SUPERCONDUCTIVITY

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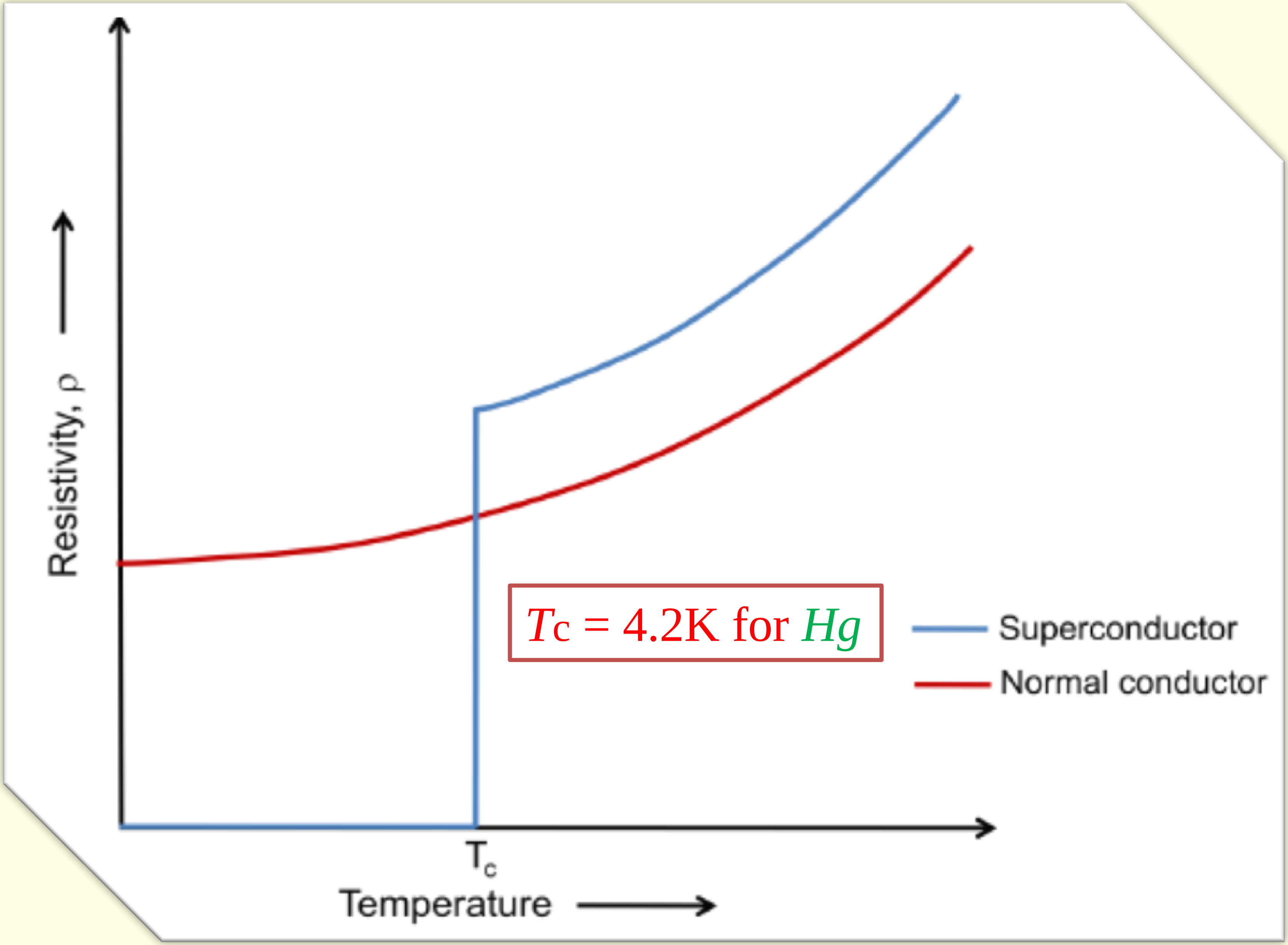
Property of complete disappearance of electrical resistance in solids when they are cooled below a characteristic temperature, called transition temperature or critical temperature (T_c)

Discovered by **Kamerlingh Onnes** in 1911 during first low *T* measurements to liquefy *He*

Nobel Prize -1913



Resistivity, ρ
T_c = 4.2K for Hg
Superconductor
Normal conductor
T_c
Temperature

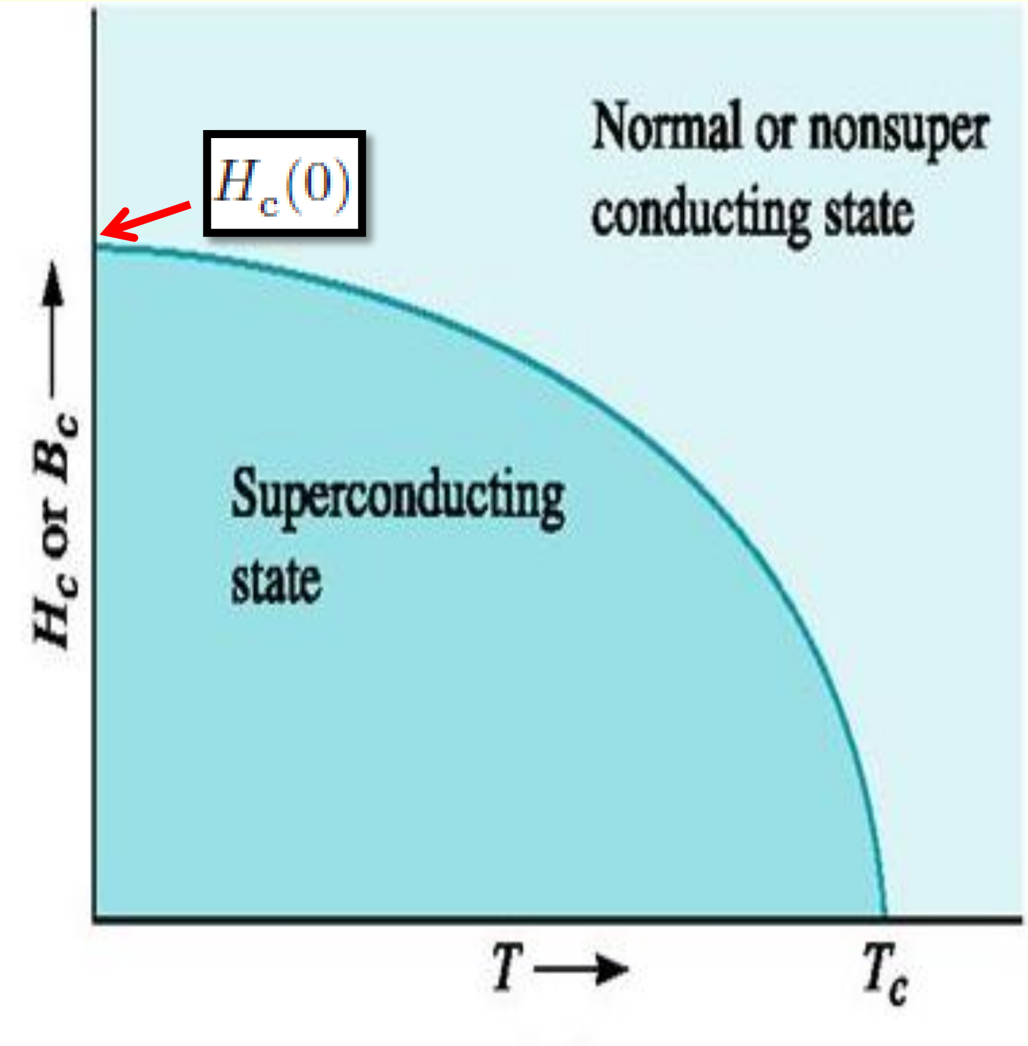
Features of Superconductors

- The T_c is sharp for pure and perfect crystal, but has a short range for crystal with impurities or imperfection
- Favoured by materials which are ***not so good*** conductors
- Noble matals ***-Au, Ag and Cu*** do not become superconductor
- Discontinuous change in specific heats at T_c
- Sudden but small decrease in volume at T_c
- Perfect diamagnetism below T_c

Effect of Magnetic Field/Critical Field

Application of magnetic field to a superconducting specimen brings a stage when for $H=H_c$, the critical field, superconductor beccomes normal i.e. superconductivity disappears

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

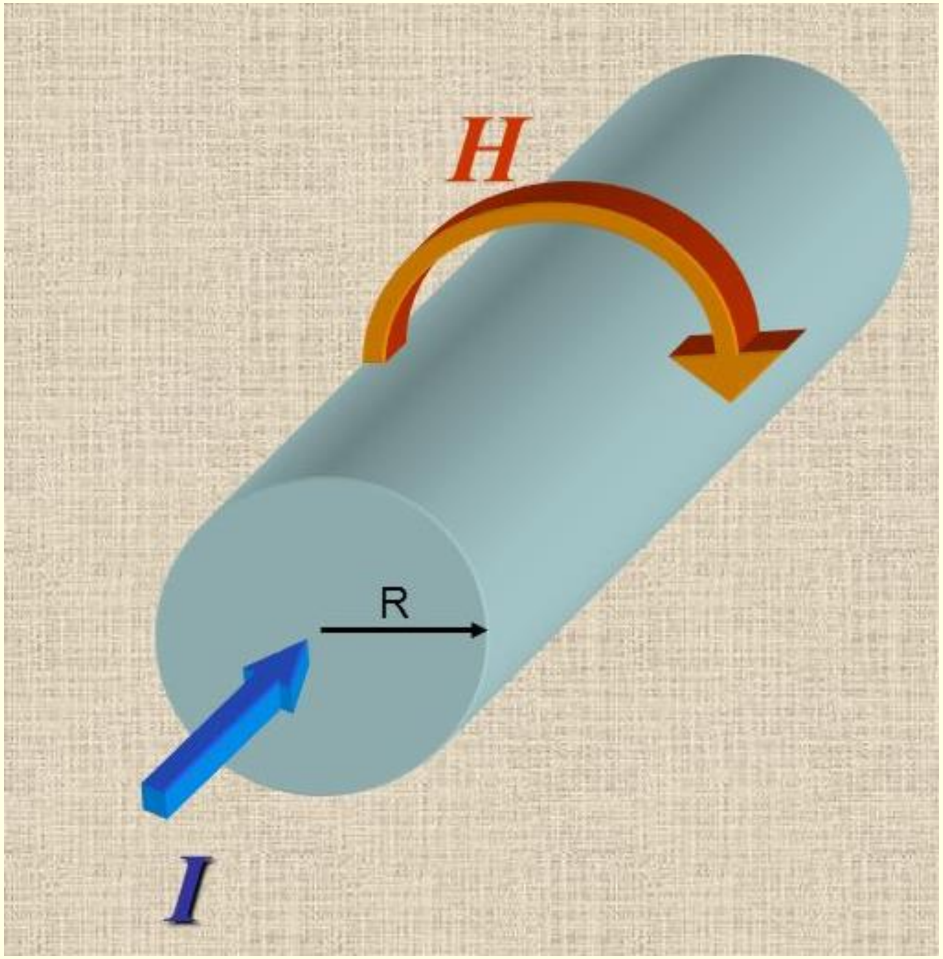


Effect of Current/Critical current

$$H = I / 2\pi R < H_c$$

$$I_c = 2\pi R H_c$$

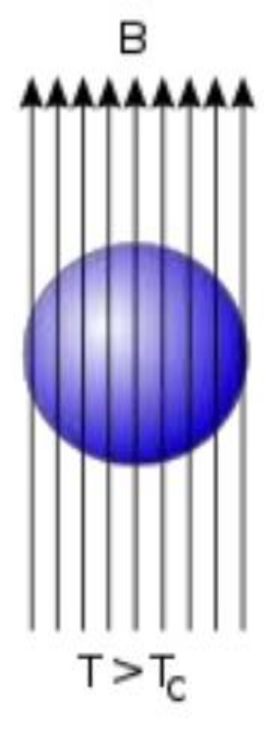
$$I_C = I_0 \left[1 - \left(\frac{T}{T_C} \right)^2 \right]$$

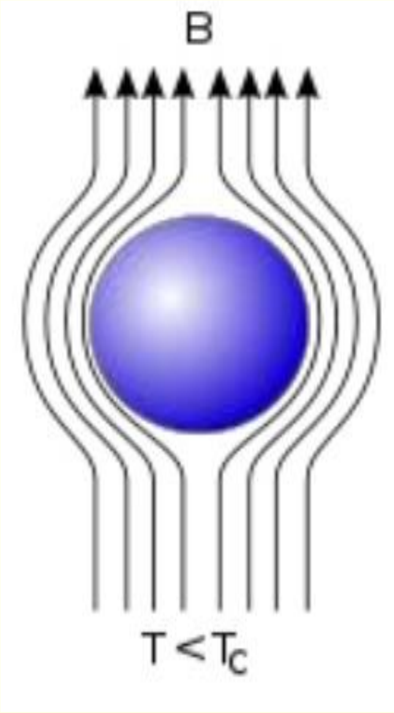


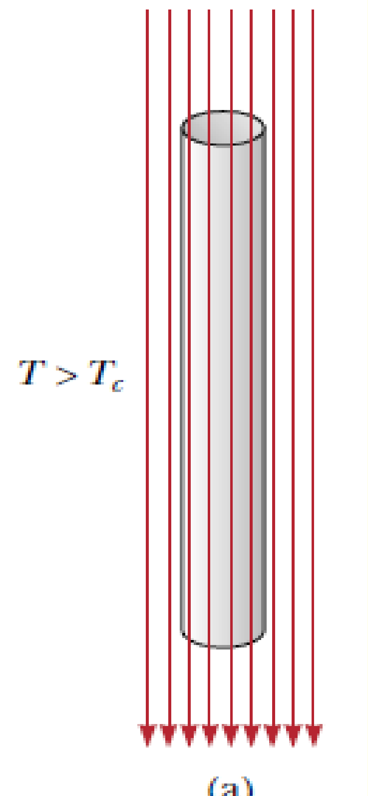
Meissner Effect

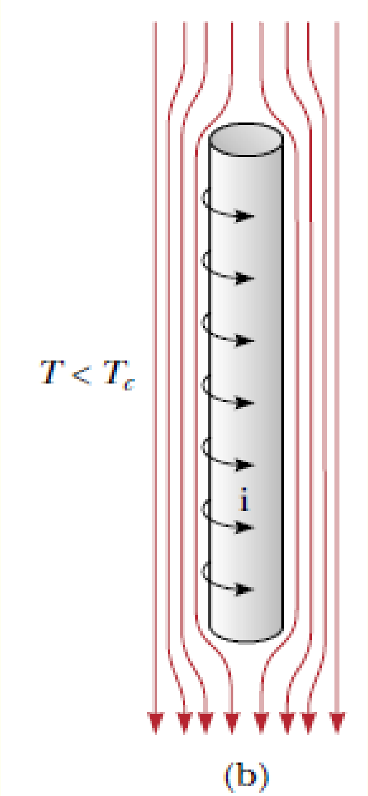
Expulsion of magnetic **flux line out** of the volume of conductor when it becomes a superconductor

Walther Meissner - Robert Ochsenfeld





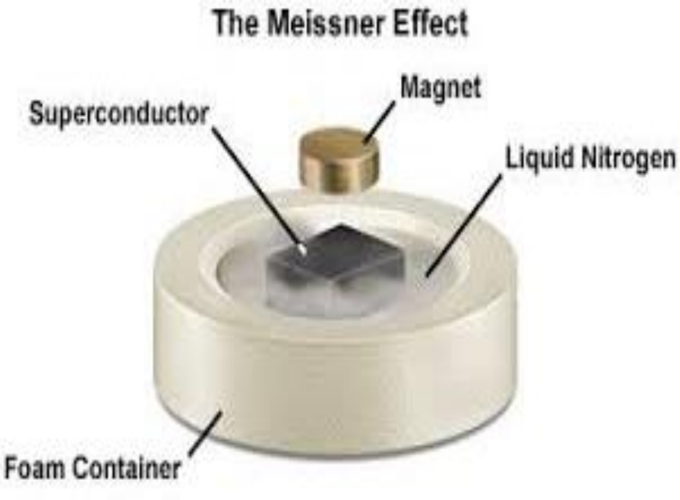




For perfect conductor, $\sigma = \infty$.
Since $\vec{J} = \sigma \vec{E} < \infty$, $\vec{E} = 0$.

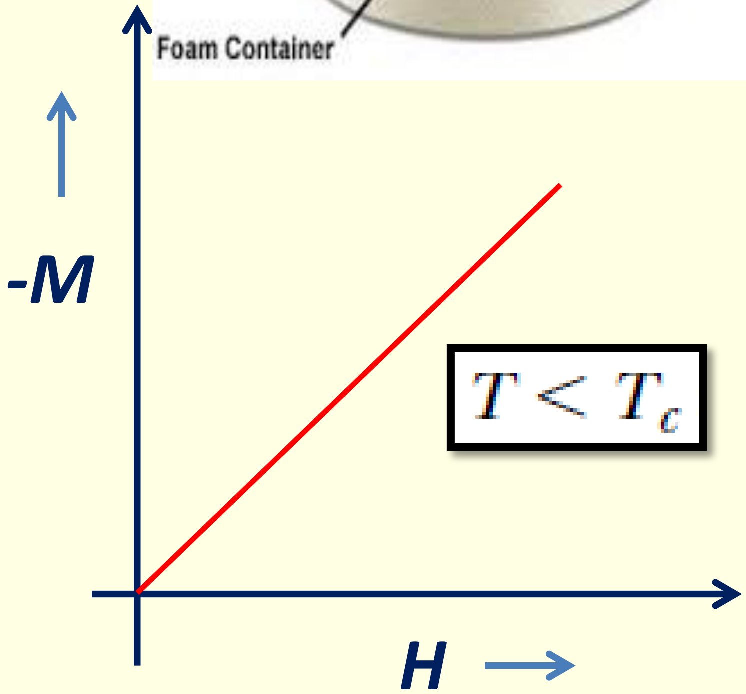
By definition,

$$\vec{B} = \mu_0(\vec{H} + \vec{M})$$



But, ***B* = 0** inside superconductor, as there is **no flux** inside

$$\Rightarrow \quad \vec{M} = -\vec{H}$$



Perfect Diamagnetism

Inside superconductor
$E = 0, B = 0$

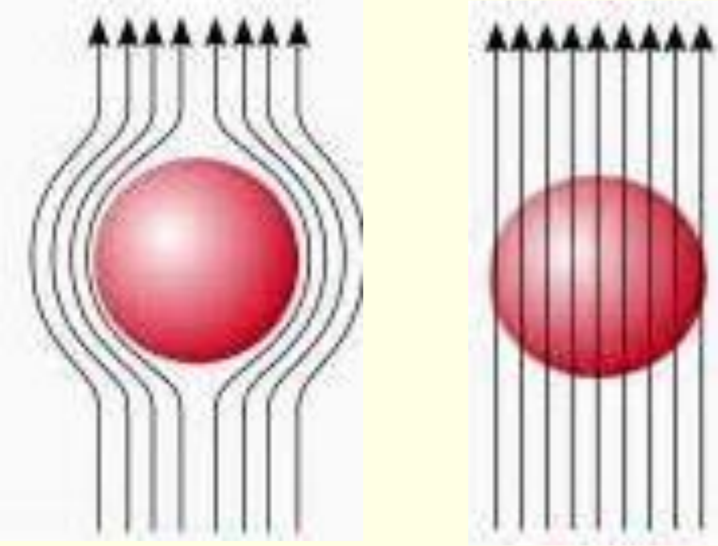
Classification: *Type–I* and *Type–II* Superconductor

Type I Superconductors

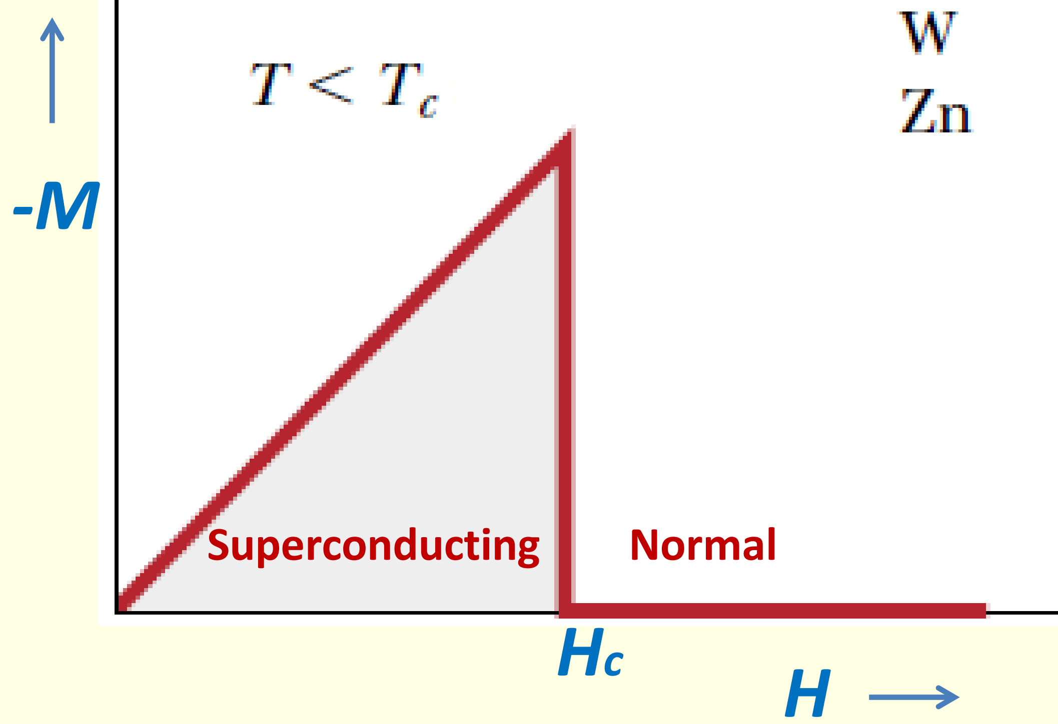
- ► Which show complete Meissner effect
- ► Possess only one value of Critical field

Al, Ga, Hg, In, Pb, Sn, Ta, Ti, V, W, Zn

$T < T_c$



$H < H_c$ $\qquad$ $H \geq H_c$

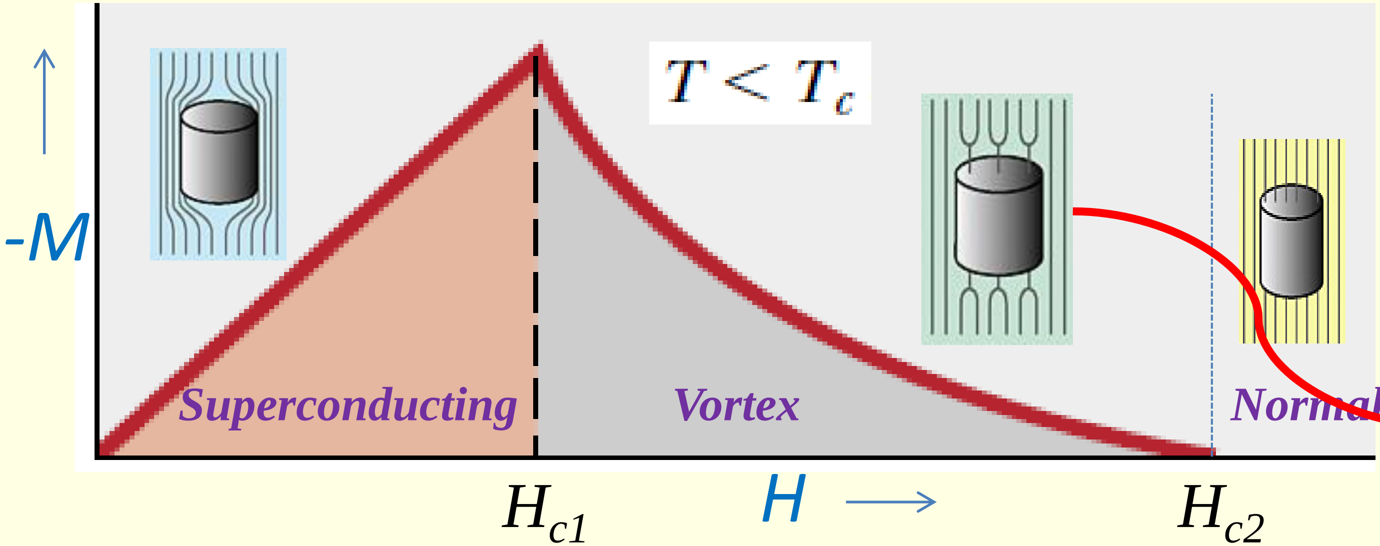


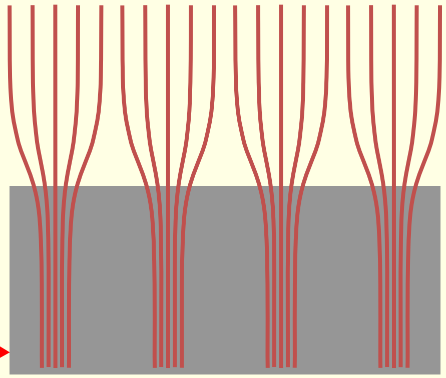
TYPE II SUPERCONDUCTORS

- Show **incomplete** Meissner effect
- Possess **two** values of **Critical fields**
- At lower Critical field H_{c1}, flux starts threading sample
- Sample becomes normal at higher Critical field H_{c2}
- Sample is in mixed or **Vortex state** for $H_{c1} < H < H_{c2}$.

For $H < H_{c1}$ *-Superconducting State*
For $H > H_{c2}$ *-Normal State*
For $H_{c1} < H < H_{c2}$ *-Vortex State*

Nb, V, alloys & compounds.





BCS THEORY

Nobel Prize (1972)

John Bardeen
(1908-1991)

Leon Neil
Cooper
(1930 -)

John Robert
Schrieffer
(1931-)

"for their development of a theory of superconductivity"

Many best minds in Physics **(including Einstein)** tried to understand superconductivity, but only **40 years** after **K.Onnes's discovery**, a convincing theory was established

According to **Classical Physics**, part of the resistivity of a metal is due to **collisions** between free electrons and thermally displaced ions of the metal lattice, and part is due to **scattering of electrons** from impurities or defects in the metal

Soon after the discovery of superconductivity, scientists recognized that this **classical model could never explain** the superconducting state, because the electrons in a material always suffer some collisions, and therefore **resistivity can never be zero**

Nor could superconductivity be understood through a **simple microscopic quantum mechanical model**, where one views an individual electron as an **independent wave** traveling through the material

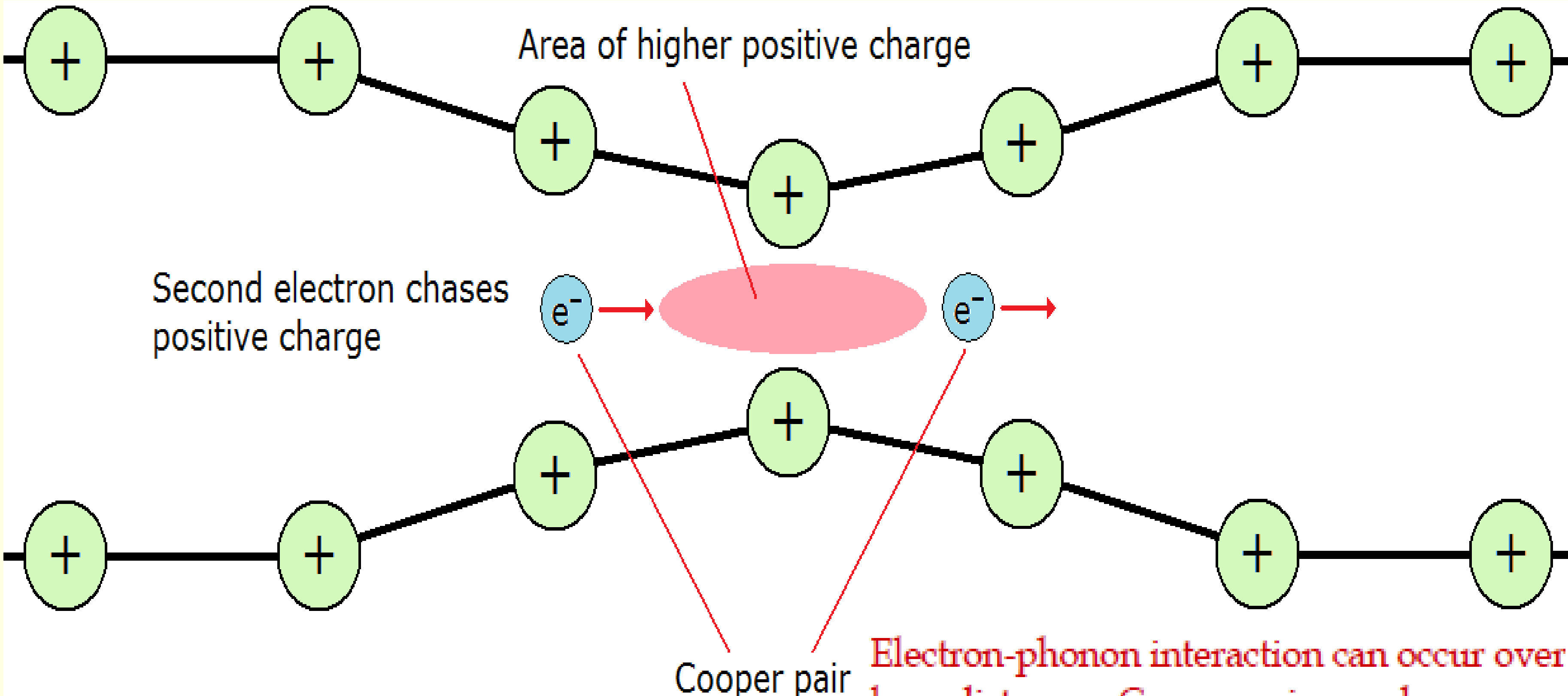
Although many phenomenological theories based on the known properties of superconductors were proposed, none could explain why electrons enter the superconducting state and why electrons in this state are not scattered by impurities and lattice vibrations

Full microscopic theory of superconductivity presented in **1957** by **Bardeen, Cooper and Schrieffer** has had good success in explaining the features of superconductors. The details of this theory, now known as the **BCS theory**, are beyond the scope of our discussion, but we can describe some of its main features and predictions.

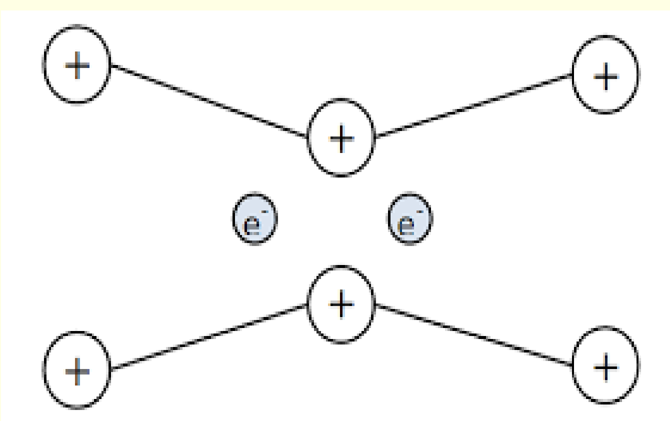
As per BCS theory, **two electrons** in a superconductor form a **bound pair** called a **Cooper pair**, as if they somehow experience an **attractive** interaction. A net attraction is achieved when electrons interact via **phonons** (quantum of lattice vibrations)

Cooper pair has a total **0 spin** whereas individual electrons in normal state have **½ spin**. So, at transition temperature ***Fermionic system*** of individual electrons make a ***phase transition*** in statistics to a ***Bosonic system*** of Cooper pairs

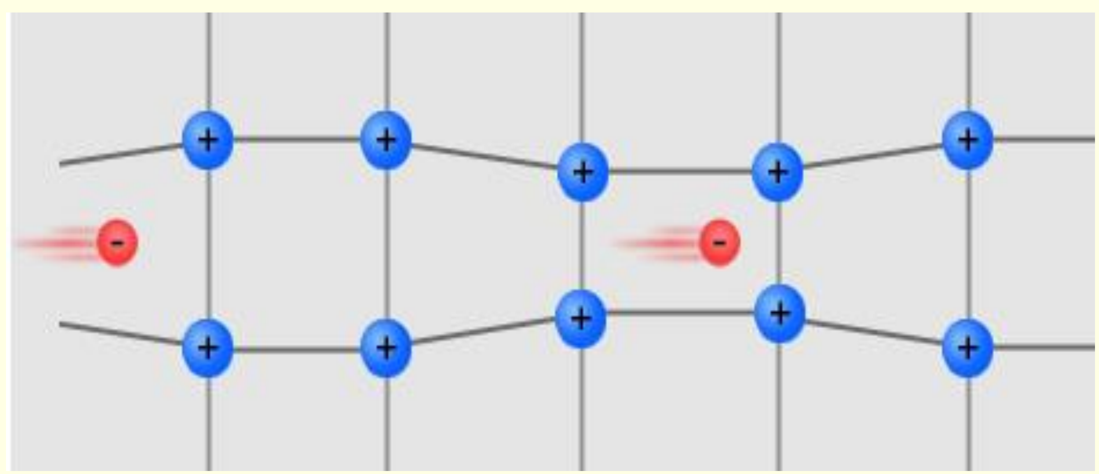
In ground state Cooper pair occupy ***same quantum state*** as they no longer obey ***Paulli's exclusion principle***, hence all electrons have a single **wave-function** *that* ***extends over the entire volume of the superconductor***



Electron-phonon interaction can occur over long distances; Cooper pairs can be separated by many lattice spacings



Cooper pair of electrons.



It is rather strange, and perhaps amazing, that the mechanism of ***lattice vibrations*** that is responsible (in part) for the resistivity of normal metals also provides the interaction that gives rise to their superconductivity.

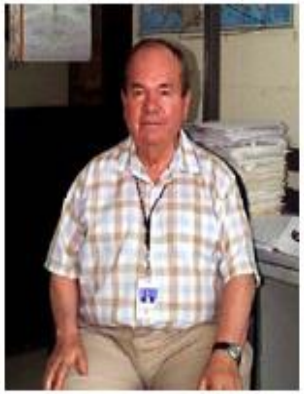
Thus, ***copper, silver, and gold***, which exhibit small lattice scattering at room temperature, are ***not superconductors***, whereas ***lead, tin, mercury***, and other modest conductors have ***strong lattice scattering*** at room temperature and become superconductors at low temperatures

Nobel Prize (2003)

Alexei A. Abrikosov

Vitaly L. Ginzburg

Anthony J. Leggett

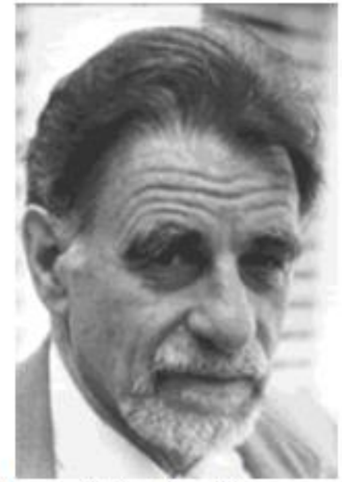


"for pioneering contributions to the theory of superconductors and superfluids"

Nobel Prize (1986)

J. Georg Bednorz (1950 -)

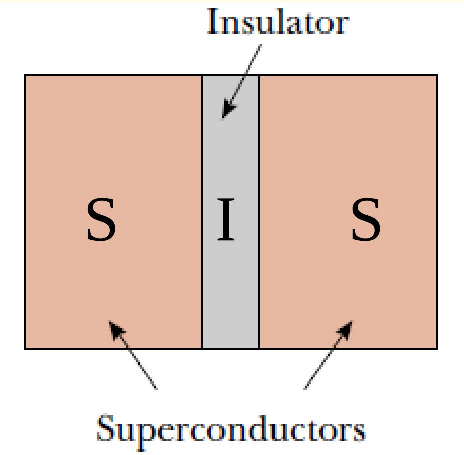
K. Alexander Müller (1927 -)



"for their important breakthrough in the discovery of superconductivity in ceramic materials"

High-temperature superconductors may lead to many important technological advances, such as highly efficient, lightweight superconducting motors. However, many significant material science problems must be overcome before such applications become reality. Perhaps the most difficult ***technical challenge*** is to mold the brittle ceramic materials into useful shapes, such as wires and ribbons for large-scale applications and thin films for small devices

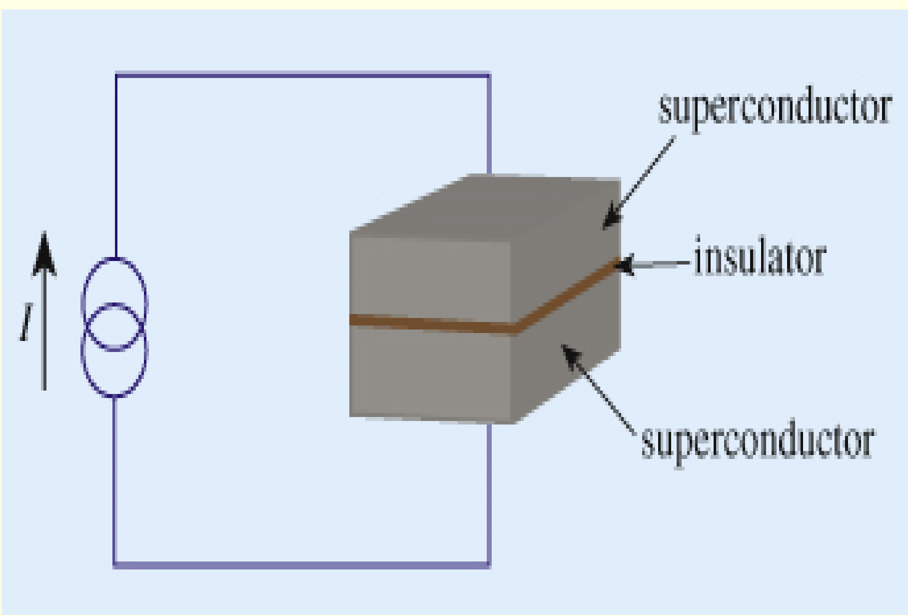
Josephson Effect

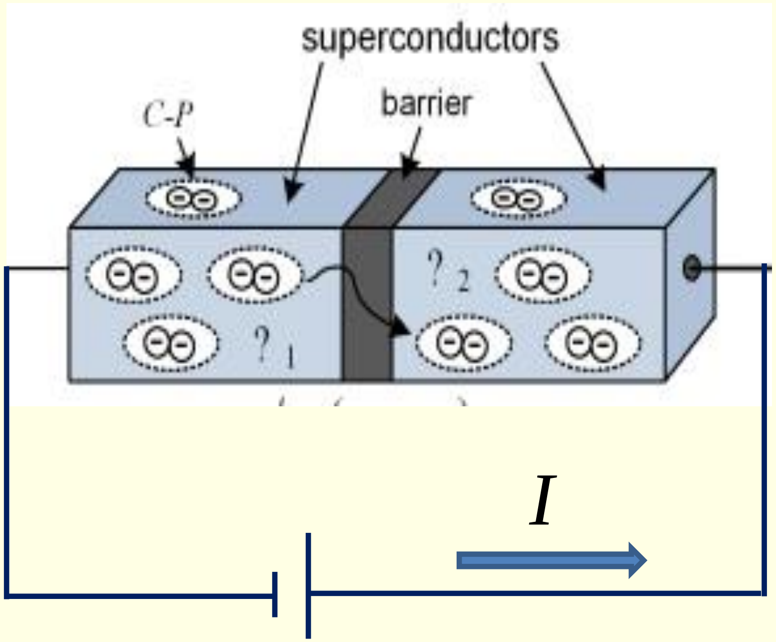


Cooper Pair tunneling through SIS device

Nobel Prize (1973)

Brian David Josephson





APPLICATIONS OF SUPERCONDUCTIVITY

(1) High current applications (based on $R = 0$):
electricity transmission, energy storage, …

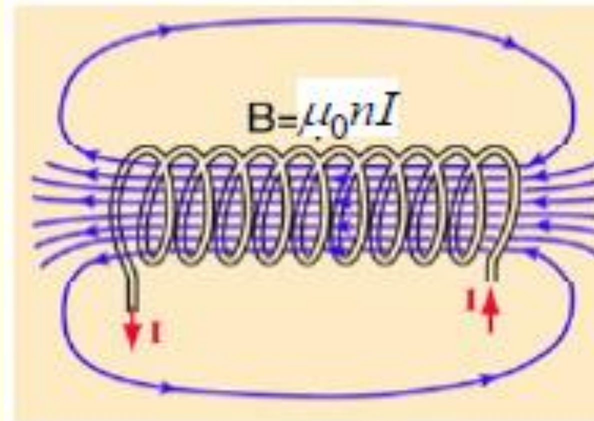
(2) High field applications (based on superconducting magnet): MRI, Maglev, motor, generator, accelerators, research equipment, …

(3) Josephson applications (based on Josephson effects):
SQUID, supercomputers, …

- Generating high fields with low power consumption. (existing)
- Magnetic resonance imaging (MRI) in the medical field as a diagnostic tool. (existing)
- Electrical power transmission through superconducting materials.
- Magnets for high-energy particle accelerators. (LHC)
- Higher-speed switching and signal transmission for computers.
- High-speed magnetically levitated trains.
- The chief deterrent to the widespread application of these superconducting materials is the difficult in attaining and maintaining extremely low temperatures.

❑ High efficiency electric generators

(a) Superconducting magnet (SM)



$$B = \mu_0 n I$$

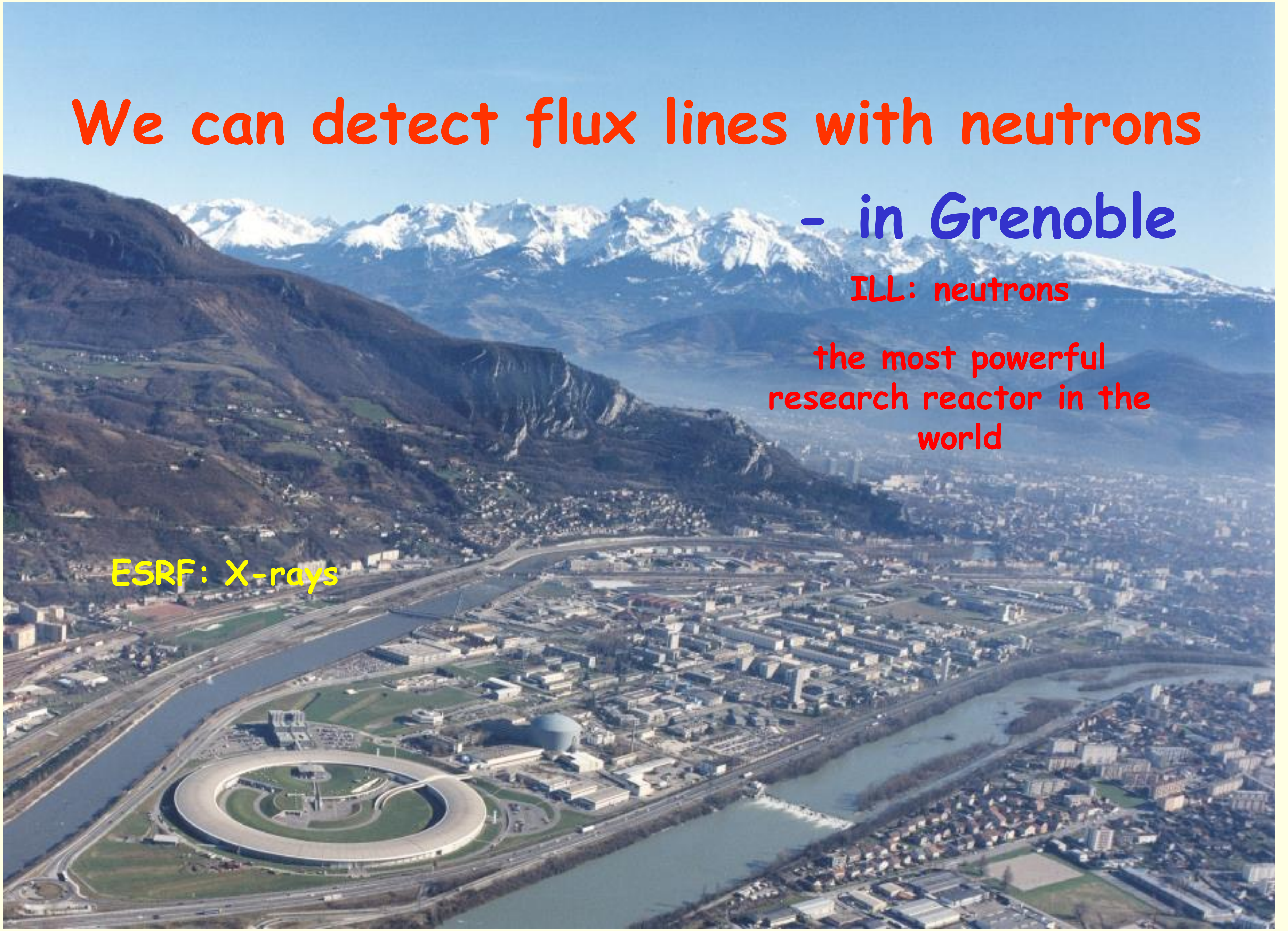
10 T   10 turns/cm   8 kA

Particle accelerator for high energy experiments:

Laboratory for Developments and Methods, Paul Scherrer Institute, 5232 Villigen PSI, Switzerland

e.g. Tevatron (proton-antiproton collider) in Fermi Lab near Chicago in USA

Circumference of the circular accelerator is ~ 6.4 km.


We can detect flux lines with neutrons
- in Grenoble
ILL: neutrons
the most powerful research reactor in the world
ESRF: X-rays

Levitation: MagLev Trains

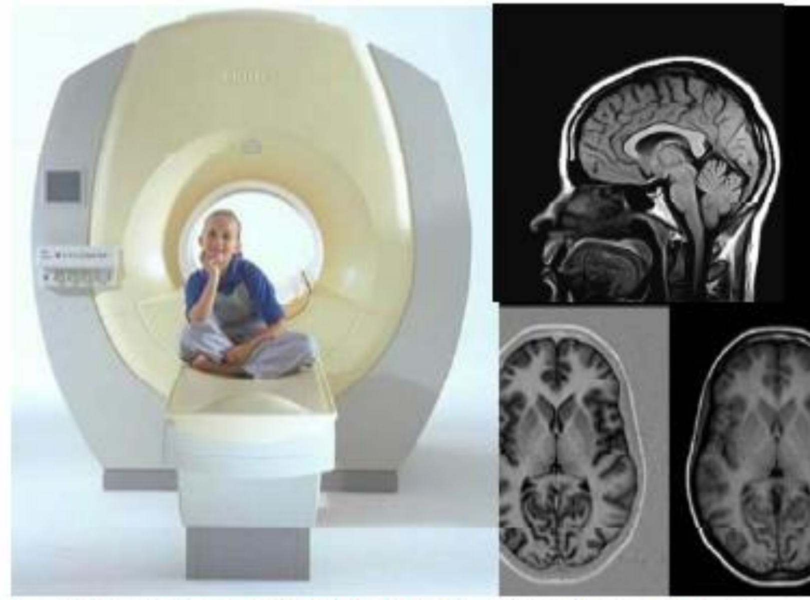
- No friction
- Super-high speed
- Safety
- Noiseless

Miyazaki Maglev Test Track, 40 km

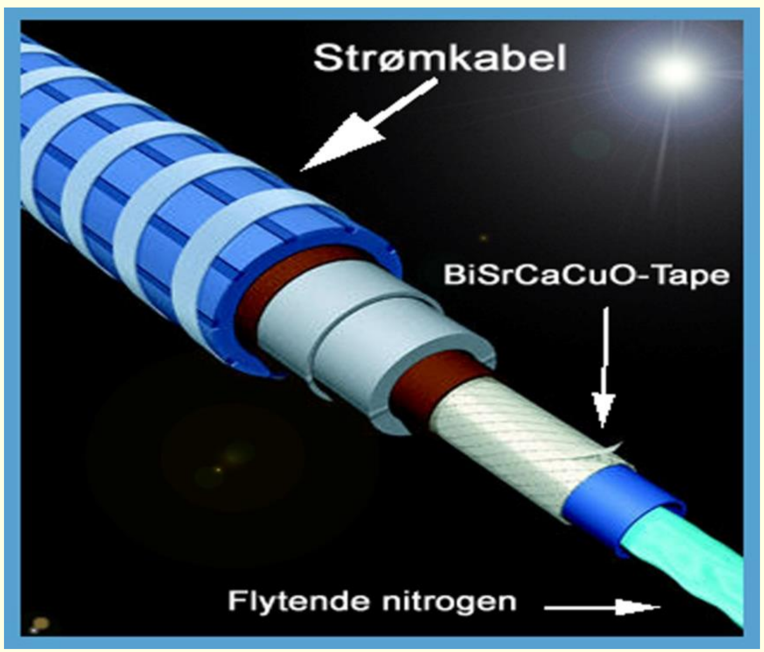
(b) SQUID for brain research

SQUID is a sensitive magnetic field sensor.

(iv) Magnetic Resonance Imaging (MRI) (1977)



Require a strong magnetic field (0.5 – 2 Tesla), usually generated by SM. (Physics World Dec. 2002, pp.31-35.)



In May of 2001 some 150,000 residents of Copenhagen began receiving their electricity through high-*Tc* superconducting material (30 meters long cable).