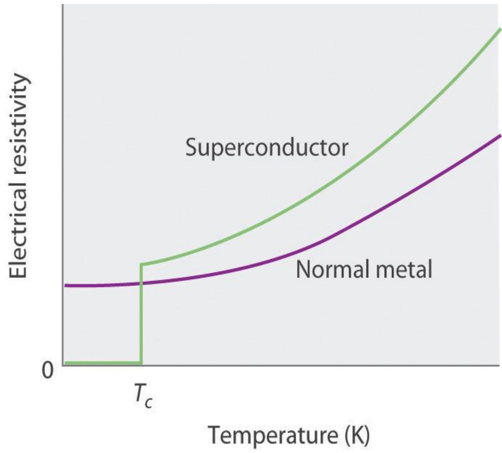
UNIT 4 - SUPERCONDUCTIVITY



SUPERCONDUCTOR

Materials which have zero electrical resistance are termed as superconductors.

CRITICAL TEMPERATURE (T_c)

The temperature at which the electrical resistivity of a material drops to zero. Below T_c the material behaves like a superconductor and above T_c it behaves like a normal metal.

CONDITIONS TO DESTROY SUPERCONDUCTIVITY

- High temperature ($T > T_c$)
- High magnetic field ($H > H_c$)
- High current ($I > I_c$)

The dependence of temperature on the magnetic field can be represented as,

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

H_c – critical field strength at temperature T
H_c (0) – critical field at OK
T_c – Critical temperature.

ISOTOPE EFFECT

It is experimentally observed that the transition temperature Tc of a superconductor varies with its isotopic mass as,

$$T_c \propto \frac{1}{\sqrt{M}}$$

CHARACTERISTICS OF SUPERCONDUCTORS

Following are the important characteristics of the superconductors:

(i) The current in the superconductors is sustained for a very long period **(Persistent current)**.

(ii) When the current is increased above its critical value (*Ic*), the superconductor behaves like a normal conductor.

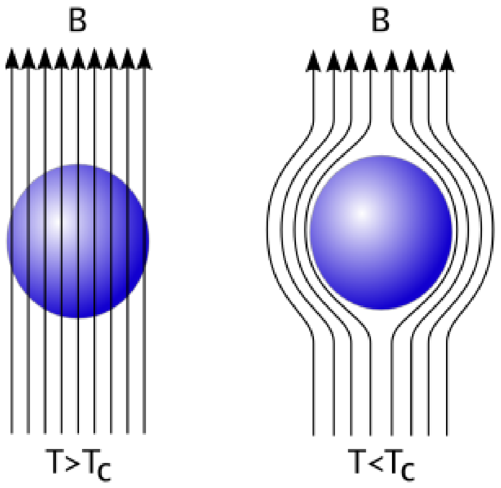
(iii) The magnetic field does not penetrate the superconductor **(Meissner effect).** However, above the critical magnetic field, the superconductor becomes a normal conductor.

(iv) Good conductors at room temperature are not superconductors and superconducting materials are not good conductors at room temperature.

(v) Ferromagnetic materials and anti-ferromagnetic materials are not superconductors.

MEISSNER EFFECT

When a material transition from normal state to superconducting state it excludes magnetic fields. This phenomenon is called Meissner effect,
When a superconductor is cooled below its critical temperature it completely repels the applied magnetic field.



. Meissner effect : Superconductors below critical temperature repel to the magnetic field

For a metal in a superconducting state, magnetic field inside is zero

$$B = \mu_0 (H+M)$$
$$0 = \mu_0 (H+M)$$
$$M = -H$$

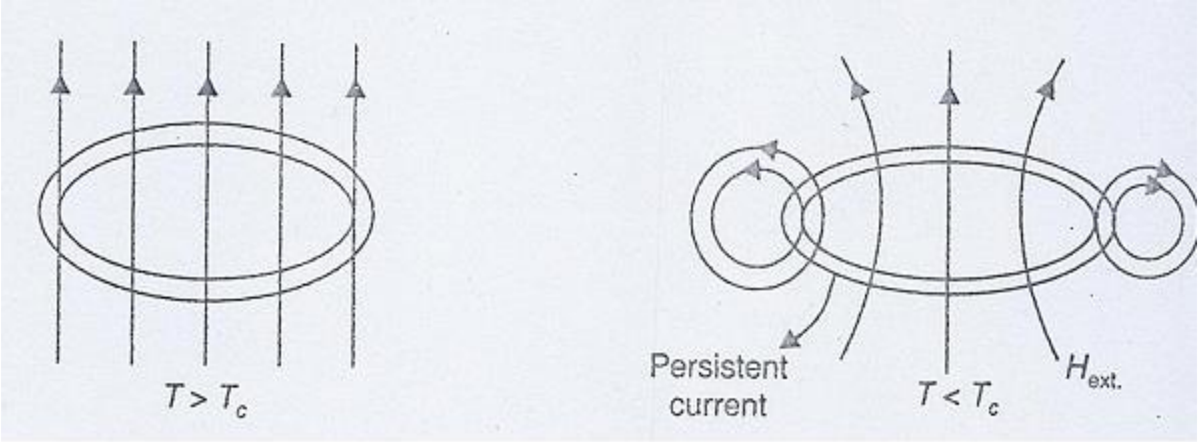
Or magnetic susceptibility, $\chi = M/H = -1$

$$\chi = -1$$

This is one of the characteristics of a perfect diamagnetic material. Thus this proves that the superconductor behaves diamagnetic.

PERSISTENT CURRENT

When a electric current is set up in a superconductor, it can persist for a long time even without an external EMF. Consider a circular ring shaped superconductor material, an induced current will flow in the ring by cooling it below transition temperature by applying magnetic field. Even when the field is switched off, the flux outside the ring disappears but it remains trapped inside the ring.

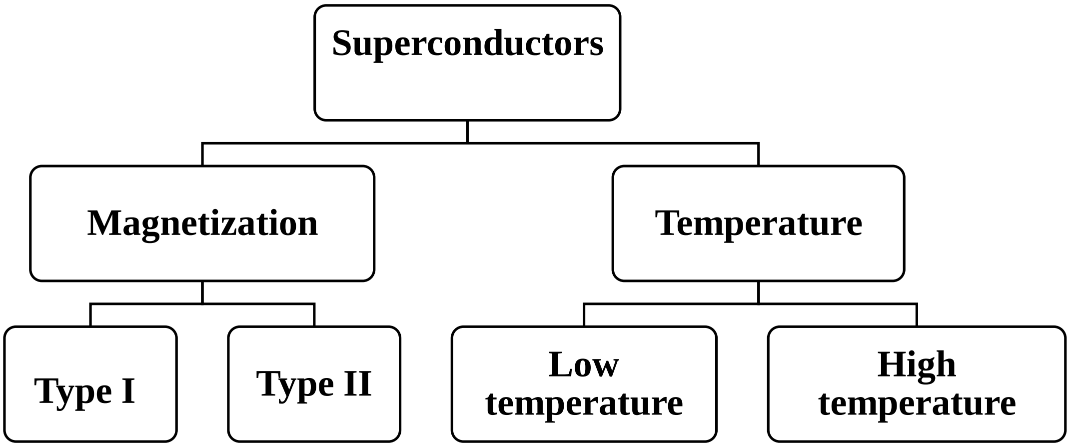


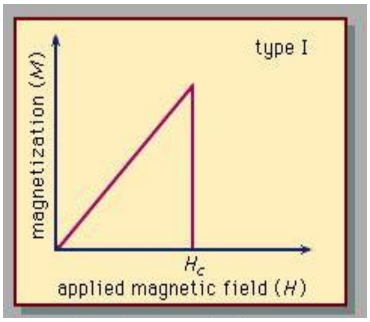
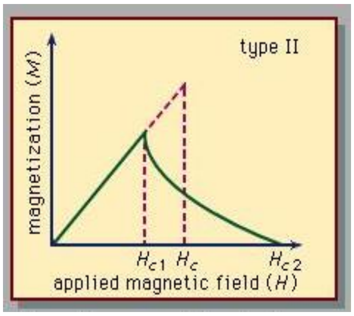
. Persistent current

Due to the zero resistance, persistent current exists. The persistent current also produces a magnetic field which makes the superconductors to be used as superconductor magnets which does not require any power supply to maintain the magnetic field.

TYPES OF SUPERCONDUCTORS

Superconductors are classified based on temperature and magnetization.



S.No.	Type – I superconductor	Type – II superconductor
1.	The material loses its magnetization suddenly	The material loses its magnetization gradually
2.	They exhibit complete Meissner effect ie., they are completely diamagnetic	They do not exhibit complete Meissner effect
3.	There is only one critical magnetic field (H_C).	There are two critical magnetic field i.e., lower critical field Hc_1 and upper critical field (Hc_2)
4.	No mixed state exists.	Mixed state is present
5.	Highest known critical magnetic field is 0.1 telsa	Critical magnetic field is much greater i.e., upto 30 tesla.
6.	They are *called soft superconductors* because of their tendency to give away their property to low magnetic field.	They are called *hard superconductors* because of they require large magnetic field to destroy the super conducting state.
7.	Examples : lead, tin and mercury etc.,	Examples : Nb – Sn, Nb – Zr, Nb – Ti, and Va – Ga, etc.
8.		

BCS THEORY

BCS theory gives the quantum mechanical explanation about the materials superconductivity behaviour. In 1957 three scientist **J. Bardeen, L.N. Cooper and John Schreiffer** formulated the BCS theory. This theory is based upon a microscopic mechanism called electron-electron interaction with phonon as a mediator.

FORMATION OF COOPER PAIRS

Cooper took the first step to explain this theory, at lower temperatures the positive lattice vibrates slowly. The electrons moving between the positive lattice attracts the positive lattice to it as shown in the Fig. 10. The positive ions in the lattice surrounding the electron gets attracted and forms a dense region of positive ions, this dense region of positive ions attracts another electron towards it (Fig. 11).

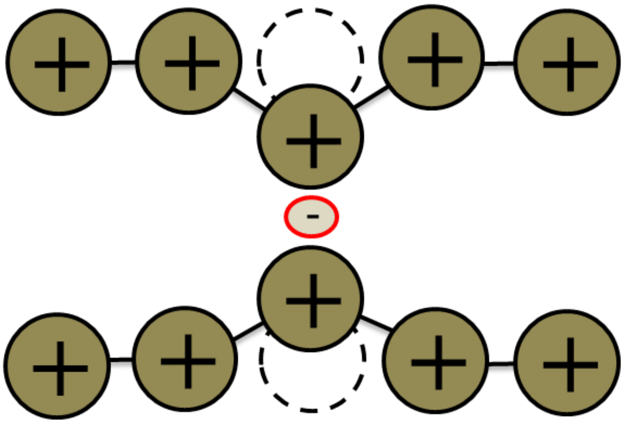


Fig. 10. Electron moving inside positive lattice, it attracts the positive lattice towards it leading to a lattice distortion.

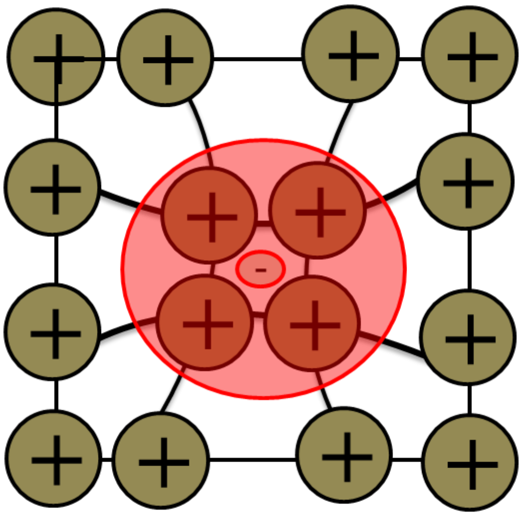


Fig. 11. Formation of dense positive region

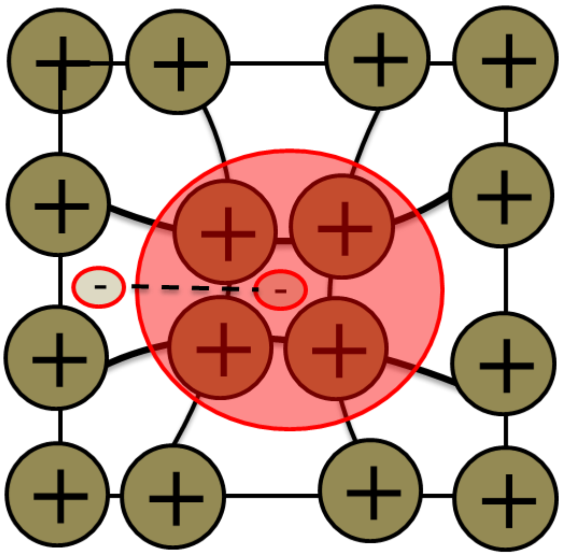
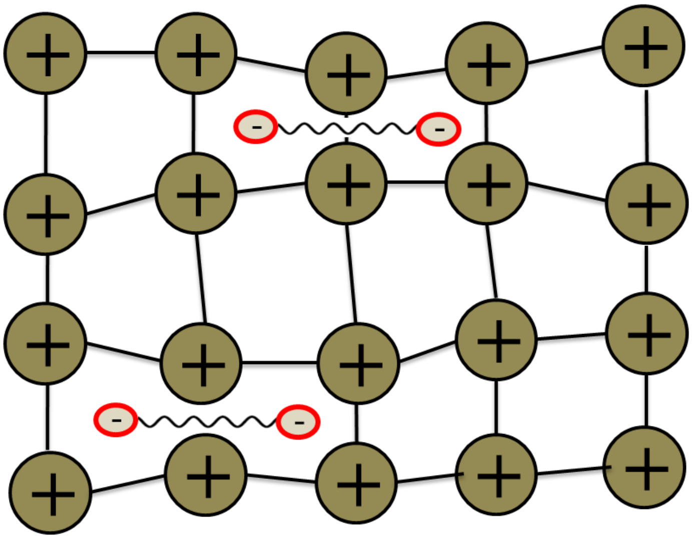


Fig. 12. Dense positive region attracts another electron towards it.



Cooper pair is free to move within the lattice without any resistance

These two electrons are connected via a phonon (quanta of energy associated with positive lattice vibration), this leads to the formation of Cooper pairs. Each cooper pair consists of two electrons having opposite moments and opposite spins. These pairs can move through the crystal without any scattering by the positive lattice. Their movement is with zero resistance. The movement of Cooper pairs without any resistance leads to the phenomena of superconductivity.

In normal conductors, conduction of electrons gets scattered by positive lattice vibrations and various impurities which obstruct their motion. In superconductors, the superconducting current is carried by Cooper pairs which does not get scattered by the lattice ions. In order to break the Cooper pair, energy equal to the energy gap between the Cooper pairs should be given. At lower temperatures, the positive lattice vibrates with a minimum energy, which is not sufficient to break the Cooper pairs. Thus Cooper pairs carry the superconducting current, which flows without any resistance at very lower temperatures. This leads to the superconducting behaviour (zero electrical resistance) for a material at very low temperatures

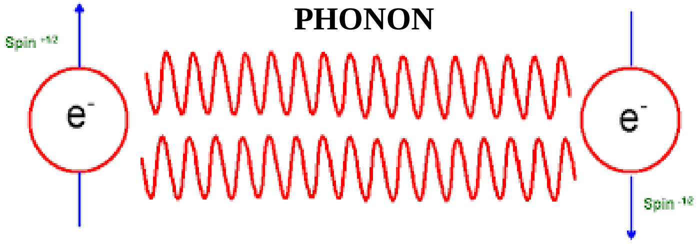


Fig. 13. Cooper pairs

JOSEPHSON EFFECT

Two superconductors separated by a thin insulator (normally an oxide) barrier is called Josephson junction (Fig. 14).

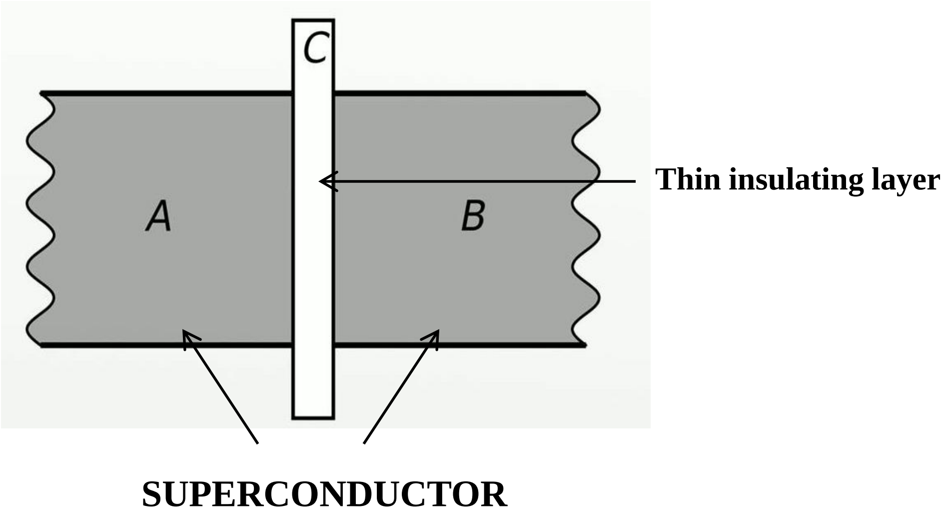


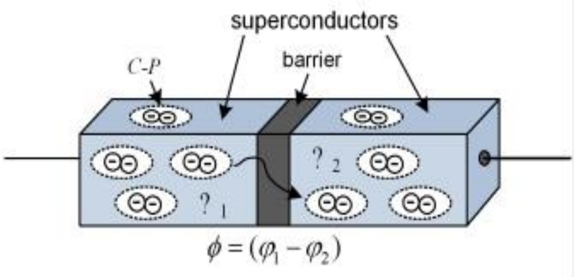
Fig. 14. Josephson junction

DC JOSEPHSON EFFECT

The tunnelling of superconducting electron pairs through Josephson junction leads to the flow of current pairs through Josephson junction leads to the flow of current without a voltage drop. This phenomenon is known as DC Josephson effect.

AC JOSEPHSON EFFECT

When a DC voltage is applied across the Josephson junction through which supercurrent is flowing, an AC current (high frequency current oscillations) is noticed. This phenomenon is known as AC Josephson effect.



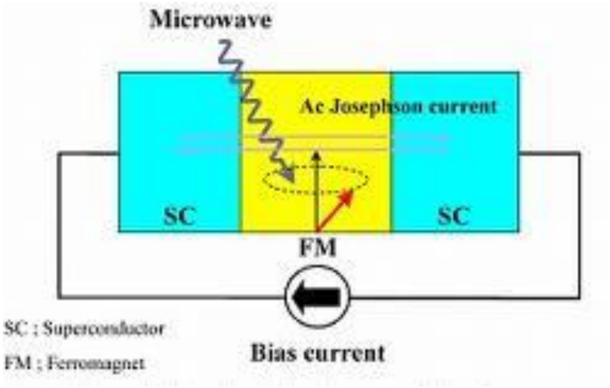


Fig. 15. DC JOSEPHSON EFFECT

Fig. 16. AC JOSEPHSON EFFECT

LONDON PENETRATION DEPTH

In superconductors, the London penetration depth characterizes the distance to which a magnetic field penetrates into a superconductor and varies exponentially to zero from the surface.

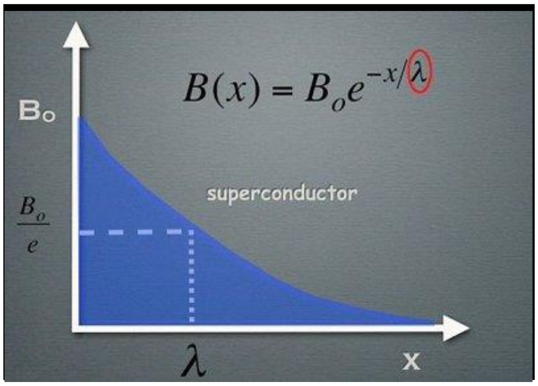


Fig. 17. Penetration depth

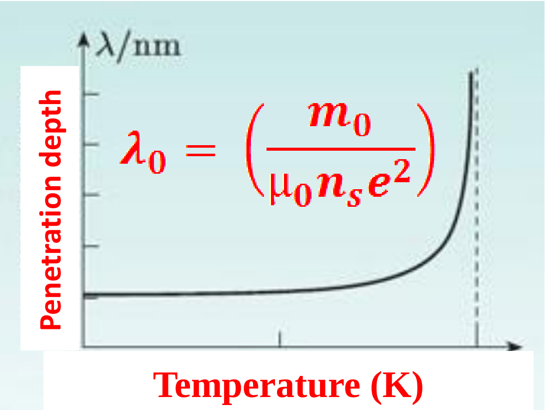


Fig. 18. Variation of λ with T

According to F. London and H. London (London theory), the magnetic field at the surface of a superconductor does not vanish suddenly, it decays exponentially to zero according to the following equation (Fig. 17),

$$B = B_0 e^{\frac{-x}{\lambda}}$$

Where B_0 is the field at the surface, x is the distance from the surface and λ is the characteristic length known as London penetration depth.

The penetration depth varies with temperature. At low temperatures it is almost constant, but higher temperatures the penetration depth increases rapidly and tends to infinity as the temperature approaches the transition temperature T_c (Fig. 18). This change is given by the relation,

$$\left(\frac{\lambda_T}{\lambda_0}\right)^2 = \frac{1}{\left[1 - \left(\frac{T}{T_c}\right)^4\right]}$$

$$\lambda_0 = \left(\frac{m_0}{\mu_0 n_s e^2}\right)$$ Penetration depth at 0K

m_0 and e are the mass and charge of electron respectively, n_s is the number of superelectrons.

APPLICATIONS OF SUPERCONDUCTORS

SQUID

SQUID stands for Superconducting Quantum Interference Device. It is an ultra – sensitive instrument used to measure very weak magnetic field of the order of 10^{-14} tesla.

Principle

We know that a small change in magnetic field produces variation in the flux quantum.

Description and Working

A SQUID consists of a superconducting ring which can have the magnetic fields of quantum values (1, 2, 3..) of flux placed in between two Josephson junctions as shown in fig. 18.

When the magnetic field is applied perpendicular to the plane of the ring, the current is induced at the two Josephson junctions. The induced current produces the interference pattern and it flows around the ring so that the magnetic flux in the ring can have the quantum value of magnetic field applied.

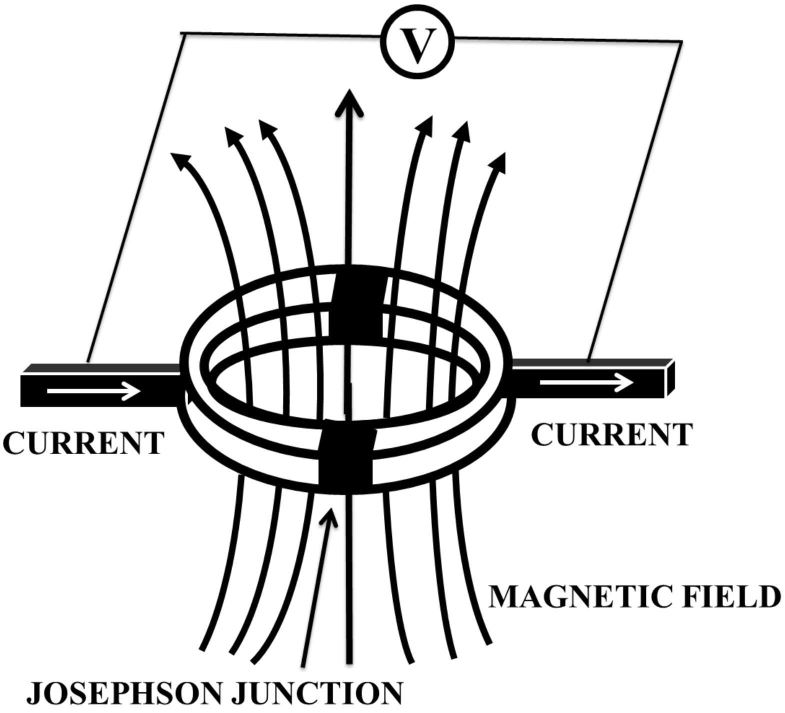


Fig. 18. SQUID

Applications

i. SQUID can be used to detect the variation of very minute magnetic signals in terms of quantum flux.
ii. It can also be used as storage device for magnetic flux.
iii. SQUID is useful in the study of earthquakes, removing paramagnetic impurities, detection of magnetic signals from the brain, heart etc.

MAGNETIC LEVITATION

We know that a superconducting material shows the Meissner effect. Due to this effect, superconducting materials strongly repel external magnets. This leads to a levitation effect.

When a magnet is placed over a superconductor, it floats as shown in Fig. 19. This phenomenon is known as magnetic levitation. This principle is used in magnetically levitated trains (super-fast trains)

In Japan, powerful superconducting magnets are being developed to levitate trains at a greater speed of 500 km / hour with minimum expenditure of energy. This magnetically levitated train is called as Maglev train.

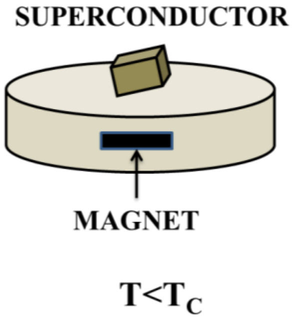


Fig. 19. Magnetic levitation

Magnetic Levitated Train (Maglev train)

The magnetic levitated train does not move over the rails but it floats above the rails.

Description and Working

This train has superconducting magnets, built into its base (Fig. 20). An aluminum guide way, above which the train will float by magnetic levitation. Magnetic levitation is brought about by enormous repulsion between two highly powerful magnetic fields, one produced by the superconducting magnet inside the train and the other by the electric current in the aluminum guide way.

The current in the guide way produces the necessary magnetic field to levitate the train and helps in propelling the train forward. The train is provided with retractable wheels. The wheels serve almost the same purpose as those of an airplane. The train runs on the guide way just as the way the airplane takes off. Once the train is levitated in air, the wheels are retracted into the body. The height at which the train levitates above the guide way is about 10 to 15 cm. While coming to halt, the wheels are drawn out and the train slowly settles on the guide way and runs over a distance, just as an airplane does while landing.

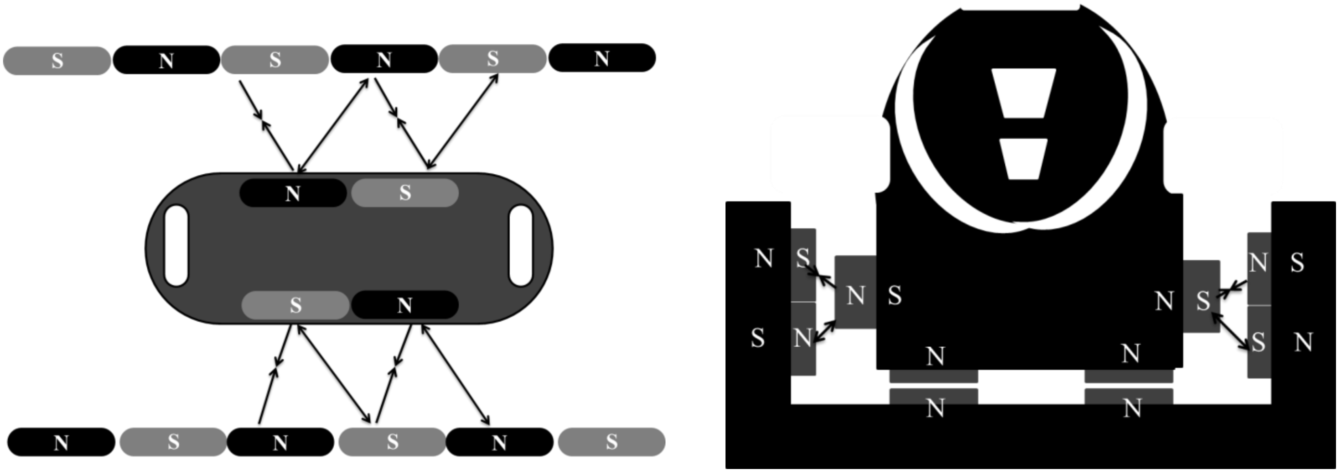


Fig. 20. Maglev train