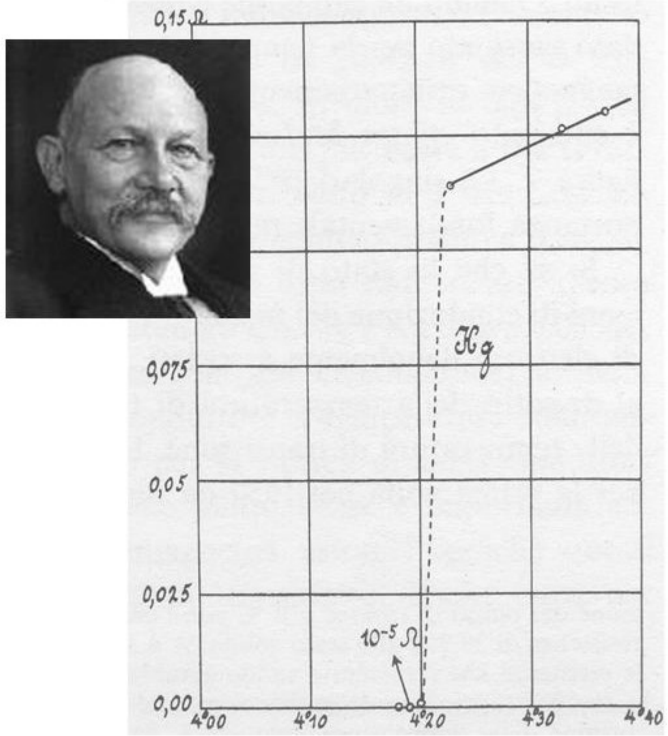
Superconductive Materials

Part 9

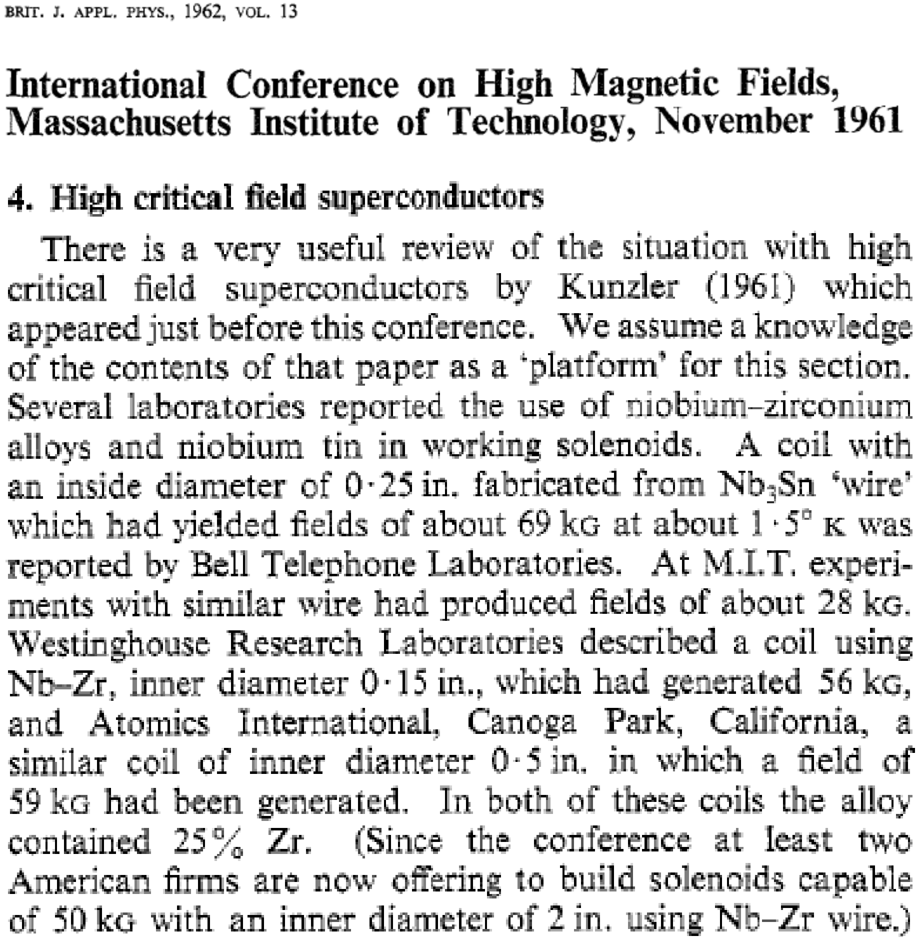
Practical Superconductors

First SC magnets

After the discovery of the superconductivity in 1911 by K. Onnes, the first practical sc wires in NbZr, NbTi and Nb_3Sn appeared 50 years later when J.K.Hulm, with co-workers at the Westinghouse Research Laboratories, developed the first commercial superconducting wires.



John K. Hulm



BRIT. J. APPL. PHYS., 1962, VOL. 13

International Conference on High Magnetic Fields, Massachusetts Institute of Technology, November 1961

4. High critical field superconductors

There is a very useful review of the situation with high critical field superconductors by Kunzler (1961) which appeared just before this conference. We assume a knowledge of the contents of that paper as a 'platform' for this section. Several laboratories reported the use of niobium–zirconium alloys and niobium tin in working solenoids. A coil with an inside diameter of 0·25 in. fabricated from Nb_3Sn 'wire' which had yielded fields of about 69 kG at about 1·5° K was reported by Bell Telephone Laboratories. At M.I.T. experiments with similar wire had produced fields of about 28 kG. Westinghouse Research Laboratories described a coil using Nb–Zr, inner diameter 0·15 in., which had generated 56 kG, and Atomics International, Canoga Park, California, a similar coil of inner diameter 0·5 in. in which a field of 59 kG had been generated. In both of these coils the alloy contained 25% Zr. (Since the conference at least two American firms are now offering to build solenoids capable of 50 kG with an inner diameter of 2 in. using Nb–Zr wire.)

First SC magnets

As John Hulm recalled some years later :

“Those tiny, primitive magnets were, of course, terribly unstable and tended to damage themselves on normalization, for reasons that are now well understood. One had to have faith to believe that these ***erratic toys of the low temperature physicists*** *would ever be of any consequence as large engineered devices”.*

Why 50 years before magnet applications?

To prevent early quenches SC wires must have the following **characteristics**:

1. **Type II** with **pinning centers**
2. **Fine filaments** and **metallic matrix**
   → to prevent jumps instabilities
3. **Twist pitch**
   → to prevent coupling currents

Flux jumps instabilities

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:

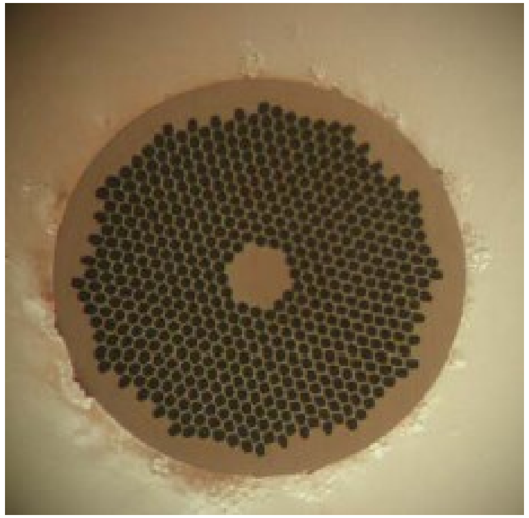
$$a \leq \sqrt{\frac{3\gamma C(T_c - T_{op})}{\mu_0 j_c^2}}$$

High conductivity **copper matrix** **reduces instability**

Flux jumps instabilities

$$a \leq \sqrt{\frac{3\gamma C(T_c - T_{op})}{\mu_0 j_c^2}}$$

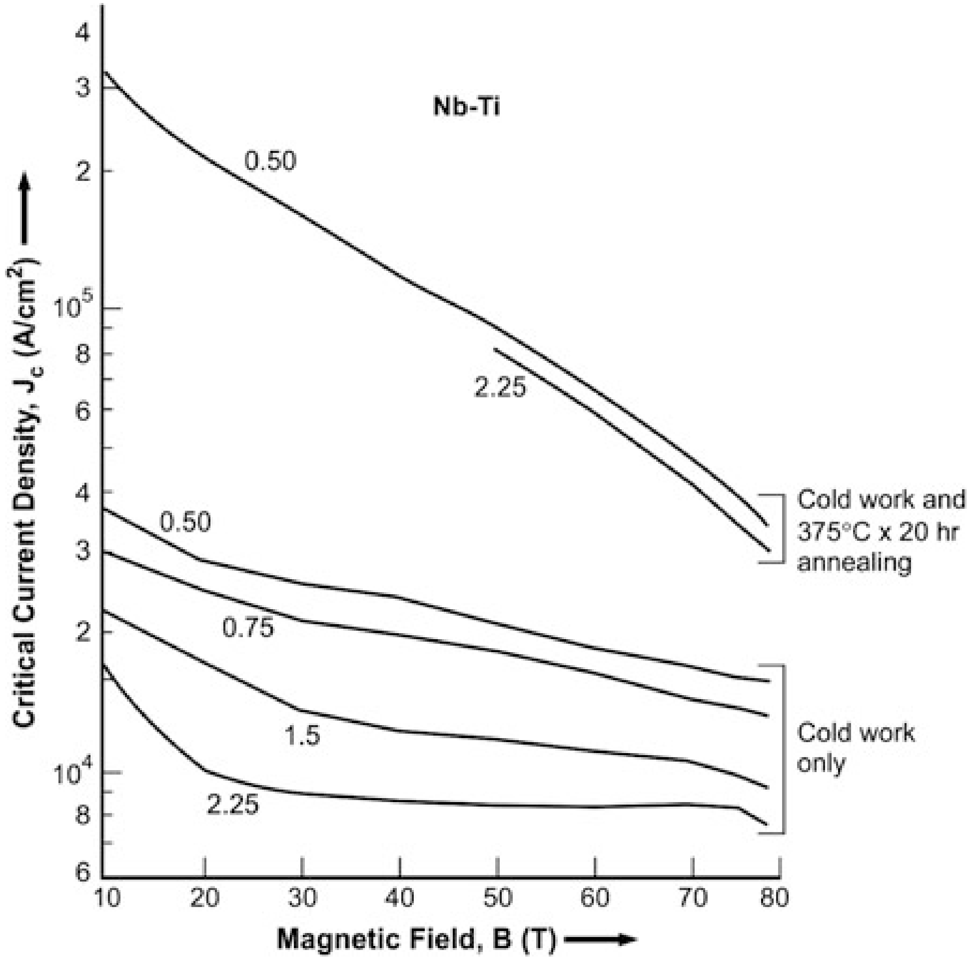
For Nb-Ti single diameter filament < 50 microns



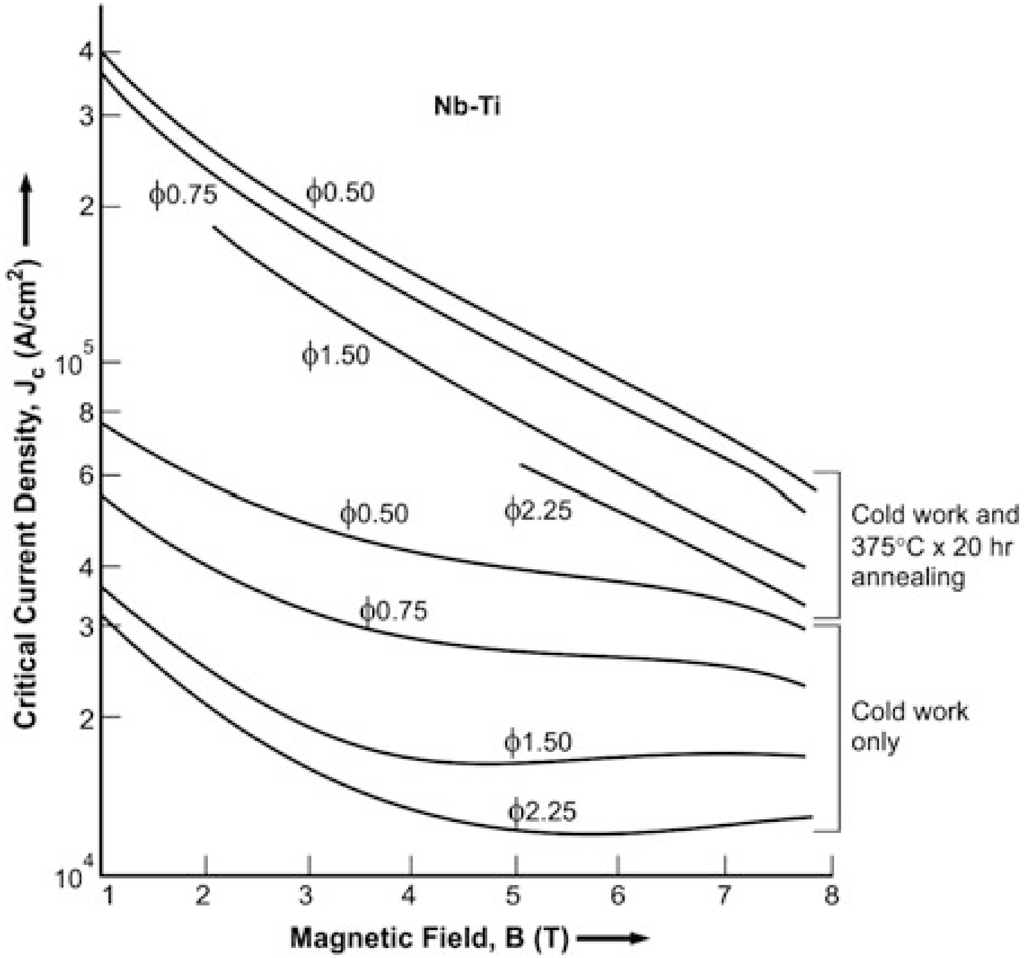
LHC (CERN) filament diameter 6-7 µm

HERA (DESY) filament diameter 14 µm

Effect of single wire diameter on Jc



Jc–B plots of Nb–Ti alloy containing 56 wt% Ti



Jc–B plots of Nb–Ti alloy containing 45 wt% Ti

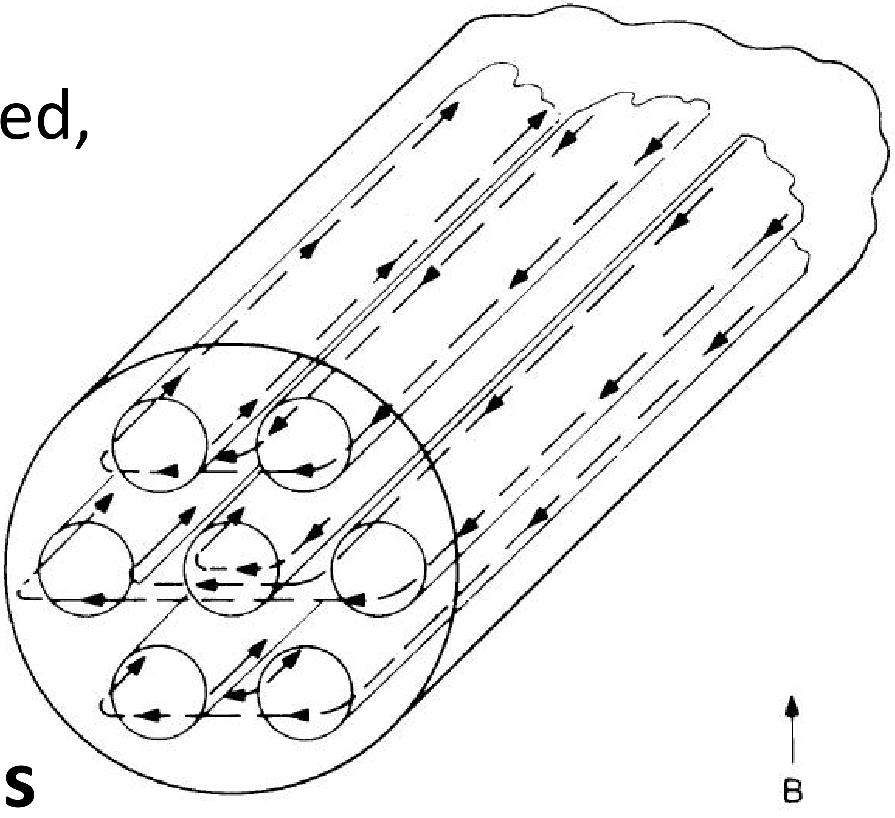
Interfilament coupling → Twist pitch

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**

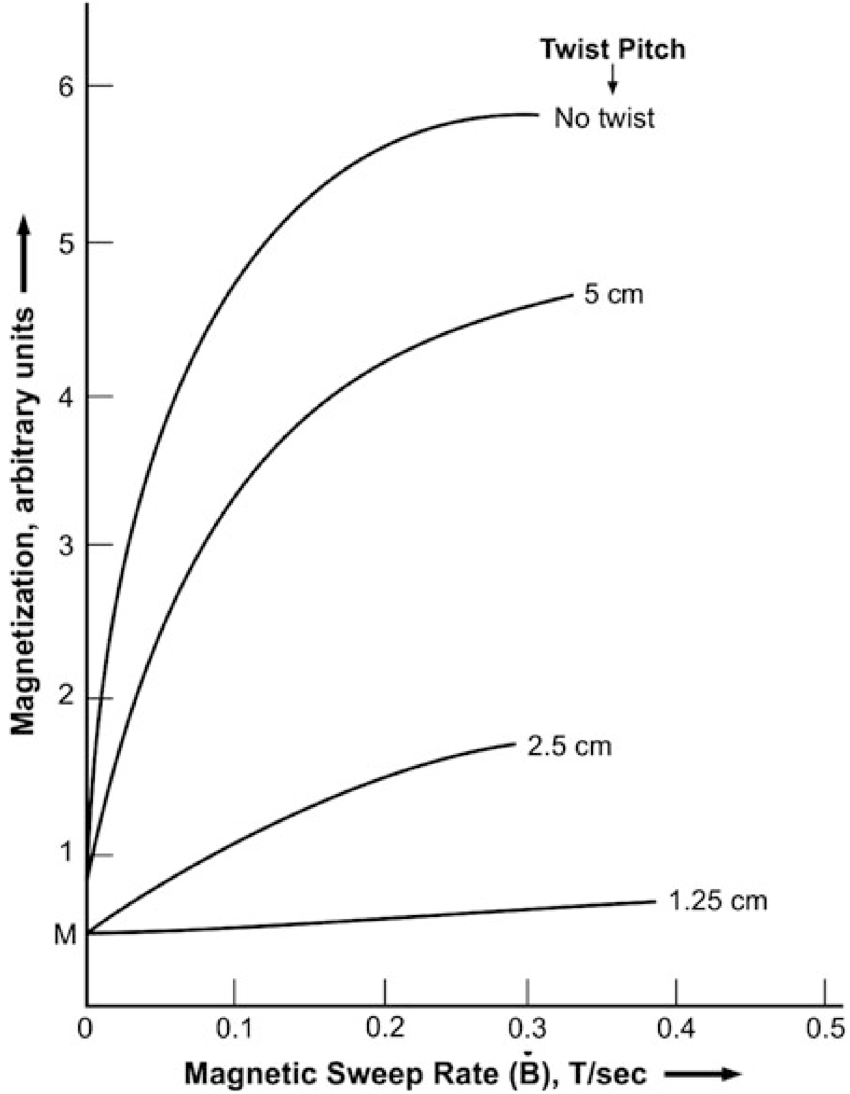
If the strands are magnetically (or physically) coupled the effective filament size is larger
→ **Flux jumps**

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

Twist Pitch effect on Magnetization



Magnetization versus field ramp rate plots at 1 T of a Cu/Nb–Ti wire with 121 strands each 0.009 mm dia. in a 0.2 mm Cu-matrix composite

Quench protection

Above Tc superconductors have a **very high resistivity**

⬇

If **quenched**, a solitary Nb-Ti filament could reach **very high temperatures in a few milliseconds**

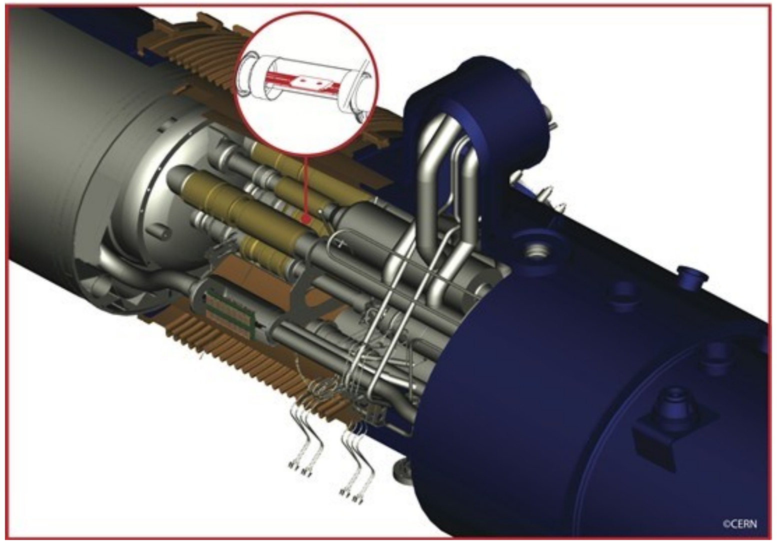
If the filament is embedded in a copper matrix:

when a quench occurs, the current redistributes into the matrix

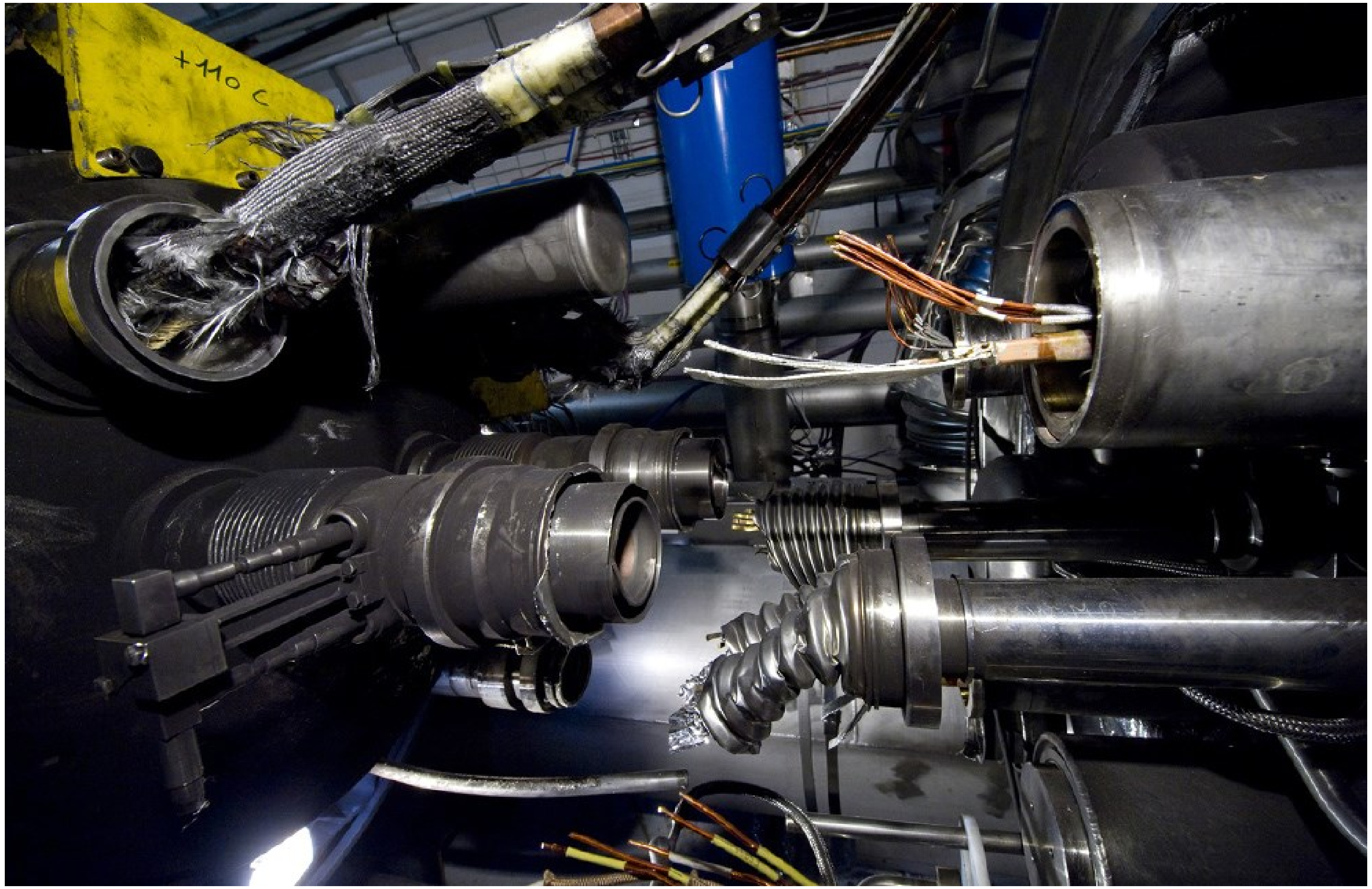
the higher heat capacity reduces Joule heating

→ the peak T can typically be maintained below 300 K
→ it allows the quench to propagate
→it provides time to act on the power circuit

LHC magnet incident - 1 year shut down



Damage of the LHC magnets in sector 3-4 of the LHC, provoked by the incident which happened on 19 September 2008



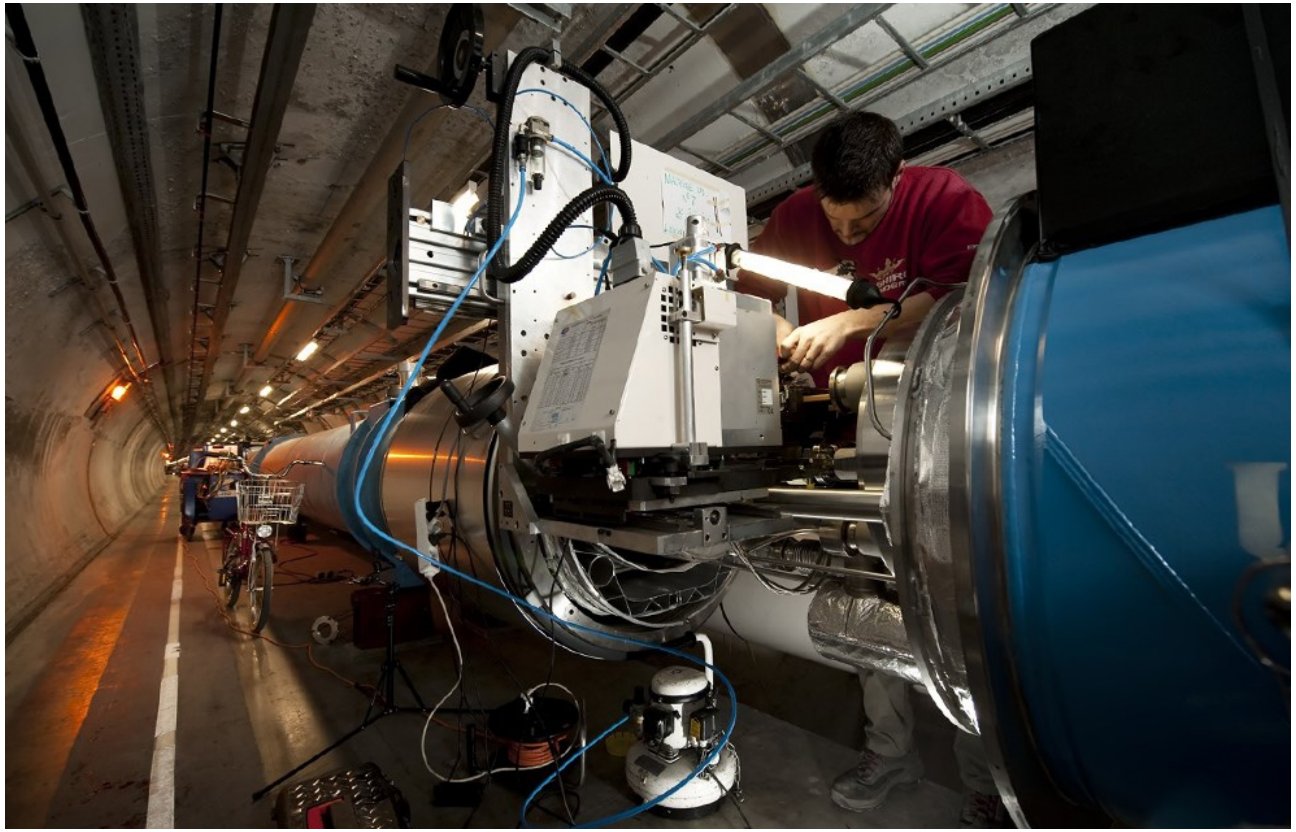
Visible damage to the LHC magnets in sector 3-4 of the LHC on November 12th, 2008. On September 19th, 2008, as the LHC was being switched on, a faulty electrical connection between two of the accelerator's magnets caused a large helium leak, which violently vented 6 tons of helium into the tunnel. The resulting temperature rise damaged some 53 magnets. (Maximilien Brice, © CERN)

LHC magnet incident (2)

Detail of some of the damage done to the LHC magnets in sector 3-4 on September 19th, 2008. (Maximilien Brice, © CERN)

Obvious damage to concrete, where a magnet has been lifted off its mount (the red boxes) that secured it to the floor (CERN)

LHC magnet incid



Views of two step of an ultrasound and induction welding to interconnection between two LHC magnet at sector 3-4 during repair operation on March 26th, 2009. (Maximilien Brice, © CERN)

A replacement magnet for LHC sector 3-4 being lowered in the tunnel on January 19th, 2009.

Moving and placement of a quadrupole at sector 3-4 in the LHC tunnel on April 30th, 2009

Why 50 years before magnet applications?

To prevent early quenches SC wires must have the following **characteristics**:

1. **Type II** with **pinning centers**

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   → to prevent jumps instabilities

3. **Twist pitch**
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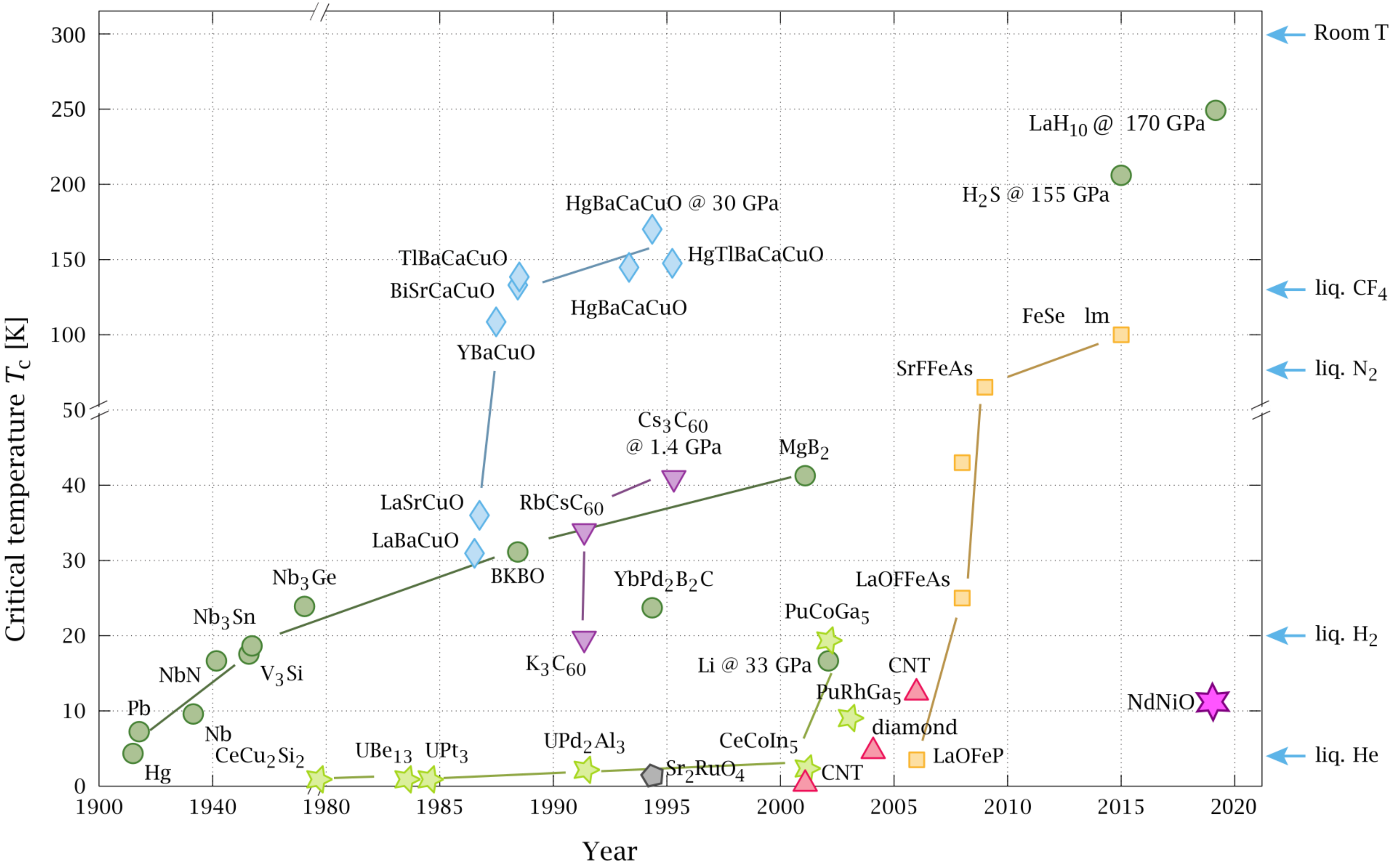
Timeline of discovery of Superconductors



BCS

Heavy-fermions-based

Cuprate

Buckminsterfullerene-based

Carbon-allotrope

Iron-pnictogen-based
(the new black)

Nichel Based

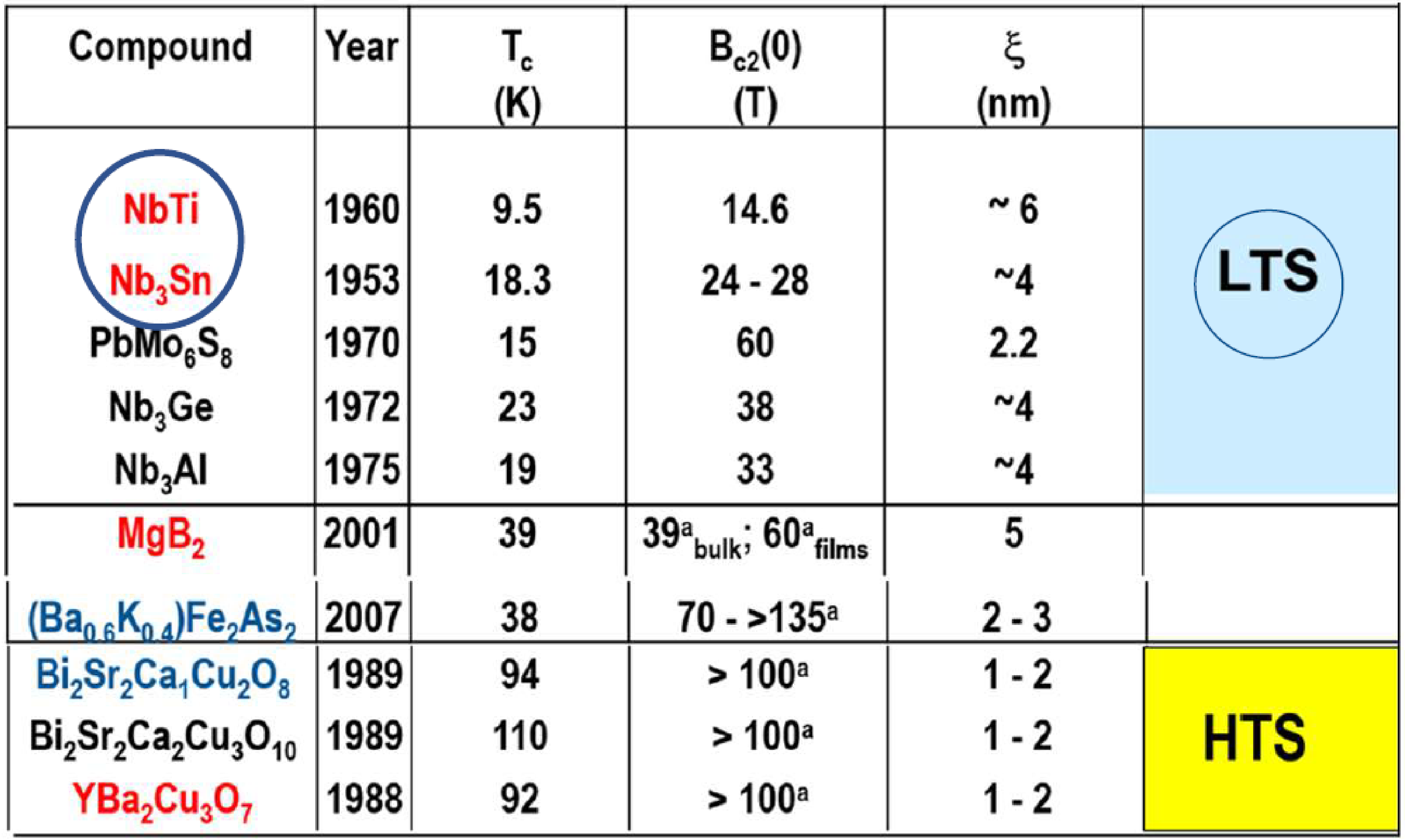
Source: Wikipedia

Practical SC

Only 3-4 superconductors have been used in **real applications** until now:

- NbTi
- Nb_3Sn
- MgB_2
- *REBCO (RE= Rare-Earth)*

Technically interesting superconductors



Compound	Year	T_c (K)	$B_{c2}(0)$ (T)	ξ (nm)	
$NbTi$	1960	9.5	14.6	~ 6	**LTS**
Nb_3Sn	1953	18.3	24 - 28	~4	
$PbMo_6S_8$	1970	15	60	2.2	
Nb_3Ge	1972	23	38	~4	
Nb_3Al	1975	19	33	~4	
MgB_2	2001	39	39^a_{bulk}; 60^a_{films}	5	
$(Ba_{0.6}K_{0.4})Fe_2As_2$	2007	38	70 - >135^a	2 - 3	
$Bi_2Sr_2Ca_1Cu_2O_8$	1989	94	> 100^a	1 - 2	**HTS**
$Bi_2Sr_2Ca_2Cu_3O_{10}$	1989	110	> 100^a	1 - 2	
$YBa_2Cu_3O_7$	1988	92	> 100^a	1 - 2	

Flukiger, ESAS Summer School, Wien 2018

Superconducting Wires

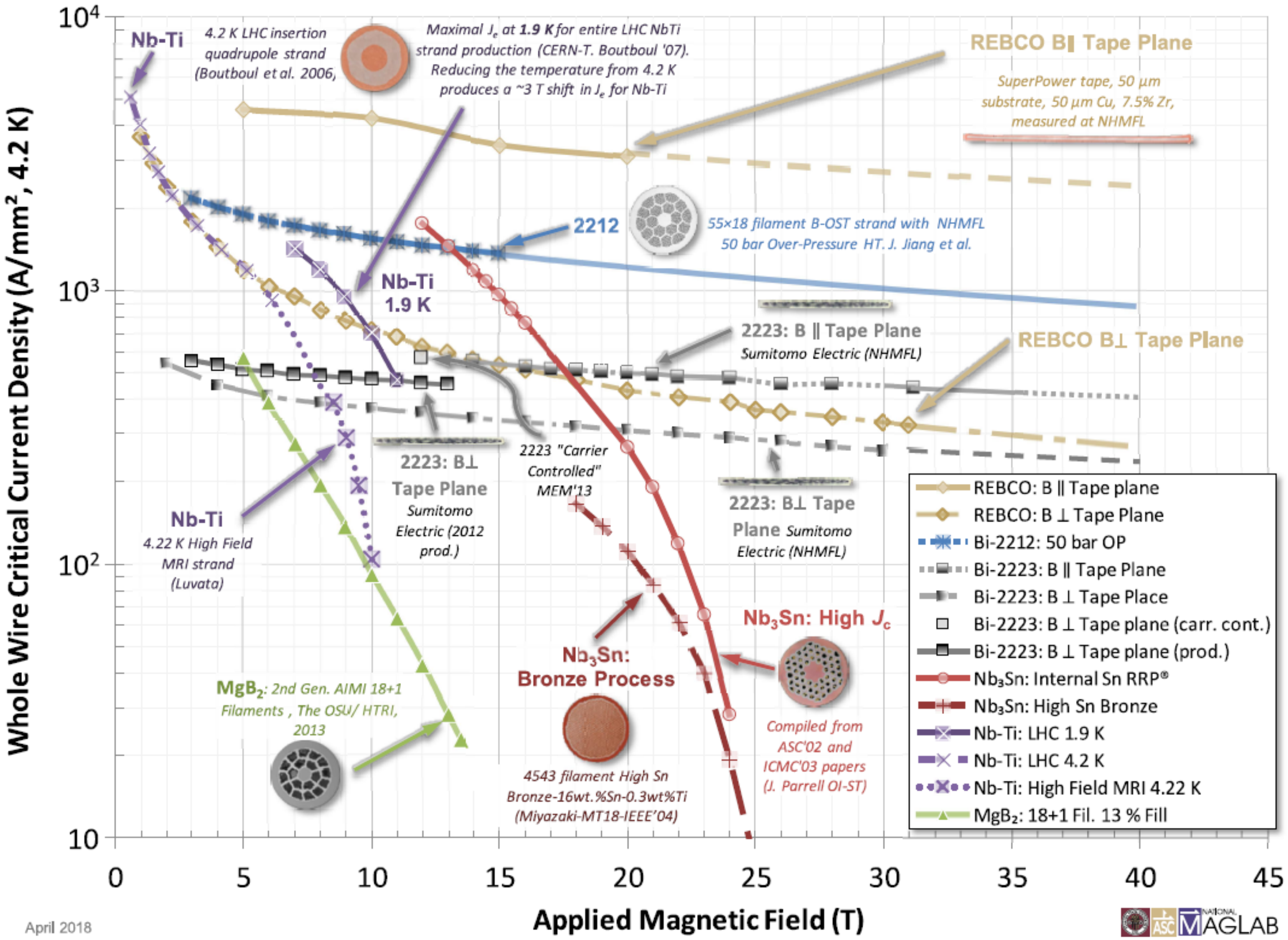
Round wires

NbTi	Still the most used wires: ~ 85 - 90% (MRI, accelerators)
Nb_3Sn	~10%: NMR lab magnets up to 23 T (accelerators LHC Upgrade)
MgB_2	Low costs; Niche applications at 10-25 K (open MRI, LINK for LHC}
Bi-2212	Possibility: Accelerators @ >20T. Problem: mechanical stability
$Ba_{0.6}K_{0.4}Fe_2As_2$ (Pnictides):	promising for very high field magnets $B_{c2} > 70$ T. Need further improvement. *Problems: Toxicity of As, complex metallurgy, weak links*

Tapes

Bi,Pb(2223)	Cables, motors at $T < 30$ K *Problems: B_{c2} @ 77 K ≤ 1 T, Costs*
YBCO	Power Cables at 77 K, Very high field magnets $B_{c2} \geq 45$T (Current limiters, wind generators, …) *Main Problem: costs Presently available: ~ 500 m {manufacturers in USA, J, Korea, Eu)*

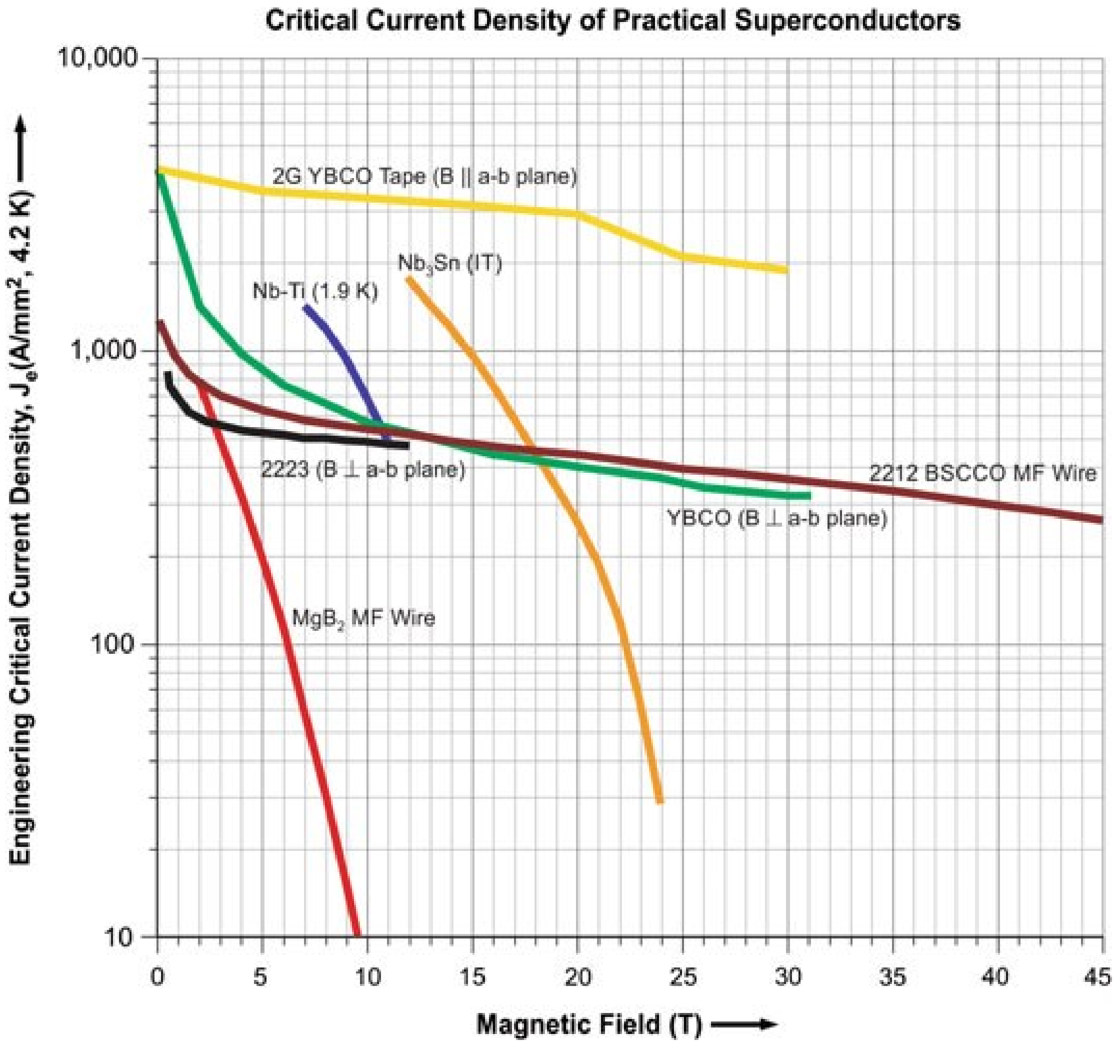
Current VS Field



April 2018

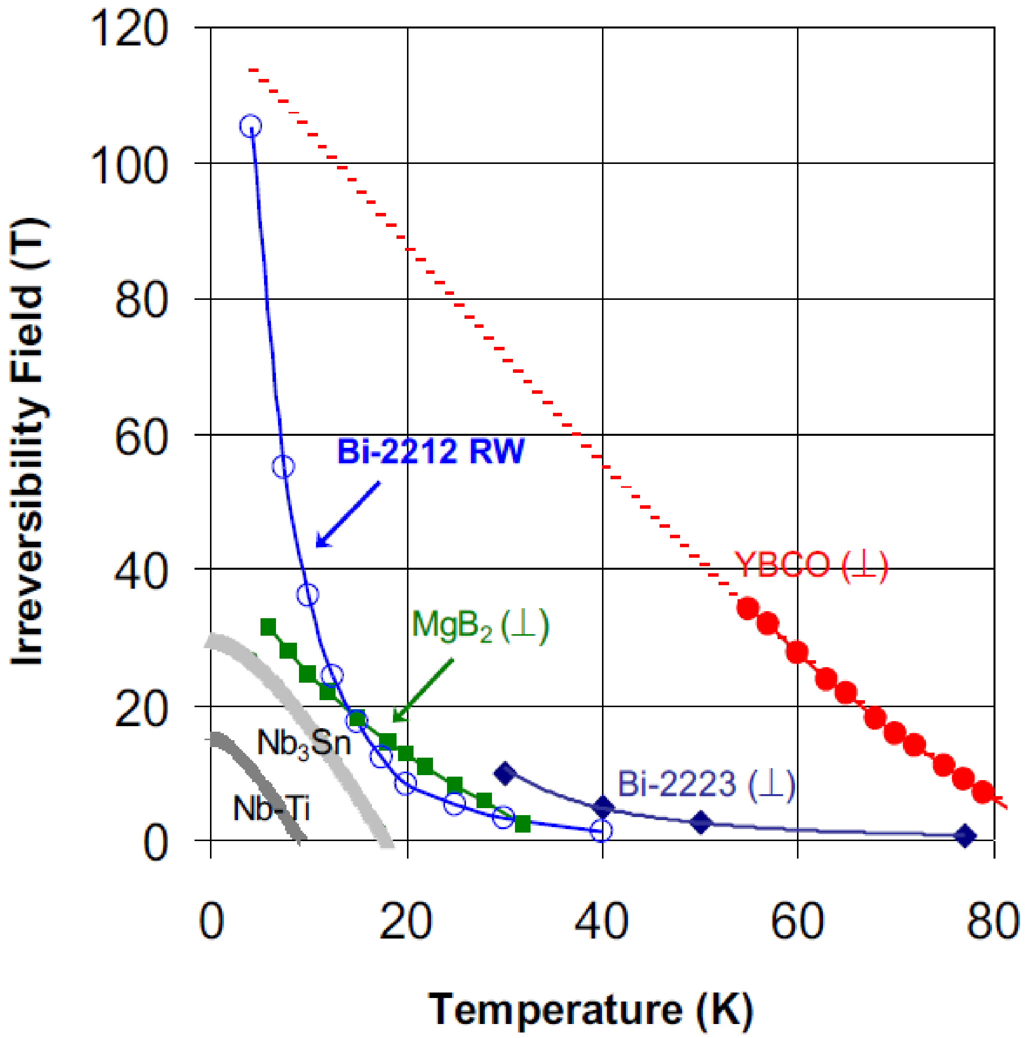
https://nationalmaglab.org/magnet-development/applied-superconductivity-center/plots

Current VS Field



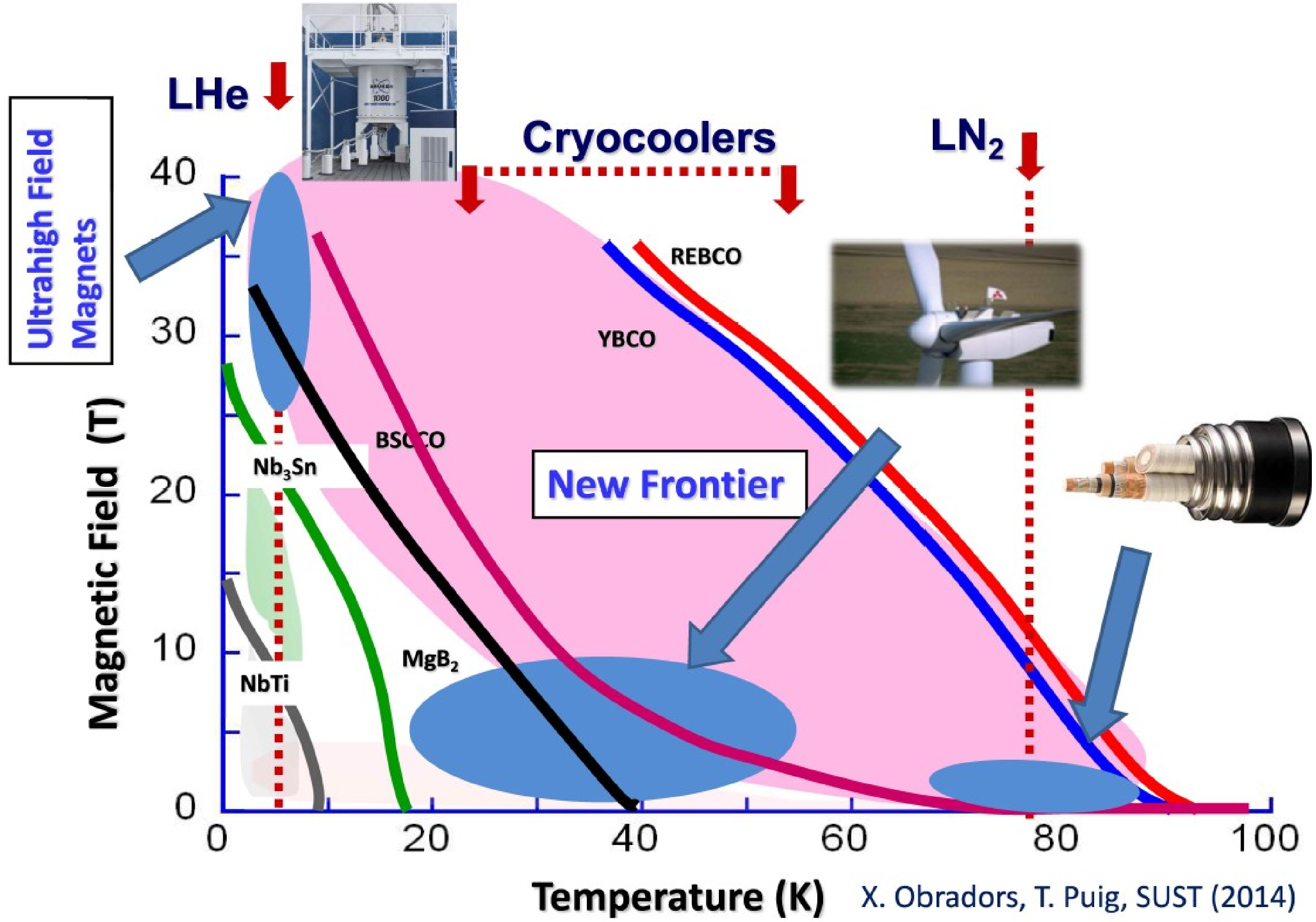
R.G. Sharma, Superconductivity Basics and Applications to Magnets, Springer 2015

Field vs Temperature



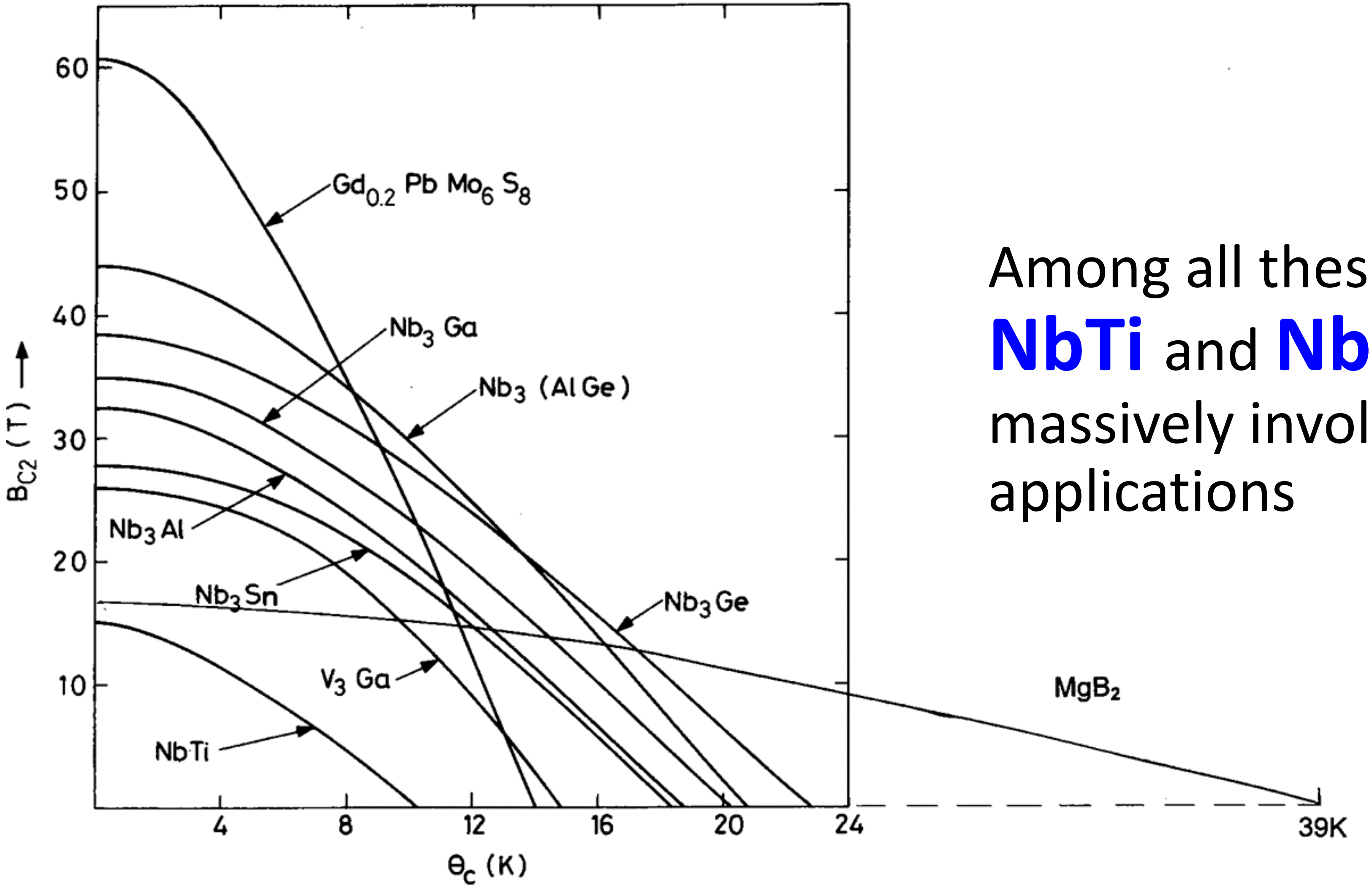
Courtesy J. Jiang, Applied Superconductivity Center
at the National High Magnetic Field Laboratory, FSU

New frontiers for HTS applications



X. Obradors, T. Puig, SUST (2014)

Low Tc SC - Field VS T



Among all these materials only **NbTi** and **Nb$_3$Sn** have been massively involved in the applications

Low Tc commercial SC properties

Nb-Ti

- B_{c2} (0K) ~ 14 T
- T_c (0T) ~ 9.5 K
- **Max practical field at 4.2 K is 7 T (9 T @ 1.8 K)**
- **Excellent mechanical properties (ductile)**

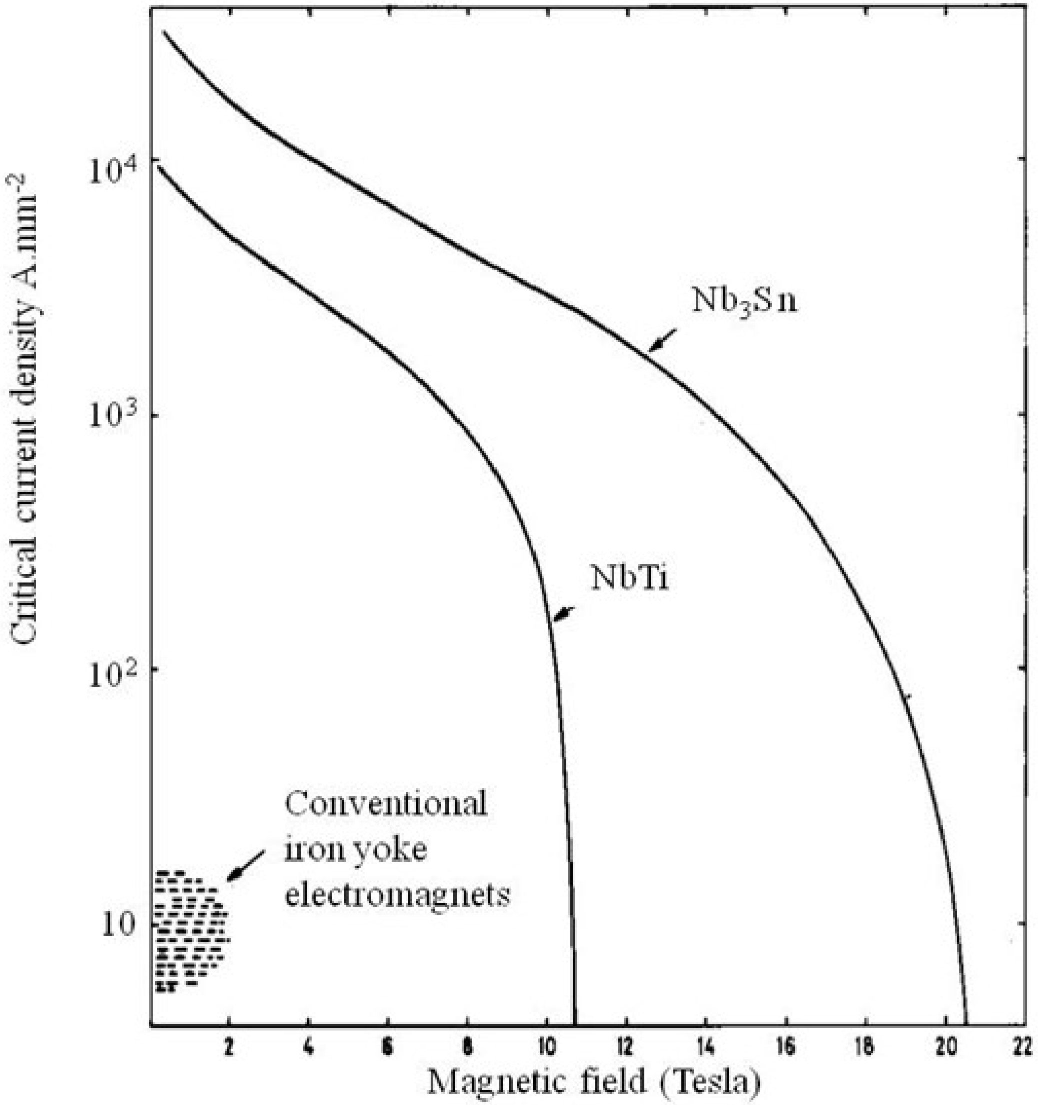
Nb_3Sn

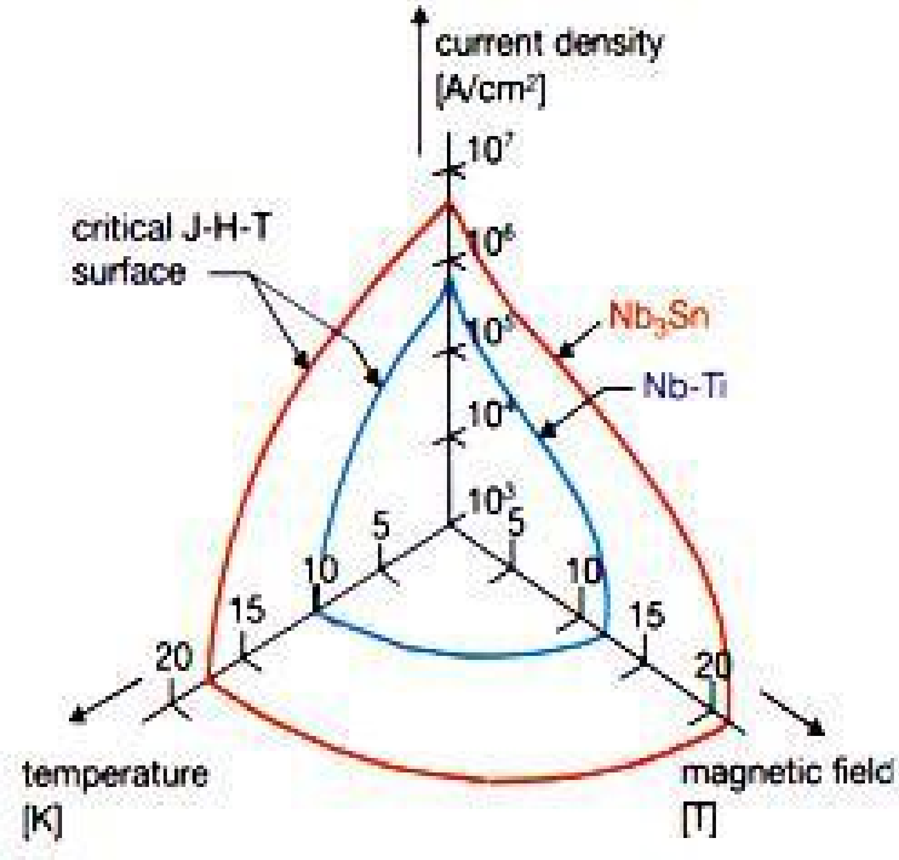
- B_{c2} (4.2 K) ~ 23 – 24 T
- T_c (0T) ~ 18 K
- **Max practical field 17 – 18 T?**
- **Brittle and strain sensitive**

Nb_3Al

- *High J_c in magnetic field < 15 T*
- *Less strain sensitive than Nb_3Sn*
- *Not commercially available*
- *Rapid-quench process requires later addition of stabilizer*
- *Actively pursued in Japan but fading from the scene*

The critical current density Jc vs the magnetic field

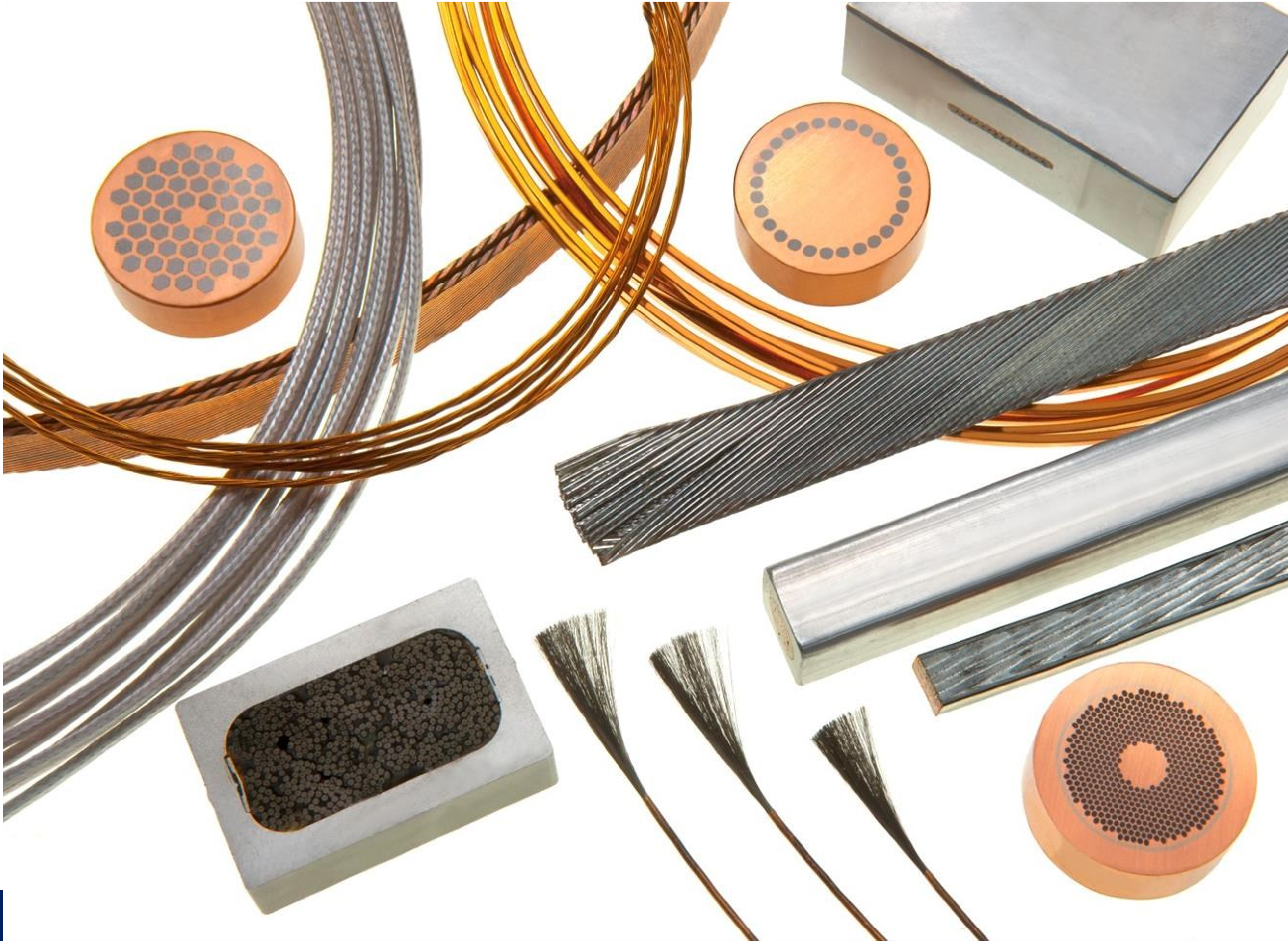




Applications involving NbTi and Nb_3Sn in High Field Magnets

APPLICATION	PRODUCED FIELD	SUPERCONDUCTOR
ITER Tokamak	12 T	Nb_3Sn
DEMO	~ 12 T	Nb_3Sn
Hilumi LHC (2024) Quadrupoles	≤ 12.5 T	Nb_3Sn
Hilumi LHC (2024) Dipoles	≤ 8 T	NbTi
FCC (2040?)	16 T	Nb_3Sn (needs further improvements) HTS possible

Nb-Ti



NbTi

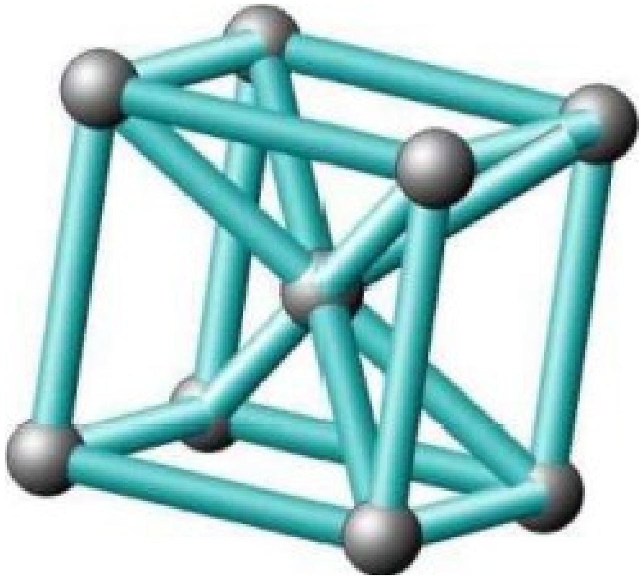
Today: ~ 90 % of all industrial SC wires are based on NbTi

The cost is approximately 100-150 US$ per kg of wire

From 1500 to 2000 metric tons are produced yearly. (Mostly MRI industry)

NbTi applications:

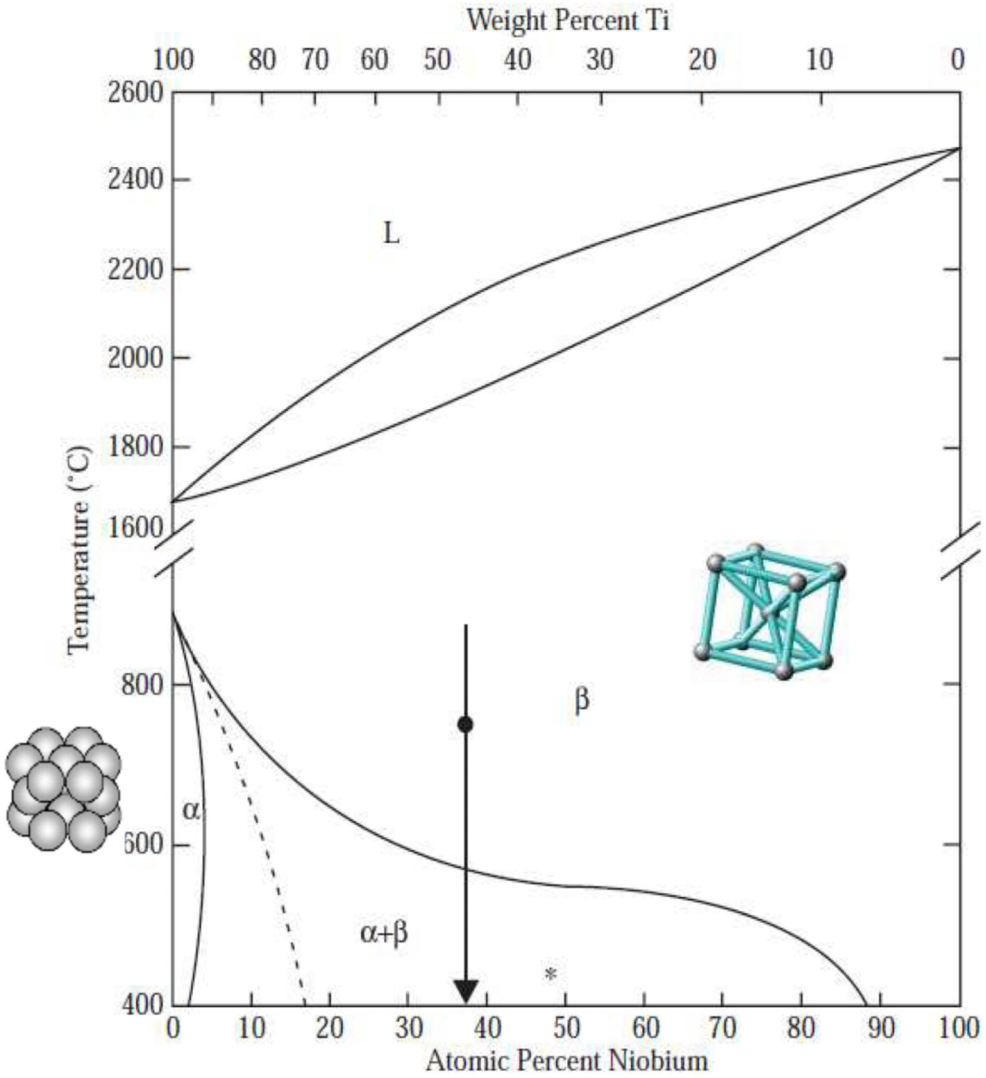
- MRI/NMR magnets up to 9T,
- For a background field in high field magnets (~ 9T)
- for accelerator magnets (dipoles in LHC, Tevatron, HERA, …)
- Poloidal field coils in ITER fusion magnets
- Levitation train in Japan Tokyo-Osaka
  (2035-2040 under construction) Later replaced by other SC?

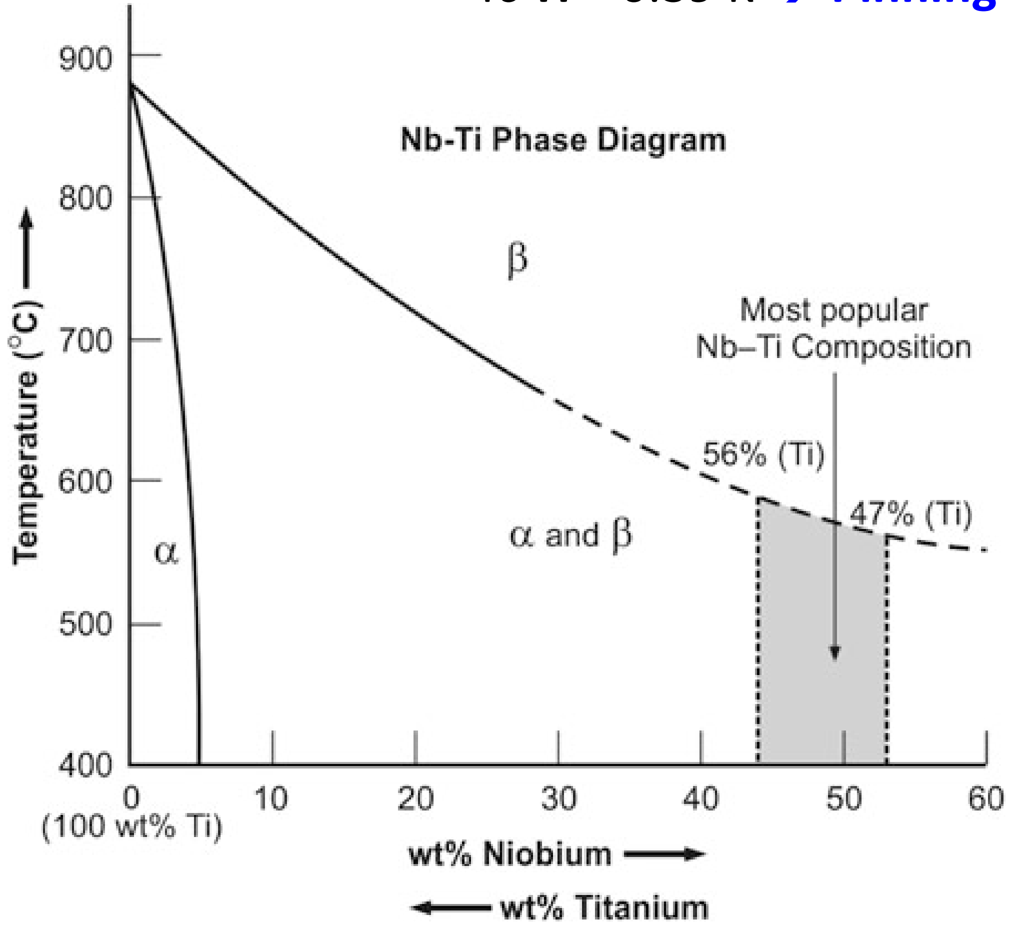


NbTi phase diagram

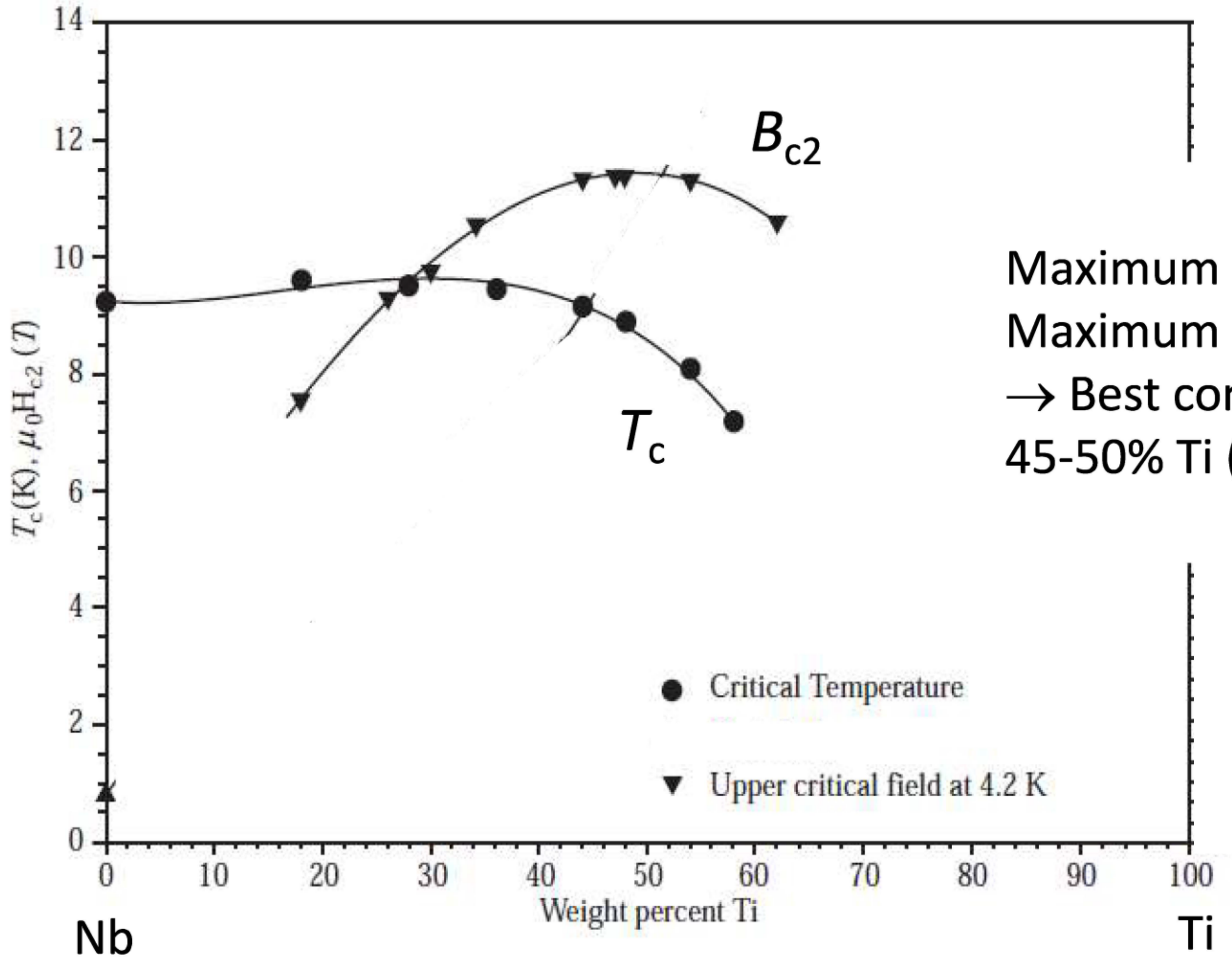
β: bcc – ductile
α: hexagonal – non ductile

Tc **Ti** = 0.39 K → **Pinning center**



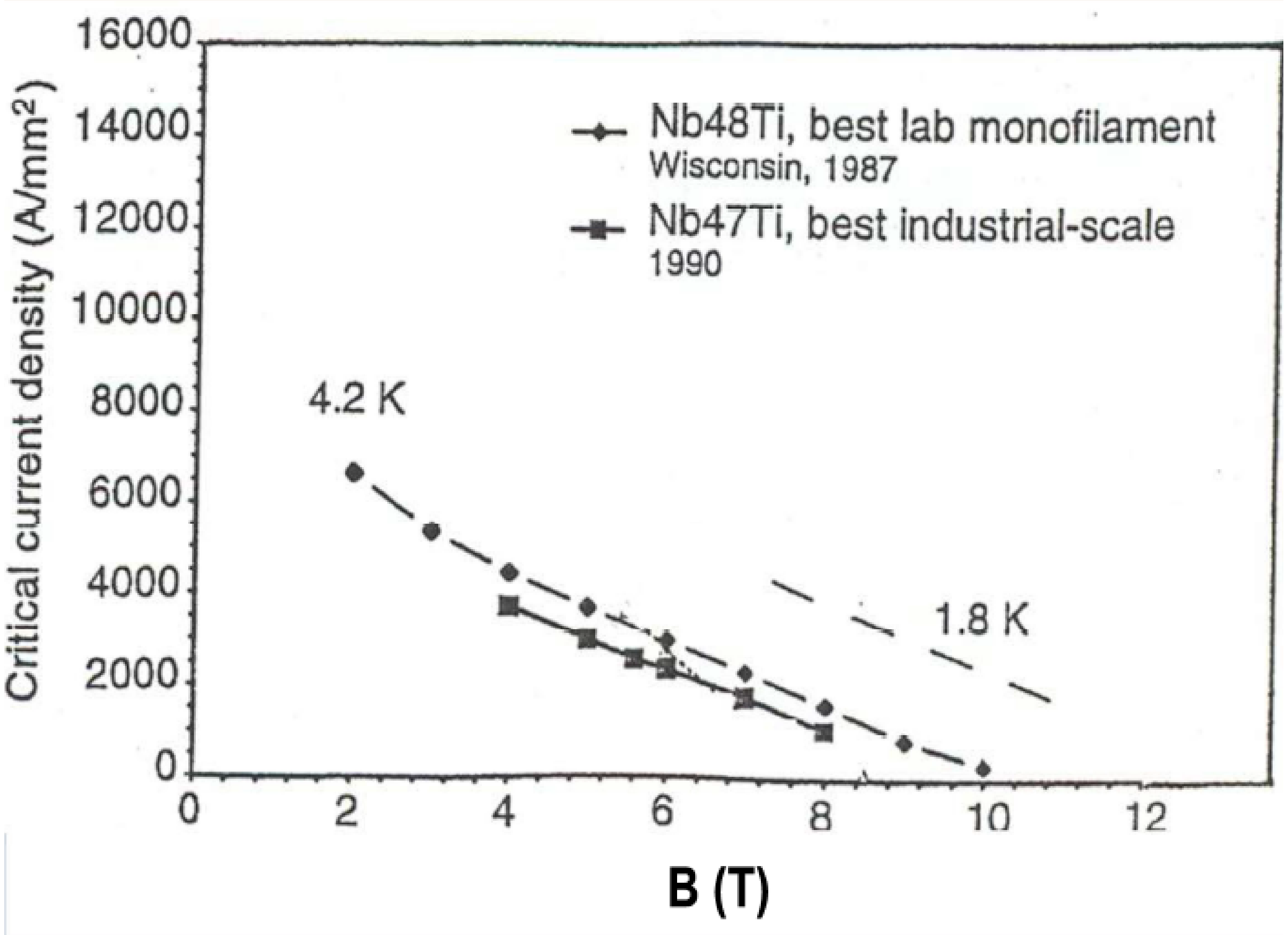


NbTi upper critical field and Tc



Maximum T_c at 30% Ti
Maximum B_{c2} at 44% Ti
→ Best composition:
45-50% Ti (most 47%)

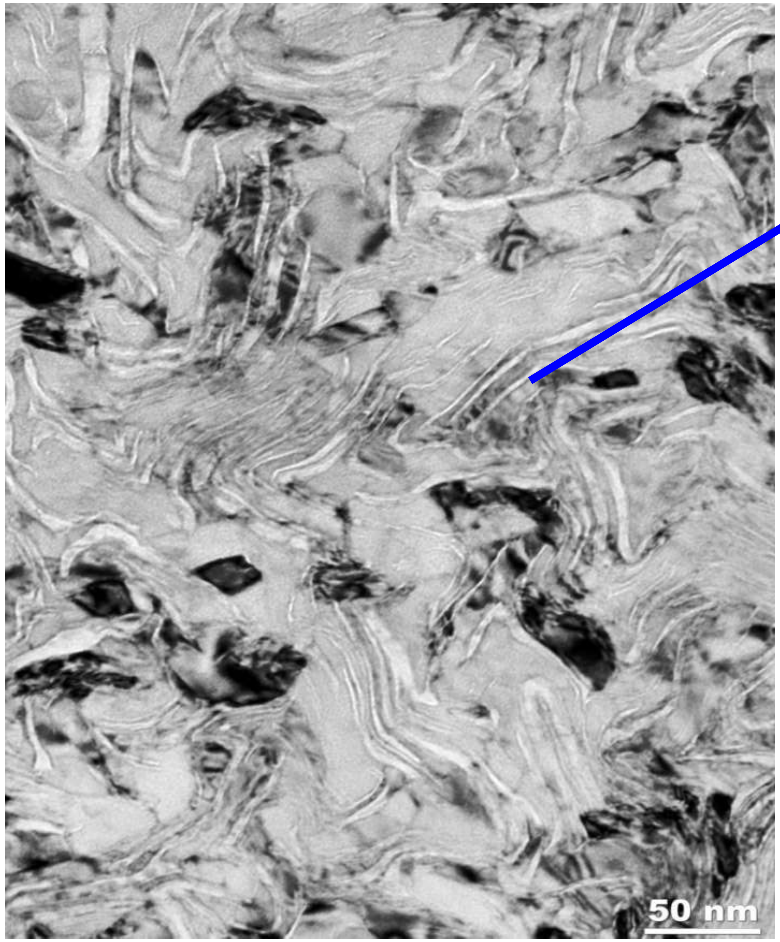
Highest known Jc values for NbTi



NbTi: Jc Enhancement adding pinning centers

- Normal conducting α-Ti precipitates act as effective pinning centers
- Precipitation of α -Ti phase can be promoted by optimized sequence of drawing steps (cold work) and heat treatments at 375 °C - 420 °C for 40h - 80h
- Precipitation of α -Ti depletes NbTi matrix in Ti close to the optimum NbTi composition for single phase material
- Cold drawing creates densely folded arrays of α-Ti precipitates
- After final cold work size of α -Ti precipitates is comparable to flux lattice spacing

TEM image of Ni-Ti filaments



TEM image of the microstructure (transverse cross-section) of a multifilamentary strand from OST, with 3700 A/mm2 (5T, 4.2 K)
D. Larbalestier and P. Lee, 1995

α-Ti ribbons

(1 - 2 nm thick - several μm long)

form during wire deformation (non-equilibrium)

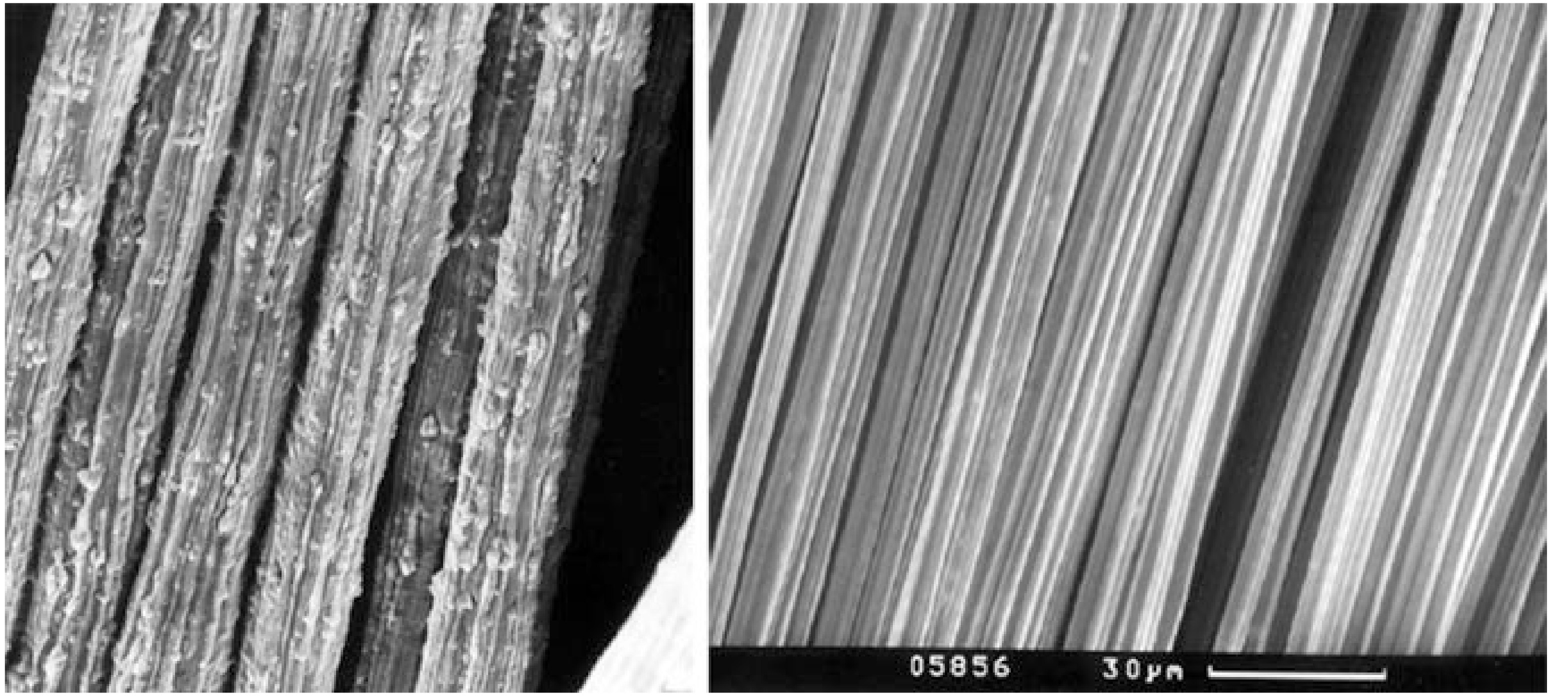
Defects at the interface with NbTi create the strong **vortex pinning**

⬇

Enhancement of Jc

Nb diffusion barrier

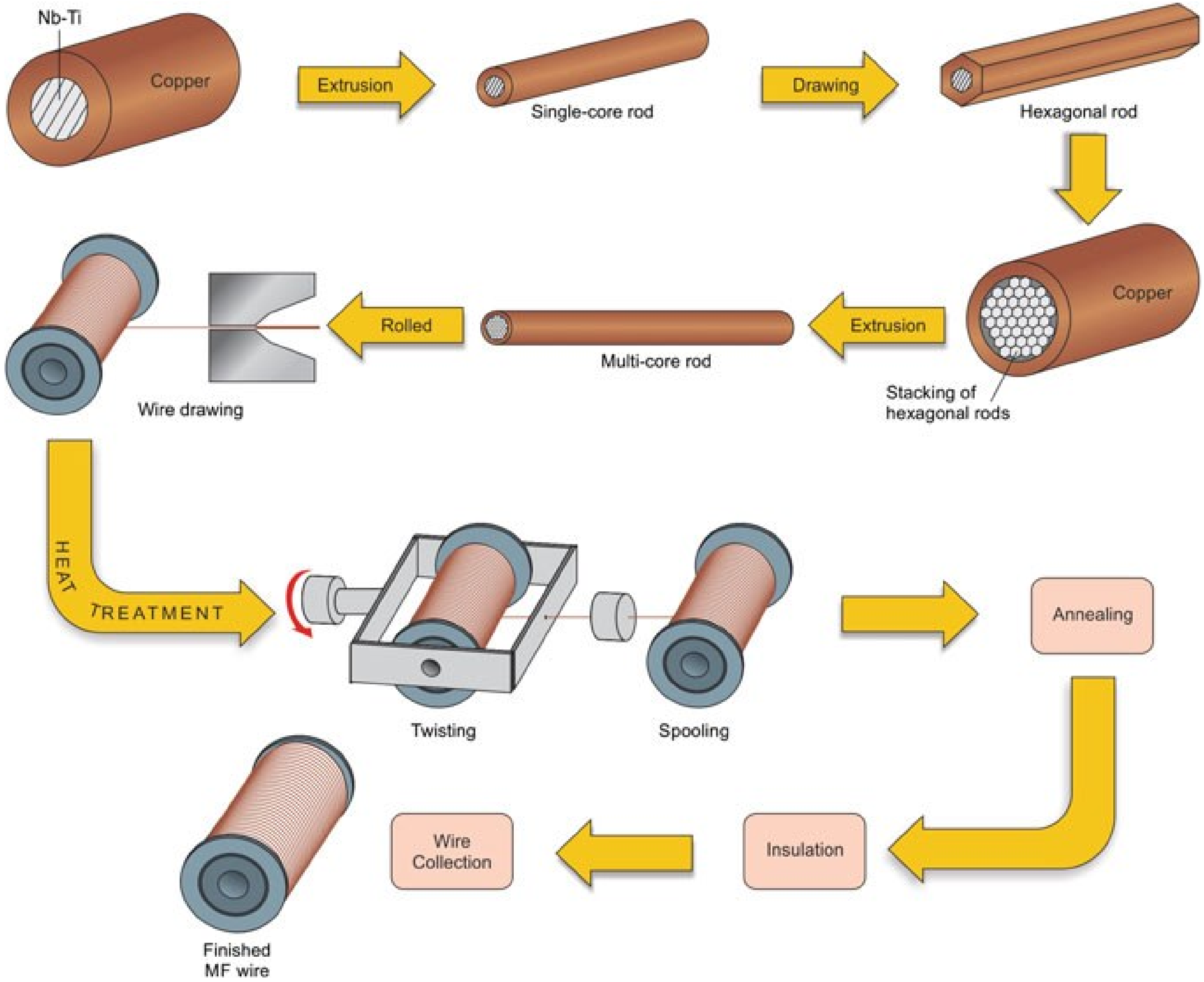
Problem of **sausages of the Nb–Ti filaments** solved by using **Nb-diffusion barrier** around each filament

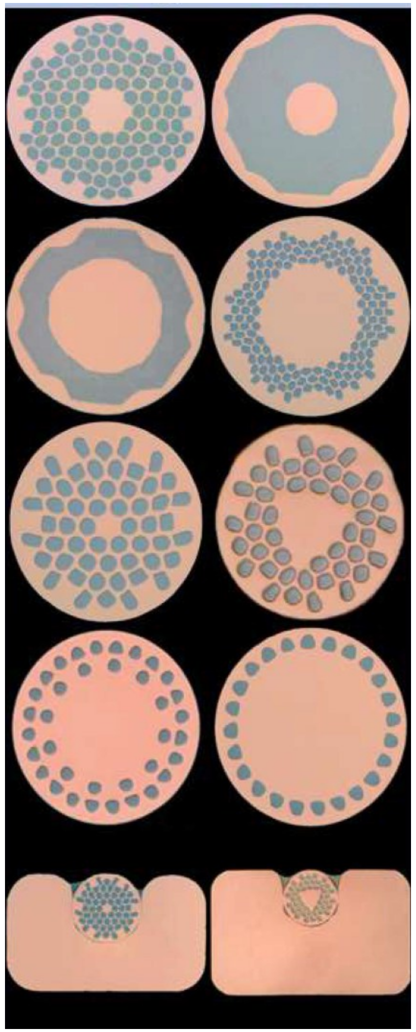


Left Nb–Ti filaments with sausages caused by Cu–Ti intermetallic particles. Right Very uniform Nb–Ti filaments when the filaments are covered by the Nb-diffusion barrier

http://cbmm.com.br/portug/sources/techlib/science_techno/table_content/sub_3/images/pdfs/014.pdf

Fabrication process of Nb-Ti Multifilament Wires





Wire possible configurations

Fabrication process of Nb-Ti Multifilament Wires

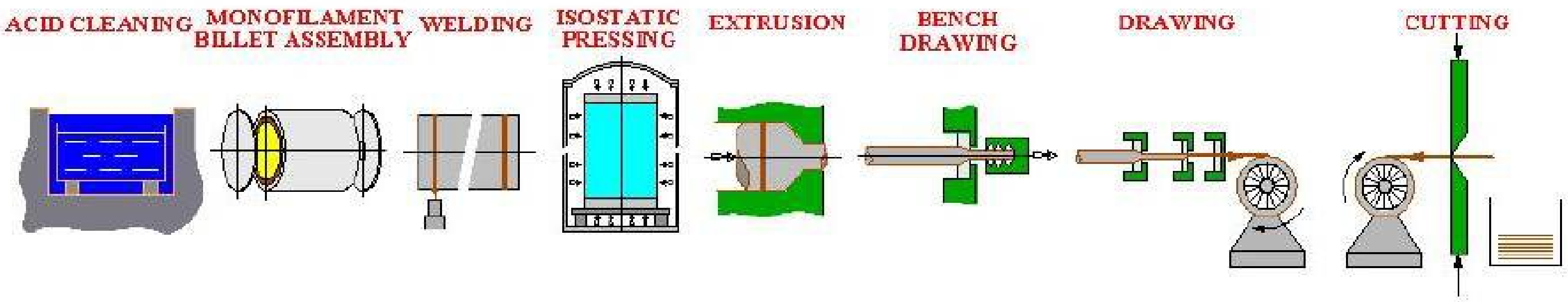
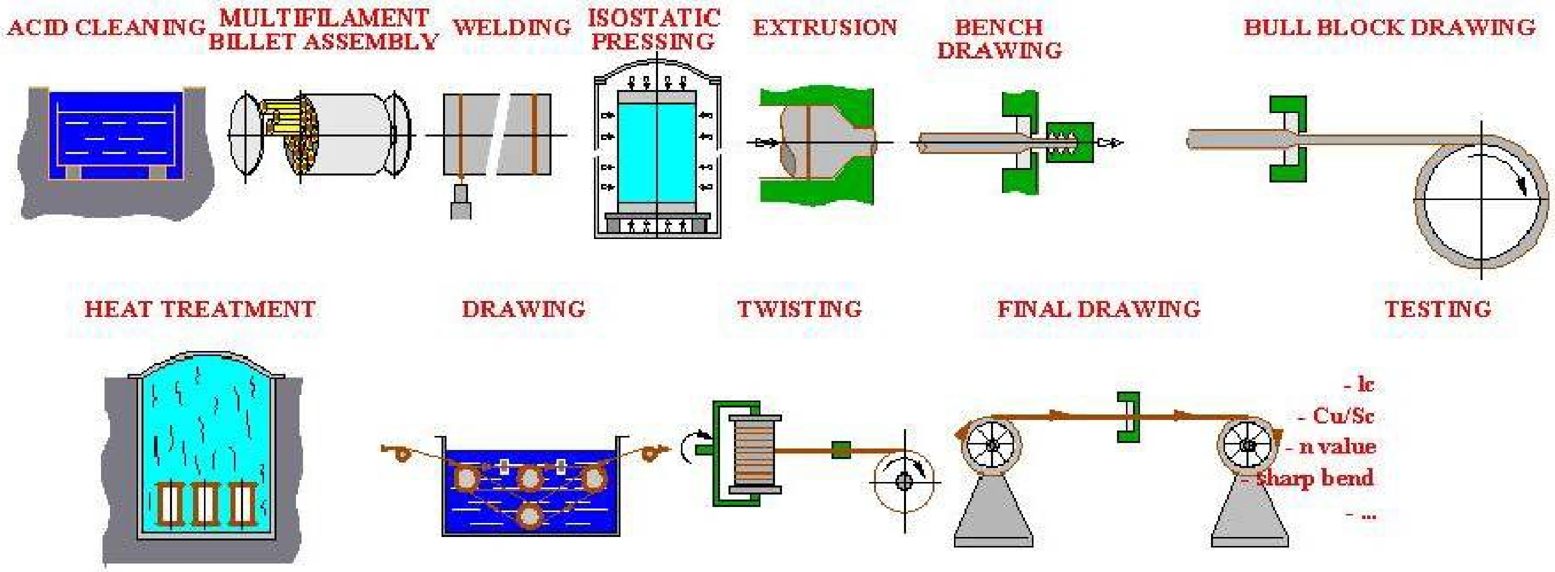


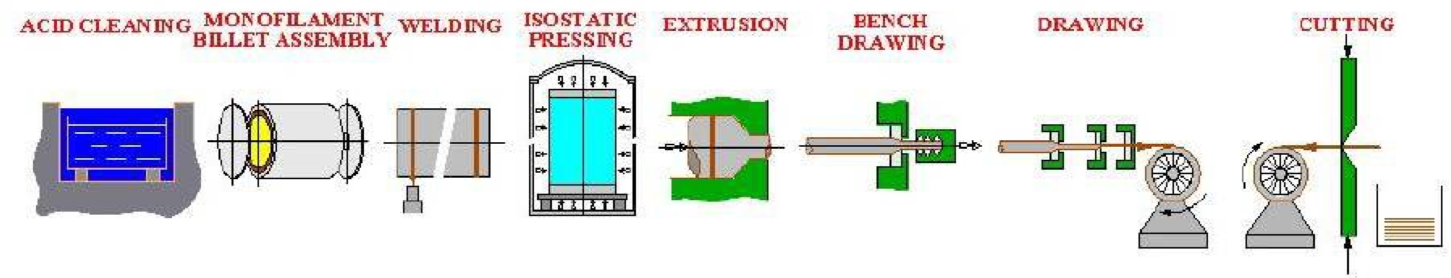
Fig. 13(a): Assembly and transformation of mono-filament billet (Courtesy of Alstom/MSA).



Detailed fabrication process of Nb-Ti 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

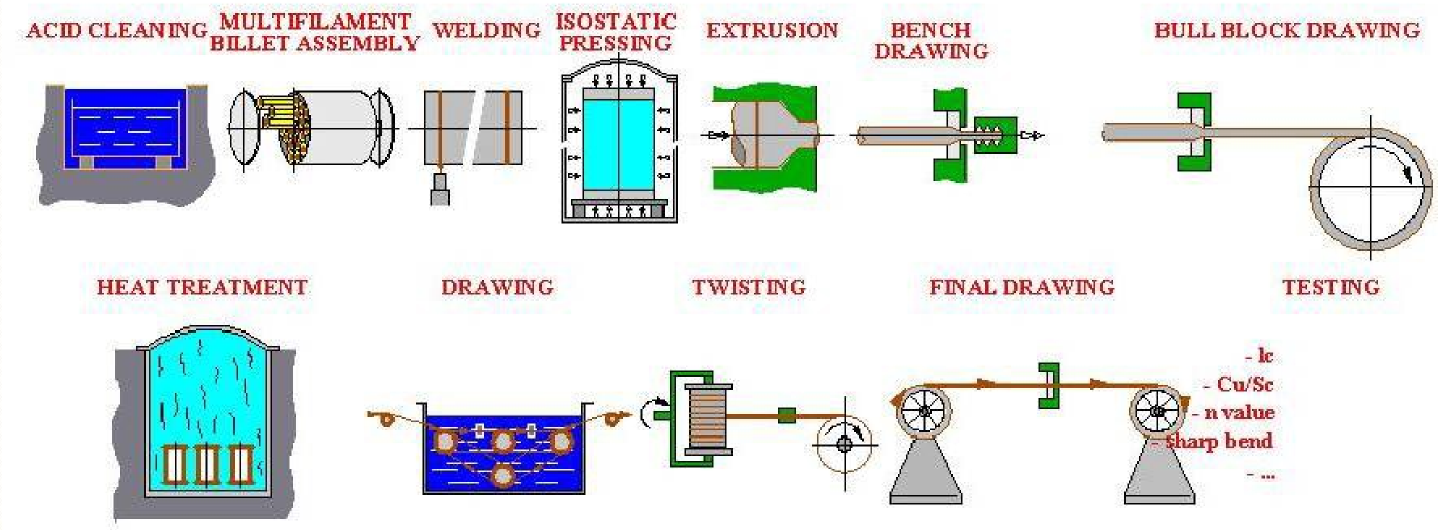


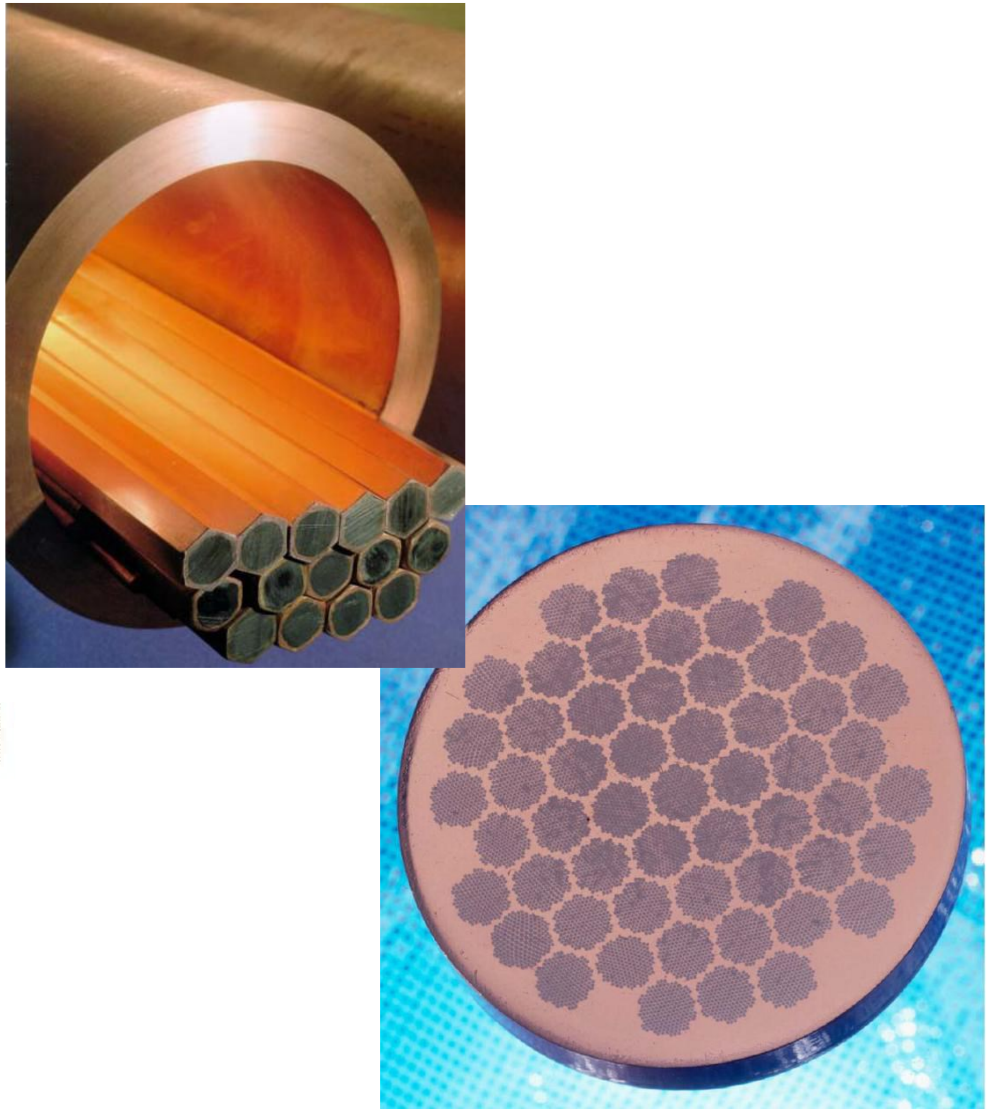
Detailed fabrication process of Nb-Ti Wires

Monofilament rods are stacked to form a multifilament billet, which is then extruded and drawn down

Heat treatments are applied to produce pinning centers (a-Ti precipitates)

When the number of filaments is very large, multifilament rods can be re-stacked (double stacking process)





Wires fabrication process consideration

- The Cu to SC ratio is specified for the application to ensure quench protection, without compromising the overall critical current of the wire.
- 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!

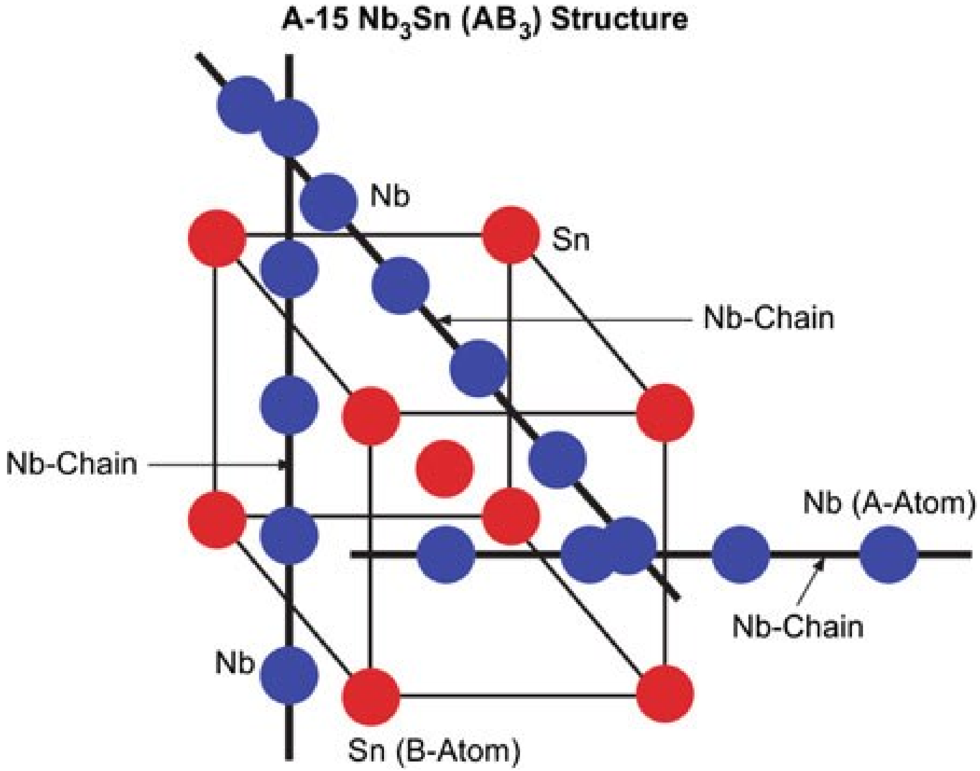
Nb_3Sn

ITER Nb_3Sn cable

Nb_3Sn

Niobium and tin can form an **intermetallic compound**, with the formula **Nb_3Sn**, from the **A15** family

- **T_C and B_{C2} depend on Sn content:**
  the optimal is 24-25 in weight%
- **T_C is ~18 K @ 0 T and zero strain**
- **B_{C2} is ~18 T @ 4.2 K**
  → up to 27 T with Ga or Ta doping
- **The critical current *Jc* depends on the microstructure** (grain structure)
- High *Jc* obtained with grains from 30 to 300 nm

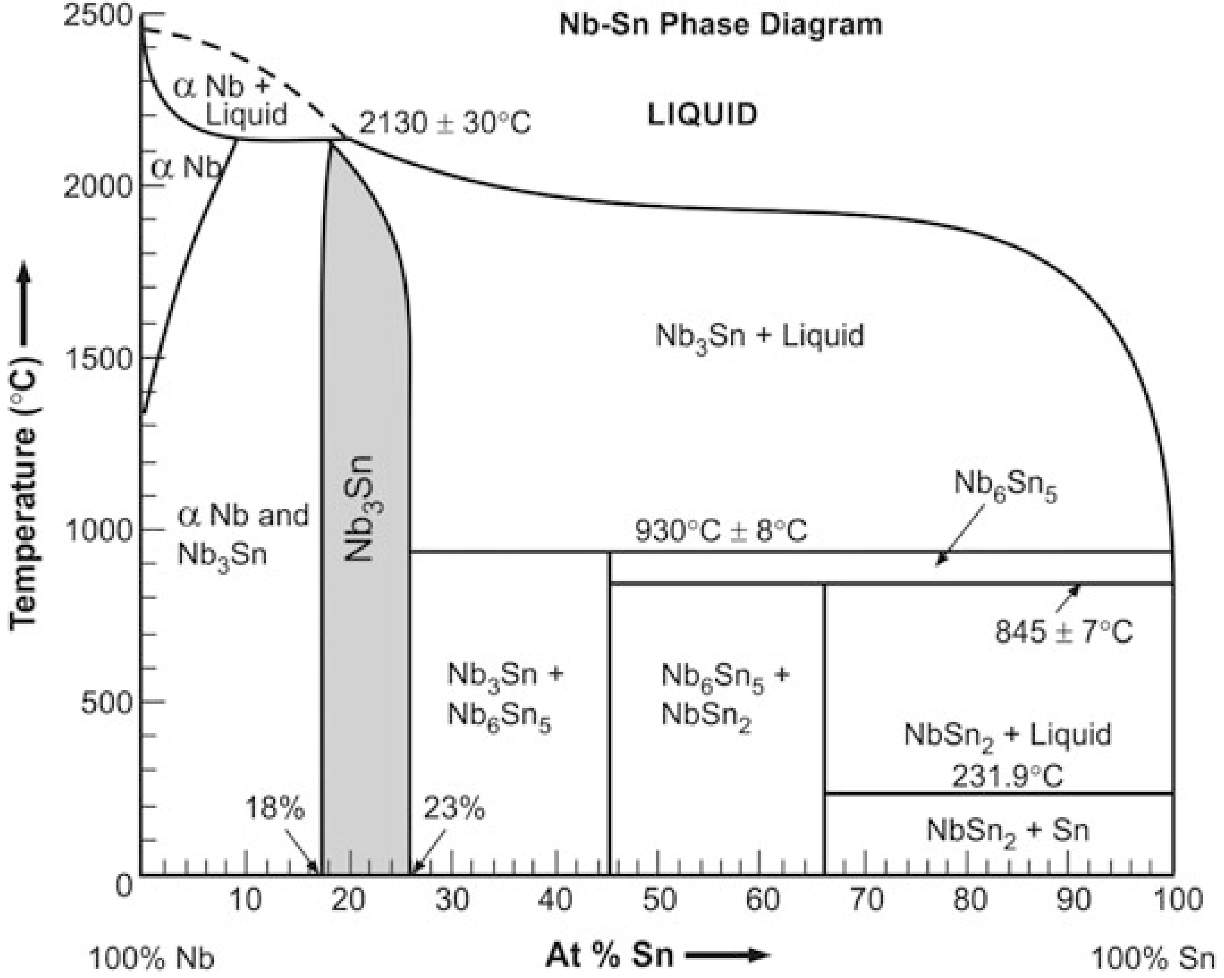


Nb_3Sn

- **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**.
- **Nb_3Sn is strain sensitive**: its critical parameters depend on the applied strain (reversible for small strain)
- The cost is approximately 700-2000 US$ per kg of wire *(NbTi 100-150 US$)*
- About 15 metric tons are produced yearly

Nb_3Sn Phase diagram

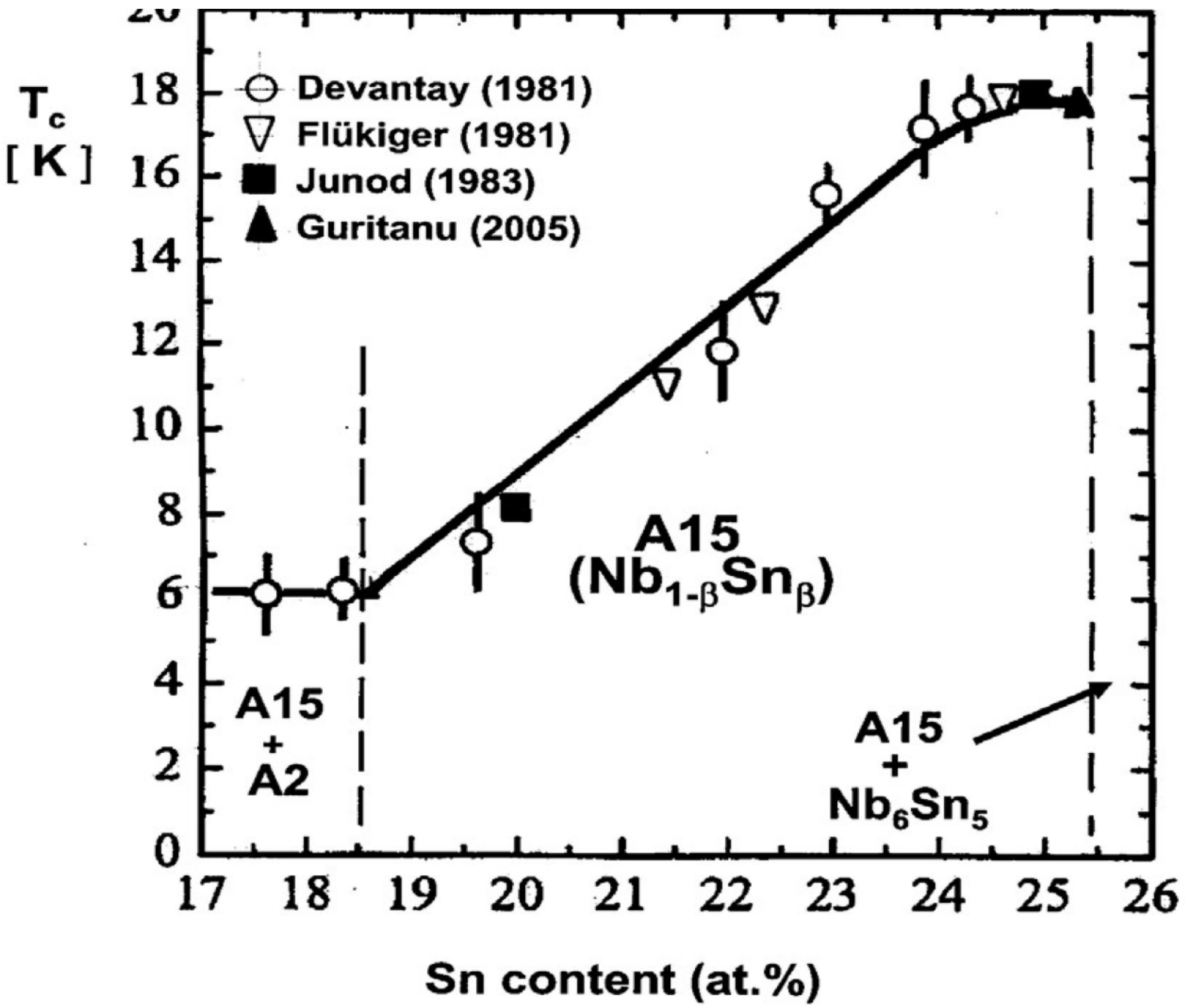
- Complex phase diagram
- Above 1000 °C Nb_3Sn is the only phase possible



Tc vs Sn content in A15 phase of Nb_3Sn

Linearity up to 24.5 at.% Sn

Saturation at > 24.5 at.%

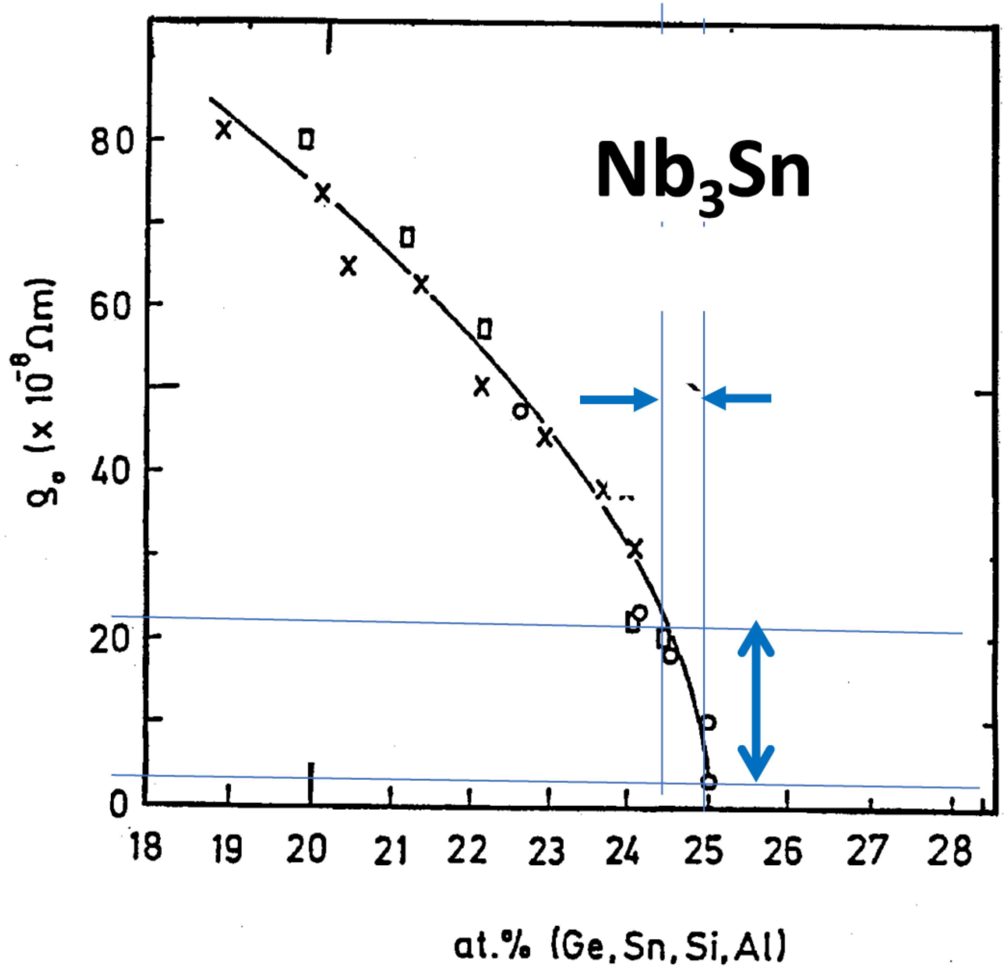


Electrical resistivity of Nb_3Sn

- **Nb_3Sn is perfectly ordered**
- **Strongest variation of ρ_0 very close to stoichiometry**
- ρ_0 increases strongly, from

~ 5 μΩcm at 25 at. % Sn

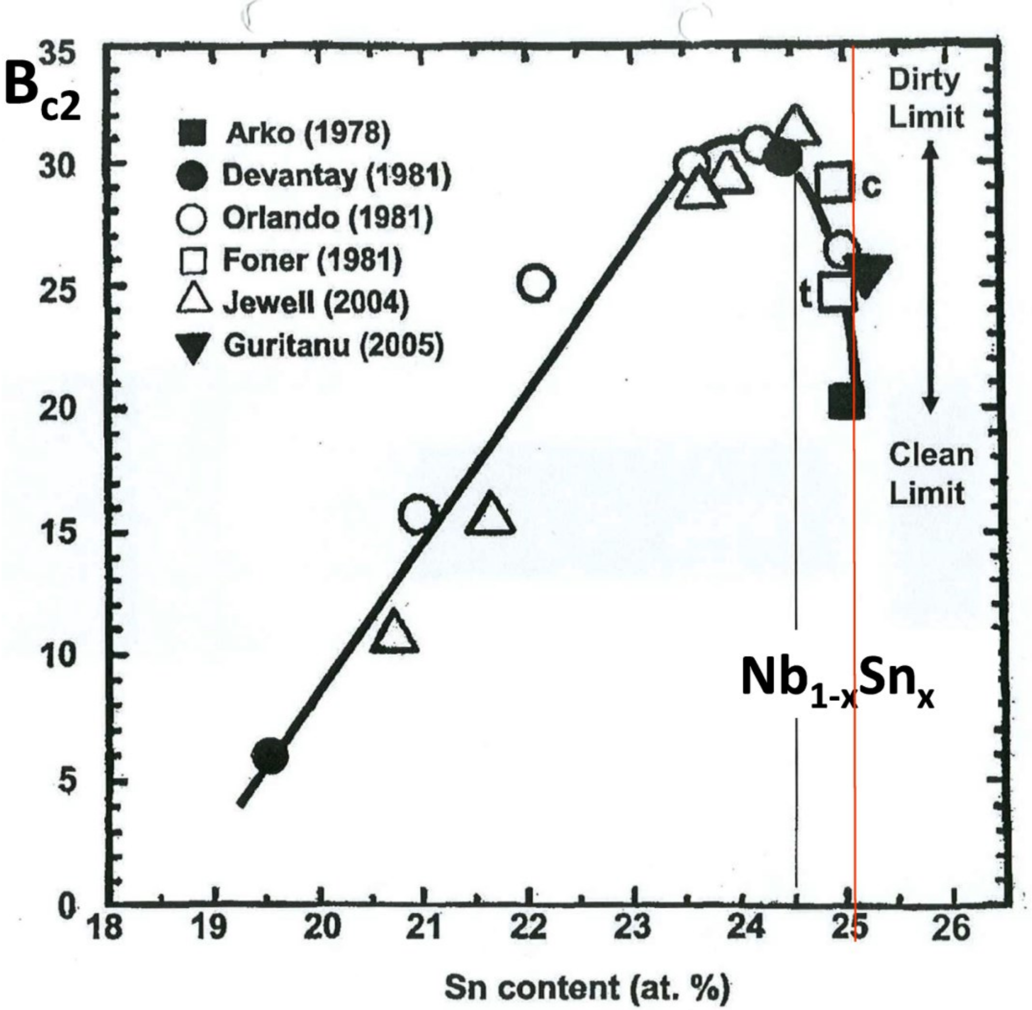
~ 20 μΩcm at 24.5 at. % Sn



B_{c2} vs Sn content in A15 phase of Nb_3Sn

Strong **reduction** of the electronic **mean free** path at **> 24.5 % Sn**

$$B_{c2} = T_c\,\gamma\,\rho_0$$



Clean and dirty limit

$$B_{c2} = T_c \, \gamma \, \rho_0$$

Clean limit

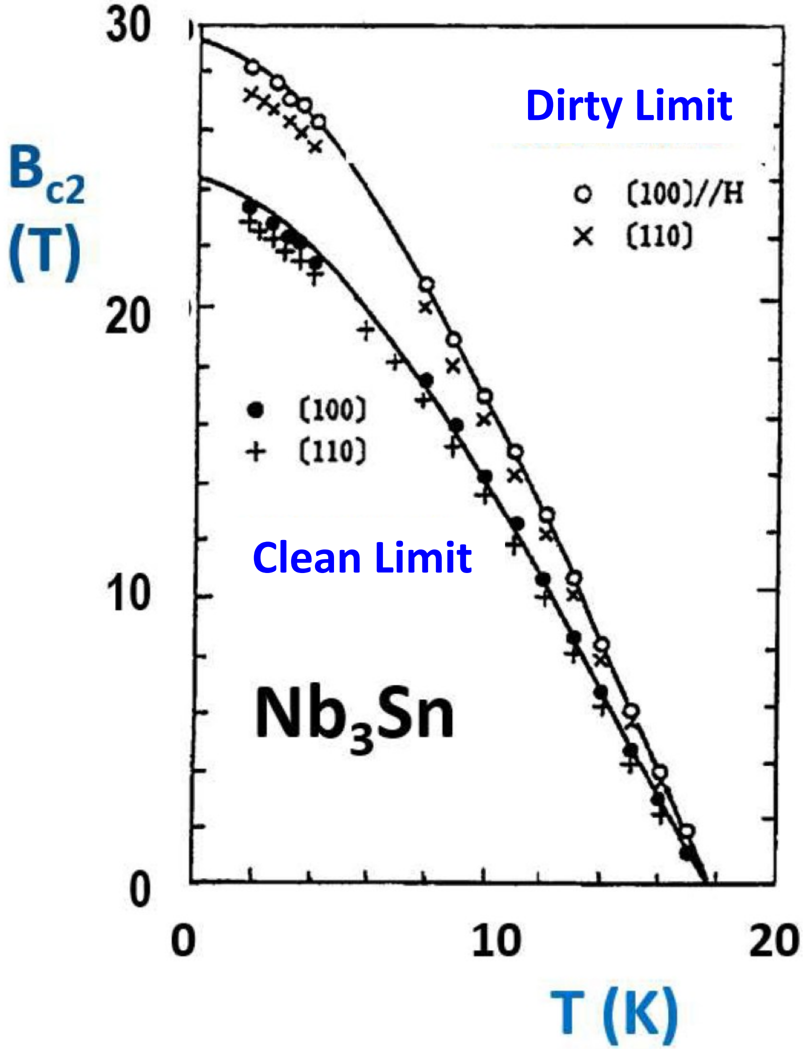
low ρ_0 < 5 µΩcm at 25

very close to stoichiometry

Dirty limit

high ρ_0 >20 µΩcm

deviation from stoichiometry or disordered



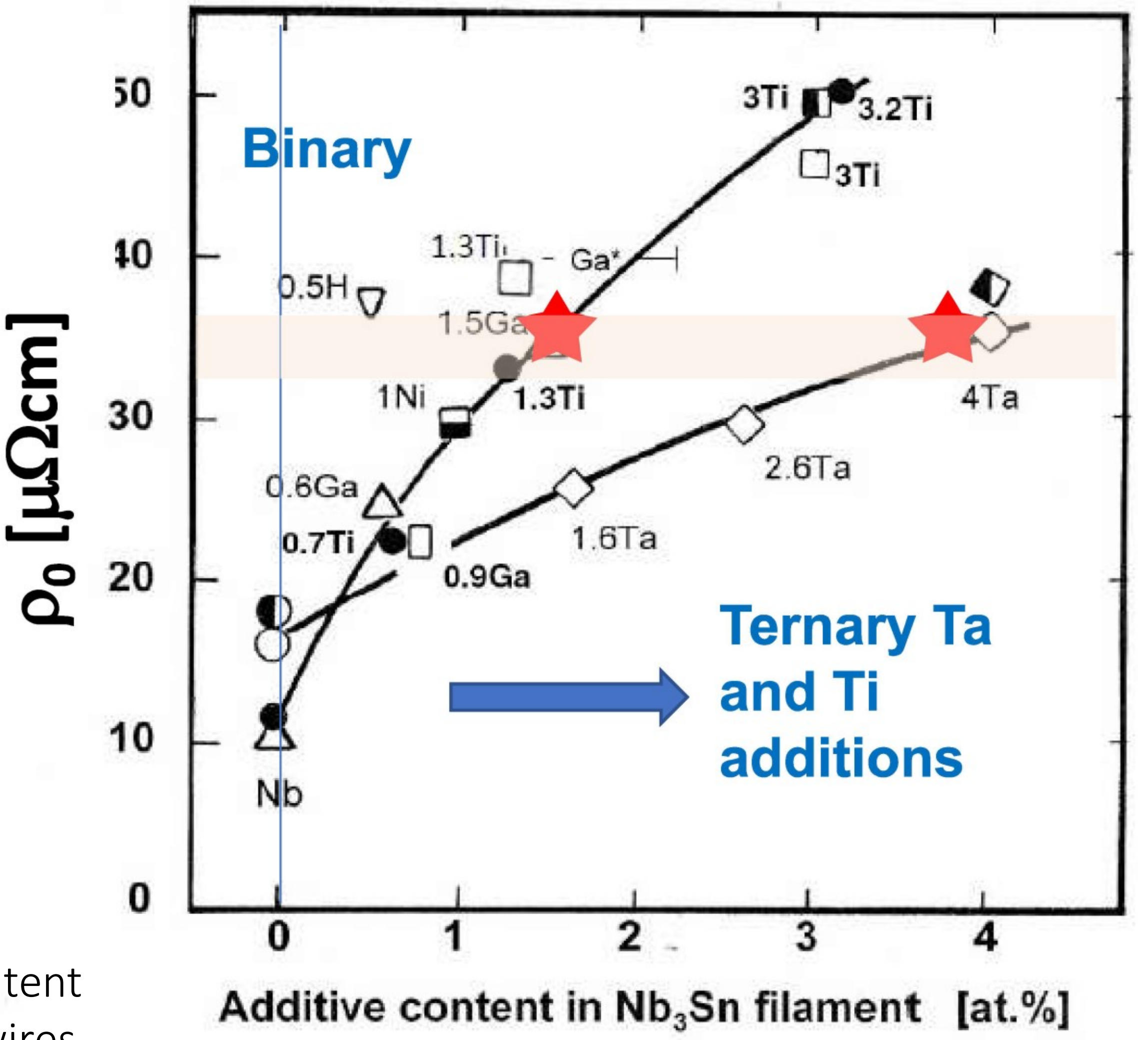
Enhancement of resistivity by Ta and Ti additives

$$B_{c2} = T_c\,\gamma\,\rho_0$$

$(Nb\text{-}Ti)_3Sn$

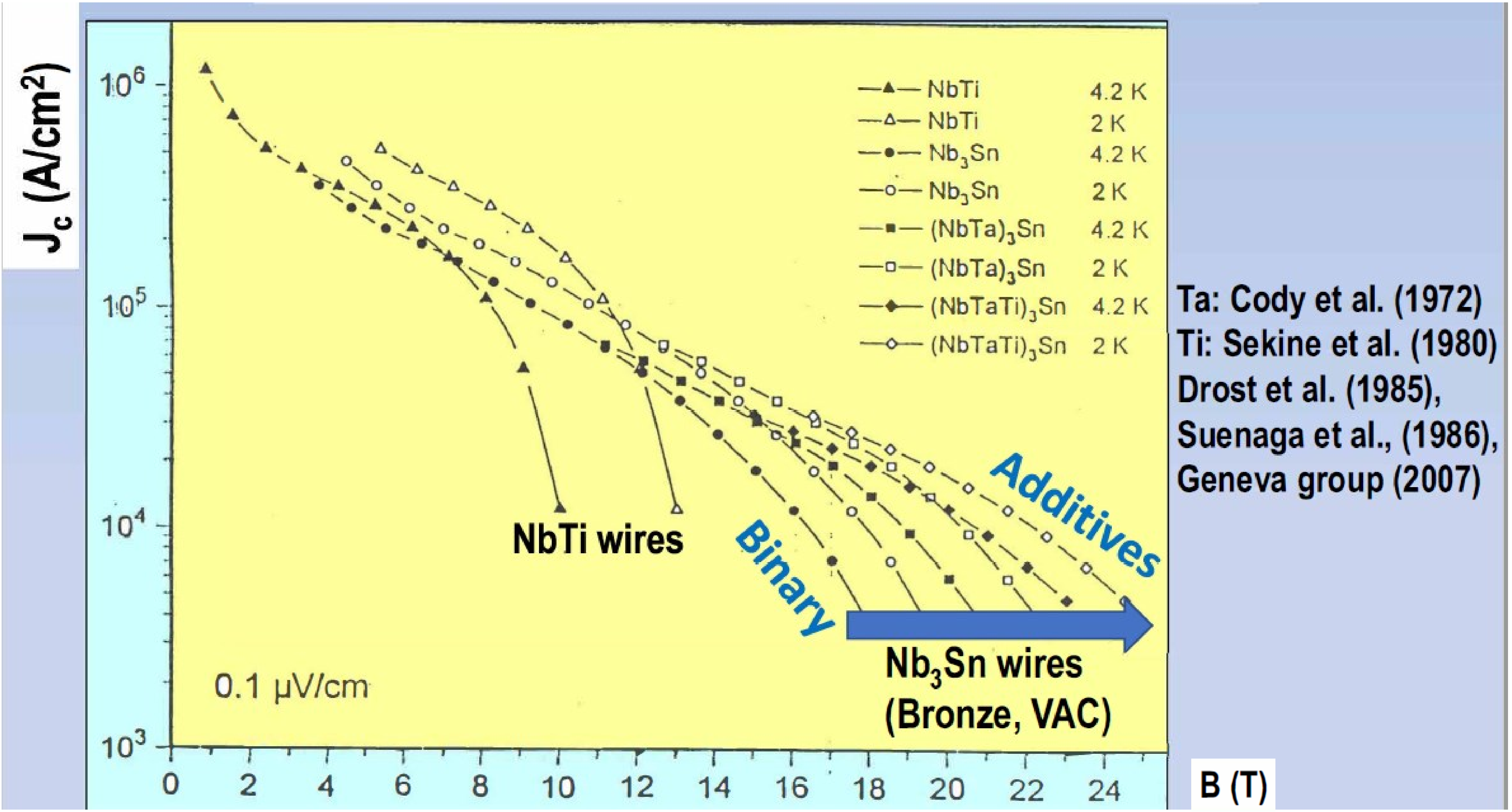
$(Nb\text{-}Ta)_3Sn$

Enhancement of B_{c2}



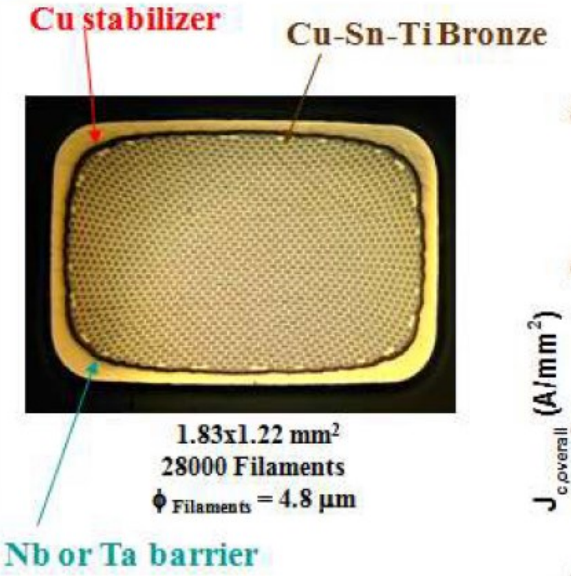
★ Effective Ta or Ti content In industrial Nb_3Sn wires

Jc VS B by Ta and Ti additives



Ta: Cody et al. (1972)
Ti: Sekine et al. (1980)
Drost et al. (1985),
Suenaga et al., (1986),
Geneva group (2007)

Nb_3Sn wires with high Sn content

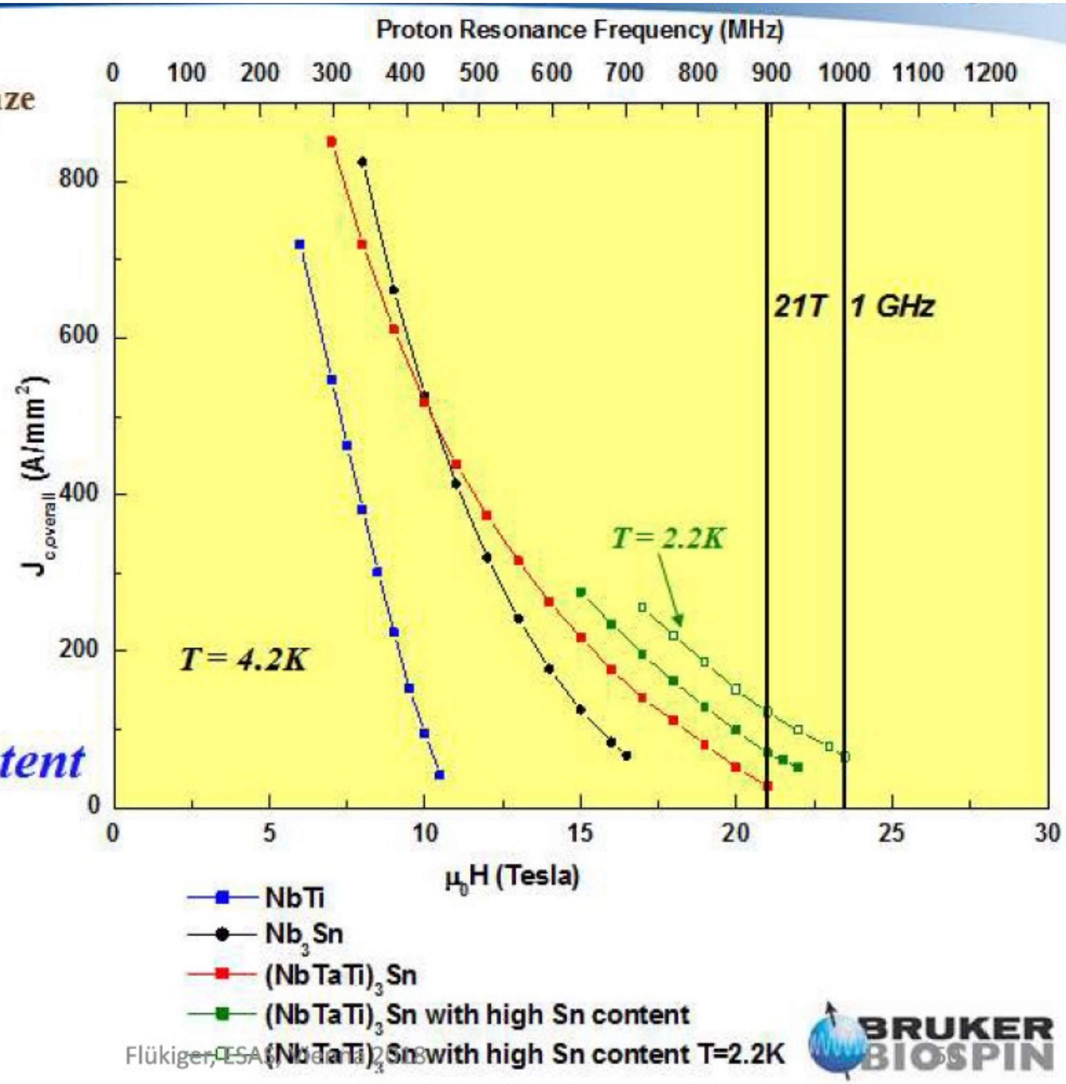


1.83x1.22 mm²
28000 Filaments
$\phi_{\text{Filaments}} = 4.8\ \mu m$

Increasing the Sn content

↓

Increase J_c

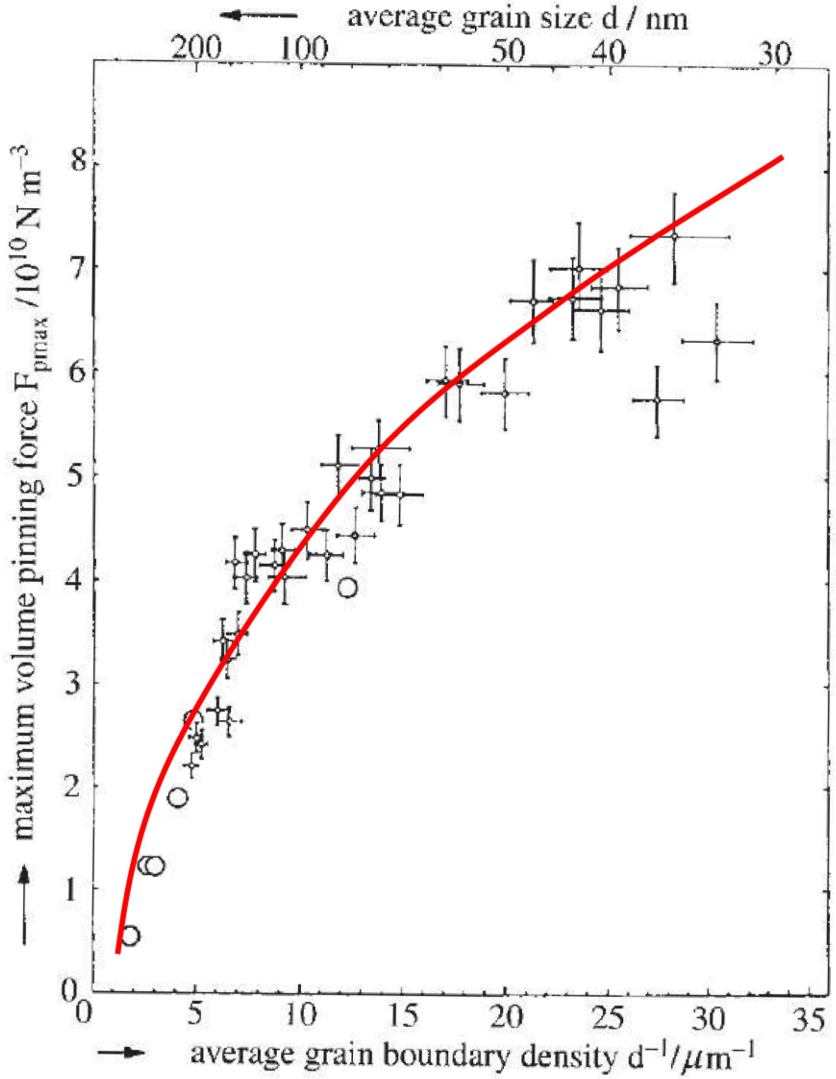


Flükiger, ESAS, Siena, 2008

How increase Jc?

J_c is determined by the achievable pinning force **F_p**

Grain boundaries are the main pinning centers in Nb_3Sn



Effects of grain size and pinning force in Nb_3Sn

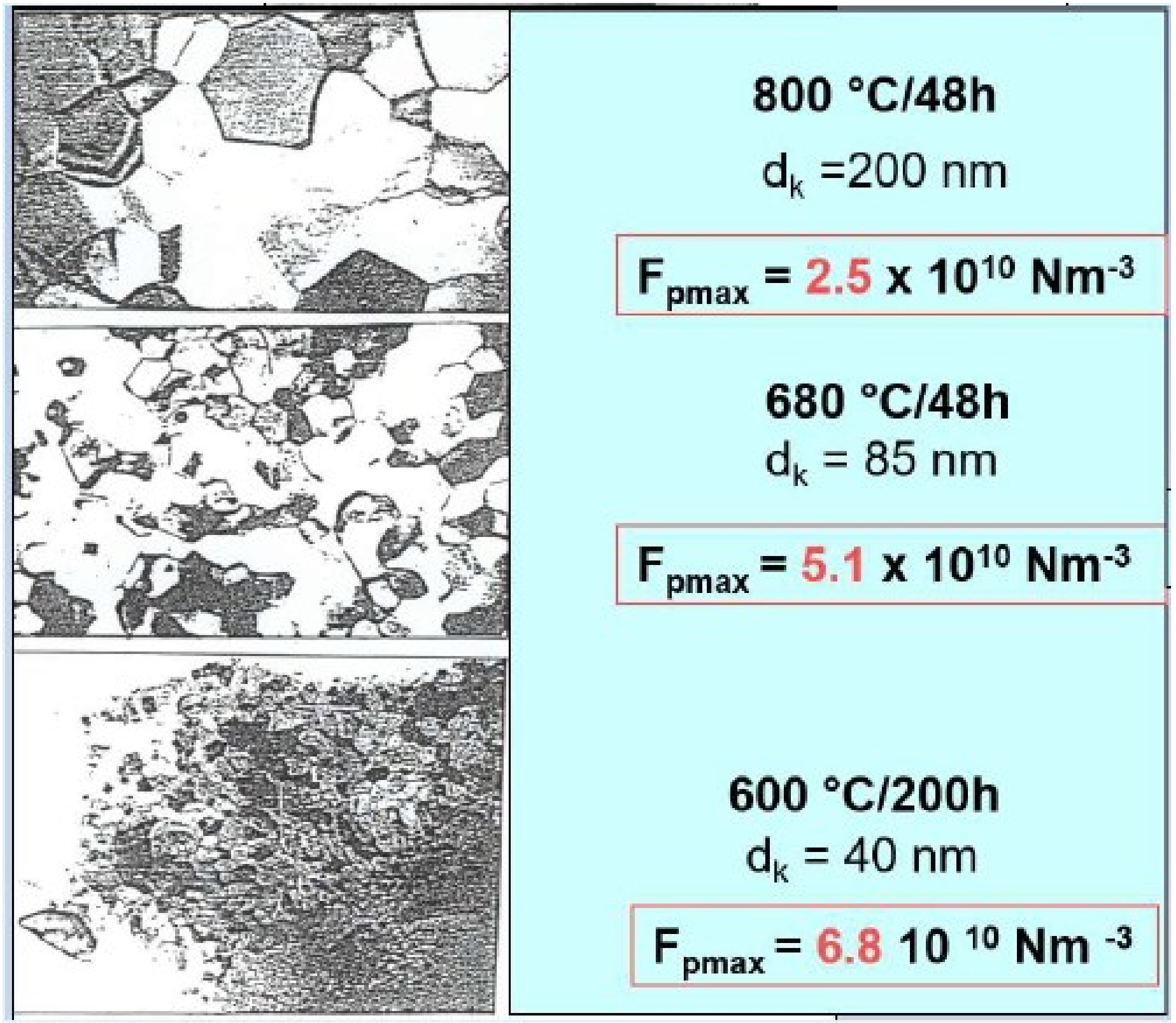
Lower reaction temperatures

↓

Decrease of grain size

↓

Increase of F_{pmax}



800 °C/48h

d_k =200 nm

$F_{pmax} = 2.5 \times 10^{10}\ Nm^{-3}$

680 °C/48h

d_k = 85 nm

$F_{pmax} = 5.1 \times 10^{10}\ Nm^{-3}$

600 °C/200h

d_k = 40 nm

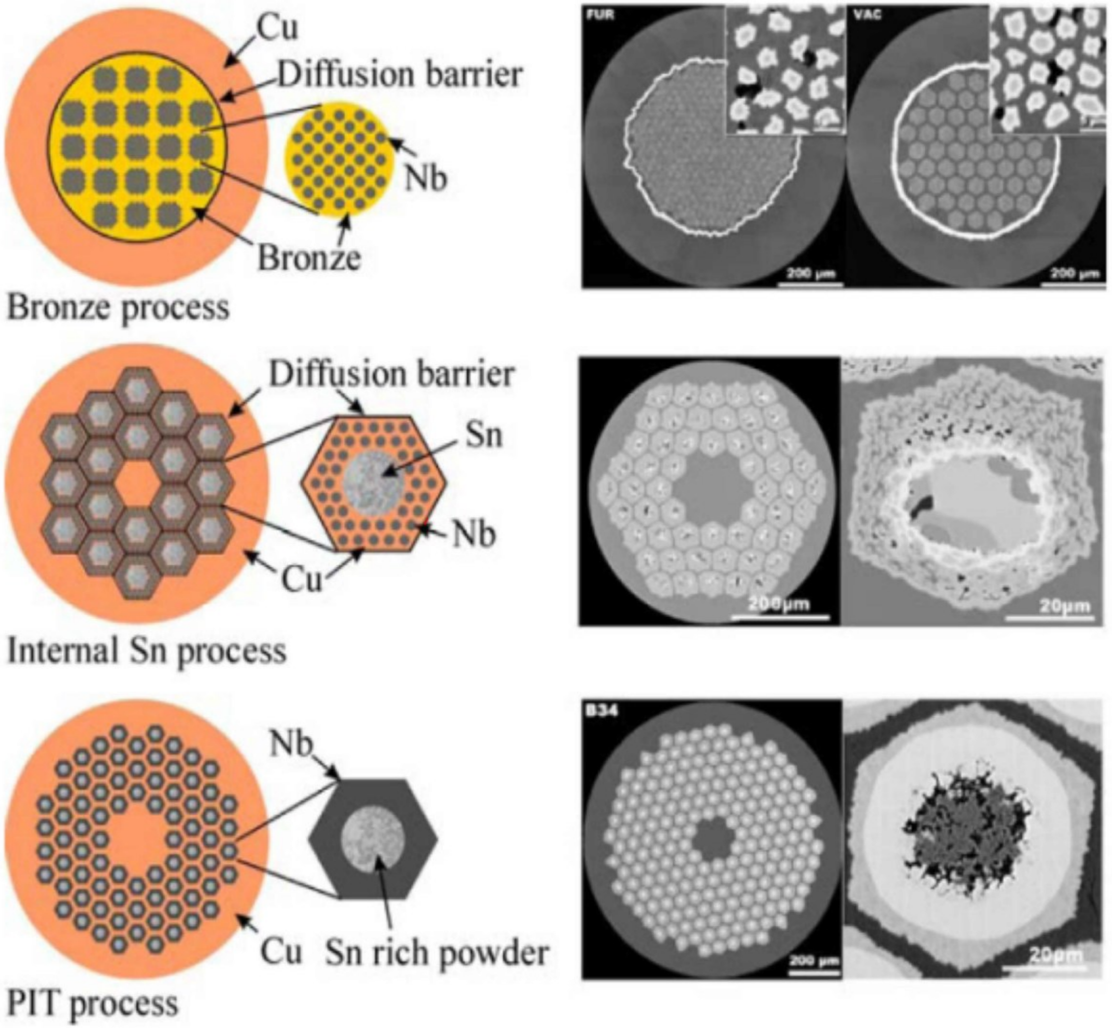
$F_{pmax} = 6.8\ 10^{10}\ Nm^{-3}$

W. Shauer et al. 1984

Nb_3Sn Production processes

3 different main synthesis route

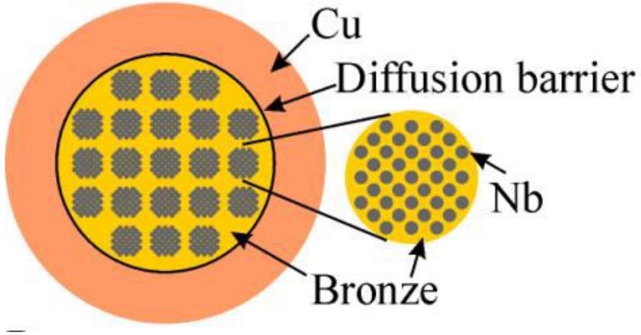
- **Bronze route**
- **Internal Sn**
- **Powder in tube (PIT)**

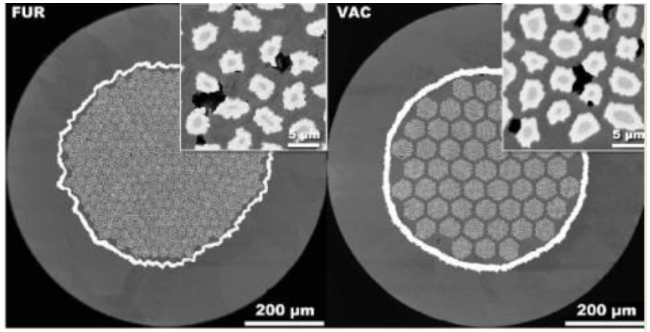


Bronze route

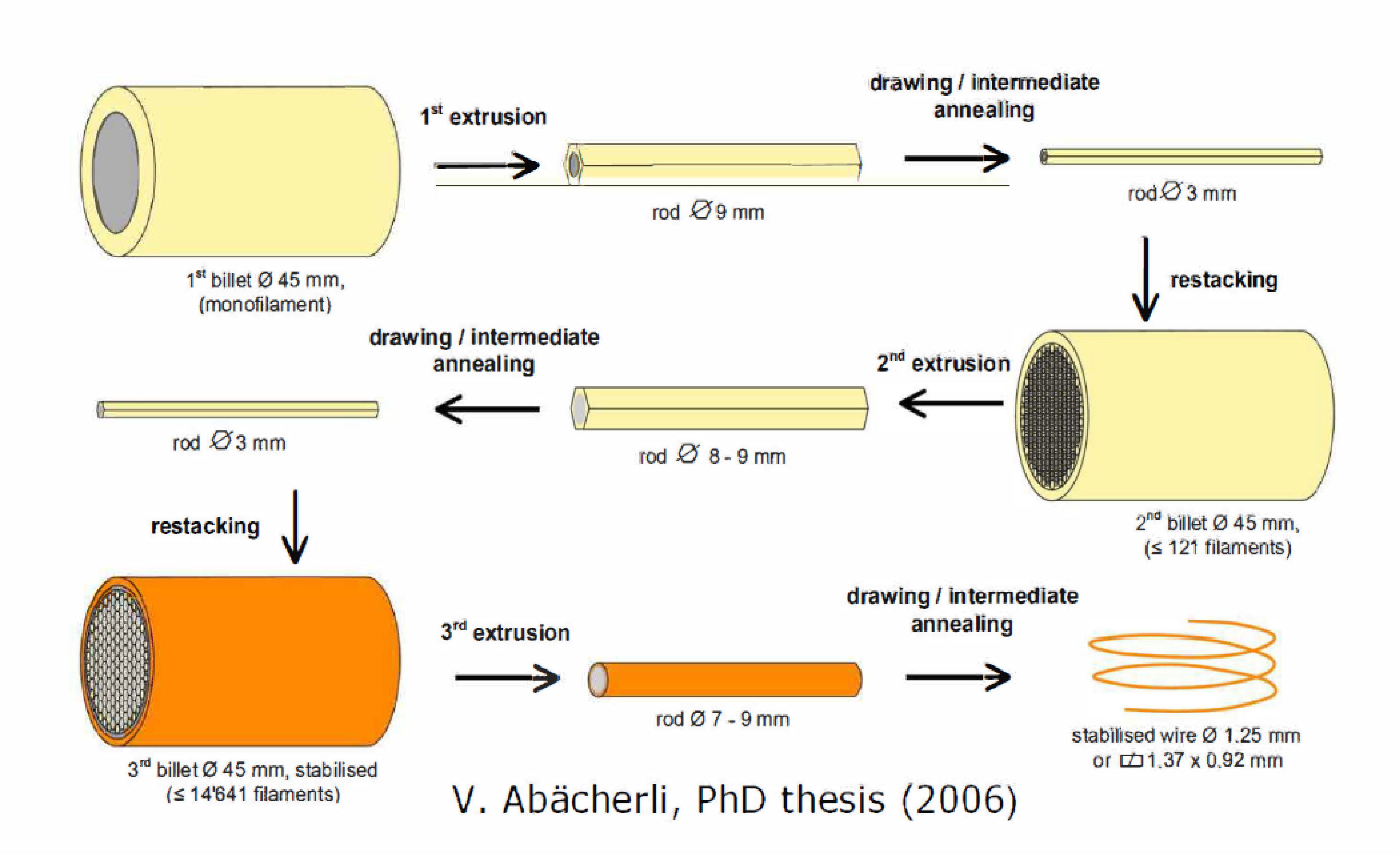
Nb rods are inserted in a bronze (CuSn) matrix. Pure copper is put in the periphery and protected with a diffusion barrier (Ta) to avoid contamination. (Preserve low resistivity of the Cu)

- **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.
- **Application in magnetic fields up to 23 T (at 1.8K)**



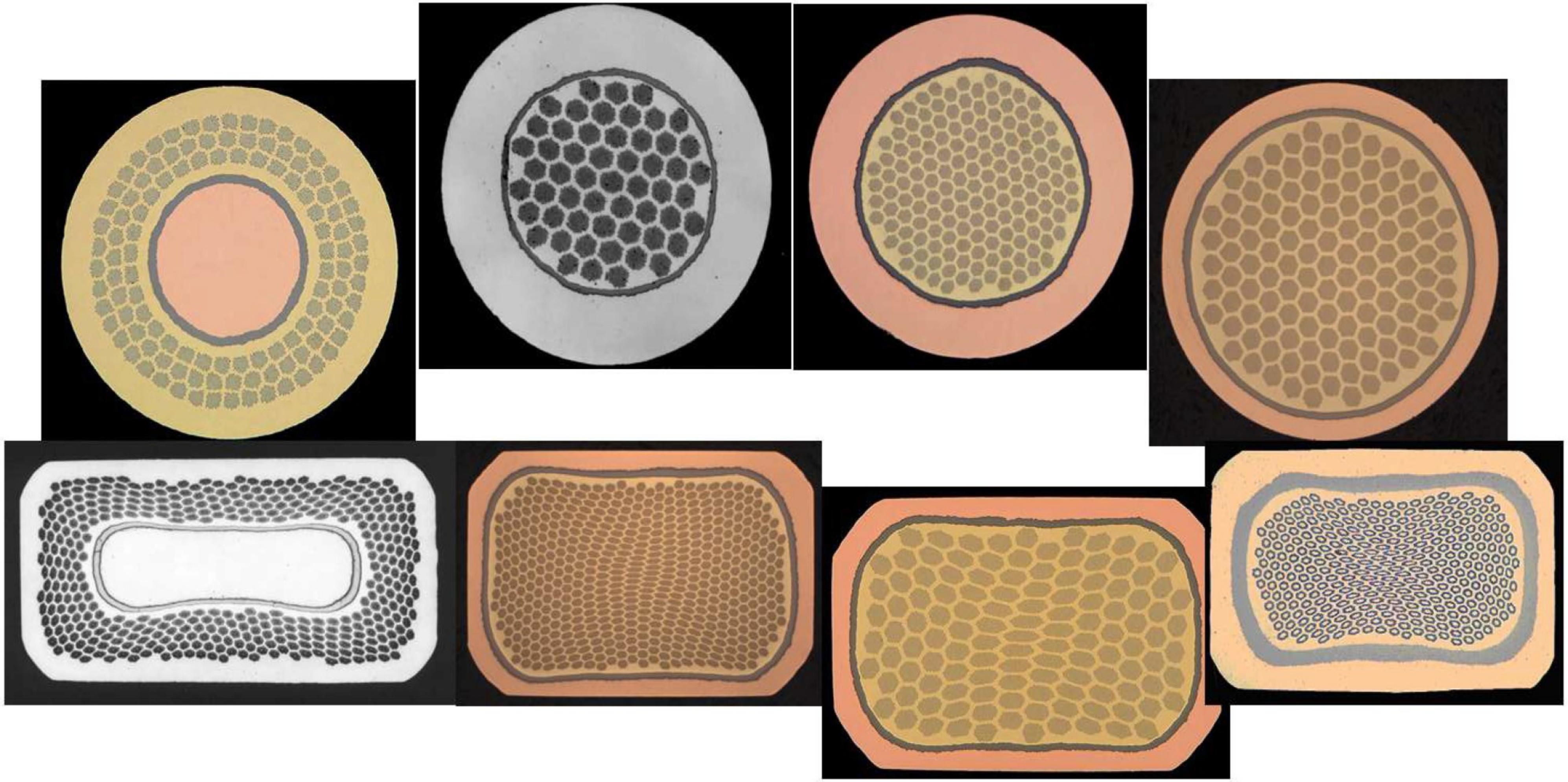


Bronze route process



V. Abächerli, PhD thesis (2006)

Bronze route variants



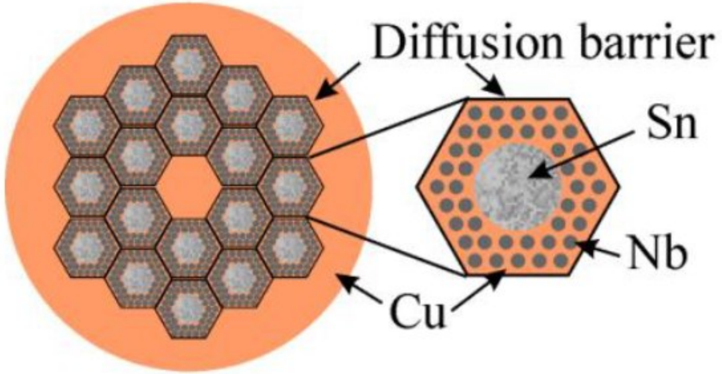
European Advanced Superconductors

Internal Tin Process

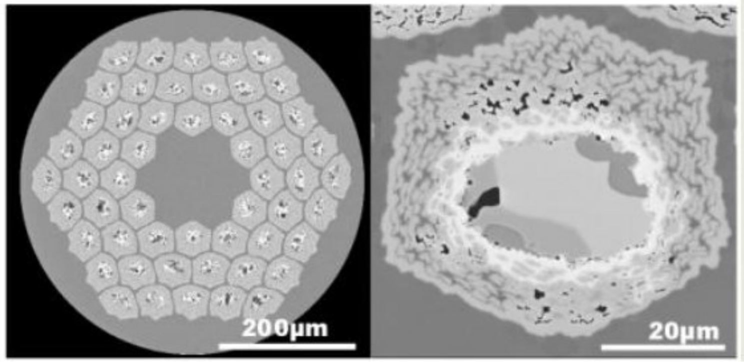
A tin core is surrounded by Nb rods embedded in Cu (Rod Restack Process, RRP) or by layers of Nb and Cu (Modify Jelly Roll, MJR)

Each sub-element has a diffusion barrier.

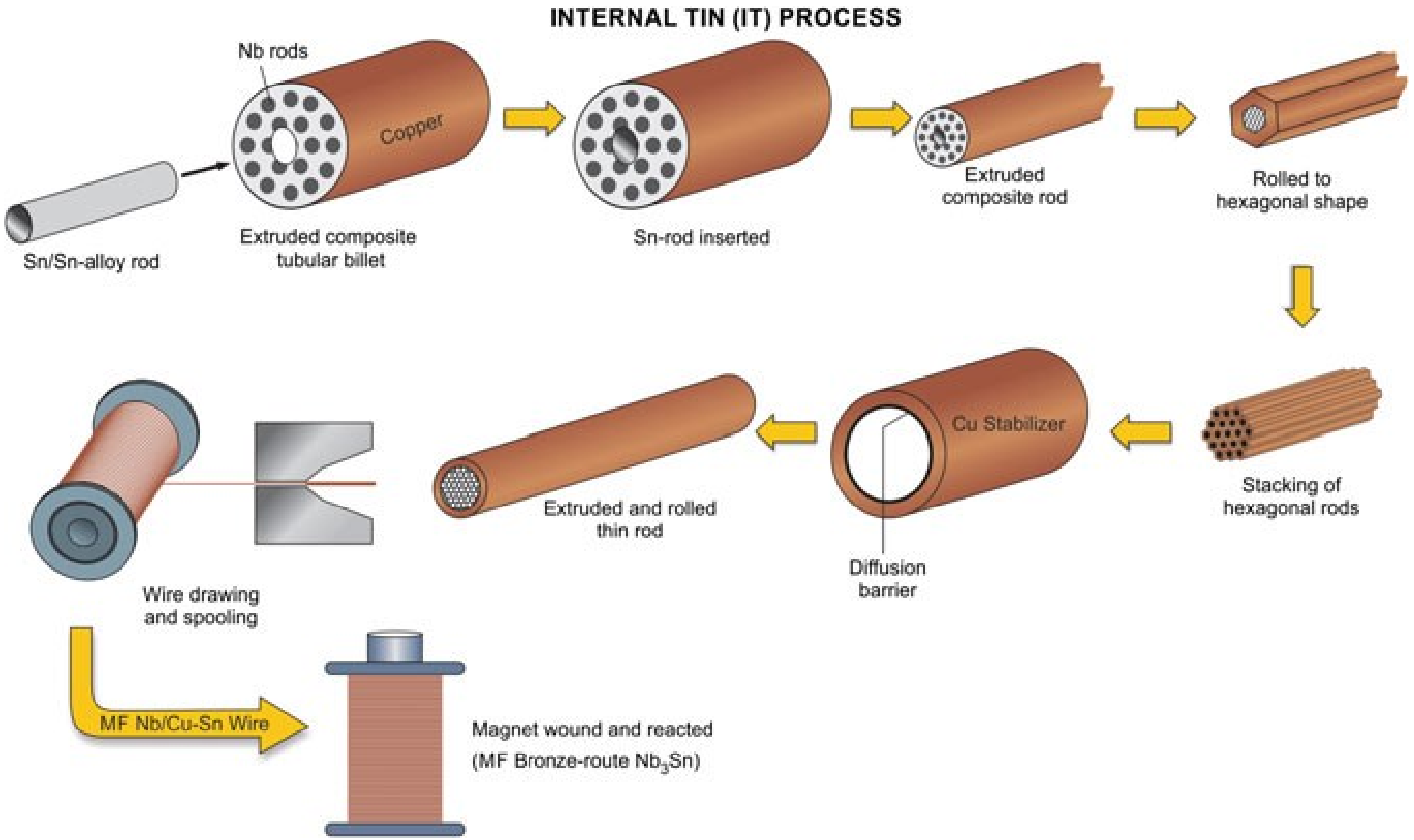
- **Advantage:** no annealing steps and more Sn in the sub-element
- **Disadvantage:** difficult to achieve small effective filaments. To get below 50 microns without giving up Jc
- **Non-Cu J_C up to 3000 A/mm^2** at 4.2 K and 12 T.



A. Godeke, [2].



Internal Tin Process

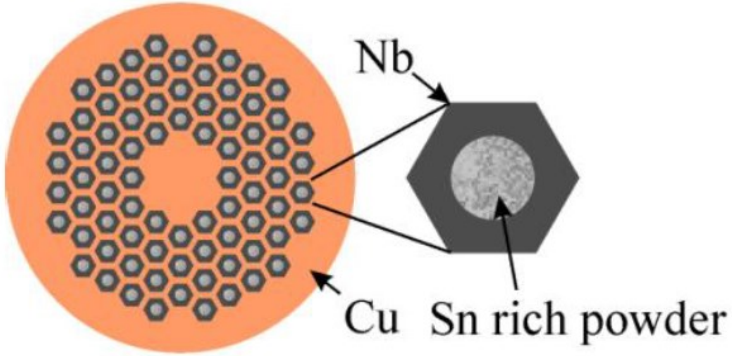


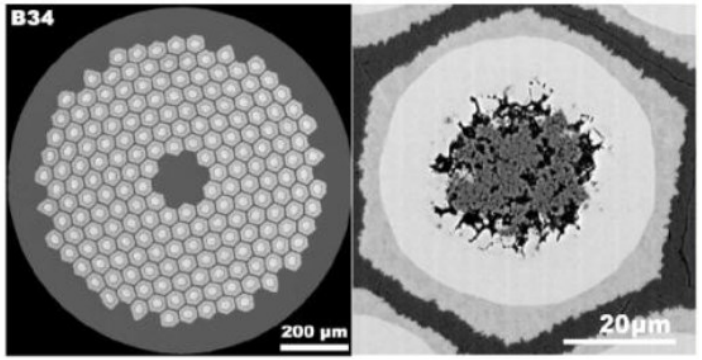
Powder on tube (PIT) process

NbSn2 powder is inserted in a Nb tube, put into a copper tube.

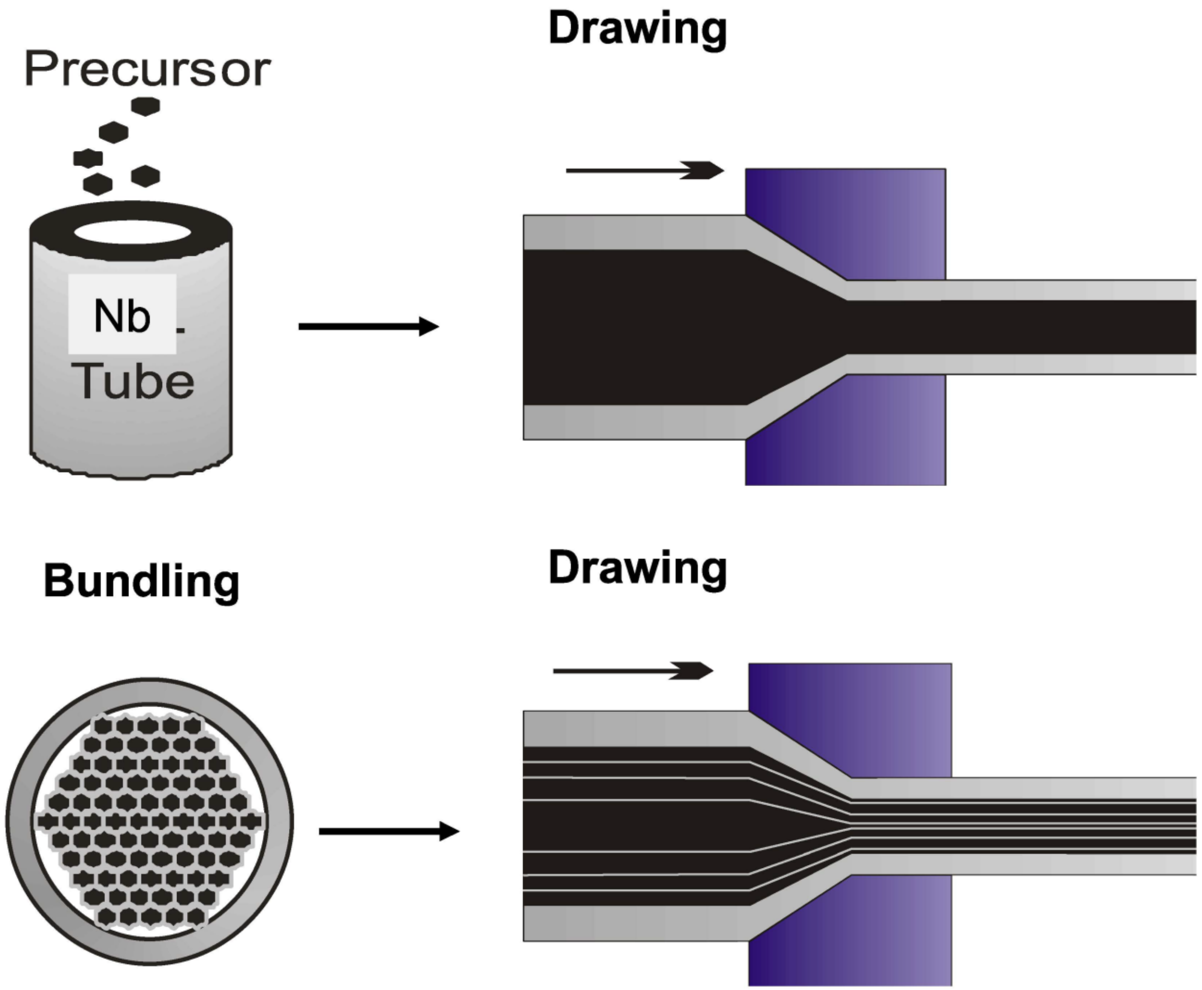
The un-reacted external part of the Nb tube is the barrier.

- **Advantage:** small filament size (30 µm) and short heat treatment
- (proximity of Sn to Nb).
- **Disadvantage**: **fabrication cost** and **Jc generally lower** than RRP.
- **Non-Cu J_C up to 2300 A/mm^2** at 4.2 K and 12 T.





Powder on tube (PIT) process



Synthesis method properties comparison

	Bronze Route	Powder in Tube (PIT)	Internal Sn
Critical current density @12T	low 1,000 A/mm²	high >2,500 A/mm²	highest j_c 3,000 A/mm²
Filament quality	excellent and small filament Ø (~5µm)	medium filament Ø (~30-50µm)	large effective filament Ø (~100µm)
Hysteresis losses	low 190 mJ/cm³ +/-3T	~ 400 mJ/cm³	high, ~1700 mJ/cm³ due to large effective filament Ø
Residual Resistance Ratio RRR	high, > 100	> 70	low, < 40, due to Sn poisening of the Cu matrix

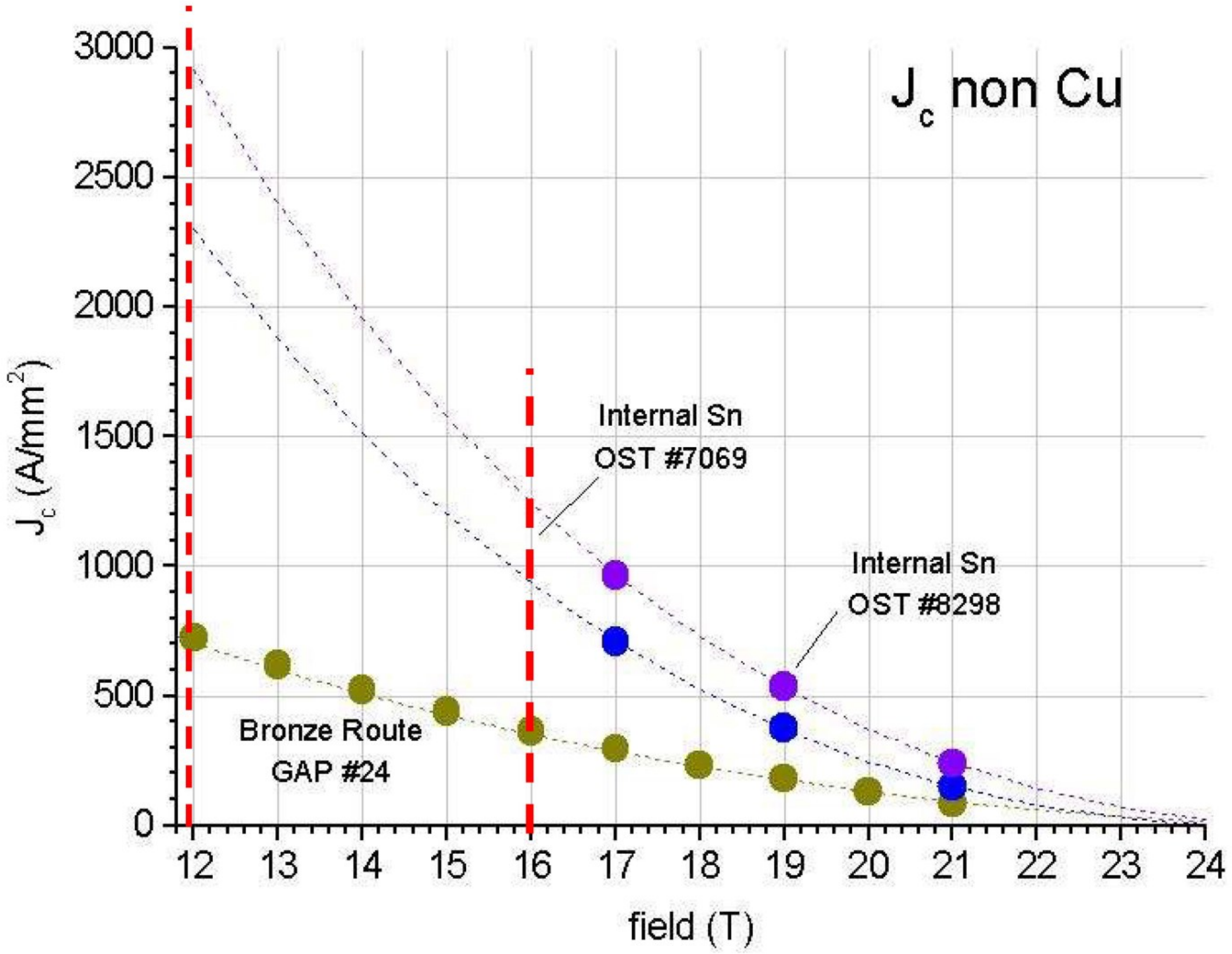
Bernhard Holzapfel, ESAS summer school 2018

Synthesis method production comparison

	Bronze Route	Powder in Tube	Internal Sn
Production	long wire length available frequent intermediate annealing required because of bronze work hardening	expensive Nb tubes and special powders	no intermediate annealing steps necessary due to bronze work hardening no hot extrusion possible due to the low melting point of Sn => additional drawing steps and reduced bonding

Bernhard Holzapfel, ESAS summer school 2018

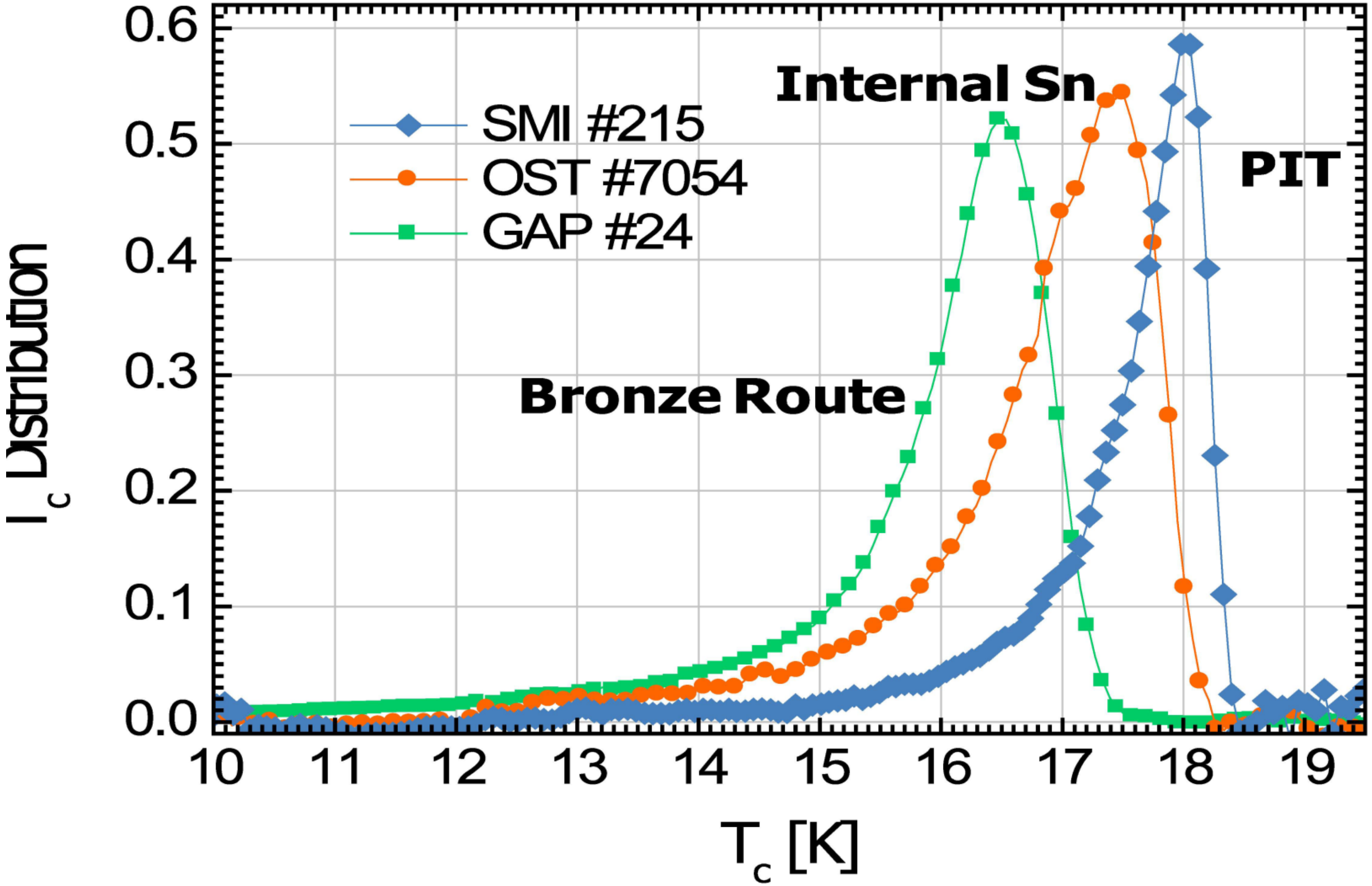
Synthesis method properties comparison



Synthesis method Tc comparison

Clear difference between Bronze route and Internal Sn (RRP) wires:

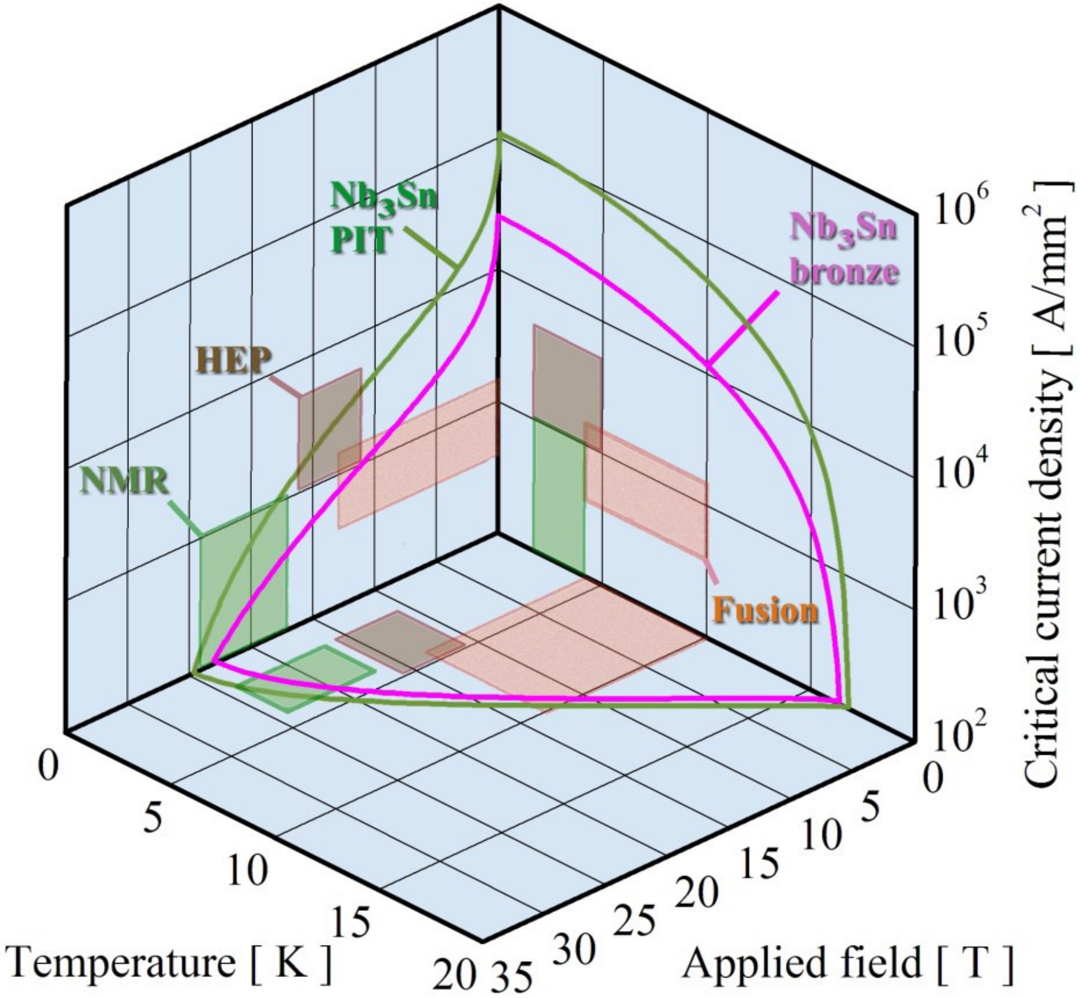
Bronze Route wires have a lower Tc - lower average Sn content



Applications requirements

Used in:

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



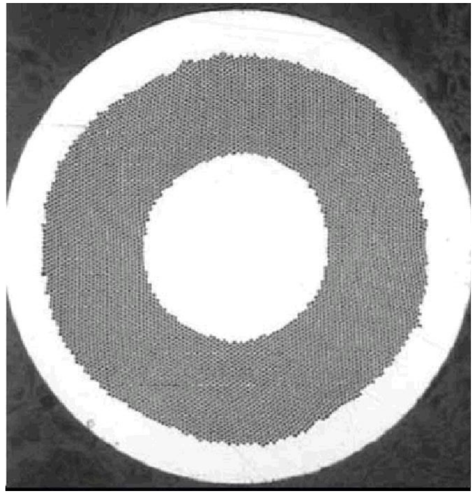
Final considerations on Nb_3Sn

- **Bronze route** wires: best suited for **"persistent mode" operation of NMR magnets**, in spite of their lower Jc value with respect to Internal wires

- **Internal Sn (RRP)** and **Powder-in-Tube (PIT)** wires satisfy conditions for **Hilumi LHC accelerator magnets**: Jc= 1500 A/mm^2 at 4.2K/12T

- **Future FCC**, requirements: Jc = 1500 A/mm^2 at 4.2K/16T → **under work**

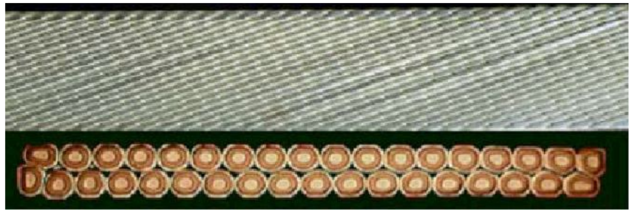
Wires and cables

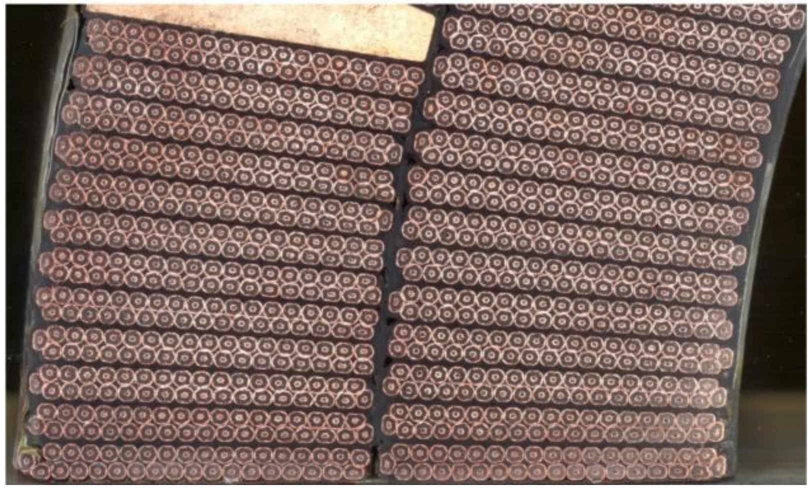


For practical applications, superconducting materials are produced in **small filaments** and **surrounded by a stabilizer** (typically copper) to form a **multifilament wire** or strand

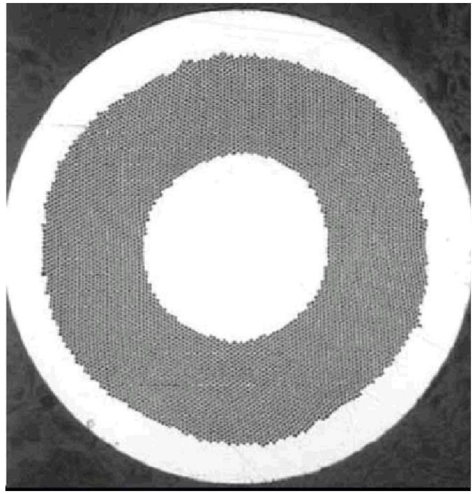
A **superconducting cable** is composed of **several wires into multistrand cable**

LHC, CERN





Wires and cables



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**

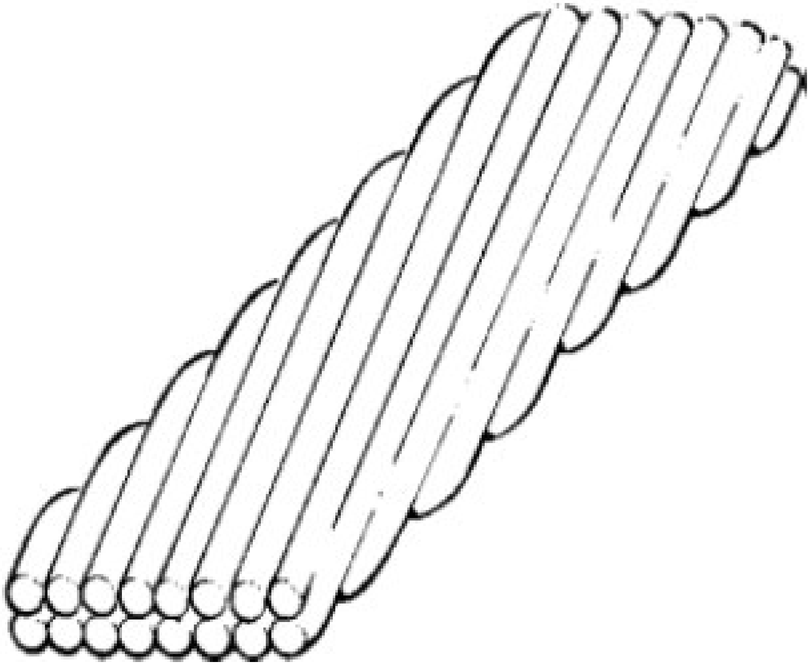
ITER

Rutherford cable

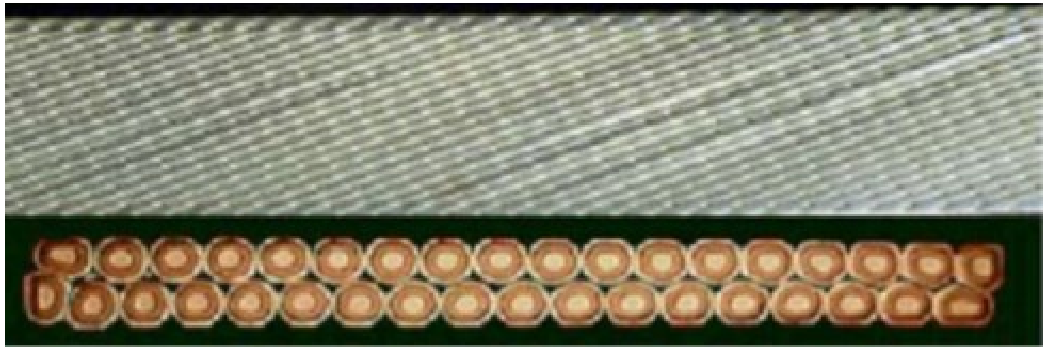
Most of the superconducting coils for particle accelerators are wound from a multi-strand cable

The **strands are twisted** to:

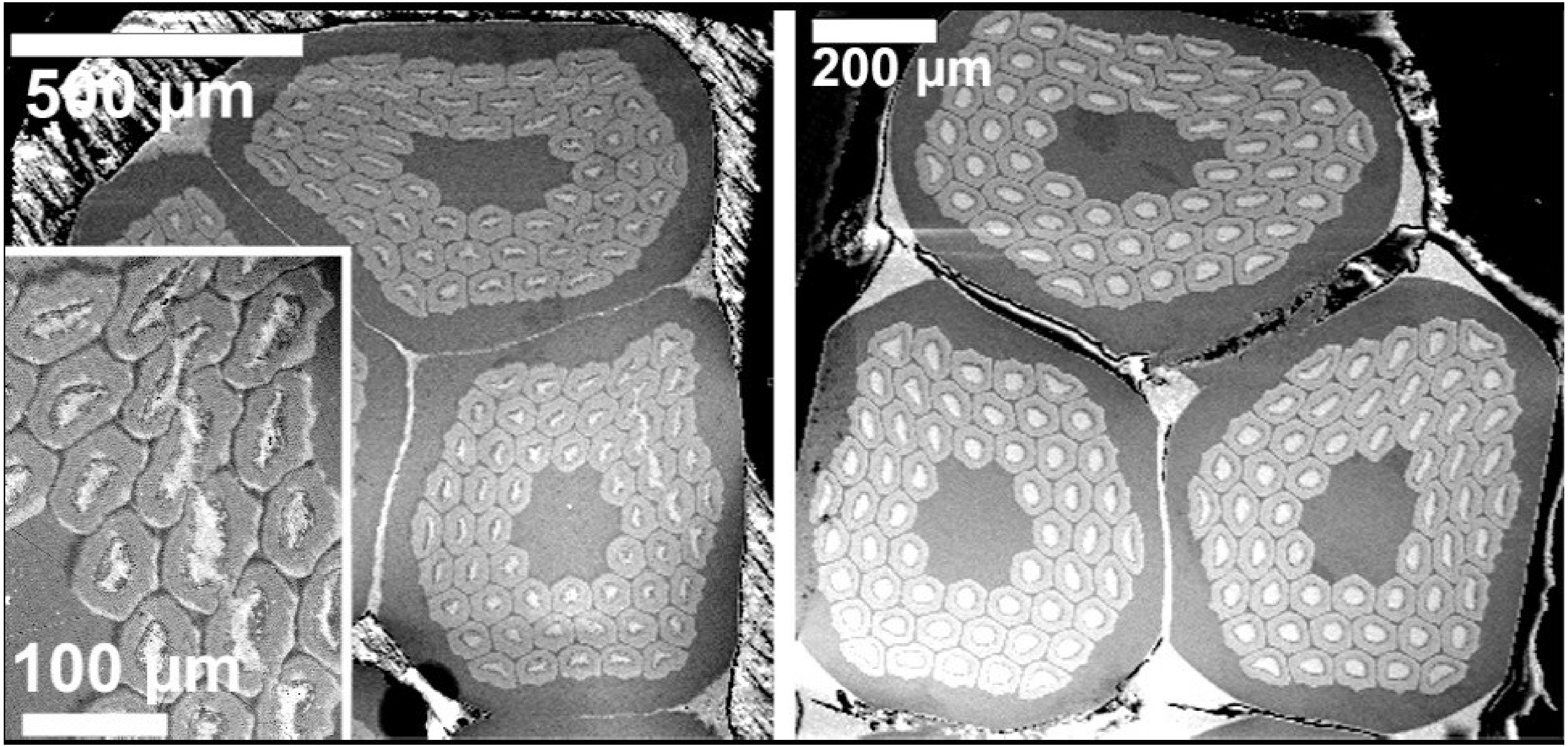
- **reduce interstrand coupling currents**
- **provide more mechanical stability**



The most commonly used multi-strand cables are the Rutherford cable

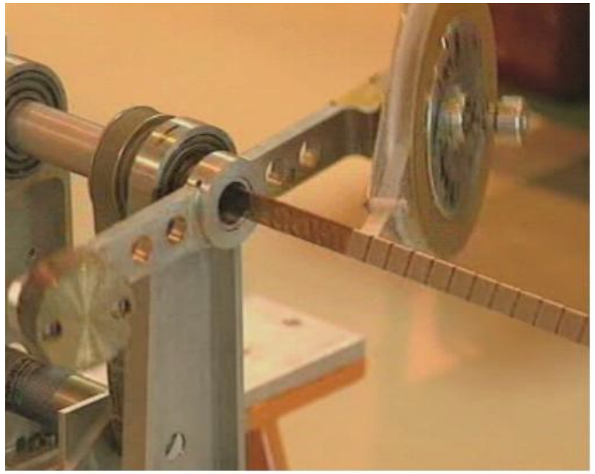


Risk of deformation



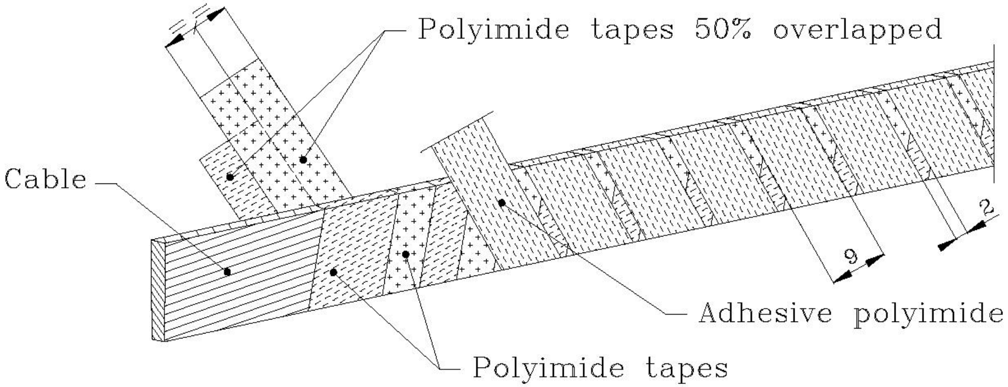
Severe edge deformation **Acceptable edge deformation**

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)

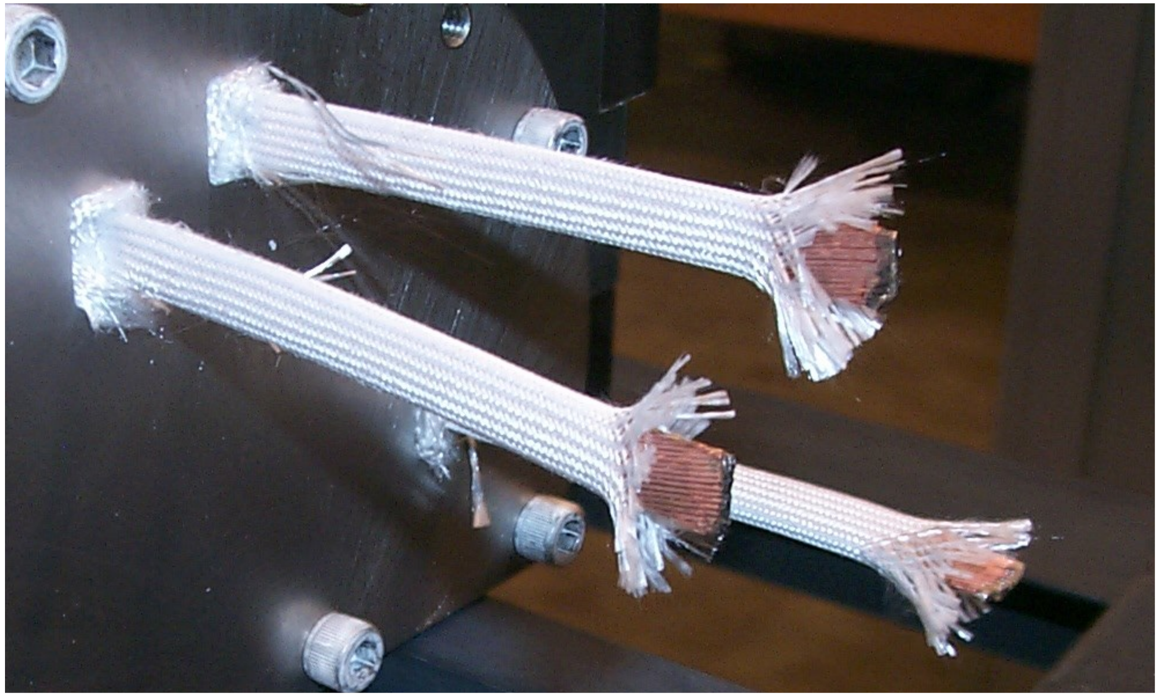
In the LHC case: two polyimide layers 50.8 μm thick wrapped around the cable with a 50% overlap, with another adhesive polyimide tape 68.6 μm thick wrapped with a spacing of 2 mm.

Cable insulation (Nb_3Sn)

In **Nb_3Sn magnets**, where coils are reacted at 600-700 °C, the most common insulation is a tape or sleeve of **fiberglass**

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

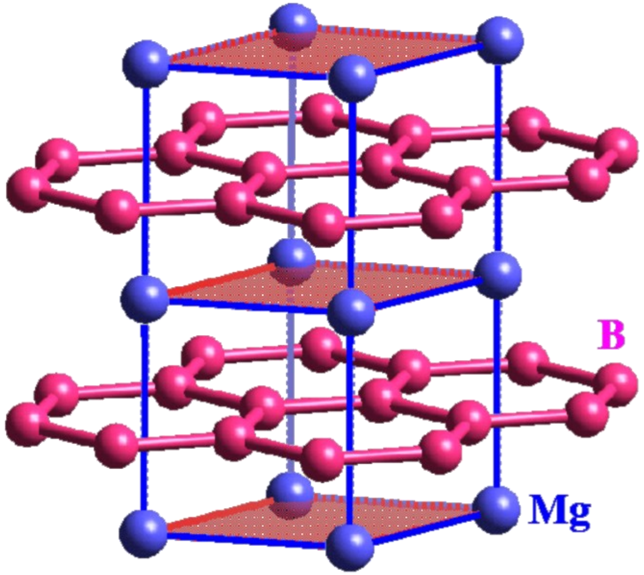


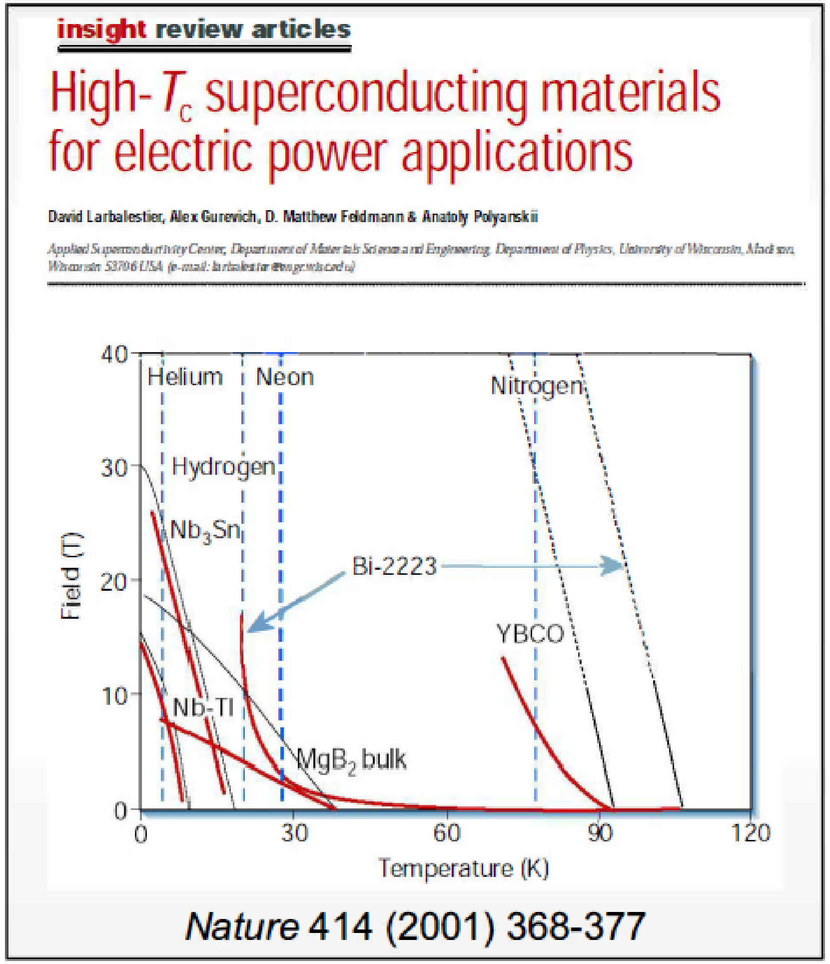
MgB_2

Nexans MgB_2Sn power cable

MgB_2 properties

- **Tc = 39 K**
- **Two gaps superconductor**
- **H_{irr} up to 15 T** (10 T in commercial applications)




insight review articles

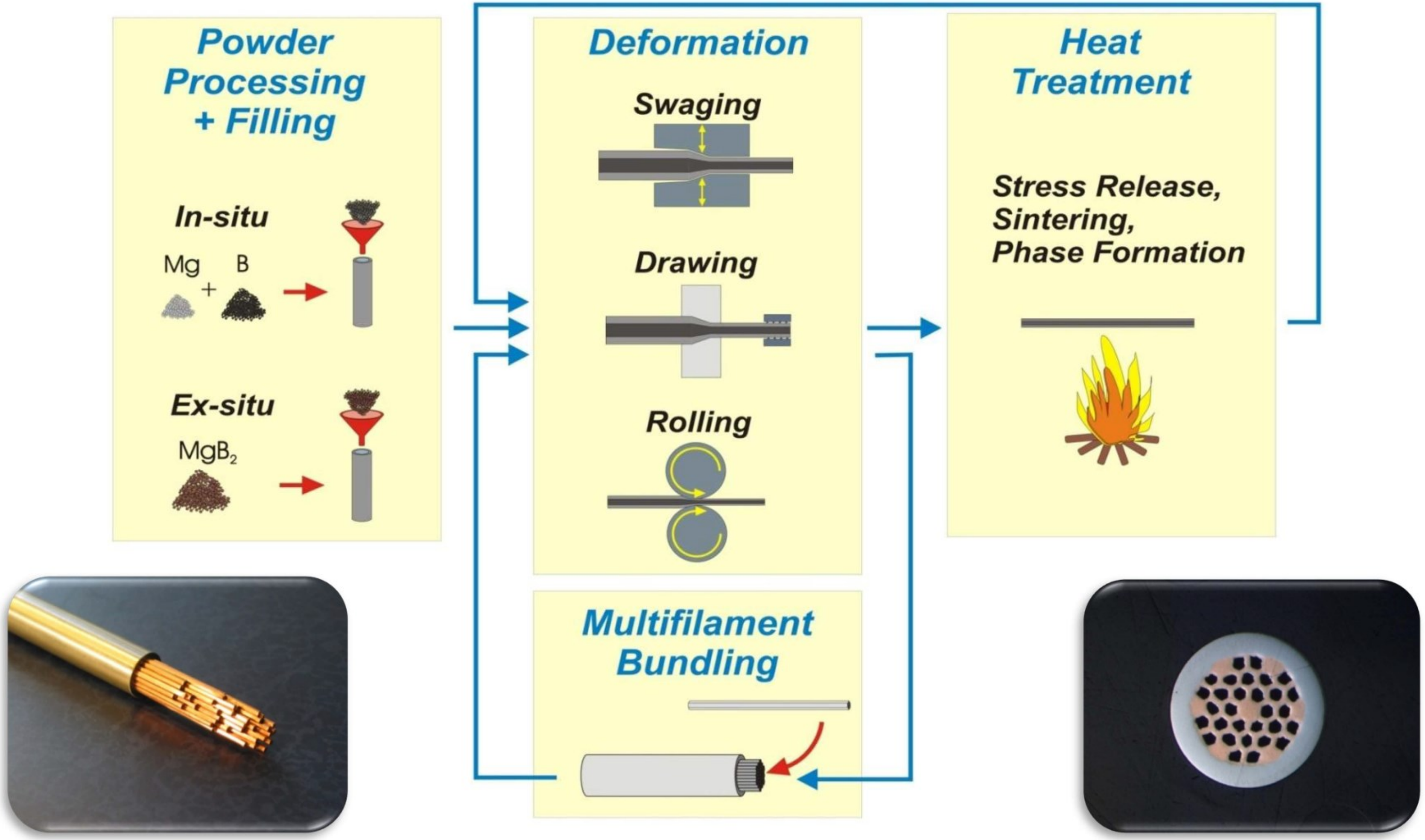
High-T_c superconducting materials for electric power applications

David Larbalestier, Alex Gurevich, D. Matthew Feldmann & Anatoly Polyanskii

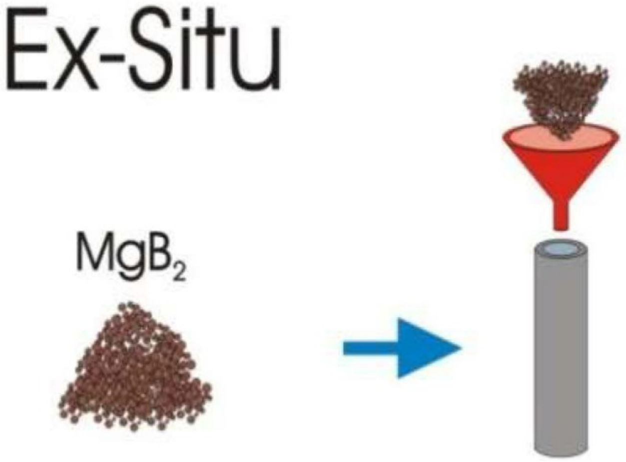
Applied Superconductivity Center, Department of Materials Science and Engineering, Department of Physics, University of Wisconsin, Madison, Wisconsin 53706 USA (e-mail: larbalestier@engr.wisc.edu)

Nature 414 (2001) 368-377

Fabrication Methods for MgB_2 Conductors
Powder-in-Tube technique (PIT)

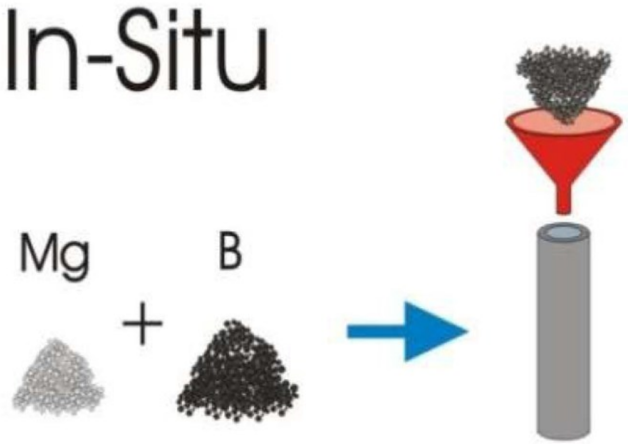


MgB_2 PIT Ex-Situ or In-Situ



Use of prereacted MgB_2 precursor powders

- Macroscopic **transport currents** even **without heat treatment**
- **Heat treatment** above **~800°C** improves grain connectivity and releases stresses ➔ **higher Jc**
- **Doping difficult**

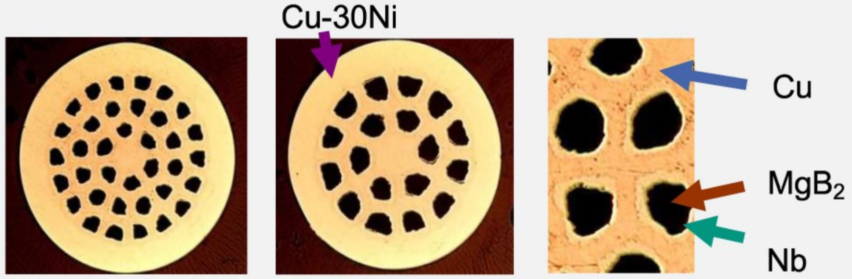


Use of Mg-B precursor powder mixtures

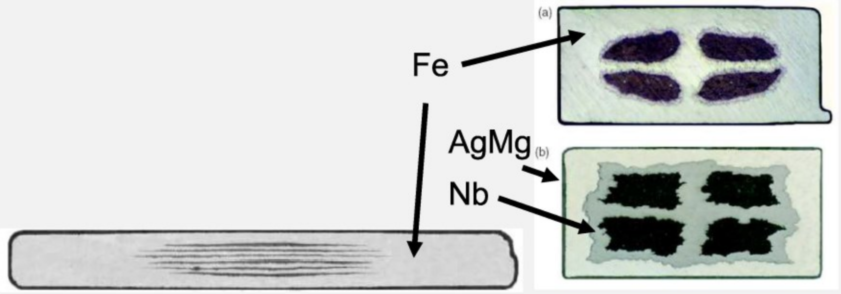
- **Heat treatment necessary** for MgB_2 phase formation
- Heat treatment at **600-700 °C** aready leads to **high Jc values**
- **Incorporation of dopants easier**

Different MgB_2 wires strategy by PIT

HyperTech Research Inc., USA

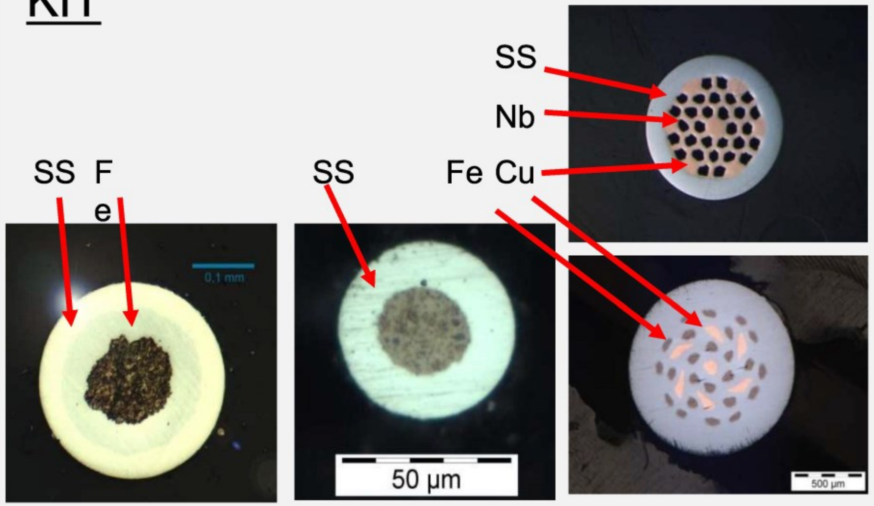


IEE, Bratislava



Columbus Superconductors srl, Genoa:

KIT



Different MgB_2 wires sheath materials

Mono- or Multi-component Sheath (depends on application)

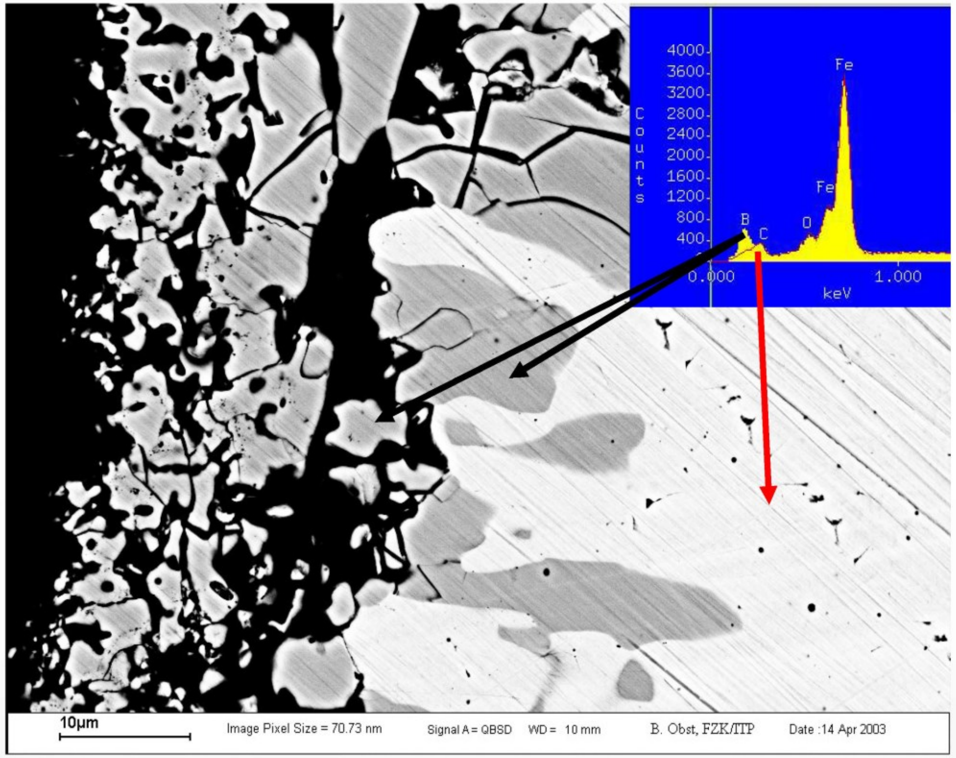
- **Fe, Ti, Ni,** alloys, e.g. **Cu-Ni, Cu-Sn, ...**
- Thermal stabilization (high electrical and therm. conductivity) ➔ Cu, Glidcop™, Al, ...
- Barriers (prevent filament-sheath reaction) ➔ **Nb, Ta, ...**
- Mechanical reinforcement ➔ **Stainless steel, Monel, ...**

Important Features

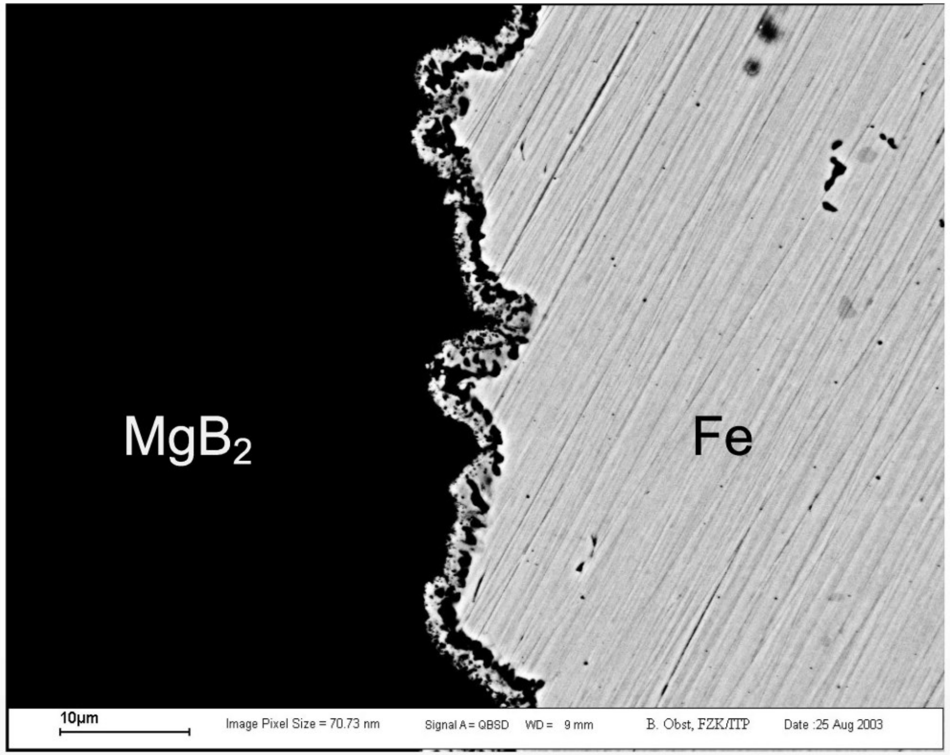
- High ductility to ensure good deformability
- Low reactivity with filament
- Adjustment of hardness of single components in composite sheaths
- Harder sheath materials for high density and good grain connectivity (volume shrinkage during $Mg + 2B \rightarrow MgB_2$ phase formation)

Conductor with Fe-Sheath

Heat treatment: 905°C
→Thick reaction layer ~ 30 µm



Heat treatment: 640°C
→ Thin reaction layer ~ 2-4 µm



Lower temperature favorable for thin filaments / thin wires

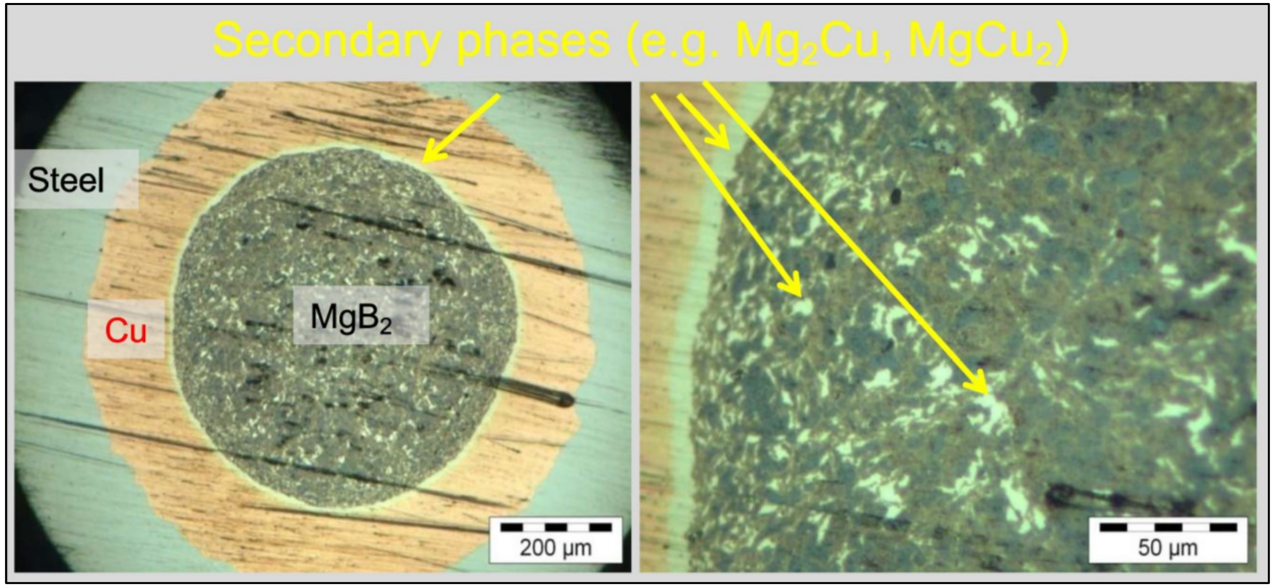
Conductor with Cu-Sheath

Heat treatment above ~ 500°C

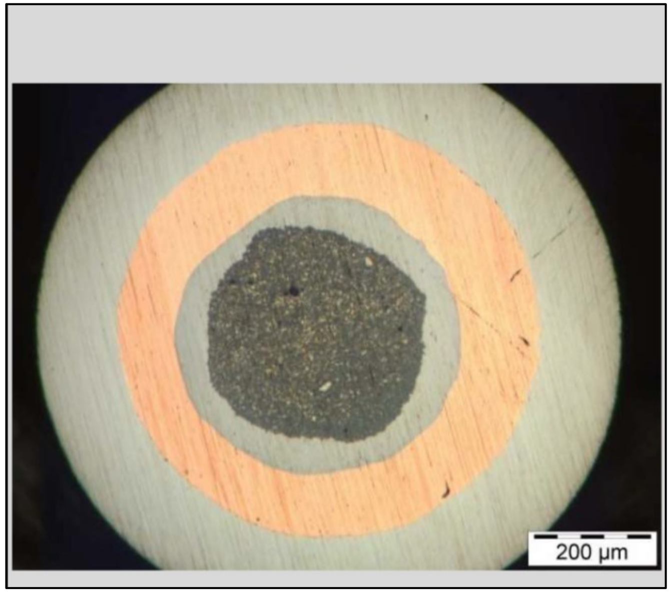
➔ **Diffusion of Cu** into whole filament, development of Mg-Cu-Phases (Mg_2Cu, $MgCu_2$)

➔ **Limitation of transport currents**

Without barrier



With Nb barrier



Solution: Nb or Ta barrier between filament and Cu

Improvement of Current Carrying Capability

Current Densities of PIT Wires and Tapes lower than in best thin Films

Intrinsic Improvements to $J_c(B)$

- Increase upper critical field B_{c2} with dopants
- Increase J_c by flux pinning

Extrinsic Improvements to $J_c(B)$

- Reduced porosity
- Improved connectivity

Improvement of Current Carrying Capability

Additions tested for Jc enhancement

(flux pinning sites, charge carrier scattering, sinter aids, etc.)

Nitrides, borides, and silicides

Si_3N_4, WB, ZrB_2, TiB_2, NbB_2, AlB_2, CaB_6, WSi_2, $ZrSi_2$, ...

Carbon and carbon inorganics

C (nanotubes), C (nanodiamond), TiC, SiC, B_4C, Na_2CO_3, ...

Metal oxides

Dy_2O_3, HoO_2, TiO_2, Pr_6O_{11}, SiO_2, ...

Metallic elements

Ti, Zr, Mo, Ta, Fe, Co, Ni, Cu, Ag, Al, Si, La, ...

Organic Dopants

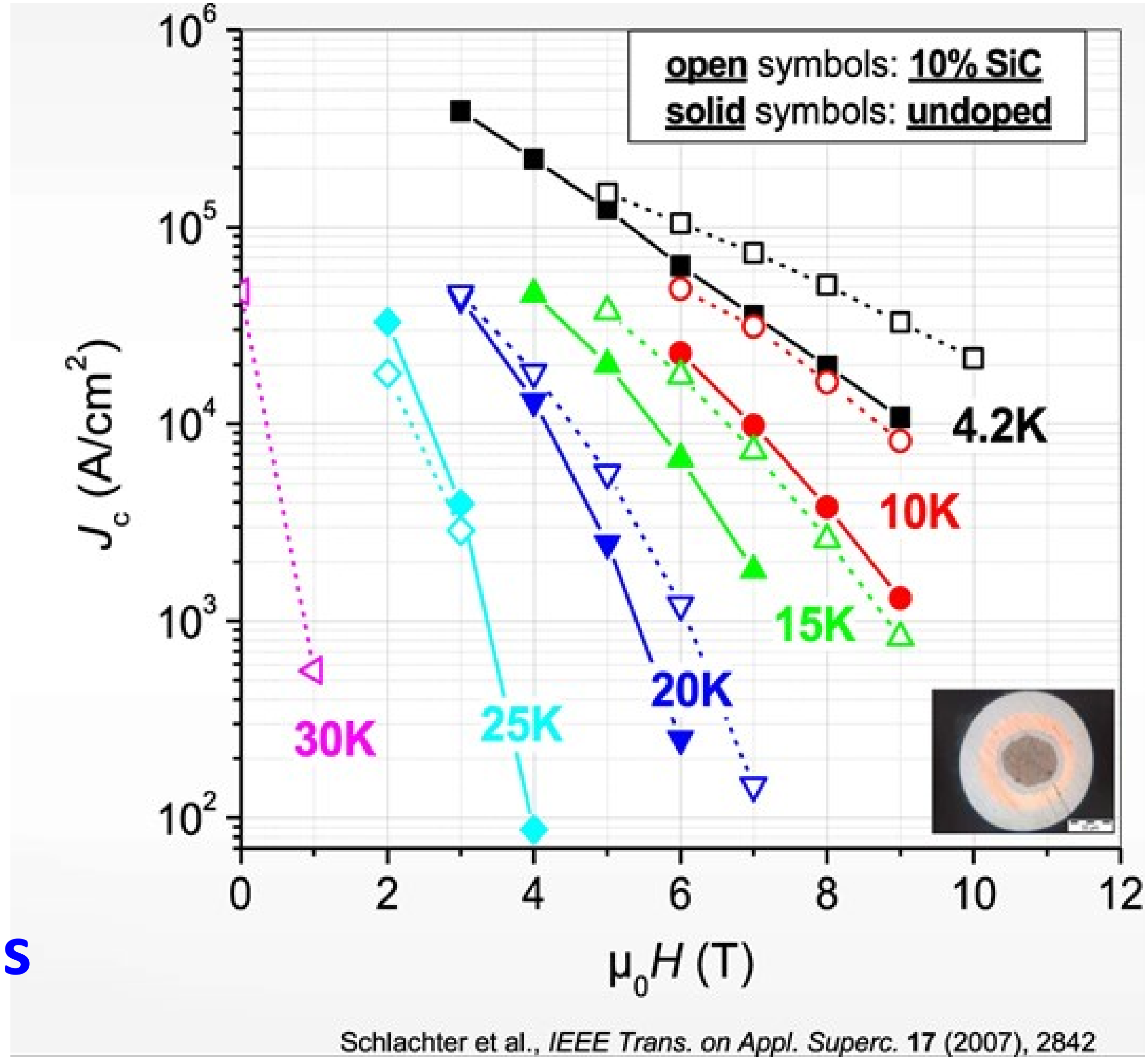
Sugar, malic acid, malic anhydride, paraffin, toluene, ethanol, acetone, polyvinyl alcohol, tartaric acid, ethyltoluene, ...

Carbon doping

- **C substitutes B**
  - disorder in B planes
  - reduction of mean free path by enhanced scattering
  - increase of upper critical field Bc2

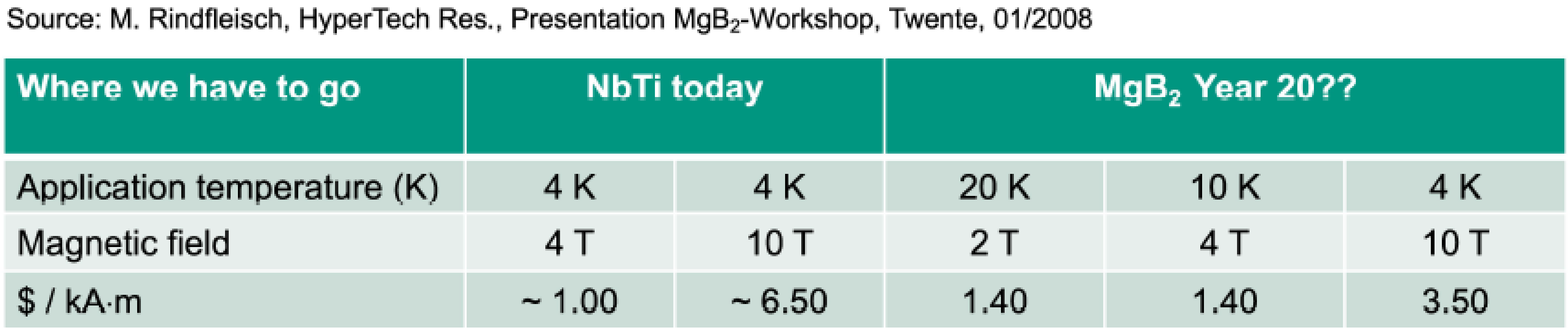
- **Introduction of nano-sized flux pinning sites**

C-Doping - up to now best results for Jc-enhancement in high magnetic fields



Schlachter et al., *IEEE Trans. on Appl. Superc.* **17** (2007), 2842

MgB$_2$ Cost estimation



Source: M. Rindfleisch, HyperTech Res., Presentation MgB$_2$-Workshop, Twente, 01/2008

Where we have to go	NbTi today		MgB$_2$ Year 20??		
Application temperature (K)	4 K	4 K	20 K	10 K	4 K
Magnetic field	4 T	10 T	2 T	4 T	10 T
\$ / kA·m	~ 1.00	~ 6.50	1.40	1.40	3.50

Advantages of MgB$_2$ compared to LTS

- *Low field (1.5 - 3 T)*
  Conduction cooled magnets @ 4-20 K (cryo coolers; **cryogen free**)
- *High field (10 T)*
  low conductor cost
- **Low weight**

MgB_2 Applications

- **MRI Magnets** (e.g. Ansaldo + Columbus Superconductors; ...)
- **Transformers** (HyperTech Res. + US Navy)
- **Motors I Generators with LH_2 -Cooling** (SupraPower)
- **Accelerator Magnets** (HyperTech Res. + Department of Energy)
- MARIMBO-Project: **dipole magnet for accelerator** (Ansaldo + INFN)
- **Superconducting Fault Current Limiter** (Ansaldo, Rolls Royce, ...)
- **Induction heater** (EU-Project "ALUHEAT", 06/2005 - 05/2008)
- **Adiabatic Demagnetization Refrigerator** (HyperTech Res. + NASA)
- **MgB_2 Cables** (Columbus + CERN)

MgB_2 Summary

- **Tc higher** than for NbTi and Nb_3Sn → higher temperature margin
- **Round conductor geometry** → cabling simple (compared to HTS)
- To replace NbTi or Nb_3Sn **Jc must be improved** (H_{c2} , flux pinning, grain connectivity)
- Extremely **good J_c(B)** properties already demonstrated for **thin films**
- Conductor **cost** in future **lower** than for Nb_3Sn und maybe even NbTi
- First applications are realized
- Interesting option for low ac-loss stator windings in electric aircrafts

REBCO

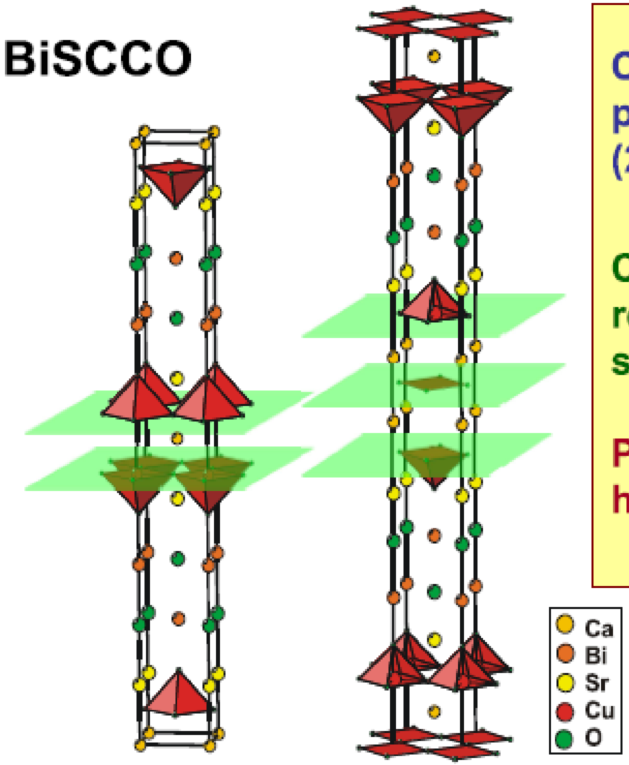
REBCO cable prototype, CERN

High Tc Superconductors - Cuprates

Bi(Pb)-2212 Bi(Pb)-2223

2212 ≈ $(Bi,Pb)_2Sr_2CaCu_2O_x$ ($x \approx 8$)
2223 ≈ $(Bi,Pb)_2Sr_2Ca_2Cu_3O_x$ ($x \approx 10$)

BiSCCO



T_C = 85K T_C = 110 K

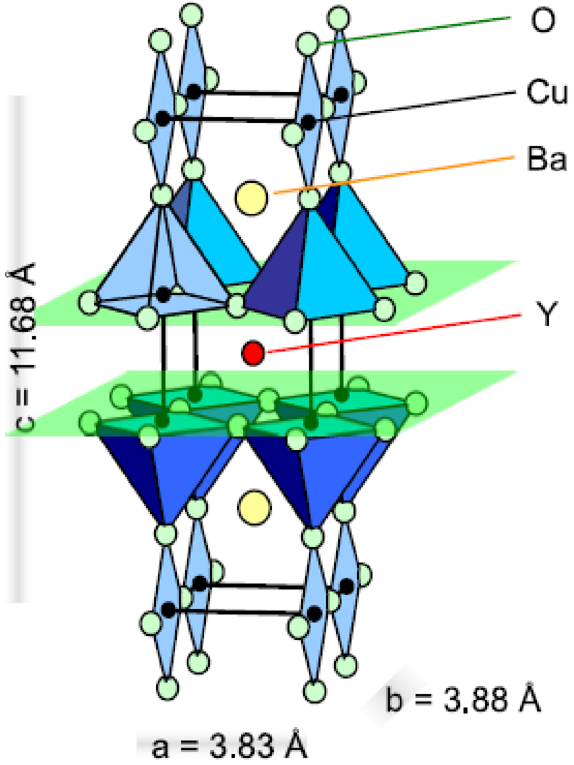
Ceramics: layered perovskite material (2-dimensionality)

CuO_2-planes responsible for superconductivity

Properties show high anisotropy

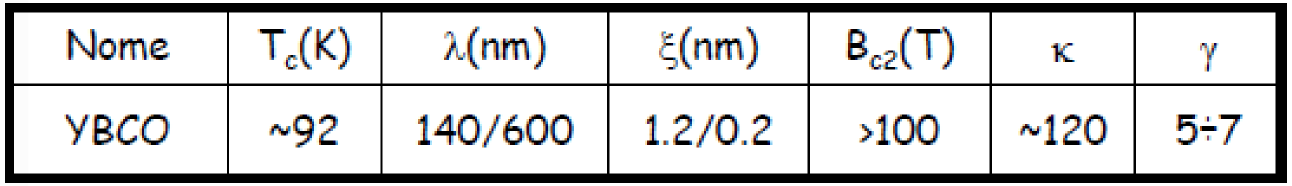
REBCO

$REBa_2Cu_3O_{7-x}$
RE: Y, Nd, Er, Gd, Eu…

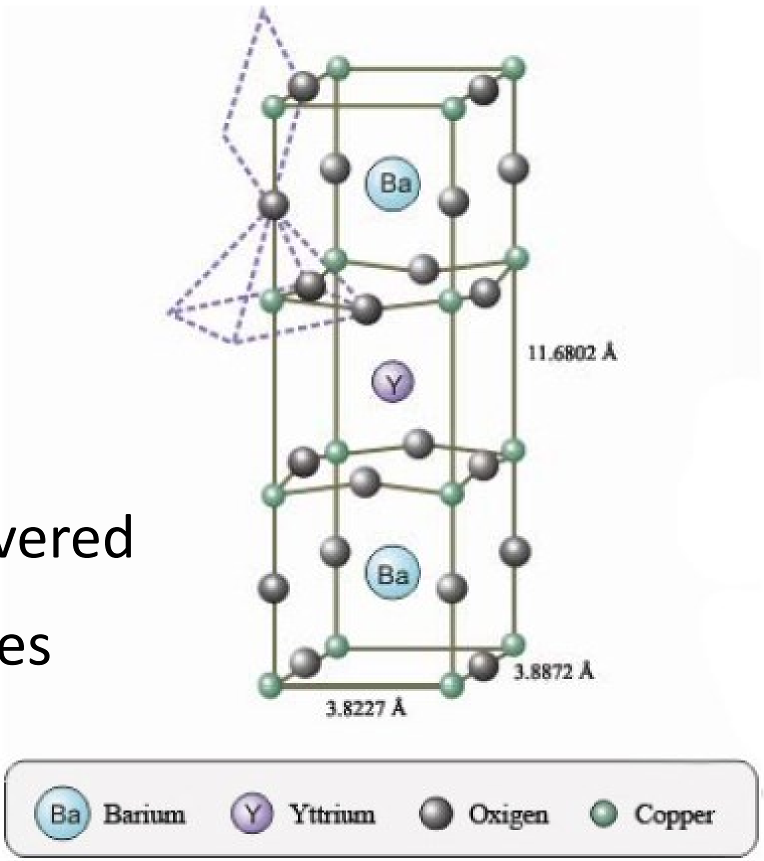


T_C = 92 K

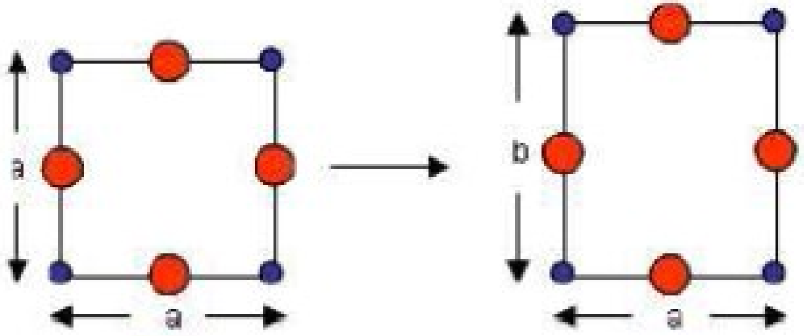
YBCO



Nome	T_c(K)	λ(nm)	ξ(nm)	B_{c2}(T)	κ	γ
YBCO	~92	140/600	1.2/0.2	>100	~120	5÷7



- It was the first superconductor with **Tc above 77 K** discovered
- It features a **simpler cell than BSCCO** with 2 CuO_2 planes
- It also has a **lower anisotropy than BSCCO**



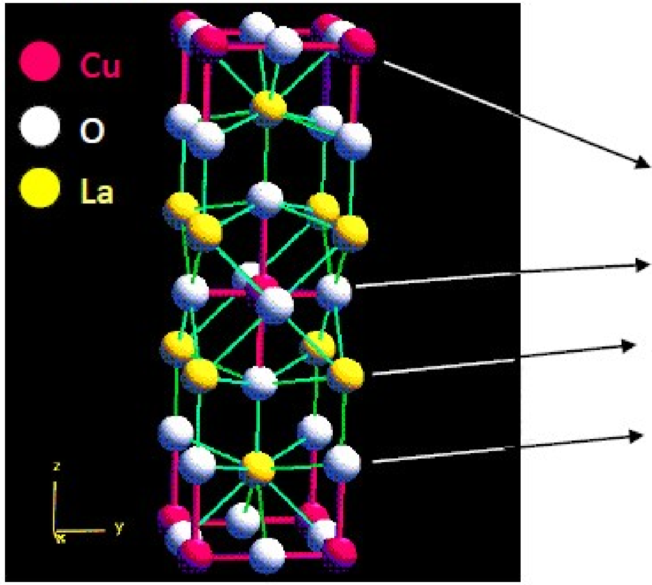
In the superconducting phase the unit cell has a slight orthorhombic basal distortion that causes one of the two base axes to be larger than the other

Cuprates - Layered structure

They present very complicated, layer-structured unit cells

Each of the layers has its own function in establishing SC properties

$(La,Ba)_2CuO_4$ T_c~38K



Cu-O chains: function as charge carrier reserves

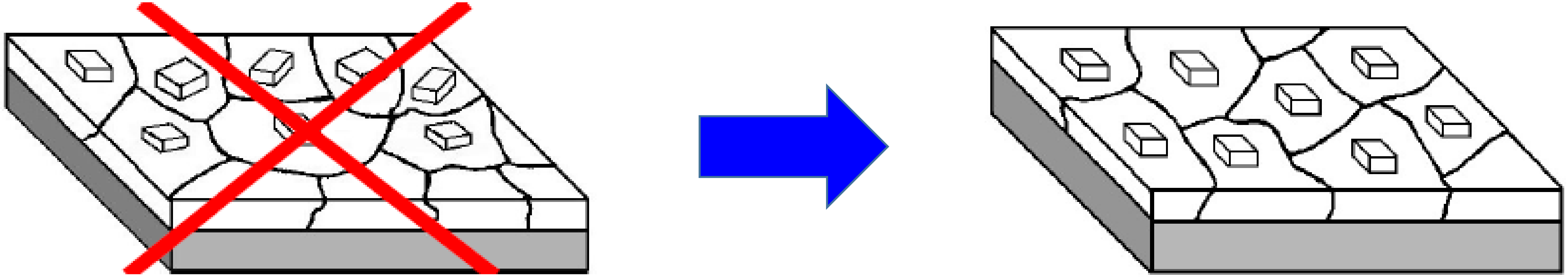
Cu-O_2 planes: are the planes where the superconductivity is located

apical oxygens: regulate the exchange of carriers between planes and chains

insulating layers: adjust the valence of copper in Cu-O planes

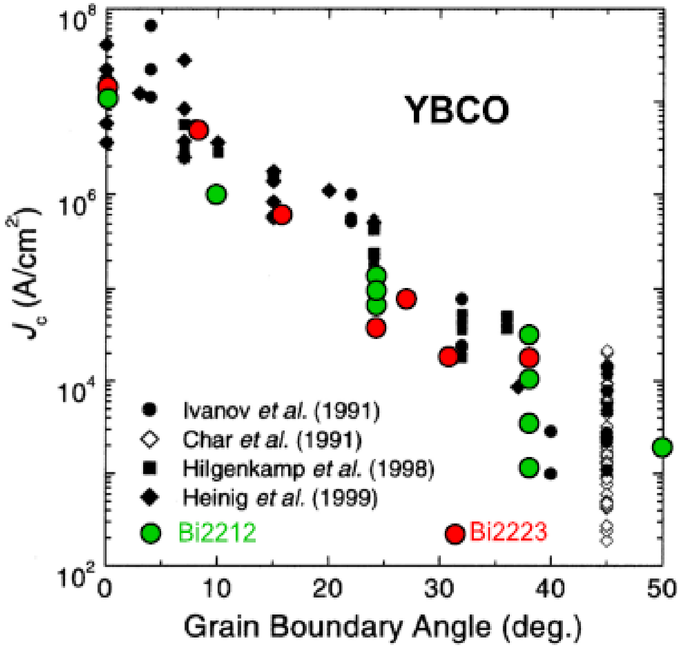
This structure results in a **strong anisotropy** of both **microscopic ($\lambda_{ab} \neq \lambda_c$, $\xi_{ab} \neq \xi_c$)** and **macroscopic properties (H_c, J_c)**

HTSC grain boundary challenge

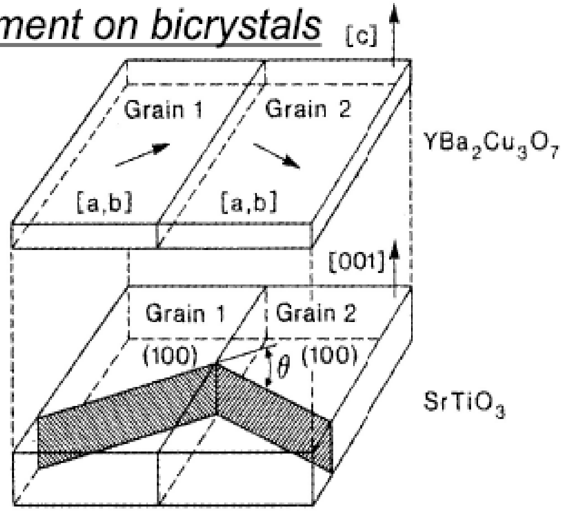


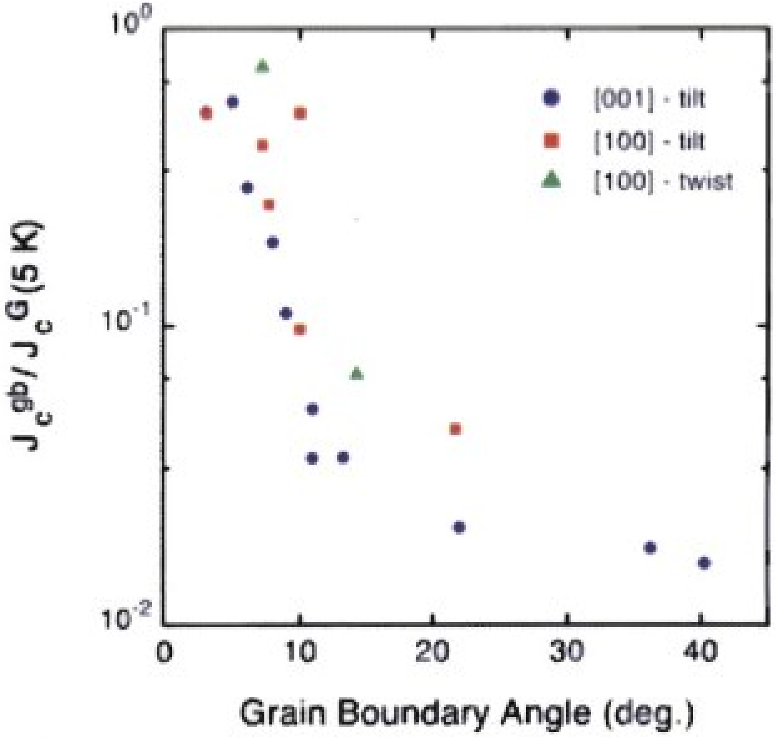
High J_c in polycrystalline materials
requires **strong biaxial texture**

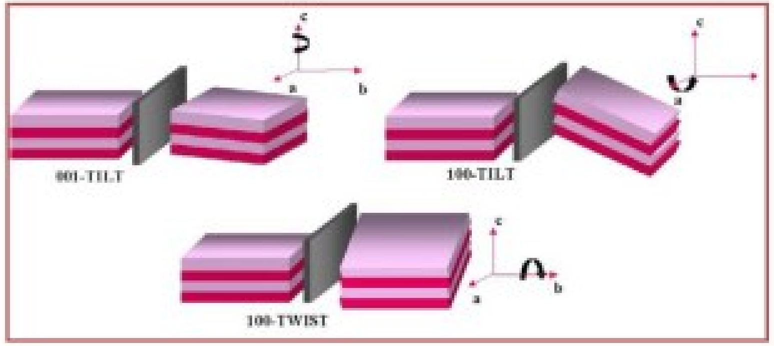
HTSC grain boundary challenge



Measurement on bicrystals







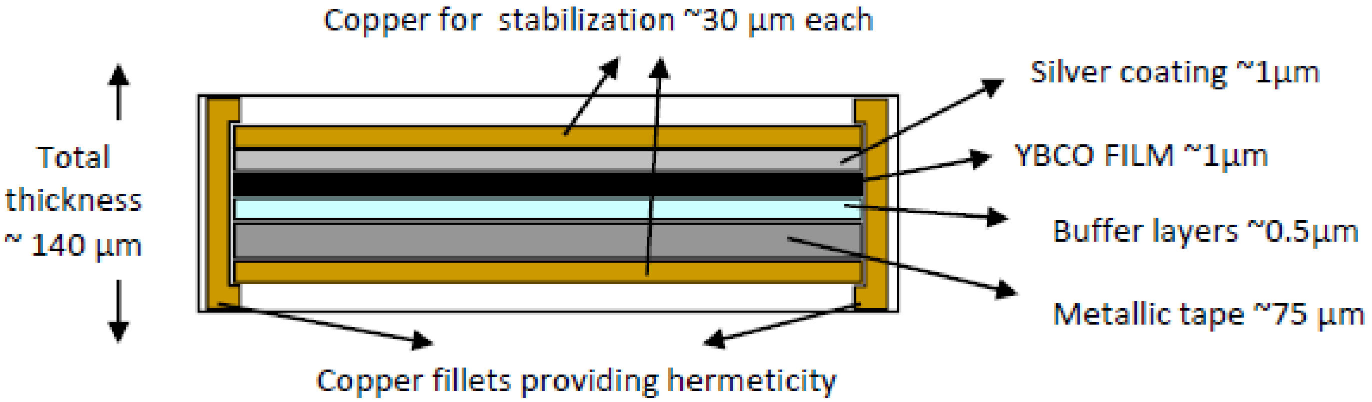
High J_c in polycrystalline materials requires **strong biaxial texture**

Bi-axial YBCO growth

Epitaxially grow the **YBCO** in the form of a **film** on a **template** already **biaxially textured**

METALLIC TAPE

- must give the conductor flexibility
- must not be magnetic



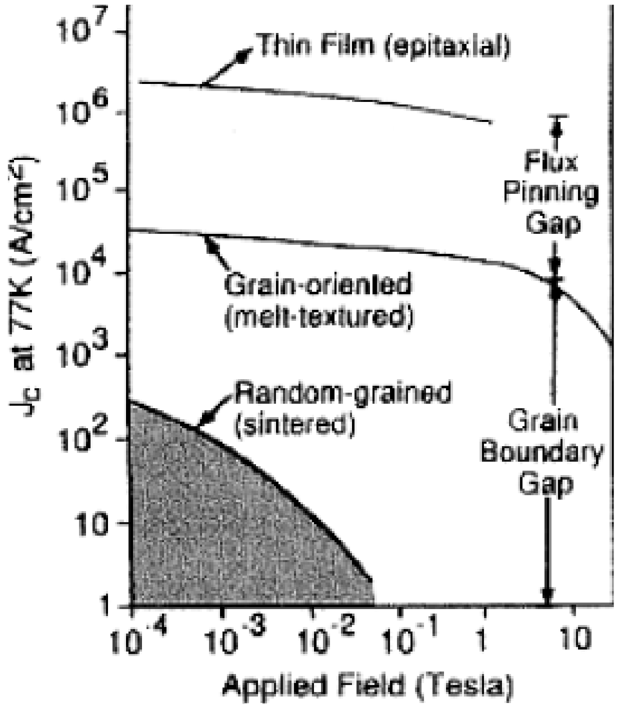
BUFFER LAYERS

- must be biaxially textured
- it should promote the epitaxial YBCO growth
- must act as a barrier to metal diffusion from the substrate
- it must be chemically YBCO compatible

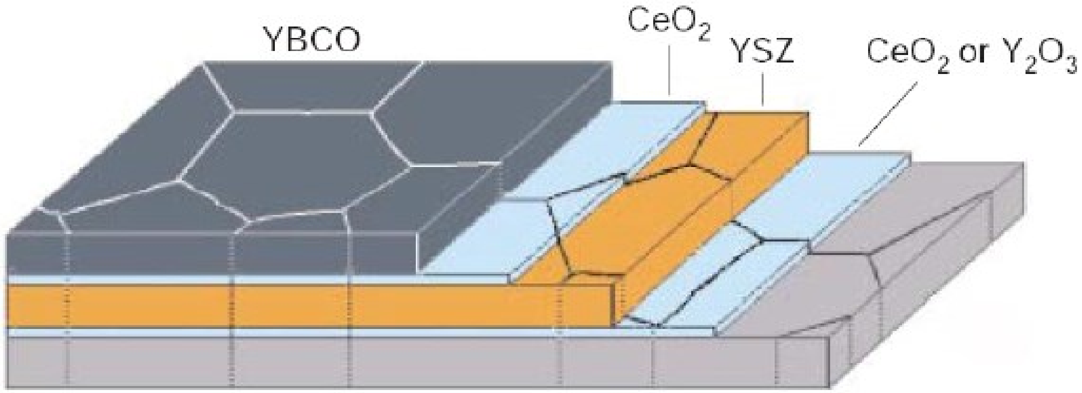
METALLIC STABILYZER (Cu, Ag)

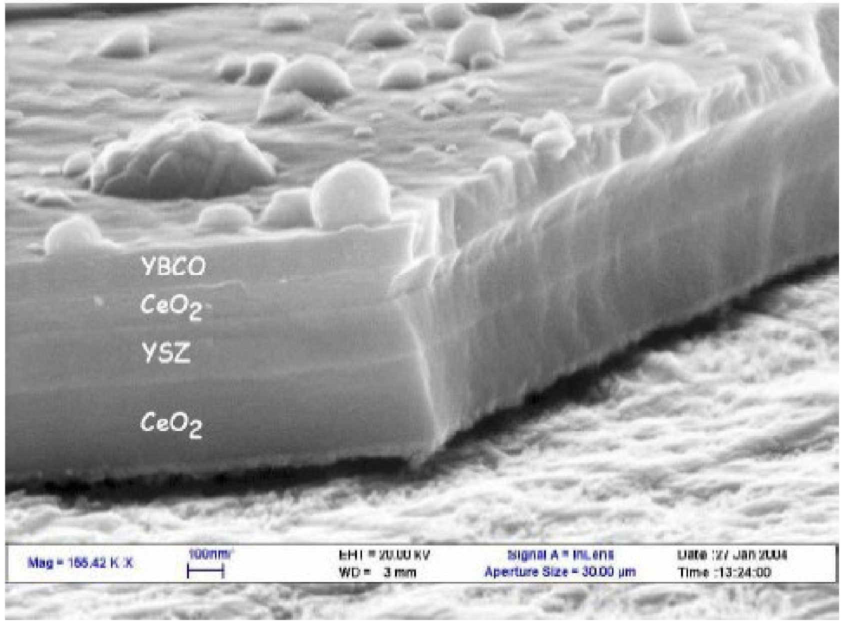
- must provide an alternative path for the current in case of quench (electrical shunt)
- must dissipate heat in case of quench (shunt thermal shunt)

Film growth



NiW - CeO_2 – YSZ - CeO_2 - YBCO





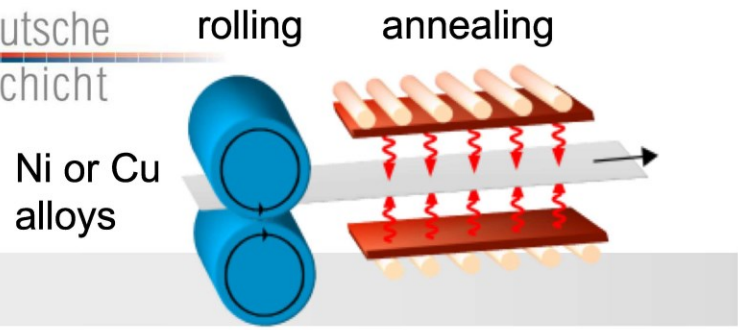
Growth YBCO as a **film**
enhance **pinning centers**

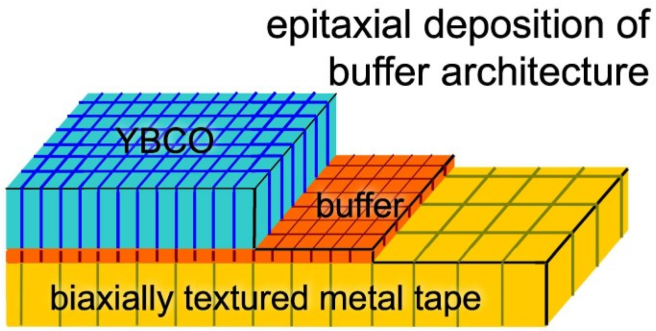
Higher Jc

Coated conductor techniques

Rolling Assisted Biaxially Textured Substrates (RABiTS)

deutsche nanoschicht

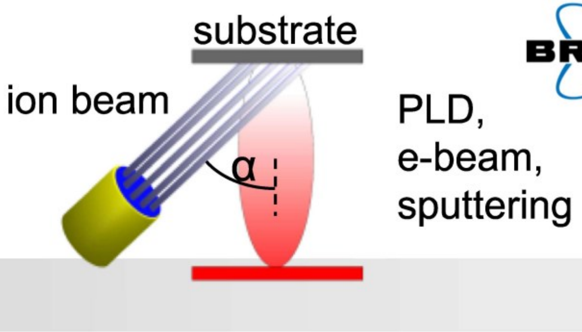


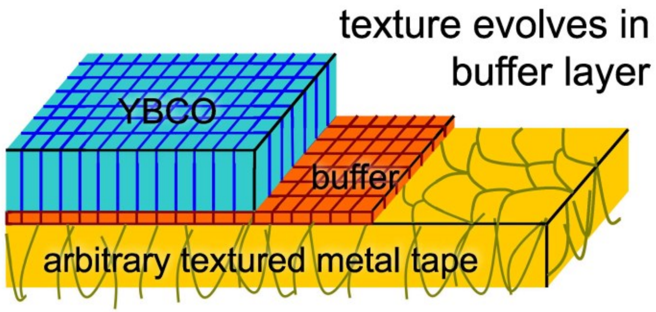


Biaxially textured substrate

Ion Beam Assisted Deposition (IBAD/ABAD)

BRUKER



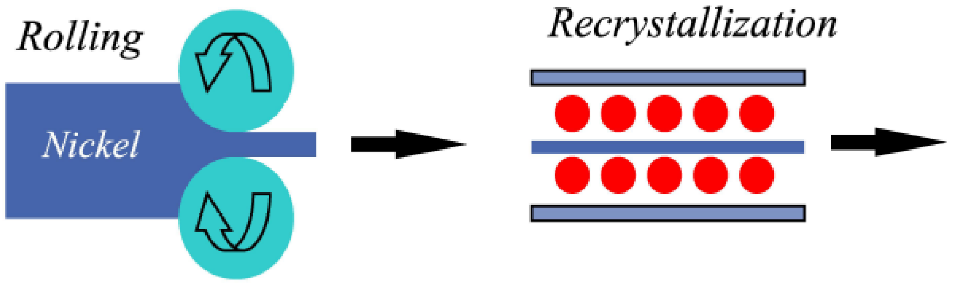


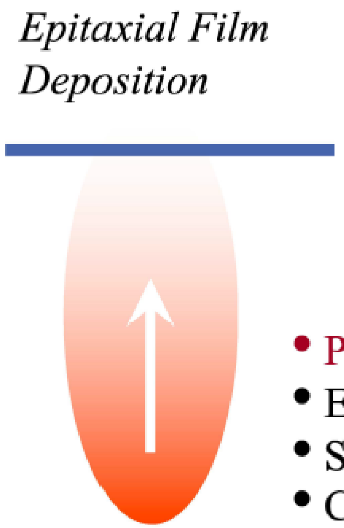
Biaxially textured bufferlayers

Rolling Assisted Biaxially Textured Substrates (RABiTS)

The **substrate** is prepared by mechanical processes (**lamination**) and thermal processes (**annealing**) in order to have a very smooth surface, clean but above all a very good **biaxial texture**

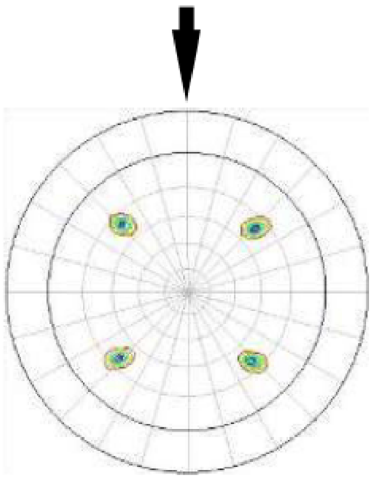
The **texture** is transferred to the YBCO, via the **buffer layers** by **epitaxial growths**. In this case the choice of the **substrate** must also take into account its crystal structure, which must be **cubic**





- Cold deformation >95%
- Pure Ni
- Microalloyed Ni :
  - Ni-0.1at%Mn
  - Ni-0.05at%Ag
- Alloyed Ni :
  - Ni-5at%W
  - Ni-9at%V
  - Ni-13at%Cr
- Composites :
  - Ni-W/Ni-Cr
  - Ni-W/Ni-W

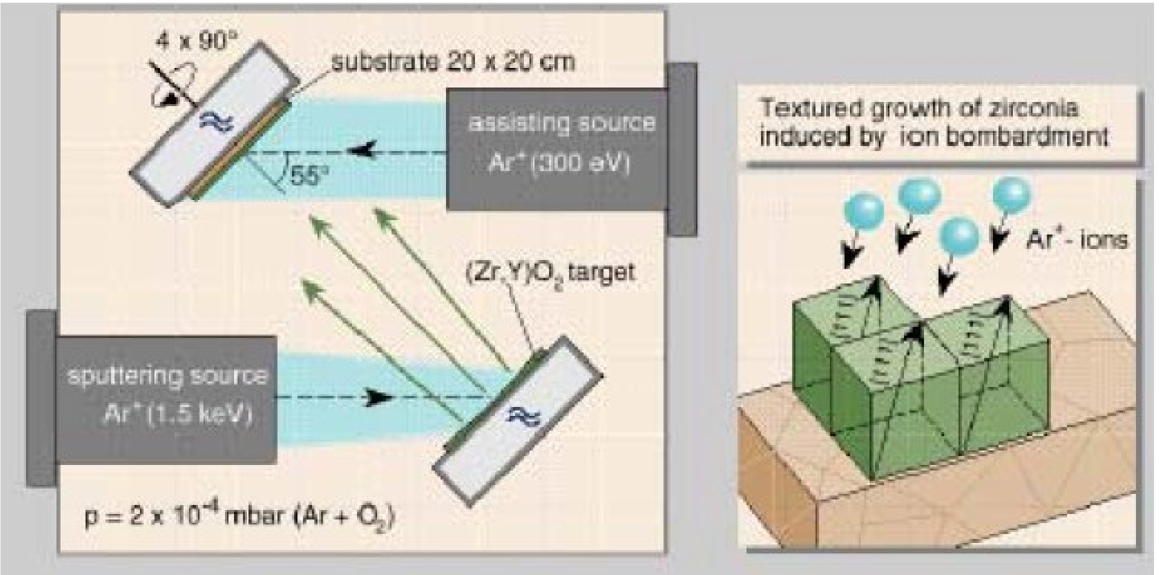
- Typical 900° C/1h
- H_2-atmosphere



(111)-pole figure of Ni-5at%W

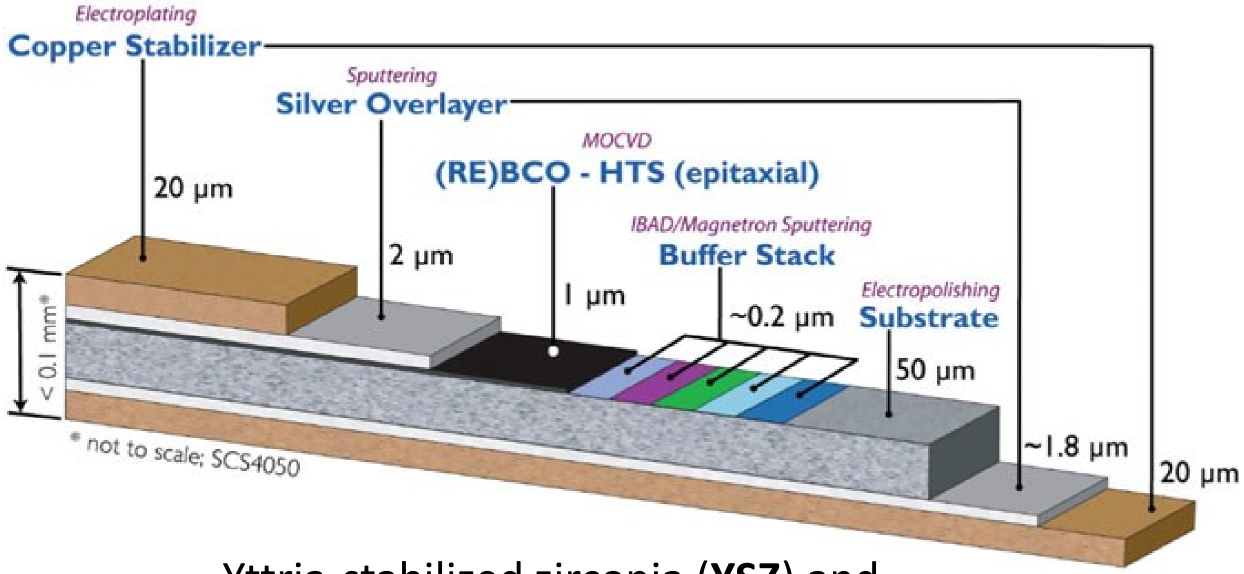
- PLD
- E-beam
- Sputtering
- CVD
- CSD

Ion Beam Assisted Deposition (IBAD/ABAD)



The metal substrate is polycrystalline (non-textured) - Hastelloy (Ni alloy)

The **texture is artificially induced** on one of the **buffer layers**



Yttria-stabilized zirconia (**YSZ**) and **MgO** are typical IBAD buffer layers

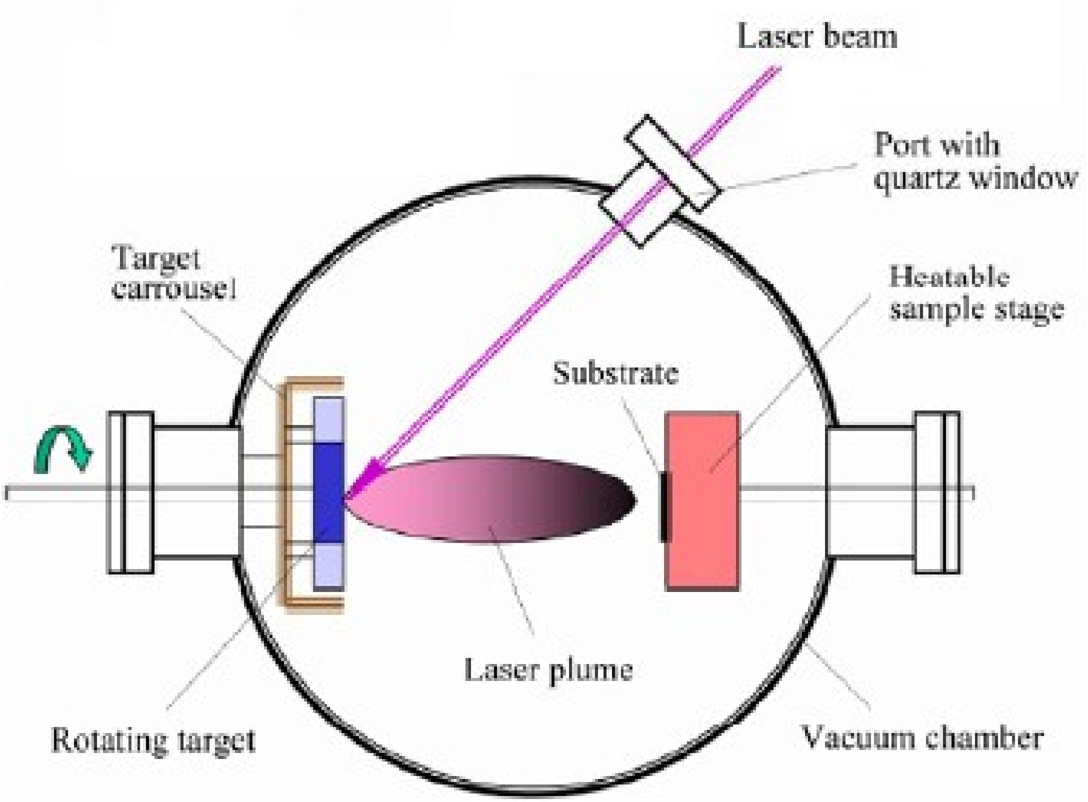
2 sputtering sources are used:

1. **Affects the target material to be deposited**
2. **Directed on the deposited material according to a precise angle.** In this way, a selective sputtering of the deposited material is obtained, which induces a tissue growth

YBCO coating methods

PLD (Pulsed Laser Deposition)

A **laser beam** etches a **target of stoichiometric material** (sintered powders) and heats it locally. An evaporation cloud called **plume** is formed, which **condenses** on the substrate placed in front and forms the **film**



YBCO coating methods

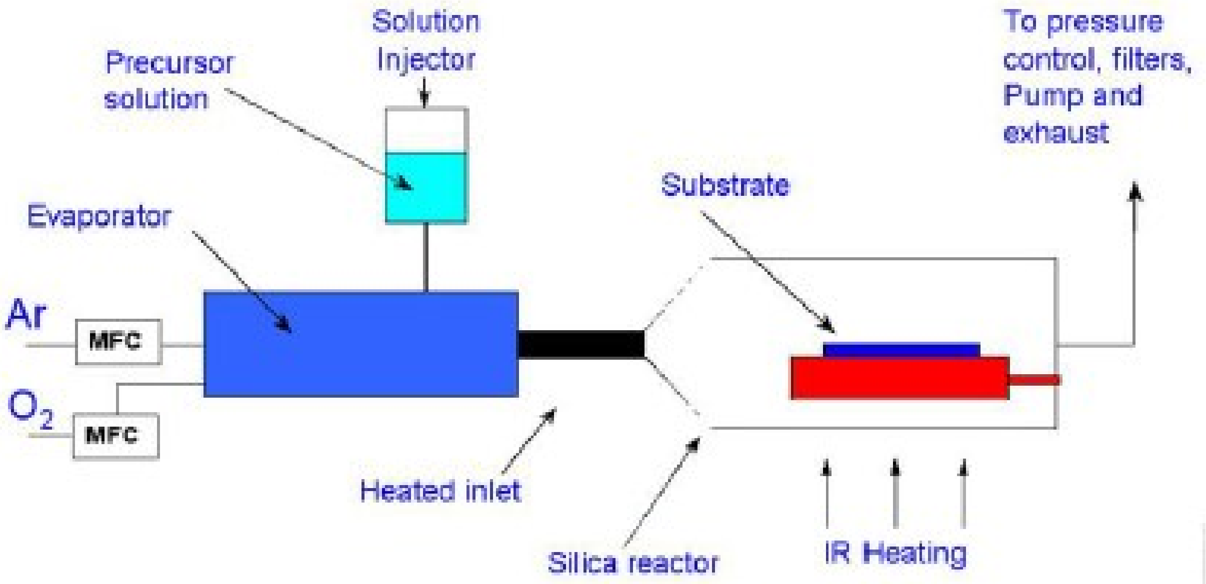
MOCVD (Metal-Organic Chemical Vapor Deposition

The **organic precursor** of the compound to be deposited is brought into the **reaction chamber** by a **lamellar flow of gas.**

The **thermal energy** of the substrate is sufficient to **decompose** the precursor causing deposition of the material and evaporation of the organic solvent.

For YBCO the precursor is
M(Tetramethyl HeptaDionate)
with M=Y, Ba, Cu

SuperPower Inc.
A Furukawa Company



REBCO final remarks

- YBCO represents only 1% of all material used in the cable
- Tapes are a bad geometry for AC losses:
  no multifilament or twisting possible
- Mechanical stability is often still an issue
- Economy of scale has still to be worked out
- Room for improvement

Bibliography of this part

- R.G. Sharma, "Superconductivity Basics and Applications to Magnets", Springer

  Chapter 6 Practical Superconductors

- R. Flukiger, B. Holzapfel, **EASISchool ESAS Summer School 2018**