MASSACHUSETTS INSTITUTE OF TECHNOLOGY
DEPARTMENT OF MECHANICAL ENGINEERING
DEPARTMENT OF NUCLEAR ENGINEERING

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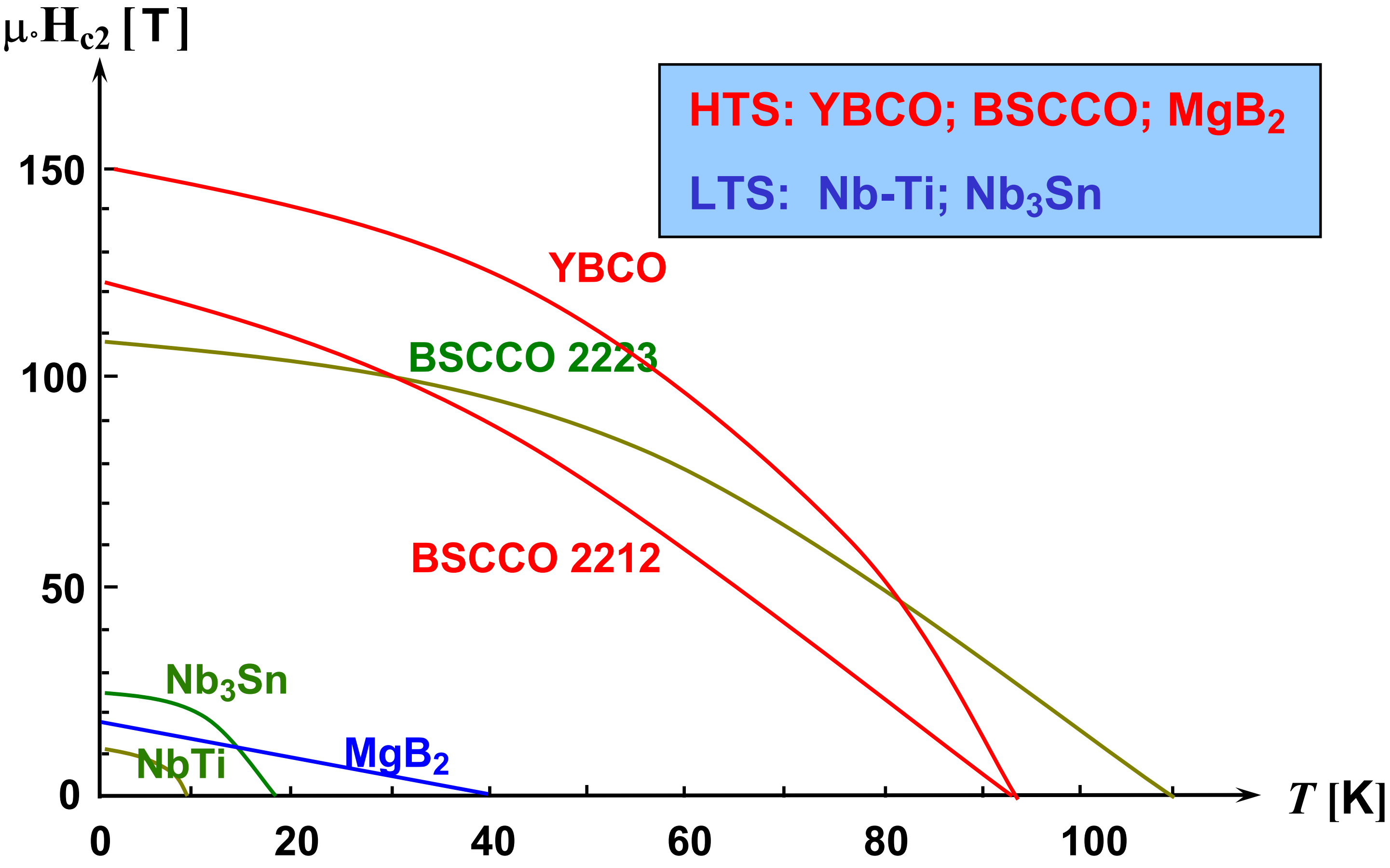
Lecture 6: Low-Temperature Superconductors

- ✵ **Concise summary of superconductor; Type I & Type II**
- ➢ **Magnet-grade conductor; Enhancement of J_c**
- ➢ **Fabrication Process of Nb-Ti/Cu Composite Wire**
- ➢ **Fabrication Processes of Nb_3Sn Composite Wire**
- ➢ **Strain: source and effects; Other A15 materials**
- ➢ **Magnet winding constituents; designer's goal**
- ➢ **Types of magnet: high-performance ("adiabatic") & cryostable**
- ➢ **CICC (Cable-in-Conduit Conductor)**
- ➢ **Examples of high-performance & cryostable magnets**
- ➢ **Selected data of Nb-Ti and Nb_3Sn**
- ➢ **Jc Scaling laws for Nb-Ti and Nb_3Sn**
- ➢ **Selected material properties**

Critical Field vs. Temperature Plots of “Magnet” Superconductors



HTS: YBCO; BSCCO; MgB_2

LTS: Nb-Ti; Nb_3Sn

Concise Summary

- **Superconductivity discovered by Kamerlingh-Onnes, 1991.**
  - **Type I (soft) superconductors: Hg, Pb, In.**
- **Critical properties: T_c; H_c; J_c.**
- **Meissner effect: perfect diamagnetism.**
- **Penetration depth (London theory, 1935).**

$$\lambda = \sqrt{\frac{m}{\mu_o e^2 n_e}} \qquad\qquad n_e = \frac{2\rho N_A}{W_A}$$

  - **Superelectrons: Copper pair.**

Concise Summary (continued)

- **Discovery of Type II (hard) superconductors: Pb-Bi (1930).**
- **Penetration of H in Type II (Mixed state)--new model.**
- **Vortex model (Abrikosov): normal vortex in super conducting sea. Coherehnce (transition) length: ξ**
  - **Type I:** $\xi \rangle \sqrt{2}\,\lambda$
  - **Type II:** $\xi \langle \sqrt{2}\,\lambda$
- **Coherence length affected by alloying. Alloying increases resistivity: $\xi \propto 1/\rho$ and $T_c \propto \rho$.**
  - **Normal state ρ_{sc} of Type II: 10^2–10^3 greater than ρ_{cu}.**

Selected Type I Superconductors

Material (Type)	T_c [K]	$\mu_o H_{c_o}$* [T]
Ti (metal)	**0.40**	**0.0056**
Zn	**0.85**	**0.0054**
Al	**1.18**	**0.0105**
In	**3.41**	**0.0281**
Sn	**3.72**	**0.0305**
Hg	**4.15**	**0.0411**
V	**5.40**	**0.1403**
Pb	**7.19**	**0.0803**

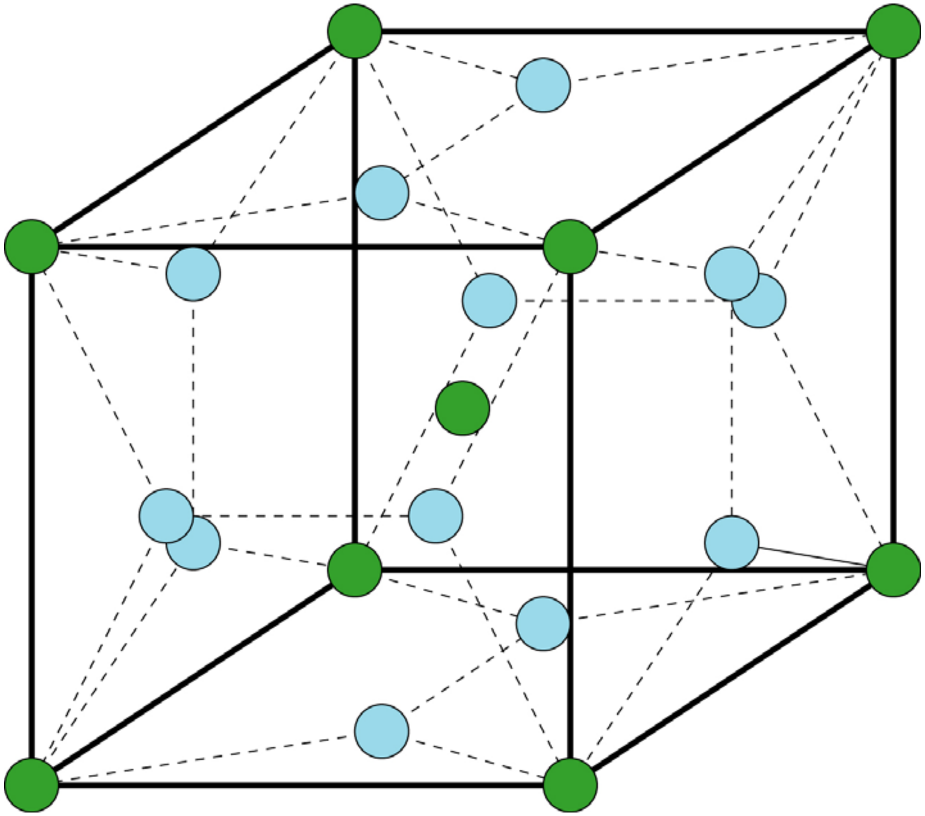
*** 0 K**

Selected Type II Superconductors

Material (Type)	T_c [K]	$\mu_o H_{c_o}$ [T]
Nb (metal)	**9.5**	**0.2***
Nb-Ti (alloy)	**9.8**	**10.5†**
NbN (metalloid)	**16.8**	**15.3†**
Nb_3Sn (intermetalic compound: A15)	**18.3**	**24.5†**
Nb_3Al	**18.7**	**31.0†**
Nb_3Ge	**23.2**	**35.0†**
MgB_2 (compound)	**39**	**~15***
$YBa_2Cu_{3-x}O_x$ (oxide: Perovskite) <YBCO>	**93**	**150***
$Bi2Sr2Ca_{x-1}Cu_xO_{2x+4}$ <BSCCO2223 or 2212>	**110**	**108***

*** 0 K   † 4.2 K**

A-15 (β-W) Structure



Nb (6/cube) **Sn (2/cube)**: **Nb_3Sn**

Materials vs. Magnet-Grade Conductors

Criterion	*Number*	*Discipline*
1. Superconductivity?	**~10,000***	**Physics**
2. T_c>10 K ($\mu_o H_{c_o}$>10 T)?	**~100***	**Physics**
3. J_c>1 MA/cm^2 (@ B>5 T)?	**~10***	**metallurgy**
4. Magnet-grade superconductor?	**~1***	**metallurgy**

*** Order of magnitude**

Magnet-Grade Conductors

- **Satisfies rigorous specifications required for use in a magnet.**
- **Readily available commercially.**
- **Currently, only three: Nb-Ti; Nb_3Sn; BSCCO2223**

R&D Stage:

BSCCO2212 (NMR); YBCO (Electric devices);
Nb_3Al (limited interest for Fusion & NMR)

Promising: MgB_2 (cost said to be comparable with Nb-Ti)

Material-to-Conductor Development Stages

—Nb_3Sn —

Stage	*Event*	*Period*
1	Discovery	Early 1950s
2	Improvement J_c	Early 1960s
3	Co-processing with matrix metal	Mid 1960s
4	Multifilament/twisting, I_c>100 A	Early 1970s
5	Long length, typically ~1 km	Mid 1970s
6	Full specifications for magnets	Late 1970s

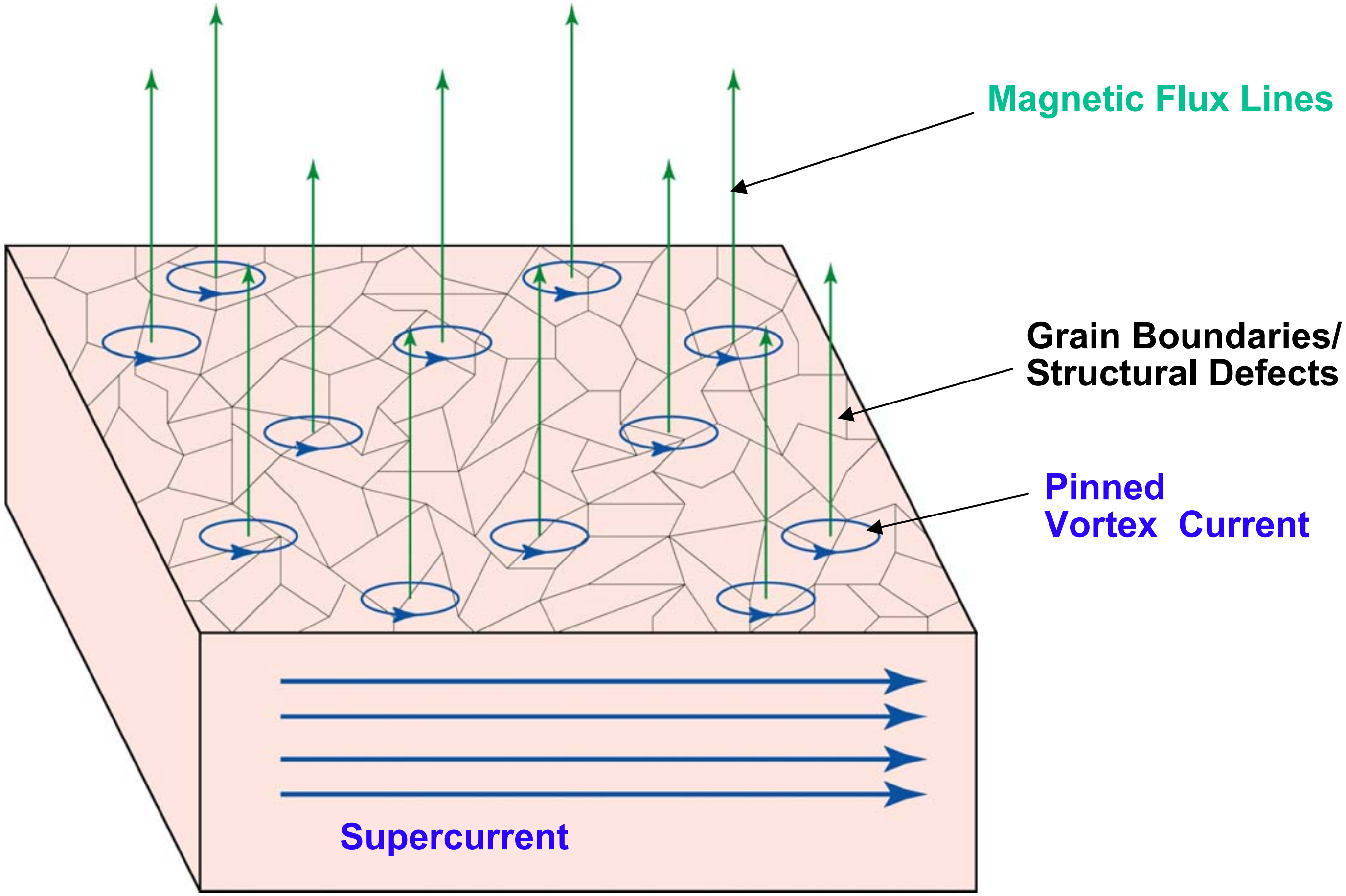
Enhancement of J_c

- **Of the three critical parameters—H_c, T_c, J_c—J_c may be improved by metallurgical processing.**
- **Alloying enhances "flux pinning" which increases J_c.**
  - **Force on vortex:**

$$\vec{F}_v = \vec{J}_c \times \mu_o \vec{H}$$

  - **Pinning of vortices: 1) crystal impurities – small crystals, grain boundary densities, dislocation density; 2) creation of artificial pinning sites by cold working, heat treatment.**

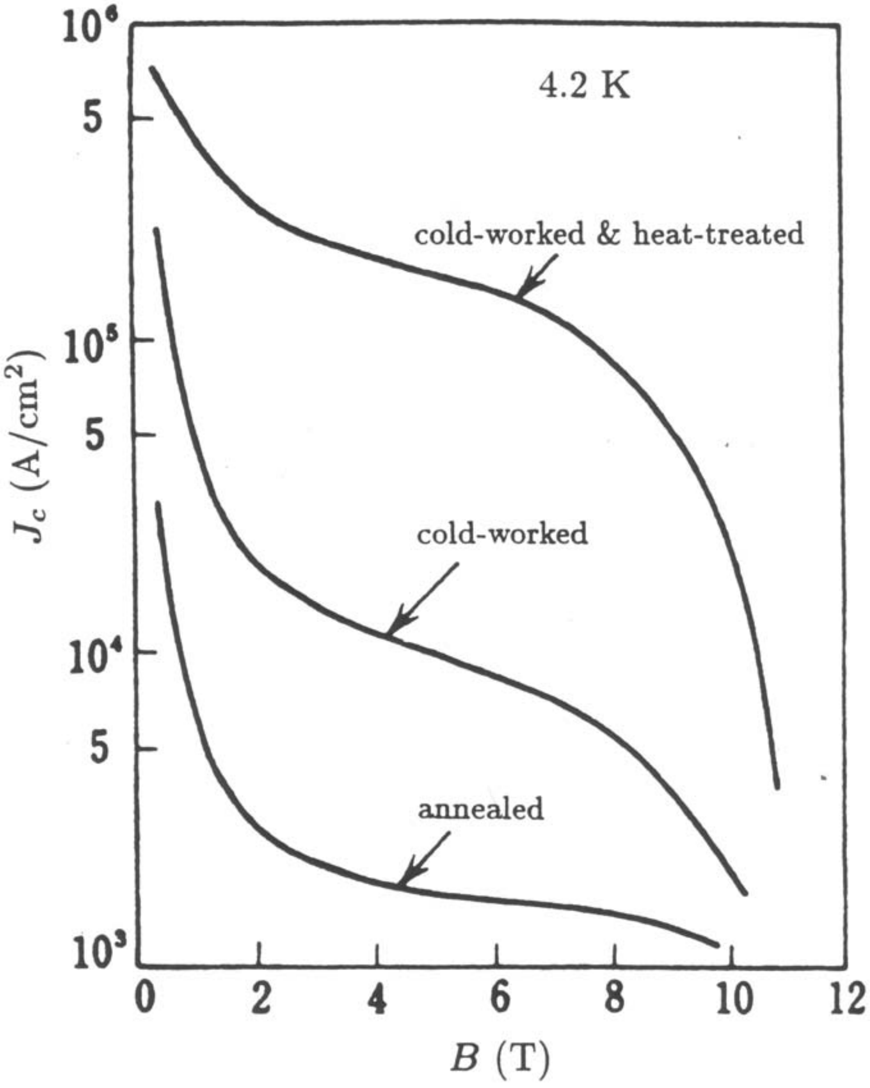
Schematic drawing of "pinned" vortices



Heat Treatment

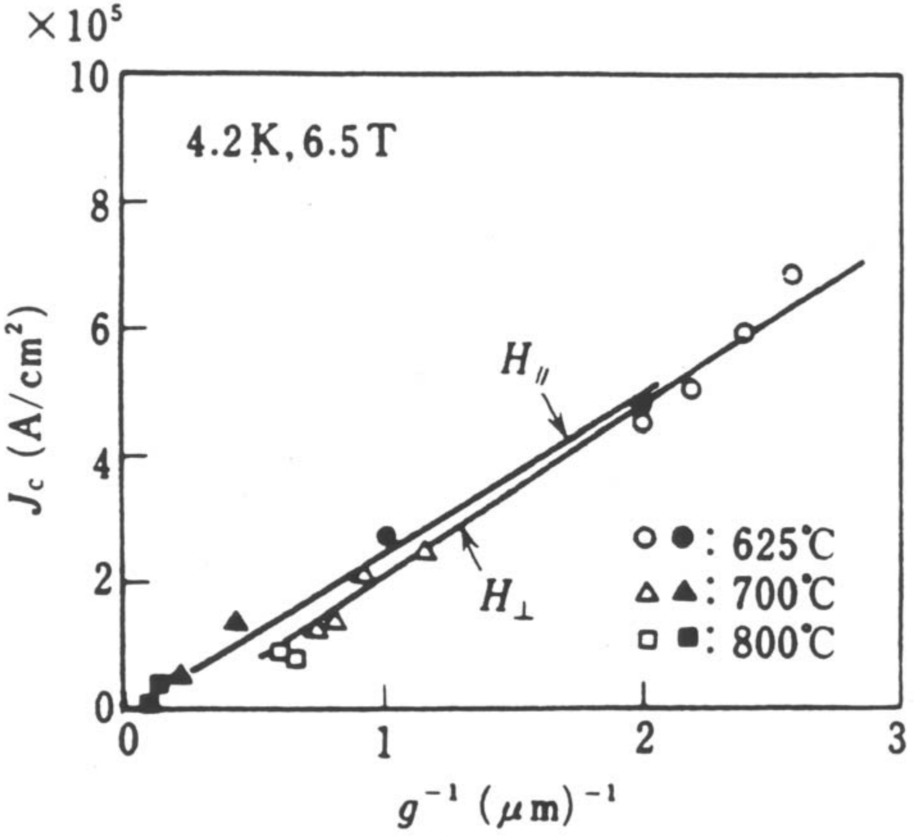
- **Window of opportunity—dependent on composition.**
- **Trade-off between grain size and boundary growth.**
- **Time/temp for heat treatment (Nb-Ti: 390˚C/~100 h).**
  - **HT time must be “reasonable” for the plant (<100 h).**

Effects of cold work and heat treatment on J_c



Cold Working (Drawing)

- **Increase dislocation density (increased J_c).**
  - **Experimental evidence of increased J_c with smaller grain size: true for every known superconductor**

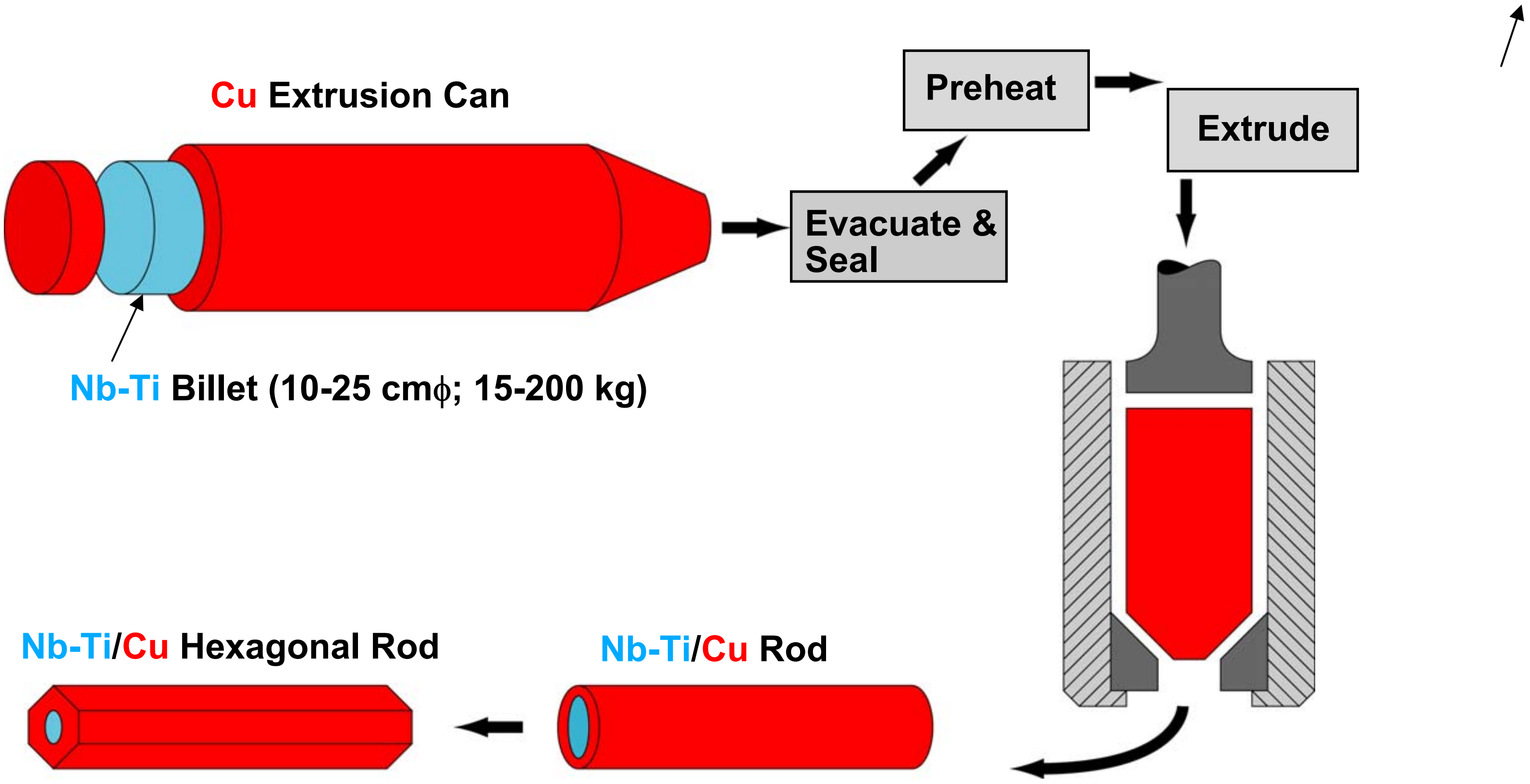


Fabrication Process of Nb-Ti/Cu Composite Wire

- **Extrusion of Nb-Ti billet co-processed with copper.**
  - **Low-resistance path during transition to the normal state.**
  - **Mechanical strength and ductility.**

Production of MF Nb-Ti/Cu Composite

Stage 1: Stacking & Hexagonal Nb-Ti/Cu Rod



Cu Extrusion Can

Nb-Ti Billet (10-25 cmφ; 15-200 kg)

Evacuate & Seal

Preheat

Extrude

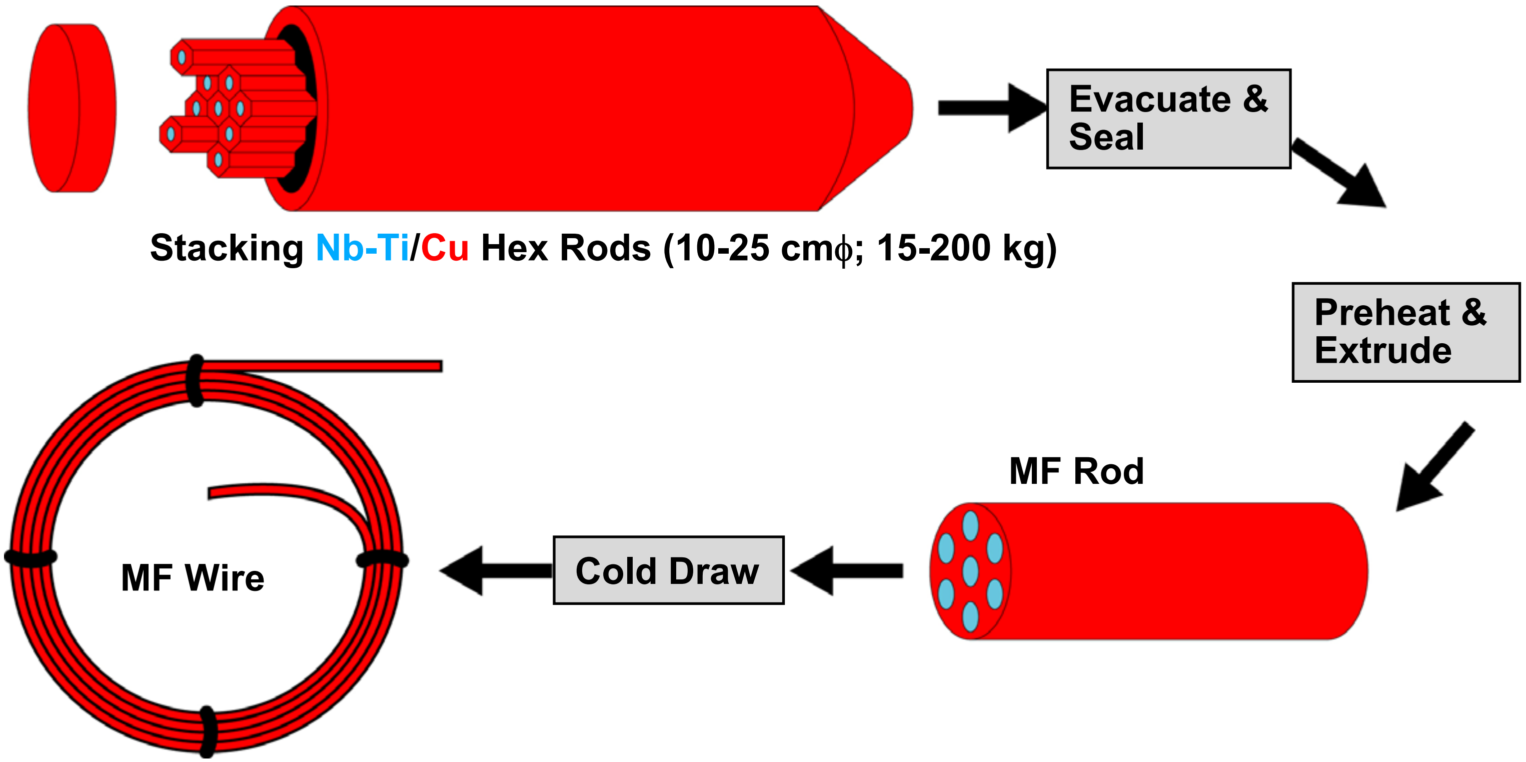
Nb-Ti/Cu Rod

Nb-Ti/Cu Hexagonal Rod

Nb-Ti (continued)

- **Multifilamentary wire**
  - **Flux jumping: filament size (<critical size)**
  - **Increased grain boundary density.**
- **Cold drawing and heat treatment (repeated).**
- **Twisting: strain limits—pitch length 5-15 times wire dia.**
- **Anneal Cu and insulate.**

Stage 2: MF Composite



Stacking Nb-Ti/Cu Hex Rods (10-25 cmϕ; 15-200 kg)

Evacuate & Seal

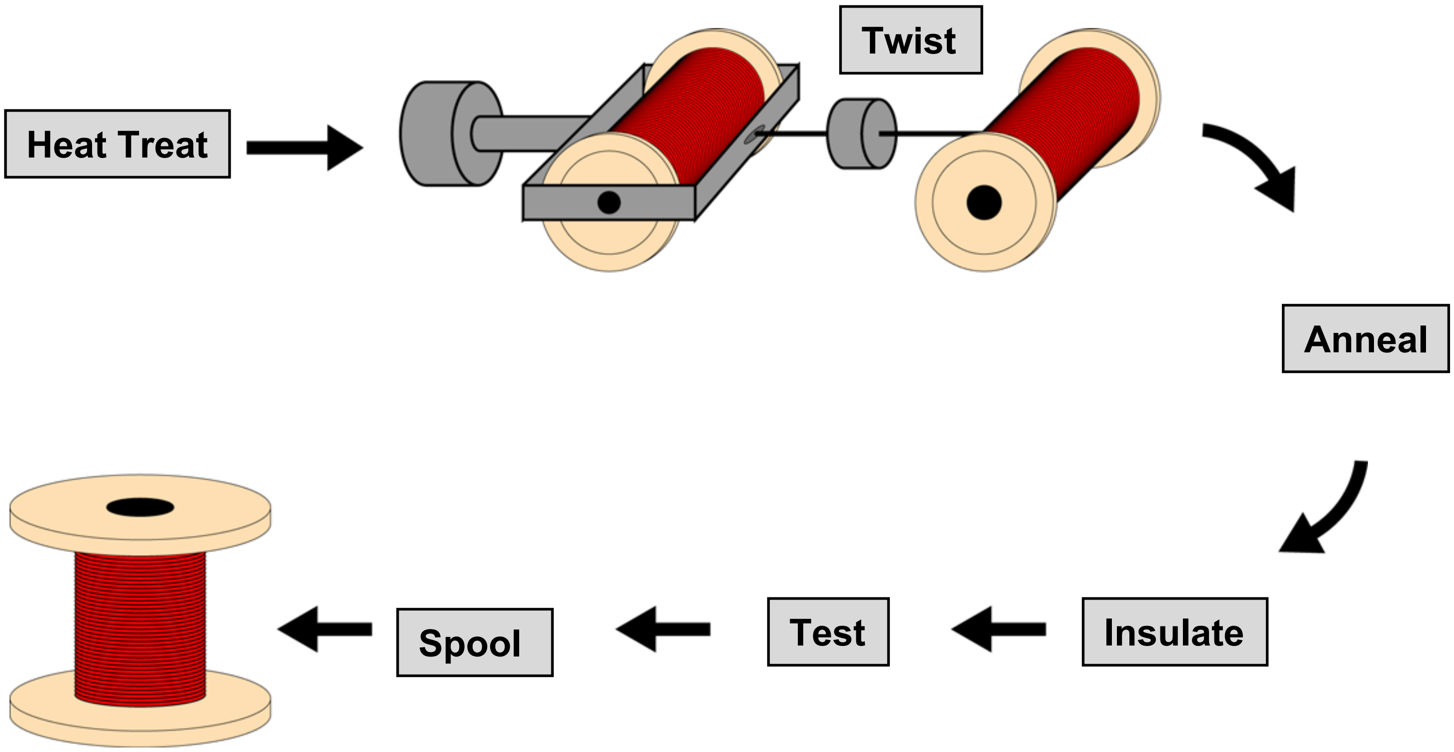
Preheat & Extrude

MF Rod

Cold Draw

MF Wire

Stage 3: Twisting & Spooling



Heat Treat

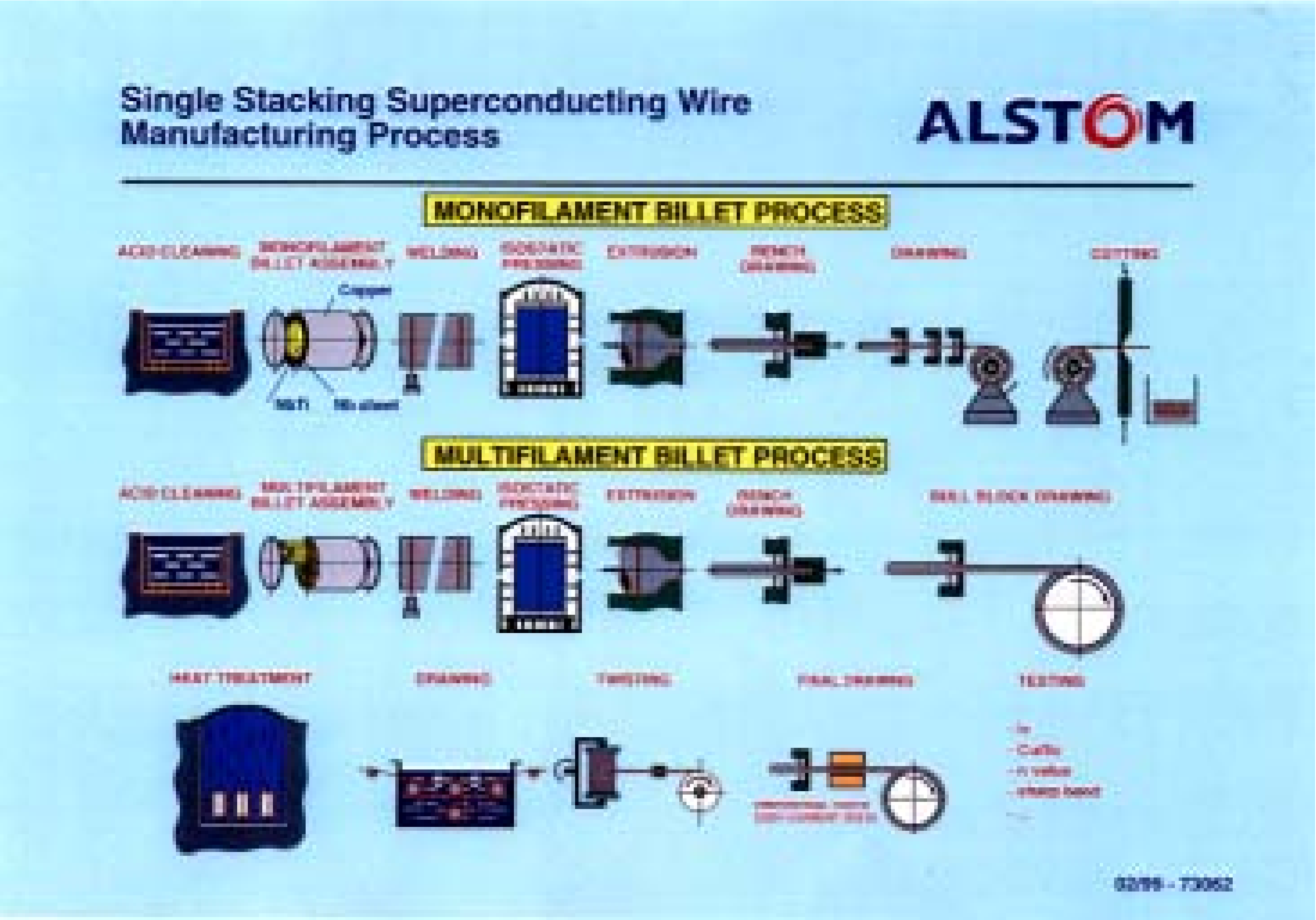
Twist

Anneal

Insulate

Test

Spool



Single Stacking Superconducting Wire Manufacturing Process

ALSTOM

02/99 - 73062

Courtesy of Claude Kohler (ALSTOM, Belfort)

Fabrication Processes of Nb_3Sn Wire

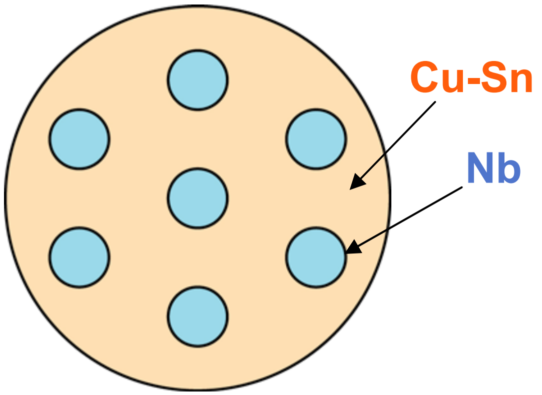
Five processes

- **Bronze**
- **External diffusion**
- **Internal Sn**
- **Nb Tube & Sn Tube**
- **Jelly Roll & Modified Jelly Roll**

Bronze

- Diffusion: Sn into Nb
  - Parameters: 700˚C, 1-10 days (max. diff. 5-10 μm).
  - Cu: prevents Nb_6Sn_5 from forming; a catalyst
  - Temperature: good stoichiometry vs. small grains
  - Bronze: 16wt.%Sn max. >13% makes drawing difficult
  - Maximum Nb_3Sn:~25wt.%
  - Addition of Cu: ~10^3 better electrically/thermally than bronze

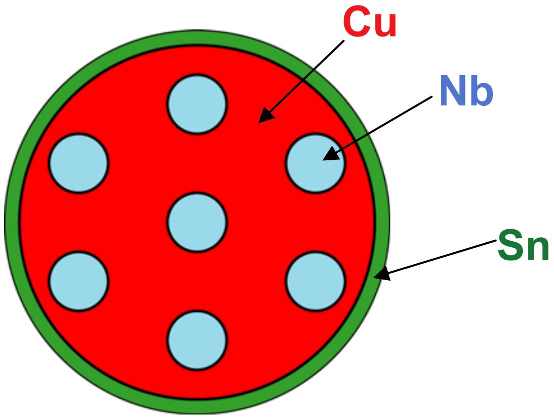
    Con: Sn diffuses more easily into Cu than Nb
  - Diffusion barrier, e.g., Ta, to maintain Cu purity



External Diffusion

- **Pros: 1) Draw first, then plate with Sn (bronze is hard to draw);**
  No intermediate annealing necessary
  2) >13 wt.%Sn possible, yielding higher J_c

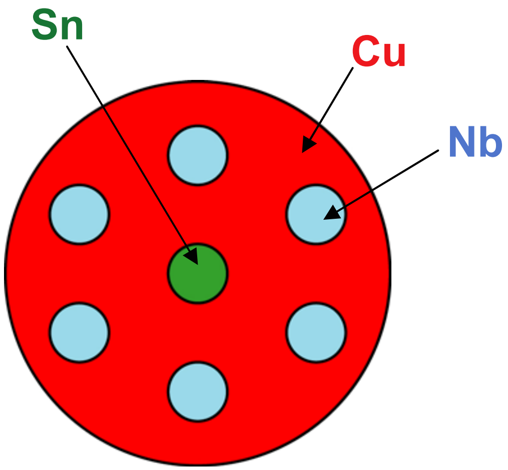
- **Cons: 1) Thick layer of (>~5 μm) of Sn tend to delaminate;**
  2) Sn melts at 230˚C, while reaction temp ~700˚C
  3) Hard to use with Ta and pure Cu



Internal Sn

- **Pros: 1) Nb intermediate anneal for bronze**
  2) Cu and Ta can easily be added
  3) As with external diffusion, higher J_c

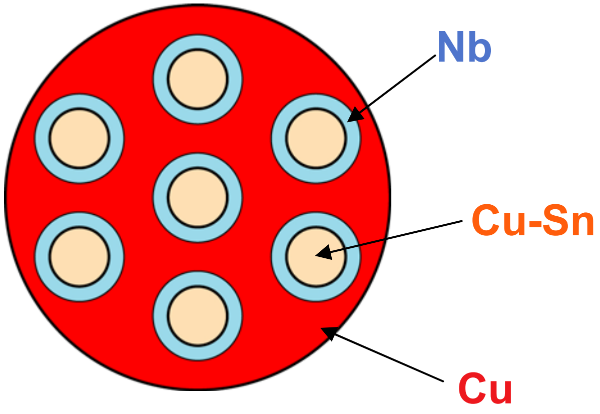
- **Cons: 1) Sn concentration limited**
  2) Extrusion of billet problems



Nb Tube

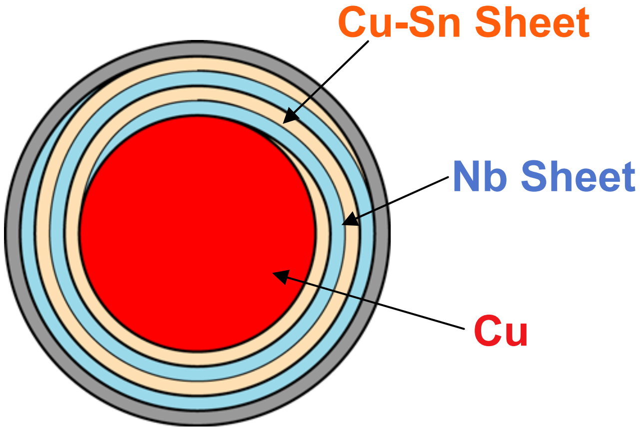
- **Pros: 1) Nb_3Sn close to Cu stabilizer**
  2) Nb acts as a diffusion barrier for Sn (Ta unnecessary)

- **Cons: 1) Limit to minimum filament size (AC losses)**
  2) Because of Nb tubes, process costly



Jelly Roll and MJR

- Pros: 1) No intermediate anneal
  2) Cu and Ta easily wrapped in roll
  3) Other trace materials can easily be added to core to improve properties



Other A15 Materials

V_3Ga

- **Inferior to Nb_3Sn in T_c and H_{c2}, but better J_c**
- **Can be processed similar to bronze process**

Cons: 1) Reaction at 500˚C for 500 h
2) More brittle than Nb_3Sn

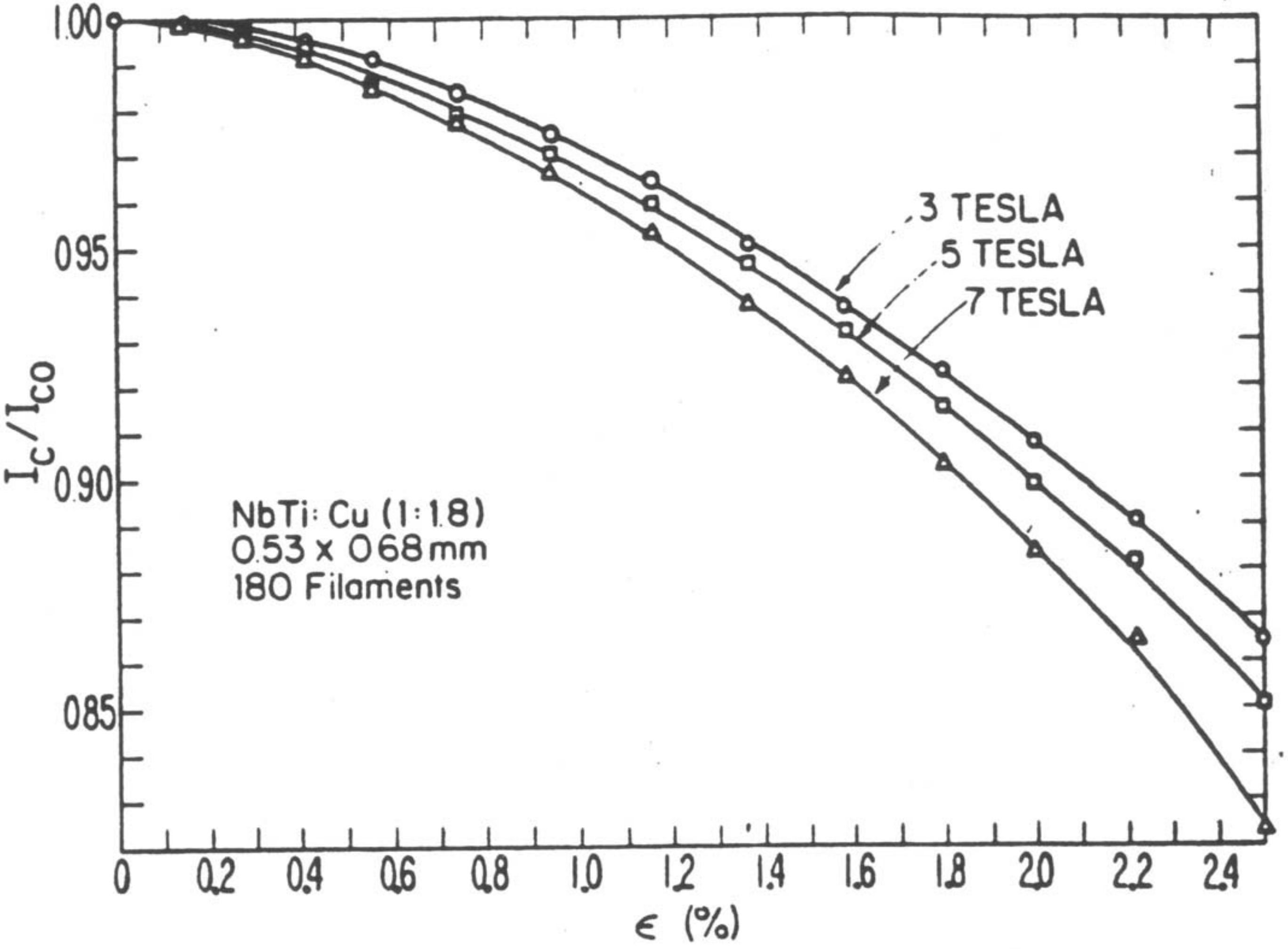
Nb_3Al

- **Fabrication difficulties; no bronze process equivalent exists**
- **Bulk Nb_3Al requires HT at >1500˚C, leading to large grain boundaries and other unwanted Al-rich compounds**
- **MJR proven quite successful in making multifilamentary composite**

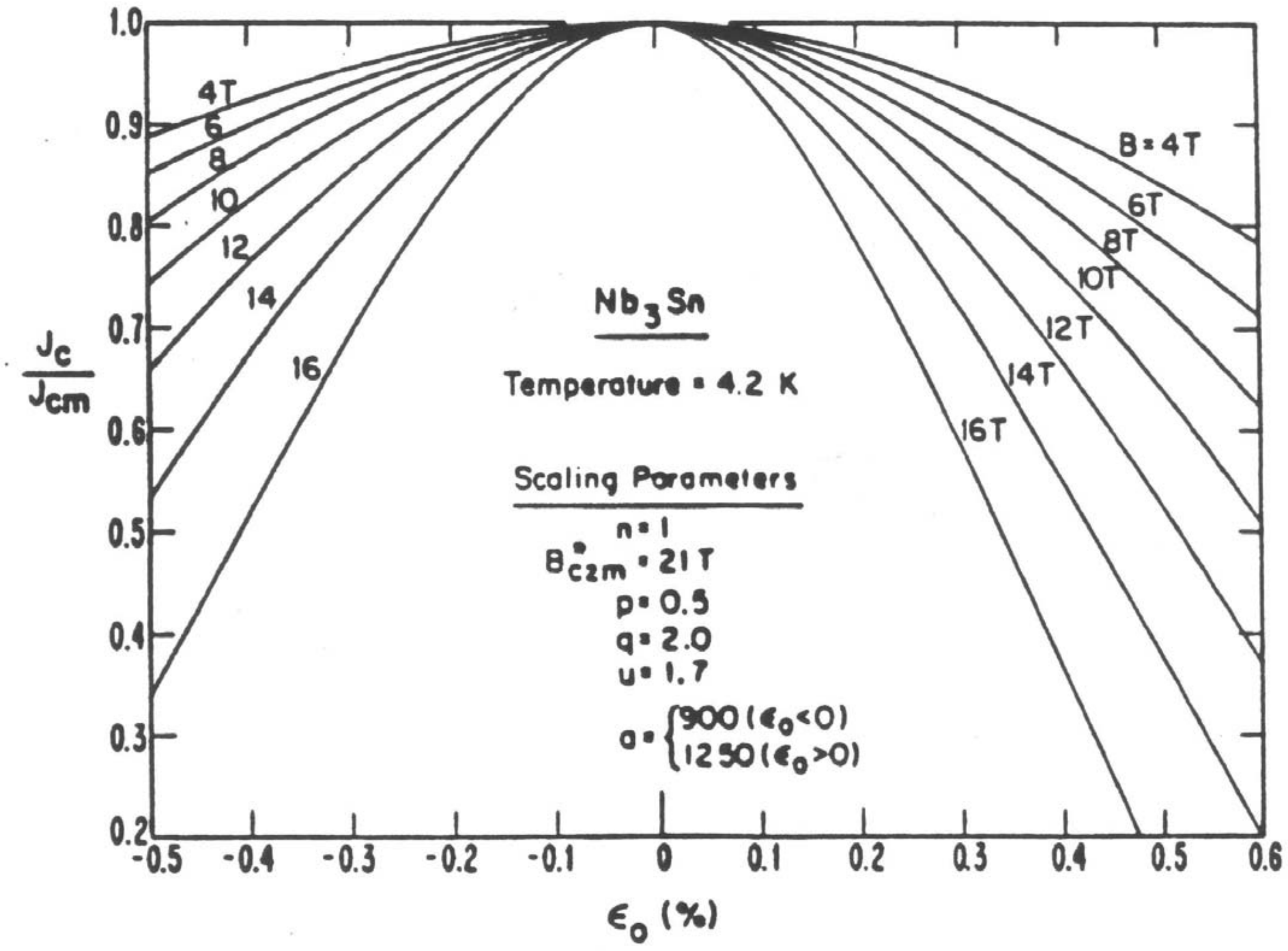
6. Strain: Source and Effects

- **Fabrication temperature to operating temperature: strain from mismatch in thermal expansion (contraction) coefficients**
- **Winding magnet: winding radius limitation**
  - **winding strain = wire dia./winding i.d.**
- **Lorentz forces**
- **Strain generally degrades J_c**
  - **Treat Nb_3Sn as you would glass**
  - **Nb_3Sn damaged for strains beyond ~0.7%**

Strain Effect on J_c: Nb-Ti



Strain Effect on J_c: Nb_3Sn



Magnet Winding Constituents

Magnet winding *generally* comprises of:

- **Superconductor—Nb-Ti, Nb3Sn, or BSCCO2223**
- **Electrically conductive normal metal for stability and protection—Cu, Al, or Ag**
- **High-strength metal for mechanical integrity—high-strength metal, or work-hardened Cu also used as stabilizer.**
- **Coolant**

Designer's Goal

Maximize overall (or engineering) current density, J_{over} (or J_e), and still satisfying requirements of:

- **Stability; protection; mechanical integrity; and *cost* — *for commercially viable units***

Types of Magnet

Basically there are two types of magnet:

I. High-performance (“Adiabatic”)
II. Cryostable

I. High-performance

- **J_{over} enhanced by:**
  - **Combining superconductor and high-strength normal metal (stability; protection; mechanical).**
  - **Eliminating *local* coolant* and impregnating the entire winding space unoccupied by conductor with epoxy, making the entire winding as one monolithic structural entity. (Presence of cooling in the winding makes the winding mechanically weak and takes up the conductor space.)**
- **High-performance approach universally used for NMR, MRI, HEP dipoles & quadrupoles in which $R \times J \times B$ manageable with a combination of "composite conductor" & "monolithic entity."**

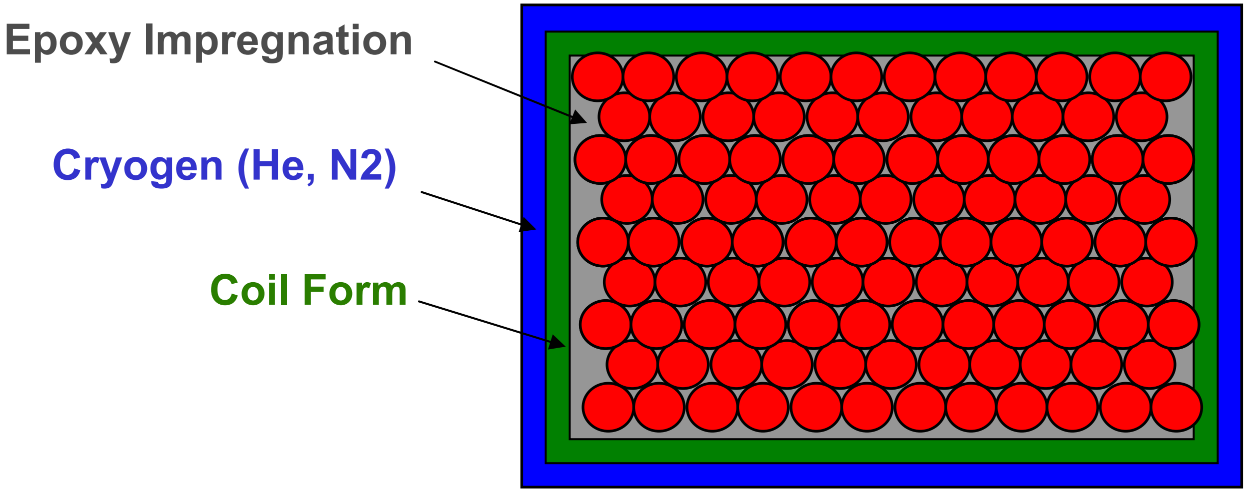
*** The conductor *always* requires cooling but not necessarily exposed directly to the coolant.**

“Adiabatic” Windings

1. Bath Cooled

- **Winding immersed in a bath of cryogen**
- **Work-hardened stabilizer or reinforcement added**

Examples: NMR; MRI

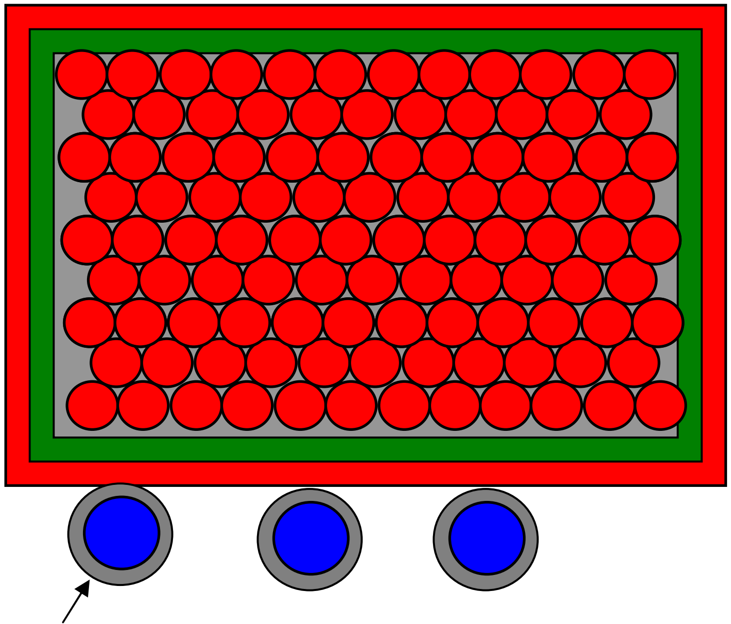


“Adiabatic” Windings (Continued)

2. Forced-Flow Cryogen

- **Winding “globally” cooled by forced-flow single-phase cryogen**
- **Work-hardened stabilizer or reinforcement added**

Examples: HEP diploes & quadrupoles



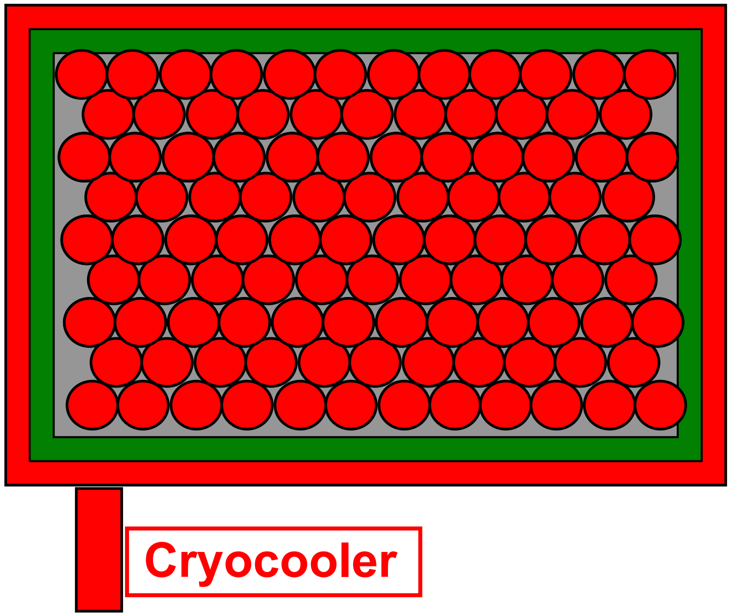
Cryogen forced through pipe

“Adiabatic” Windings (Continued)

3. Cryocooler-cooled

- ❋ Winding conduction cooled by a cryocooler
- ❋ Work-hardened stabilizer or reinforcement added

Examples: “Dry” research-purpose magnets (up to 15 T)



II. Cryostable

- **❈ Characterized by the presence of local or "near-local" cooling.**
  - **❈ Nearly universally adapted winding configuration for those magnets that must "guarantee" performance. These include "large" research-purpose high-field magnets, e.g., MIT Hybrid III, and those that are key components of the experimental devices, e.g., fusion.**

There are two types of cryostable magnets:

1. **Magnets with "small" $R \times J \times B$ (and o.d. typically <1 m), "composite conductor," i.e. combination of superconductor and *work-hardened* normal metal (stability; protection; mechanical), sufficient to meet mechanical requirements despite the presence of coolant space.**

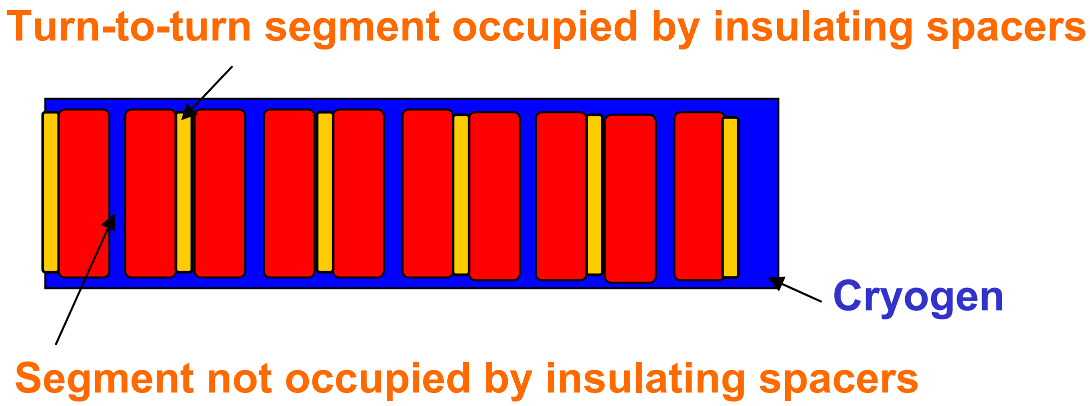
2. **Magnets with "large" $R \times J \times B$ (and o.d. typically >1 m), e.g., Fusion magnets, "composite conductor," no longer sufficient to meet mechanical requirements; CICC (cable-in-conduit conductor) or reinforced composite/forced cooling.**

Cryostable Winding

1. Cryogen Well-Ventilated within Winding

- **Work-hardened stabilizer**

Examples: Many "large" magnets of the 1960s-1990s, including MIT 35-T Hybrid; LHD TF coil

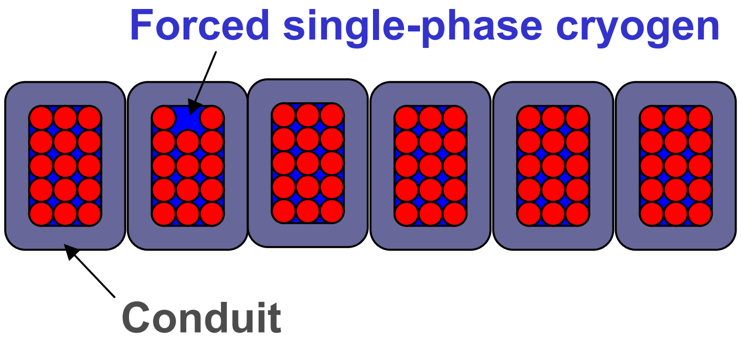


Cryostable Winding (Continued)

2. CICC (Cable-in-Conduit Conductor)

- **Single-phase cryogen forced through conduit that contains cabled Superconductor/stabilizer composite**
- **Conduit (steel alloy) reinforces the conductor**

Examples: Most fusion magnets; NHMFL 45-T hybrid

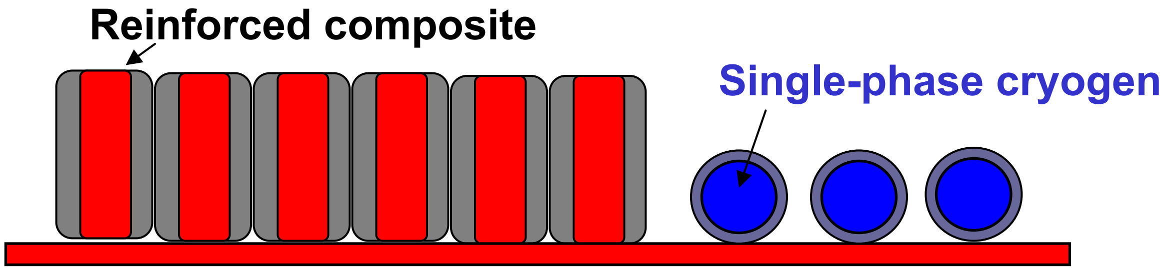


Cryostable Winding (Continued)

3. Reinforced Composite & Forced-Flow Single-Phase Cryogen

- **Single-phase cryogen forced through a set of pipes placed near the winding comprises of reinforced composite**

Example: CMS magnet of the LHC



CICC

Cabled strands of superconductor encased in a conduit, which provides mechanical strength and through which single-phase cryogen (generally helium) is forced to provide cooling to the superconductor

Advantage

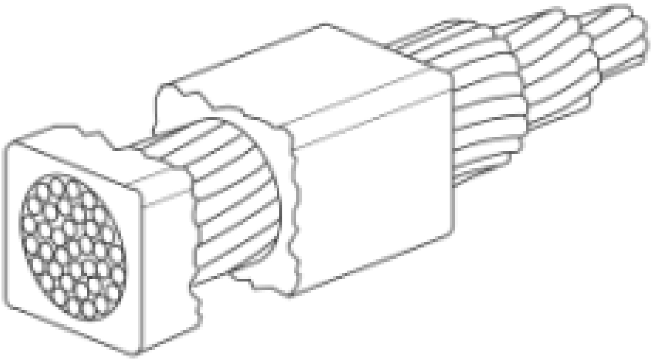
- **Integrates key requirements of a superconductor—current-carrying capacity; stability & protection; AC losses; mechanical integrity—in a single conductor configuration.**

Disadvantage

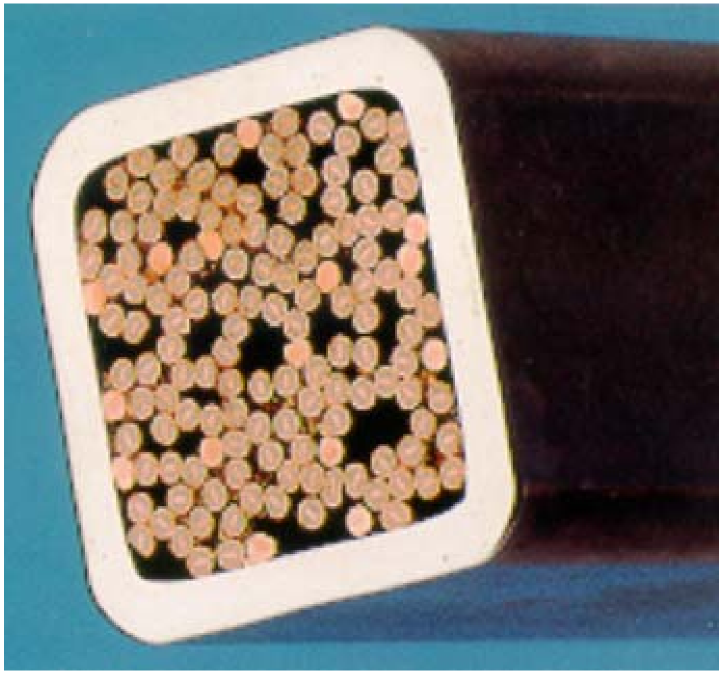
- **Because of the non-current carrying space occupied by the conduit and cryogen, I_{op} should be "large" to keep J_{over} "reasonable." Generally, I_{op} >10 kA; occasionally I_{op}> a few kA.**

Suitable Applications

- **"High" field and "large" volume magnets, i.e., fusion; SMES.**

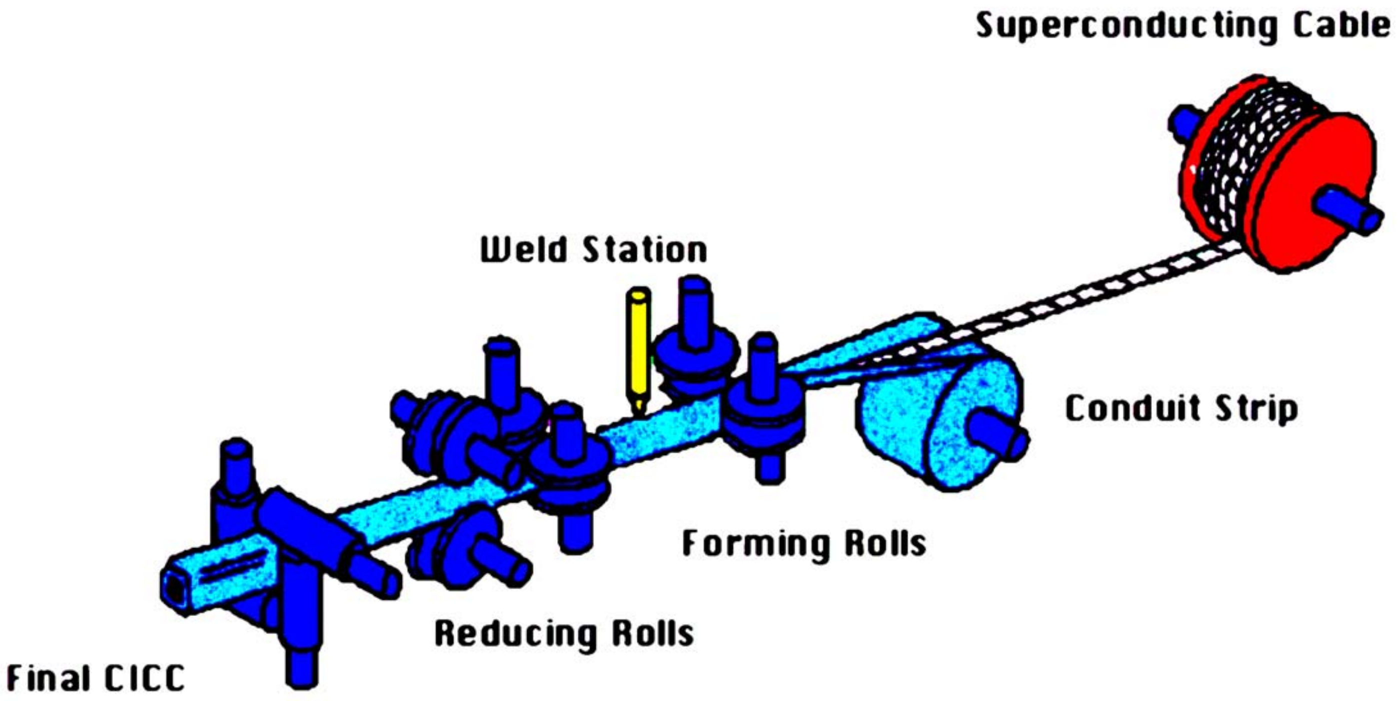


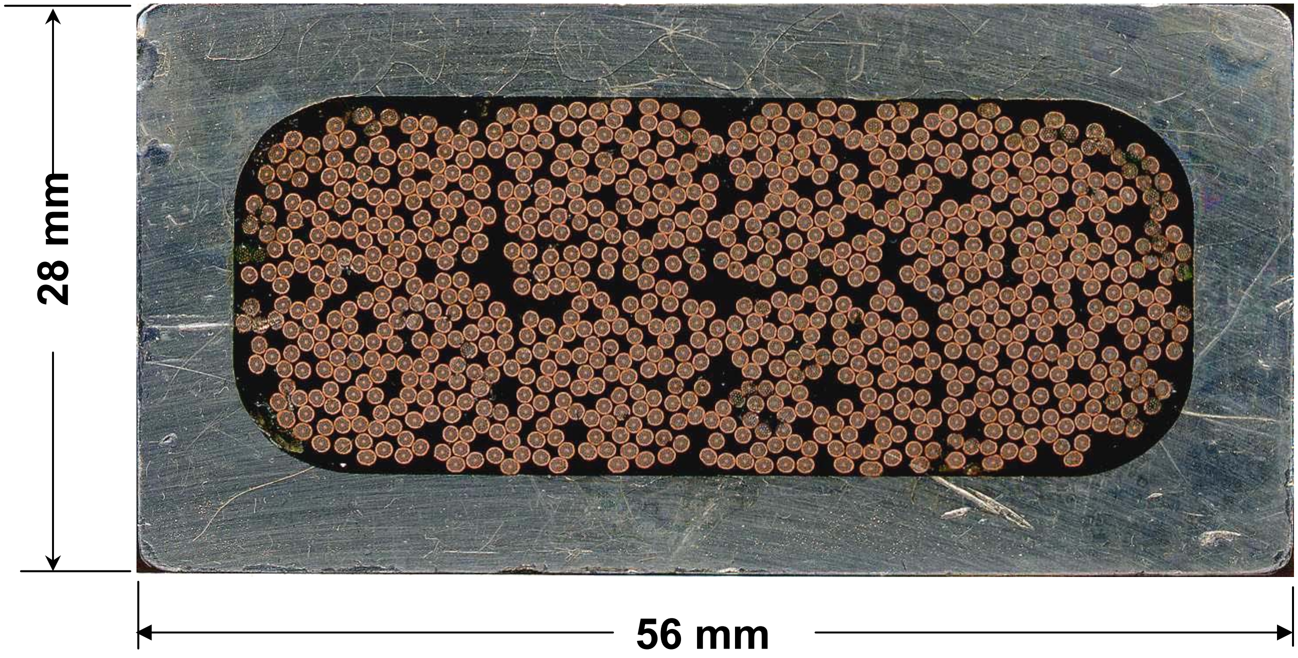
Transposed 37-Strand Cable (c. 1970)



Courtesy of Luca Bottura (CERN, Geneva)

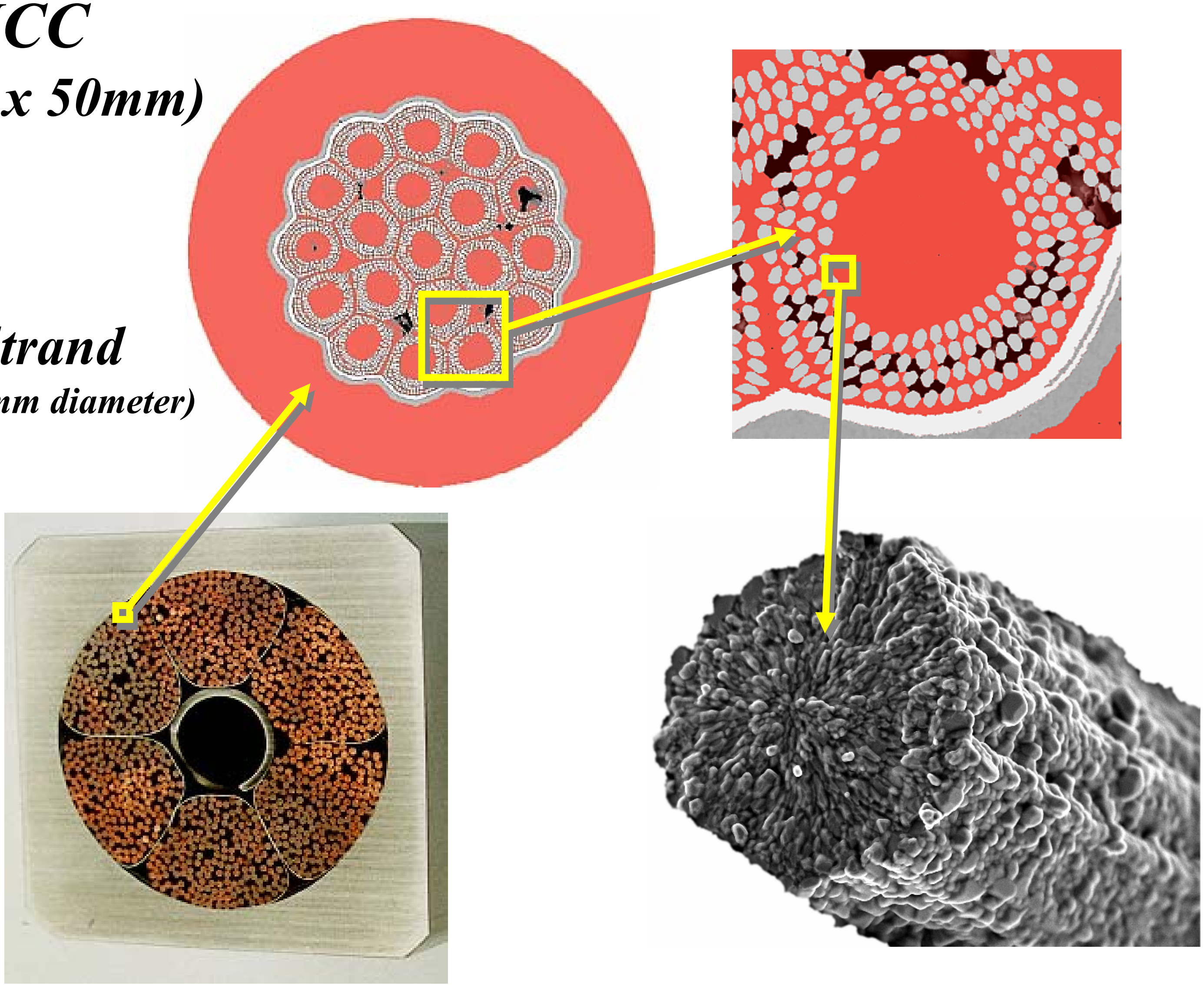
Tube-Mill Fabrication of CICC




28 mm
56 mm

ITER CICC

CICC
(50 mm x 50mm)



Strand

(0.81 mm diameter)

EURATOM Large Coil Test (LCT) Conductor (c. 1980s)

Rutherford Cable soldered to insulated SS core

Conductor force-cooled by Supercritical He

MF Nb-Ti/Cu composites

SS Jacket seam-welded