11th Mini Lecture - CERN, Switzerland

26-11-2020

Introduction to Superconductivity and Superconducting Magnets

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(*) ce (**) Bundesministerium für Bildung und Forschung

STEAM

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(**) The Gentner program of the German Federal Ministry of Education and Research (grant no. 05E12CHA).

Outline

1. Introduction
2. Historical Background
3. Type-I and –II Superconductors
4. Practical Superconductors

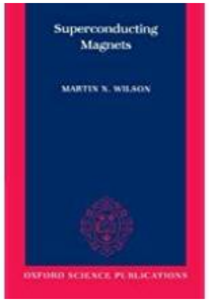
Introductory Comment

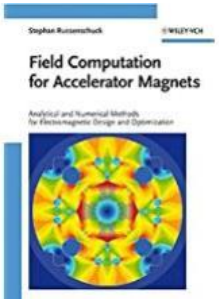
Presentation inspired by:

1. L. Bottura “*Introduction to Accelerator Physics - Superconducting Magnets*”. CERN accelerator School, Czech Republic, 2014. Reference mark (*)
2. D. Schoerling “*Superconducting accelerator magnets*”. CERN accelerator School, Denmark, 2019. Reference mark (**)

Source: https://cas.web.cern.ch/

Recommended literature:





1. Martin N. Wilson, Superconducting Magnets, 1983, Oxford Science Publications.

2. Stephan Russenschuck, Field computation for Accelerator Magnets, 2010 Wiley.

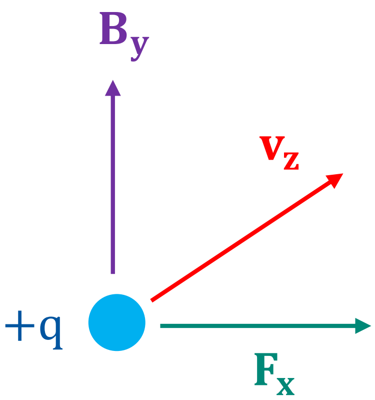
Please do not hesitate to ask if you have any questions!

Introduction

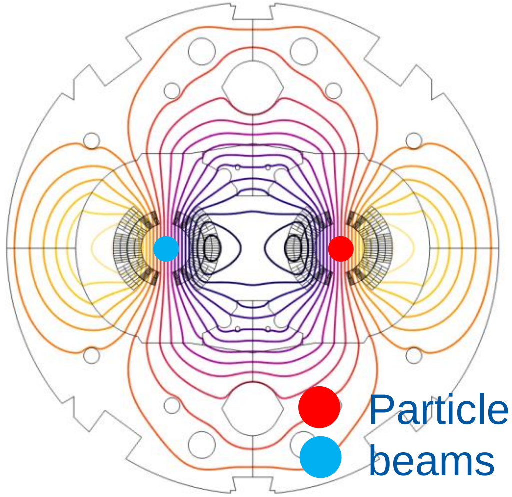
Accelerator Magnets (1/3)

Key-enabling technology for particle physics

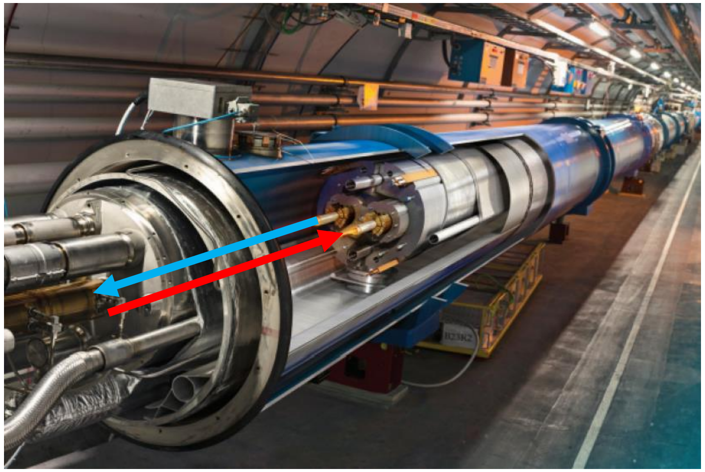
Magnetic fields for steering and focusing particle beams



Lorentz' force on a charged particle



Magnetic field lines in the LHC dipole cross-section



Superconducting dipoles in the LHC tunnel at CERN

Advantages (2/3)

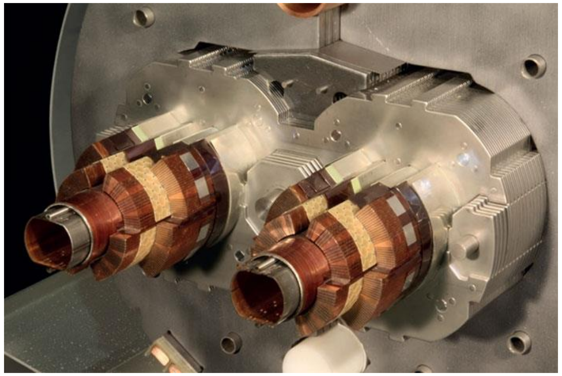
Superconducting magnets for Science and Research

Forget about Ohm's law (and Joule losses)!

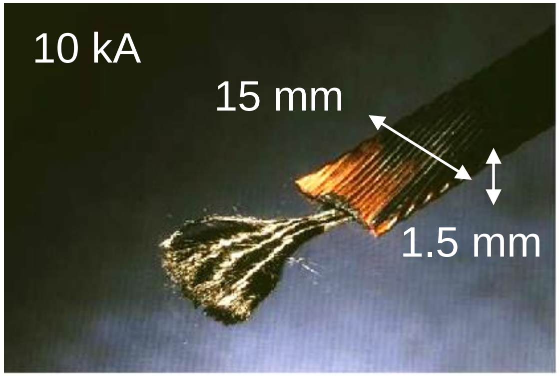
1. No power consumption in the superconductor
2. Extremely high current density (up to 10^3 factor w.r.t. normal conducting materials)
3. Ampere turns cheaper than iron

Consequences

1. High current density → minimizing coil volume and magnet cost
2. Higher magnetic fields economically available
3. New research possibilities
4. Lower operational cost → new commercial possibilities

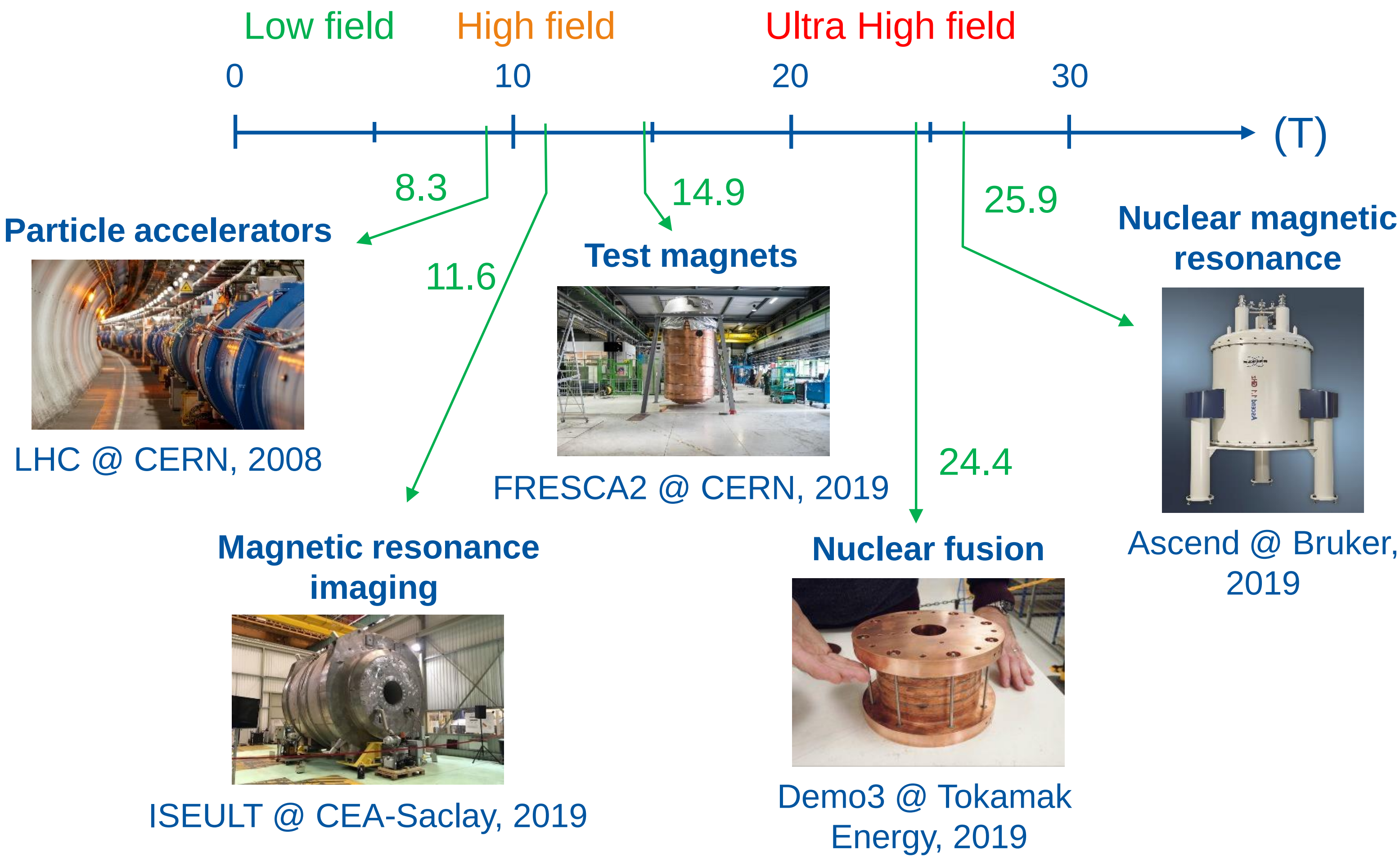


Detail of the LHC main dipole



Detail of the LHC Nb-Ti cable

Applications (3/3)



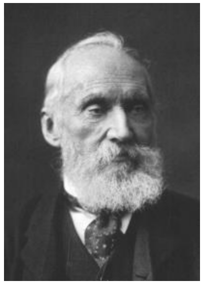
Introduction

Historical Background

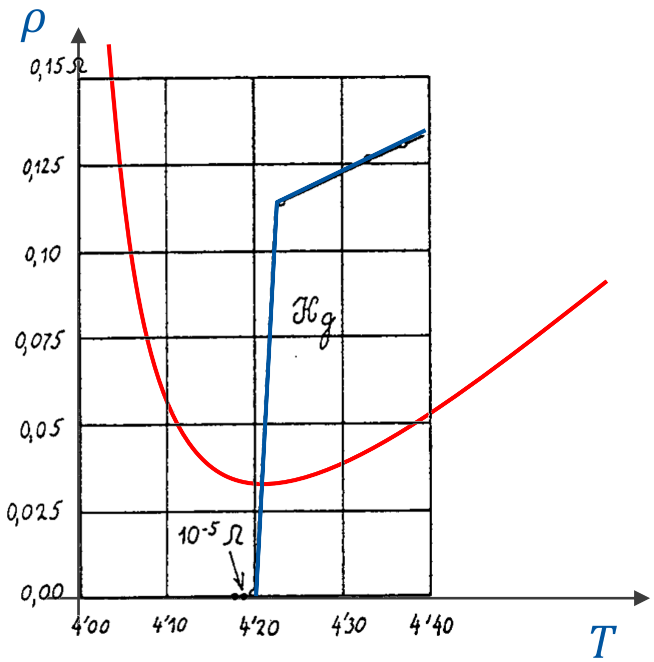
Discovery (1/4)

What is the limit of electrical resistivity at the absolute zero?

… electrons flowing through a conductor would come to a complete halt or, in other words, metal resistivity will become infinity at absolute zero.



W. Thomson (Lord Kelvin)



[…] The experiment left no doubt that, as far as accuracy of measurement went, the resistance disappeared. […] Thus, the mercury at 4.2K has entered a new state, which […] can be called the state of superconductivity.

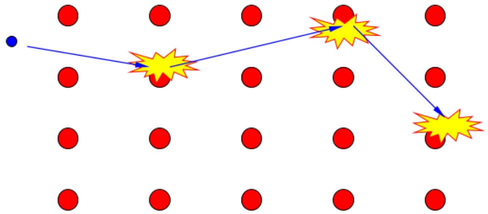
H. Kamerlingh-Onnes (1911)

BCS Theory (2/4)

Bardeen, Cooper and Schrieffer

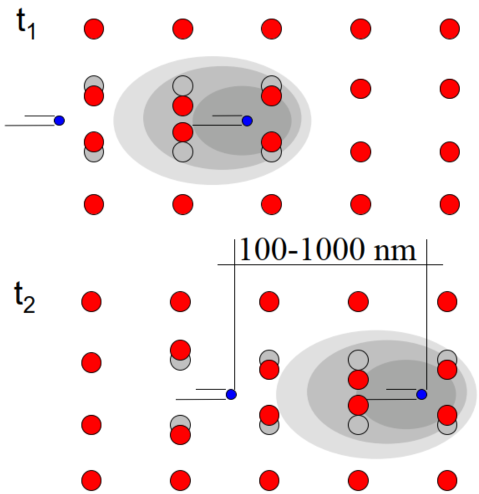
Normal conductor

- Interaction with the crystal lattice, electrons scattering
- energy dissipation → finite resistance



Superconductor: BCS theory (1957)

- electrons-vibrating crystal lattice interaction (phonons)
- Space charge formation
- Electrons coupled into Cooper pairs
- Pairs combined into a Bose-Einstein condensate
- Electrons flow as a macro-particle, no resistance



Figures from (*)

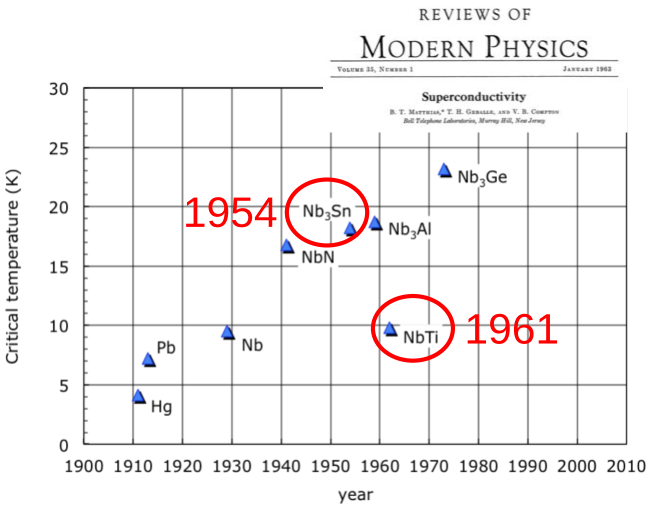
Implications

- Condensate stable only at low temperature
- Thermal activation → lattice oscillation
- Critical temperature T_c → loss of condensate state

Beyond BCS Theory (3/4)

BCS theory:
- T_c theoretical limit around 30 K
- Mostly metallic compounds
- Known as **Low-Temperature Superconductors**

1986 – A Big Surprise
Discovery of **High temperature Superconductors**
- Found in Lanthanum barium copper oxide (LBCO)
- Mostly ceramic compounds
- $T_c > 77K$ (boiling point of liquid nitrogen)



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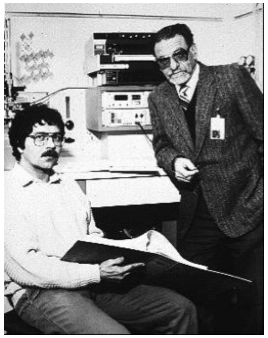

Bednorz and Mueller

Nobel Prize 1987

To date, there is no singularly recognised theory for high-temperature superconductivity.

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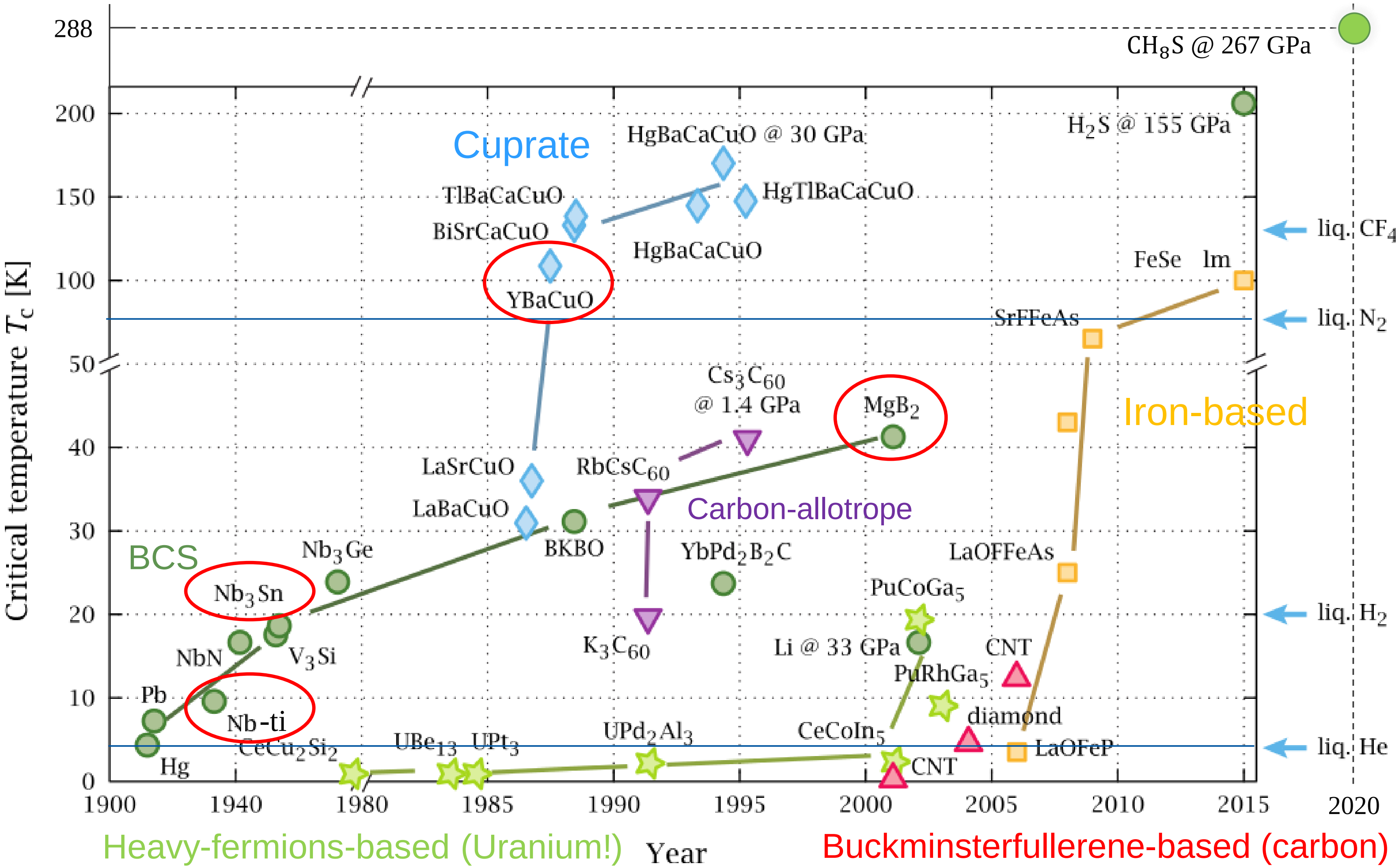
Superconducting Family (4/4)



Introduction

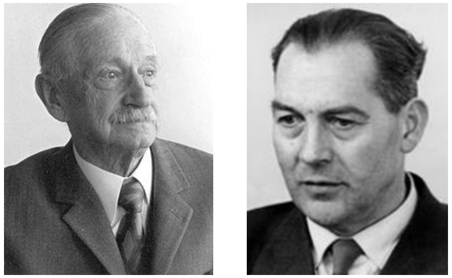
Historical Background

Type-I and –II Superconductors

Meissner-Ochsenfeld effect

Meissner-Ochsenfeld effect (1933):

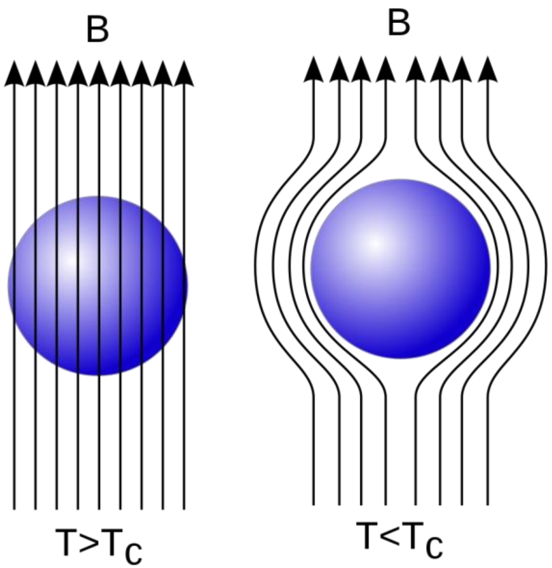
Expulsion of a magnetic field from a superconductor during its transition to the superconducting state when it is cooled below the **critical temperature $\mathbf{T_c}$**.



Meissner, Ochsenfeld

Remarks

- Static magnetic field during cool-down
- No flux change ($d_t\boldsymbol{B} = 0$)
- Screening currents not induced
- Faraday's Law not working ?!



Superconductor: more than just a perfect conductor!

$\boldsymbol{B}$ increase → loss of the Meissner state

Two possible behaviors during the breakdown :

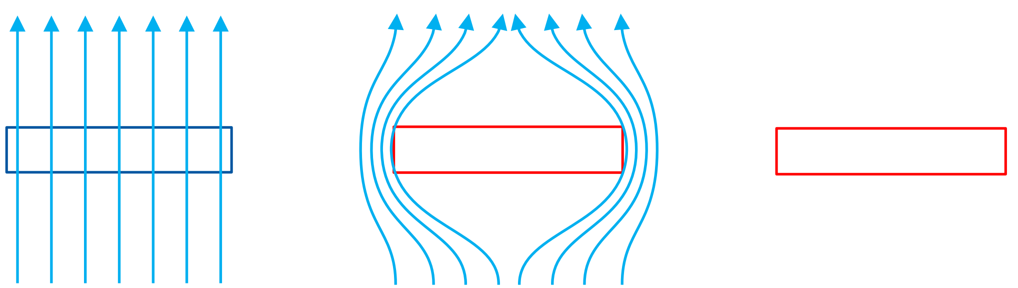
- Type-I (soft) superconductors
- Type-II (hard) superconductors

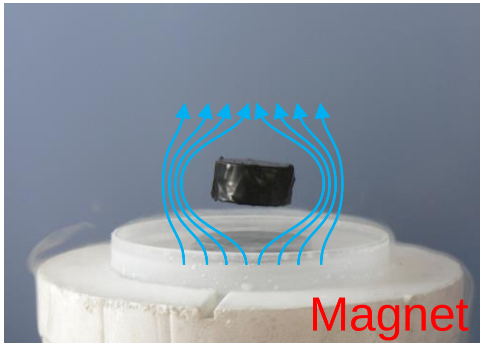
Type-I (1/3)

Type-I Superconductors:

- $T < T_c$, expulsion of magnetic field by means of screening currents
- Perfect diamagnetism, $\chi_m = -1$
- No magnetic field inside the superconductor

→ No transport current inside a round conductor ($\nabla \times \boldsymbol{H} = J$, but if $\boldsymbol{H} = 0\ldots$)





Example of magnetic levitation

Type-I (2/3) - London Equations

Hypothesis: free movement for electrons

From Lorentz Law $\boldsymbol{F} = e\boldsymbol{E}$
→ Electrons uniformly accelerated

1st equation: constitutive Law

$$d_t\boldsymbol{J} \propto \boldsymbol{E}$$

2nd equation: from Faraday's Law

$$d_t\left(\nabla \times \boldsymbol{J} + \frac{\mathbf{1}}{\boldsymbol{\mu_0}\boldsymbol{\lambda_L^2}}\mathbf{B}\right) = 0$$

Constant nonzero solution unphysical
($\mathbf{B} = 0$ always zero inside sc), therefore

$$\nabla \times \boldsymbol{J} + \frac{\mathbf{1}}{\boldsymbol{\mu_0}\boldsymbol{\lambda_L^2}}\mathbf{B} = 0$$

H. and F. London, 1935

Solution: exponential field decay

$$B(x) = B_0 e^{-\frac{x}{\lambda_L}}$$

London penetration depth (m mass, n number density, q charge):

$$\lambda_L = \sqrt{\frac{m}{\mu_0 n q^2}}$$

$\lambda_L \sim 100\ nm$ material dependent

After all, Faraday's Law was ok!

Type-I (3/3) - Critical Field

Gibbs free energy G of a material in a magnetic field

$$G = U - TS - MB$$

Thermal Magnetic

Observations:

- G minimized for systems in equilibrium
- $(G_{sc} < G_{nc})_{H=0}$ (Condensate)
- Perfect diamagnetism, $\mu_0 M = -B$

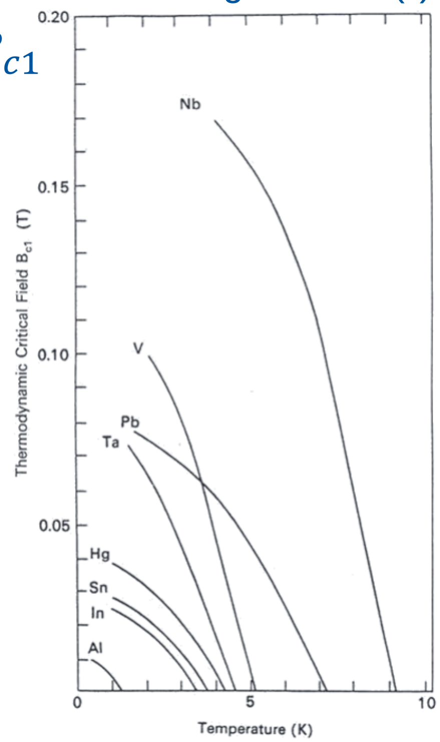
Thermodynamic critical field B_{c1}:

$$\frac{B_{c1}^2}{2\mu_0} = G_{nc} < G_{sc}$$

Field expulsion, until the free energy of the superconducting phase in field equals the free energy of the normal state

Figure from (*)

B_{c1}



range of few mT

Not useful for engineers

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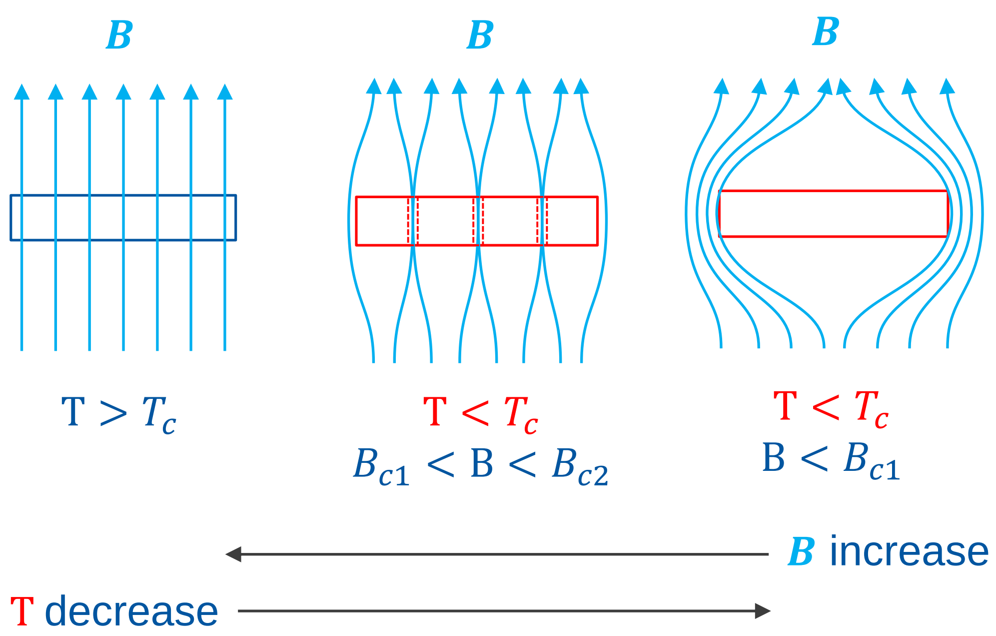
Type-II (1/6)

Type-II superconductors (Discovered in the 50's):

- Perfect diamagnetism below B_{c1}
- Mixed phase between B_{c1} and **upper critical field $\mathbf{B_{c2}}$**
- B_{c2} tens (hundreds) of Tesla
- transport current! ($\boldsymbol{H} \neq 0$ inside the superconductor)

Landau, Ginzburg and Abrikosov



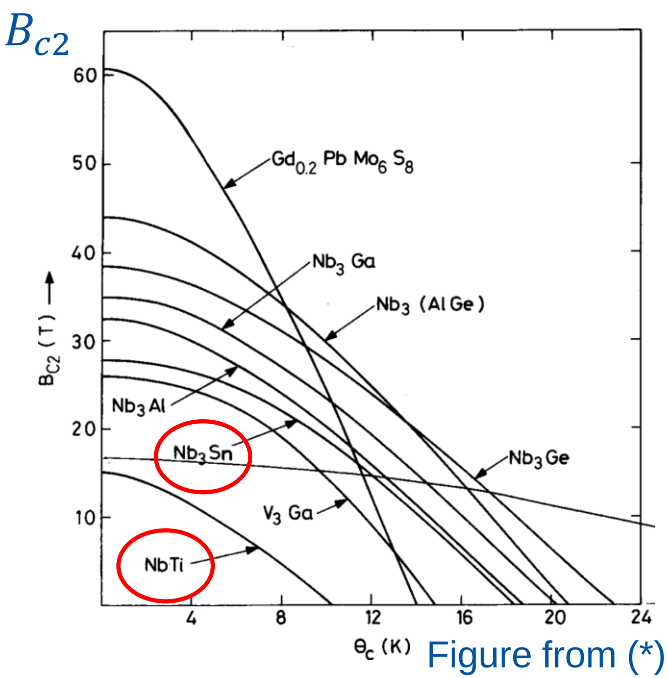


Figure from (*)

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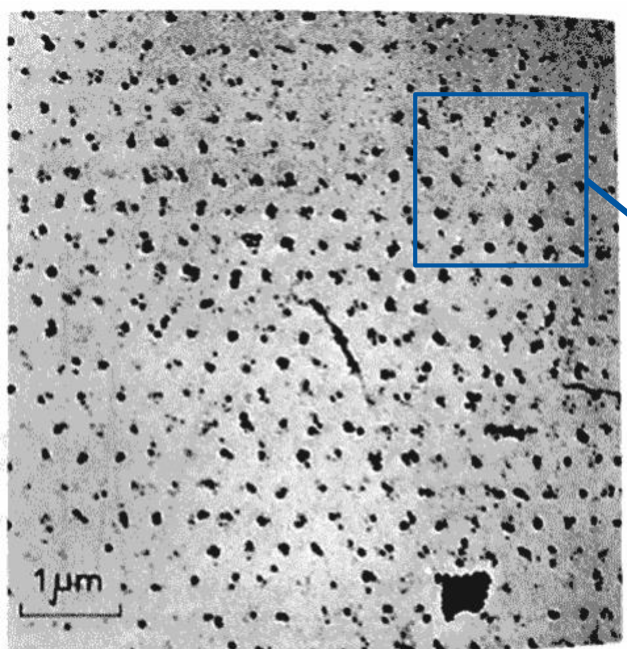
Type-II (2/6) - Fluxons

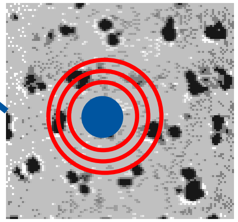
Magnetic field penetration in the superconducting material

Magnetic flux organized in a lattice of quantum Fluxes

Flux lines determining resistive regions confined by screening currents



Observation on Pb-4% Indium in a field of 300 mT, decorated by Cobalt particles



● Flux quantum (Fluxoid)

○ Screening current (Abriskov vortex)

Fluxoid:

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

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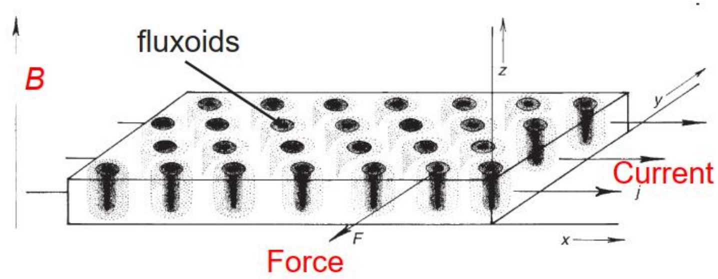
Type-II (3/6) - Transport Current

Current in a type II superconductor

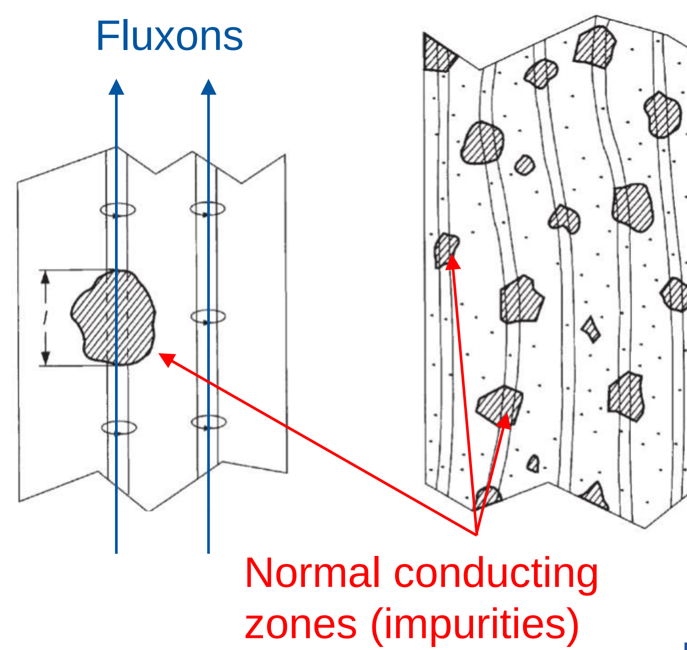
1. Lorentz force on the fluxoids $\boldsymbol{f} = \boldsymbol{J} \times \boldsymbol{B}$
2. Motion of tubes (drift)
3. Flux motion ($d\boldsymbol{B}/dt$) → energy dissipation!



Figures from (**)

Fluxons locked by pinning centres, resistive defects or impurities in the structure:

1. Pinning force as long as $\boldsymbol{f} \le \boldsymbol{J} \times \boldsymbol{B}$
2. No flux motions → no dissipation



Critical current density J_c

current density at which, for a given B and at a given T the pinning force is exceeded by the Lorentz force

Type-II (4/6) - Pinning Centers

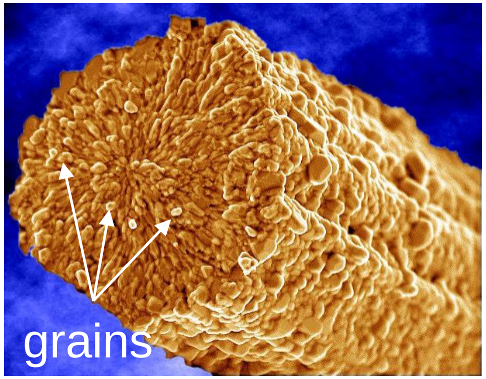
$J_c \propto$ pinning force → Stronger, denser pinning centres highly desirable!

Pinning centers obtained from:

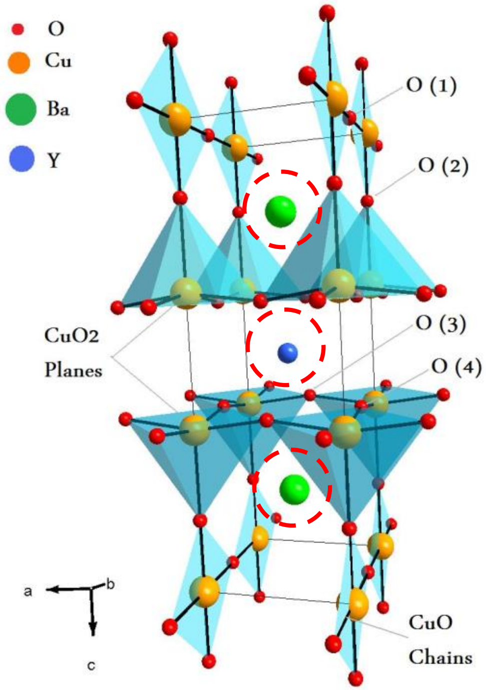
- Precipitates in alloys
- Grain boundaries in inter-metallic compounds
- Doping in ceramic compounds

Figures from (*)

Microstructure of Nb-Ti



Microstructure of Nb3Sn



Unit cell for the Cuprate of Barium and Yttrium (YBCO)

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Type-II (5/6) - Power Law

Phenomenological power law, describing the collective motion of the fluxons within the superconductor

$$E = E_c \left(\frac{J}{J_c}\right)^n$$

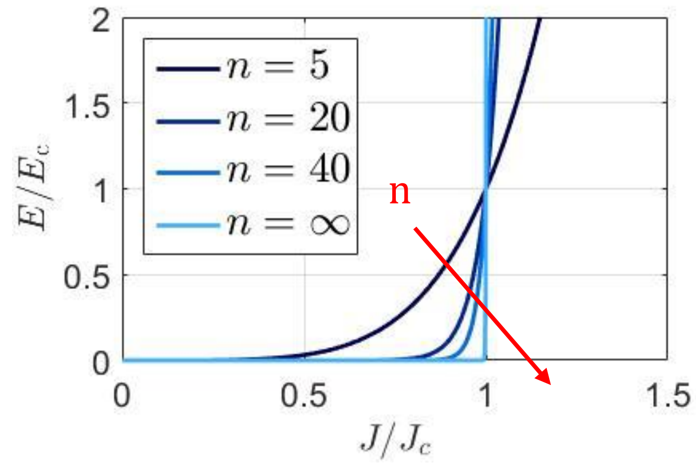
where

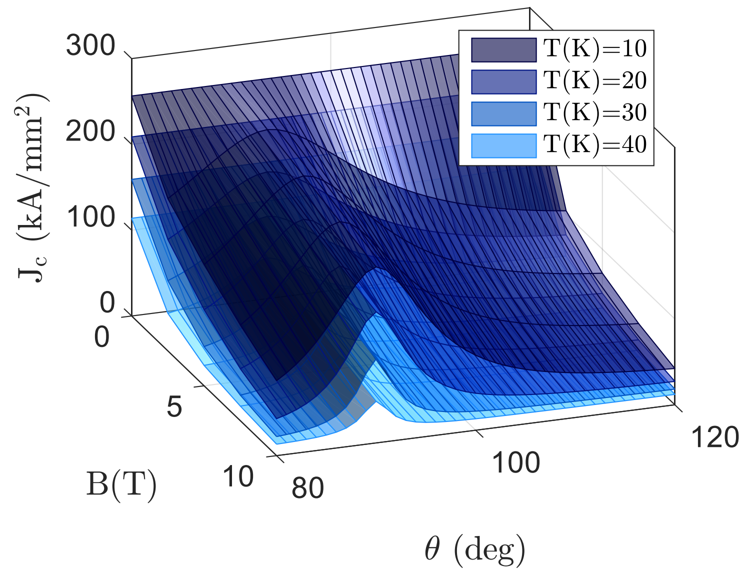
- E_c critical voltage ($1e^{-4}$ V)
- J_c critical current density
- n power-law index (material quality)

$n \approx 20$ for HTS
$n \approx 40$ for LTS

J_c features (most general case):

- nonlinear
- anisotropic
- field- and temperature-dependent





Type-II (6/6) - Critical surface

A type-II material is superconductor below the critical surface defined by:

1. Critical temperature T_c (material property)
2. Upper critical field B_{c2} (material property)
3. Critical current density J_c (pinning-centre dependent, heavily affected by the manufacturing technique)

If the critical surface is exceeded → transition from superconducting to normal conducting state

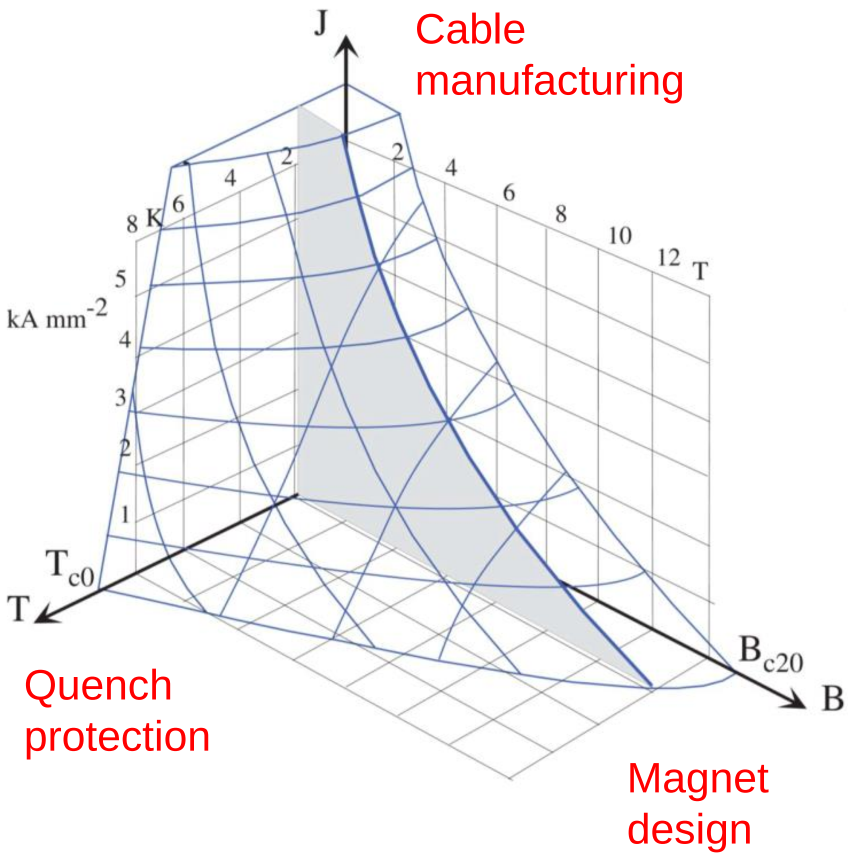


Figure from (**)

… To sum up

Vanishing of electrical resistivity ρ

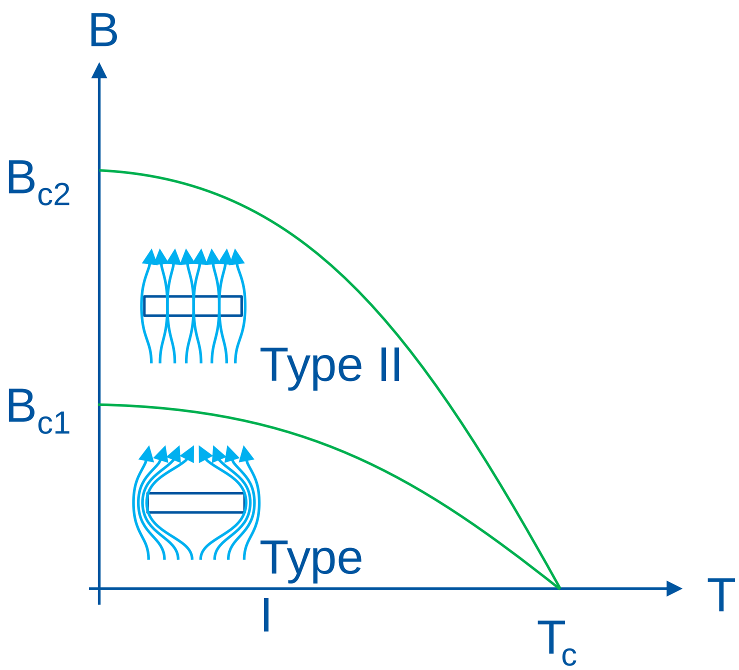
Expulsion of magnetic flux fields

Type I (soft):

- Low coercive field ~10^{-3} T
- Elemental metals (e.g. Pb, Hg)
- **Not suitable for industrial use**

Type II (hard):

- High coercive field ~10^{1-2} T
- Made of metal alloys (e.g. Nb-Ti)
- **Suitable for industrial use**



Superconducting materials are only useful if
they are dirty (type II - high critical field) and messy (strong pinning centers)

Introduction

Historical Background

Type-I and –II Superconductors

Practical Superconductors

Overview (1/6)

Commercially available superconductors

higher operational temperature,
potentially cheaper magnets

- MRI

Table from (*)

		LTS				HTS	
Material		Nb-Ti	Nb_3Sn	Nb_3Al	MgB_2	YBCO	BSCCO
Year of discovery		1961	1954	1958	2001	1987	1988
Tc	(K)	9.2	18.2	19.1	39	≈93	95(*) 108(#)
Bc	(T)	14.5	≈30	33	36…74	120(†) 250(‡)	≈200

NOTES:
(†) B parallel to *c*-axis
(‡) B parallel to *ab*-axes
(*) BSCCO-2212
(#) BSCCO-2223

- HL-LHC

- Tevatron
- HERA
- RHIC
- LHC

High-field applications 20 Tesla and beyond

- Fusion magnets
- Next generation accelerator magnets?

Low-Temperature Superconductors (2/6)

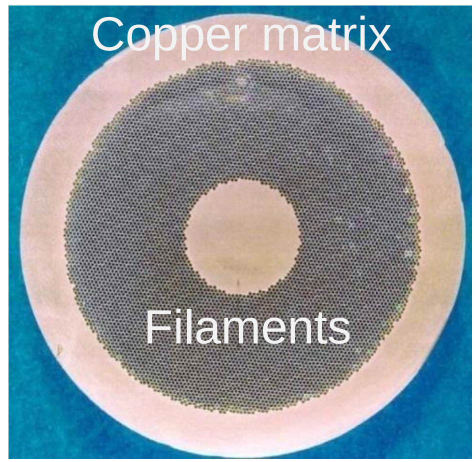
Superconductors embedded in high-current wires, tapes and cables for use in magnets

Cables arranged in coils, under the action of static and dynamic mechanical forces, thermal stresses, possibly in a radioactive environment

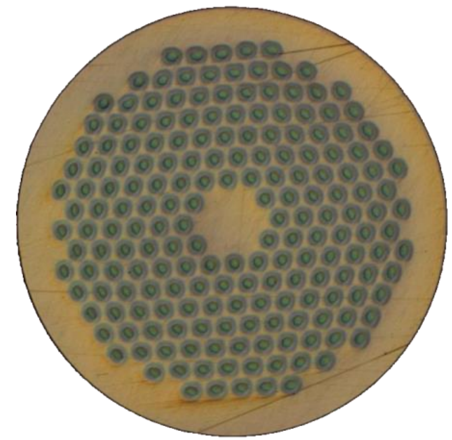
Electrical, mechanical, chemical, thermal, cryogenic, radiation-hardness requirements

Moreover, manufacturing process must be both scalable for long cable lengths (e.g.~km), and economically sustainable!

"Classic" low temperature superconductors



Nb-Ti
Je ~ 600-700 A/mm2
I ~ 300-400 A
B = 8-9 T



Nb3Sn
Je ~ 600-700 A/mm2
I ~ 300-400 A
B = 12-16 T

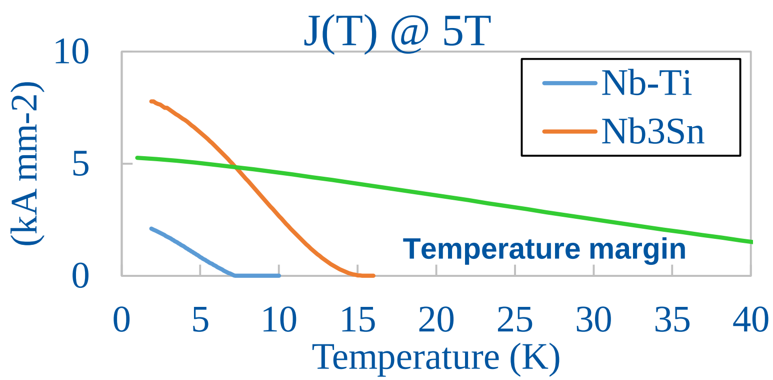
For comparison, Je in Cu ~ 5 A/mm2

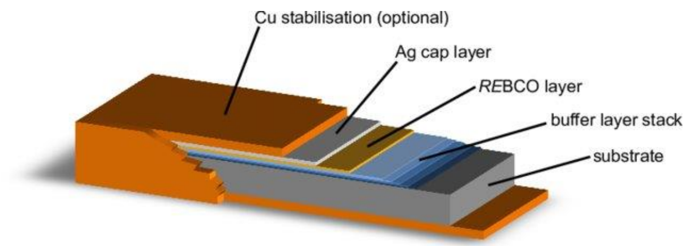
Figures from (**)

High-Temperature Superconductors (3/6)

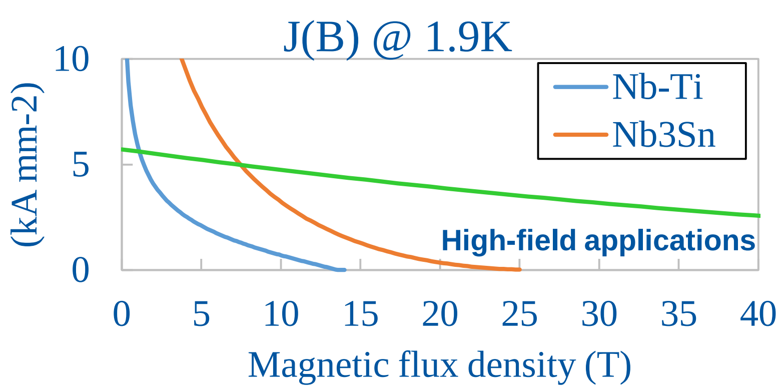
Copper oxides (CuO_2) doped with rare earths (La, Bi-Sr-Ca, Y-Ga-Ba etc.)

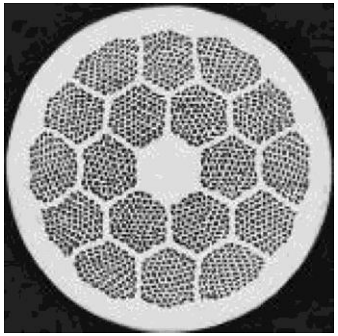
Higher critical temperature and coercive field with respect to the traditional low-temperature superconductors (LTS), such as Nb-Ti or Nb3Sn





Multi-layer ReBCO tape



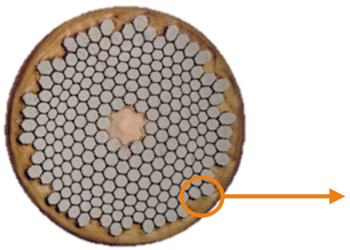


Stranded BSCCO-2212/Ag wire

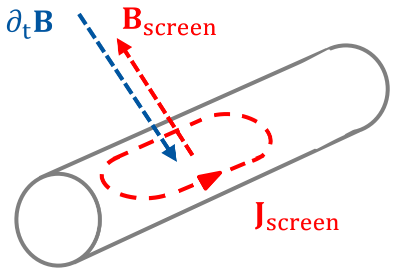
Persistent Magnetization (4/6)

Superconducting coil in a changing magnetic field $\partial_t \mathbf{B}$

- Screening currents $\mathbf{J}_{\mathrm{screen}}$
- Screening magnetic field $\mathbf{B}_{\mathrm{screen}}$
- $\sigma \to +\infty$ → no decay → persistent magnetization



Example:
LHC Nb-Ti strand



Filament magnetization

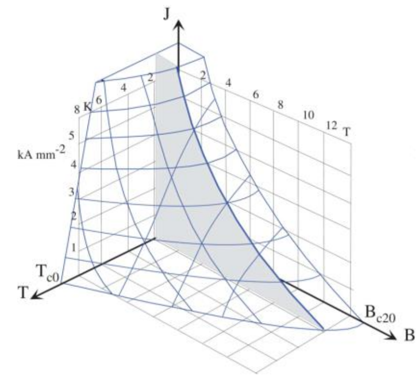
Smaller filaments → smaller $\mathbf{B}_{\mathrm{screen}}$

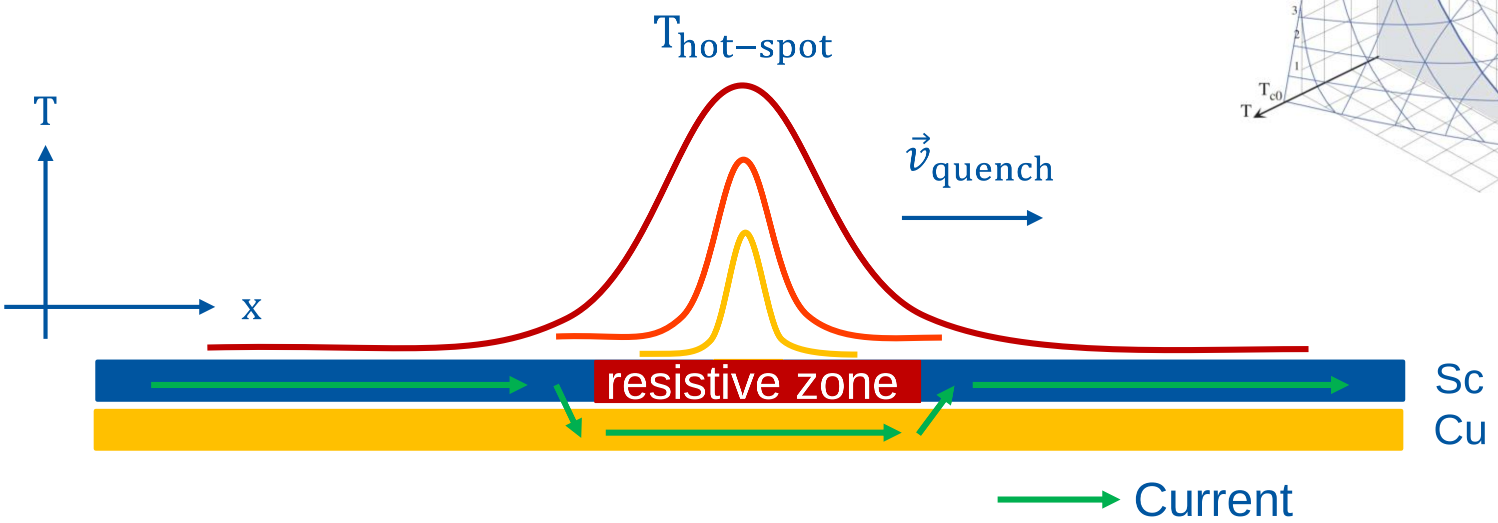
Coils made of **HTS tapes**:

- Wide filaments, 4-12 mm → **~1000x more than in Nb-Ti / Nb_3Sn strands!**
- Significant $\mathbf{B}_{\mathrm{screen}}$
- **Magnetic field quality degradation**, especially at low current

Quench (5/6)

Local transition from superconducting to normal conducting state (i.e., crossing of the critical surface!)





Resistive zone growth determined by $\vec{v}_{quench}$

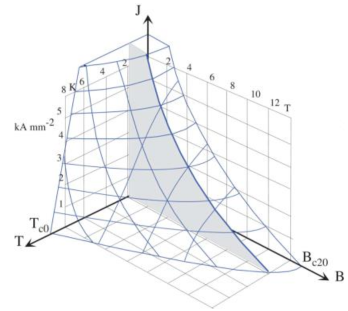
Potential degradation determined by $T_{hot-spot}$

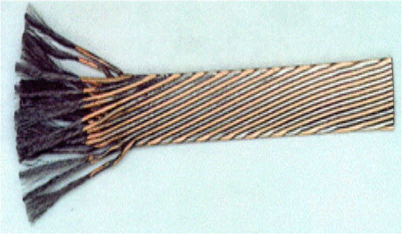
- Energy dissipated in the resistive zone
- Potentially irreversible effects
- Copper matrix as a current bypass!

Thermal Stability 6/6

- Motion
- Flux jump
- Particle Showers
- Magnetization loss
- Quench protection

- Coupling currents
- Joule losses
- Heat leaks
- Cryo-failure





LHC cable

- Cooling
- Conduction
- Heat capacity

…more details in the next mini lectures!

Take-Away

- High current density for minimizing coil volume and magnet cost
- High magnetic fields for new research possibilities
- Type-I superconductors, low $\mathbf{B_{c1}}$, no transport current
  Type-II superconductors as only option for practical applications (mixed state)
- Superconductivity determined by:
  - Critical temperature T_c (thermal activation)
  - Critical field $\mathbf{B_{c2}}$ (Breakdown of fluxons lattice)
  - Critical current density J_c (fluxons depinning)

  → Critical surface
- Magnet design and manufacture:
  materials, wires, cables, and their electric and thermal properties, electro-thermo-mechanical requirements, thermal stability, quench protection, etc… cryogenic for cooling is a field of applied science by its own

Superconductivity is a 100-year old science, and still a lot of room for research!