Superconductivity
Practical Days at CERN

28th Feb and 1st March 2019

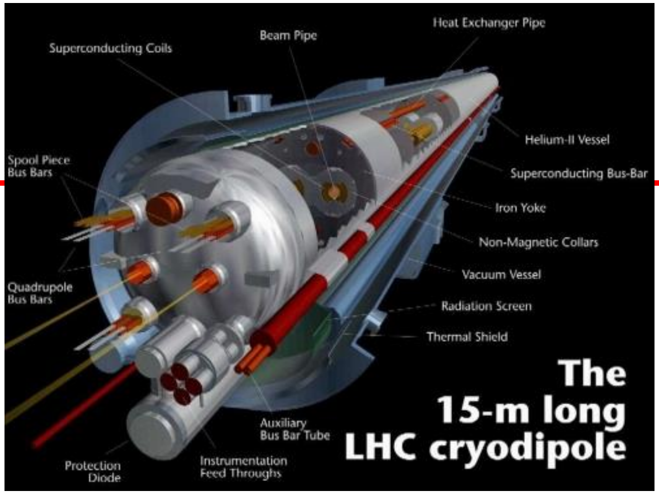
Jerome Fleiter

Introduction

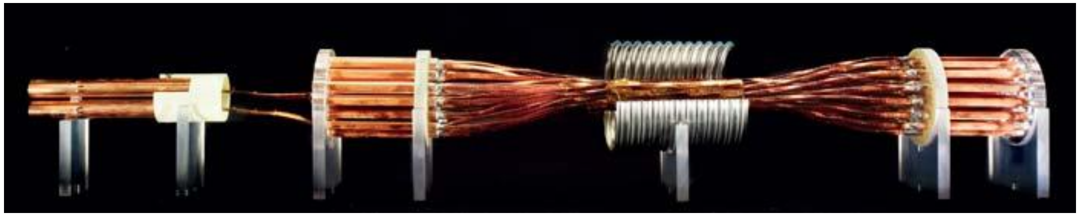
- Superconductivity Applications
- Main properties of Superconductors
- Practical work
- Agenda of the days

Superconductivity Applications

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



The 15-m long LHC cryodipole



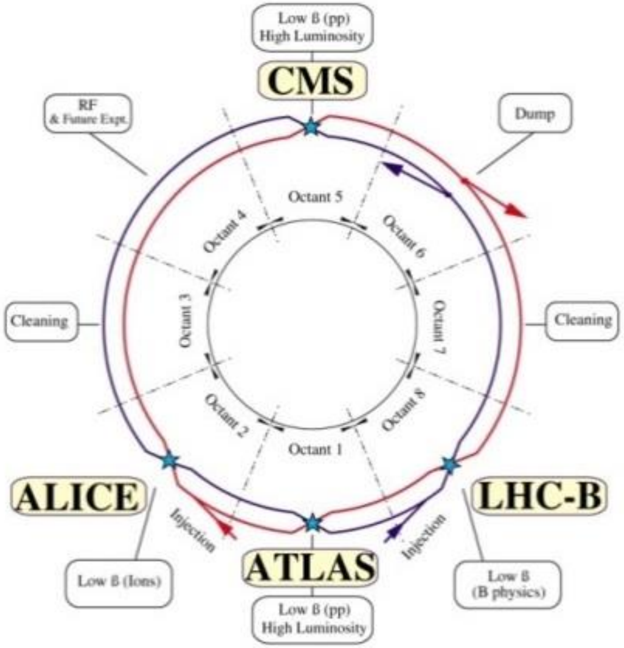
High field for particle physics

- In circular collider energy of beam proportional to field:

$$\boxed{\boldsymbol{E_{beam}}[\text{TeV}] \approx \mathbf{0.3}\, \boldsymbol{B_0}\, [\text{T}]\, \boldsymbol{R_b}\, [\text{km}]}$$

=>Further particle discovery => high energy => high field

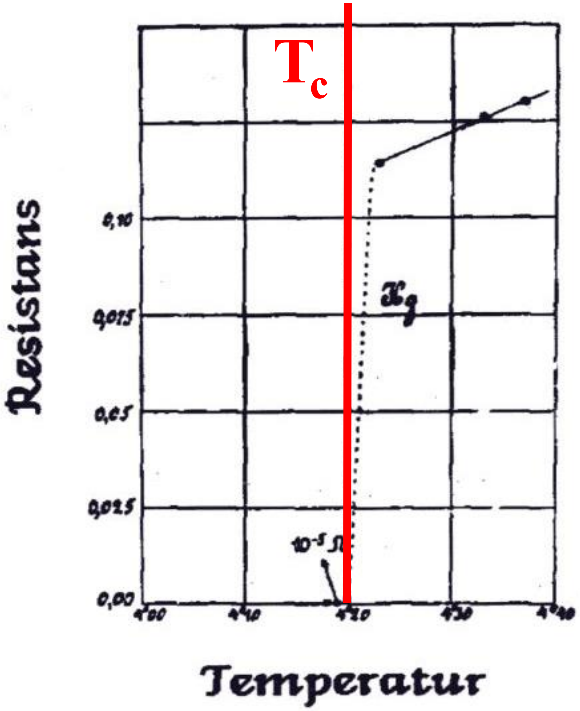
- **Why superconducting magnets:**
  - **Normal conducting** iron dominated magnet **limited to 2 T** (saturation of Iron)
  - **Superconducting magnets**: limited by **properties of Sc material**. Field of 8.3 T for LHC dipole, up to 16 T for Nb_3Sn…

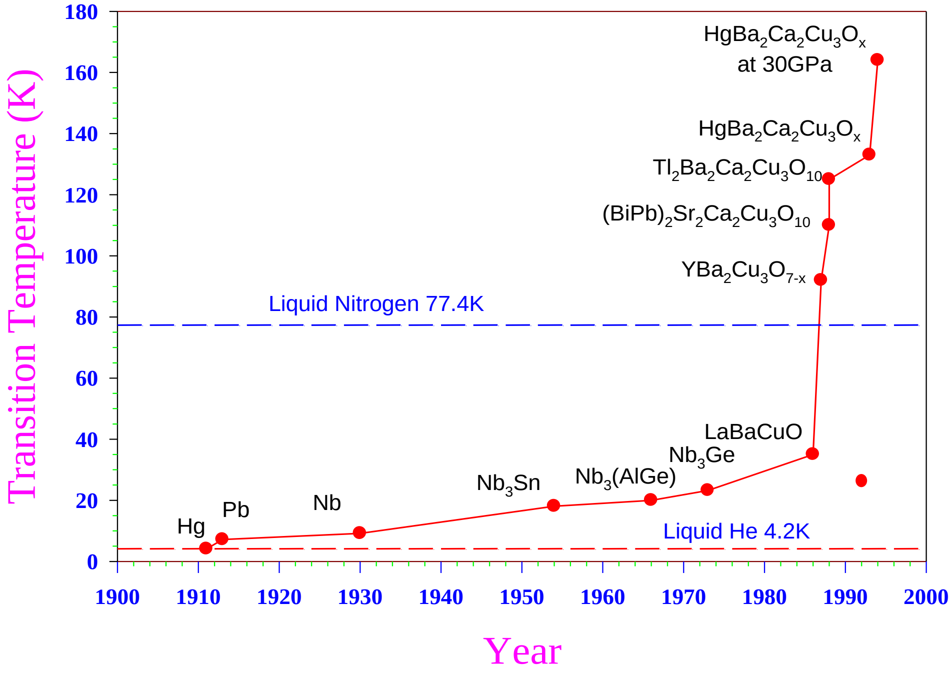


High energy colliders made from superconducting materials (Tevatron, RHIC, HERA, LHC)

Main Properties of Superconductors

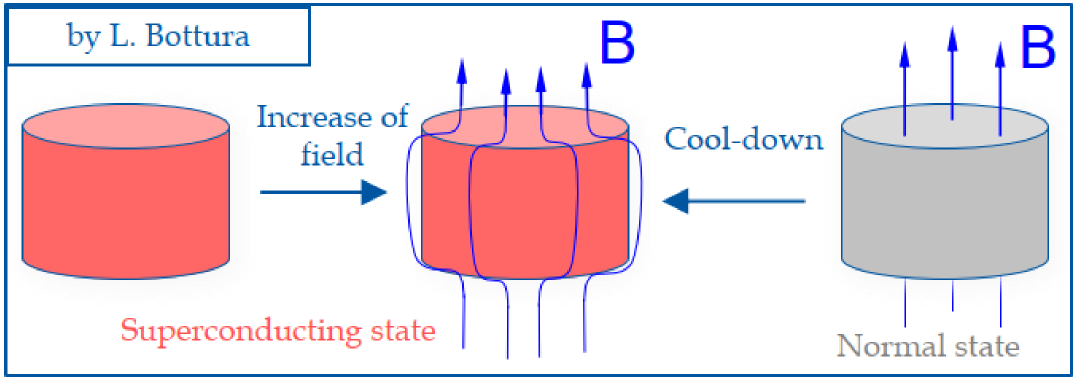
- **1911: Superconductivity discovered** by Kammerlingh-Onnes: ZERO resistance of mercury wire at 4.2 K.
- **Critical temperature T_c :** Temperature at which the transition takes place.
- Many others superconductors discovered since one century.

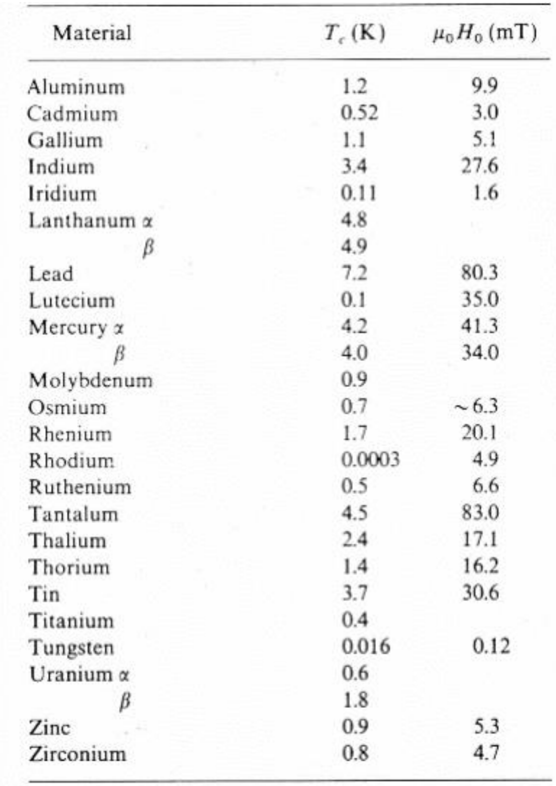




Type 1 Superconductors

- **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





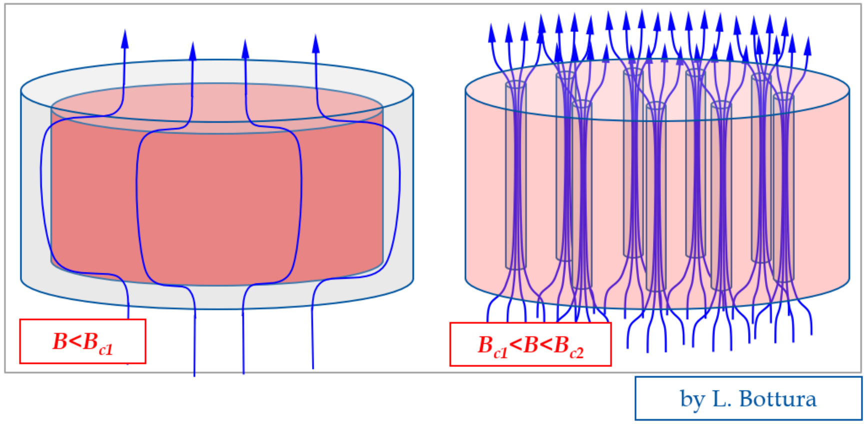
Material	T_c (K)	$\mu_0 H_0$ (mT)
Aluminum	1.2	9.9
Cadmium	0.52	3.0
Gallium	1.1	5.1
Indium	3.4	27.6
Iridium	0.11	1.6
Lanthanum α	4.8	
β	4.9	
Lead	7.2	80.3
Lutecium	0.1	35.0
Mercury α	4.2	41.3
β	4.0	34.0
Molybdenum	0.9	
Osmium	0.7	~6.3
Rhenium	1.7	20.1
Rhodium	0.0003	4.9
Ruthenium	0.5	6.6
Tantalum	4.5	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

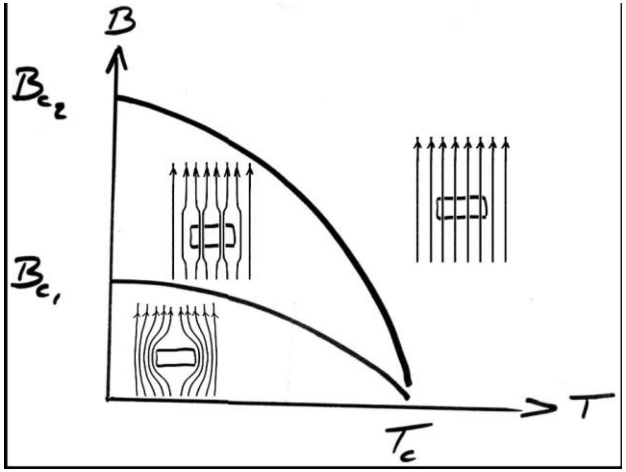
for T<Tc and B<Bc

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 $\Phi_0 = h/2e = 2\ .10^{-15}$ Wb
  - For $\mathbf{B>B_{c2}}$ material is fully penetrated, no more superconducting

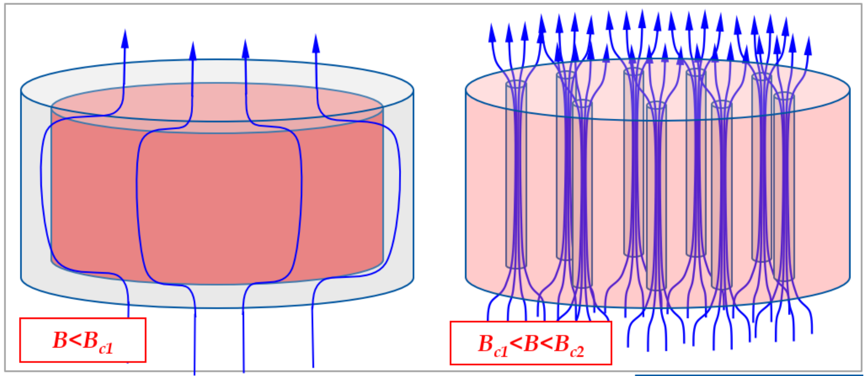


by L. Bottura



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



by L. Bottura

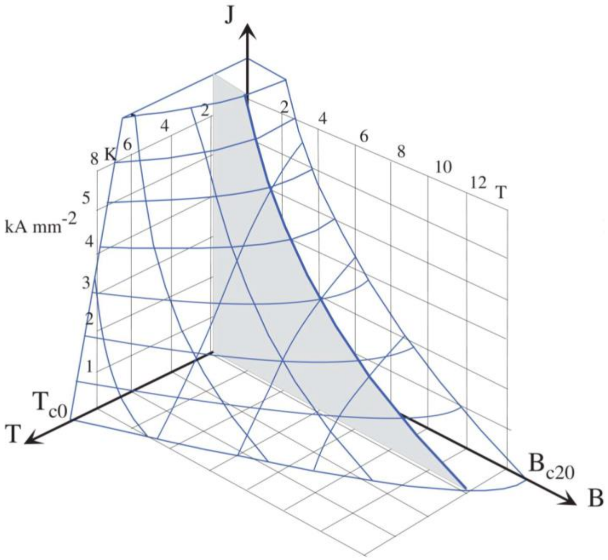
	Tc (K)	Bc(T)
NbTi	10	15
V_3Ga	14.8	2.1
NbN	15.7	1.5
V_3Si	16.9	2.35
Nb_3Sn	18	24.3
Nb_3Al	18.7	32.4
$Nb_3(AlGe)$	20.7	44
Nb_3Ge	23.2	38

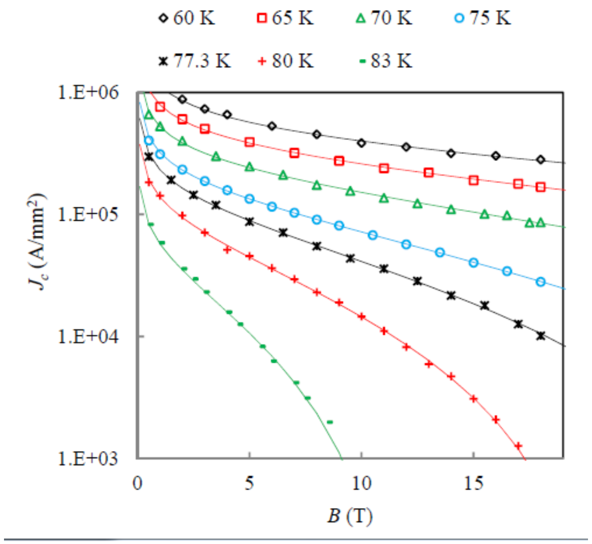
Example of Type II Sc materials

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)





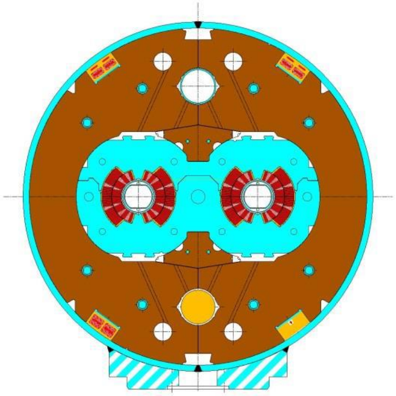
For a given temperature (T_0) $J_c(B) = \frac{A}{B} b^p (1-b)^q$

$b = B/B_{c2}(T_0)$

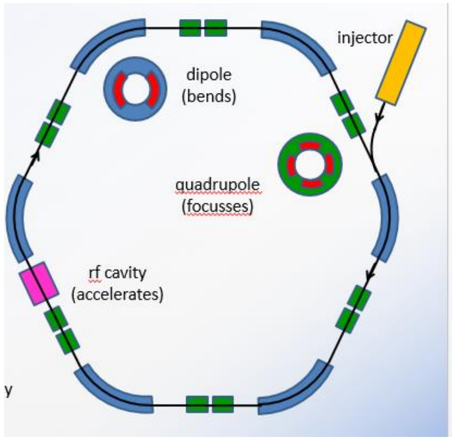
Superconducting devices in LHC

Magnets

More details in next slides



- **LHC ring magnets** (Nb-Ti): **Rutherford cables**
  - **1232** main dipoles: **8.3 T** x **15 m**
  - **392** Main quadrupoles **223 T/m (7 T)** x **4 m**
  - Zoo of **7600 others (cable or wire)**
- **LHC detector magnets** (Nb-Ti): **Rutherford cables**
  - ATLAS: Toroid **4 T**, **25 m x20 m**
  - CMS solenoid: 4 T, **12 mx15 m**



Scheme from M.N. Wilson

Other devices

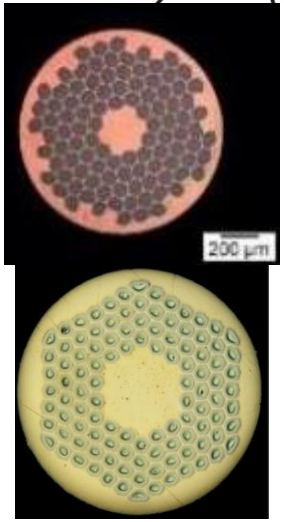
- **LHC current leads** (HTS BSCCO): stack of tapes
  - ~**1000**, rated for transport current 0.6-13 kA
- **RF cavities (N_b coating)**

➢ **Superconductivity is a key technology of LHC**

Superconducting strands (for magnets)

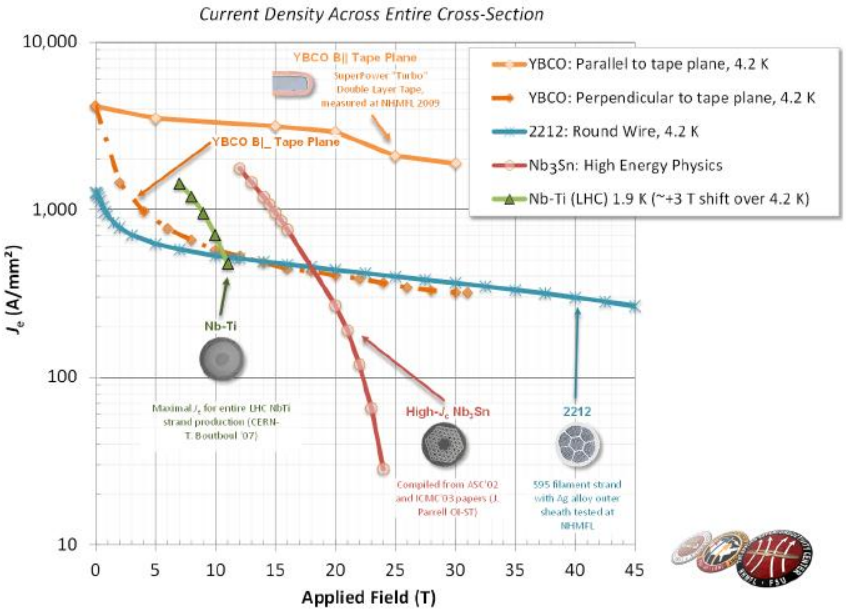
Relevant parameters for accelerator magnets (Nb-Ti, Nb_3Sn..)

- 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

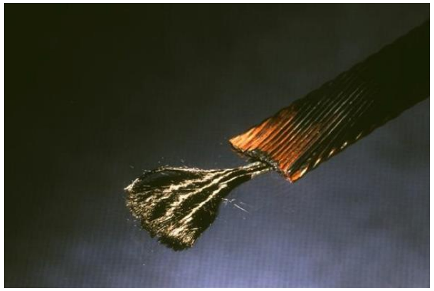
- **Nb-Ti** B_{0max}= **9 T**
- **Nb_3Sn** B_{0max}=**16 T**
- **REBCO** B_{0max}> **30T**
- **BSCCO** B_{0max}> **30T**

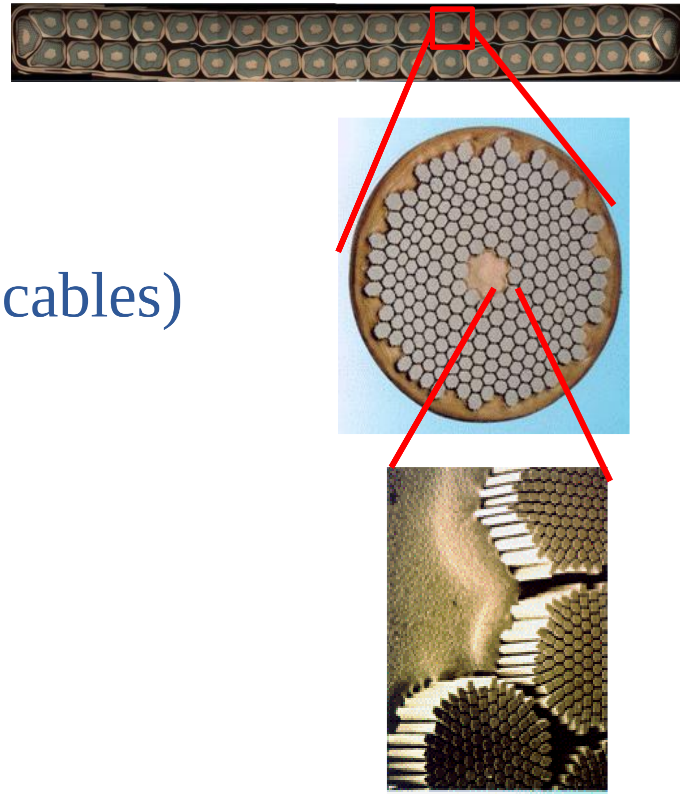


Beam energy: E [TeV]~**0.3 B**[Tesla] **R**[km]

Rutherford cables

- **Why cables**:
  - Needs for High current (10-20 kA)
  - Reduce piece length of conductor (~1 km)
  - Improve stability
  - Make easier the winding
- **The use of large current cables implies also**
  - to deal with dynamic effects
  - Less freedom for magnetic optimization
- **Advantages of Rutherford cables** (vs. other cables)
  - Good packing factor
  - Transposition of strands
  - Good control of dimensions (+/- 6 μm on thickness)
  - Good windability

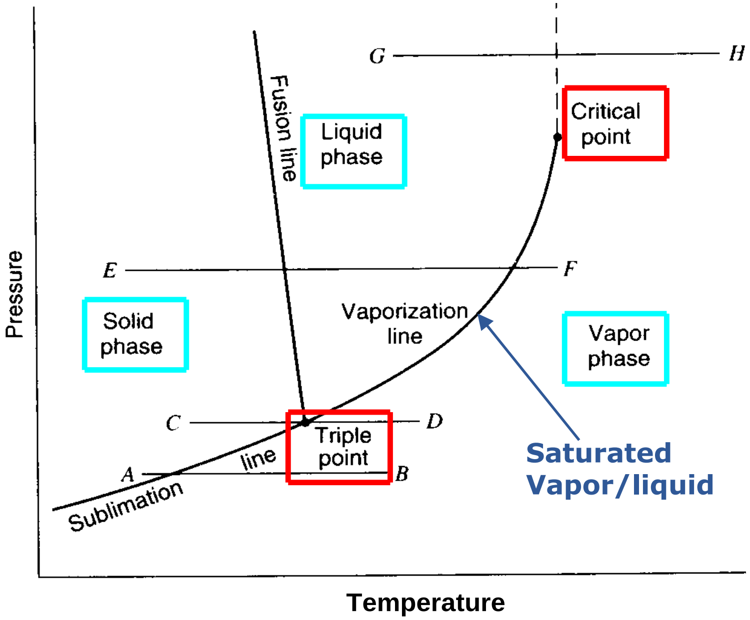




Superconductors needs Cryogens

Cryogenic: for Greek “kryos", which means cold or freezing, and "genes" meaning born or produced.

	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**
Neon	24.6	27.1	44.4
Hydrogen	13.8	20.4	33.2
Helium	**λ-point**	**4.2**	**5.2**



Low Temperature Superconductor operated in Liquid Helium

High temperature Superconductor operated in Liquid Helium or Liquid Nitrogen

Superconductivity Practical Days at CERN

We will measure electrical, magnetic and thermal characteristics of superconducting samples with the purpose of understanding the fundamental characteristics of superconductors.

Experiments will be performed with High Temperature Superconductors and liquid Nitrogen (boiling point of 77 K @ 1 atm)

1. Levitation experiment
2. Critical temperature experiment
3. Zero resistance experiment
4. Critical current experiment

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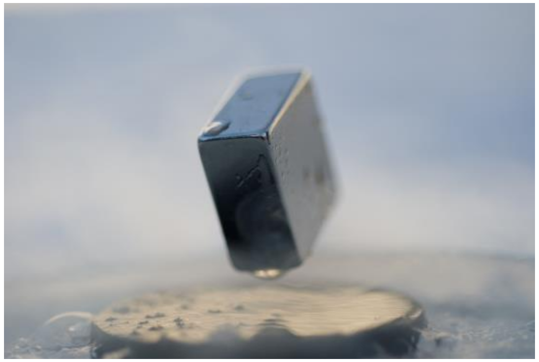
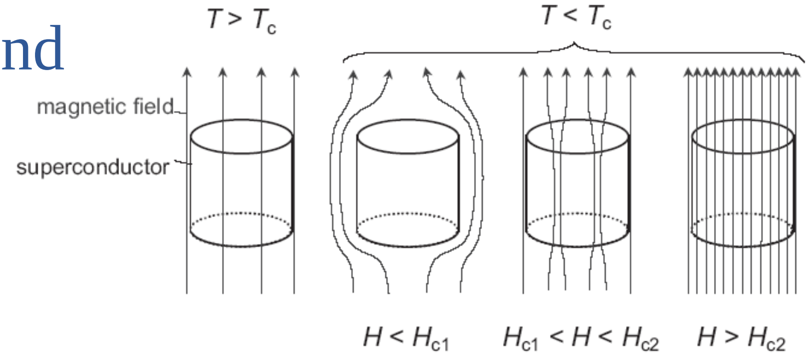
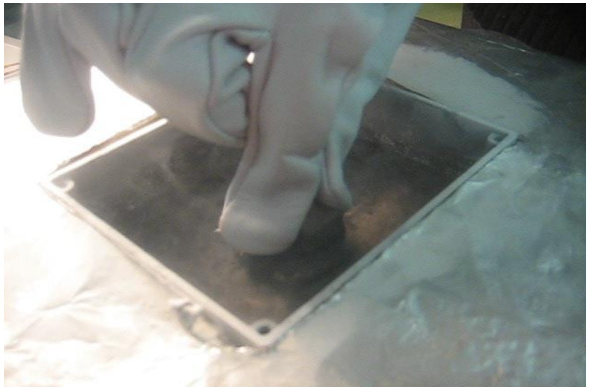
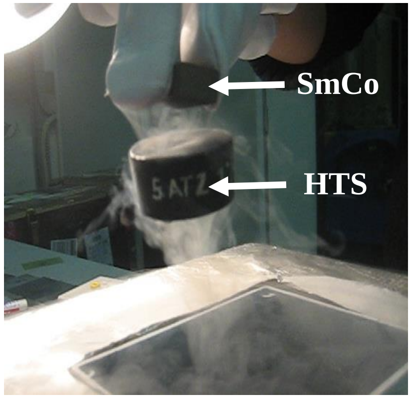


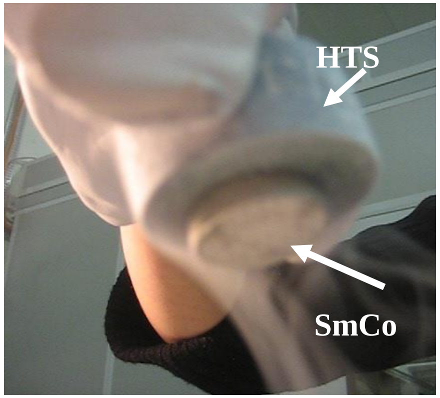
Levitation experiment

- Using HTS materials, nitrogen and permanent magnets you will:
  - Understand the Meissner effect and flux pinning
  - Appreciate the intensity of the levitation force !



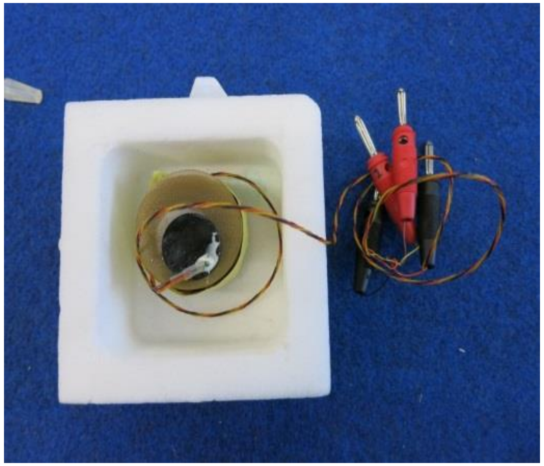


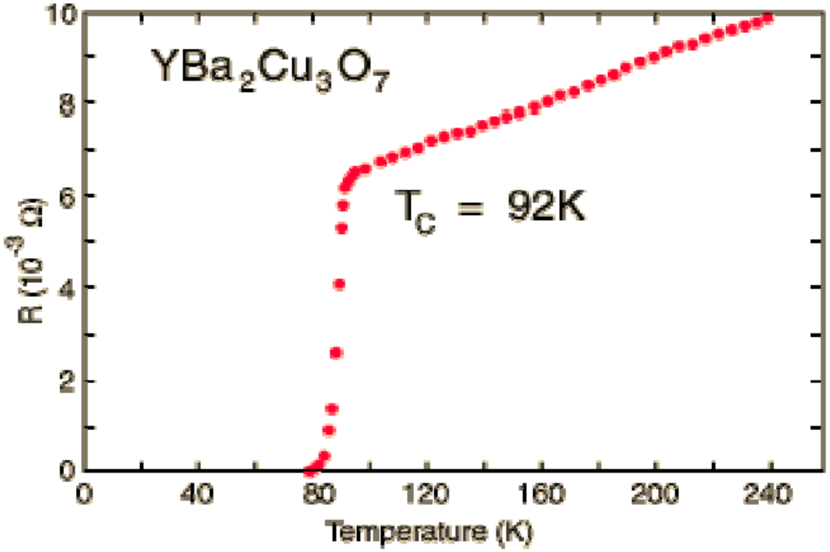




Critical temperature experiment

You will measure the critical temperature of a superconducting sample by using the Meissner effect.

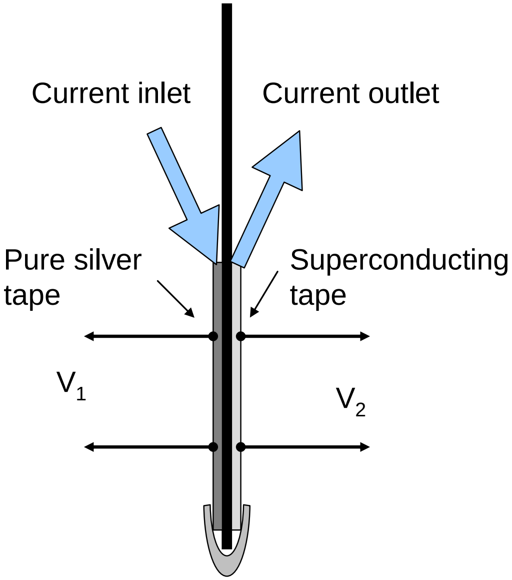


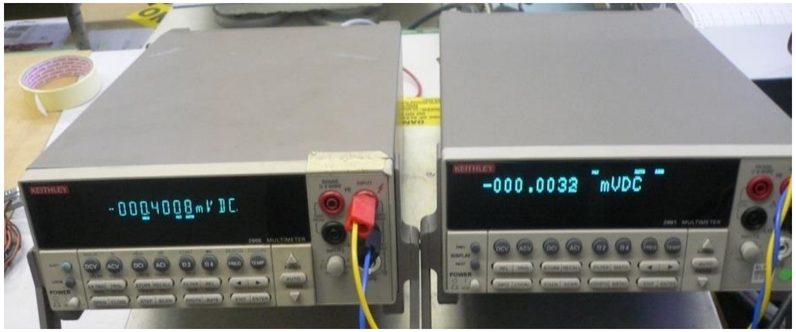


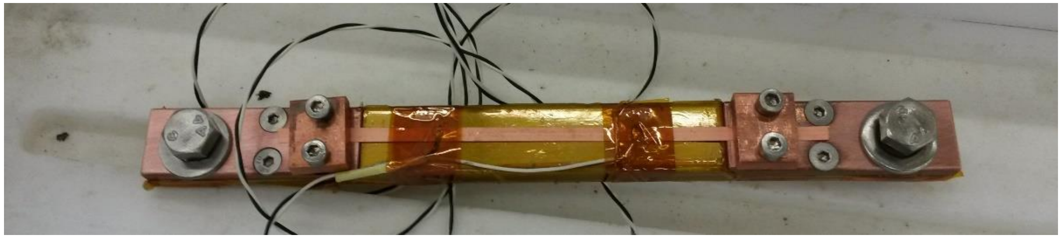
The critical temperature is defined as the temperature measured on the superconductor when the permanent magnet levitating on it comes to complete rest on the superconductor’s surface.

Zero resistance and Ic measurements

- You will experience the zero resistivity of superconducting materials.
- You will measure the resistive transition of HTS tape from Sc state to normal state





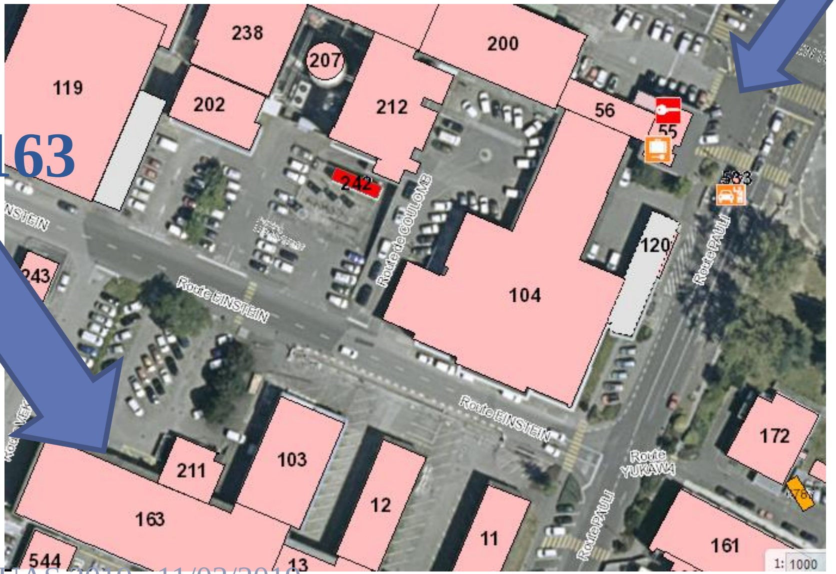


Program and Organization (1/2)

- **Up to 12** participants per day
- Hands-on **practical work** in CERN laboratories
- Guided by **experts**
- **When** ? On the 28th of Feb and 1st of March
- **Where** ? In the Superconductor Laboratory, Building 163

Main entrance

B. 163



Program and Organization (2/2)

Practical work in building 163

Visit of Superconductor Laboratory, Building 163

- **Critical current** of superconductors (strands and cables) at liquid He temperature (1.9 K and 4.2 K, up to 15 T and up to 32-70 kA);
- **Magnetic properties** of superconductors (magnetization curves) at variable temperatures and fields (VSM);
- **Electrical Resistivity** as function of temperature;

Visit Rutherford Cabling facility

Visit of Laboratory, SM 18 :Test stations for Sc magnets

We are looking forward to

working with you at CERN !