Superconductivity
Practical Days at CERN

4-5th March 2020

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Few Definitions to start

Superconductivity

“Superconductivity is a phenomenon occurring in certain materials at very low temperatures , characterized by exactly zero electrical resistance and the exclusion of the interior magnetic field (the Meissner effect).

from Wikipedia

Superconductor

A conductor that exhibit superconducting properties. It is an assembly of low resistive metal and superconducting material.

Cryogenics

Cryogenic: for Greek “kryos", which means cold or freezing, and "genes" meaning born or produced.“In physics, cryogenics is the study of the production and the behaviour of materials at very low temperature (<-150-180°C) ”

from Wikipedia

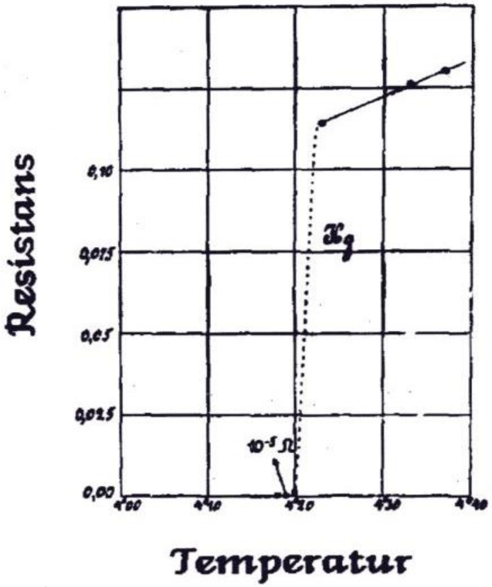
Main properties of superconductors

For T<T$_c$

Zero resistance → Perfect conductors

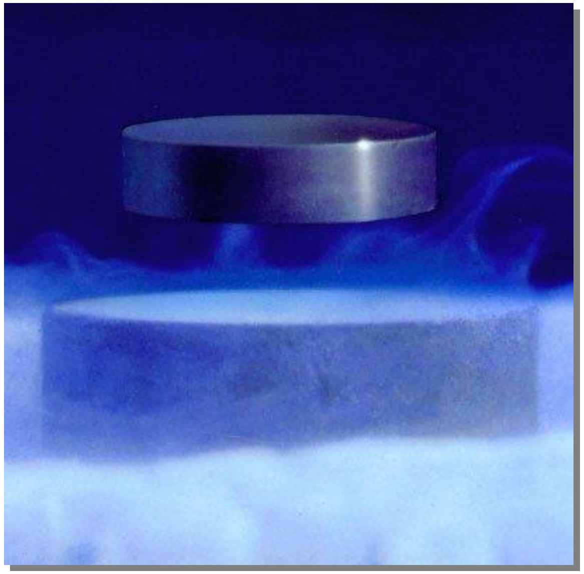
Exclusion of magnetic field → Perfect diamagnets

Zero resistance



Onne’s measurement on mercury (1911)

Meissner effect

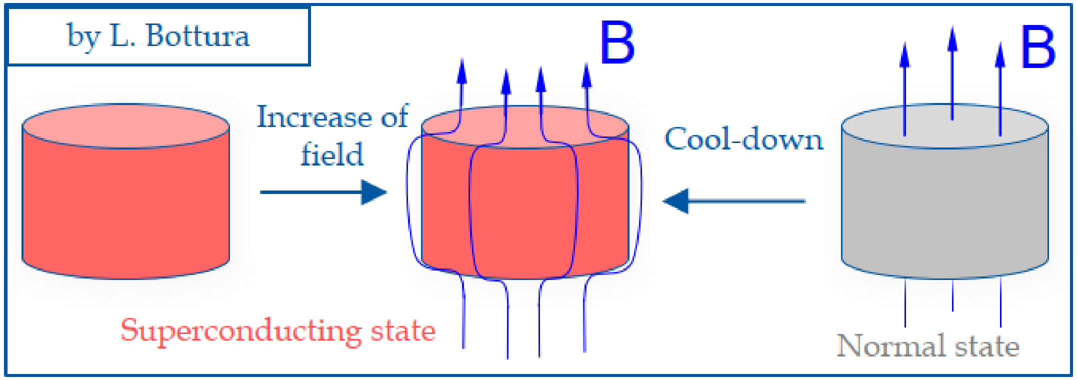


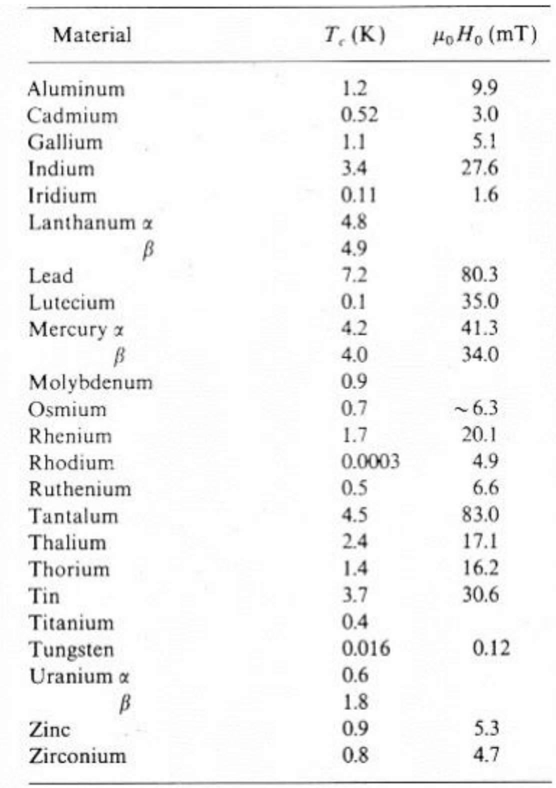
Discovered by Meissner and Oschenfeld (1933)

Perfect conductivity + perfect diamagnetism = superconductors

Type 1 Superconductors

- **1933**:Meissner effect discovered: magnetic field is expelled from Type 1 superconductors for **$T<T_c$** and **$B<B_{c1}$**.
- **B_{c1} is the critical field.**
- For **$B>B_{c1}$** material is in normal state
- For **$T>T_c$** material is in normal state





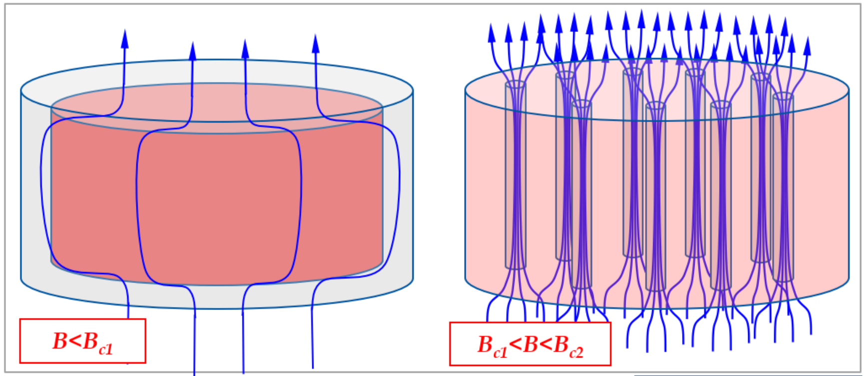
Material	T_c (K)	$\mu_0 H_0$ (mT)
Aluminum	1.2	9.9
Cadmium	0.52	3.0
Gallium	1.1	5.1
Indium	3.4	27.6
Iridium	0.11	1.6
Lanthanum α	4.8	
β	4.9	
Lead	7.2	80.3
Lutecium	0.1	35.0
Mercury α	4.2	41.3
β	4.0	34.0
Molybdenum	0.9	
Osmium	0.7	~6.3
Rhenium	1.7	20.1
Rhodium	0.0003	4.9
Ruthenium	0.5	6.6
Tantalum	4.5	83.0
Thalium	2.4	17.1
Thorium	1.4	16.2
Tin	3.7	30.6
Titanium	0.4	
Tungsten	0.016	0.12
Uranium α	0.6	
β	1.8	
Zinc	0.9	5.3
Zirconium	0.8	4.7

Superconductors = zero resistance+ perfect diamagnetism

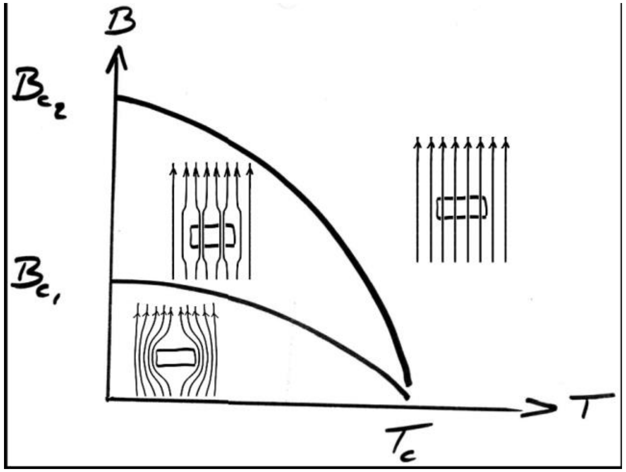
for T<Tc and B<Bc

Type 2 Superconductors

- **1952**: Abrikosov Vortices: In the mixed state, $\mathbf{B_{c1}<B<B_{c2}}$ magnetic flux penetrates the superconductor as a small independent vortices. In the vortex core the material is in normal state.
  - For $\mathbf{B<B_{c1}}$ => perfect diamagnet, no vortices
  - For $\mathbf{B_{c1}<B<B_{c2}}$, mixed state magnetic flux penetrates locally the material as vortex with a flux quanta $\Phi_0 = h/2e = 2\ .10^{-15}$ Wb.
  - For $\mathbf{B>B_{c2}}$ material is fully penetrated, no more superconducting

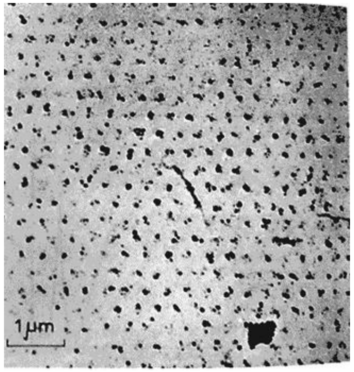


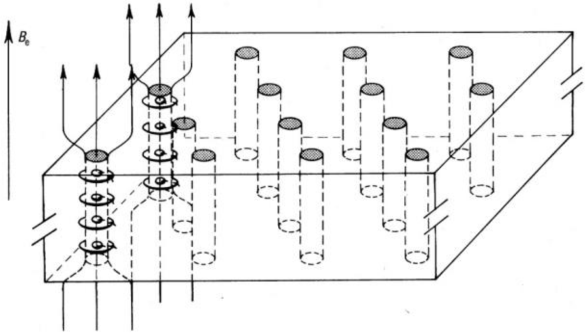
by L. Bottura

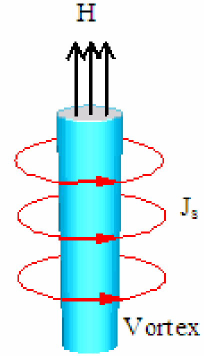


Flux pinning

- In the **mixed state** the transport current (use to generate the field in a electromagnet) interact with each of the vortices: **F= J x B**
- The **motion of the vortex** cause **energy dissipation** that may induce a **lost of Sc state**
- To **transport current**, the **vortex** must be **pinned** to the microstructure of the **material**.
- Some defects, dislocation, impurities act as pinning centers, exerting a pinning force (f_p)on the vortex.
- The maximum current (Jc) than can be transported without losses by a superconductor is defined as Jc =f_p/B







One Vortex

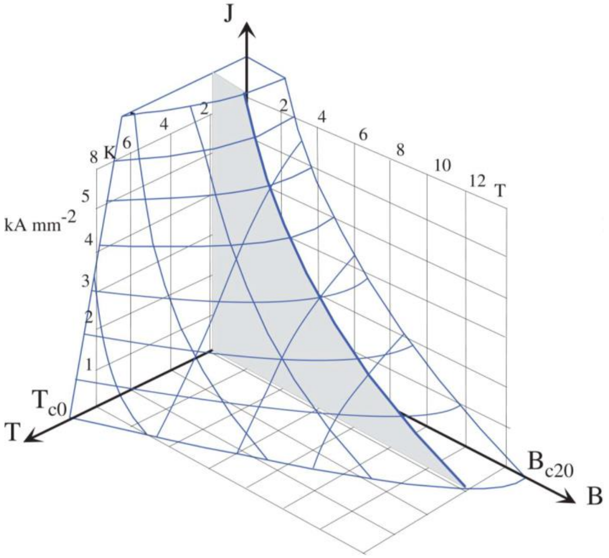
	Tc (K)	Bc(T)
NbTi	10	15
V_3Ga	14.8	2.1
NbN	15.7	1.5
V_3Si	16.9	2.35
Nb_3Sn	18	24.3
Nb_3Al	18.7	32.4
$Nb_3(AlGe)$	20.7	44
Nb_3Ge	23.2	38

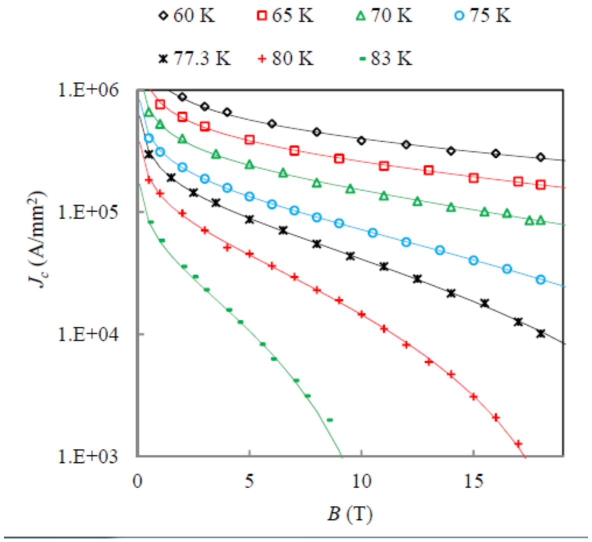
Example of Type II Sc materials

Critical surface of Superconductors

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

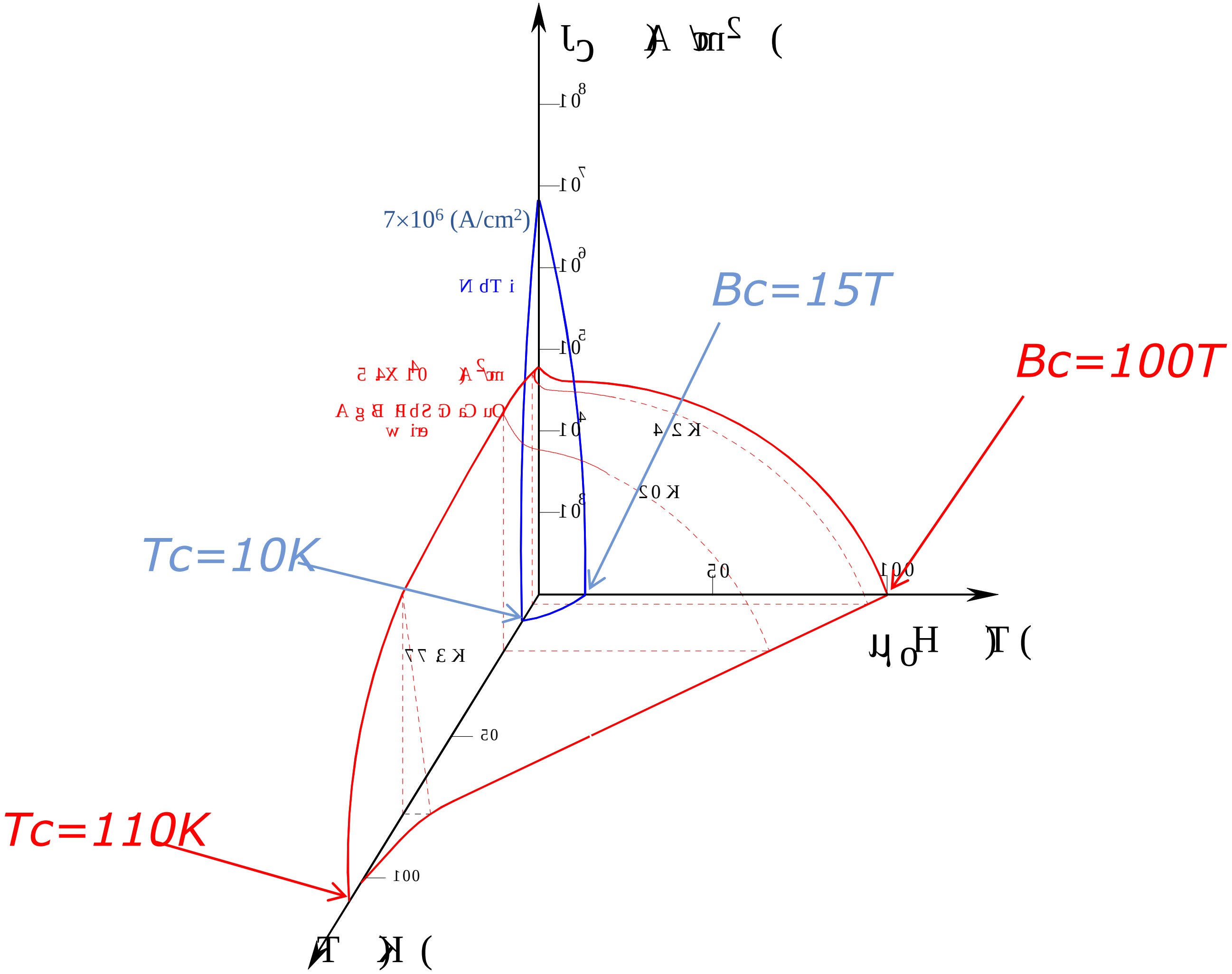
- **Critical temperature (T_c)** intrinsic of material
- **Critical field (B_c)** intrinsic of material
- **Critical current density (J_c)** extrinsic (pinning centers induced during fabrication)





For a given temperature (T_0) $J_c(B) = \frac{A}{B} b^p (1-b)^q$ $b = B/B_{c2}(T_0)$

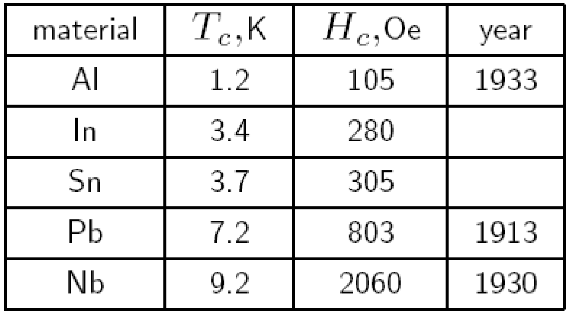
Critical surface of LTS vs HTS



Various Superconducting materials

Low Temperature Superconductors (LTS) $T_c<39K$

Pure metals



material	T_c,K	H_c,Oe	year
Al	1.2	105	1933
In	3.4	280	
Sn	3.7	305	
Pb	7.2	803	1913
Nb	9.2	2060	1930

Alloys and Intermetallic compounds

	Tc (K)	Bc(T)
NbTi	10	15
V_3Ga	14.8	2.1
NbN	15.7	1.5
V_3Si	16.9	2.35
Nb_3Sn	18	24.3
Nb_3Al	18.7	32.4
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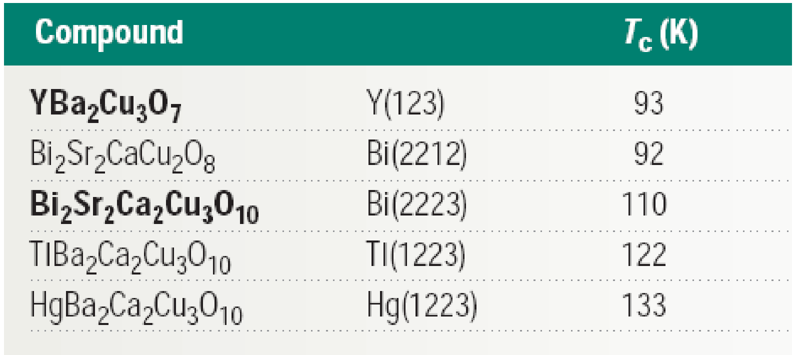
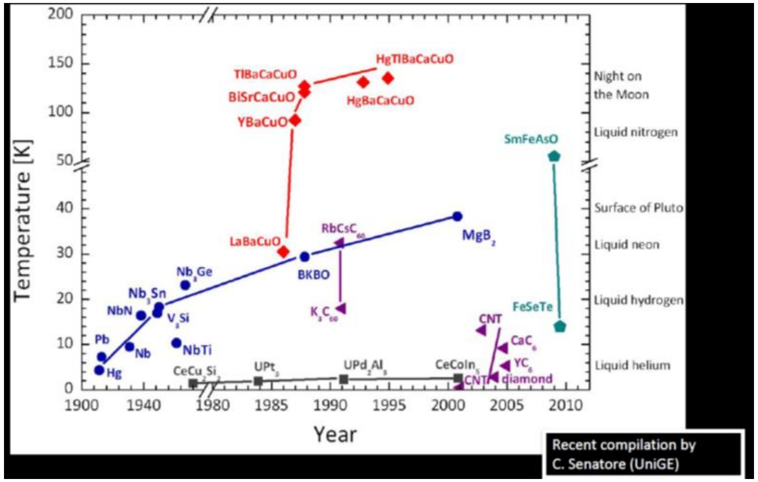
High Temperature Superconductors (HTS) $T_c>39K$

Cuprates



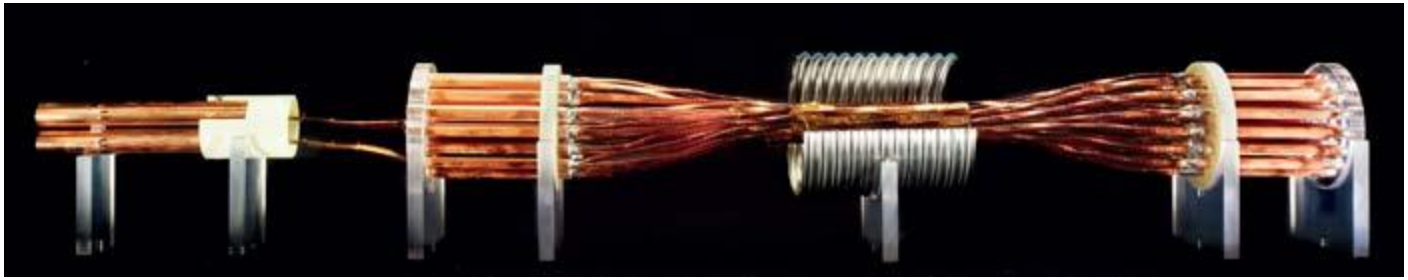
Compound		T_c (K)
$YBa_2Cu_3O_7$	Y(123)	93
$Bi_2Sr_2CaCu_2O_8$	Bi(2212)	92
$Bi_2Sr_2Ca_2Cu_3O_{10}$	Bi(2223)	110
$TlBa_2Ca_2Cu_3O_{10}$	Tl(1223)	122
$HgBa_2Ca_2Cu_3O_{10}$	Hg(1223)	133



Recent compilation by C. Senatore (UniGE)

Superconductivity applications

- Generate high DC field: (MRI, NMR, particle Physics)
- Current limiters
- Electronics, detectors (SQUIDS)
- Power transmission
- Magnetic levitation (Maglev)
- Current leads
- RF cavities



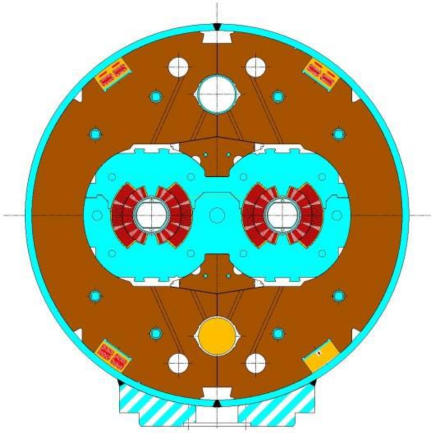
Superconducting devices @CERN

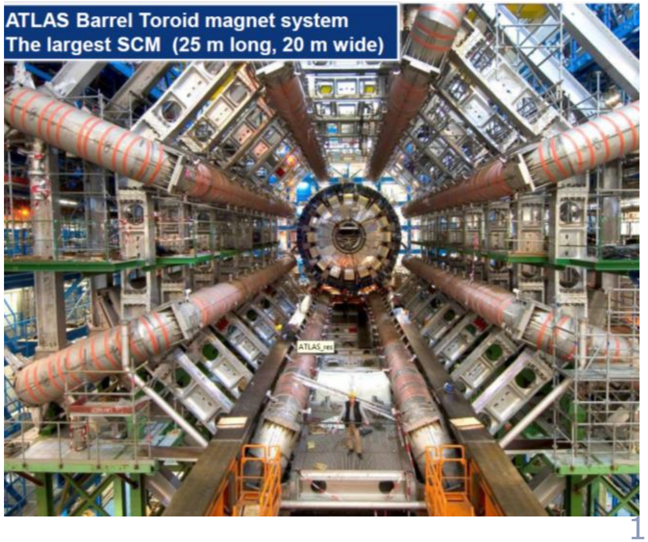
Superconductivity = a core technology of LHC

- **LHC ring magnets (**Nb-Ti)**:**
  - 1232 main dipoles: **8.3 T** x 15 m
  - 392 Lattice quadrupoles **223 T/m (7 T)** x 4m
  - Zoo of 7600 others

- **LHC detector magnets (**Nb-Ti)**:**
  - ATLAS: Toroid 4 T, 25 x20 m
  - CMS solenoid: 4 T, 12 x15 m

- **LHC current leads (**HTS BSCCO)
  - ~1000, rated for I ϵ[0.6,13 kA]
- **RF cavities (N_b coating)**



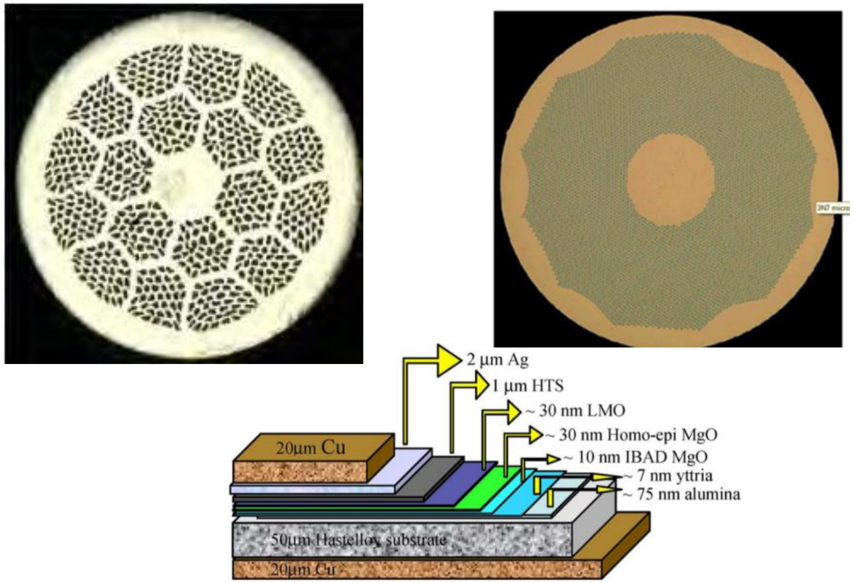


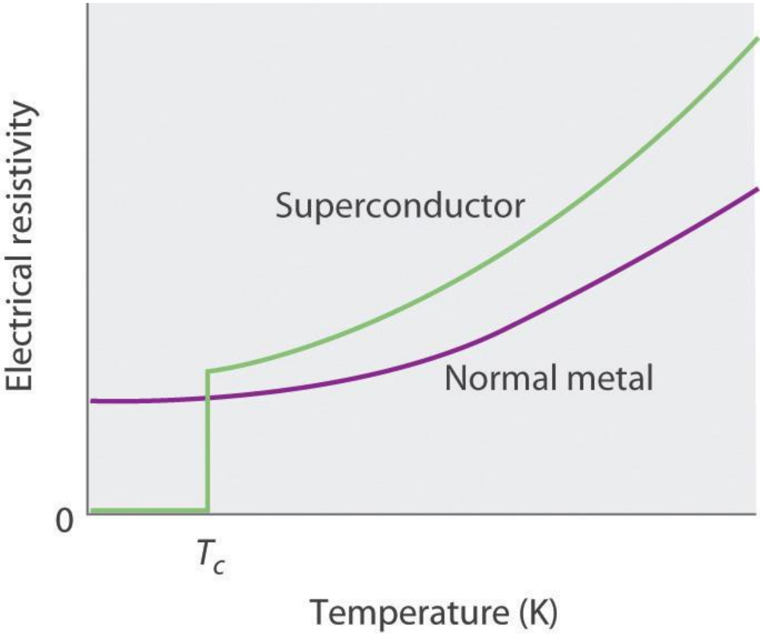
ATLAS Barrel Toroid magnet system
The largest SCM (25 m long, 20 m wide)

Superconductor for accelerator magnets

Superconductor = numerous small **superconducting filaments** embedded in **a low resistance matrix**

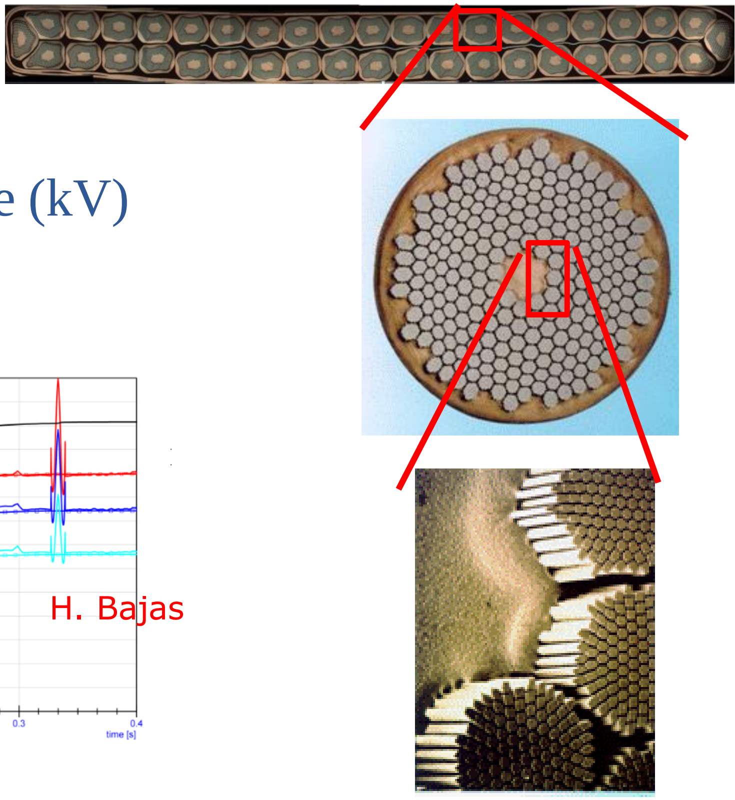
- **Small filaments to reduce the hysteresis losses**
- **Low resistance matrix to carry the large current for the few millisecond after a quench (see next slide)**

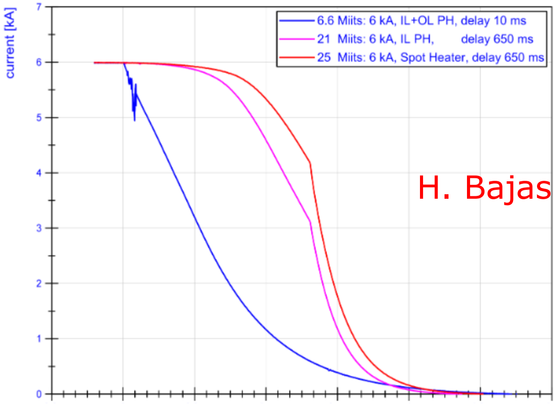




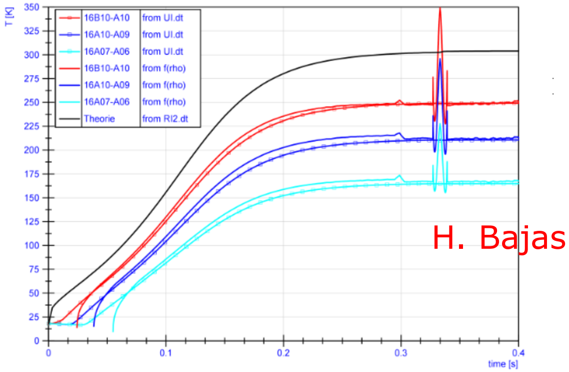
Accelerator magnets use large current cable

- **Large** stored **magnetic energy**
- Use of large current cable to reduce inductance **(10-20 kA)**
- Wires are assembled in **Rutherford cables (18-50 strands)**
- This allows for:
  - short piece length of conductor
  - Low inductance magnet
  - Made the winding stage shorter
  - Allow for reliability (current sharing)
  - Reduce the dumping time (for a given voltage (kV)





H. Bajas

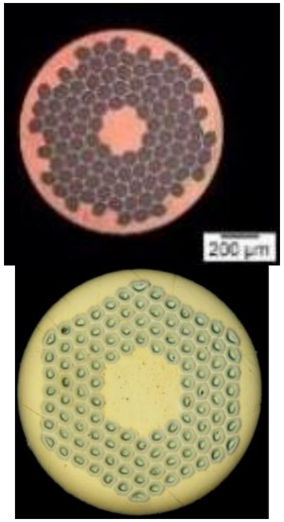


H. Bajas

Superconducting strands (for magnets)

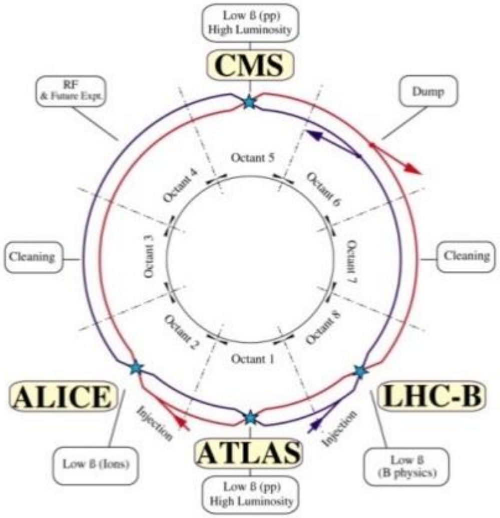
Relevant parameters for accelerator magnets (Nb-Ti, Nb_3Sn..)

- Large overall current density ~**400–500 A/mm^2**
- **Cu fraction** of about **50%** with **RRR >100**
- **Small filaments** to reduce magnetization and flux jumps
- **Twist** of the **filaments**
- Sufficient **mechanical properties** (axial and **transverse**)
- **Long** piece **length** (~1 km)
- **Good uniformity** of electrical performances
- …



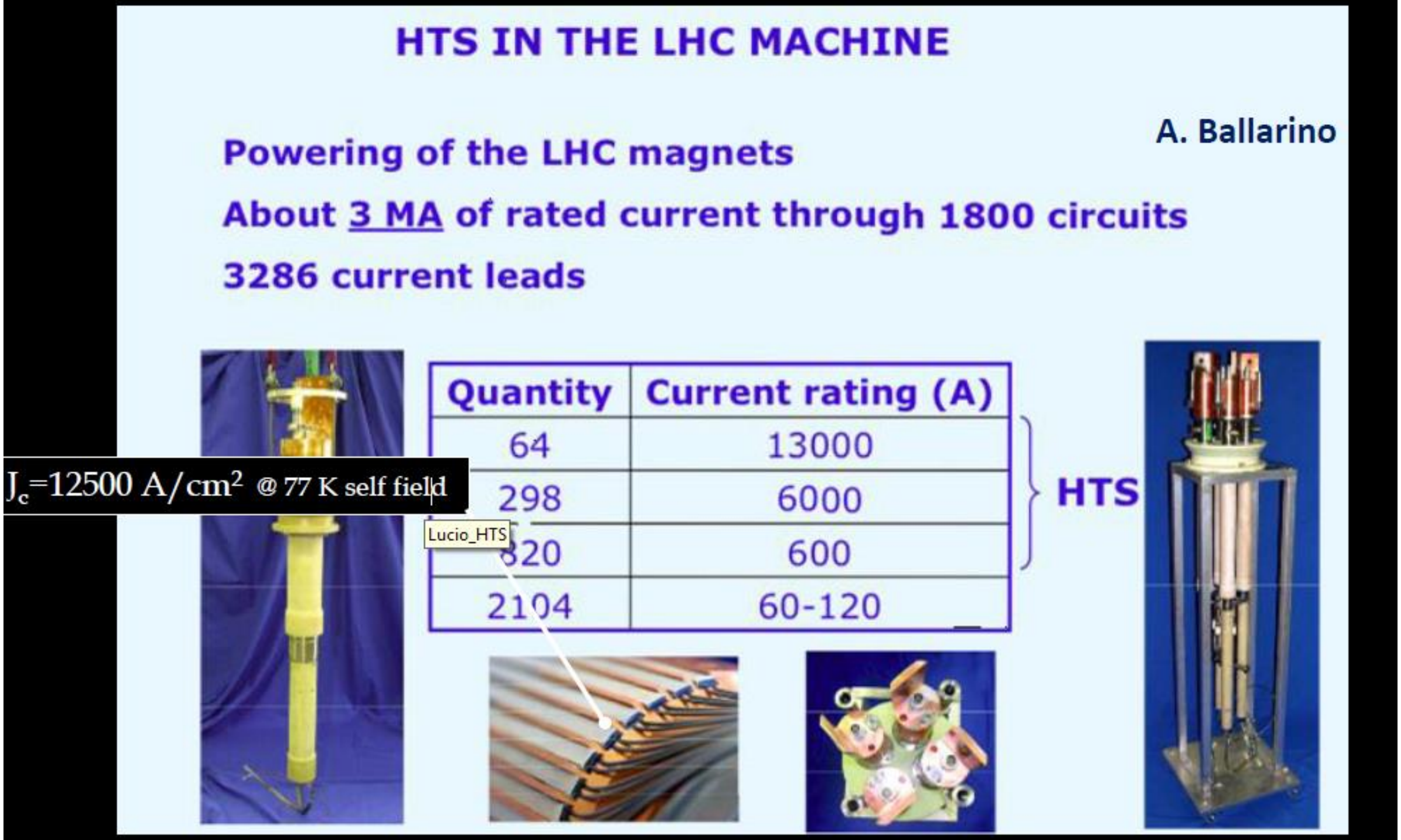
Practical superconductors

Nb-Ti	B_{0max}= **9 T**
Nb_3Sn	B_{0max}=**16 T**
REBCO	B_{0max}> **30T**
BSCCO	B_{0max}> **30T**



Beam energy: E [TeV]~**0.3 B**[Tesla] **R**[km]

Magnet need powering! HTS CLs



HTS IN THE LHC MACHINE

A. Ballarino

Powering of the LHC magnets

About 3 MA of rated current through 1800 circuits

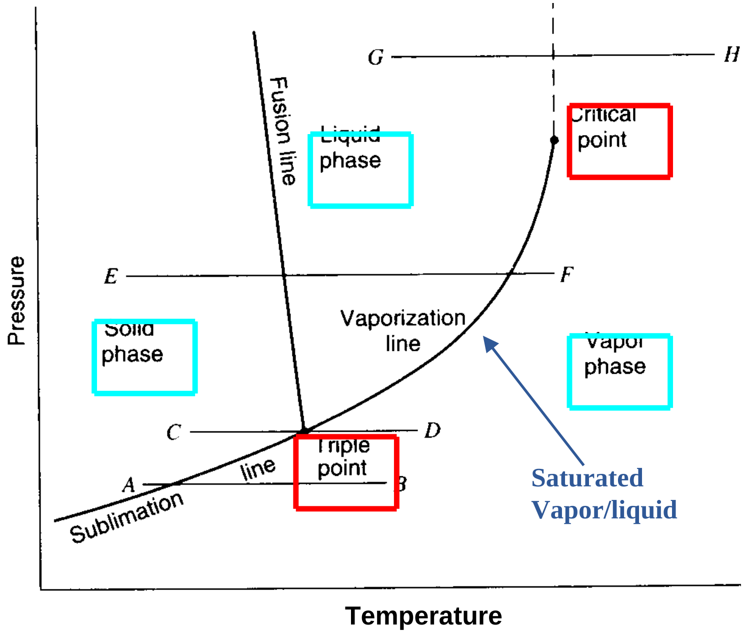
3286 current leads

Quantity	Current rating (A)
64	13000
298	6000
820	600
2104	60-120

J_c=12500 A/cm^2 @ 77 K self field

Cryogens for superconductor

	Triple point (K)	**Boiling point (1 atm, K)**	**Critical Point (K)**	
Methane	90.7	111.6	190.5	
Oxygen	54.4	90.2	154.6	
Argon	83.8	87.3	150.9	
Nitrogen	**63.1**	**77.3**	**126.2**	**HTS low fied**
Neon	24.6	27.1	44.4	
Hydrogen	13.8	20.4	33.2	
Helium	**λ-point**	**4.2**	**5.2**	**HTS high field and LTS**



Today we will use HTS material with nitrogen. In accelerator LTS are operated in Helium bath. This will be most likely the case for HTS (larger Bc2)

Properties of Liquid Nitrogen (1/2)

- Nitrogen=78% of atmosphere
- Colorless, odorless, non-toxic. The liquid is similar in appearance to water.
- Boiling point (1 atm): 77 K (-196 °C). It is colder than liquid oxygen (boiling point = -183 °C): oxygen in the air condenses out.
- Critical temperature: 126 K (-147 °C).
- Latent heat of vaporization: 197 J/g. 1 W boils off 22.5 cc/hour.
- Volume of **expansion** liquid to gas (15 °C, 1 atm): **682**. Closed containers very likely burst.

1 liter LN_2  → 3 ×  Gaz N_2

Standard liquid nitrogen dewars:150-200 liters….136m^3 of gas

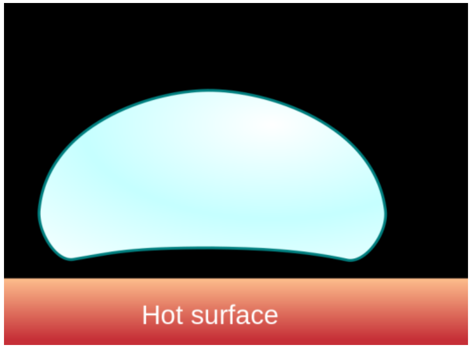
Properties of Liquid Nitrogen (2/2)

Nitrogen (liquid and gas) is colorless. But it appears as a cloudy white vapor when exposed to air.

Why does liquid nitrogen smoke?

The vapor spreads itself out through the air and condenses the water out of it. The water droplets scatter light and produced the smoking effect.

Leidenfrost effect: on a smooth surface with a temperature much higher than the nitrogen boiling point, the liquid vaporizes quickly and lifts itself above the surface. If the surface is irregular, this effect doesn't occur and the vaporization is even more rapid.



Mechanical properties at cold

Most of the common materials becomes brittle at cryogenic temperature.
What happens to a rose when immersed in liquid nitrogen?

Dewar for Liquid Nitrogen

- LN_2 is stored in vacuum insulated storage vessels (dewars), with a vacuum space and a special thermal insulation. However, leaks into the vessel cause the cryogenic liquid to vaporize and build up pressure. In optimum conditions, the liquid-to-gas conversion rate per day is about 2.3 %.
- Pressure relief valve to protect the vessel against over-pressure.
- Level gauge.
- Rupture disk.

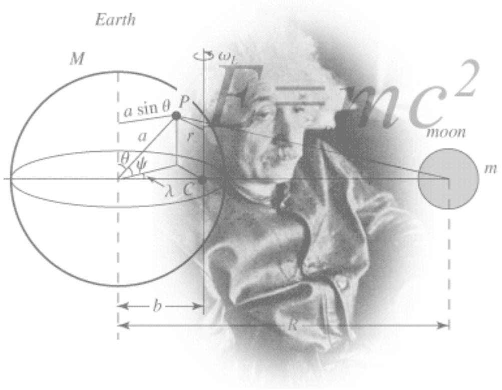
Annular Space

Dealing with LN2: safety first

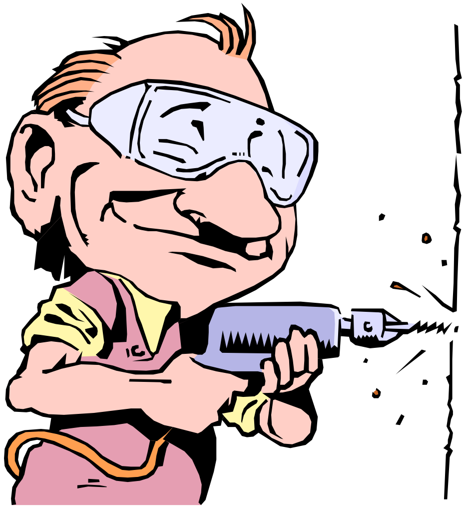
Like other cryogens, **may be harmful if not handled properly!**

- The extremely low temperature of the liquid nitrogen (LN_2) can cause severe **burn-like damage to the skin** either by contact with the fluid, surfaces cooled by the fluid or evolving gas.
- **Skin can freeze and adhere** to LN_2 cooled surfaces causing tearing on removal. Thermal gloves must be worn when handling objects cooled by LN_2 (transfer lines, test materials,…). DO NOT touch cold surfaces with bare hands to avoid severe cold-burns !
- **Boiling and splashing** will always occur when filling a warm container. Protection glasses must be worn.
- **Oxygen condenses** and collects on objects cooled in LN2 (nitrogen smokes, but you should not do it in his presence !).
- Many materials (common glass, plastics, iron…) become brittle and may shatter when cooled in LN2.
- Nitrogen can easily replace air in poorly ventilated areas (**risk of asphyxiation**).

Superconductivity Practical Days at CERN



We will work with **cryogenics and superconductivity** to understand and verify the unique properties of superconductors



YBCO 123 bulk

BSCCO and YBCO tape

SmCo, NeFeB **magnets**

Liquid nitrogen

………

Levitation

Flux pinning

Zero resistance

Jc,Tc,Hc

………

Experiments

Experiments will be performed with HTS superconductors and liquid nitrogen

1.Levitation experiment,

2.Flywheel demonstration.

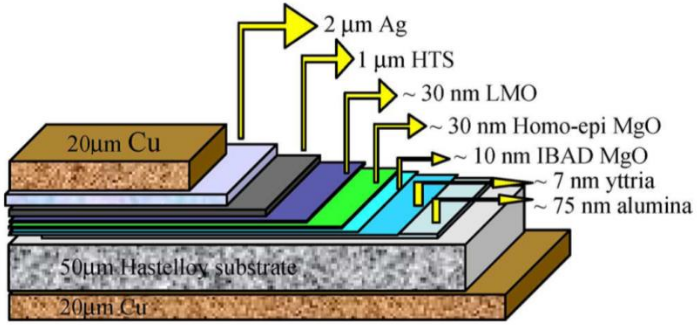
2.Critical temperature experiment

3.Zero resistance experiment

4.Critical current experiment

.

➢**YBCO** 123 Melt Textured Bulk. Tc= 92 K.



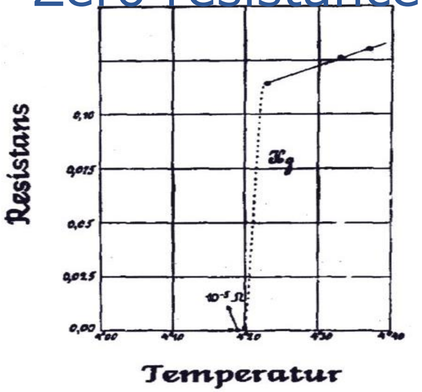
➢**YBCO** 123 Tape. Tc= 92 K.

Properties of Superconductors

Zero resistance → Perfect conductors

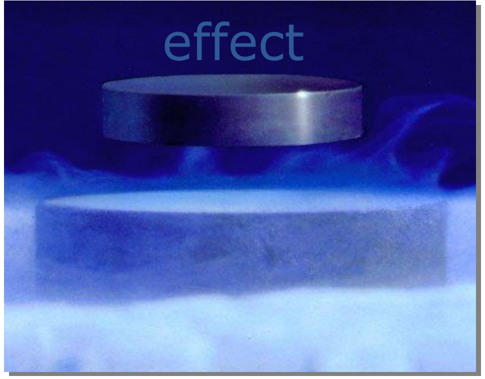
Exclusion of magnetic field → Perfect diamagnets

Zero resistance



Onne’s measurement on mercury (1911)

Meissner effect



Discovered by Meissner and Oschenfeld (1933)

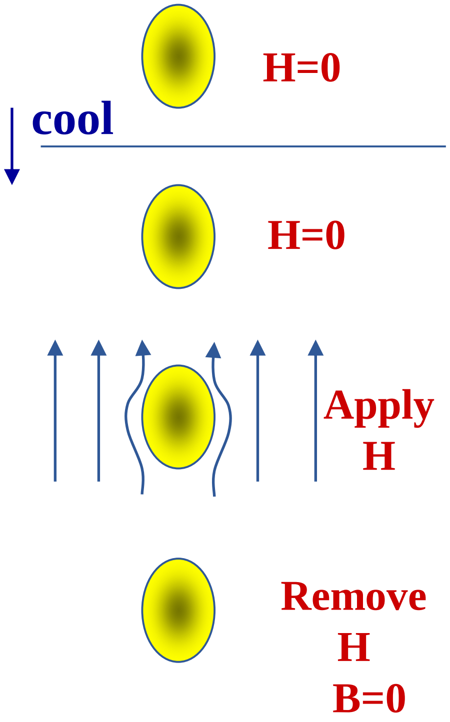
The magnetic behavior of a superconductor follows the Faraday-Lenz’s law of electromagnetism. A superconductor reacts to changes in externally applied magnetic field. Circulating currents are induced to oppose the build-up of magnetic field in the conductor.

Perfect conductivity + perfect diamagnetism = superconductors

Meissner effect

Zero field-cooled method: the materials are first cooled and then placed in an external magnetic field.

“Perfect” conductor (zero resistance)



H=0

cool

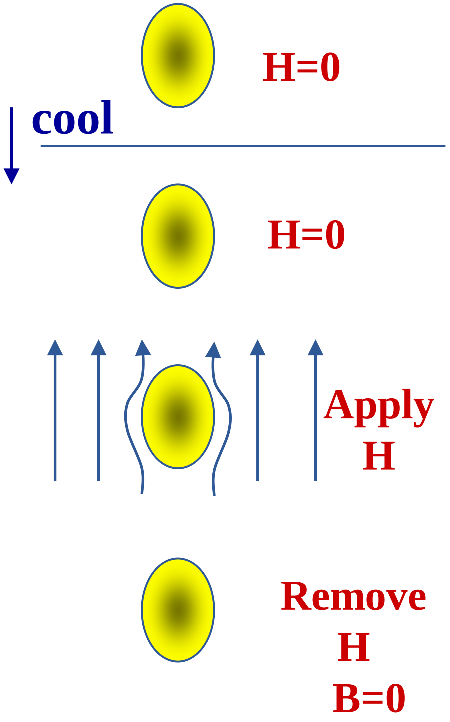
H=0

Apply H

Remove H

B=0

Superconductor



H=0

cool

H=0

Apply H

Remove H

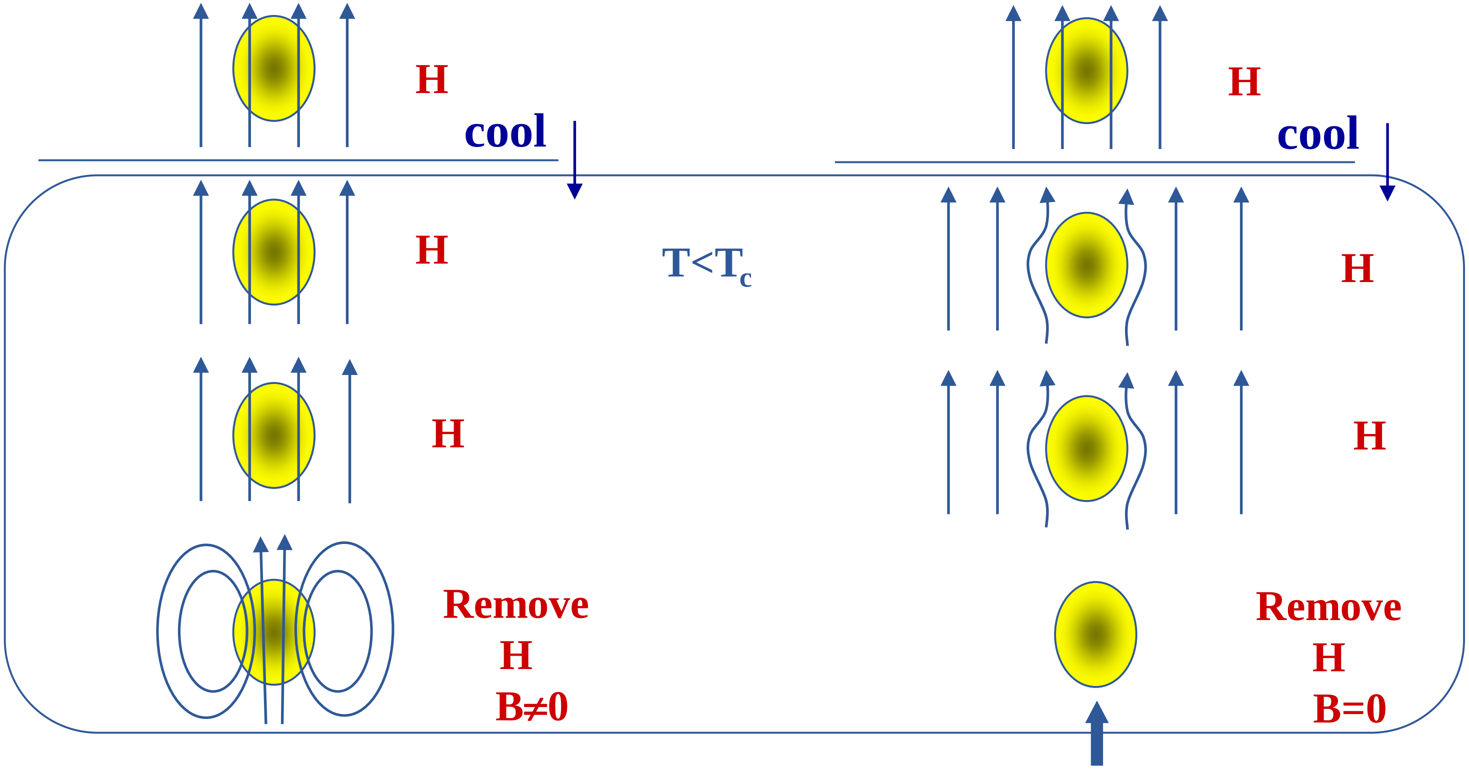
B=0

Meissner effect

Field-cooled method: the materials are in the presence of an external magnetic field at room temperature. After they are cooled.

“Perfect” conductor Zero resistance

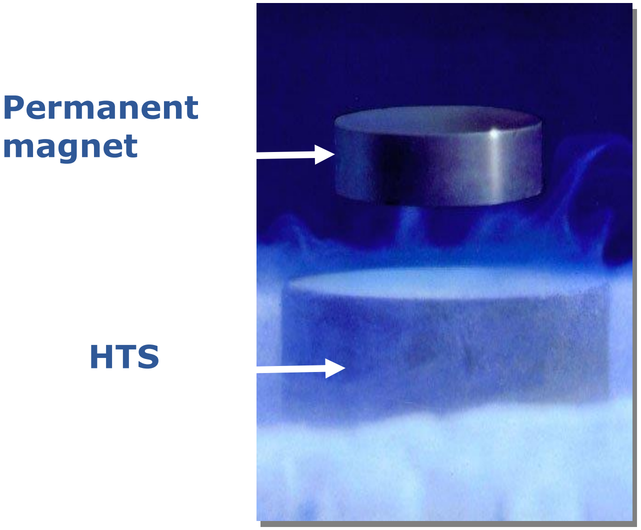
Superconductor

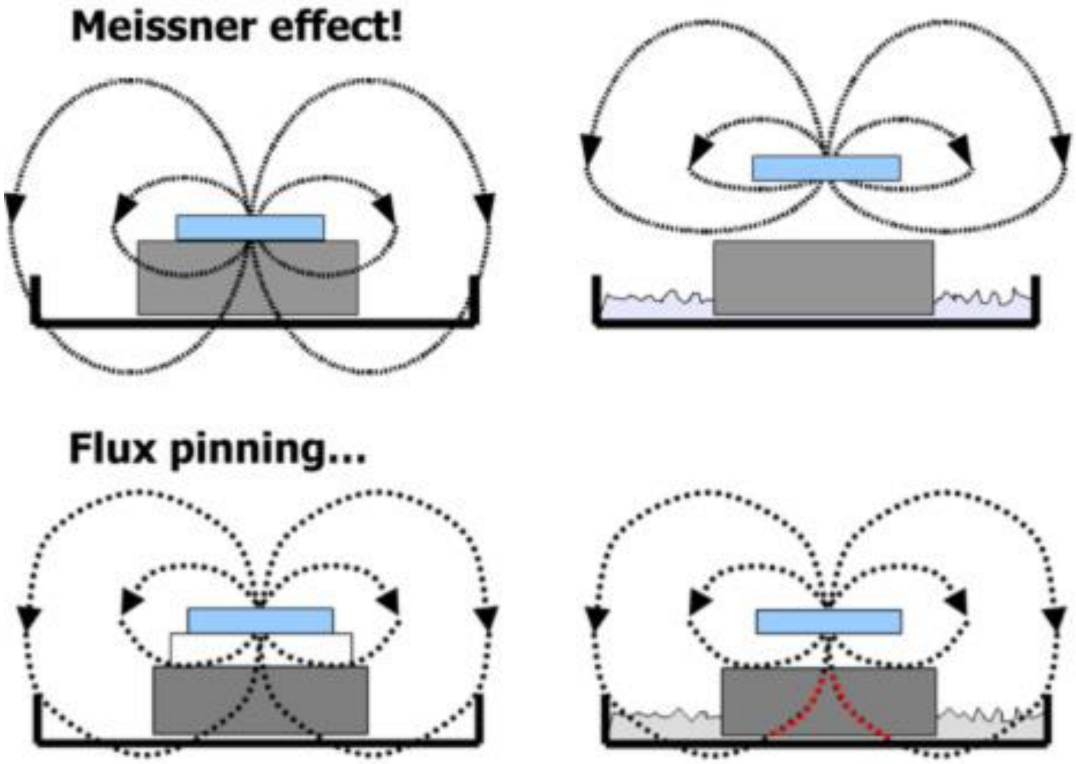


Meissner effect

Levitation experiment

Levitation experiment





T>Tc:

No levitation

T<Tc:

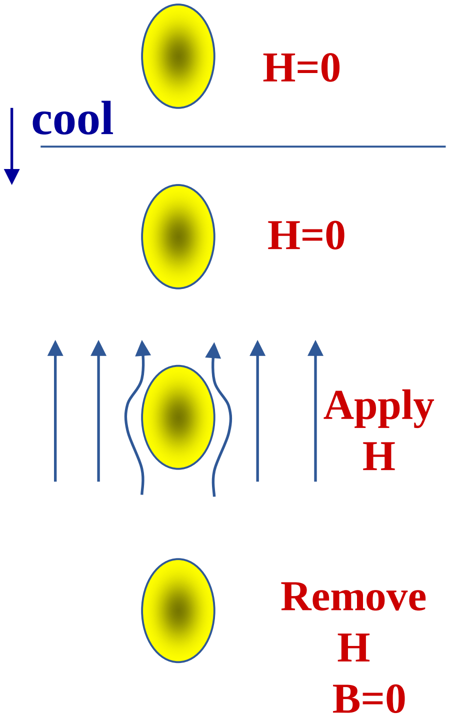
Levitation

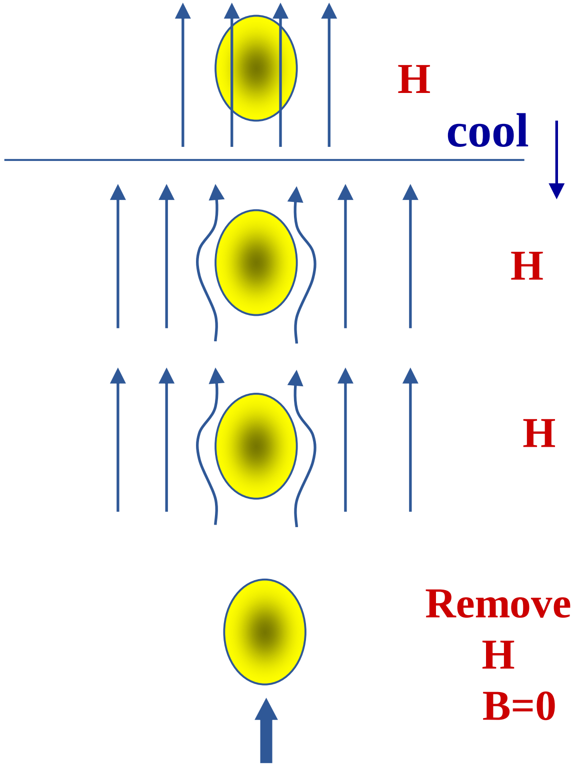
Levitation experiment

We will perform two experiments:

Field-cooled conditions: the field is applied to the superconductor at room temperature, before cool-down in liquid nitrogen.

Zero field-cooled conditions: the superconductor is cooled-down in zero field conditions. Only when the temperature is below Tc, the field is applied.





Meissner effect

Field-cooled Levitation experiment

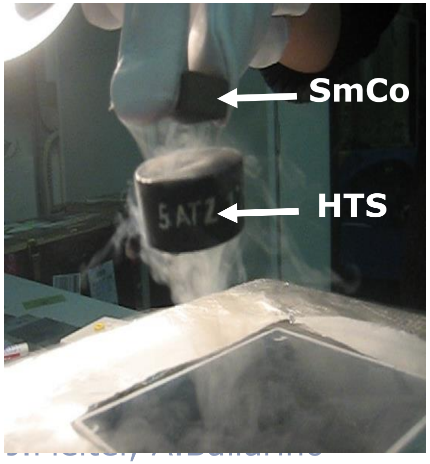
The magnet is put, at room temperature, on the top of the superconductor (no levitation).

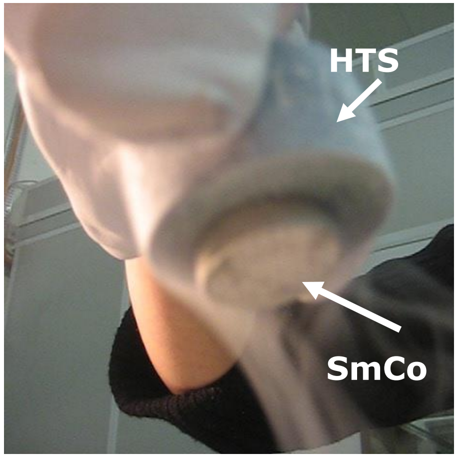
The assembly is cooled with LN_2 to 77 K. The YBCO becomes superconducting and the magnet jumps up in the air.

The magnet levitates stably in mid air and can be moved in the vertical position only by applying a strong force. It will rotate in the air when kicked with a non-magnetic material.

Observe also stability in the horizontal plane due to the magnetization of the residual flux.

Appreciate the intensity of the max levitation force !

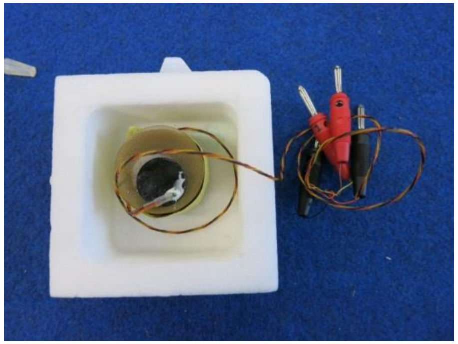


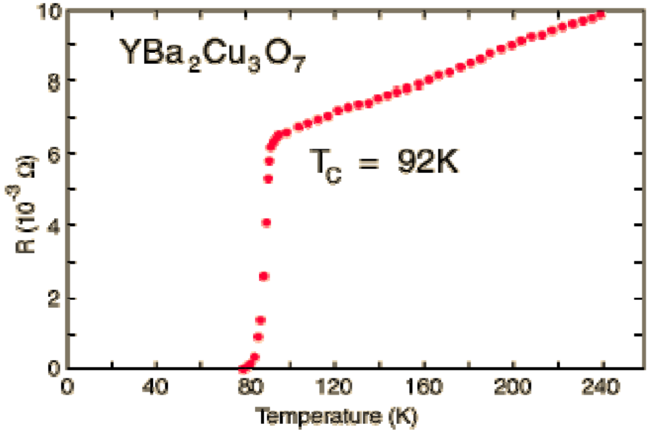


Critical temperature experiment

Measurement of critical temperature by using the Meissner effect.

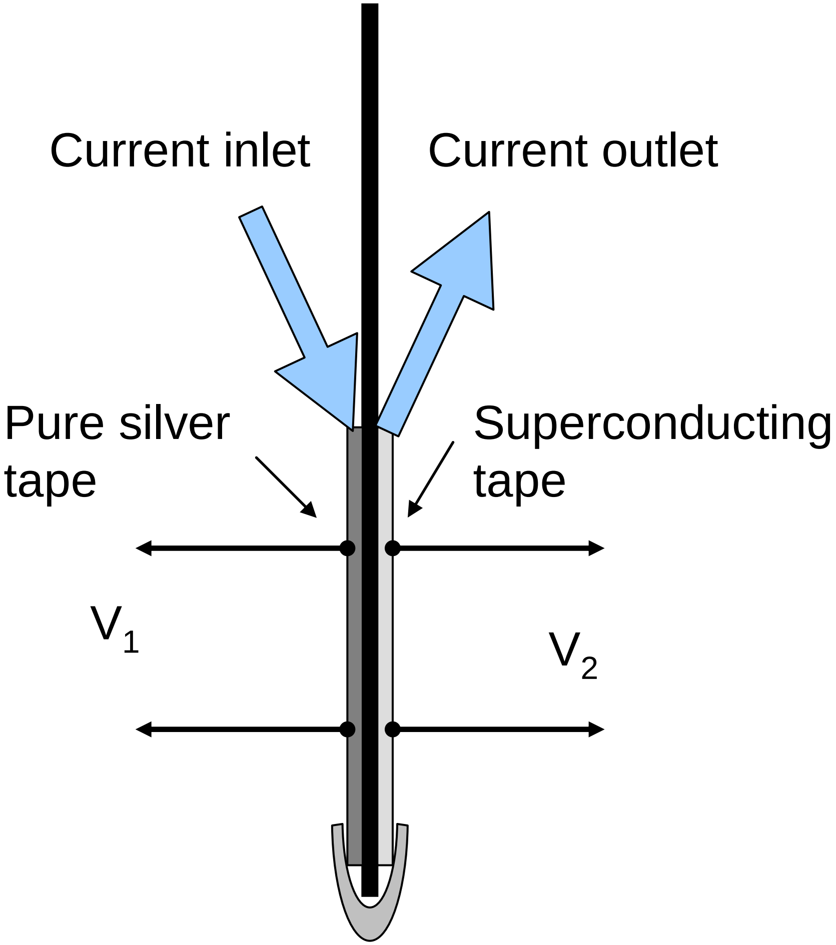
The critical temperature is defined as the temperature measured on the superconductor when the permanent levitating on it comes to complete rest on the superconductor's surface.



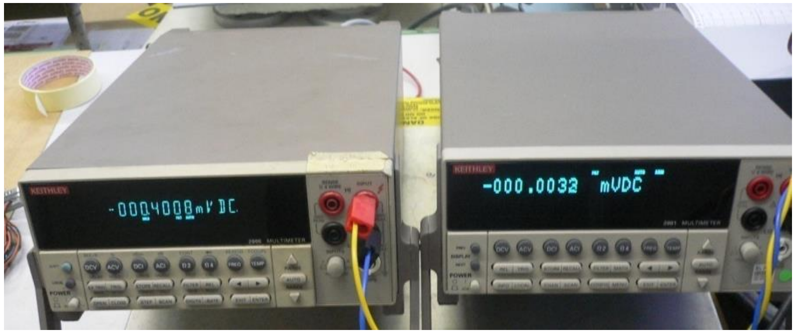


In reality, the critical temperature is defined as the temperature below which a material exhibits superconductivity at zero magnetic field strength.

Zero resistance direct current experiment



A superconducting tape and a pure silver tape are connected in series, Measure the voltages (resistances) as the specimens are inserted into liquid nitrogen and cooled to 77 K.



$\rho_{Ag}(293\ K) \sim 1.46 \cdot 10^{-6}\ \Omega \cdot m$
$\rho_{Ag}(77\ K) \sim 0.2 \cdot \rho_{Ag}(293\ K)$

A see-through glass walled dewar is used for the LN_2.

HTS:BSCCO 2223 multi-filamentary tape in silver alloy matrix.

DC Critical current experiment

Critical current (**I$_c$**): current at which a specified electric field criterion E$_c$, or resistivity criterion ρ_c is achieved in the specimen. Losses through a Type II superconductors ($H_{c1}<H<H_{c2}$) depend on the sample geometry and on the vortex pinning.

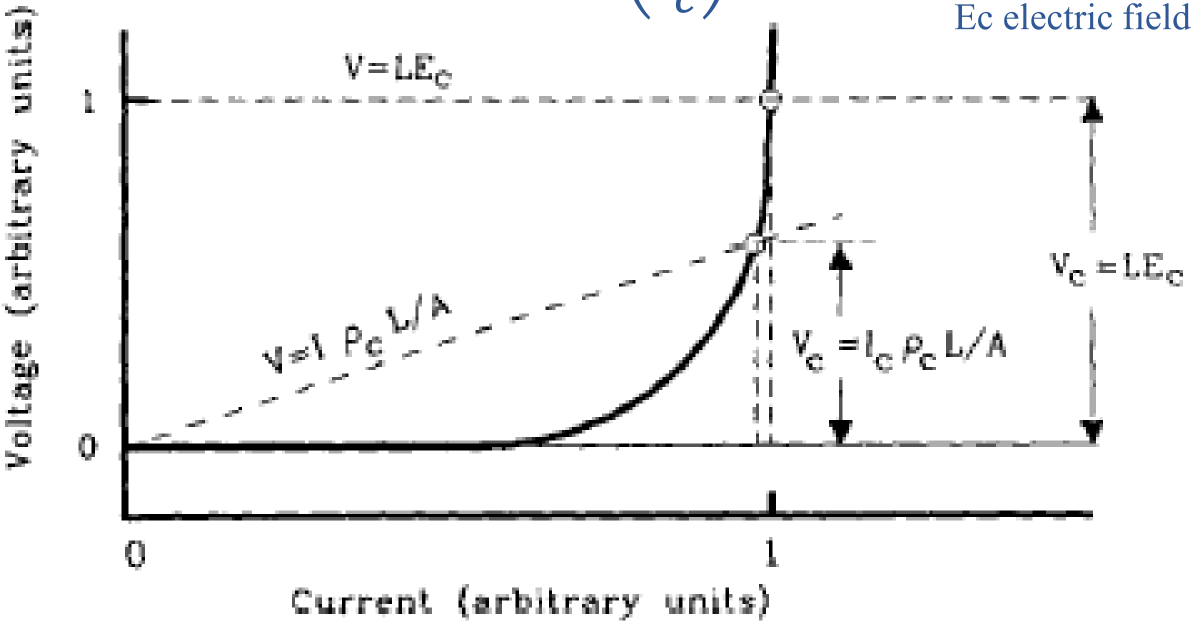
$$E = E_c\left(\frac{I}{I_c}\right)^n$$

n=n-value (-)

Ic critical current (A)

E electric field (V/m)

Ec electric field criterion (1 uV/cm)



H=const

T=const

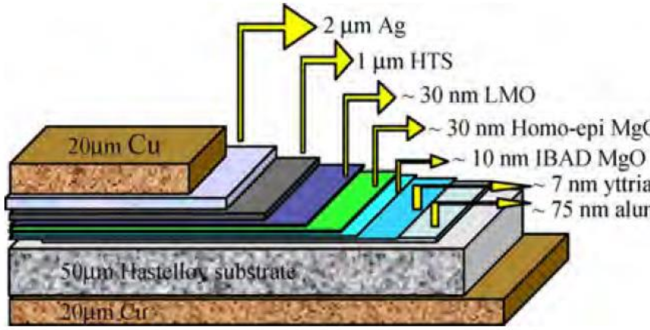
Critical current experiment self-field and with perpendicular field

E_c= 1 μV/cm
Measure I_c in liquid nitrogen.

f=filling factor=A_{HTS}/Atot
f=1%

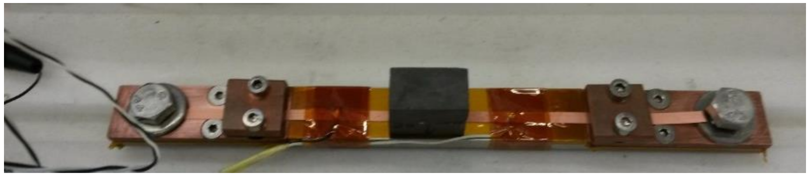
Derive
J_{eng} (Engineering critical current density=current over the total cross section of the tape) and
J_{ph} (Physical critical current density=current in the HTS).

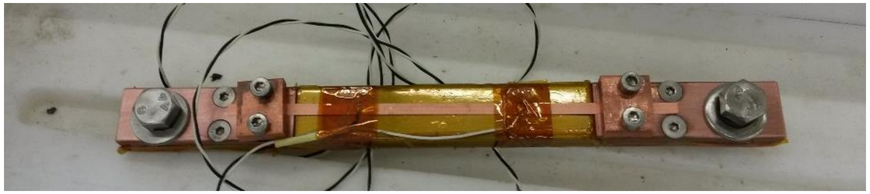
T=77 K



YBCO tape: 4mm wide

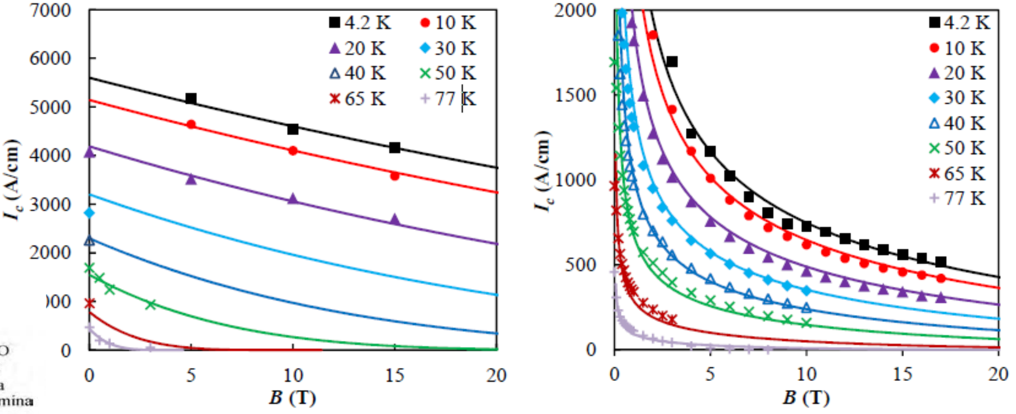
0.1 mm thick



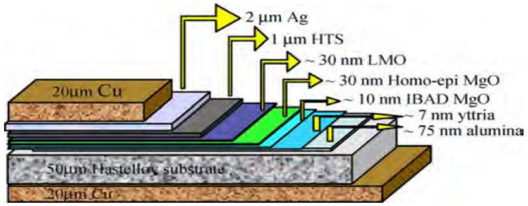


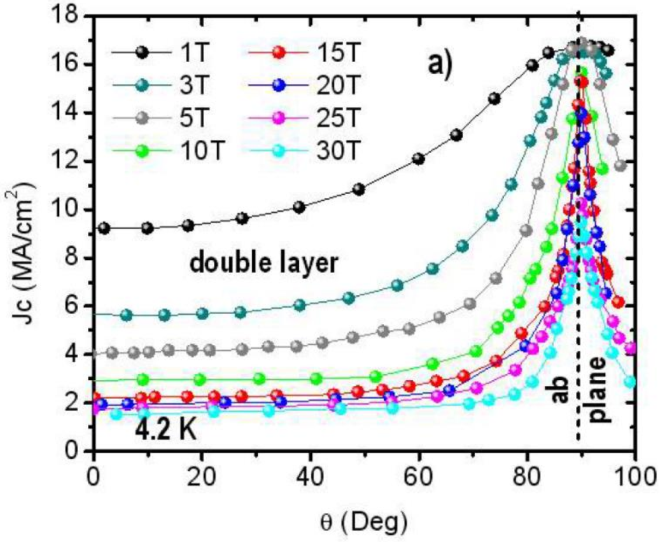
Critical current experiment: anisotropy

Orientation of field is important, because HTS materials are highly anisotropic.



igure 1. *Field dependence of the I_c of Fujikura REBCO coated conductors, for parallel (left) and perpendicular field (right). Markers are measurements, lines are fit.*





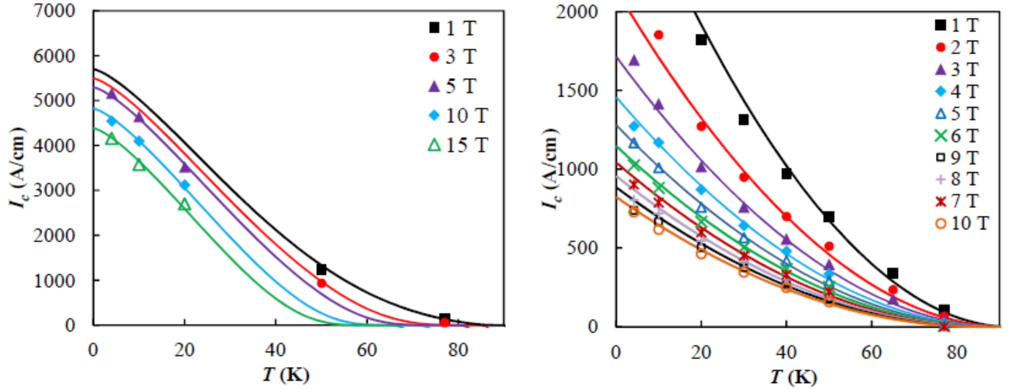


Figure 2. Temperature dependence of the I_c of Fujikura REBCO coated conductors for parallel (left) and perpendicular field (right). Markers are measurements, lines are fit.

Thanks for your attention

A few reference books

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