SUPERCONDUCTIVITY AND OPTICAL FIBERS

UNIT-VI

The Phenomenon of exhibiting *zero electrical resistivity* and *complete diamagnetism* is called Superconductivity and the materials which exhibit these property are called Superconductors. In superconducting materials there exists *critical values for temperature, magnetci field and current.* Above the critical values the material passes into normal state.

The electrical resistivity of a metallic conductor decreases gradually as the temperature is lowered. Even near absolute zero a real sample of *copper,gold and silver etc., shows a non-zero resistance.* The resistance of a superconductor, on the other hand, drops abruptly to zero when the material is cooled below its "critical temperature", typically 20 kelvins or less. Superconductivity is a quantum mechanical phenomenon. It cannot be understood simply as the idealization of "perfect conductivity" in classical physics.

Superconductivity occurs in a wide variety of materials, including simple elements like tin and aluminium, various metallic alloys, some heavily-doped semiconductors and a family of cuprate-perovskite ceramic materials known as high-temperature superconductors. *Superconductivity does not occur in noble metals like gold and silver, nor in most ferromagnetic metals*. Today superconductivity is being applied to many diverse areas such as: *medicine, theoretical and experimental science, the military, transportation, power production, electronics, as well as many other areas.*

The physicist, *Heike Kammerlingh Onnes*, first discovered superconductivity in *1911*. In 1908, he successfully liquefied helium by cooling it to 4.2 K at atmospheric pressure. Using liquid helium as a coolant in 1911, Onnes passed a current through a very pure mercury wire and measured its resistance as he steadily lowered the temperature *at 4.15 K* the resistance suddenly vanished. Figure (1) shows the abrupt change in resistance of mercury at liquid helium temperature discovered by onnes.

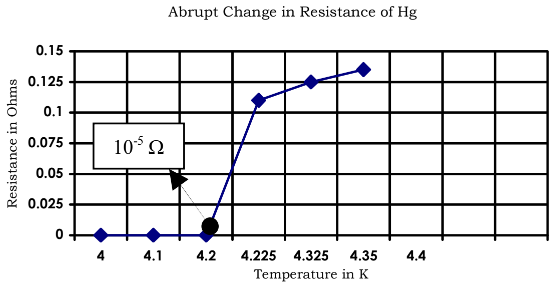


Figure 1: -Abrupt change in resistance of mercury at liquid helium temperature.

To explain the zero electrical resistivity to the simple circuit, according to ohm's law the potential difference disappears across the superconducting material. A sensitive method to explain this was developed by Onnes. It consists of measuring the decrease *of a current in a closed ring of superconducting wire. The superconducting ring is kept in a magnetic field. In addition, it is cooled to below the critical* *temperature so that it becomes superconducting. When the external magnetic field is switched off, a current induced in the ring would decrease according to the equation* $I(t) = I(0)e^{-\frac{Rt}{L}}$ *, if there were finite resistance R in the circuit. Where L is the inductance of the ring. The decay of current may be monitored by a change in the magnetic flux through a test coil held close to the superconducting ring. Any change in the magnetic flux of the superconducting ring will induce an emf in the test coil. Careful measurements established that the resistivity of superconductors could be assumed zero. A Superconductor is therefore an ideal or perfect conductor, which does not cause* I^2R *losses.*

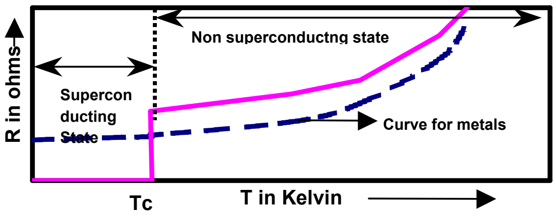
Persistent current:-

- Persistent current is a steady current, which flows with undiminishing strength with in the superconductors. The persistent current does not need external power to maintain it because there does not exist I^2R losses.
- Calculations show that once the current flow is initiated, it persists for more than 10^5 years. Superconductor coils with persistent currents produce magnetic fields and can therefore serve as magnets. Such a superconducting magnet does not require a power supply to maintain its magnetic field.

Effect of temperature/magnetic field/current density.

- Temperature, magnetic field and current influence the Superconducting state. There exist critical values for these three parameters, above which values the material passes into normal state.
- Since all metals have loosely bound electrons in their outermost shells they shows good conductivity of electricity. Loosely bounded electrons become free electrons in presence of electric field and starts to move in the crystal lattice. The atoms, which lost the electrons, become positive ion cores. Due to the thermal excitation, the ions oscillate about fixed positions of the metal. These vibrations are called lattice vibrations. The scattering of the conduction electrons by lattice vibrations causes the resistance of a metal to the flow of current. When the temperature increases, the amplitude of lattice vibrations also increases thereby increasing the resistance.
- The resistance of superconductor in the non-superconducting state decreases with decrease in temperature as in the case of a normal metal. At temperature Tc called critical temperature, the resistance abruptly drops to zero and signifies the transition from normal state to the superconducting state. The critical temperature is different for different superconductors. The variation of resistance with temperature for both metals and superconductors is as below:

Dependence of R on T



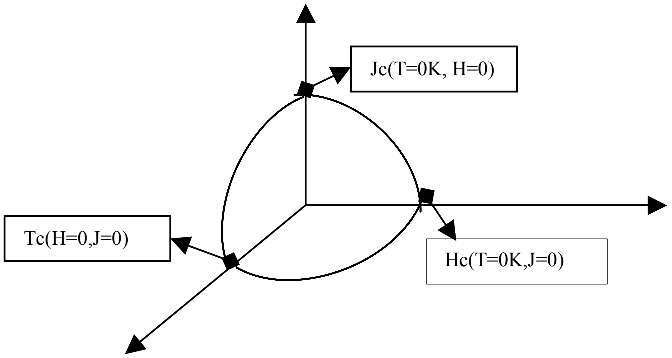
- Superconductivity vanishes both with external strong magnetic field and with the field produce because of current flow in the superconductor ring. There exists a Critical Values for the external magnetic field (Hc) and Critical current density (Jc).
- The value of H_C varies with temperature as

$$H_c(t) = H_c(0)\left[1 - \left(\frac{T}{T_c}\right)^2\right]$$

where Hc(0) is the critical magnetic field at 0K.
- If a superconducting material carried a current and if the magnetic field produced by this current is equal to Hc, the superconductivity disappears. The current density at which the superconductivity disappears is called the critical current density Jc.
- The current density below the critical value sustain itself where as above the critical value the current cannot sustain itself inside the superconducitng material is called Silsbee effect. A superconducting ring of radius R ceases to be a superconductor when the current is

$$I_c = 2\pi RH_c$$

- The Phase diagram of a superconductor showing the combined effects of temperature, current density and magnetic field, and the boundary separating superconducting and normal states is shown below:



Meissner Effect (or Meissner-Ochsenfeld effect)

- Superconductor completely expels any magnetic field lines that were initially penetrating it in its normal state is called Meissner Effect, discovered by Meissner and Ochsenfeld in 1933.(Fig2)
- The magnetic induction inside the specimen is given by

$B = \mu_0(H + M)$ where H is the extenal applied magnetic field and M is the intensity of magnetisation produced within the specimen.

At T<Tc, B=0 and M=-H The susceptibility of the material $\chi = \frac{M}{H} = -1$ a condition for perfect diamagnetism.
- According to Ohm's law the electric field within a conductor carrying a given current density is directly proportional to the resistivity

$$E=\rho J.$$

A perfect conductor is a conductor having zero resistivity i.e., E=0 for a perfect conductor. It means that electric field cannot exist inside the perfect conductor. If such a perfect conductor is in a magnetic field and the magnetic field is switched off, the changing magnetic flux will not induce an emf in it. According to the Maxwell's equation $\nabla x E = \frac{-\partial B}{\partial t}$ If

E=0, implies that B is constant. Consequently, the magnetic flux through the perfect conductor remains unchanged, and the applied magneitic field is trapped in the perfect conductor.

- In case of superconductor Meissner effect shows that along with $\frac{-\partial B}{\partial t}$=0 B is also zero(B=0). To sum up, the two mutually independent properties, namely zero resistivity and perfect diamagnetism are essential properties that characterize the superconducting state.

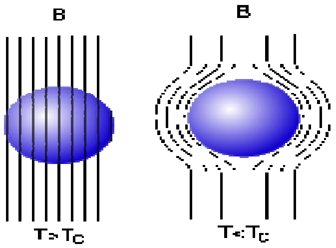


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Figure 2: - Figure shows the expulsion of magnetic flux during the transition from the normal to the superconductor state is called Meissner Effect.

London Penetration Depth(λ)

- In order to exclude an applied magnetic field from the interior of a material, it is necessary that a current be induced in the material. The magnetic field due to such currents causes a concellation of magnetic field in the volume of a superconeductor
- The Current flow in a thin layer on the surface of the superconducting material The existence of a surface current implies that the applied magnetic field penetrates some distance into the superconductor, decaying esponentially to zero over a length λ. The length λ is called *London Penetration Depth*.
- The decrease of magentic field penetration is descibed by the London equation $H(x) = H(0)e^{\frac{-x}{\lambda}}$ where H(0) is the field on the surface at x=0. λ is of the order of 10^{-3} to 10^{-4} A^0. It is independent of frequency of the magnetic field but it strongly depends on temperature. The temperature dependence of λ is given by $\left(\frac{\lambda_T}{\lambda_0}\right)^2 = \frac{1}{\left(1-(T/T_c)^4\right)}$ where λ_T and λ_0 are the penetration depths at T and 0K respectively.

Type-I Superconductors

- Type I superconductors are superconductors that cannot be penetrated by magnetic flux lines (Meissner-Ochsenfeld effect). Elementary superconductors, such as aluminium,lead, indium and niobium are typical Type I superconductors.
- The critical field Hc is relatively low for Type I superconductors. They would generate fields of about 0.01 Wb/m^2 to 0.2 Wb/m^2 only.
- In the variation of resistivity of a Type I superconductor as a function of applied magnetic field strength. The resistivity abruptly jumps from zero to a high value at Hc as shown in Fig(3).

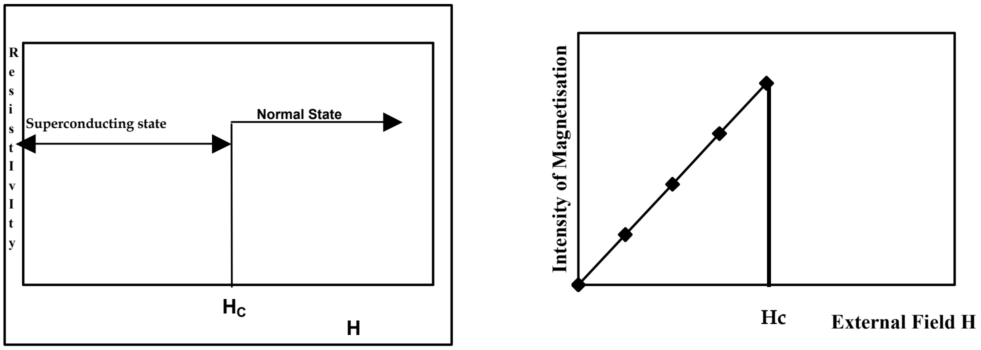


Figure 3: - Variation of Resistitity of a Type I Superconductor as a function of applied magnetic field strength and Magnetization curve for a Type I superconductor.

Type II Superconductors:-

- A Type-II superconductor is one of the two main types of superconductor. It is characterised by its gradual transition from the superconducting to the normal state. They are characterized by two critical fields H_{c1} and H_{c2} are the transition from superconducting state to normal state occurs gradually as the magnetic field is increased from H_{c1} to H_{c2}. Type-II superconductors tend to be made of metal alloys.
- The magnetization of the material grows in proportion to the external field upto the lower critical field H_{c1}. At H_{c1}, the magnetic field lines begin penetrating the material. As the magnetic field increases further, the magnetic flux through the material increases. At the upper critical field H_{c2}, the magnetization vanished completely and the external field has completely penetrated and destroys the superconductivity. Between H_{c1} and H_{c2} material is magnetically mixed state but electrically it is a superconductor. The region between H_{c1} and H_{c2} is the mixed or vortex state. Below H_{c1}, it exhibits complete diamagnetism and above H_{c2} behaves like a normal conductor.
- Type II are very useful in applications of creating very high magnetic fields.

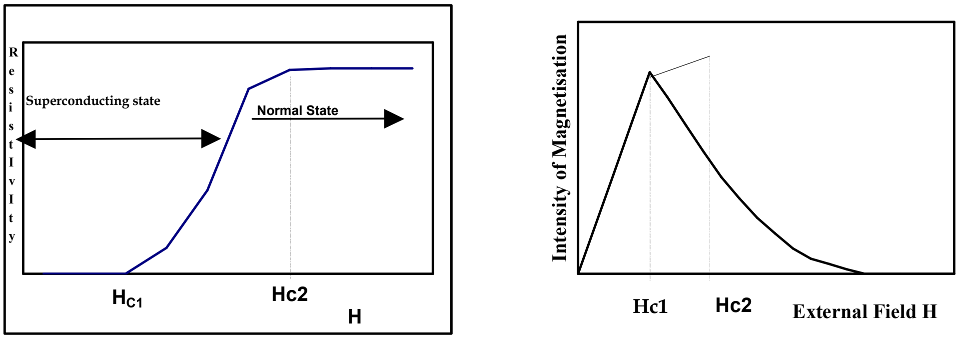
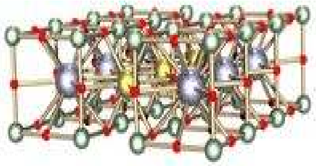


Figure 4: - Variation of the resistivity of a Type II superconductor as a function of applied magnetic field. And Magnetization curve for a Type II superconductor.

High-Temperature Superconductors

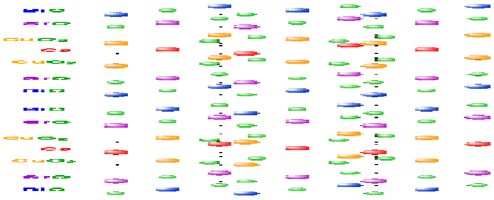
High-temperature superconductors are generally considered to be those that demonstrate superconductivity at or above the temperature of liquid nitrogen, or −196 °C (77 K), since this is the most easily attainable cryogenic temperature.

- Conventional superconductors, by contrast, require temperatures not higher than a few degrees above absolute zero (−273.15 °C). Though it is extremely cold by everyday standards, in the field of superconductivity, 77 K is considered high temperature.
- The term 'high-temperature superconductor' was first used to designate the new family of cuprate-perovskite ceramic materials discovered by J.G. Bednorz and K.A. Müller in 1986. Their discovery of the first high-temperature superconductor LBCO, with a transition temperature of 35 K, generated much excitement because it was previously widely assumed to be impossible for superconductivity to occur at such "high" temperatures.
- Recently, other unconventional superconductors have been discovered. Some of them also have unusually high values of the critical temperature T_c, and hence they are sometimes also called high-temperature superconductors, although the record is still held by a cuprate perovskite material (T_c=138 K, that is −135 °C).
- Most prominent materials in the high-T_c range are the so-called cuprates, such as $La_{1.85}Ba_{0.15}CuO_4$, YBCO (Yttrium-Barium-Copper-Oxide: Formula



$Yba_2Cu_3O_{7-x}$) and related substances.

- All known high-T_c superconductors are so-called Type-II superconductors. A Type-II superconductor allows magnetic field to penerate its interior in the units of flux quanta, creating 'holes' (or tubes) of normal metallic regions in the superconducting bulk. This property makes high-T_c superconductors capable of sustaining much higher magnetic fields.
- One of the top unsolved problems in modern physics is the question of how superconductivity arises in these materials, that is, what mechanism causes the electrons in these crystals to form Cooper pairs.
- One reason for less intensive grow of superconductor filed is that the materials in question are generally very complex, multi-layered crystals making theoretical modeling difficult.. For example, Bismuth strontium calcium copper oxide, or BSCCO (pronounced "bisko"), is a family of high-temperature Superconductors having the generalized chemical formula $Bi_2Sr_2Ca_nCu_{n+1}O_{2n+6}$.



Josephson effect

The Josephson effect is the phenomenon of current flow across two superconductors weakly coupled, separated by a very thin insulating barrier for example arrangement of two superconductors linked by a non-conducting oxide barrier—is known as a Josephson junction; the current that crosses the barrier is the Josephson current. It has important applications in quantum-mechanical circuits. The Josephson junction's properties are exploited in SQUIDs used to measure magnetic flux at the quantum level. It is also speculated that Josephson junctions may allow the realisation of qubits, the key elements of a future quantum computer.The basic equations governing the dynamics of the Josephson effect are

$U(t) = \frac{\hbar}{2e}\frac{\partial \phi}{\partial t}$ (superconducting phase evolution equation)

$I(t) = I_c \sin(\phi(t))$ (Josephson or weak-link current-phase relation)

where $U(t)$ and $I(t)$ are the voltage and current across the Josephson junction, $\varphi(t)$ is the phase difference between the wave functions in the two superconductors comprising the junction, and I_c is a constant, the *critical current* of the junction. The critical current is an important parameter of the device that can be affected by temperature as well as by an applied magnetic field. The physical constant, ($\hbar$/2e) is the magnetic flux quantum, the inverse of which is the Josephson constant.

1. The DC Josephson effect. This refers to the phenomenon of a direct current crossing the insulator in the absence of any external electromagnetic field, owing to tunneling. This DC Josephson current is proportional to the sine of the phase difference across the insulator, and may take values between $-I_c$ and I_c.
2. The AC Josephson effect. With a fixed voltage U_{DC} across the junctions, the phase will vary linearly with time and the current will be an AC current with amplitude I_c and frequency $\frac{h}{2e}U_{DC}$. This means a Josephson junction can act as a perfect voltage-to-frequency converter.

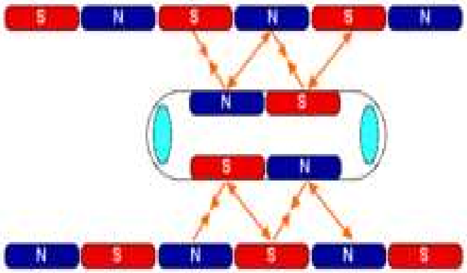
Technological applications of superconductivity

Some of the technological applications of superconductivity include the production of magnetometers based on SQUIDs, digital circuits . Magnetic Resonance Imaging(MRI), control magnets in particle accelerators and fusion reactors (tokamaks), power cables, and microwave filters (e.g., for mobile phone base stations).Many promising applications of superconductivity have been stalled by the impracticality of maintaining large systems (e.g. long stretches of cable) at cryogenic temperatures. These problems may soon be alleviated with the continued development of high temperature superconductors (HTS), as these can be cooled by using liquid nitrogen rather than liquid helium However, the currently known high-temperature superconductors are brittle ceramics which are expensive to manufacture and not easily turned into wires or other useful shapes.

Commercial quantities of HTS wire based on BSCCO are now available at around 5 times the price of the equivalent copper conductor. Pilot plants are being developed that use YBCO to produce coated conductors in a semi-continuous process. Manufacturers are claiming the potential to reduce the price in volume to 50% to 20% of BSCCO. If the latter occurs HTS wire will be competitive with copper in all large industrial applications.

Promising future industrial and commercial applications include transformers, power storage, motors, fusion reactors and magnetic levitation devices. Most applications employ the well-understood conventional superconductors, but it is expected that high-temperature superconductors will soon become more cost-effective in many cases.

Magnetic levitation, **maglev**, or **magnetic suspension** is a method by which an object is suspended above another object with no support other than magnetic fields. Maglevs could potentially reach velocities comparable to turboprop and jet aircraft (500 to 580 km/h). Since much of a Maglev's propulsion system is in the track rather than the vehicle, Maglev trains are lighter and can ascend steeper slopes than conventional trains. They can be supported on lightweight elevated tracks. Maglevs have operated commercially since 1984. However, scientific and economic limitations have hindered the proliferation of the technology. Maglev technology has minimal overlap with wheeled train technology and is not compatible with conventional railroad tracks. Because they cannot share existing infrastructure, maglevs must be designed as complete transportation systems. Due to the lack of physical contact between the track and the vehicle, the only friction exerted is that between the vehicles and the air. If it were the case that air-resistance were only a minor form of friction, it would be appropriate to say "Consequently maglevs can potentially travel at very high speeds with reasonable energy consumption and noise levels. Systems have been proposed that operate at up to 650 km/h (404 mph), which is far faster than is practical with conventional rail transport". But this is not true. In an ordinary high speed train, **most of the friction is air resistance.** The very high maximum speed potential of maglevs make them competitors to airline routes of 1,000 kilometers (600 miles) or less. The world's first commercial application of a high-speed maglev line is the IOS (initial operating segment) demonstration line in Shanghai that transports people 30 km (18.6 miles) to the airport in just 7 minutes 20 seconds (top speed of 431 km/h or 268 mph, average speed 250 km/h or 150 mph). Other maglev projects worldwide are being studied for feasibility.



SQUIDS

SQUIDs, or **Superconducting Quantum Interference Devices**, are used to measure extremely small magnetic fields; they are currently the most sensitive such devices (magnetometers). Some processes in animals produce very small magnetic fields; typically sized between a microtesla (10^{-6} T) and a nanotesla (10^{-9} T). There are two main types of SQUID: DC and RF (or AC). RF SQUIDs have only one Josephson junction whereas DC SQUIDs have two or more junctions. This makes DC SQUIDs more difficult and expensive to produce, but DC SQUIDs are much more sensitive.

SQUIDs are basically a superconducting loop with a “weak link” to measure magnetic flux changes with in the loop. A weak link is a region that has lower critical current than the resot of superconducting ring. When the current in the link exceeds the critical current, the link becomes normal. It allows fluxons to pepetrate the link. When flucons penetrate the link, the current falls to critical value and the linkreverts to superconducting state. The weak link thus acts as a gate. The critical curretn in the weak link varies periodically as the total flux through the area enclosed by the superconducting loop changes. The current executes one cycle each time the flux changes by one fluxon. The changing magnetic field due to changes in squid current induce emf and current in the sensing coil. The emf induced in the coil may be used to drive an electronic counting circuit.

Most SQUIDs are fabricated from lead or pure niobium. The lead is usually in the form of an alloy with 10% gold or indium, as pure lead is unstable when its temperature is repeatedly changed. The base electrode of the SQUID is made of a very thin niobium layer, formed by deposition, and the tunnel barrier is oxidised onto this niobium surface. The top electrode is a layer of lead alloy deposited on top of the other two, forming a sandwich arrangement. To achieve the necessary Superconducting characteristics, the entire device is then cooled to within a few degrees of absolute zero with liquid helium.

More recently developed "high temperature" SQUIDS are made of a substance called YBCO (chemical formula $YBa_2Cu_3O_{7-x}$), and are cooled by liquid nitrogen which is cheaper and more easily handled than liquid helium. They are less sensitive than conventional "low temperature" SQUIDS but many applications do not require the extreme sensitivity of the SQUID. The basic principle of operation is closely linked to flux quantisation. In this phenomenon, favoured flux states within a loop of superconductor are a multiple of the flux quantum.

The extreme sensitivity of SQUIDs make them ideal for studies in biology. For example, measurements from an array of SQUIDs to make inferences about neural activity inside brains. Because SQUIDs can operate at acquisition rates much higher than the highest temporal frequency of interest in the signals emitted by the brain (kHz). Probably the most common use of SQUIDs is in magnetic property measurement systems. Another application is the scanning SQUID microscope, which uses a SQUID immersed in liquid helium as the probe. The use of SQUIDs in oil prospecting, mineral exploration, earthquake prediction and geothermal energy surveying is becoming more widespread as superconductor technology develops; they are also used as precision movement sensors in a variety of scientific applications, such as the detection of gravity waves. Four SQUIDs are currently employed on Gravity Probe in order to test the limits of the theory of general relativity.

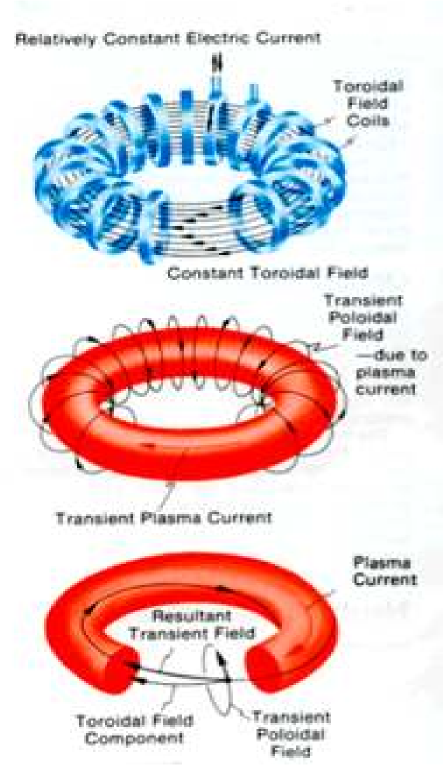
MANGETIC RESONANCE IMAGING (It is not their in the VTU syllabus)

Magnetic Resonance Imaging (MRI), formerly referred to as *Magnetic Resonance Tomography (MRT)* or *Nuclear Magnetic Resonance (NMR)*, is a method used to visualize the inside of living organisms as well as to detect the composition of geological structures. When the object to be imaged is placed in a powerful, uniform magnetic field the spins of the atomic nuclei with non-zero spin numbers (essentially, an unpaired proton or neutron) within the tissue all align in one of two opposite directions: parallel to the magnetic field or antiparallel. Common magnetic field strengths range from 0.3 to 3 teslas. The magnetic dipole moment of the nuclei precesses around the axial field. While the proportion is nearly equal, slightly more are oriented at the low energy angle. The frequency with which the dipole moments process is called the Larmor frequency. The tissue is then briefly exposed to pulses of electromagnetic energy (RF pulses) in a plane perpendicular to the magnetic field, causing some of the magnetically aligned hydrogen nuclei to assume a temporary non-aligned high-energy state. The frequency of the pulses is governed by the Larmor equation. From this we get the set of data. Images can be created from the acquired data using the discrete Fourier transform (DFT). The above figure shows the Magnetic Resonance Image showing a vertical cross section through a human head.

One advantage of an MRI scan is that it is harmless to the patient. It uses strong magnetic fields and non-ionizing radiation in the radio frequency range. By Comparing this to CT (Computed Tomography) scans and traditional X-rays which involve doses of ionizing radiation and may increase the risk of malignancy, especially in a fetus.

Tokomaks (It is not their in the VTU Syllabus)

A **tokamak** is a machine producing a toroidal (doughnut-shaped) magnetic field for confining a plasma. It is one of several types of magnetic confinement devices and the leading candidate for producing fusion energy. The tokamak is characterized by azimuthal (rotational) symmetry and the use of the plasma current to generate the helical component of the magnetic field necessary for stable equilibrium. This can be contrasted to another toroidal magnetic confinement device, the stellarator, which has a discrete (e.g. five-fold) rotational symmetry and in which all of the confining magnetic fields are produced by external coils with a negligible current flowing through the plasma



For General Information

The following table gives the information about the existing applications and the emerging applications of the superconductor

	Current	**Emerging**
medical		
magnetic resonance imaging	X	
biotechnical engineering		X
electronics		
SQUIDs	X	
transistors		X
Josephson Junction devices		X
circuitry connections		X
particle accelerators	X	
sensors	X	
Industrial		
separation	X	
magnets	X	
sensors and transducers		X
magnetic shielding		X
Power Generation		
Motors		X
Generators		X
Energy Storage		X
Transmission		X
Fusion		X
Transformers and Inductors		X
Transportation:		
Magnetically levitated vehicles		X
Marine propulsion		X

Note: - The type of the questions and the Numerical for reference will be uploaded by next week.