DSE CLASS

CONDENSED MATTER PHYSICS

Lecture-5

01/10/2020

Superconductors are characterized by a material-dependent magnetic field, above which the superconducting state disappears.

The existence of a critical magnetic field implies the existence of a maximum current in a wire of the superconducting material because the current itself generates a magnetic field according to Ampere's law.

Critical current density :

when the current through a SC exceeds a certain critical value superconducting property is destroyed.

Current density corresponding to critical magnetic field is called **critical current density J_c**

As, **$B = \mu_0 I / 2\pi r$**

hence, **$I_c = 2\pi r B_c / \mu_0$**

is called Silsbee rule; Minimum current in the material without destroying superconductivity

So, Critical current density is

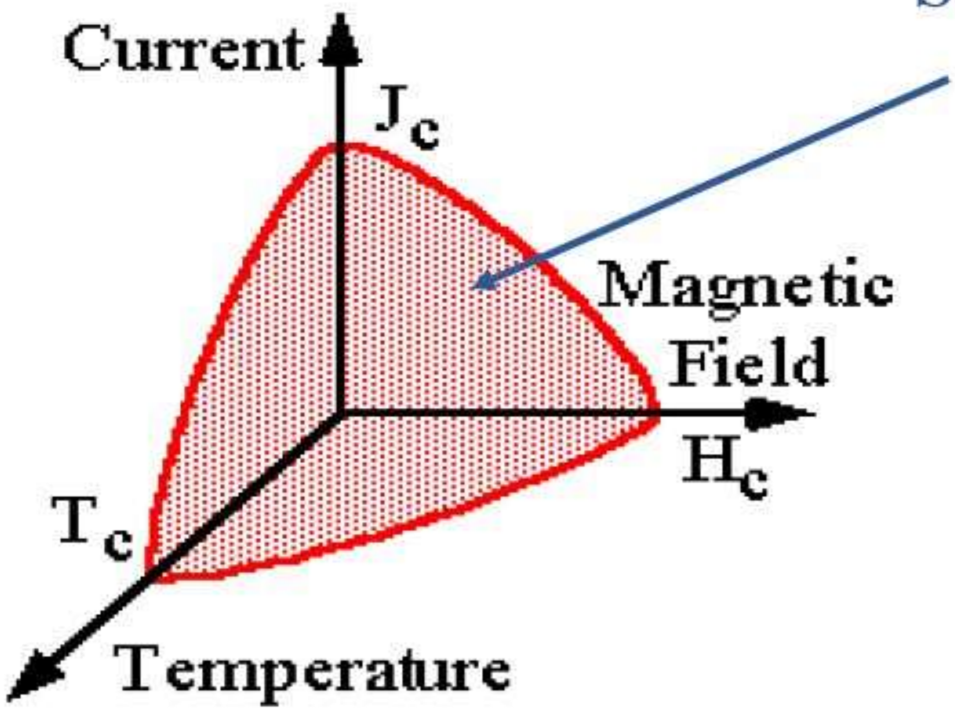
$$J_c = \frac{2B_c}{\mu_0 r}$$

Phase diagram of superconductors

Critical temperature (T_c)

Critical field (H_c)

Critical current density (J_c)



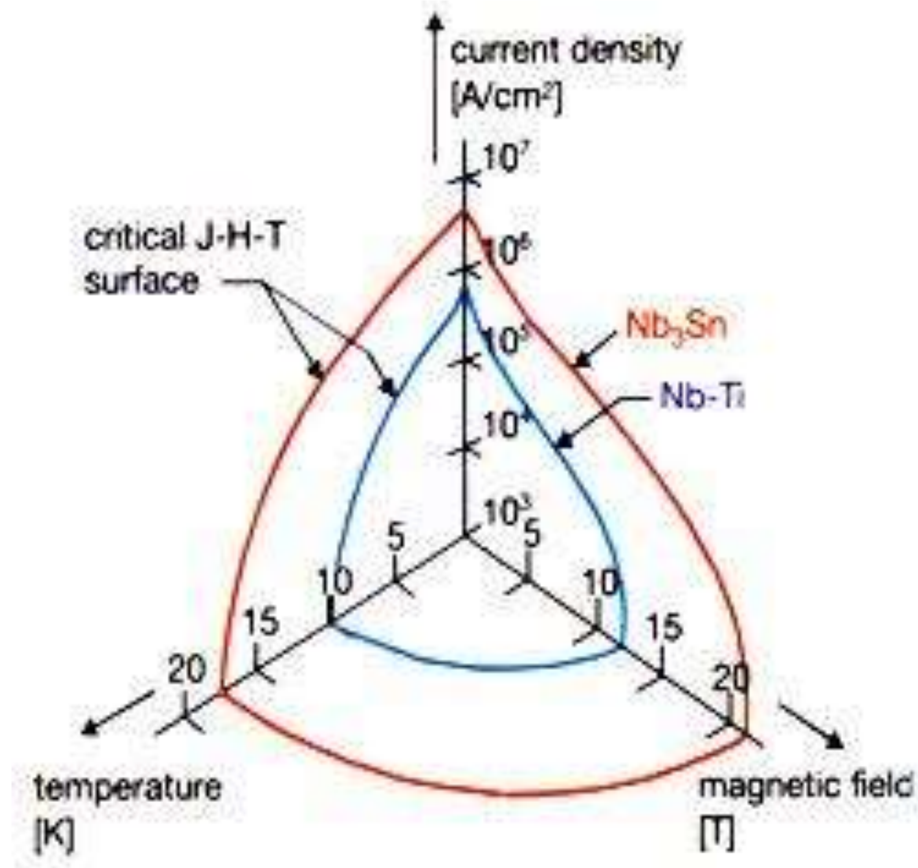
Superconducting state if:

$T<T_c$

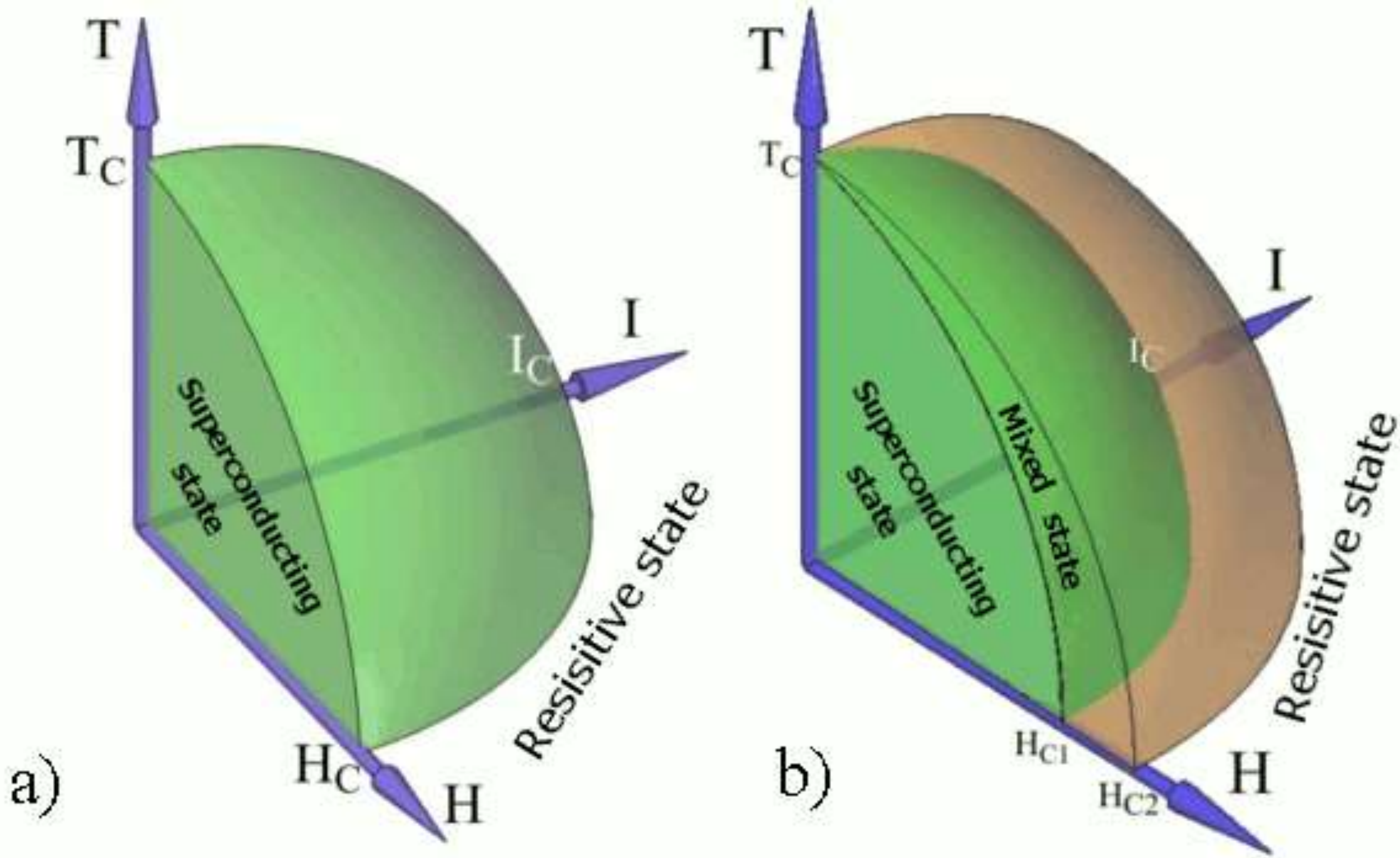
$H<H_c$

$J<J_c$

The maximum values of temperature, electrical current and magnetic field are interdependent and when plotted in 3 axes form a "**critical surface**".



Nb-Ti and Nb_3Sn, the **upper critical fields**are **13** T and **27** T respectively and current densities > **10^5 A/cm²** can be carried. The **critical temperatures for Nb-Ti and Nb_3Sn** are **10 K and 18 K** respectively.



T
T_C
I
I_C
Superconducting state
Resisitive state
H_C
H
a)
T
T_C
I
I_C
Superconducting state
Mixed state
Resisitive state
H_{C1}
H_{C2}
H
b)

Another important parameter associated with superconductivity is the coherence length ξ.

Concept of coherence length

The density of states n_s decreases to zero near a superconducting /normal interface, with a characteristic length ξ (coherence length, first introduced by Pippard in 1953). The two length scales ξ and λ_L define much of the superconductors behavior.

The coherence length is the smallest dimension over which superconductivity can be established or destroyed.

The Pippard coherence length

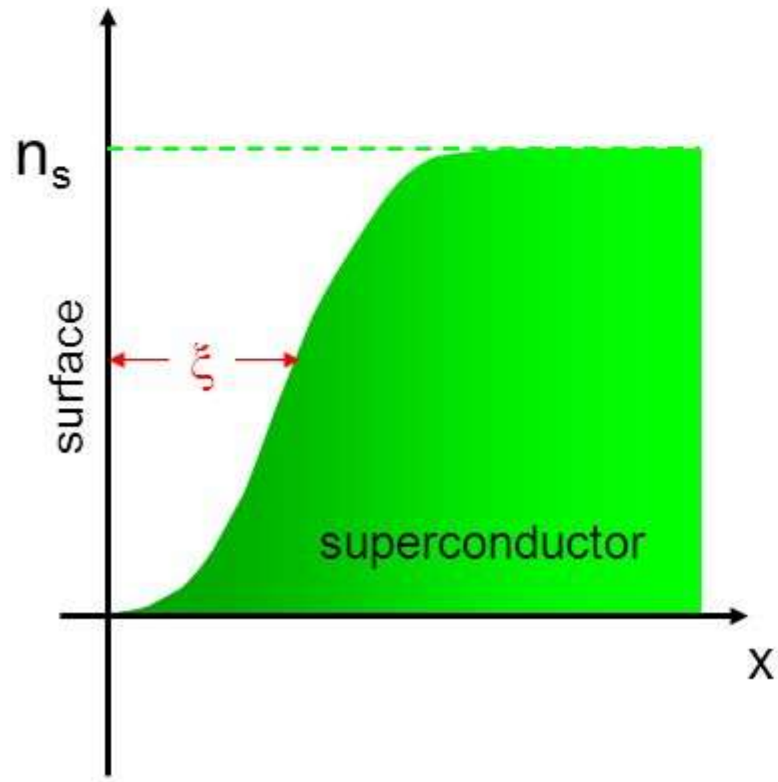
The superconducting electron density n_s cannot change rapidly with position...

….it can only change appreciably of a distance

The boundary between normal and superconducting regions therefore cannot be sharp….

…..n_s has to rise from zero at the boundary to a maximum value over a distance ξ

ξ is the Pippard coherence length



A transition from the superconducting state to a normal state will have a transition layer of finite thickness which is related to the coherence length.

Ginzburg-Landau Parameter

- The coherence length is proportional to the mean free path of conduction electrons; e.g. for pure metals it is quite large, but for alloys (and ceramics…) it is often very small. Their ratio, the GL parameter, determines flux penetration:

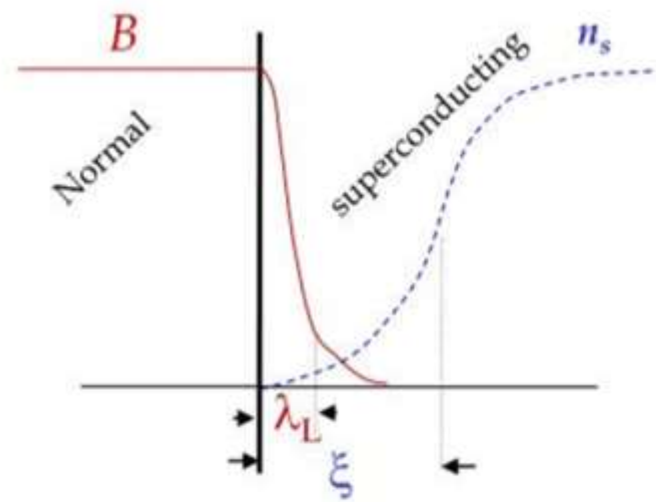
$$\kappa = \lambda_L / \xi$$

From "GLAG" theory, if:

$\kappa < 1/\sqrt{2}$ Type I superconductor

$\kappa > 1/\sqrt{2}$ Type II superconductor

Note: in reality ξ and λ_L are functions of temperature



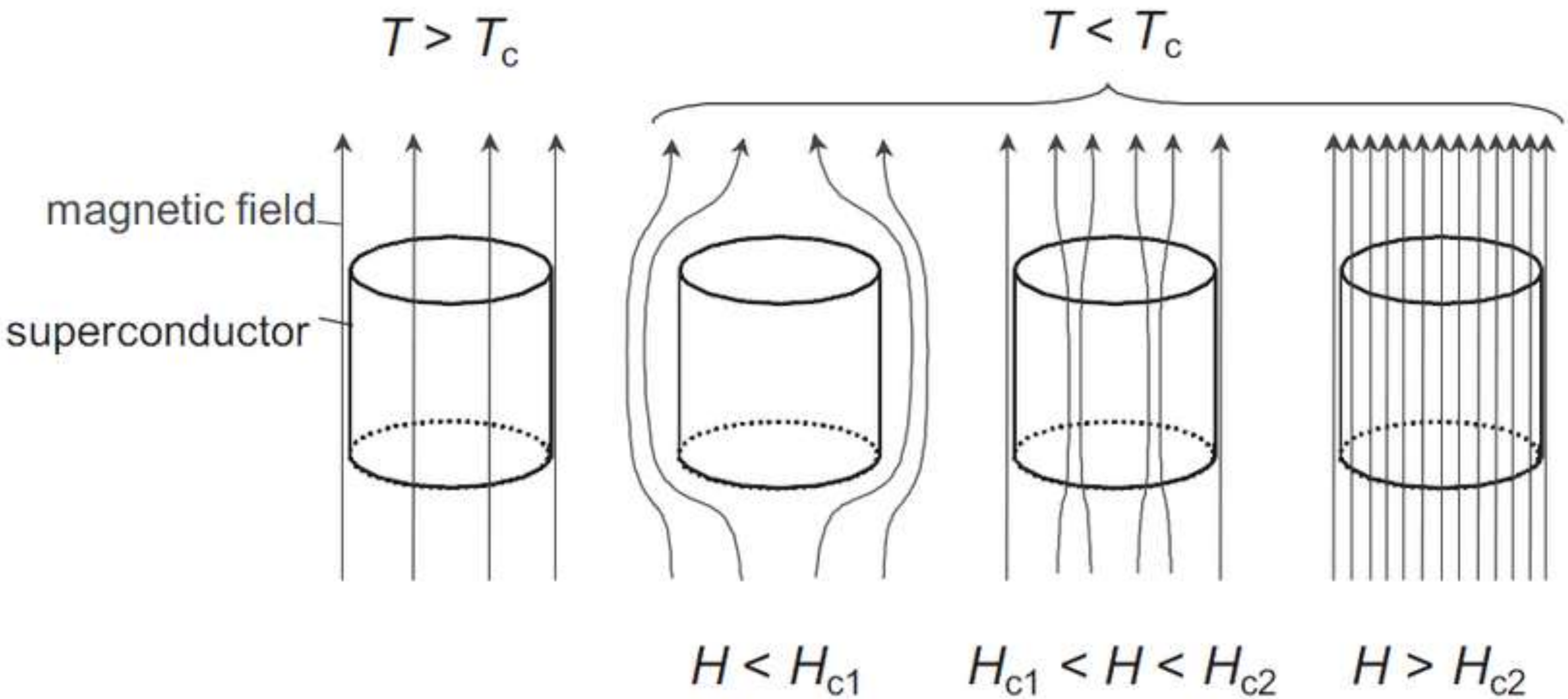
The mean free path of a metal can be reduced by the addition of impurities to the metal, which causes the penetration depth to increase while coherence length decreases.

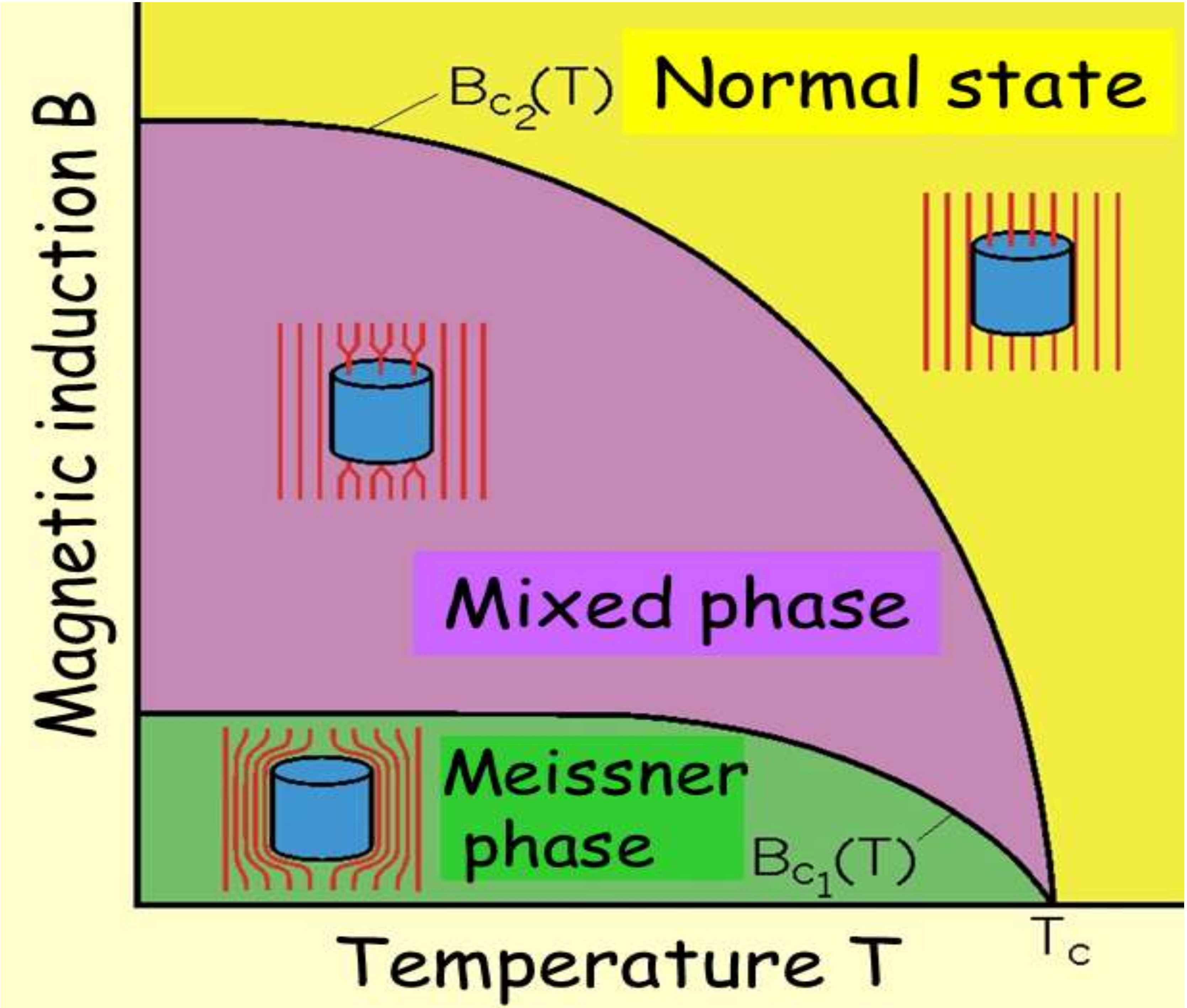
Thus one can cause a metal to change from type I to type II by introducing an alloying element.

Superconductor	**λ (nm)**	**ξ (nm)**
Al	16	160
Cd	110	760
Pb	37	83
Nb	39	38
Sn	34	23

	ξ (nm)	λ (nm)	T_c (K)	H_{c2} (T)
Nb_3Sn	11	200	18	25
YBCO	1.5	200	92	150
MgB_2	5	185	37	14

Type II Superconductor



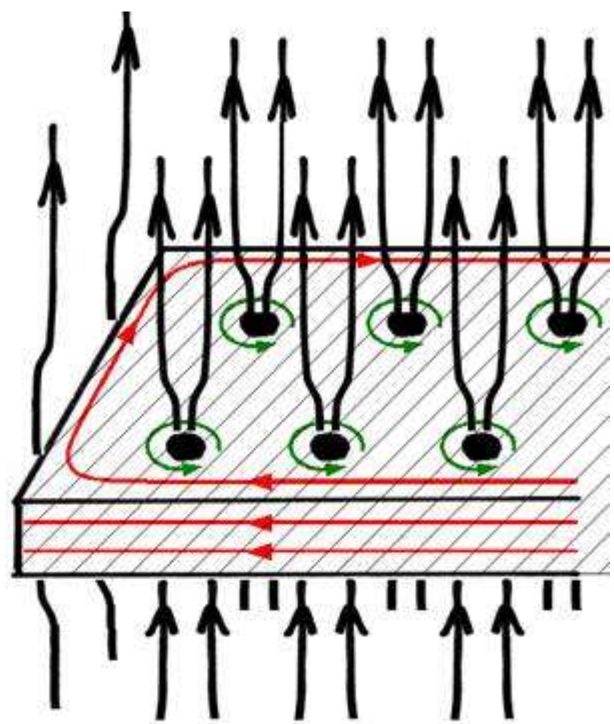

Normal state
$B_{c_2}(T)$
Mixed phase
Meissner phase
$B_{c_1}(T)$
Magnetic induction B
Temperature T
T_c

Let a magnetic field is applied.

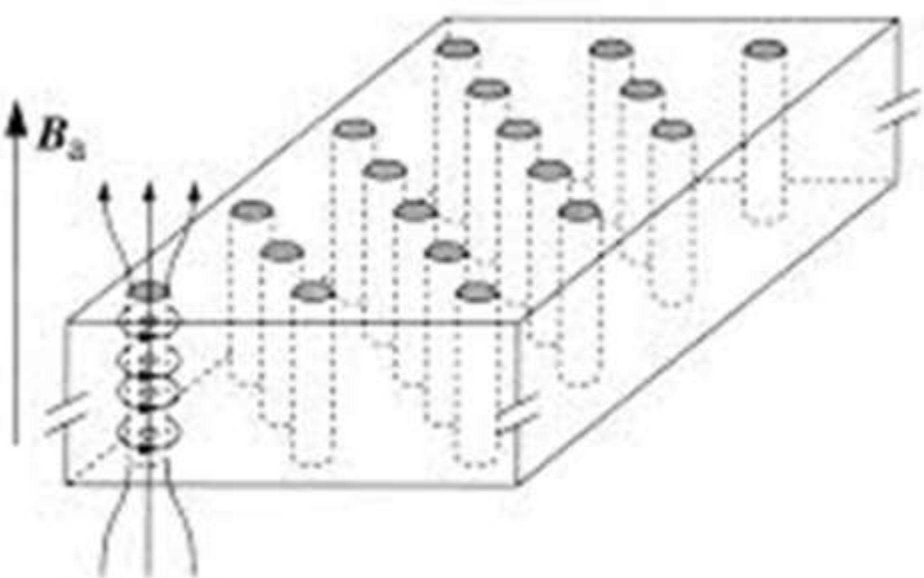
Superconducting currents develop on the surface in order to make a screen against this field; responsible for the Meissner effect.

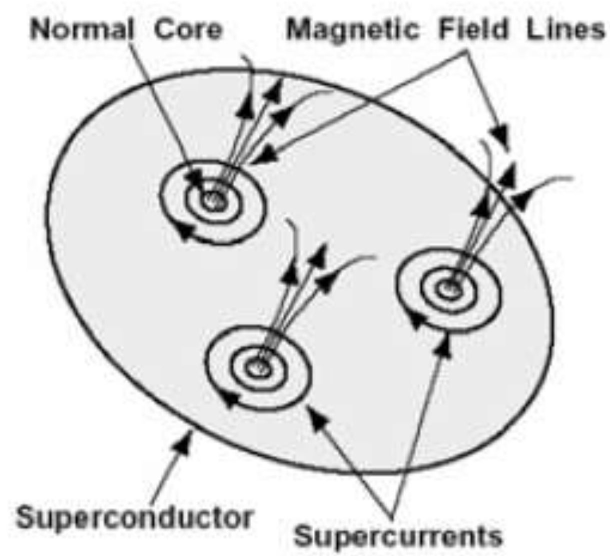
Other **superconducting currents** develop creating vortices (like non superconducting "tunnels").

These vortices allow a quantum of magnetic flux to go through them and thus enable part of the applied magnetic field to go through the superconducting sample.

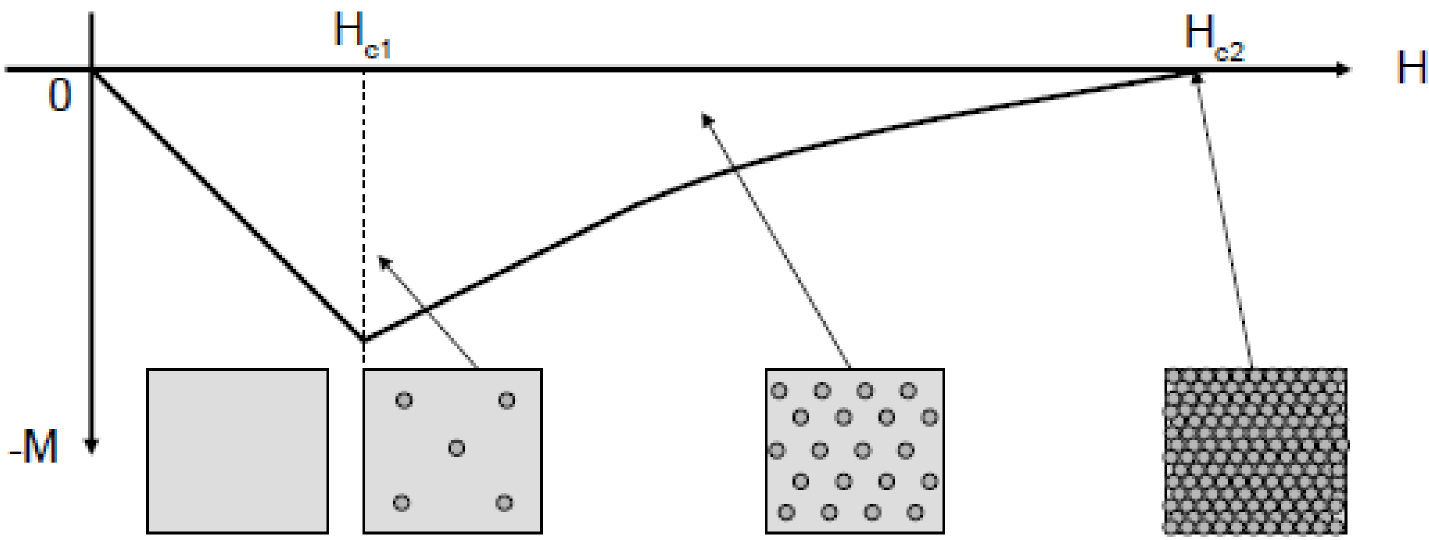


Vortex regions are essentially filaments of normal material that run
through the sample when the external field exceeds the lower critical field.

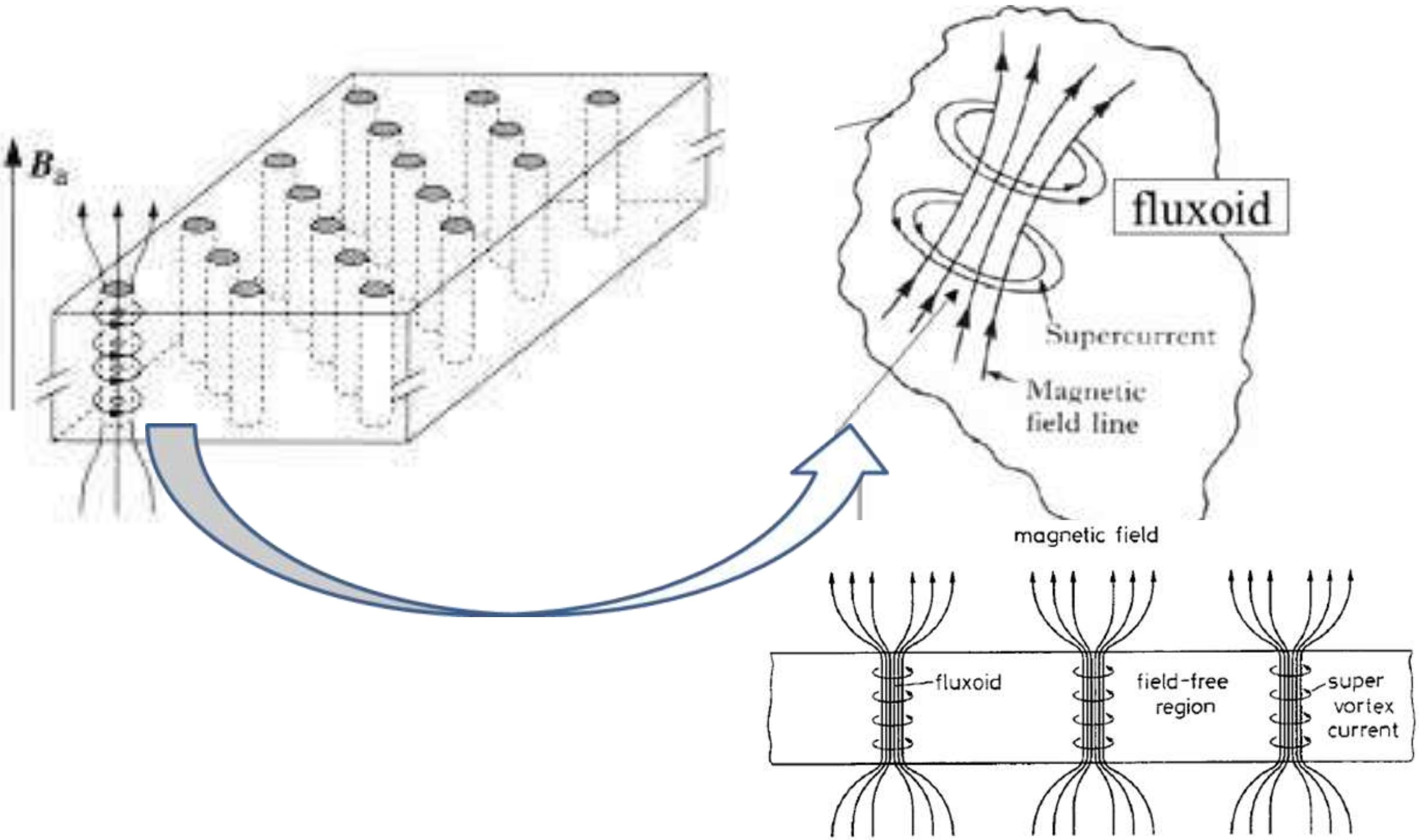




As the strength of the external field increases, the number of filaments increases until the field reaches the upper critical value, and the sample becomes normal.



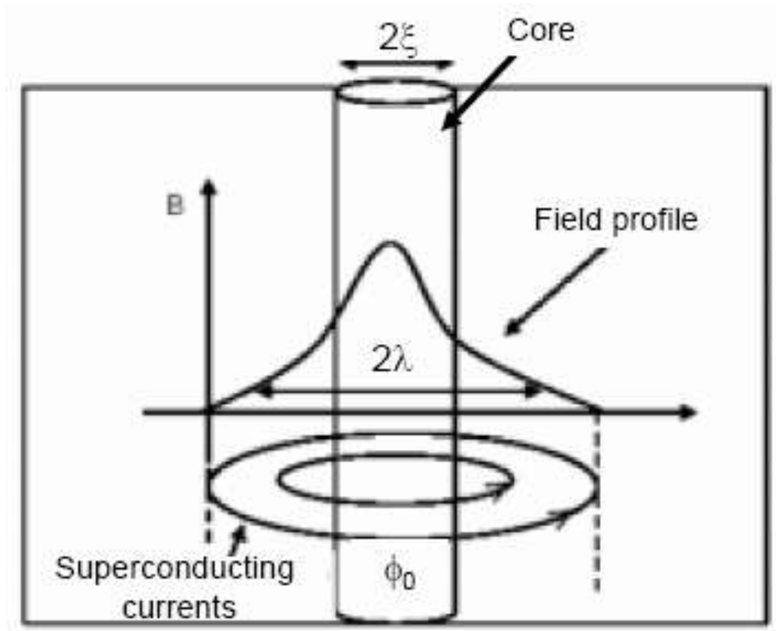
One can view the vortex state as a cylindrical swirl of supercurrents surrounding a cylindrical normal-metal core that allows some flux to penetrate the interior of the type II superconductor.

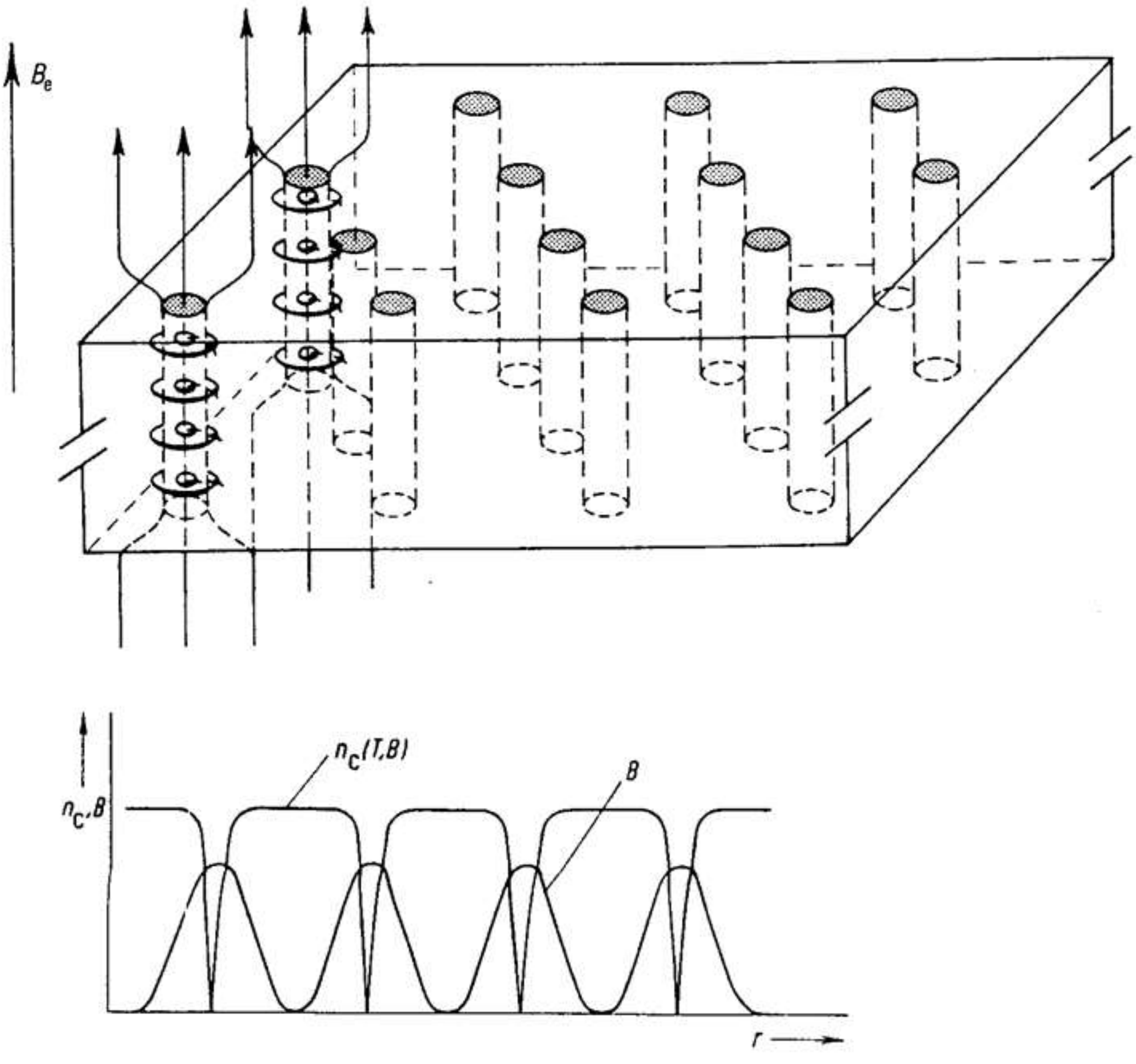


Associated with each vortex filament is a magnetic field that is greatest at the core center and falls off exponentially outside the core with the characteristic penetration depth .

The supercurrents are the “source” of B for each vortex.

In type II superconductors, the radius of the normal-metal core is smaller than the penetration depth.





B_e
$n_c(T,B)$
B
n_c, B
r

Fluxoids in type II superconductors

- Fluxoids, or flux lines, are continuous thin tubes characterized by a normal core and shielding supercurrents.
  - Size: $\pi\xi^2$ where ξ is the coherent length
- The flux contained in a fluxoid is quantized:

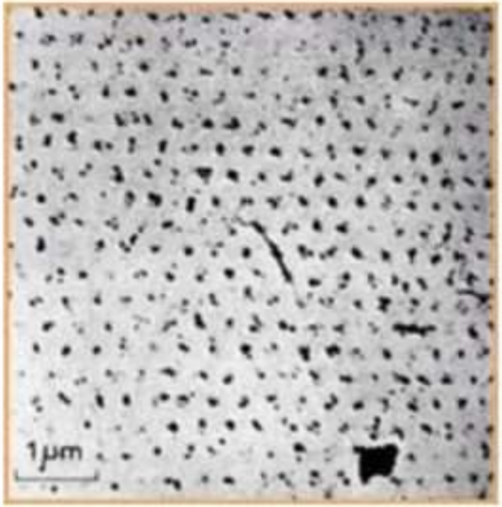
$$\Phi_0 = h/(2e)$$

$$h = \text{Planck's constant}=6.62607\times10^{-34}\ \text{Js}$$

$$e = \text{electron charge}=1.6022\times10^{-19}\ \text{C}$$

- The fluxoids in an idealized material are uniformly distributed in a triangular lattice so as to minimize the energy state
- Fluxoids in the presence of current flow (e.g. transport current) are subjected to Lorentz force:

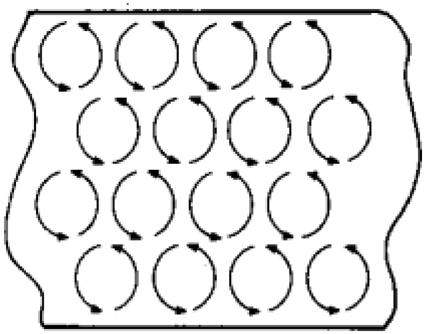
$$\vec{F} = \vec{J}\times\vec{B}$$



First photograph of vortex lattice,
U. Essmann and H. Trauble
Max-Planck Institute, Stuttgart
Physics Letters 24A, 526 (1967)

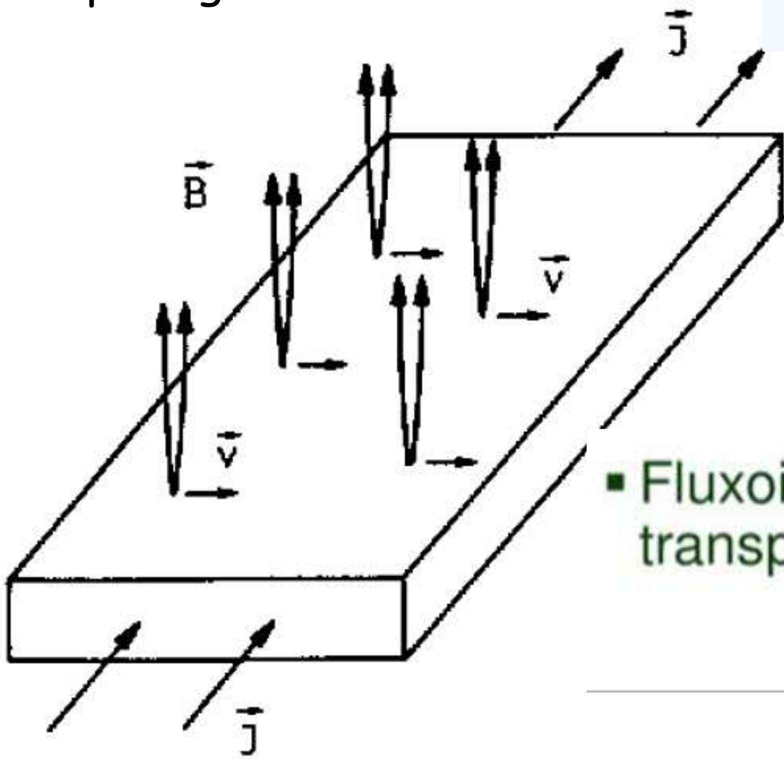
More on fluxoids

Fluxoids consist of resistive cores with super-currents circulating round them.



a single fluxoid encloses flux $$\phi_o = \frac{h}{2e} = 2\times10^{-15} Webers$$

spacing between the fluxoids $$d = \left\{\frac{2}{\sqrt{3}}\frac{\phi_o}{B}\right\}^{\frac{1}{2}} = 22nm \text{ at 5T}$$



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Pinning of fluxoids

- If fluxoids move, they generate heat
- Fluxoids can be pinned by a wide variety of material defects
  - Inclusions
    - » Under certain conditions, small inclusions of appropriate materials can serve as pinning site locations; this suggests tailoring the material artificially through manufacturing
  - Lattice dislocations / grain boundaries
    - » These are known to be primary pinning sites. Superconductor materials for wires are severely work hardened so as to maximize the number and distribution of grain boundaries.
  - Precipitation of other material phases
    - » In NbTi, mild heat treatment can lead to the precipitation of an a-phase Ti-rich alloy that provides excellent pinning strength.

Vortices are affected not only by the *Lorentz force* but also by *repulsive vortex-vortex forces*, and *vortex-pinning centre* interactions that restrict motion.

If the pinning force is larger than the sum of the Lorentz force and the vortex-vortex interaction, then the vortex cannot move.

Hence, for an unchanging pinning force, the vortices will be forced to move if either the Lorentz force or the vortex-vortex interactions become too large.

The Lorentz force will increase linearly with the size of the transport current, and the vortex-vortex interactions will increase as the density of vortices increases with the applied magnetic field .