IEEE/CSC & ESAS EUROPEAN SUPERCONDUCTIVITY NEWS FORUM (global edition), October 2016.
Plenary presentation 4PL-02 given at ASC 2016; Denver, Colorado, USA, September 4 – 9, 2016.

UNIVERSITÉ DE GENÈVE
FACULTÉ DES SCIENCES

FNSNF
FONDS NATIONAL SUISSE DE LA RECHERCHE SCIENTIFIQUE

30 years to HTS

Status and Perspectives

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With special thanks to Christophe Berthod (UNIGE) for the theory, Xavier Ravinet (UNIGE) for the help of an artist, Matteo Alessandrini (Bruker BioSpin) for giving some numbers, Amalia Ballarino (CERN) for using HTS in LHC, Enrico Giannini (UNIGE) for his Bi2223 memories and my great team at UNIGE, Marco Bonura, Christian Barth, Alex Fête, Davide Matera, Florin Buta and Damien Zurmuehle

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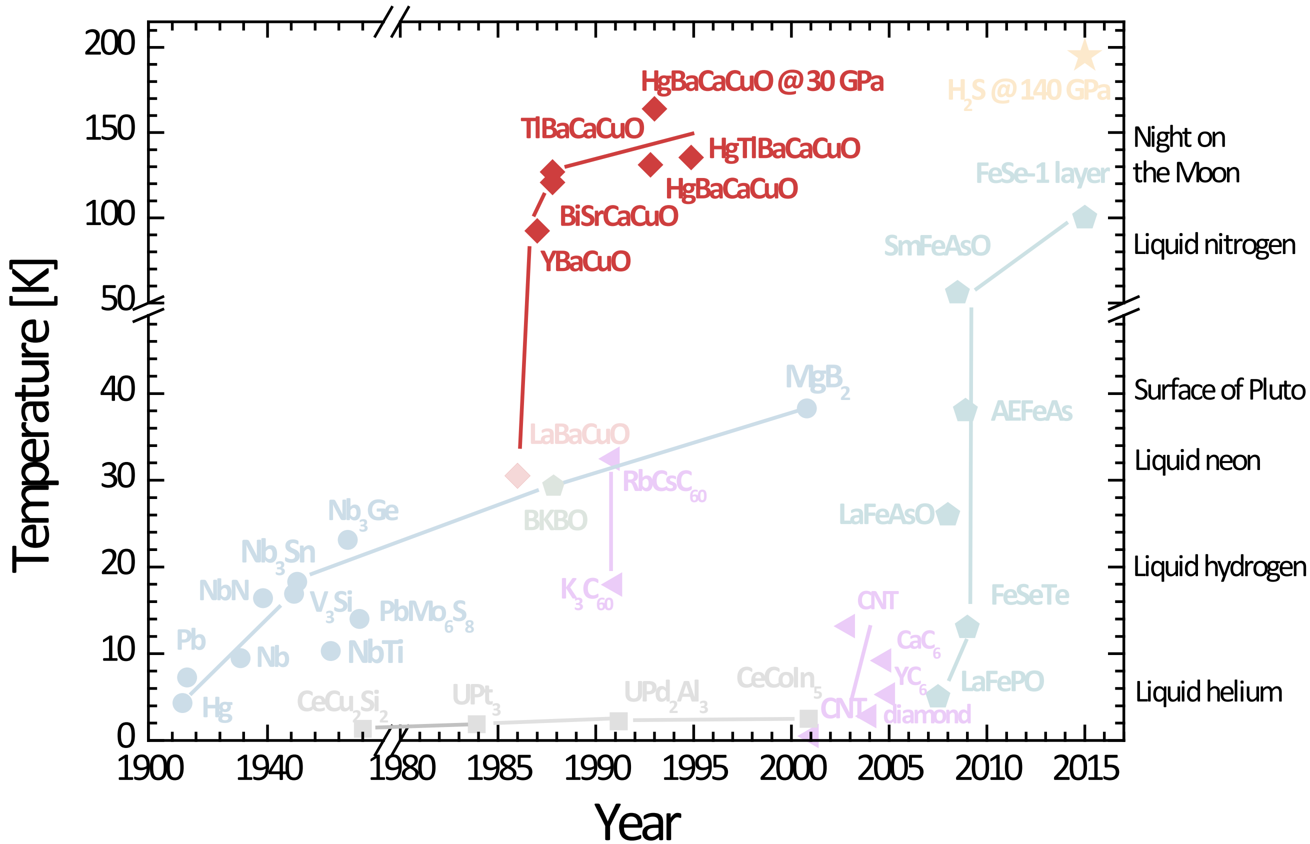
Timeline of Superconductivity



The talk will focus on superconductors
- *discovered after 1986*
- *with a T_c above the LN_2 temperature*
- *available as industrial conductors*

Outline

What is special with HTS

How to make technical conductors out of HTS

- ***How to deal with anisotropy***
- ***How to deal with grain boundaries***
- ***High critical current, and***

What we can do with HTS

Focus on large scale applications

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The cookbook for new superconductors before 1986

Matthias' Rules

from a compilation of superconducting elements, binary compounds and solid solutions

0. Valence number per atom between 2 and 8 — Favorable valance numbers: 3, 4.7, 6.9
1. Seek high symmetry — Cubic is better
2. Seek peaks in density of state — $T_c = 1.14\omega_{ph} \exp\left(-\frac{1}{N(E_F)V_{ph}}\right)$
3. Stay away from oxygen
4. Stay away from magnetism
5. Stay away from insulators

BCS, PR 108 (1957) 1175

B. Matthias et al., RMP 35 (1963) 1

Record T_c = 23.2 K in Nb_3Ge

HTS are copper oxides

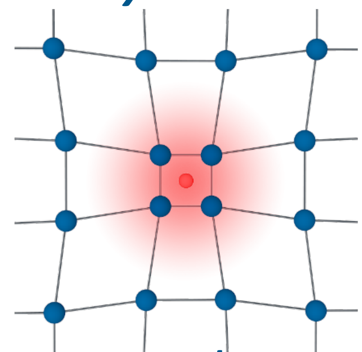
The undoped parent compounds are antiferromagnetic Mott insulators

1986: Superconductivity in $La_{2-x}Ba_xCuO$ at $T_c \approx 30$ K

In the 1980's Bednorz and Müller were looking for superconductivity in the oxides

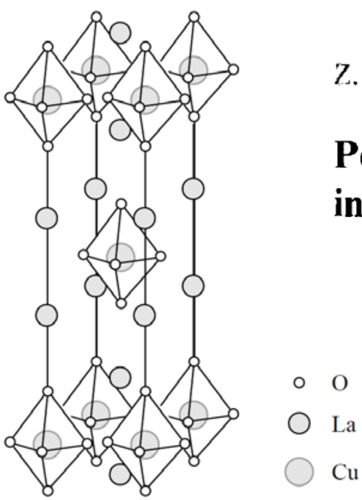
$$T_c = 1.14\omega_{ph}\exp\left(-\frac{1}{N(E_F)V_{ph}}\right)$$

V_{ph} is rather strong
Look for Jahn-Teller polarons



$N(E_F)$ is low
Look for increased $N(E_F)$ in mixed valence compounds

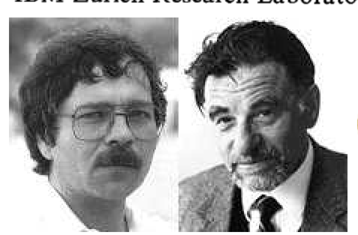
In particular, they investigated the 2 systems: ~~La-Ni-O~~ and La-Cu-O



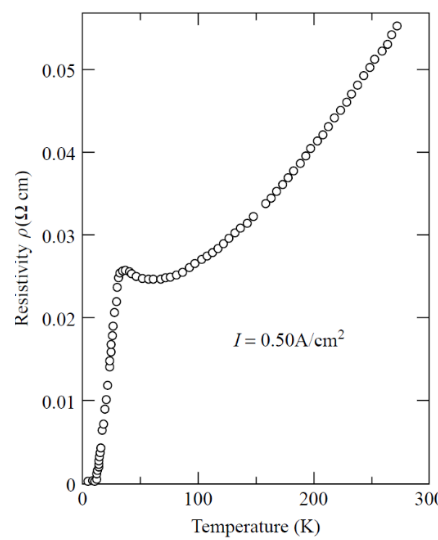
Z. Phys. B – Condensed Matter 64, 189–193 (1986)

Possible High T_c Superconductivity in the Ba – La – Cu – O System

J.G. Bednorz and K.A. Müller
IBM Zürich Research Laboratory, Rüschlikon, Switzerland



1987



And only few months later…

VOLUME 58, NUMBER 9 PHYSICAL REVIEW LETTERS 2 MARCH 1987

Superconductivity at 93 K in a New Mixed-Phase Y-Ba-Cu-O Compound System at Ambient Pressure

M. K. Wu, J. R. Ashburn, and C. J. Torng
Department of Physics, University of Alabama, Huntsville, Alabama 35899

and

P. H. Hor, R. L. Meng, L. Gao, Z. J. Huang, Y. Q. Wang, and C. W. Chu[a]
Department of Physics and Space Vacuum Epitaxy Center, University of Houston, Houston, Texas 77004
(Received 6 February 1987; Revised manuscript received 18 February 1987)

A stable and reproducible superconductivity transition between 80 and 93 K has been unambiguously observed both resistively and magnetically in a new Y-Ba-Cu-O compound system at ambient pressure. An estimated upper critical field $H_{c2}(0)$ between 80 and 180 T was obtained.

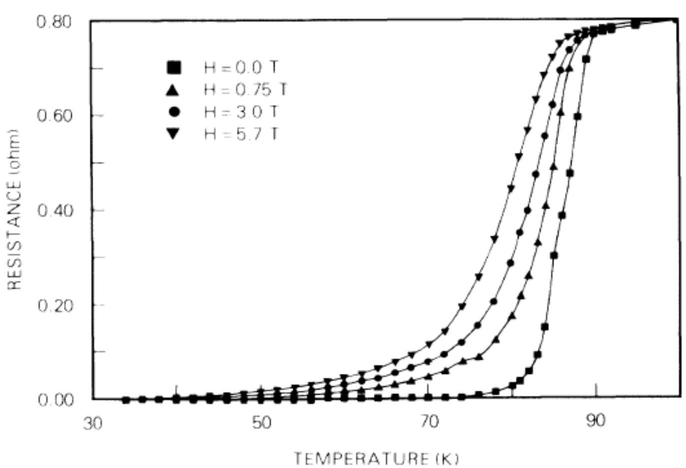
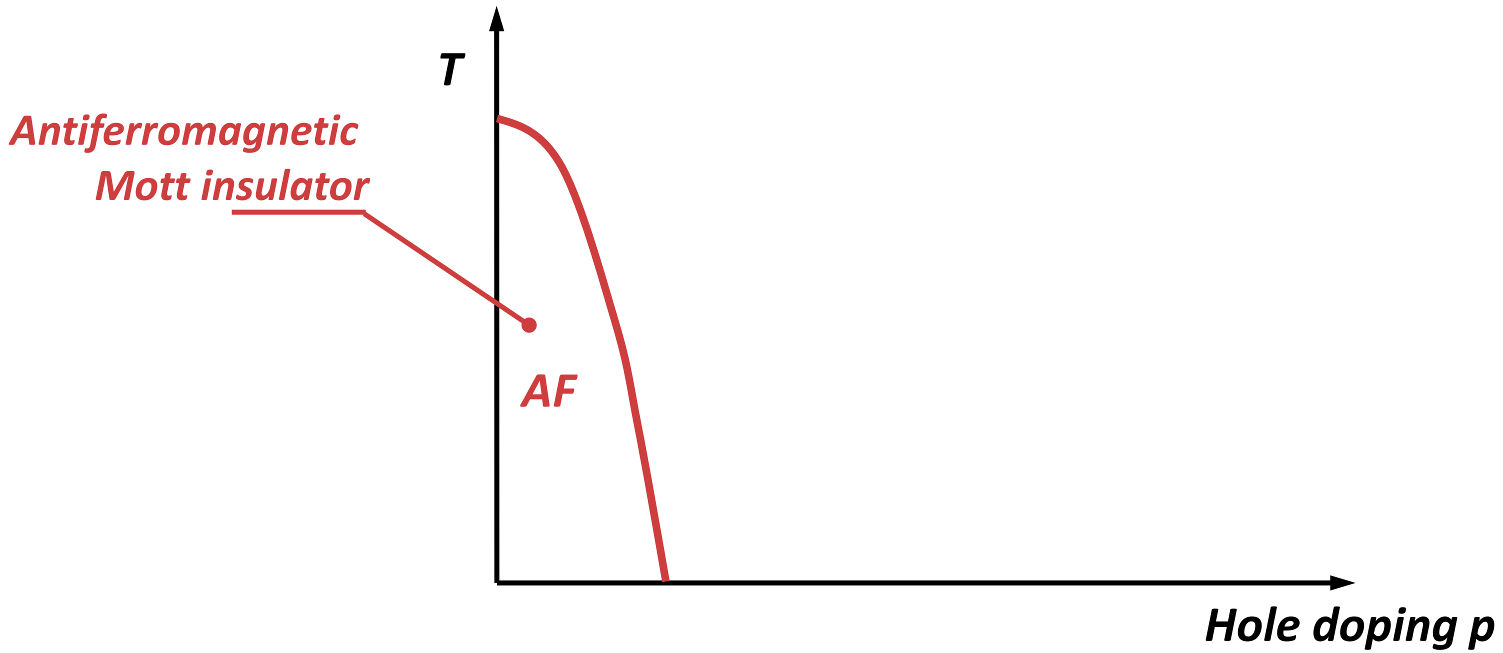


FIG. 1. Temperature dependence of resistance determined in a simple liquid-nitrogen Dewar.

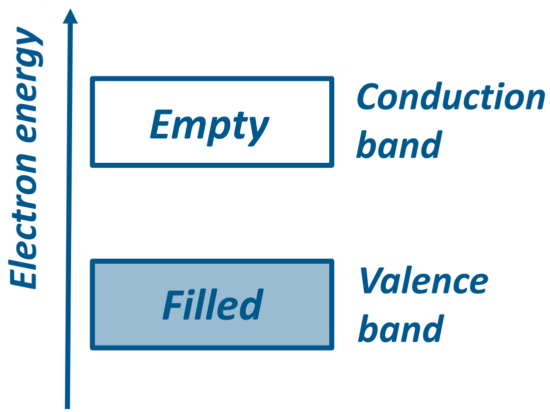
The 1st SC with T_c above the LN_2 temperature!

And BSCCO came in 1988

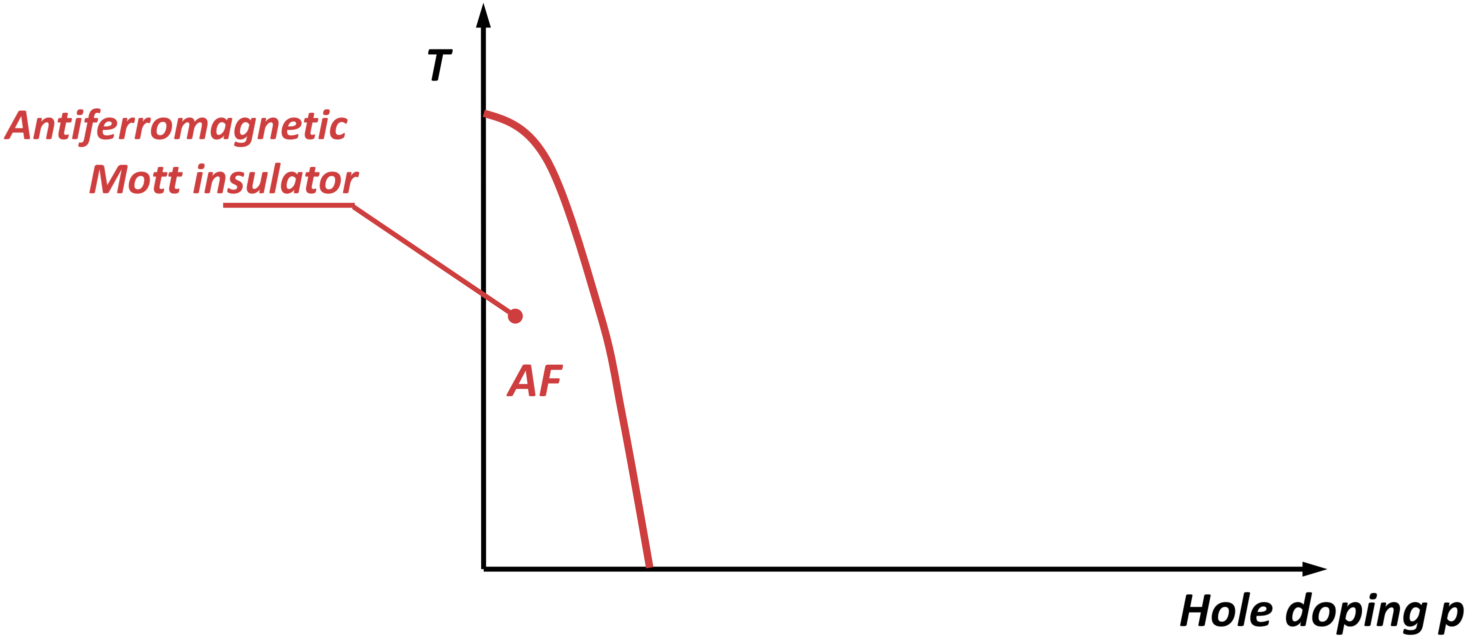
A quick introduction to the HTS phase diagram



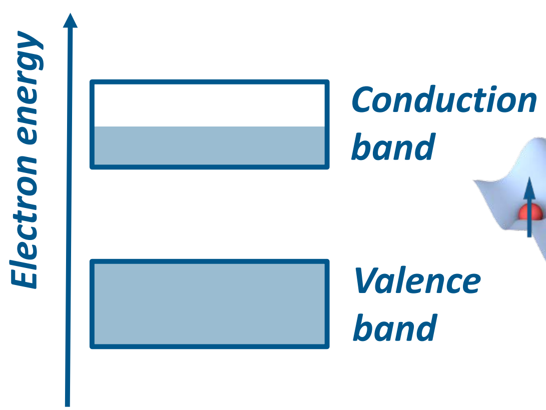
Band (Bloch-Wilson) insulator

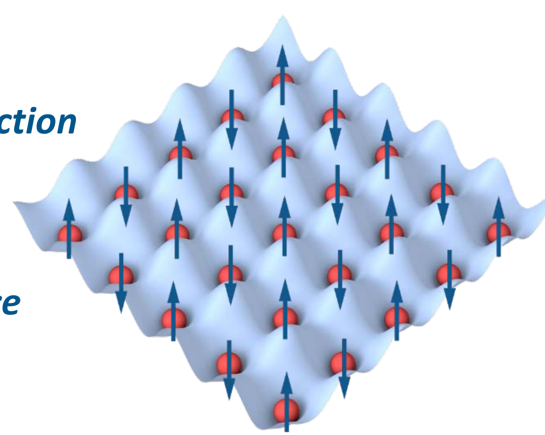


A quick introduction to the HTS phase diagram



Mott insulator

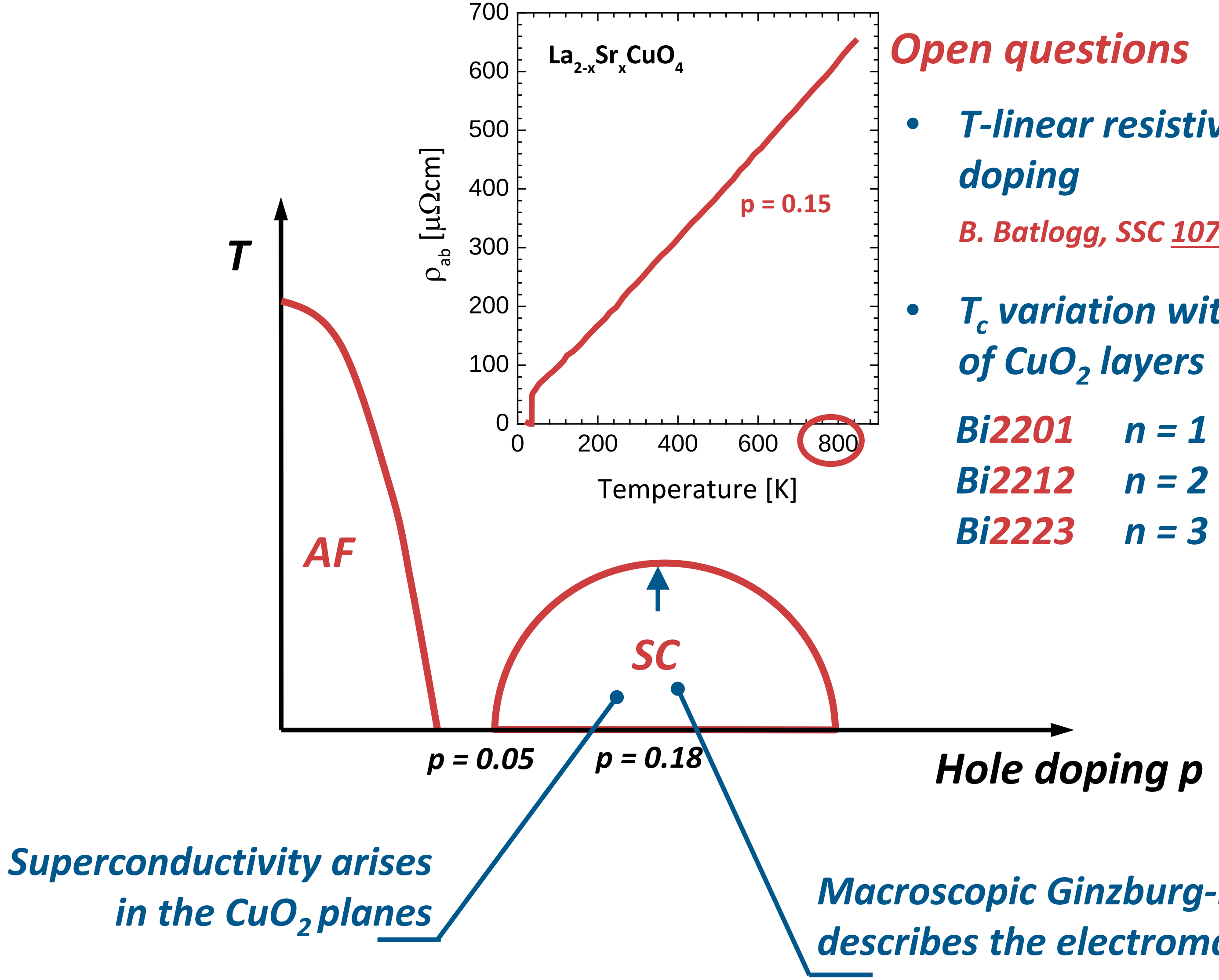




Only one electron per site
but the strong Coulomb repulsion
between the electrons impedes
their flow

On the top of that the
antiferromagnetic interaction

A quick introduction to the HTS phase diagram



Open questions

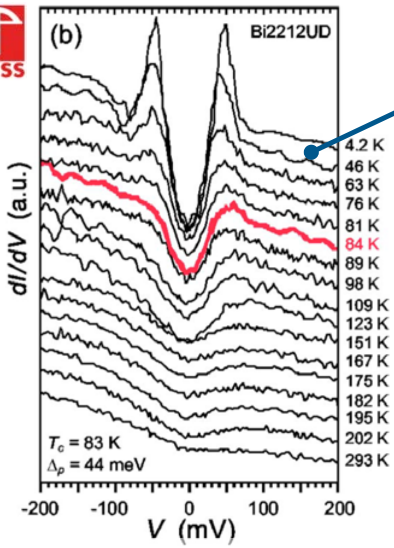
- T-linear resistivity at optimal doping

  B. Batlogg, SSC 107 (1998) 639

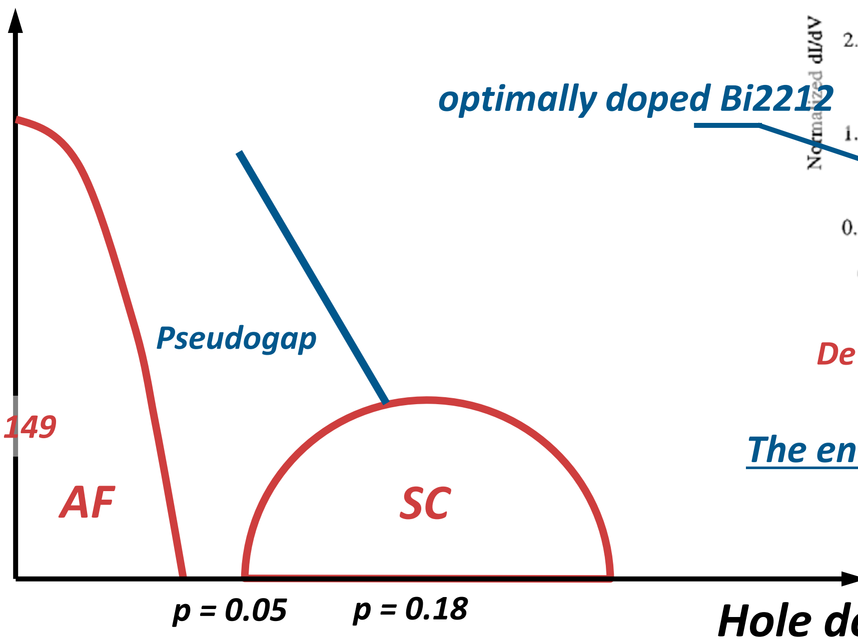
- T_c variation with the number of CuO_2 layers

Bi2201	n = 1	T_c = 15 K
Bi2212	n = 2	T_c = 91 K
Bi2223	n = 3	T_c = 110 K

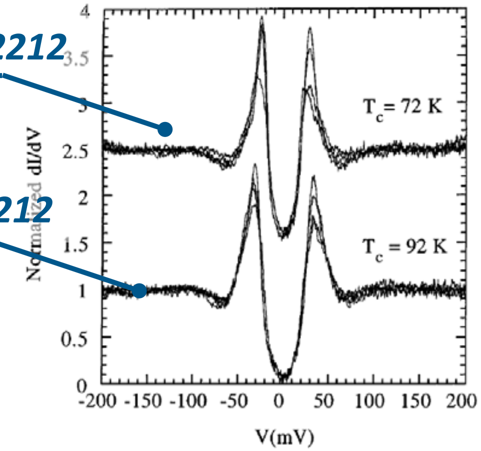
A quick introduction to the HTS phase diagram



Renner et al., PRL 80 (1998) 149



Tunneling spectra



DeWilde et al., PRL 80 (1998) 153

The energy gap Δ goes to zero at T_c

The energy gap Δ does not go to zero at T_c

The pseudogap exists only in the underdoped regime, up to T*(p)

Other phenomena take place in the underdoped regime

- Charge density waves
- Stripes
- Spin fluctuations

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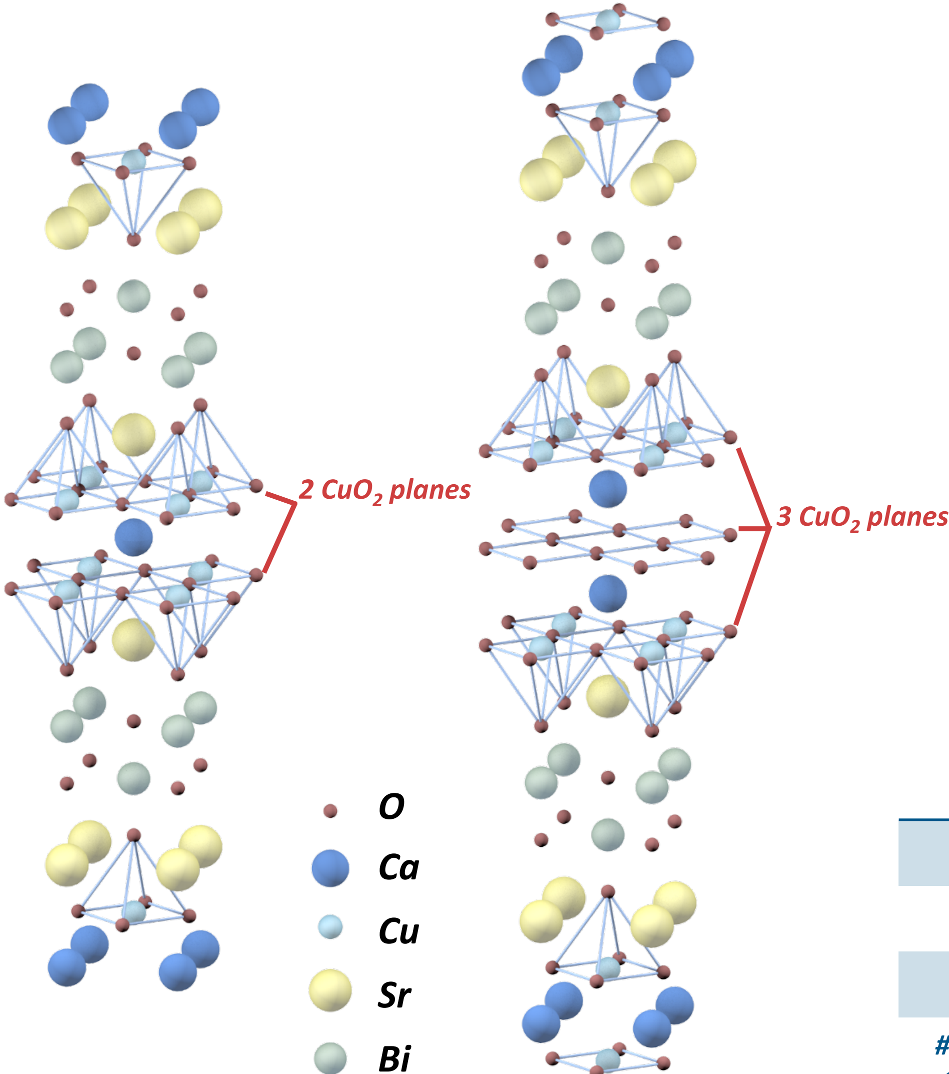
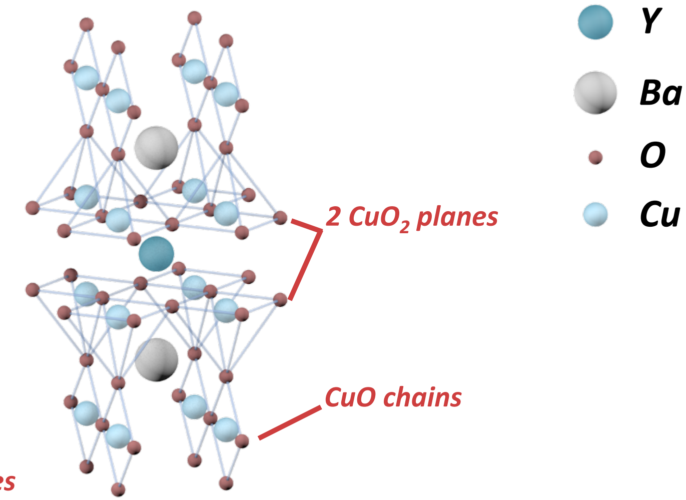
HTS materials for practical applications: the Trinity





Bi2212
$Bi_2Sr_2CaCu_2O_{8+x}$

Bi2223
$Bi_2Sr_2Ca_2Cu_3O_{10+x}$

Y123
$YBa_2Cu_3O_{7-x}$

	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

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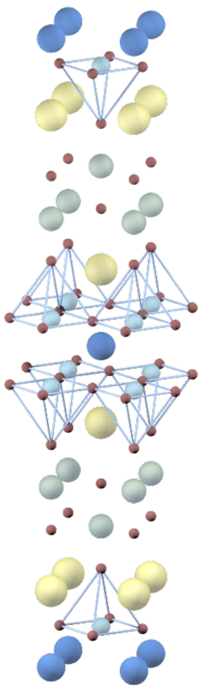
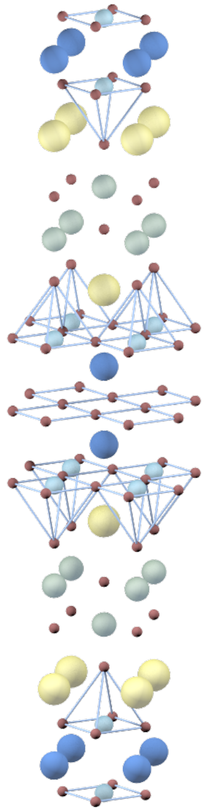
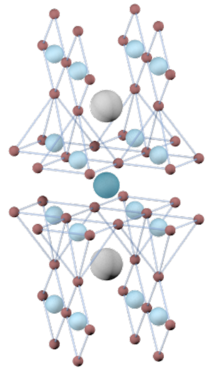
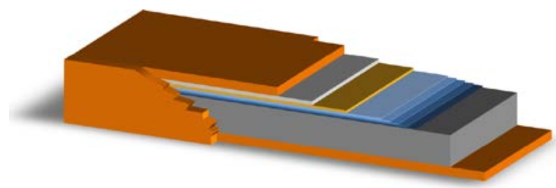
The evolution to the present wires and tapes

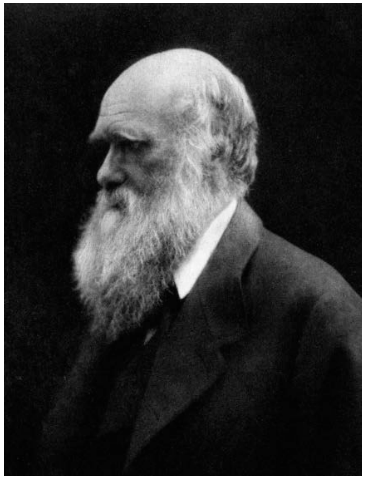




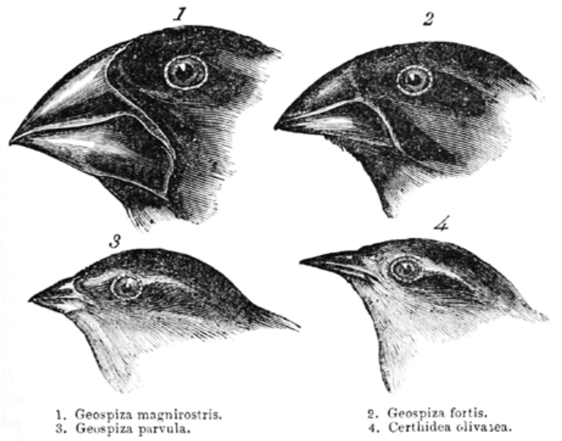


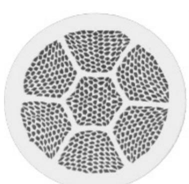


Y123 Coated Conductor



Darwin's finches





Bi2223 Powder-In-Tube tape

Bi2212
Powder-In-Tube wire

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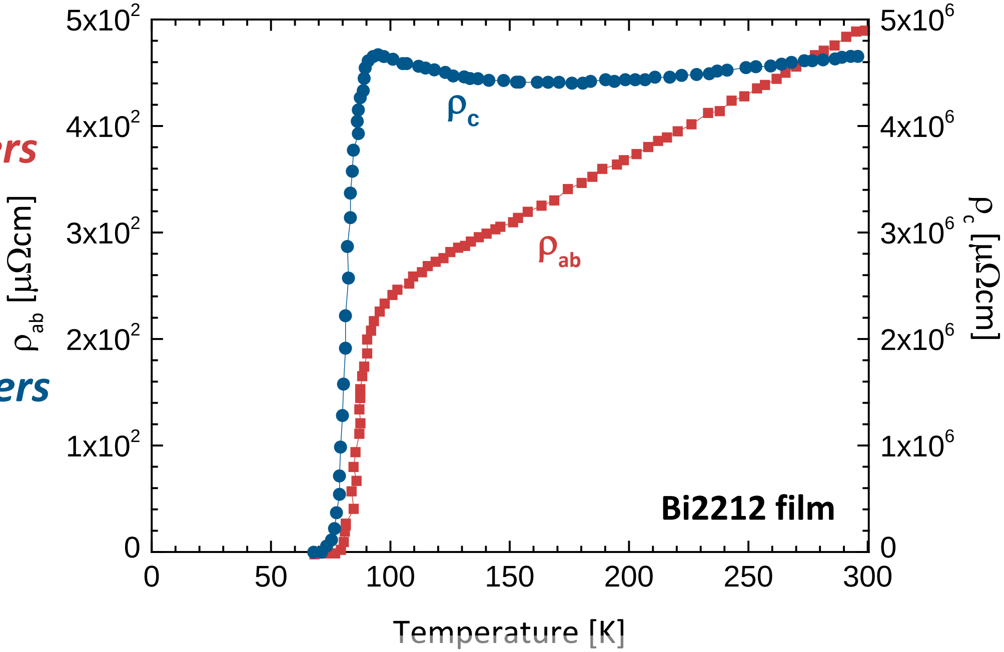
Layered structure and Anisotropy



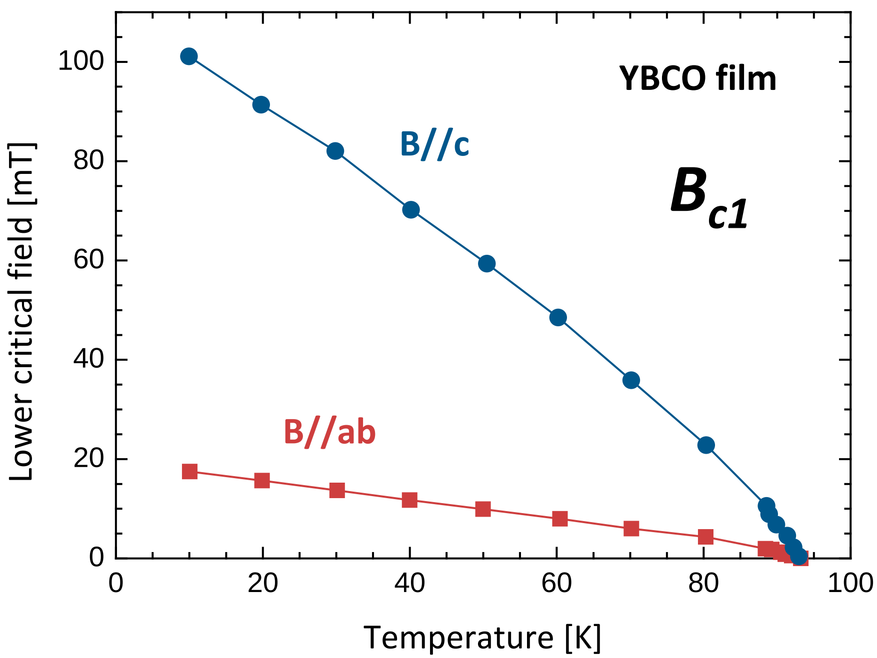
Raffy et al., Physica C 460-462 (2007) 851

Charge carriers have effective masses that depend on the crystallographic orientation

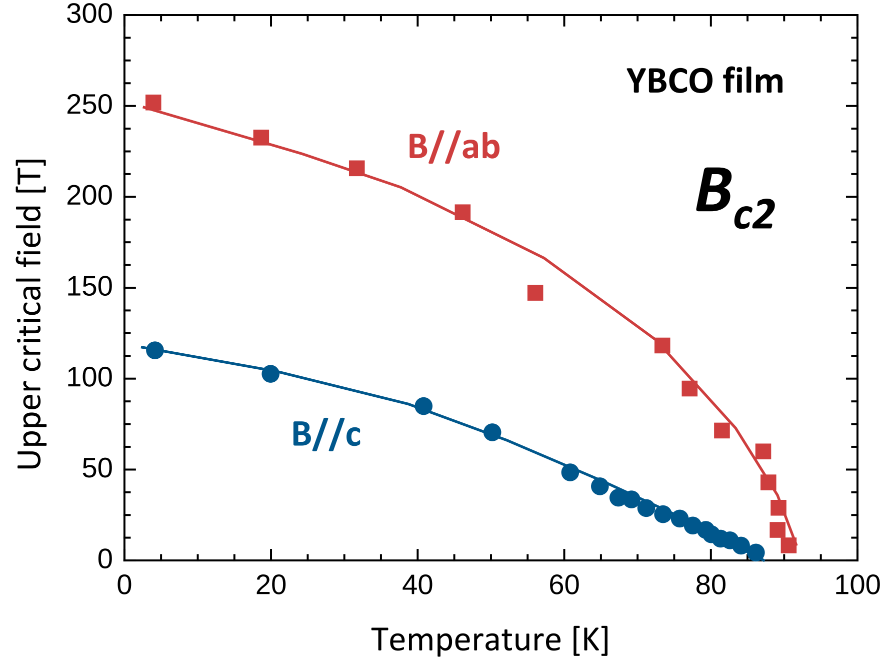
$\frac{m_c}{m_{ab}}$ ***ranges between 50 and 10'000 in cuprates***

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

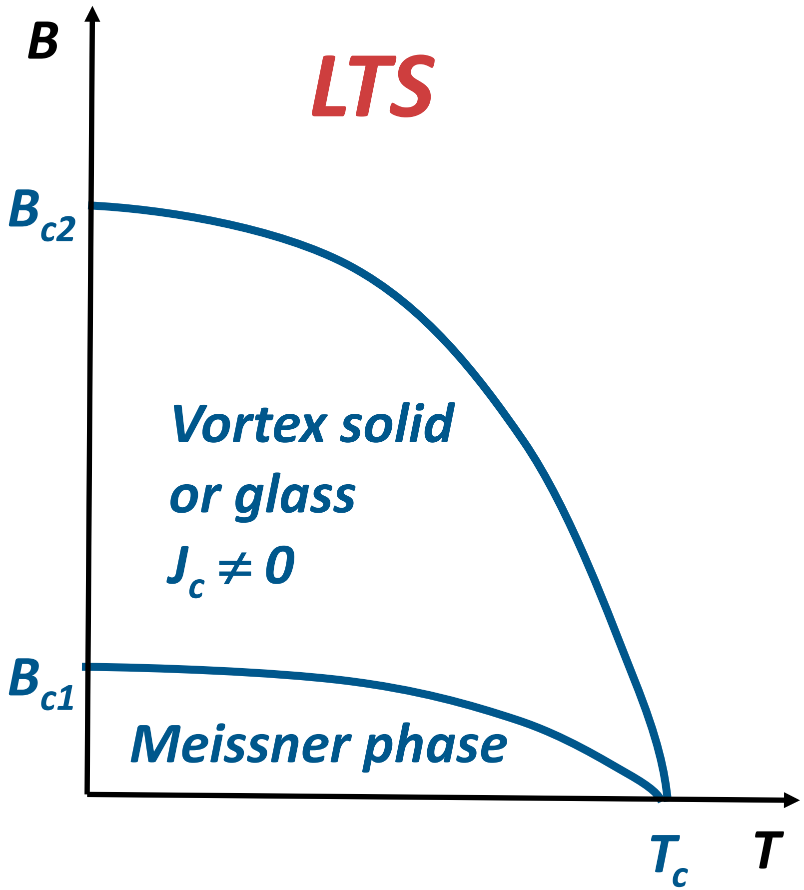
Sekitani et al., NJP 9 (2007) 47

The superconductor anisotropy parameter

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

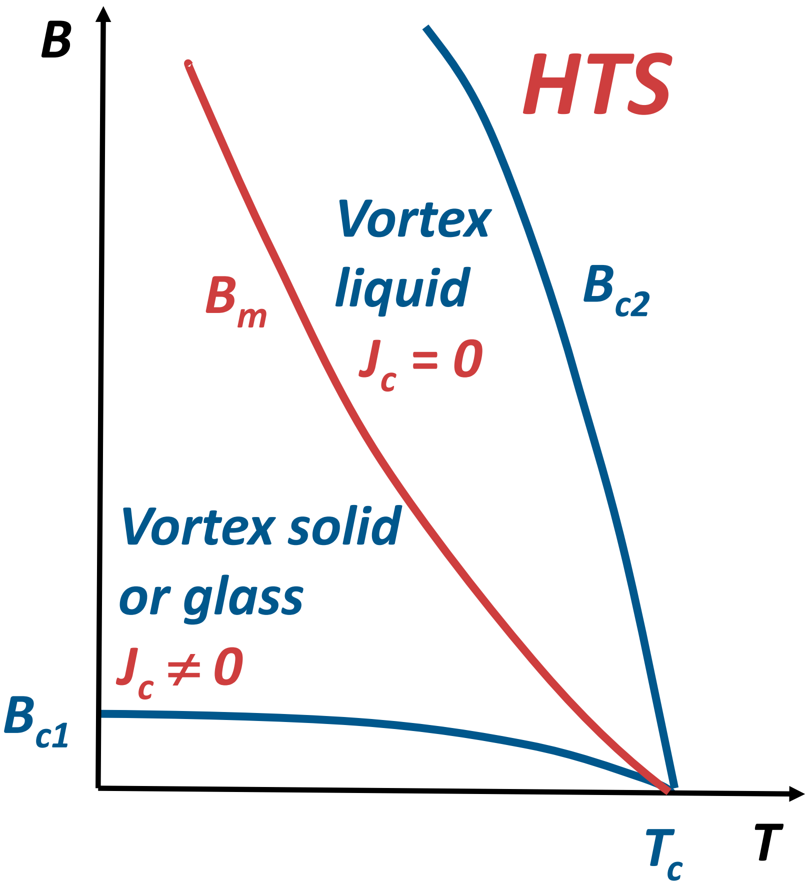
	Bi2212	Bi2223	Y123
γ	~150	~30	~7

Anisotropy, magnetic phase diagram & critical current



LTS: in-field $J_c \rightarrow 0$ close to B_{c2}

Anisotropy, magnetic phase diagram & critical current



In the case of a anisotropic 3D superconductor

$$\frac{B_m}{B_{c2}} \propto \frac{c_L^4 \Phi_0^4 \xi_{ab}^2}{(k_B T)^2 \lambda_{ab}^4 \gamma^2}$$

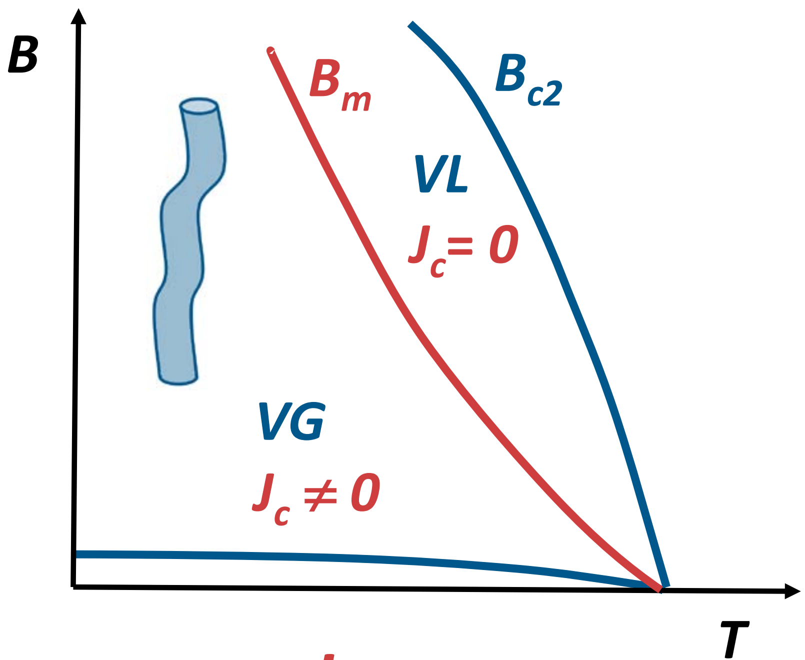
And high anisotropy makes the things worse

HTS: in-field $J_c \rightarrow 0$ at the melting field B_m

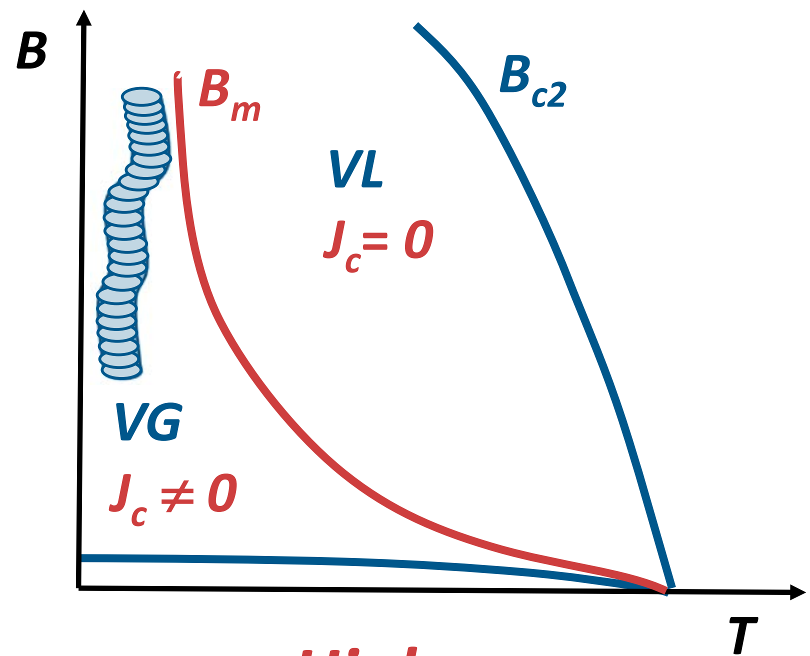
Anisotropy brings a field limitation in applications

3-D melting vs. 2-D melting

Magnetic field perpendicular to the CuO_2 planes



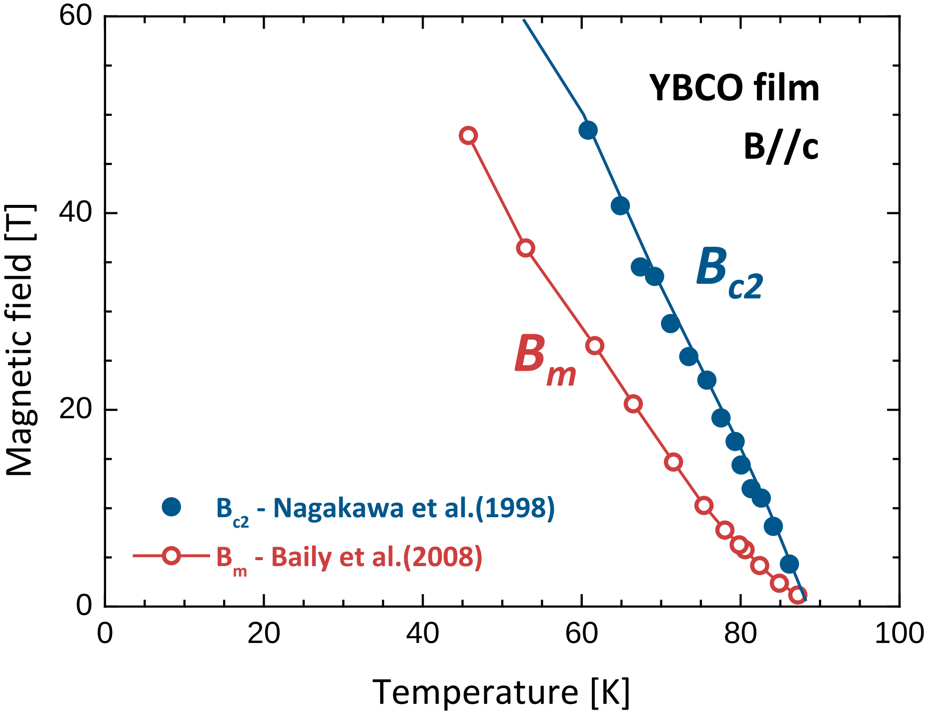
Low γ

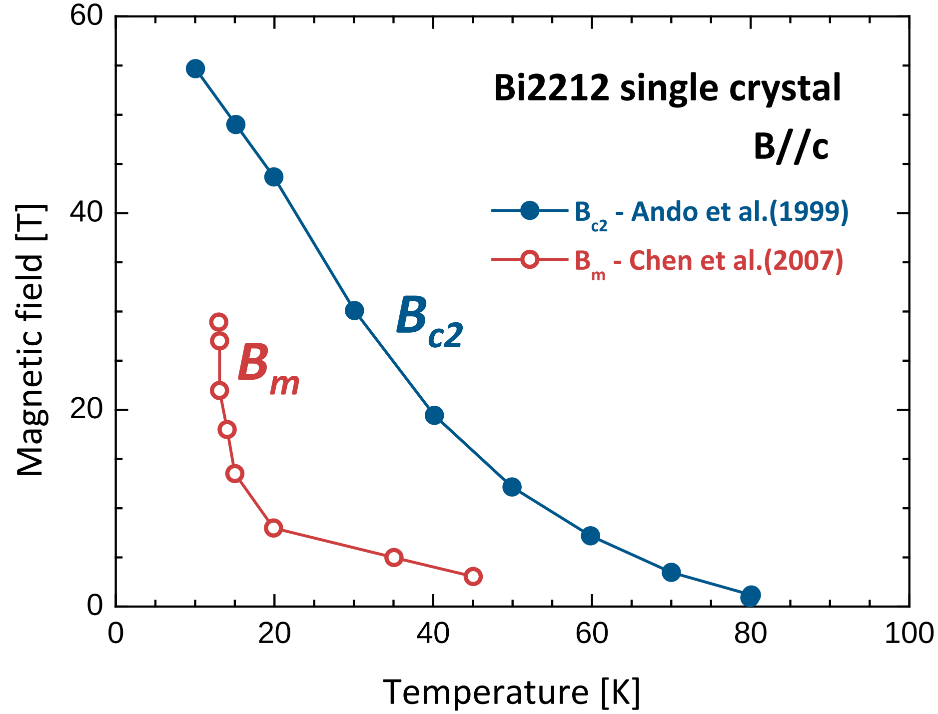


High γ

High γ : transition from vortex lines in 3-D to vortex "pancakes" in 2-D

3-D melting vs. 2-D melting





Low γ : YBCO

High γ : Bi2212

YBCO has in-field $J_c \neq 0$ even at 77 K

Bi2212 in-field J_c drops rapidly to zero with temperature

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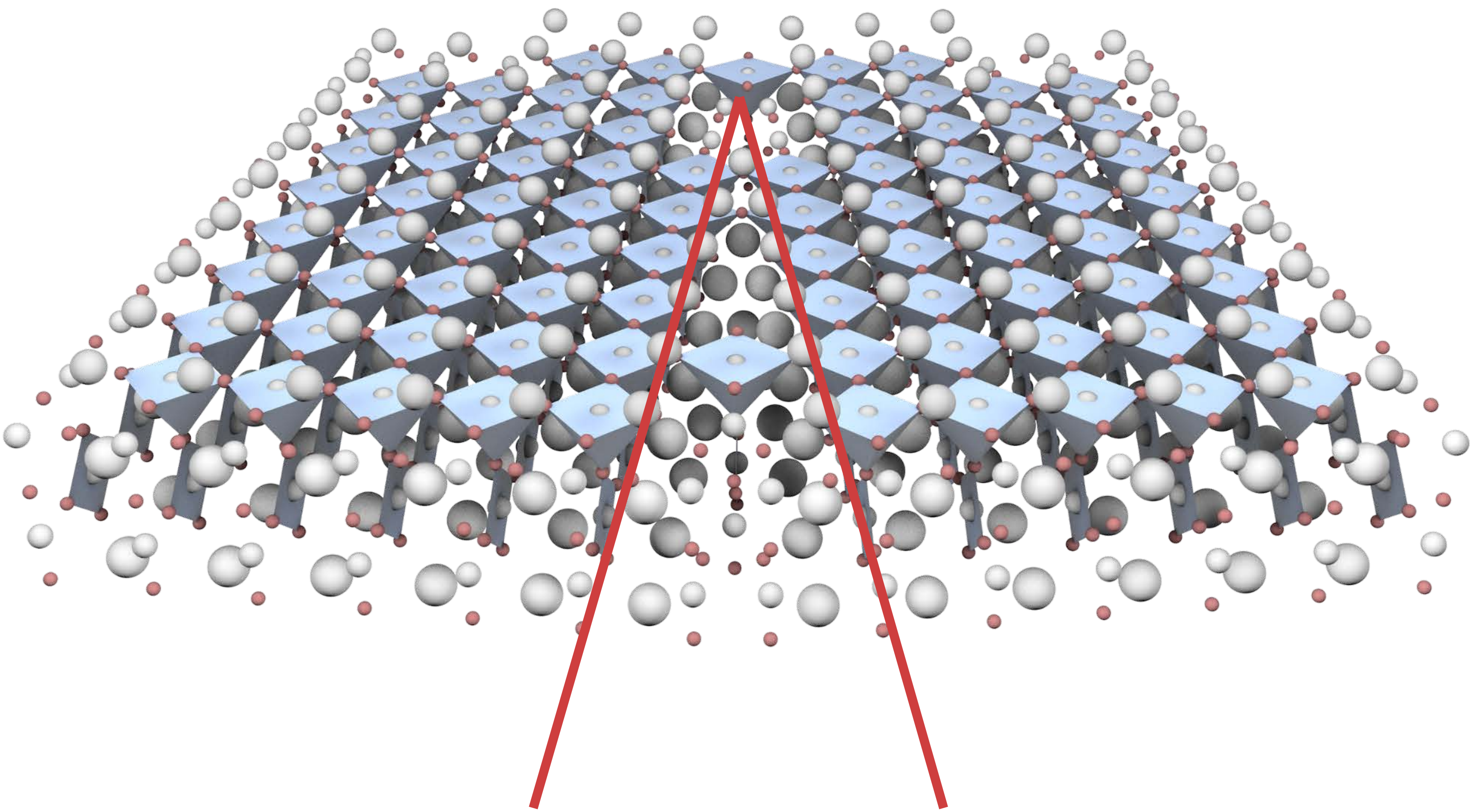
Grain Boundaries in HTS



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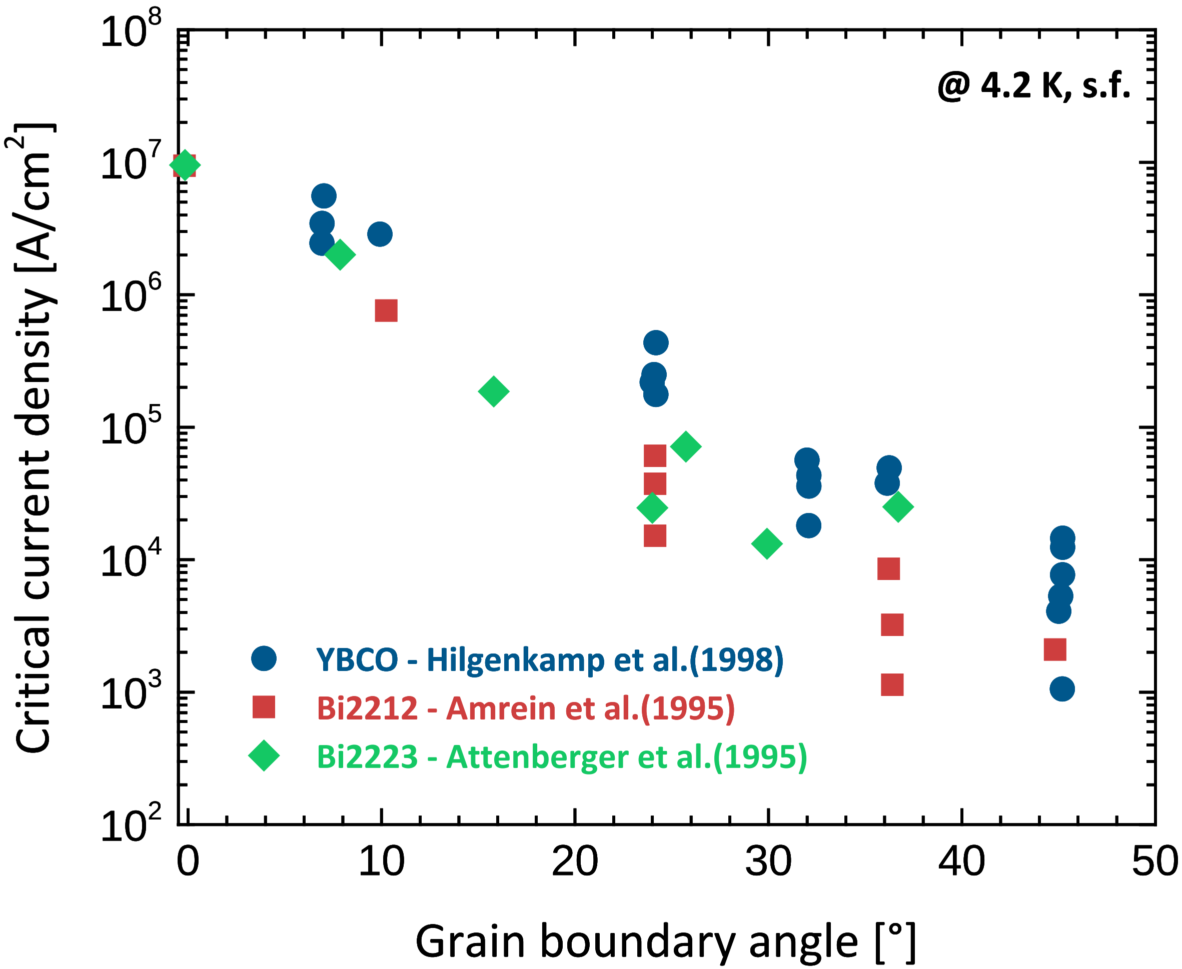
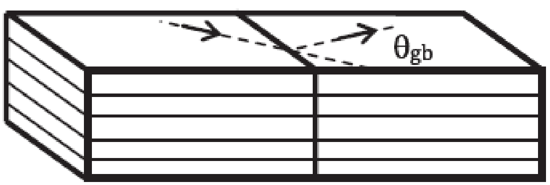
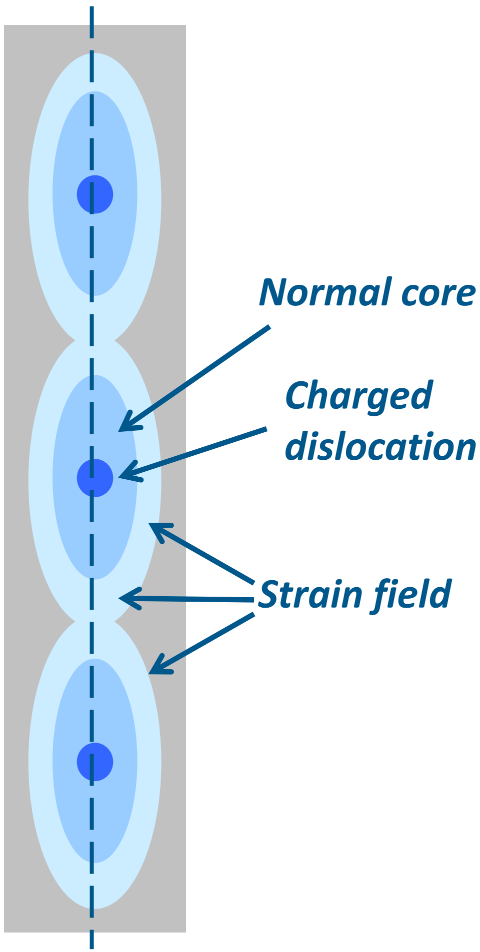
Grain Boundaries in HTS



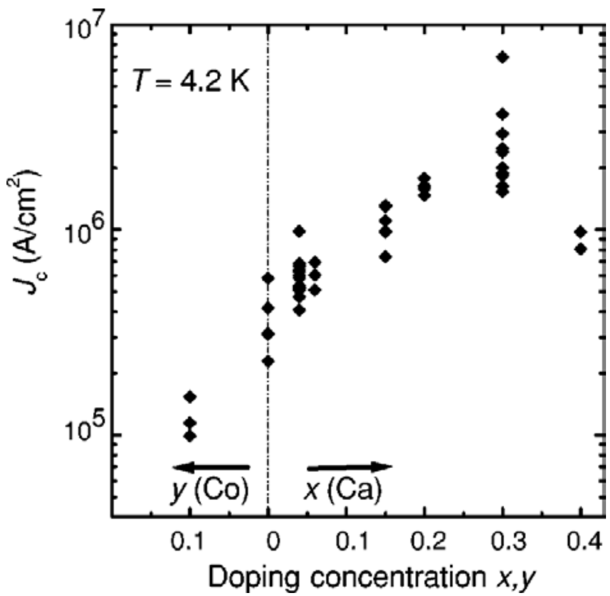


[001] tilt boundary

Factors limiting the Grain Boundary J_c in HTS

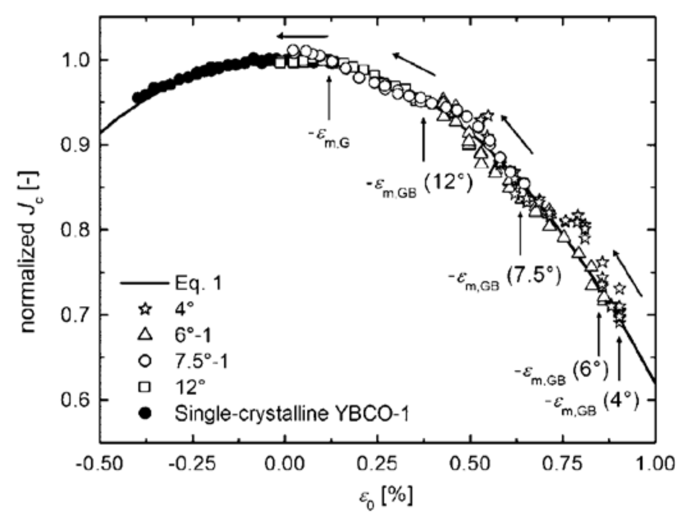


Reduction of the charge carrier concentrations



Schmehl et al., EPL 47 (1999) 110

Local strain field



Van der Laan et al., PRL 103 (2009) 027005

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Which mechanism is dominating ?

The question is still open…

And the solutions to overcome the problem are very different and depend on the HTS material

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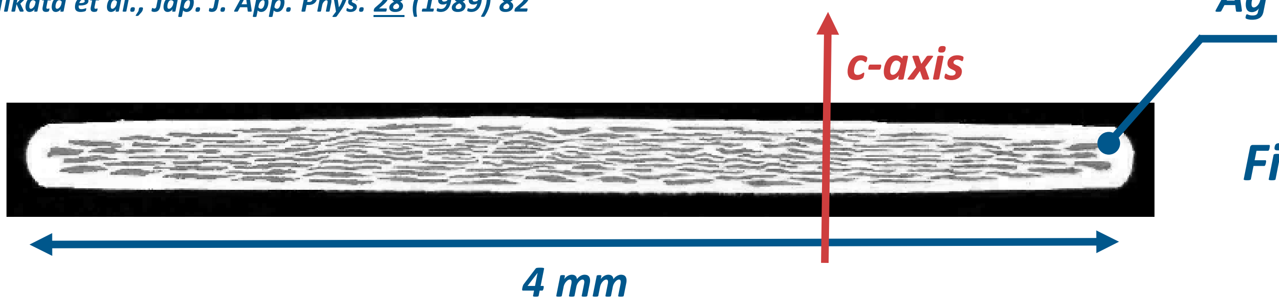
Bi2223: Powder-In-Tube tapes

Hikata et al., Jap. J. App. Phys. 28 (1989) 82

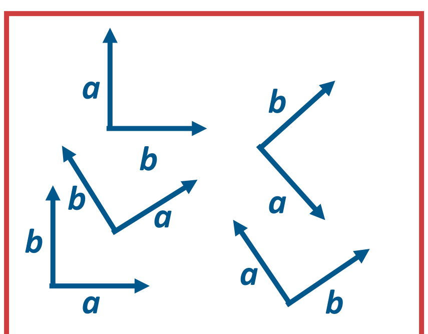


Filling factor is ~40%

Precursor powders are a mixture of Bi2212, Bi2201, Ca_2PbO_4, CuO…

Platelet-like Bi2212 grains are aligned with c-axis texturing during the wire-to-tape deformation

The texturing is kept after reaction by Bi2223

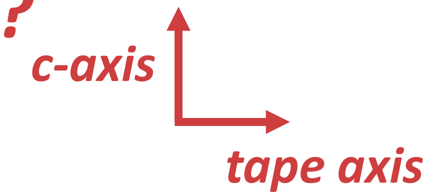


Looking from above

How does the current flow without in-plane texturing ?

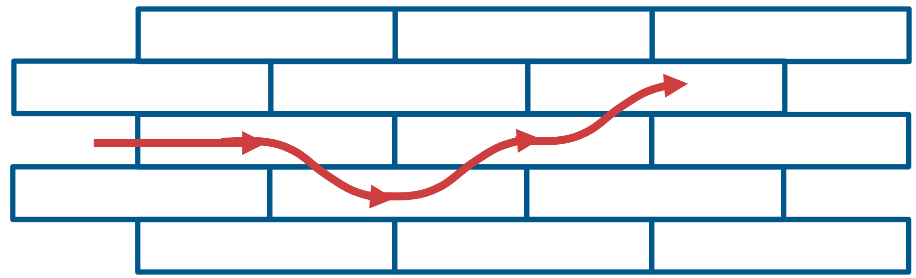
Presently produced by SUMITOMO ELECTRIC, InnoST 英纳超导

How does the current flow in Bi2223 tapes ?



BRICK WALL model

Bulaevskii et al., PRB 45 (1991) 2545

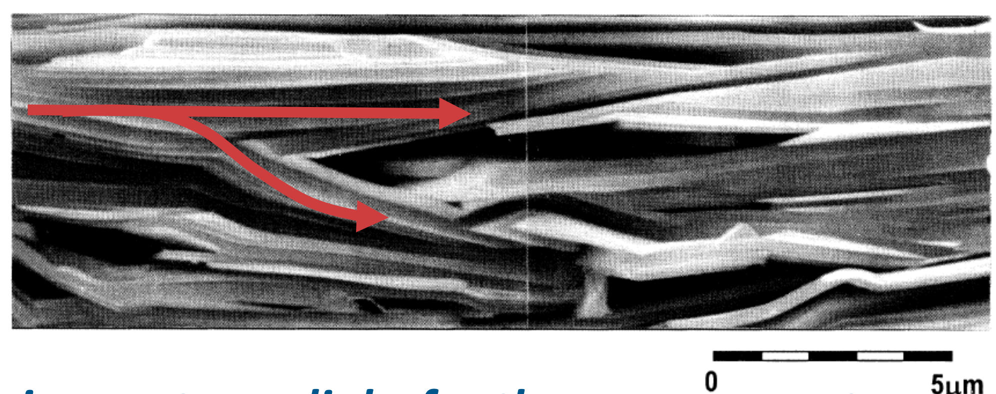


Grain thickness << Grain length

c-axis current transfer among the grains (weak links)

RAILWAY SWITCH model

Hensel et al., PRB 51 (1995) 15456

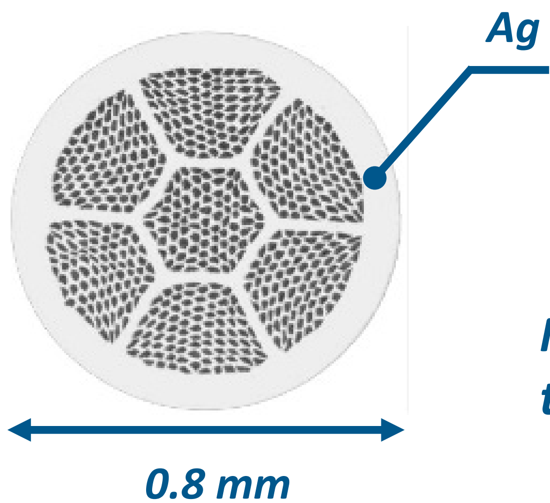


Small-angle c-axis tilted grain boundaries as strong links for the supercurrent

Bi2212: Powder-In-Tube round wires

Heine et al., APL 55 (1989) 2441

Enomoto et al., Jap. J. App. Phys. 29 (1990) L447

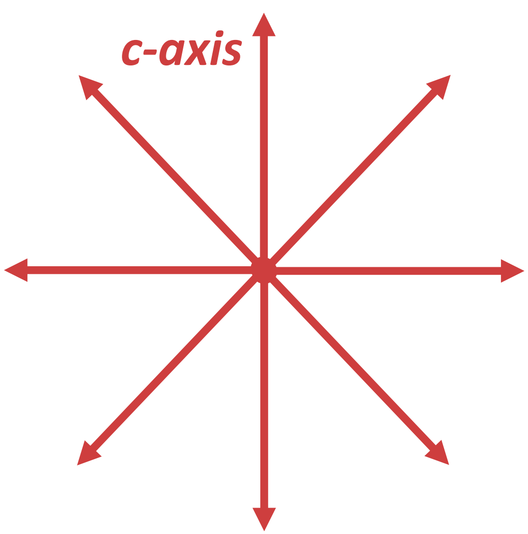


Filling factor is ~25-30%

Melting and recrystallization during the heat treatment determines:

- ***a gradual rotation of the c-axis of grains around the wire axis***
- ***a local spontaneous a-axis texture along the filament axis (within ~ 15°)***

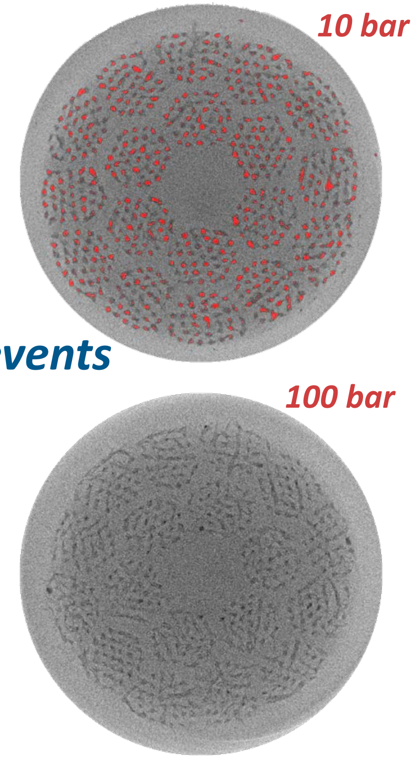
Kametani et al., Sci. Rep. 5 (2015) 8285



Presently produced by OXFORD INSTRUMENTS

How do we get high J_c in Bi2212 wires ?

The "secrets" of its recent success



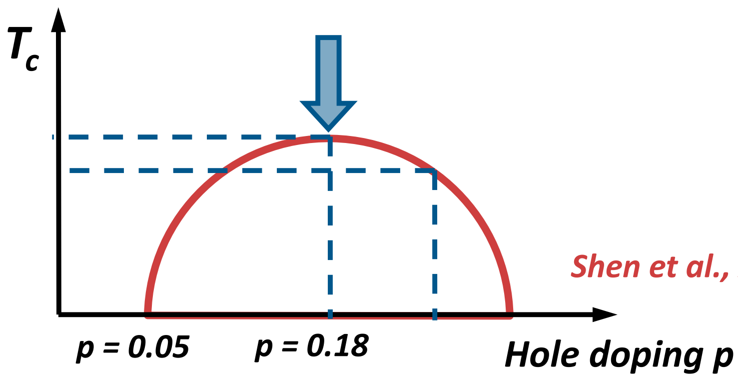
C. Barth, 4MPo2D-05

OVERPRESSURE (up to 100 bar) during the heat treatment prevents the formation of bubbles

To increase the current carrying cross section

Larbalestier et al., Nat. Mat. 13 (2014) 375

*OVERDOPING**



Shen et al., APL 95 (2009) 152516

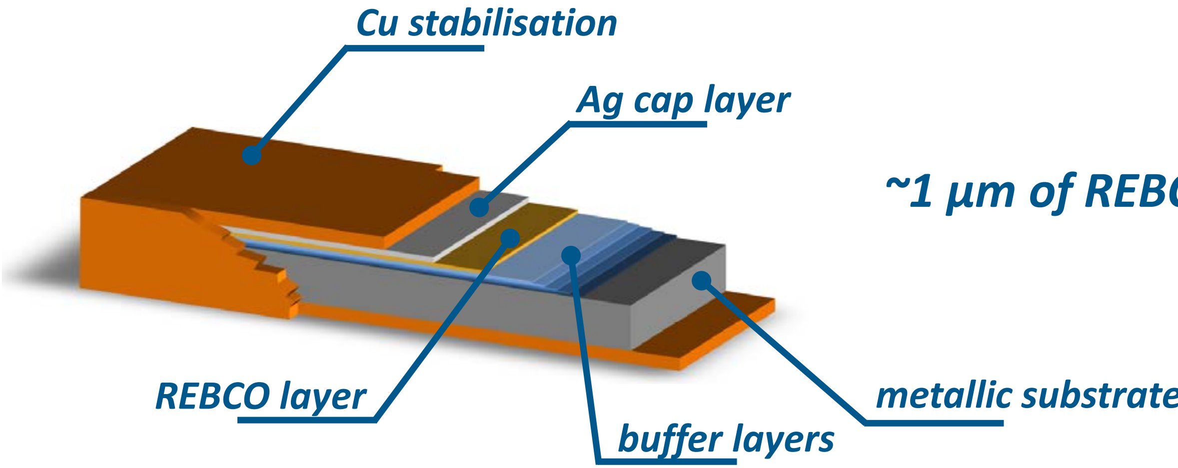
The intragrain region is overdoped, but grain boundaries are optimally doped

The anisotropy is reduced → better pinning

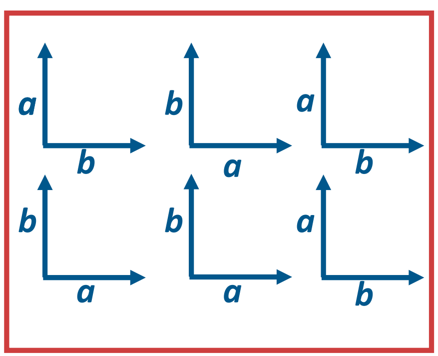
** it doesn't work with Bi2223 and YBCO*

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 needed to overcome the grain boundary problem

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

IEEE/CSC & ESAS EUROPEAN SUPERCONDUCTIVITY NEWS FORUM (global edition), October 2016.
Plenary presentation 4PL-02 given at ASC 2016; Denver, Colorado, USA, September 4 – 9, 2016.

The technology of REBCO coated conductors

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

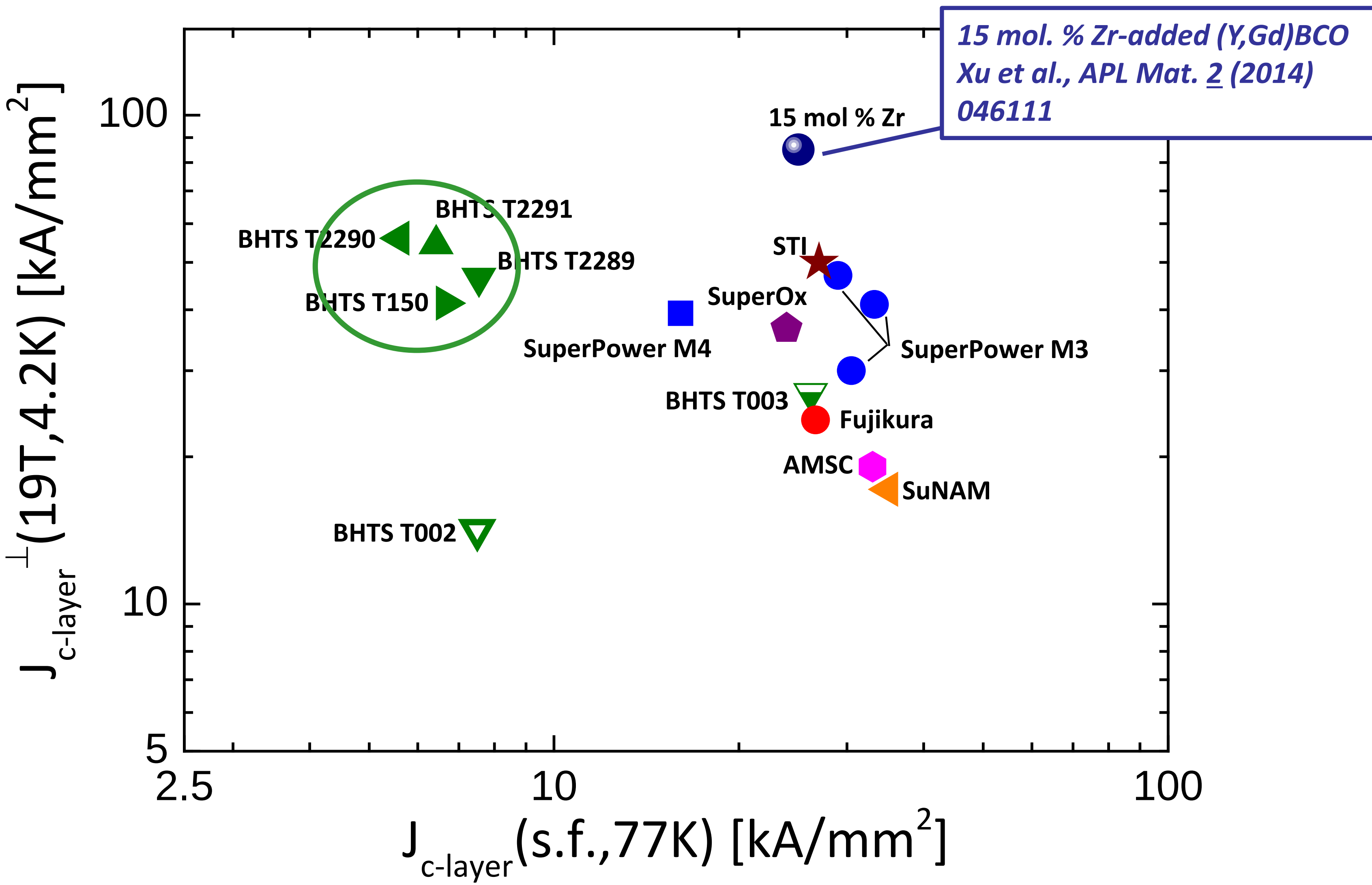
Substrate texturing

- **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.

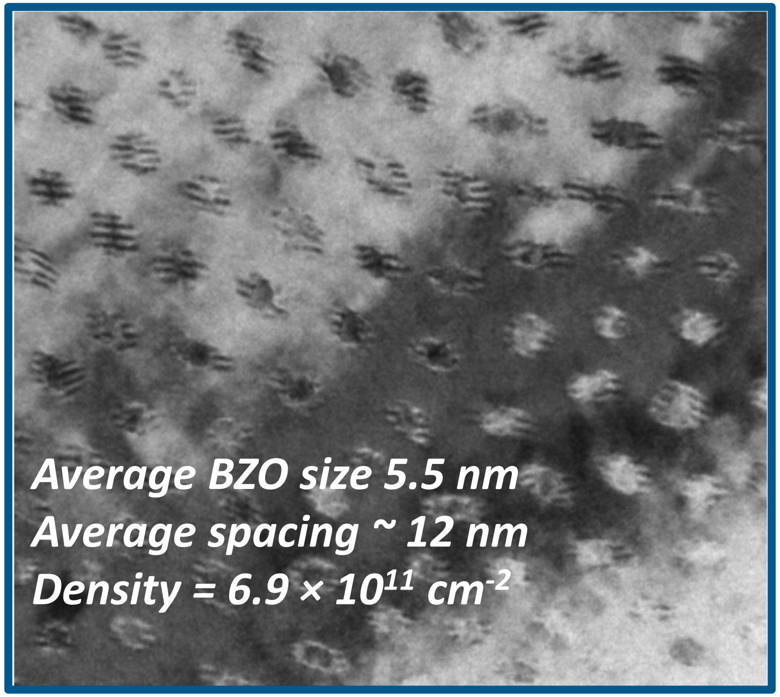
Performance overview: J_c(s.f.,77K) vs. $J_c^{\perp}$(19T,4.2K)



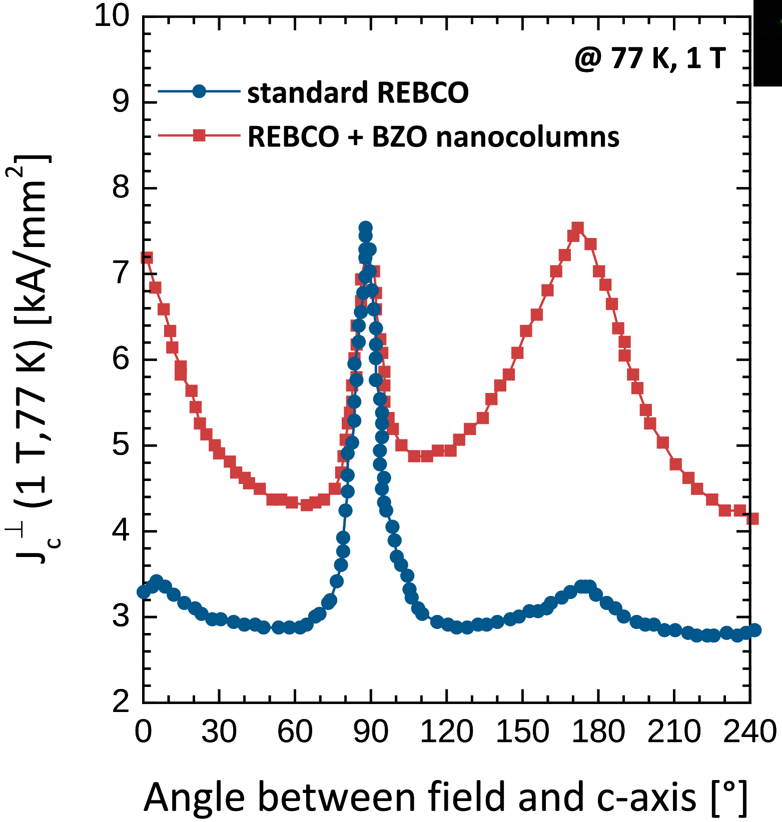
Artificial pinning:"genetically-modified" REBCO

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

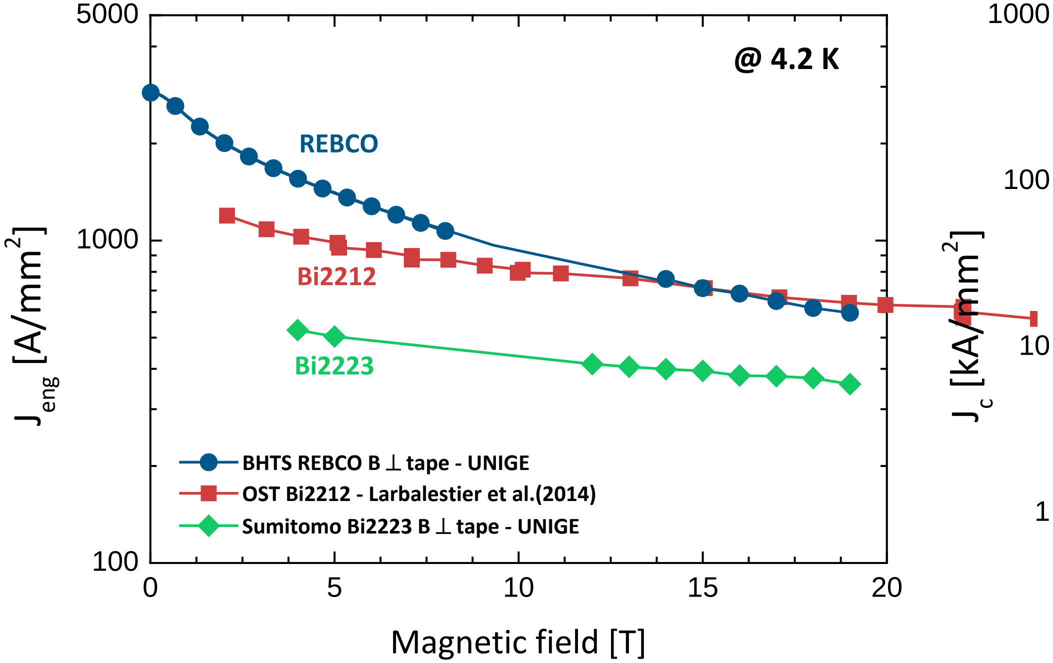


Selvamanickam el al., APL 106 (2015) 032601

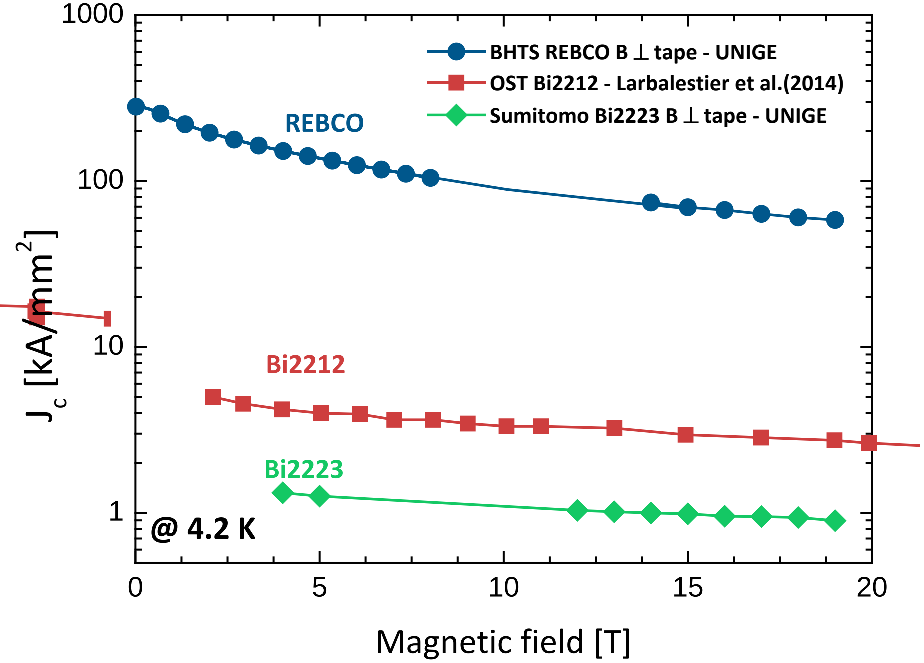


Selvamanickam et al., IEEE TASC 21 (2011) 3049

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

Outline

What is special with HTS

How to make technical conductors out of HTS

- *How to deal with anisotropy*
- *How to deal with grain boundaries*
- ***High critical current, and*** What else ?

What we can do with HTS

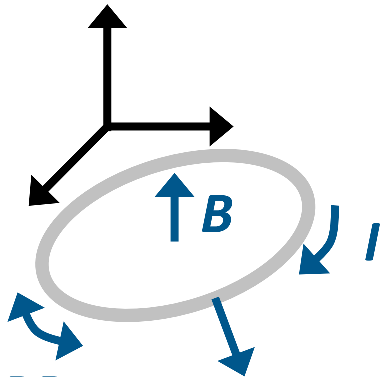
Focus on large scale applications

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



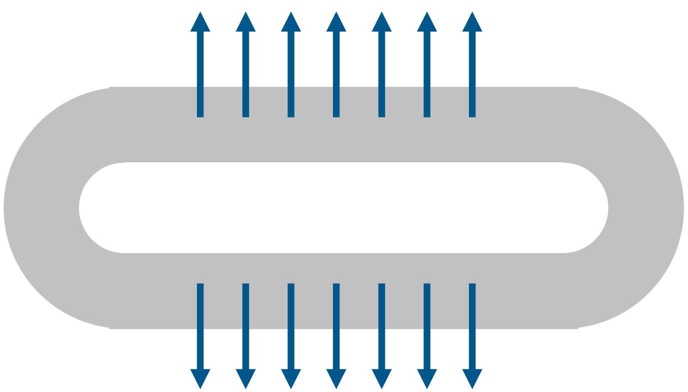
$$\sigma_{hoop} = \frac{I}{S_{wire}} BR$$

$$F = I \times B$$

Hoop stress levels above 100 MPa are common

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

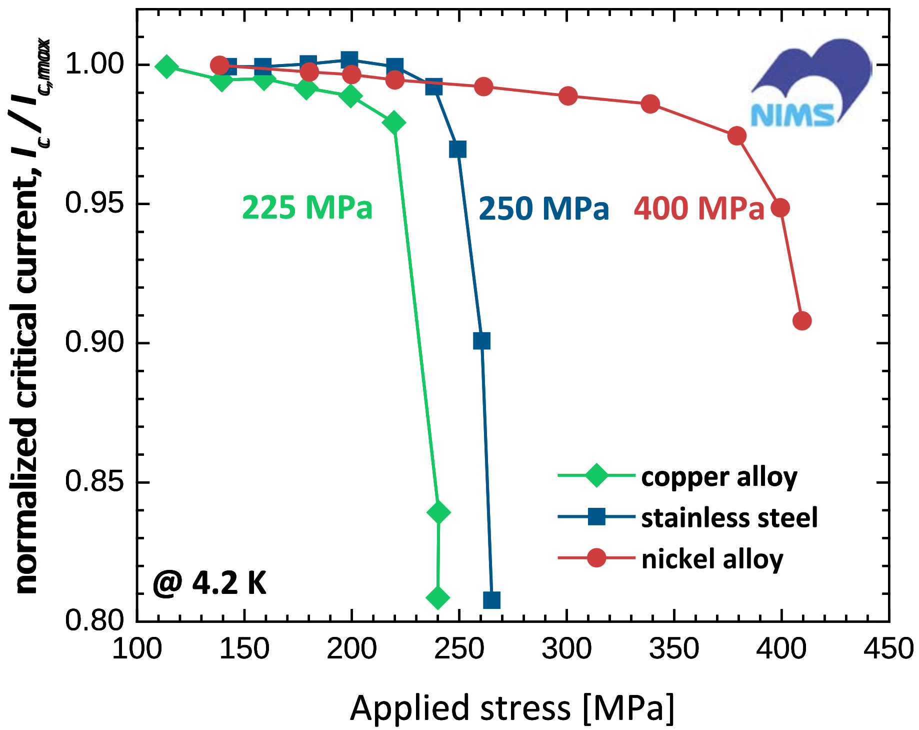
In a real winding adjacent turns press on each other and develop 3-D stresses



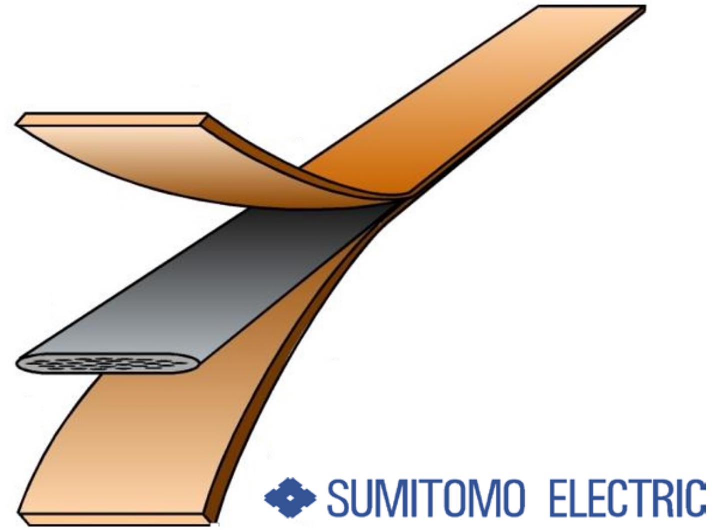
In straight-sided coils such as accelerator magnet, the conductor experiences large transverse forces

F = 175 ton/m in a LHC dipole

Bi2223 tapes: axial stress sensitivity



Miyoshi et al., SUST 28 (2015) 075013



Bi2223 tapes are inherently weak because of the soft Ag matrix

Sumitomo introduced reinforcement with high strength lamination *

Irreversible stress limit at 400 MPa with Ni alloy (Type HT-NX)

**at the cost of a reduced J_{eng} by ~25%*

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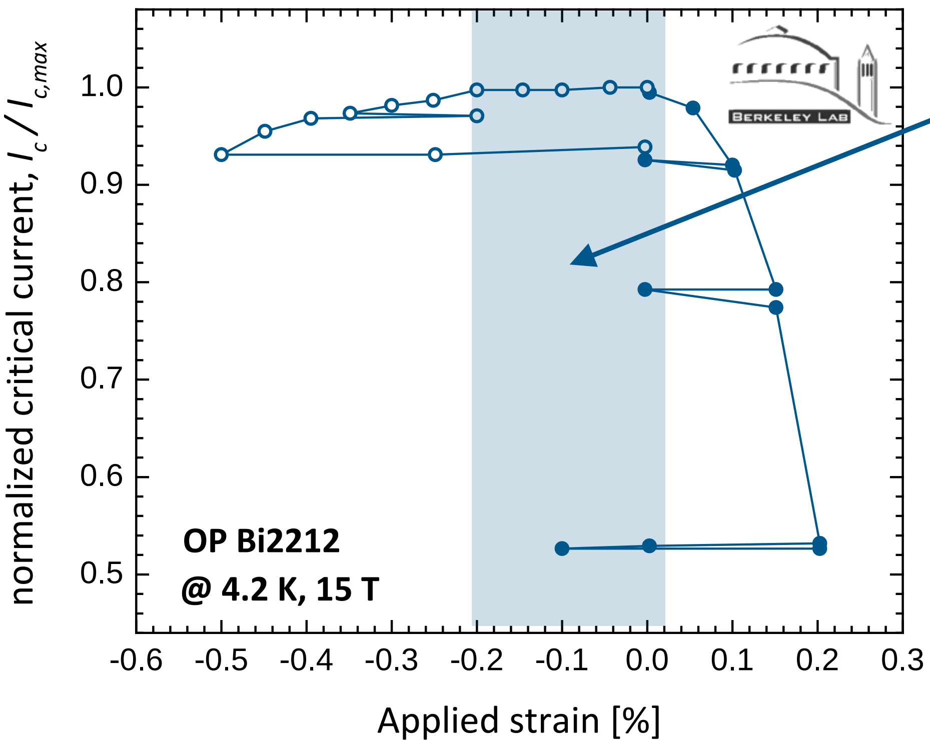
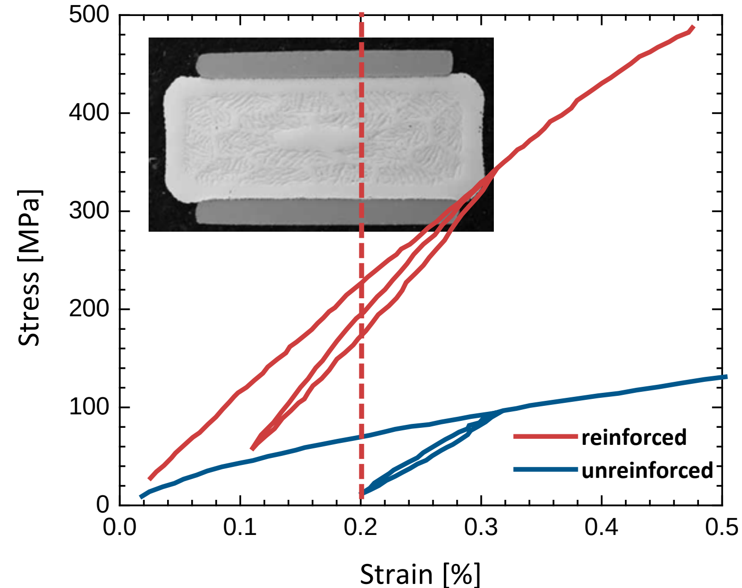
Bi2212 wires: axial strain sensitivity

Reversible region of less than 0.3%



Godeke et al., SUST 28 (2015) 032001



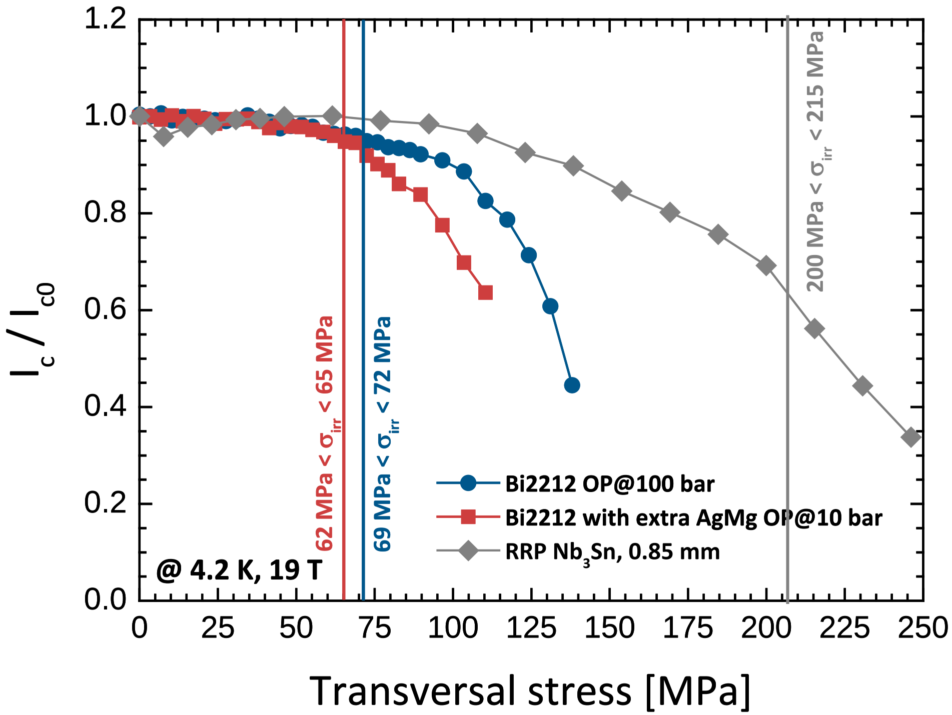
A. Otto, 1MOr1A-08

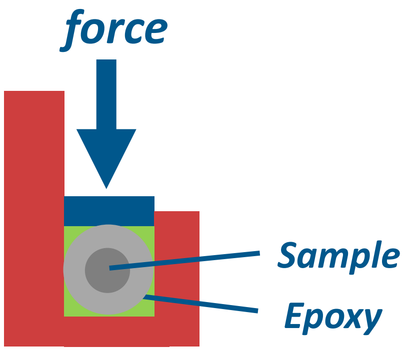
Bi2212 wires are inherently weak because of the soft Ag matrix

Reinforcement is being prototyped by lamination as for Bi2223

Stress for ε = 0.2% raised from 70 MPa to 230 MPa

Bi2212 wires: transversal stress sensitivity





Wire impregnated with epoxy applied stress uniformly distributed

C. Barth, 4MPo2D-05

Irreversible stress limit at ~ 75 MPa

No substantial improvement with OP or extra Mg

Results consistent with previous tests on Rutherford cables

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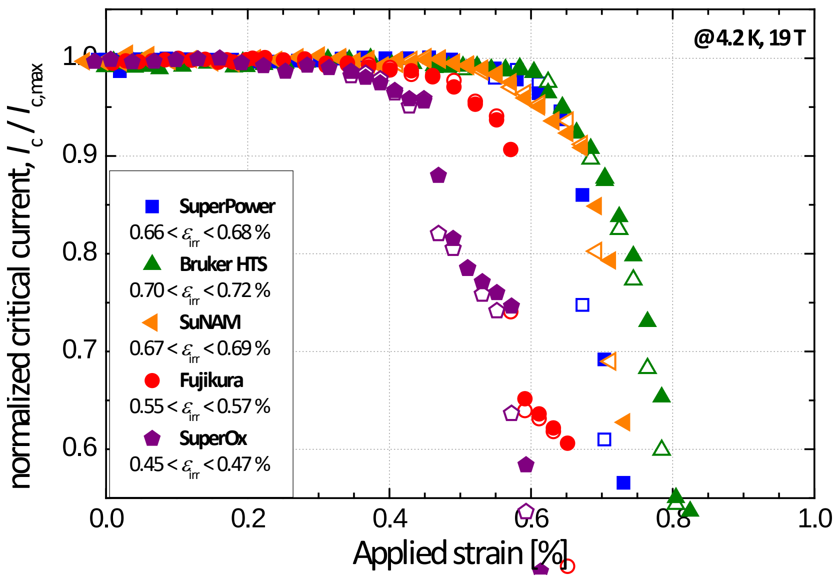
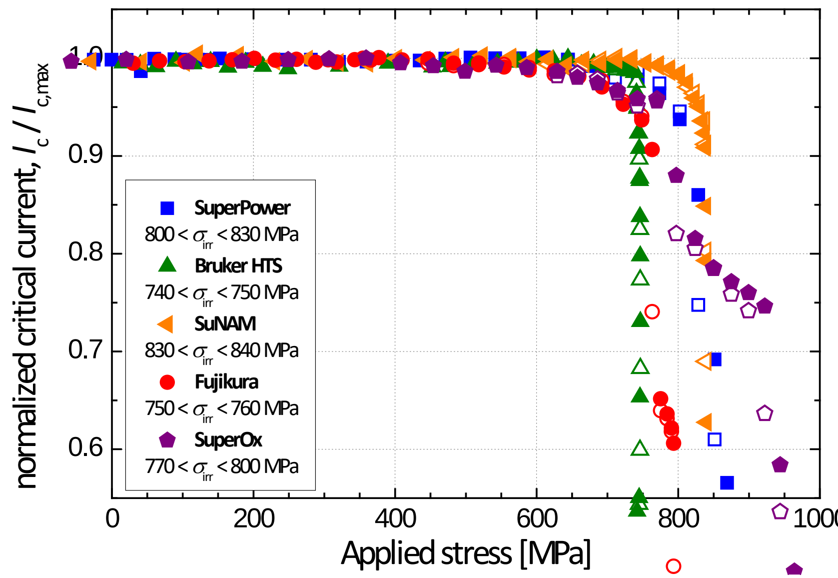
REBCO CCs: Dependence of I_c on axial loads

I_c vs. axial strain



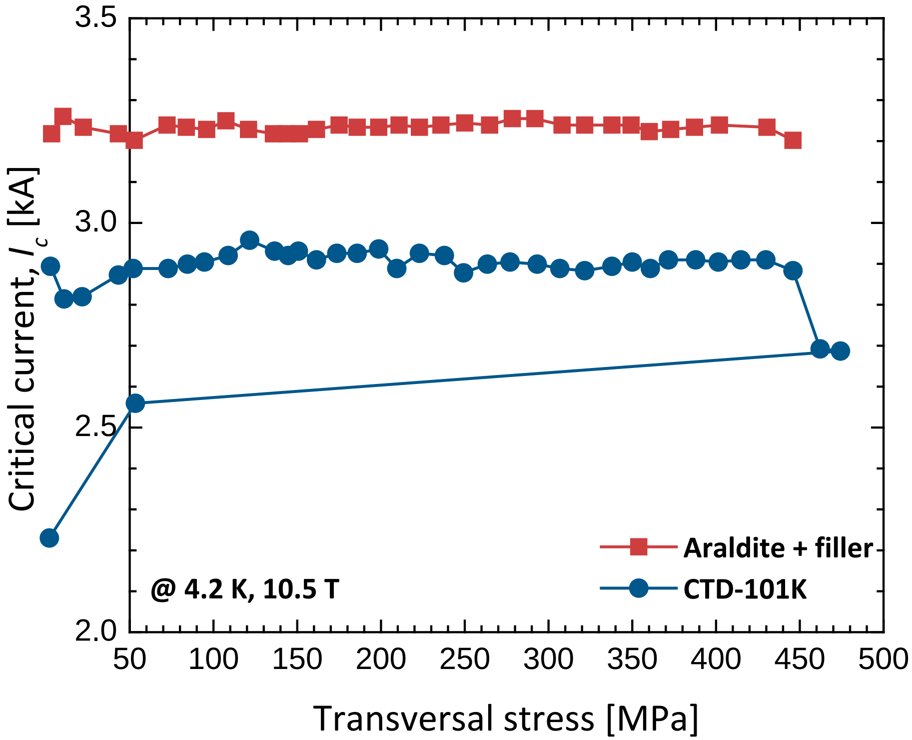
I_c vs. axial stress

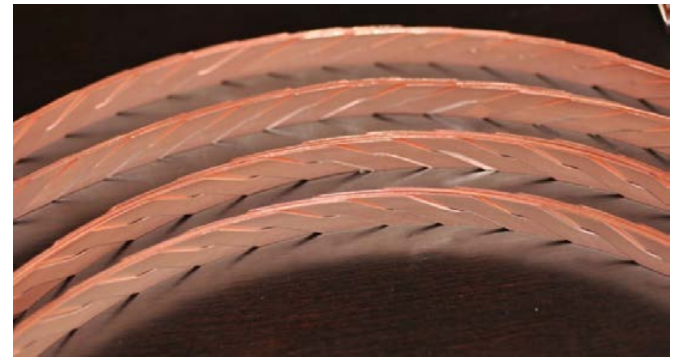


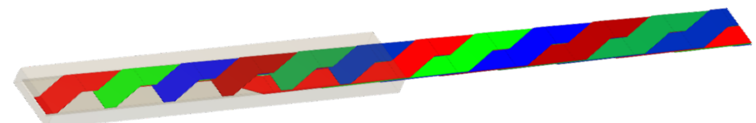
- *REBCO CCs are inherently strong, ~50% is a high strength alloy*
- *Very low stress effect → curves are flat in rev. region*
- *Irreversible stress limits above 500 MPa*
- *The only weakness is delamination…*

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

REBCO Roebel cables under transversal compression







P. Gao, 2LPo2D-06

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

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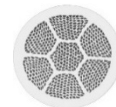
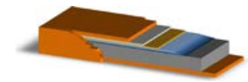
HTS technical conductors at a glance

	 Bi2223	 Bi2212	 REBCO
Geometry	tape	round wire	tape
SC fraction	40%	25%	~1%
In-field Anisotropy	~2	1, Isotropic	~5
Multifilamentary	Yes, untwisted	Yes, twisted	No, single layer
Operation boundaries	4.2 K, UHF 77 K, SF	4.2 K, UHF	4.2 K, UHF 77 K, ~3 T
Mechanical properties	OK with lamination, but lower J_{eng}	Still an issue, work in progress	Almost OK, but delamination issues
Disadvantages	One size, coil grading not possible Still margin for improvement?	Complex reaction at 100 bar to get high I_c Wind & react	Long lengths under development

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Since 30 years we're learning how to tame these WILD materials

… but who needs HTS ??

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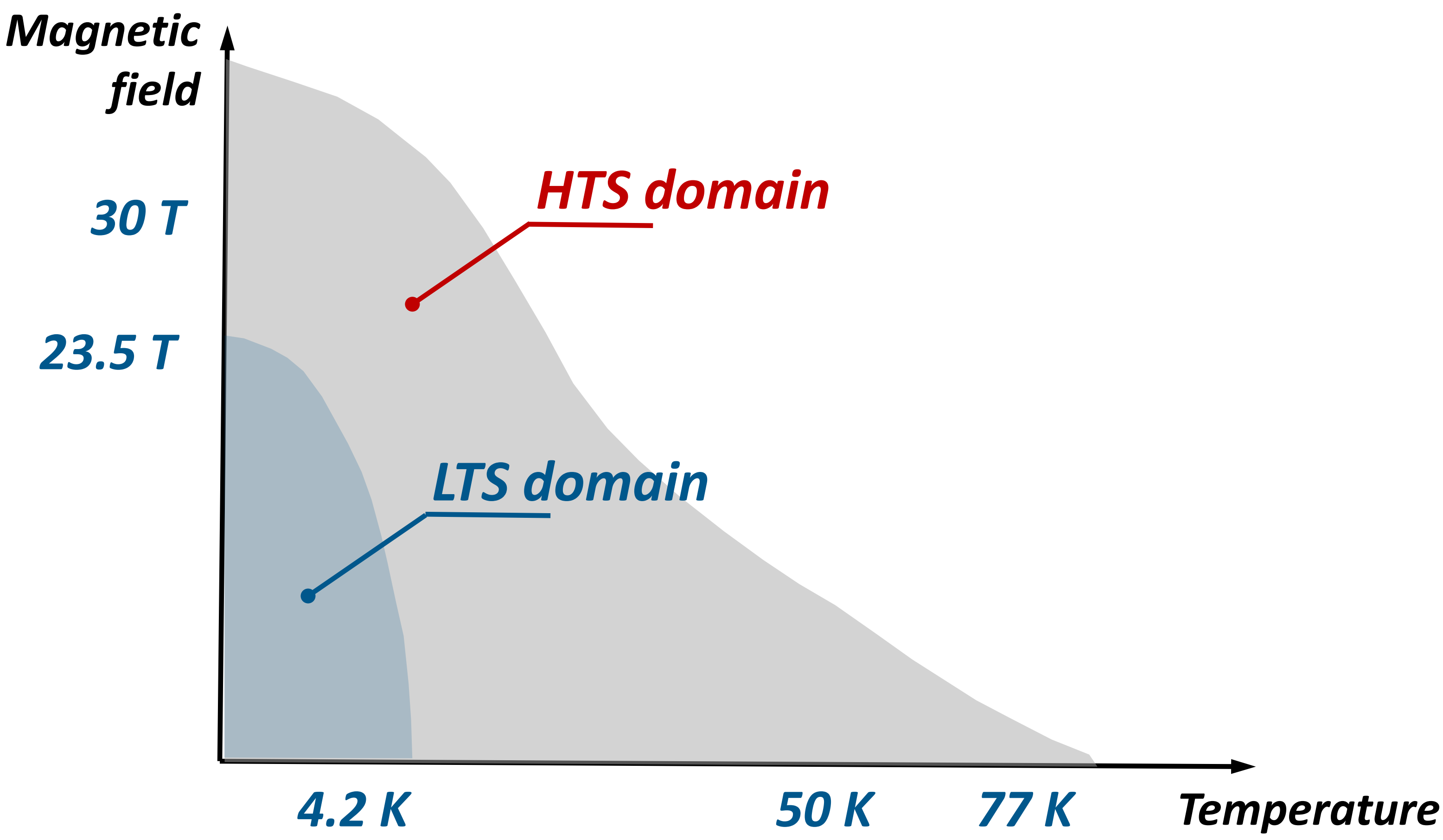
What can we do with HTS ?



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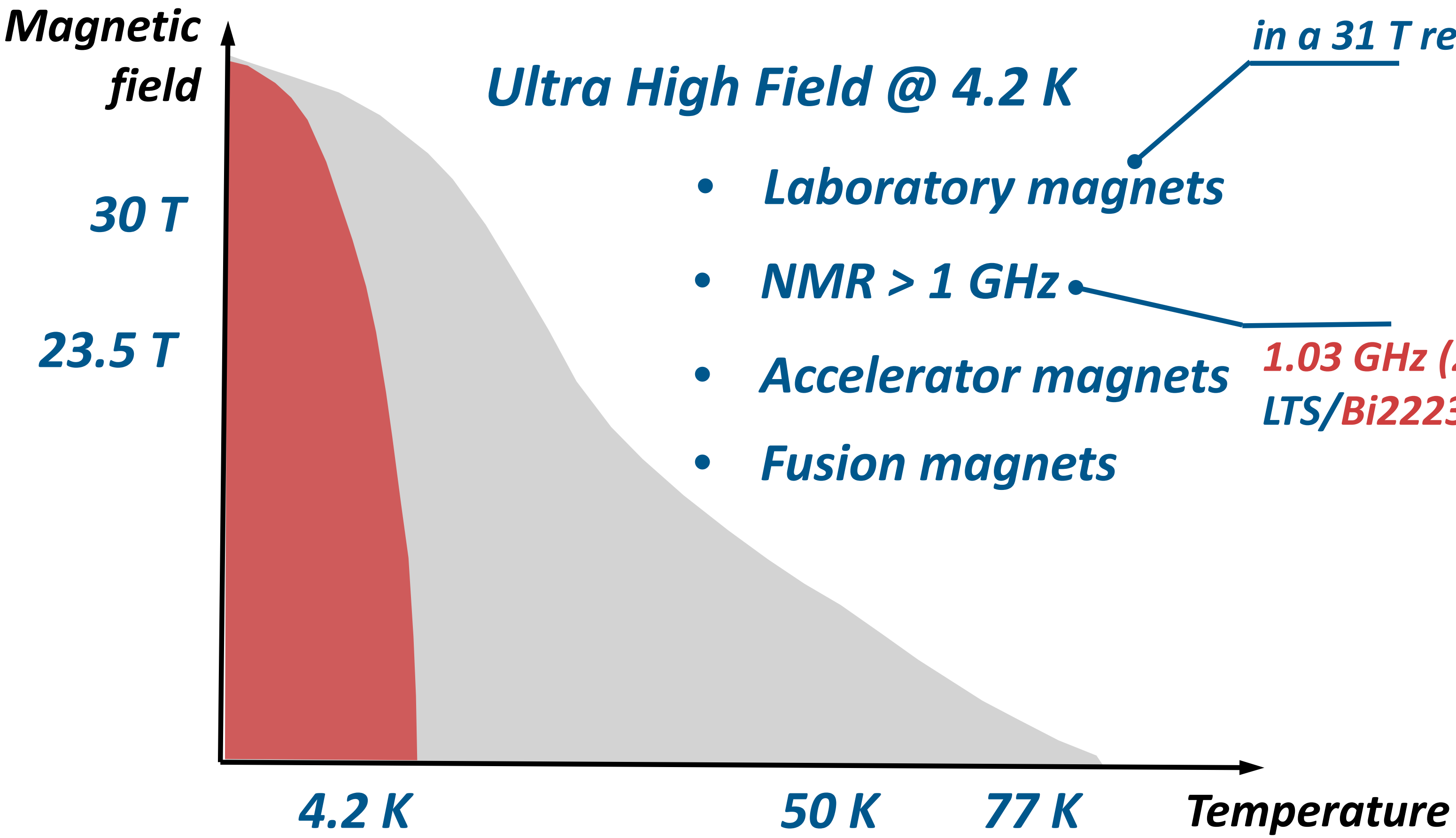
What can we do with HTS ?

The record @ MagLab
40 T with REBCO
in a 31 T resistive magnet



Ultra High Field @ 4.2 K

- *Laboratory magnets*
- *NMR > 1 GHz*
- *Accelerator magnets*
- *Fusion magnets*

1.03 GHz (24.2 T) @ NIMS
LTS/Bi2223 NMR magnet

HTS as high field superconductors

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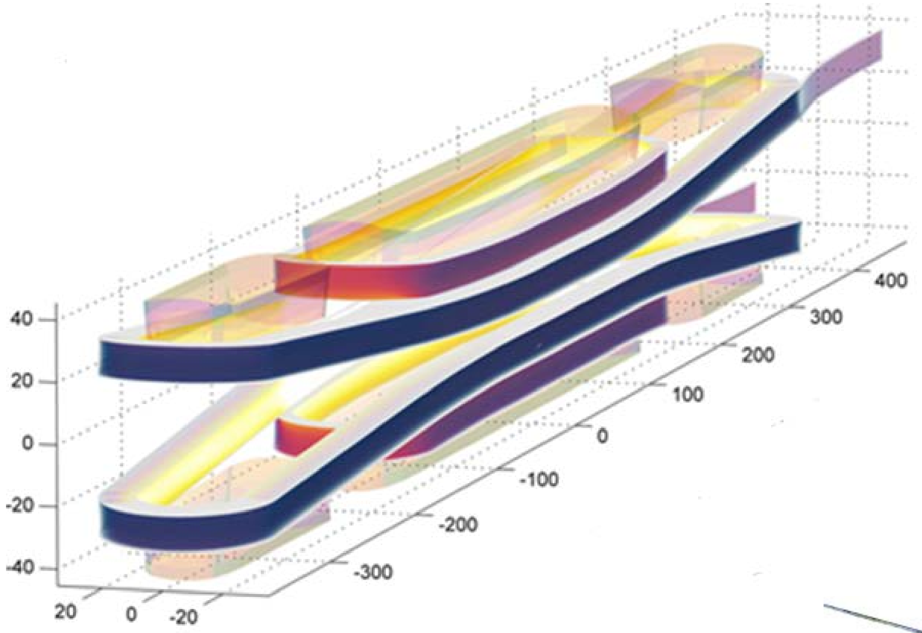
All superconducting magnets beyond LTS
The Olympics of high magnetic fields

	Maximum field [T]	HTS insert	HTS coil field [T]	Winding technology
RIKEN	27.6	Bi2223 / REBCO	4.5 (Bi2223) 6 (REBCO)	LW
	27	REBCO	12	DP
SuNAM MIT	26.4	REBCO	26.4	DP
UNIVERSITÉ DE GENÈVE FACULTÉ DES SCIENCES BRUKER	25	REBCO	4	LW
TOHOKU UNIVERSITY HFLSM	24.6	Bi2223	10.6	DP
NIMS	24.2	Bi2223	3.66	LW

A dipole demonstrator magnet based on HTS
Towards 20 T dipole magnets



~1000 m of REBCO tape

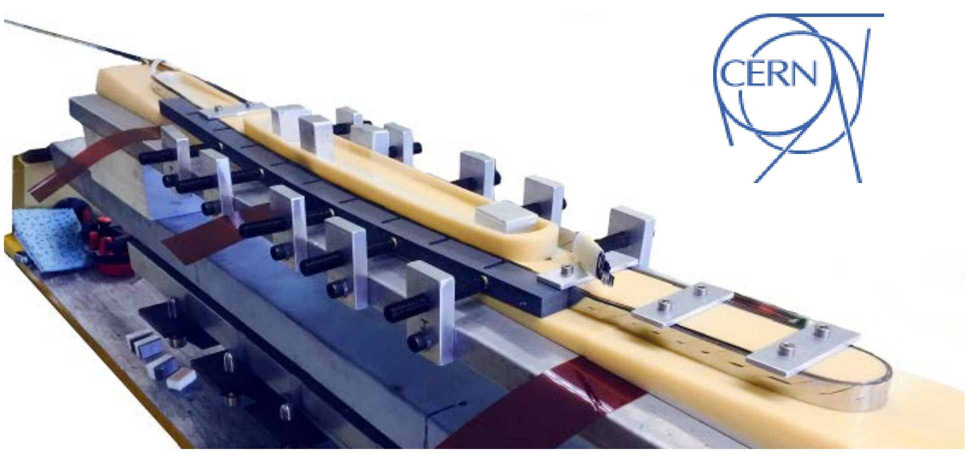
~70 m of Roebel cable

5 T in a background of 15 T

40 mm aperture

G. Kirby, 1LOr1B-01

Winding blocks canted to align with field lines



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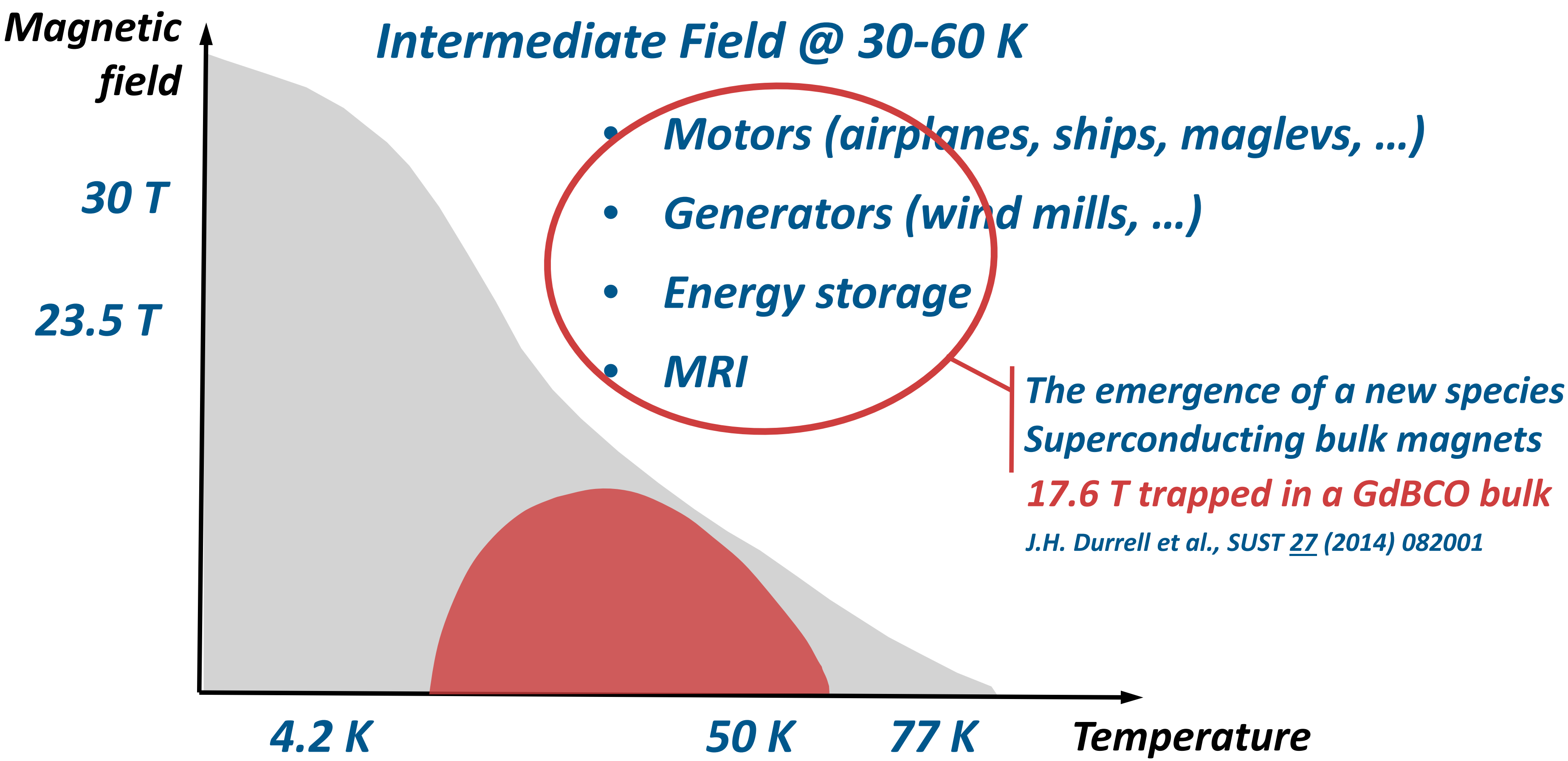
What can we do with HTS ?



A lot of activity with many prototypes around the world

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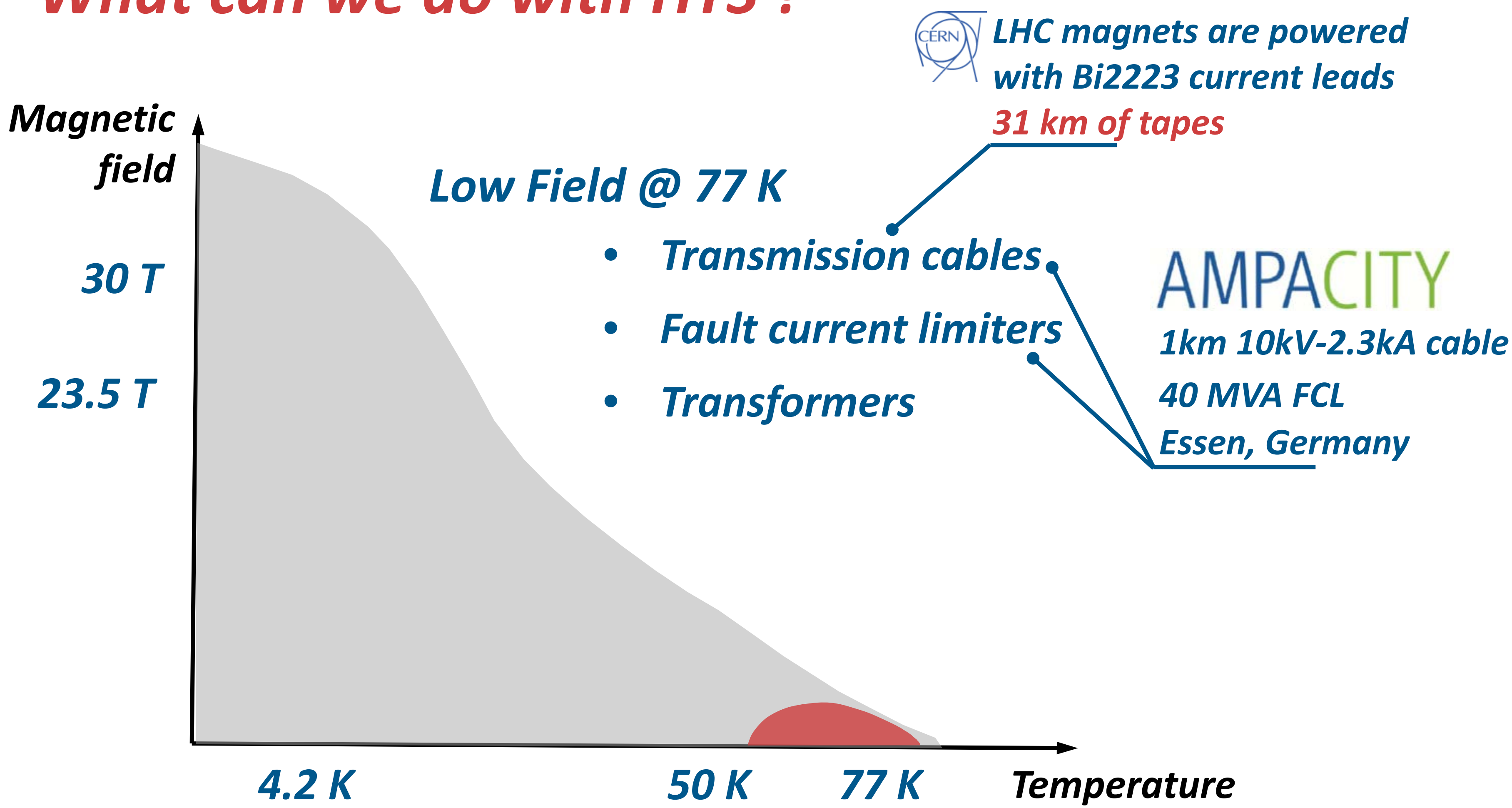
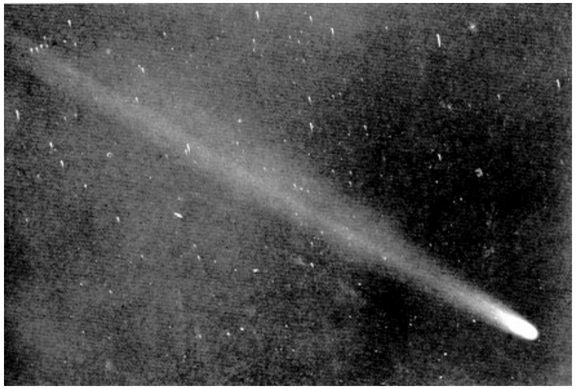
What can we do with HTS ?



The future paradigm for the electric power distribution ?

Many devices already in the grid

To conclude...



The transit of Halley's comet in 1911

Discovery of Superconductivity

The transit of Halley's comet in 1986

Discovery of High Temperature Superconductivity

The next transit will be in 2061
Should we wait so long for the next revolution ?

To conclude…

30 years after the discovery, high performance technical conductors based on HTS are on the market and available from multiple sources

The input of fundamental science has been essential to get there, and we are not yet at the end of the story

But there is still work to do on conductor architecture, available lengths and cost

Two categories of applications:

- ***Applications where HTS are the enabling technology, e.g., Ultra High Fields***
  Things are going pretty well

- ***Applications where HTS bring advantages vs. existing technologies, e.g., Power Applications***
  Many demonstrators around the world, but the high costs are delaying the introduction in large market. Things are gently improving

Thank You !

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http://supra.unige.ch

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