Unit 4
Practical superconductors for accelerator magnets

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Outline

- Introduction and history
- Superconducting materials
  - Nb-Ti, Nb_3Sn, and their critical surfaces
- Multifilament wires
  - Required Properties and fabrication
- Superconducting cables
  - Required Properties and fabrication
- Cable insulation
- Filling factor
- Summary

Introduction and history

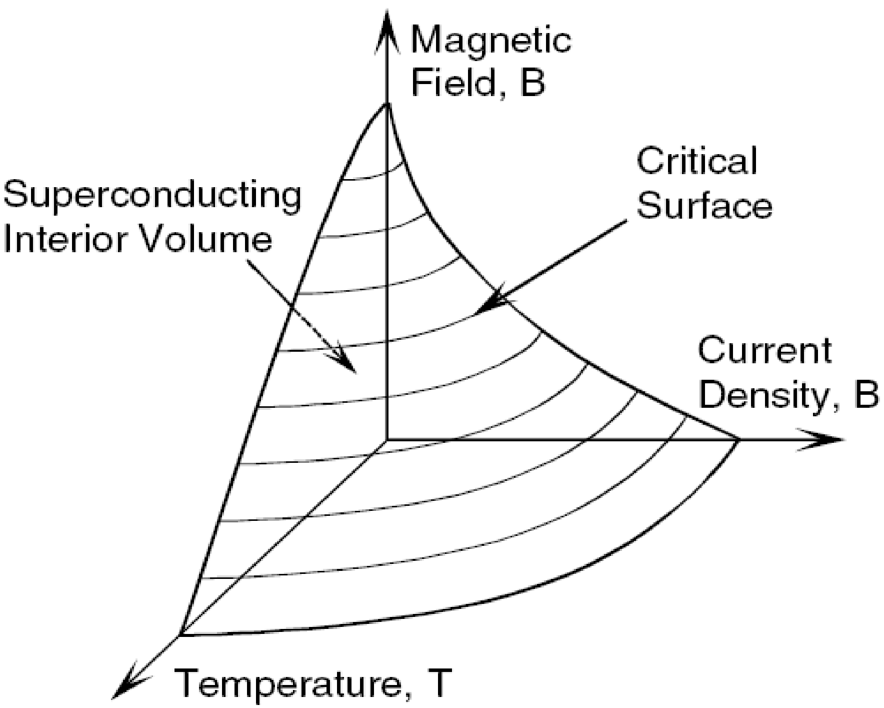
- Superconductivity was discovered in 1911 by Kammerling-Onnes who observed that the resistance of a mercury wire disappeared (immeasurably small value) at 4.2 K (Unit 3).
- For 40-50 years, superconductivity remained a research activity, until material suitable for practical application were discovered: type II superconductors.
- Nb_3Sn and Nb-Ti, discovered in 1954 and 1963, are the most commonly used type II superconductors (80-90% of all superconducting devices with Nb-Ti the majority).
- Since their critical temperature T_c is 9 K (for Nb-Ti) and 18 K (for Nb_3Sn) at 0 T, they are defined as low temperature superconductors.
  - High temperature superconductors (HTS) have a T_c up to 80-120 K.

Conductors for Accelerator Magnets

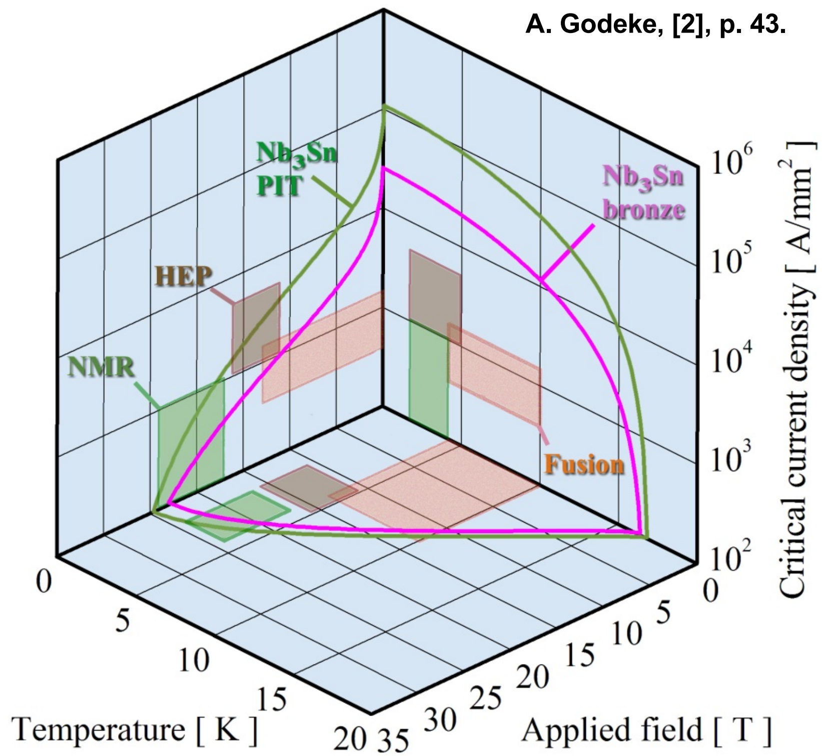
- Conductor ultimately determines magnet performance
  - You can't do any better than the virgin conductor
  - But . . . you can do worse!

- With few exceptions all accelerator magnets use Rutherford-style cables
  - Multi-strand/high current – can use shorter strand lengths, fewer turns (lower inductance)
  - High current density
  - Precise dimensions – controlled conductor placement (field quality)
  - Current redistribution – stability
  - Twisting to reduce interstrand coupling currents (field quality)

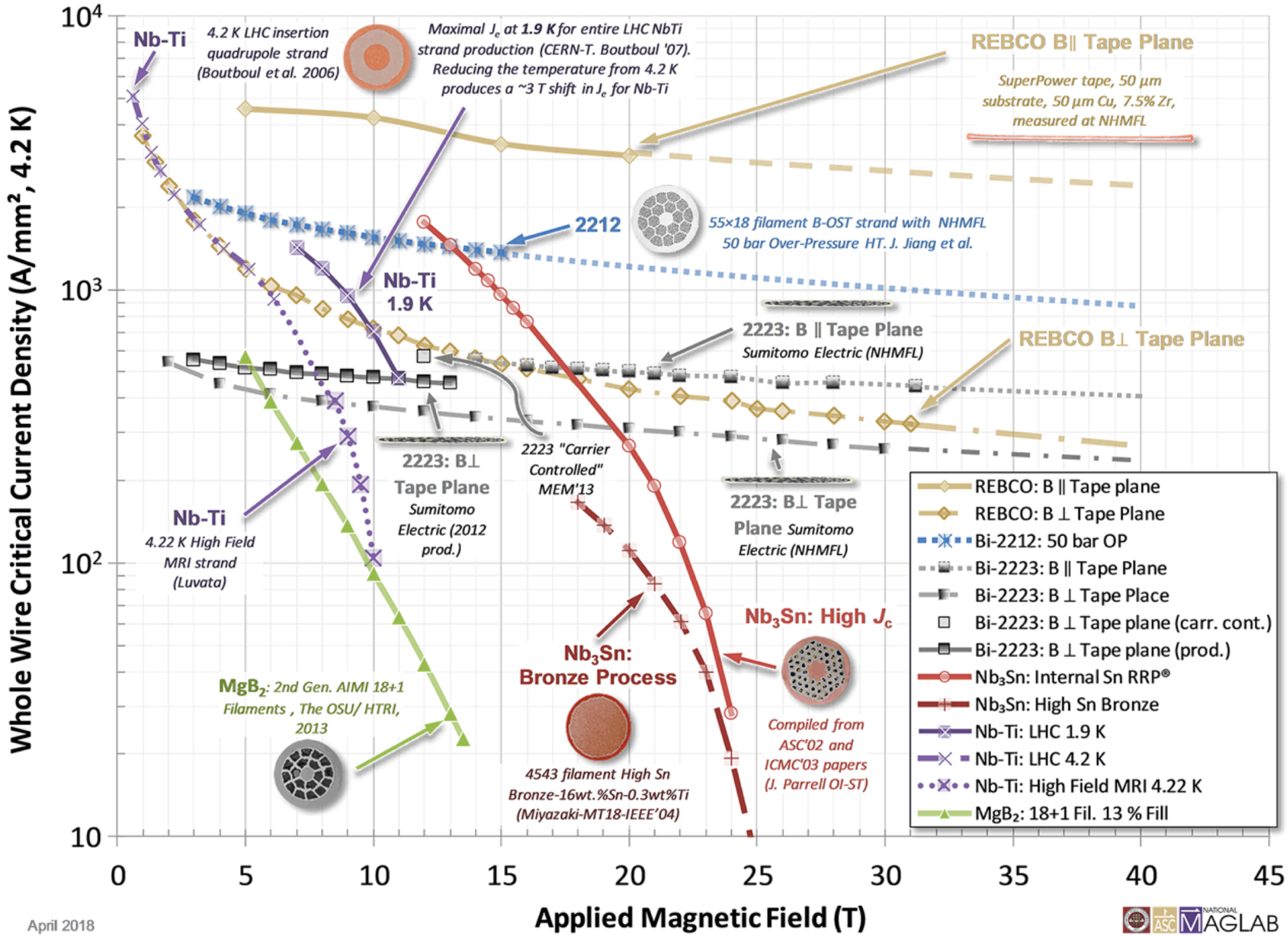
- The critical surface defines the boundaries between the superconducting state and the normal conducting state in the space defined by temperature, magnetic field, and current densities.
- The surface, determined experimentally, can be fit with parameterization curves.



A. Godeke, [2], p. 43.

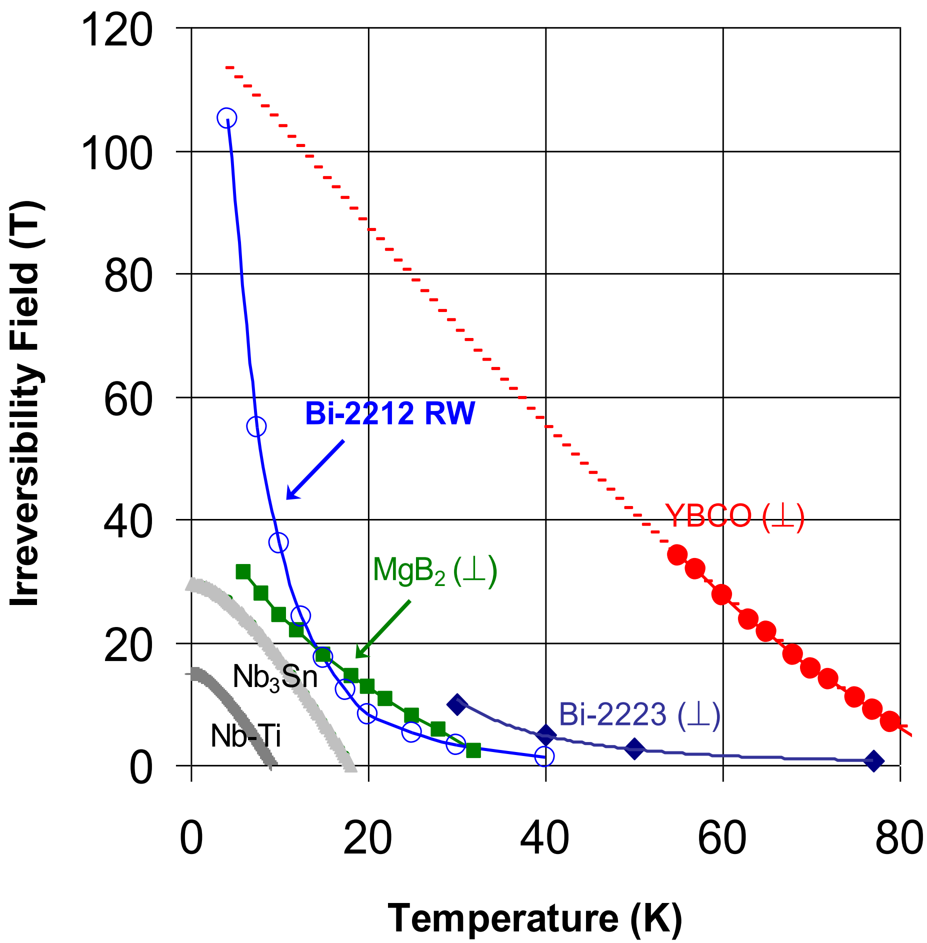


Engineering Current Density (J_e) vs Field



Whole wire critical current density (J_e) of accelerator magnet conductors as a function of external magnetic field. Courtesy of Peter J. Lee, Applied Superconductivity Center, Florida State University and the National High Magnetic Field Laboratory http://fs.magnet.fsu.edu/~lee/plot/plot.htm

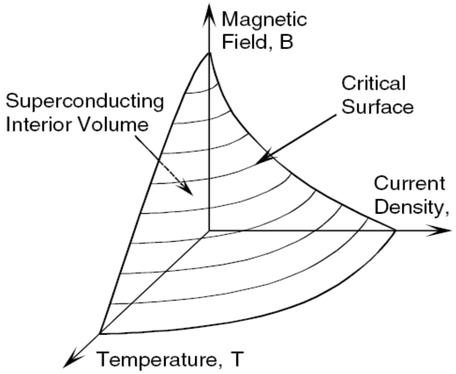
Field vs Temperature



Courtesy J. Jiang, Applied Superconductivity Center
at the National High Magnetic Field Laboratory, FSU

Materials for Accelerator Magnets

Application/performance ⟺ material properties and engineering



- **Nb-Ti**
  - B_{c2} (0K) ~ 14 T
  - T_c (0K) ~ 9.5 K
    - Max practical field at 4.2 K is 7 T (9 T @ 1.8 K)
    - Excellent mechanical properties (ductile)
- **Nb_3Sn**
  - B_{c2} (4.2 K) ~ 23 – 24 T
  - T_c (0T) ~ 18 K
    - Max practical field 17 – 18 T?
    - Brittle and strain sensitive
- **Nb_3Al**
  - High J_c in magnetic field < 15 T
  - Less strain sensitive than Nb_3Sn
  - But not commercially available
    - Rapid-quench process requires later addition of stabilizer
    - Actively pursued in Japan but fading from the scene
      - National Institute for Materials Science (NIMS)

Materials with Potential for Accelerator Magnets

Application/performance ⟷ **material properties and engineering**

Oxides

- **Bi-2212 ($Bi_2Sr_2CaCu_2O_8$)**
  - Round strands in long lengths
  - React and wind only option for large coils?
- **Bi-2223 ($Bi_2Sr_2Ca_2Cu_3O_{10}$)**
  - Tapes in long lengths
  - Applications for high temperature
- **YBCO ($YBa_2Cu_3O_7$) (ReBCO where Re = rare earth)**
  - Tapes (not wires!)
  - High critical current but length is a problem
  - Work being done to improve 4.2K performance

All are more strain sensitive than Nb_3Sn

B, Fe, As

- **MgB_2 (not so HT HTS)**
  - Better at T < 25K
  - Anisotropic
  - Low J_c (so far)
  - Stabilization

But . . .

  - Potential to exceed H_{c2} of Nb_3Sn
  - Low cost materials

- **Sr/$BaFe_2As_2$:K (Iron-Based)**
  - T_c = 38K
  - H_{c2} > 70T at 20K!
  - Round wire (no significant length yet)
  - Low anisotropy
  - Potentially low cost

Superconducting materials
Nb-Ti

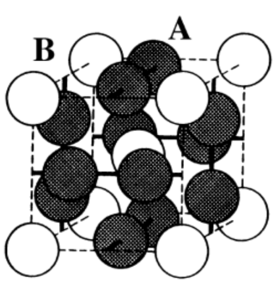
- Niobium and titanium are both soluble and at high temperature they combine to form a ductile alloy (called β phase).
    - It is easy to process by extrusion and drawing techniques.
- When cooled down to about 9 K it becomes a type II superconductor.
- The critical current J_c depends on the microstructure.
    - Cold work and low temperature heat treatments determine the formations of other phases; in particular the α phase does the flux pinning
- 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

Superconducting materials
Nb-Ti

- Nb-Ti is the most widely used superconductor.
- The Tevatron accelerator, built at Fermilab in the early 80s, was the first project where Nb-Ti was implemented on large scale.
- In High Energy Physics, Nb-Ti has also been used for
  - HERA at DESY
  - RHIC at BNL
  - SSC (project canceled in 1993)
  - LHC at CERN
- Other important applications are MRI magnets and fusion magnets (Tore Supra Tokamak in Cadarache, France).
- The cost is approximately 100-150 US$ per kg of wire.
- From 1500 to 2000 metric tons are produced yearly. (Mostly MRI industry)

Superconducting materials
Nb_3Sn

- Niobium and tin can form an intermetallic compound, with the formula Nb_3Sn, from the A15 family (like Nb_3Al).
- When cooled down to about 18 K it becomes a type II superconductor.
- Critical temperature T_{C0m} and upper critical magnetic field B_{C20m} depend on Sn content: the optimal is 24-25 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



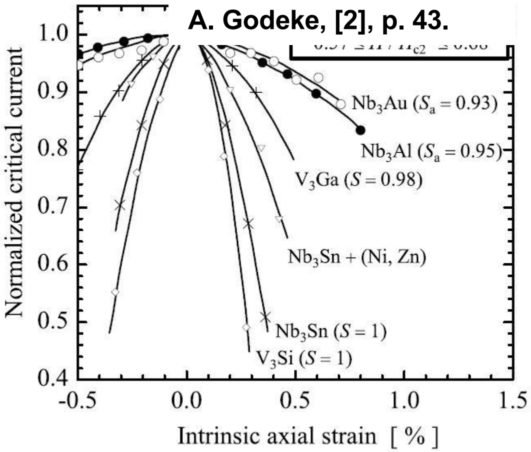
A. Devred, [1]

Superconducting materials
Nb_3Sn

- Nb_3Sn is brittle, therefore it cannot be extruded as NbTi.
  - The formation of Nb_3Sn must occur only at the end of the cable and/or coil fabrication process.

- In addition, it is strain sensitive: its critical parameters depend on the applied strain (reversible for small strain).

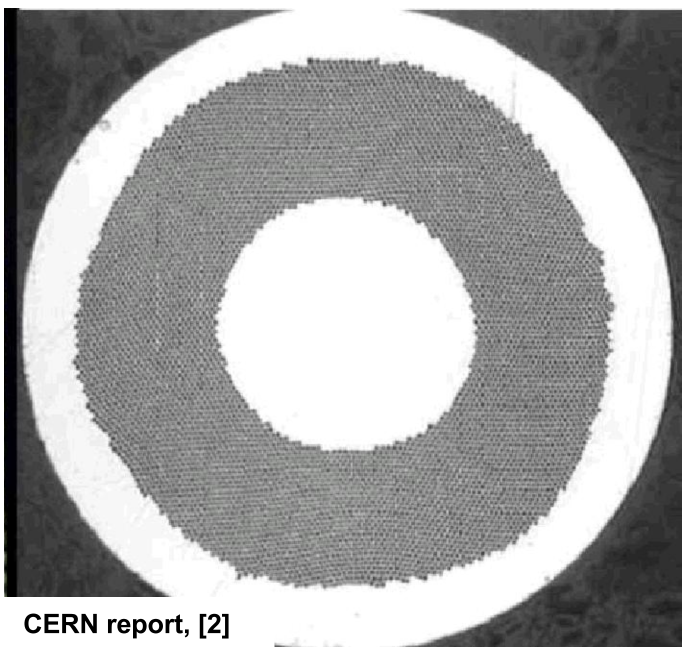
- Used in
  - NMR, with field of about 20 T
  - Model coils for ITER
  - High energy physics (Laboratory R&D)



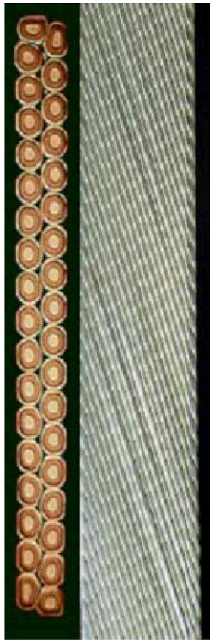
- The cost is approximately 700-2000 US$ per kg of wire.

- About 15 metric tons are produced yearly.

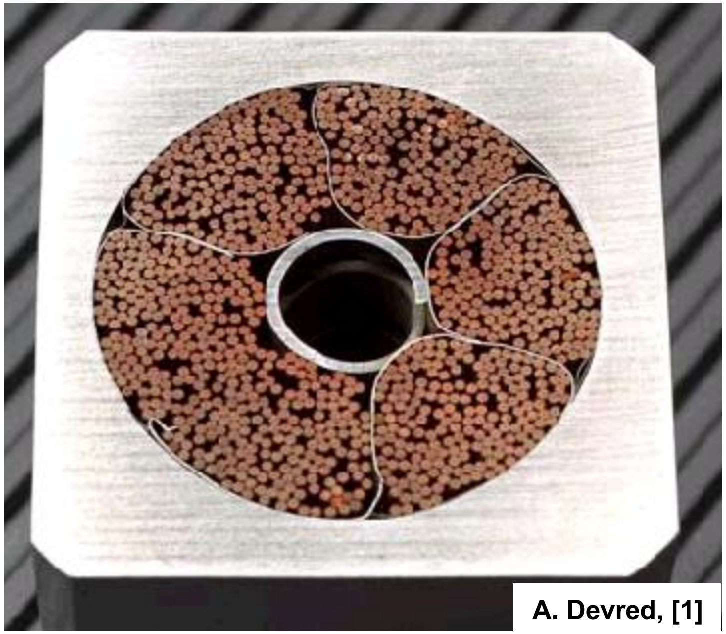
- For practical applications, superconducting materials are produced in small filaments and surrounded by a stabilizer (typically copper) to form a *multifilament wire* or *strand*.
- A superconducting cable is composed of several wires into *multistrand cable*.



CERN report, [2]



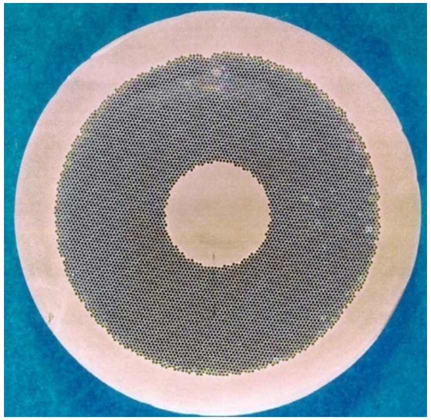
Nb-Ti ITER CIC



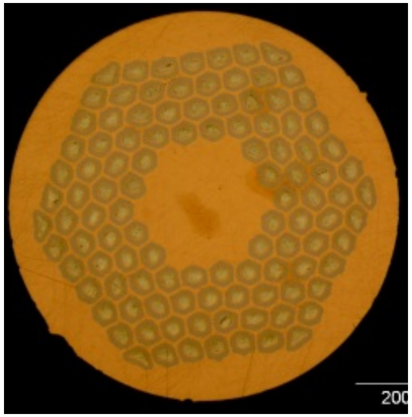
A. Devred, [1]

Multilfilament Wires

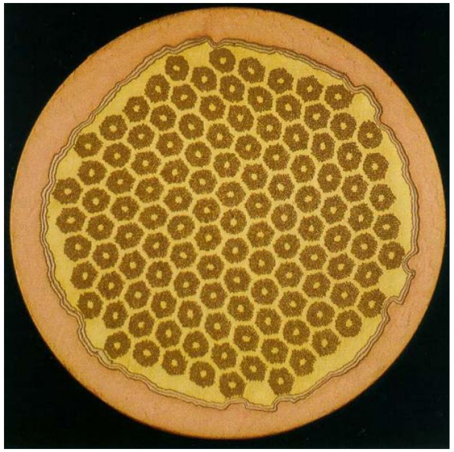
- Strands for superconducting Magnets
  - Array of small diameter filaments in a copper matrix
    - Small diameter reduces magnetization instabilities (flux jumps)
    - Twisted to reduce interfilament coupling and AC losses
    - Cu provides thermal stability
      - Heat capacity for energy deposition – mechanical, flux jumps
    - Minimal amount of Cu for drawing



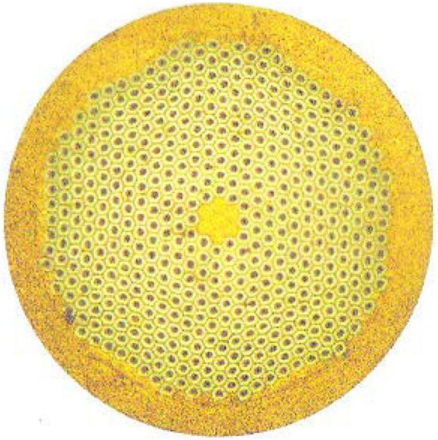
NbTi SSC wire (A. Devred, [1])



HL-LHC Nb_3Sn RRP



Nb_3Sn bronze-process wire (A. Devred, [1])



Nb_3Sn PIT process wire (A. Devred, [1])

Multifilament Wires – Flux Jumps

- An external magnetic field penetrates a type-II superconductor in the mixed state through fluxoids. Fluxoid distribution depends on the applied magnetic field and on the current J_c.
  - If the superconductor is subjected to a thermal disturbance, the local change in J_c produces a motion or "jump" of fluxoids, which is accompanied by power dissipation.
  - The stability criteria for a slab in the adiabatic condition is

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

For Nb-Ti d_{eff} < 50 microns

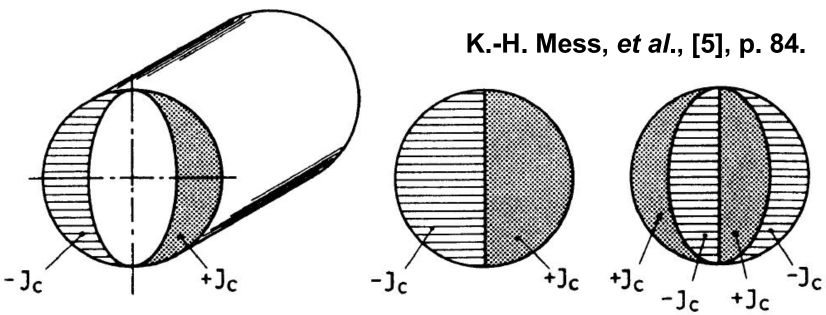
d_{eff} = effective filament diameter

where 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}], and θ_c is the critical temperature.

  - High conductivity copper reduces instability.

Multilfilament Wires

- Superconductor magnetization
  - According to the critical state model, when a filament is in a varying external field, its inner part is shielded by a current distribution in the filament periphery.
  - These shielding currents are proportional to the amplitude of the applied field and they do not decay when the external field is held constant.



K.-H. Mess, *et al.*, [5], p. 84.

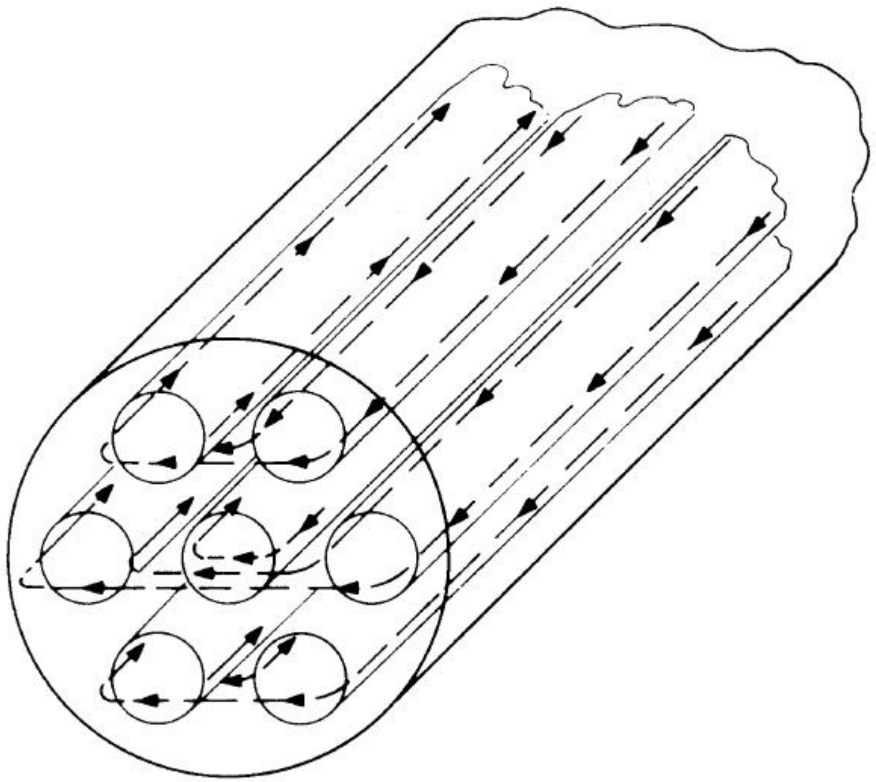
  - When the filament is fully penetrated, the magnetization M is proportional to $J_c d_{eff}$.
  - Field distortions are proportional to d_{eff}.
    - LHC filament diameter 6-7 μm.
    - HERA filament diameter 14 μm.

Multifilament Wires

- Interfilament coupling
  - When a multifilamentary wire is subjected to a time varying magnetic field, current loops are generated between filaments.
  - If filaments are straight, large loops are generated, with large currents
    - High losses
  - If the strands are magnetically(or physically) coupled the effective filament size is larger
    - Flux jumps
  - The effect is significantly reduced by twisting the filaments (strand) just prior to final draw with a twist pitch on the order of 20-30 times the wire diameter.

(Twist pitch = 12 – 30 mm)

M.N. Wilson, [4], p. 148.

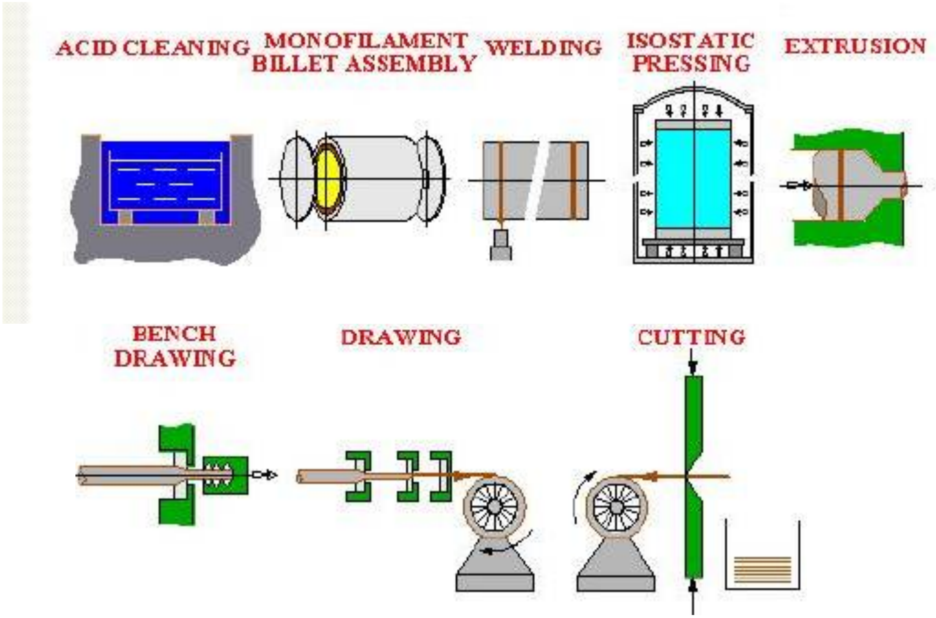


Multifilament Wires

Quench protection

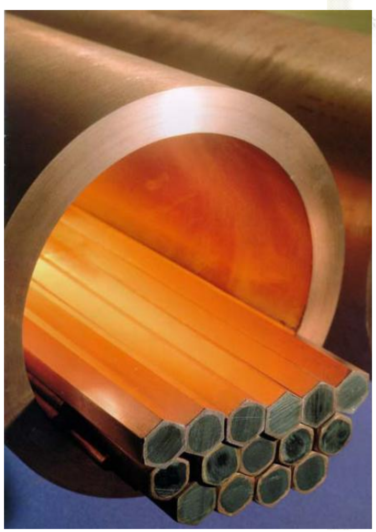
- When they are not superconducting, superconductors have a very high resistivity. If quenched, a solitary Nb-Ti filament could reach very high temperatures in a few milliseconds.
  - If the filament is embedded in a copper matrix, then when a quench occurs, the current redistributes into the low-resistivity matrix that, along with the higher heat capacity produces less Joule heating, and the peak temperature can typically be maintained below 300 K.
  - 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 return to the superconducting state.
    - The matrix also helps stabilize the conductor against flux jumps (dynamic stability).

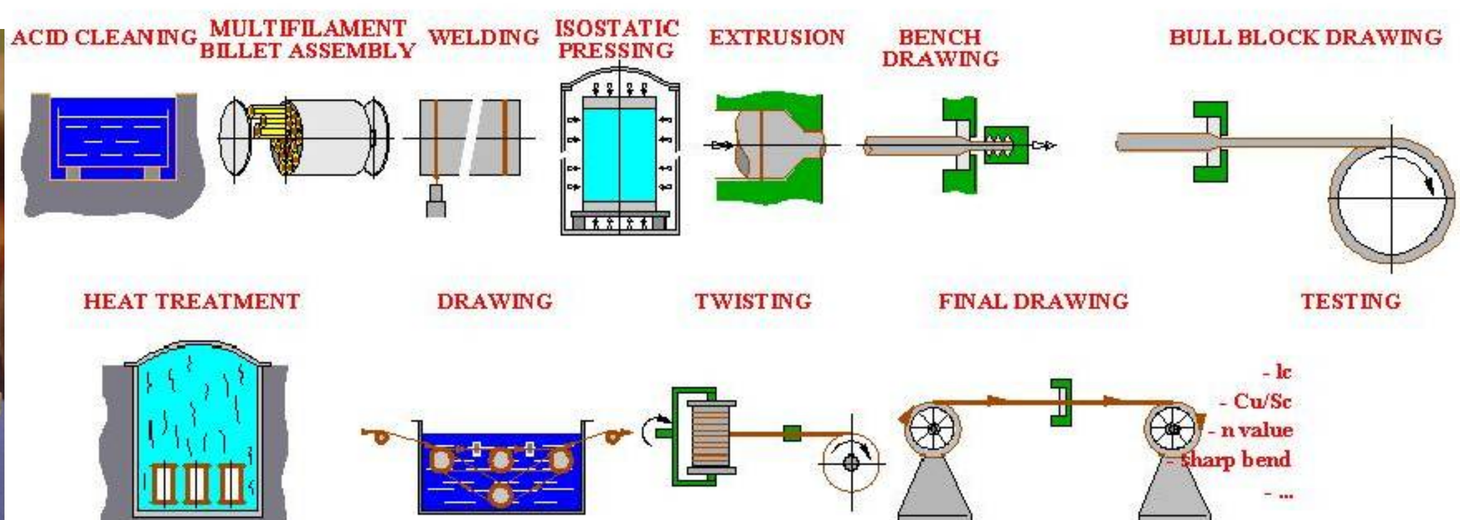
- The fabrication of Nb-Ti wire starts from the production of Nb-Ti ingots (with a 200 mm diameter and 750 mm height).
- A monofilament billet is assembled, extruded, and drawn down in small pieces (monofilament rods) about 800 mm long and 50 mm in diameter.



A. Devred, [1]

- 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]

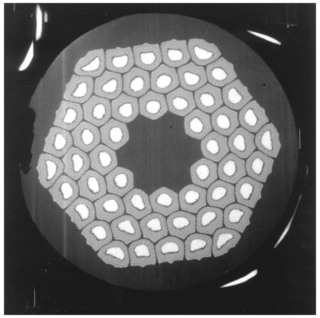
Fabrication of Nb-Ti Multilfilament Wires

- The copper to superconductor ratio is specified for the application to ensure quench protection, without compromising the overall critical current of the wire. (There are trade-offs)
- The filament diameter is chosen to minimize flux jumps and field errors due to persistent currents, at the same time minimizing the wire processing cost.
- The interfilament spacing is kept small so that the filaments, harder than copper, support each other during drawing. At the same time, the spacing must be large enough to prevent filament coupling or distortion.
- A copper core and sheath is added to increase the copper fraction and for processing.
- Nb sheath around Nb-Ti to prevent formation of Cu-Ti intermetallics.
- The main manufacturing issue is the piece length.
  - It is preferable to wind coils with a single-piece wire (to avoid cold welding). LHC required piece lengths longer than 1 km.

Fabrication of Nb_3Sn Multifilament Wires

- Since Nb_3Sn is brittle, it cannot be extruded and drawn like Nb-Ti. It must be developed at the end of the fabrication of the cable (or the coil).

- The process requires several steps:
  - Assembly multifilament billets from Nb_3Sn precursor (Sn or CuSn, Nb and Cu).
  - Fabrication of the wire through an 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



Courtesy of D. Dietderich, LBNL

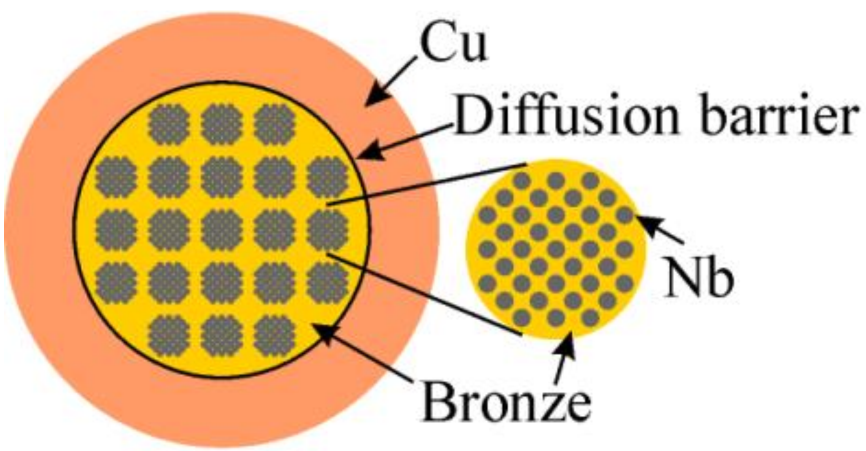
- During the "reaction", the CuSn and Nb are heated to about 600-700 ^{0}C in vacuum or inert gas (argon) atmosphere, and the Sn diffuses into the Nb and reacts to form Nb_3Sn.

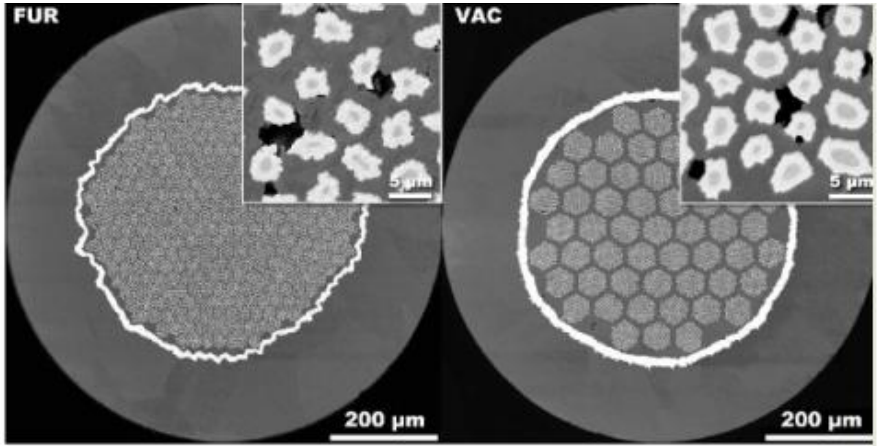
There are 4 main types of processes to form Nb_3Sn wires.

Fabrication of Nb_3Sn Multifilament Wires

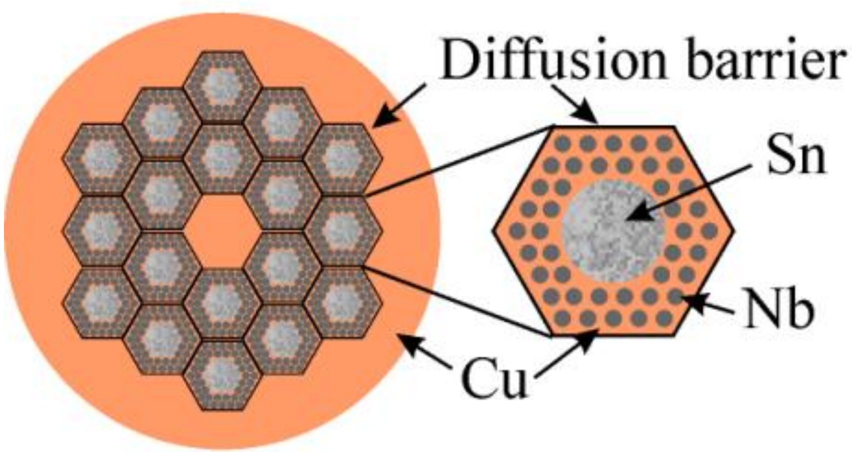
- Bronze process
  - Nb rods are inserted in a bronze (CuSn) matrix. Pure copper is put in the periphery and protected with a diffusion barrier (Ta) to avoid contamination. (Preserve low resistivity of the Cu)
  - Advantage: small filament size
  - Disadvantage: limited amount of Sn in bronze and annealing 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].

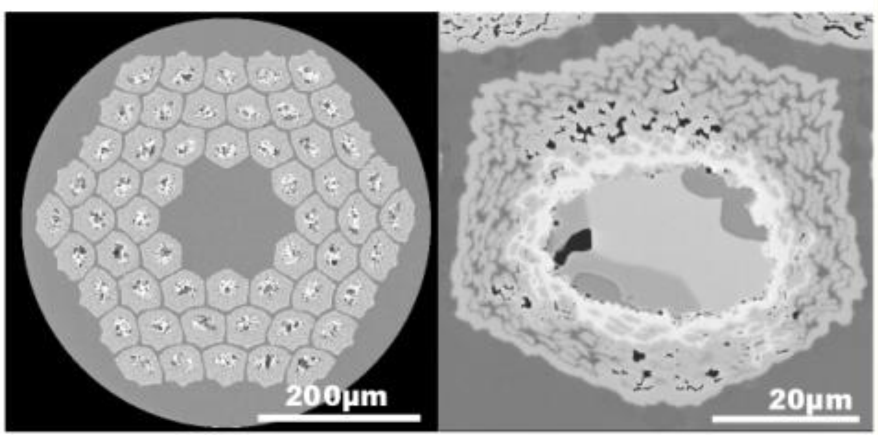




- Internal tin process
  - A tin core is surrounded by Nb rods embedded in Cu (Rod Restack Process, RRP) or by layers of Nb and Cu (Modify Jelly Roll, MJR).
  - Each sub-element has a diffusion barrier.
  - Advantage: no annealing steps and more Sn in the subelement.
  - Disadvantage: difficult to achieve small effective filaments. To get below 50 microns without giving up J_c)
  - Non-Cu J_C up to 3000 A/mm^2 at 4.2 K and 12 T.



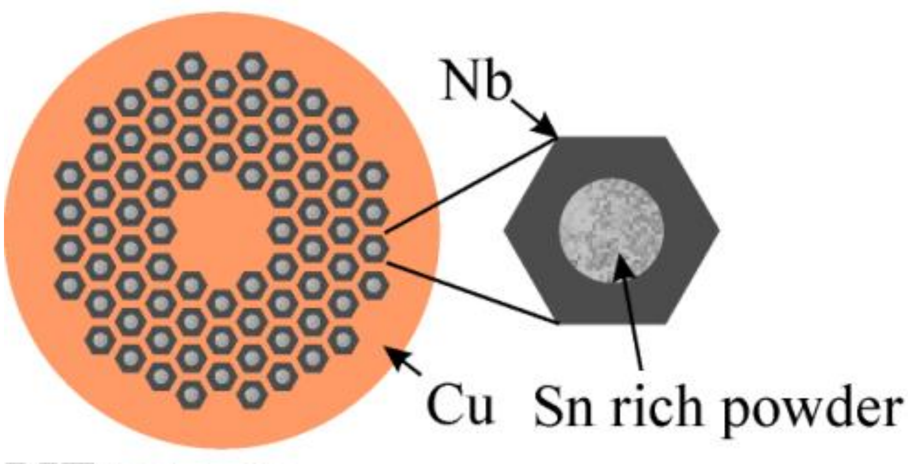
A. Godeke, [2].

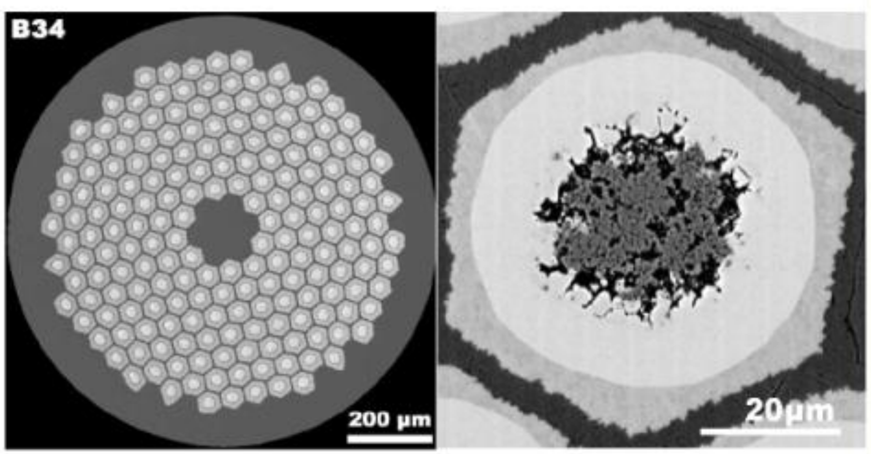


Fabrication of Nb_3Sn Multifilament Wires

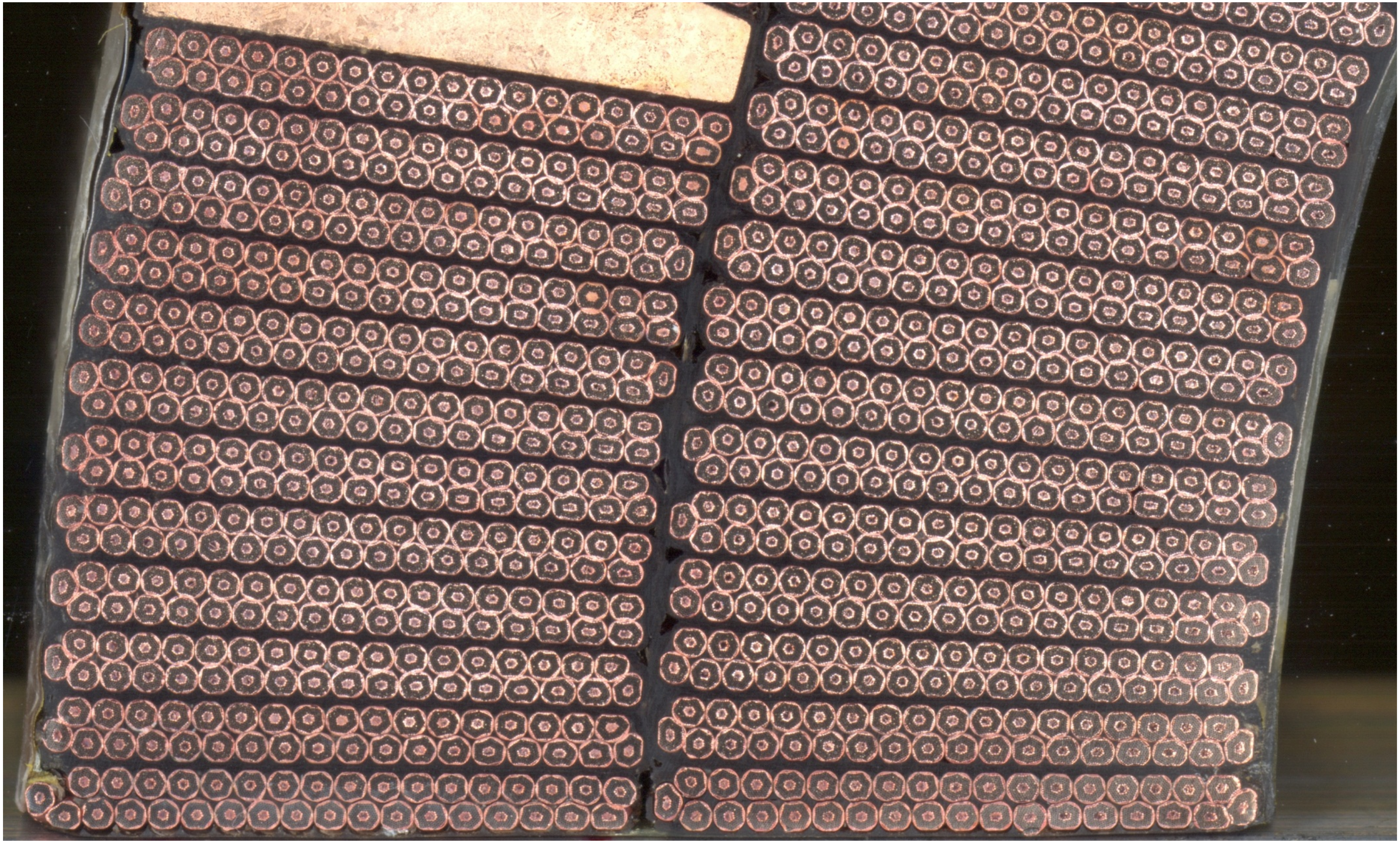
- Powder in tube (PIT) process
  - $NbSn_2$ powder is inserted in a Nb tube, put into a copper tube.
  - The un-reacted external part of the Nb tube is the barrier.
  - Advantage: small filament size (30 μm) and short heat treatment (proximity of Sn to Nb).
  - Disadvantage: fabrication cost and J_c generally lower than RRP.
  - Non-Cu J_C up to 2300 A/mm^2 at 4.2 K and 12 T.

A. Godeke, [2].



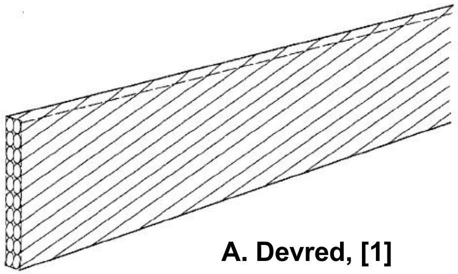


Superconducting Cables



Superconducting Cables

- 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.

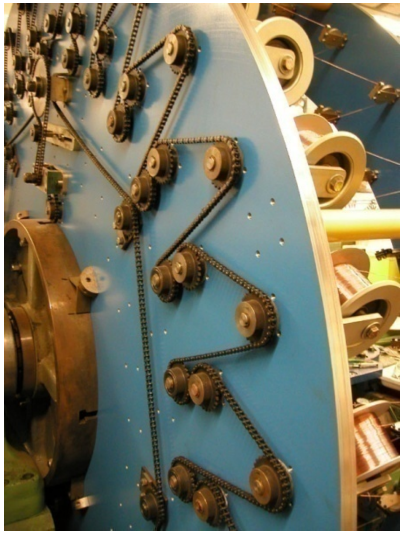


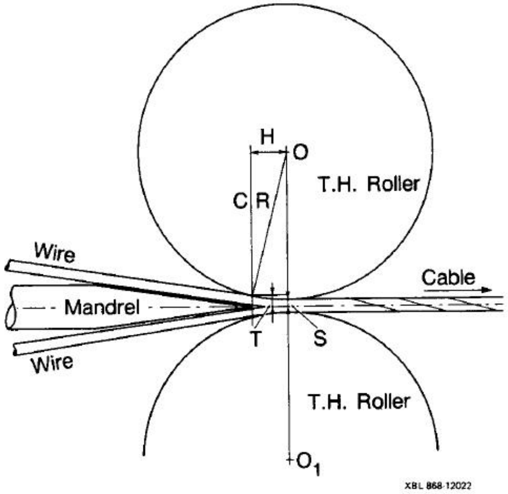
A. Devred, [1]

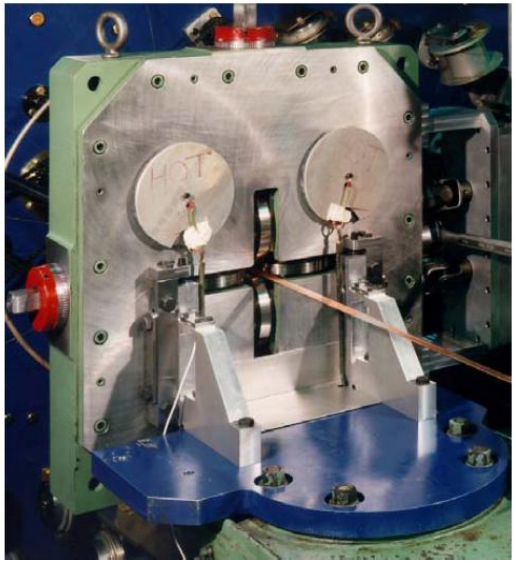
- The strands are twisted to
  - reduce interstrand coupling currents (see interfilament coupling currents)
    - Losses and field distortions
  - provide more mechanical stability
- The most commonly used multi-strand cables are the Rutherford cable and the cable-in-conduit.

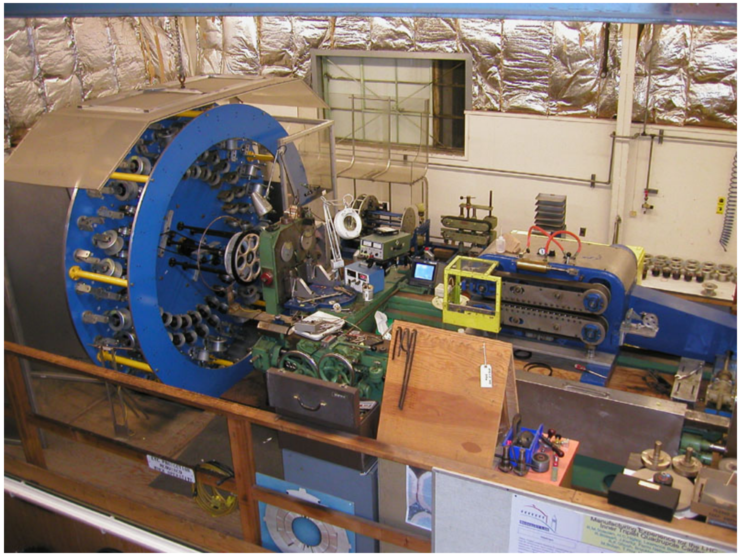
Superconducting Cables

- 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.





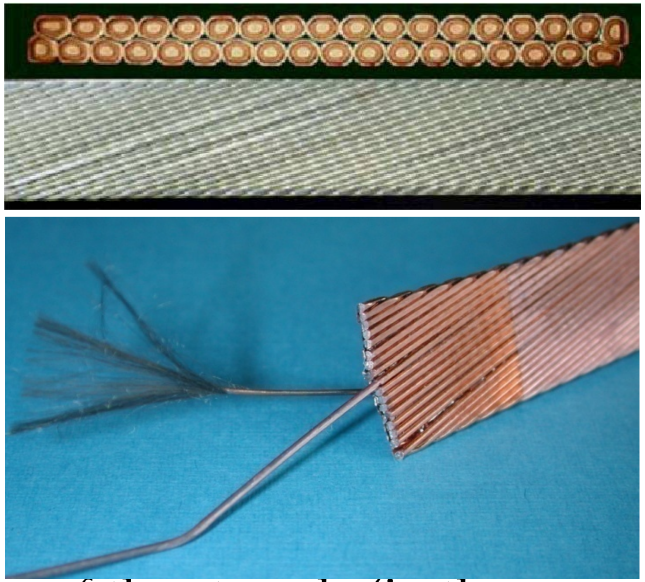




LBNLCabling machine, 60 strands, power rolls

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}

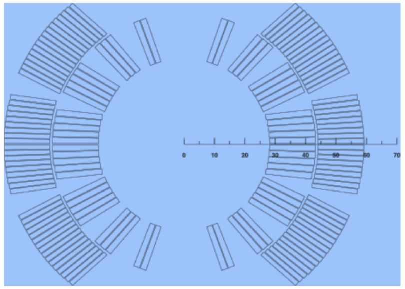


$$k_{cable} = \frac{N_{wire}\pi d^2_{wire}}{4 w_{cable} t_{cable} \cos\psi_{cable}}$$

  - 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).
  - Why the difference?

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 allows 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

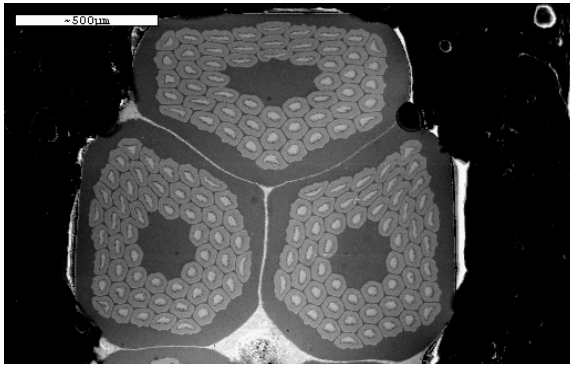


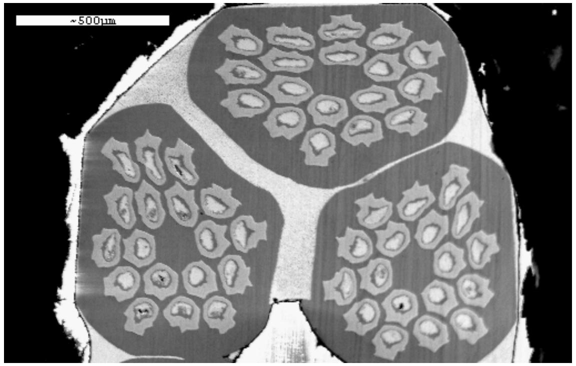
$$\tan\varphi_{cable} = \frac{t_{cable\_out} - t_{cable\_in}}{w_{cable}}$$

- Degradation of the critical current (relative to the performance of a virgin strand) due to damage of the strands during the cabling process is a constant concern.

Fabrication of Rutherford cable

- Strands are severely deformed at the hairpin bends at the cable edges. Especially the thin edge.
  - Filament breakage (Nb-Ti)
  - Breakage of reaction barrier in Nb_3Sn (filament coalescing or incomplete reaction).

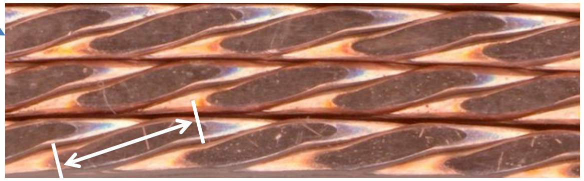


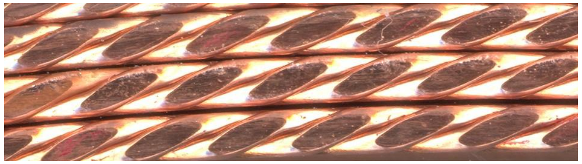


- Identifying degradation
  - Etching the cable to expose filaments (Nb-Ti)
  - Extracting strands for short sample measurements
  - Visual inspection of edges (flashing or oversized facets)
  - Examination of strand cross-section after cabling

- Avoiding degradation
  - Limit keystone angle to 1 or 2°.
  - The narrow edge packing factor is defined as 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, $\pi d/2t_{in}$.
  - Usually it ranges from 0.95 to 1.03. (for Nb_3Sn 0.9 – 0.95)

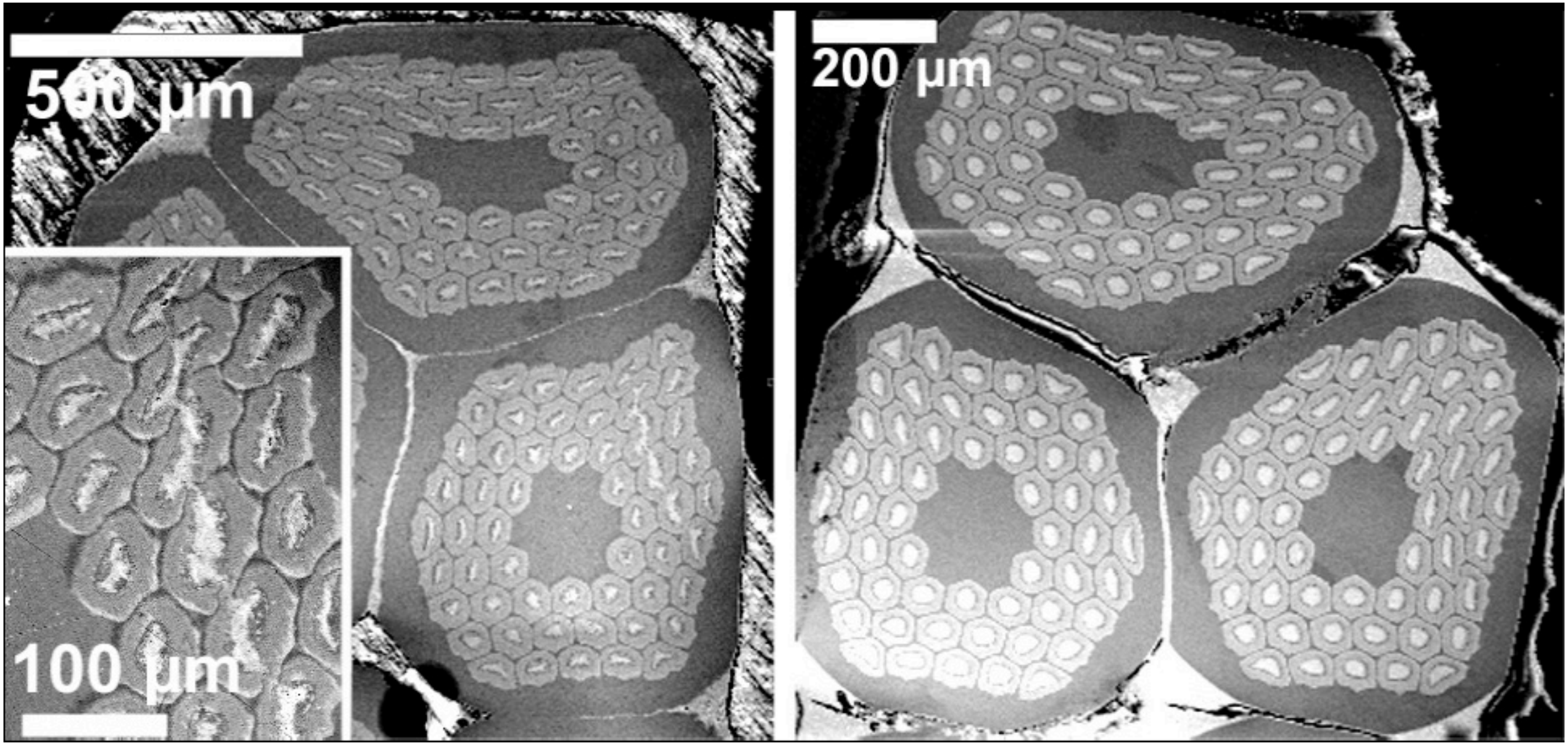
Large facets. Not good!





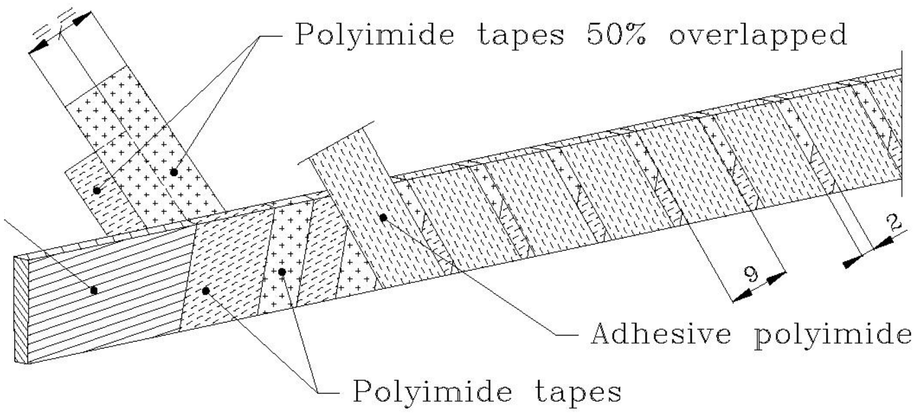
Severe edge deformation | Acceptable edge deformation

D. Dietderich, [6].



Cable Insulation

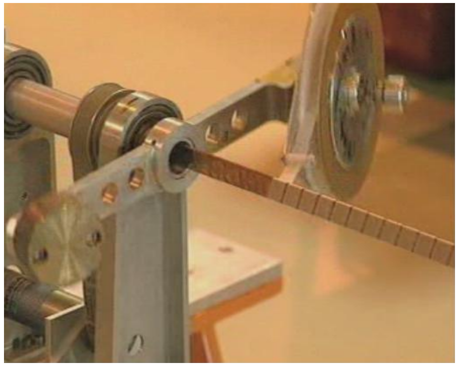
- The cable insulation must feature
  - Good electrical properties to withstand high turn-to-turn voltages after a quench.
  - Good mechanical properties to withstand high pressure conditions
  - Porosity to allow penetration of helium (or epoxy)
  - Radiation hardness



- In Nb-Ti magnets the most common insulation is a series of overlapped layers of polyimide (kapton).

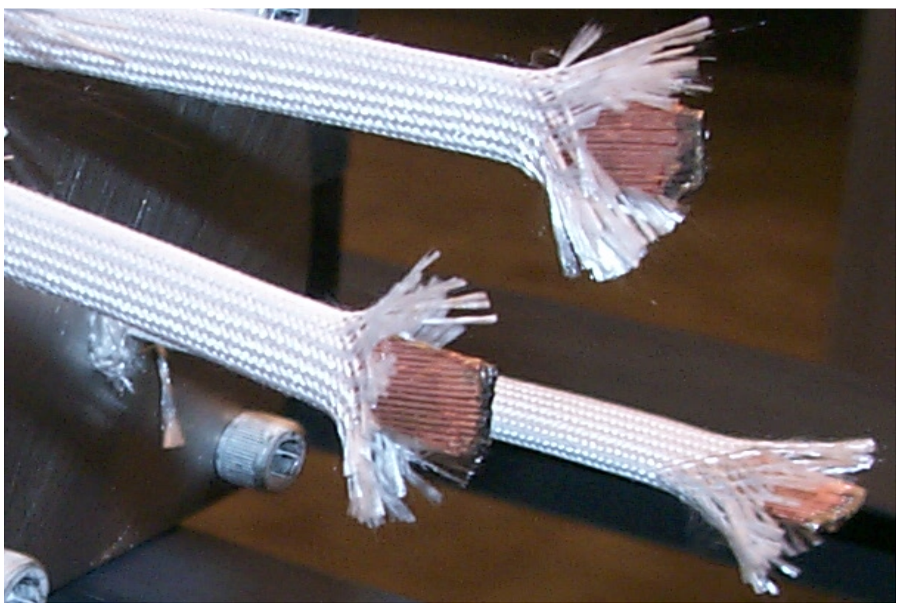
- In the LHC case:

  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.



Cable Insulation

- In Nb_3Sn magnets, where coils are reacted at 600-700 °C, the most common insulation is a tape or sleeve of fiber-glass.
- Typically the insulation thickness varies between 100 and 200 μm.
- For short lengths sleeve can be put on by hand. For longer lengths it is braided directly on the cable.



Filling Factor

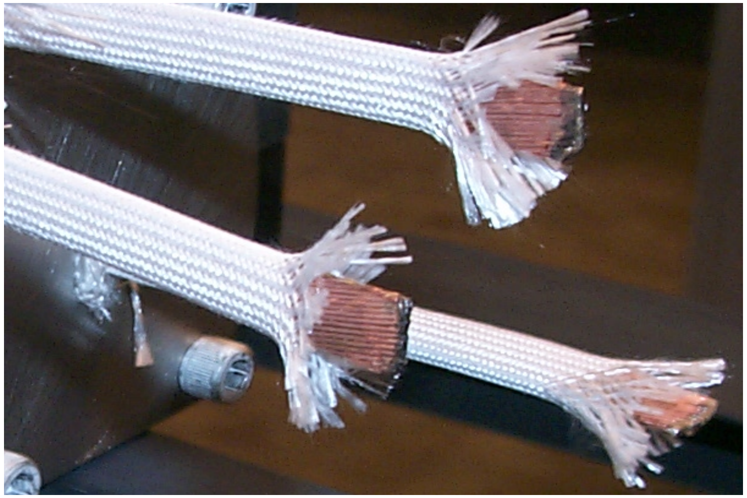
- Each strand is characterized by a copper to superconductor (Nb-Ti) or copper to non-copper area (Nb_3Sn).
- Each cable includes voids.
- The insulation occupies additional area.
- The filling factor κ is defined as the ratio of the superconductor or non-copper area to the total area of the cable, including insulation, i.e,

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

  where N_{wire} is the number of strands per cable, A_{sc} is the area of superconductor per strand, and $A_{ins\text{—}cable}$ is the area of insulated cable.
- κ indicates how much area in a coil is covered by current carrying materials.
- With J_c the critical current in the superconductor, we define as the engineering current density (or overall current density)

$$J_e = \kappa J_c$$

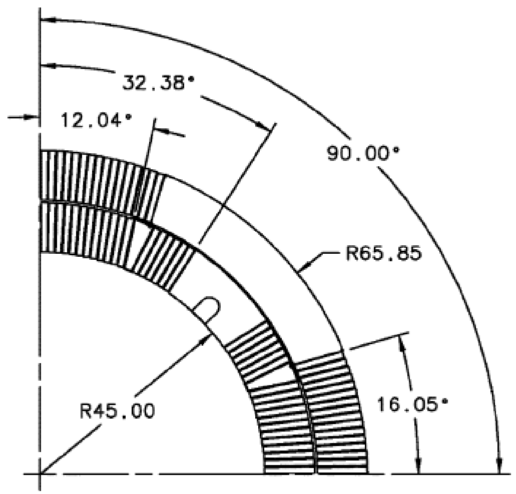
Coil J_e – This is what counts



- Start with J_c of Superconductor
  - NbTi ~ 3,000 A/mm^2 @ 5T and 4.2K
  - Nb_3Sn ~ 3,000 A/mm^2 @ 12T and 4.2K
- Add copper/non-Superconductor
  - Typically ~50%
- Cable compaction ~88%
- Insulation – order of 100 microns (X2) compared to ~2 mm cable thickness
- Filling factor, $\kappa = (N_{wire} A_{sc})/A_{ins\_cable}$
- Engineering current density defined as $J_e = \kappa J_c$
  - Typically on the order of 1,000 A/mm^2

An Example

- Let's consider the Nb_3Sn 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
  - $N_{wire}\, A_{sc} = (N_{wire}\, \pi\, d^2_{wire} / 4) / (Cu/SC+1) = 5.498\ mm^2$
  - $A_{ins\_cable} = 15.553\ mm^2$
  - $\kappa = 0.35$

Summary

- Nb-Ti is still the workhorse conductor for most applications
- Nb_3Sn now finding a niche for high field accelerator magnets
- HTS still a promise and a hope
- Key elements of conductors for superconducting accelerator magnets
  - Subdivided into small diameter filaments
  - Filaments are twisted
  - Embedded in a copper matrix (usually > 50%)
  - Combined into a multistrand cable.
- Parameters to characterize superconducting cable.
  - Cable compaction k_{cable}
  - Keystone angle φ_{cable}
  - Filling factor κ

Acknowledgement

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References

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

[2] *"LHC design report v.1: the main LHC ring"*, CERN-2004-003-v1, 2004.

[3] A. Godeke, *"Performance boundaries in Nb_3Sn superconductors"*, PhD thesis, 2005.

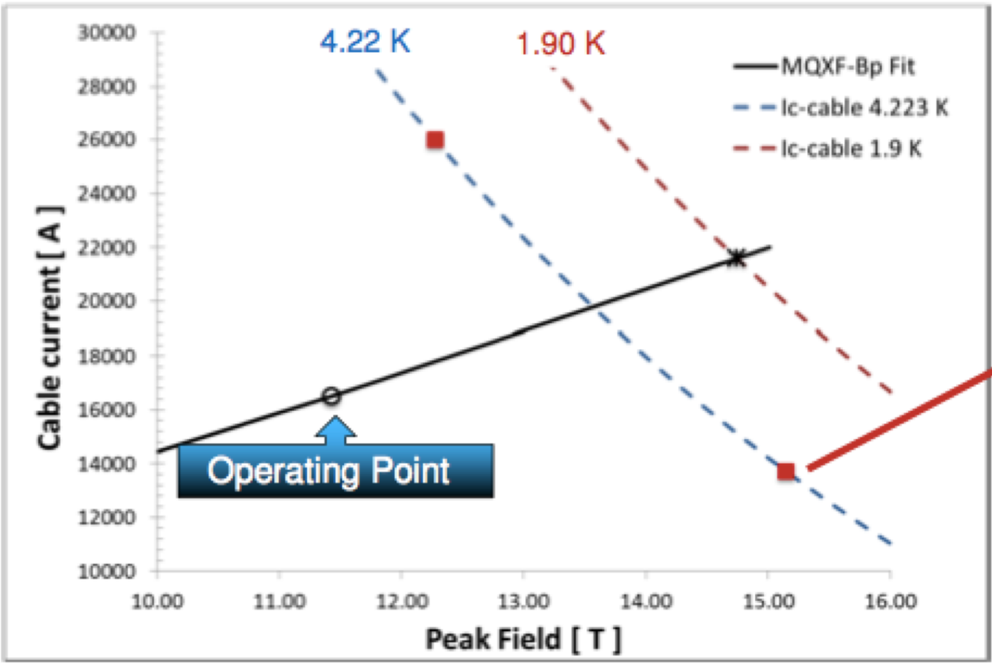
[4] M. Wilson, *"Superconducting magnets"*, Oxford UK: Clarendon Press, 1983.

[5] K.-H. Mess, P. Schmuser, S. Wolff, *"Superconducting accelerator magnets"*, Singapore: World Scientific, 1996.

[6] D. Dietderich, *"Development of High Current Nb_3Sn Rutherford Cables for NED and LARP"*, WAMSDO 2008, CERN, Geneva, 2008.

Aux Slides

Margin along Load Line



Present Spec.

Ic(12 T), A	684
Ic(15 T), A	361

B [Peak], T	95% Strand Ic	Cable Ic
12.27	650	25992
15.14	343	13720

Grad [T/m]	%SSL-LL	I, A	Bp, T	Tcs, K	ΔT, K
132.6	0.765	16511	11.43	6.97	5.07