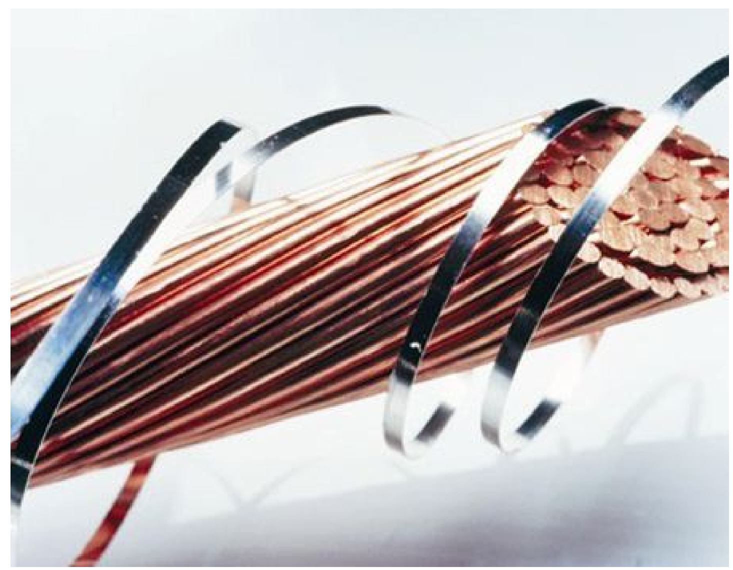
ICEC27-ICMC 2018
27th International Cryogenic Engineering Conference
International Cryogenic Materials Conference 2018
September 3-7 2018 Oxford England

Superconducting materials



Jorge Pelegrín Mosquera

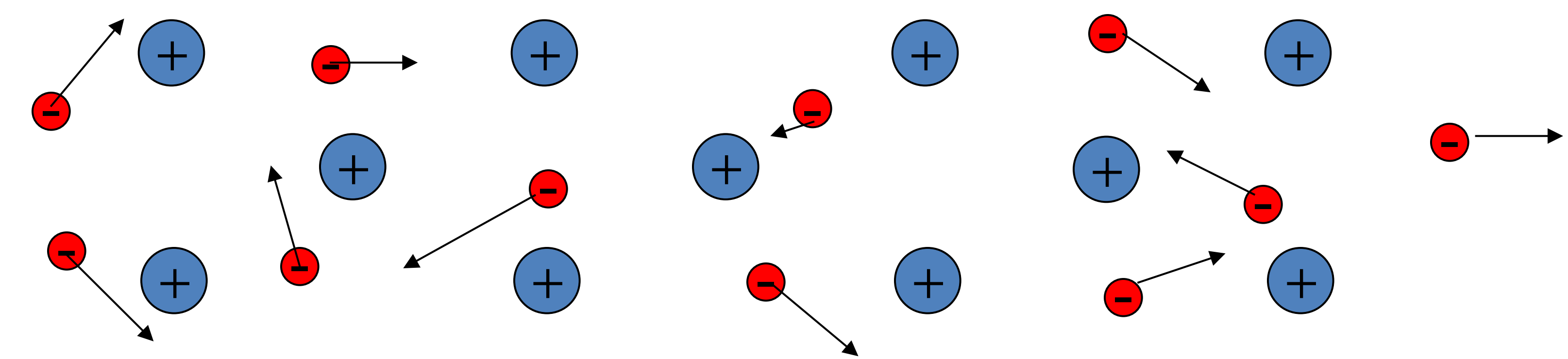
Summary

- Superconductivity
    - Resistivity
    - Meissner effect
- Superconducting materials
- Applications of superconductivity
    - High magnetic field production
    - Power applications

Summary

- **Superconductivity**
    - **Resistivity**
    - Meissner effect
- Superconducting materials
- Applications of superconductivity
    - High magnetic field production
    - Power applications

A simple model for electrical resistivity



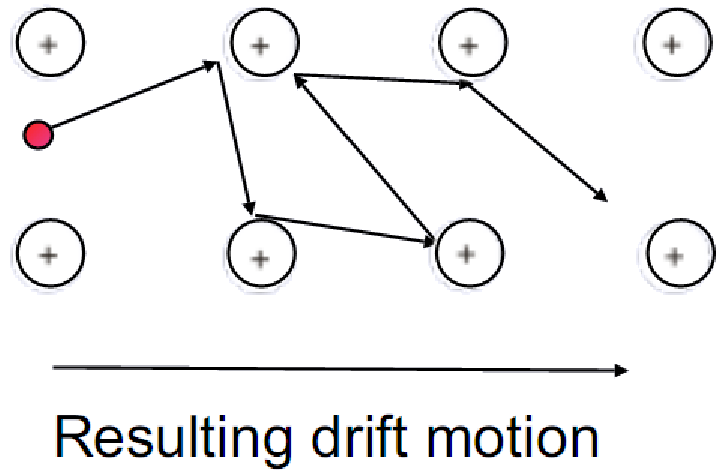
Electric resistance is the result of collisions between the electrons and the ions of the crystal lattice, and among the electrons themselves. Under an applied electrical field E (voltage V), the electrons move to higher potential end driven by force $-eE$. The electrons are accelerated by this force but slowed down by collisions with the crystal lattice (phonons) and impurities. The "free" electrons are only free for a short period τ between the collision (known as scattering), by the mean free path l and the velocity of the electrons v: $\tau = l/v$;

The mean free path is about the lattice constant ~ 1nm and the velocity (105 m/s) is given by the random Brownian motion: $mv^2 \sim k_B T$, hence $\tau \sim 10^{-14}$ s.

Resistivity

In steady state, the electrons gain an average collective drift velocity $\overline{\boldsymbol{v}}$ to sustain the current flow. The drift velocity is gained during the free period τ by the acceleration of the electrical field:

$$\frac{m\overline{\boldsymbol{v}}}{\tau} = -e\boldsymbol{E},$$



leading to a current flow of $\boldsymbol{J} = -ne\overline{\boldsymbol{v}} = \frac{Ene^2\tau}{m}$,

i.e. it leads to Ohm's Law $\boldsymbol{J} = \sigma\boldsymbol{E}$ or $\boldsymbol{E} = \rho\boldsymbol{J}$

with resistivity $\rho = \frac{m}{ne^2\tau}$. The mean free-time τ increases with reducing temperature as thermal activated random motion decreases..

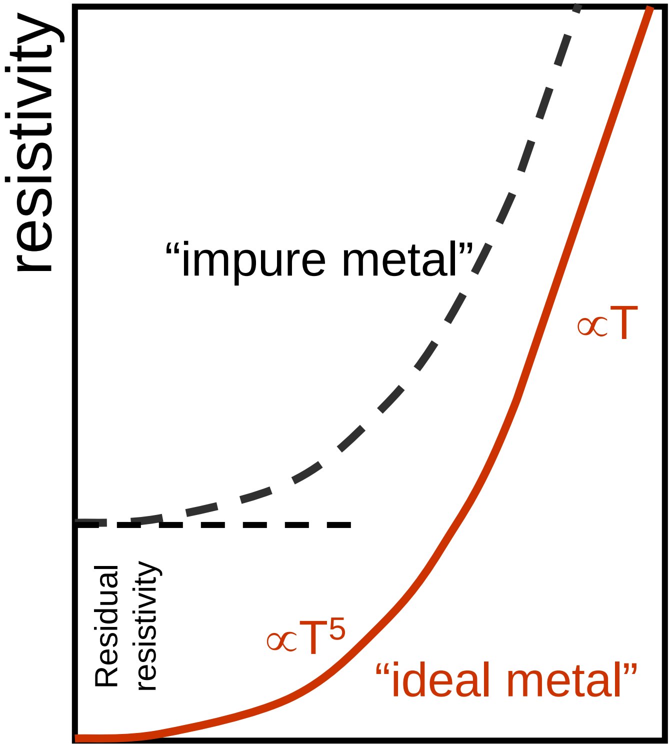
For copper $\tau = \frac{m}{ne^2\rho} \sim 10^{-17} s$

- Resistivity at low temperature

- Thermal velocity reduces with temperature, so resistivity reduces smoothly with temperature.

- Due to Pauli's exclusion principle resistivity remain finite at finite temperature

- For defect free metals resistivity reduces with T^5, real materials have a residual resistivity due to scattering with impurities.

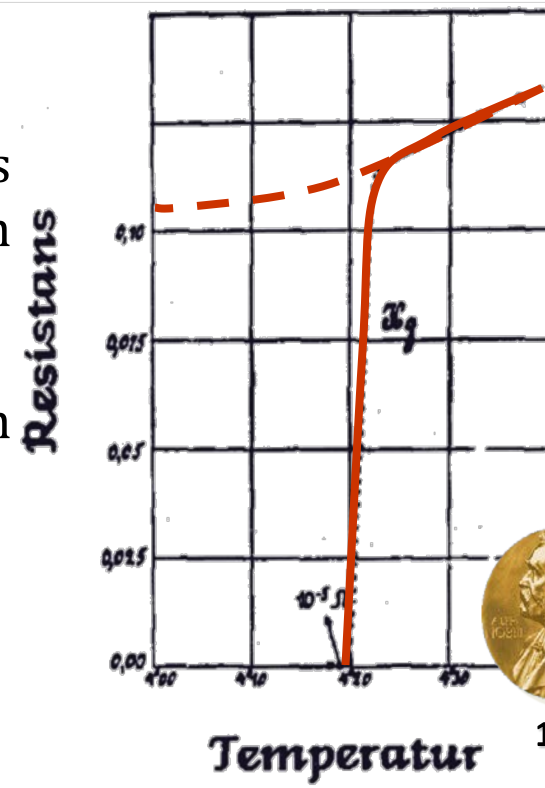


- Resistivity and superconductivity

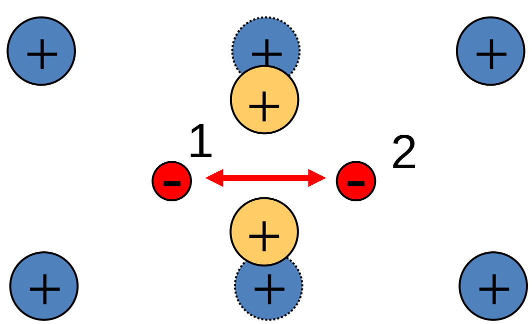
- Discovered by Heike Kamerlingh Onnes on 1911

- Below a the critical temperature, T_c, electrons form Cooper's pairs to avoid Pauli's exclusion principle.

- When applying an electrical field a certain momentum is neccesary to break the pairs → I_c



1913

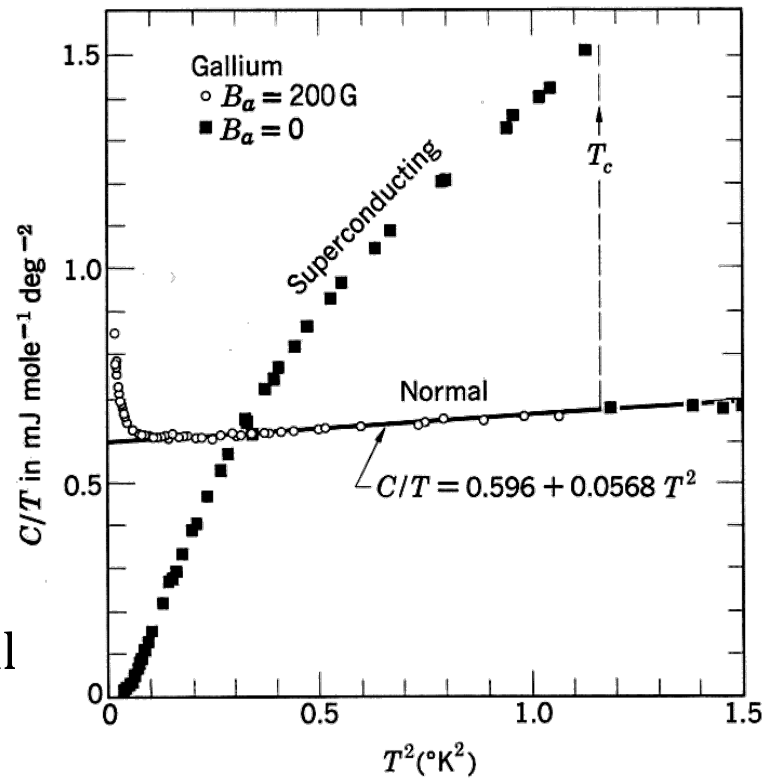


Cooper pairs have an over all spin of 0, in contrast to ½ for a single electron, hence are not restricted by Pauli's exclusion principle and can occupy the same state with many others. So condensation becomes possible.

With reduction of temperature, the net attractive force becomes significant greater than thermal excitation, and ground state Copper's pair are formed as a condensate.

This phase transition for the electron pairs is similar to normal matter condensation with a well defined discontinuity in the specific heat.

Condensation Confirmed by Heat Capacity Measurement



Summary

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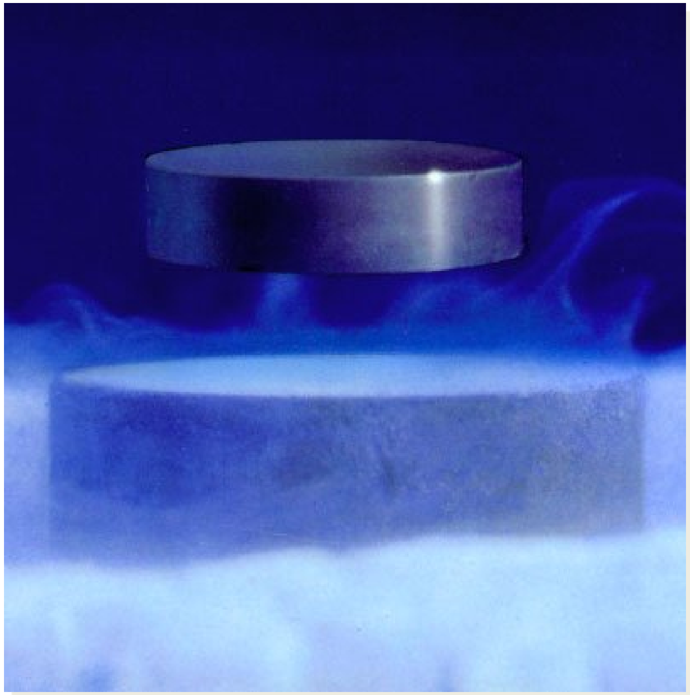
  - Resistivity
  - **Meissner effect**
- Superconducting materials
- Applications of superconductivity
  - High magnetic field production
  - Power applications

What is the difference between a "perfect conductor" and a "superconductor"?

In 1933 Meissner and Oschenfeld made the discovery which distinguished between the two

The Meissner Effect

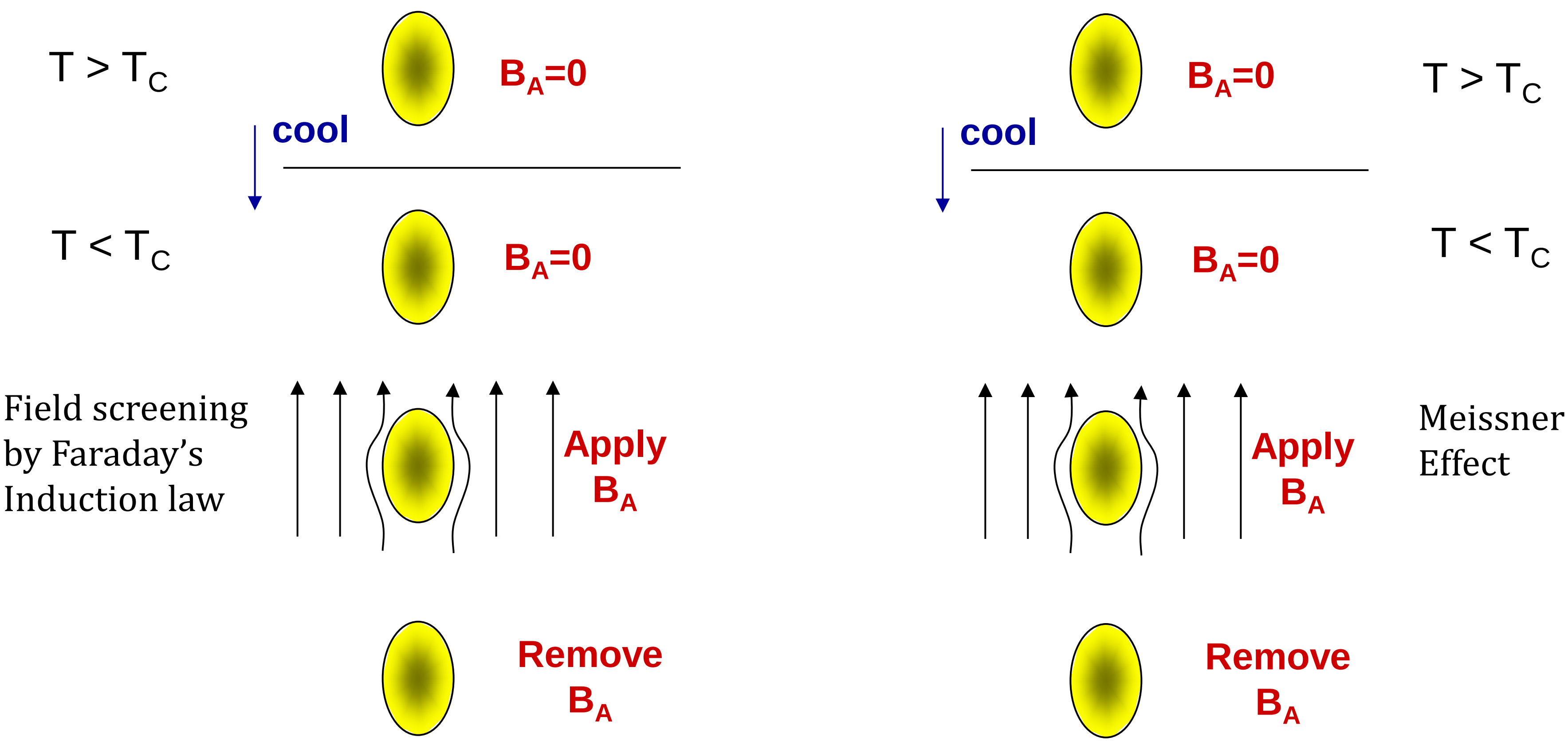
"A superconductor excludes all magnetic flux from its interior"



- Magnetic properties of superconductors

Perfect conductor / Superconductor

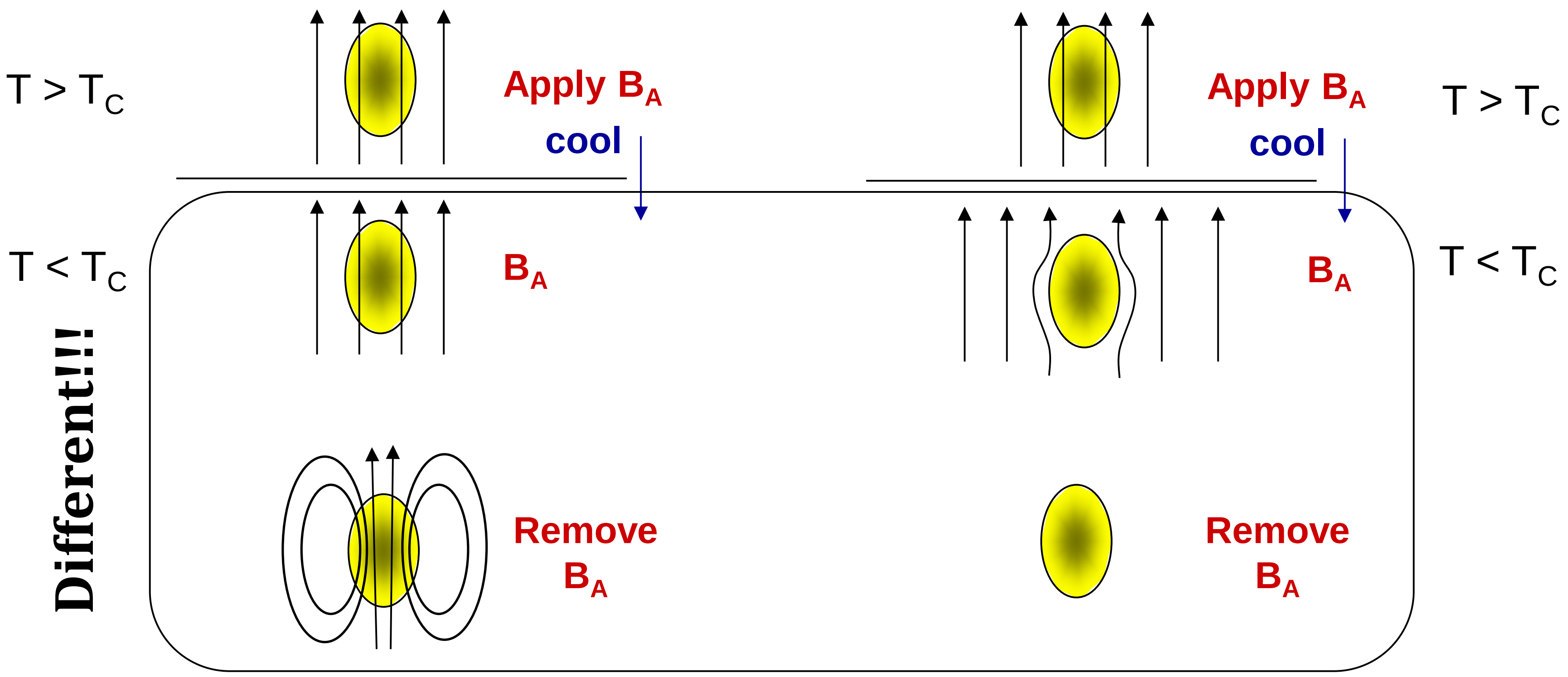
Zero field cooled, field applied when the sample is already below T_C



- **Magnetic properties of superconductors**

Perfect conductor | Superconductor

<u>Field cooled</u>, field applied when the sample is normal

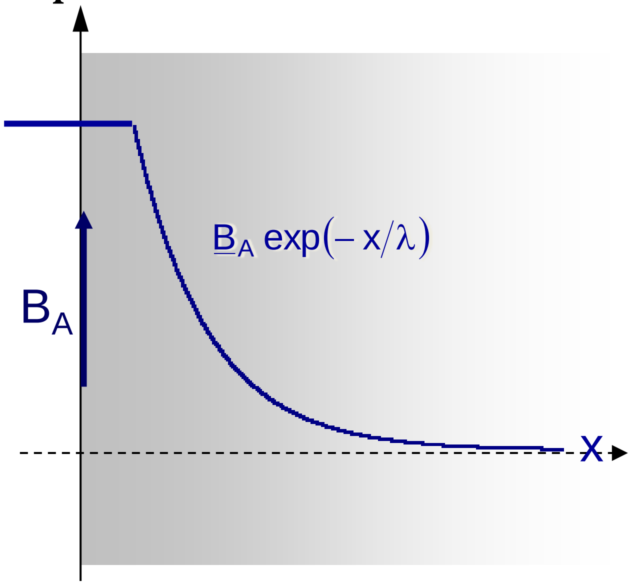


A superconductor is not a perfect conductor, Meissner effect is a thermodynamic property independent of history of the magnetic field.

Basic properties: London penetration depth

Meissner Effect is due to a surface current flowing on the outer skin, which shields the magnetic field from the interior.
This current is not caused by induction upon change of applied field.

Field profile near the surface



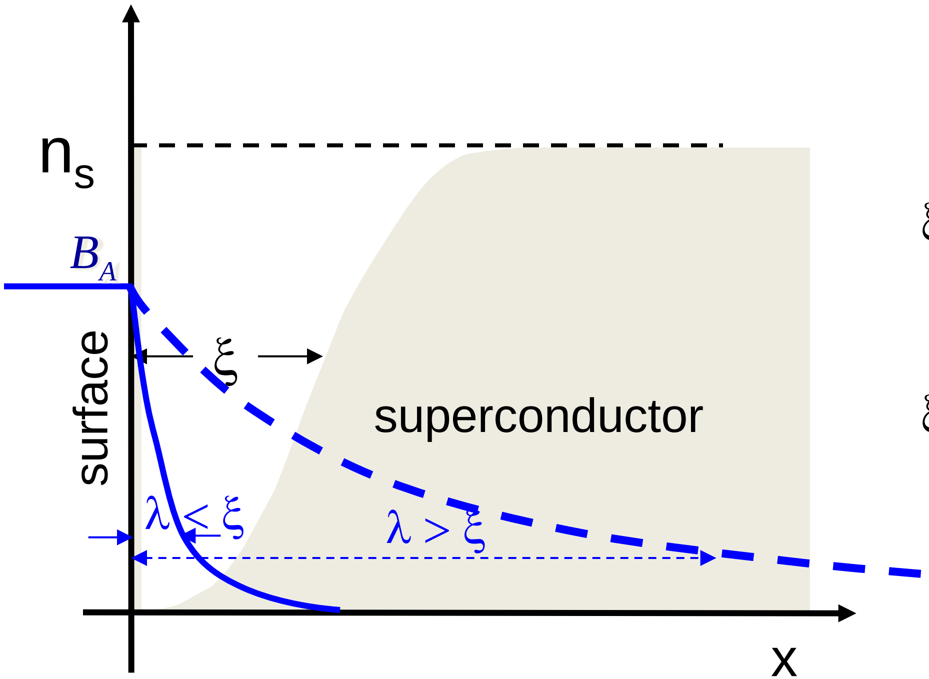
λ_L is known as the London penetration depth:

It is a fundamental length scale of the superconducting state. The typical penetration length is very short (<μm)

$$\lambda_L(T) = \left(\frac{m}{\mu_0 n_s(T) e^2} \right)^{\frac{1}{2}}$$

Basic properties: Coherence length

<u>The physical size of Cooper pairs</u>, effectively the distance between the paired electrons, is *small but finite*. Consequently, a finite length is required to set up a full superconducting state from a normal/superconductor interface. This length scale is known as the <u>coherence length</u> ξ,

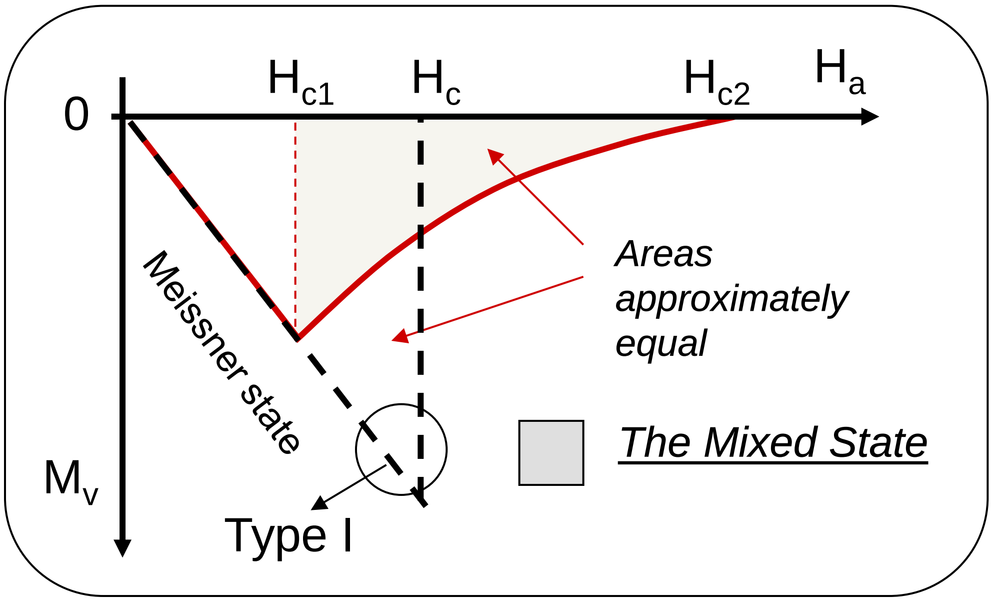


$$n_s(x,T) = n_s(T)\left(1 - e^{-x/\xi}\right)$$

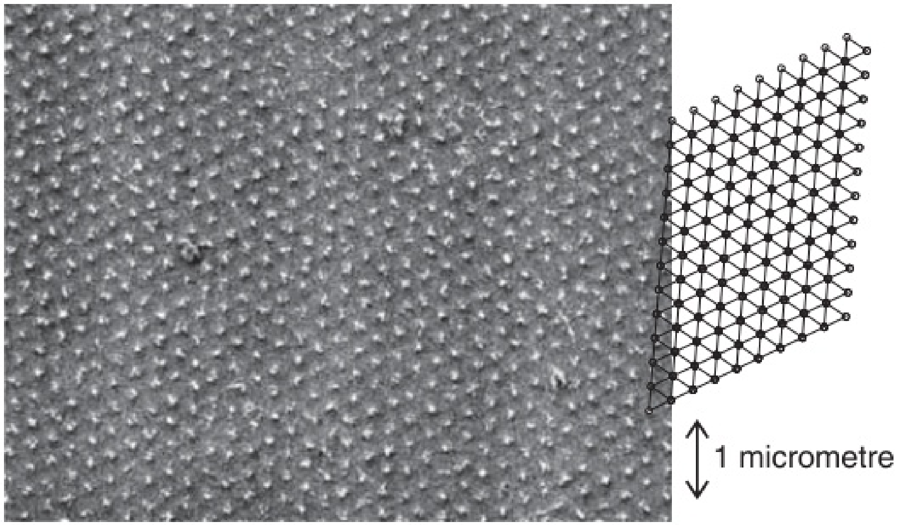
ξ> λ: smaller field penetration → Type I

ξ < λ: larger field penetration → Type II

Magnetisation of type II superconductors



Flux line lattice of the mix state shown by Bitter decoration

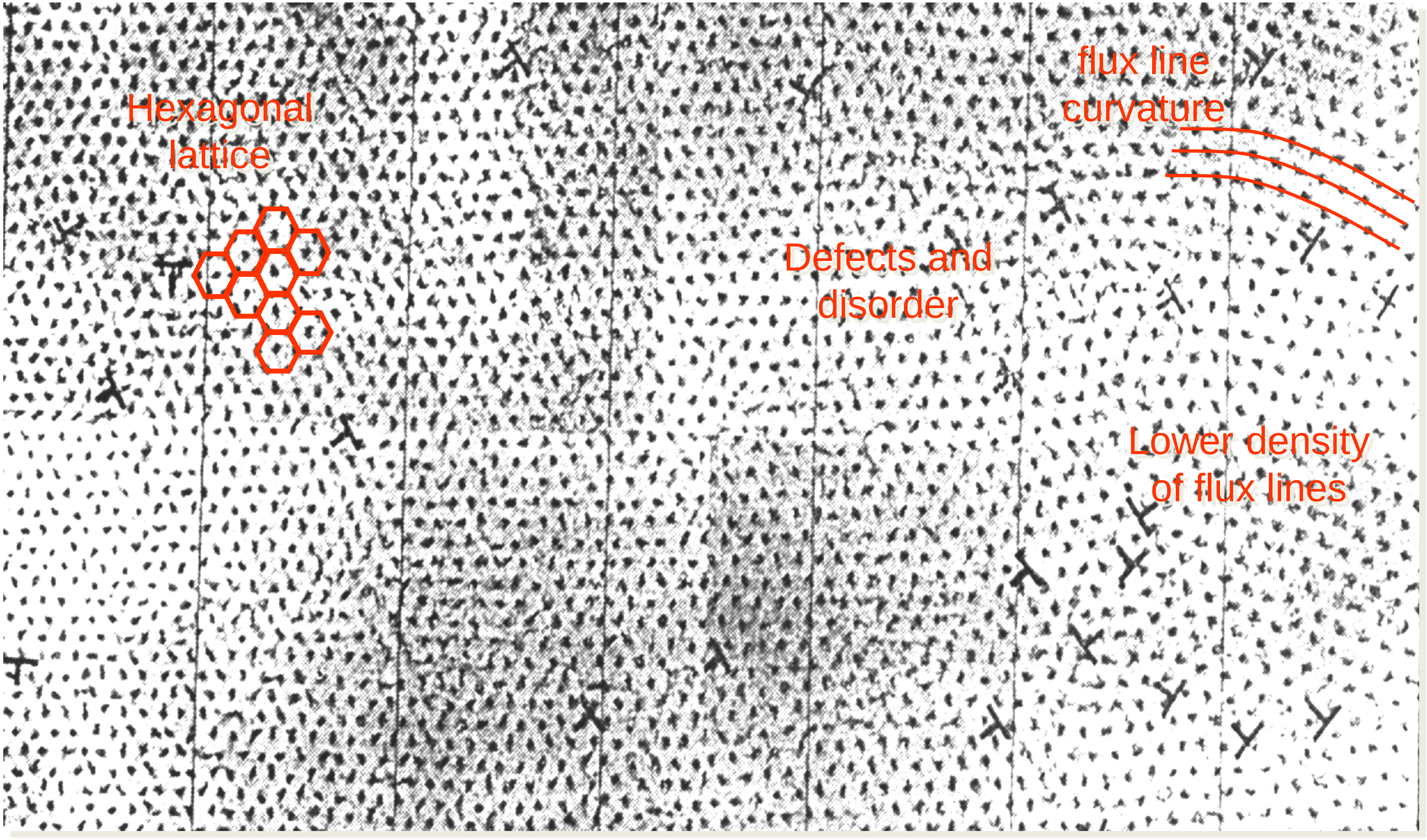


In Type II superconductors the magnetic flux penetrates in quantised magnetic flux lines. These quantised normal regions are long threads with a diameter of the coherence length ξ and is arranged in a hexagonal lattice.

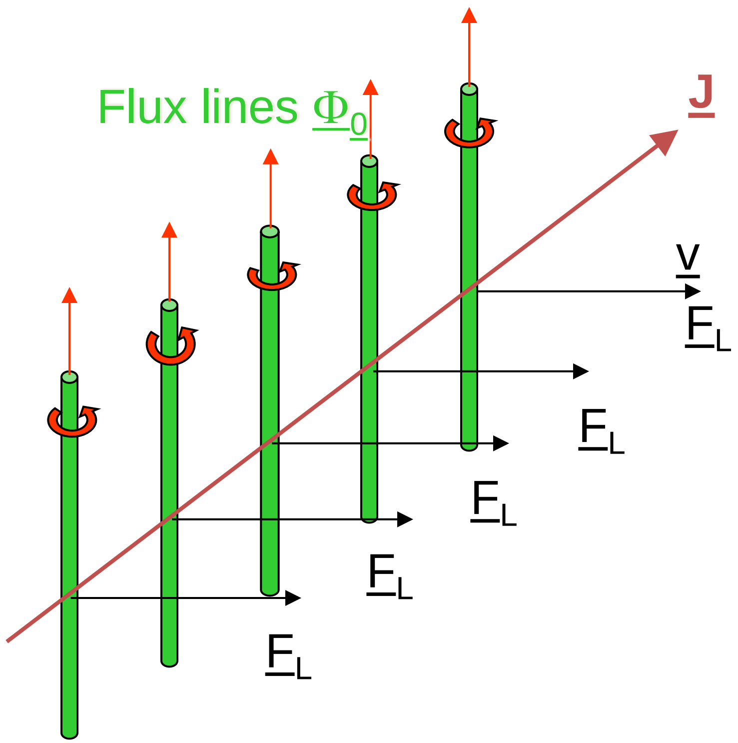
$$\Phi_0 = \frac{h}{2e} = 2.07 \times 10^{-15}\ \text{Tm}^2$$

Only type II superconductors are useful for practical power applications.

Basic properties: Pinning centres through correlated material defects



Basic properties: Flux Pinning and critical current



When carrying a transport current, the flux line lattice in the mixed state is subjected to the Lorentz force:

$$\underline{F}_L = \underline{J} \times \underline{\Phi}_o$$

$\underline{v}$ = velocity of flux lines

The flux lines tend to move at $\underline{v}$ along $\underline{F}_L$ perpendicular to the current.

The movement is perpendicular to the field direction, inducing an electric field:

$$\underline{E} = \underline{B} \times \underline{v}$$

$\underline{E}$ is parallel to $\underline{J}$, so acts like a resistive voltage, and $E \cdot J$ is the energy loss.

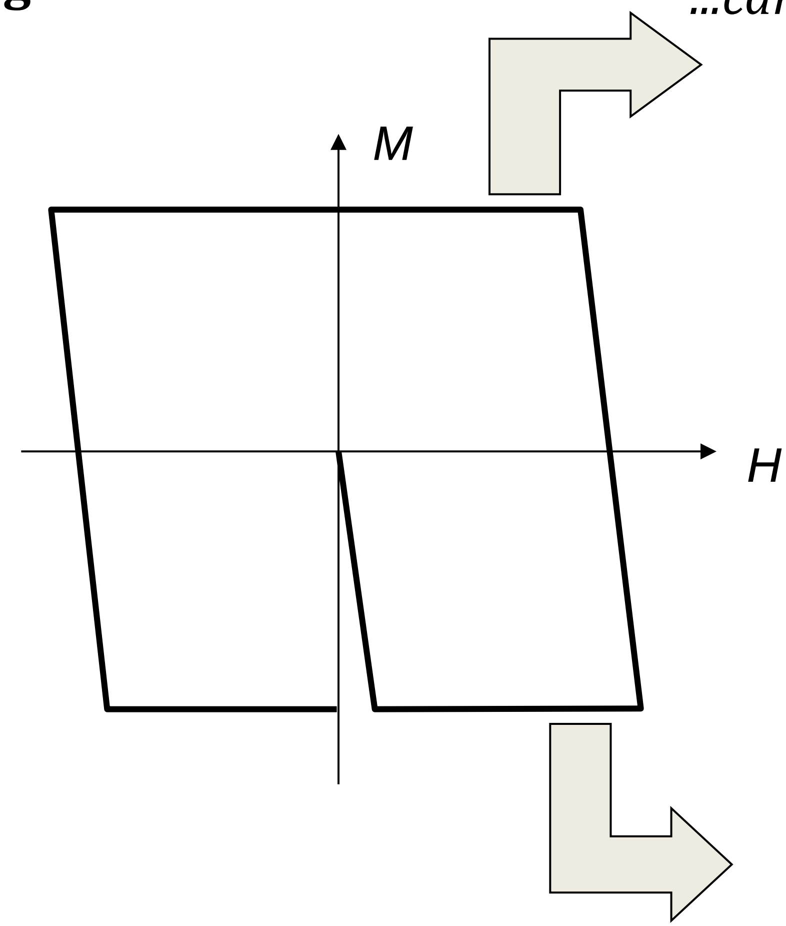
For zero dissipation, the motion of flux lines must be stopped, usually by "pinning centres". Critical current J_C is the maximum current before the Lorentz force F_L exceeds the pinning force.

Basic properties: Flux Pinning and magnetic hysteresis

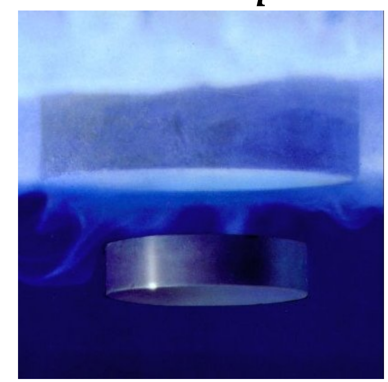
The existence of pinning force automatically leads to irreversibility:

For increasing field, pinning force resists magnetic flux from penetration and expels magnetic field, similar to Meissner effect.

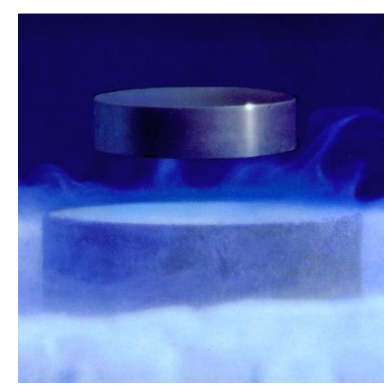
For reducing field, pinning force prevents the penetrated flux from leaving and retains flux, opposite to Meisnner effect.



...can become suspension



Levitation...



Summary

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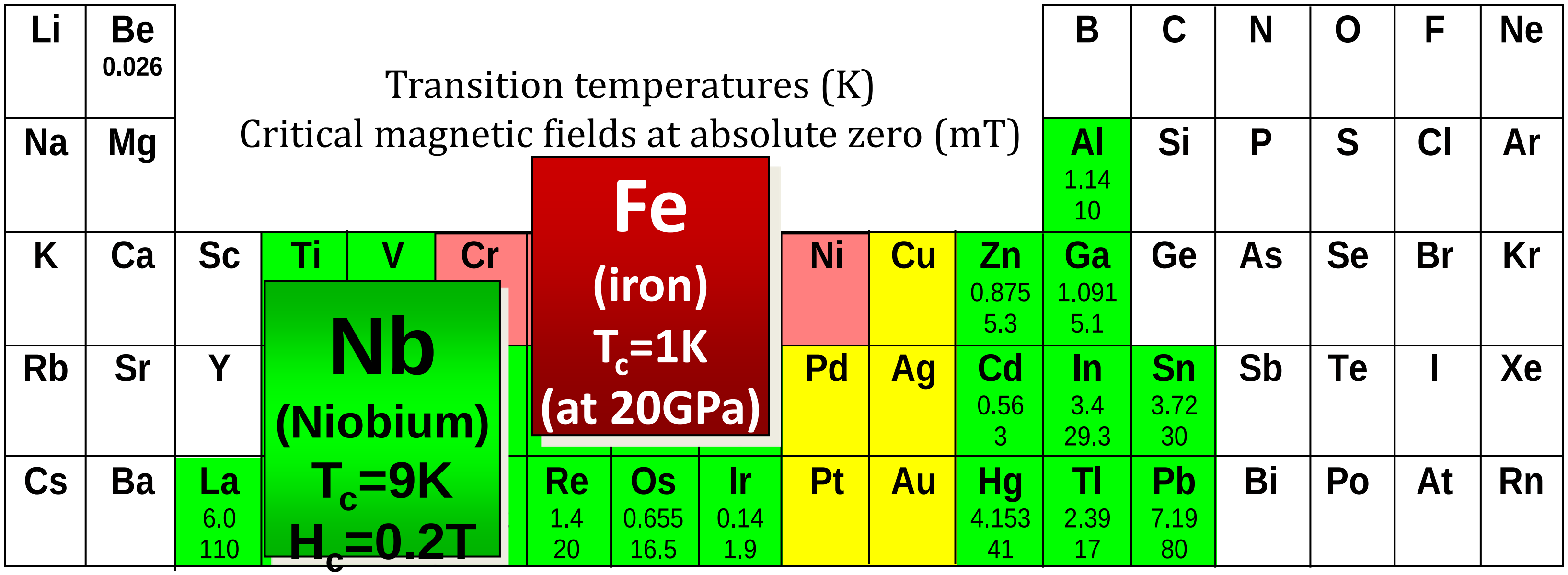
Superconductor → Material with zero resistance under given experimental conditions (*T, I, B*)

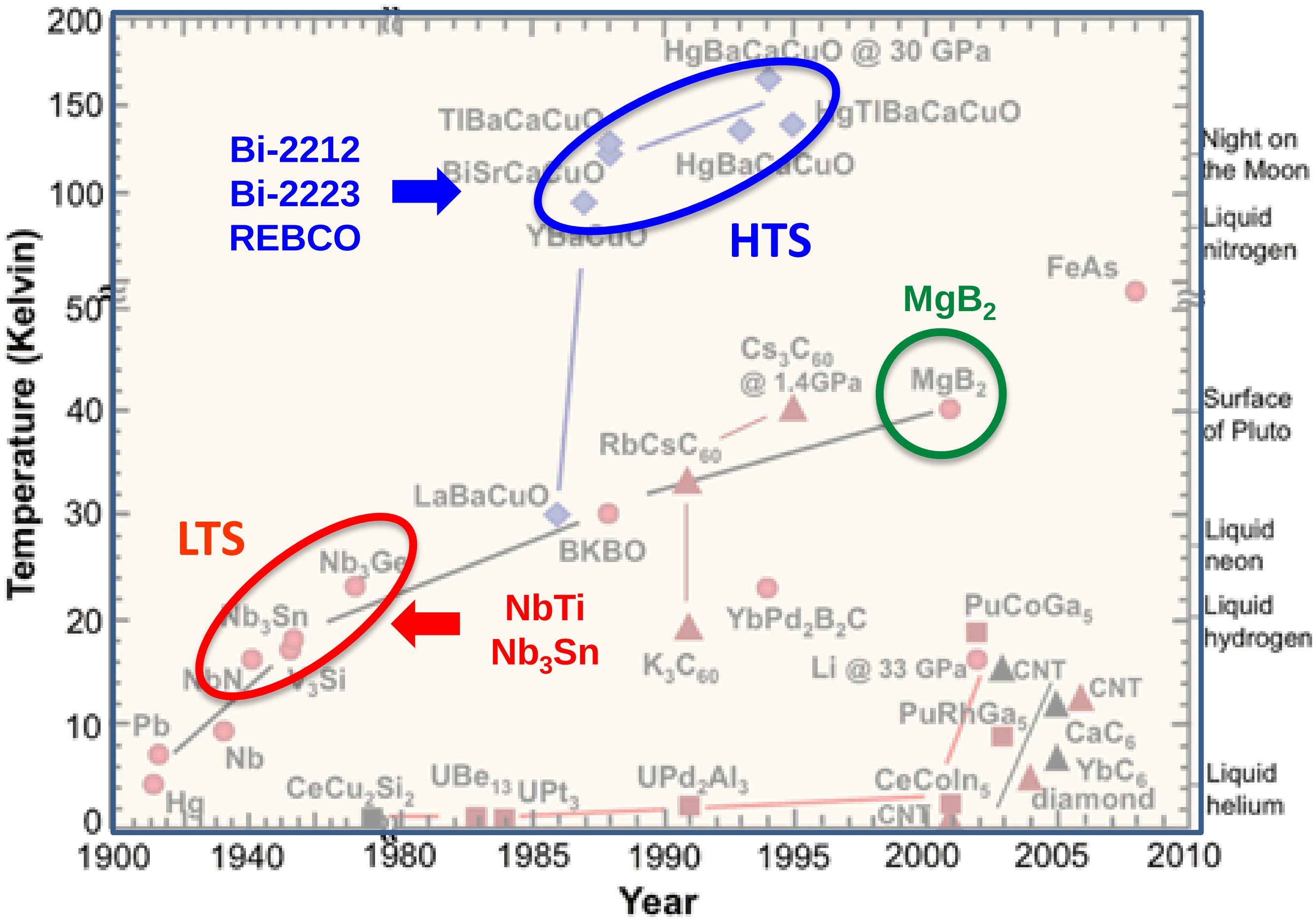


- Transition temperatures (K) and critical fields are generally low
- Metals with the highest conductivities are not superconductors
- The magnetic 3d elements are not superconducting

Superconductor → Material with zero resistance under given experimental conditions (*T*, *I*, *B*)

There are many superconducting compounds

Few compounds available in the shape of wires and tapes



2018 Superconductivity discovered in ultra thin layers of Rhenium below 6 K.

NbTi and Nb_3Sn conductors

- **NbTi** T_c = 9.6 K, B_{c2}(0 K)= 14 T

- Wires fabricated by cold work.

- **Nb_3Sn** T_c = 18.3 K, B_{c2}(0 K)= 28 T

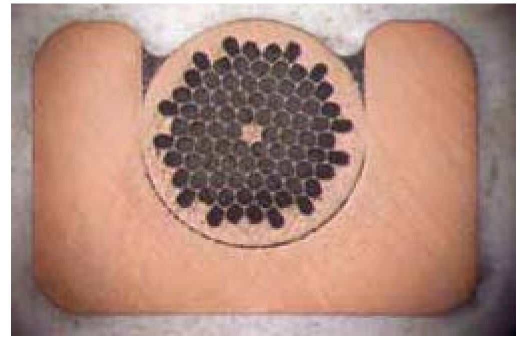
- Extremely brittle material.

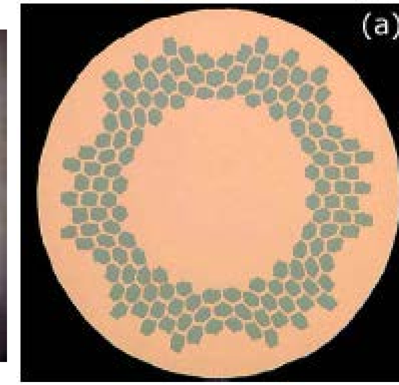
- The precursors are drawn inside a metal matrix and then reaction is done.

- Companies: Bruker and Luvata

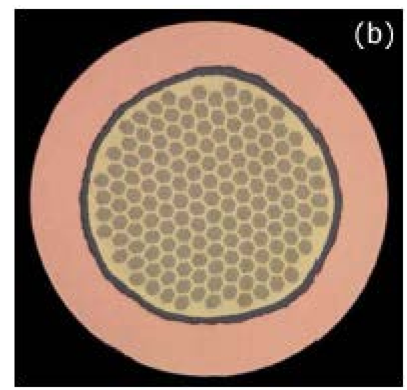
- **NbTi** I_c/A = 35 kA cm^{-1} at 8 T and 4.2 K.

- **Nb_3Sn** I_c/A = 150 kA cm^{-1} at 8 T and 4.2 K.





NbTi



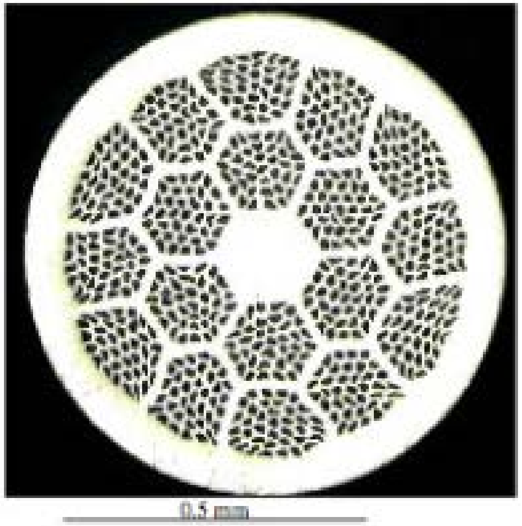
Nb_3Ti

BSCCO wires and tapes

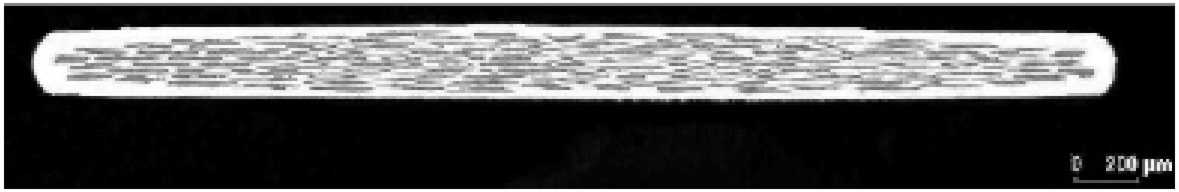
- $Bi_2Sr_2CaCu_2O_{8+\delta}$ (Bi-2212)
- T_c = 92 K, B_{irr}(77 K)= 0.2 T
- $Bi_2Sr_2Ca_2Cu_3O_{10+\delta}$ (Bi-2223)
- T_c = 110 K, B_{irr}(77 K)= 0.3 T
- Oxide-powder in tube technique is used.
- Alignment of the grains is obtained by cold work of a silver matrix.

-Companies: Sumitomo, American Superconductor or Oxford instruments.

-- I_c/w = 500 A cm^{-1} in km length at 77 K and self field.

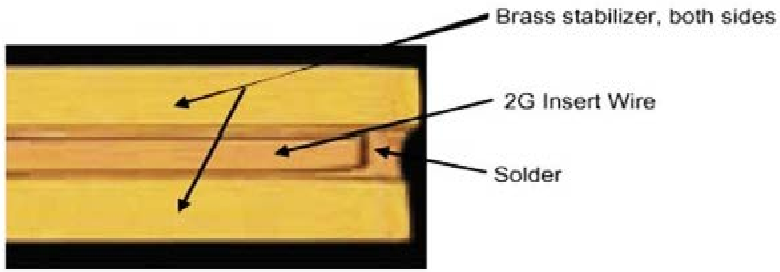


Bi-2223

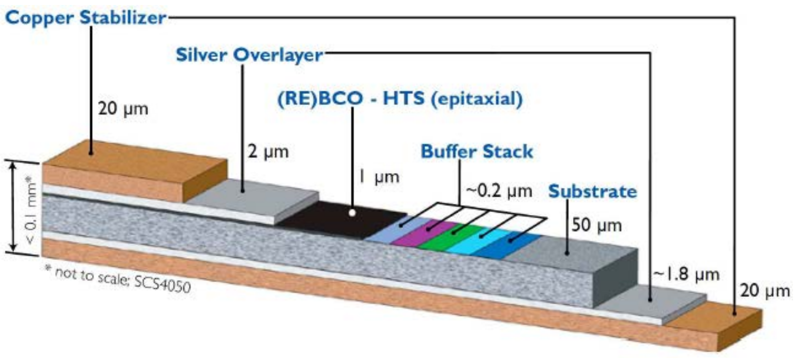


Bi-2212

REBCO tapes



- $REBa_2Cu_3O_{7-\delta}$ RE = Y, Rare earth
- T_c = 90 K, B_{irr}(77 K)= 5-7 T
- Biaxial texture must be induced due to weak grain boundaries
    - IBAD: Texture induced on an oxide layer
    - RABiTS: Texture induced on a substrate by rolling of a metal slab.
- 1 µm epitaxial REBCO is deposited over different buffer layers.
- Silver, copper or brass are used as stabilizer.
- Companies: AMSC and SuperPower Inc.
- I_c/w = 200 A cm^{-1} for 500 m length at 77 K and self field.



MgB_2

- T_c = 39 K, B_{c2}(4 K)= 15 T

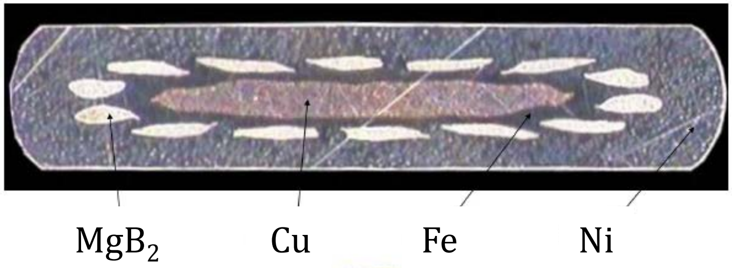
- Fabricated by PIT (ex-situ and in-situ) and diffusion.

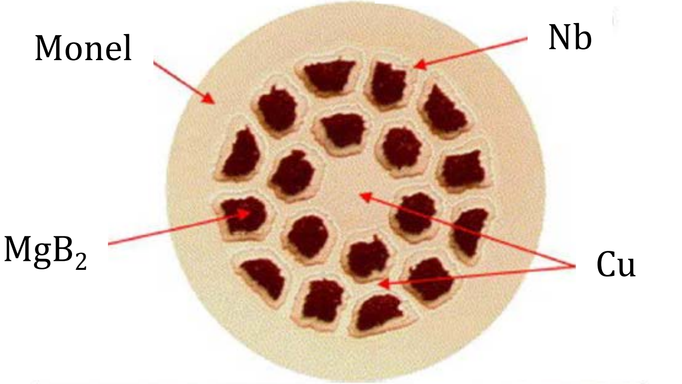
- Wires are produced by cold work of metal matrix with the powders inside

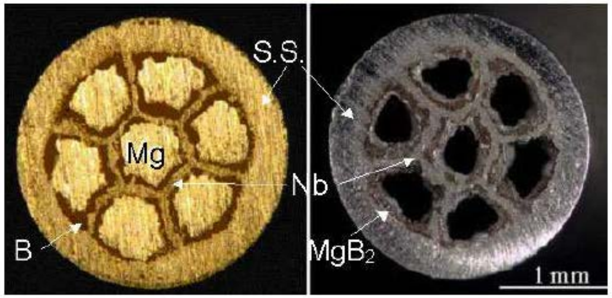
- Cu is used as stabilizer

- Companies: Columbus and Hypertech

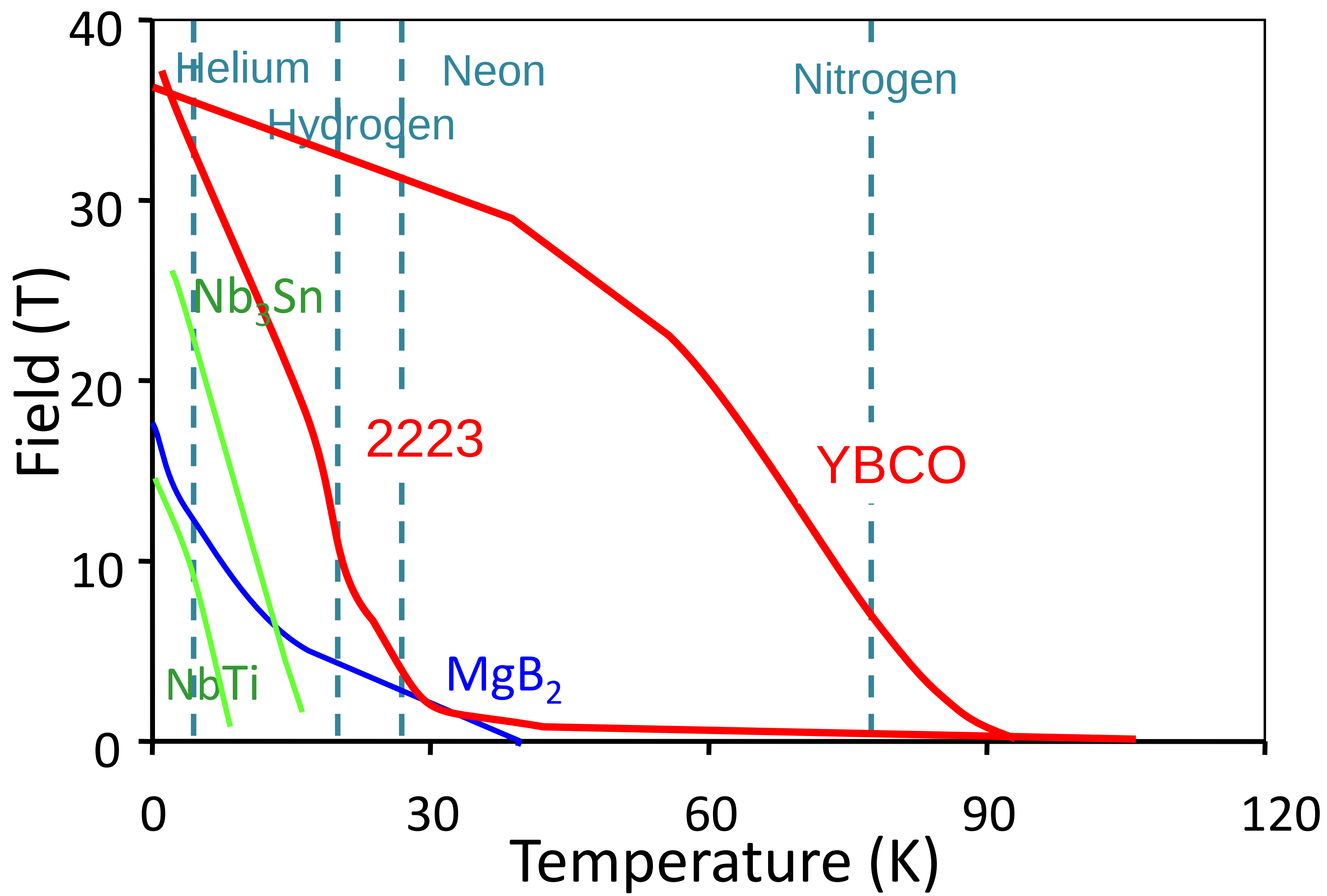
- Available lengths of 5 km with I_c = 1.5 kA cm^{-1} at 20 K and 1 T.







The material selection is also affected by cryogenics.

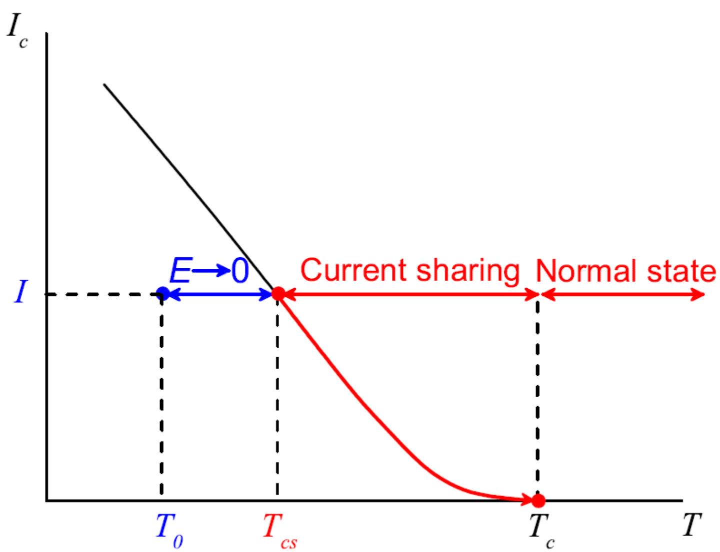


Thermal stability

Cryogens and cryocoolers need to be capable of cope with possible thermal instabilities.

$$d_0 c_p \frac{\partial T}{\partial t} = \frac{\partial}{\partial x}\left(k(T)\frac{\partial T}{\partial x}\right) - \frac{Ph}{A}(T - T_{ref}) + G(T,I) + P_{ext}(x,t)$$

Thermal conduction | Exchanged heat | Internal heat generation | External heat perturbation



Current sharing

$$I = I_m(T) + I_{sc}(T)$$

$$E(T,I) = E_0\left(\frac{I_{sc}(T)}{I_c(T)}\right)^{n(T)} = I_m(T)\cdot R_m(T)$$

Normal state

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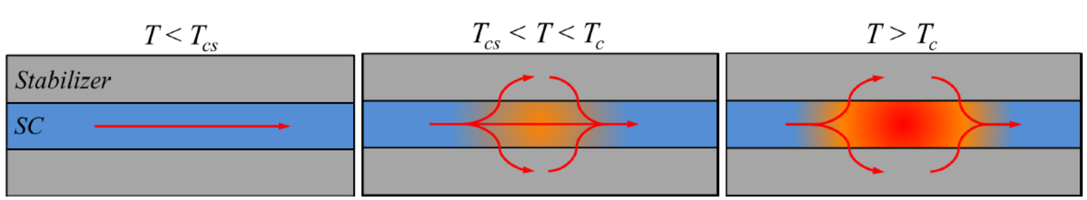

If the instability is not recovered a quench is produced.

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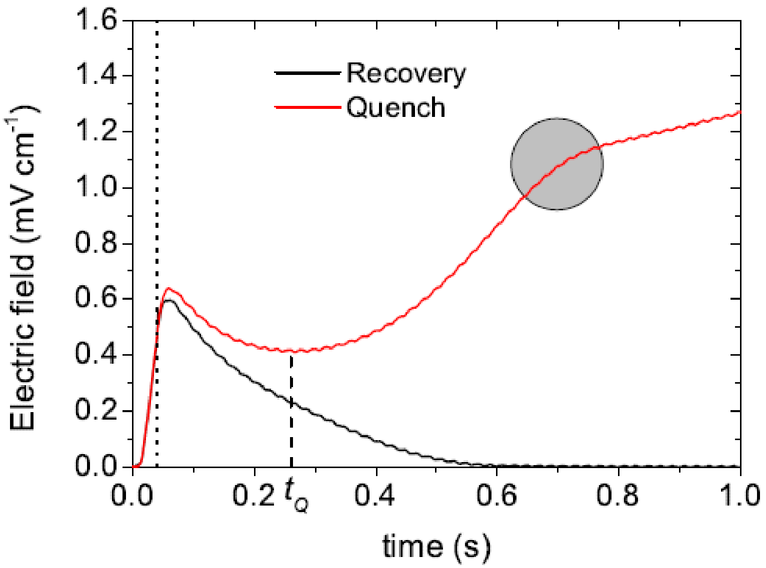

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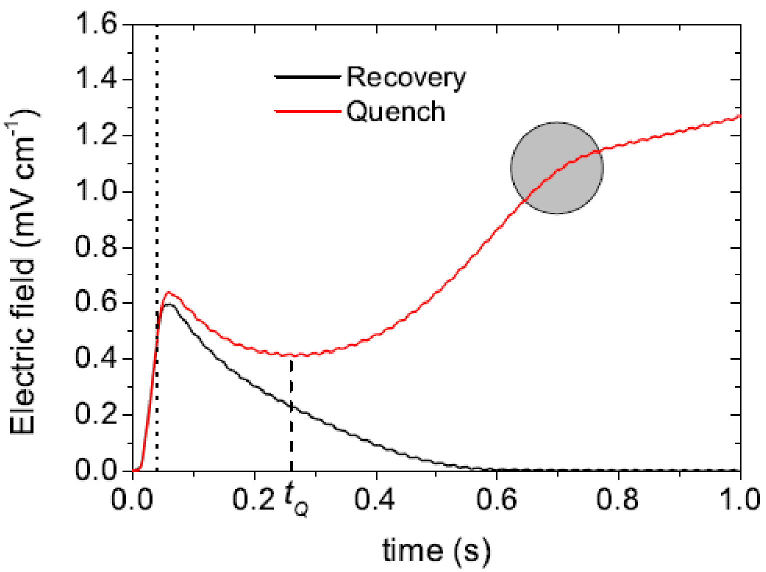

Important parameters

- Minimum propagation zone (*MPZ*)
- Minimum quench energy (*MQE*)
- Quench propagation velocity (v_p)

Strongly dependents on c_p, k and ρ

High *MQE*, long *MPZ* and high v_p

Summary

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  - Meissner effect
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  - **High magnetic field production**
  - Power applications

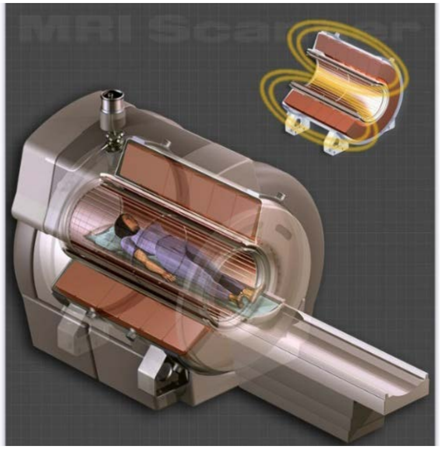
NMR: Nuclear Magnetic Resonance

- A molecule in a static magnetic field produces characteristic magnetic oscillation, proportional to the magnetic field strenght, if perturbed with an oscillating field.
- They are used to unravel complex molecules for drug discovery and genomics. .

1020 MHz NMR using 24T at 2.2K

MRI: Magnet Resonance Imaging

- NMR of Tissues with Computerized Tomography.
- Large bore magnet up to 3T for whole body scanning.



Other scientific systems.

There are other equipment capable of measuring the properties of samples at low temperature.

Physical Properties Measurement System (PPMS) can measure resistivity, thermal conductivity and heat capacity from room temperature to liquid helium temperatures.

SQUID magnetometers can measure the magnetic properties of samples at different temperatures.

Physical Properties Measurement System (PPMS)

SQUID magnetometer

Colliders

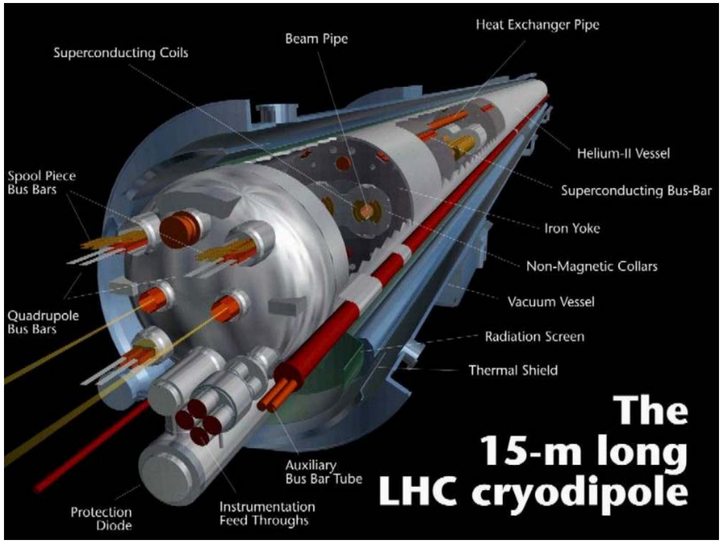
Colliders have helped with the discovery of many particles in the standard model (The most recent is the Higgs boson).

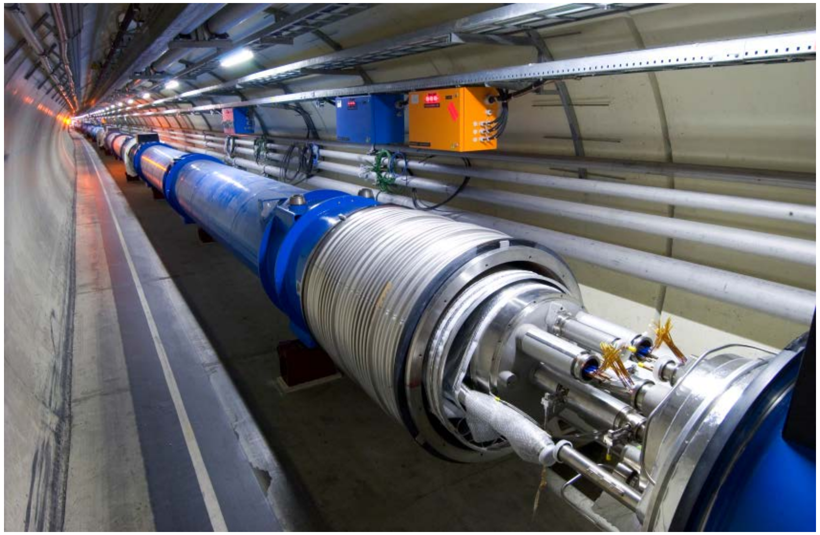
Tevatron at Fermilab (US)

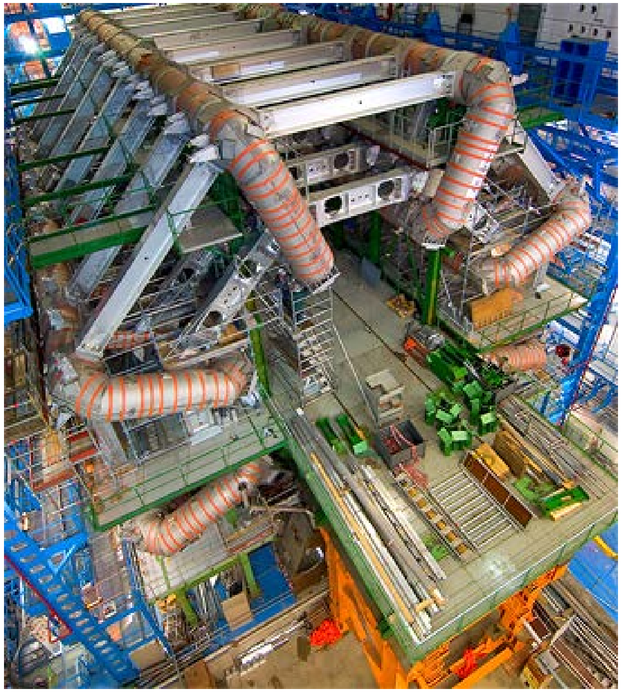
Relativistic Heavy Ion Collider at Brookhaven national lab (US)

Large Hadron Collider (LHC): Located at CERN (Switzerland)

1232 15 m long dipole magnets and 392 quadrupole to form a 27km ring. It uses <u>10080 tonnes</u> of liquid nitrogen and <u>120 tonnes</u> of liquid He.



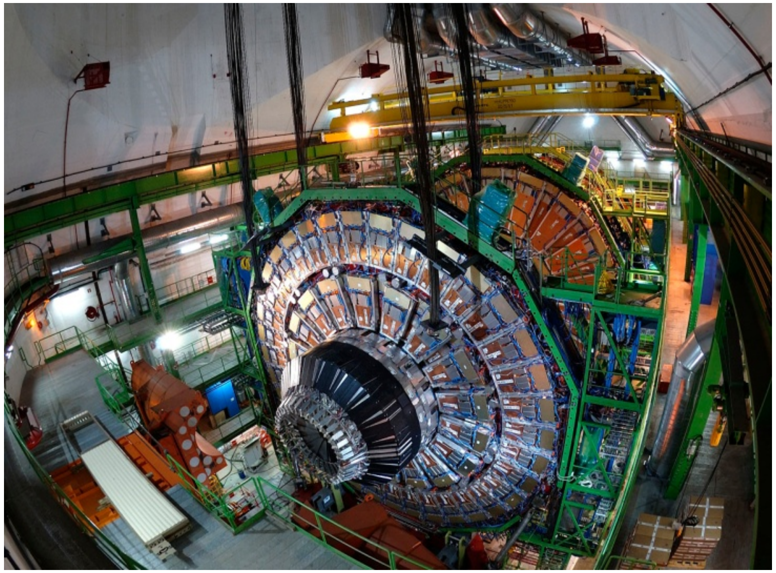




Large scale applications

- Production of high and stable magnetic fields

- <u>ATLAS</u> consists of a superconducting inner solenoid and an outer toroidal magnetic field is produced by eight air-core superconducting barrel loops. It is 26 metres long and 20 metres in diameter, and it stores 1.6 GJ.

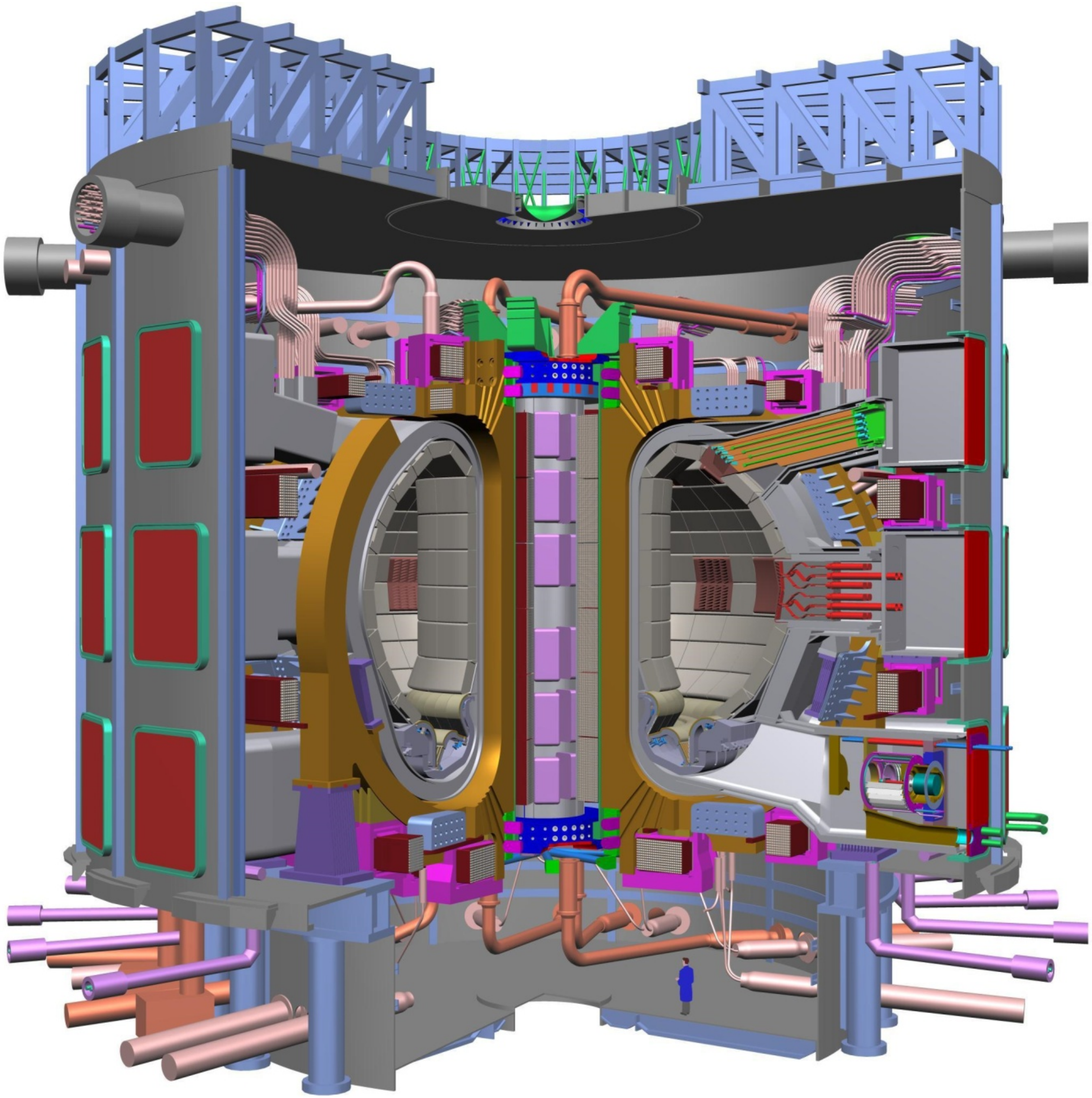


- <u>CMS</u> consists of a superconducting magnet of 3.8 T at 18 kA with a stored energy of 2.3GJ

Large scale applications

ITER is an International Experimental (Tokamak) Reactor being built in France.

The central solenoid coil will use superconducting niobium-tin, to carry 46 kA and produce a field of 13.5 T. The 18 toroidal field coils will also use niobium-tin. At maximum field of 11.8 T they will store 41 GJ.



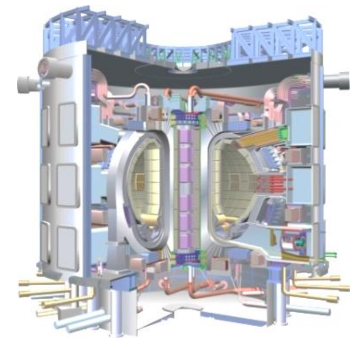
Large scale applications

- Production of high and stable magnetic fields
- Applications well established with LTS

Magnetic resonance imaging

Nuclear magnetic resonance

Accelerators



Fusion

Open MRI (MgB_2)

Fabrication with other materials

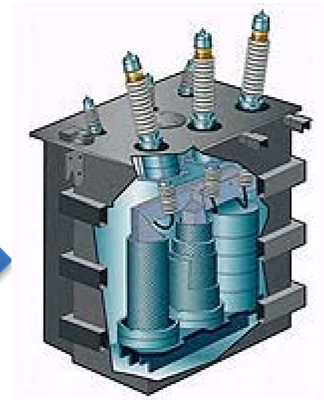
Under continuous research

Summary

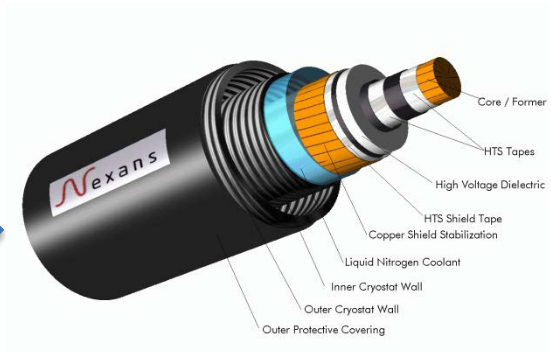
- Superconductivity
  - Resistivity
  - Meissner effect
- Superconducting materials
- **Applications of superconductivity**
  - High magnetic field production
  - **Power applications**

Superconductors in electric power applications

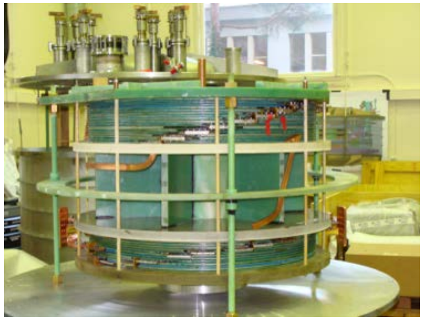
Power generation
(Rotating machines)



Sub-station
(Transformers)

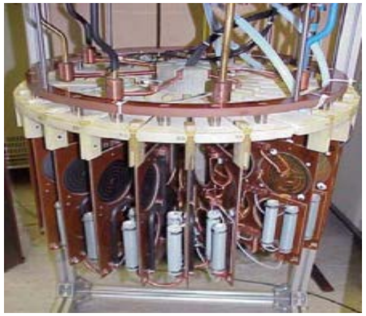


Transmission
(Cables)



Energy storage
(SMES)

Consumption
(Rotating machines)



Network stability
(FCL)

Main advantages

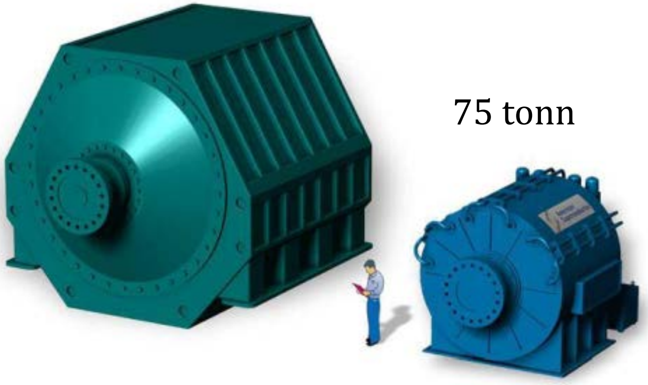
- Improved efficiency → loss reduction
- Higher power density → Volume and weight reduction
- LN used as coolant is environment-friendly
- New application (SMES)

Train transformer

Drawbacks

- Need for cryocooling
- Material costs elevated
- Reliability limitations

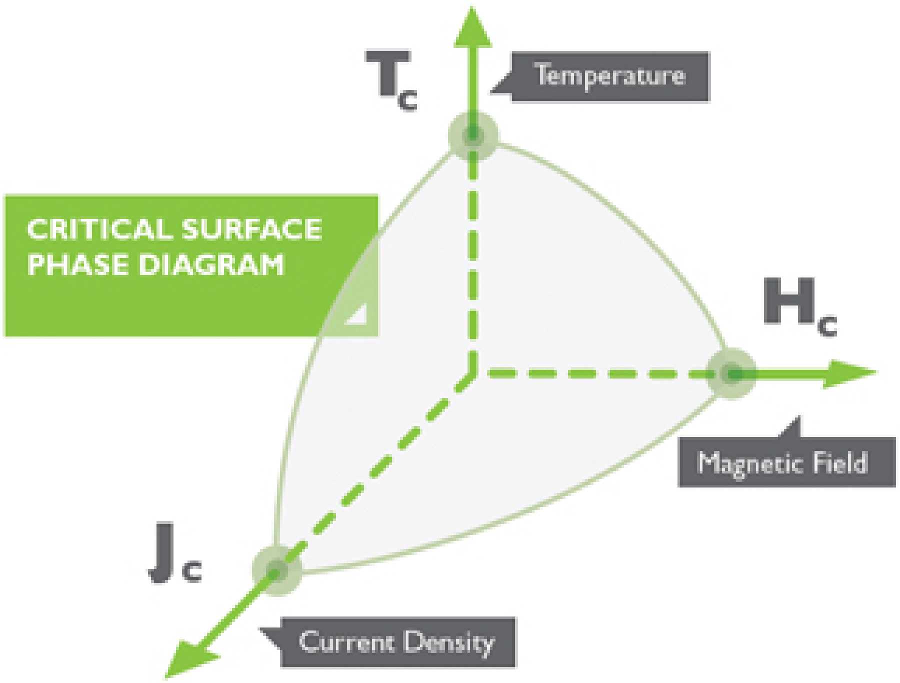
280 tonn



75 tonn

35 MW ship propulsion motor

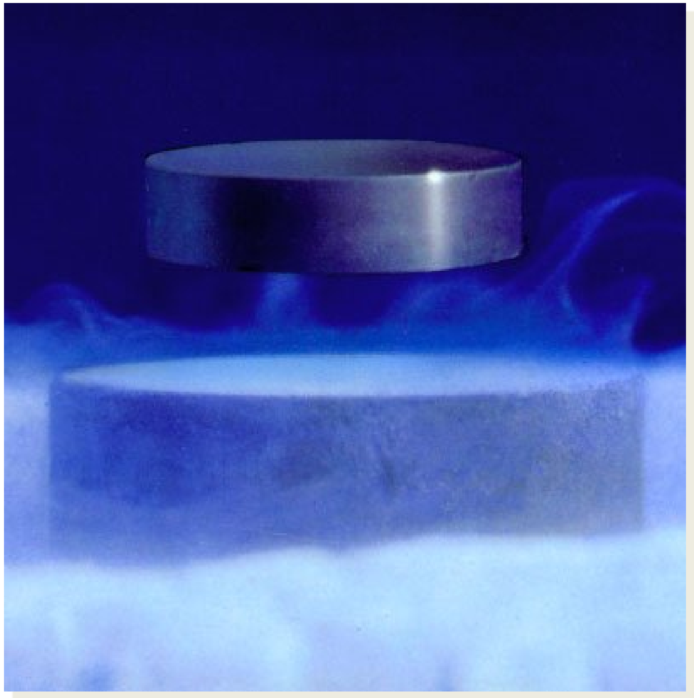
- Superconductor: Material with zero resistance under 3 given experimental conditions B_c, I_c and T_c.



Conclusions

- Superconductor: Material with zero resistance under 3 given experimental conditions B_c, I_c and T_c.

- More than a perfect conductor. It presents Meissner Effect.



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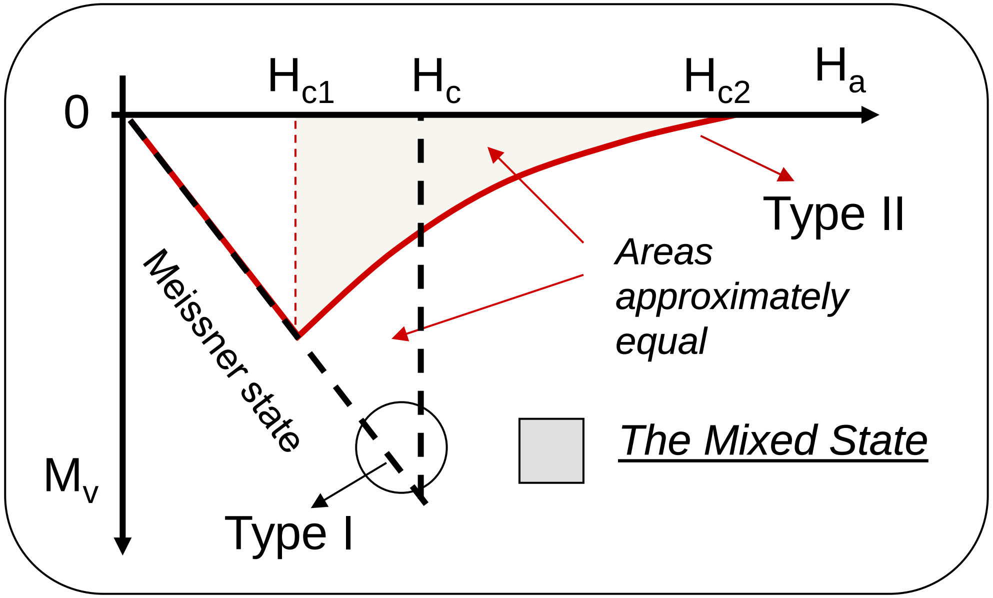
- Type I and Type II



ξ : Coherence length

λ : London penetration length

ξ > λ: → Type I

ξ < λ: → Type II

Conclusions

- Superconductor: Material with zero resistance under 3 given experimental conditions B_c, I_c and T_c.
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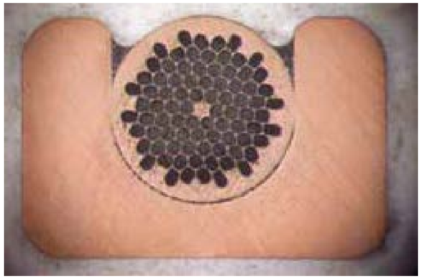
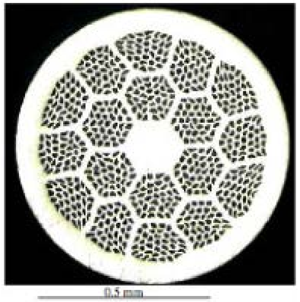
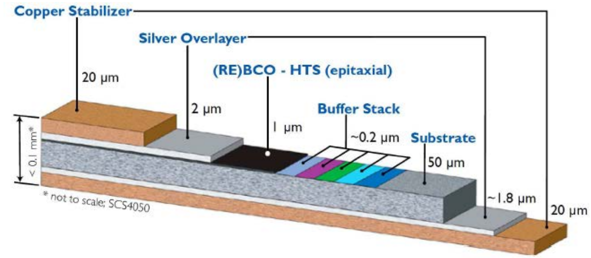
- Type I and Type II
- Commercial materials are Type II: BSCCO, YBCO, MgB_2 (HTS), NbTi, Nb_3Sn, (LTS)

NbTi

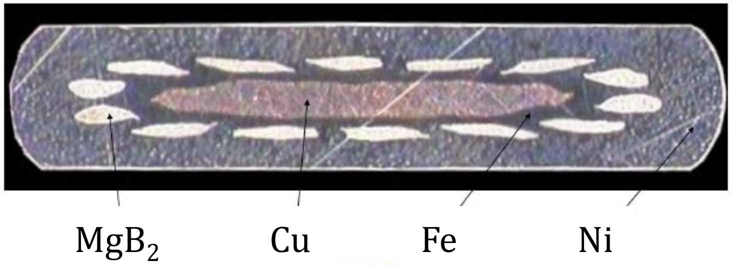




BSCCO



YBCO



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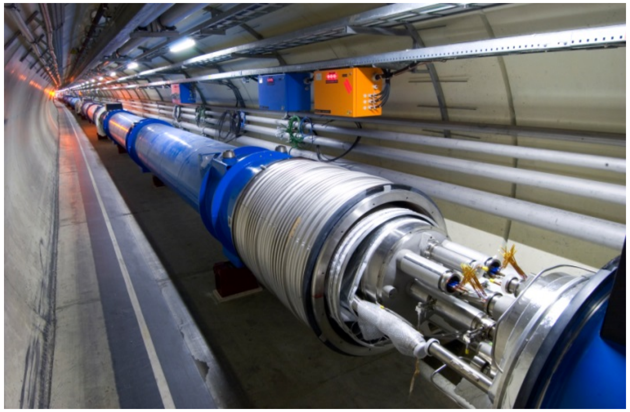

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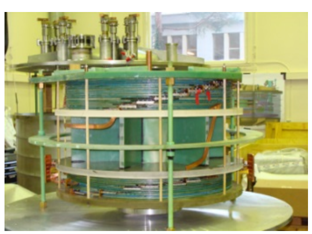
- Applications with high magnetic field. NMR, MRI, LHC, ITER.

- Power applications: FCL, SMES, wind turbines, cables, transformers.



Energy storage
(SMES)

Transmission
(Cables)

Power generation
(Rotating machines)

Thank you for your attention