Superconductivity at Future Hadron Colliders

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Outline

1. Superconductivity and Energy: general applications
2. Accelerators: history
3. Requirements for Superconducting Wires and Cables
4. Superconductors and magnets: fundamentals and applications
5. Superconductors in the LHC Accelerator
6. Superconducting wires and cables: fabrication
7. Conclusions

5. Superconductors in accelerators

a. NbTi

b.Nb_3Sn

c. MgB_2

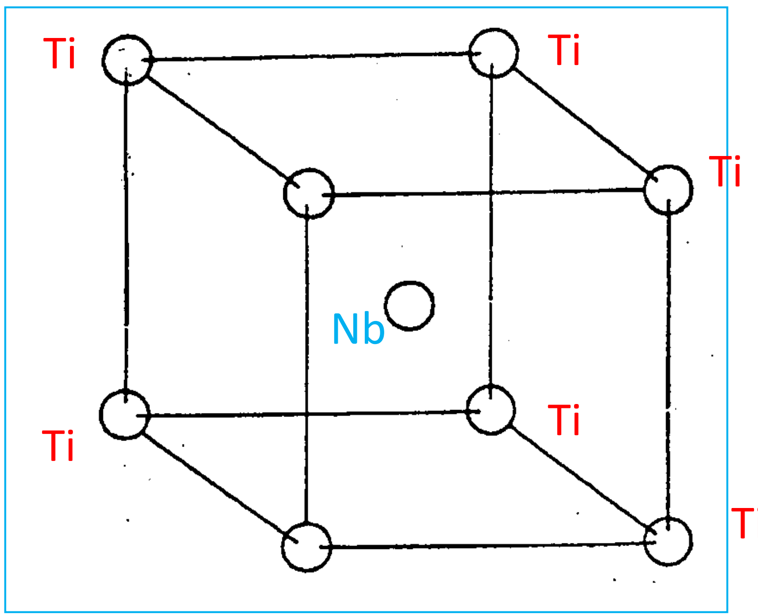
d. Bi-2223

e. YBaCuO

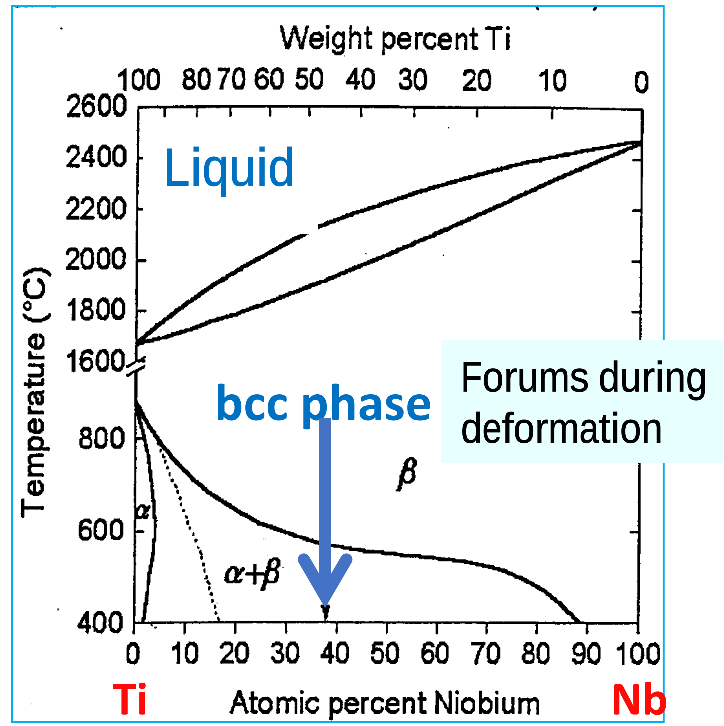
a. The system NbTi

T_c = 10 K
B_{c2} = 14 T

Body cubic cented structure



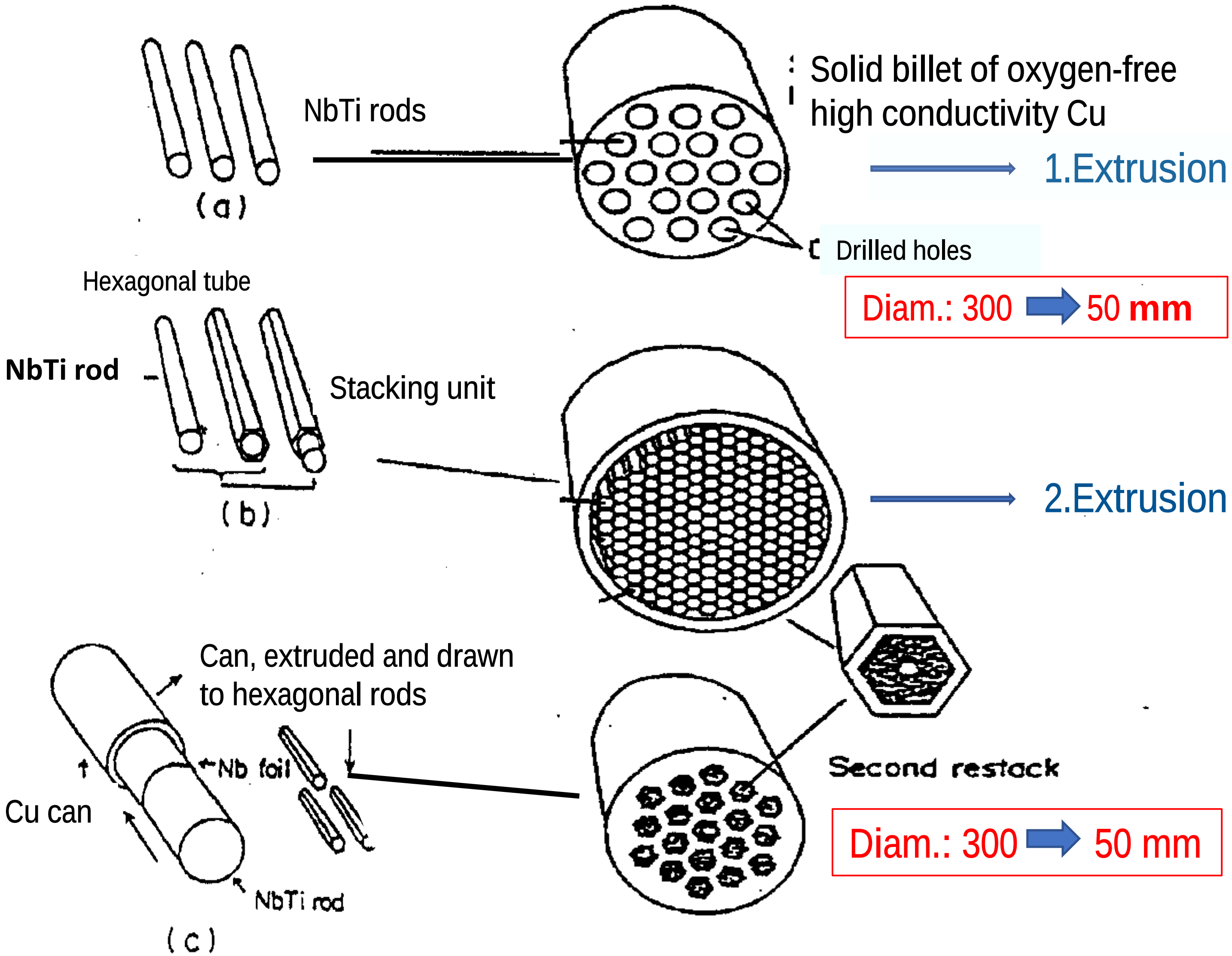
Phase diagram



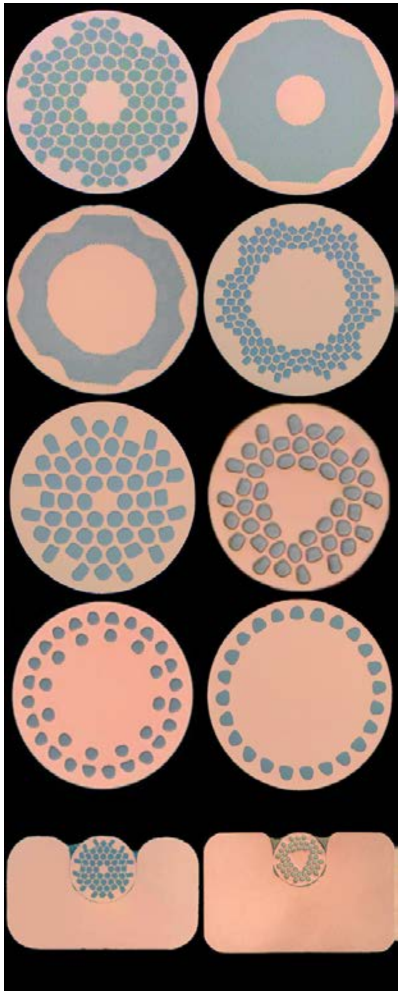
Nb-Ti phase diagram. The low temperature boundaries are based on calculations by Kaufman et al. The dashed line represents the martensitic transformation inferred by Moffatt and Larbalestier.

The fabrication of NbTi wires

A sequence of extrusions



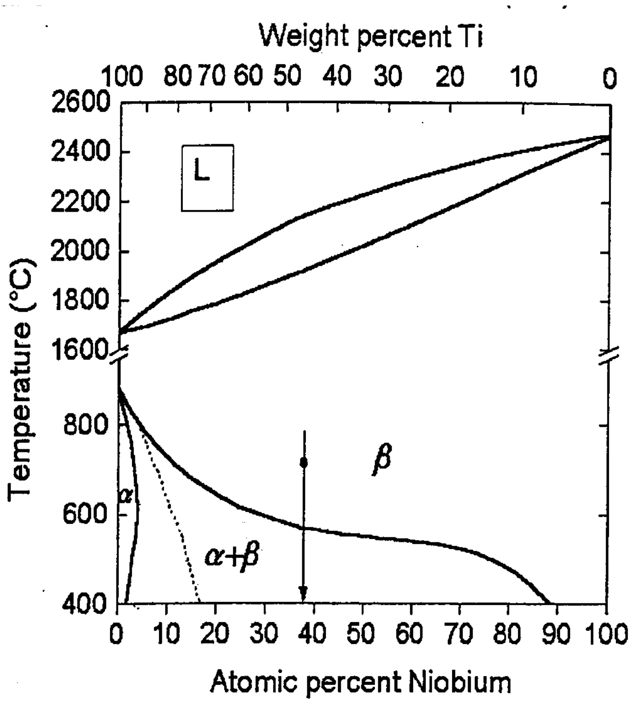
Configurations



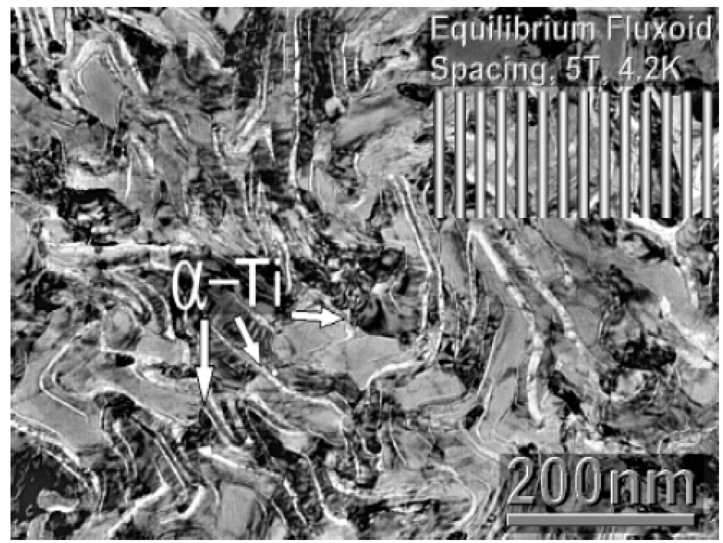
Naturally formed nanosize α-Ti during deformation

At the interface between the α – Ti precipitations and the NbTi matrix are formed during the thermomechanical treatment:

* creation of defects
* creation of normal conducting centers: new vortices → Enhancement of J_c



« Natural » additional pinning by α –Ti precipitates



D. Larbalestier and P. Lee, 1995

NbTi wires today

Today: ~ 90 % of all industrial wires are based on NbTi
Future: Increase of other s.c.: Nb_3Sn, MgB_2, HTS

No further work for enhancing J_c in industrial NbTi wires is performed today: NbTi development is close to its optimum state

NbTi applications:

* NMR magnets up to 9T,
* for a background field **in high field magnets (≥ 9T)**
  * for accelerator magnets (dipoles in LHC)

* Levitation trains in Japan
  Already tested trains
  Tokyo-Osaka (2035-2040); later replaced by other s.c. ?

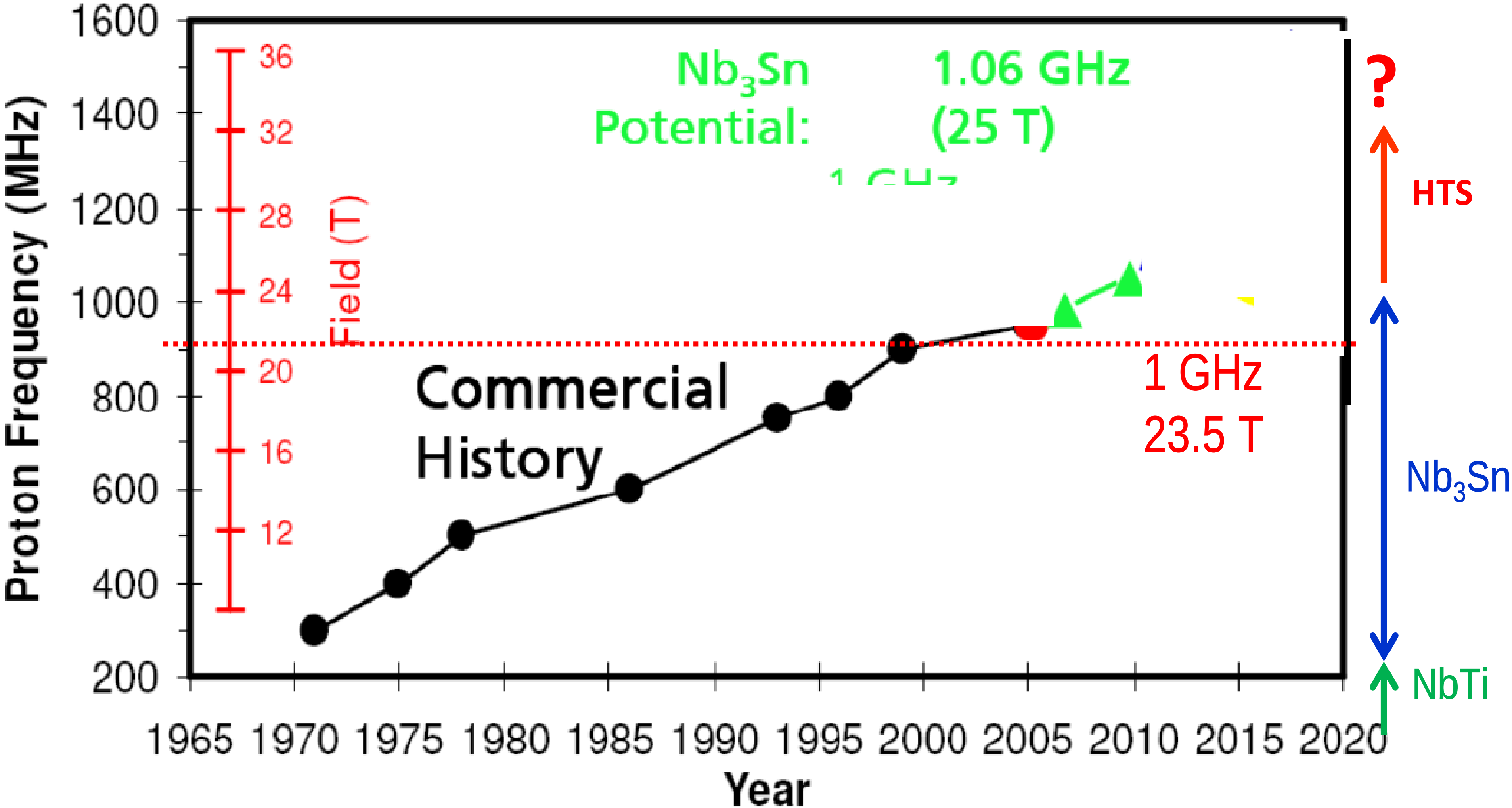
b. The system Nb_3Sn

LHC-Upgrade: Dipoles: NbTi
Quadrupoles: Nb_3Sn

High Field Magnets: Applications involving NbTi and Nb_3Sn

Solenoids	Produced Field	Superconductor
MRI	≤ 9 T at 4.2K	NbTi
	≤ 10.5T at 1.8K	NbTi
	≤ 24 T	NbTi + Nb_3Sn
	≥24T – ≥32T	Nb_3Sn + HTS
ITER tokamaks	12T	Nb_3Sn
DEMO	~12 T	Nb_3Sn
LHC Upgrade		
Quadrupoles	≤ 12.5T	Nb_3Sn
Dipoles	≤ 8T	NbTi
FCC	16T	Nb_3Sn, HTS?

Magnetic field in a superconducting coil



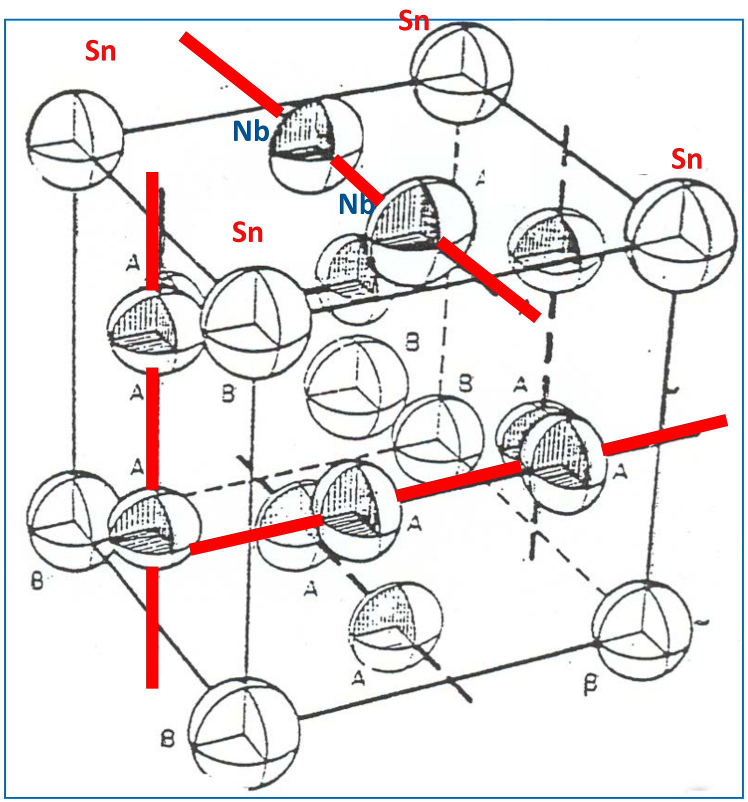
Physical Properties of Nb_3Sn

A. Properties of bulk Nb_3Sn

T_c , T_c vs. Sn content
T_c distribution
Residual electrical resistivity r_o (just above T_c)
B_{c2}

The superconducting compound Nb_3Sn

Cubic A15 type structure A_3B



Orthogonal Nb-Nb chains

The system Nb_3Sn

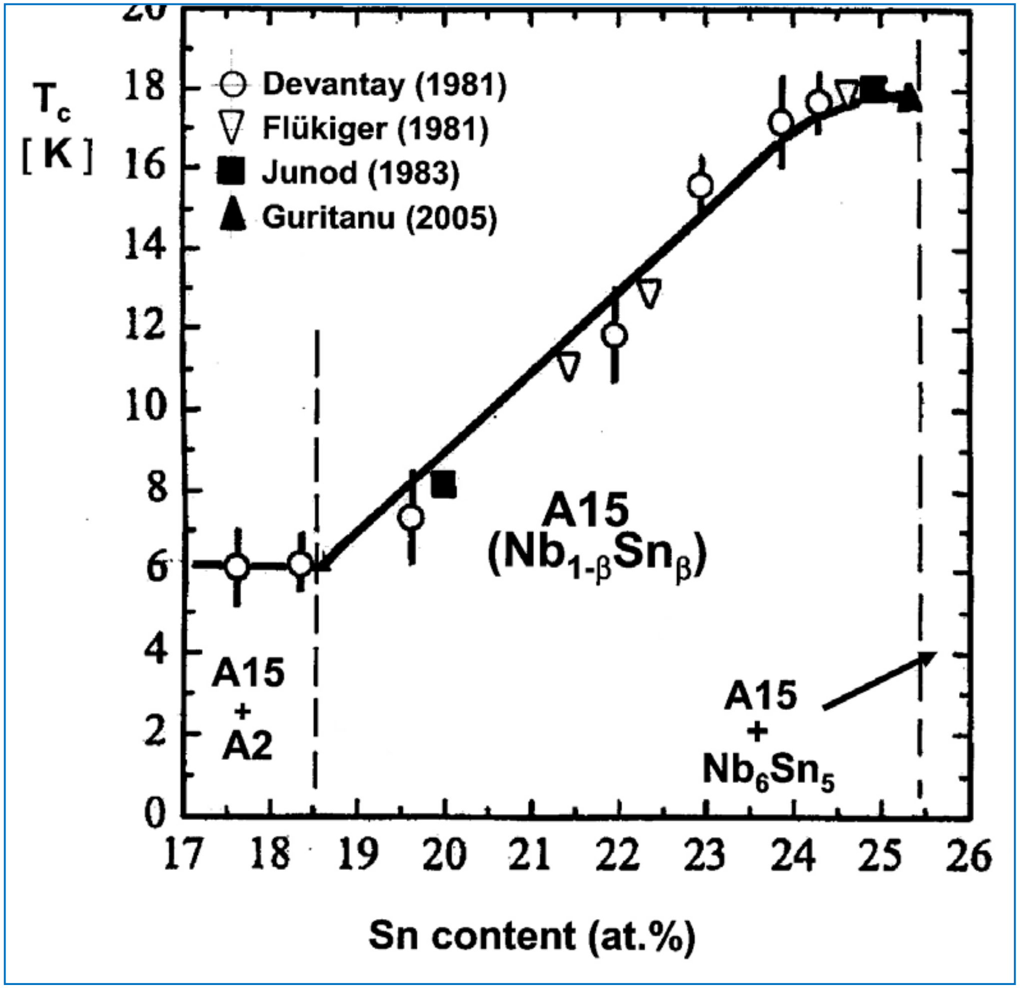
Very brittle phase ; $T_c = 18$ K, $B_{c2} = 22$T (clean limit : $l >> \xi_0$)
$B_{c2} = 30$ T (dirty limit : $l \approx \xi_0$)

Perfectly ordered phase : all cubic sites occupied by Sn
all chain sites occupied by Nb

→ very low normal state electrical resistivity $\rho(T>T_c)$, or ρ_0

at 25 at.%Sn: $\rho_0 \sim 5\ \mu\Omega$cm

T_c vs. Sn content in the A15 phase of Nb_3Sn



Linearity up to 24.5 at.% Sn

Saturation at > 24.5 at.%:
(due to phonon softening)

1'000°C: homogeneity range between 18 and 25 at.% Sn

Electrical resistivity of Nb_3Sn and V_3Si

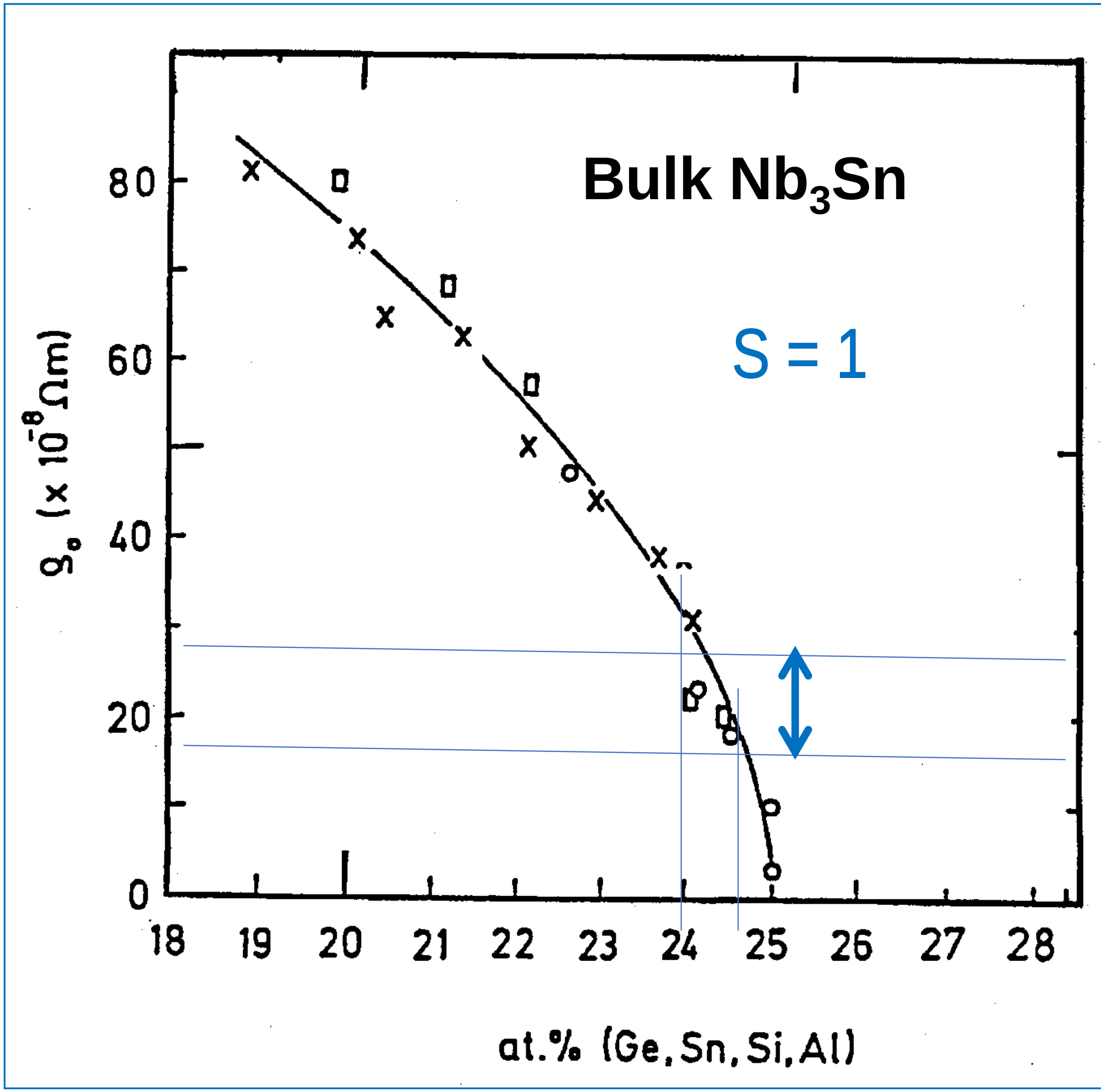
Strongest variation of ρ_o: close to stoichiometry:

-0.5 at.% Sn at 24.5at.%Sn:

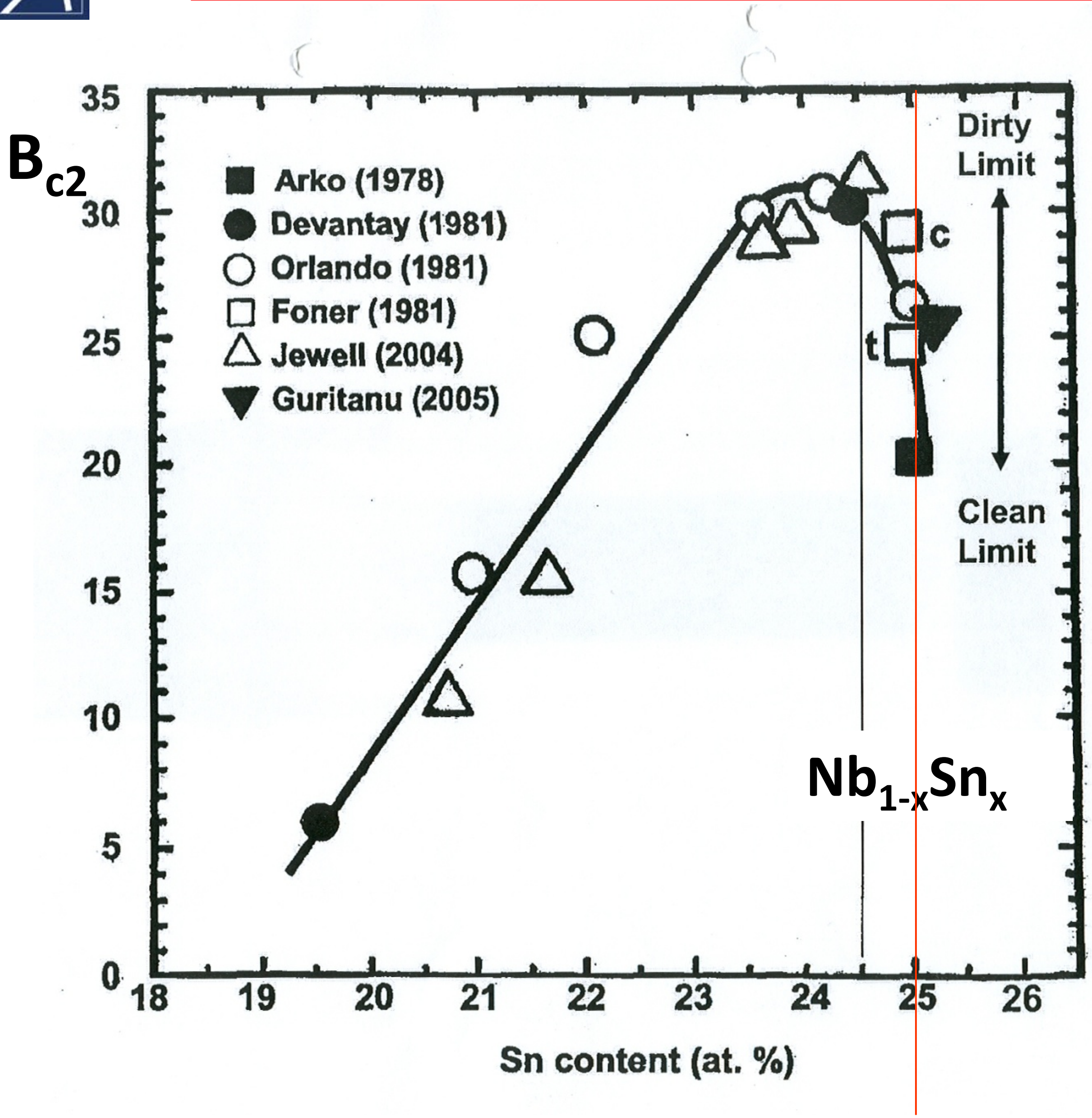
ρ_o increases by 50% !

Composition gradient close to stoichiometry (24.5 at%Sn)
Influences optimization of J_c
(specific heat measurements: later)

R. Flükiger, et al.,



B_{c2} vs. Sn content in the A15 phase Nb_3Sn



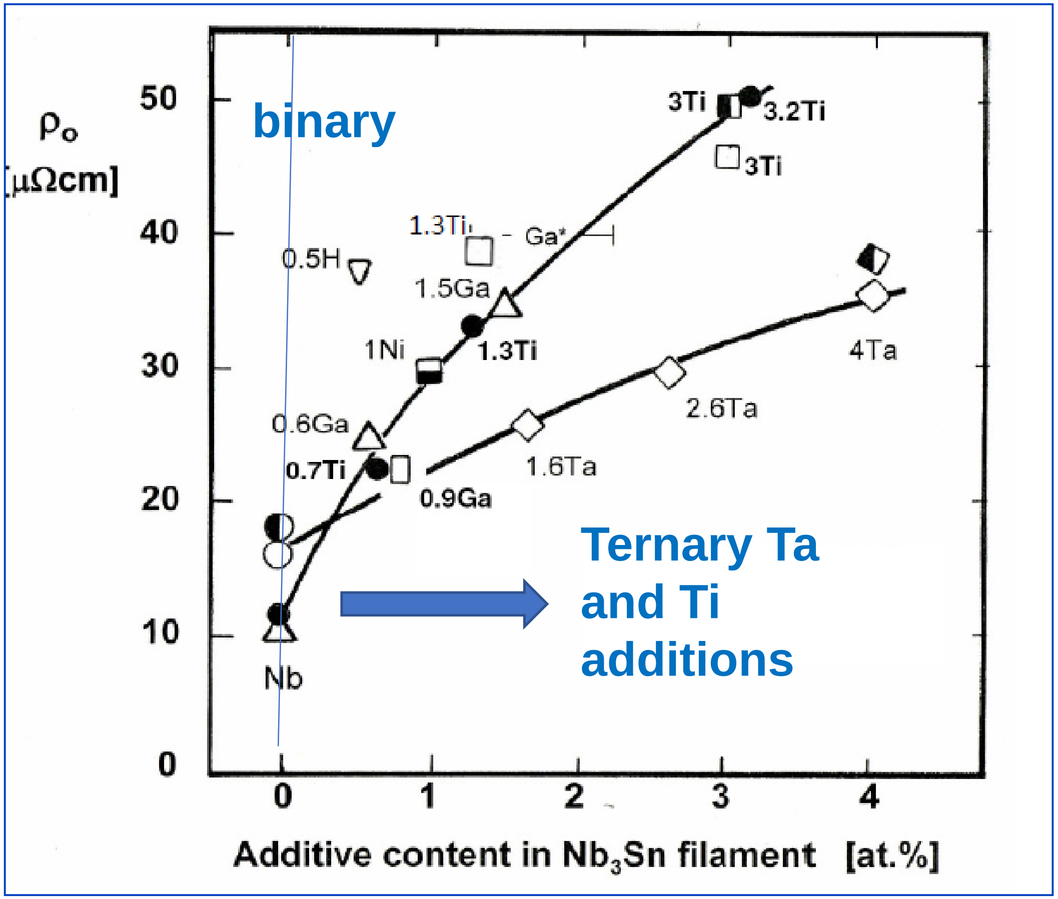
Strong reduction of the electronic mean free path at > 24.5%Sn.

The correlation

$$B_{c2} \sim T_c\ \gamma\ \rho_o$$

explains the sharp reduction of B_{c2} in this composition rage.

Enhancement of J_c at high fields by Ta and Ti additives



Effect of Ta and Ti additives:

→ Enhancement of ρ_o

Since $B_{c2} \sim T_c\ \gamma\ \rho_o$,
and ΔT_c and $\Delta\rho_o$ small:

$\rho_o \nearrow \;\rightarrow\; B_{c2} \nearrow$

Wire Fabrication Techniques

Nb_3Sn fabrication techniques

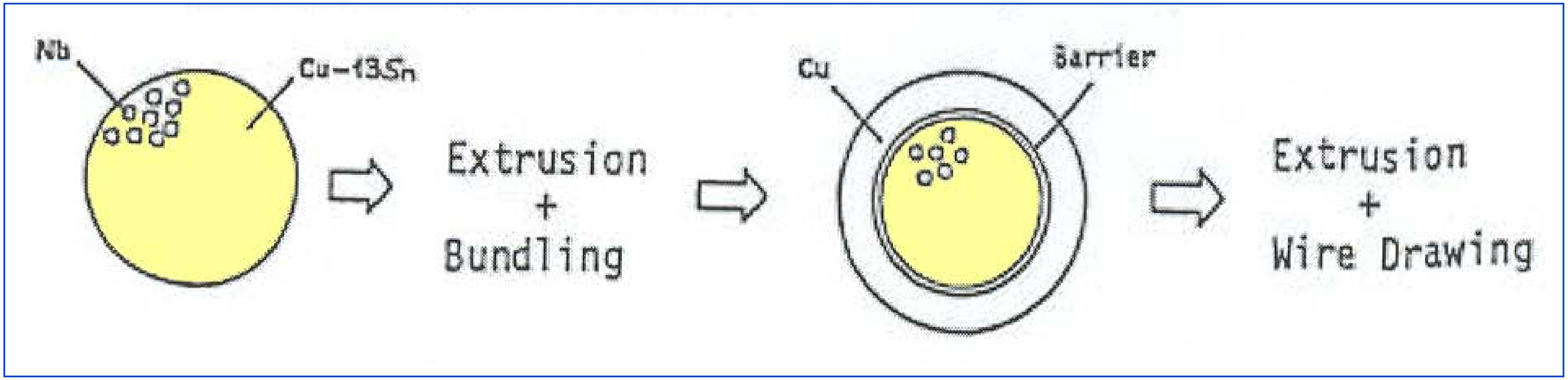
50 years after the discovery of Nb_3Sn, there is still a considerable potential for improvements of J_c !

3 main industrial fabrication techniques:

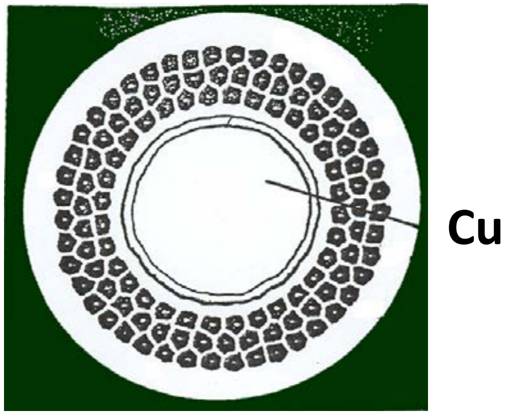
Bronze Route	**NMR magnets (≤23.5T)**
RRP (Internal Sn Diffusion)	**High field magnets**
PIT (Powder In Tube)	**Accelerator magnets**

The Nb_3Sn Bronze Route

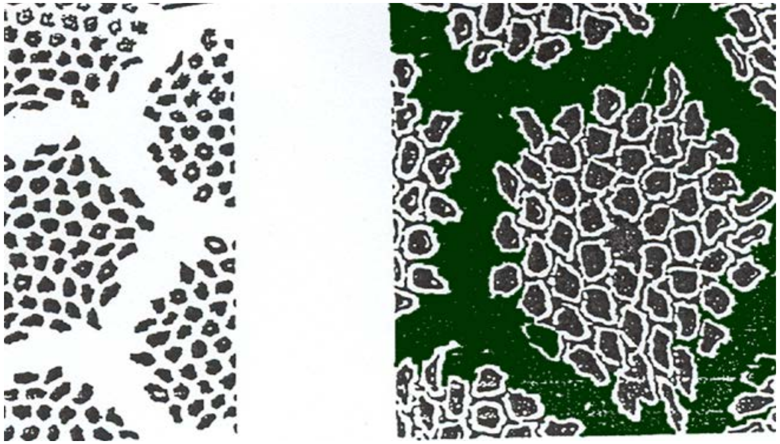
Work hardening of Cu-15 wt.%Sn bronze: Intermediate anneals are needed



Multifilamentary wire

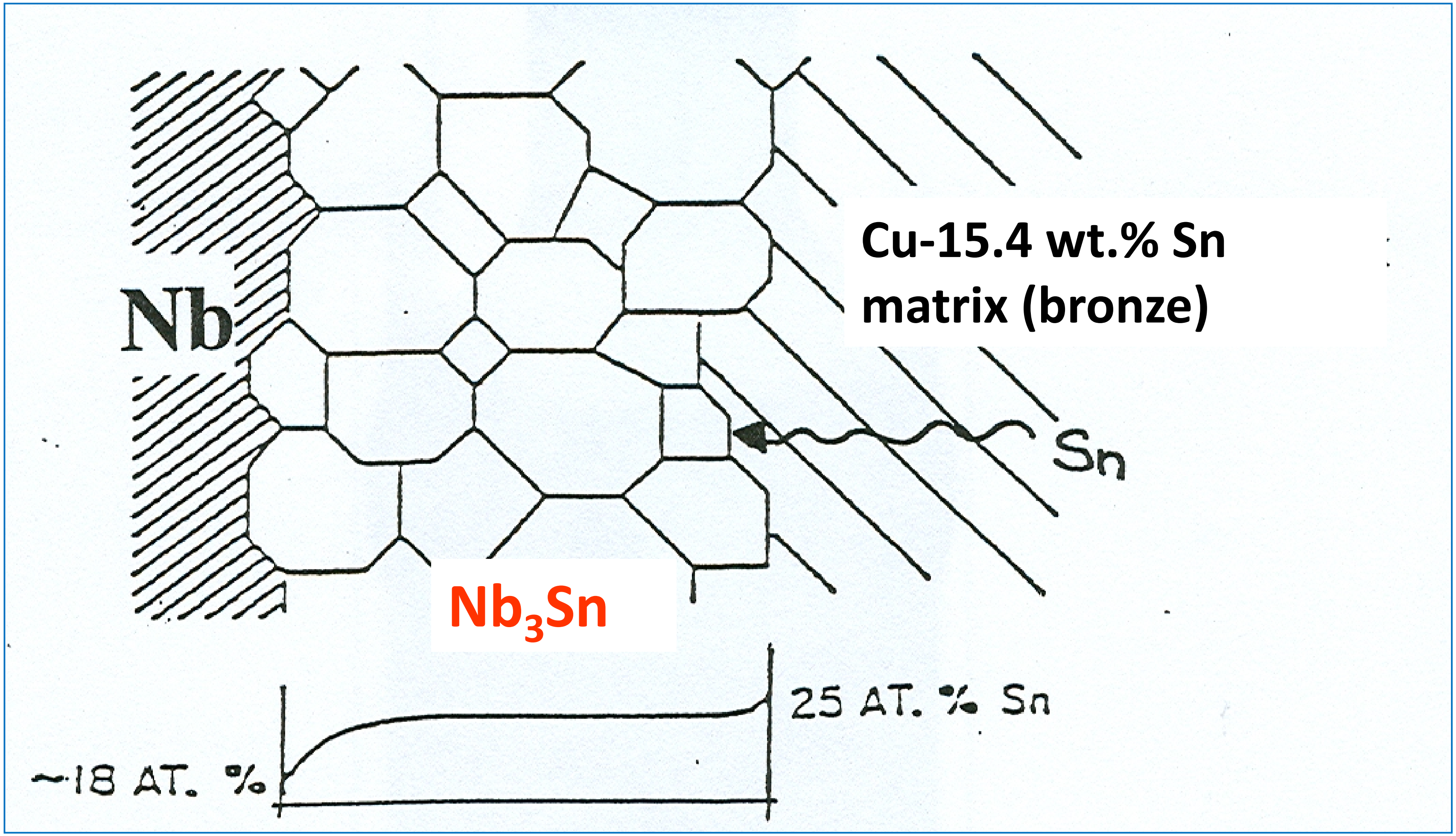


Filament bundles

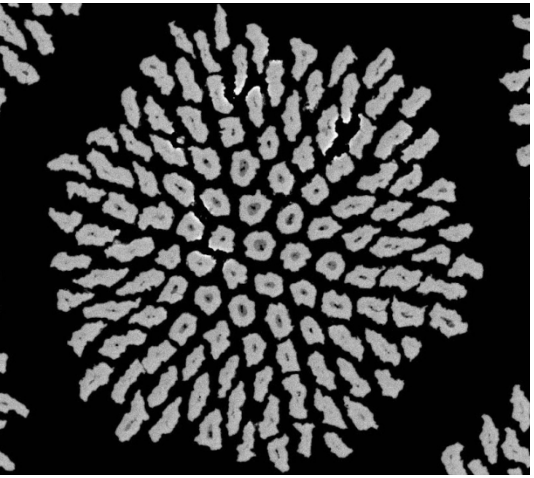


Up to 10'000 filaments

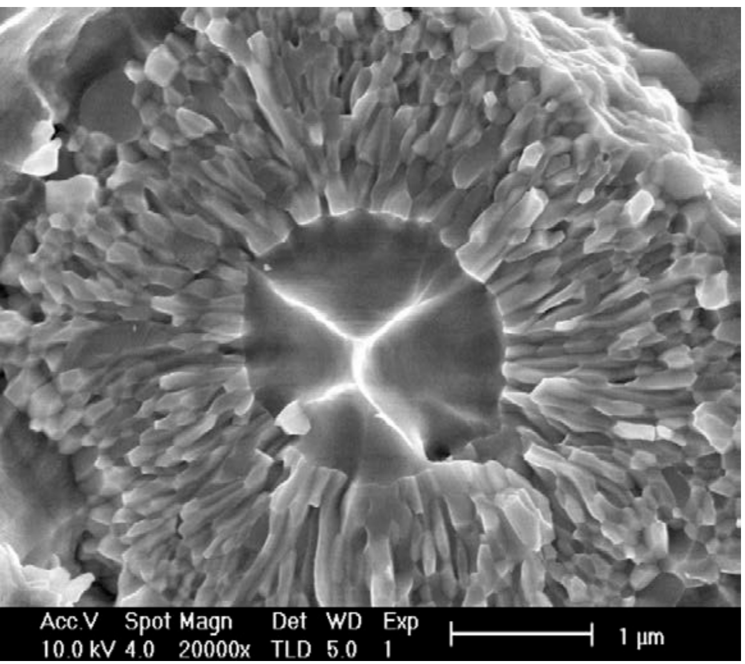
The Sn diffusion reaction

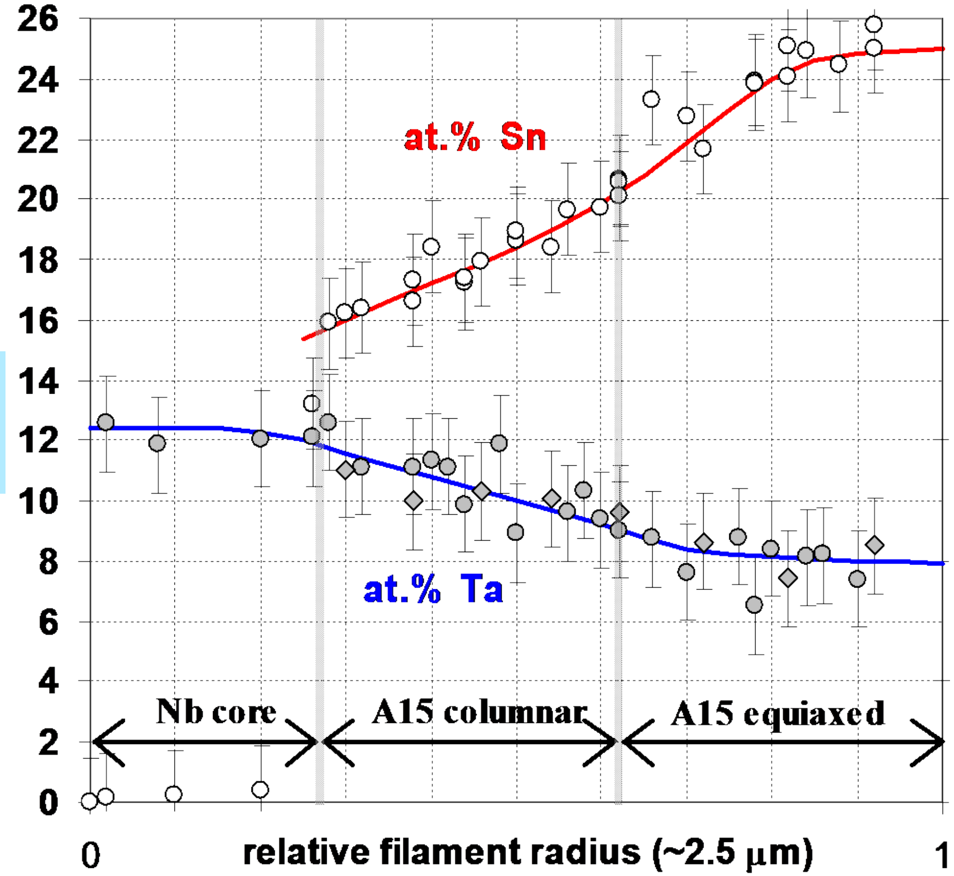


Filaments in Nb_3Sn Bronze Route wires



Filament diameter
4 - 5 µm



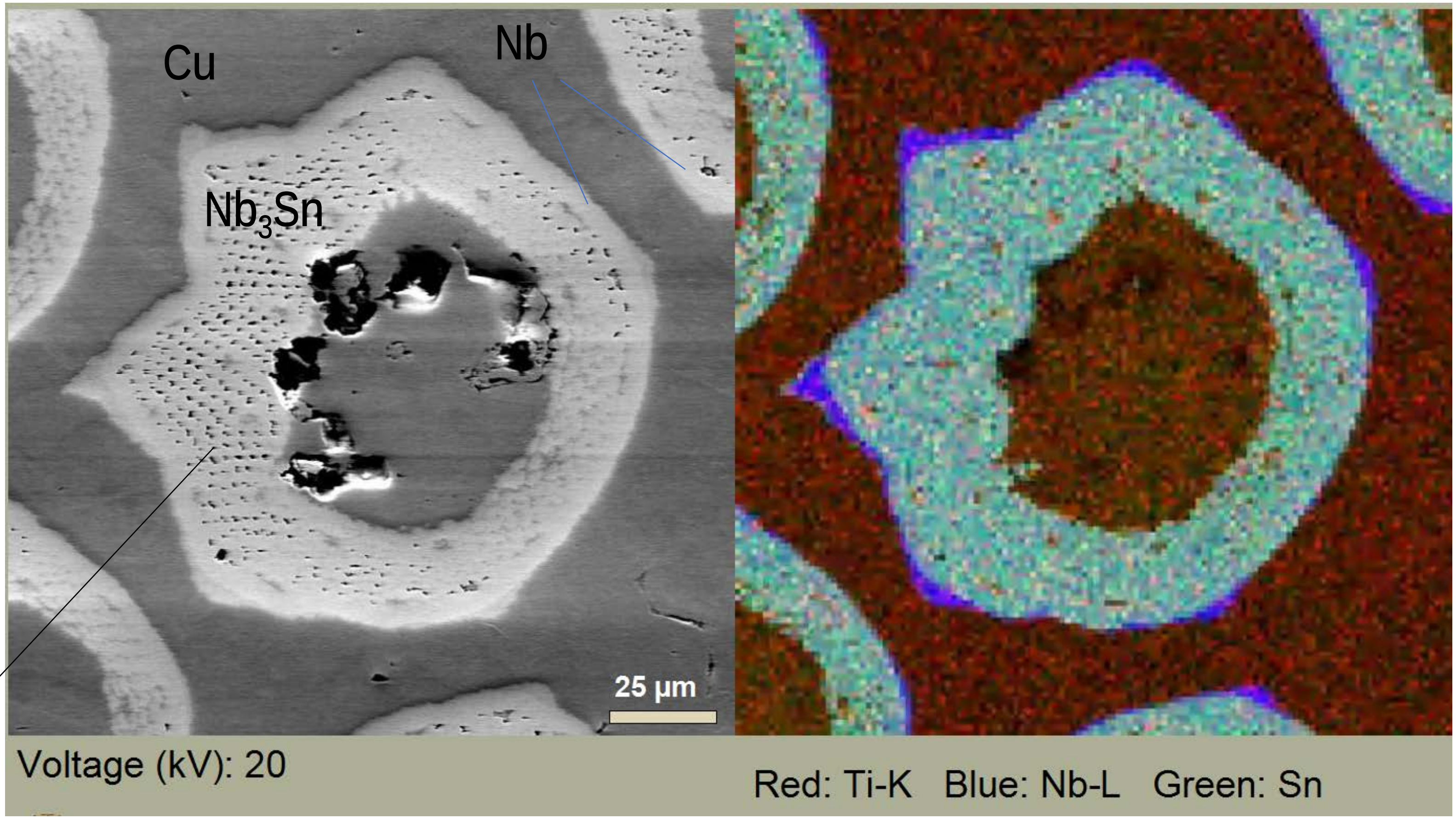


Limitation: only a small part of the filament carries supercurrent !

V. Abächerli et al., ASC 2004

NbTi addition in Internal Sn wires (OST)

Ti additives introduced by NbTi rods.



Ti (from NbTi)

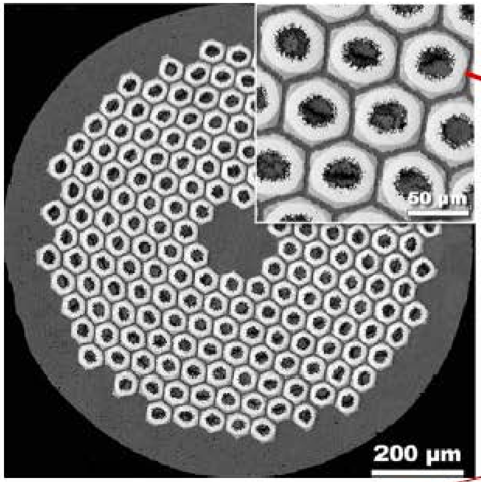
P. Lee, D. Larbalestier, J.A. Parrell, M.B. Field, Y. Zhang, S. Hong, ICMC 05, Keystone, USA

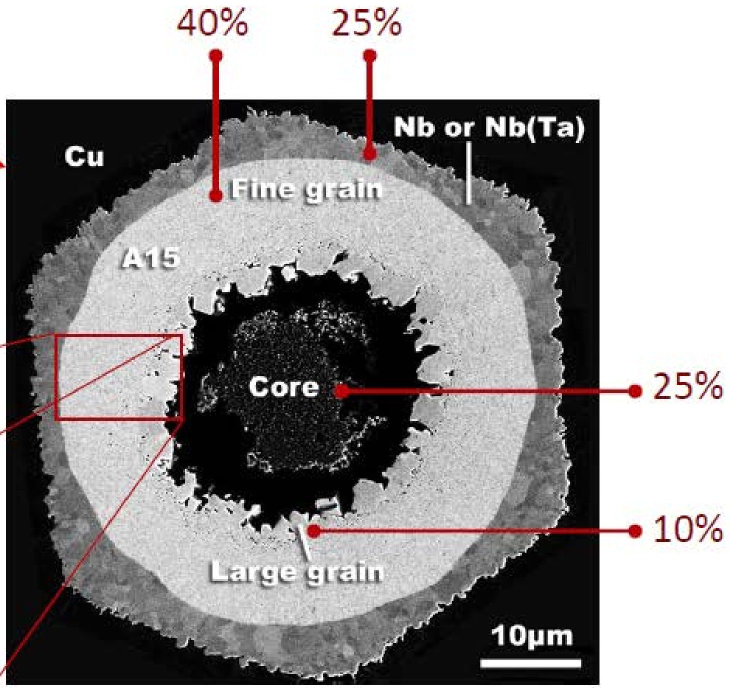
The PIT Process

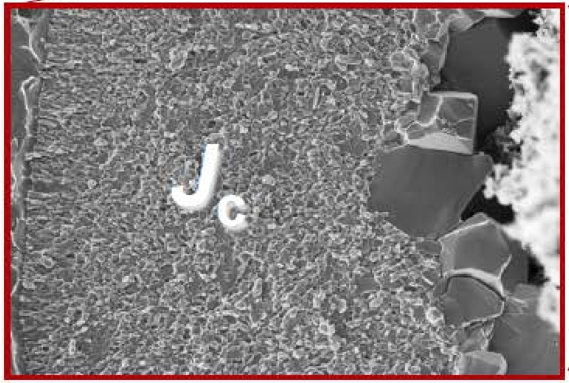
What determines J_c?

Powder-in-Tube wire

50% non-Cu fraction → **non-Cu J_c**



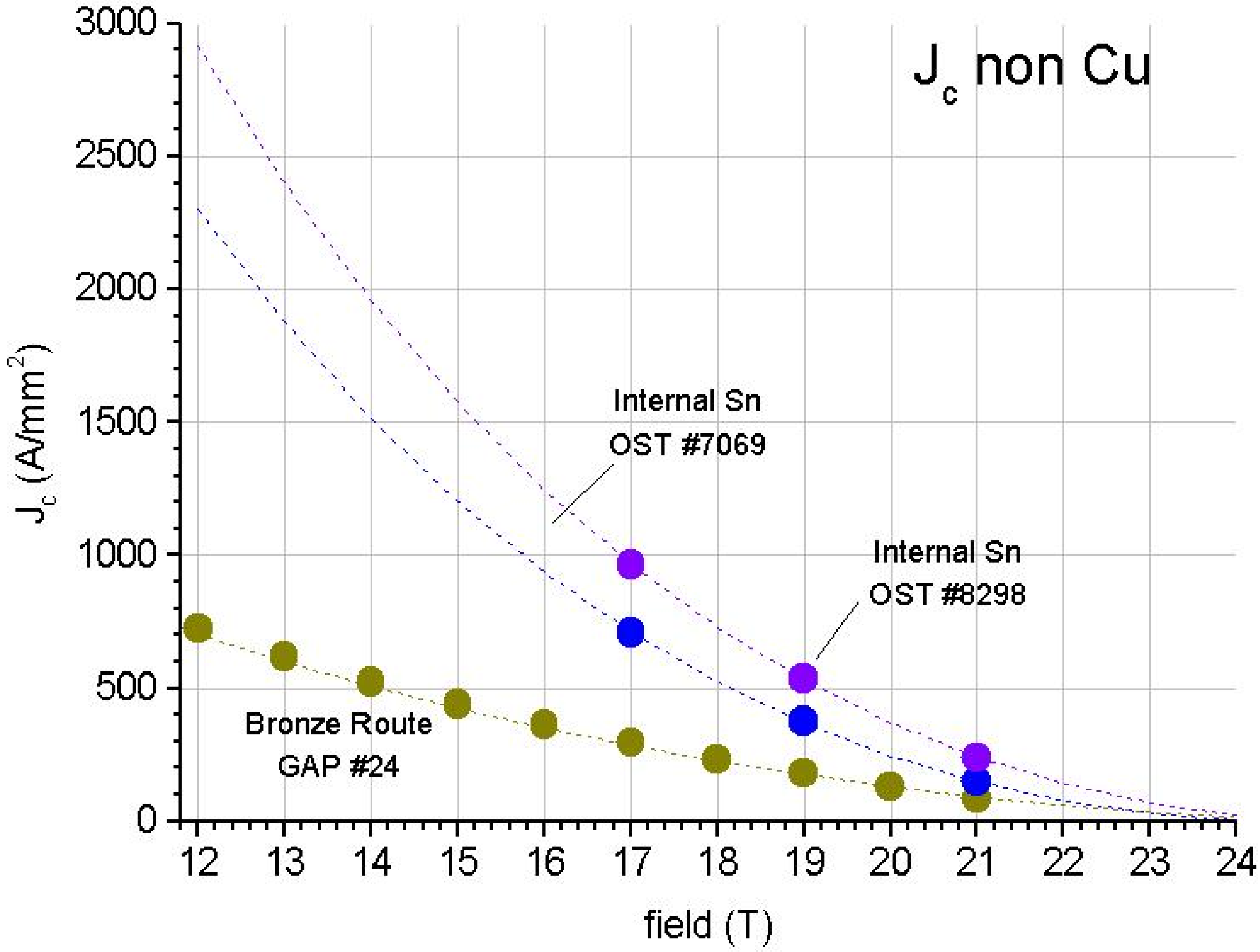




Only 20% of a wire carries current

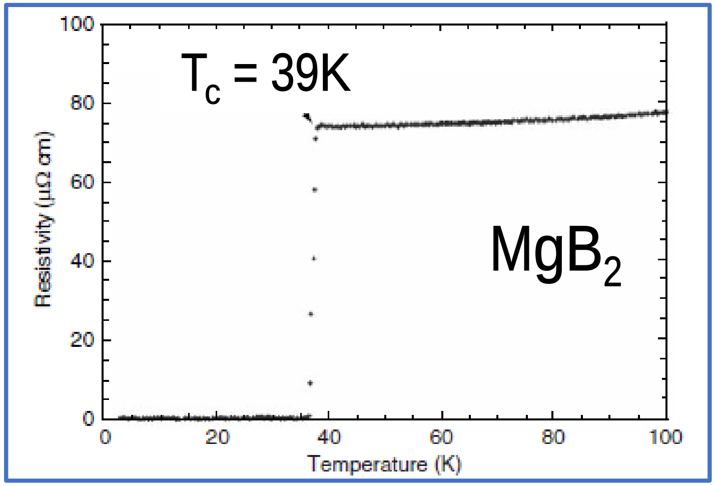
Godeke et al., Cryogenics,48,308 (2008)

Comparison : Nb_3Sn wires by 3 different routes



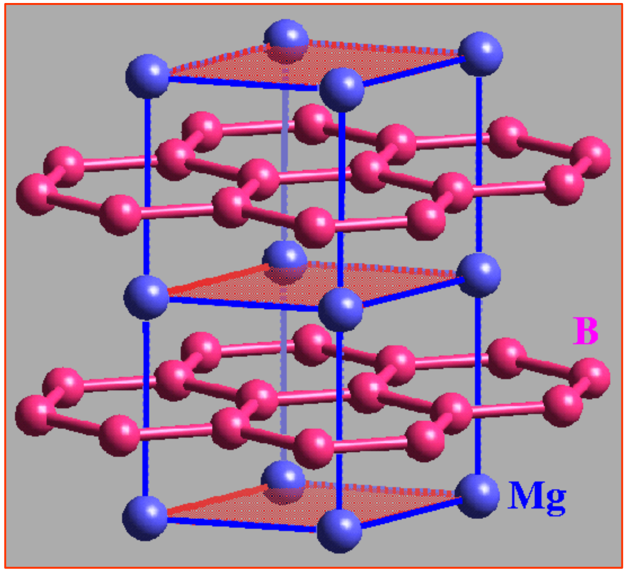
c. The System MgB_2

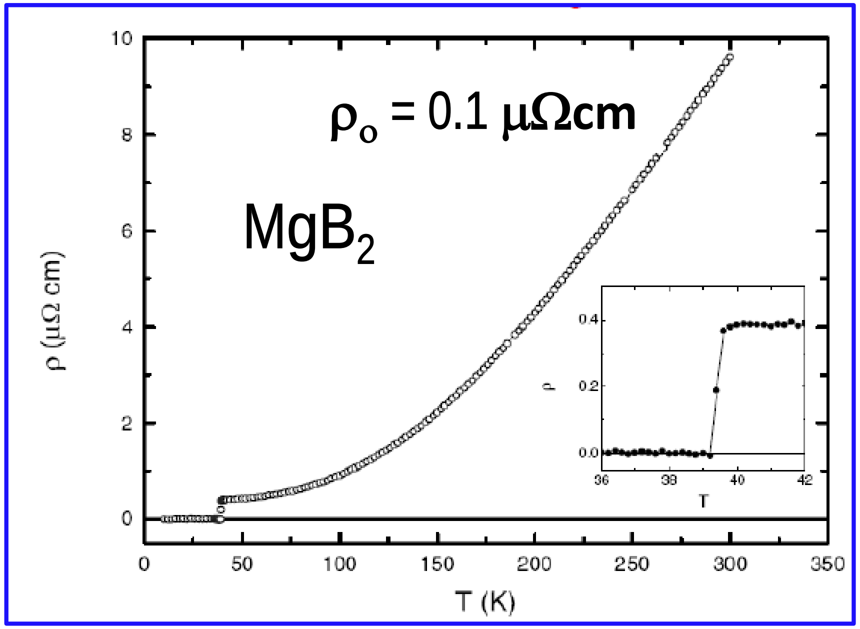
The MgB_2 compound



Akimitsu et al.,
Nature 410,163(2001).

P6/mmm:
a = 3.0852(8) Å
c = 3.5202(8) Å

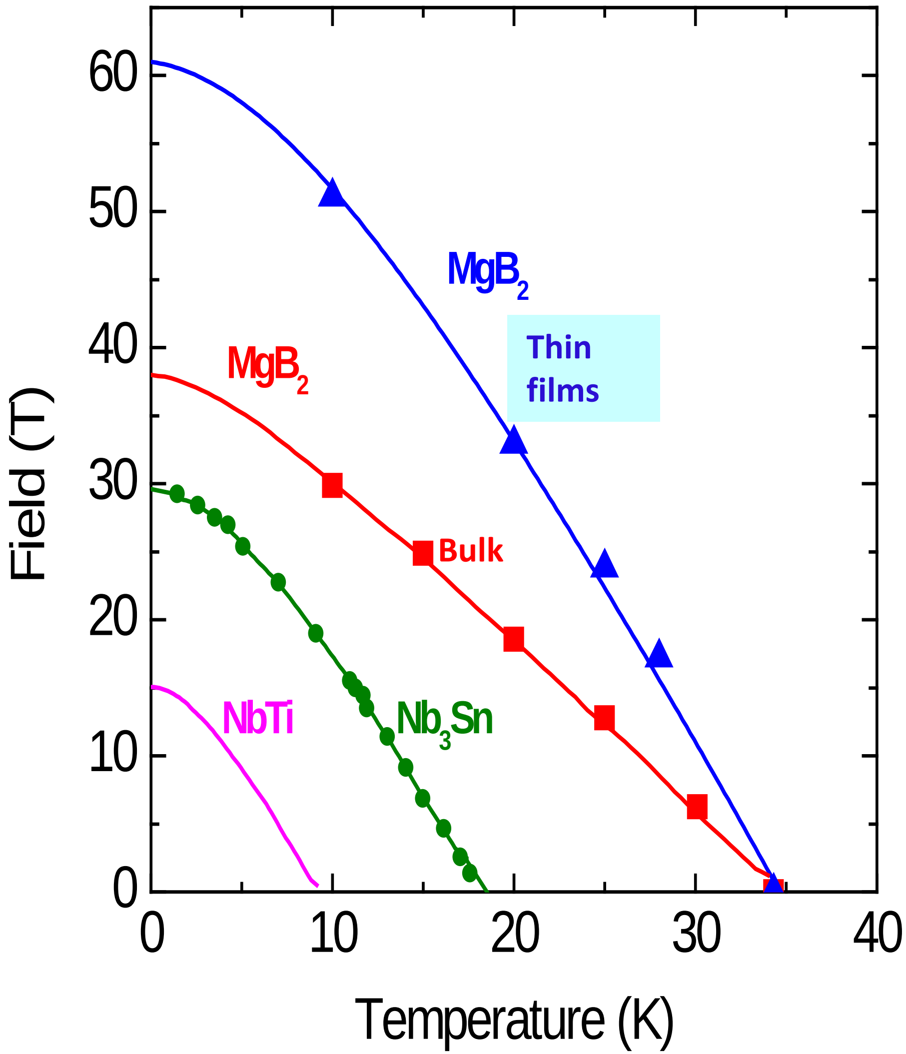




MgB_2 is a layered compound.
It is perfectly ordered, like Nb_3Sn.

P.C. Canfield et al.,
Phys. Rev. Lett., 86,2423(2001)

Upper critical field of MgB_2: films and wires



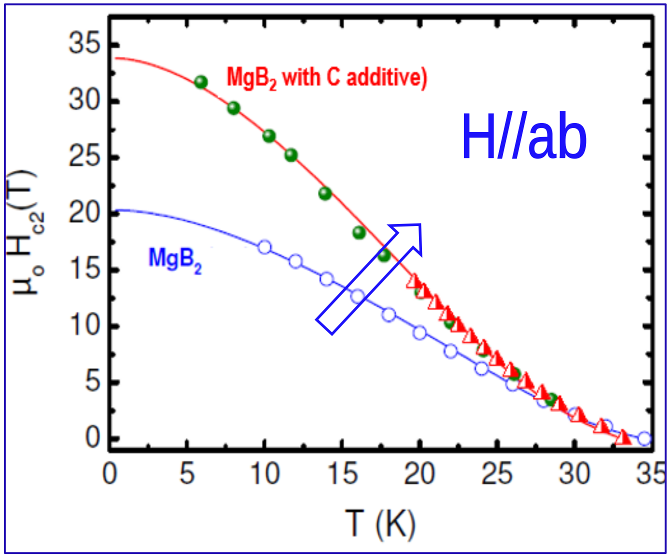
Films: B_{c2} = 60 T

Bulk, wires: B_{c2} = 30 - 40 T

The reason for this difference is still unknown

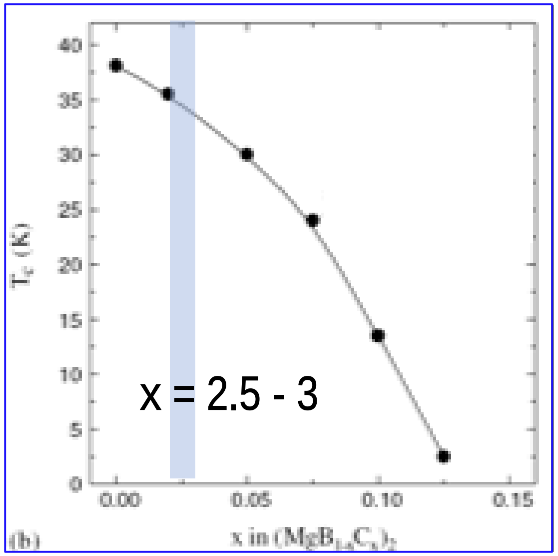
Effect of Carbon Substitution on T_c and B_{c2} of MgB_2

Enhancement of B_{c2}



W. Hässler et al., SuST 21,062001(08)

Slight Decrease of T_c



S. Lee et al., Physica C 397,7(2003)

x = 2.5 - 3: corresponds to J_c(max)

Substitution of B by C: enhanced electrical resistivity ρ_o

Enhancement at B_{c2} (and B_{Irr}): $B_{c2} \sim T_c \, \gamma \, \rho_o$ ➡ Higher J_c at the same field

Disordering: gradual transition: 2 bands ➡ 1 band

* By C substitution of B
* By high energy irradiation M. Putti et al., SuST, 21(2008)043001

C.Tarantini et al., Physica C 463-465(2007)211 (2007)

II. MgB_2 wires: fabrication and properties

Key to high J_c values in MgB_2 wires:

High quality Boron powder:

> 98% purity
Amorphous
Particle size < 100 nm

Two manufacturers: SMI (Specialty Materials, Inc). (USA)
Pavezyum (Turkey)

Different Boron powders * Pure Boron powder
* Boron encapsulated in a thin Carbon layer

Industrial production of MgB_2 multifilamentary wires

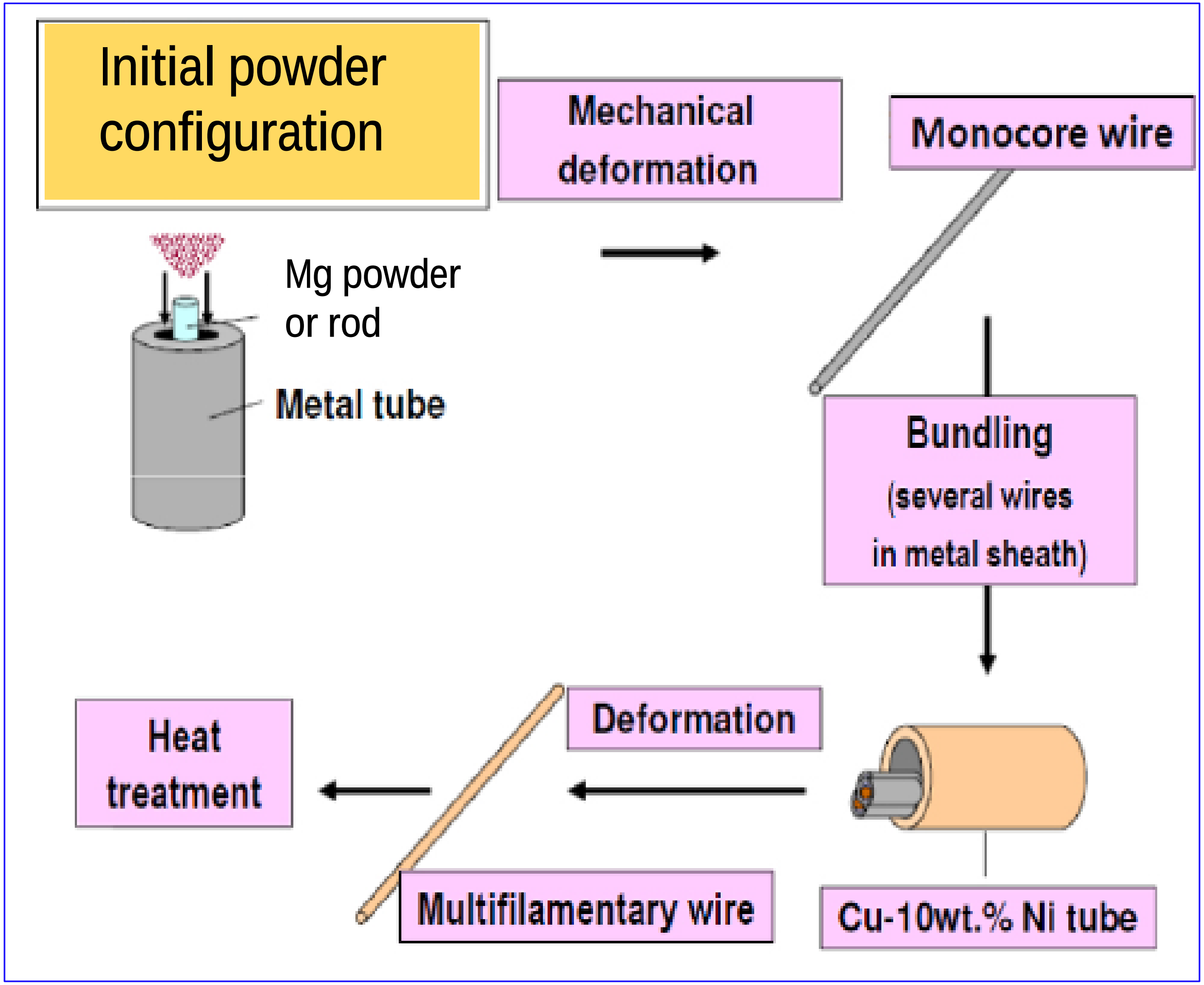
Columbus Superconductors,
Genoa, Italy

Hypertech Research Inc.,
Columbus, Ohio, USA

Laboratory production of long prototype wire lengths:

OSU, Columbus, OH, USA
NIMS, Tsukuba, Japan
EEL, Bratislawa, Slowakia
KIT, Karlsruhe (D)
IEE, Beijing, China
IFW, Dresden (D)
University of Cambridge (GB)
DPMC, Geneva, Switzerland
....

Common steps for MgB_2 multifilamentary wires and tapes

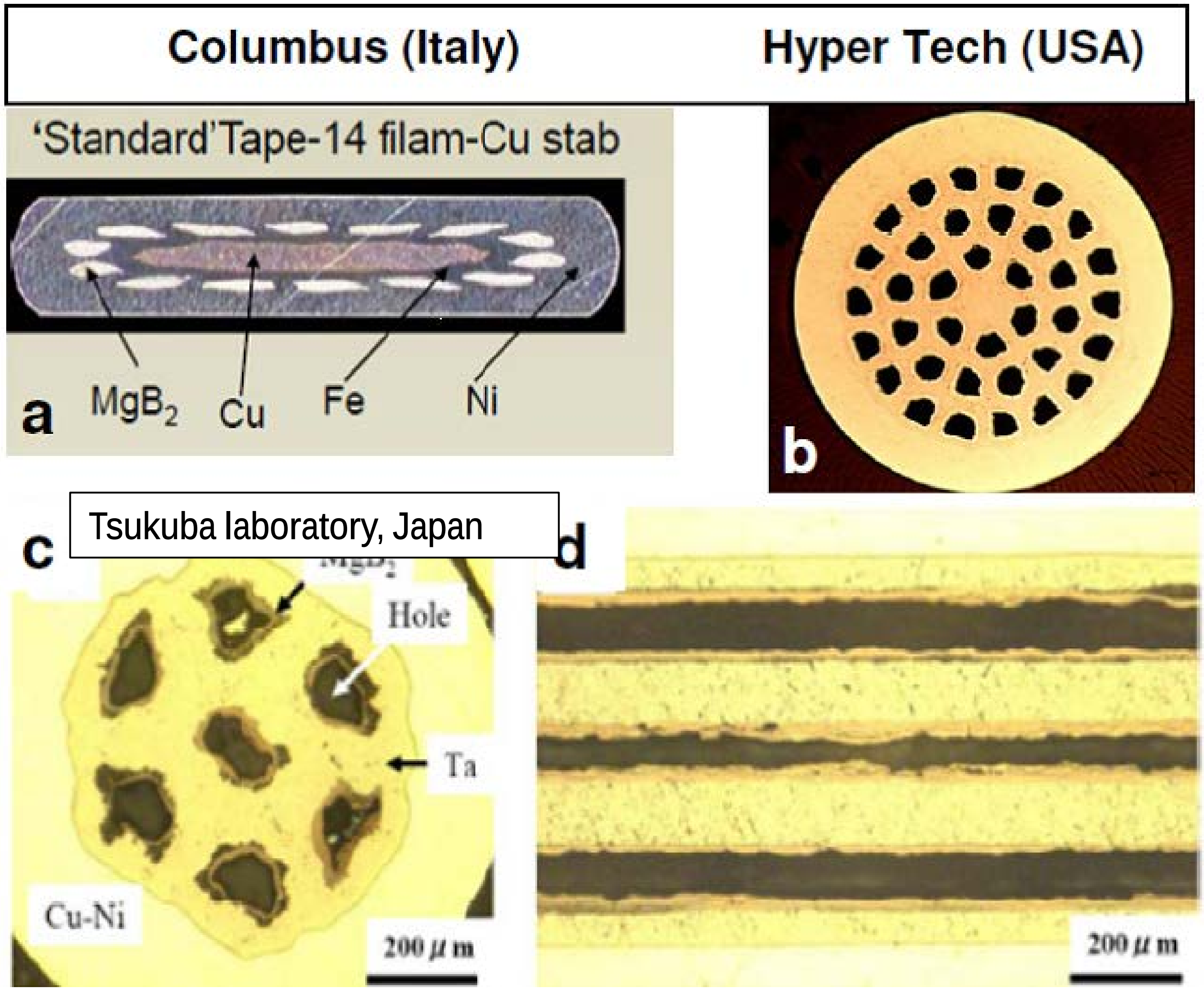


Known MgB_2 wire configurations

In situ

Ex situ

IMD



Latest developments in USA and in Japan

OSU as at NIMS: advanced developments, based on the IMD process.

In both cases, the reaction kinetics has been taken into account.

Various details have been added:

hancement of the MgB_2 layer and thus of the fill factor (>20%)

ancement of J_c.

The two new wire types are denominated:

IMD-PIT (NIMS) and

AIMI (OSU, Hypertech)

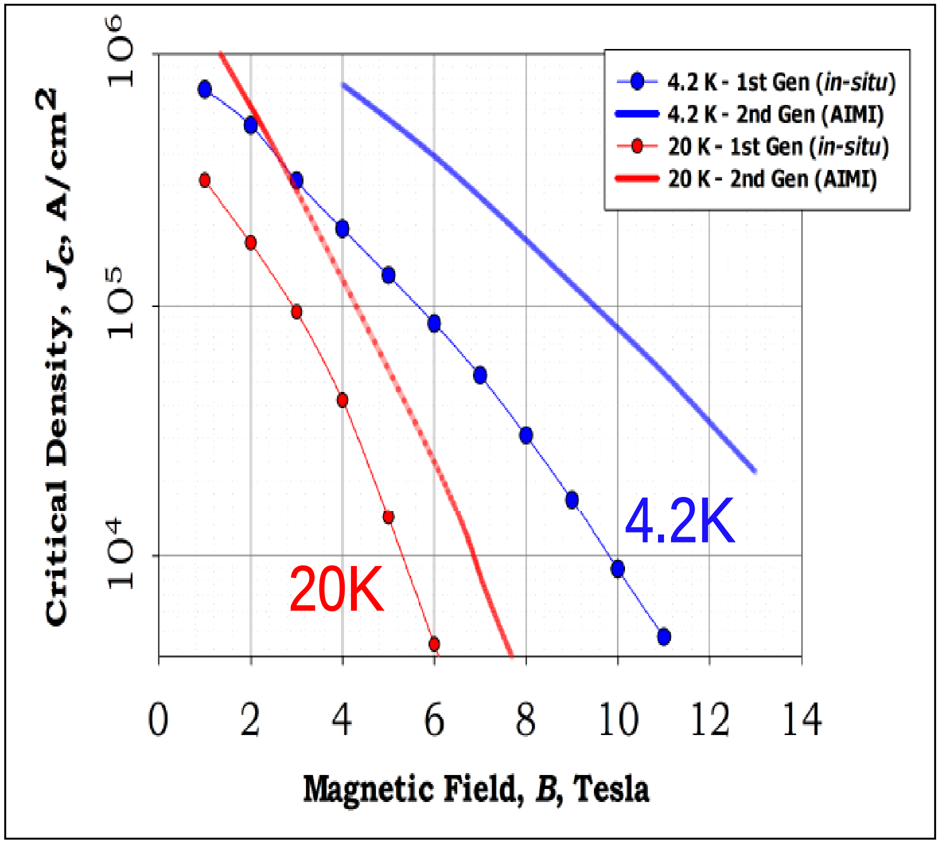
Both types of wires belong to the "second generation".

Industrial 1G (in situ) and 2G(AIMI) MgB_2 wires

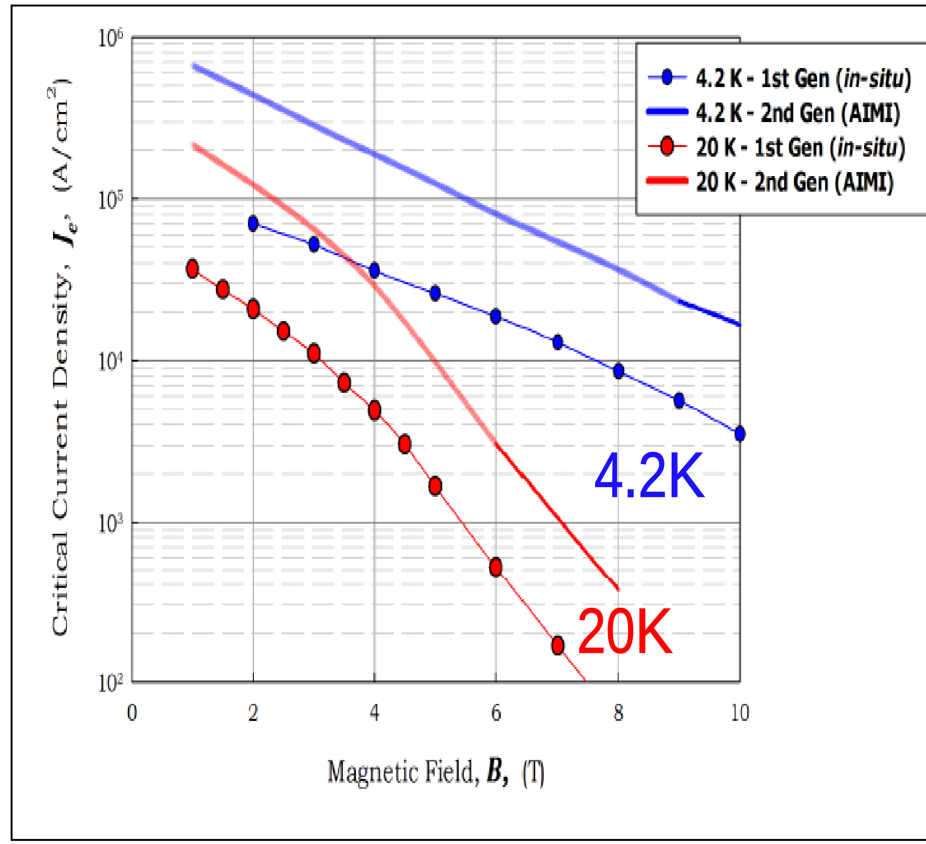
AIMI = Advanced Internal Mg Infiltration

Hyper Tech

J_c



J_e



6. High current cables

High Current MgB_2 cables

Successful prototypes:

A) The LINK cable for LHC Upgrade: 20 kA at 24K
CERN, Geneva

B) Energy Transfer by MgB_2 cables with LH2 cooling
Russian Scientific R&D Cable Institute, Moscow

R & D Projects

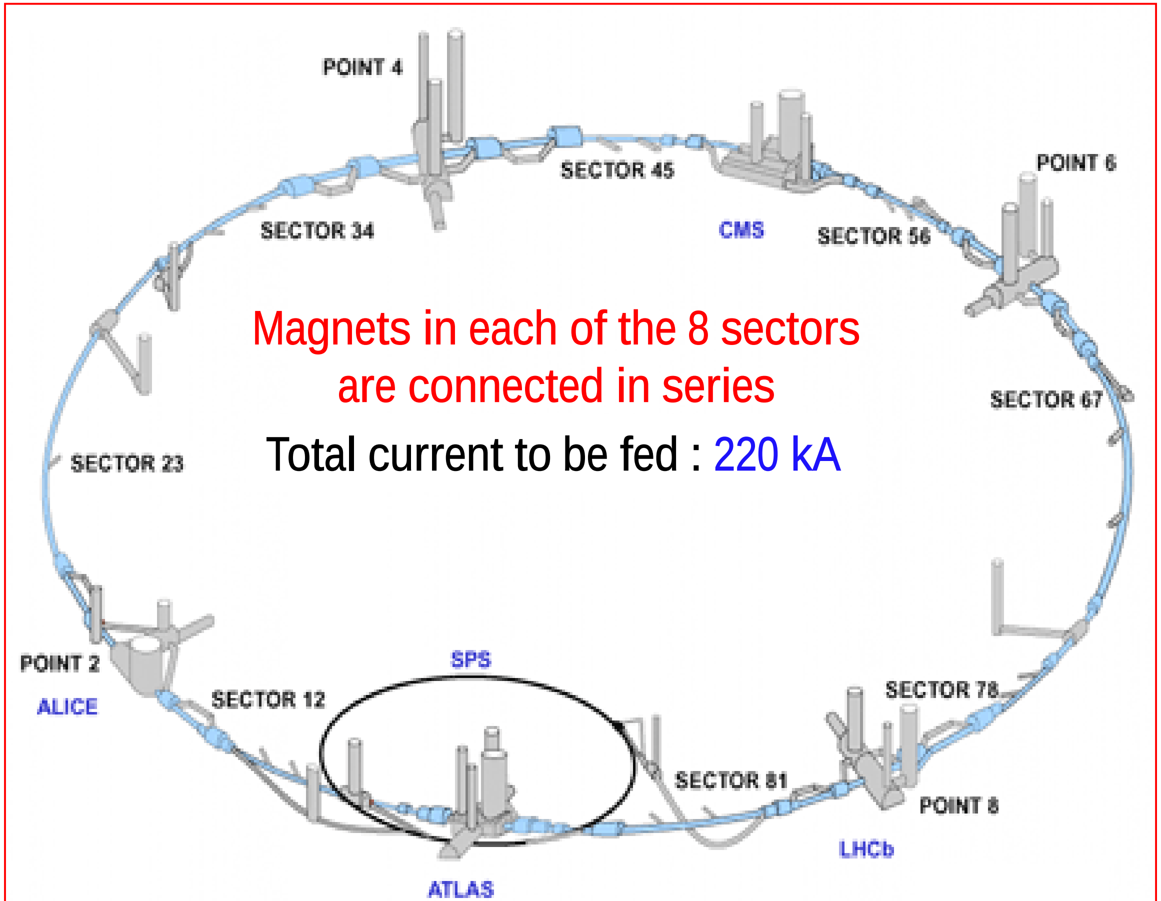
Energy Transfer by Underground MgB_2 cables with LHe (or LH_2) cooling: * IASS-CER
* Nexans

MgB_2 cables for Hi-Lumi LHC Upgrade: LINK

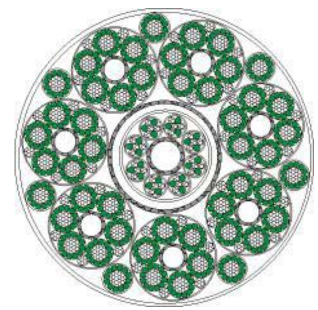
LINK: Cold powering of CERN LHC magnets using superconducting cables

Columbus Superconductors

Amalia Ballarino and coworkers, CERN: ASC 2014 presentations

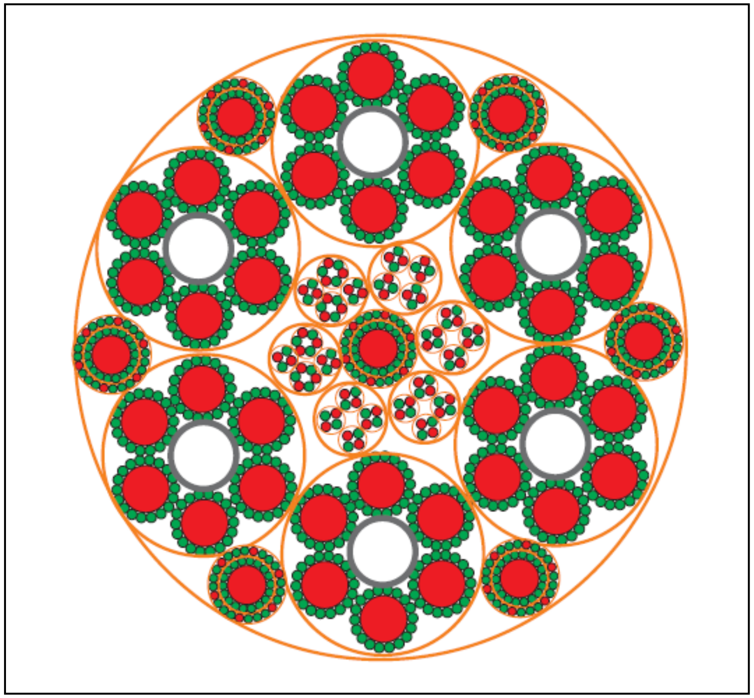


LHC Upgrade: Magnets in the tunnel become radioactive – moving power supplies far away from the beam: LINK Cables

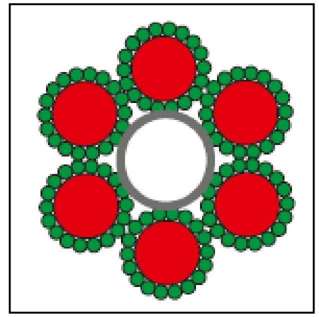


2011: 12x1.1 mm strand subcable tested successfully up to 17.8 kA at 5 K with no quench

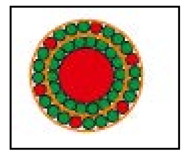
LINK Cable for LHC-Hi-Luminosity Magnets CERN)



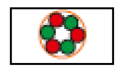
$|I_{tot}|$ = 150 kA
f_{ext} ~ 65 mm
Mass ~ 11 kg/m



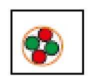
20 kA
Six cables, ϕ = 19.5 mm



Concentric ± 3 kA
Seven cables, ϕ = 8.4 mm



0.4 kA
Four cables



0.12 kA
Eighteen cables

Construction 2013-2020: total amount of 1'000 Km MgB_2 wires

Superconducting Link for Hi-Lumi LHC Upgrade

Superconducting Link Test Station at CERN

February 2014: I_c = 20 kA at 24K !

MgB_2 reacted “ex situ” round wire

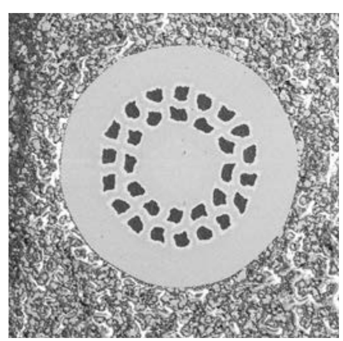
Length of the line = 20 m

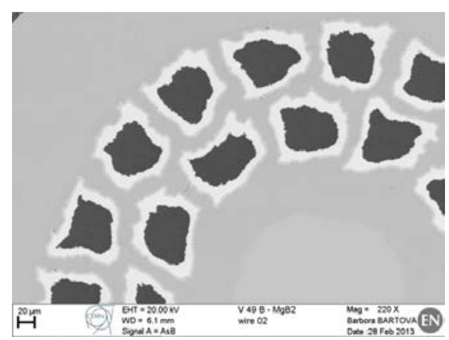
Length of the cable = 2 × 20 m

Cooling with forced flow of He gas

ΔT across line < 1 K

MgB_2 cable: Joint development: CERN - Columbus Superconductors





0.98 mm dia.
Monel Matrix
30 MgB_2 filaments
Nb barrier + Ni
Fill factor ~ 10.4 %

HTS Superconductor for HiLumi-LHC: Bi-2223

LHC Current Leads

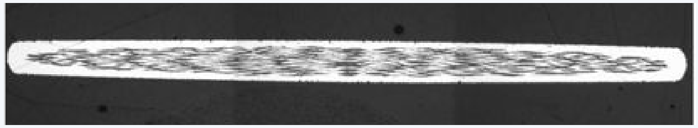
Work on HTS current leads started at CERN in the early 1990s, a few years after the discovery of High Temperature Superconductivity, and intense R&D program has led to their application to the LHC machine

This has been the first large scale commercial application of HTS

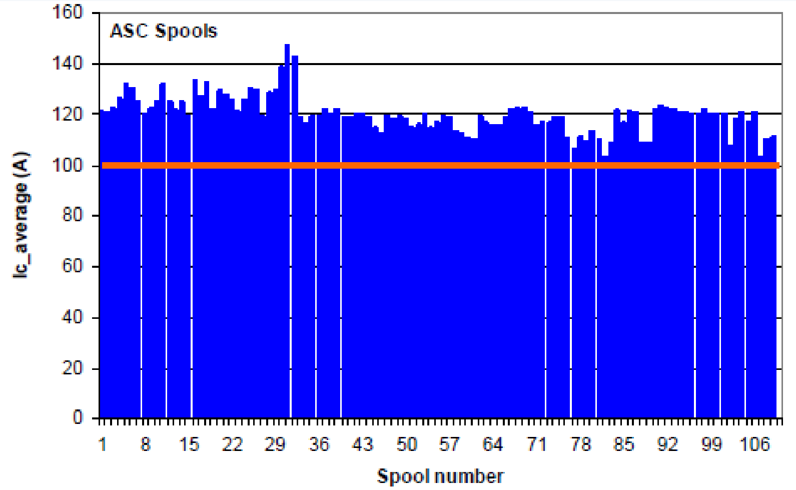
Following this development, the fusion community has also adopted the LHC HTS lead design (ITER, up to 68 kA, W7-X and JT-60)

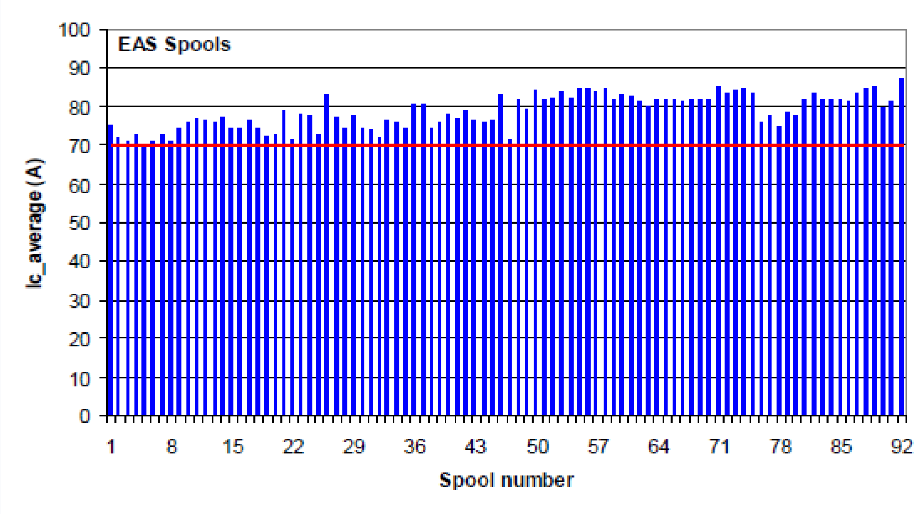
HTS Current Leads: a successful example of a replacement technology

Bi-2223 in the LHC Current Leads



Bi-2223 tape: **31 km** in total
AgAu5 (wt%)
ULs=100...300 m

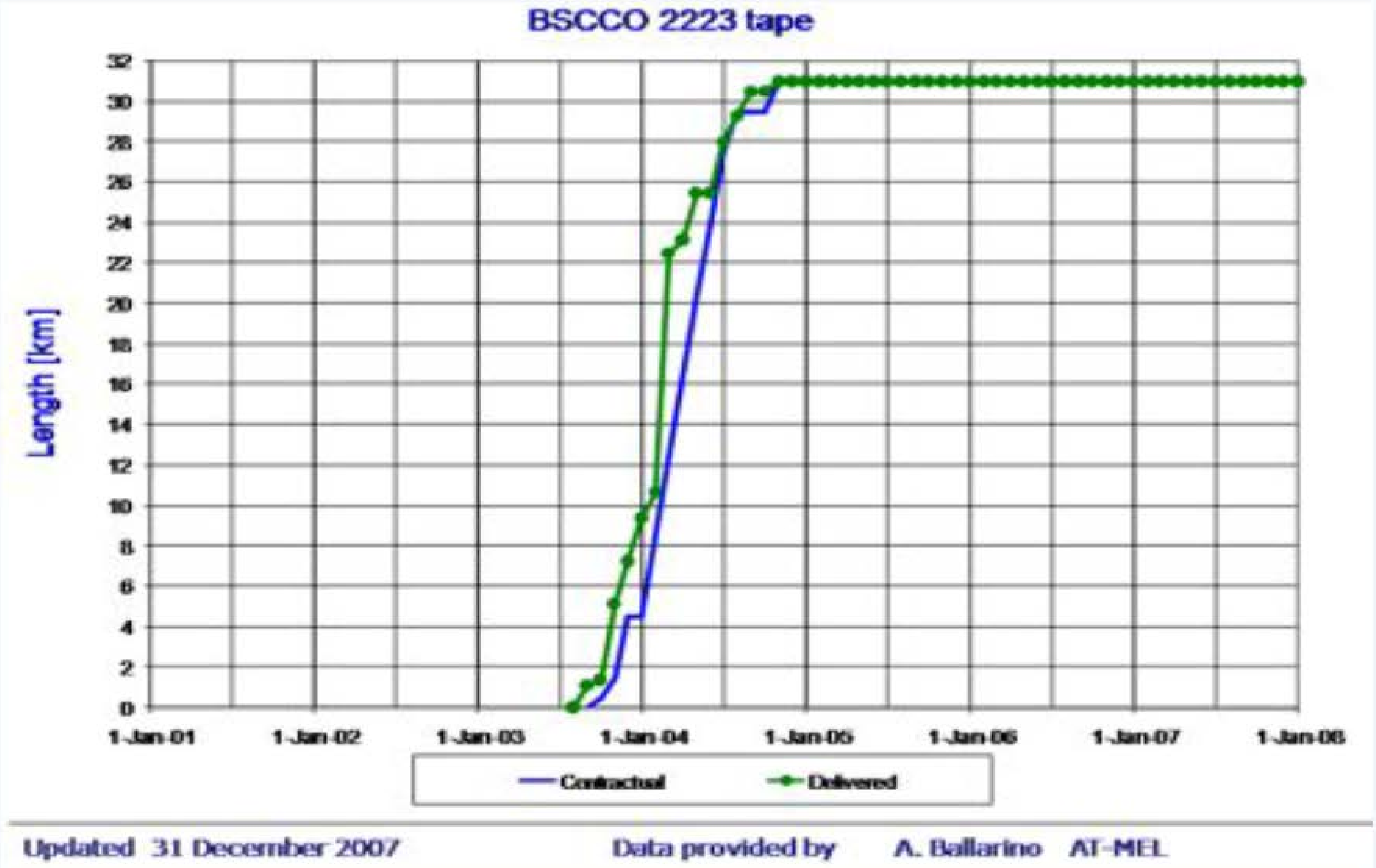




Ic_min (A)	Ic_av (A)	Ic_max (A)	σ (A)
103	120	147	7

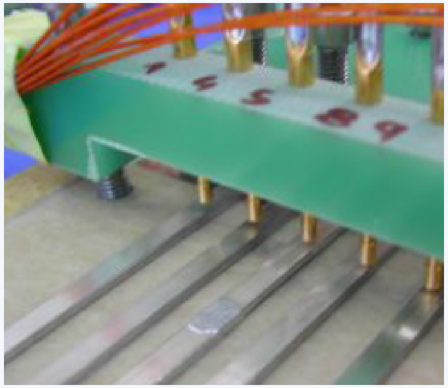
Ic_min (A)	Ic_av (A)	Ic_max (A)	σ (A)
70	79	87	4

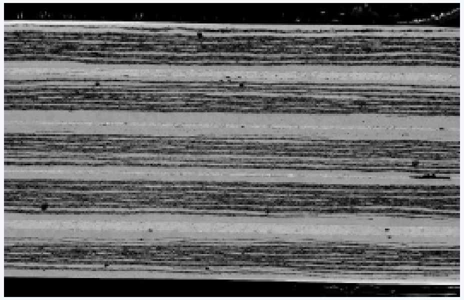
Bi-2223 Tape Delivery

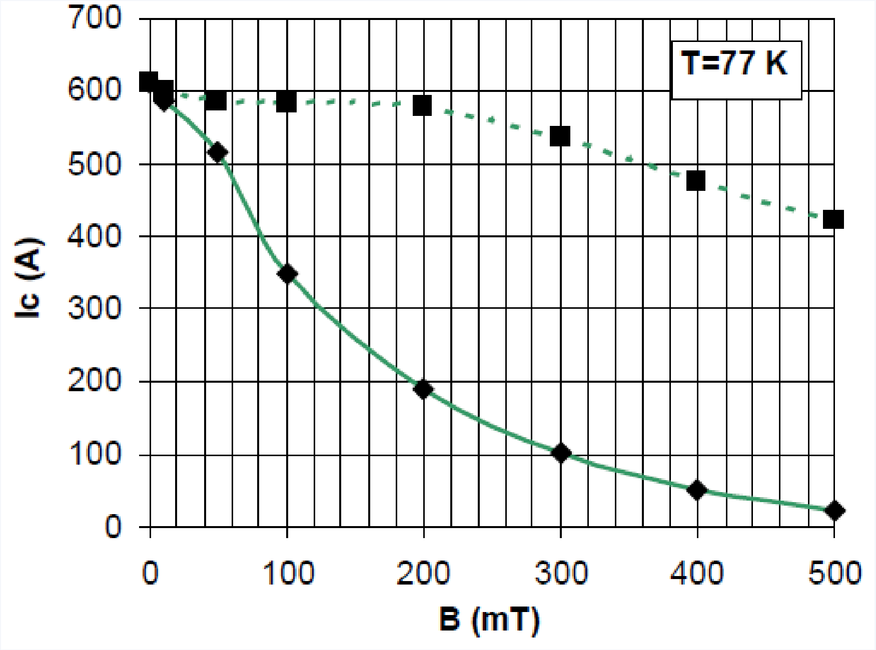


Stacks of Bi-2223 Tapes

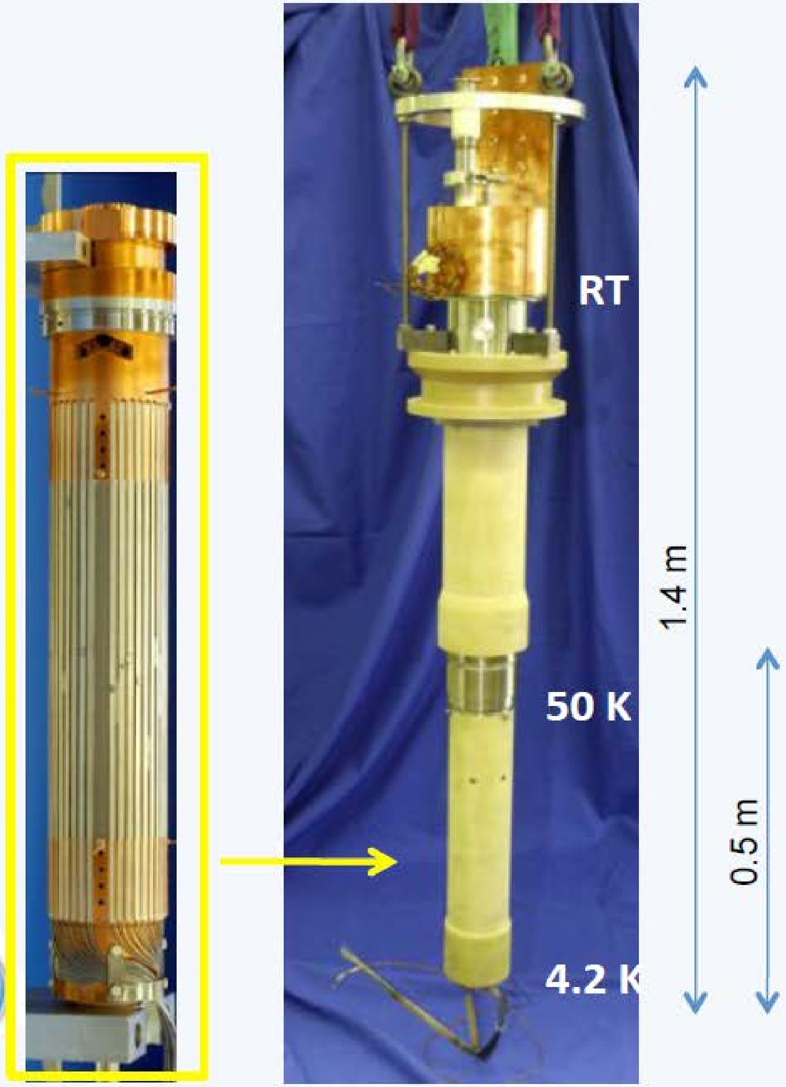
About **10 000** vacuum soldered stacks of tapes







HTS 13’000 A Current Lead



HTS Superconducting Link For LHC

HTS Superconducting Link

-Transfer of **high currents** (up to about **14 kA**) in superconducting cables

-**Multi-cable system** containing up to about 60 electrically insulated cables transferring in all a maximum current of about **180 kA**;

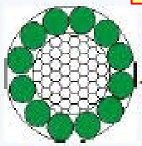
-**Compact transfer** of about 180 kA over long **horizontal and vertical lengths**. Optimization of differential thermal contractions and of cable supporting structure in particular for the vertical option;

-Optimization of a **new cold powering system** with respect to cryogenic, electrical and mechanical requirements

The project will enable to continue to accumulate expertise with HTS conductors - of interest for future application to magnet technology

Novel Cables

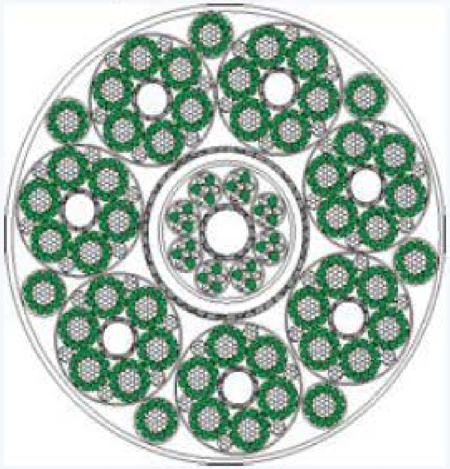
Development of Novel Cable Assemblies



11.8 kA @ 4.2 K

12 wires

Φ = 6 mm

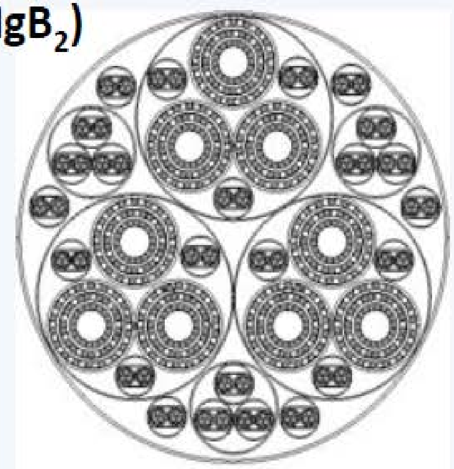


Φ = 62 mm

Itot=100 kA @ 20 K

Cable structure using wires

(MgB_2)

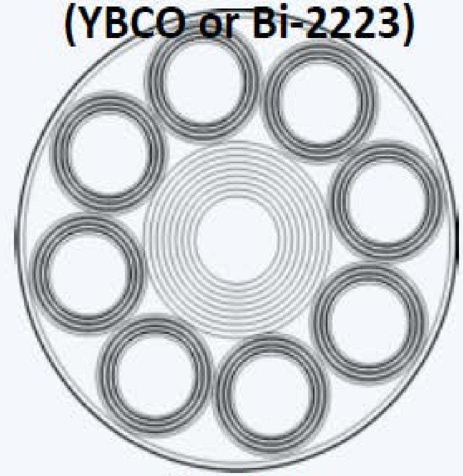


Φ = 75 mm

27 × 6000 A
48 × cables 600 A
Itot = 190 kA

Cable structure using tapes

(YBCO or Bi-2223)

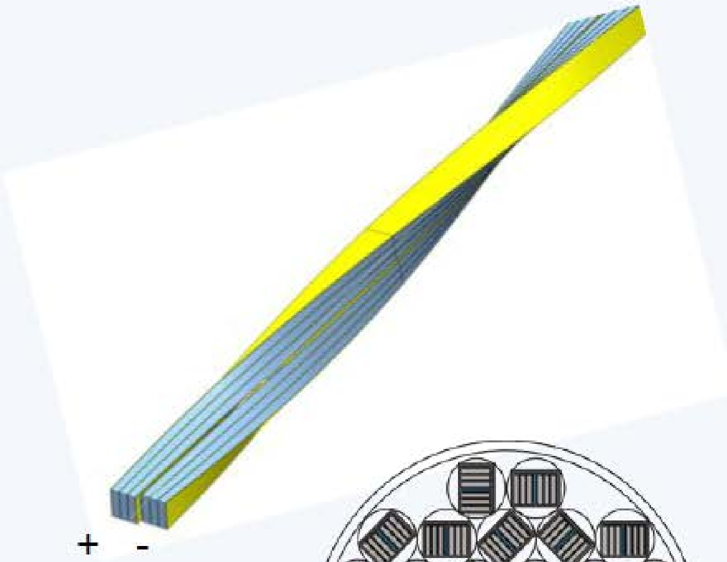


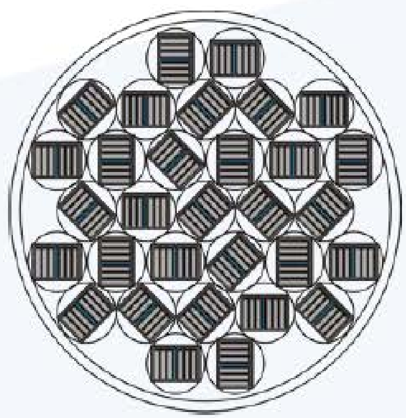
Φ = 70 mm

24 × 6000 A
42 × 600 A
Itot = 169 kA

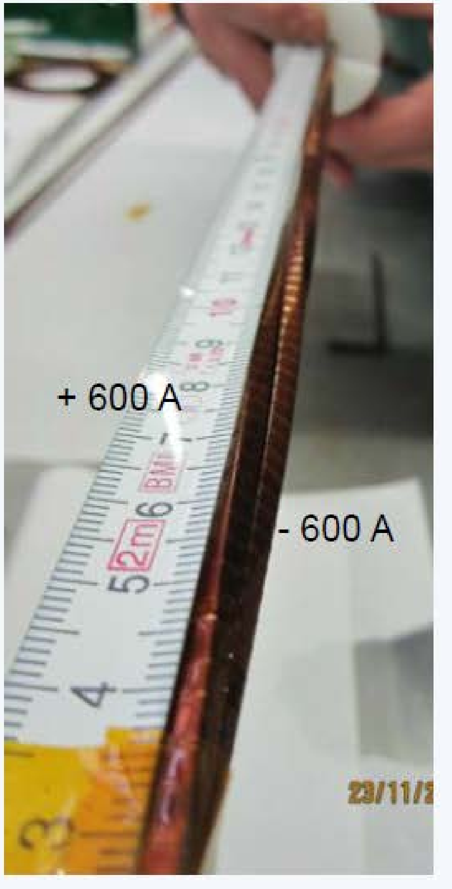
Development of Novel Cable Assemblies

Twisted pair 600 A cable

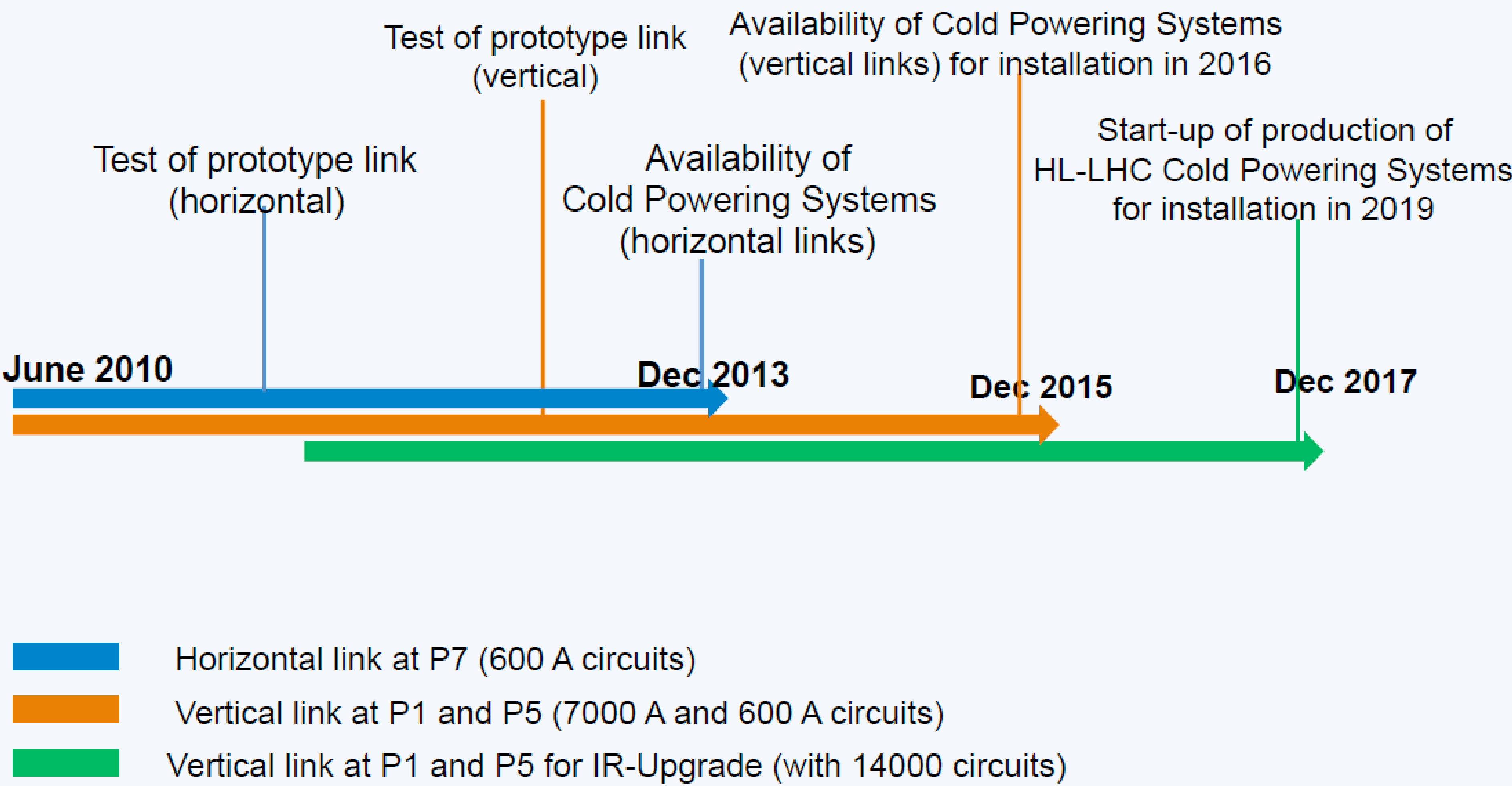




Φ= 27 mm
50 YBCO cables 600 A @ 70 K

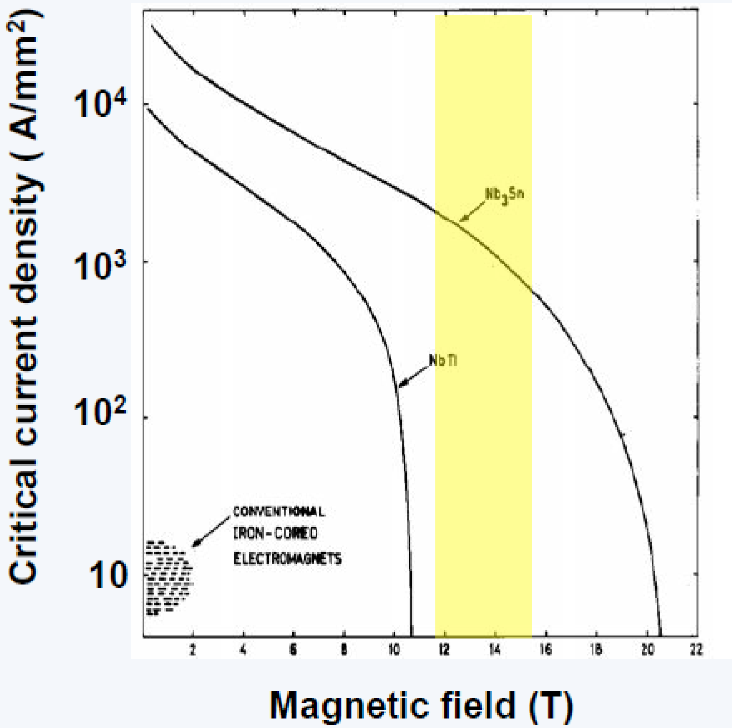


HTS Link Project TimeLine



Material Needs for HiLumi LHC
Operational 2023

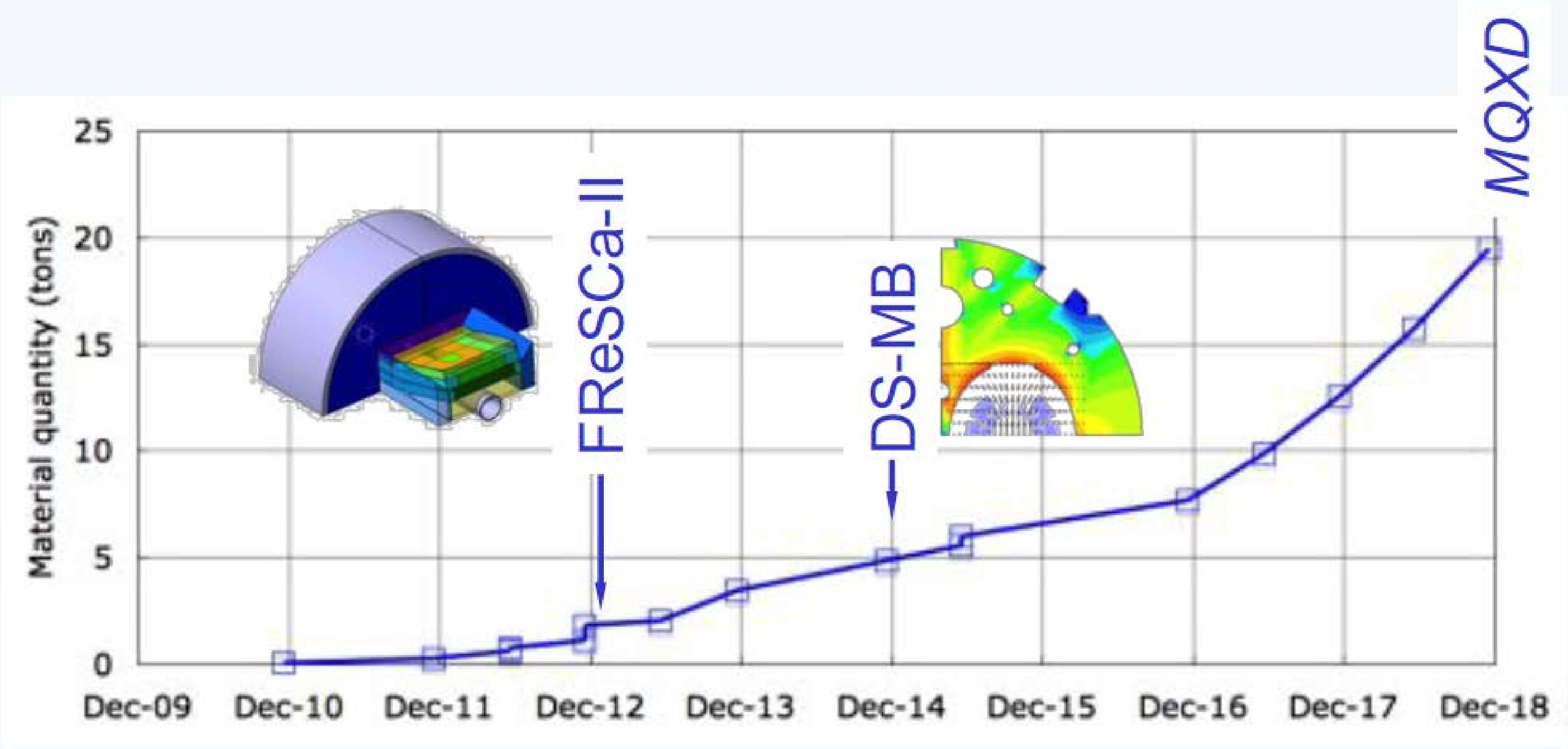
Nb_3Sn



Based on CERN and EuCARD procurements

	(4.5 K)	NED	FReSCa-II	DS-MB
Strand diameter	(mm)	1.25	1	0.7
Sub-element diameter	(μm)	50	50	≈ 50
Copper:non-Copper	(-)	1.25	1.25	1.13
J_C(12 T, 4.2 K)	(A/mm^2)	3000	2500	**2650**
J_C(15 T, 4.2 K)	(A/mm^2)	1500	**1250**	1400
n-index	(-)	30	30	-
RRR	(-)	200	150	60
Piece length	(m)	>300	800	350

Material Needs: LTS



- Approximately 20 tons of *HEP-grade* Nb_3Sn are presently been constructed

L. Bottura

Material Needs: HTS

- Conductor needs for R2E and HL-LHC amount to a length in excess of **2000 km of HTS** wire or tape, to be used in cables rated at currents ranging from 600 A to 14000 A

		Φ (mm)	W (mm)	Th (mm)	Tmax (K)	Ic (‡) (A)
(†) MgB_2	wire	1.1	-	-	25	≥ 400
MgB_2	tape	-	3.7	0.67	25	≥ 400
YBCO	tape	-	4	0.1	35	≥ 400
BSCCO 2223	tape	-	4	0.2	35	≥ 400

NOTES:
(†) bending radius $R_B \leq 80$ mm
(‡) at applied field $B \leq 0.5$ T

Conclusions

- Superconductivity has played a major role in the evolution of HE accelerators

- The work-horse conductor has been up to now Nb-Ti. For many applications Nb-Ti remains the conductor of choice

- To go to higher fields, or for specific applications where higher operating temperature is an advantage, A15 type conductor and High Temperature Superconductors are needed. This requirement defines the present and future R&D effort at CERN