Unit 9 and 10
Practical superconductors for accelerator magnets

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Outline

1. Introduction and history
2. Superconducting materials
    1. NbTi, Nb_3Sn, and their critical surfaces
3. Multifilament wires
    1. Motivations and fabrication
4. Superconducting cables
    1. Motivations and fabrication
5. Cable insulation
6. Filling factor
7. Conclusions

References

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[8] Presentations from Luca Bottura and Martin Wilson

References

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  - L. Bottura, "A practical fit for the critical surface of NbTi," *IEEE Trans. Appl. Supercond.*, Vol. 10, No. 1, pp. 1054–1057, 2000.
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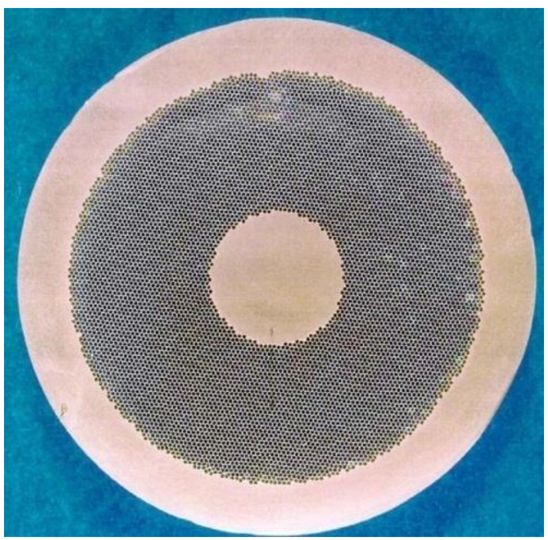
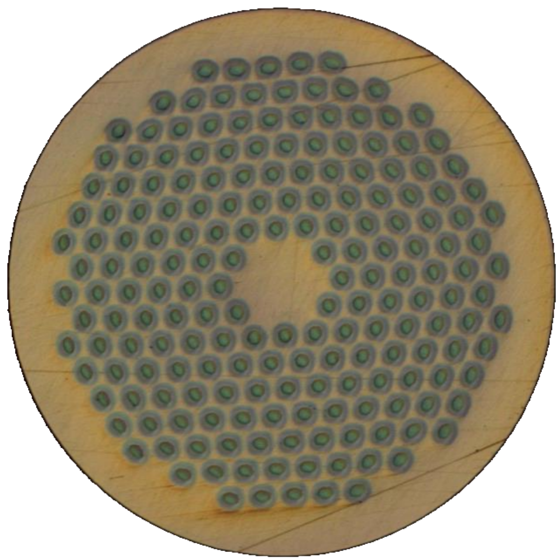
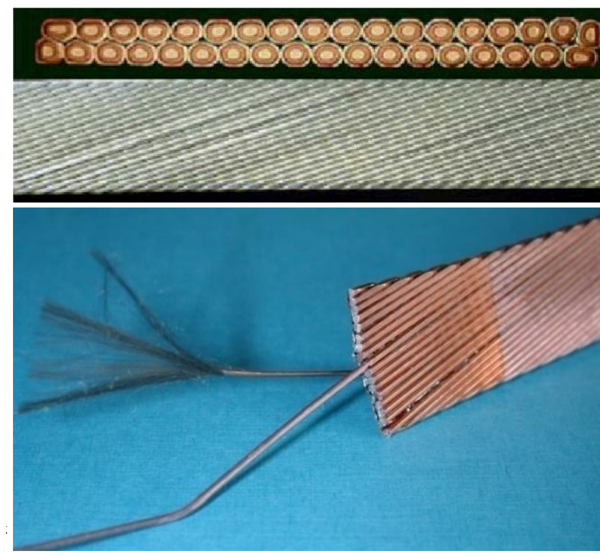
1. Introduction and history

- For practical applications, superconducting materials are usually produced in small filaments and surrounded by a stabilizer (typically copper) to form a ***multifilament wire* or *strand***.
- A superconducting cable is usually composed by several wires: ***multistrand cable***.
- In this unit we will describe how and why superconducting cables are fabricated in such a geometry.

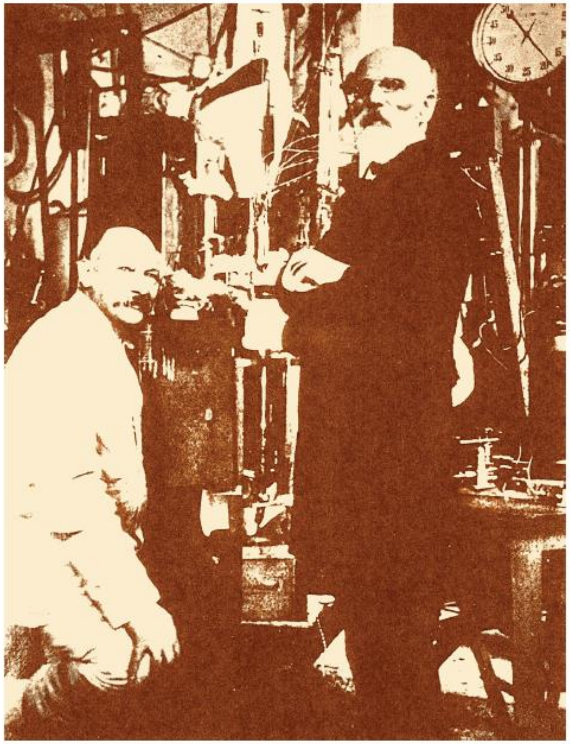


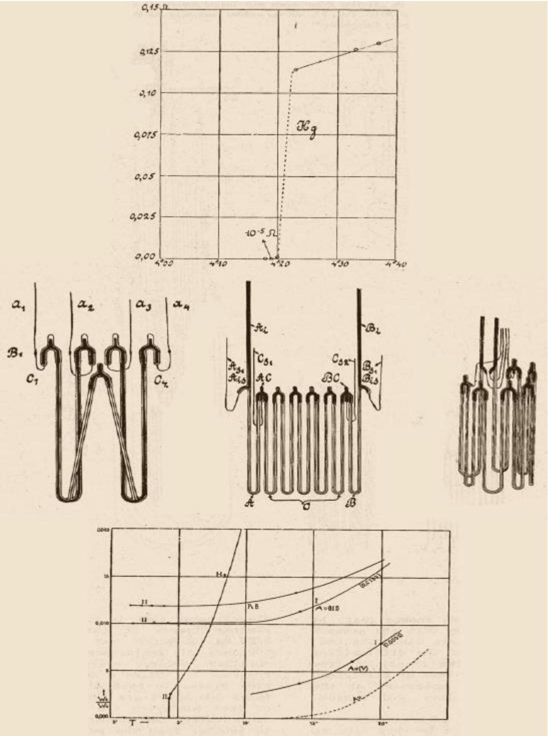


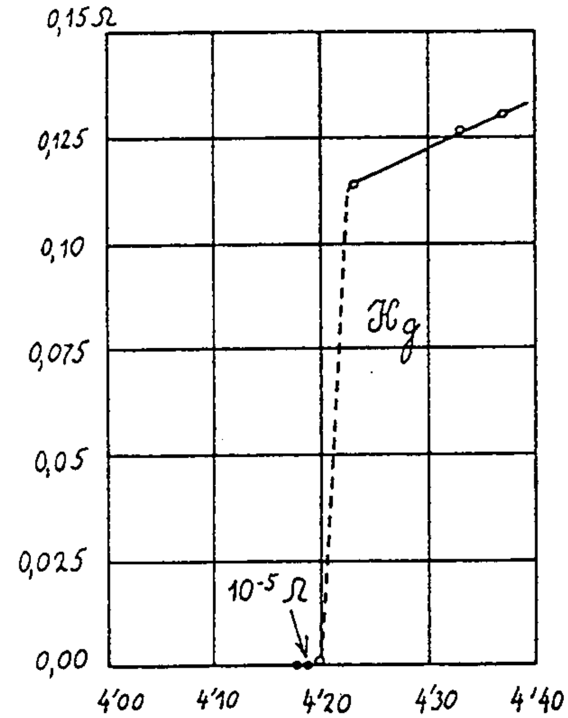


1. Introduction and history
The discovery

- 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**







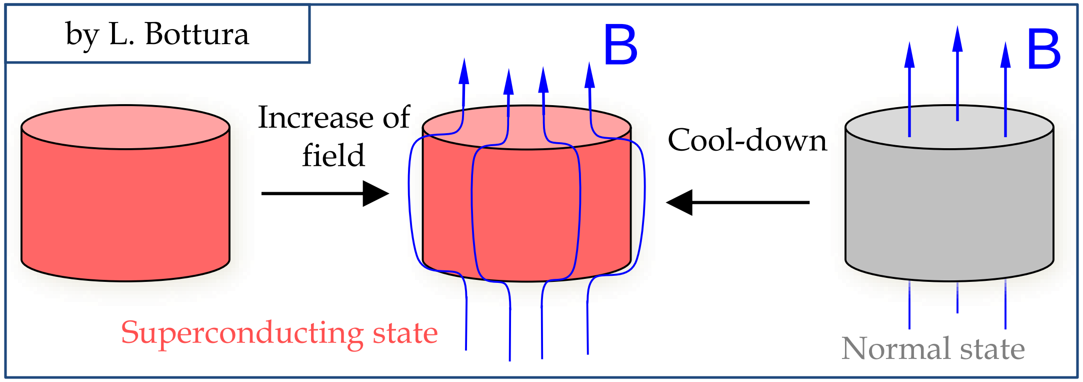
1. Introduction and history
Critical temperature

- 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

1. Introduction and history
Type I superconductors

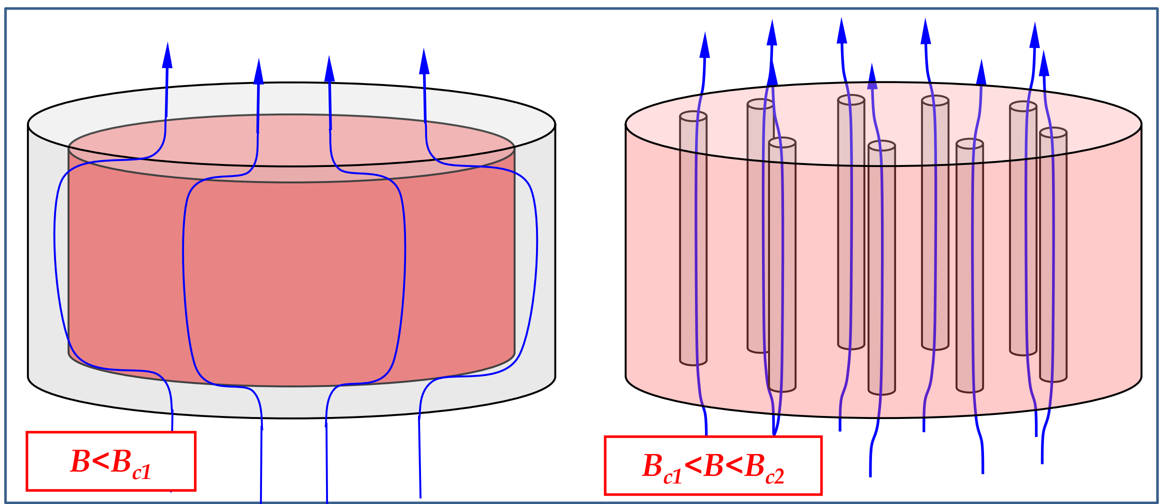
- Meissner-Ochsenfeld effect (1933)
- Perfect diamagnetism
  - With $T<T_c$ magnetic field is expelled
- But, the ***B*** must be < **critical field B_c**
  - Otherwise superconductivity is lost



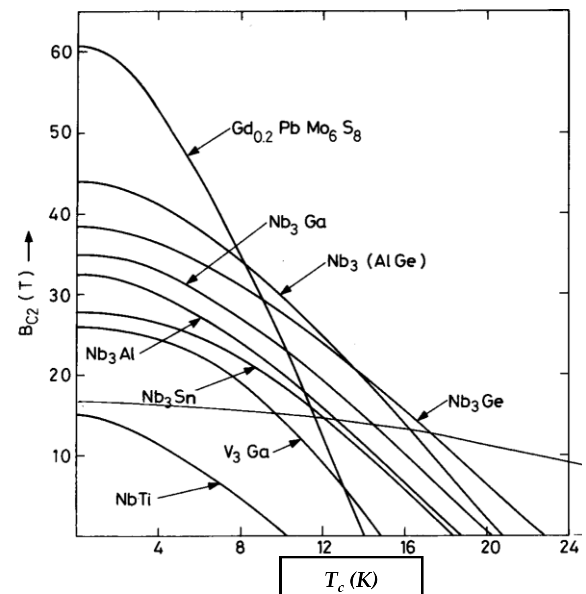
- Unfortunately, first discovered superconductors (**Type I**) with **very low B_c** (≤ 0.1 T)
  - not practical for electro-magnets

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

- 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}



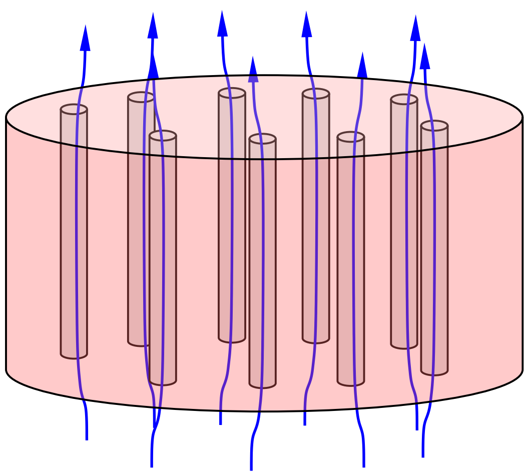
by L. Bottura

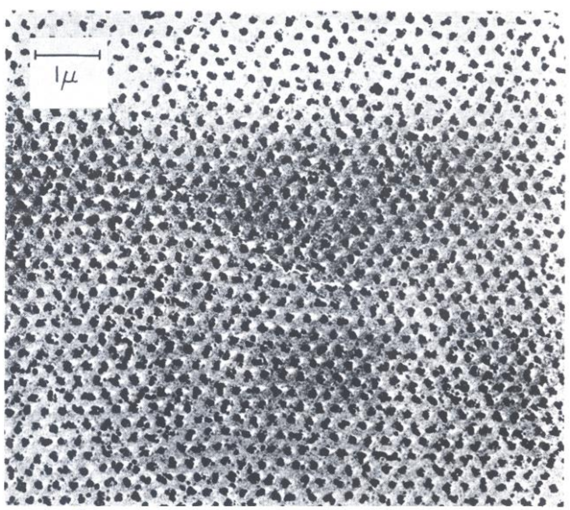


- Field penetrated in the form of flux tubes (*fluxoids*), each with a flux of

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

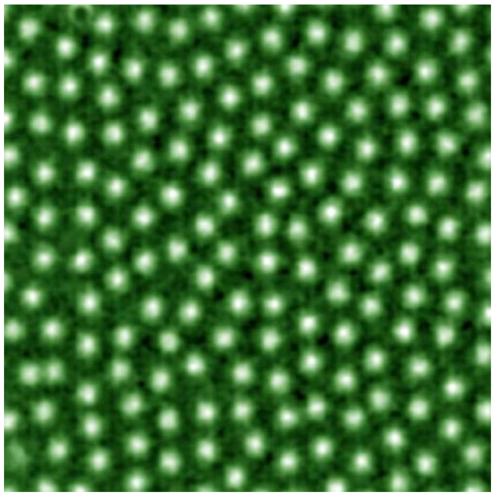
- Observed both in a photo by Essmann & Träuble (1967) and with magneto-optical imaging technique by Oslo Univerisity





PATTERN OF INDIVIDUAL FLUXONS IN A TYPE-II SUPERCONDUCTOR

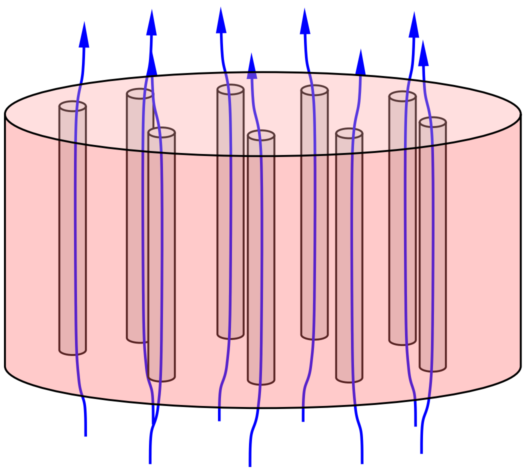
This photograph shows the triangular pattern of fluxons in a type-II superconductor (see Chapter 12). The pattern is revealed by allowing very small (500 Å) ferromagnetic particles to settle on the surface of a magnetized specimen (lead–indium alloy). The particles locate themselves where the magnetic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



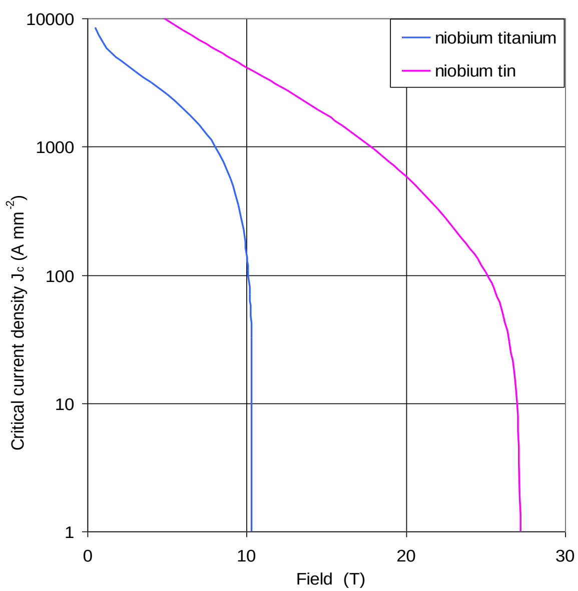
http://www.mn.uio.no/fysikk/english/research/groups/amks/superconductivity/

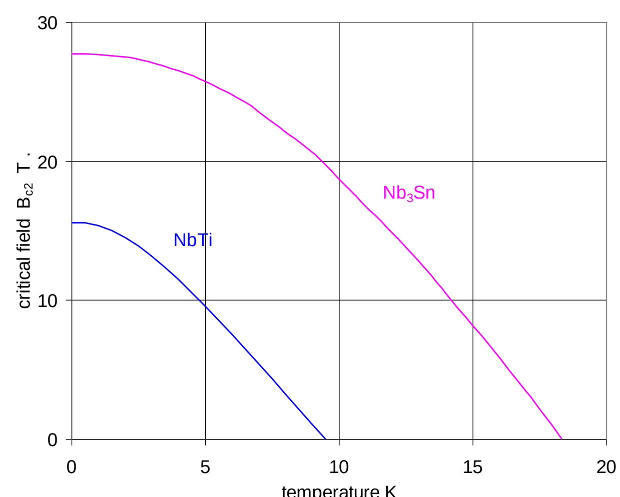
Superconductivity
Hard superconductors

- …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



- 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

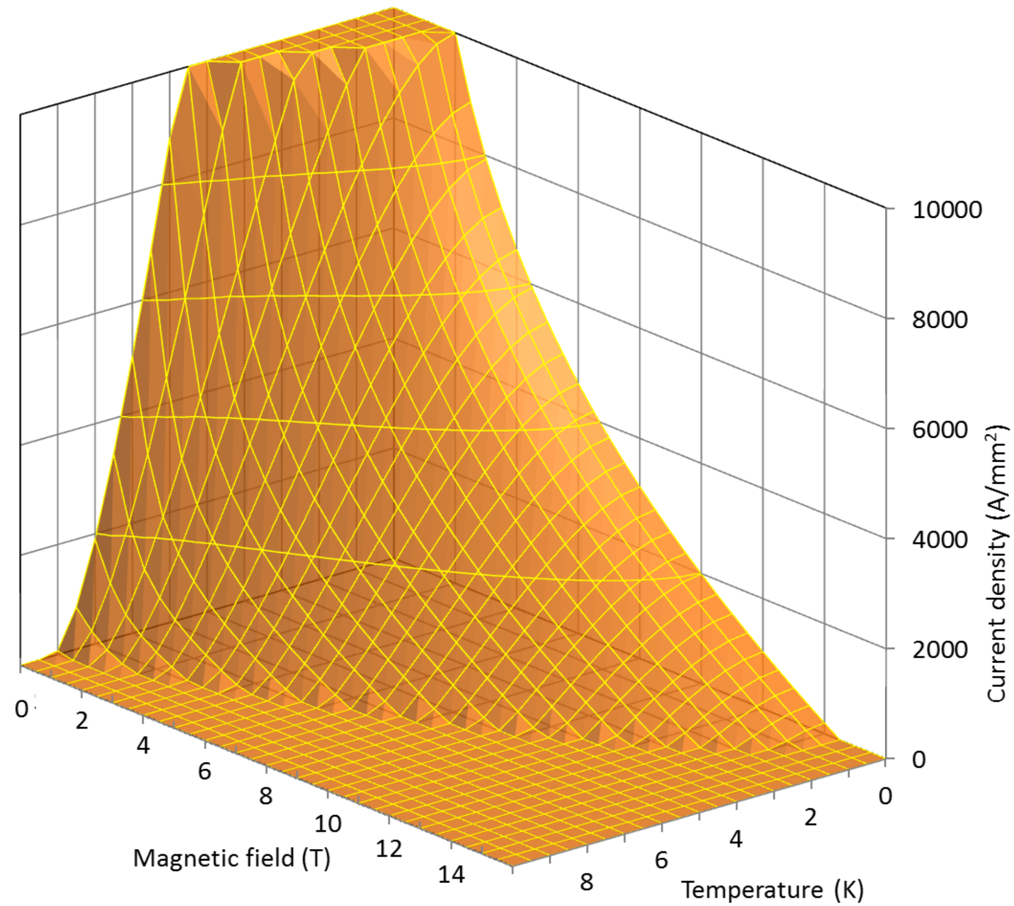




by M. Wilson

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



Outline

1. Introduction and history
2. **Superconducting materials**
    1. Nb-Ti, Nb_3Sn, and their critical surfaces
3. Multifilament wires
    1. Motivations and fabrication
4. Superconducting cables
    1. Motivations and fabrication
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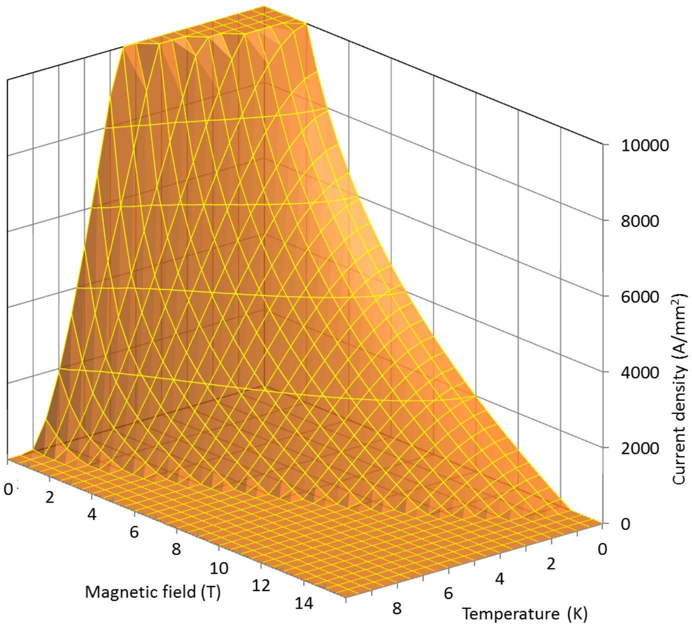
6. Filling factor
7. Conclusions

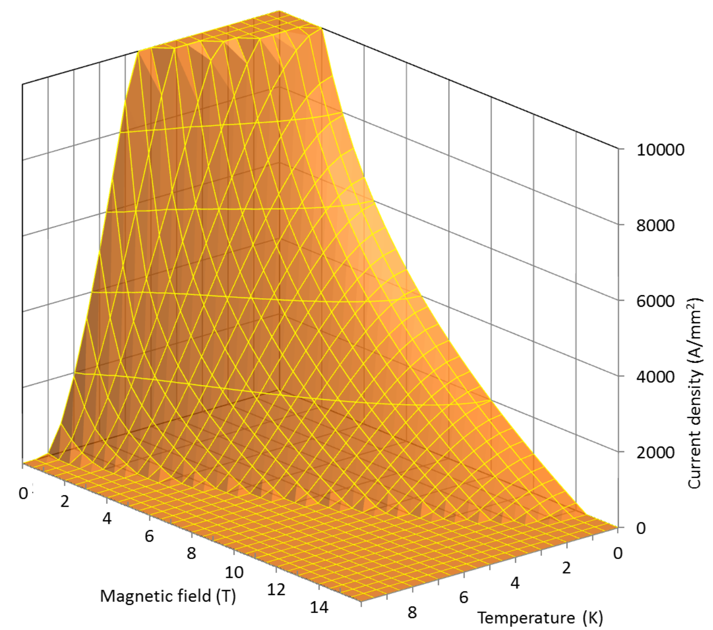
2. Superconducting materials Nb-Ti

- **Niobium and titanium** are both soluble and at high temperature they combine in a ductile alloy (called β phase).
  - It is easy to process by **extrusion and drawing** techniques.
- When cooled down to about **9 K** it becomes a type II superconductor.
- Critical temperature T_c and upper critical magnetic field 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 the microstructure.
  - Cold works and heat treatments determine the formations of other phases; in particular the α phase is used for flux pinning.



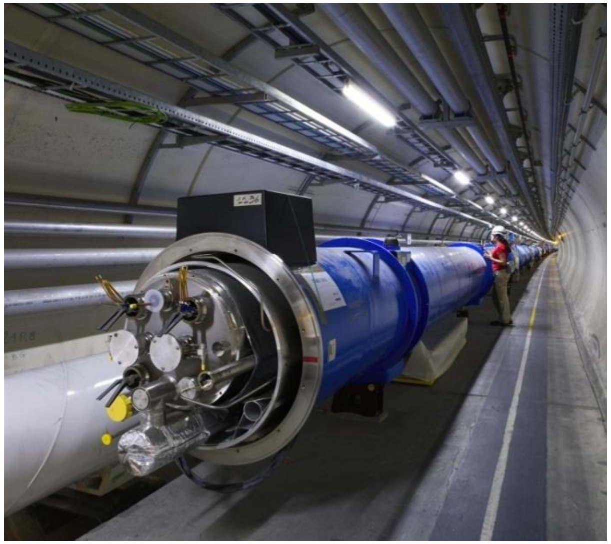
2. Superconducting materials
Nb-Ti

- LHC pushed this technology to its limit with 8 T magnets
  - Why 8 T and not 15 T ?
  - One cannot operate at 0 K, at 1.9 K critical field is 13 T
  - Critical field decreases with current density, so practical limit is 10 T
  - Some margin must be taken to avoid instabilities, so about 8 T is the limit – we will come on this point



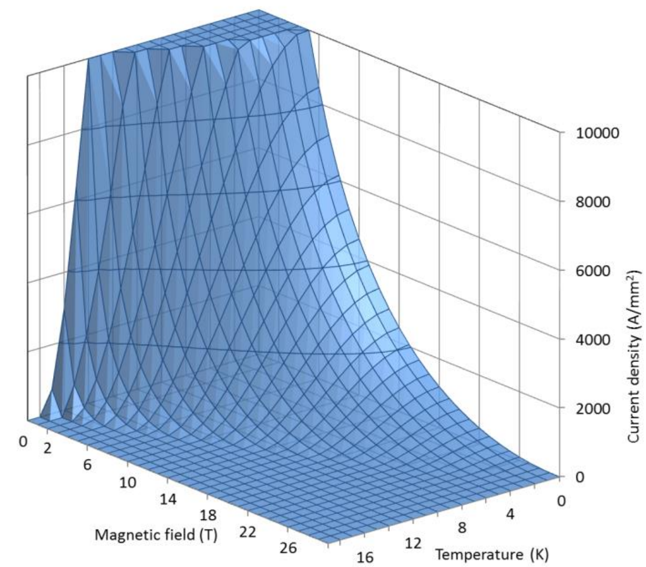
2. Superconducting materials
Nb-Ti

- 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
  - HERA at DESY
  - RHIC at BNL
  - SSC (project canceled in 1993)
  - LHC at CERN
- 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)



Nb$_3$Sn

- **Niobium and tin** can form an intermetallic compound, with the formula Nb$_3$Sn, from the A15 family (like Nb$_3$Al).
- When cooled down to about **18 K** it becomes a type II superconductor.
- Critical temperature T_{C0m} and upper critical field B_{C20m} depend on Sn content: the optimal is 20-25 in weight%.
  - T_{C0m} is **~18 K** at 0 T and zero strain.
  - B_{C20m} is **~28 T** at 0 K and zero strain.
- The critical current J_c depends on the microstructure (grain structure).
  - High J_c obtained with grains from 30 to 300 nm

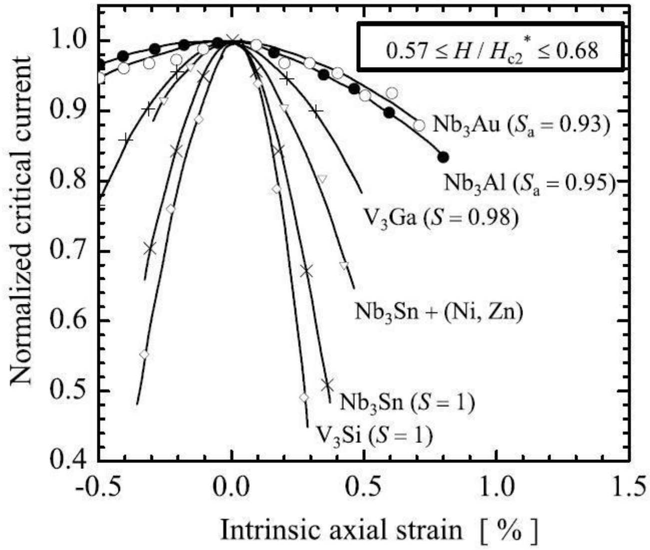


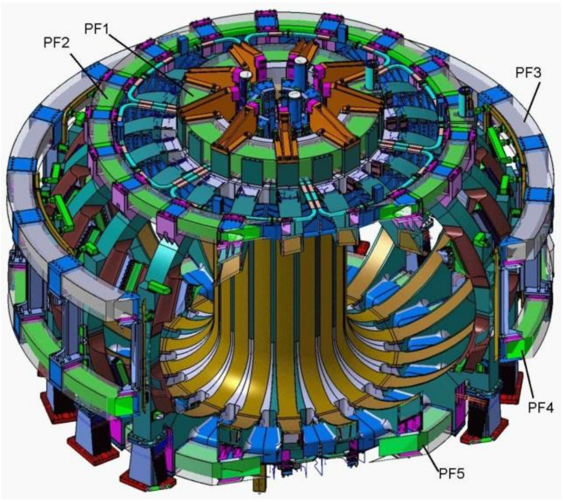
2. Superconducting materials Nb_3Sn

- 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

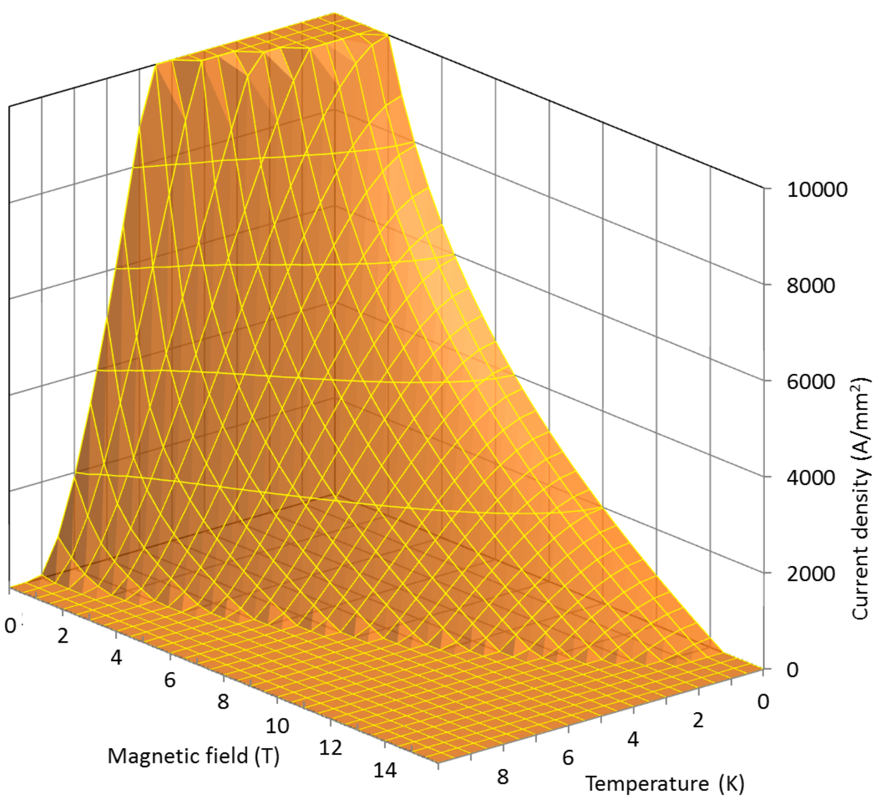
by A. Godeke



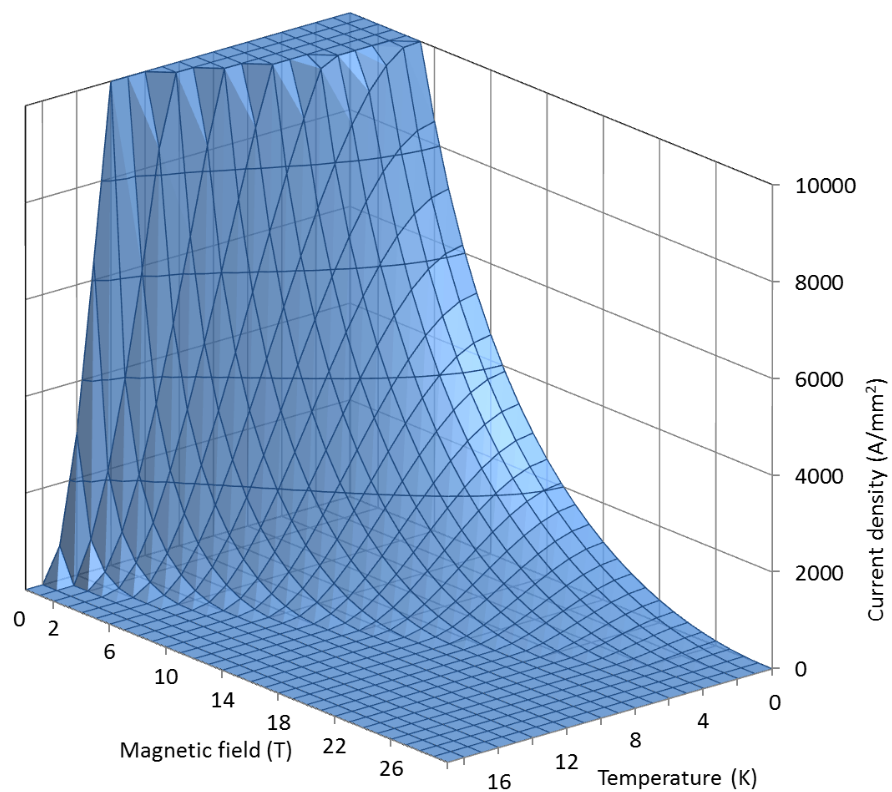


2. Superconducting materials
Nb-Ti vs. Nb_3Sn

Nb-Ti

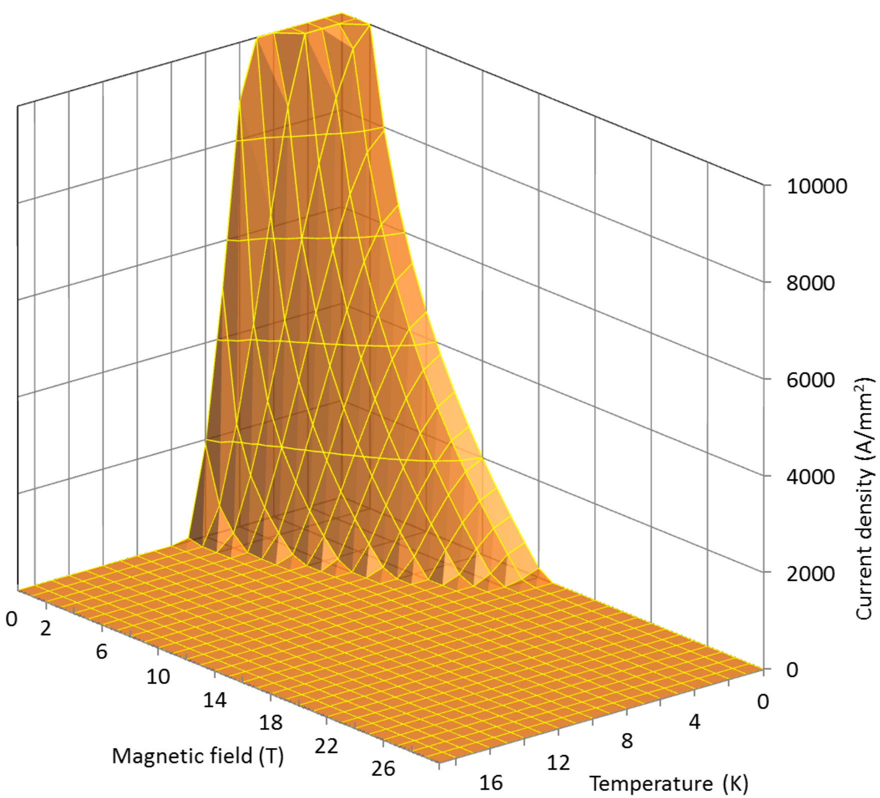


Nb_3Sn

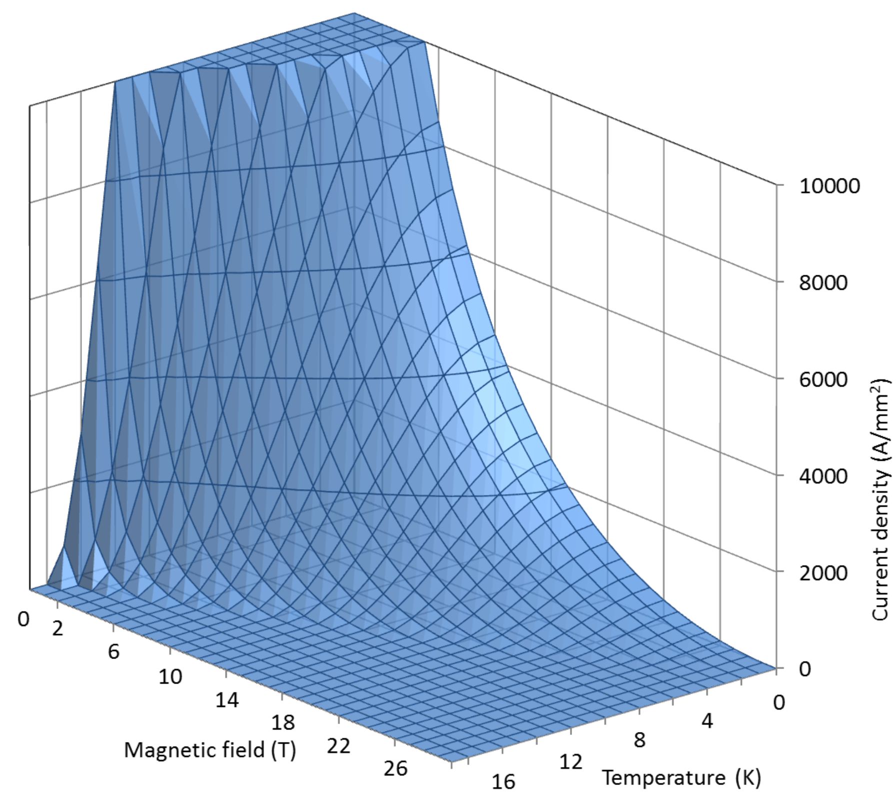


2. Superconducting materials Nb-Ti vs. Nb_3Sn

Nb-Ti

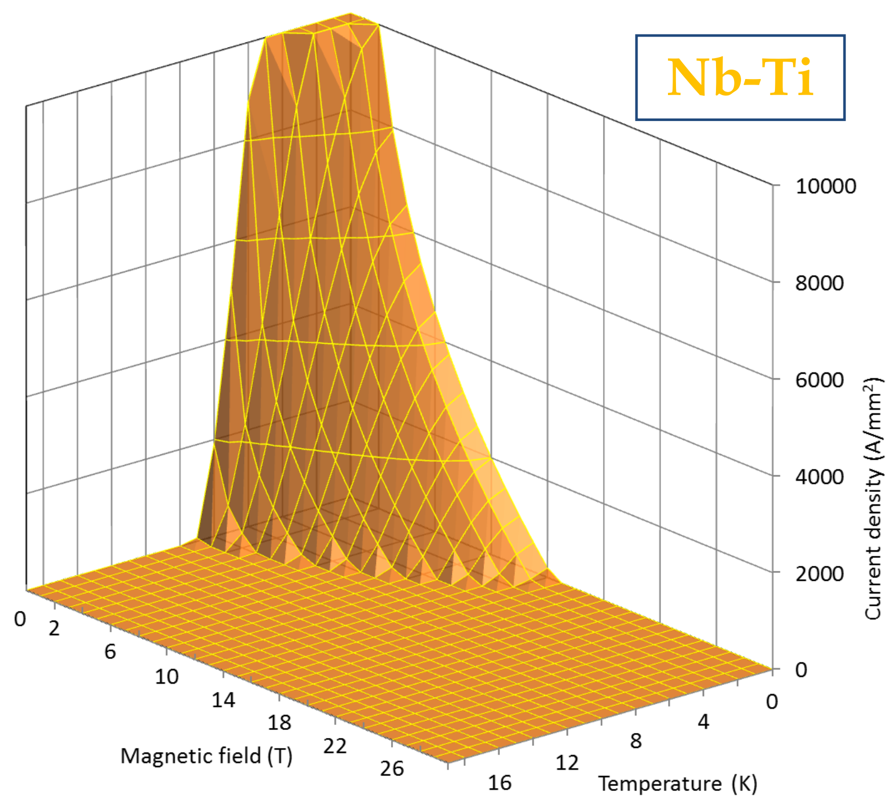


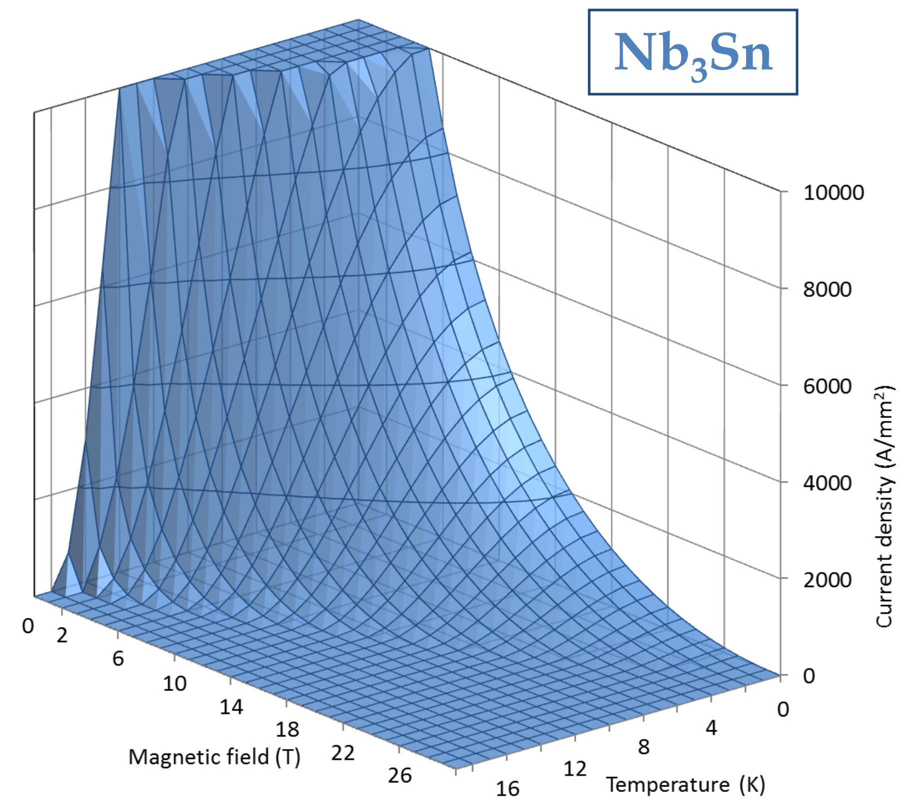
Nb_3Sn



2. Superconducting materials
Critical surfaces

- The **critical surface** defines the boundaries between superconducting state and normal conducting state in the space defined by **temperature**, magnetic **field**, and **current** densities.
- The surface, determined experimentally, can be fitted with parameterization curves.





Nb-Ti parameterization curve (LHC dipole)

- Nb-Ti parameterization
  - Temperature and field dependence of B_{C2} and T_C are provided by Lubell's formulae:

$$B_{C2}(T) = B_{C20}\left[1-\left(\frac{T}{T_{C0}}\right)^{1.7}\right] \qquad T_C(B)^{1/1.7} = T_{C0}\left[1-\left(\frac{B}{B_{C20}}\right)^{1/1.7}\right]$$

    where B_{C20} is the upper critical flux density at zero temperature (14.5 T), and T_{C0} is critical temperature at zero field (9.2 K)
  - Temperature and field dependence of *Jc* is given by Bottura's formula

$$\frac{J_C(B,T)}{J_{C,ref}} = \frac{C_{NbTi}}{B}\left[\frac{B}{B_{C2}(T)}\right]^{\beta_{NbTi}}\left[1-\frac{B}{B_{C2}(T)}\right]^{\beta_{NbTi}}\left[1-\left(\frac{T}{T_{C0}}\right)^{1.7}\right]^{\gamma_{NbTi}}$$

    where $J_{C,Ref}$ is critical current density at 4.2 K and 5 T (3000 A/mm^2) and $C_{Nb\text{-}Ti}$ (27 T), $\alpha_{Nb\text{-}Ti}$ (0.63), $\beta_{Nb\text{-}Ti}$ (1.0), and $\gamma_{Nb\text{-}Ti}$ (2.3) are fitting parameters.

Nb_3Sn parameterization curve (typical values for HEP magnets)

- Nb_3Sn parameterization
  - Temperature, field, and strain dependence of *Jc* is given by Summers' formula

$$J_C(B,T,\varepsilon)=\frac{C_{Nb_3Sn}(\varepsilon)}{\sqrt{B}}\left[1-\frac{B}{B_{C2}(T,\varepsilon)}\right]^2\left[1-\left(\frac{T}{T_{C0}(\varepsilon)}\right)^2\right]^2$$

$$\frac{B_{C2}(T,\varepsilon)}{B_{C20}}=\left[1-\left(\frac{T}{T_{C0}(\varepsilon)}\right)^2\right]\left\{1-0.31\left(\frac{T}{T_{C0}(\varepsilon)}\right)^2\left[1-1.77\ln\left(\frac{T}{T_{C0}(\varepsilon)}\right)\right]\right\}$$

$$C_{Nb_3Sn}(\varepsilon)=C_{Nb_3Sn,0}\left(1-\alpha_{Nb_3Sn}|\varepsilon|^{1.7}\right)^{1/2}$$

$$B_{C20}(\varepsilon)=B_{C20m}\left(1-\alpha_{Nb_3Sn}|\varepsilon|^{1.7}\right)$$

$$T_{C0}(\varepsilon)=T_{C0m}\left(1-\alpha_{Nb_3Sn}|\varepsilon|^{1.7}\right)^{1/3}$$

where α_{Nb3Sn} is 900 for ε = -0.003, T_{Com} is 18 K, B_{C20m} is 27.6 T, and $C_{Nb3Sn,0}$ is a fitting parameter equal to 43100000000 $AT^{1/2}m^{-2}$ for a *Jc*=2900 A/mm^2 at 4.2 K and 12 T.

Assume ε = 0.000

2. Superconducting materials from Cu to Nb_3Sn

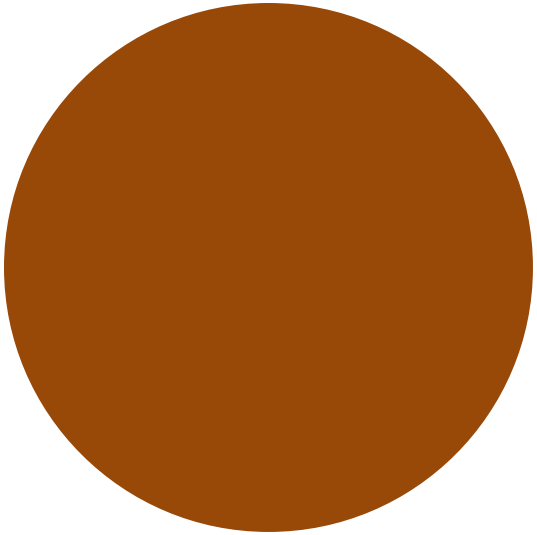
- Typical operational conditions (0.85 mm diameter strand)

Cu	Nb-Ti	Nb_3Sn
J_e ~ 5 A/mm^2	J_e ~ 600-700 A/mm^2	J_e ~ 600-700 A/mm^2
I ~ 3 A	I ~ 300-400 A	I ~ 300-400 A
B = 2 T	B = 8-9 T	B = 12-13 T

2. Superconducting materials from Cu to Nb_3Sn

- Typical operational conditions (0.85 mm diameter strand)

Cu

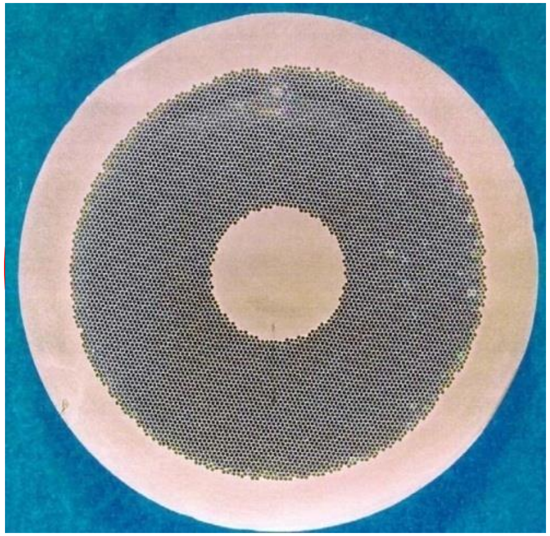


$J_e \sim 5$ A/mm^2

$I \sim 3$ A

$B = 2$ T

Nb-Ti

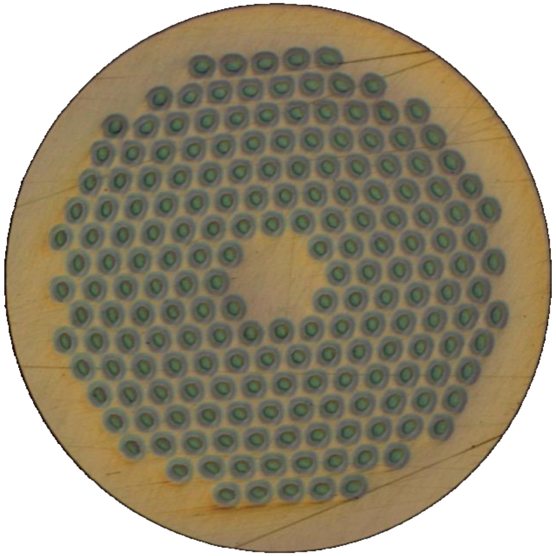


$J_e \sim 600\text{-}700$ A/mm^2

$I \sim 300\text{-}400$ A

$B = 8\text{-}9$ T

Nb_3Sn



$J_e \sim 600\text{-}700$ A/mm^2

$I \sim 300\text{-}400$ A

$B = 12\text{-}13$ T

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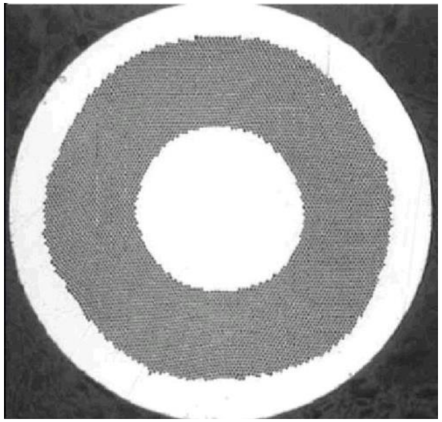
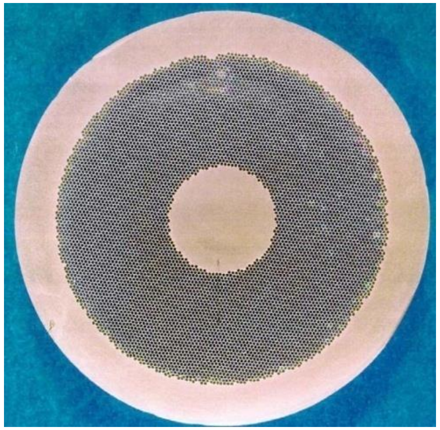
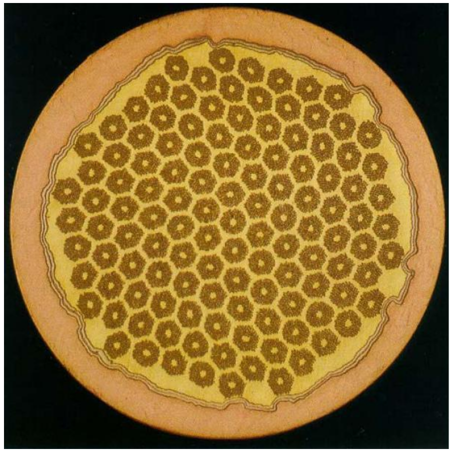
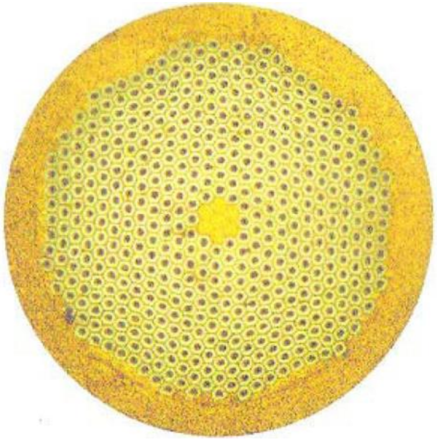
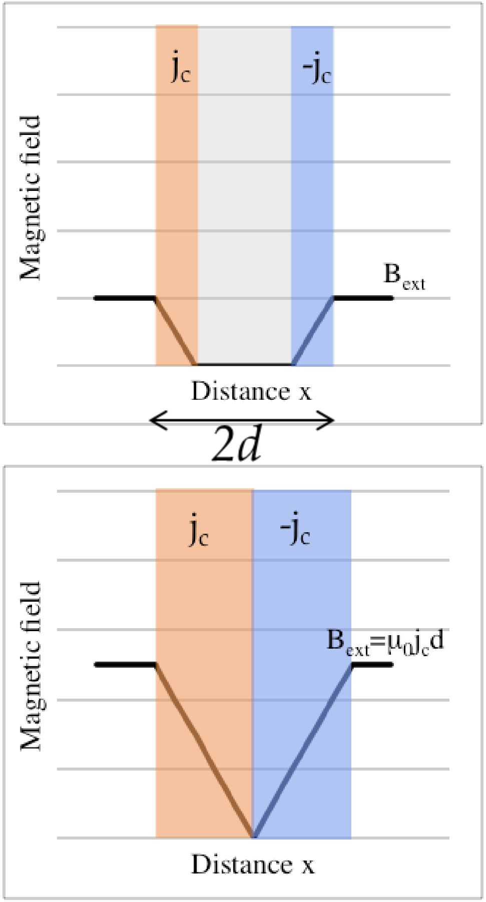
3. Multilfilament wires
Motivations

- The superconducting materials used in accelerator magnets are
  - subdivided in **filaments** of small diameters
  - **twisted** together
  - embedded in a **copper matrix**

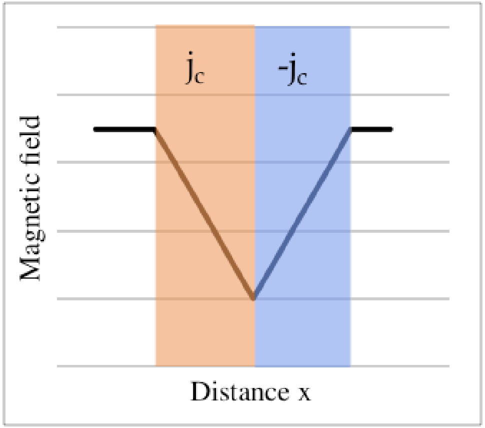





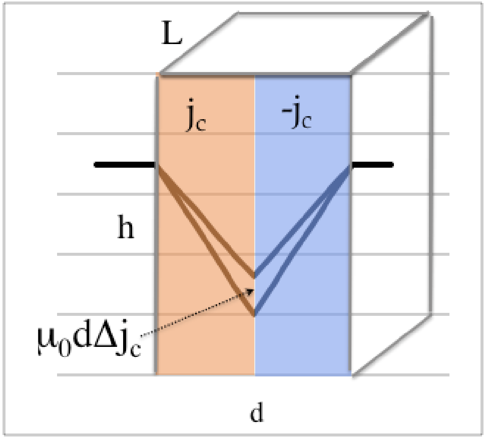
- **Filament size: magneto-thermal instabilities (flux jumps)**
  - Let's use the critical state model (CSM): a superconductor carries either current at j_c or no currents at all
  - Let us consider a simple geometry of a infinite slab of superconductor, of thickness $2d$ and we bring the external field to B_{ext}
  - A j_c over a thickness of Δx start flowing to shield the internal part of the slab
    - $B_{ext} = \mu_0 j_c \Delta x$
  - Since superconducting, this is a persistent current
  - The maximum field that can be shielded is the penetration field
    - $B_p = \mu_0 j_c d$



by E. Todesco

- **Filament size: magneto-thermal instabilities (flux jumps)**
  - If the external field increase further, the current cannot shield anymore and the field start increasing inside the slab
    - $B(x) = B_{ext} - \mu_0 j_c x$
  - Now let's have an increase of temperature ΔT_0 (local heat deposition by the beam, or mechanical movements and friction)
  - This induces a reduction of critical current density
  - Less critical current means less shielding, and therefore a change of magnetic field in the superconductor





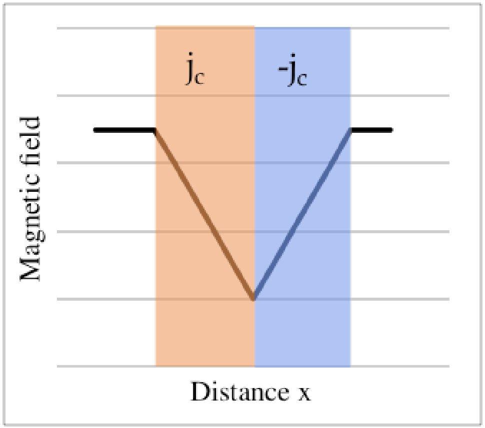
by E. Todesco

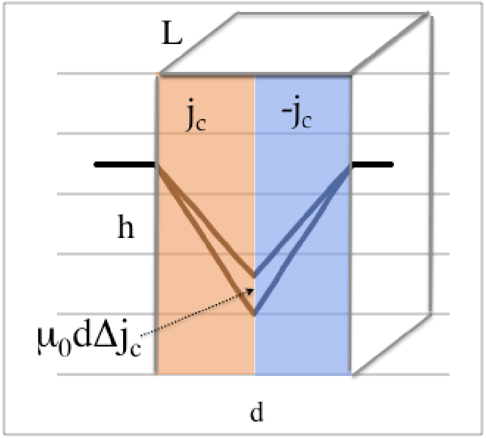
3. Multifilament wires
Motivations

- **Filament size: magneto-thermal instabilities (flux jumps)**
  - The change of magnetic field flux induces a voltage according to Maxwell

$$\Phi = \int B\, ds \qquad V = \frac{d\Phi}{dt}$$

  - The voltage and current induce a dissipation VI
  - The dissipation induces heat and a change of temperature ΔT_1
  - This induces a further reduction of critical current density….. ΔT_2 ….. ΔT_3 …..
  - If the sum $\Sigma\, \Delta T_k$ converges we are stable, otherwise there is a mechanism providing a divergence of temperature





by E. Todesco

3. Multifilament wires
Motivations

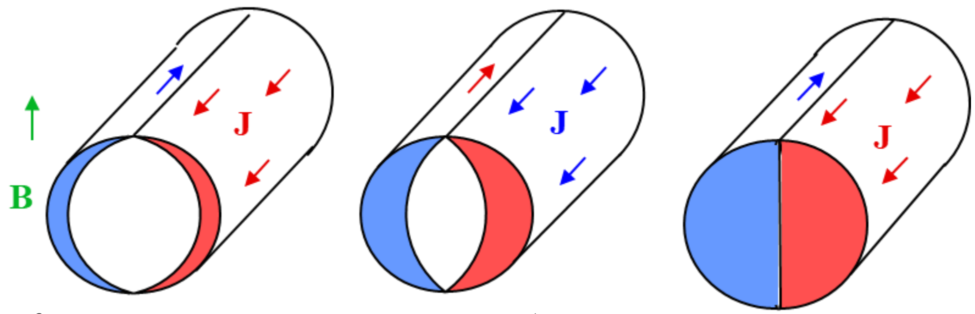
- **Filament size: magneto-thermal instabilities (flux jumps)**
  - Stability criteria

$$\frac{d}{2} < \frac{1}{j_c}\sqrt{\frac{3\gamma C_p\left(T_c - T\right)}{\mu_0}}$$

- C_p: specific heat
- J_c: critical current density
- γ: density
- T_c-T: difference between operational temperature and critical temperature

- Finer superconductor more stability
- Larger critical current less stability
- Filament diameters are usually less than 50 μm.

3. Multifilament wires
Motivations

- **Filament size: superconductor magnetization → field errors**
  - 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**
  - 

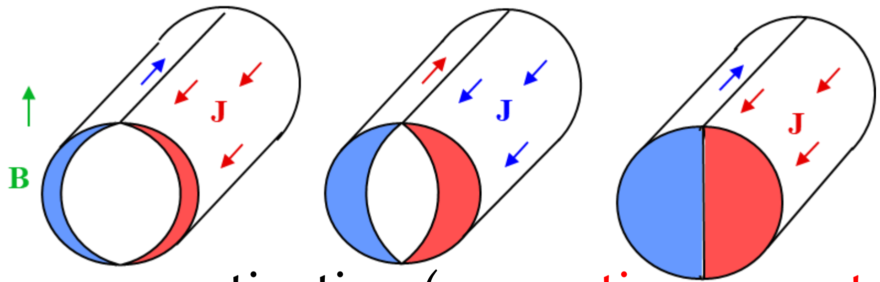
  - We can define a magnetization (magnetic moment per unit volume [J/T/m^3) for a filament with diameter d_f when fully penetrated

$$M_s = \frac{4}{3\pi} J_c a = \frac{2}{3\pi} J_c \boxed{d_f}$$

  - Perturbation of the magnetic field → Field errors
  - Finer superconductor, smaller critical current, less field errors
    - LHC filament diameter 6-7 μm, HERA filament diameter 14 μm.

3. Multifilament wires
Motivations

- **Filament size: superconductor magnetization → AC losses within the filaments**



  - We can define a magnetization (magnetic moment per unit volume [J/T/m^3) for a filament with diameter d_f when fully penetrated

$$M_s = \frac{4}{3\pi} J_c a = \frac{2}{3\pi} J_c d_f$$

  - This produce an AC loss power (W/m^3)

$$P = \dot{B} M = \frac{4}{3\pi} \dot{B} J_c a = \frac{2}{3\pi} \dot{B} \ J_c \boxed{d_f}$$

  - Again, finer superconductor, smaller critical current, less AC losses within the filament

3. Multifilament wires
Motivations

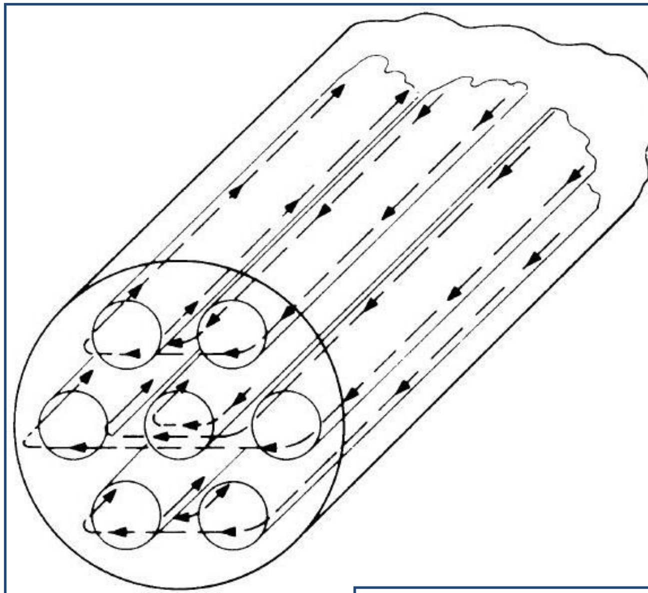
- Filament size: some examples

- Nb-Ti:
  - for the LHC main magnets filaments of 6-7 μm were used
  - For SIS-300 (fast ramped magnet) filament of 3 μm was used
- Nb_3Sn:
  - Today RRP technology can reach a minimum of 45 μm, PIT a bit less
  - LARP initially used a 70 μm (54/61 RRP), and then a 50 μm (108/127 RRP)
  - HL-LHC relies on RRP 108/127, and also used PIT with finer filaments (45 μm)

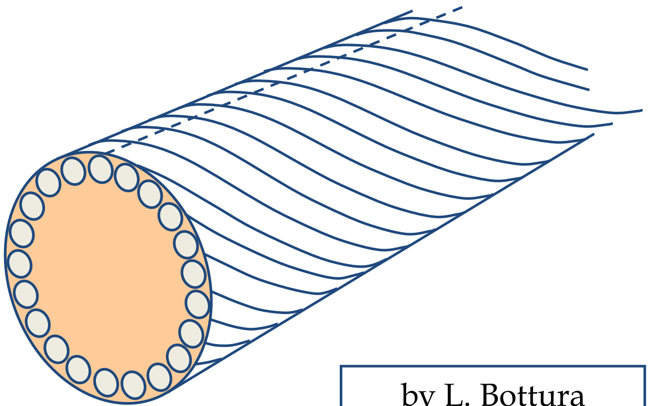
- **Filament twist: AC losses between the filaments**
  - When a multi-filamentary wire is subjected to a time varying magnetic field, **current loops** are generated between filaments.
  - If filaments are straight, large loops with large currents → **ac losses**
  - If the strands are magnetically coupled the effective filament size is larger → **flux jumps**
- Filaments are **twisted** to reduce the AC loss power (P_e $[W/m^3]$) with ρ_t resistivity across matrix and p_w wire twist pitch

$$P_e = \dot{B}M_e = \dot{B}^2 \frac{1}{\rho_t}\left[\frac{p_w}{2\pi}\right]^2 = \frac{\dot{B}^2}{\mu_o}2\tau$$

- Twist pitch p_w of the order of 20-30 times of the wire diameter.



by M. Wilson



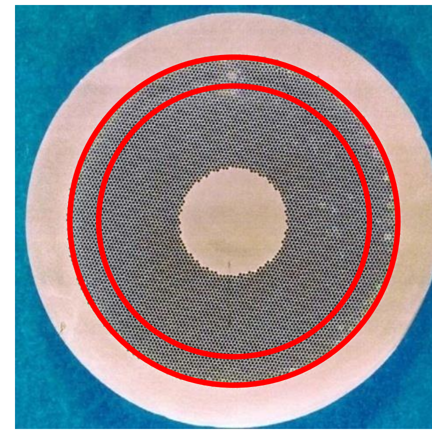
by L. Bottura

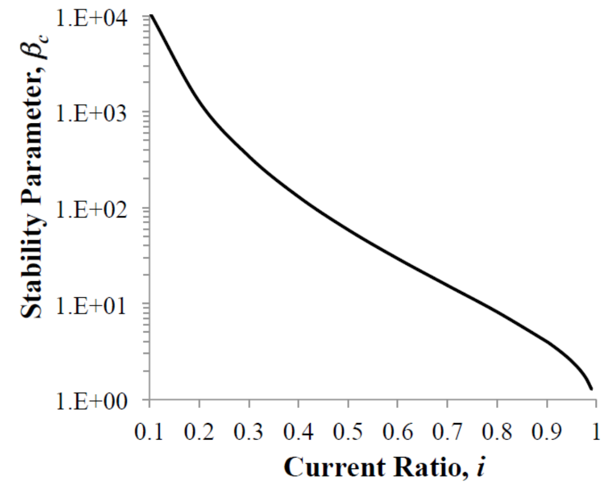
See work by B. Bordini

- **Strand diameter: magneto-thermal instabilities (self-field instability)**
  - When a transport current is ramped-up, the current flows only in the outermost filaments, with a j_c (again the CSM)
  - Similarly to the flux jump described before….thermal input → reduction j_c → $\Delta\Phi$ → VI → ….→
  - A simplified criterion:

$$\beta = \mu_0 \lambda^2 \left|\frac{dj_c}{dT}\right| \frac{R^2}{\upsilon} j_c \leq \beta_c = \left\{-\frac{1}{2}\ln(\varepsilon) - \frac{3}{8} + \frac{\varepsilon^2}{2} - \frac{\varepsilon^4}{8}\right\}^{-1}$$

  - Where λ is the superconductor fraction, ν volumetric specific heat of the strand, ***R*** strand radius, I –I/I_c -1-ε^2
  - Usually strand are within 0.5 and 1.1 mm diameter.





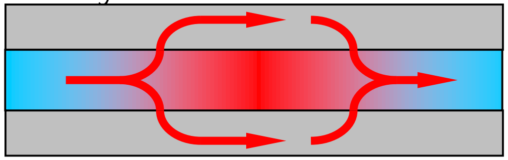
3. Multifilament wires Motivations

- Strand diameter: some examples

- Usually between 0.5 mm and 1.1 mm
  - 0.48-mm-diameter Nb-Ti strand used in LHC matching sections MQM and MQY magnets, in HL-LHC used for nested correctors MCBXF (CIEMAT, Spain)
  - LHC Nb-Ti strand for main dipoles:
    - 0.825-mm-diameter
    - 1.065-mm-diameter
  - Nb_3Sn strands:
    - 0.7 mm diameter for TQ, 11 T
    - 0.8 mm diameter for HD2, HQ
    - 0.85 mm diameter for MQXF
    - 1.0 mm for Fresca2, MCBPCTD
    - 1.25-mm-diameter strand proposed for NED Nb_3Sn magnet, very rigid and difficult to wind – used in racetrack coils
    - Large diameter strand also suffer from larger instabilities

3. Multifilament wires
Motivations

- **Cu matrix**
  - Superconductors have a very high normal state resistivity. It can be shown that a filament of Nb-Ti, if quenched in free space, could reach **very high temperatures** in few ms.
  - If the filament is embedded in a copper matrix, when a quench occurs, the **current redistributes** in the low-resistivity matrix and the peak temperature can typically be maintained below 300 K.



by L. Bottura

  - The copper matrix facilitates quench protection: it allows the quench to **propagate** and it provides time to act on the power circuit.
  - In the case of a small volume of superconductor heated beyond the critical temperature (for instance because of a flux jump), the current can flow in the copper for a short moment, allowing the filament to **cool-down and recover** superconductivity.
    - The matrix also helps stabilizing the conductor against flux jumps (dynamic stability).

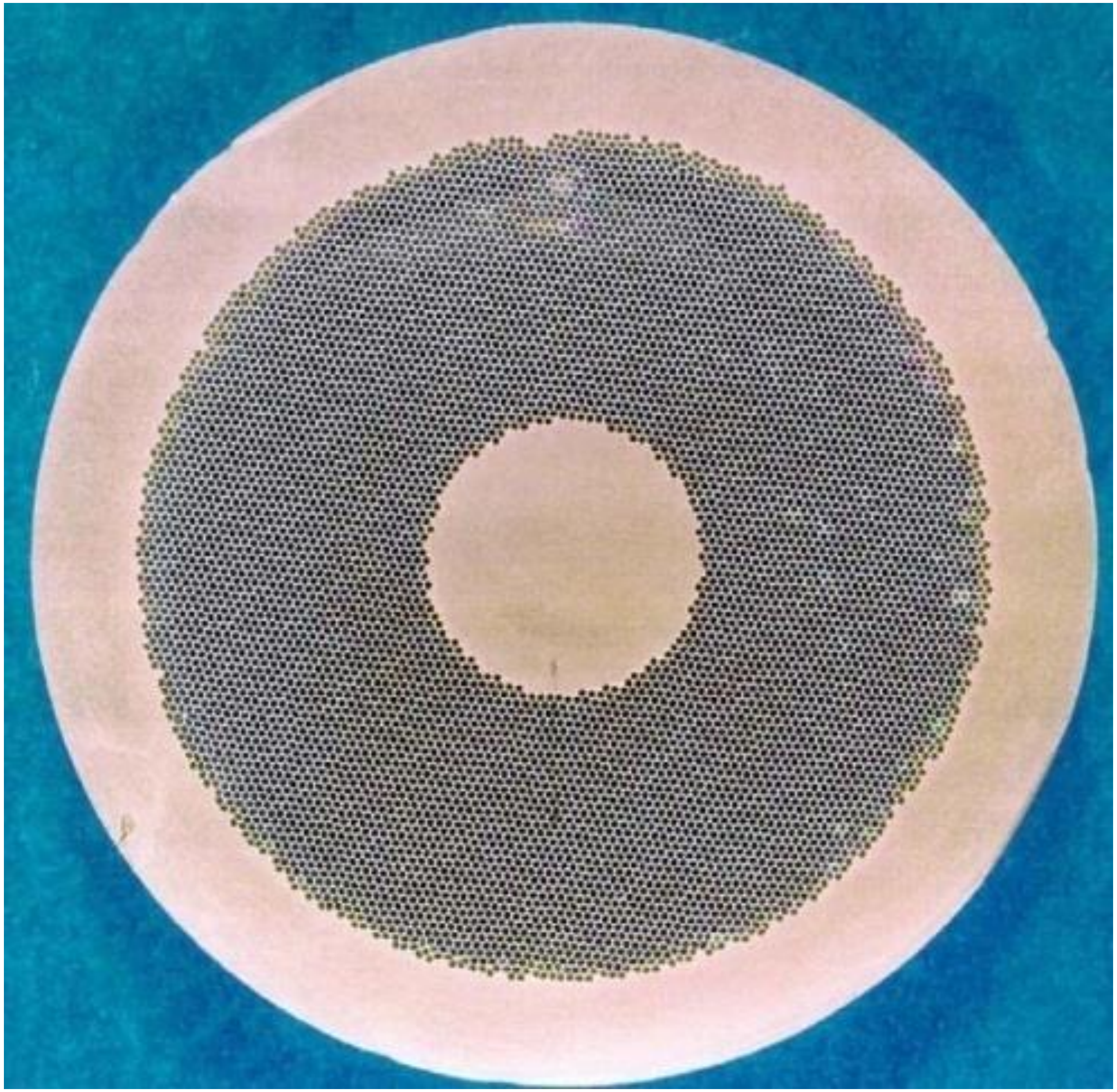
3. Multifilament wires
Motivations

- **Cu matrix:** some examples

- Copper ratio definition
  - Cu/non-Cu of x means that in the strand cross-section one has a quantity 1 of superconductor and a quantity x of Cu
  - Example: Cu/non-Cu = 2 means 1/(1+2) = 33% of superconductor and 2/(1+2) = 67% of Cu
- Usually between 1 and 2
  - Corrector magnets where current density is not critical can have much larger (above 2)
  - For main magnets current density is critical, but one needs some Cu to stabilize and protect the magnet
  - LHC dipoles: 1.65 (inner layer) and 1.95 (outer layer)
  - HL-LHC: 1.1 (11 T) and 1.2 (MQXF)
  - LARP TQ: 0.89
  - A ratio of 0.4 was used (successfully) in D20, a short model magnet – not viable for long magnets
- Cu RRR (the ratio of Cu resistivity at 293 K to the resistivity at 4.2 K)
  - The residual resistivity ratio of copper is an important parameter for stability – larger than 100 in cables, larger than 150 in wires

3. Multifilament wires
Motivations

- Filament size
  - Flux jumps
  - Magnetization
    - AC losses within filament
    - Persistent current (effect on magnetic field)
- Filament twisting
  - AC losses
  - Flux jumps (less filament coupling)
- Strand size
  - Self field stability
- Cu matrix
  - Quench protection/stability
  - Flux jump and self-field

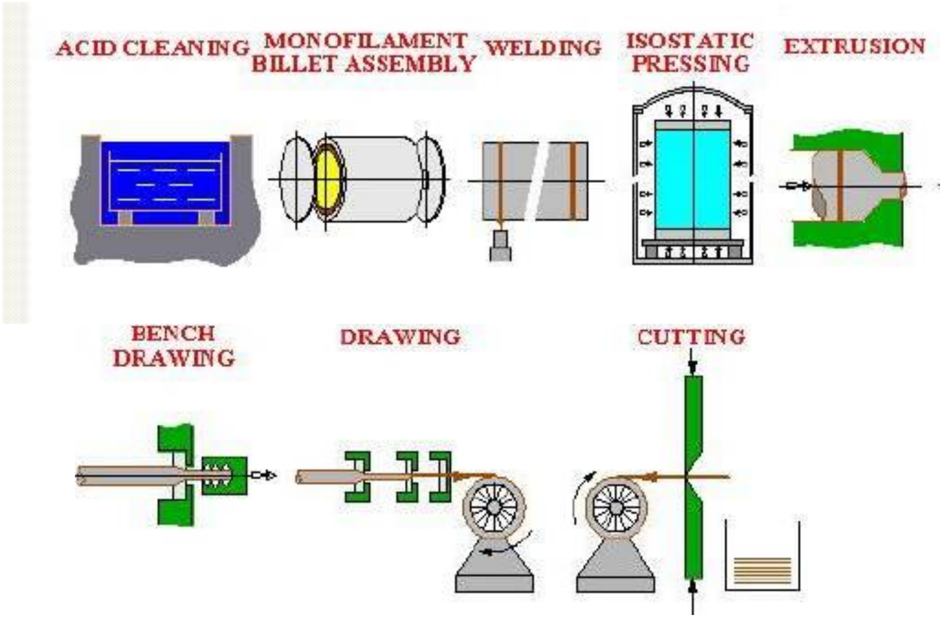


Outline

1. Introduction and history
2. Superconducting materials
    1. Nb-Ti, Nb_3Sn, and their critical surfaces
3. **Multifilament wires**
    1. Motivations and fabrication
4. Superconducting cables
    1. Motivations and fabrication
5. Cable insulation
6. Filling factor
7. Conclusions

3. Multifilament wires
Fabrication of Nb-Ti multifilament wires

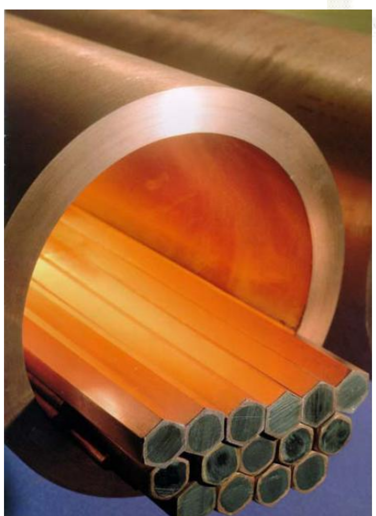
- The fabrication of Nb-Ti wire starts from the production of **Nb-Ti ingots** (with a 200 mm diameter and 750 mm height).
- A monofilament billet is assembled, extruded, and drawn down in small pieces (**monofilament rods**) about 800 mm long and 50 mm in diameter.

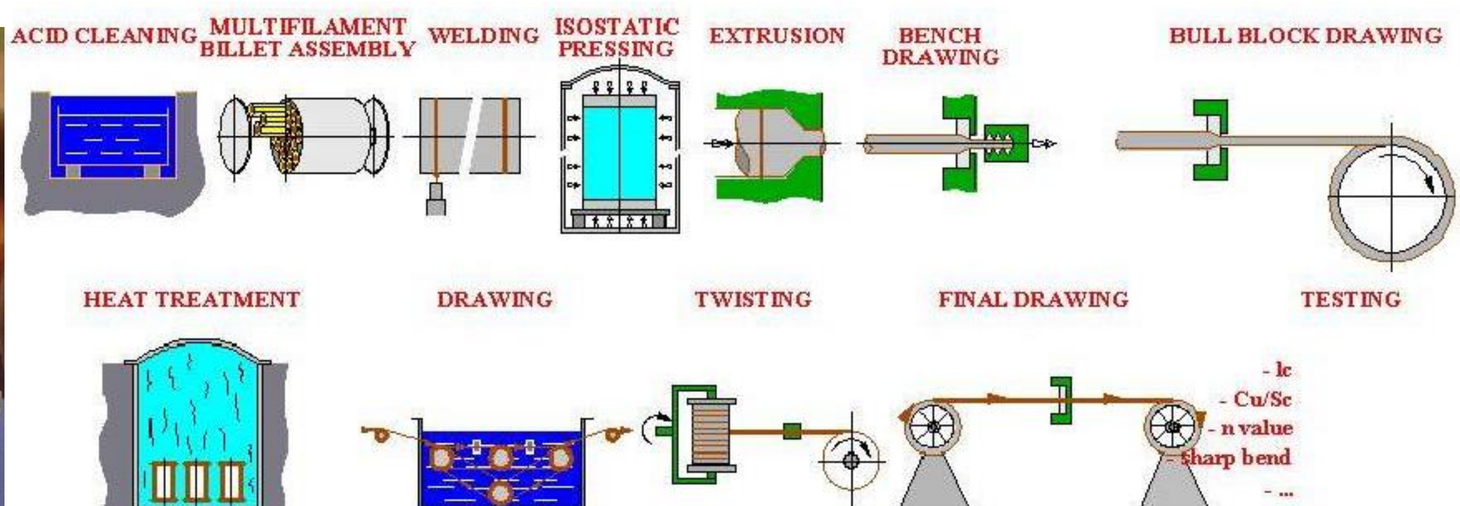


A. Devred, [1]

3. Multifilament wires
Fabrication of Nb-Ti multifilament wires

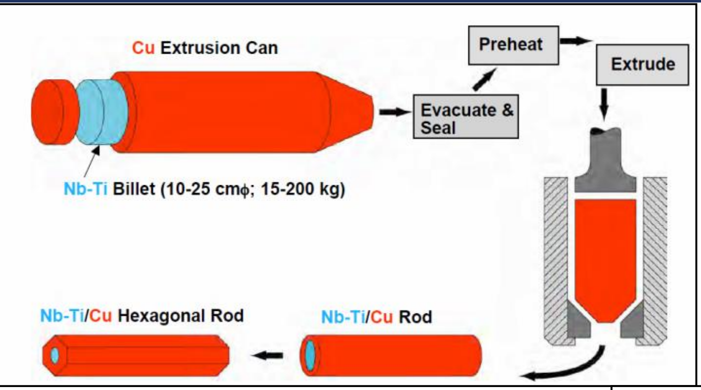
- Monofilament rods are stacked to form a **multifilament billet**, which is then extruded and drawn down.
- Heat treatments are applied to produce **pinning centers** (α-Ti precipitates).
- When the number of filaments is very large, multifilament rods can be **re-stacked** (double stacking process).

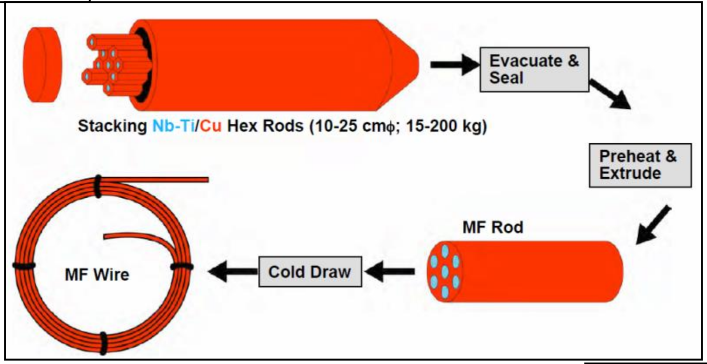


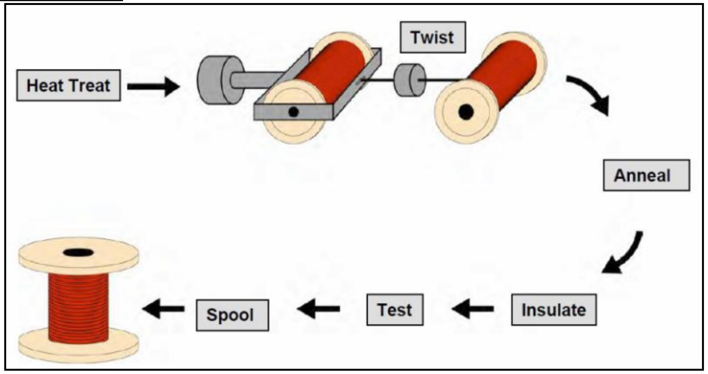


A. Devred, [1]

3. Multifilament wires
Fabrication of Nb-Ti multifilament wires

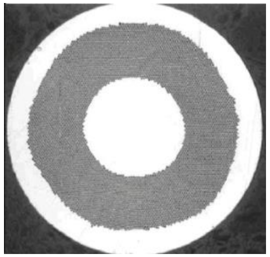






3. Multifilament wires
Fabrication of Nb-Ti multifilament wires

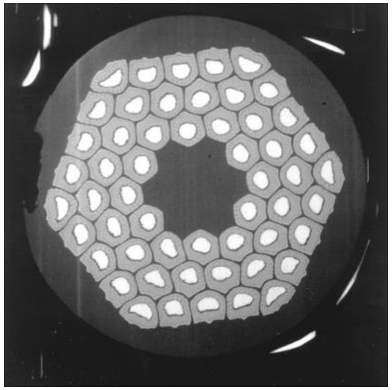
- The **copper to superconductor ratio** is specified for the application to ensure quench protection, without compromising the overall critical current of wire.
- The **filament diameter** is chosen to minimize flux jumps and field errors due to persistent currents, at the same time maintaining the wire processing cost down.



- The **inter-filament spacing** is kept small so that the filaments, harder then copper, support each other during drawing operation. At the same time, the spacing must be large enough to prevent filament couplings.
- A **copper core and sheath** is added to reduce cable degradation.
- The main manufacturing issue is the **piece length**.
  - It is preferable to wind coils with single-piece wire (to avoid welding). LHC required piece length longer than 1 km.

3. Multifilament wires
Fabrication of Nb_3Sn multifilament wires

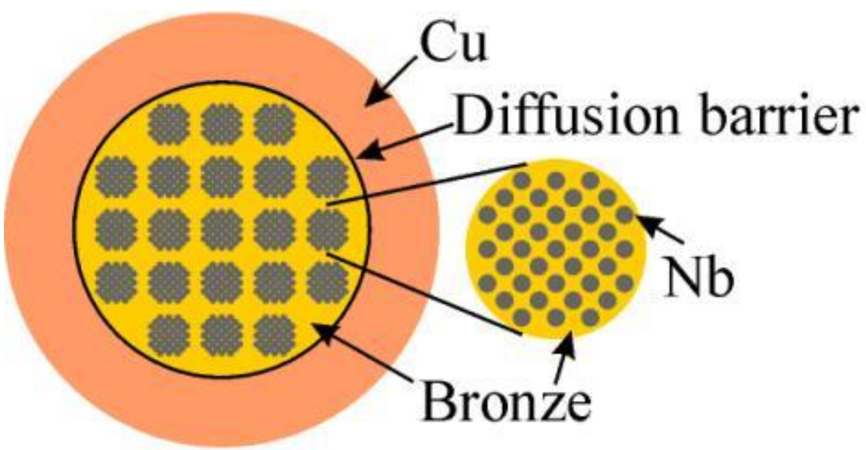
- Since Nb_3Sn is brittle, it **cannot be extruded** and drawn like NbTi. It must be formed at the end of the fabrication of the cable (or the coil).
- The process requires **several steps**:
  - Assembly multifilament billets from Nb_3Sn precursor (CuSn and Nb).
  - Fabrication of the wire through extrusion-drawing technique.
  - Fabrication of the cable.
  - Fabrication of the coil: two different techniques
    - **"Wind & react"** (more common)
      - First coil winding and then formation of Nb_3Sn
    - **"React & wind"**
      - First formation of Nb_3Sn and then coil winding



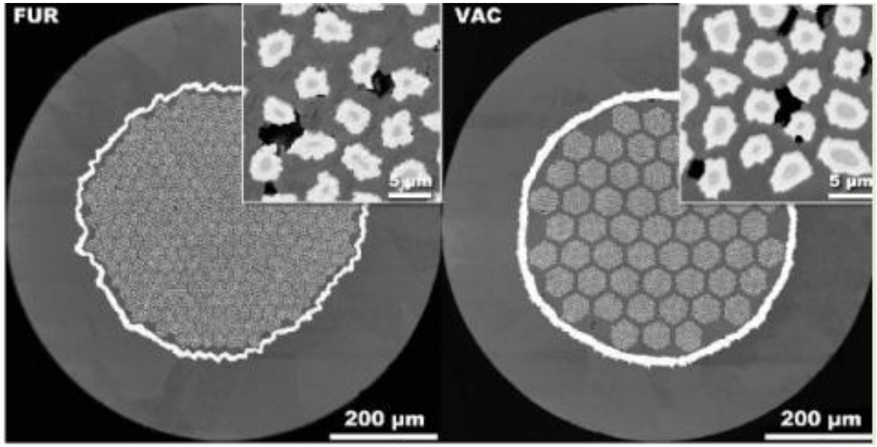
- During the **"reaction",** the CuSn and Nb are heated to about 600-700 C in vacuum or inert gas (argon) atmosphere, and the Sn diffuses in Nb and reacts to form Nb_3Sn.
- There are 4 main types of processes to form Nb_3Sn wires.

Fabrication of Nb_3Sn multifilament wires

- **Bronze process**
  - Nb rods are inserted in a bronze (CuSn) matrix. Pure copper is put in the periphery and protected with a diffusion barrier (Ta) to avoid contamination.
  - Advantage: small filament size
  - Disadvantage: limited amount of Sn in bronze and annealing steps during wire fabrication to maintain bronze ductility.
  - Non-Cu J_C up to 1000 A/mm^2 at 4.2 K and 12 T.

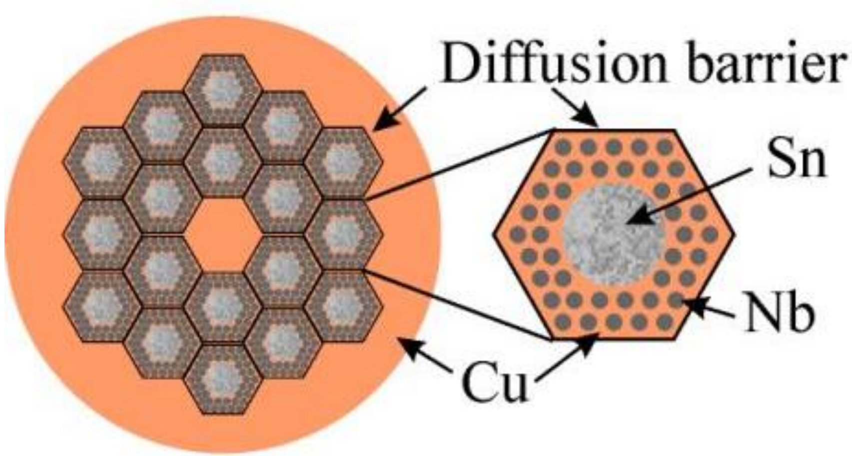


A. Godeke, [2].

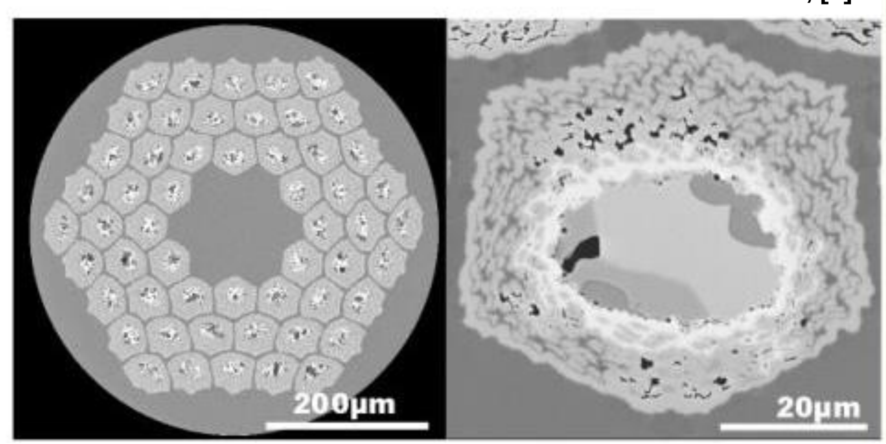


Internal tin process

- 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 (50 μm) and large magnetization effect and instability.
- Non-Cu J_C up to 3000 A/mm^2 at 4.2 K and 12 T.



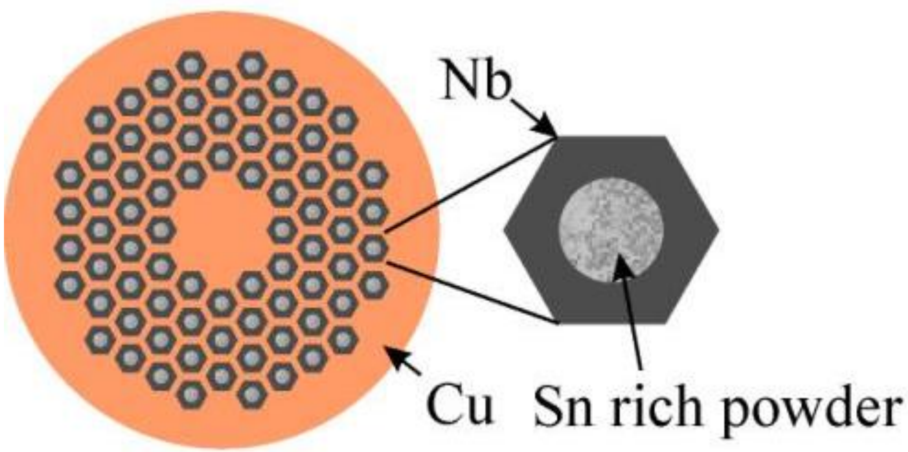
A. Godeke, [2].

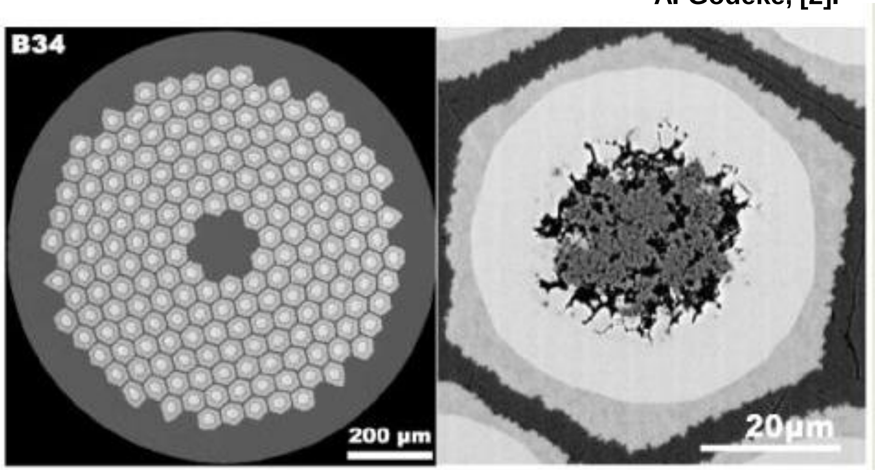


Fabrication of Nb_3Sn multifilament wires

- **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 2400 A/mm^2 at 4.2 K and 12 T.

A. Godeke, [2].

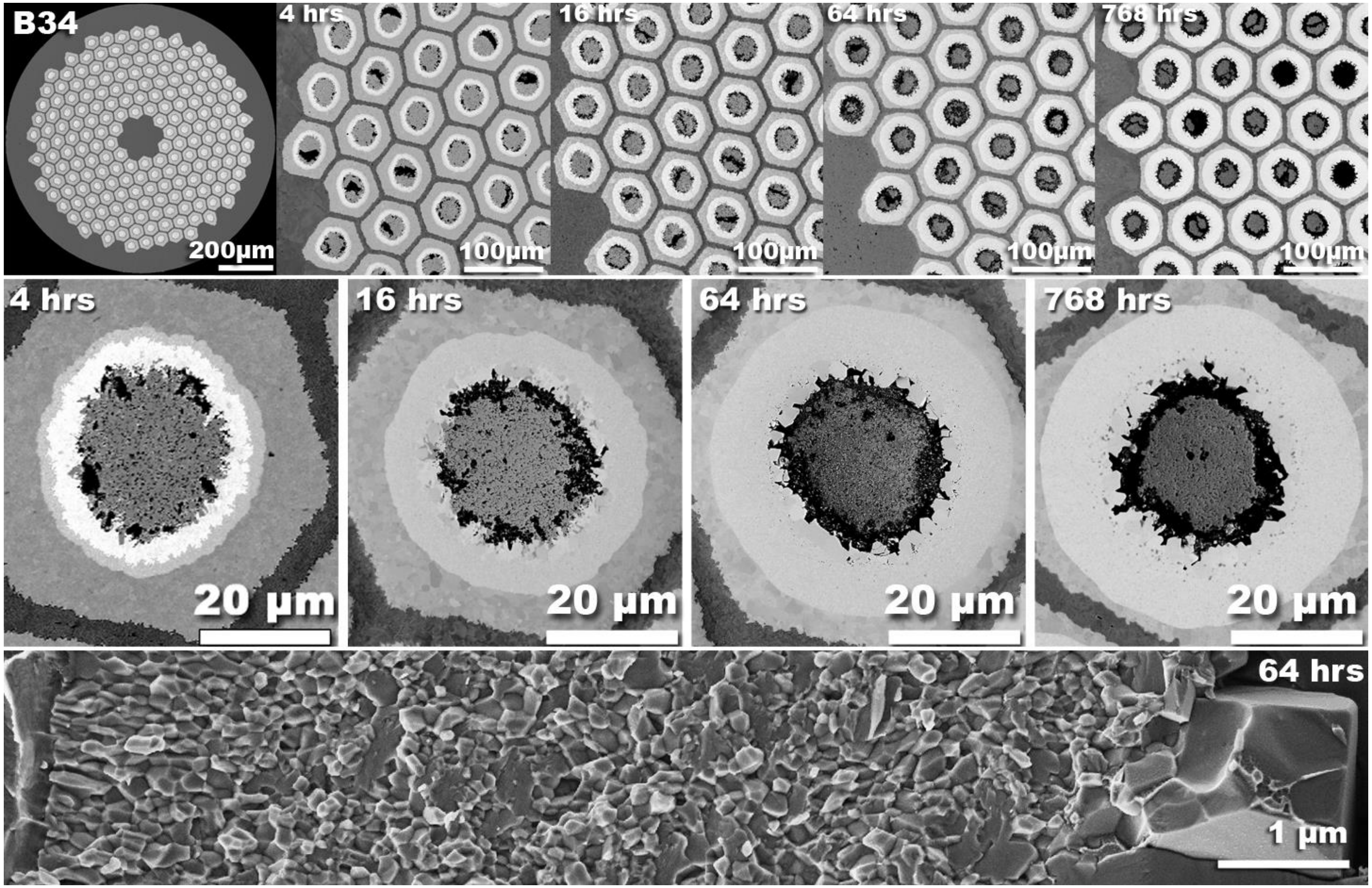




Fabrication of Nb_3Sn multifilament wires

- Reaction of a PIT wire:

A. Godeke, [2].



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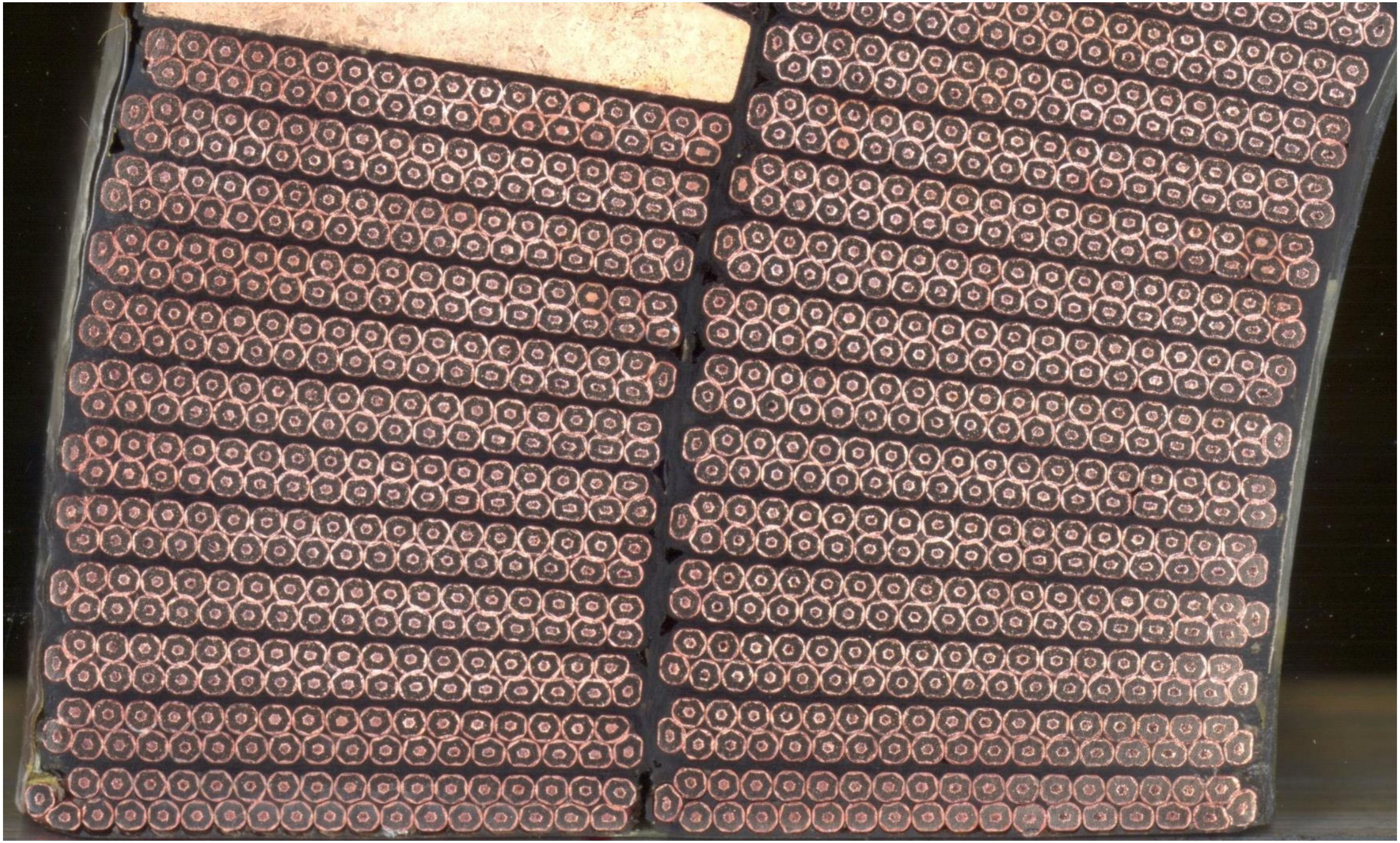
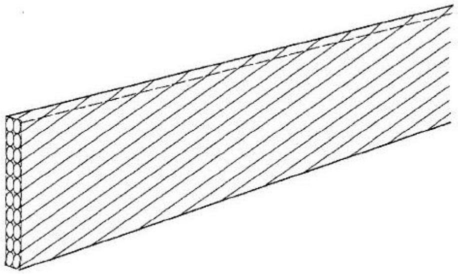
6. Filling factor
7. Conclusions

4. Superconducting cables



4. Superconducting cables
Motivations

- Most of the superconducting coils for particle accelerators are wound from a **multi-strand cable**.
- The advantages of a multi-strand cable are:
  - reduction of the strand piece length;
  - reduction of number of turns
    - easy winding;
    - smaller coil inductance
      - less voltage required for power supply during ramp-up;
      - after a quench, faster current discharge and less coil voltage.
  - current redistribution in case of a defect or a quench in one strand.



- The most commonly used multi-strand cables are the **Rutherford cable** and the cable-in-conduit.

4. Superconducting cables Motivations

- The strands are **twisted** to
  - reduce interstrand coupling currents (see interfilament coupling currents): losses
  - Considering a cable with N strands
    - transverse field crossover resistance power W.m^{-3}

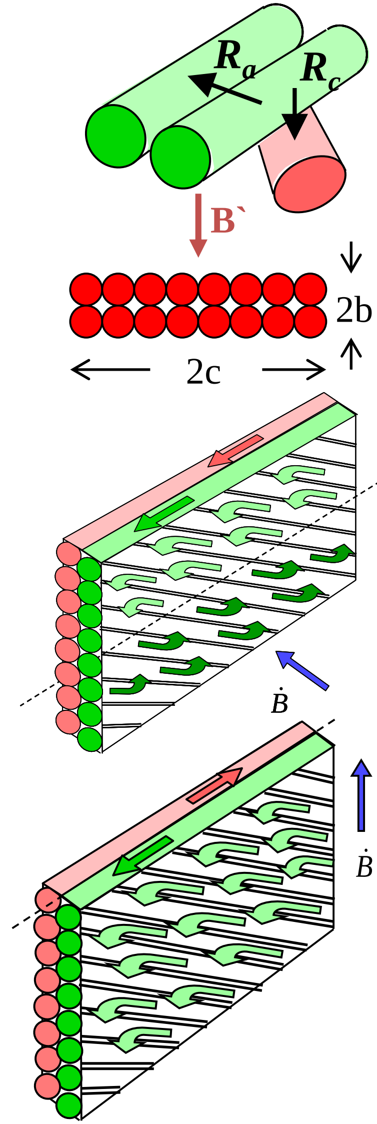
$$P_{tc} = \lambda_{cu} \frac{1}{120} \frac{\dot{B}_t^2}{R_c} \frac{c}{b} \boxed{p_c} N(N-1)$$

    - transverse field adjacent resistance power W.m^{-3}

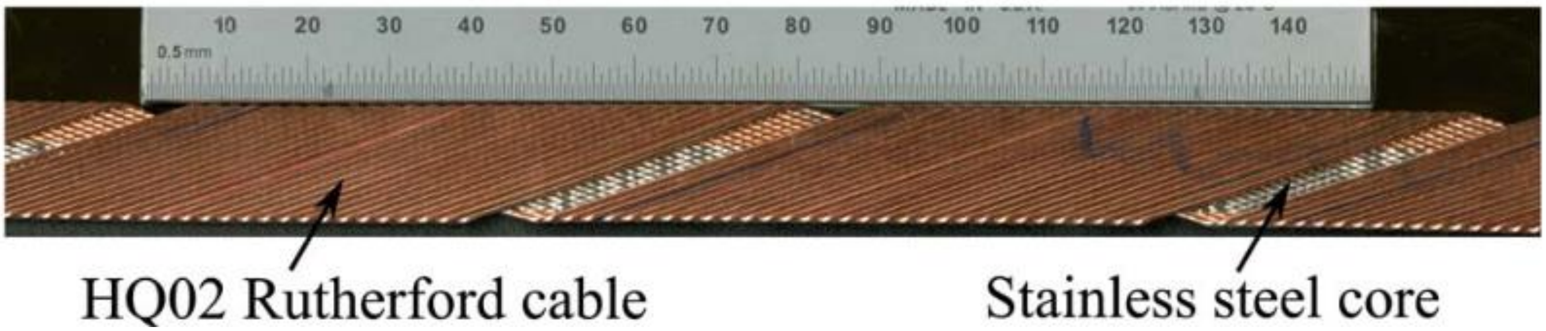
$$P_{ta} = \lambda_{cu} \frac{1}{6} \frac{\dot{B}_t^2}{R_a} \boxed{p_c} \frac{c}{b}$$

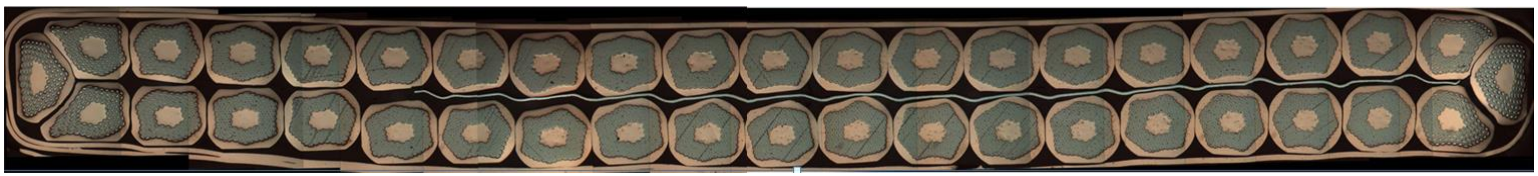
    - parallel field adjacent resistance power W.m^{-3}

$$P_{pa} = \lambda_{cu} \frac{1}{8} \frac{\dot{B}_p^2}{R_a} \boxed{p_c} \frac{b}{c}$$

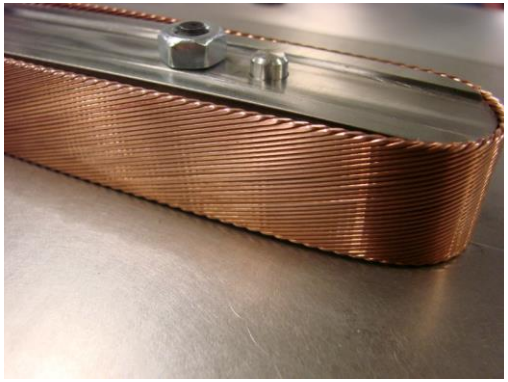


- The coupling currents can have a significant impact also on the field quality: ss core to further reduce them



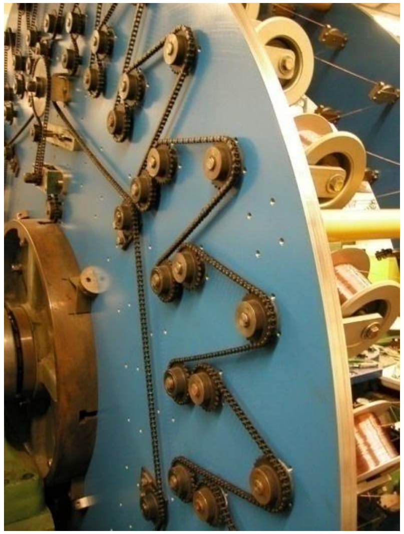


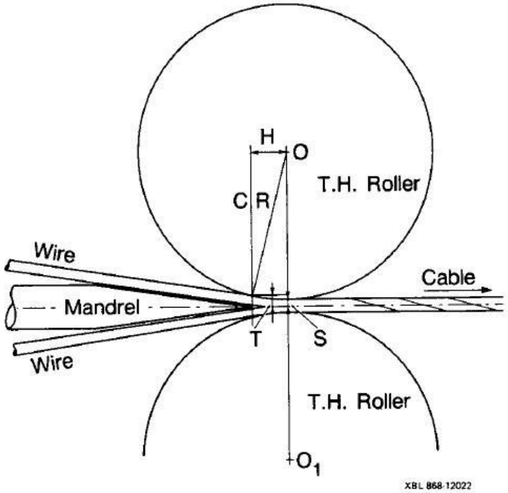
- The twist provide also more mechanical stability for winding

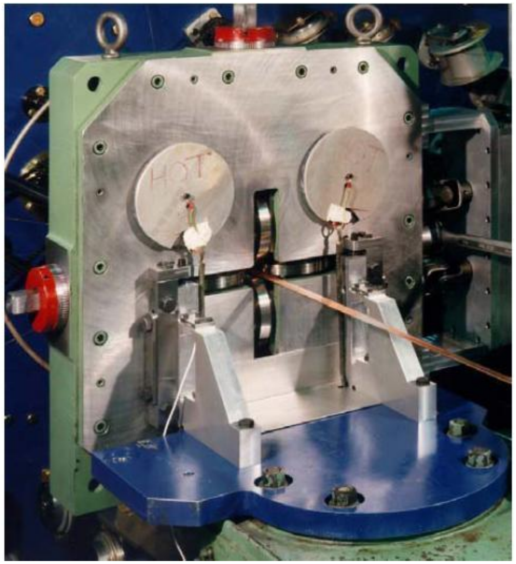


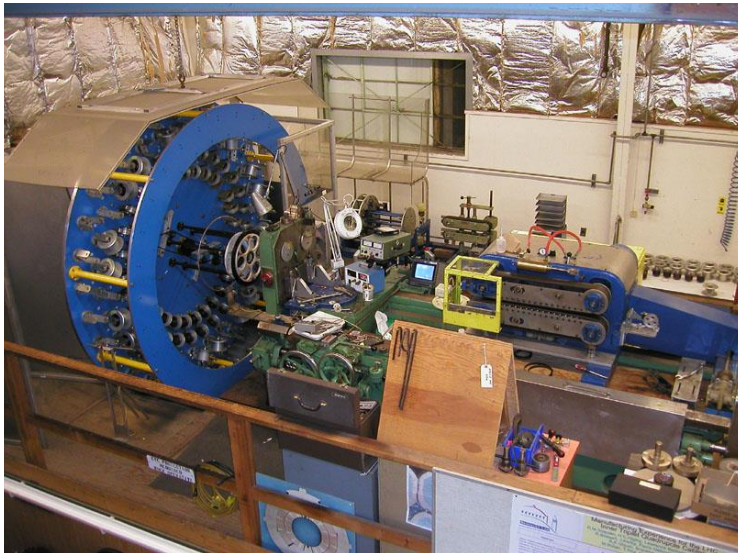
4. Superconducting cables
Fabrication of Rutherford cable

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









4. Superconducting cables
Fabrication of Rutherford cable

- How many strands ?
  - As low as 6 (correctors, undulators, subscales…)
  - LHC dipoles had 28 and 36 strand cables
  - Cabling machine at CERN is limited at 40 strands – this is the number used for MQXF and 11 T
  - Cabling machine in FNAL is limited by 42 strands
  - Cabling machine in LBNL is limited by 60 strands – HD2 cable used 51 strands

4. Superconducting cables
Fabrication of Rutherford cable

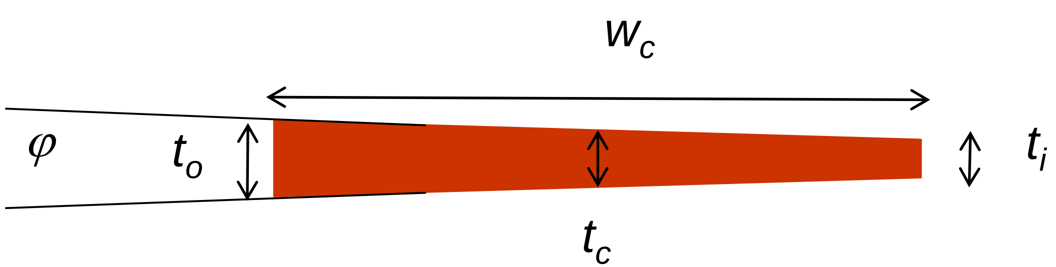
- The final shape of a Rutherford cable can be **rectangular or trapezoidal.**
- The cable design parameters are:
  - Number of wires N_{wire}
  - Wire diameter d_{wire}
  - Cable mid-thickness t_{cable}
  - Cable width w_{cable}
  - Pitch length p_{cable}
  - Pitch angle ψ_{cable} ($\tan\psi_{cable} = 2\, w_{cable} / p_{cable}$)
  - **Cable compaction** (or packing factor) k_{cable}

$$k_{cable} = \frac{N_{wire} \pi d_{wire}^2}{4 w_{cable} t_{cable} \cos\psi_{cable}}$$

  - i.e the ratio of the sum of the cross-sectional area of the strands (in the direction parallel to the cable axis) to the cross-sectional area of the cable.
- Typical cable compaction: from 88% (Tevatron) to 92.3% (HERA).

4. Superconducting cables
Fabrication of Rutherford cable

- The cable compaction is chosen to provide good **mechanical stability** and high current capability at the same time leaving enough space for helium cooling or epoxy impregnation.
- The trapezoidal shape allow stacking cables in an **arc-shaped coil** around the beam pipe of a dipole or quadrupole.
- When a cable has a trapezoidal (or keystone) shape, the defining parameter is the **keystone angle** φ_{cable} given by



$$t_o = t_c\left(1 + \frac{w_c}{2}\cos\varphi\right)$$

$$t_i = t_c\left(1 - \frac{w_c}{2}\cos\varphi\right)$$

$$\tan\varphi_{cable} = \frac{t_{cable\_out} - t_{cable\_in}}{w_{cable}}$$

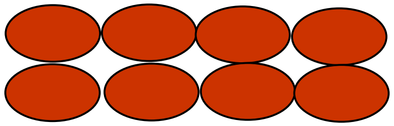
- Cables often exhibit **degradation**: critical current density of a virgin wire before cabling is higher then the one of a wire after cabling.

4. Superconducting cables
Fabrication of Rutherford cable

- Keystone angle
  - Nb-Ti accepts a larger keystone angle – it can be order of 1 degree
  - It was 1.25° for inner layer cable, 0.90° for outer layer
  - 2.16° used for MQY inner layer cable
  - For Nb_3Sn 0.7° used in 11 T, 0.4° used in MQXF (larger aperture)

4. Superconducting cables
Fabrication of Rutherford cable

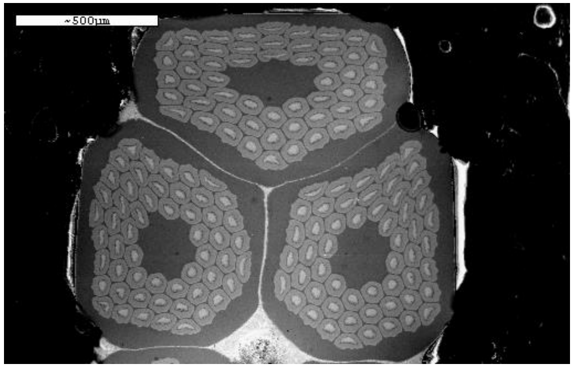
- The size is given after cabling, at room temperature, with some azimuthal pressure: be careful about the following details
  - The level of azimuthal pressure has to be defined (5 MPa ?)
  - Cable could be given at 1.9 or 4.2 K (already with thermal contraction)
  - In case of Nb_3Sn, there is a difference between before/after reaction that can be of few percent
- Pitch length
  - The transposition of the wires makes the cross section composed of elliptic strands, not circular
  - Pitch length p_{cable}
  - Pitch angle ψ_{cable} ($\tan\psi_{cable} = 2\, w_{cable} / p_{cable}$)

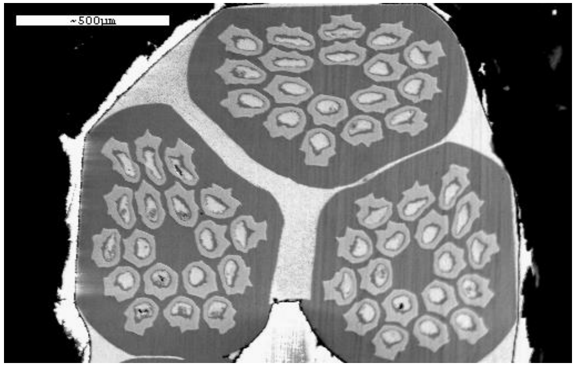


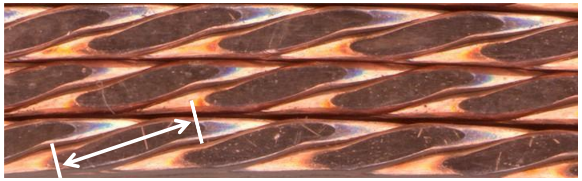
  - The area if the ellipse is $1/\cos\psi_{cable}$ larger than the area of the strand

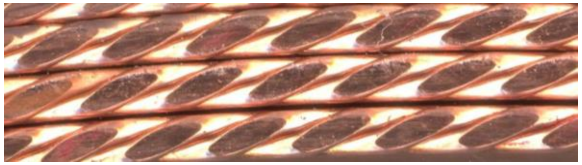
4. Superconducting cables
Fabrication of Rutherford cable

- In the cable sides, the **strands are deformed**; the deformation determines
  - a reduction of the filament cross-sectional area (Nb-Ti) or
  - breakage of reaction barrier with incomplete tin reaction (Nb_3Sn).
- In order to avoid degradation
  - The strand cross-section after cabling is investigated
  - Edge facets are measured
    - General rule: no overlapping of consecutive facets
- Keystone angle is usually **limited** to 1 or 2°.
- We define as **narrow edge compaction or packing factor** the ratio of the area of two non-deformed strands to that of a rectangle with dimensions of the narrow edge thickness times the wire diameter, that is $\pi d/2t_{in}$.
- Usually it ranges from 0.95 to 1.03.





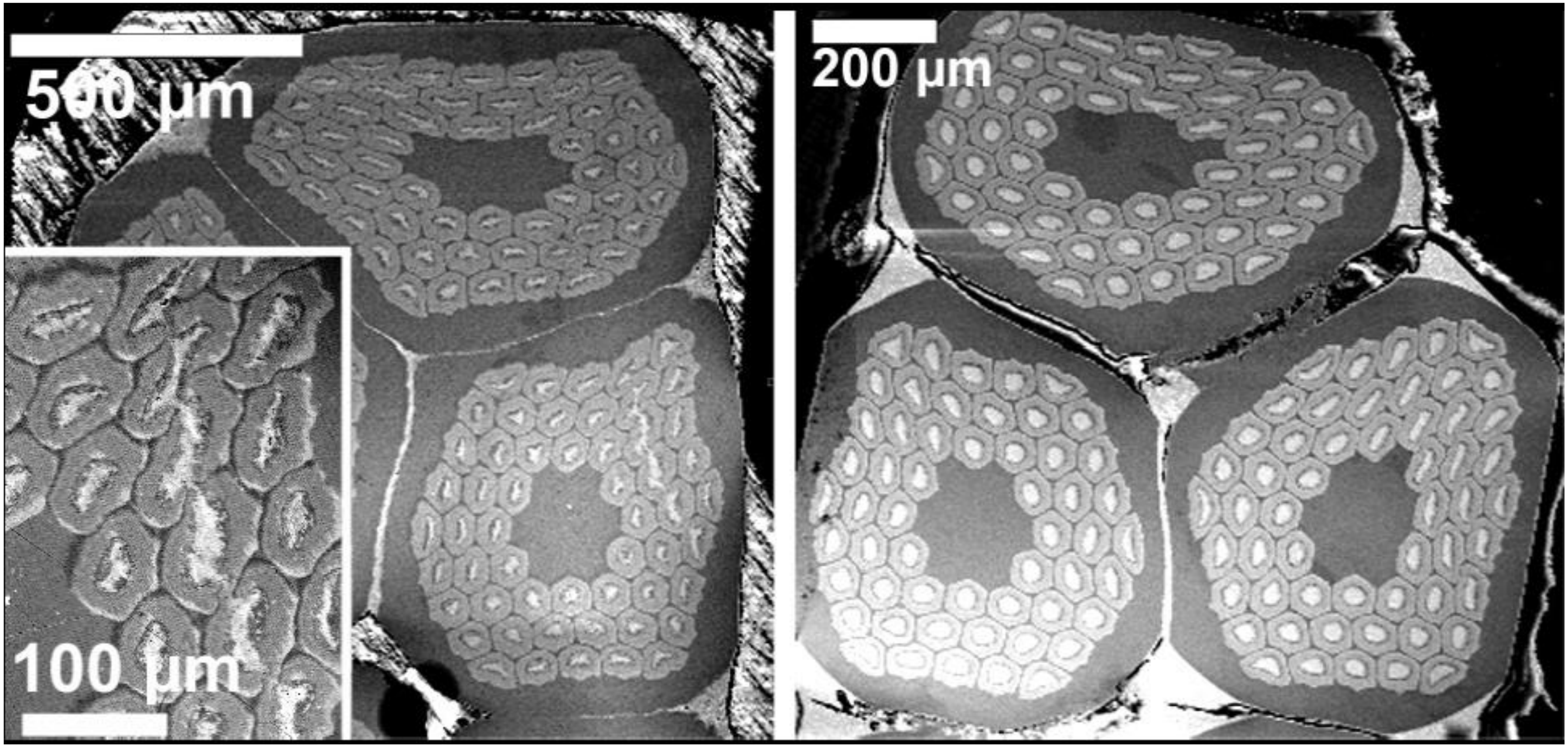




4. Superconducting cables
Fabrication of Rutherford cable

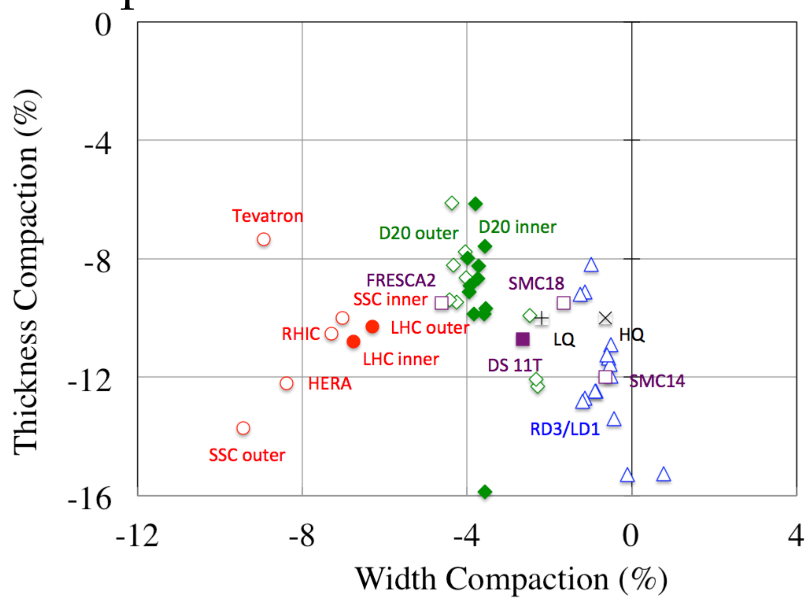
- Bad edge deformation
- Good edge deformation

D. Dietderich, [6].



- Compaction
  - We can distinguish between thickness and width compaction
  - Nb-Ti is more compacted than Nb_3Sn to avoid the danger of roping
  - Nb_3Sn is less compacted than Nb-Ti to avoid the danger of degradation

$$c_t = \frac{t_c}{2d_s} - 1$$



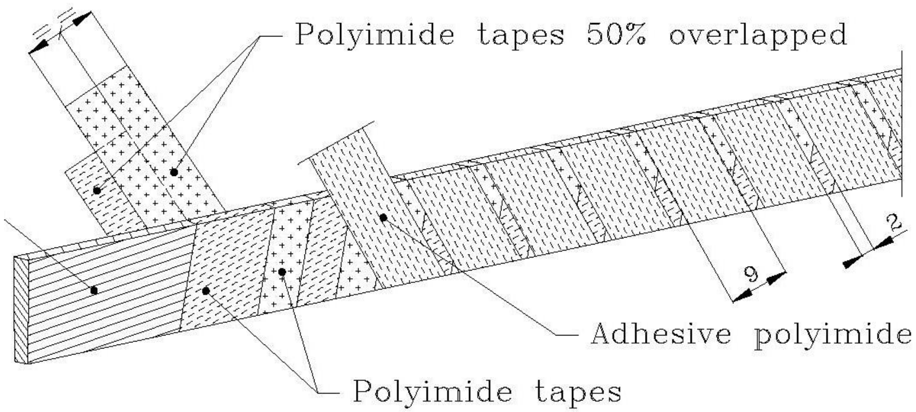
$$c_w = \frac{w_c}{\left(\frac{N_s}{2\cos\psi_c} + 0.732\right)d_s} - 1$$

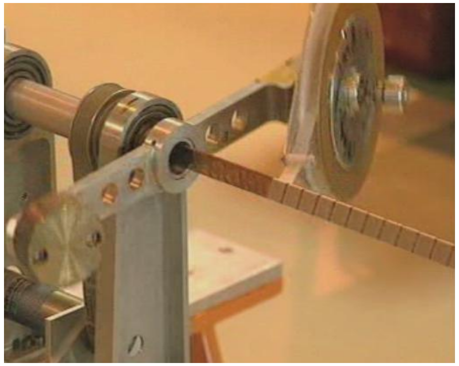
Outline

1. Introduction and history
2. Superconducting materials
    1. NbTi, Nb_3Sn, and their critical surfaces
3. Multifilament wires
    1. Motivations and fabrication
4. Superconducting cables
    1. Motivations and fabrication
5. **<u>Cable insulation</u>**
6. Filling factor
7. Conclusions

5. Cable insulation

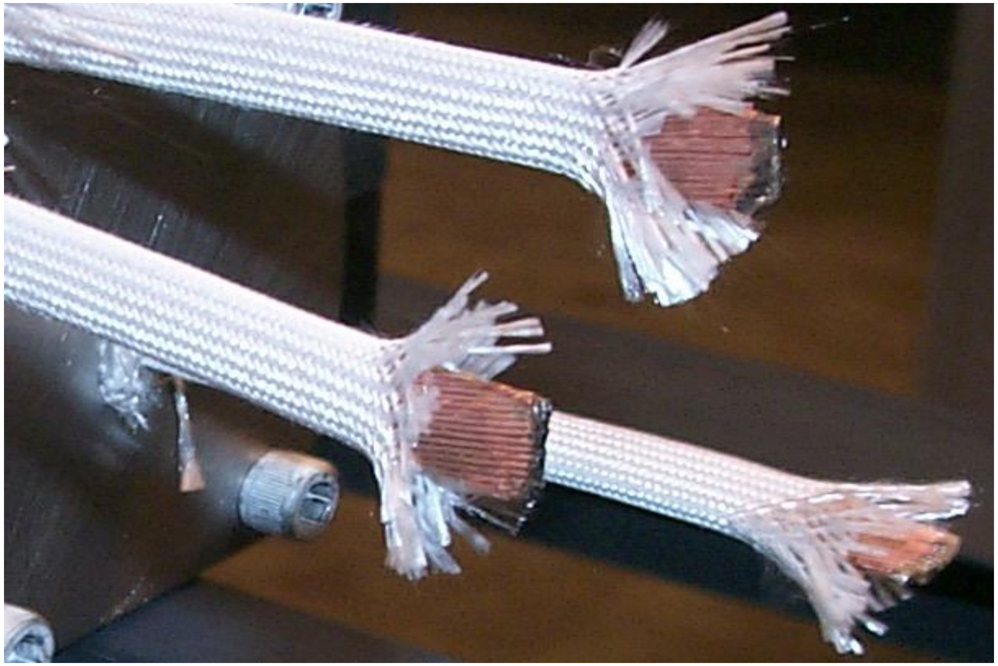
- The **cable insulation** must feature
  - Good electrical properties to withstand high turn-to-turn voltage after a quench.
  - Good mechanical properties to withstand high pressure conditions
  - Porosity to allow penetration of helium (or epoxy)
  - Radiation hardness
- In Nb-Ti magnets the most common insulation is a series of overlapped layers of **polyimide** (kapton).
- In the LHC case:
  - two polyimide layers 50.8 μm thick wrapped around the cable with a 50% overlap, with another adhesive polyimide tape 68.6 μm thick wrapped with a spacing of 2 mm.





5. Cable insulation

- In Nb_3Sn magnets, where cable are reacted at 600-700 °C, the most common insulation is **fiberglass**: tape or sleeve or braided.
- Typically the insulation thickness varies between 100 and 200 μm.



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5. Cable insulation
6. **Filling factor**
7. Conclusions

6. Filling factor

- Each strand is characterized by a **copper to superconductor** (Nb-Ti) or copper to non-copper area.
- Each cable includes **voids**.
- The **insulation** occupies additional area.
- The **filling factor κ** is defined as the ratio of the superconductor or non copper area to the total area of the cable, including insulation, i.e,

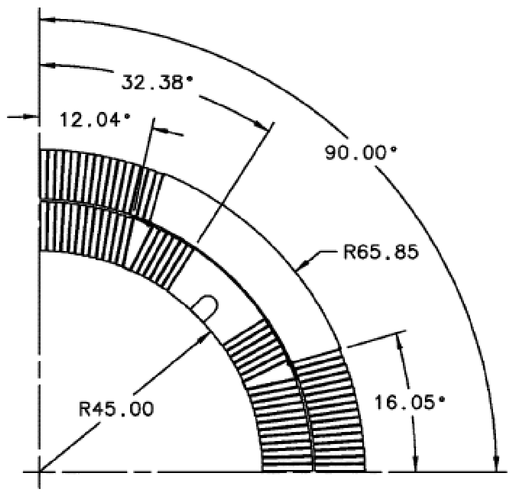
$$\kappa = (N_{wire} A_{sc})/A_{ins-cable}$$

  where N_{wire} is the number of strands per cable, A_{sc} is the area of superconductor per strand, and $A_{ins-cable}$ is the area of insulated cable.
- κ indicates how much area in a coil is covered by current carrying materials.
- Being J_{sc} the current density in the superconductor, we define as the **overall current density**

$$J_0 = \kappa J_{sc}$$

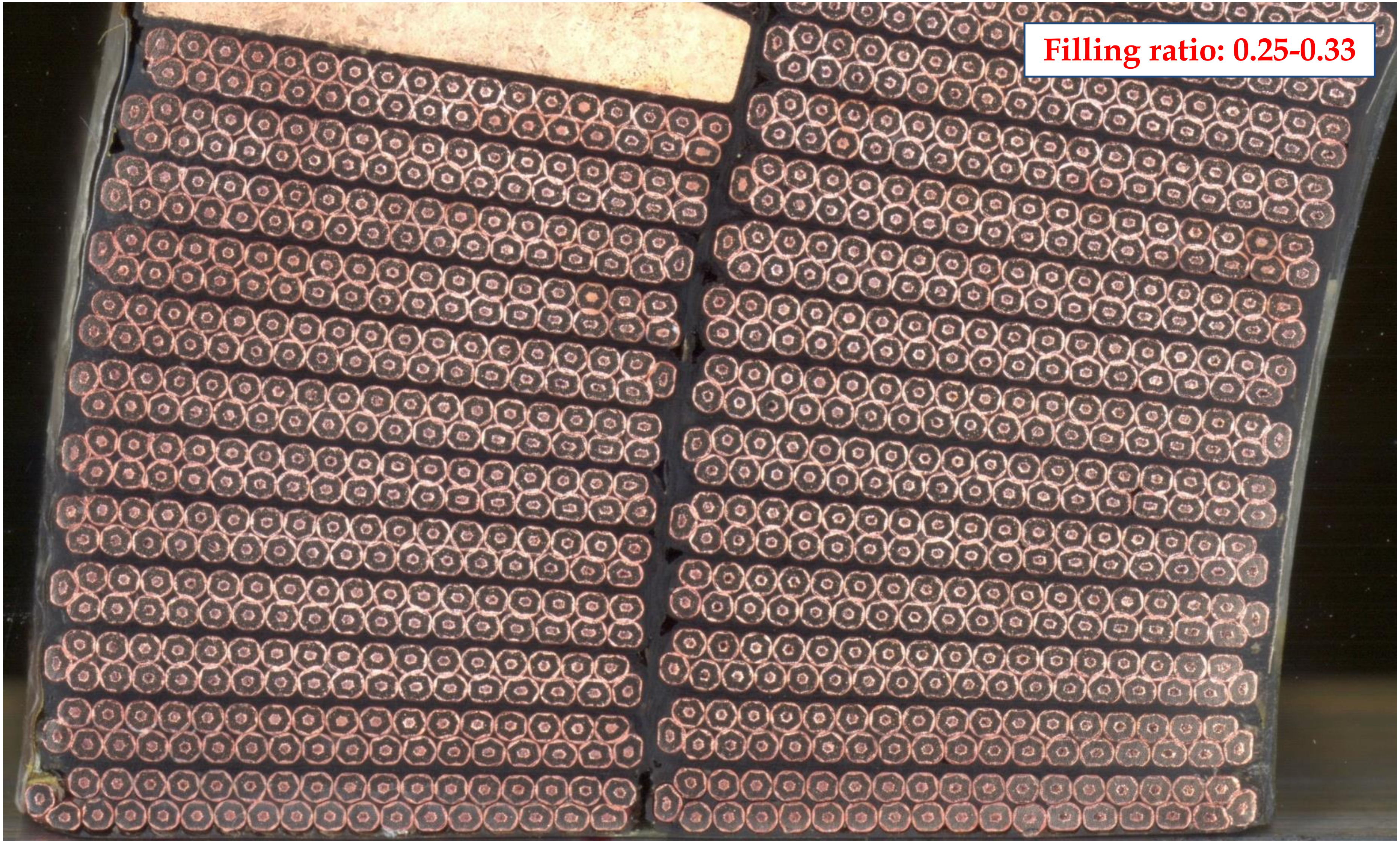
6. Filling factor

- Let's consider the Nb$_3$Sn quadrupole magnet TQC.
  - Strand diameter d_{wire} : 0.7 mm
  - Cu/SC: 0.89
  - Number of strand per cable N_{wire} : 27
  - Cable width w_{cable} : 10.050 mm
  - Cable mid-thickness t_{cable} : 1.260 mm
  - Cable inner edge thickness t_{cable_in} : 1.172 mm
  - Cable outer edge thickness t_{cable_out} : 1.348 mm
  - Cable insulation thickenss t_{ins} : 0.125 mm



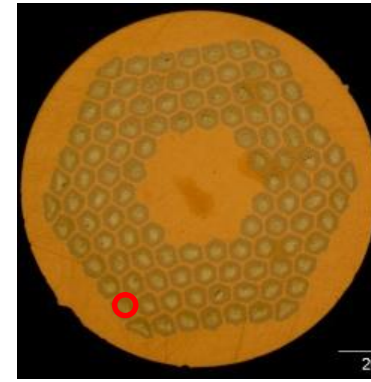
- Therefore
  - $N_{wire}\ A_{sc} = (N_{wire}\ \pi\, d^2_{wire}\ /\ 4)\ /\ (Cu/SC+1) = 5.498\ \text{mm}^2$
  - $A_{ins\_cable} = 15.553\ \text{mm}^2$
  - $\kappa = 0.35$

6. Filling factor

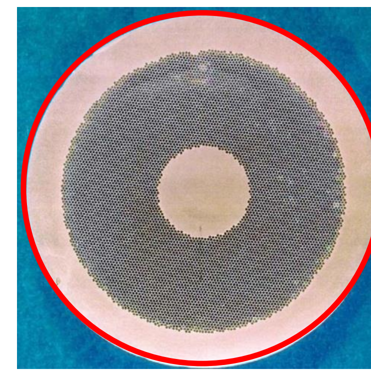


Different j

- $J_{sc} = J_{supercondutor} = I_{strand} / A_{superconductor}$



- $J_{e} = J_{engineering} = I_{strand} / A_{strand}$



- $J_{o} = J_{overall} = I_{cable} / A_{insulated\_cable}$

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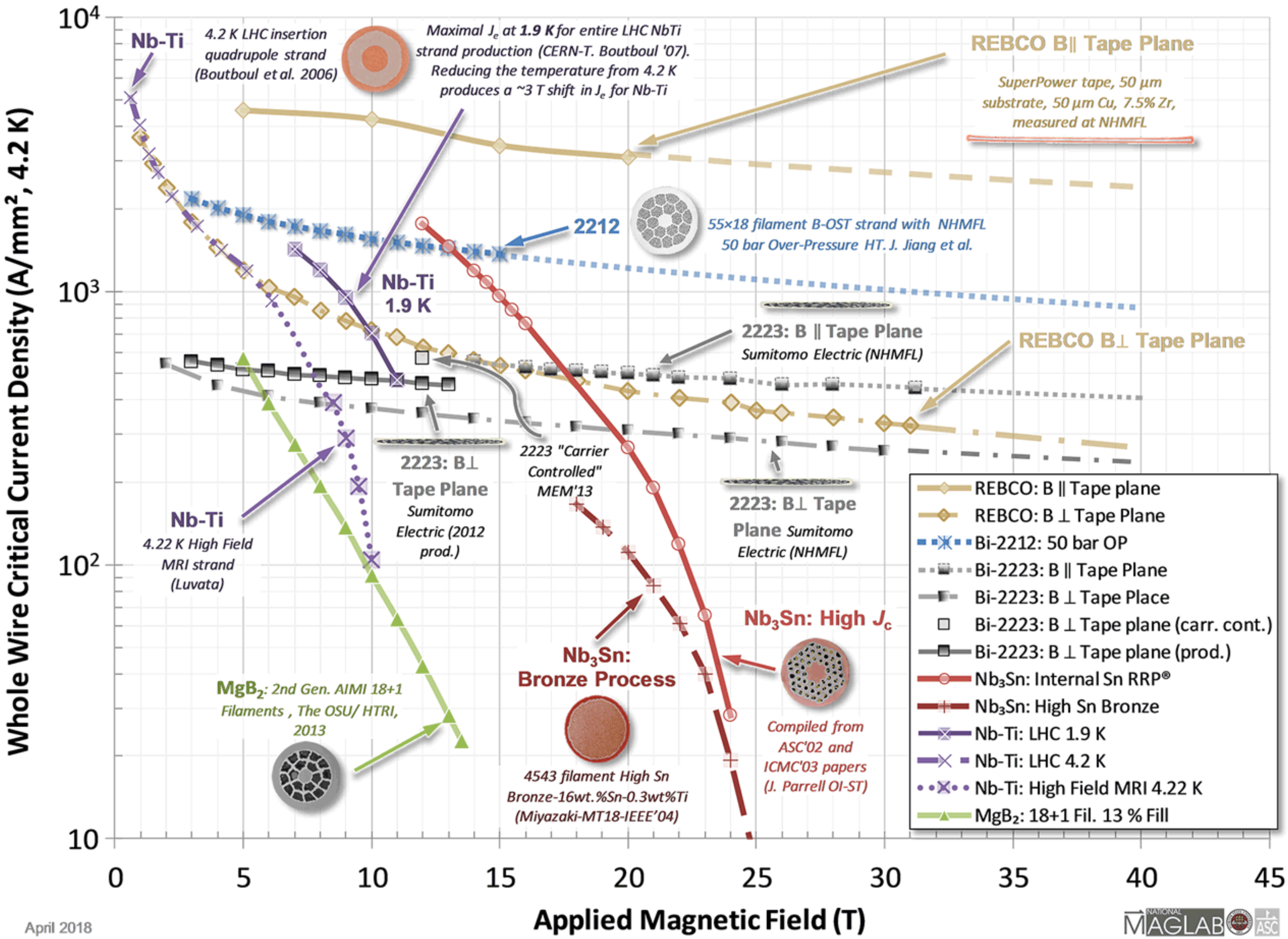
6. Filling factor
7. **Conclusions**

7. Conclusions

- In this unit we briefly explained why **superconducting materials** used in accelerator magnets are
  - subdivided in filaments of small diameters
  - twisted together
  - embedded in a copper matrix
  - and finally combined in a multistrand cable.

- We then described how **strands** are fabricated and we introduced some parameters used to characterize a **superconducting cable**
  - Cable compaction k_{cable}
  - Keystone angle φ_{cable}
  - Filling factor κ

Appendix



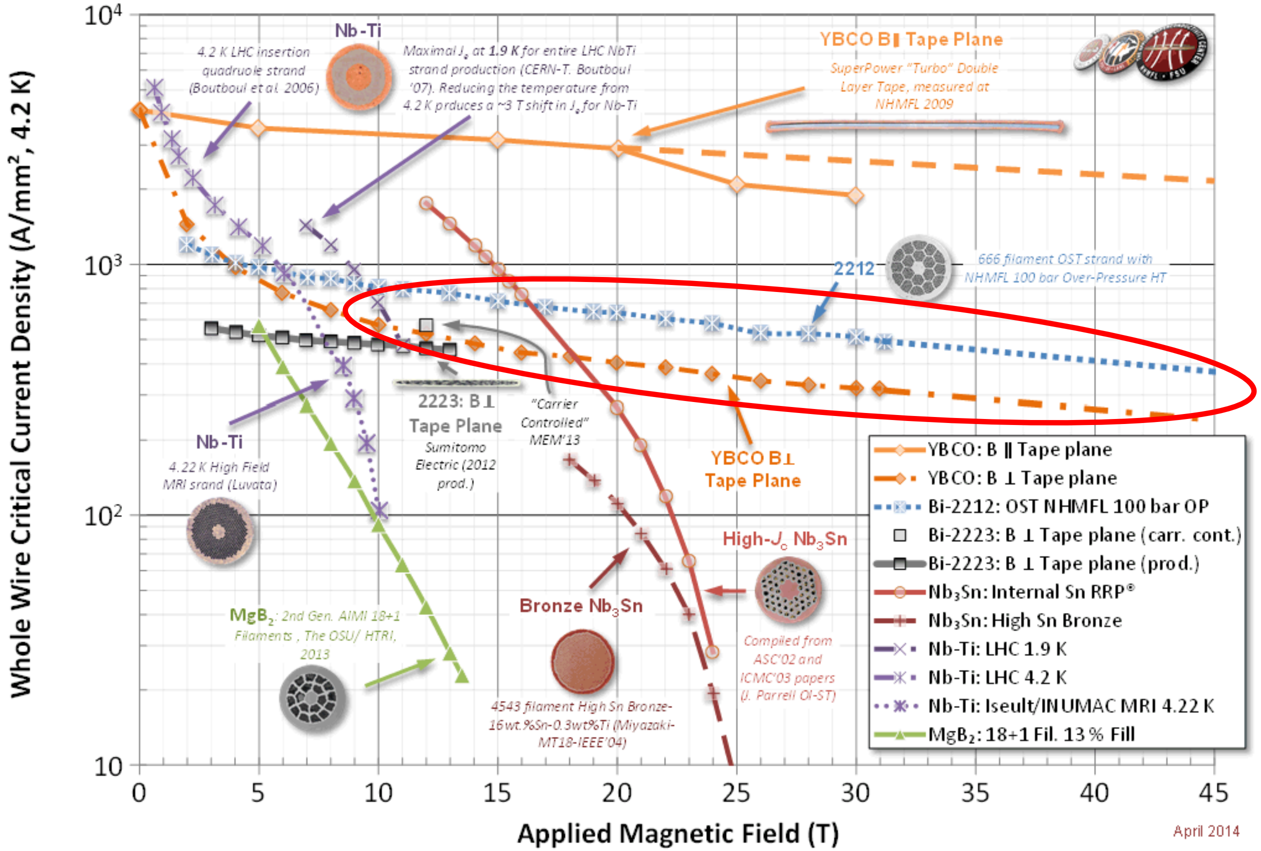
Whole Wire Critical Current Density (A/mm², 4.2 K)
Applied Magnetic Field (T)
Nb-Ti
4.2 K LHC insertion quadrupole strand (Boutboul et al. 2006)
Maximal J_e at 1.9 K for entire LHC NbTi strand production (CERN-T. Boutboul '07). Reducing the temperature from 4.2 K produces a ~3 T shift in J_e for Nb-Ti
REBCO B|| Tape Plane
SuperPower tape, 50 μm substrate, 50 μm Cu, 7.5% Zr, measured at NHMFL
2212
55×18 filament B-OST strand with NHMFL 50 bar Over-Pressure HT. J. Jiang et al.
Nb-Ti 1.9 K
2223: B || Tape Plane
Sumitomo Electric (NHMFL)
REBCO B⊥ Tape Plane
2223: B⊥ Tape Plane
Sumitomo Electric (2012 prod.)
2223 "Carrier Controlled" MEM'13
2223: B⊥ Tape Plane Sumitomo Electric (NHMFL)
Nb-Ti
4.22 K High Field MRI strand (Luvata)
MgB_2: 2nd Gen. AIMI 18+1 Filaments , The OSU/ HTRI, 2013
Nb_3Sn: Bronze Process
4543 filament High Sn Bronze-16wt.%Sn-0.3wt%Ti (Miyazaki-MT18-IEEE'04)
Nb_3Sn: High J_c
Compiled from ASC'02 and ICMC'03 papers (J. Parrell OI-ST)
REBCO: B || Tape plane
REBCO: B ⊥ Tape Plane
Bi-2212: 50 bar OP
Bi-2223: B || Tape Plane
Bi-2223: B ⊥ Tape Place
Bi-2223: B ⊥ Tape plane (carr. cont.)
Bi-2223: B ⊥ Tape plane (prod.)
Nb_3Sn: Internal Sn RRP®
Nb_3Sn: High Sn Bronze
Nb-Ti: LHC 1.9 K
Nb-Ti: LHC 4.2 K
Nb-Ti: High Field MRI 4.22 K
MgB_2: 18+1 Fil. 13 % Fill
April 2018

MgB_2

- MgB_2 is a recent discovery
  - Discovered in 2001
  - Critical temperature of 39 K, critical field of less than 10 T
  - Anomaly in the classification: low temperature or high temperature superconductor?
  - Low field but low cost and easy manufacturing
    - Interesting for power lines or low field (<10 T) magnets
    - Project for superconducting link in MgB_2 in High Luminosity LHC

    www.cern.ch/hilumi and A. Ballarino et al., IEEE Trans Appl Supercond **21** (2011) 980-983
    - Technological development of superferric magnet in the HL-LHC framework www.cern.ch/hilumi and M. Sorbi, M. Statera, S. Mariotto et al., IEEE Trans Appl Supercond **29** (2019) 4004505

- BSCCO and YBCO



Critical current density in the superconductor versus field for different materials at 4.2 K [P. J. Lee, et al]
https://nationalmaglab.org/images/magnet_development/asc/plots/JeChart041614-1022x741-pal.png

BSCCO AND YBCO

- BSSCO and YBCO are the two main HTS (high temperature superconductors
  - Discovered in 1988/86
  - Large critical temperature ≈100 K
  - Very large critical field above 150 T
  - Flat critical surface (little dependence on field)
  - Large progress in reaching good current density
  - Both expensive (more than 10 times Nb-Ti …)
  - Drawbacks:
    - YBCO round wires are not trivial – most application on tapes
    - BSCCO requires a heat treatment at 800 C , and 100 bar of oxygen to increase *j*
  - NMR/MRI solenoids with HTS tapes have been developed
  - Projects of dipole inserts for accelerator magnets are onging in many labs (LBNL, BNL, CERN, CEA, …)

- For the **large solenoids** in an accelerator experiment, copper around filament may not be enough to avoid overheating after a quench.
  - Large inductance and slow current discharge.
- **Additional stabilizer** (low resistivity material) is added around the strands.
- High purity aluminum is transparent to particles and reduced weight with respect to copper.
- Cable are fabricated by **co-extrusion**. This ensure good contact between strands and superstabilizer.