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Superconductors for magnets

From the materials to the technical conductors

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Outline

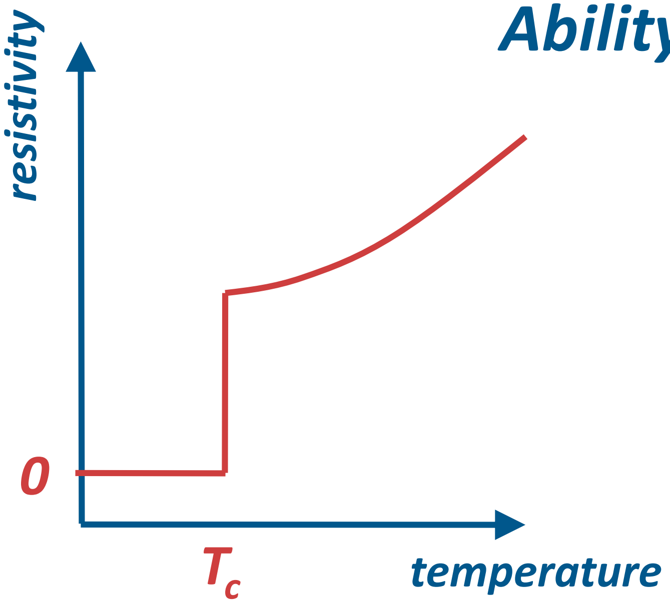
A short introduction to superconductivity

- *Type-I vs. Type-II – why Type-II is better?*
- *Vortex pinning and critical current*

From the materials to the technical conductors

- *LTS : Nb_3Sn properties and wire technology*
- *HTS : YBCO properties and wire technology*

Discovery of Superconductivity in 1911



Ability to carry a current without dissipation

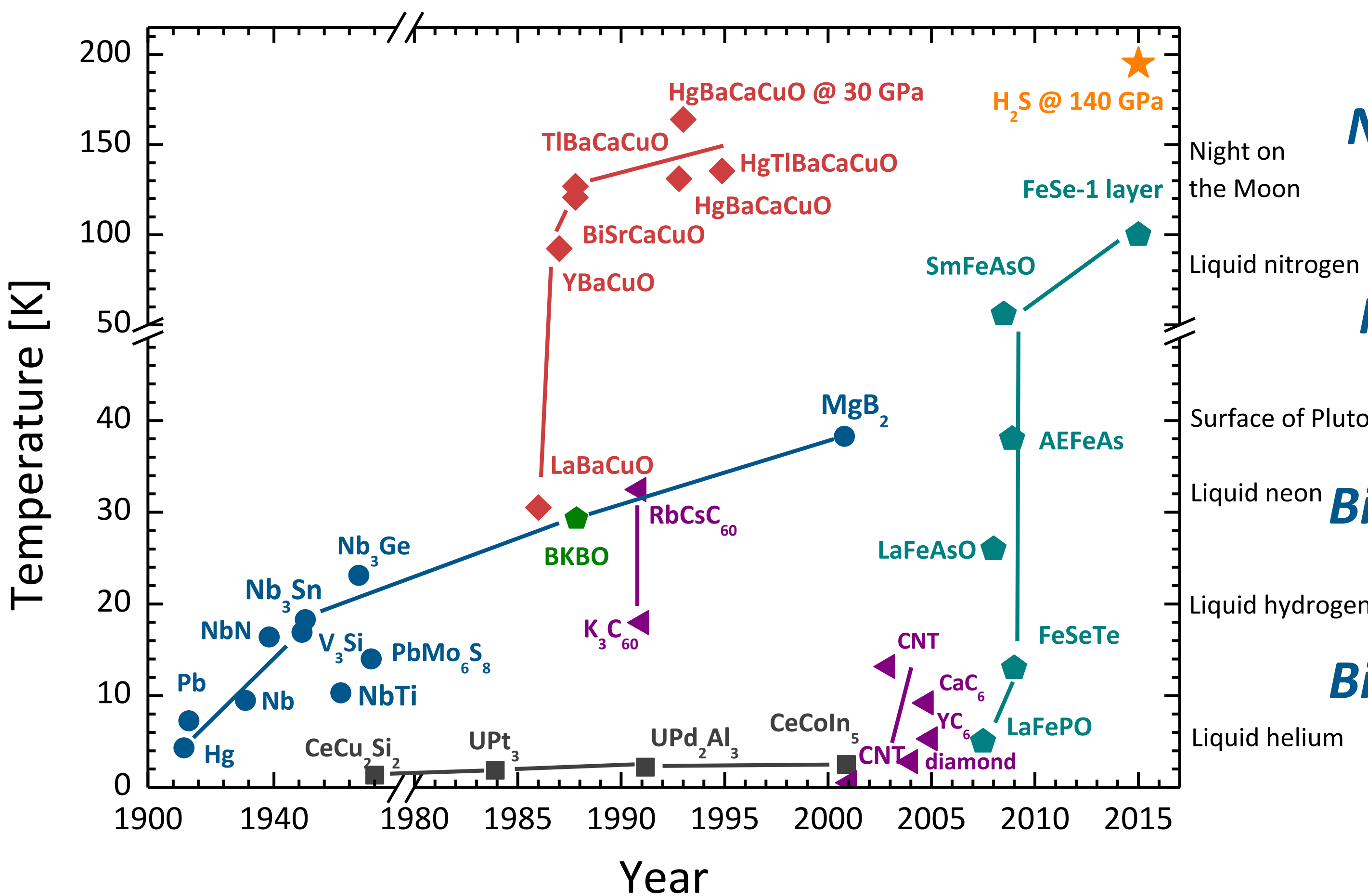
- ***Transport of energy***
- ***Generation of high magnetic fields***

Drawbacks:

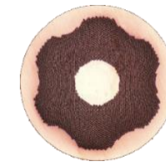
Loss-less currents cannot exceed the critical current I_c

1000+ superconducting compounds, very few for practical use

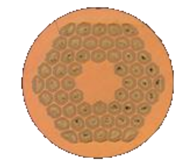
Superconductors History



NbTi

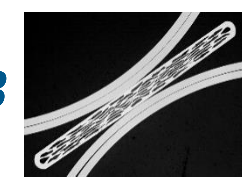


Nb_3Sn

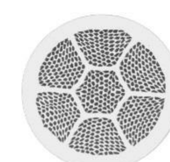


MgB_2

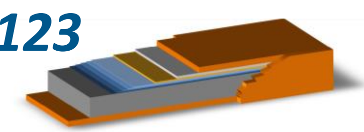
Bi2223



Bi2212



Y123



Key facts about superconductors

1) There are two characteristic lengths in a superconductor

$$\xi = \frac{\hbar}{\sqrt{2m^*|\alpha|}}$$

coherence length

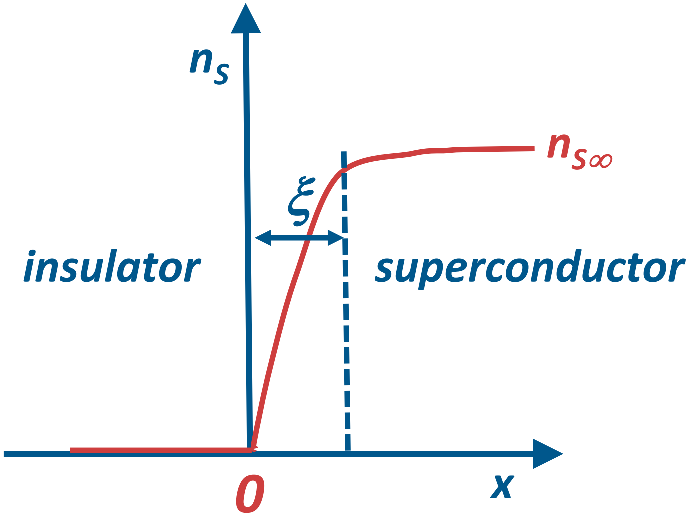
and

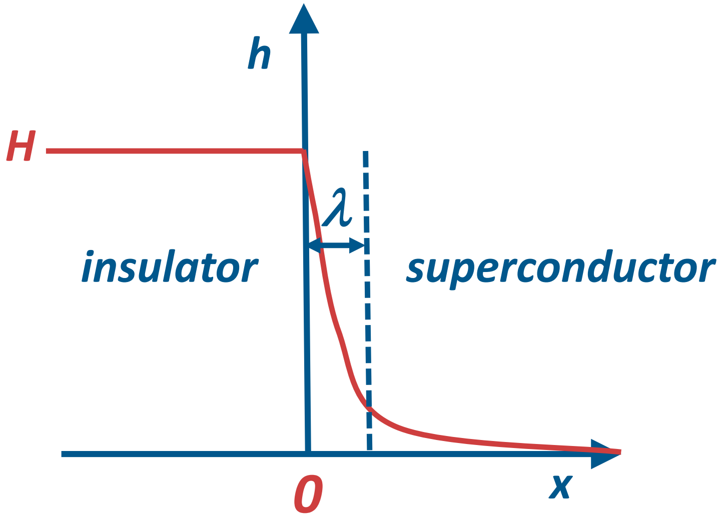
$$\lambda = \sqrt{\frac{m^* c^2}{4\pi n_s^2 e^{*2}}}$$

penetration depth

ξ defines the space modulation of the "superelectron" density n_s

λ characterizes the distance to which a magnetic field penetrates into a superconductor





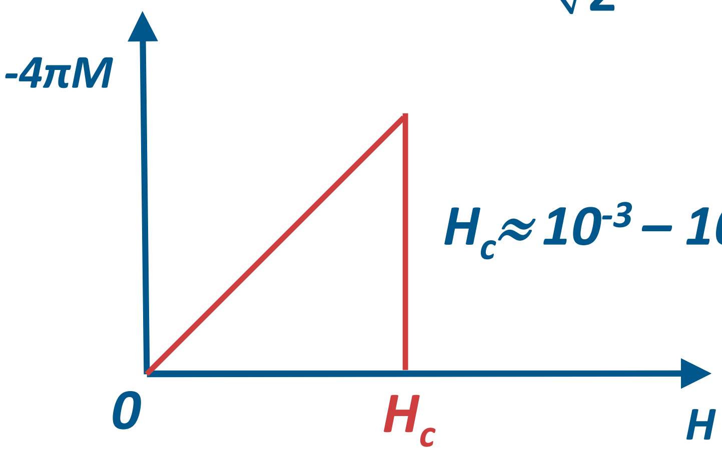
Key facts about superconductors

2) There are two types of superconductors, depending on $\kappa = \dfrac{\lambda}{\xi}$

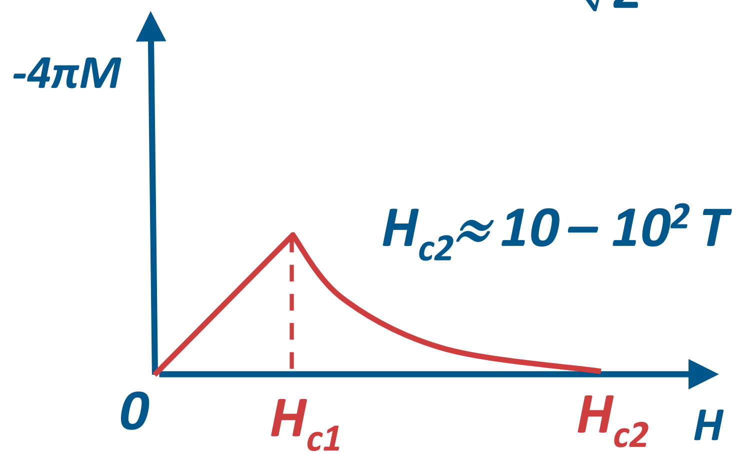
Ginzburg-Landau parameter

Type-I for $\kappa < \dfrac{1}{\sqrt{2}}$

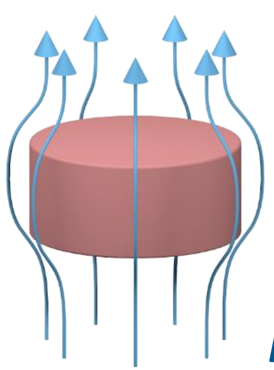
Type-II for $\kappa > \dfrac{1}{\sqrt{2}}$



$H_c \approx 10^{-3} - 10^{-2}$ T



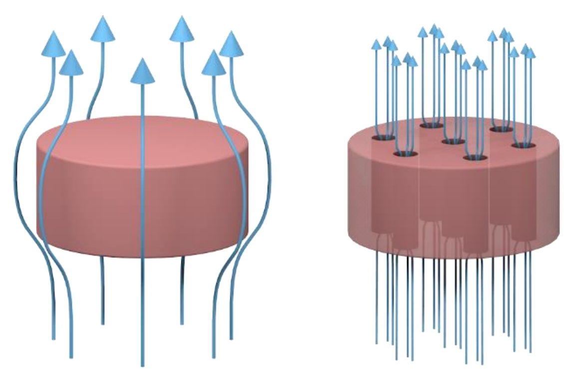
$H_{c2} \approx 10 - 10^2$ T



$H < H_c$

The Meissner Effect

$-4\pi M = H - B$



$H < H_{c1}$ $\quad$ $H_{c1} < H < H_{c2}$

Key facts about superconductors

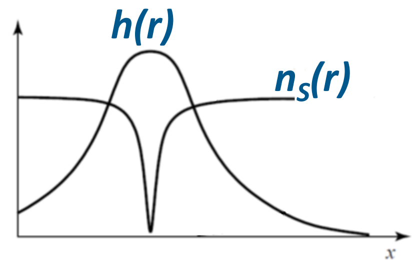
3) *In a type-I superconductor, superconducting currents are confined to the surface in a λ-thick layer*

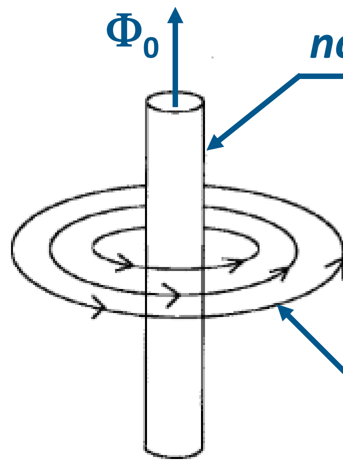
4) *In a type-II superconductor, the critical fields are related to the characteristic lengths*

$$H_{c1} = \frac{\Phi_0}{4\pi\lambda^2} \ln\kappa = \frac{H_c}{\sqrt{2}\kappa} \ln\kappa \qquad H_{c2} = \frac{\Phi_0}{2\pi\xi^2} = \sqrt{2}\kappa\, H_c$$

5) *In a type-II superconductor, magnetic flux penetrates beyond H_{c1} The entering flux is fractionated in vortices, each one carrying a flux quantum* $\Phi_0 = hc/2e$

What is a vortex?

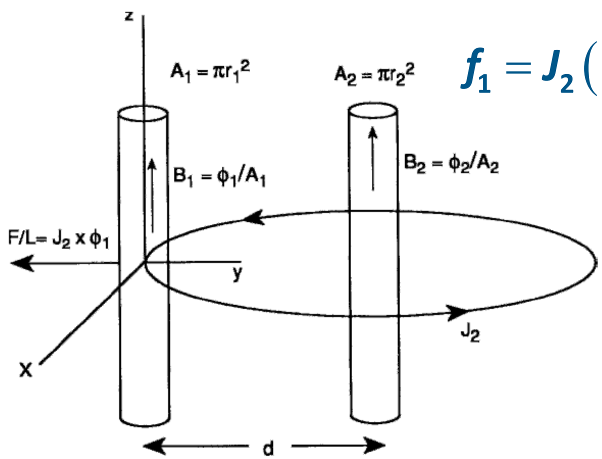




normal core diameter ≈ 2ξ

superconducting currents over a distance ~λ

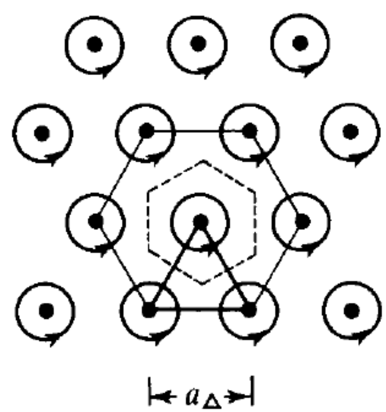
Vortices repel each other…

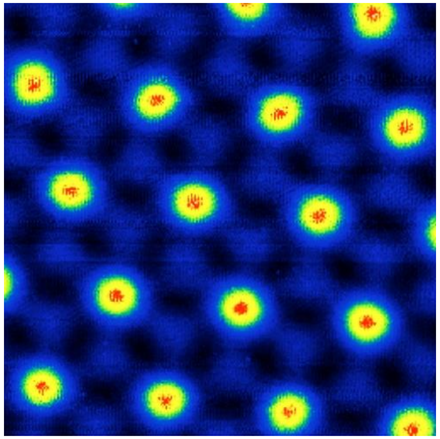


$$f_1 = J_2(r_1) \times \frac{\Phi_0}{c}\hat{z}$$

The Abrikosov lattice

… and arrange on a regular lattice





Vortex motion and dissipation: the Flux Flow

Let's focus on the effects of a transport current density J

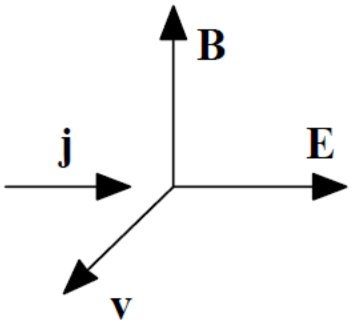
On a single vortex

$$f = J \times \frac{\Phi_0}{c}\hat{z}$$

On the vortex lattice

$$F = \sum f = n_v f = J \times n_v \frac{\Phi_0}{c}\hat{z} \quad = J \times \frac{B}{c}$$

Therefore, vortices tend to move transverse to J . If v is their velocity



$$E = B \times \frac{v}{c}$$

DISSIPATION !!

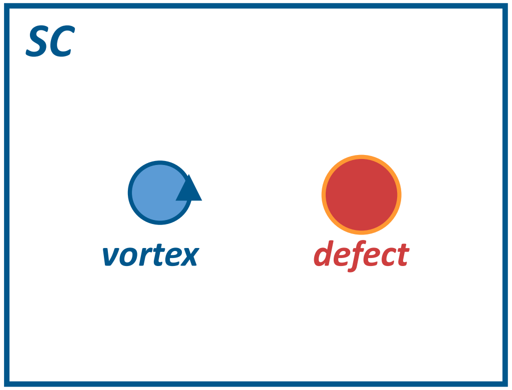
The Flux Flow resistivity

$$\rho_{ff} = \rho_n \frac{B}{B_{c2}}$$

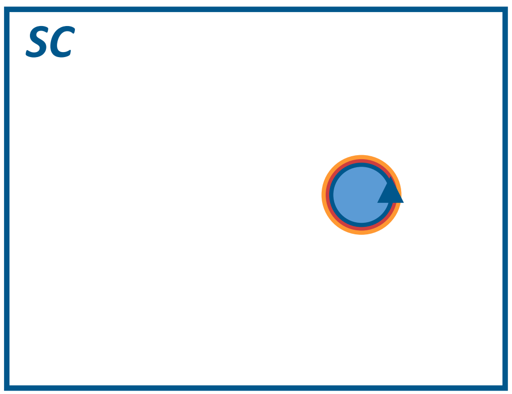
Bardeen and Stephen, PR 140 (1965) A1197

Vortex-defect interaction

Let's consider defects – precipitates, grain boundaries, etc. – whose size is comparable with the coherence length ξ



$$\Delta G = \underbrace{\Delta G_{condensation}(defect) + \Delta G_{condensation}(vortex)}_{energy\ loss} - \underbrace{\Delta G_{mag}}_{energy\ gain}$$



$$\Delta G = \underbrace{\Delta G_{condensation}(defect)}_{energy\ loss} - \underbrace{\Delta G_{mag}}_{energy\ gain}$$

The defect acts as a potential well U(r)

The vortex is pinned at the defect position

The force to extract the vortex from the defect is $f_p = -\nabla U(r)$

Vortex-defect interaction

$$f = J \times \frac{\Phi_0}{c}\hat{z}$$

Force exerted from J

$$f_p = J_c \times \frac{\Phi_0}{c}\hat{z}$$

Pinning Force exerted from defects

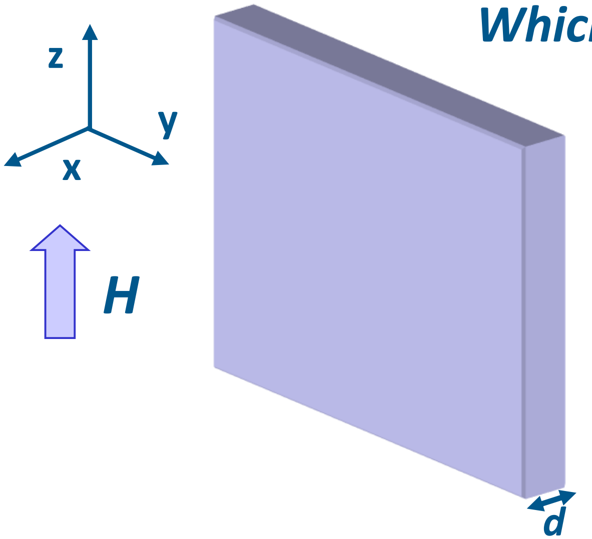
J_c is the critical current density

If $f < f_p$ then $v = 0$ and $\rho = 0$

If $f > f_p$ then $v \neq 0$ and $\rho \neq 0$

Only superconductors with defects are truly superconducting ($\rho = 0$) !!

Vortex pinning and critical state: the Bean model

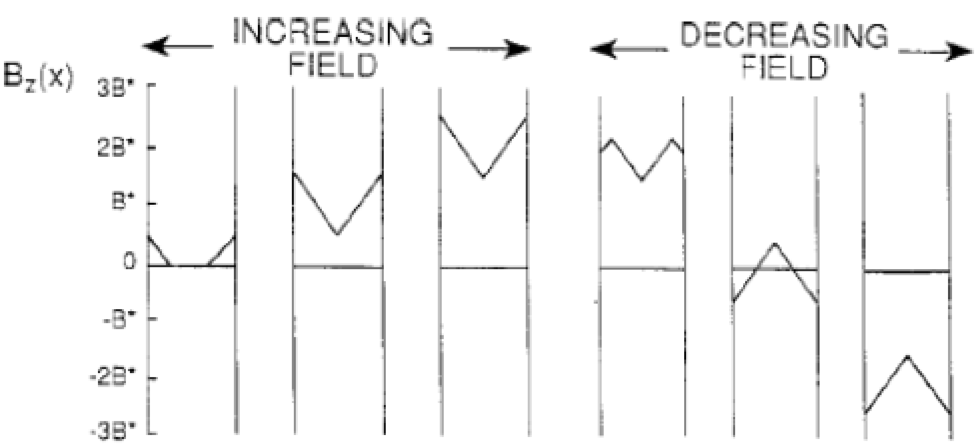


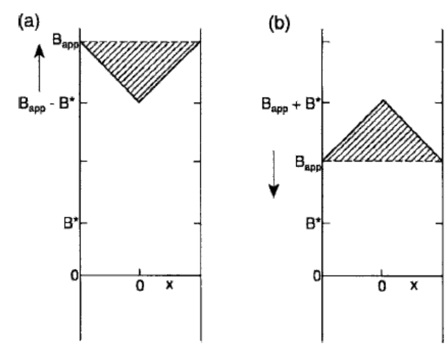
Which is the shape of the field profile in the superconductor?

1) $$\nabla \times H = \frac{4\pi}{c} J$$

2) $$F = \frac{JB}{c} = \frac{1}{4\pi} B \frac{dB}{dx} \le F_p = \frac{J_c B}{c}$$

The assumption of the Bean model is $F = F_p \Rightarrow \frac{dB}{dx} = \frac{4\pi}{c} J_c$

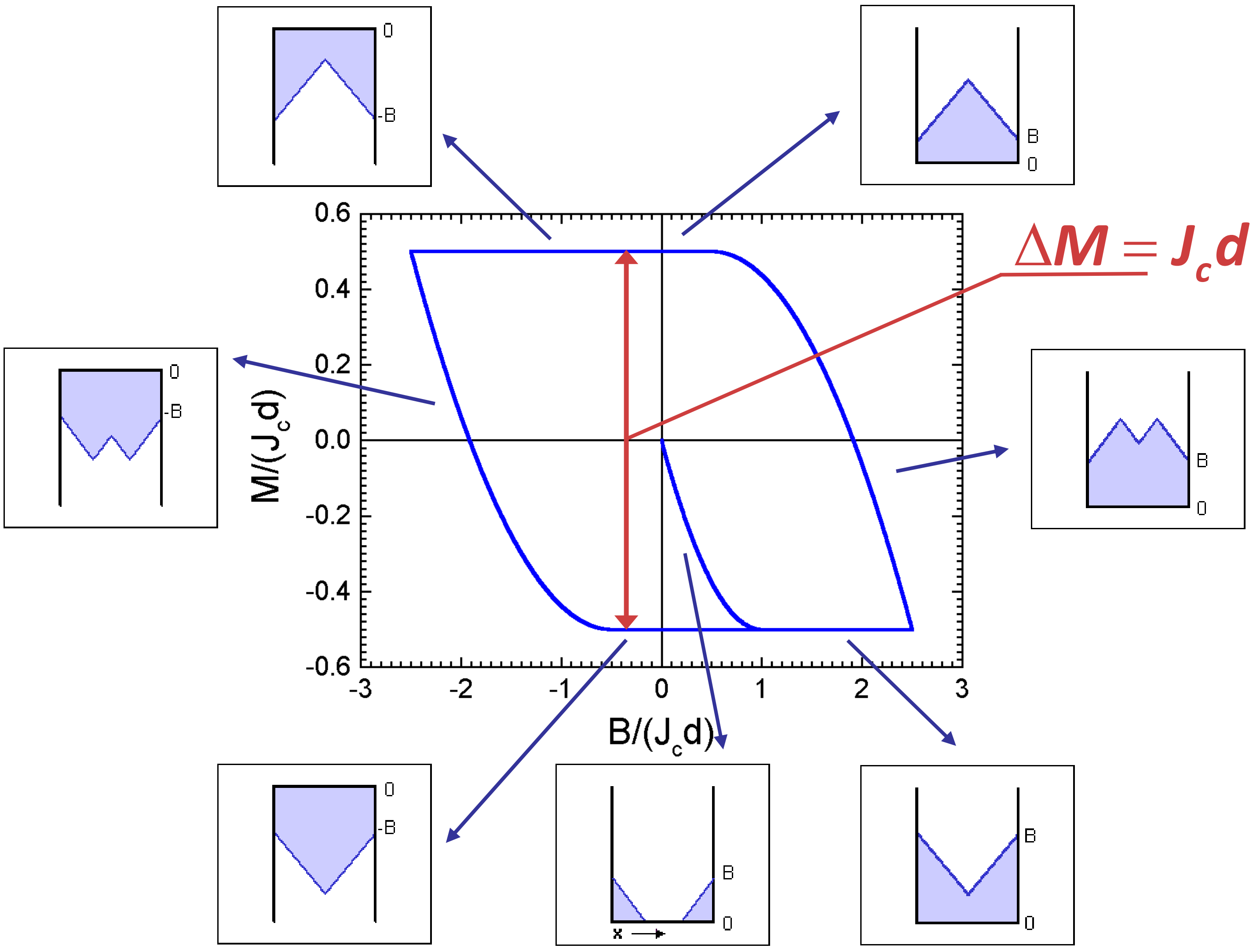




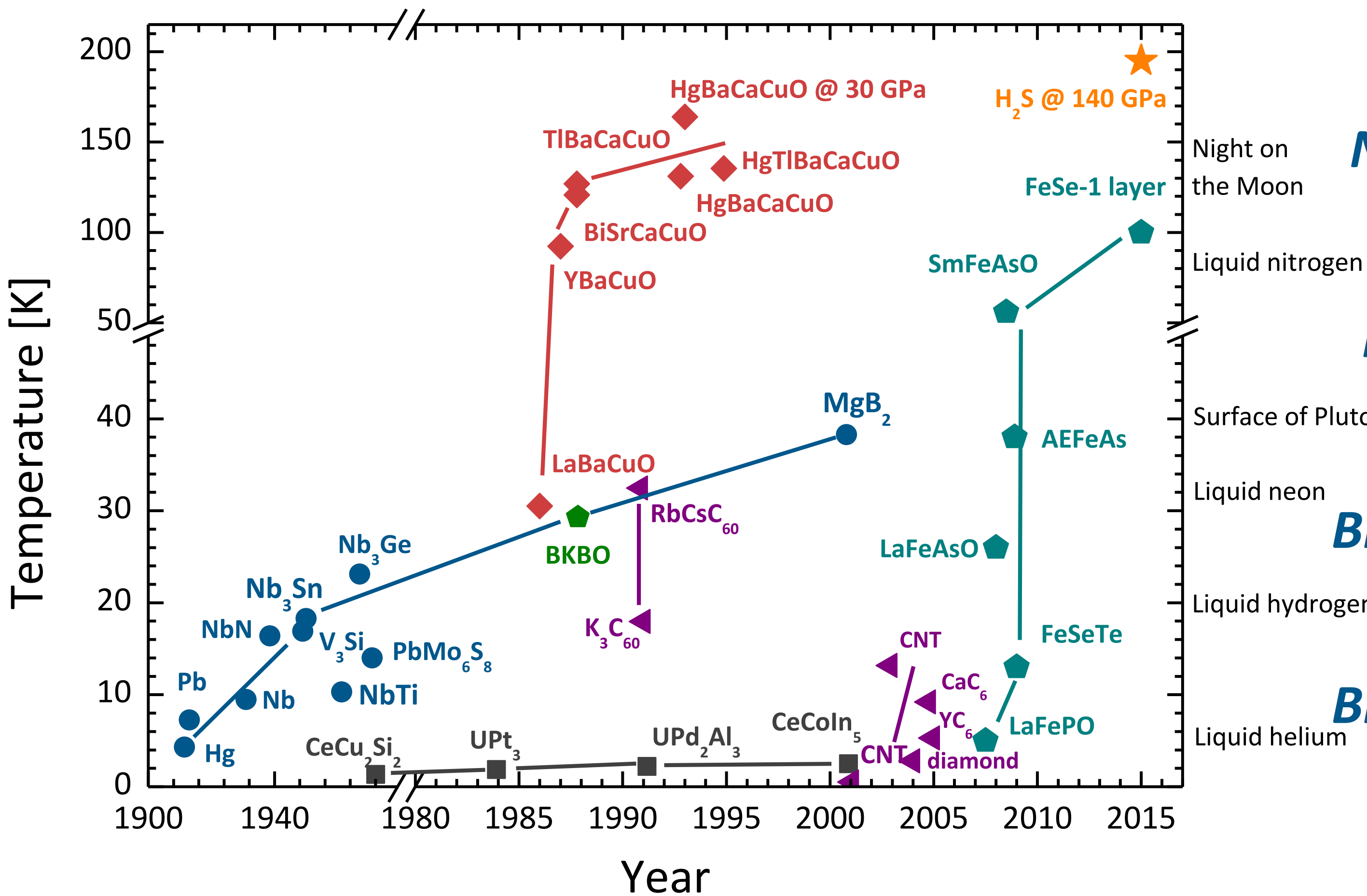
The triangle area is the magnetization of the sample

Critical state: Hysteresis loop

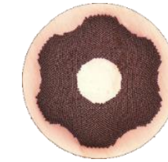
Hysteresis ≡ LOSSES



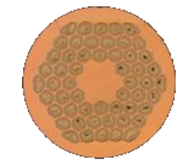
Superconductors History



NbTi

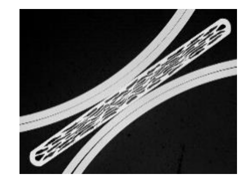


Nb_3Sn



MgB_2

Bi2223



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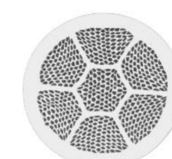
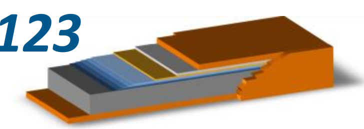
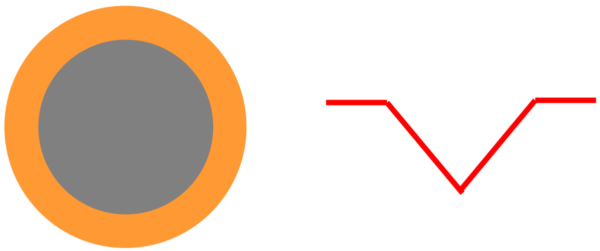


Y123



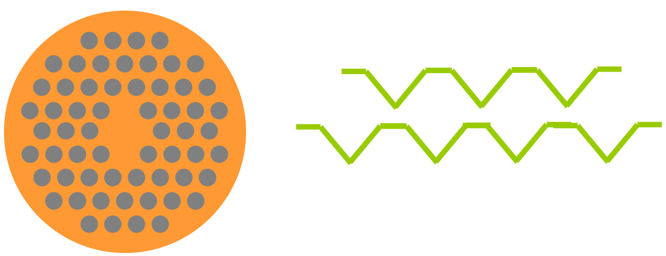
Why superconducting wires are (almost) all multifilamentary ?

Why superconducting wires are all multifilamentary ?



$$\Delta M \propto J_c d$$

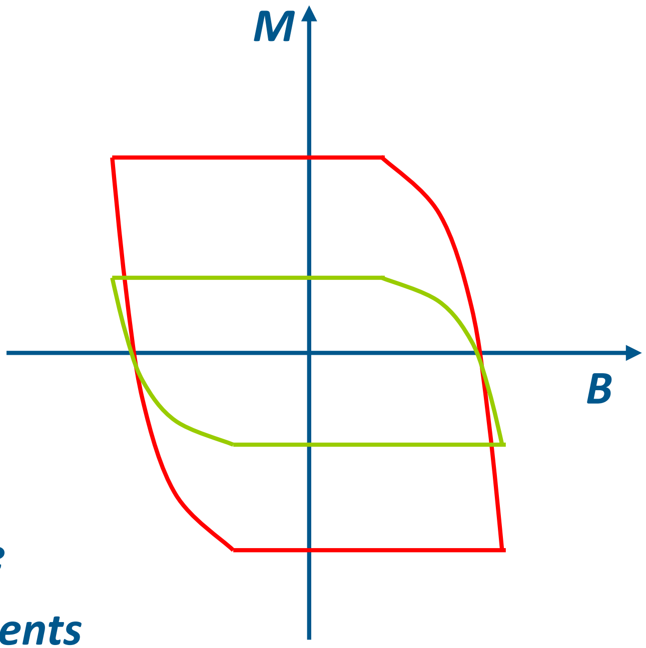
d is the filament size



$$\Delta M \propto n J_c d$$

d is the filament size

n is the number of filaments



With the subdivision of the superconducting layer in filaments, hysteretic losses are reduced but the critical current $I_c = J_c A_{SC}$ is unchanged

… but this is not the only reason …

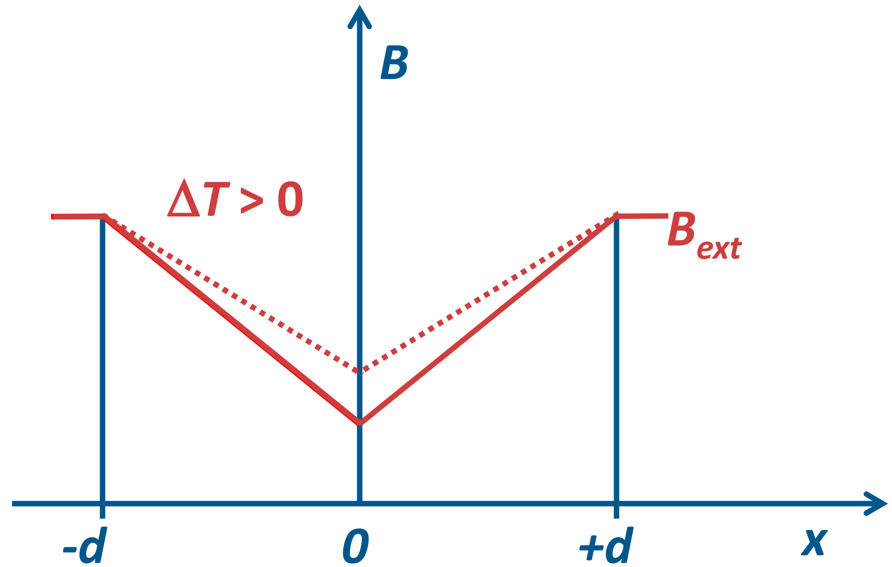
Flux jumps and Thermal instabilities

In the adiabatic approximation

$$\Delta T > 0 \quad \Rightarrow \quad \Delta J_c < 0$$

$$\Uparrow \qquad\qquad \Downarrow$$

$$\Delta Q > 0 \quad \Leftarrow \quad \Delta E > 0$$



If ΔQ_{ext} is the initial perturbation, the heat balance for the slab is

$$c\Delta T = \Delta Q_{ext} + \frac{\mu_0 J_c^2 d^2}{3\left(T_c - T_{op}\right)}\Delta T$$

Because of the energy stored in the current, the effective specific heat is

$$c_{eff} = \frac{\Delta Q_{ext}}{\Delta T} = c - \frac{\mu_0 J_c^2 d^2}{3\left(T_c - T_{op}\right)}$$

c_{eff} can become zero $\Rightarrow$ ultimate thermal catastrophe !!

Flux jumps and Thermal instabilities

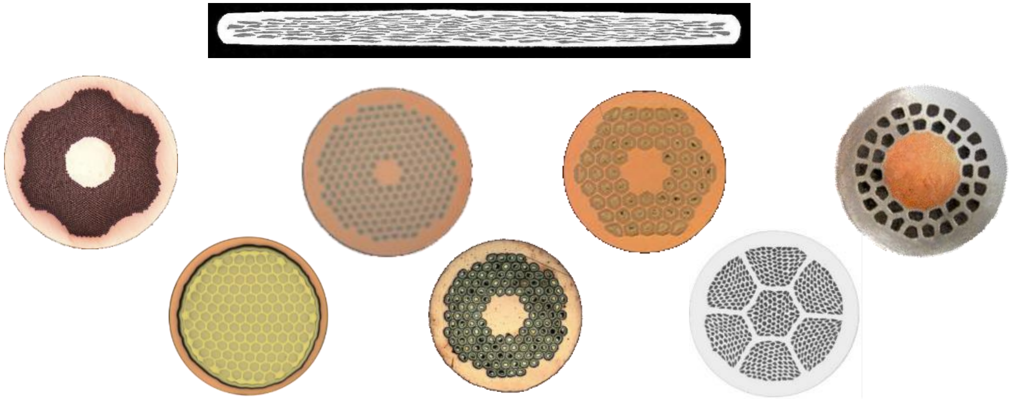
The stability condition is

$$c_{eff} = c - \frac{\mu_0 J_c^2 d^2}{3\left(T_c - T_{op}\right)} > 0$$

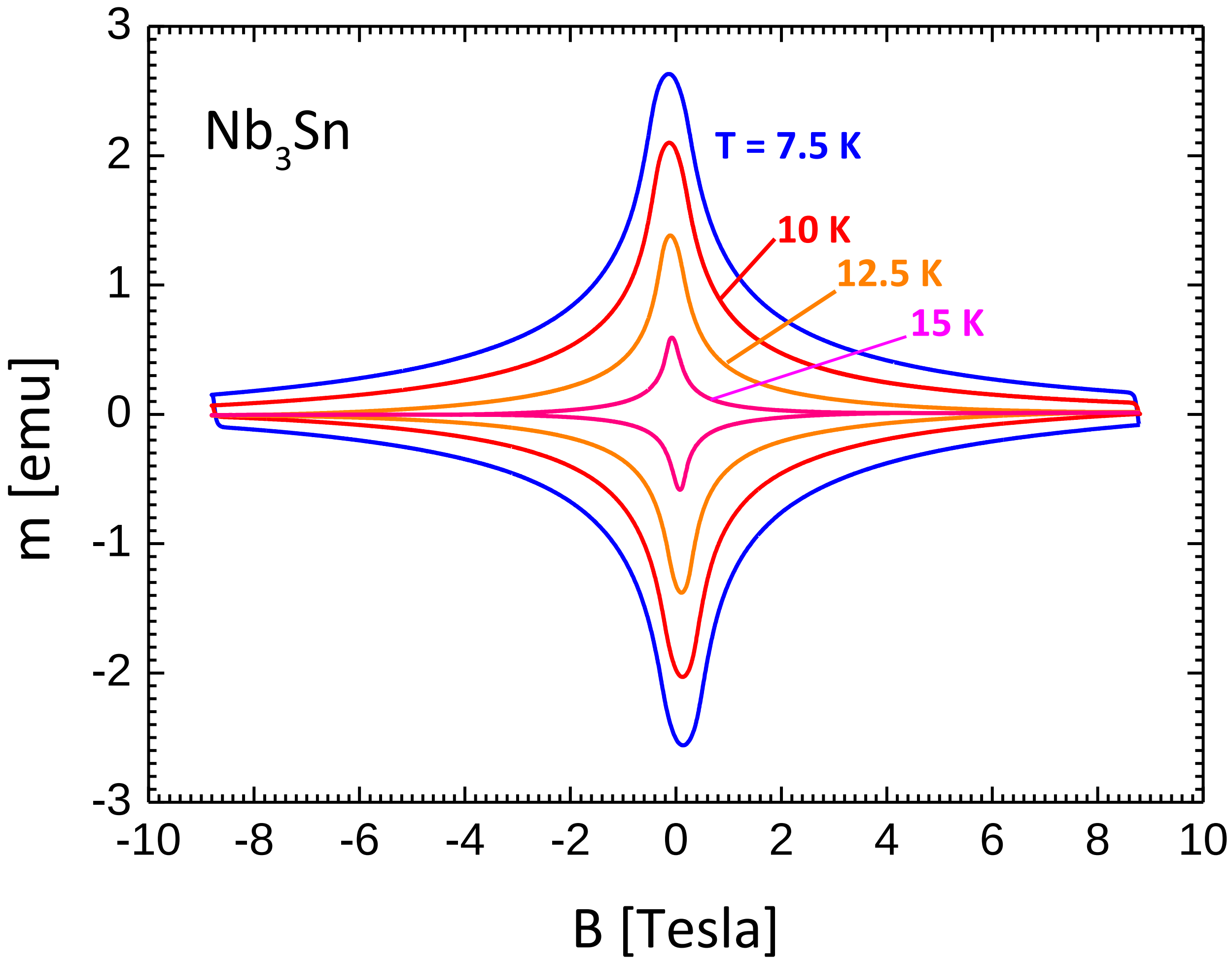
A superconducting wire must be designed in such a way that

$$\frac{\mu_0 J_c^2 d^2}{c\left(T_c - T_{op}\right)} < 3$$

And this demands the subdivision of the superconductor in fine filaments

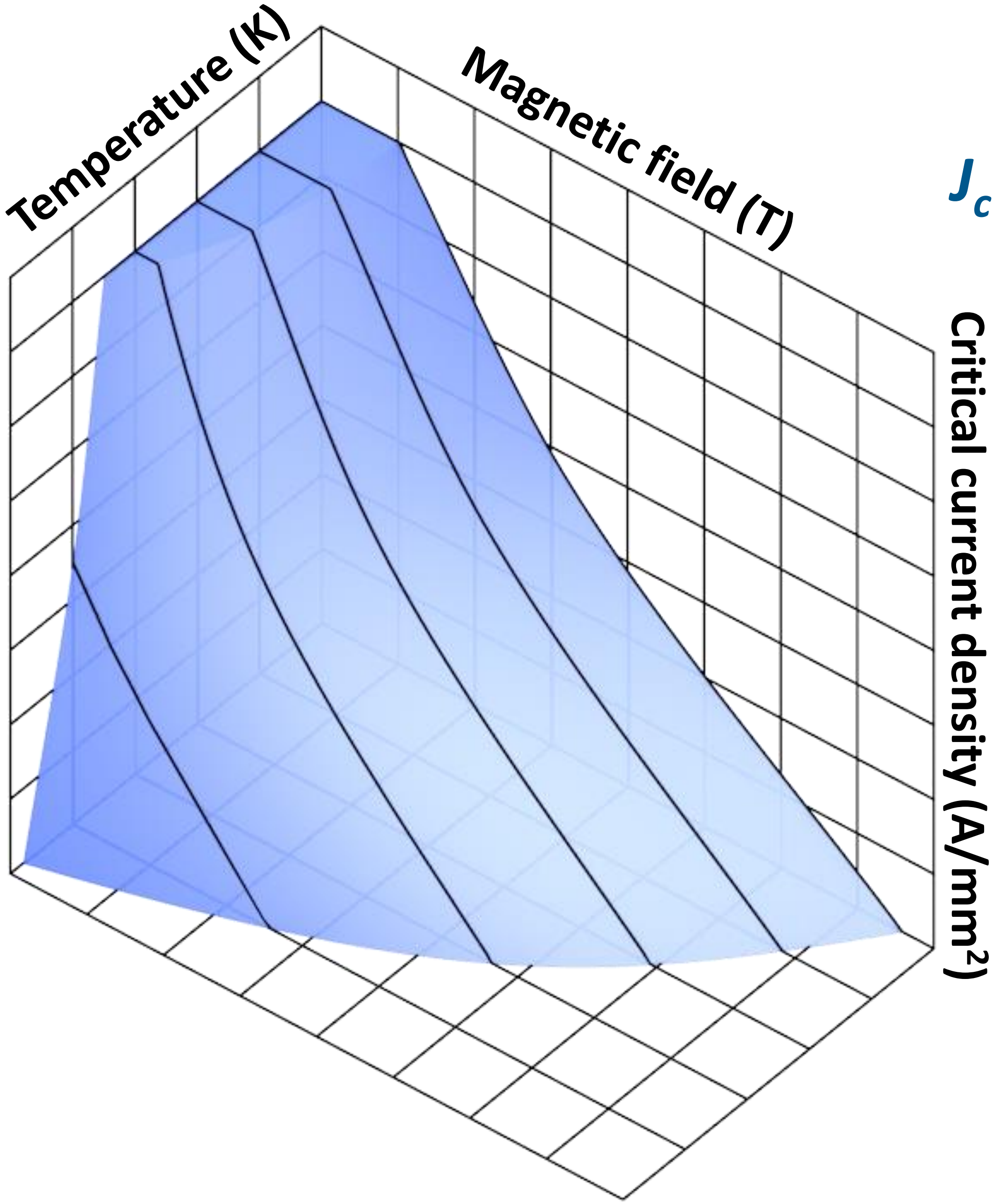


Field and temperature dependence of J_c



$$\Delta M = \Delta M(B,T) \;\Rightarrow\; J_c = J_c(B,T)$$

The critical surface $J_c(B,T,...)$

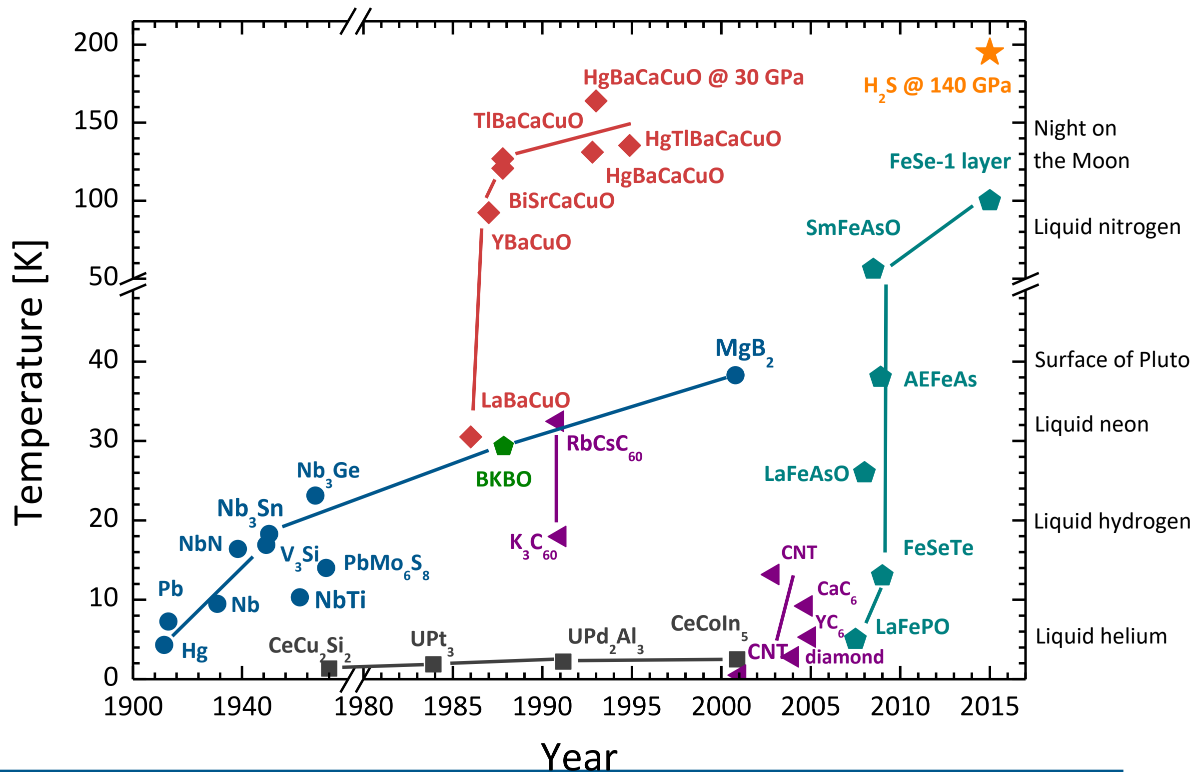


J_c depends also on:

- *the applied stress*
- *the magnetic field orientation (only for anisotropic superconductors)*

From superconducting materials…

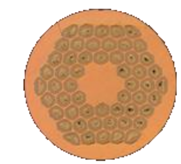
…to technical superconductors



1. *Superconducting ?* *10'000*
2. *T_c>4.2K & B_{c2}>10T ?* *100*
3. *J_c>1000 A/mm² ?* *~10*

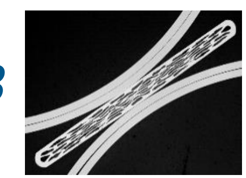
NbTi

Nb_3Sn

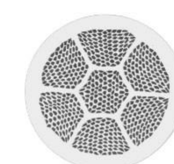


MgB_2

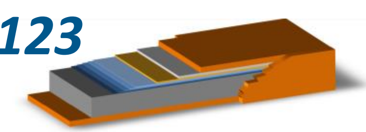
Bi2223



Bi2212



Y123



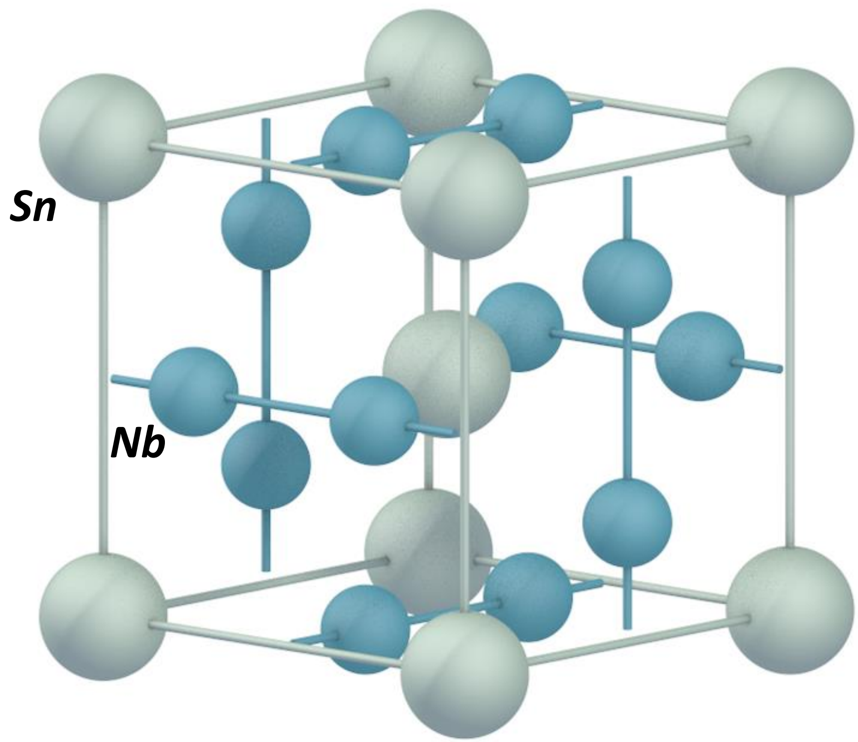
In the following…

Nb_3Sn → the HiLumi HL-LHC PROJECT superconductor and only candidate material for the 16 T dipoles of FCC hh ee he EuroCirCol

YBCO → the way to get 20 T dipoles and beyond

EuCARD² ARIES

Introduction to Nb_3Sn



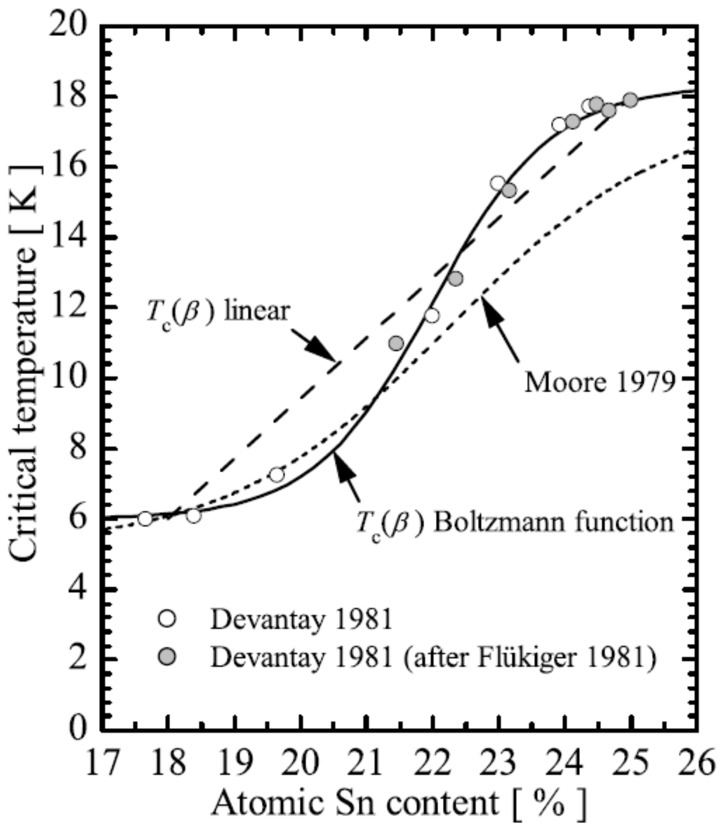
B \ A_3	Ti	Zr	V	Nb	Ta	Cr	Mo
	4	4	5	5	5	6	6
Al 3			11.8	18.8			0.6
Ga 3			16.8	20.3			0.8
In 3			13.9	9.2			
Tl 3				9			
Si 4			17.1	19			1.7
Ge 4			11.2	23.2	8.0	1.2	1.8
Sn 4	5.8	0.9	7.0	18.0	8.4		
Pb 4		0.8		8.0	17		
As 5			0.2				
Sb 5	5.8		0.8	2.2	0.7		
Bi 5		3.4		4.5			
Tc 7							15.0
Re 7							15.0
Ru 8						3.4	10.6
Os 8			5.7	1.1		4.7	12.7
Rh 9			1.0	2.6	10.0	0.3	
Ir 9	5.4		1.7	3.2	6.6	0.8	9.6
Pd 10			0.08				
Pt 10	0.5		3.7	10.9	0.4		8.8
Au 11		0.9	3.2	11.5	16.0		

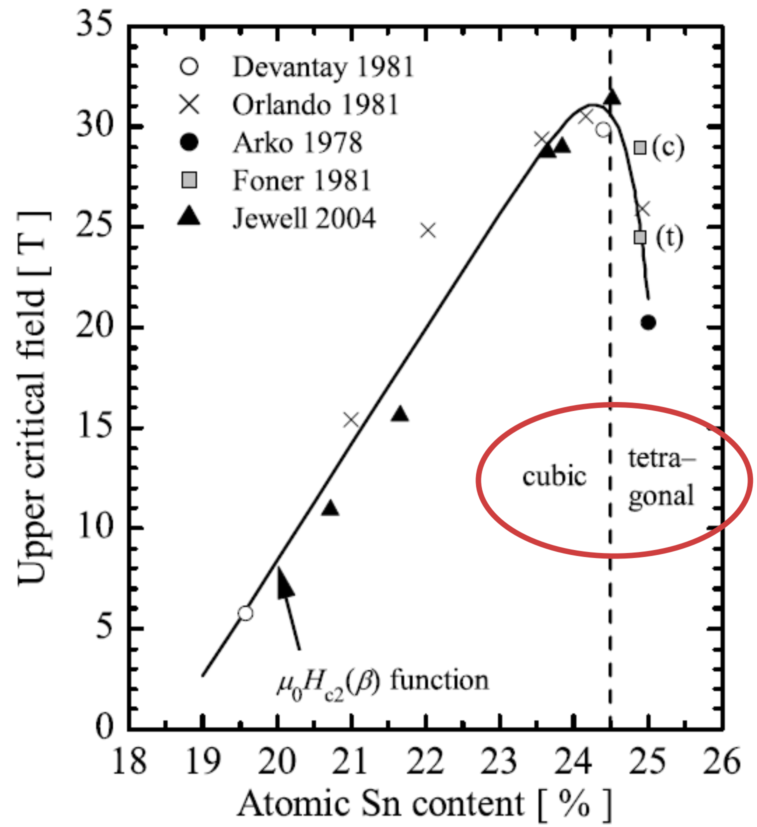
Nb_3Sn is the prototype of A15 superconductors

B.T. Matthias et al., PR 95 (1954) 1435

A15 are intermetallic compounds with A_3B formula

Nb_3Sn : the Superconductor for high fields (today)





	T_c [K]	B_{c2} [T]
Nb_3Sn	18.0	30+

$Nb_{3+x}Sn_{1-x}$ is superconducting also when deviates from stoichiometry

A. Godeke, SuST 19 (2006) R68

How to rise H_{c2} – Let's play it dirty

For a clean, ordered superconductor

$$H_{c2} = \frac{\Phi_0}{2\pi\xi^2}$$

Disorder reduces the electron mean free path ℓ, which in turn leads to decrease of ξ

$$\frac{1}{\xi(\ell)} = \frac{1}{\xi(\infty)} + \frac{1}{\ell}$$

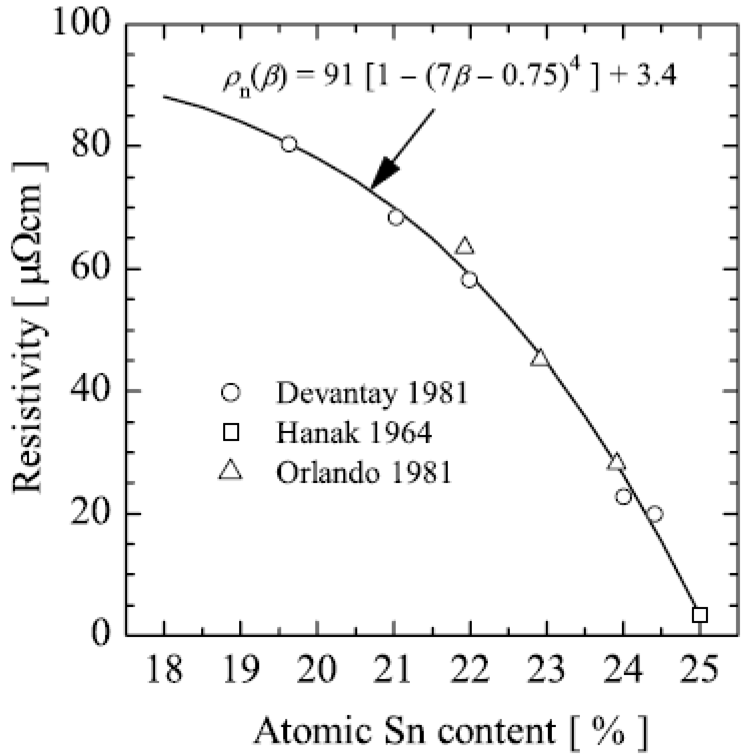
An useful expression of H_{c2} in the dirty limit

$$H_{c2}(T=0) \cong \frac{k_B e}{\mu_0} N(E_F)\rho_n T_c \propto \gamma\rho_n T_c$$

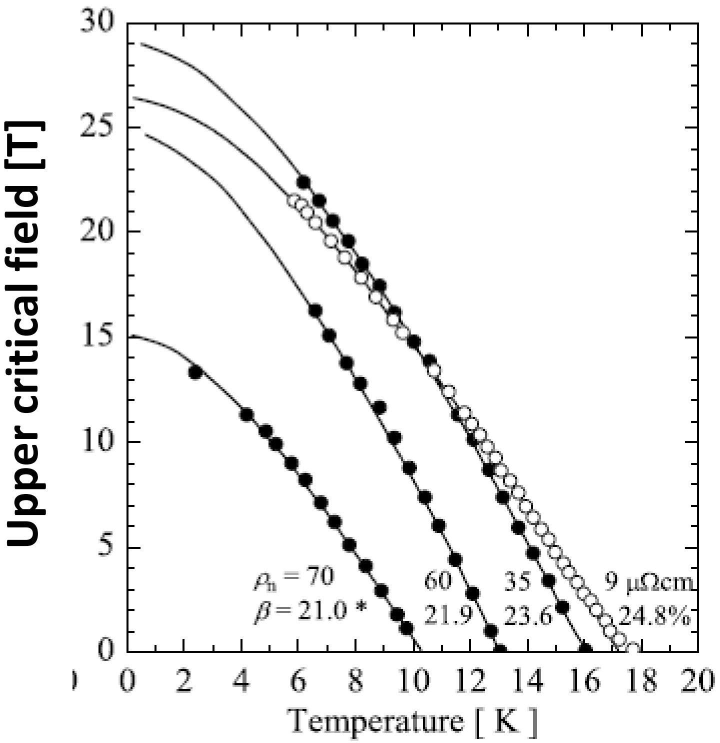
How to rise H_{c2} in Nb_3Sn

$H_{c2} \propto \gamma \rho_n T_c$

Resistivity vs. Sn at.%



H_{c2} vs. T at various Sn at.%



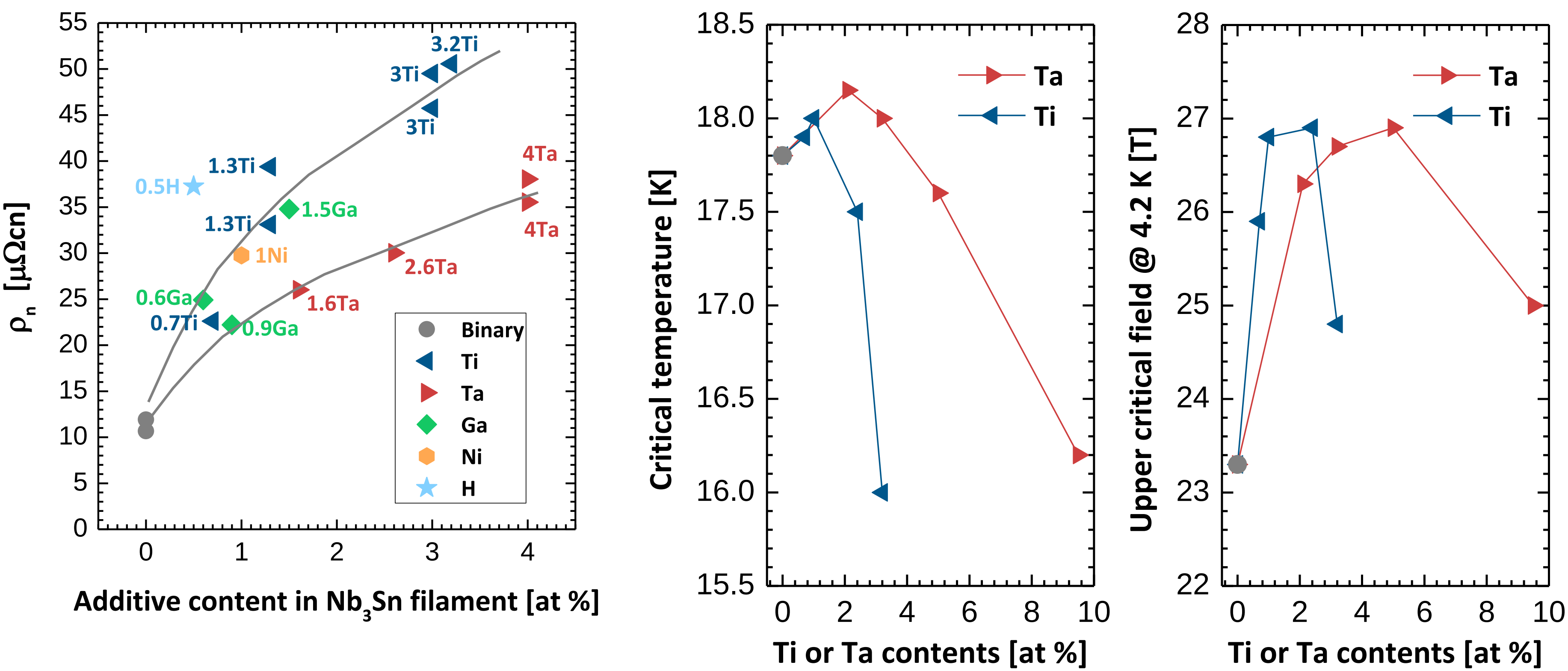
Reducing Sn content rises ρ_n, but reduces T_c. Other ideas ?

Graphs from A. Godeke, PhD Thesis, UTwente

Alloying (doping) Nb_3Sn to rise H_{c2}

$$H_{c2} \propto \gamma \rho_n T_c$$

The additions of Ta and Ti are particularly beneficial



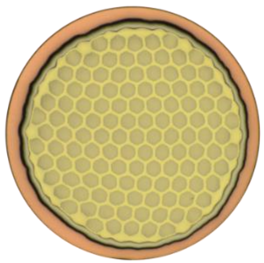
(Nb,Ta)$_3$Sn and Nb$_3$(Sn,Ti)

$$\frac{H_{c2}(4.2\ K)}{H_{c2}(0\ K)} = 0.89$$

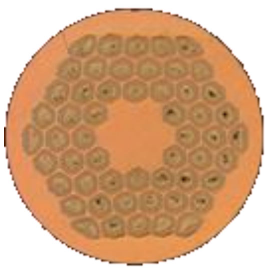
M. Suenaga et al., JAP 59 (1986) 840
R. Flükiger et al., Cryogenics 48 (2008) 293

Industrial fabrication of Nb_3Sn wires

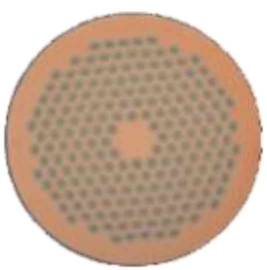
Three technologies have been developed at industrial scale



- *Bronze route*



- *Internal Sn diffusion*

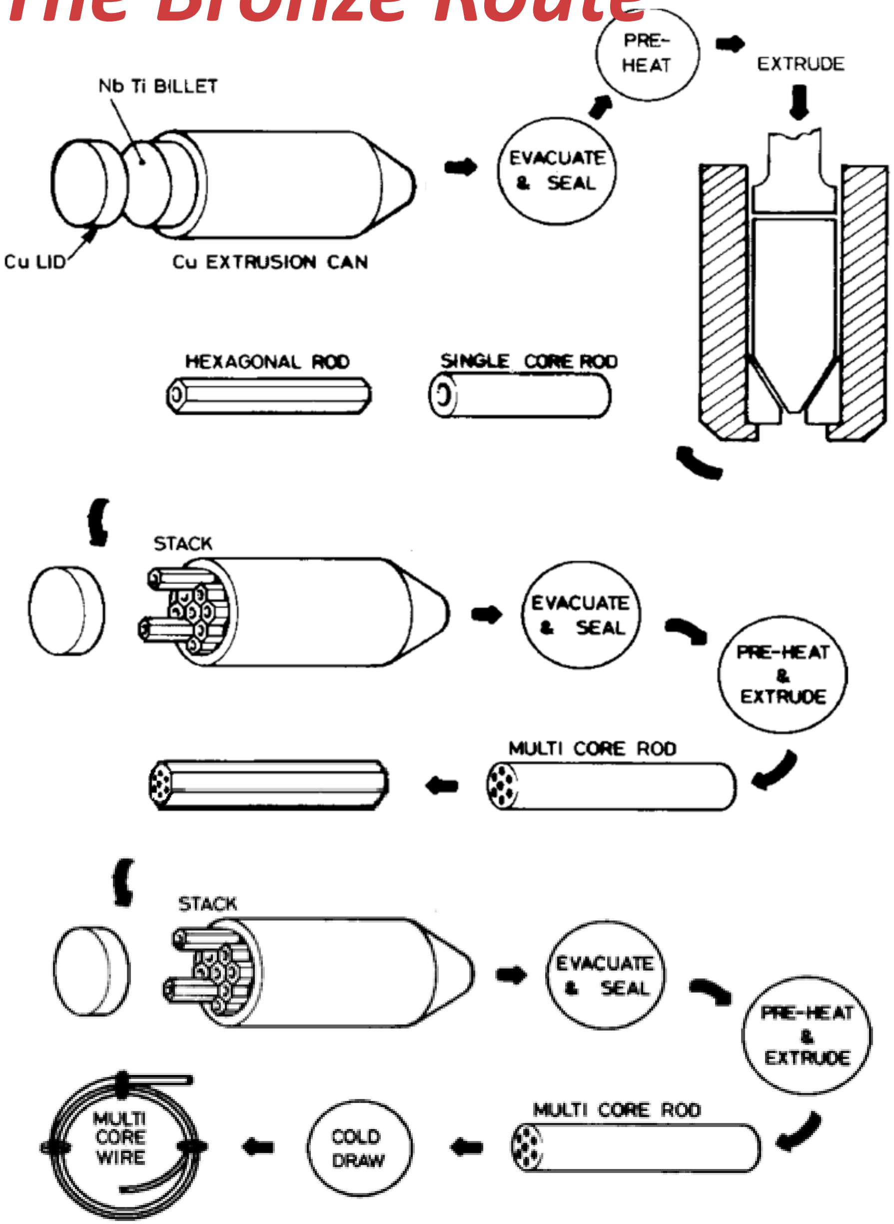


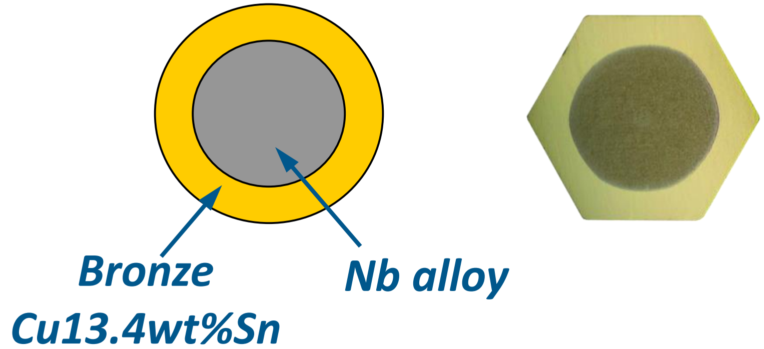
- *Powder in tube*

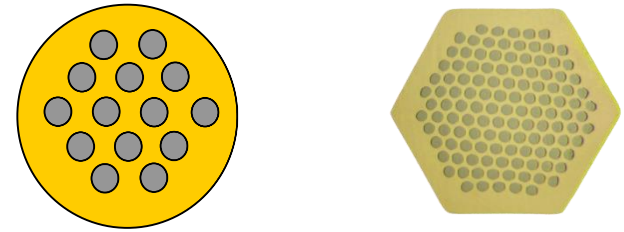
The Sn source is the main difference

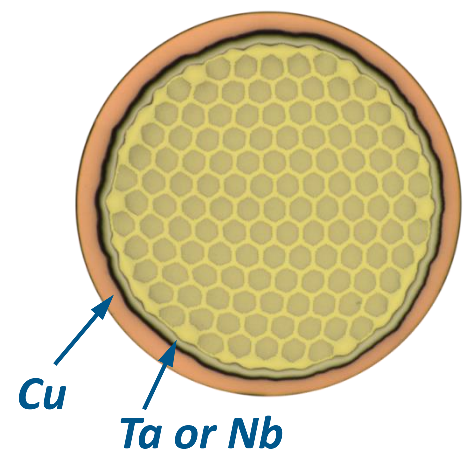
Presently produced by BRUKER, LUVATA, Western Superconducting Technologies Co.,Ltd., BOCHVAR INSTITUTE OF INORGANIC MATERIALS JSC VNIINM, Kiswire, KOBELCO KOBE STEEL, LTD., JASTEC SUPERCONDUCTOR

The Bronze Route







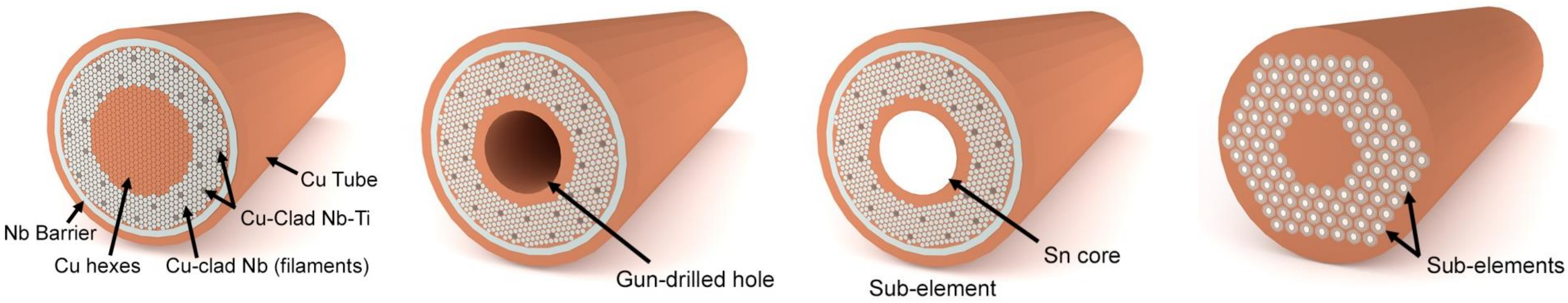


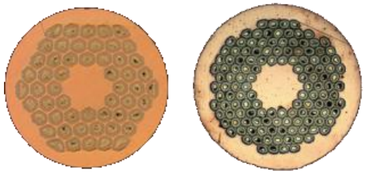
Cu-Sn bronze is used as Sn source

The final filament size is ~5 µm

Wires are then reacted at ~650°C for >100 hours to form Nb_3Sn

The Internal Sn diffusion process

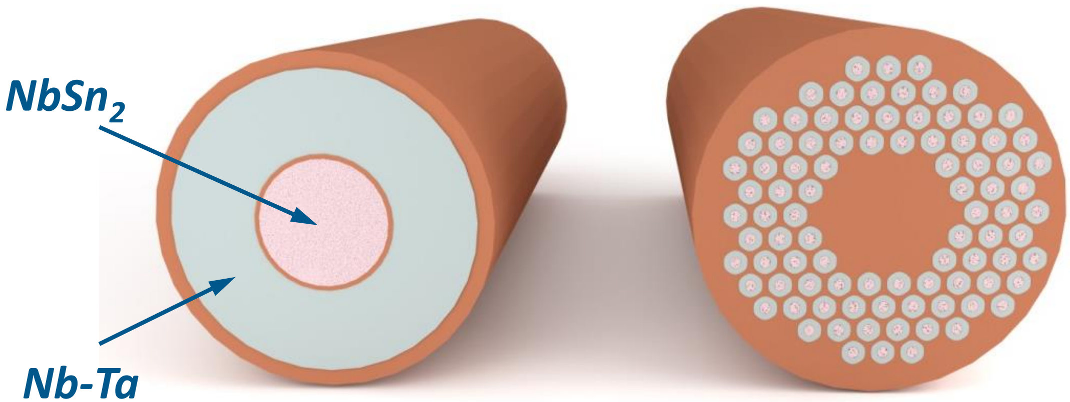




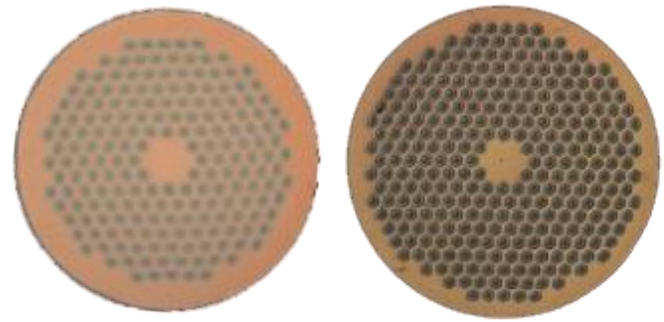
- A Sn rod is inserted in the subelement core
- After the insertion of Sn, only cold deformations are possible
- Subelement size ranges between 20 and 100 µm
- A long-duration multistep reaction schedule is required to form Nb_3Sn

Pictures from C. Sanabria, PhD Thesis, FSU

The Powder-In-Tube method



Powder-in-Tube filament   Powder-in-Tube stack

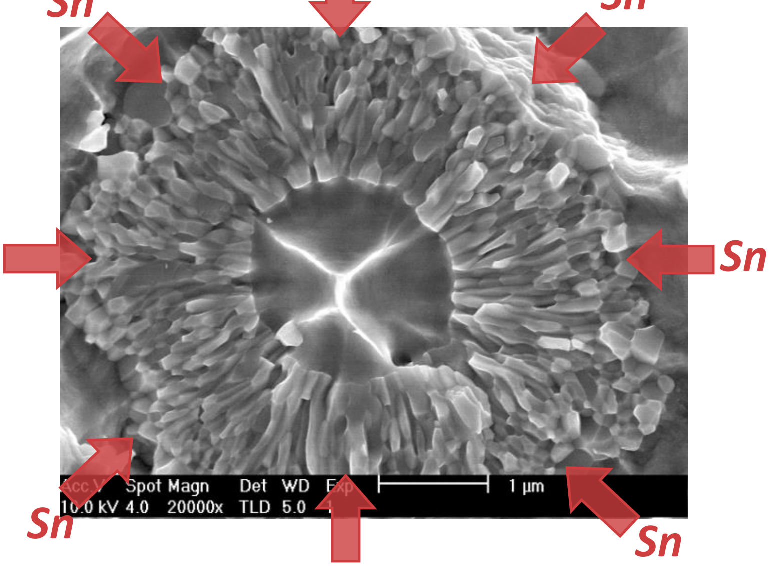


- ***$NbSn_2$ and Sn powders are used as Sn source***
- ***Subelement size ranges between 20 and 100 µm***
- ***A long-duration multistep reaction schedule is required to form Nb_3Sn***

Pictures from C. Sanabria, PhD Thesis, FSU

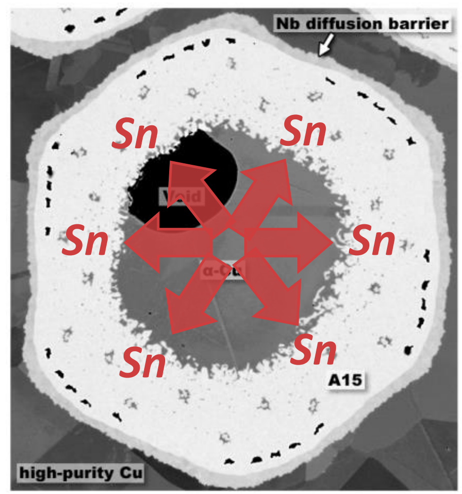
Microstructure of the A15 phase after reaction

Bronze route



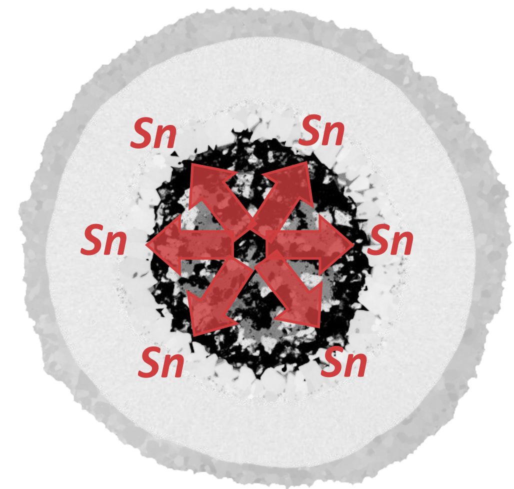
Filament size ~5 µm

Internal Sn



Subelement size ~50 µm

Powder-In-Tube



Filament size ~50 µm

High Sn content & appropriate Ta/Ti doping to get high B_{c2} and thus high in-field J_c

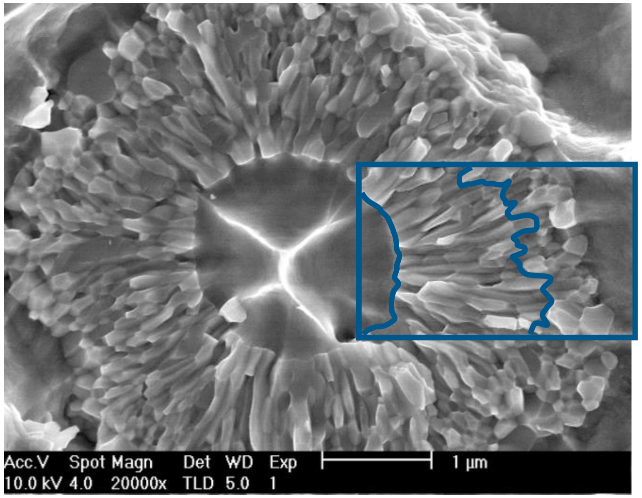
Also microstructure is directly related to the J_c performance

Grain boundaries act as the main vortex pinning centers

Small grain size implies high grain boundary density and thus high J_c

Microstructure of the A15 phase after reaction

Bronze route

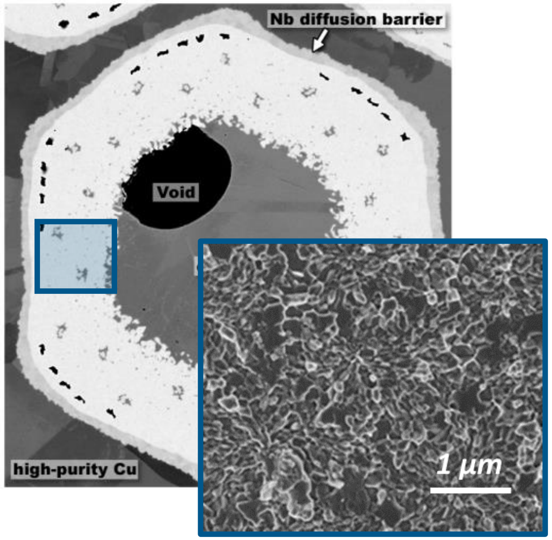


Filament size ~5 µm

Outer region
Equiaxed grains ~ 150 nm
21-25 at.% Sn

Inner region
Columnar grains ~ 400 nm
18-21 at.% Sn

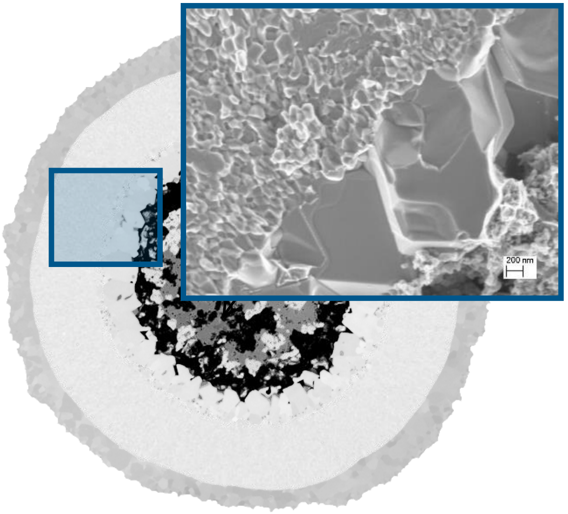
Internal Sn



Subelement size ~50 µm

Almost everywhere
Fine grains ~ 150 nm
24-25 at.% Sn

Powder-In-Tube



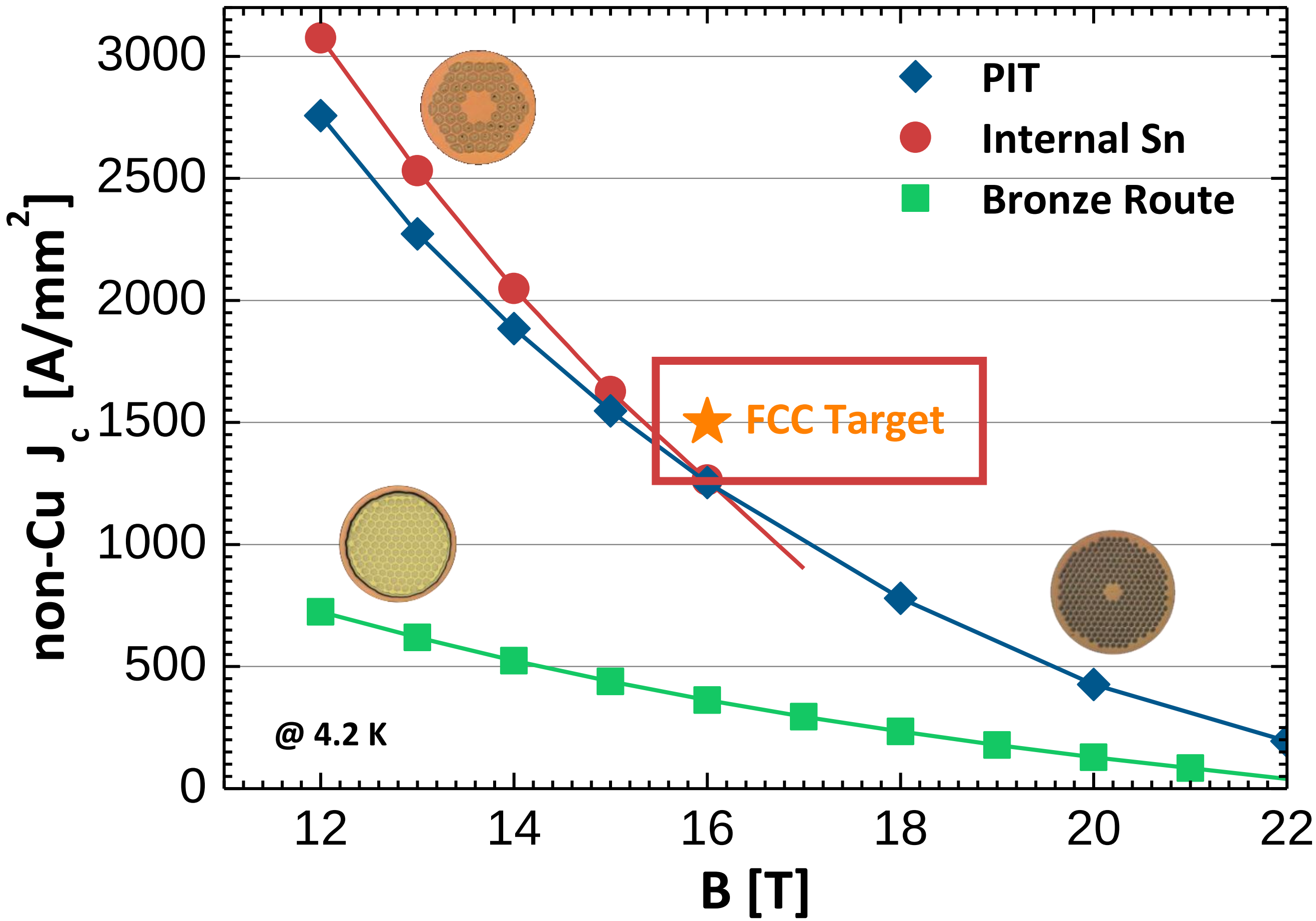
Filament size ~50 µm

Outer region
Fine grains ~ 150 nm
23-24 at.% Sn

Inner region
Large grains ~ 1 µm
25 at.% Sn

Critical current density vs. magnetic field

Best performance achieved so far in industrial wires



How do we get the ultimate Nb_3Sn?

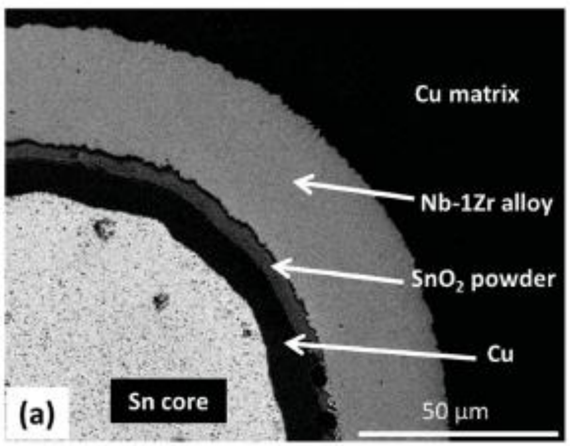
Internal oxidation and grain refinement in Nb_3Sn

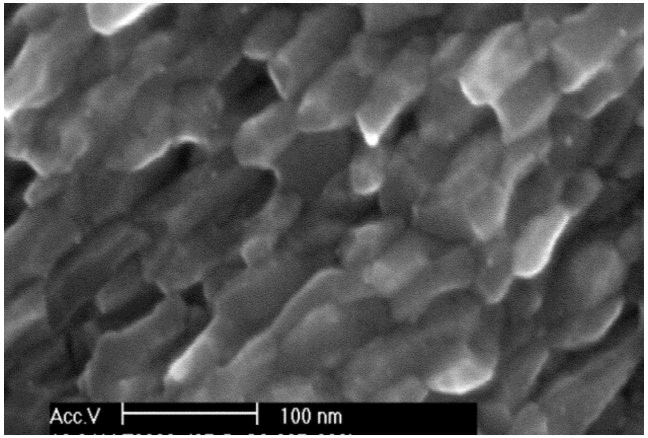
@ Ohio State University

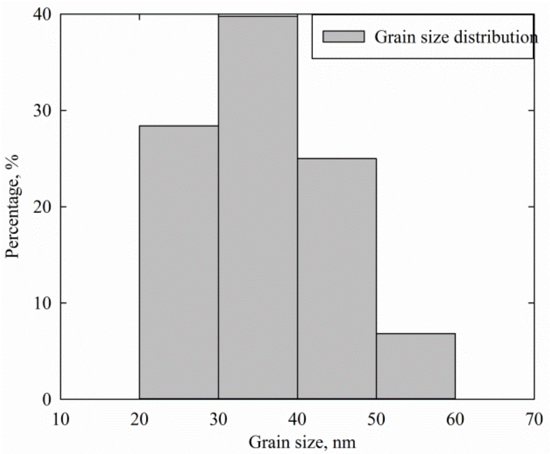
Idea to form fine precipitates in Nb to impede the A15 grain growth

Use of a Nb-Zr alloy: Zr has stronger affinity to oxygen than Nb

Oxygen supply added to the composite: oxidation of Zr and formation of nano-ZrO_2







X. Xu et al., APL 104 (2014) 082602

X. Xu et al., Adv. Mat. 27 (2015) 1346

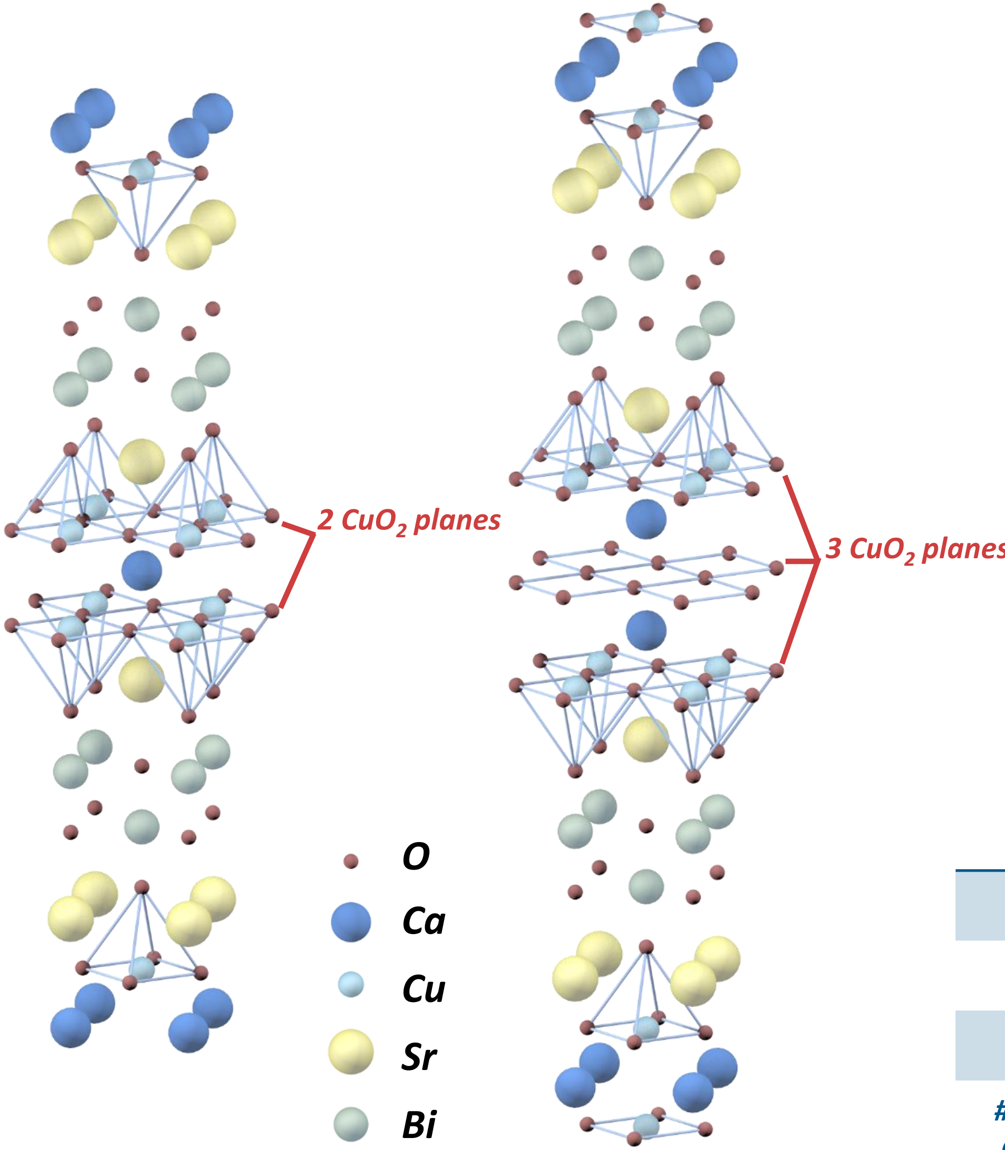
Average grain size is reduced down to 36 nm

Greatly enhanced pinning in binary Nb_3Sn

Result need to be transferred to Ti- and Ta- alloyed Nb_3Sn

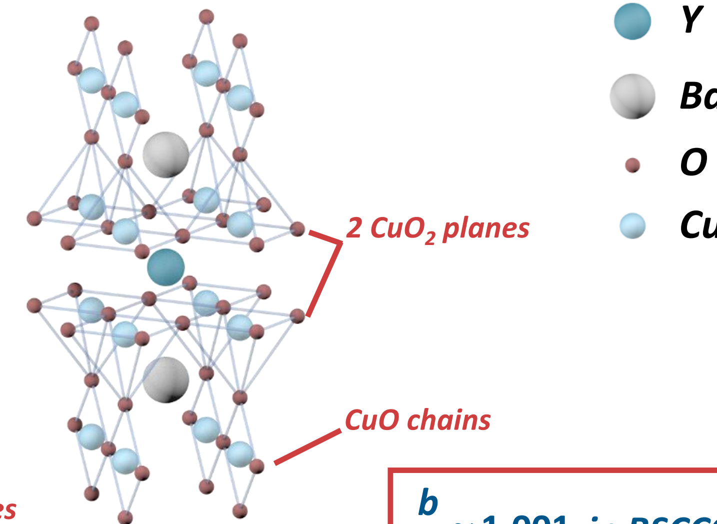
High Temperature Superconductors are different animals …

HTS materials for applications



Bi2212
$Bi_2Sr_2CaCu_2O_{8+x}$

Bi2223
$Bi_2Sr_2Ca_2Cu_3O_{10+x}$



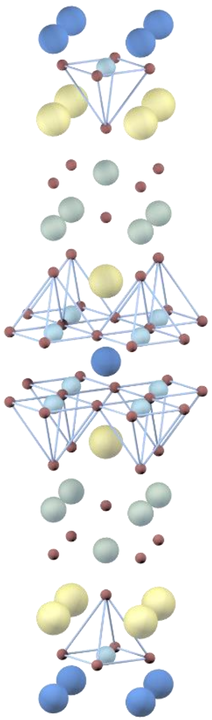
Y123
$YBa_2Cu_3O_{7-x}$

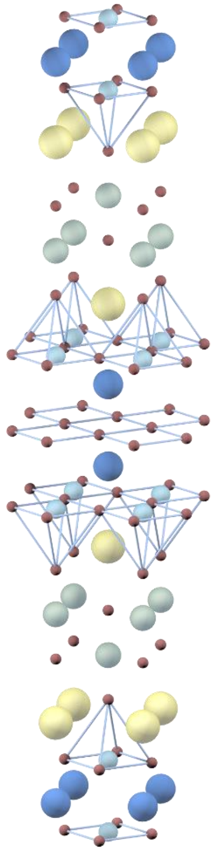
$$\frac{b}{a} \approx 1.001 \text{ in BSCCO}$$

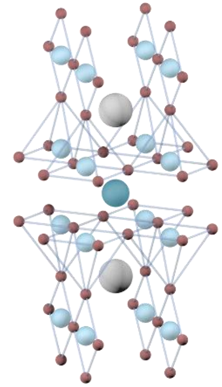
$$\frac{b}{a} \approx 1.02 \text{ in YBCO}$$

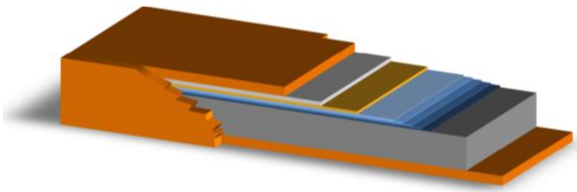
	Bi2212	Bi2223	Y123
a [Å]	5.415	5.413	3.8227
b [Å]	5.421	5.421	3.8872
c [Å]	30.880	37.010	11.680
# of adjacent CuO_2 planes	2	3	2
T_c [K]	91	110	92

The evolution to the present wires and tapes

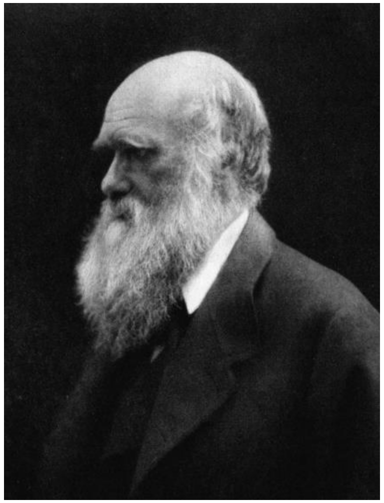




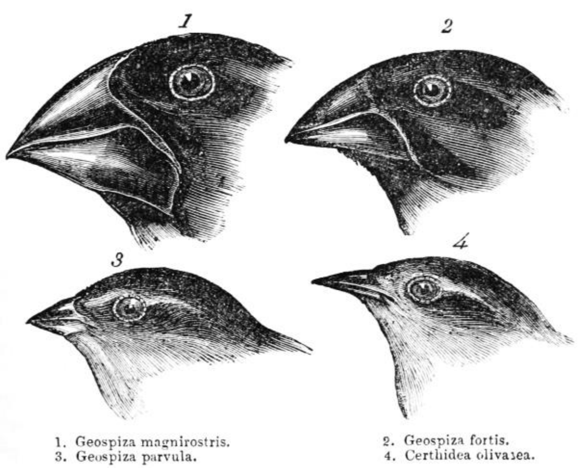


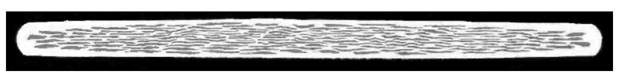


Y123 Coated Conductor



Darwin's finches

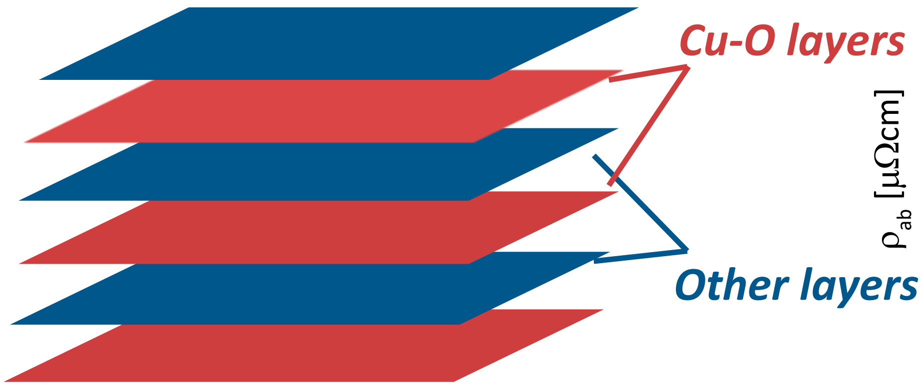


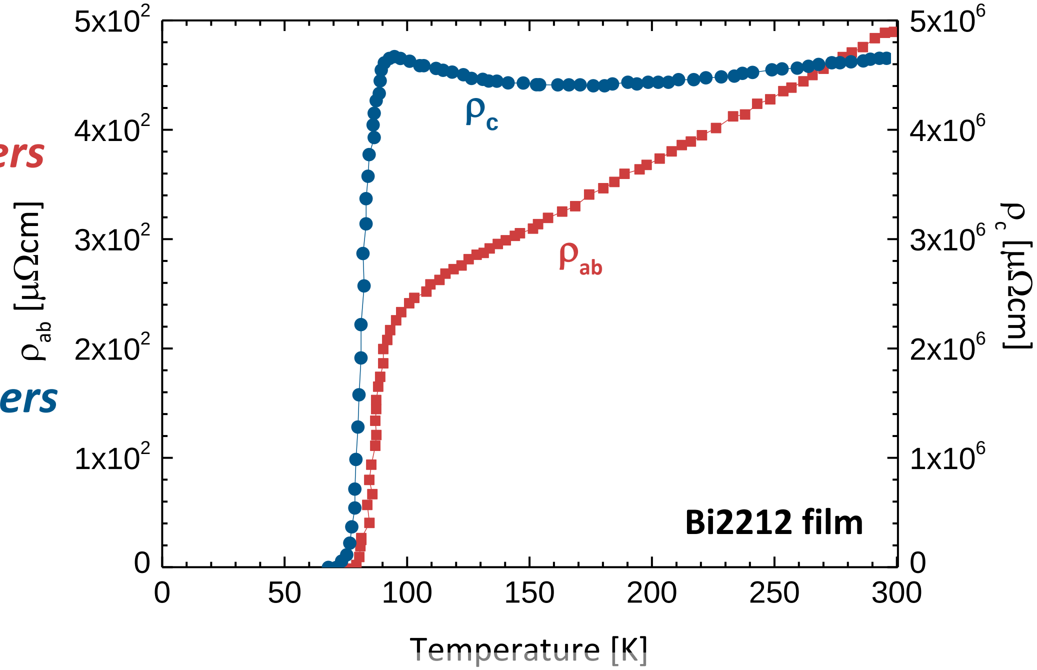


Bi2223 Powder-In-Tube tape

Bi2212
Powder-In-Tube wire

Layered structure and Anisotropy





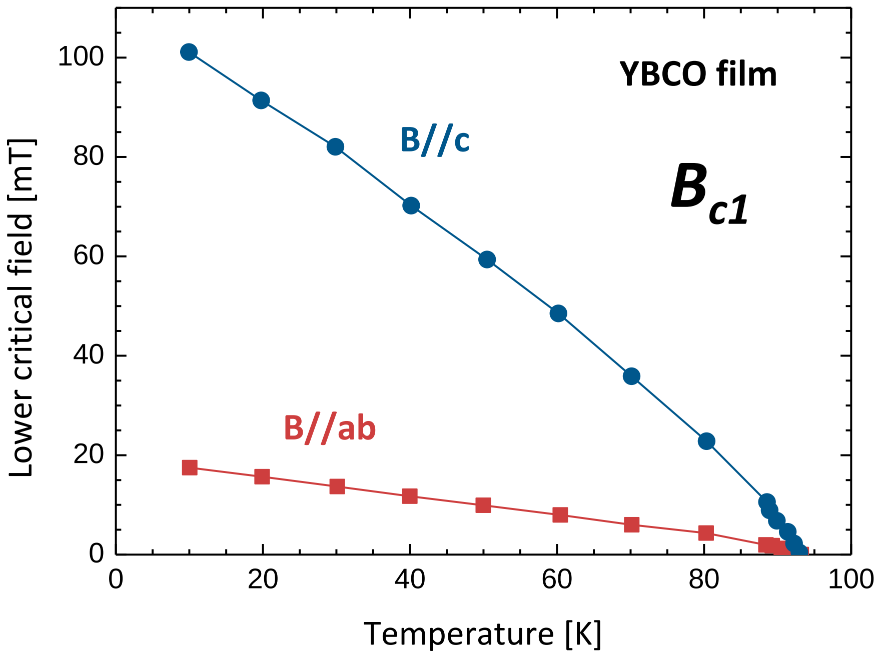
Raffy et al., Physica C 460-462 (2007) 851

Charge carriers have effective masses that depend on the crystallographic orientation

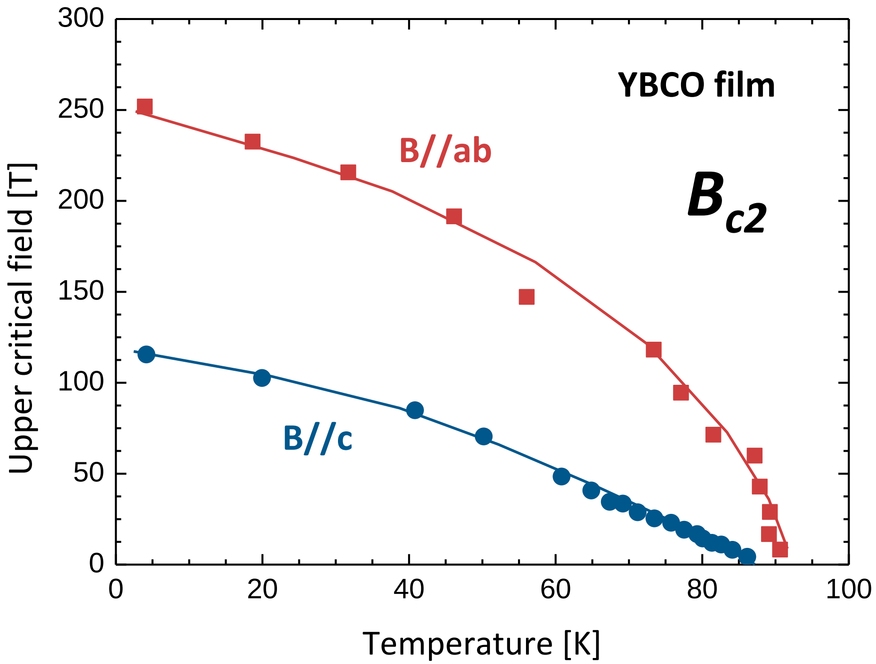
$\frac{m_c}{m_{ab}}$ ***ranges between 50 and 10'000 in cuprates***

The superconductor lengths depend on the carrier mass: $\xi \propto \frac{1}{\sqrt{m}}$ ***and*** $\lambda \propto \sqrt{m}$

Anisotropy of the critical fields B_{c1} and B_{c2}



Liang et al., PRB 50 (1994) 4212



Nagakawa et al., JPCM 10 (1998) 11571

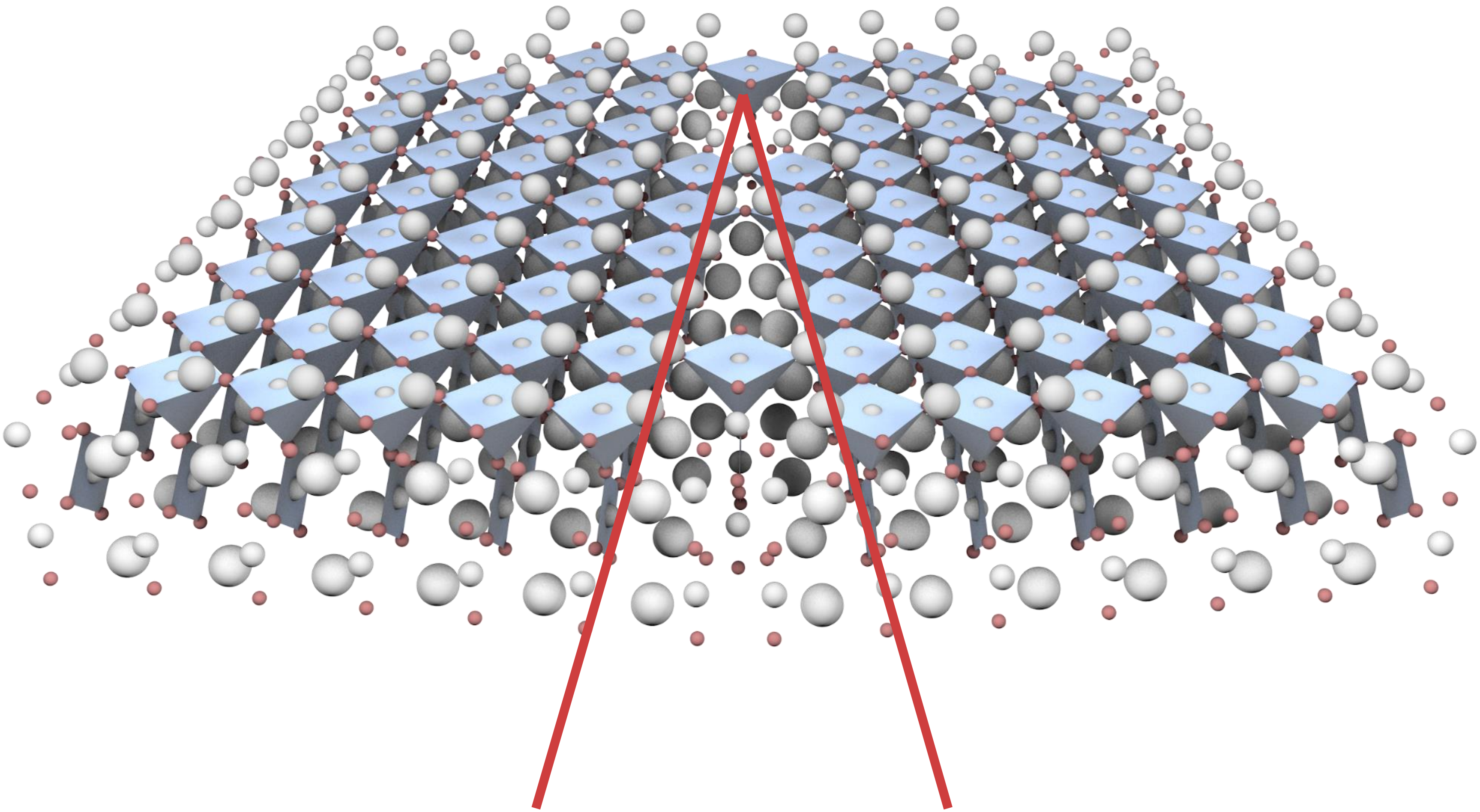
Sekitani et al., NJP 9 (2007) 47

The superconductor anisotropy parameter

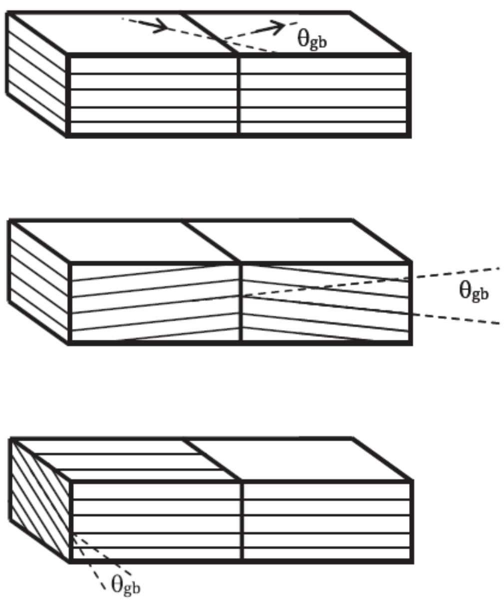
$$\gamma = \sqrt{\frac{m_c}{m_{ab}}} = \frac{\lambda_c}{\lambda_{ab}} = \frac{\xi_{ab}}{\xi_c}$$

	Bi2212	Bi2223	Y123
γ	~150	~30	~7

Grain Boundaries in HTS



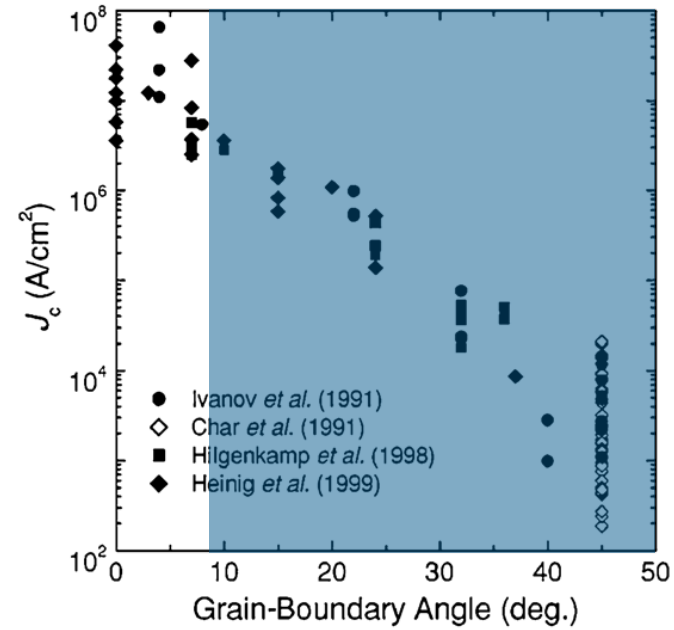
Grain boundaries in Y123 (YBCO)



[001] tilt boundary

[100] tilt boundary

[100] twist boundary



Hilgenkamp and Mannhart, RMP 74 (2002) 485

For angles above 8-10°, the J_c^{GB} is reduced by a factor >100 !!

In order to get high J_c in the conductor, biaxial texturing is needed

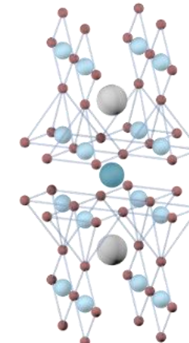
Alignment of the grains is needed in all crystallographic orientations

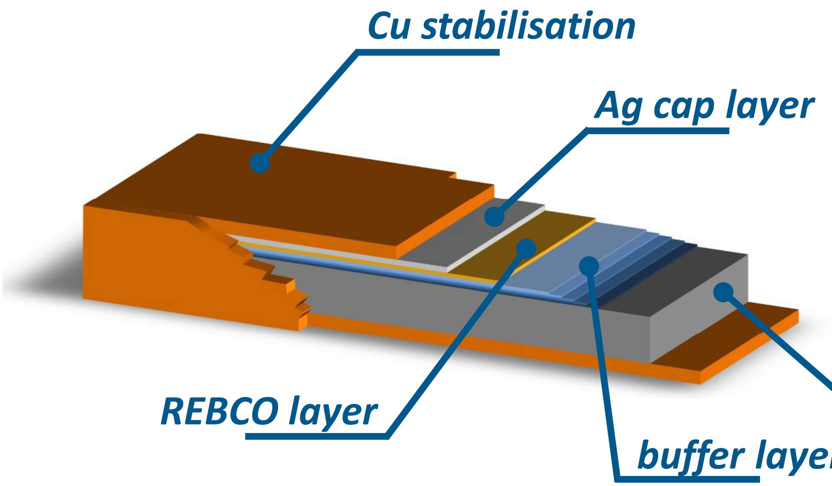
RE = Rare Earth

YBCO (REBCO) coated conductors

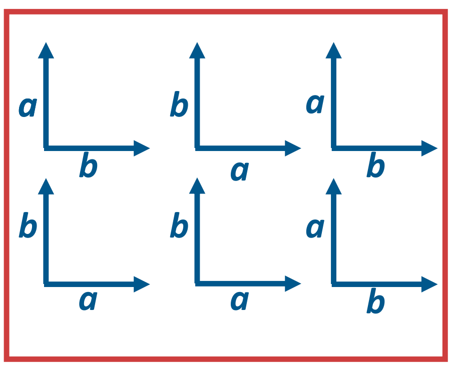
Iijima et al., APL 60 (1992) 769

Goyal et al., APL 69 (1996) 1795





~1 µm of REBCO in a ~100 µm thick tape



Looking from above

The template is a metallic substrate coated with a multifunctional oxide barrier

Biaxial texturing – within < 3° – is obtained

but with some also drawbacks:

- *pronounced anisotropic behaviour*
- *complex and expensive manufacturing process*

Presently produced by American Superconductor, BRUKER, Fujikura, SuNAM, SuperOx, SuperPower Inc. A Furukawa Company, STI, THEVA, Shanghai 上海超导, OXOLUTIA, deutsche nanoschicht, MetOx

The technology of REBCO coated conductors

Alternative approaches for growing epitaxial REBCO on flexible metallic substrates in km-lengths

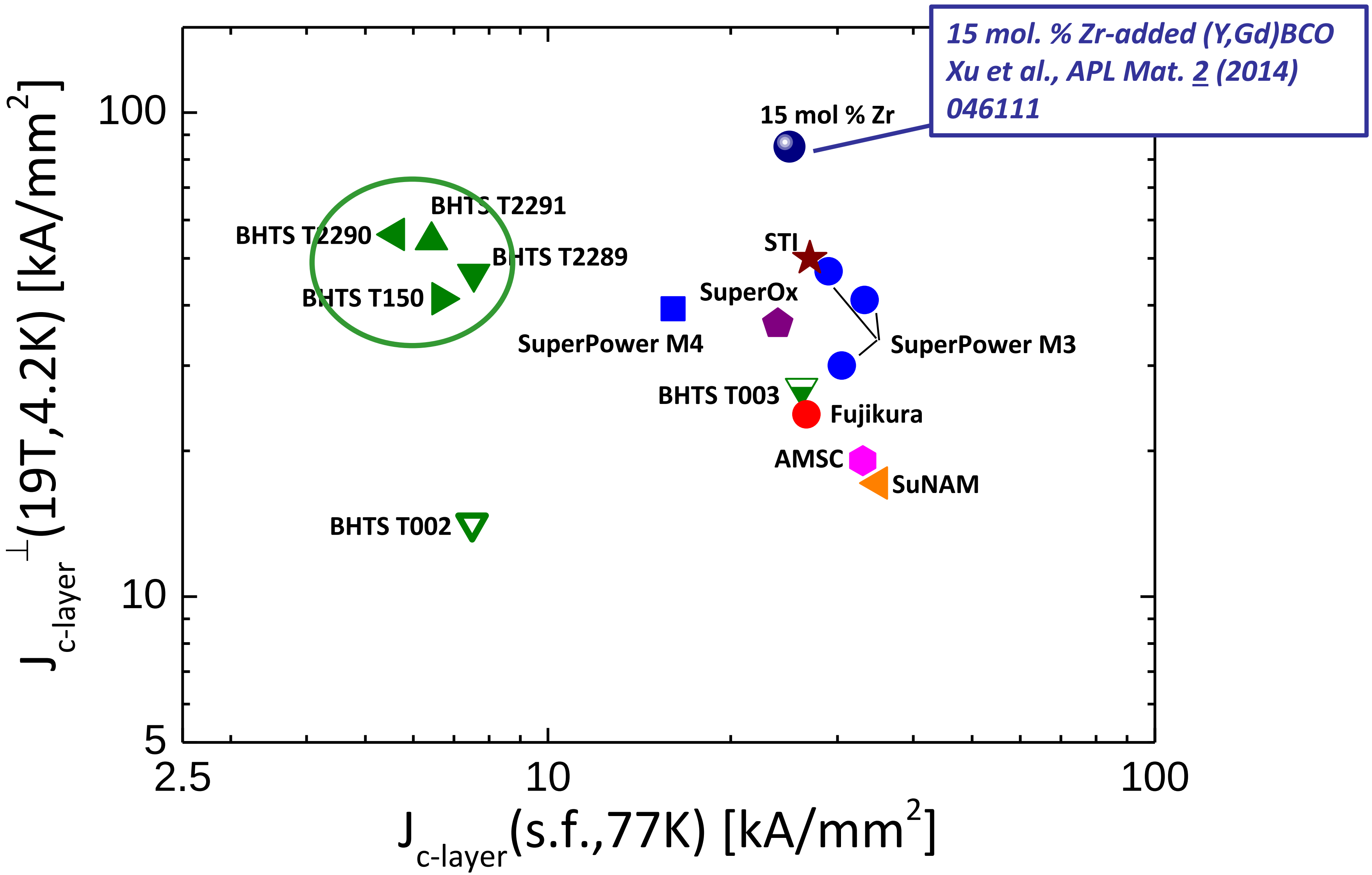
Substrate texturing

- **RABiTS : Rolling-Assisted, Biaxially Textured Substrates**
  Texture is created in NiW by a rolling-and-recrystallization process
- **IBAD : Ion Beam Assisted Deposition**
  A biaxially textured MgO layer is grown on polycrystalline Hastelloy

REBCO layer deposition

- **Physical routes**
  - **PLD** Pulsed Laser Deposition
  - **RCE** Reactive Co-Evaporation
- **Chemical routes**
  - **MOD** Metal-Organic Deposition
  - **MOCVD** Metal-Organic Chemical Vapor Dep.

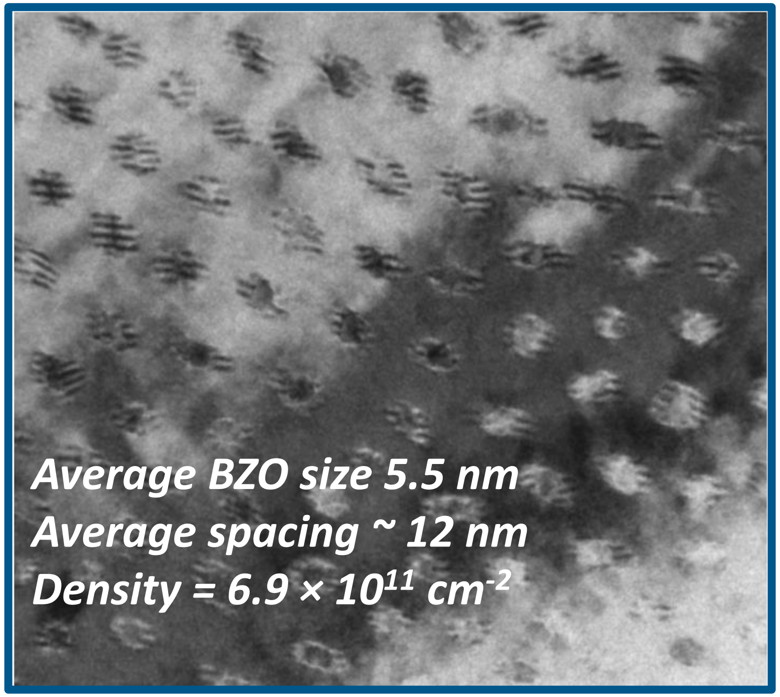
Performance overview: J_c(s.f.,77K) vs. $J_c^{\perp}$(19T,4.2K)



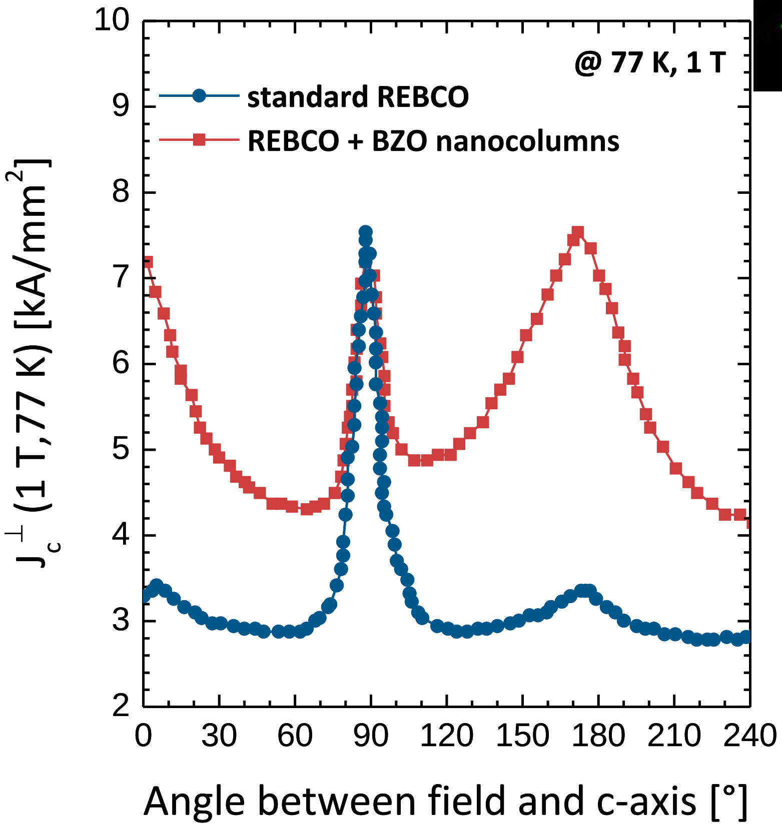
Artificial pinning:“genetically-modified” REBCO

Introduction of artificial nano-defects to control vortex pinning, reduce anisotropy and enhance performance

$BaZrO_3$ (BZO) precipitates are in form of nano-columns oriented along the c-axis

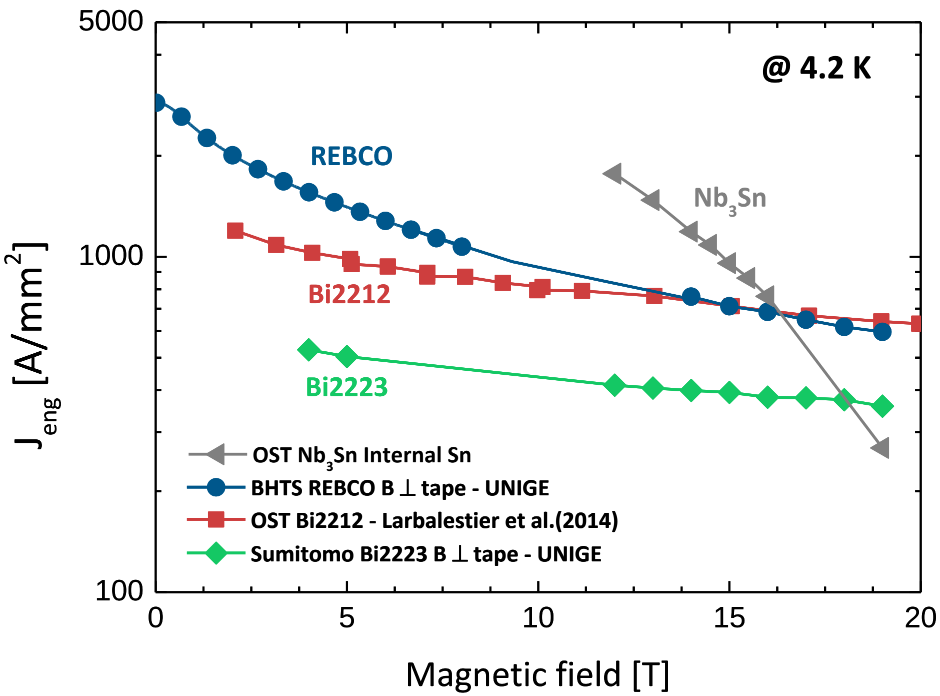


Selvamanickam el al., APL 106 (2015) 032601

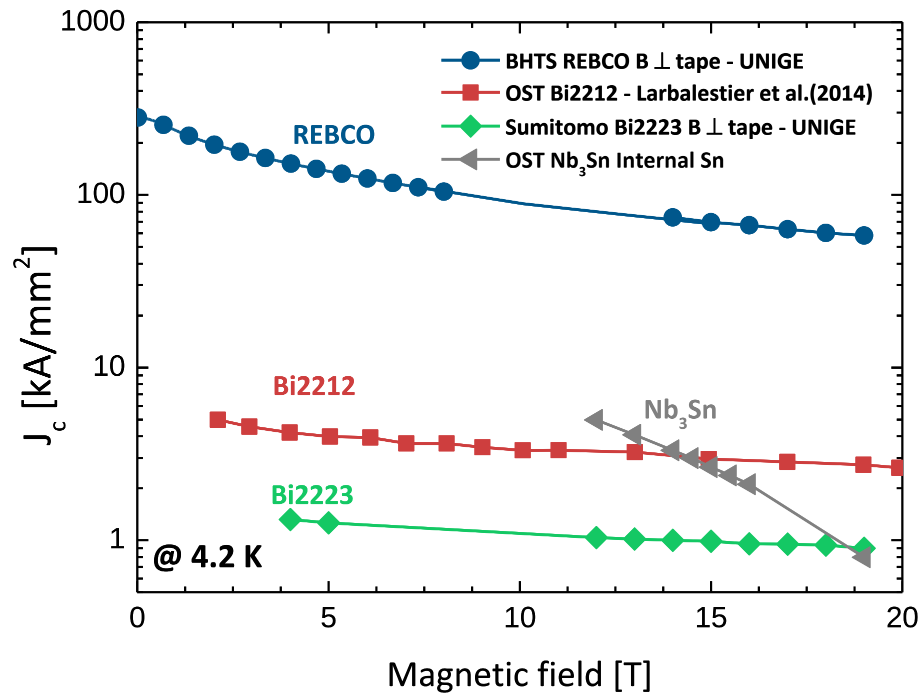


Selvamanickam et al., IEEE TASC 21 (2011) 3049

Engineering vs. superconducting layer performance



Engineering current density



Critical current density

REBCO and Bi2223 tapes retain the anisotropic properties of the superconductor

Data shown here correspond to the unfavorable orientation wrt the field

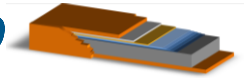
The in-field properties of Bi2212 wires are fully isotropic

Operate at high current density is a necessary condition, but it is not sufficient

Other crucial requirements:

- *Have high tolerance to stress* *Magnetic forces*
- *Be safe in case of magnet quench* *Quench detection, NZPV*
- *Have low magnetization* *Applications to NMR, MRI, HEP magnets*
- *Have a persistent joint technology* *Applications to NMR, MRI*

Conductor contest: Nb_3Sn vs REBCO

	Nb_3Sn 	REBCO 
Geometry	*round wire*	*tape*
SC fraction	*~35%*	*~1%*
In-field Anisotropy	*1, Isotropic*	*~5*
Multifilamentary	*Yes, twisted*	*No, single layer*
Operation boundaries	*2.2 K, 23.5 T ** *4.2 K, 19 T **	*4.2 K, UHF* *77 K, ~3 T*
Mechanical properties	*Some issues with transversal loads*	*Almost OK, but delamination issues*
Disadvantages	*Still margin to improve the performance?* *Cost!!*	*Long lengths under development* *Cost!!*

** in solenoidal coils*

Practical conductors for accelerator magnets : Why cables ?

Superconducting wires have current capability of few hundred Amps

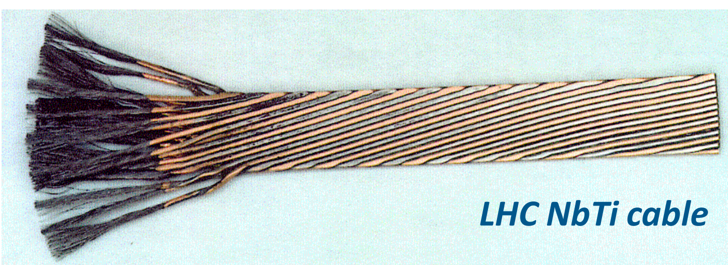
Dipoles and quadrupoles require large operating currents ~ 10 kA

- **To keep the inductance low**
- **To lower the charging voltage**
- **To ease magnet protection**

$$E = \frac{1}{2} L I^2 \qquad V = L\frac{I}{t} = \frac{2E}{It}$$

$$V\left(I_{op} = 250A\right) = 40 \times V\left(I_{op} = 10kA\right)$$

Round wires → Rutherford cables



LHC NbTi cable

HL-LHC Nb_3Sn cable

REBCO tapes → Roebel cables

Both are fully transposed cables. Transposition length and number of wires or tapes can be adapted to the needs of the application

Summary

What we have learned

- ***How to carry a current without dissipation***

  Why just being a superconductor is not enough

- ***How to enhance the critical current***

  Avoid perfection → Defects to pin vortices

- ***How to make a superconducting wire***

  "classical" metallurgy and Nb_3Sn

  thin film technology and REBCO coated conductors

Thank you for the attention !

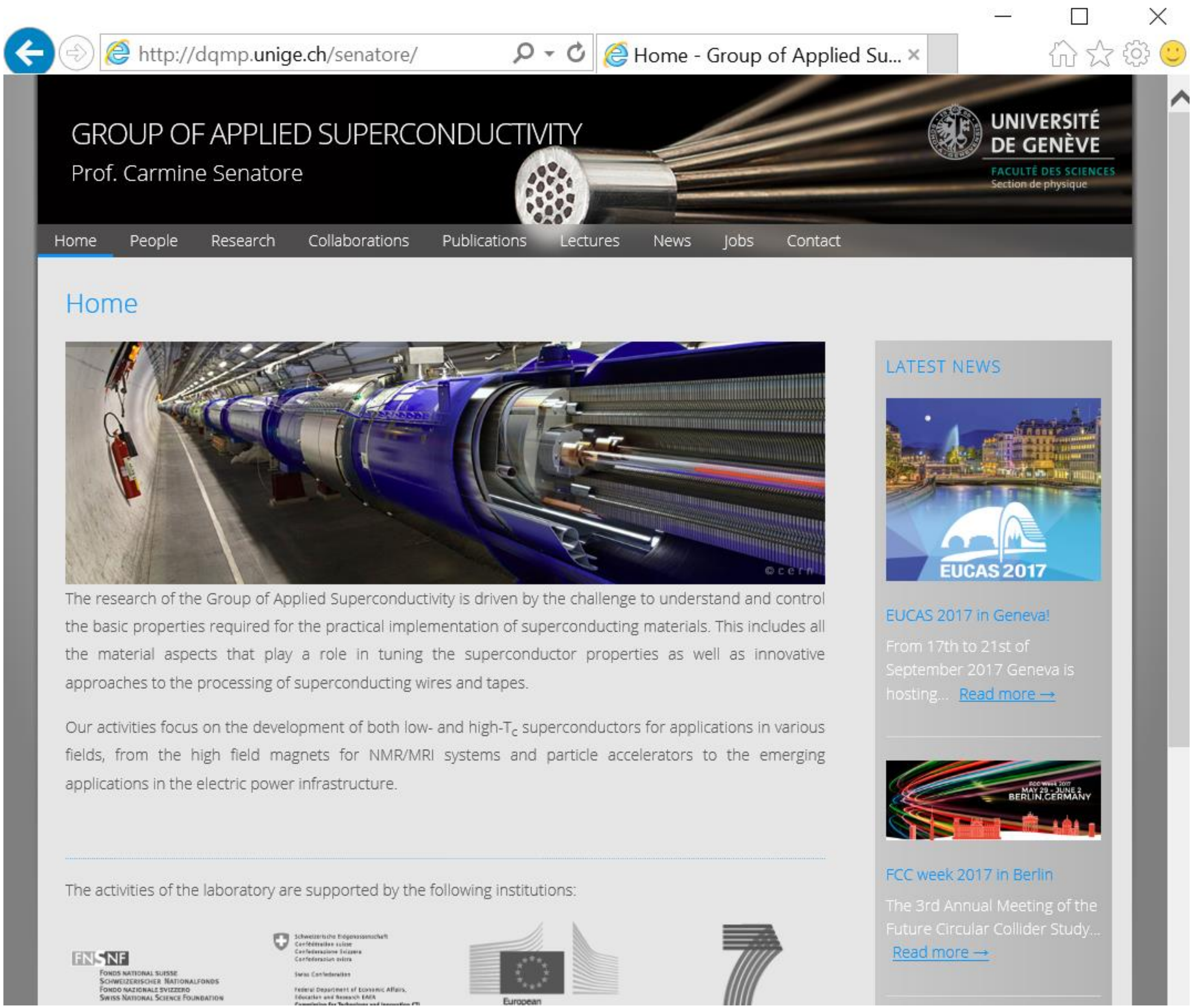
…time for questions…

Carmine SENATORE

carmine.senatore@unige.ch

http://supra.unige.ch

If you want to know more about applied superconductivity in Geneva, visit http://supra.unige.ch

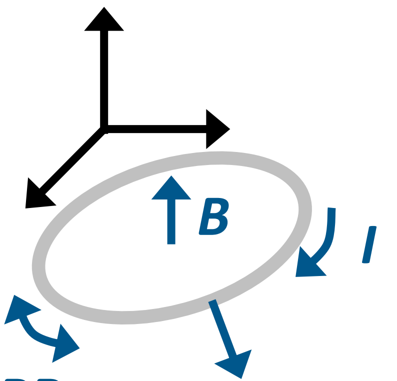


Operate at high current density is a necessary condition, but it is not sufficient

Other crucial requirements:

- ***Have high tolerance to stress*** *Magnetic forces*
- ***Be safe in case of magnet quench*** *Quench detection, NZPV*
- ***Have low magnetization*** *Applications to NMR, MRI, HEP magnets*
- ***Have a persistent joint technology*** *Applications to NMR, MRI*

Magnetic stresses in the winding



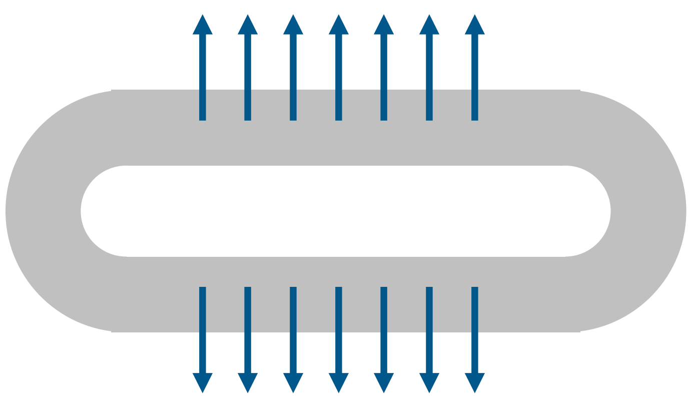
$$\sigma_{hoop} = \frac{I}{S_{wire}} BR$$

$$F = I \times B$$

Hoop stress levels above 100 MPa are common

As an example, the NHMFL 32 T magnet will operate at 400 MPa

In a real winding adjacent turns press on each other and develop 3-D stresses

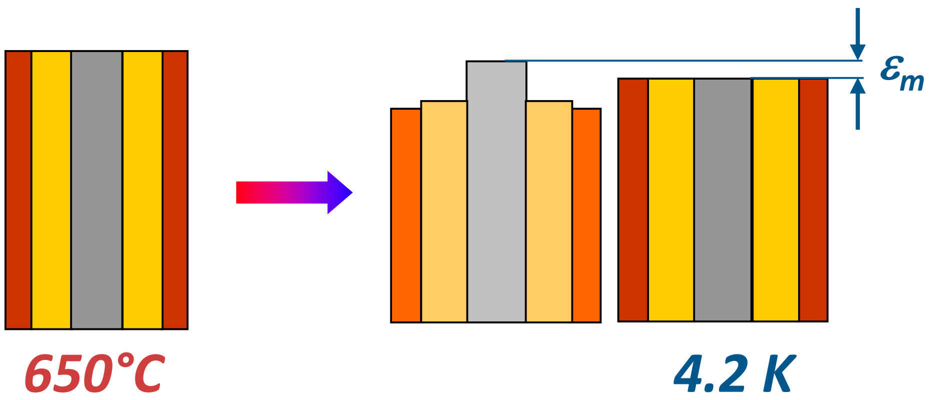


In straight-sided coils such as accelerator magnet, the conductor experiences large transverse forces

F = 175 ton/m in a LHC dipole

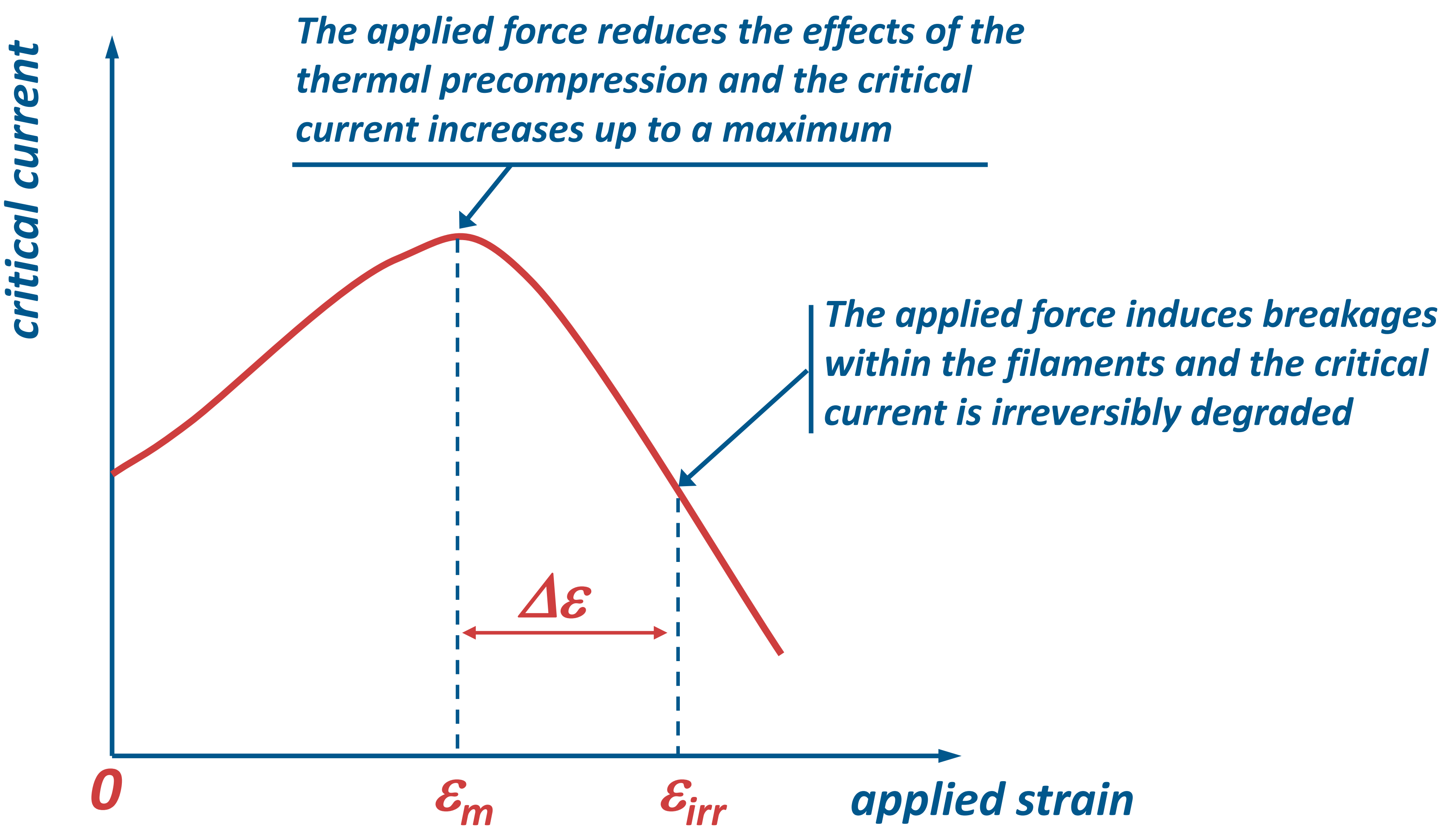
And also thermal stresses

Mismatch in thermal contraction at the cooldown



Strain-induced changes in the critical current

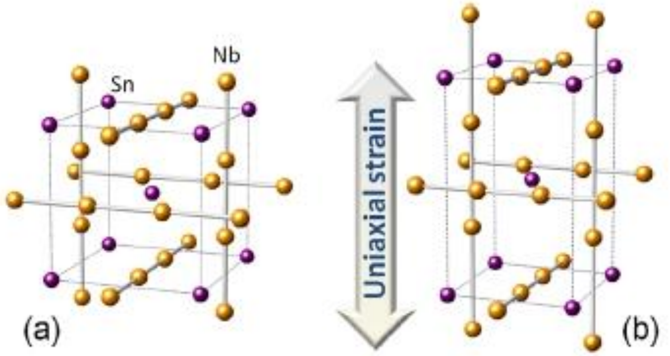
The case of Nb_3Sn

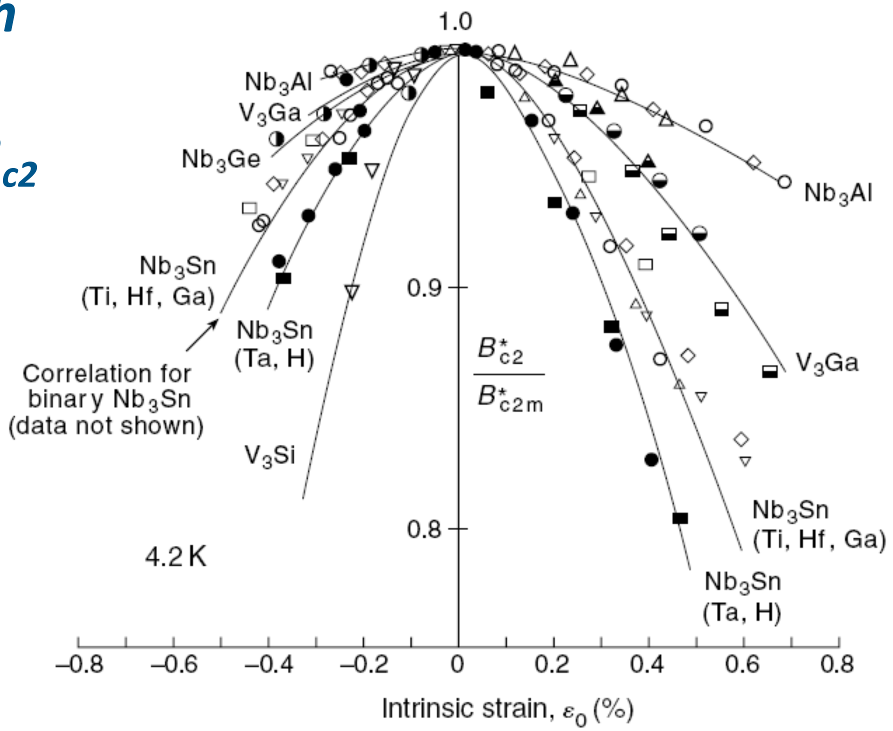


Reversible strain effects

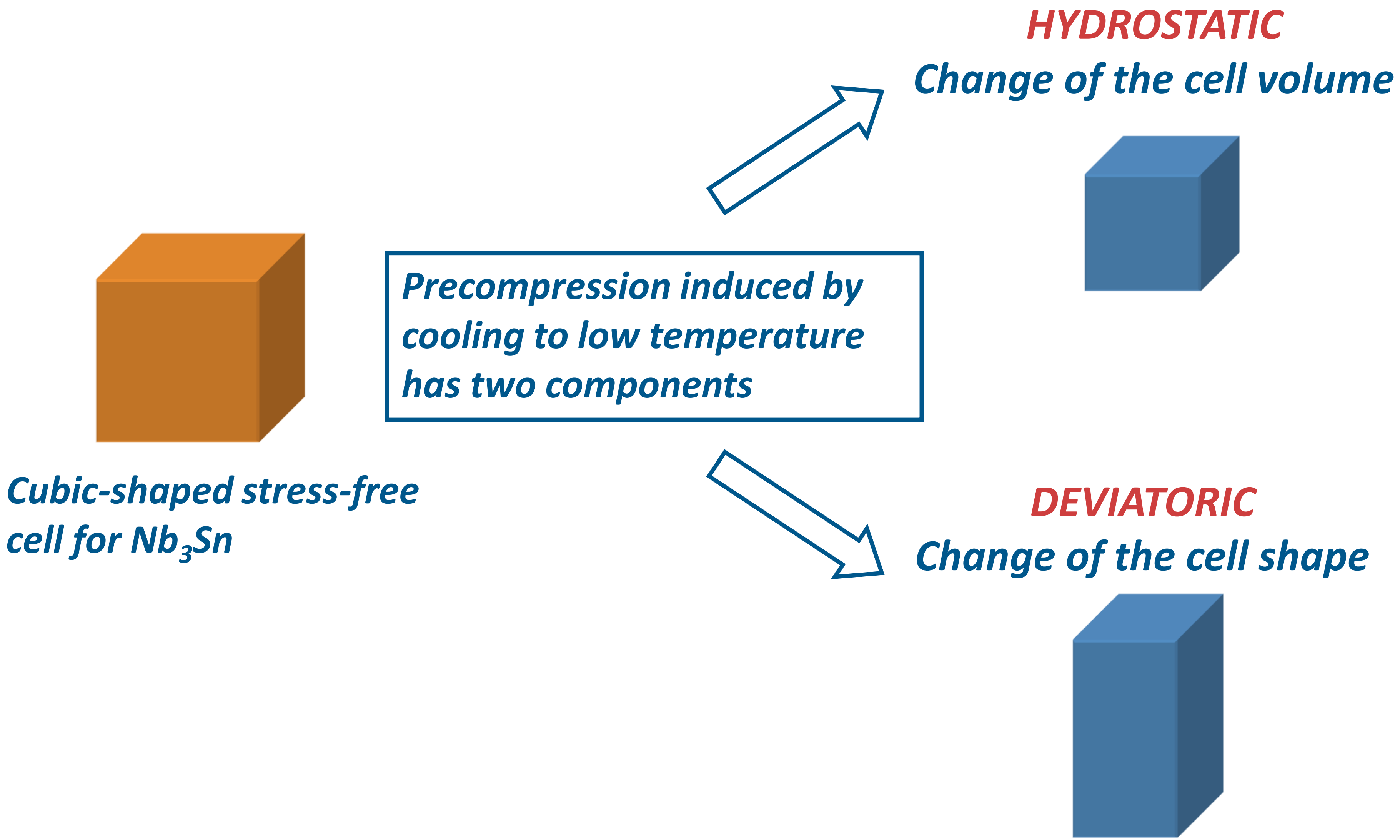
Why superconducting properties depend on strain

Under strain the crystal structure deforms and this induces change both in the phonon spectrum and the electronic bands and thus on T_c and B_{c2}



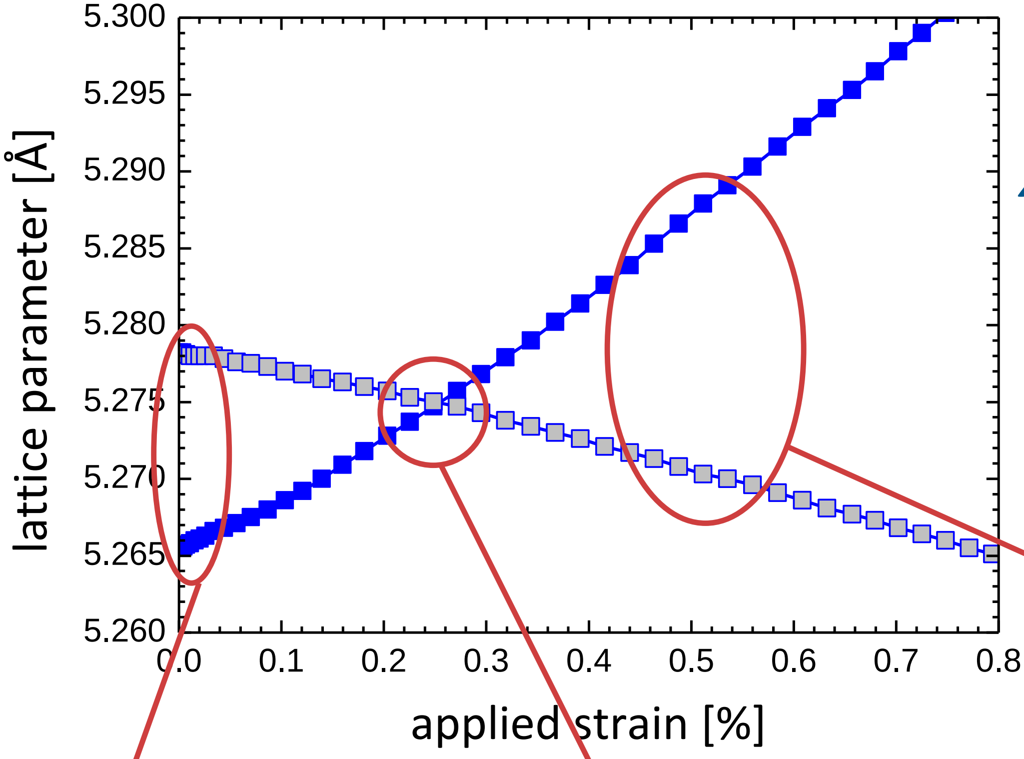


Reversible strain effects in Nb_3Sn wires



Reversible strain effects in Nb_3Sn wires: lattice parameters

Bronze route wire: Nb_3Sn lattice parameters vs axial strain @ 4.2K



XRD experiments @ ESRF Grenoble

C. Scheuerlein et al., IEEE TAS 19 (2009) 2653

L. Muzzi et al., SUST 25 (2012) 054006

HIGH APPLIED STRAIN

Again Hydrostatic+Deviatoric

ZERO APPLIED STRAIN

Nb_3Sn is precompressed

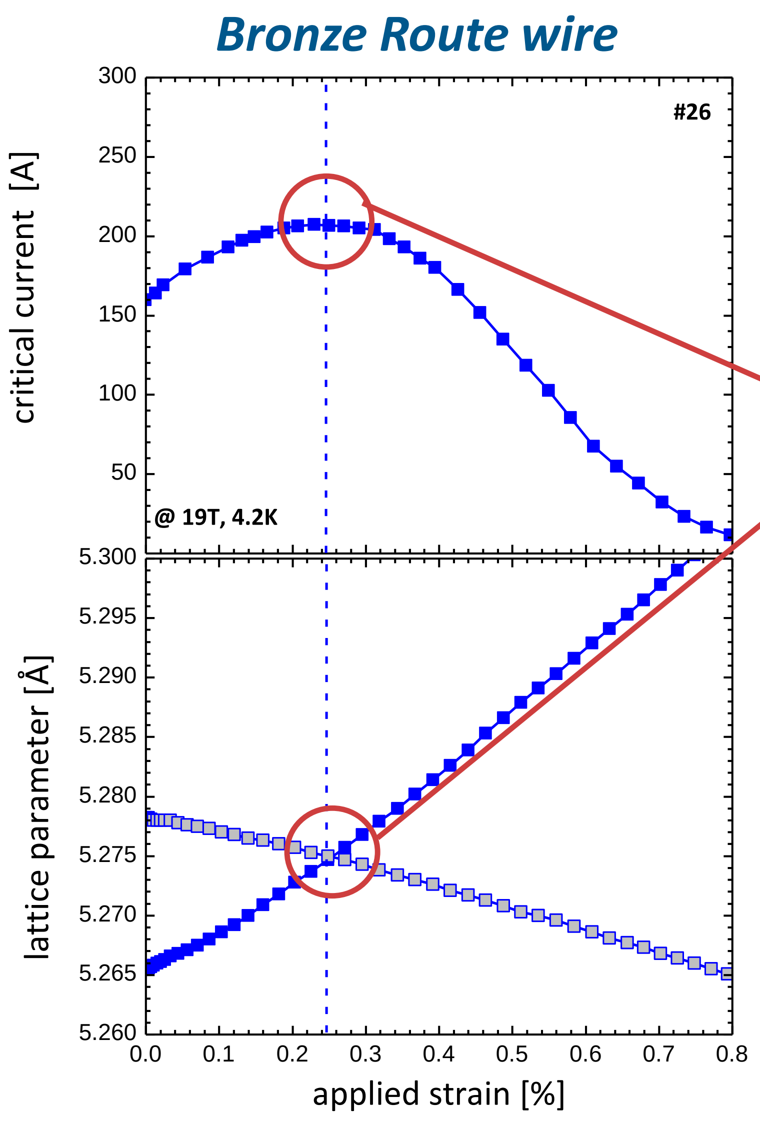
Hydrostatic+Deviatoric

CROSSING POINT

Cubic cell recovered

Hydrostatic component still present

Lattice parameters and I_c under axial strain

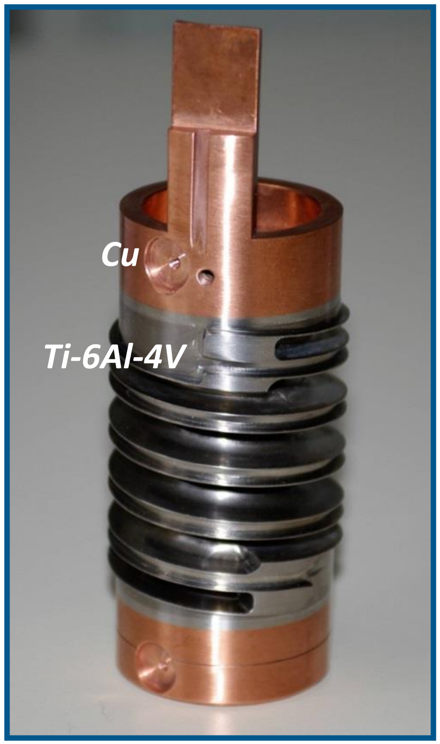


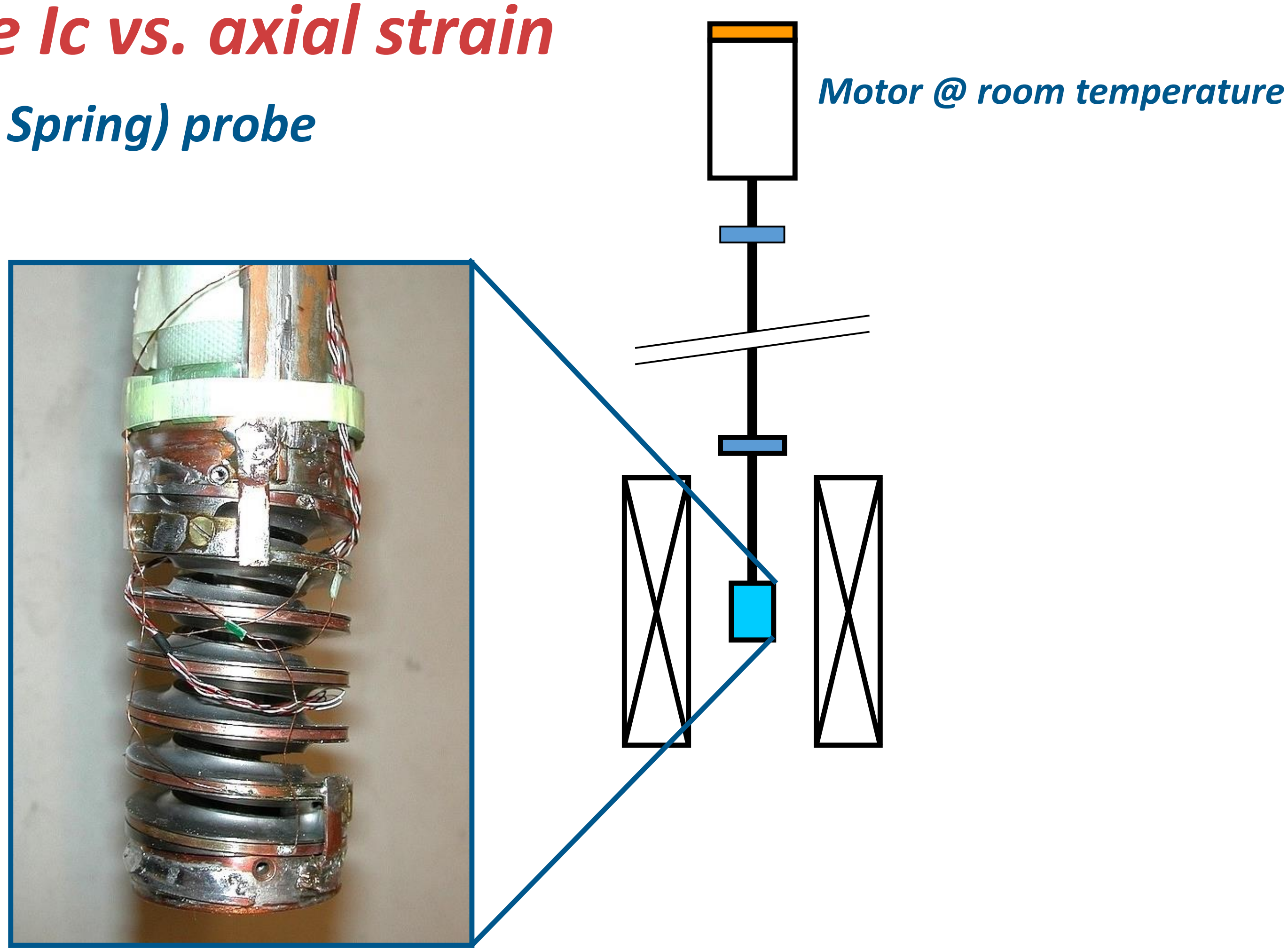
MAXIMUM OF I_c

The maximum of the critical current occurs when the cubic cell is restored

How to mesure Ic vs. axial strain

The WASP (Walters Spring) probe



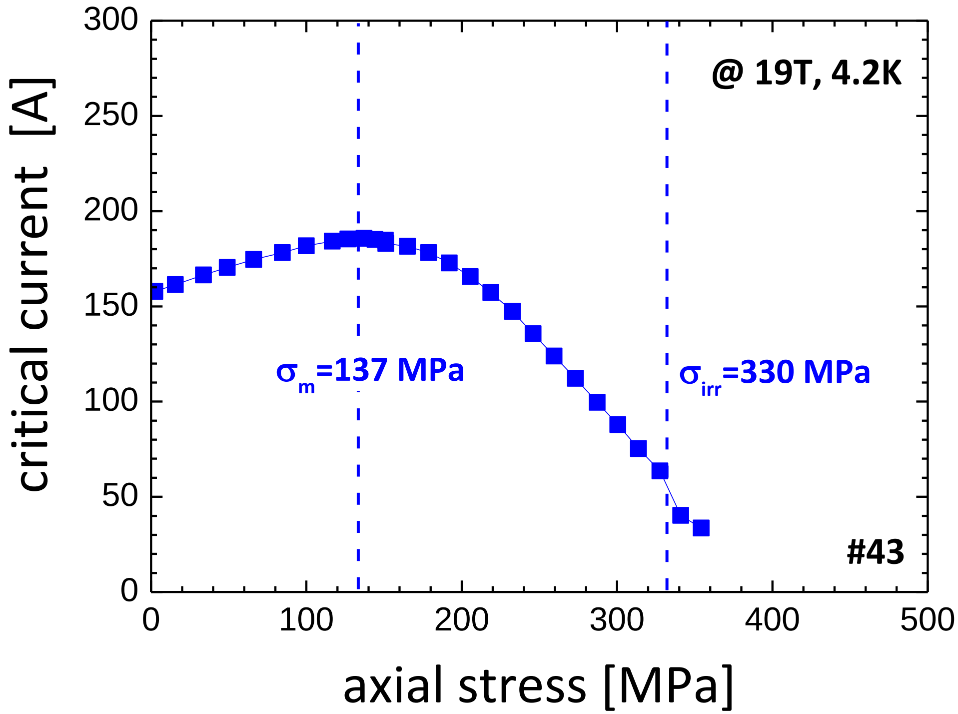


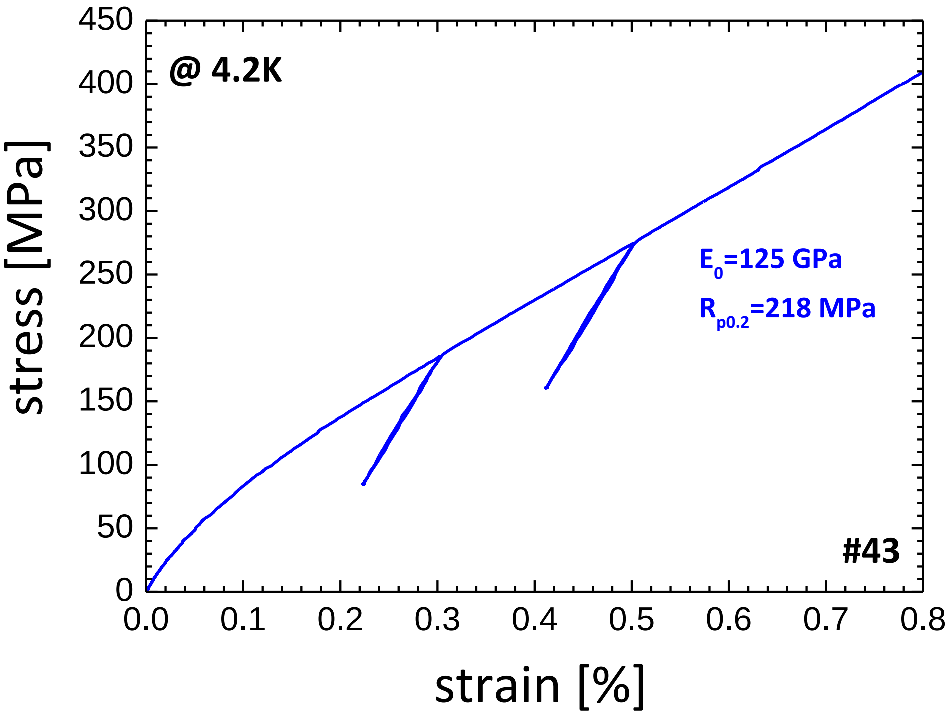
B. Seeber et al., Rev. Sci. Instr. 76 (2005) 093901

Max current	1000 A
Sample length	1.1 meter
Voltage taps distance	126 mm
Electrical field criterion	0.01 µV/cm
Strain (ε)	up to ± 1.2 %

From I_c vs. strain to I_c vs. stress

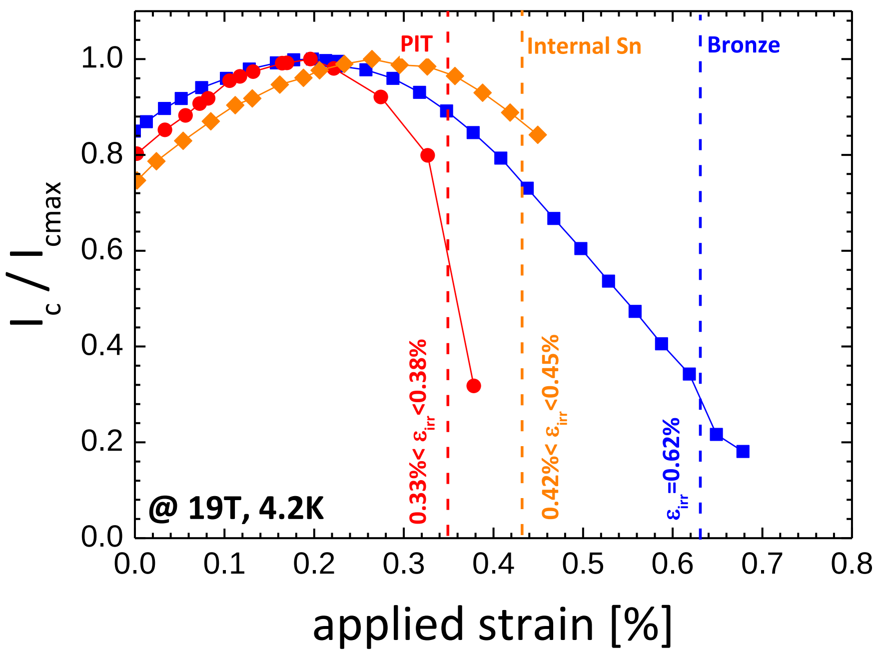
Bronze Route wire 



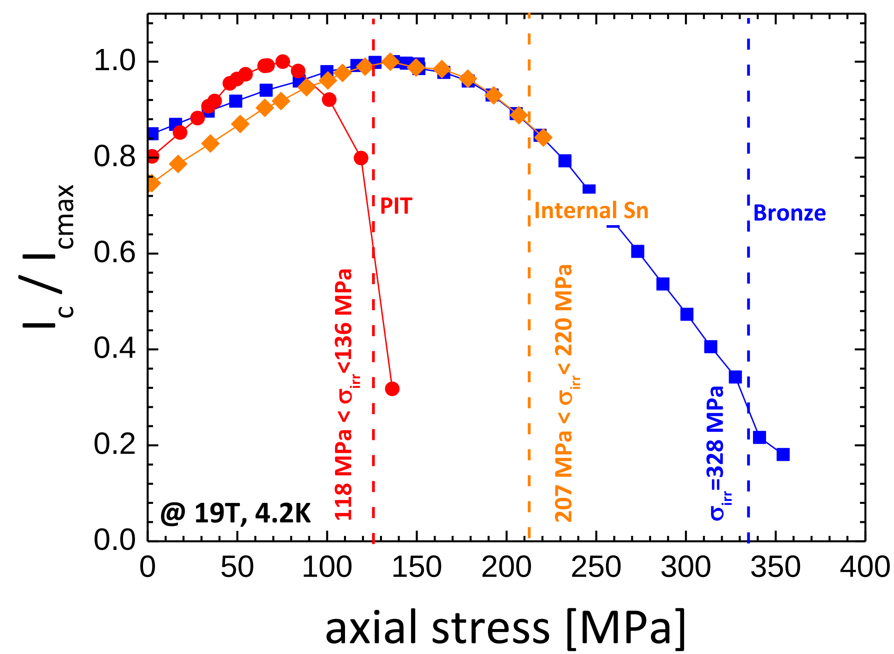


Bronze Route, Internal Sn and PIT: a comparison

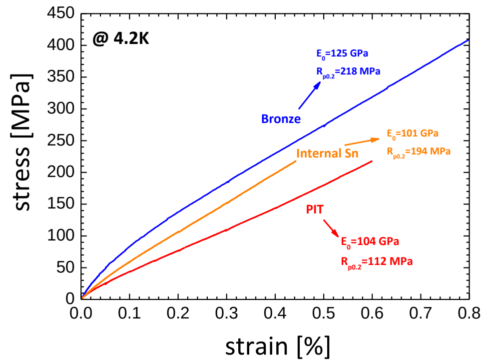
I_c vs. axial strain



I_c vs. axial stress



Technology	σ_{irr}
Bronze Route	330 MPa
Internal Sn	210 MPa
Powder-In-Tube	120 MPa



Degradation upon transverse loads

High field dipoles based on high J_c Nb_3Sn Rutherford cables require coil pre-stresses larger than 100 MPa, with peak stress of ~200 MPa at operation

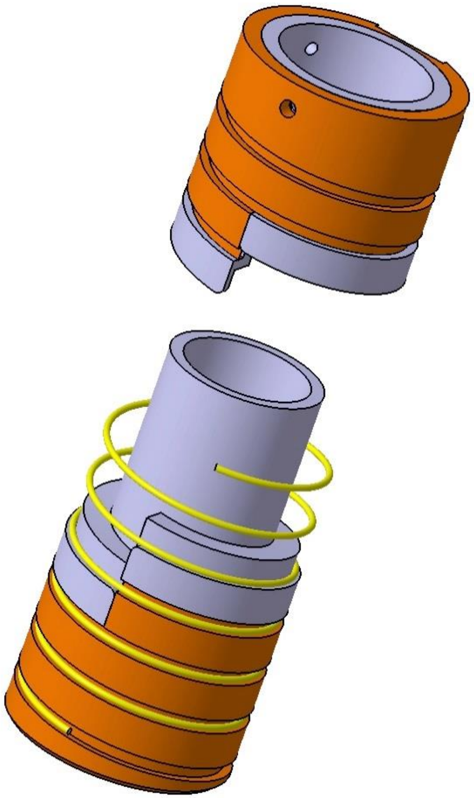
Are the Nb_3Sn wires in the cable able to withstand such a high stress level? Which degradation is tolerable?

Nb_3Sn Rutherford cable for HL-LHC, 40 strands

- Nb_3Sn wires are deformed during cabling
- Cables are braided with glass fiber
- The winding is impregnated with resin

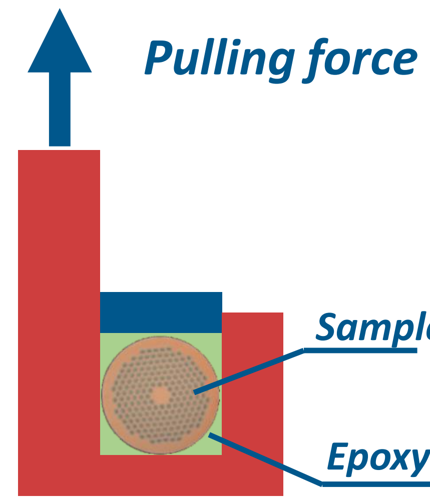
Is it possible to extrapolate the behaviour of the cable from a single wire experiment?

The WASP concept for I_c vs. transverse stress



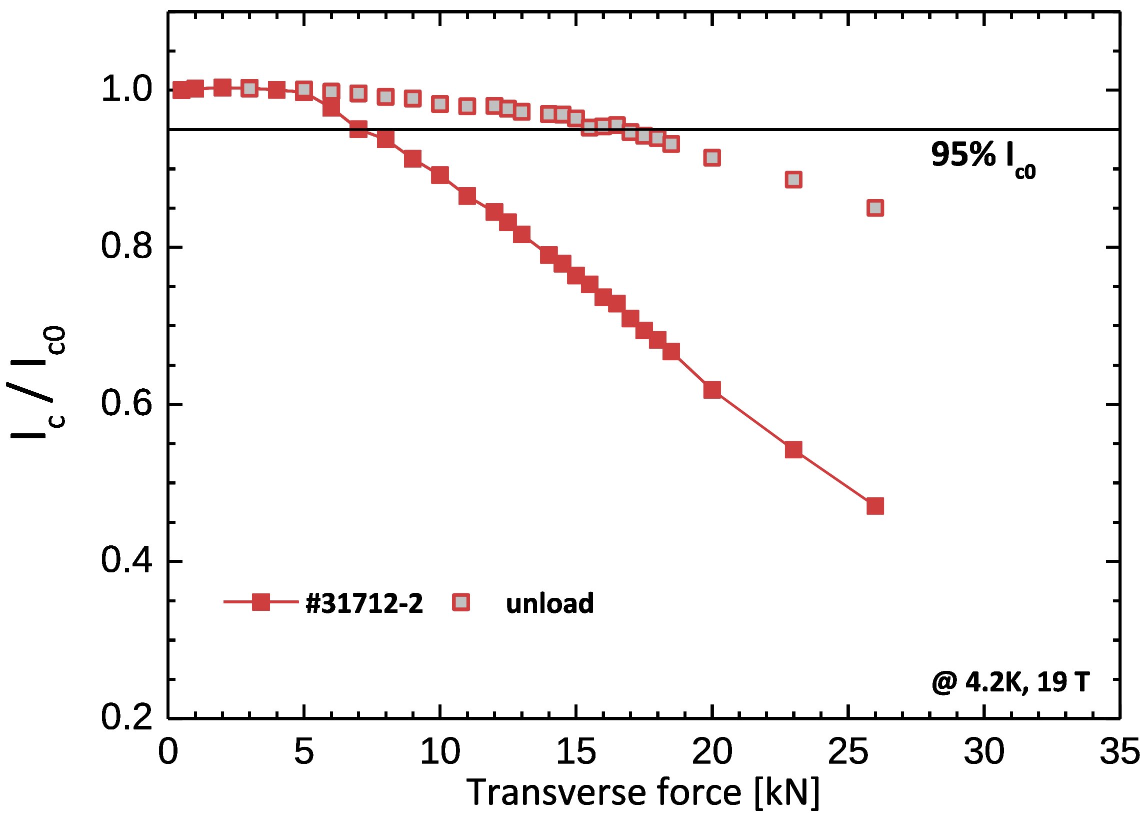
3 groove widths
- 1.30 mm
- 1.15 mm
- 1.00 mm

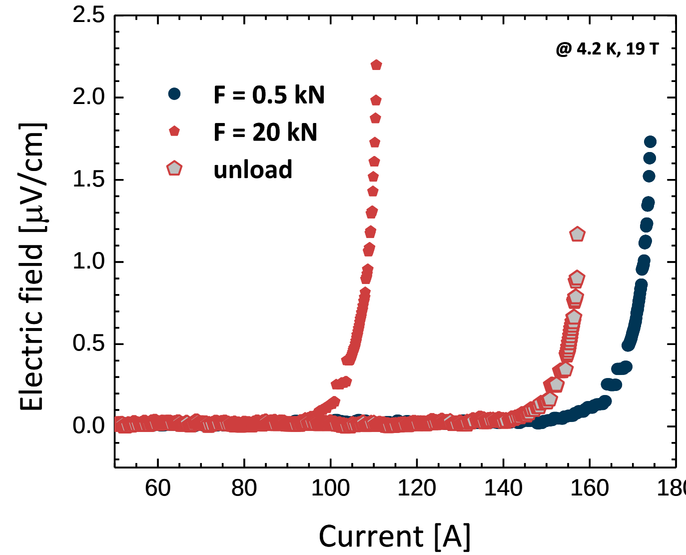
4-WALL + impregnation



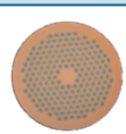
Wire impregnated with epoxy applied stress uniformly distributed

How the measurement works

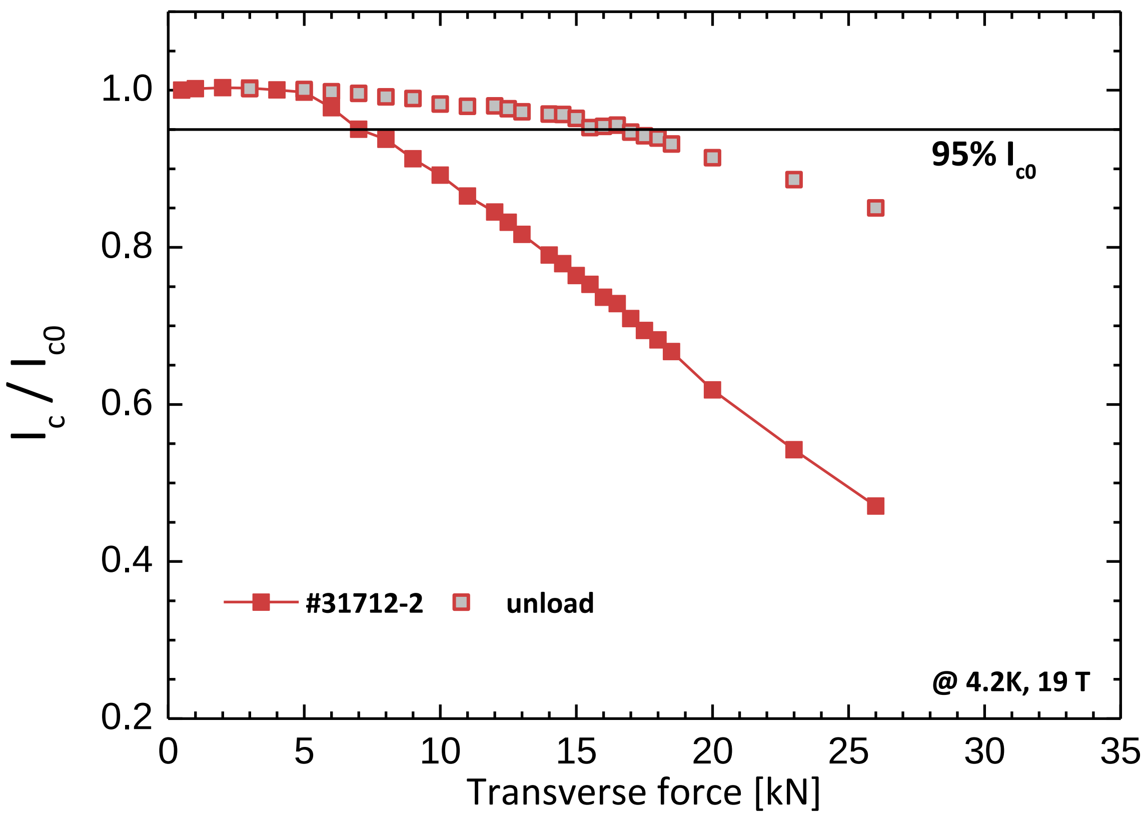




Bruker EST

	Wire ID	*Diameter [mm]*	*# of filaments*	*Filament size/shape*	*Cu/nonCu*	*Non-Cu J_c(12T,4.2K) [A/mm^2]*
	*#31712* *#14310* *Fresca2*	1.0	192	~50 μm round	1.22	2450

How the measurement works



The irreversible limit is defined at the force level leading to a 95% recovery of the initial I_c after unload

Here

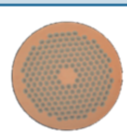
$$F_{irr} = 16 \text{ kN}$$

The corresponding irreversible stress limit is

$$\sigma_{irr} = 110 \text{ MPa}$$

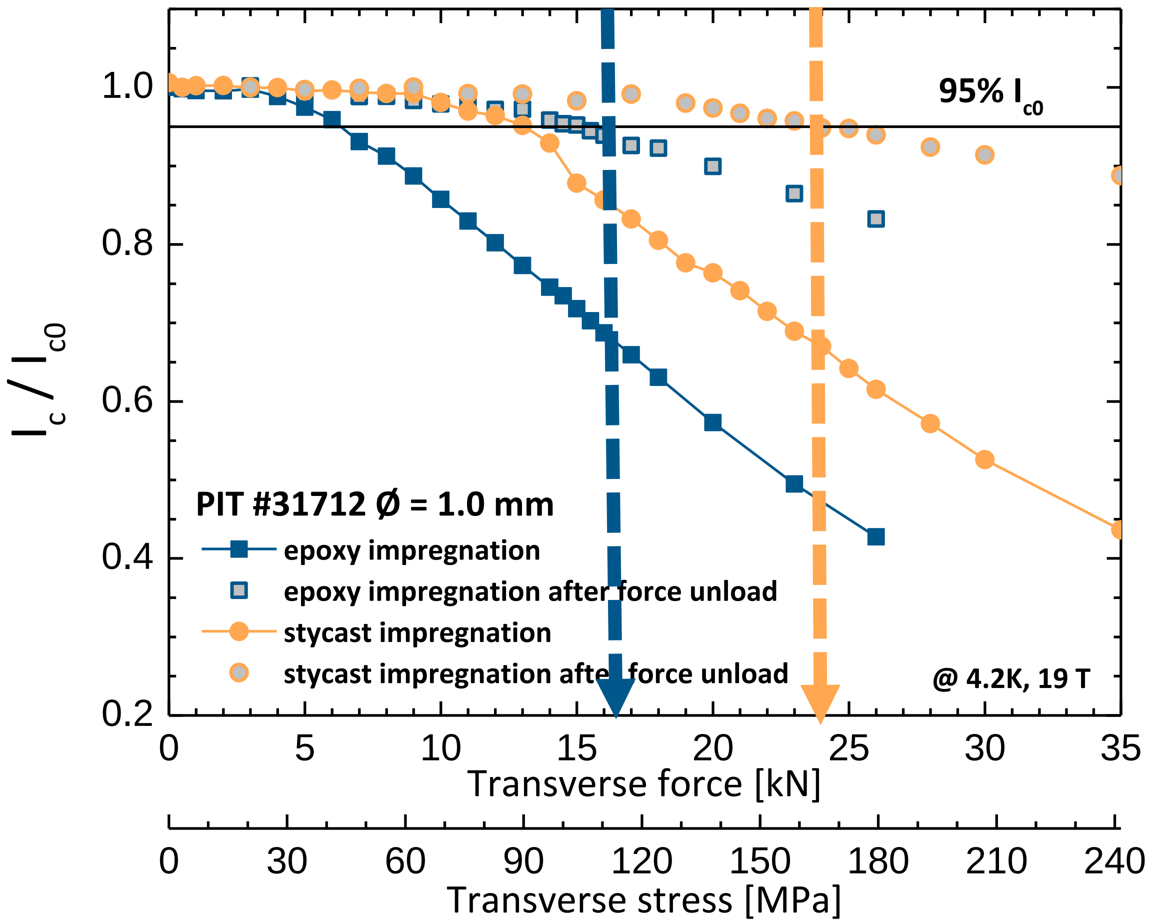
where

$$Stress = \frac{Force}{groove\ length \times groove\ width}$$

	Wire ID	Diameter [mm]	# of filaments	Filament size/shape	Cu/nonCu	Non-Cu J_c(12T,4.2K) [A/mm²]
	#31712 #14310 Fresca2	1.0	192	~50 µm round	1.22	2450

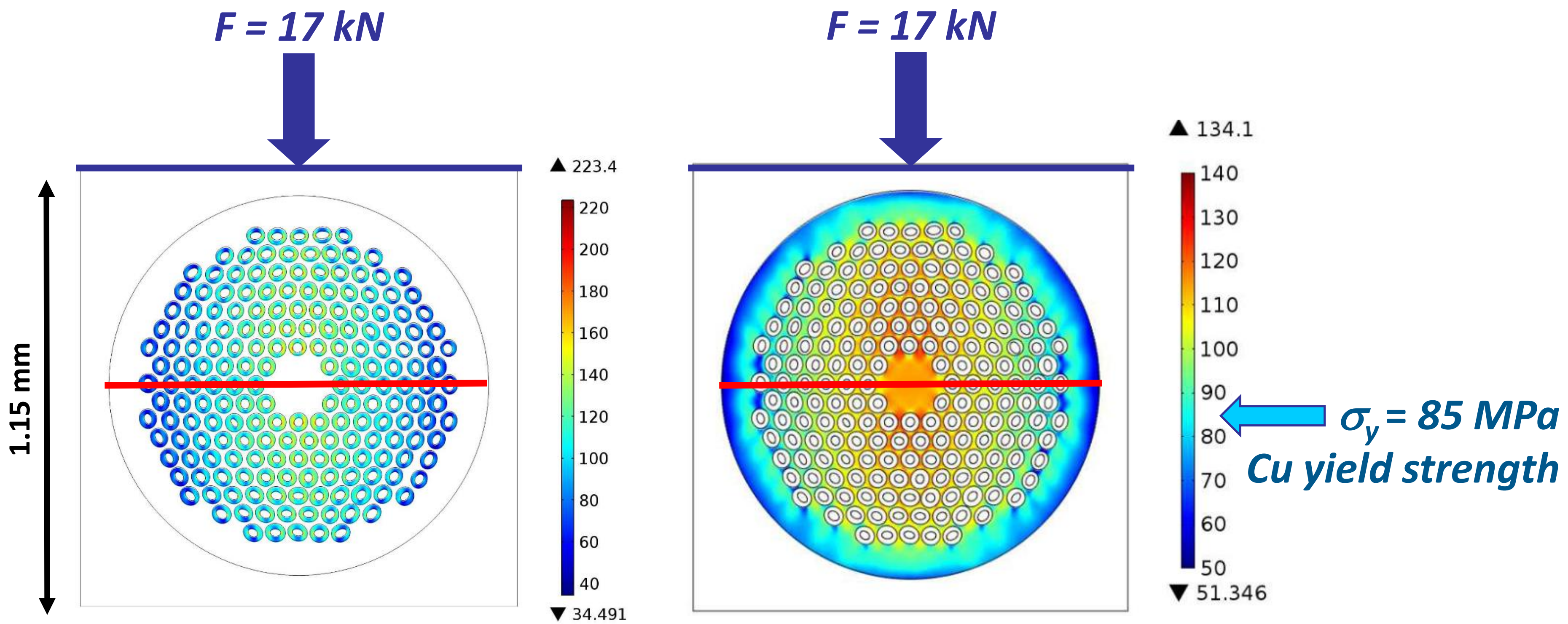
Bruker EST

I_c vs. transverse stress: epoxy vs. stycast



The change of resin, from epoxy to stycast, leads to an increase of σ_{irr} by > 50 MPa
The result is comparable to the value found with epoxy + glass fiber sleeve

FEM: stress redistribution in the wire



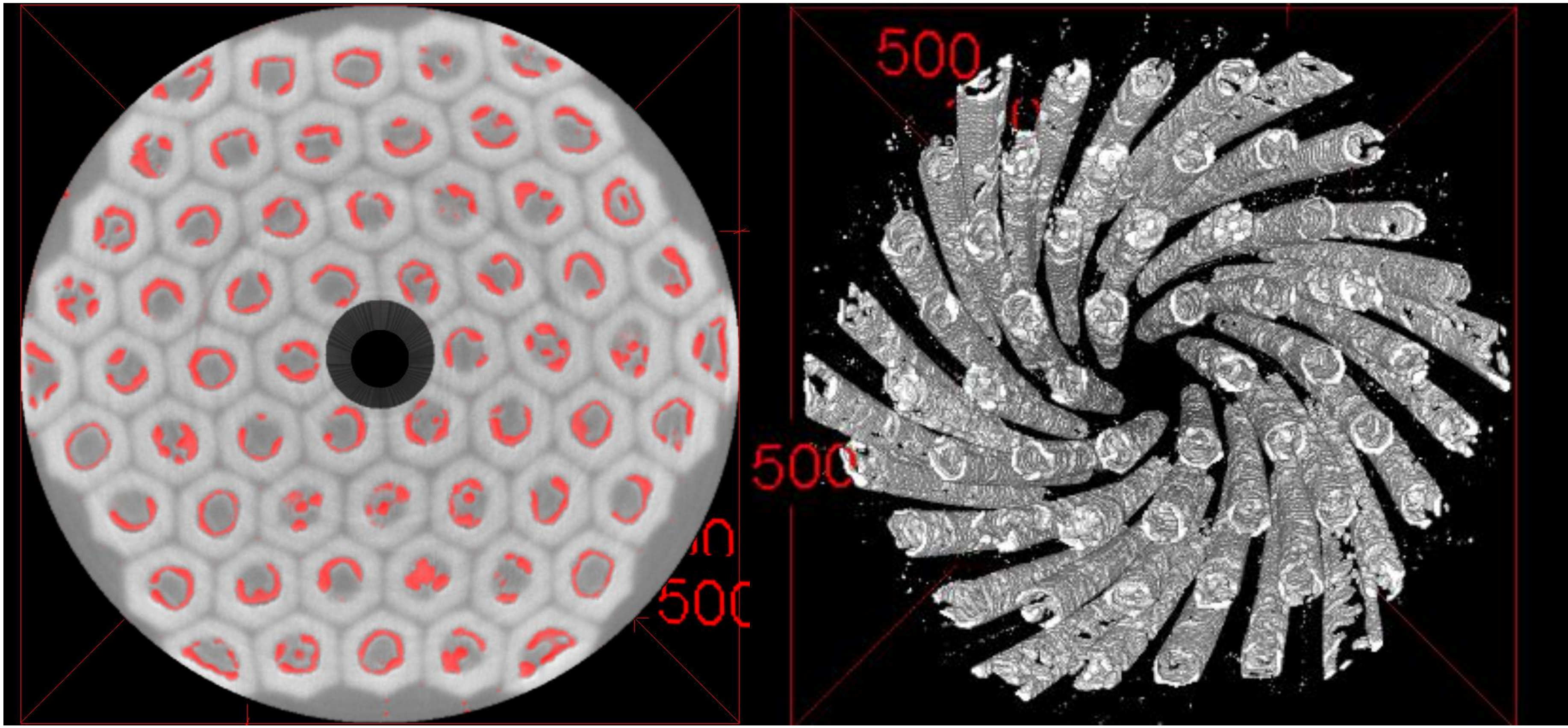
Irreversible degradation is determined by filament cracks and residual strain on Nb_3Sn imposed by plastically deformed Cu

FEM suggests that smaller filaments and higher Cu/nonCu ratio lead to higher stress tolerance

C. Calzolaio, CS et al., SuST 28 (2015) 055014

XRD Microtomography
Void morphology in RRP wires

ESRF

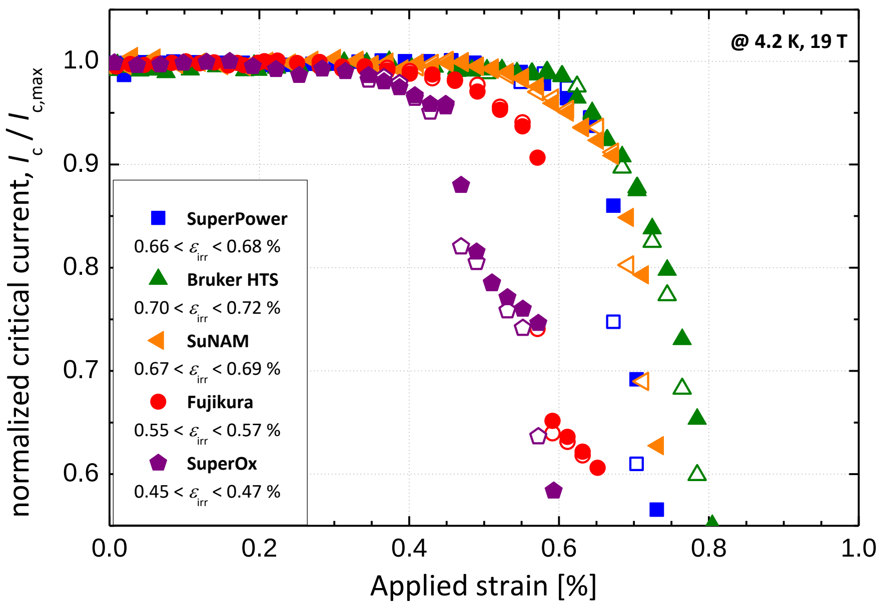


Experiments performed at the European Synchrotron Radiation Facility
from Sep 30 to Oct 02 2015

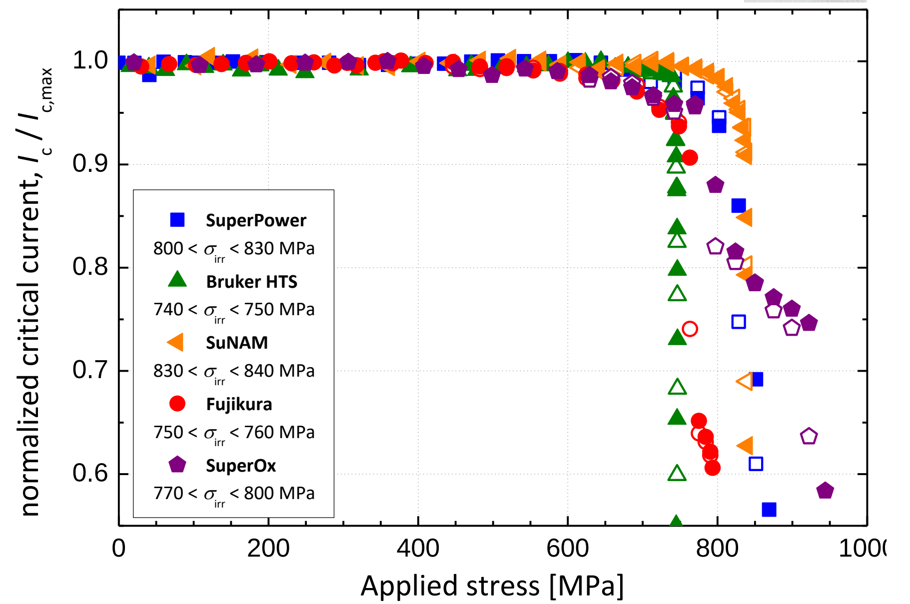
And what about REBCO tapes ?

REBCO CCs: Dependence of I_c on axial loads

I_c vs. axial strain



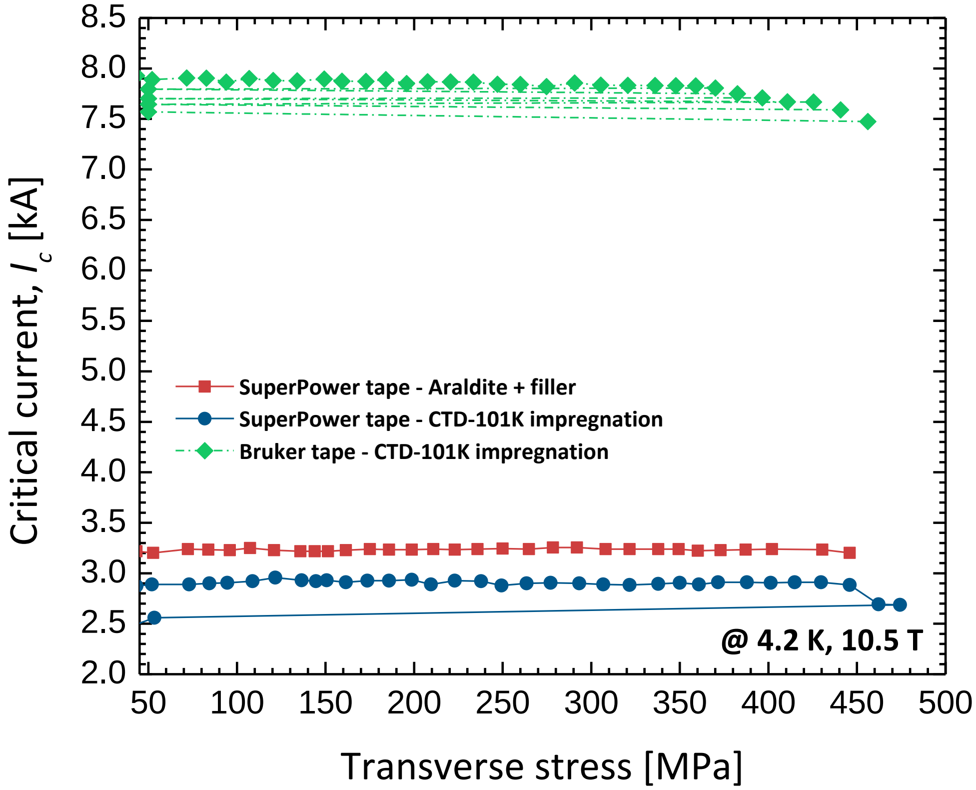
I_c vs. axial stress

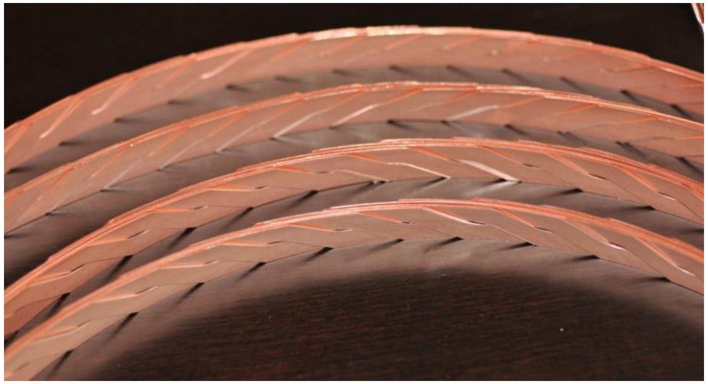


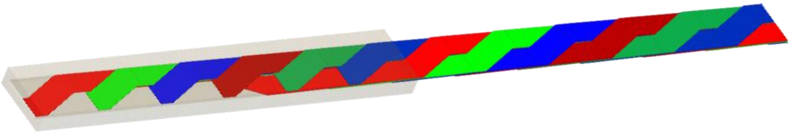
- *REBCO CCs are inherently strong, ~50% is a high strength alloy*
- *Very low stress effect → curves are flat in rev. region*
- *Irreversible stress limits above 500 MPa*
- *The only weakness is delamination...*

C. Barth, G. Mondonico and CS, SUST 28 (2015) 045011

REBCO Roebel cables under transverse compression







- *2 REBCO tape manufacturers*
- *2 different impregnation resins*
- *Irreversible stress limit > 400 MPa*

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