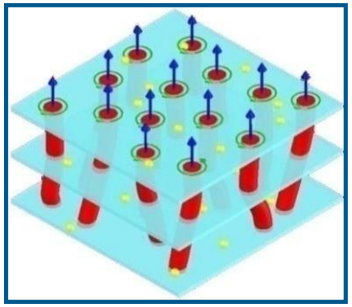
UNIVERSITÉ DE GENÈVE
FACULTÉ DES SCIENCES

DQMP
http://supra.unige.ch

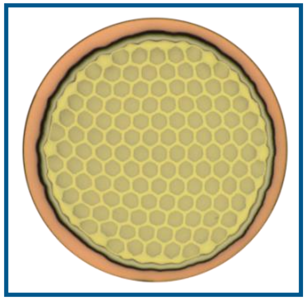
Superconductivity and its applications

Lecture 7



Carmine SENATORE

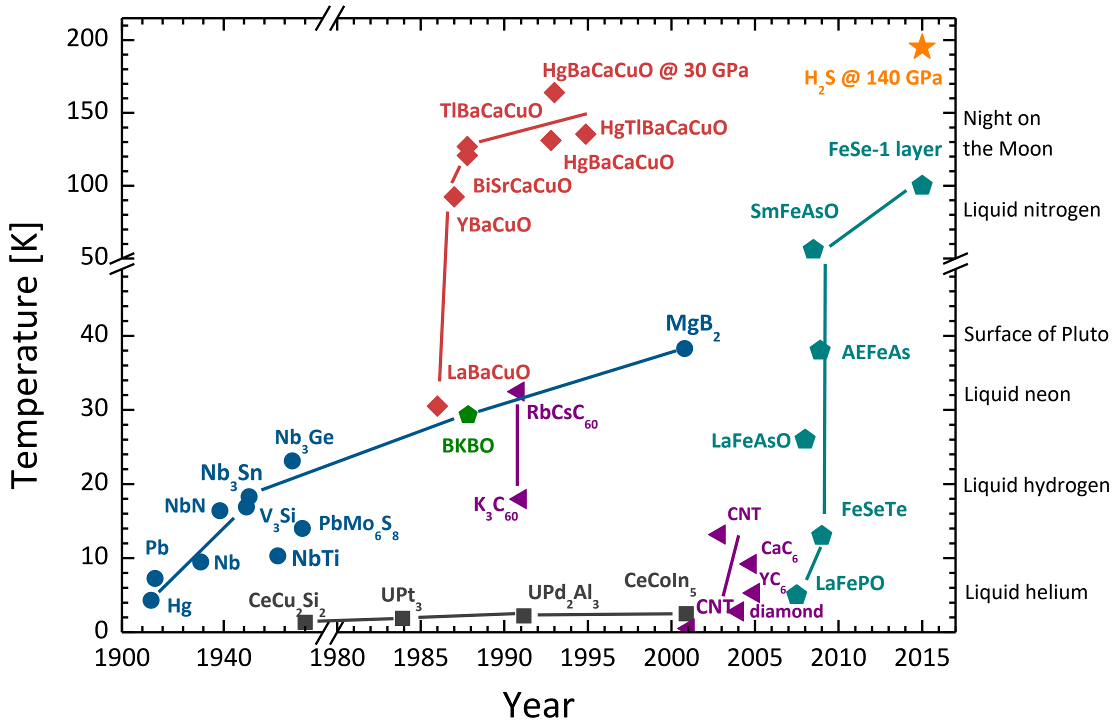
Group of Applied Superconductivity
Department of Quantum Matter Physics
University of Geneva, Switzerland



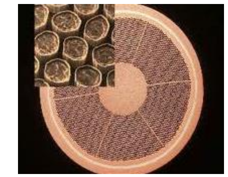
Previously, in lecture 6

From superconducting materials…

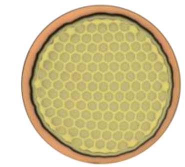
…to technical superconductors



NbTi

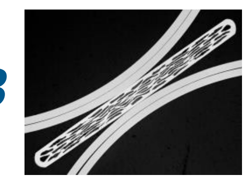


Nb_3Sn

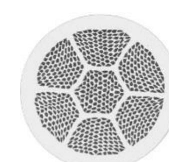


MgB_2

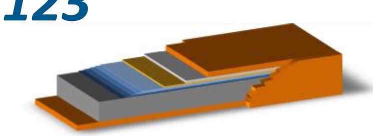
Bi2223



Bi2212



Y123

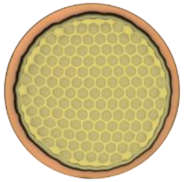


1.	***Superconducting ?***	***10'000***
2.	***T_c>4.2K & B_{c2}>10T ?***	***100***
3.	***J_c>1000 A/mm^2 ?***	***~10***

Previously, in lecture 6
Industrial fabrication of Nb_3Sn wires

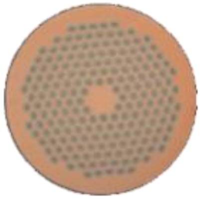
Three technologies have been developed at industrial scale

- ***Bronze route***
  Sn source = CuSn bronze

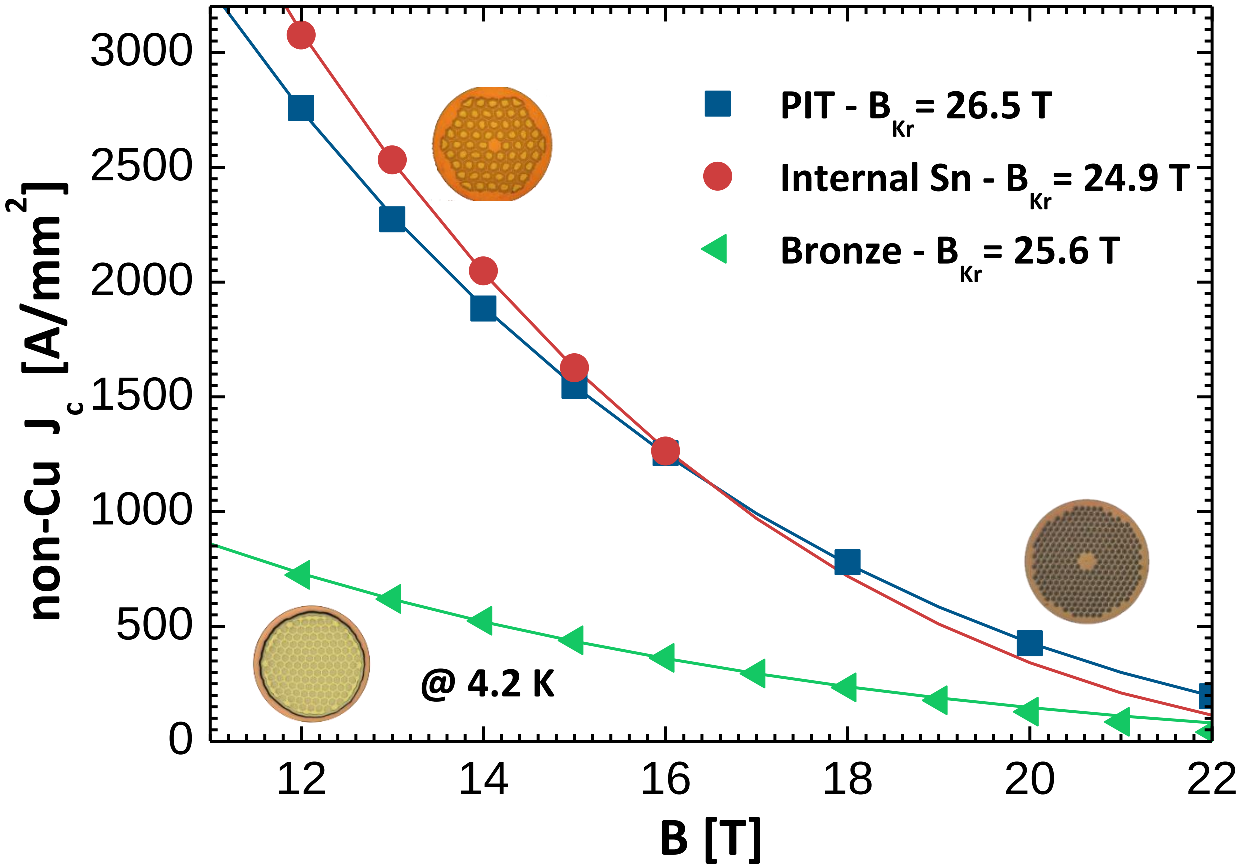


- ***Internal Sn diffusion***
  Sn source = Sn rod

- ***Powder in tube***
  Sn source = $NbSn_2$ powders



Previously, in lecture 6
Critical current density vs. magnetic field
Best performance achieved so far in industrial wires



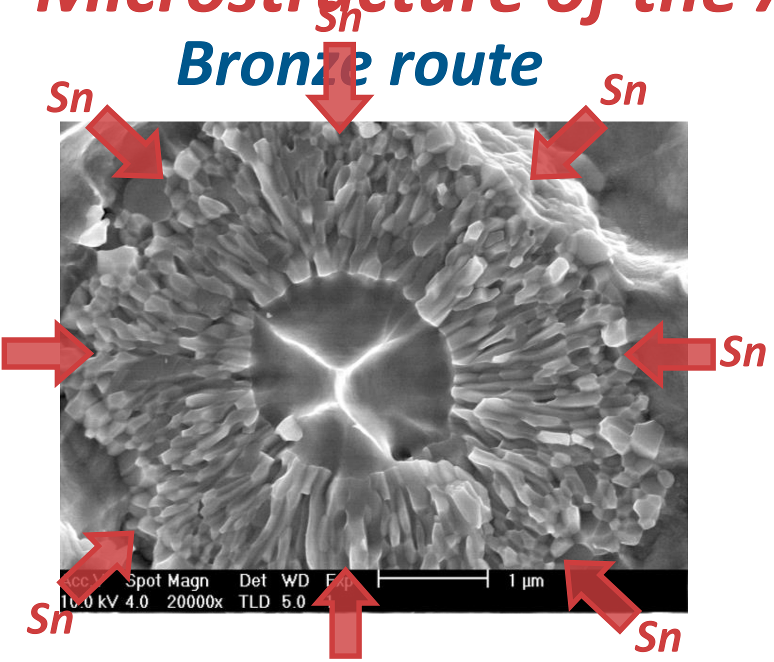
T. Boutboul et al., IEEE TASC 19 (2009) 2564

J. Parrell et al., AIP Conf. Proc. 711 (2004) 369

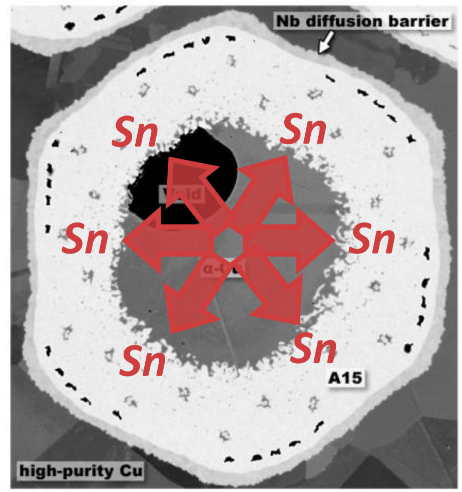
V. Abächerli et al., IEEE TASC 17 (2007) 2564

Previously, in lecture 6
Microstructure of the A15 phase after reaction

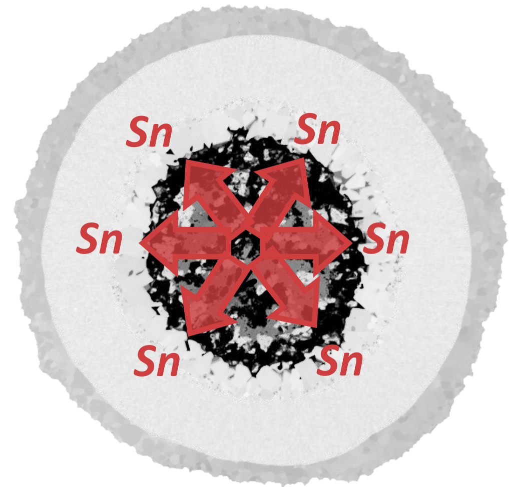
Bronze route	Internal Sn	Powder-In-Tube



Filament size ~5 µm



Subelement size ~50 µm



Filament size ~50 µm

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

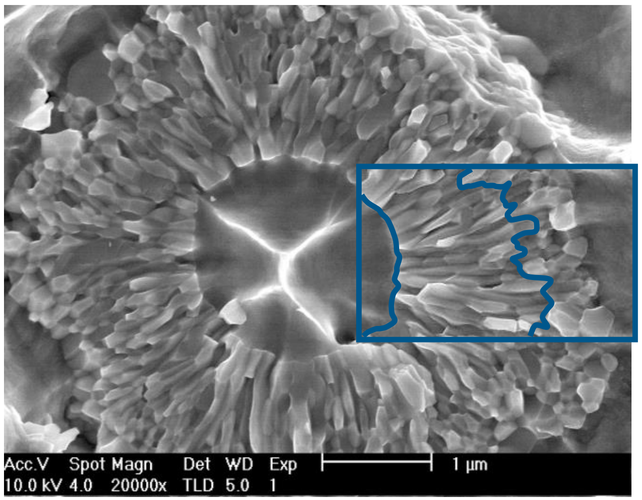
Also microstructure is directly related to the J_c performance

Grain boundaries act as the main vortex pinning centers

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

Previously, in lecture 6
Microstructure of the A15 phase after reaction

Bronze route



Filament size ~5 µm

Outer region

Equiaxed grains ~ 150 nm

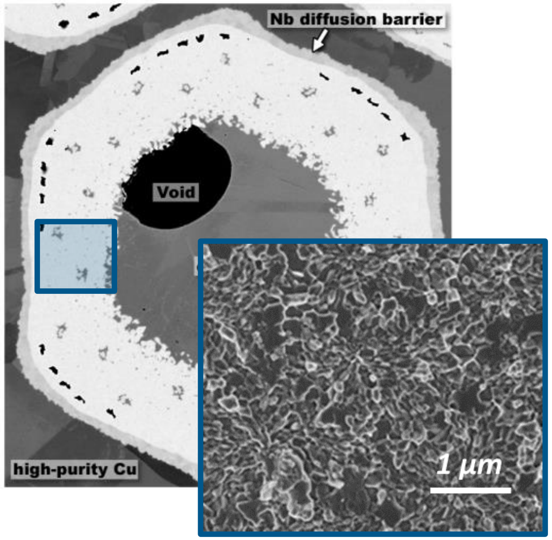
21-25 at.% Sn

Inner region

Columnar grains ~ 400 nm

18-21 at.% Sn

Internal Sn



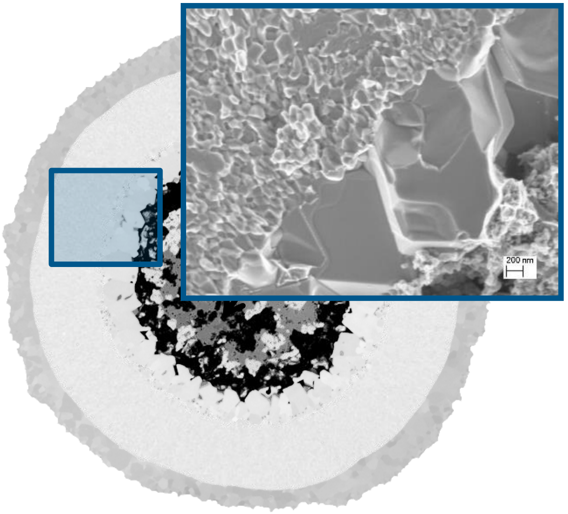
Subelement size ~50 µm

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

MgB_2: the LTS with the highest T_c

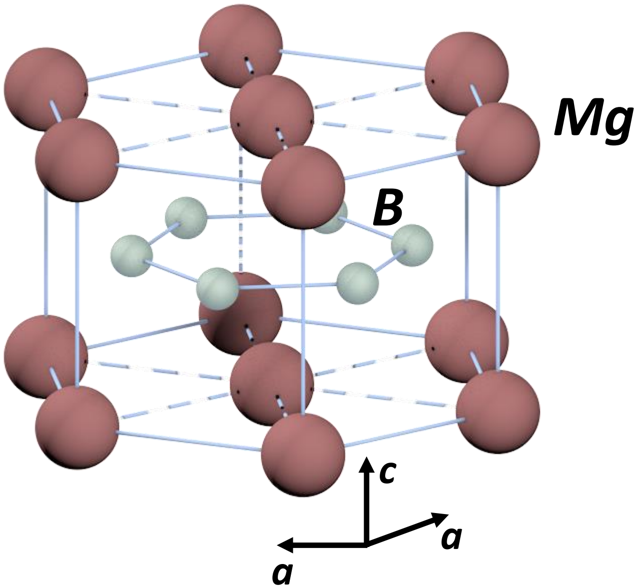


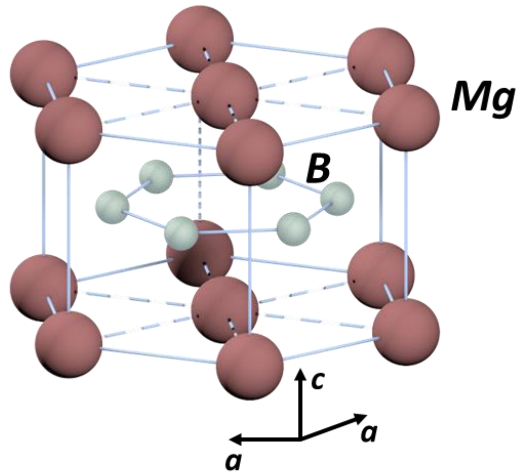
Table 9.2 Basic physical properties of the superconductor MgB_2. Some parameters are anisotropic, with only average values listed here.

Superconducting transition temperature T_c	39K*
Coherence length ξ_0	5 nm*
Penetration depth λ	140 nm*
Ginzburg-Landau parameter κ	$\cong$ 25
electron mean free path ℓ	$\cong$ 60 nm*
Residual resistivity ratio RRR = $\rho(300K)/\rho(42K)$	$\cong$ 20
Debye temperature Θ_D	340K
Fermi surface electron velocity V_F	4.8×10^5 m/sec*
Isotope effect constant α	0.32
Upper critical field B_{c2}, clean sample ($\ell \gg \xi_0$)	16T*
dirty sample ($\ell \ll \xi_0$)	30T*
Irreversibility field B_{irr}, clean sample	7T*
dirty sample	15T*
Thermodynamic critical field B_c	0.43T
Lower critical field B_{c1}	30mT

Akimitsu et al., Nature 410 (2001)63

- ***Superconductivity unespectedly discovered in 2001***
- ***The material was known since 1957*** *R.M. Swift, D. White, J. Am. Soc. 79 (1957) 354*
- ***Intermetallic compound with very high T_c***
- ***Layered structure: alternate layers of Mg and B***
- ***Anisotropic properties: B_{c2} // a is different from B_{c2} // c***

What is special with MgB_2 ?



- Multiple bands are crossing the Fermi surface
- 2D σ-band originates within the B planes
- 3D π-band originates "between" the B planes (boron p_z orbital hybridization)
- Superconductivity arises simoultaneously in the two bands

$\boxed{MgB_2 \text{ is a kind of "2 superconductors in 1"}}$

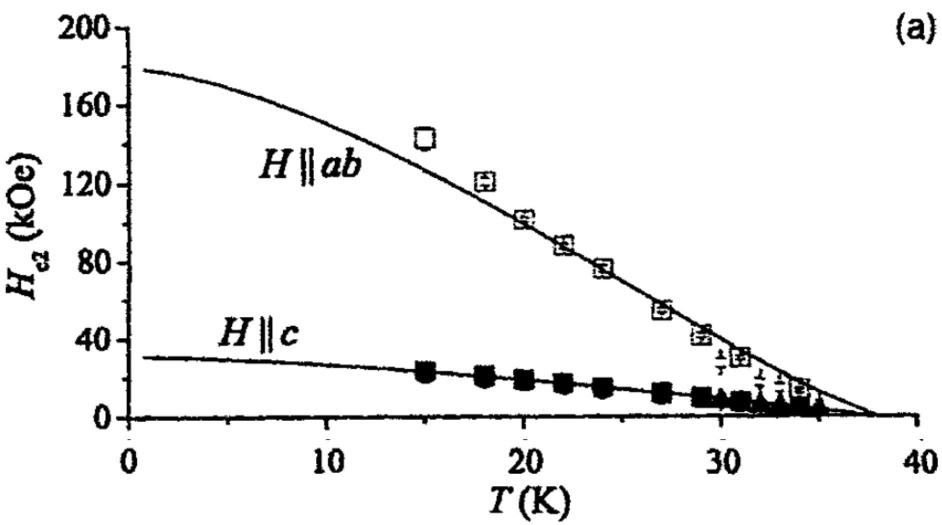
T_c is surprisingly (?) high

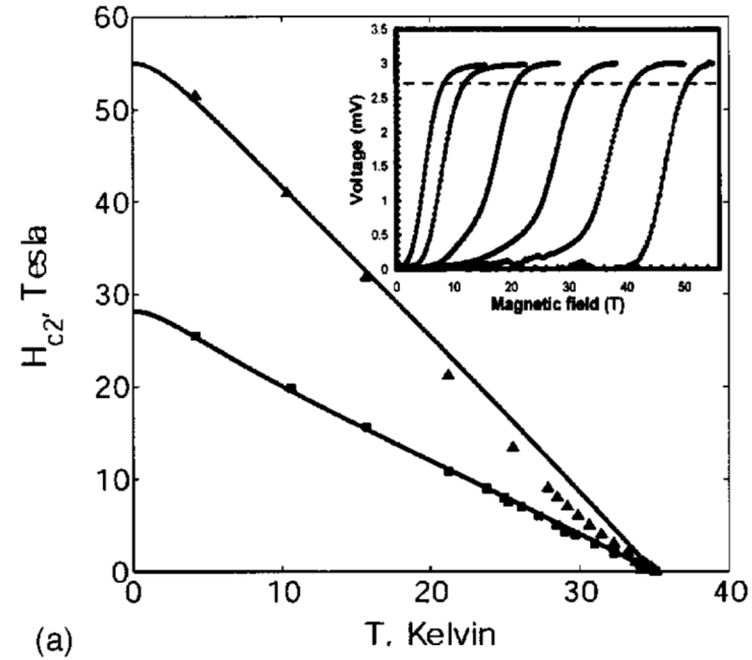
$$T_c = 1.14\omega_{ph} \exp\left(\frac{-1}{N(0)V}\right)$$

MgB_2 $\Theta_D = 800$ K
Nb_3Sn $\Theta_D = 230$ K

MgB_2 $\gamma = 2.5$ mJ/mol K^2
Nb_3Sn $\gamma = 52$ mJ/mol K^2

MgB_2 : Upper critical field





single crystal: B_{c2} (// ab) = 18 T; B_{c2} (// c) = 3.8 T

C-doped thin film: B_{c2} (// ab) = 55 T; B_{c2} (// c) = 28 T

Substitution of B by C leads to enhanced electrical resistivity ρ_n and thus of $B_{c2} \propto \gamma \rho_n T_c$

Vanishing two-band character is observed with increasing C content

V. Braccini et al., PRB 71 (2005) 012504

Other attempts to raise B_{c2}

Many dopants have been tested to enhance B_{c2} and J_c

Table 1. List of dopants added to MgB_2.

Nitrides Borides Silicides	Carbon and carbon inorganics	Metal oxides	Metallic elements	Organic compounds
Si_3N_4 [46–48]	C nanotubes [54–57]	Dy_2O_3 [69]	Ti [75–77]	Sugar [86]
WB [49]	Nanodiamond [57–59]	HoO_2 [70]	Zr [77]	Malic acid [87]
ZrB_2 [5, 44]	TiC [60, 61]	Al_2O_3 [71]	Mo [78]	Maleic anhydride [41]
TiB_2 [5]	SiC [38, 42, 62–65]	MgO [45]	Fe [79]	Paraffin [88]
NbB_2 [5]	B_4C [40, 66, 67]	TiO_2 [72]	Co [80]	Toluene [89]
	Na_2CO_3 [68]	Pr_6O_{11} [73]	Ni [80]	Ethanol [89]
CaB_6 [50]		SiO_2 [74]	Cu [81]	Acetone [89]
WSi_2 [51–53]			Ag [82]	Tartaric acid [90]
$ZrSi_2$ [51, 52]			Al [83]	Ethyltoluene [91]
			Si [84]	
			La [85]	

E.W. Collings et al., SuST 21 (2008) 103001

Industrial fabrication of MgB_2 wires

Three technologies have been developed at industrial scale

- ***ex-situ* Powder-In-Tube**
  precursors: prereacted MgB_2 powders

A heat treatment of the wire at 900°C for <60' is required to sinter the MgB_2 powders

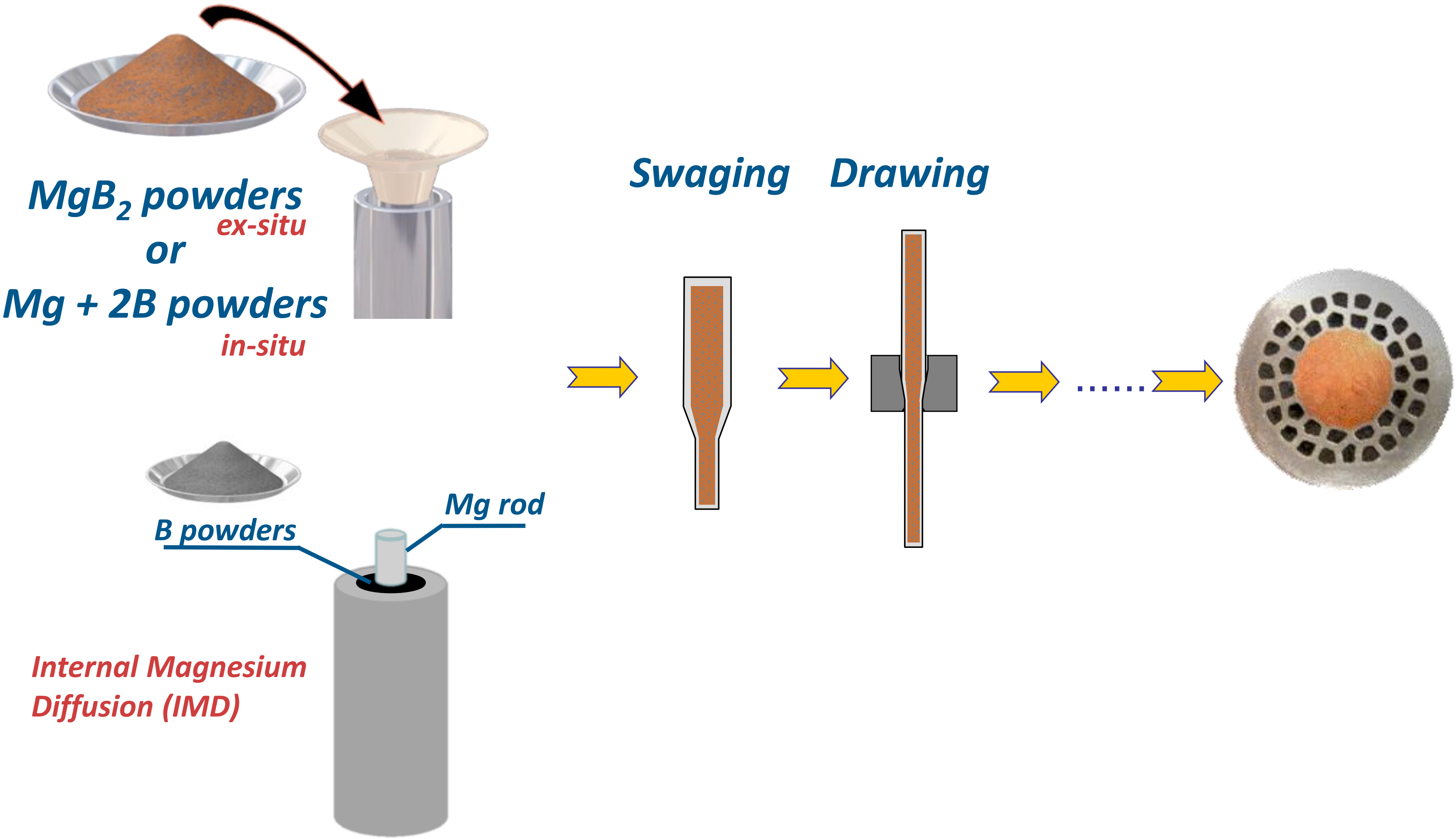
- ***in-situ* Powder-In-Tube**
  precursors: Mg + B powders

- ***internal Mg diffusion (IMD)***
  precursors: Mg rod + B powders

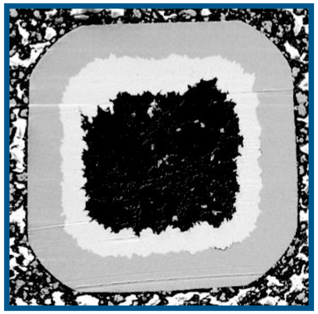
A heat treatment of the wire at 650°C for 1-4 hrs is required to react the precursors and form the MgB_2 superconducting phase

R. Flükiger et al., Physica C 387 (2003) 419
G. Giunchi et al., SuST 16 (2003) 285
J.M. Hur et al., SuST 21 (2008) 032001

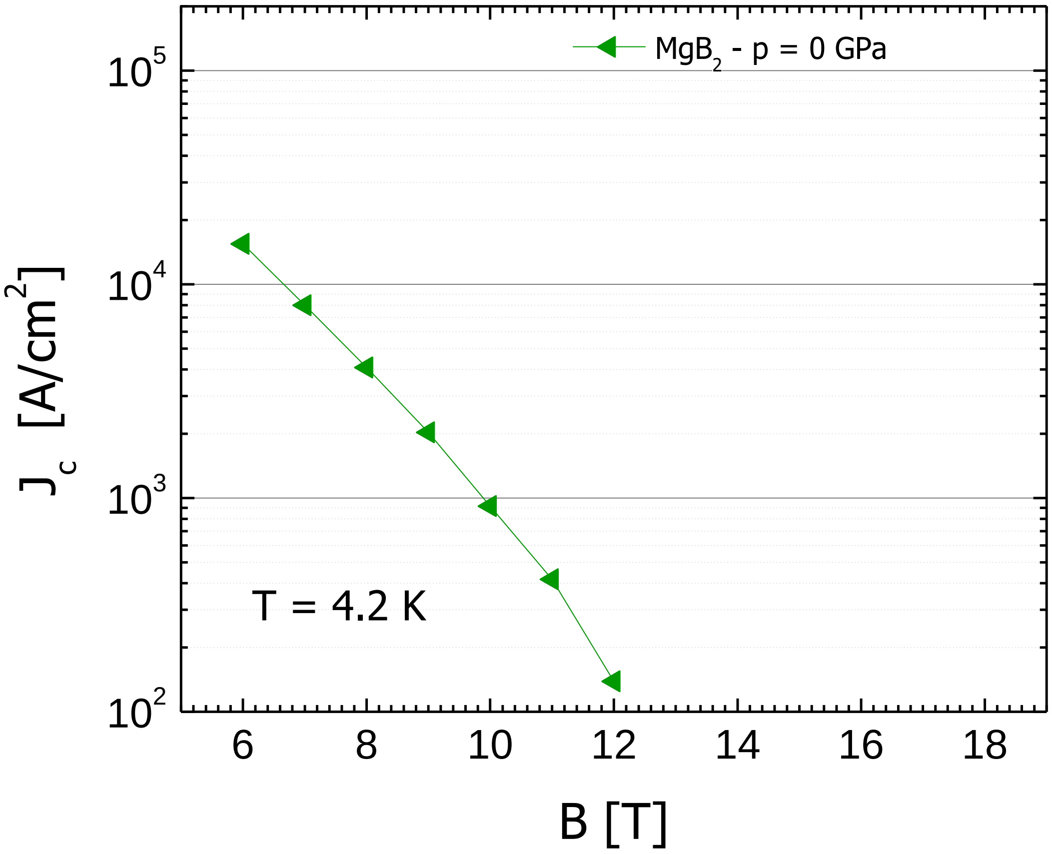
MgB_2 wires: fabrication by powder metallurgy



Ways for enhancing J_c of MgB_2 wires



in-situ MgB_2 wire cross section



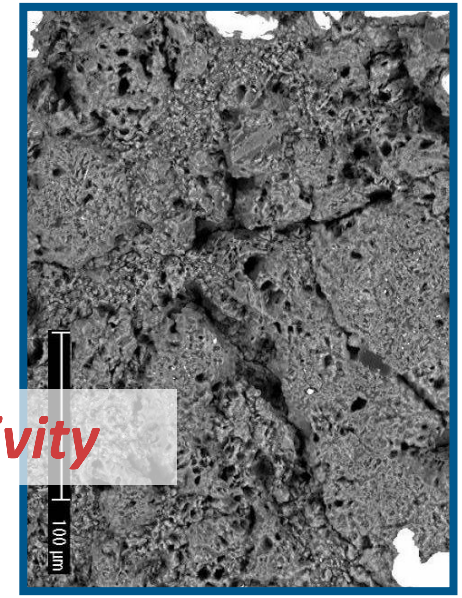
Ways for enhancing J_c of MgB_2 wires

Factors affecting the critical current density J_c

Intrinsic properties intragranular → *Upper critical field B_{c2}*

Intrinsic properties intragranular → *Vortex pinning*

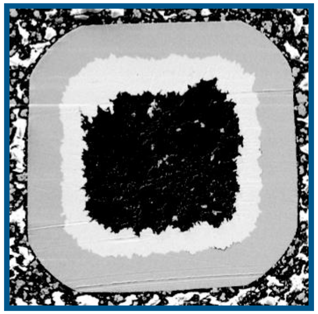
Extrinsic properties intergranular → *Porosity and Connectivity*



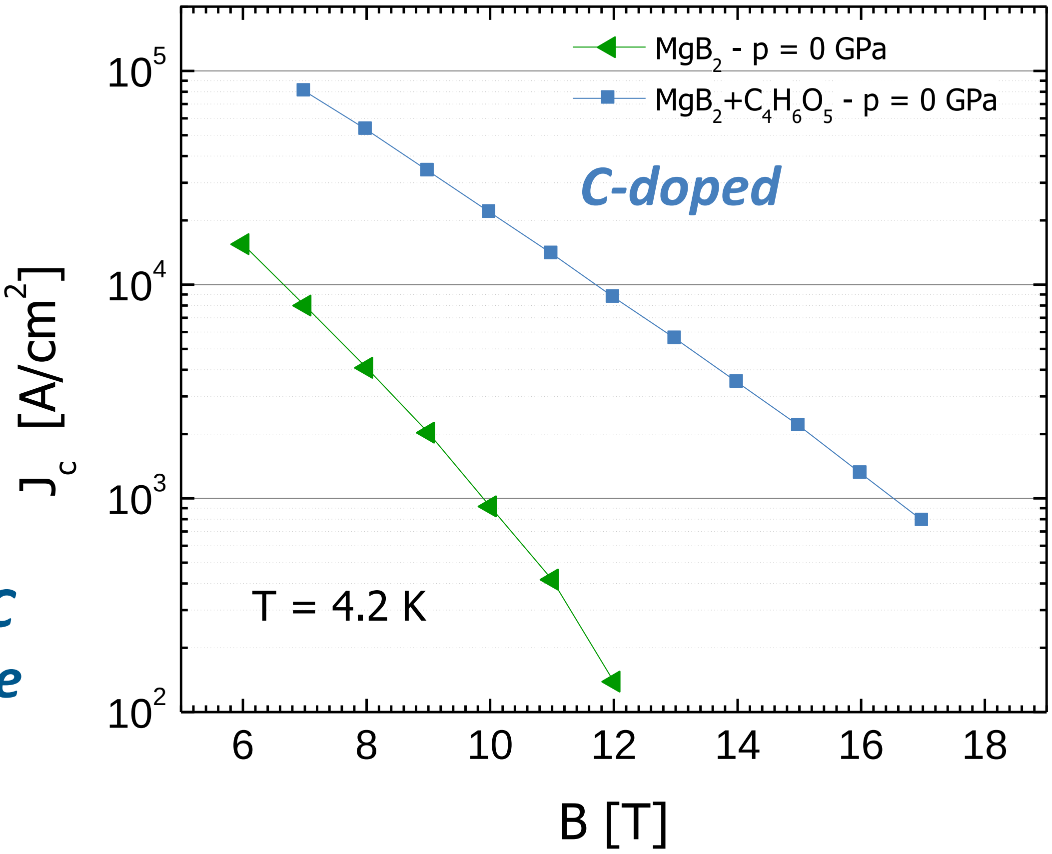
Low connectivity in MgB_2 wires is consequence of the low density of the precursors powders in the metallic tube, necessary to allow the deformation in the fabrication process

In in-situ wires, the reaction of Mg and B to form MgB_2 is accompanied by a volume contraction (and thus formation of pores)

Ways for enhancing J_c of MgB_2 wires



in-situ MgB_2 wire cross section

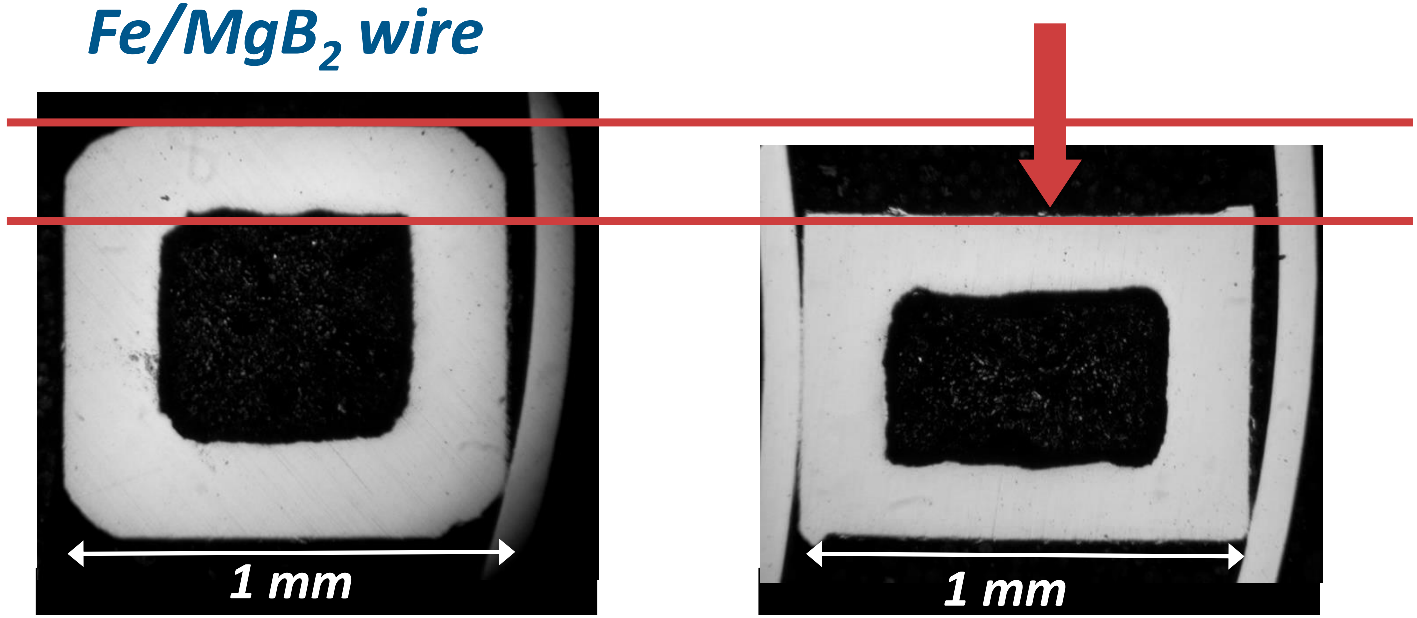


The substitution of B by C increases B_{c2} and thus the in-field J_c

Cold High Pressure Densification

A new industrial wire densification process developed at UNIGE

Fe/MgB_2 wire



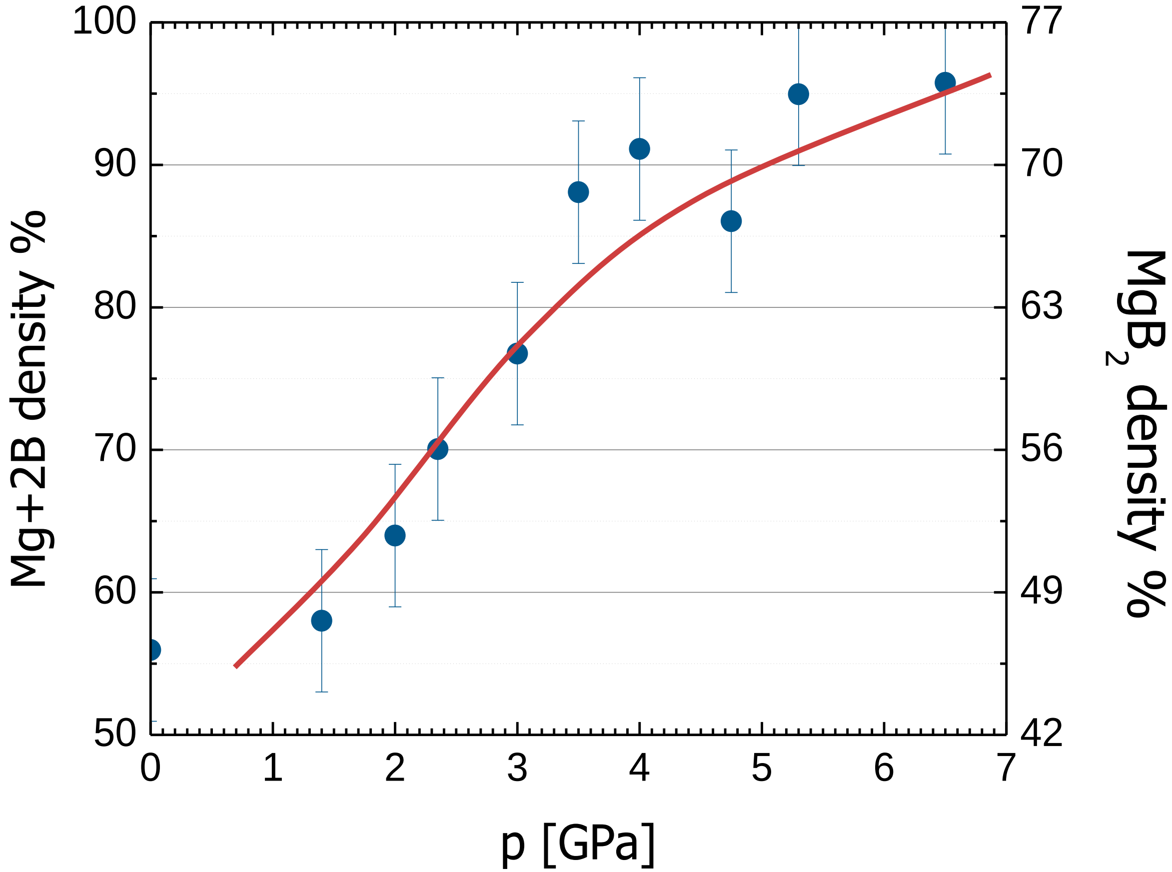
<u>as drawn</u>

<u>densified @ p = 2 GPa</u>

Filament density vs Pressure

Left scale: relative density of unreacted (Mg+2B) mixture

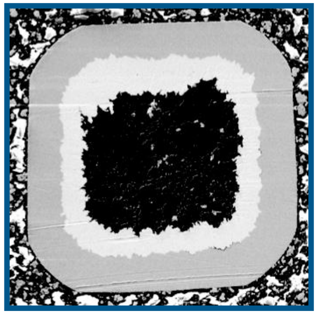
Right scale: relative mass density of reacted MgB_2 filaments



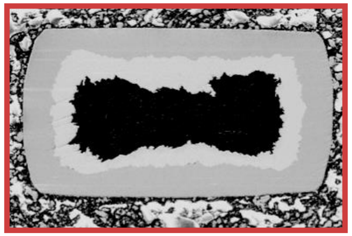
Theoretical Mg+2B density 2.05 g/cm^3

Theoretical MgB_2 density 2.61 g/cm^3 (volume contraction)

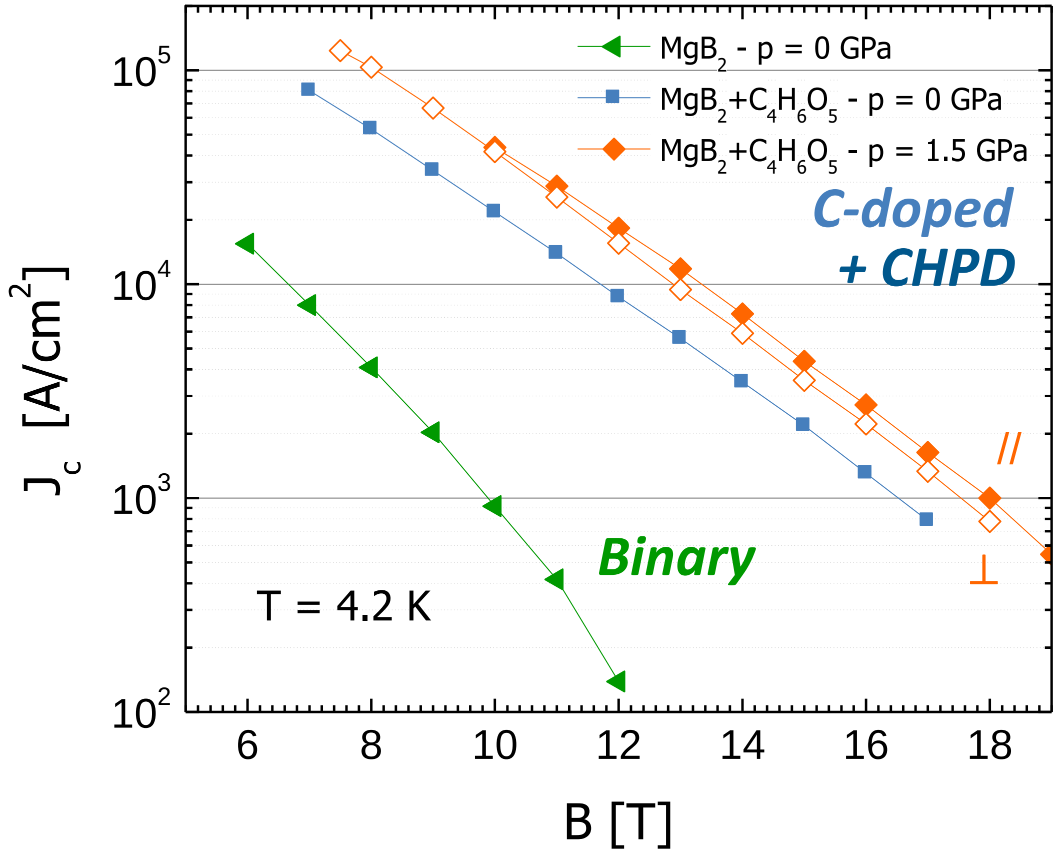
Enhancement of B_{c2} & Improvement of Connectivity



Square wire without Densification



after Cold High Pressure Densification

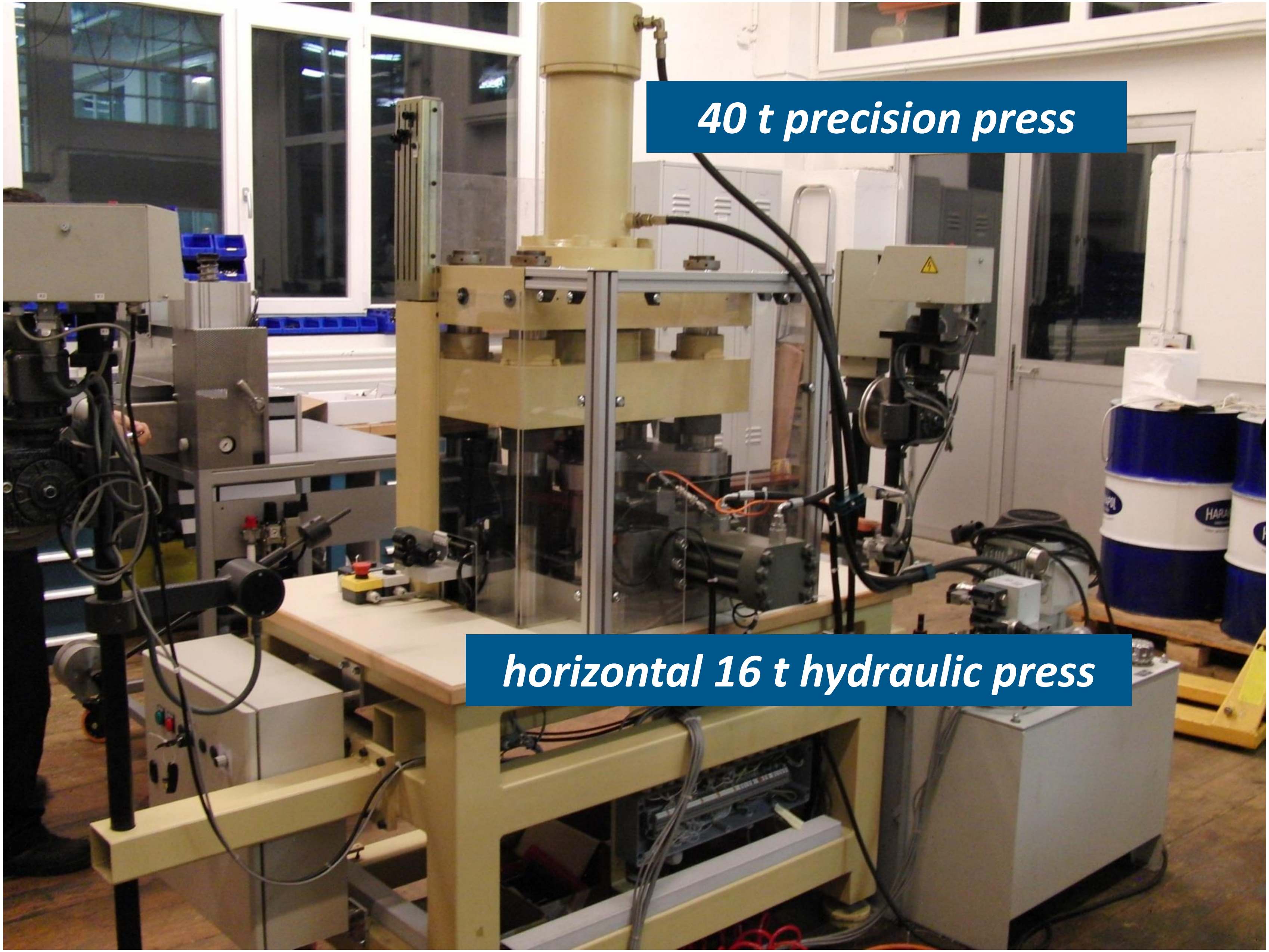


in parallel field 10^4 A/cm² @ 13.4 T

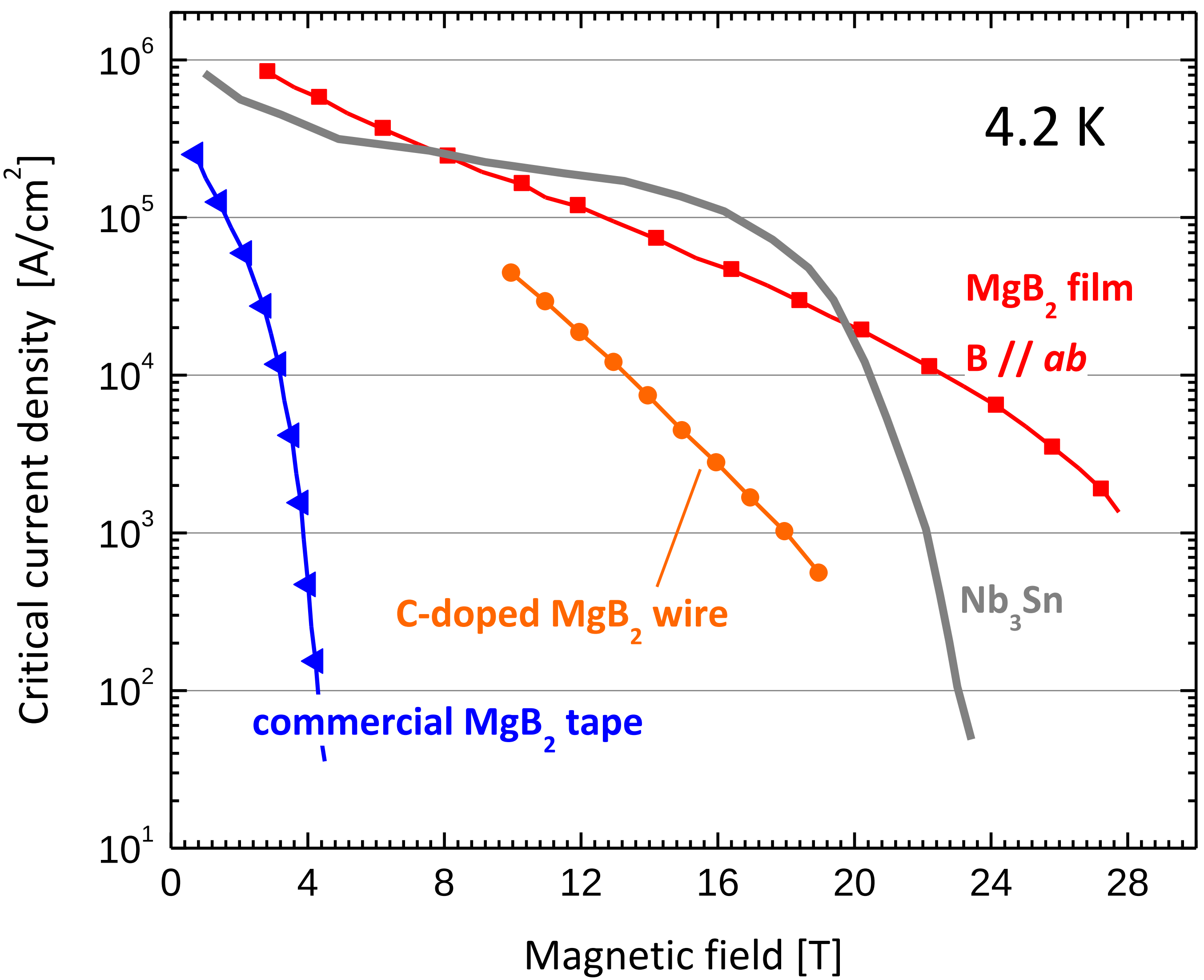
in perpendicular field 10^4 A/cm² @ 12.9 T

M.S.A. Hossain et al., SuST 24 (2011) 075013

CS et al., IEEE TAS 21 (2011) 2680


40 t precision press
horizontal 16 t hydraulic press

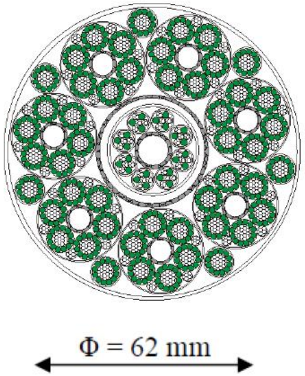
Still margin to improve MgB_2 wire performance



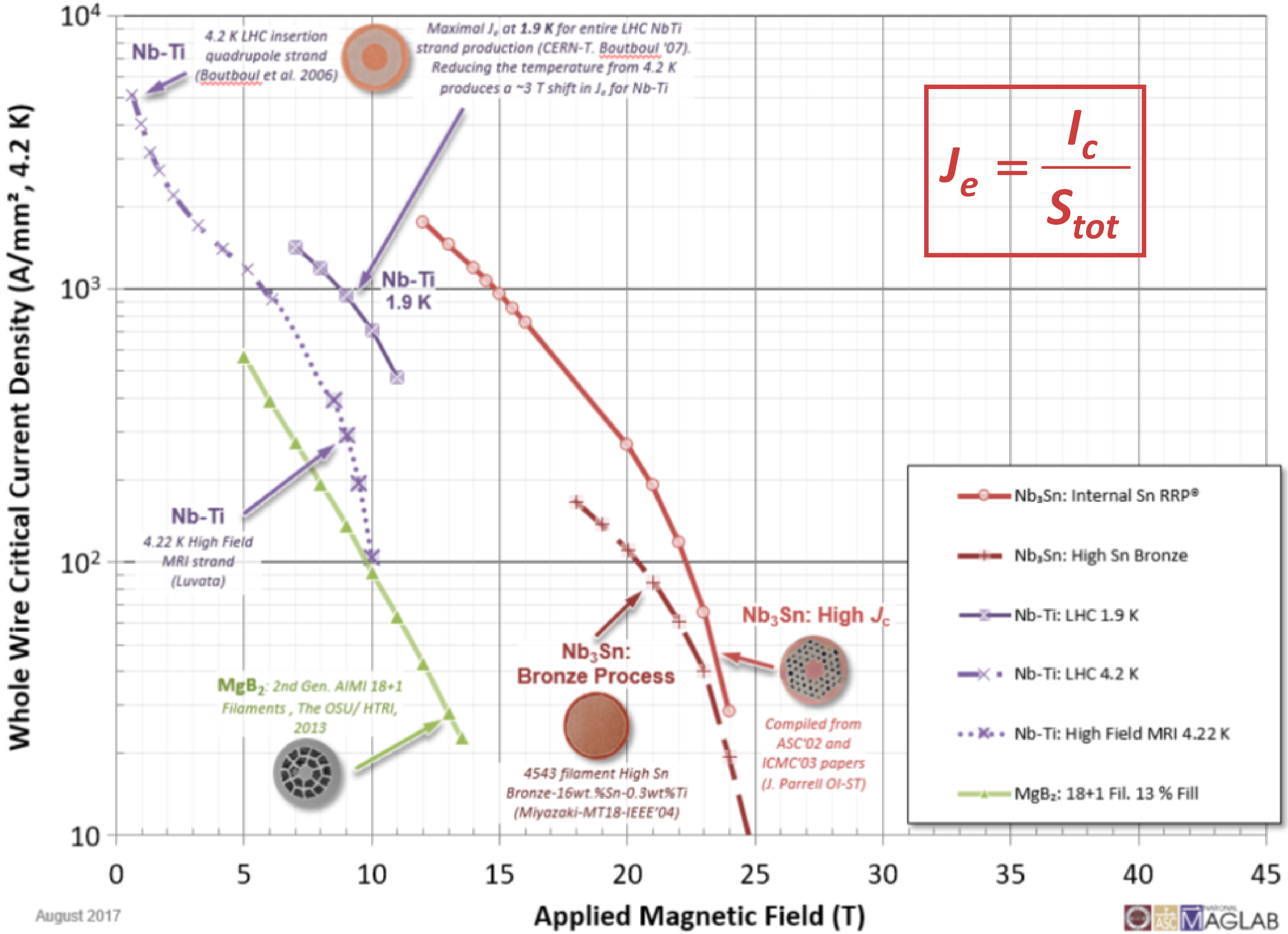
Envisaged applications of MgB_2 at $T > 4.2K$

Applications of MgB_2 at 20+ K

- Cryogen-free open MRI for whole body scan
- Cryogen-free ≥200MHz NMR magnets (≥ 4.7 T)
- High T_c links for the LHC machine
- Wind turbine / eolic generators ≥ 10 MW
- …



The engineering critical current density J_e



$$J_e = \frac{I_c}{S_{tot}}$$

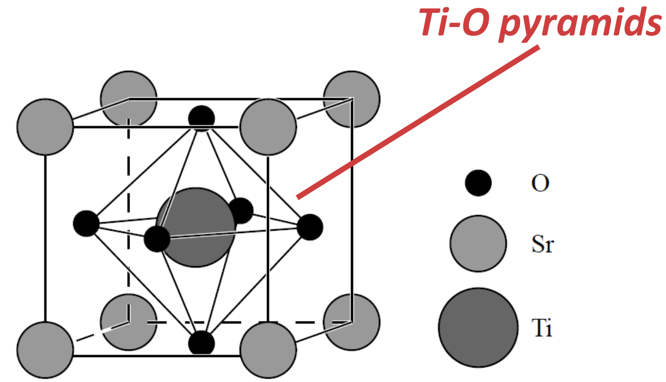
http://fs.magnet.fsu.edu/~lee/plot/plot.htm

Towards the high-T_c cuprate superconductors

Matthias' Rules

0. Valence number per atom between 2 and 8
1. Seek high symmetry
2. Seek peaks in density of state
3. Stay away from oxygen
4. Stay away from magnetism
5. Stay away from insulators

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



Superconductivity in perovskite oxides

ABX_3 structure, an example $SrTiO_{3-\delta}$ with $T_c \approx 1$ K

In the 1980's Bednorz and Müller were looking for strong electron-phonon interactions in oxides

In particular, they investigated the 2 systems

La-Ni-O

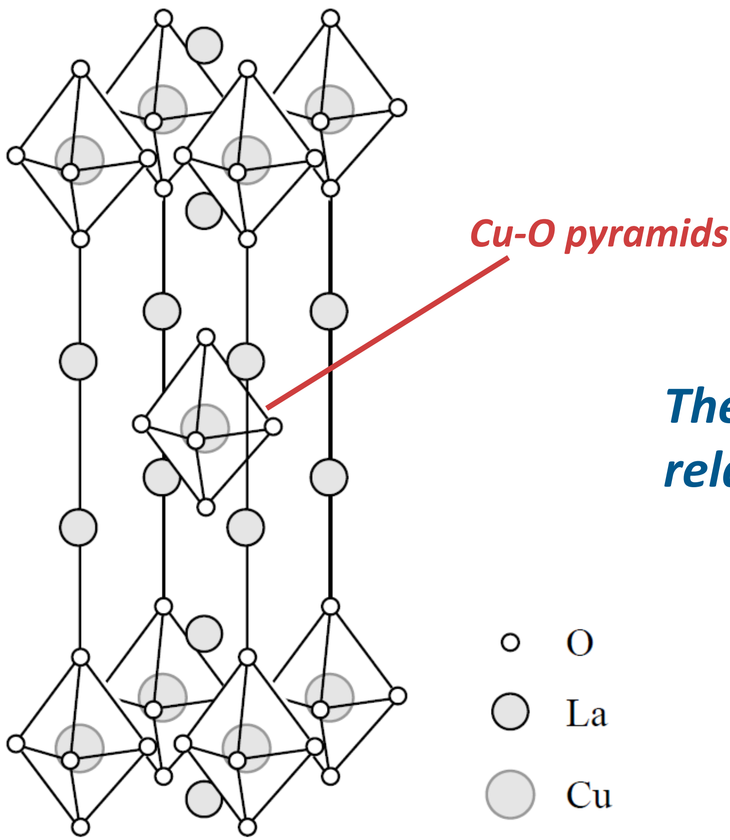
La-Cu-O

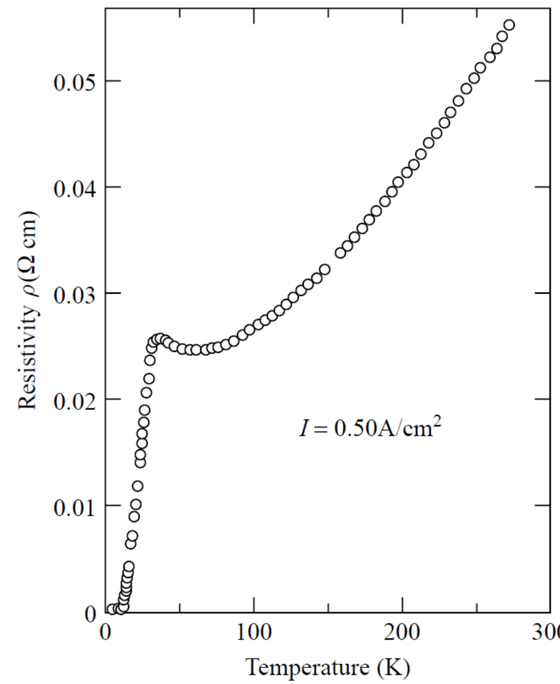
1986: Superconductivity in $La_{2-x}Ba_xCuO$ at $T_c \approx 30K$

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





The key feature of HTS superconductivity is related to the Cu-O pyramids

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.

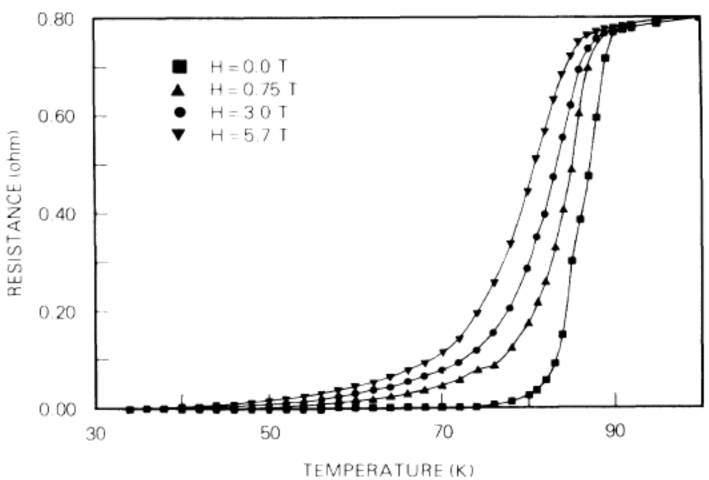


FIG. 1. Temperature dependence of resistance determined in a simple liquid-nitrogen Dewar.

The 1st SC with T_c above the LN_2 temperature!

And BSCCO came in 1988

Relevant HTS families

		Compound	T_c [K]	Short name
		$La_{1.85}Sr_{0.15}CuO_4$	39	LaSCO
	REBCO	$YBa_2Cu_3O_7$	92	Y123 or YBCO
		$Bi_2Sr_2CuO_6$	15	Bi2201
	Bi family	$Bi_2Sr_2CaCu_2O_8$	91	Bi2212
		$Bi_2Sr_2Ca_2Cu_3O_{10}$	110	Bi2223 or BSCCO
		$Tl_2Ba_2CuO_6$	90	
hole-doped		$Tl_2Ba_2CaCu_2O_8$	110	
	Tl families	$Tl_2Ba_2Ca_2Cu_3O_{10}$	125	Tl2223 or TBCCO
		$TlBa_2CaCu_2O_7$	91	
		$TlBa_2Ca_2Cu_3O_9$	116	
		$TlBa_2Ca_3Cu_4O_{11}$	122	
		$HgBa_2CuO_4$	95	
	Hg family	$HgBa_2CaCu_2O_6$	122	
		$HgBa_2Ca_2Cu_3O_8$	133	Hg1223
electron-doped		$Nd_{1.85}Ce_{0.15}CuO_4$	25	NCCO

Record T_c of ~165 K under high pressure

Bibliography

Rogalla & Kes
100 Years of Superconductivity
Chapter 3 Section 7
Chapter 11 Section 6 (MgB_2)

Fosshein & Sudbø
Superconductivity: Physics and Applications
Chapter 2

Papers cited in the slides