SUPERCONDUCTORS

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SUPERCONDUCTIVITY

- Property of complete disappearance of electrical resistance in solids when they are cooled below a characteristic temperature.
  - Called transition temperature or critical temperature.

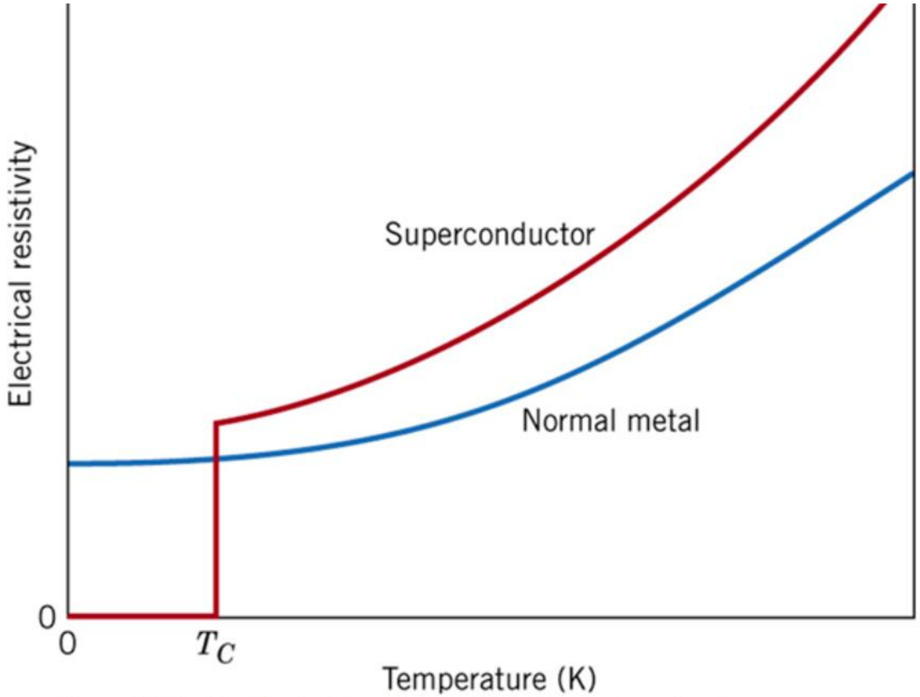


Figure 1. Graph of electrical resistivity versus temperature for a superconductor and a normal metal.

- Superconductivity was discovered in 1911 accidentally by a Dutch physicist, H. K. Onnes (1853–1926) when he used liquid helium to cool down mercury.
- Onnes was the first person to liquefy helium a few years earlier
- Later he was surprised to observe that keeping a mediocre conductor like mercury in liquid helium to cool it to a temperature of 4.2 K, leads to sudden drop in its electrical resistivity.

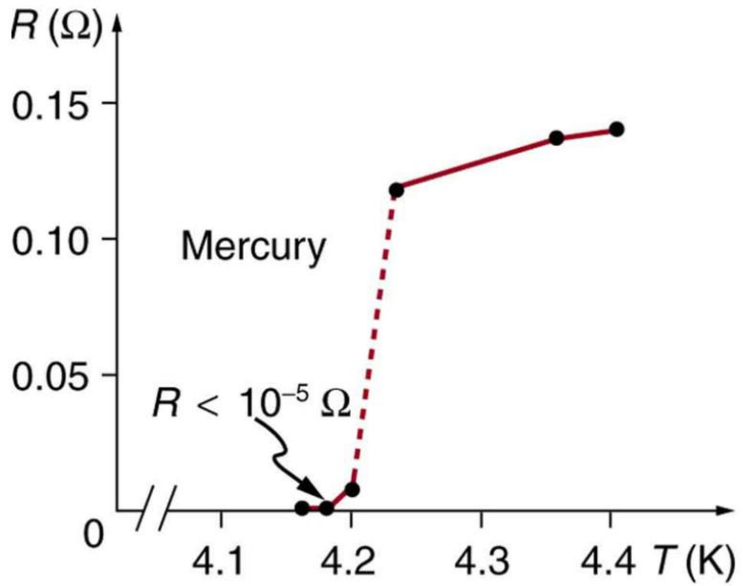


Figure 2. Electrical resistivity versus temperature for a superconductor shows a sharp transition to zero at the critical temperature T_c.

CLASSICAL ELEMENTAL SUPERCONDUCTORS

Element	Transition temperature, K
Zinc	0.88
Aluminum	1.20
Indium	3.41
Tin	3.72
Mercury	4.15
Lead	7.19

- Until 1983 record T_c = 23.3 K was that of Nb_3Ge alloy.
- **High temperature superconductors discovered in** 1986: T_c = 80-93 K, parent structure $YBa_2Cu_3O_7$.
- Around 1990, the record transition temperature (TBCCO) was at T_C= 134 K.

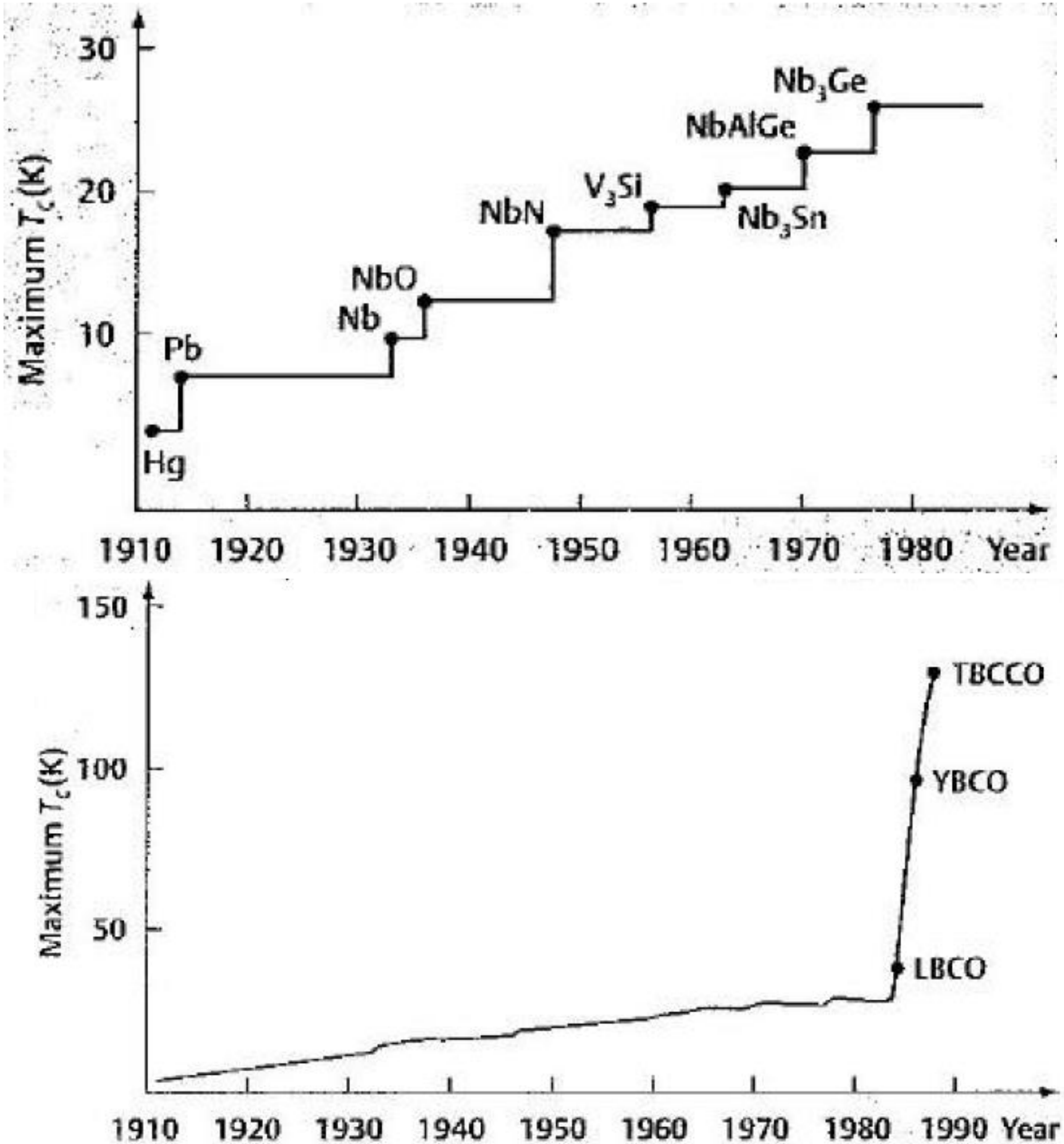


Figure 3. Maximum Tc of superconductors discovered over the year

- In 1986, a ceramic compound was found to have an unprecedented T_c of 35 K.
- It was a breakthrough suggesting that much higher critical temperatures could be possible.
- By early 1988 another ceramic (this of thallium, calcium, barium, copper, and oxygen) had been found to have T_c = 125 K
- The first commercial use of a high temperature superconductor is in an electronic filter for cellular phones.
- High-temperature superconductors are used in experimental apparatus, and they are actively being researched, particularly in thin film applications
- The search is on for even higher T_c superconductors, many of complex and exotic copper oxide ceramics, sometimes including strontium, mercury, or yttrium as well as barium, calcium, and other elements.
- Room temperature (about 293 K) would be ideal, but any temperature close to room temperature is relatively cheap to produce and maintain.
- There are persistent reports of T_c s over 200 K and some in the vicinity of 270 K. Unfortunately, these observations are not routinely reproducible.

EFFECT OF TRAPPED MAGNETIC FLUX: PERSISTENT CURRENT

Consider a ring made out of superconductive material and follow following steps:

1. At $T > T_c$ the material is normal state.
2. When the external magnetic field is now turned on, it penetrates through the ring.

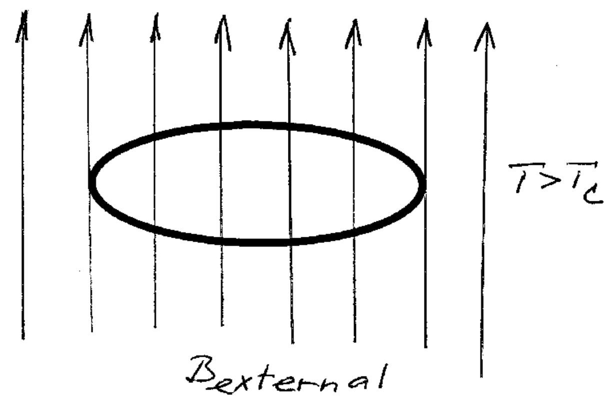
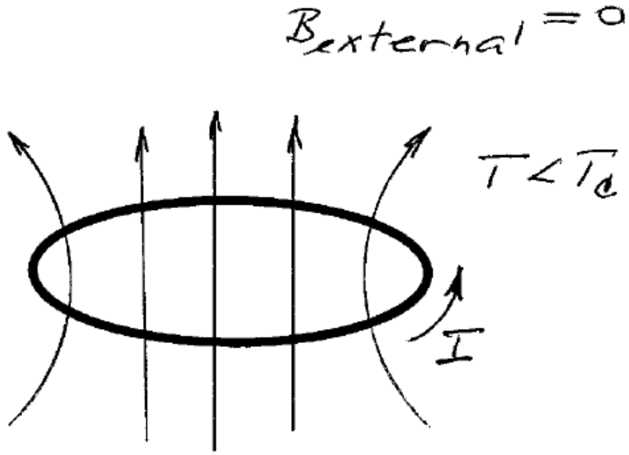


Figure 4. A ring in its normal state, is placed in an external magnetic field at T > Tc

3. Reduce the temperature so that $T < T_c$ and remove the external magnetic field.
4. You discover that the magnetic field that was penetrating through the opening of the ring remains there. The magnetic flux remains trapped in the ring opening.



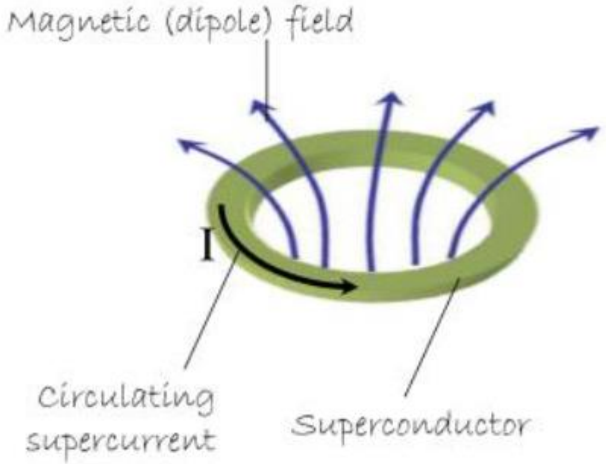


Figure 5. Trapped magnetic flux in the superconducting ring after the external magnetic field is switched off

This effect can be explained in terms of Faraday's law of induction:

$$\oint \vec{E}.d\vec{l} = -\frac{d\Phi}{dt}$$

E : Electric field along the closed loop,
Φ : Magnetic flux through the opening of the ring.

Below T_c, the resistivity of superconductor = 0, i.e. the electric field inside the superconductor must be zero as well. In view of this,

$$\oint \vec{E}.d\vec{l} = 0 \qquad \text{Or,} \qquad \frac{d\Phi}{dt} = 0$$

i.e. $\Phi = B(\text{area}) = \text{const}$

The magnetic flux Φ through the ring must remain constant. For this reason the magnetic flux remains trapped in the opening of the ring after the external magnetic field has been turned off.

- The trapped magnetic field passing through the ring is due to the current induced in the ring when the external magnetic field was turned off.
- The induced current is called the *persistent current*.
- The current persists, it does not decay because the resistance of the ring is zero.
- Actually no decrease of current was observed over the period of three years!
- Theoretically, the relaxation time of current carriers in the superconductor is greater than the age of universe.

MEISSNER EFFECT

- *Expulsion of magnetic field from the interior of the superconductor.*
- Consider a solid made out of superconductive material.
- At T>Tc the material is in normal state.
- When external magnetic field is turned on, the external magnetic field will penetrate through the material.
- As the material is cooled down such that T < Tc, complete expulsion of these magnetic field lines are observed.

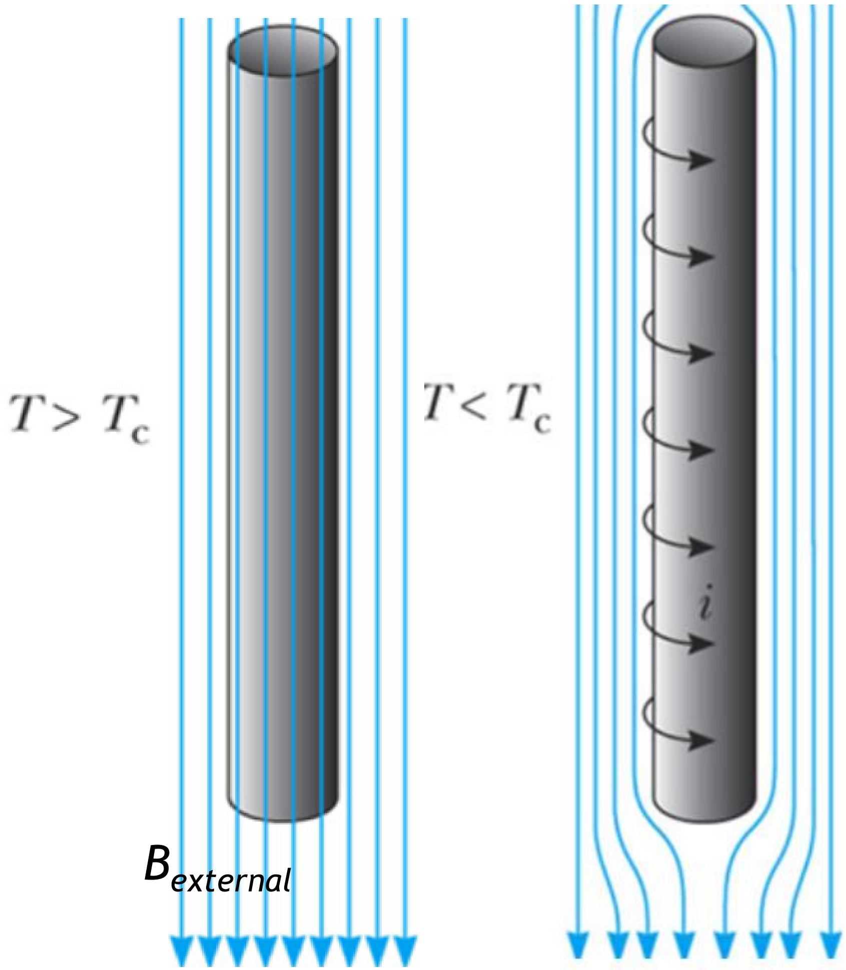


Figure 6. Magnetic field lines penetrate inside the material at room temperature (normal state) but get expelled at temperature T < Tc (superconducting state)

This is what happens:

- Superconductor expels magnetic field from the interior by setting up electric current at the surface.
- The surface current creates magnetic field that exactly cancels the external magnetic field!
- This electric current at the surface of the superconductor appears at $T<T_c$ in order that $B = 0$ inside the superconductor.

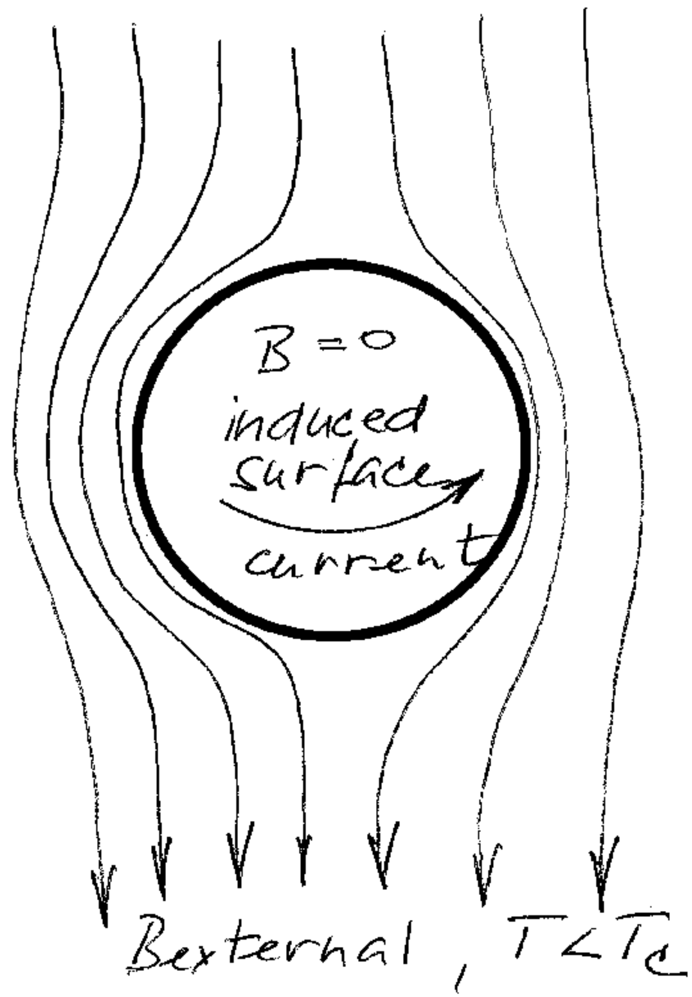


Figure 7. Induced surface current imitates the external magnetic field inside the material
in opposite direction such that the net magnetic field cancels out.

- The Meissner effect is so strong that a magnet can actually be *levitated* over a superconductive material.

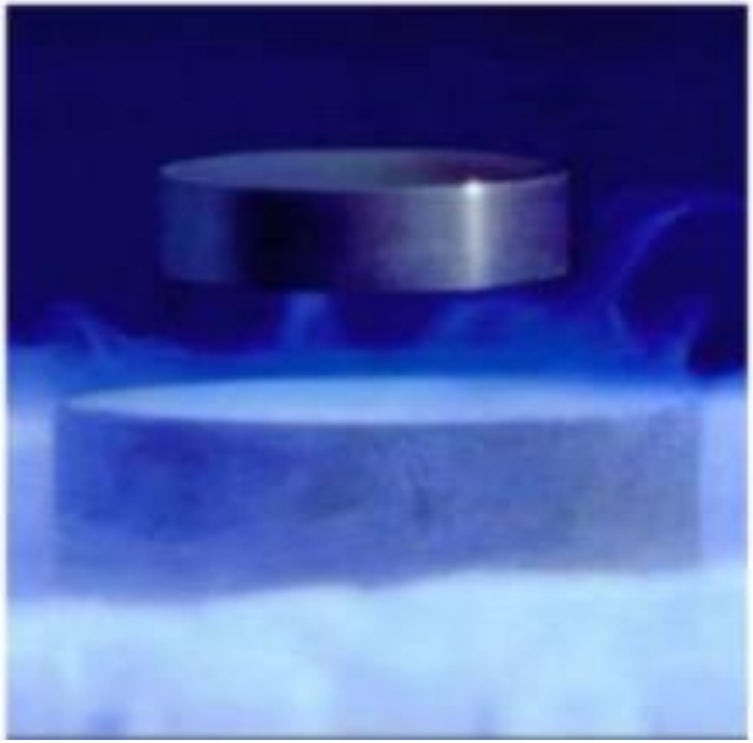


Figure 8. One characteristic of a superconductor is that it excludes magnetic flux and, thus, repels other magnets. The small magnet levitated above a high-temperature superconductor, which is cooled by liquid nitrogen, gives evidence that the material is superconducting. When the material warms and becomes conducting, magnetic flux can penetrate it, and the magnet will rest upon it.

- B = 0: $$B = \mu_0(H + M) = 0$$ $$M = \chi H = -H$$
- Susceptibility = -1 : Perfect diamagnetism

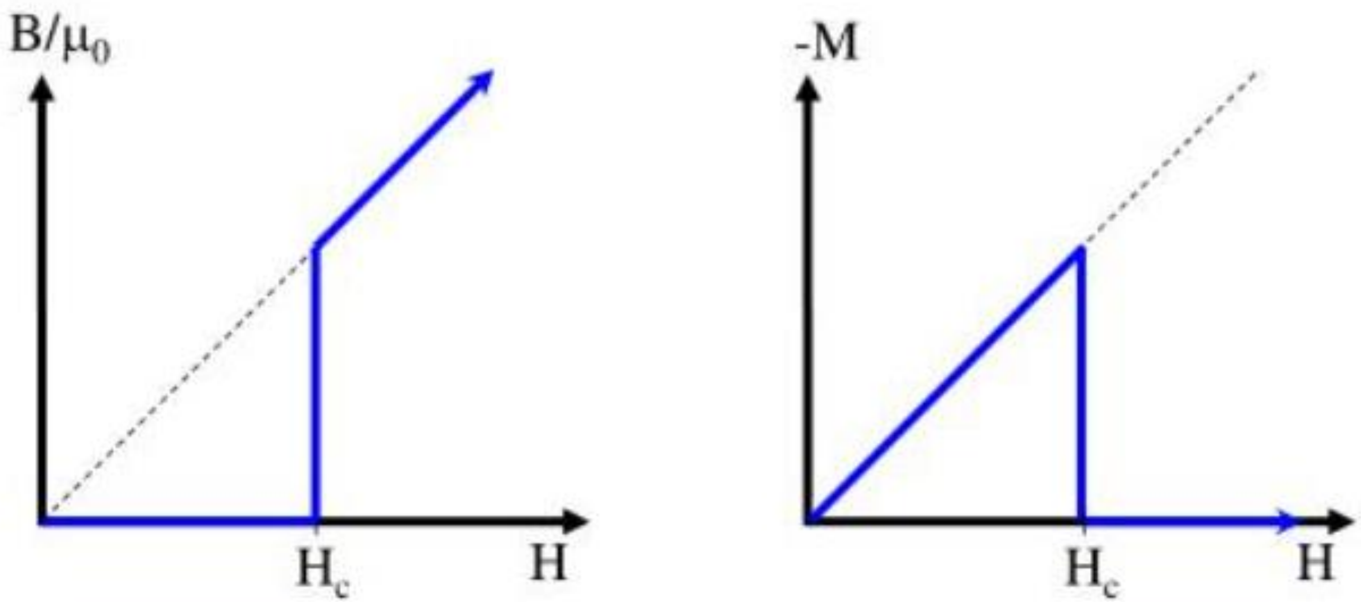


Figure 9. Magnetic field induction versus applied magnetic field and, magnetization versus applied magnetic field in superconductors

Penetration Of Magnetic Field Below The Surface Of Superconductors

- The surface current is distributed in the surface layer
- Layer carrying the electric current has a finite thickness, and because of this, the external magnetic field partially penetrates into the interior of the superconductor.
- London's equation:

$$B(x) = B_{external} \exp\left(-\frac{x}{\lambda}\right)$$

where, λ = penetration distance at temperature T

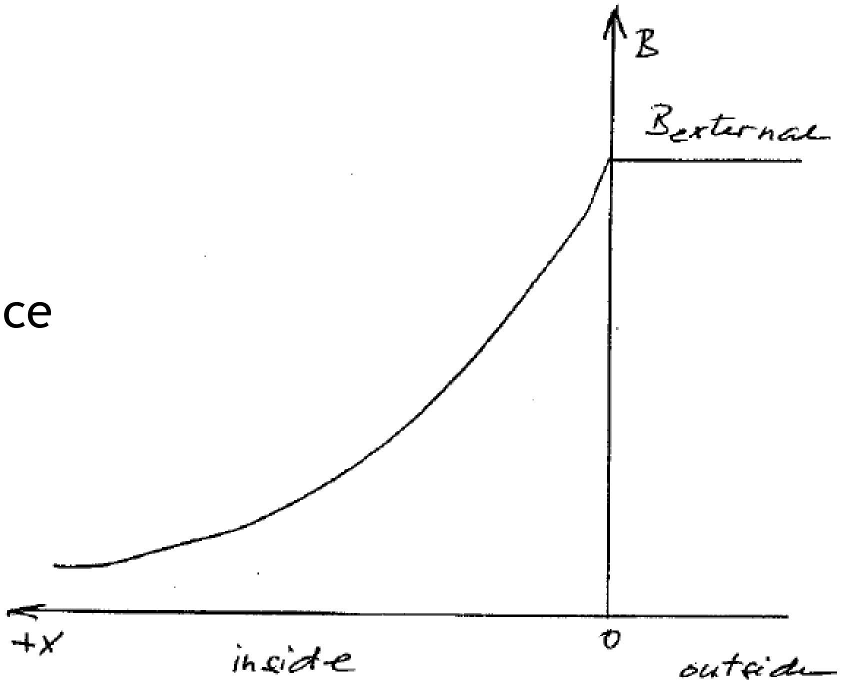


Figure 9. Meissner effect inside the superconductors are not perfect

Temperature Dependence Of Penetration Distance

λ = penetration distance at temperature T
λ_0 = penetration distance at temperature T= 0.

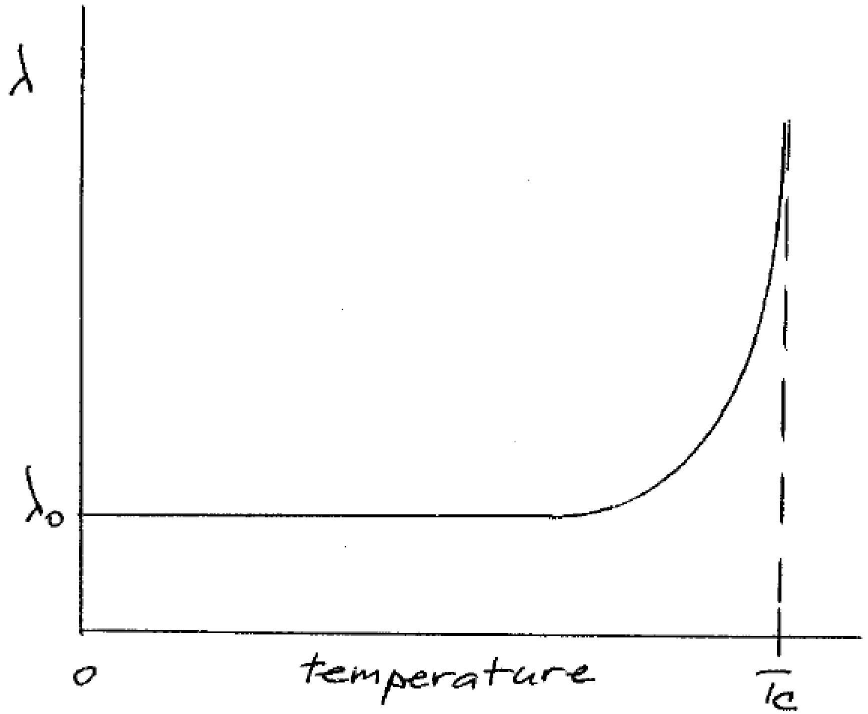


Figure 10. Temperature dependence of penetration depth

λ_0 = 30 - 130 nm, depending on the superconductor material

THE MAGNETIC PROPERTIES OF SUPERCONDUCTORS

- In addition to the loss of resistance, superconductors prevent external magnetic field from penetrating the interior of the superconductor.
- This expulsion of external magnetic fields takes place for magnetic fields that are less than the critical field B_C.
- Magnetic field $B > B_C$ destroys the superconductive state.

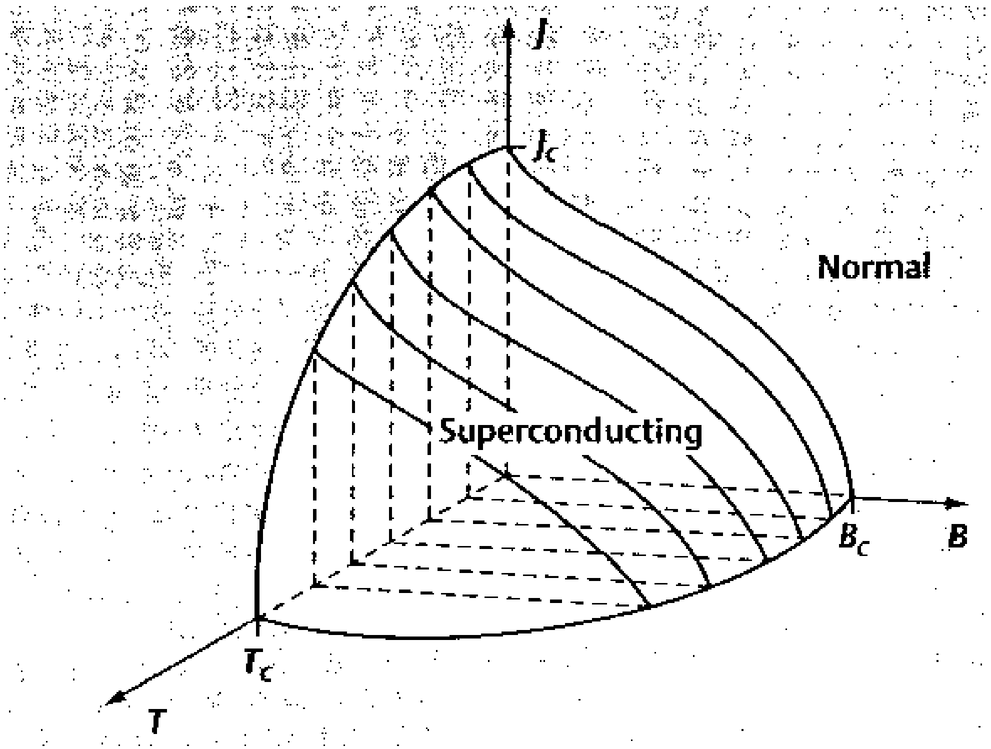
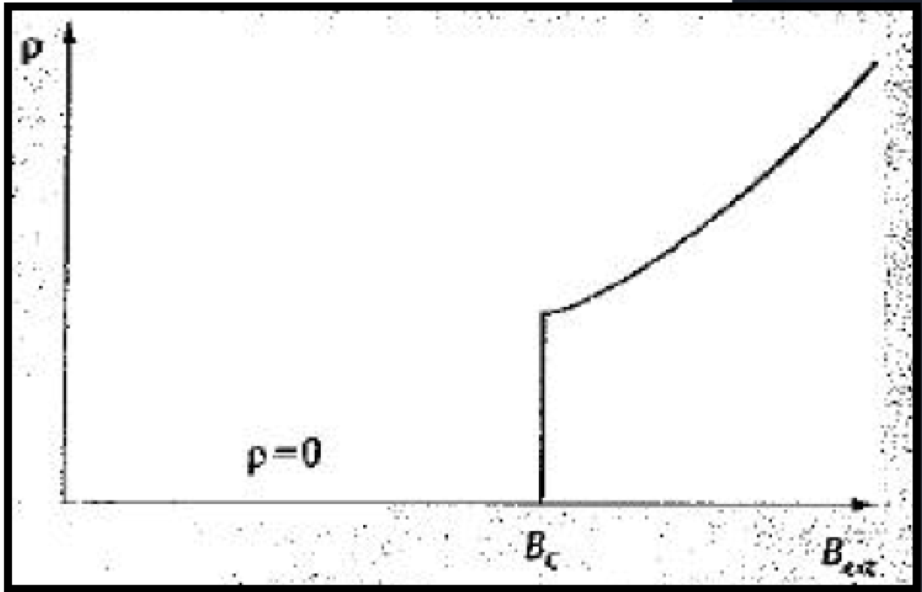


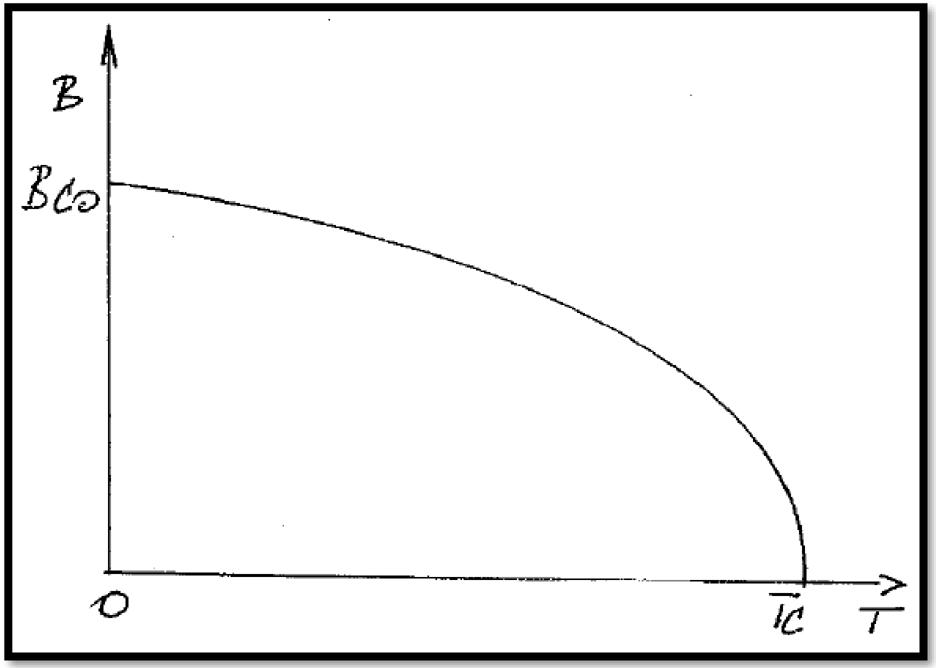
Figure 10. Critical values for the existence of superconducting state

Critical Magnetic Field

$$B_C(T) = B_{C0}\left(1 - \left(\frac{T}{T_C}\right)^2\right)$$

B_{C0} = critical magnetic field at T = 0.





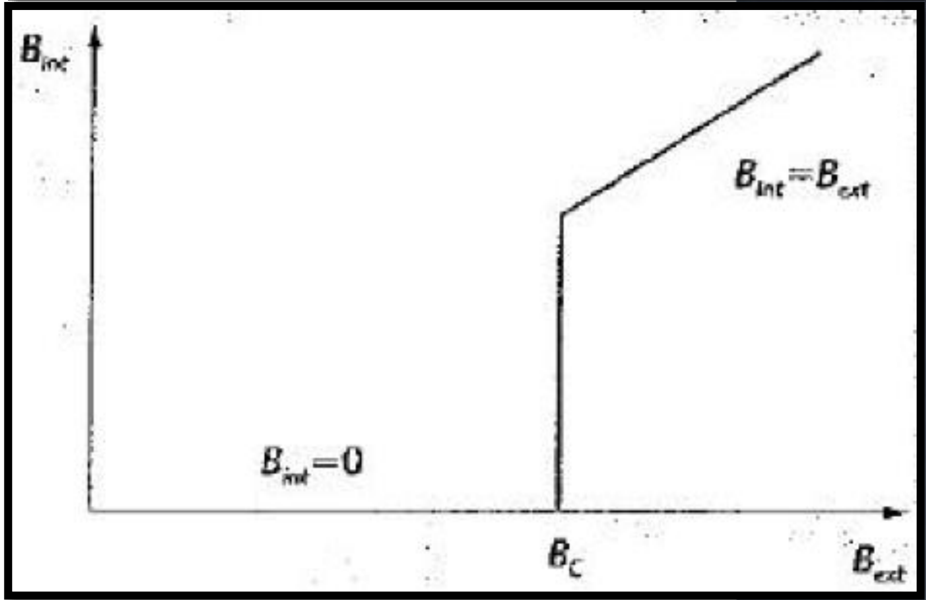


Figure 11. Critical magnetic field effect

Critical Current

- Superconductive state is destroyed by magnetic field.
- Consider a straight wire. Since electric current in the wire creates magnetic field:

$$B = \frac{\mu_0 I}{2\pi r}$$

- The wire can carry maximum superconductive current I_c, corresponding to the critical magnetic field B_c at the surface of the wire, $r = R$,

$$I_C = \frac{2\pi R B_C}{\mu_0}$$

$$\mu_0 = 4\pi\ 10^{-7}\ \mathrm{Tm/A}$$

TYPE I AND TYPE II SUPERCONDUCTORS

- **Type I superconductor:** Magnetic field is completely expelled from the interior for $B < B_C$.

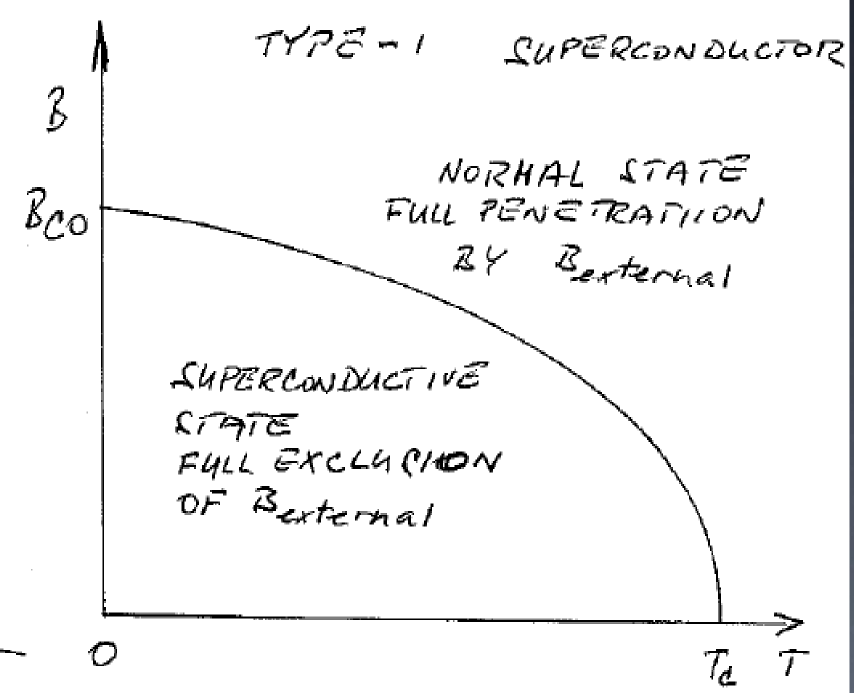


Figure 12. Critical magnetic field with temperature in Type-I superconductors

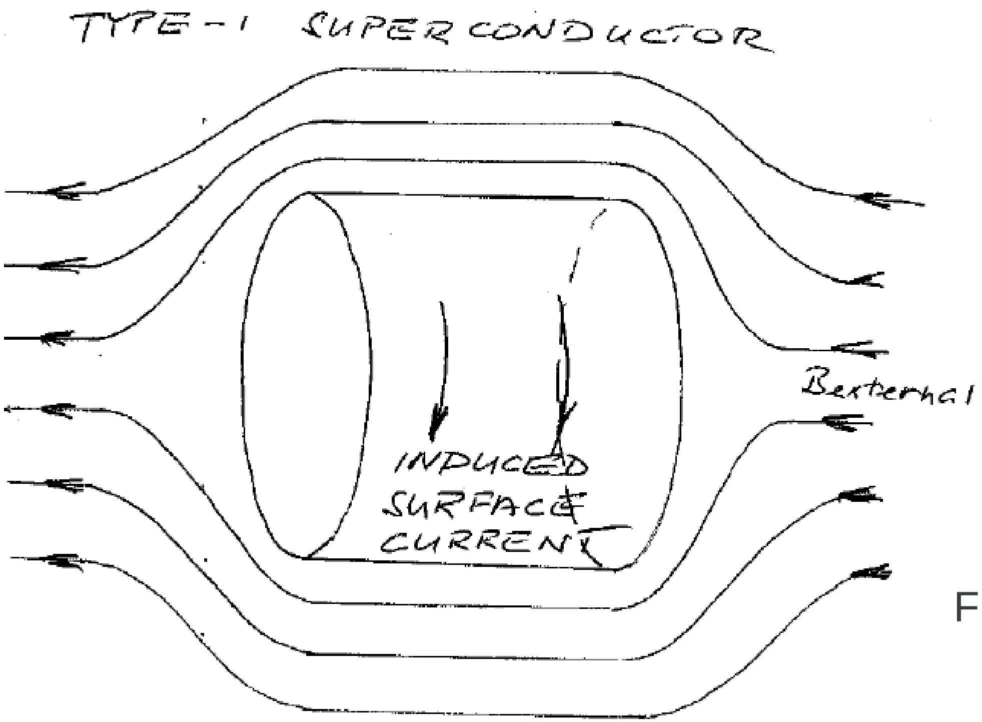


Figure 13. Induced surface current in Type-I superconductors

- **Type II superconductors have two values of critical magnetic field**, for $B < B_{C1}$ the magnetic field is completely expelled (Type-I behavior), whereas for $B_{C1} < B < B_{C2}$ the magnetic field partially penetrates through the material.
- The bulk of superconductor material breaks down into two regions: superconductive from which the external field is completely expelled, and normal through which the external field penetrates.

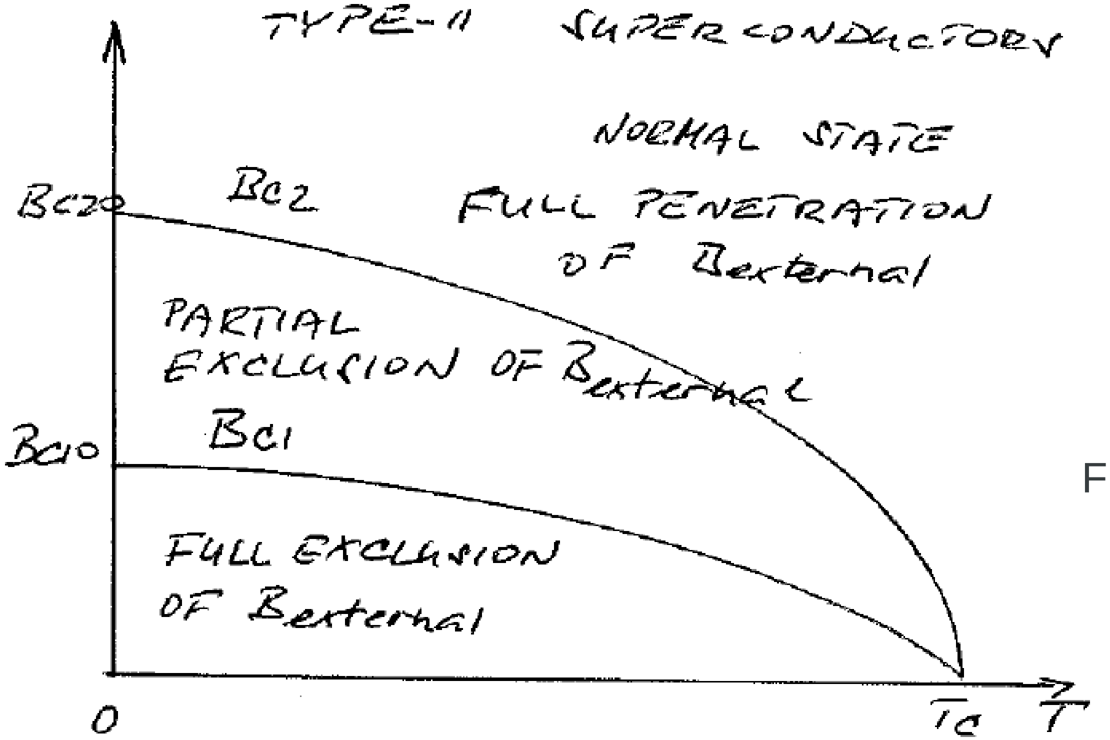


Figure 13. Critical magnetic field with temperature in Type-II superconductors

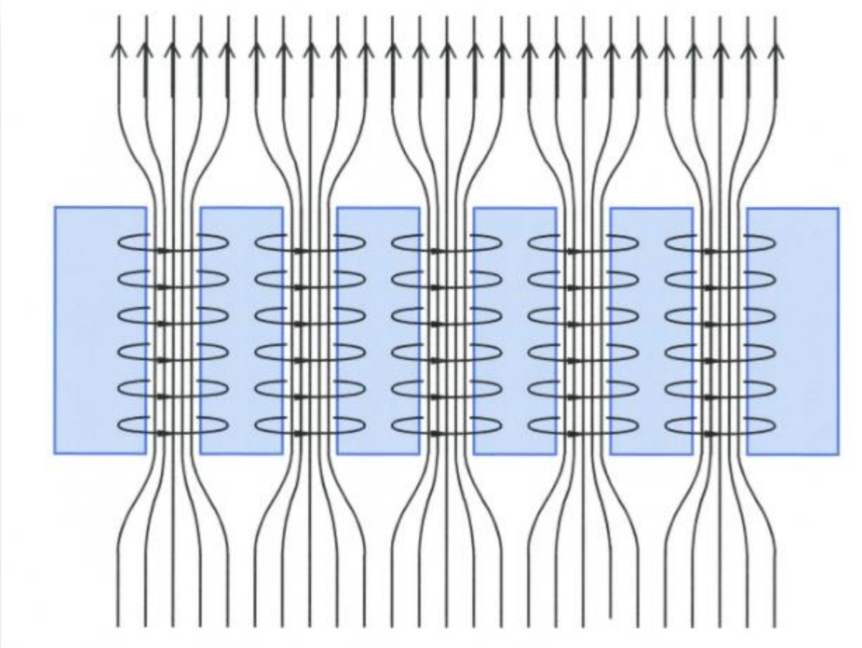
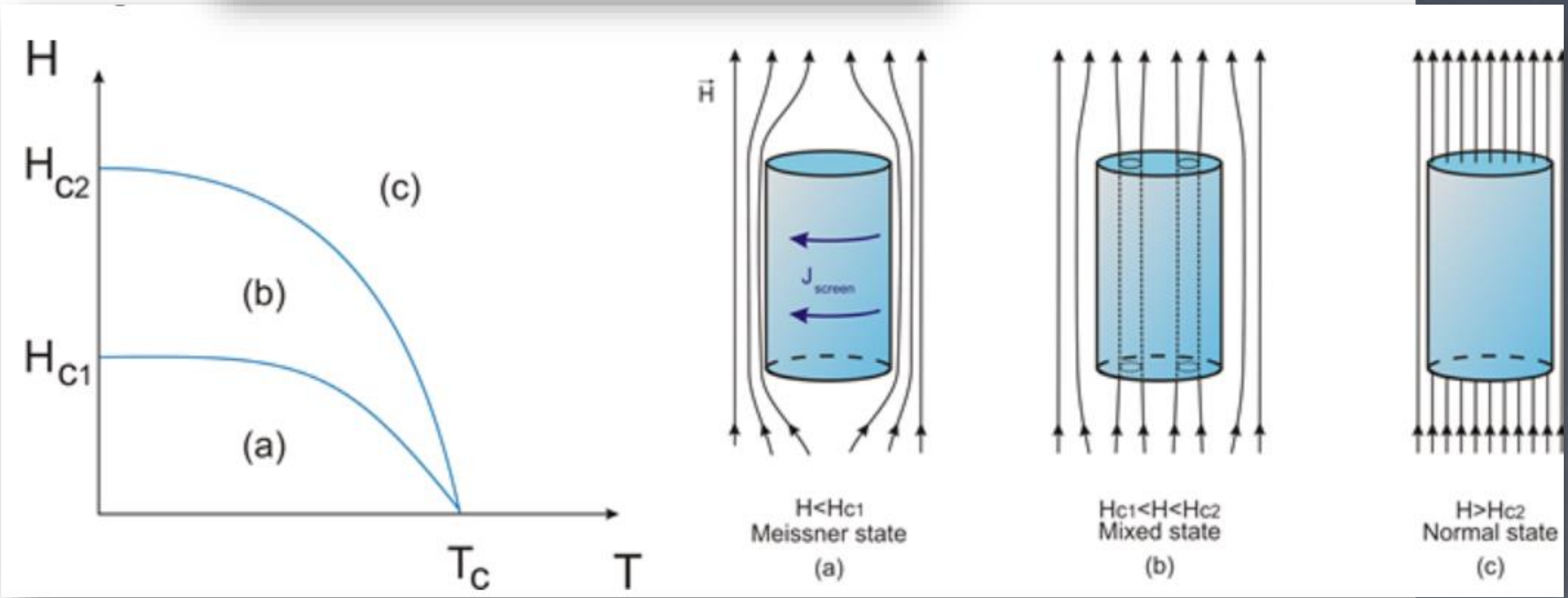
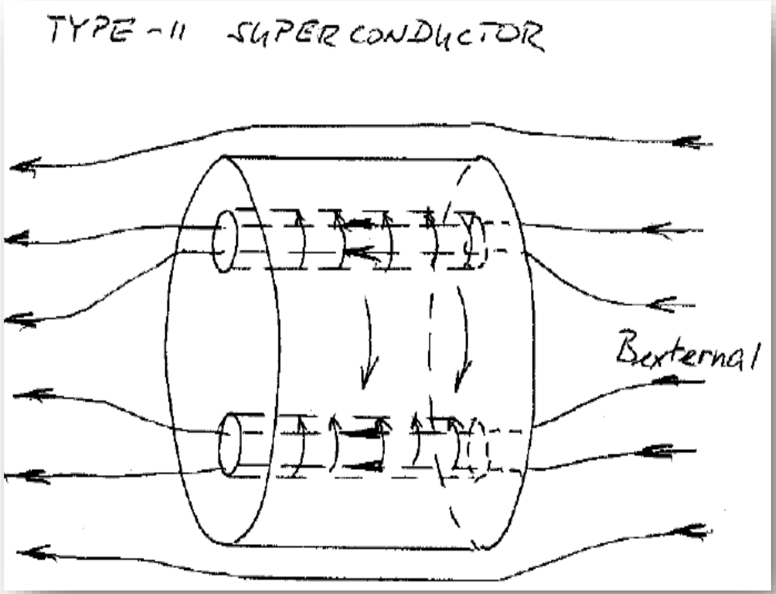


Figure 14. Quantized magnetic flux inside Type-II superconductors



- The normal regions are distributed as filaments filled with the external magnetic field.
- Flux of magnetic field through the filaments is quantized ($\Phi = n\Phi_0$, n being an integer). The quantum of flux is $\Phi_0 = \frac{h}{2e} = 2.07 \times 10^{-15}$ weber
- Electric current is induced at the interface between the normal and the superconductive regions, the "surface" of filaments is "wrapped" in current which cancels the magnetic field in the superconductive regions.



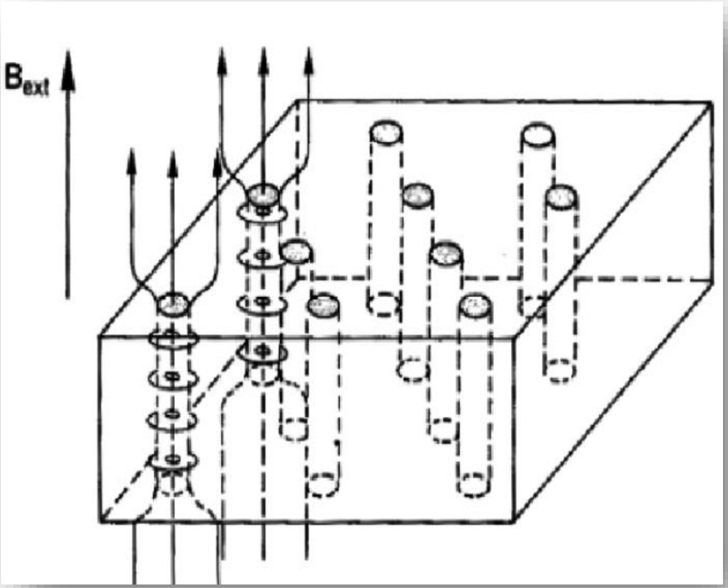


Figure 15. Schematic of Current filaments in Type-II superconductors

SUMMARY OF SUPERCONDUCTIVITY

The superconducting material shows some extraordinary properties which make them very important for modern technology.

1. Zero Electric Resistance (Infinite Conductivity)
2. Meissner Effect: Expulsion of magnetic field
3. Persistent Currents (Frozen magnetic field flux)
4. Critical Temperature/Transition Temperature
5. Critical Magnetic Field
6. Critical Current

TYPE-I VERSUS TYPE-II SUPERCONDUCTORS

Type – I superconductors	Type – II superconductors
Low critical temperature T_c (typically in the range of 0 – 10 K) – LOW TEMPERATURE SUPERCONDUCTORS	High critical temperature T_c (typically greater than 10 K) – HIGH TEMPERATURE SUPERCONDUCTORS
Low critical magnetic field, B_c (typically in the range of 0.0000049 – 1 T)	Low critical magnetic field, B_c (typically greater than 1 T)
Exhibit single critical magnetic field – transition from superconductive to normal state due to external magnetic field is sharp and abrupt	Exhibit two critical magnetic fields – at 1st critical field, transition from superconductive to mixed state occur while at 2nd critical field, transition from mixed to normal state occur
Easily lose superconducting state by low intensity magnetic field – SOFT Superconductor	Does not easily lose superconducting state by external magnetic field – HARD Superconductor
Perfectly obeys Meissner effect – complete diamagnetic behavior	Partly obeys Meissner effect
Cannot be used for manufacturing electromagnets that are employed for producing strong magnetic field	Can be used for manufacturing electromagnets that are employed for producing strong magnetic field
Slight impurity does not affect the superconductivity	Slight impurity greatly affect the superconductivity
Generally pure metals (e.g. Hg, Pb, Zn)	Generally alloys or complex oxides of ceramics (e.g.NbTi, Nb_3Sn)

THANK YOU