ions and electrons collides with other atoms, ionizing them. As long as the potential is maintained, a population of ions and electrons remains.

Glow discharge around a cathode of a nixie tube

Some of the ions' kinetic energy is transferred to the cathode. This happens partially through the ions striking the cathode directly. The primary mechanism, however, is less direct. Ions strike the more numerous neutral gas atoms, transferring a portion of their energy to them. These neutral atoms then strike the cathode. Whichever species (ions or atoms) strike the cathode, collisions within the cathode redistribute this energy until a portion of the cathode is ejected, typically in the form of free atoms. This process is known as sputtering. Once free of the cathode, atoms move into the bulk of the glow discharge through drift and due to the energy they gained from sputtering. The atoms can then be collisionally excited. These collisions may be with ions, electrons, or other atoms that have been previously excited by collisions with ions, electrons, or atoms. Once excited, atoms will lose their energy fairly quickly. Of the various ways that this energy

can be lost, the most important is radiatively, meaning that a photon is released to carry the energy away. In optical atomic spectroscopy, the wavelength of this photon can be used to determine the identity of the atom (that is, which chemical element it is) and the number of photons is directly proportional to the concentration of that element in the sample. Some collisions (those of high enough energy) will cause ionization. In atomic mass spectrometry, these ions are detected. Their mass identifies the type of atoms and their quantity reveals the amount of that element in the sample.

The figure above shows the main regions that may be present in a glow discharge. Regions described as "glows" emit significant light; regions labeled as "dark spaces" do not. As the discharge becomes more extended (i.e., stretched horizontally in the geometry of the figure), the positive column may become striated. That is, alternating dark and bright regions may form. Relatedly, compressing the discharge horizontally will result in fewer regions. The positive column will be compressed while the negative glow will remain the same size, and, with small enough gaps, the positive column will disappear altogether. In an analytical glow discharge, the discharge is primarily a negative glow with dark region above and below it.

Below the ionization voltage or breakdown voltage there is no glow, but as the voltage increases to the ionization point the Townsend discharge happens just as glow discharge becomes visible; this is the start of the normal glow range. As the voltage is increased above the normal glow range, abnormal glow begins. If the voltage is increased to the point the cathode glow covers the entire cathode arc discharge begins.

Use in analytical chemistry

Glow discharges can be used to analyze the elemental, and sometimes molecular, composition of solids, liquids, and gases, but elemental analysis of solids is by far the most common. In this arrangement, the sample is used as the cathode. As mentioned earlier, gas ions and atoms striking the sample surface knock atoms off of it (a process known as sputtering). The sputtered atoms, now in the gas phase, can be detected by atomic absorption, but this is a comparatively rare strategy. Instead, atomic emission and mass spectrometry are usually used. Collisions between the gas-phase sample atoms and the plasma gas pass energy to the sample atoms. This energy can excite the atoms, after which they can lose their energy through atomic emission. By observing the wavelength of the emitted light, the atom's identity can be determined. By observing the intensity of the emission, the concentration of atoms of that type can be determined. Energy gained through collisions can also ionize the sample atoms. The ions can then be detected by mass spectrometry. In this case, it is the mass of the ions that identified the element and the number of ions that reflects the concentrationin. This method is referred to as glow discharge mass spectrometry (GDMS) and it has detection limits down to the sub-ppb range for most elements that are nearly matrix-independent.

Both bulk and depth analysis of solids may be performed with glow discharge. Bulk analysis assumes that the sample is fairly homogeneous and averages the emission or mass spectrometric signal over time. Depth analysis relies on the fact that the depth

increases as time goes by. Tracking the signal in time, therefore, is the same as tracking the elemental composition in depth. Depth analysis requires greater control over operational parameters. For example, conditions (current, potential, pressure) need to be adjusted so that the crater produced by sputtering is flat bottom (that is, so that the depth analyzed over the crater area is uniform). In bulk measurement, a rough or rounded crater bottom would not adversely impact analysis. Under the best conditions, depth resolution in the single nanometer range has been achieved (in fact, within-molecule resolution has been demonstrated).

The chemistry of ions and neutrals in vacuum is called gas phase ion chemistry and is part of the analytical study that includes Electric glow discharge.

Powering modes

In analytical chemistry, glow discharges are most often operated in direct-current mode. For this mode, the cathode (which is the sample in solids analysis) must be conductive. The potential, pressure, and current are interrelated. Only two can be directly controlled at once, while the third must be allowed to vary. The pressure is most typically held constant, but other schemes may be used. The pressure and current may be held constant, while potential is allowed to vary. The pressure and voltage may be held constant while the current is allowed to vary. The power (product of voltage and current) may be held constant while the pressure is allowed to vary.

Glow discharges may also be operated in radio-frequency. The use of this frequency will establish a negative DC-bias voltage on the sample surface. The DC-bias is the result of an alternating current waveform that is centered about negative potential; as such it more or less represent the average potential residing on the sample surface. Radio-frequency has ability to appear to flow through insulators (non-conductive materials). A particular frequency of wave will be adsorbed by electrons that are vibrating in resonance to the wave. Then, electrons will re-emit the same frequency of energy to be detected by the optical emission spectroscopy (OES). Hence, this method greatly expanding the applicability of the technique.

Both radio-frequency and direct-current glow discharges can be operated in pulsed mode, where the potential is turned on and off. This allows higher instantaneous powers to be applied without excessively heating the cathode. These higher instantaneous powers produce higher instantaneous signals, aiding detection. Combining time-resolved detection with pulsed powering results in additional benefits. In atomic emission, analyte atoms emit during different portions of the pulse than background atoms, allowing the two to be discriminated. Analogously, in mass spectrometry, sample and background ions are created at different times.

Types
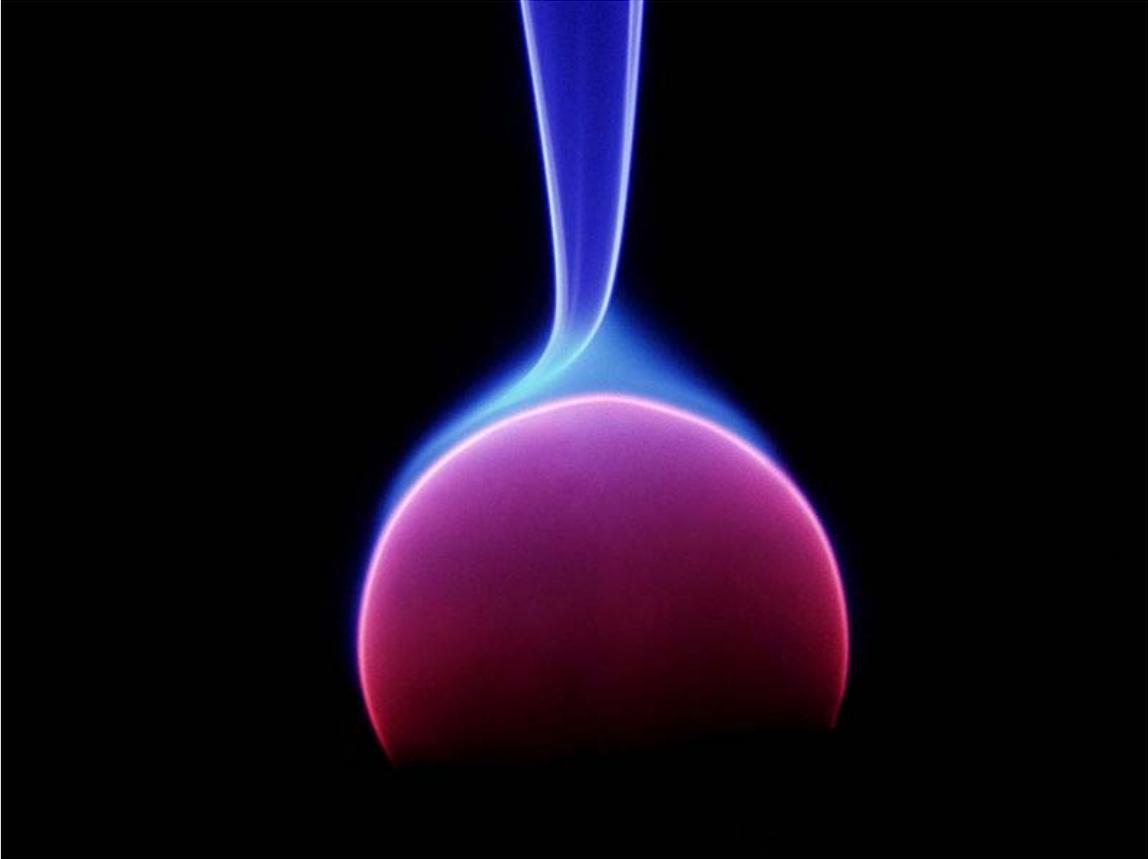
Central electrode of a plasma globe showing a glow discharge

There are various types of glow discharge examples include: highpressure glow discharge, hollow cathode discharge, spray discharge.

Chapter-13

Electromagnetic Compatibility

Anechoic RF chamber used for EMC testing (radiated emissions and immunity). The furniture has to be made of wood or plastic, and not metal

Electromagnetic compatibility (EMC) is the branch of electrical sciences which studies the unintentional generation, propagation and reception of electromagnetic energy with reference to the unwanted effects (Electromagnetic interference, or EMI) that such energy

may induce. The goal of EMC is the correct operation, in the same electromagnetic environment, of different equipment which use electromagnetic phenomena, and the avoidance of any interference effects.

In order to achieve this, EMC pursues two different kinds of issues. **Emission** issues are related to the unwanted generation of electromagnetic energy by some *source*, and to the countermeasures which should be taken in order to reduce such generation and to avoid the escape of any remaining energies into the external environment. **Susceptibility** or **immunity** issues, in contrast, refer to the correct operation of electrical equipment, referred to as the *victim*, in the presence of unplanned electromagnetic disturbances.

Interference, or noise, mitigation and hence electromagnetic compatibility is achieved primarily by addressing both emission and susceptibility issues, i.e., quieting the sources of interference and hardening the potential victims. The coupling path between source and victim may also be separately addressed to increase its attenuation.

Types of interference

Electromagnetic interference divides into several categories according to the source and signal characteristics.

The origin of noise can be man made or natural.

Continuous interference

Continuous, or Continuous Wave (CW), interference arises where the source regularly emits a given range of frequencies. This type is naturally divided into sub-categories according to frequency range, and as a whole is sometimes referred to as "DC to daylight".

- Audio Frequency, from very low frequencies up to around 20 kHz. Frequencies up to 100 kHz may sometimes be classified as Audio. Sources include:
    - Mains hum from power supply units, nearby power supply wiring, transmission lines and substations.
    - Audio processing equipment, such as audio power amplifiers and loudspeakers.
    - Demodulation of a high-frequency carrier wave such as an FM radio transmission.
- Radio Frequency Interference, RFI, from 20 kHz to a limit which constantly increases as technology pushes it higher. Sources include:
    - Wireless and Radio Frequency Transmissions
    - Television and Radio Receivers
    - Industrial, scientific and medical equipment
    - Digital processing circuitry (For example microcontrollers)
- Broadband noise may be spread across parts of either or both frequency ranges, with no particular frequency accentuated. Sources include:

- o Solar Activity
- o Continuously operating spark gaps such as arc welders
- o CDMA mobile telephony

Pulse or transient interference

Electromagnetic Pulse, EMP, also sometimes called Transient disturbance, arises where the source emits a short-duration pulse of energy. The energy is usually broadband by nature, although it often excites a relatively narrow-band *damped sine wave* response in the victim.

Sources divide broadly into isolated and repetitive events.

- Sources of isolated EMP events include:
  - o Switching action of electrical circuitry, including inductive loads such as relays, solenoids, or electric motors.
  - o Electrostatic Discharge (ESD), as a result of two charged objects coming into close proximity or even contact.
  - o Lightning Electromagnetic Pulse (LEMP), although typically a short series of pulses.
  - o Nuclear Electromagnetic Pulse (NEMP), as a result of a nuclear explosion.
  - o Non-Nuclear Electromagnetic Pulse (NNEMP) weapons.
  - o Power Line Surges/Pulses

- Sources of repetitive EMP events, sometimes as regular *pulse trains*, include:
  - o Electric Motors
  - o Gasoline engine ignition systems
  - o Continual switching actions of digital electronic circuitry.

Coupling Mechanisms

Some of the technical words employed can be used with differing meanings.

The basic arrangement of noise source, coupling path and victim, receptor or sink is shown in the figure below. Source and victim are usually electronic hardware devices, though the source may be a natural phenomenon such as a lightning strike, electrostatic discharge (ESD) or, in one famous case, the Big Bang at the origin of the Universe.
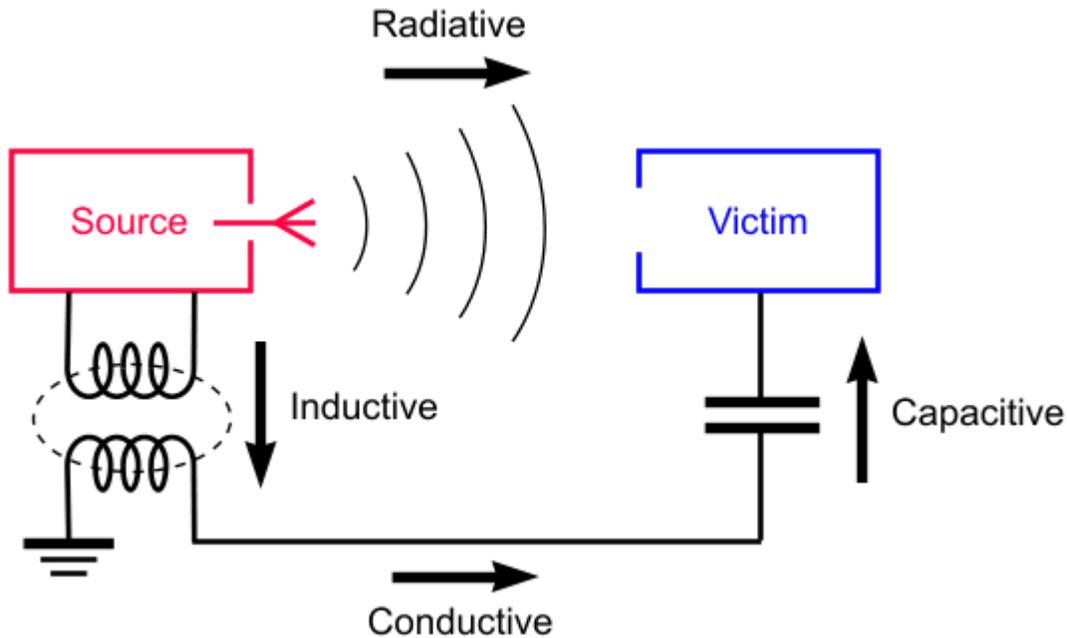
The four electromagnetic interference (EMI) coupling modes.

There are four basic coupling mechanisms: conductive, capacitive, magnetic or inductive, and radiative. Any coupling path can be broken down into one or more of these coupling mechanisms working together. For example the lower path in the diagram involves inductive, conductive and capacitive modes.

Conductive coupling

Conductive coupling occurs when the coupling path between the source and the receptor is formed by direct contact with a conducting body, for example a transmission line, wire, cable, PCB trace or metal enclosure.

Conduction modes

Conducted noise is also characterised by the way it appears on different conductors:

- **Common-mode** or **common-impedance**) coupling: noise appears in phase (in the same direction) on two conductors .
- **Differential-mode** coupling: noise appears out of phase (in opposite directions) on two conductors.

Inductive coupling

Inductive coupling occurs where the source and receiver are separated by a short distance (typically less than a wavelength). Strictly, "Inductive coupling" can be of two

kinds, electrical induction and magnetic induction. It is common to refer to electrical induction as *capacitive coupling*, and to magnetic induction as *inductive coupling*.

Capacitive coupling

Capacitive coupling occurs when a varying electrical field exists between two adjacent conductors typically less than a wavelength apart, inducing a change in voltage across the gap.

Magnetic coupling

Inductive coupling or **magnetic coupling (MC)** occurs when a varying magnetic field exists between two parallel conductors typically less than a wavelength apart, inducing a change in voltage along the receiving conductor.

Radiative coupling

Radiative coupling or **electromagnetic coupling** occurs when source and victim are separated by a large distance, typically more than a wavelength. Source and victim act as radio antennas: the source emits or radiates an electromagnetic wave which propagates across the open space in between and is picked up or received by the victim.

EMC control

The damaging effects of electromagnetic interference pose unacceptable risks in many areas of technology, and it is necessary to control such interference and reduce the risks to acceptable levels.

The control of electromagnetic interference (EMI) and assurance of EMC comprises a series of related disciplines:

- Characterising the threat.
- Setting standards for emission and susceptibility levels.
- Design for standards compliance.
- Testing for standards compliance.

For a complex piece of equipment, this may require the production of a dedicated *EMC control plan* summarizing the application of the above and specifying additional documents required.

Characterising the threat

Characterisation of the problem requires understanding of:

- The interference source and signal.
- The coupling path to the victim.

- The nature of the victim both electrically and in terms of the significance of malfunction.

The risk posed by the threat is usually statistical in nature, so much of the work in threat characterisation and standards setting is based on reducing the probability of disruptive EMI to an acceptable level, rather than its assured elimination.

Laws and regulators

Regulatory and standards bodies

Several international organizations work to promote international co-operation on standardization (harmonization), including publishing various EMC standards. Where possible, a standard developed by one organization may be adopted with little or no change by others. This helps for example to harmonize national standards across Europe. Standards organizations include:

- International Electrotechnical Commission (**IEC**), which has several committees working full time on EMC issues. These are:
  - Technical Committee 77 (**TC77**), working on electromagnetic compatibility between equipment including networks.
  - Comité International Spécial des Perturbations Radioélectriques (**CISPR**), or International Special Committee on Radio Interference.
  - The Advisory Committee on Electromagnetic Compatibility (**ACEC**) co-ordinates the IEC's work on EMC between these committees.
- International Organization for Standardization (**ISO**), which publishes standards for the automotive industry.

Among the more well known national organizations are:

- Europe:
  - Comité Européen de Normalisation (**CEN**) or European Committee for Standardization).
  - Comité Européen de Normalisation Electrotechniques (**CENELEC**) or European Committee for Electrotechnical Standardisation.
  - European Telecommunications Standards Institute (**ETSI**).
- United States:
  - The Federal Communications Commission (**FCC**).
  - The Society of Automotive Engineers (**SAE**).
- Britain: The British Standards Institution (**BSI**).
- Germany: The Verband der Elektrotechnik, Elektronik und Informationstechnik (**VDE**) or Association for Electrical, Electronic and Information Technologies.

Laws

Compliance with national or international standards is usually required by laws passed by individual nations. Different nations can require compliance with different standards.

By European law, manufacturers of electronic devices are advised to run EMC tests in order to comply with compulsory CE-labeling. Undisturbed usage of electric devices for all customers should be ensured and the electromagnetic field strength should be kept on a minimum level. EU directive 2004/108/CE (previously 89/336/EEC) on EMC announces the rules for the distribution of electric devices within the European Union. A good overview of EME limits and EMI demands is given in List of EMC directives.

EMC design

Electromagnetic noise is produced in the source due to rapid current and voltage changes, and spread via the coupling mechanisms described earlier.

Since breaking a coupling path is equally effective at either the start or the end of the path, many aspects of good EMC design practice apply equally to potential emitters and to potential victims. Further, a circuit which easily couples energy to the outside world will equally easily couple energy in and will be susceptible. A single design improvement often reduces both emissions and susceptibility.

Grounding and shielding

Grounding and shielding aim to divert EMI away from the victim by providing an alternative, low-impedance path. Techniques include:

- **Shielded Housings**.
- **Shielded Lines**.
- Grounding or earthing schemes such as **Star Earthing** for audio equipment, or **Ground planes** for RF.

Other general measures

- **Decoupled Cable Entries** (Line filter, Signal filter) using RF chokes, or RC elements.
- **Transmission line** techniques for cables and wiring, such as balanced differential signal and return paths, and impedance matching.
- **Avoidance of Antenna Structures**, such as loops of circulating current, resonant mechanical structures, unbalanced cable impedances or poorly grounded shielding.

Emissions suppression
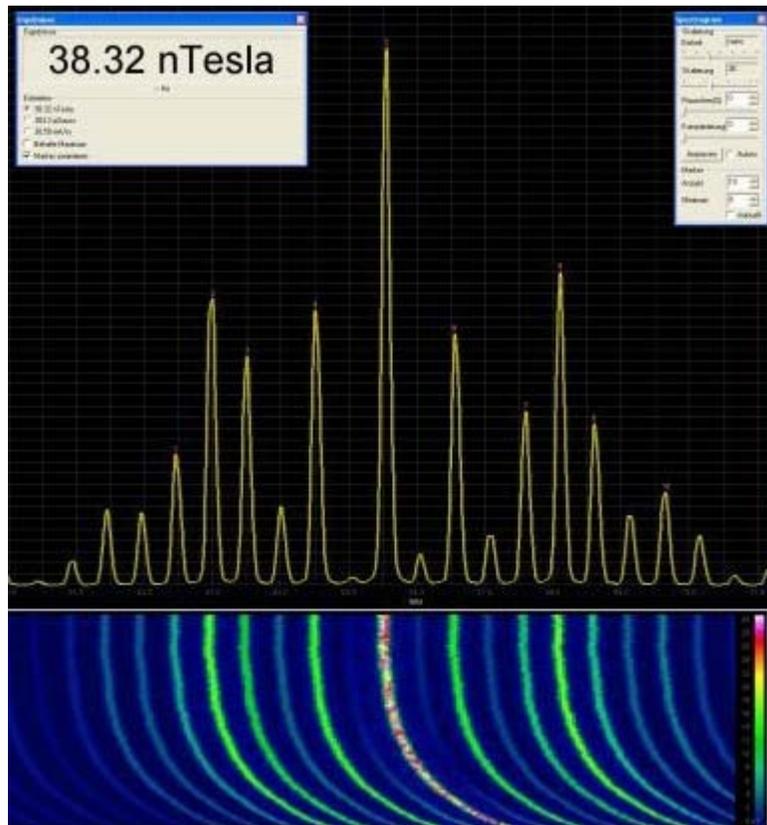
Spread spectrum method reduces EMC peaks. Frequency spectrum of the heating up period of a switching power supply which uses the spread spectrum method incl. waterfall diagram over a few minutes

Additional measures to reduce emissions include:

- Avoid unnecessary switching operations. Necessary switching should be done as slowly as technically possible.
- Noisy circuits (with a lot of switching activity) should be physically separated from the rest of the design.
- High peaks can be avoided by using the spread spectrum method.
- **Harmonic Wave Filters**.
- Design for operation at lower signal levels, reducing the energy available for emission.

Susceptibility hardening

Additional measures to reduce susceptibility include:

- Fuses, trip switches and circuit breakers.
- Transient absorbers.

- Design for operation at higher signal levels, reducing the relative noise level in comparison.

EMC testing

Testing is required to confirm that a particular device meets the required standards. It divides broadly into emissions testing and susceptibility testing.

RF testing of a physical prototype is most often carried out in a radio-frequency anechoic chamber.

Open-air test sites, or OATS, are the reference sites in most standards. They are especially useful for emissions testing of large equipment systems.

Sometimes computational electromagnetics simulations are used to test virtual models.

Like all compliance testing, it is important that the test equipment, including the test chamber or site and any software used, be properly calibrated and maintained.

Typically, a given run of tests for a particular piece of equipment will require an *EMC test plan* and follow-up *Test report*. The full test program may require the production of several such documents.

Susceptibility testing

Radiated field susceptibility testing typically involves a high-powered source of RF or EM pulse energy and a radiating antenna to direct the energy at the potential victim or device under test (DUT).

Conducted voltage and current susceptibility testing typically involves a high-powered signal or pulse generator, and a current clamp or other type of transformer to inject the test signal.

Transient immunity is used to test the immunity of the DUT against powerline disturbances including surges, lightning strikes and switching noise. In motor vehicles, similar tests are performed on battery and signal lines.

Electrostatic discharge testing is typically performed with a piezo spark generator called an "ESD pistol". Higher energy pulses, such as lightning or nuclear EMP simulations, can require a large current clamp or a large antenna which completely surrounds the DUT. Some antennas are so large that they are located outdoors, and care must be taken not to cause an EMP hazard to the surrounding environment.

Emissions testing

Emissions are typically measured for radiated field strength and where appropriate for conducted emissions along cables and wiring. Inductive (magnetic) and capacitive (electric) field strengths are near-field effects, and are only important if the device under test (DUT) is designed for location close to other electrical equipment.

Typically a spectrum analyzer is used to measure the emission levels of the DUT across a wide band of frequencies (frequency domain). Specialized spectrum analyzers for EMC testing are available, called EMI Test Receivers or EMI Analyzers. These incorporate bandwidths and detectors as specified by international EMC standards. EMI Receivers along with specified transducers can often be used for both conducted and radiated emissions. Pre-selector filters may also be used to reduce the effect of strong out-of-band signals on the front-end of the receiver.

For conducted emissions, typical transducers are the LISN (Line Impedance Stabilisation Network) also sometimes called as the AMN (Artificial Mains Network) and the RF current clamp.

For radiated emission measurement, antennas are used as transducers. Typical antennas specified include dipole, biconical, log-periodic, double ridged guide and conical log-spiral designs. Radiated emissions must be measured in all directions around the DUT.

Some pulse emissions are more usefully characterized using an oscilloscope to capture the pulse waveform in the time domain.

History

The earliest EMC issue was lightning strike (Lightning Electromagnetic Pulse, or LEMP) on buildings. Lightning rods or lightning conductors began to appear in the mid-18th century. With the advent of widespread electricity generation and power supply lines from the late 19th century on, problems also arose with equipment short-circuit failure affecting the power supply, and with local fire and shock hazard when the power line was struck. Power stations were provided with output circuit breakers. Buildings and appliances would soon be provided with input fuses, and later in the 20th century miniature circuit breakers (MCB) would come into use.

As radio communications developed in the first half of the 20th century, interference between broadcast radio signals began to occur and an international regulatory framework was set up to ensure interference-free communications.

As switching devices became commonplace, typically in petrol powered cars and motorcycles but also in domestic appliances such as thermostats and refrigerators, transient interference with domestic radio and (after World War II) TV reception became problematic, and in due course laws were passed requiring the suppression of such interference sources.

After World War II the military became increasingly concerned with the effects of nuclear electromagnetic pulse (NEMP), lightning strike, and even high-powered radar beams, on mobile vehicles of all kinds, and especially aircraft electrical systems.

ESD problems first arose with accidental electric spark discharges in hazardous environments such as coal mines and when refuelling aircraft or motor cars. Safe working practices had to be developed.

When high RF emission levels from other sources became a potential problem (such as with the advent of microwave ovens), certain frequency bands were designated for Industrial, Scientific and Medical (ISM) use, allowing unlimited emissions. A variety of issues such as sideband and harmonic emissions, broadband sources, and the increasing popularity of electrical switching devices and their victims, resulted in a steady development of standards and laws.

From the 1970s, the popularity of modern digital circuitry rapidly grew. As the technology developed, with faster switching speeds (increasing emissions) and lower circuit voltages (increasing susceptibility), EMC increasingly became a source of concern. Many more nations became aware of EMC as a growing problem and issued directives to the manufacturers of digital electronic equipment, which set out the essential manufacturer requirements before their equipment could be marketed or sold. Organizations in individual nations, across Europe and worldwide, were set up to maintain these directives and associated standards. This regulatory environment led to a growing EMC industry supplying specialist devices and equipment, analysis and design software, and testing and certification services.

Low-voltage digital circuits, especially CMOS transistors, became more susceptible to ESD damage as they were miniaturised, and a new ESD regulatory regime had to be developed.

From the 1980s, the ever-increasing use of mobile communications and broadcast media channels has put huge pressure on the available airspace. Regulatory authorities are squeezing band allocations closer and closer together, relying on increasingly sophisticated EMC design methods, especially in the digital communications arena, to keep cross-channel interference to acceptable levels. Digital systems are inherently less susceptible than the old analogue systems, and also offer far easier ways (such as software) to implement highly sophisticated protection measures.

Most recently, even the ISM bands are being used for low-power mobile digital communications. This approach relies on the intermittent nature of ISM interference and use of sophisticated error-correction methods to ensure lossless reception during the quiet gaps between bursts of interference.