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2020 Joint Universities Accelerator School

Superconducting Magnets
Section I

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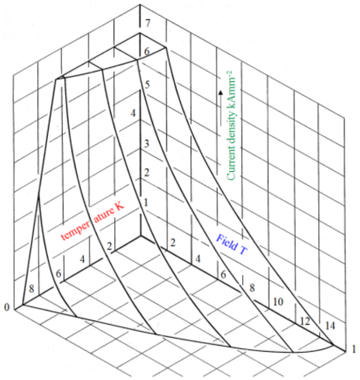
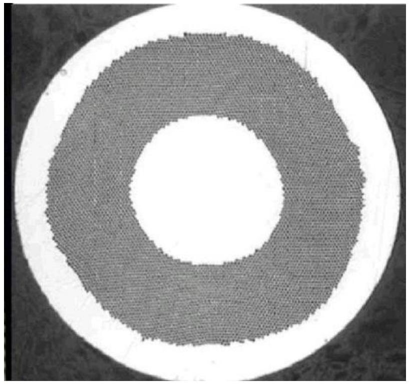
Introduction
Goal of the course

- Overview of **superconducting magnets** for particle accelerators (dipoles and quadrupoles)
  - Description of the components and their function
- From the superconducting material to the full magnet

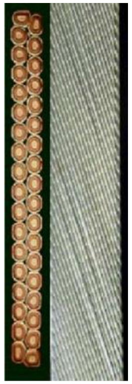
Superconducting material



Superconducting strand

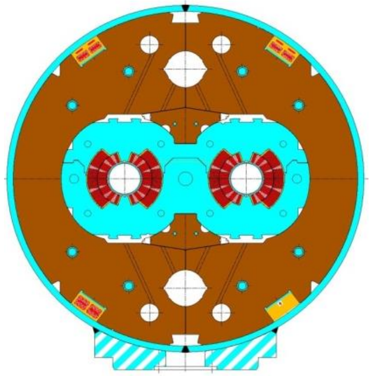


Superconducting cable



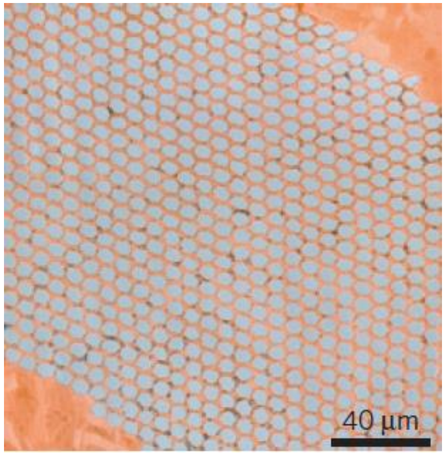
Superconducting coil

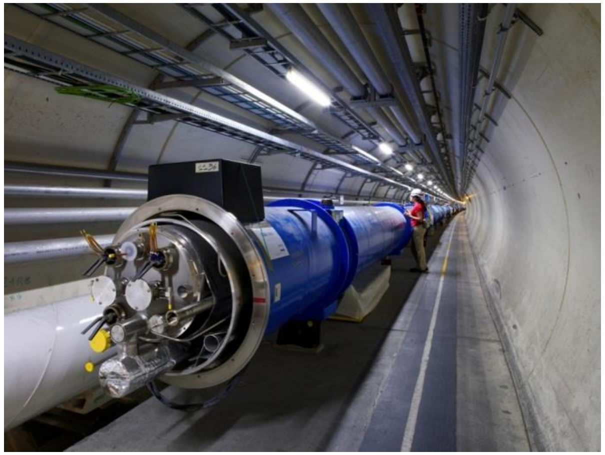
Superconducting magnet



Introduction
Superconducting magnet technology

- Multidisciplinary field: mixture of
  - Chemistry and material science: **superconducting materials**
  - Quantum physics: the key mechanisms of **superconductivity**
  - Classical electrodynamics: **magnet design**
  - Mechanical engineering: **support structures**
  - Electrical engineering: powering of the magnets
  - Cryogenics: keep them **cold**…
- Very different order of magnitudes





Outline

- **Section I**
  - Particle accelerators and magnets
  - Superconductivity and practical superconductors
- **Section II**
  - Magnetic design
- **Section III**
  - Coil fabrication
  - Forces, stress, pre-stress
  - Support structures
- **Section IV**
  - Quench, protection, training

References

- Particle accelerators and magnets
- Superconductivity and practical superconductors

  - K.-H. Mess, P. Schmuser, S. Wolff, "*Superconducting accelerator magnets*", Singapore: World Scientific, 1996.
  - Martin N. Wilson, "*Superconducting Magnets*", 1983.
  - Fred M. Asner, "*High Field Superconducting Magnets*", 1999.

  - P. Ferracin, E. Todesco, S. Prestemon, "*Superconducting accelerator magnets*", US Particle Accelerator School, www.uspas.fnal.gov.
    - **Units 2 by E. Todesco**

  - A. Devred, "*Practical low-temperature superconductors for electromagnets*", CERN-2004-006, 2006.

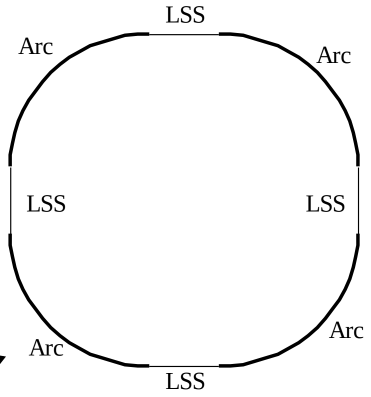
  - Presentations from Luca Bottura and Martin Wilson

Particle accelerators and magnets

by E. Todesco

- Principle of synchrotrons
  - Driving particles in the same accelerating structure several times
- Electro-magnetic field accelerates particles

$$\vec{F} = e\vec{E} \longrightarrow$$



- Magnetic field steers the particles in a ~circular orbit

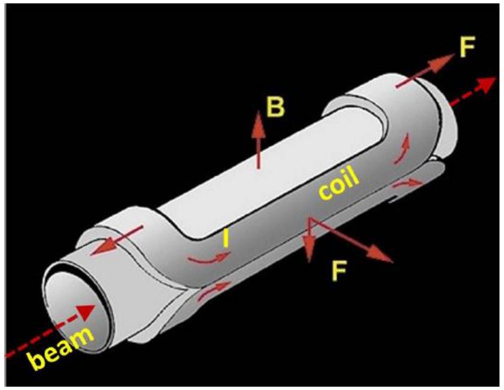
$$\vec{F} = e\vec{v} \times \vec{B}$$

- Particle accelerated → energy increased → magnetic field increased (“synchro”) to keep the particles on the same orbit of curvature ρ

$$\overset{\uparrow}{p} = e\overset{\uparrow}{B}\underset{\searrow\ \text{Constant}}{\rho}$$

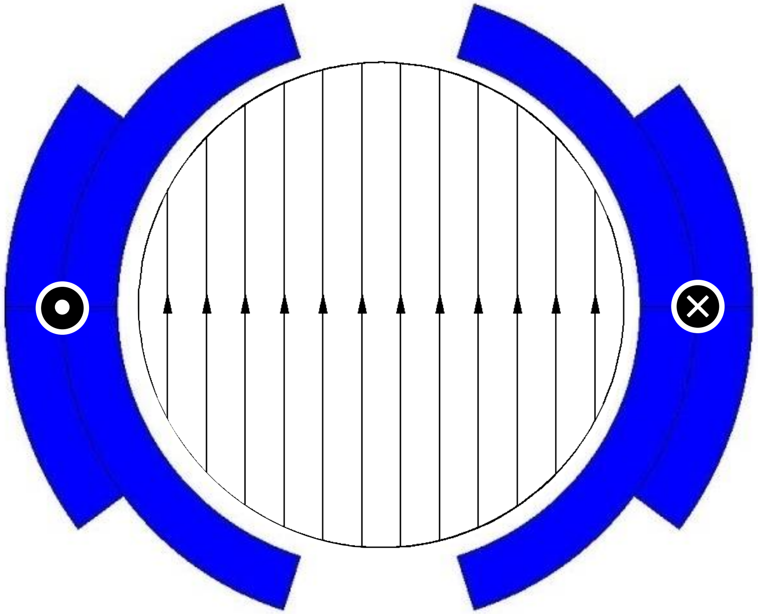
Particle accelerators and magnets
Dipoles

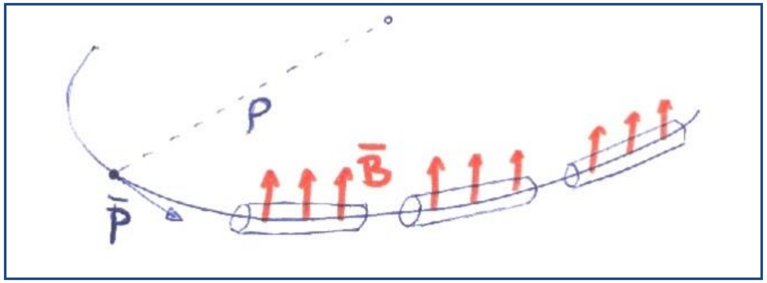
- Main field components is B_y
  - Perpendicular to the axis of the magnet z
- Electro-magnets: field produced by a current (or current density)



$$\boxed{B_y = -\frac{\mu_0 J_0}{2}(r_{out} - r_{in})}$$

- **Magnetic field steers (bends) the particles in a ~circular orbit**



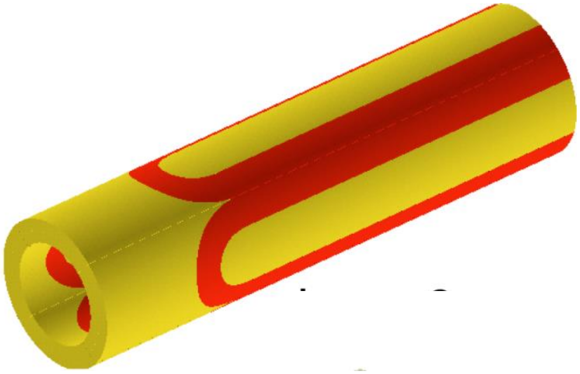


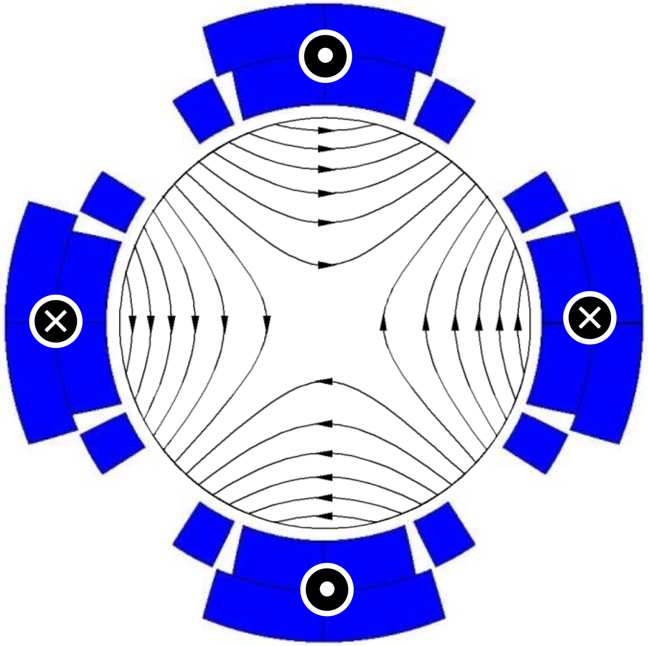
by E. Todesco

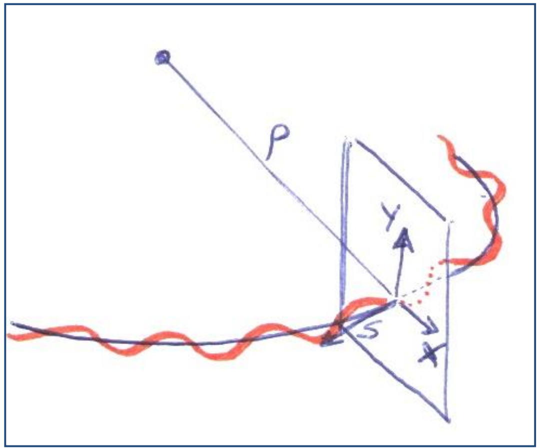
$$\boxed{p = eB\rho}$$

Particle accelerators and magnets
Quadrupoles

- The force necessary to stabilize linear motion is provided by the quadrupoles
  - They provide a field
    - equal to zero in the center
    - increasing linearly with the radius
- They act as a spring: **focus the beam**
- Prevent protons from **falling** to the bottom of the aperture due to the **gravitational force**
  - it would happen in less than 60 ms





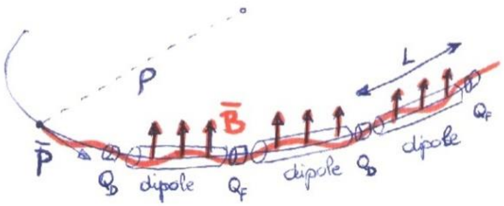


by E. Todesco

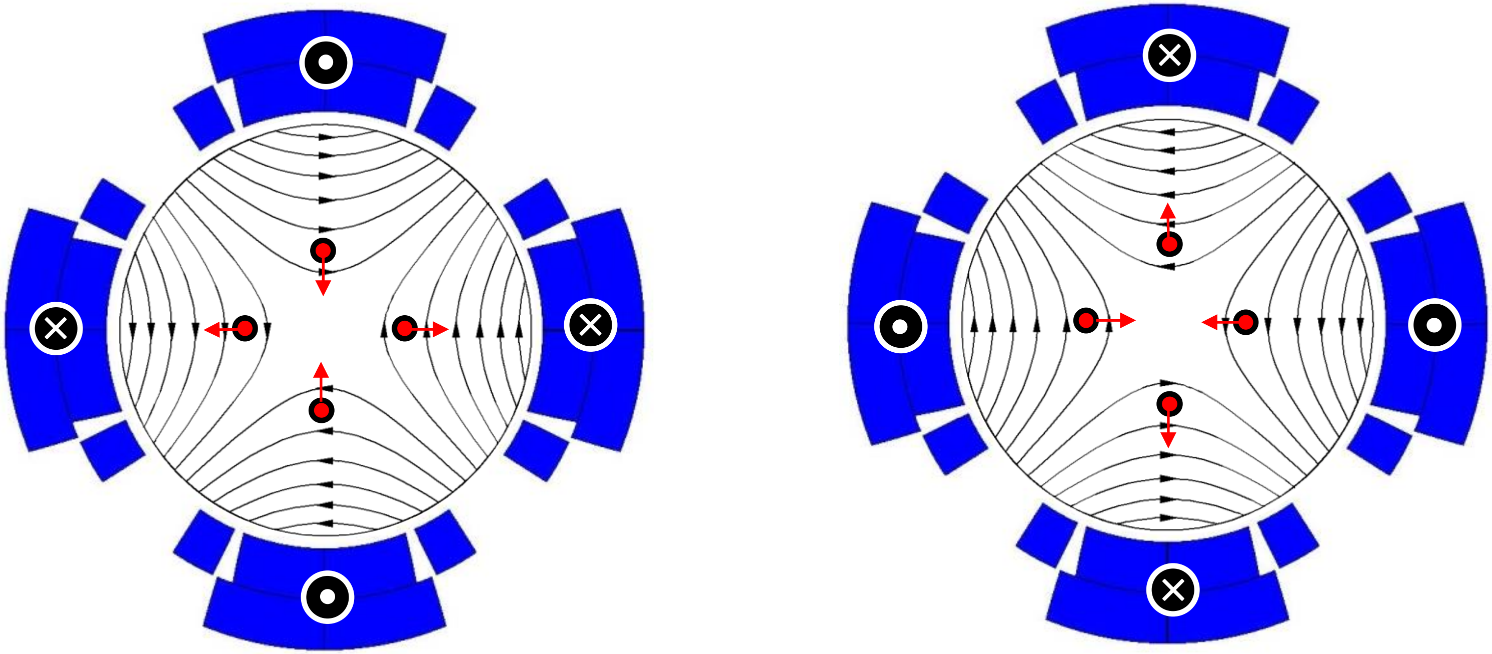
$$G = \frac{B_y}{r} = -\frac{\mu_0 J_0}{2} \ln \frac{r_{out}}{r_{in}}$$

Particle accelerators and magnets
Quadrupoles

- A typical accelerator structure is the FODO cell
  - Alternating quadrupoles spaced by length *L* of similar gradient
- One can prove that this gives positive focusing in both transverse planes

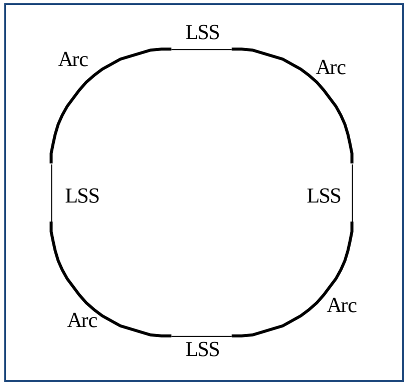


by E. Todesco

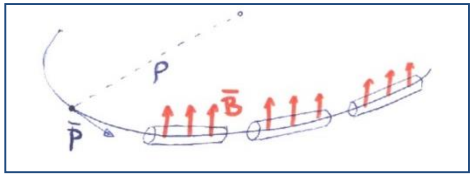


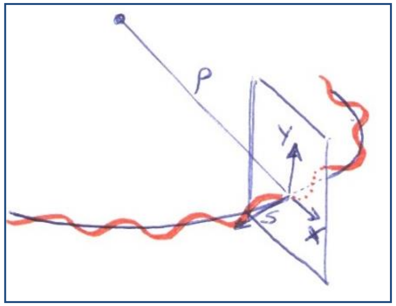
Particle accelerators and magnets

- Dipoles: the larger B, the larger the energy
- Quadrupoles: the larger B, the larger the focusing strength
- For an electro-magnet, the larger B, the larger must be J

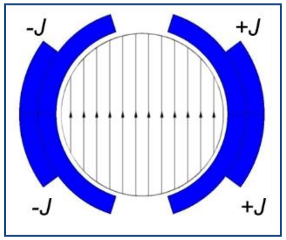


$$p = eB\rho$$

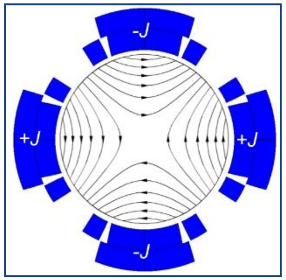




$$B_y = -\frac{\mu_0 J_0}{2}(r_{out} - r_{in})$$



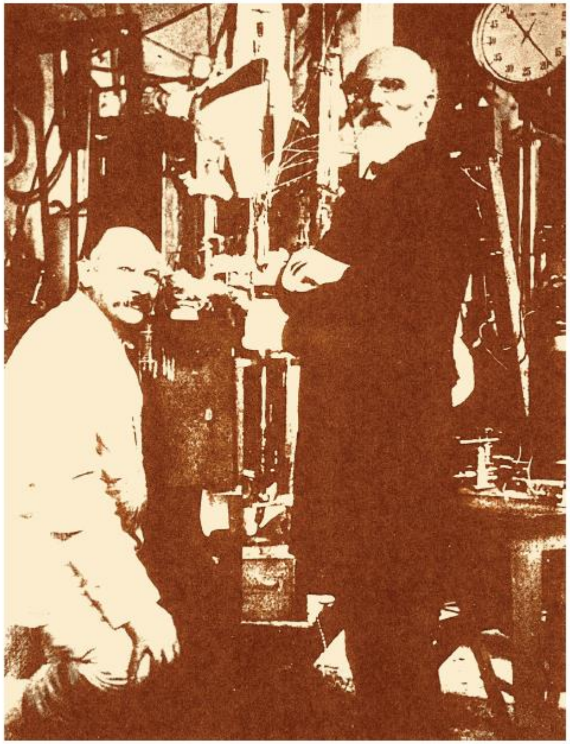
$$G = \frac{B_y}{r} = -\frac{\mu_0 J_0}{2}\ln\frac{r_{out}}{r_{in}}$$

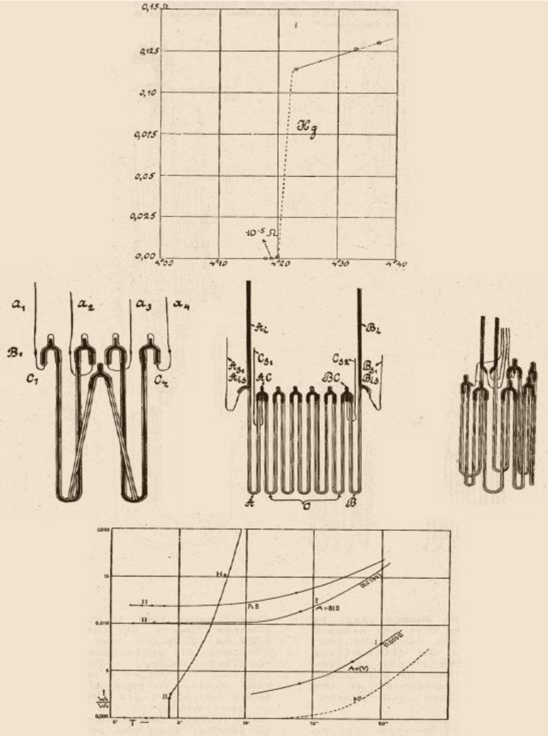


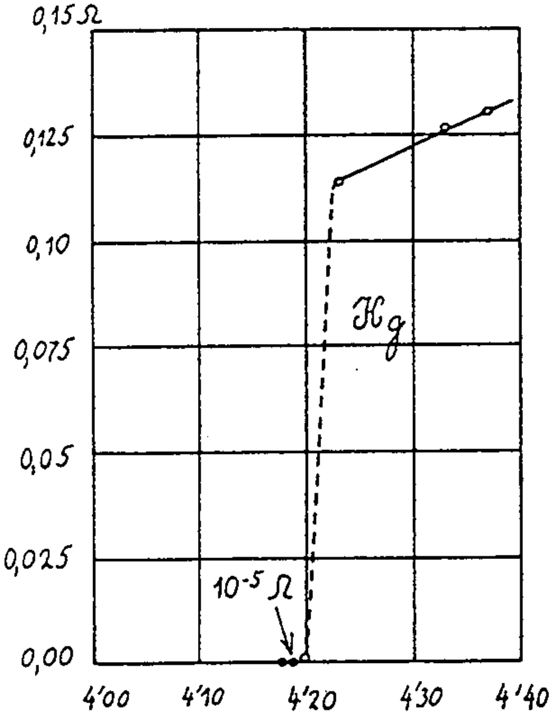
- In normal conducting magnets, J ~ 5 A/mm^2
- In superconducting magnets, J$_e$ ~ 600-700 A/mm^2

Superconductivity
The discovery

- Superconductivity was discovered in 1911 by Kammerling-Onnes who observed that the resistance of a mercury wire disappeared (immeasurably small value) at 4.2 K
  - Not just "little" resistance - truly **ZERO resistance**

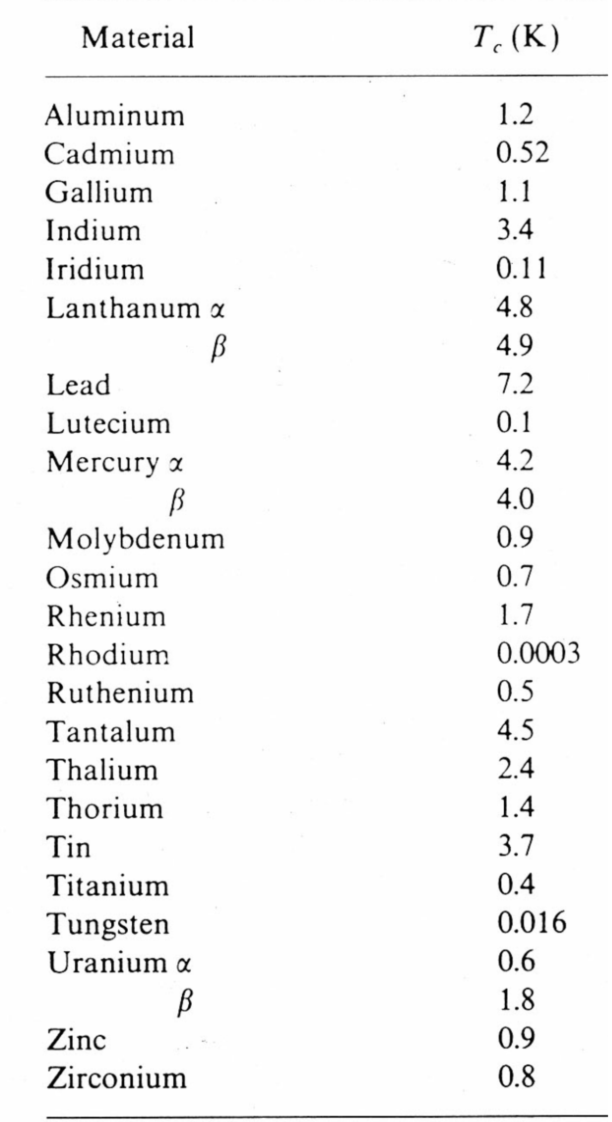






Superconductivity
Critical temperature

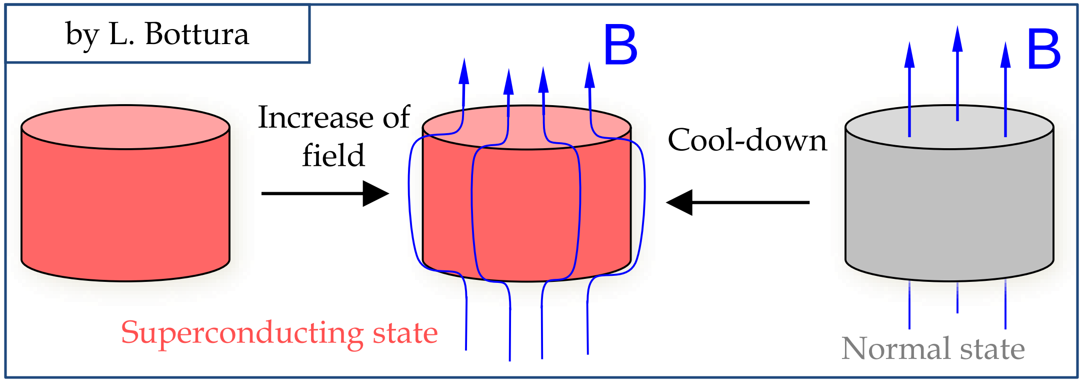
- The temperature at which the transition takes place: **critical temperature T_c**
- Below $T_{c,}$ → no resistance
- Observed in may materials
  - but not in the typical best normal conductors (copper, silver, gold…)
- At a temperature > T_c, a superconductor is a very poor conductor
- 2 kinds of superconductors
  - **Type I and Type II**
    - Different behaviour with magnetic field



Material	T_c (K)
Aluminum	1.2
Cadmium	0.52
Gallium	1.1
Indium	3.4
Iridium	0.11
Lanthanum α	4.8
β	4.9
Lead	7.2
Lutecium	0.1
Mercury α	4.2
β	4.0
Molybdenum	0.9
Osmium	0.7
Rhenium	1.7
Rhodium	0.0003
Ruthenium	0.5
Tantalum	4.5
Thalium	2.4
Thorium	1.4
Tin	3.7
Titanium	0.4
Tungsten	0.016
Uranium α	0.6
β	1.8
Zinc	0.9
Zirconium	0.8

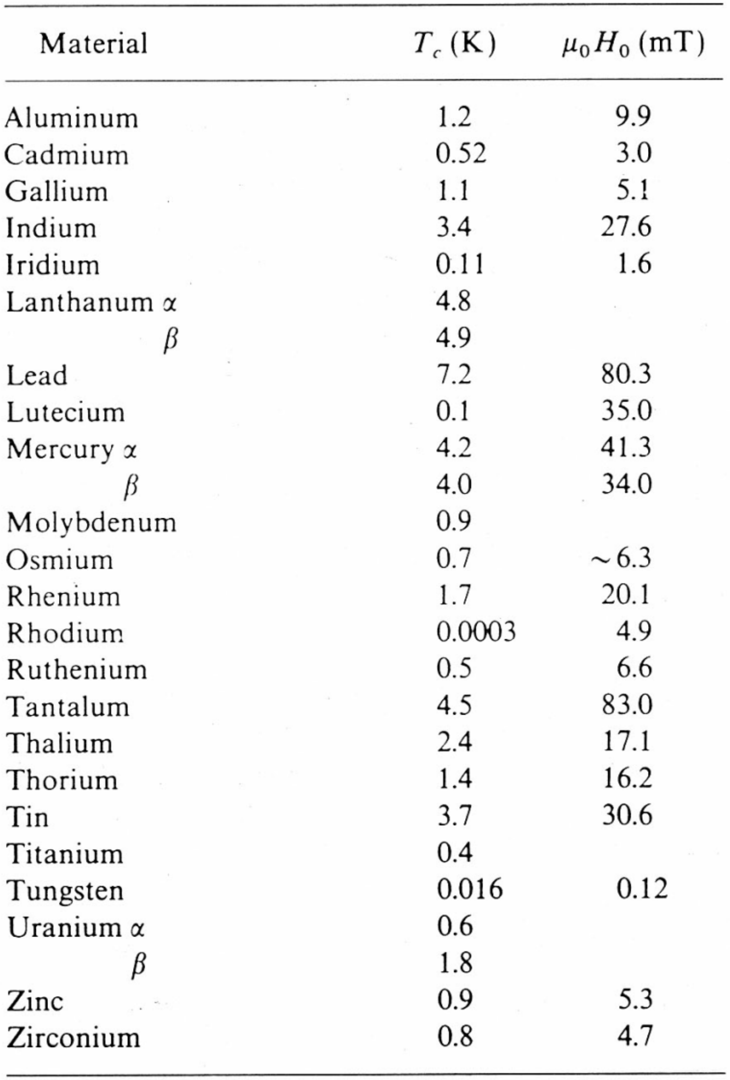
Superconductivity
Type I superconductors

- Meissner-Ochsenfeld effect (1933)
- Perfect diamagnetism
  - With $T<T_c$ magnetic field is expelled
- But, the B must be < **critical field B_c**
  - Otherwise superconductivity is lost



by L. Bottura

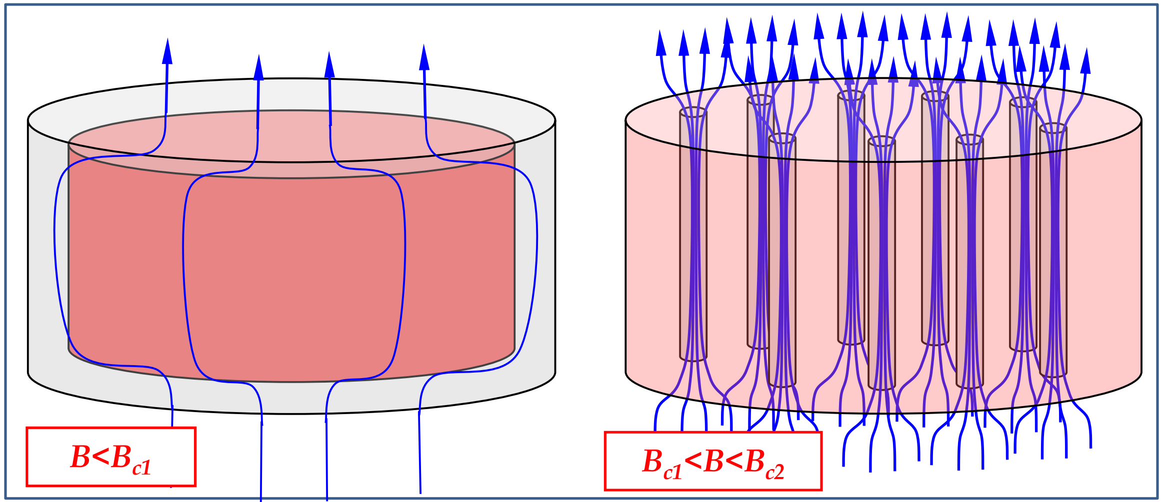
- Unfortunately, first discovered superconductors (**Type I**) with **very low B_c** ($\leq$ 0.1 T)
  - not practical for electro-magnets



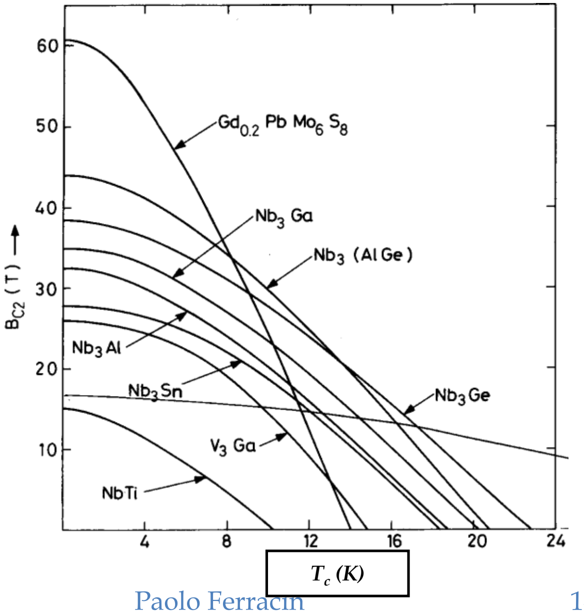
Material	T_c (K)	$\mu_0 H_0$ (mT)
Aluminum	1.2	9.9
Cadmium	0.52	3.0
Gallium	1.1	5.1
Indium	3.4	27.6
Iridium	0.11	1.6
Lanthanum α	4.8	
β	4.9	
Lead	7.2	80.3
Lutecium	0.1	35.0
Mercury α	4.2	41.3
β	4.0	34.0
Molybdenum	0.9	
Osmium	0.7	~6.3
Rhenium	1.7	20.1
Rhodium	0.0003	4.9
Ruthenium	0.5	6.6
Tantalum	4.5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

Superconductivity
Type II superconductors

- So, for 40-50 years, superconductivity was a research activity
- Then, in the 50's, **type II superconductors**
  - Between B_{c1} and B_{c2} : <u>mixed phase</u>
    - *B* penetrates as flux tubes: *fluxoids*
      - with a flux of $\phi_o = h/2e = 2 \cdot 10^{-15}\ Wb$
- Much higher fields and link between T_c and B_{c2}



by L. Bottura

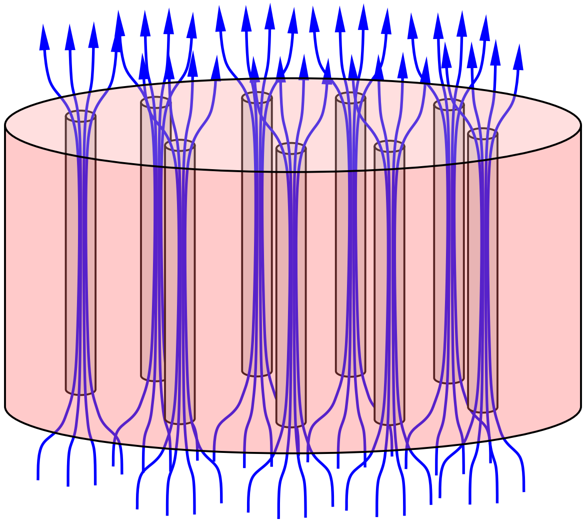


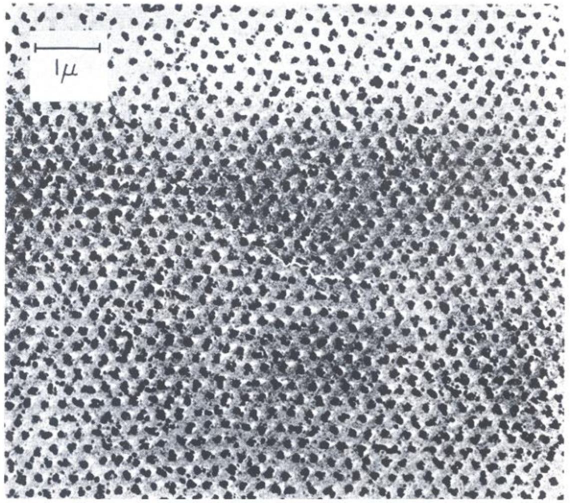
Superconductivity
Type II superconductors

- Field penetrated in the form of flux tubes (*fluxoids*), each with a flux of

$$\phi_o = h/2e = 2 \cdot 10^{-15}\ Wb$$

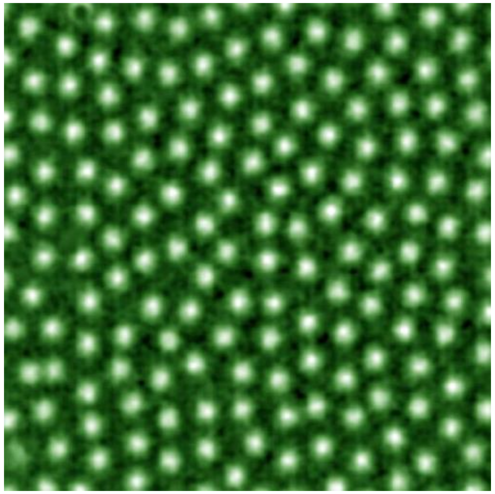
- Observed both in a photo by Essmann & Träuble (1967) and with magneto-optical imaging technique by Oslo Univerisity





PATTERN OF INDIVIDUAL FLUXONS IN A TYPE-II SUPERCONDUCTOR

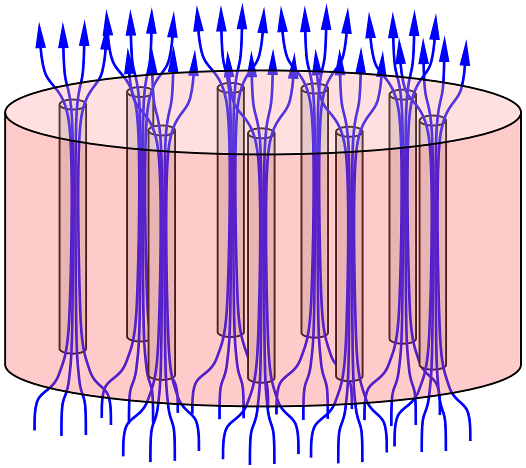
This photograph shows the triangular pattern of fluxons in a type-II superconductor (see Chapter 12). The pattern is revealed by allowing very small (500 Å) ferromagnetic particles to settle on the surface of a magnetized specimen (lead–indium alloy). The particles locate themselves where the magnetic flux intersects the surface.



http://www.mn.uio.no/fysikk/english/research/groups/amks/superconductivity/

Superconductivity
Hard superconductors

- …but, if a current is passed through the type II superconductor under a field **>B_{c1}**
  - Lorentz force on the fluxoids
    - ***F = J x B***

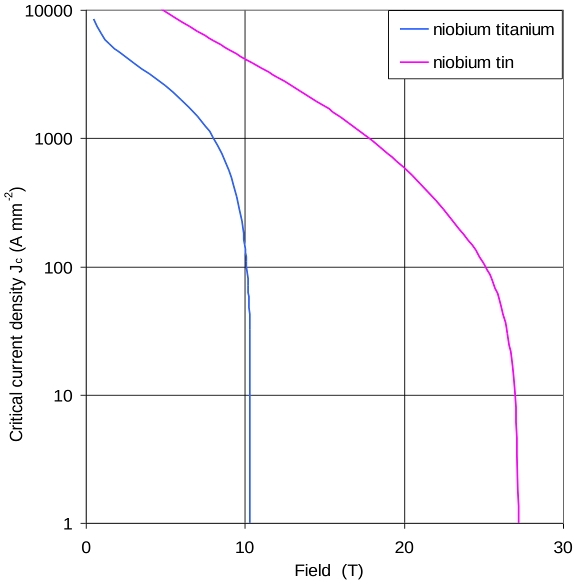


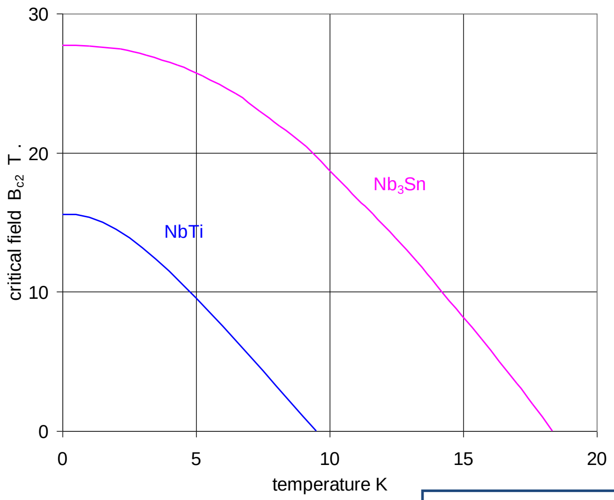
- The force causes a **motion** of tubes
  - Flux motion (dB/dt)→ voltage (V)→ dissipation ($V \cdot I$)

- The fluxoids are therefore locked in **pinning centers**
  - Defects or impurities in the structure: precipitates or grain boundaries
    - Produced during fabrication

Superconductivity
Hard superconductors

- The pinning centres exert a pinning force F_p
- As long as $F_p \geq J \times B$
  - No flux motions (flux tubes pinned) → no dissipation
- The critical current density of the superconductor J_c is the current density at which, for a given B and at a given T the pinning force is exceeded by the Lorentz force
- So, there is a **mutual link** between maximum J, B, and T

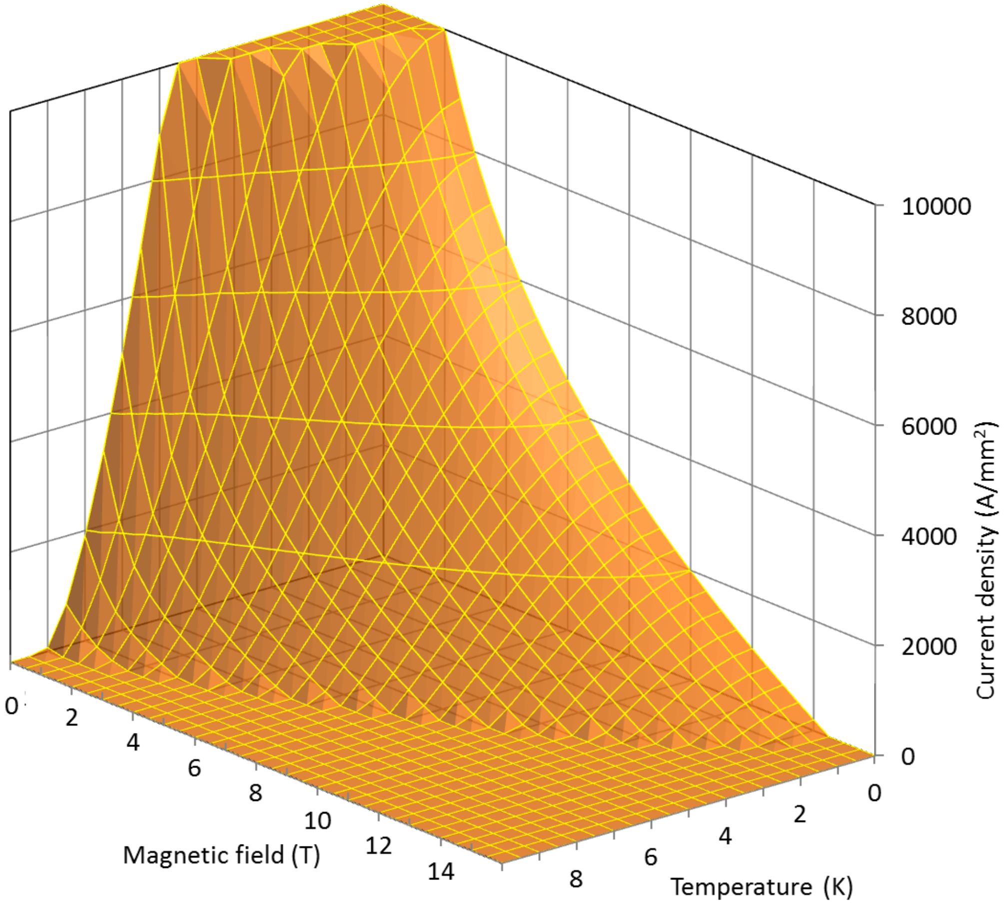




by M. Wilson

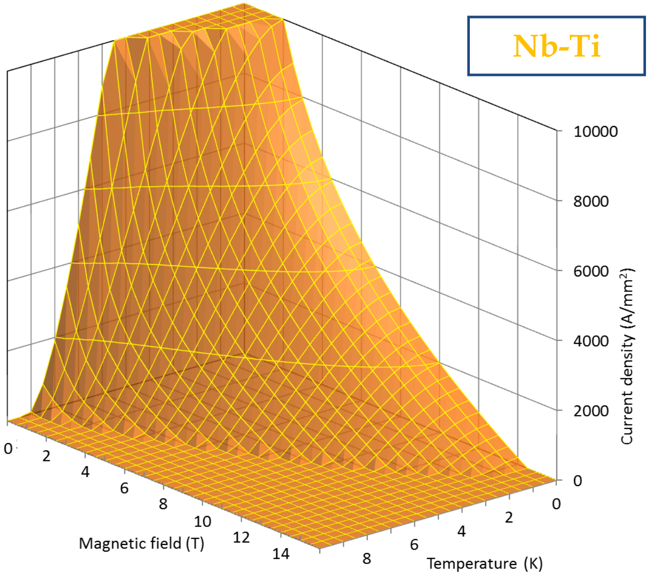
Superconductivity
Critical surface

- A type II material is supercond. below the **critical surface** defined by
  - Critical temperature *Tc*
    - Property of the material
  - Upper critical field B_{c2}
    - Property of the material
  - Critical current density J_c
    - Hard work by the producer

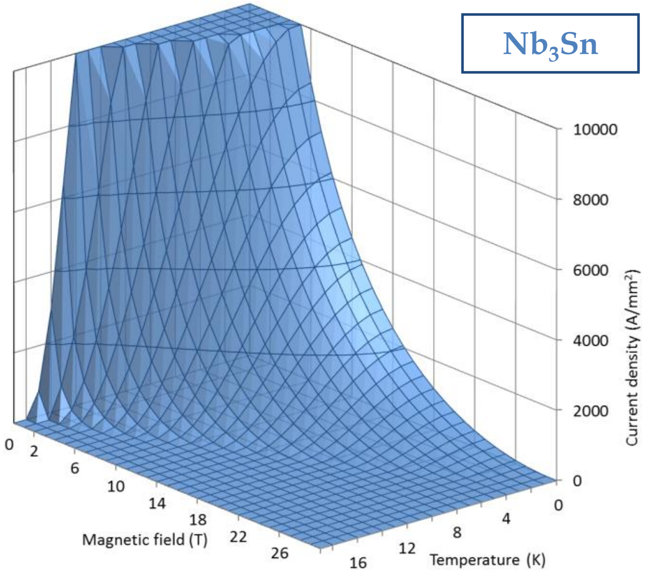


Superconductivity
Materials

- **Nb_3Sn** and **Nb-Ti**, discovered in 1954 and 1961, are the most commonly used type II superconductors (80-90% of all devices).
- Since their critical temperature T_c is 9 K (for Nb-Ti) and 18 K (for Nb_3Sn), they are defined as low T superconductors.
  - High temperature superconductors (HTS) have a T_c up to 80-120 K.



Nb-Ti

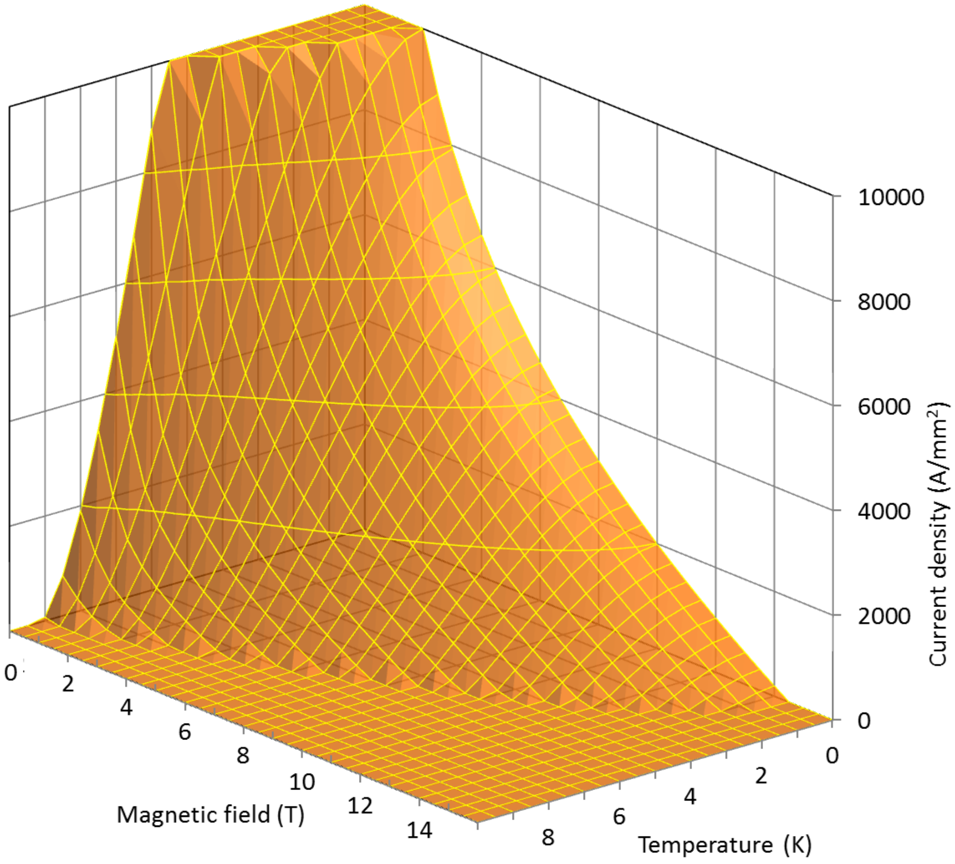


Nb_3Sn

Superconductivity
Nb-Ti

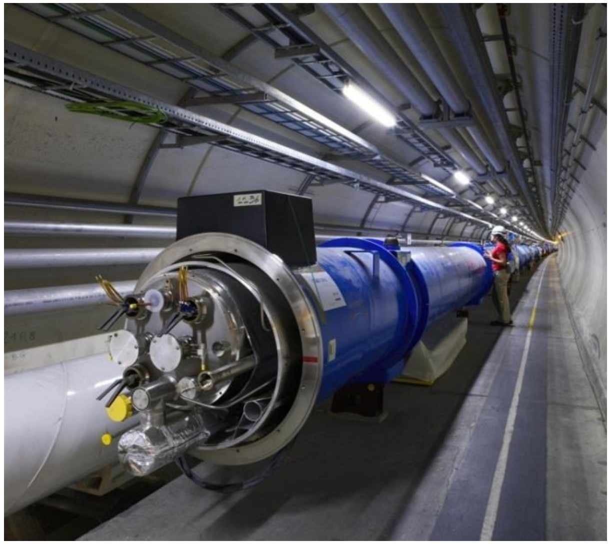
- Nb and Ti combine in a ductile alloy (called β phase)
  - Easy to process by extrusion and drawing techniques.

- T_c and B_{C2} depend on Ti content: the optimal is 46.5-47 in weight %.
  - T_c is ~**9.2 K** at 0 T.
  - B_{C2} is ~**14.5 T** at 0 K.



- The critical current J_c depends on microstructure
  - Cold works and heat treatments form **α-Ti** phase for flux pinning

Superconductivity
Nb-Ti



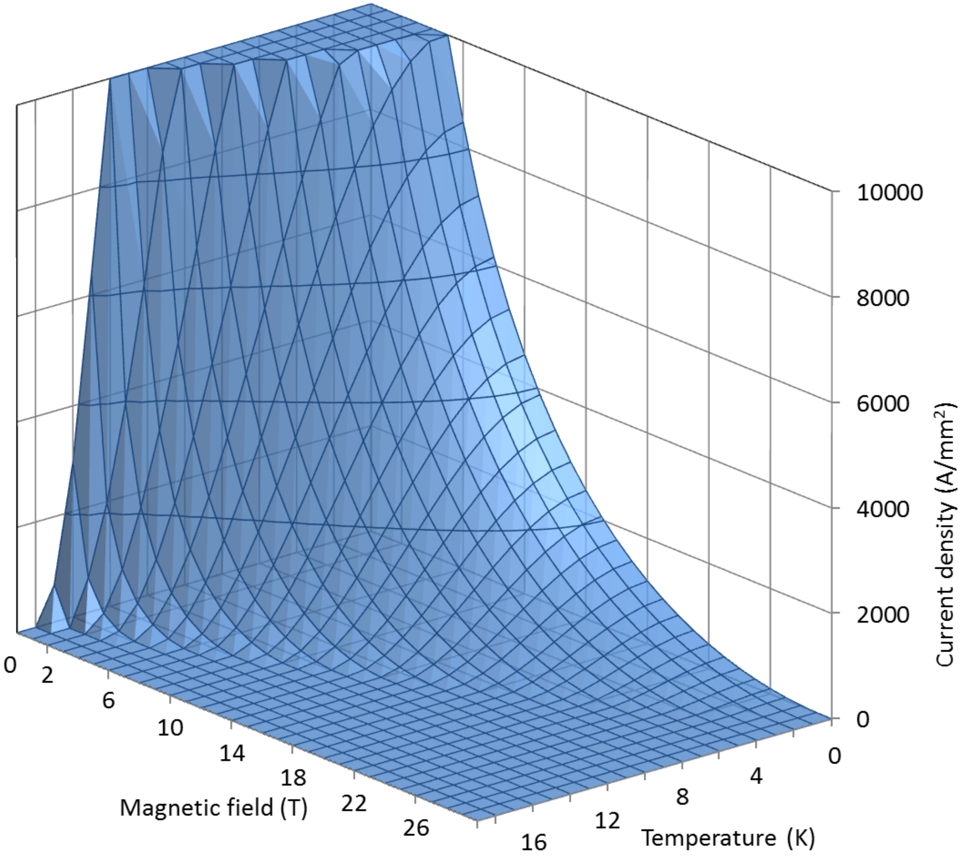
- Most widely used superconductor
- Implemented on large scale for the first time in the the **Tevatron** accelerator, built at Fermilab in the early 80s
- In **High Energy Physics**, used also for all the post-Tevatron accelerators
- Other important applications
  - **MRI /NMR** magnets
  - **Fusion magnets** (Tore Supra, France).

- The cost is ~ 200 US $ per kg of wire (about 1 euro per m of strand)

Superconductivity
Nb_3Sn

- Nb and Sn can form an intermetallic compound from the A15 family (like Nb_3Al).

- T_C and B_{C2} depend on Sn content: the optimal is 20-25 in weight%.
  - T_C is ~**18 K** at 0 T
  - B_{C2} is ~**28 T** at 0 K

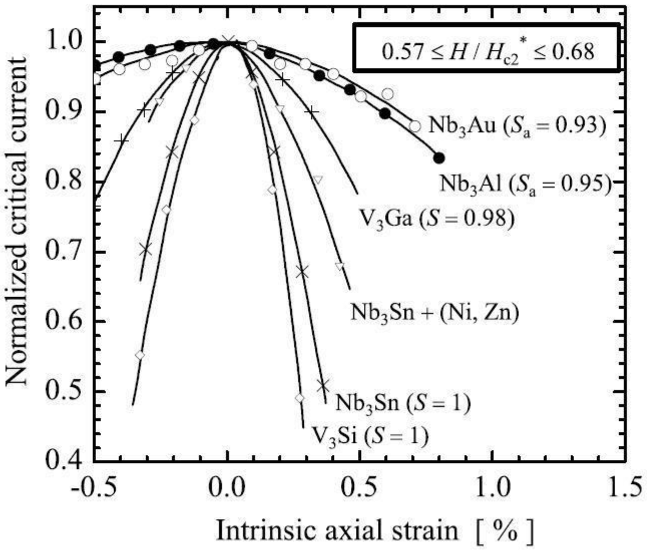


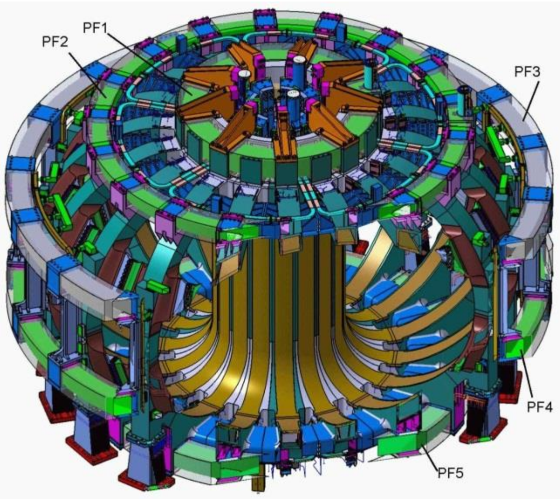
- The critical current J_c depends on the micro (grain) structure
  - High J_c obtained with grains from 30 to 300 nm

Superconductivity
Nb_3Sn

- Nb_3Sn is **brittle**
  - Cannot be extruded as Nb-Ti.
  - Its formation must occur only at the end of the cable and/or coil fabrication process.
- In addition, it is **strain sensitive**
  - critical parameters ← → applied strain
- Used in
  - **NMR**, with field of about 20 T
  - Model coils for **ITER**
  - High energy physics (**R&D**)
- The cost is approximately ~1500 US $ per kg of wire.
  - ~5 euro per m of strand

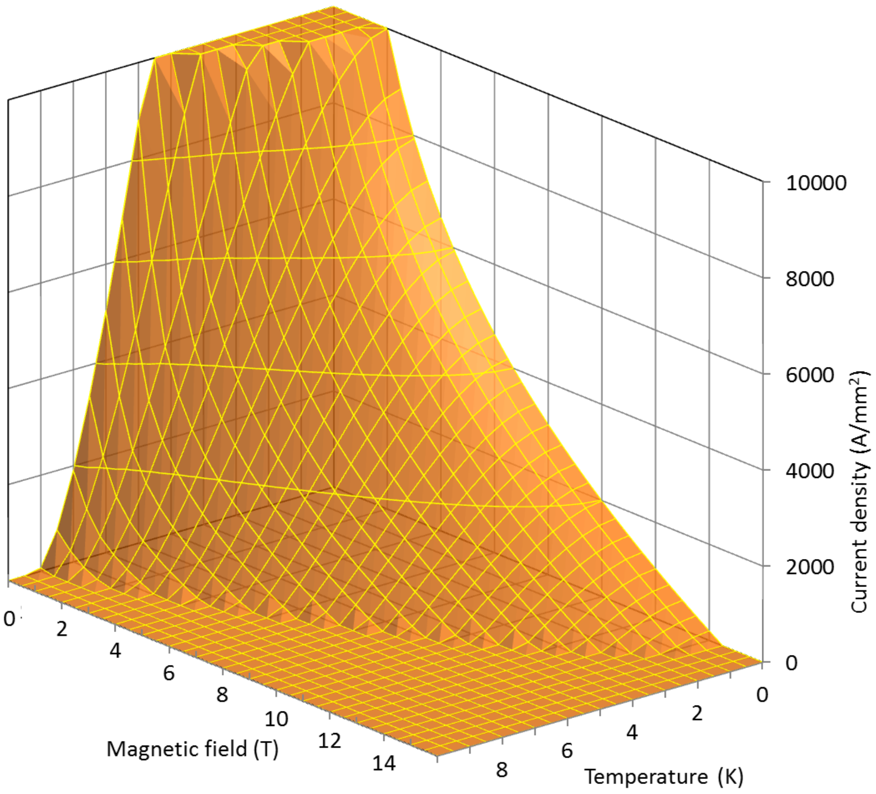
by A. Godeke



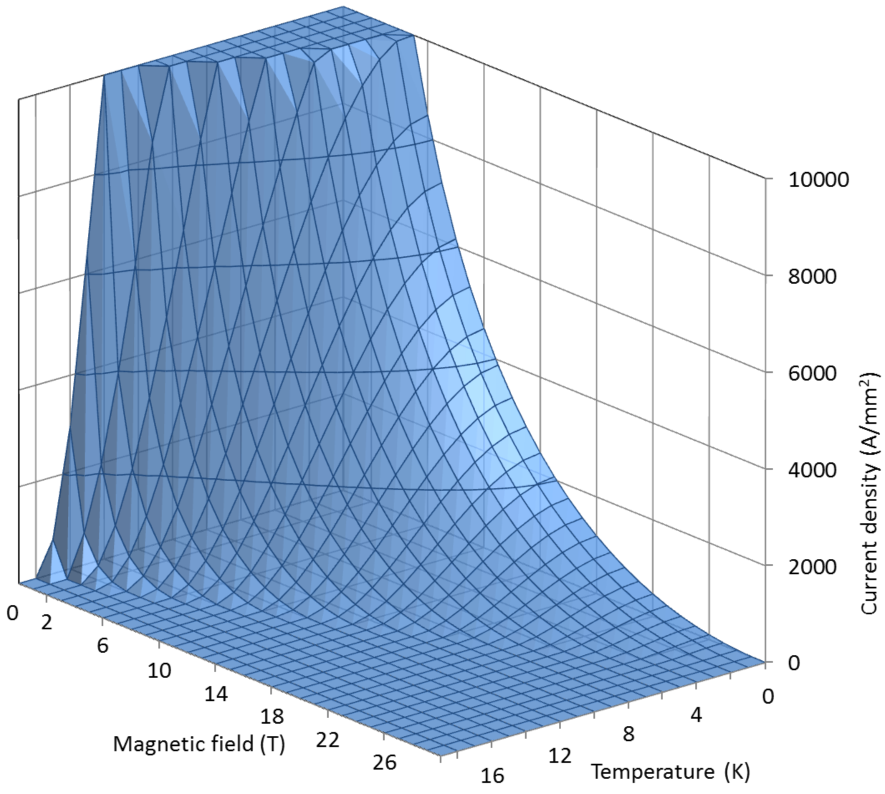


Superconductivity
Nb-Ti vs. Nb_3Sn

Nb-Ti

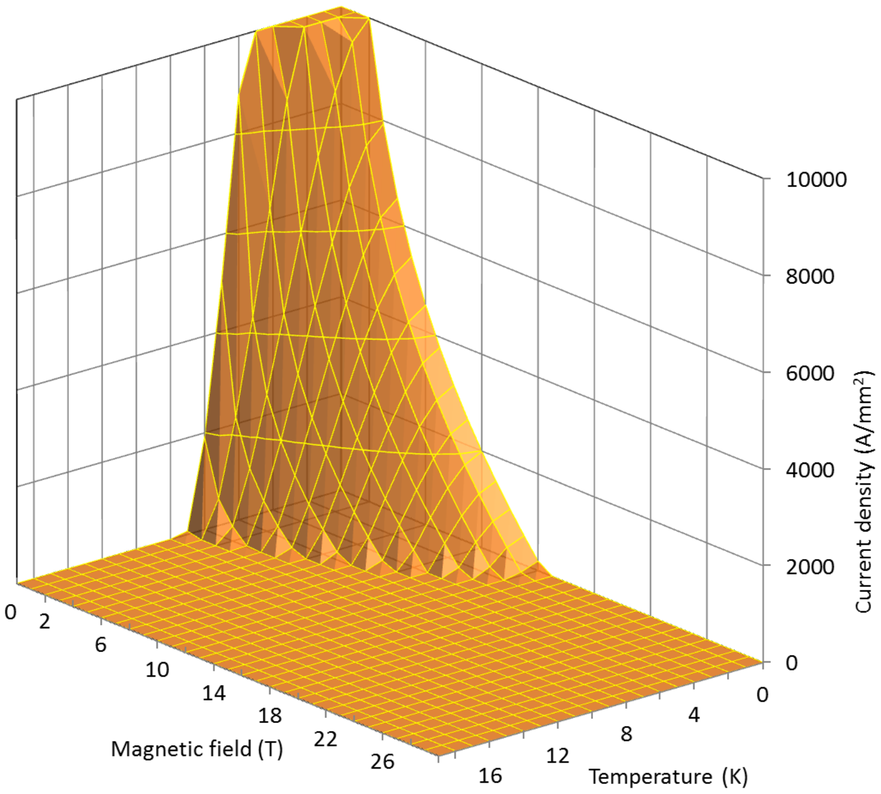


Nb_3Sn

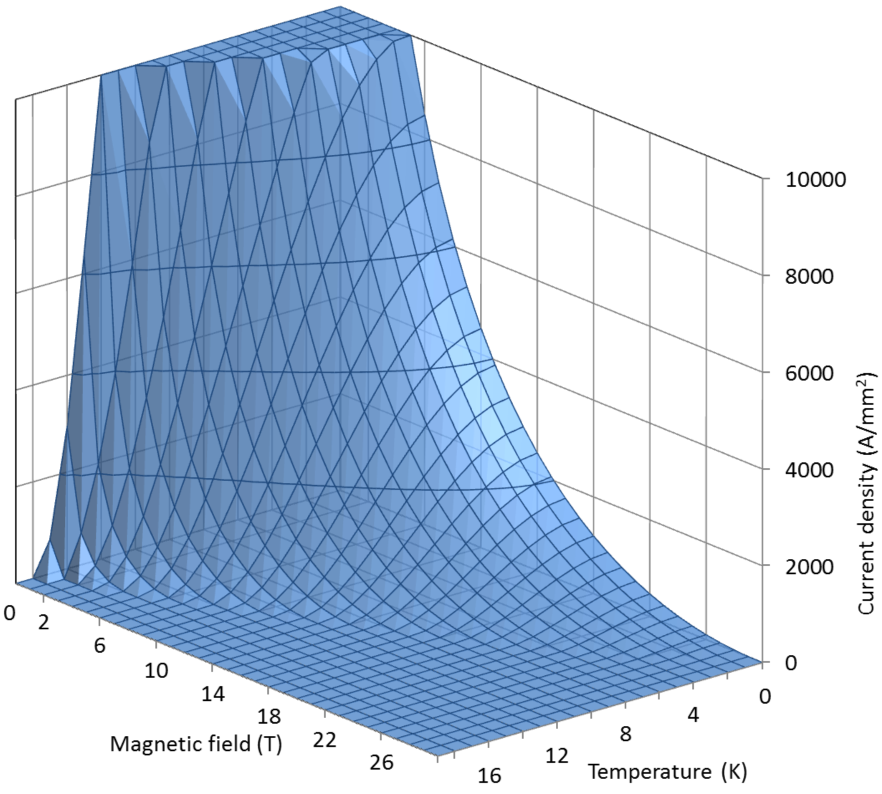


Superconductivity
Nb-Ti vs. Nb_3Sn

Nb-Ti

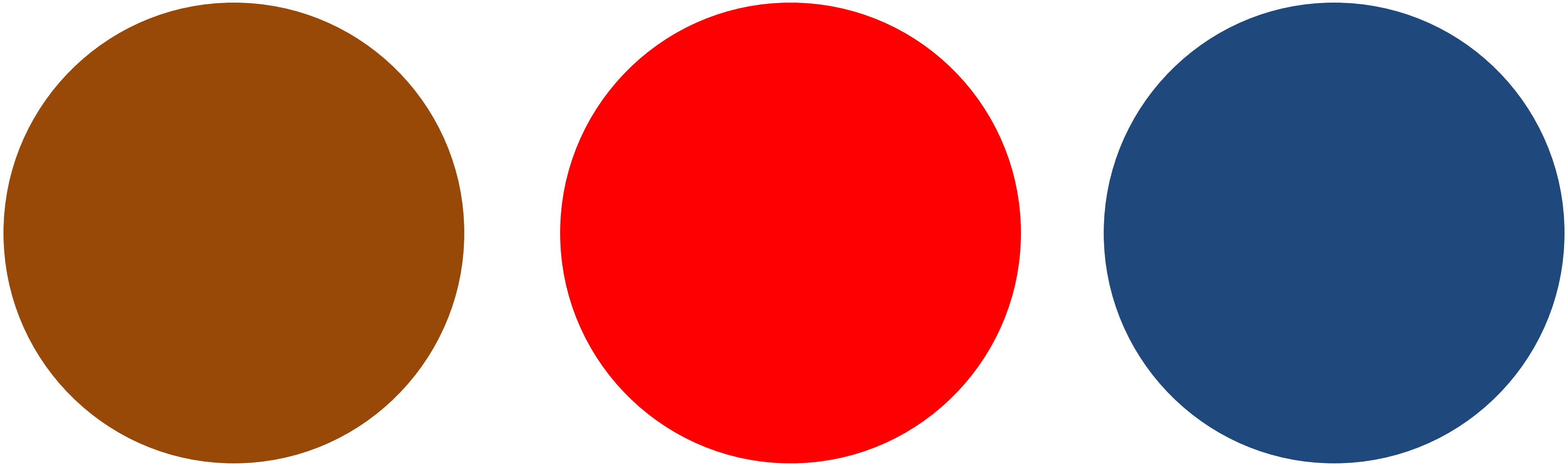


Nb_3Sn



Superconductivity from Cu to Nb$_3$Sn

- Typical operational conditions (0.85 mm diameter strand)

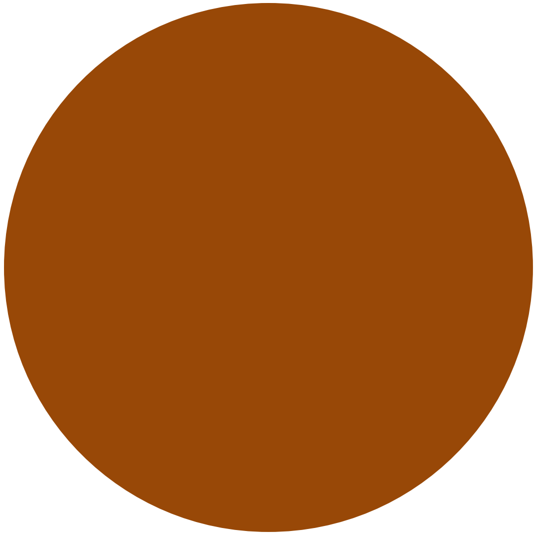


Cu	Nb-Ti	Nb$_3$Sn
$J_e \sim 5$ A/mm^2	**$J_e \sim 600\text{-}700$ A/mm^2**	**$J_e \sim 600\text{-}700$ A/mm^2**
$I \sim 3$ A	**$I \sim 300\text{-}400$ A**	**$I \sim 300\text{-}400$ A**
$B = 2$ T	**$B = 8\text{-}9$ T**	**$B = 12\text{-}13$ T**

Practical superconductors

- Typical operational conditions (0.85 mm diameter strand)

Cu

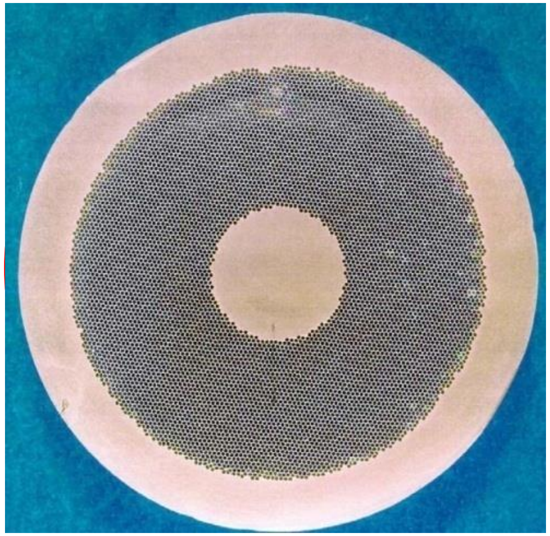


J_e ~ 5 A/mm^2

I ~ 3 A

B = 2 T

Nb-Ti

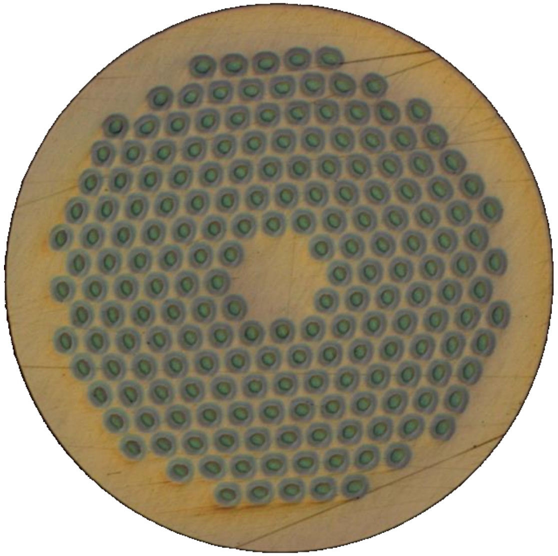


J_e ~ 600-700 A/mm^2

I ~ 300-400 A

B = 8-9 T

Nb_3Sn



J_e ~ 600-700 A/mm^2

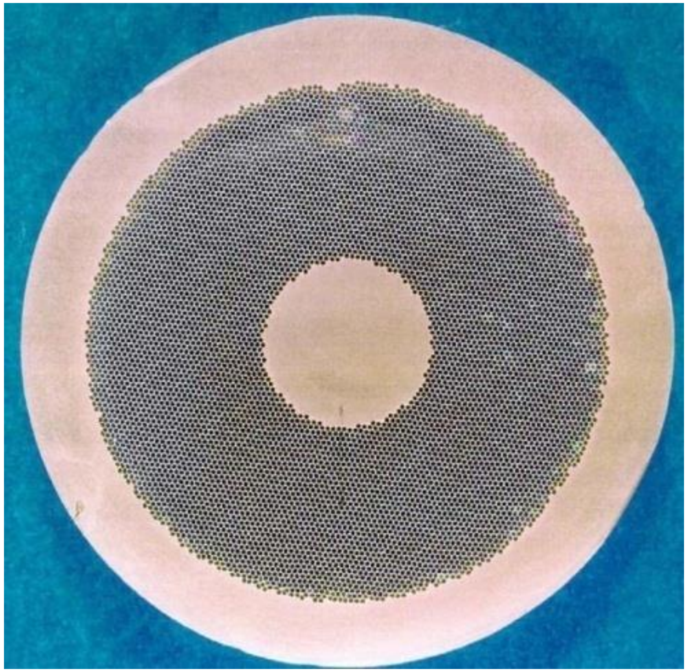
I ~ 300-400 A

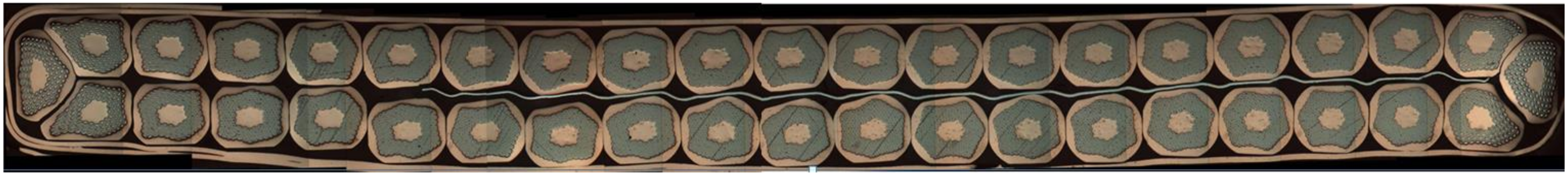
B = 12-13 T

Practical superconductors
Introduction

- Superconducting materials are produced in small filaments and surrounded by a stabilizer (typically copper) to form a *multi-filament wire* or *strand*.

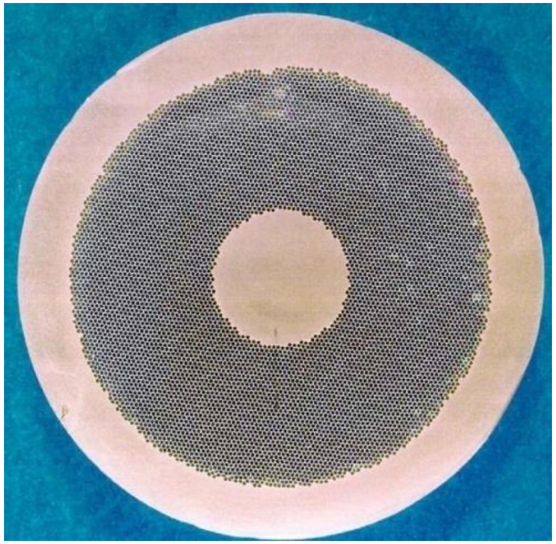
- A superconducting cable is composed by several wires: *multi-strand cable*.

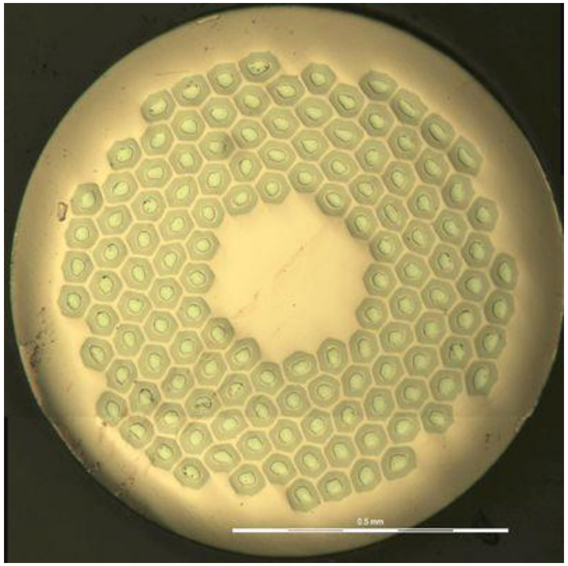




Practical superconductors
Multi-filament wires motivations

- The superconducting materials used in accelerator magnets are
  - subdivided in filaments of small diameters
    - to reduce magnetic instabilities called **flux jumps**
    - to minimize field distortions due to superconductor **magnetization**
  - twisted together
    - to reduce interfilament coupling and **AC losses**
  - embedded in a copper matrix
    - to **protect** the superconductor **after a quench**
    - to reduce magnetic instabilities called flux jumps





Practical superconductors
Multi-filament wires motivations

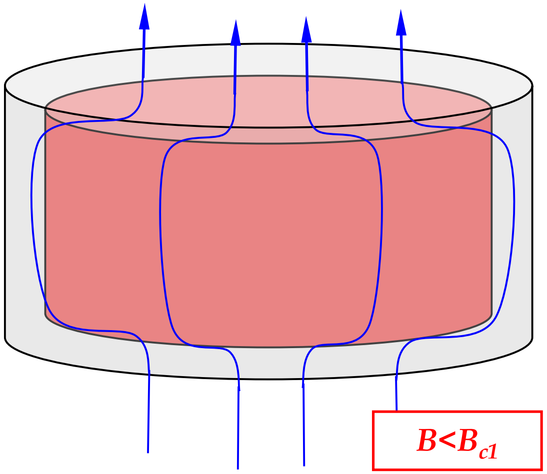
- Fluxoid distribution depends on the applied **B** and on J_c.
- Thermal disturbance → the local change in J_c → motion or "**flux jump**" → power dissipation

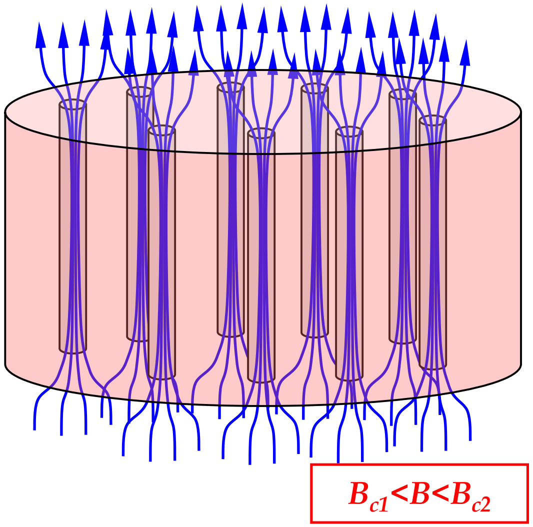
- Stability criteria for a slab (adiabatic condition)

$$\boxed{a \leq \sqrt{\frac{3\gamma C(\theta_c - \theta_0)}{\mu_0 j_c^2}}}$$

  - a is the half-thickness of the slab
  - j_c is the critical current density [A m^{-2}]
  - γ is the density [kg m^{-3}]
  - C is the specific heat [J kg^{-1}]
  - θ_c is the critical temperature.

- Nb-Ti filament diameters usually < 50 μm

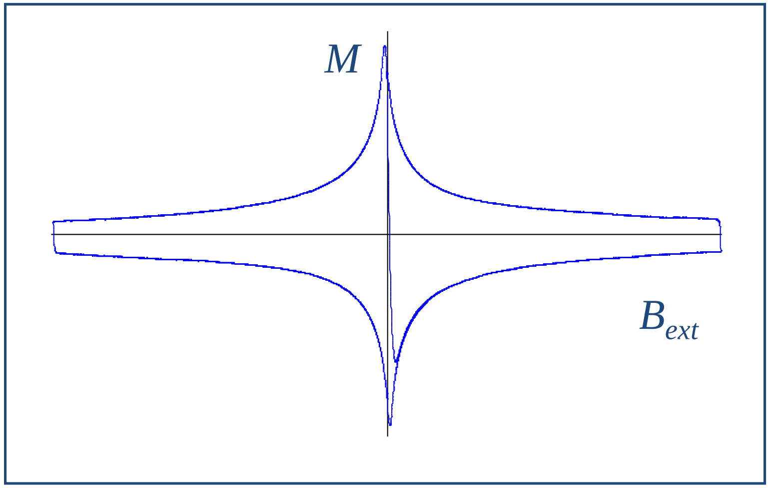


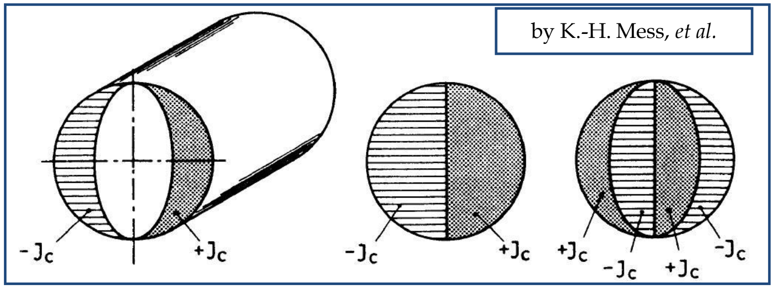


by L. Bottura

Practical superconductors
Multi-filament wires motivations

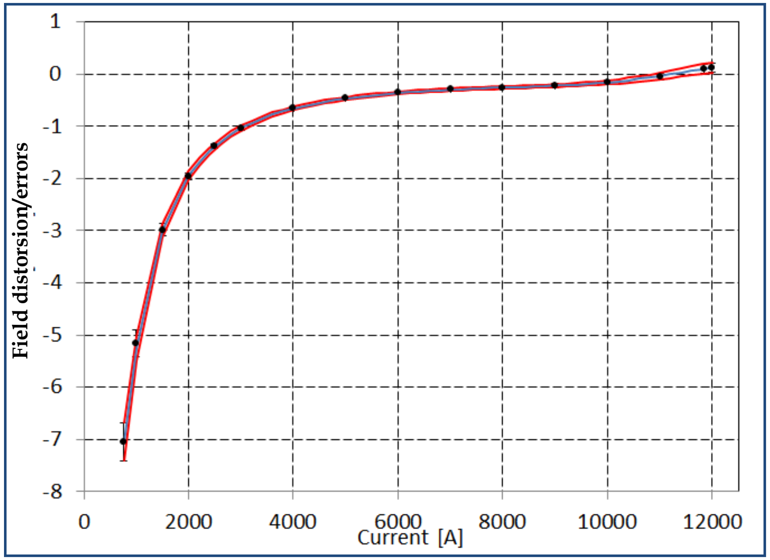
- **Superconductor magnetization**
  - When a filament is in a varying B_{ext}, its inner part is shielded by currents distribution in the filament periphery
    - They **do not decay** when B_{ex} is held constant → **persistent currents**





by K.-H. Mess, *et al.*

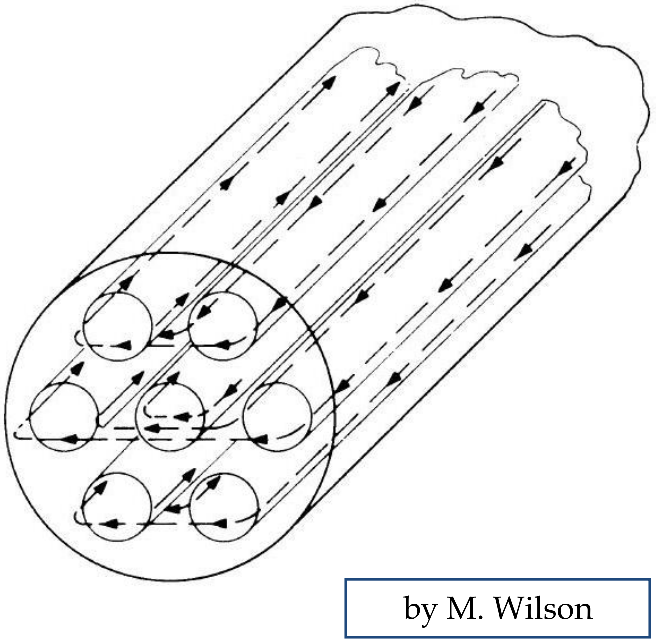
- These currents produce **field errors** and **ac losses** proportional to $J_c r_f$
  - LHC filament diameter 6-7 μm.
  - HERA filament diameter 14 μm.



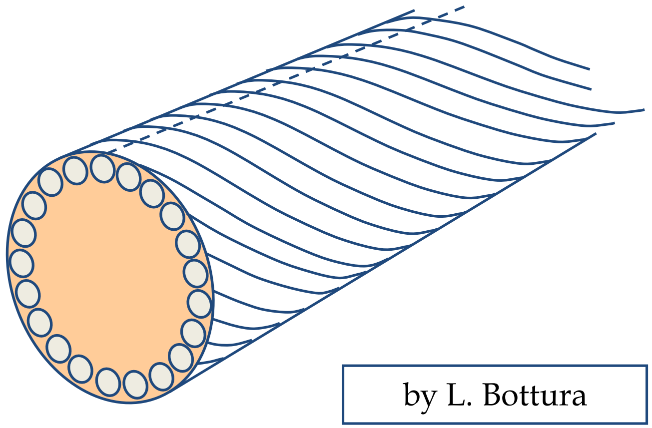
Practical superconductors
Multi-filament wires motivations

- **Inter-filament coupling**
    - When a multi-filamentary wire is subjected to a time varying magnetic field, **current loops** are generated between filaments.
    - If filaments are straight, large loops with large currents → **ac losses**
    - If the strands are magnetically coupled the effective filament size is larger → **flux jumps**

- To reduce these effects, filaments are **twisted**
    - twist pitch of the order of 20-30 times of the wire diameter.



by M. Wilson

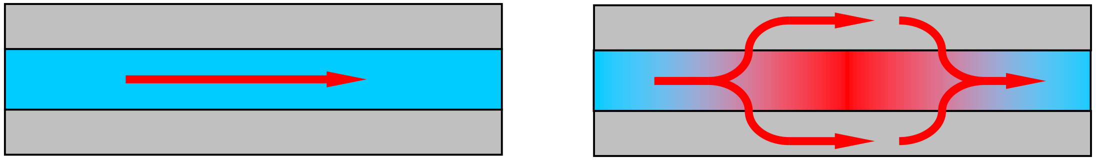


by L. Bottura

Practical superconductors
Multi-filament wires motivations

Quench protection

- Superconductors have a very high normal state resistivity
  - If quenched, could reach very high temperatures in few ms.
- If embedded in a **copper matrix**, when a quench occurs, current redistributes in the low-resisitivity matrix → **lower peak temperature**

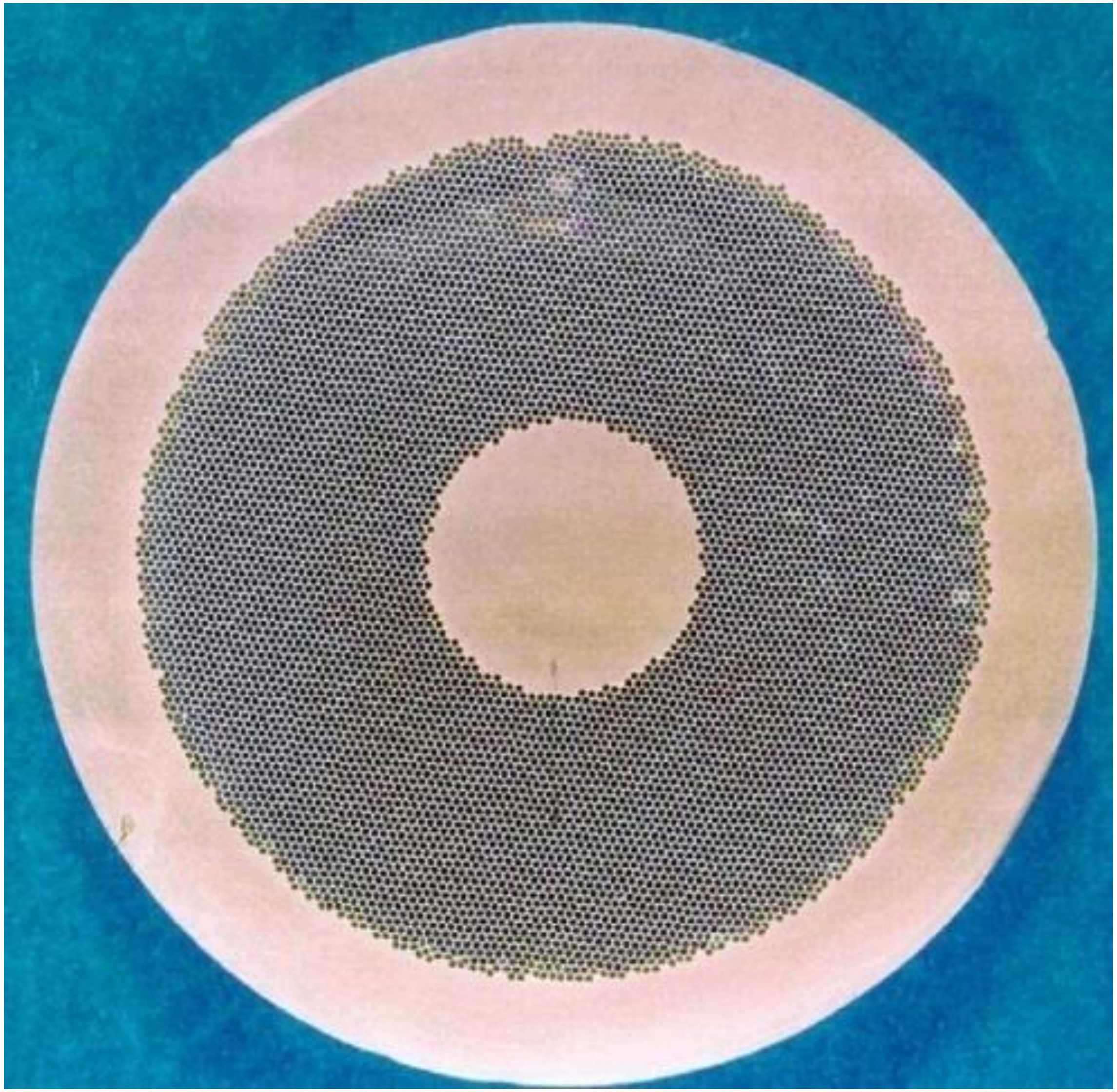


by L. Bottura

- The copper matrix provides **time to act** on the power circuit
- In the case of a small volume of superconductor heated beyond the critical temperature the current can flow in the copper for a short moment, allowing the filament to **cool-down and recover** supercond.
- The matrix also helps stabilizing the conductor against **flux jumps**

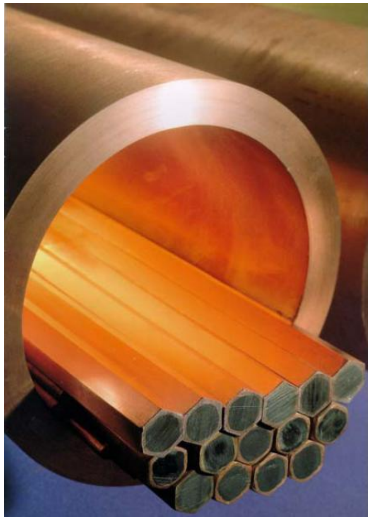
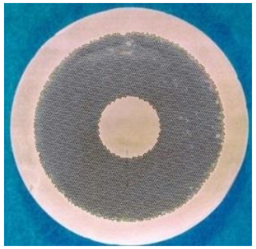
Practical superconductors
Multi-filament wires motivations

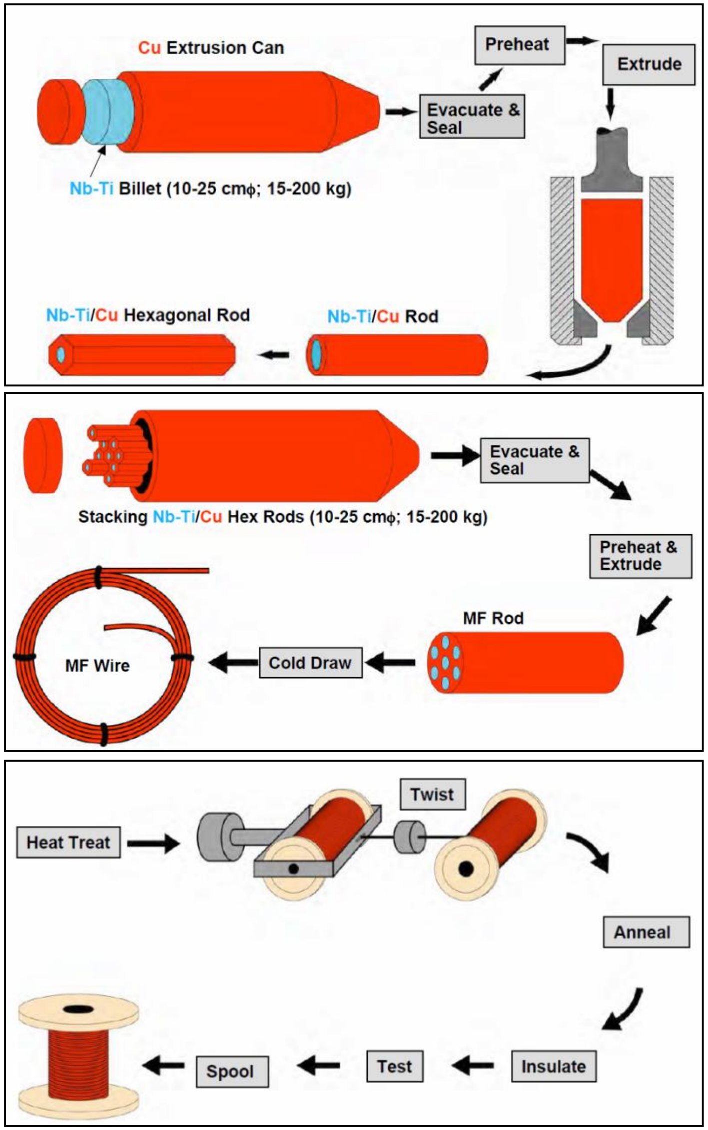
- **Flux jumps**
- **Persistent currents**
- **AC losses**
- **Quench protection**



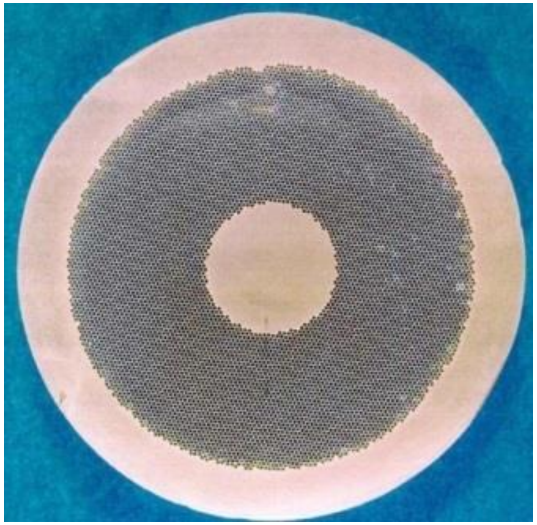
Practical superconductors
Fabrication of Nb-Ti multifilament wires

- Nb-Ti **ingots**
  - 200 mm Ø, 750 mm long
- **Monofilament rods** are stacked to form a **multifilament billet**
  - then extruded and drawn down
  - can be re-stacked: double-stacking process



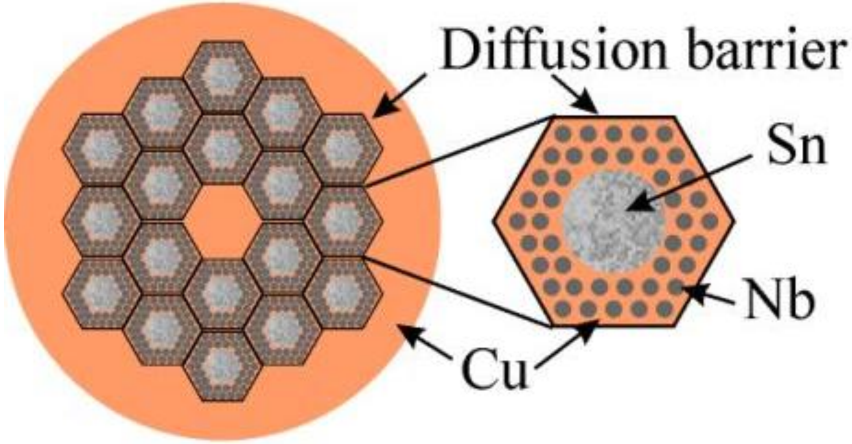
Practical superconductors
Fabrication of Nb-Ti multifilament wires



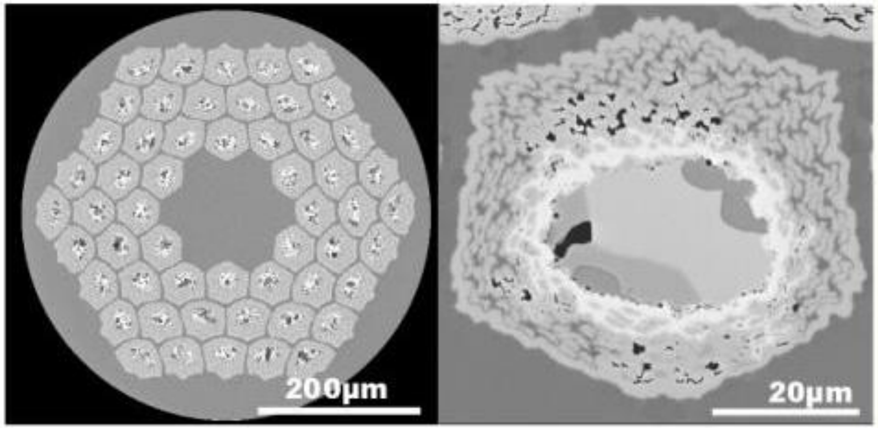
- **Copper to superconductor ratio**
  - ensure quench protection without compromising the overall critical current of wire.
- **Filament diameter**
  - Minimize flux jumps and persistent currents
  - Minimizing the wire processing cost
- **The inter-filament spacing**
  - small so that the filaments, harder then Cu, support each other during drawing operation
  - large enough to prevent filament couplings
- Cu **core** and **sheath** to reduce cable degradation
- Main manufacturing issue: **piece length**
  - It is preferable to wind coils with single-piece wire (to avoid welding)
    - LHC required piece length longer than 1 km

Practical superconductors
Fabrication of Nb_3Sn multifilament wires

- **Internal tin process**
  - A tin core is surrounded by Nb rods embedded in Cu (Rod Restack Process, RRP) or by layers of Nb and Cu (Modify Jelly Roll, MJR).
  - Each sub-element has a diffusion barrier.
  - Advantage: no annealing steps and not limited amount of Sn
  - Disadvantage: small filament spacing results in large effective filament size (100 μm) and large magnetization effect and instability.
  - Non-Cu J_C up to 3000 A/mm^2 at 4.2 K and 12 T.



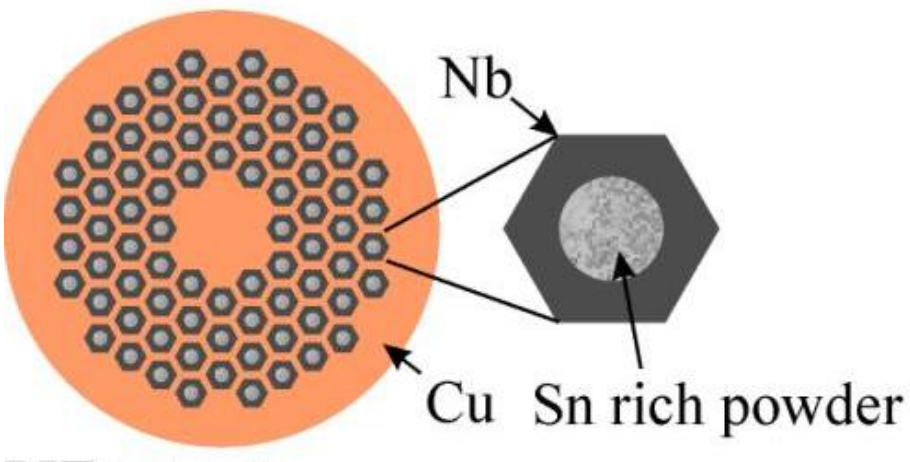
by A. Godeke



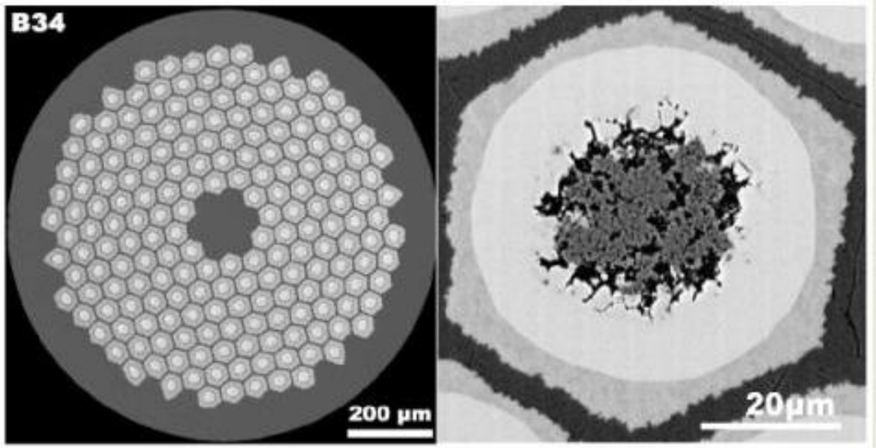
Practical superconductors

Fabrication of Nb$_3$Sn multifilament wires

- **Powder in tube (PIT) process**
  - NbSn$_2$ powder is inserted in a Nb tube, put into a copper tube.
  - The un-reacted external part of the Nb tube is the barrier.
  - Advantage: small filament size (30 μm) and short heat treatment (proximity of tin to Nb).
  - Disadvantage: fabrication cost.
  - Non-Cu J_C up to 2300 A/mm^2 at 4.2 K and 12 T.



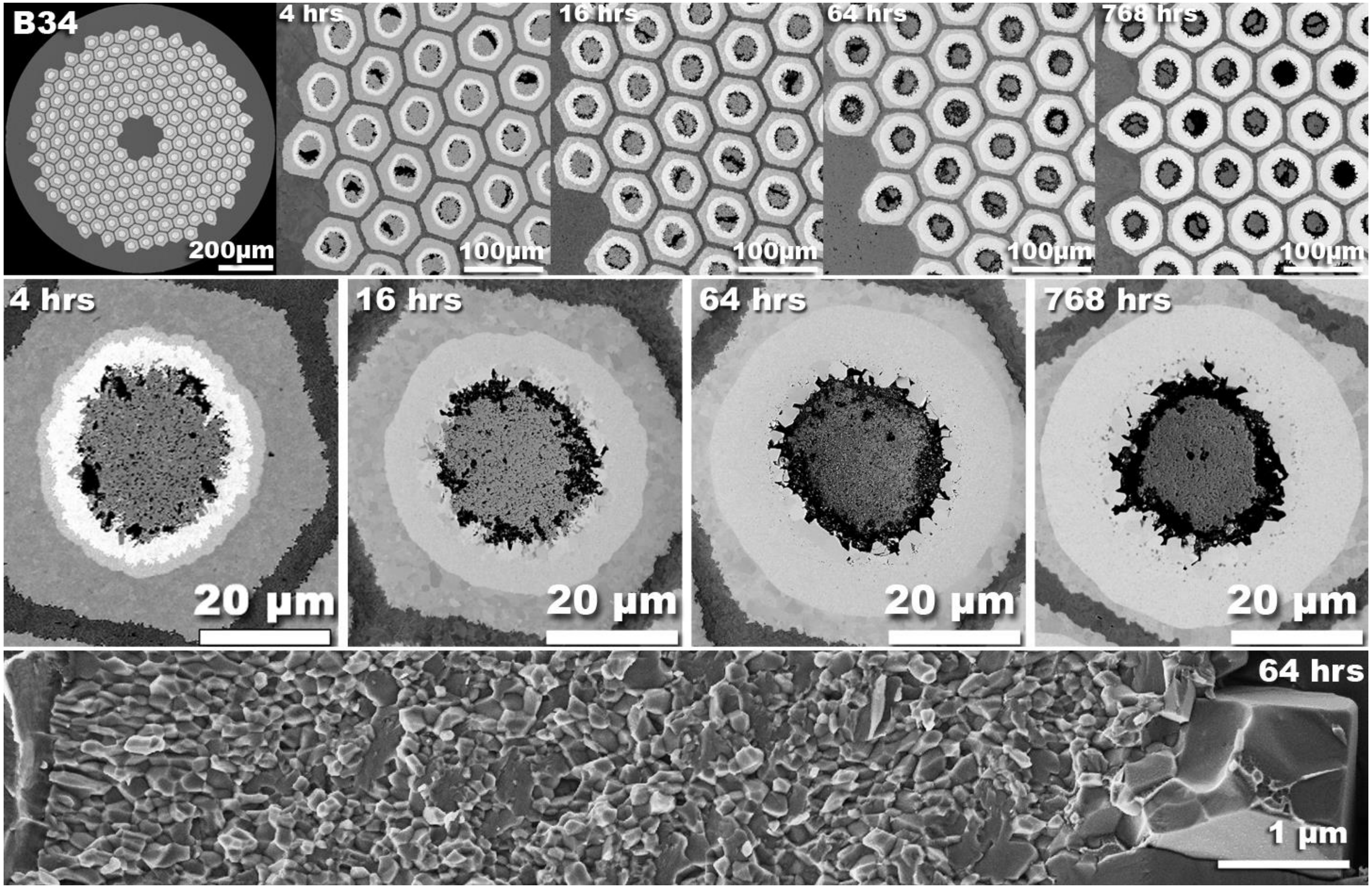
by A. Godeke



Practical superconductors
Fabrication of Nb_3Sn multifilament wires

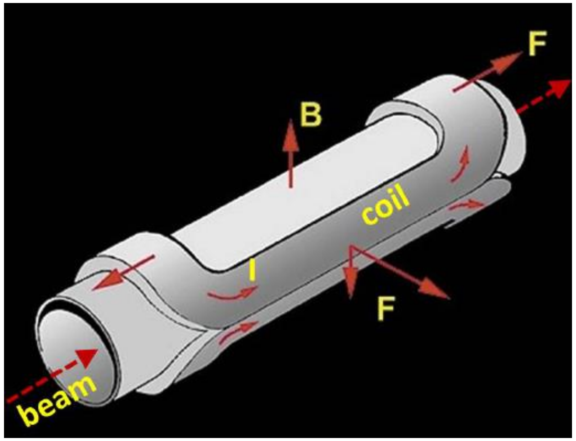
- Reaction of a PIT wire

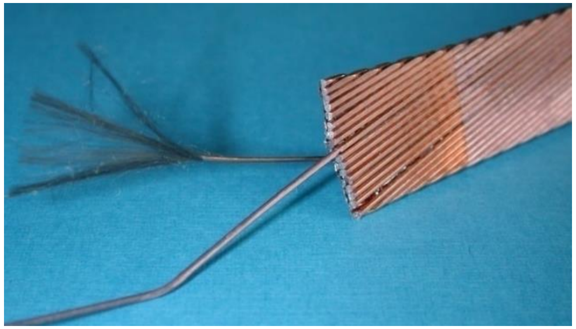
by A. Godeke

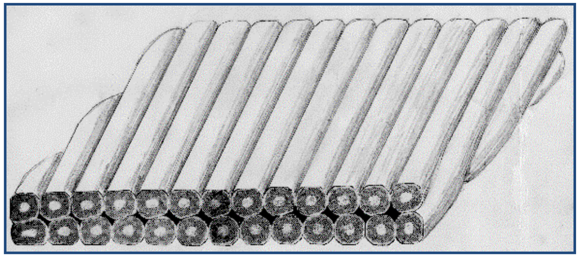


Practical superconductors
Multi-strand cables motivations

- Most of the superconducting coils for particle accelerators wound from a multi-strand cable (**Rutherford cable**)
  - Reduction of strand **piece length**
  - reduction of **number of turns**
    - easy winding
    - smaller coil inductance
      - less V for power supply during ramp-up;
      - after a quench, faster discharge and V
  - **current redistribution** in case of a defect or a quench in one strand
- The strands are **twisted** to
  - Reduce **inter-strand coupling currents**
    - Losses and field distortions
  - Provide more **mechanical stability**



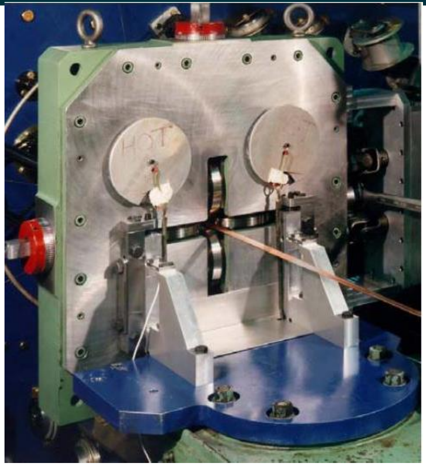


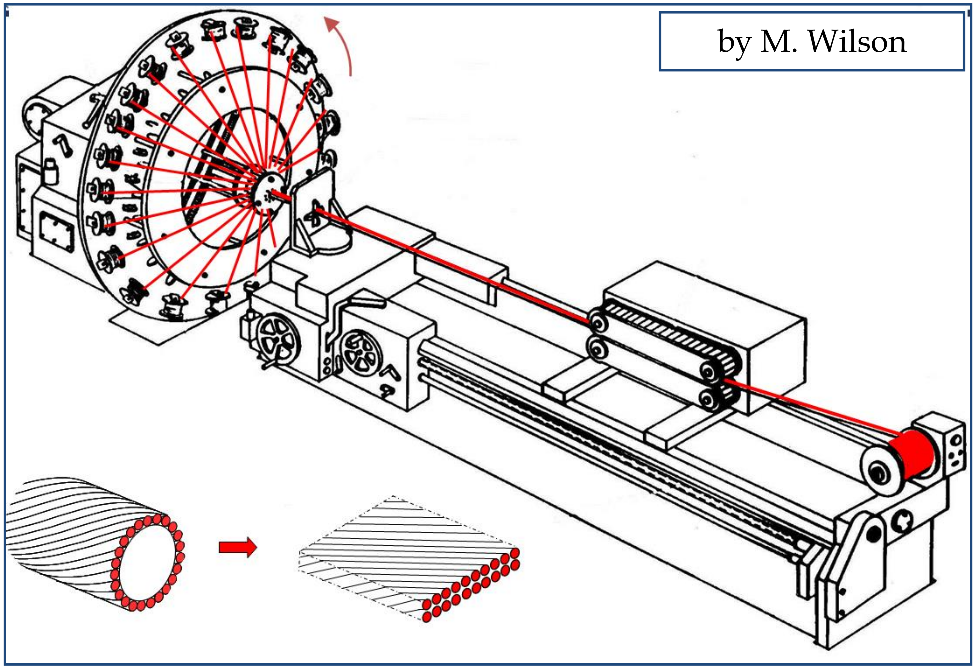


by M. Wilson

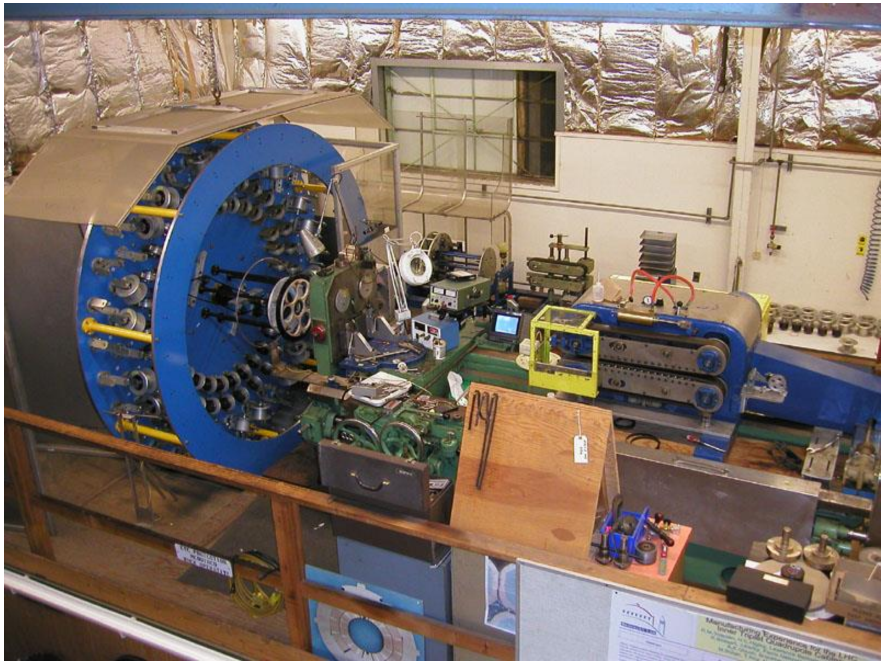
Practical superconductors
Multi-strand cables motivations

- Rutherford cables fabricated by **cabling machine**
  - Strands wound on spools mounted on a rotating drum
  - Strands twisted around a conical mandrel into rolls (Turk's head)
  - The rolls compact the cable and provide the final shape



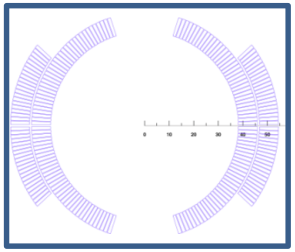


by M. Wilson

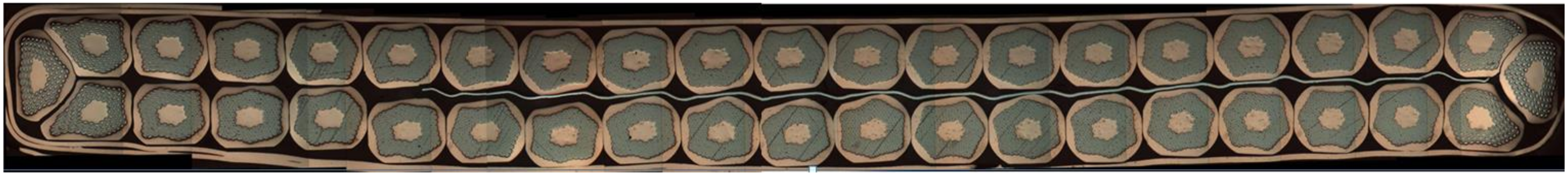


Practical superconductors
Multi-strand cables

- A Rutherford cable can be **rectangular** or **trapezoidal**
  - To stacking cables in an arc-shaped coil around the beam pipe

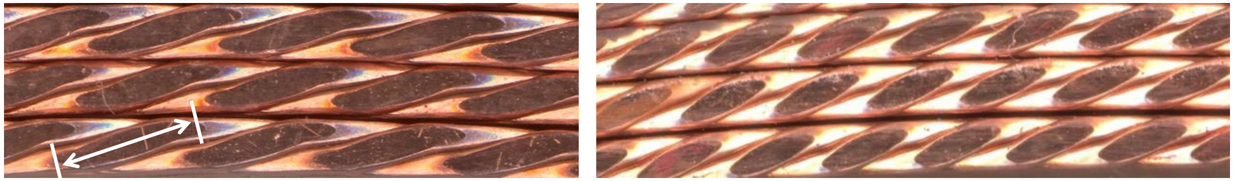


- **Cable compaction**
  - Ratio of the sum of the cross-sectional area of the strands (direction parallel to the cable axis) to the cross-sectional area of the cable
    - 88% (Tevatron) to 92.3% (HERA).
  - Chosen to provide good mechanical stability + high current capability + enough space for helium cooling or epoxy impregnation.
- **Cables degradation**
  - Critical current density of a virgin wire before cabling is higher then the one of a wire after cabling

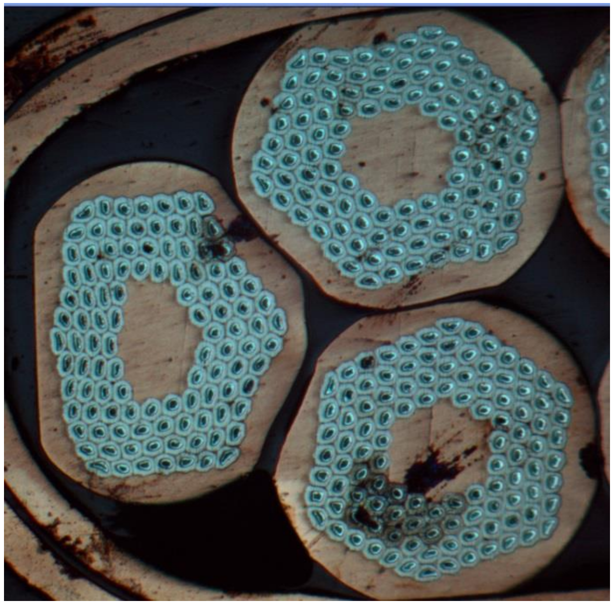


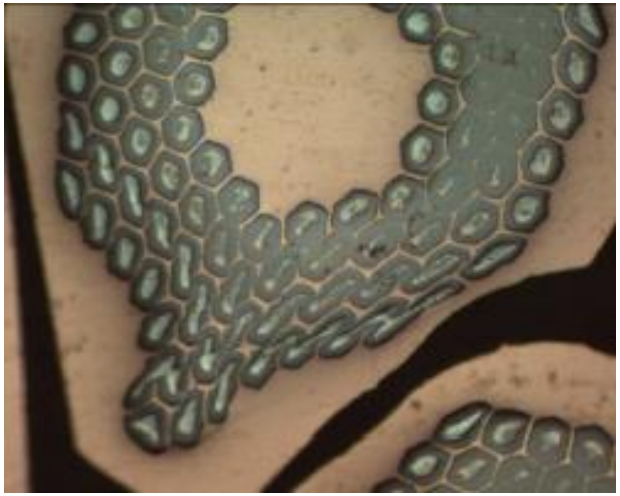
Practical superconductors
Multi-strand cables

- **Edge deformation** may cause
  - reduction of the filament cross-sectional area (Nb-Ti)
  - breakage of reaction barrier with incomplete tin reaction (Nb_3Sn)
- In order to **avoid degradation**
  - strand cross-section investigated
  - Edge facets are measured
    - General rule: no overlapping of facets



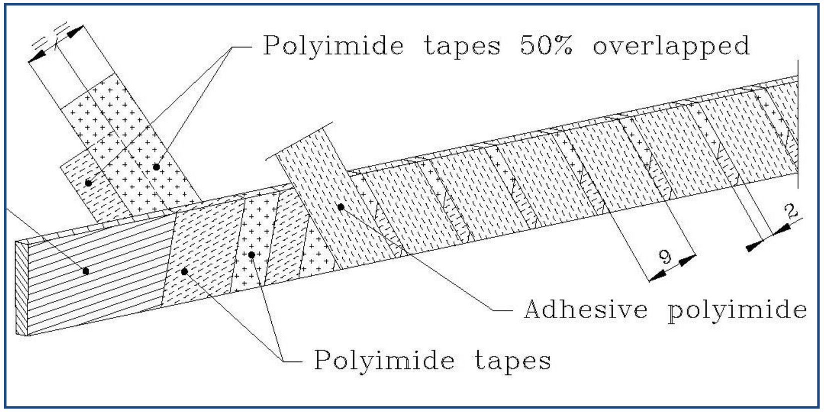
- **Keystone angle** is usually of ~ 1° to 2°



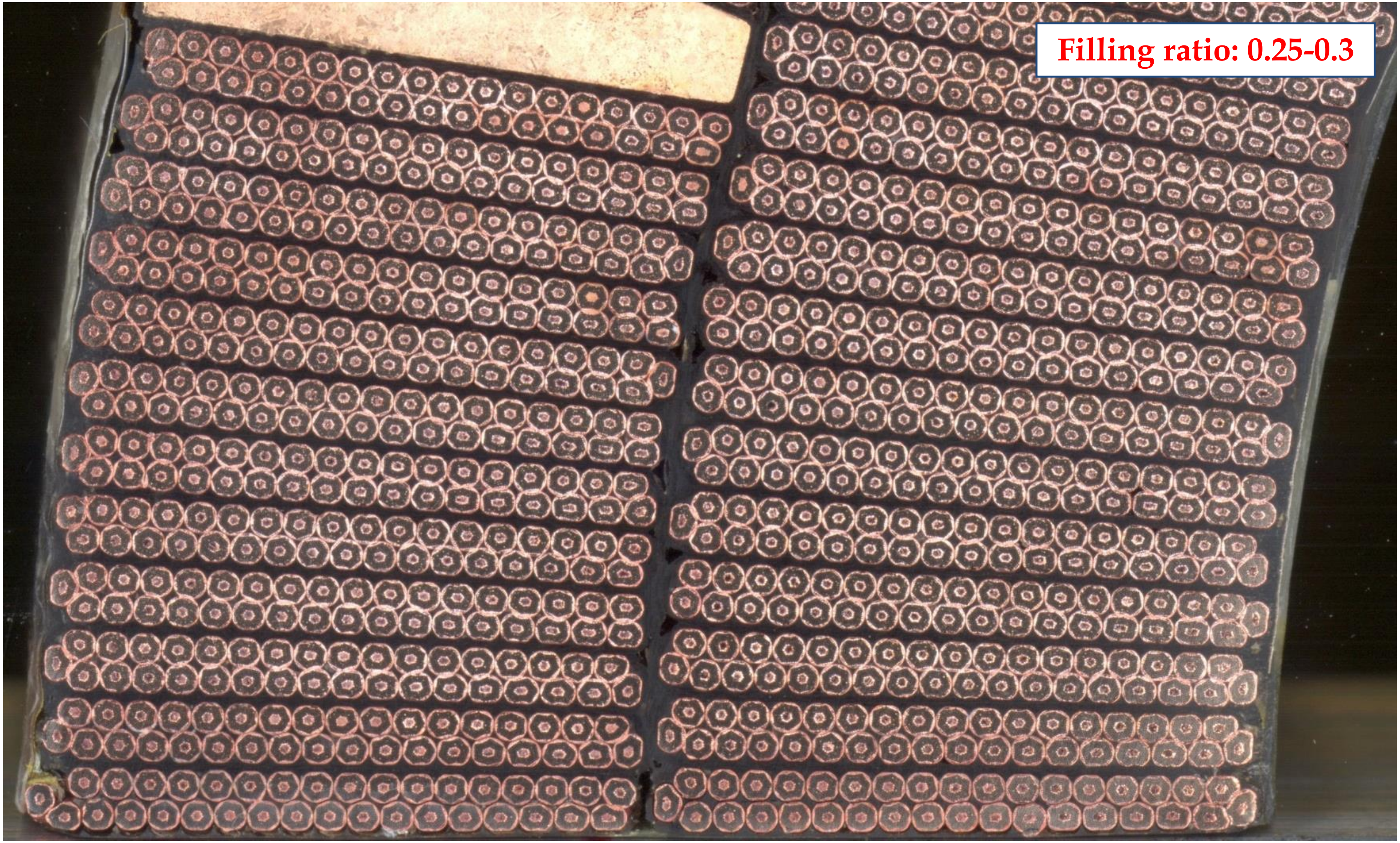


Practical superconductors
Cable insulation

- The cable insulation must feature
  - Good **electrical properties** to withstand turn-to-turn *V* after a quench
  - Good **mechanical properties** to withstand high pressure conditions
  - **Porosity** to allow penetration of helium (or epoxy)
  - **Radiation hardness**
- In Nb-Ti magnets overlapped layers of **polyimide**
- In Nb_3Sn magnets, **fiber-glass** braided or as tape/sleeve.
- Typically the insulation thickness: 100 and 200 μm.



Practical superconductors
Superconducting cables



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