Superconductors for magnets II

René Flükiger

CERN
TE-MSC

Outline

1. Nb_3Sn wires in magnets: mechanical stress effects
2. MgB_2 wires for high current leads in LHC Upgrade
3. Other s.c. round wires for high field accelerators
    - A. Bi-2212 wires (HTS)
    - B. Pnictides
4. BaCuO tapes (Coated conductor HTS)

Annex: Wires for NMR magnets

1. Nb_3Sn wires in magnets: mechanical stress effects

Question:

How is J_c of a Nb_3Sn wire influenced by the strong Lorentz forces at high fields in large magnets?

The 3 D situation is analyzed by studying the effect of stress applied parallel and perpendicular to the wire:

Effect of uniaxial stress

Effect of compressive stresses

Origin of mechanical precompression in Nb_3Sn wires

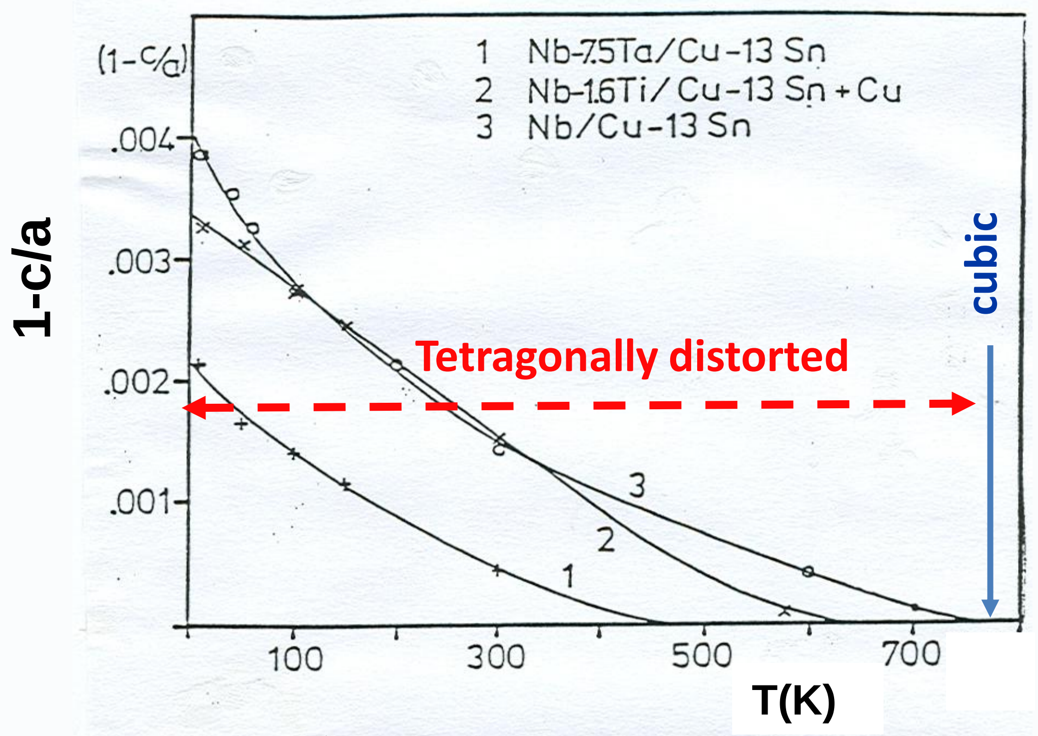
Reaction at 650 °C → Operation at 4.2K: ΔT = 1000K !

Differential thermal contraction α :

Bronze : $\alpha = 18 \times 10^{-6}\ K^{-1}$
Nb_3Sn : $\alpha = 8 \times 10^{-6}\ K^{-1}$

After cooling by 1'000 K, the filaments are under compression (called «precompression»)

As a consequence, the A15 phase in the Nb_3Sn filaments undergoes an elastical tetragonal distortion.
High temperature neutron diffraction shows that the distortion occurs below 500°C



Effect of uniaxial tensile strain

Electronic or phononic effects?

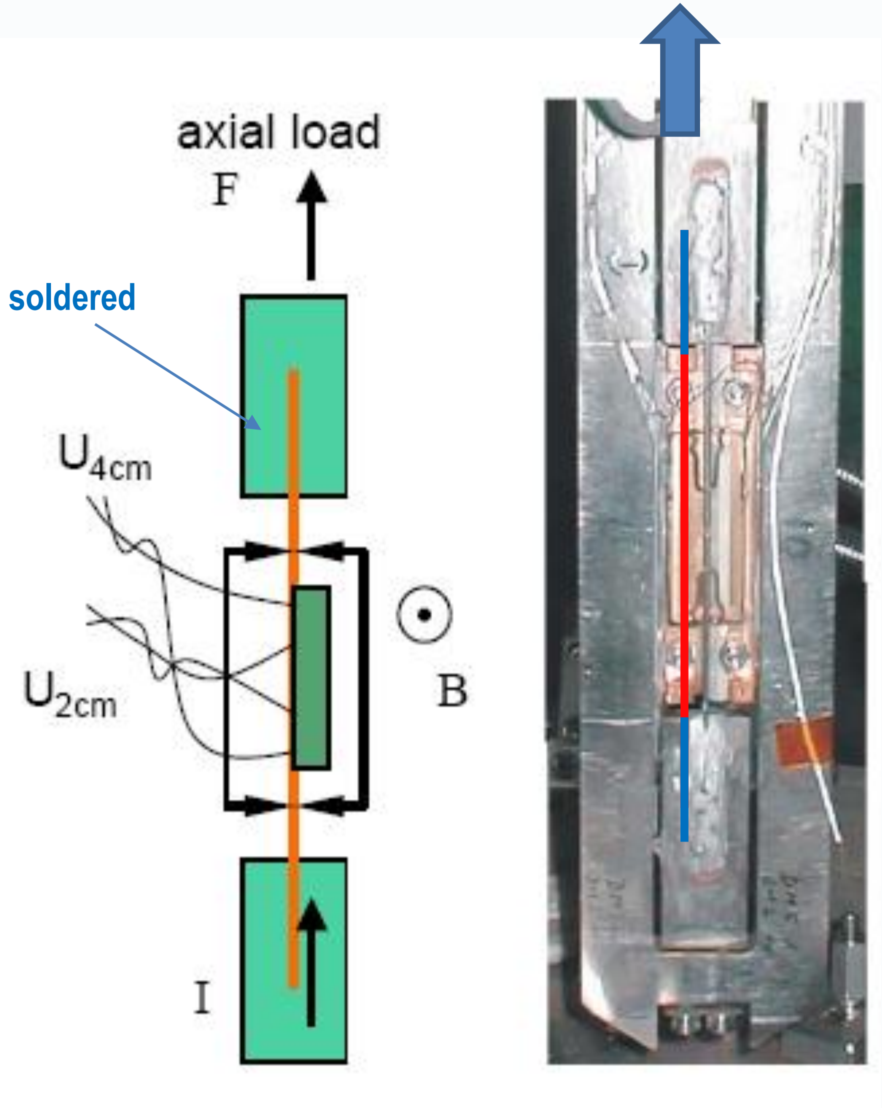
The effect is mainly correlated to changes in the phonon spectrum (Markowski et al.), the change of the electronic density of states having a minor effect (Hampshire et al.).

Hydrostatical or non-hydrostatical effects?

Hydrostatical pressure components: small effect of T_c and J_c. The observed effect on T_c, B_{c2} and J_c in Nb_3Sn wires submitted to mechanical stresses is correlated to the non-hydrostatic stress components.

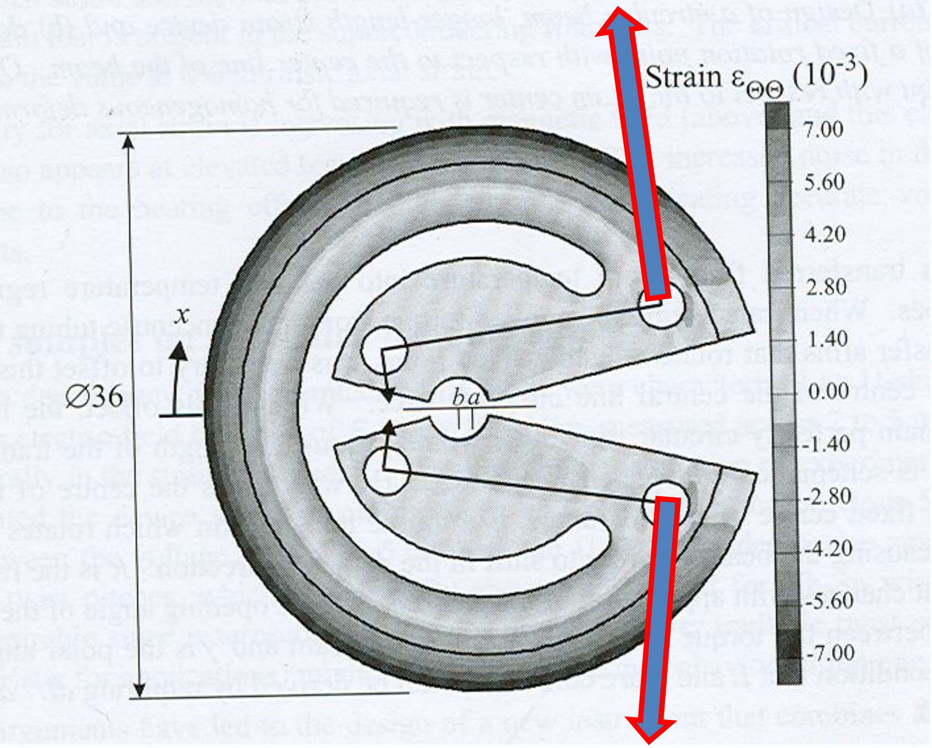
Various measuring devices:	Uniaxial (Linear) strain rig (J. Ekin)
	Pacman (Univ. Twente)
	Walters spiral (Univ. Geneva)

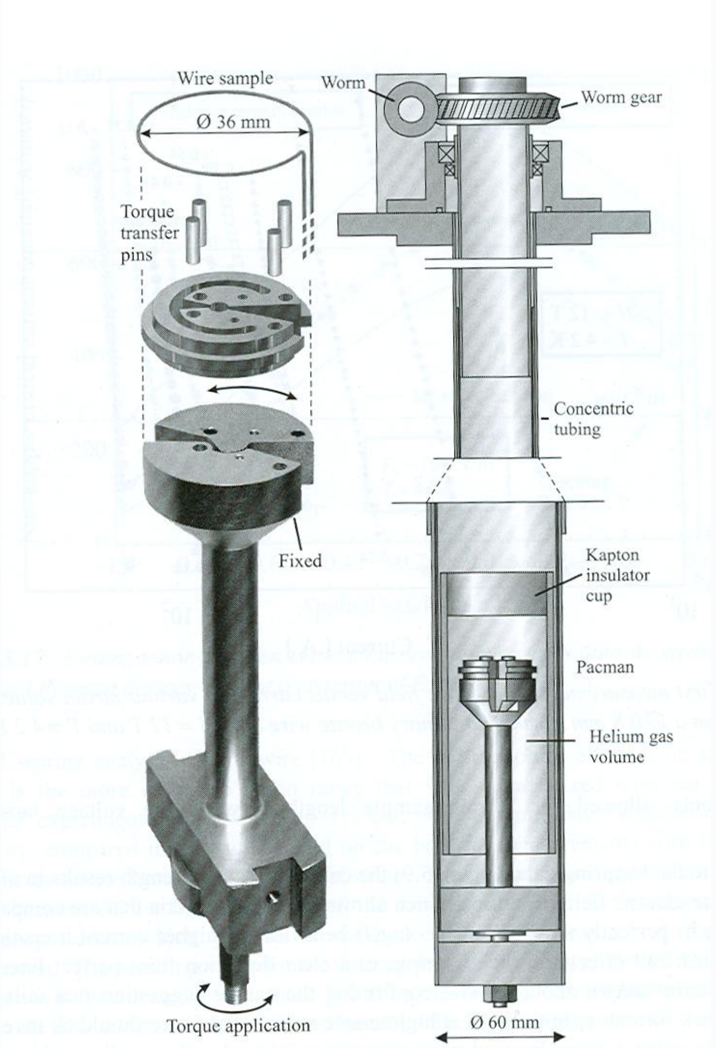
Uniaxial strain rig (KTI Karlsruhe)



Wire length: 200 mm
Magnetic field: 13.5 T (split coil)
Maximum force: 1 kN
Maximum current: 1’000 A
Temperature: 4.2K
Strain values: extensometers
I_c criterion: 1 μV/cm

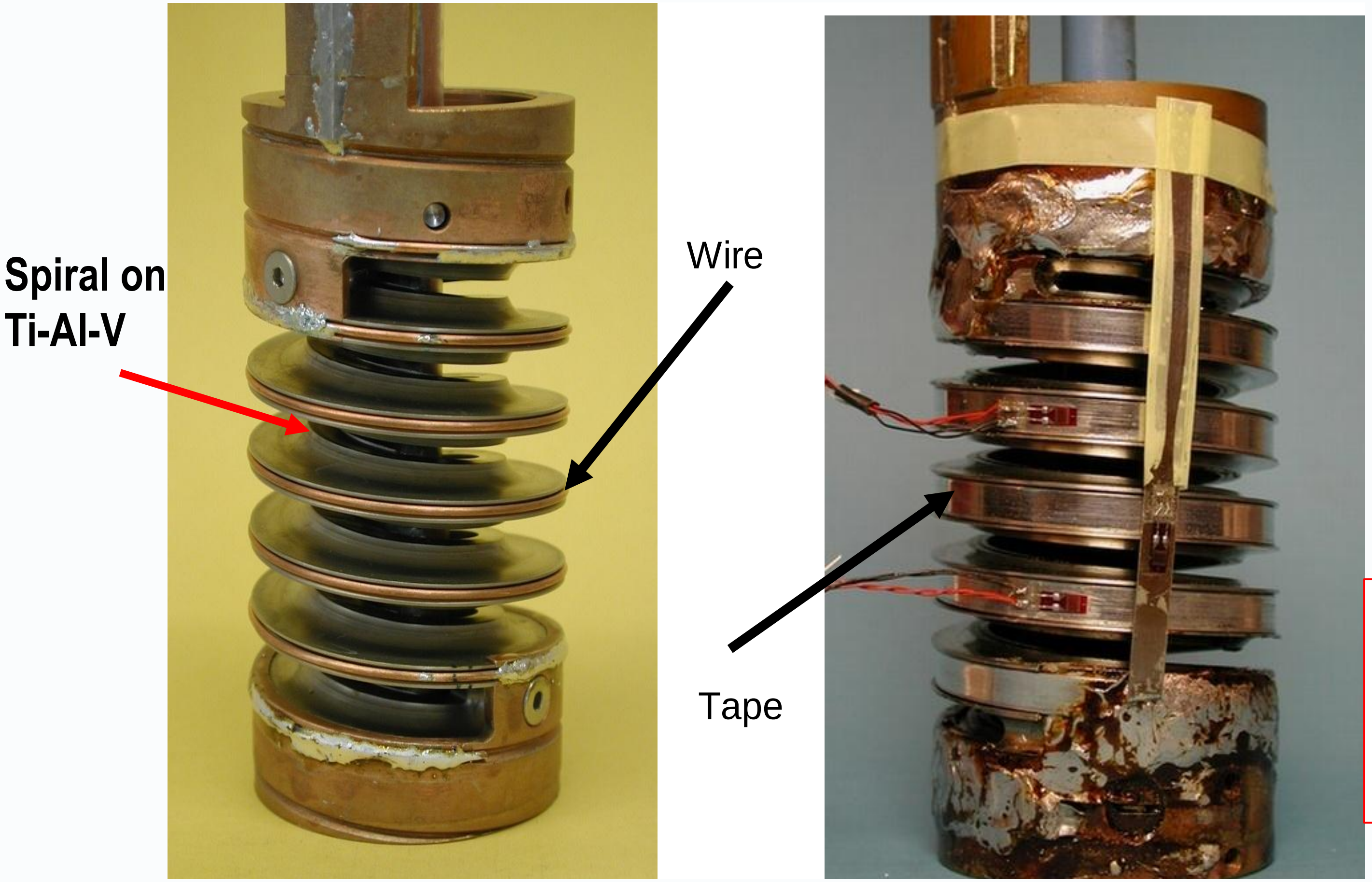
The Pacman strain device (University of Twente)





Force can be applied for axial tensile and axial compressive loads

Modified Walters Spiral (WASP), Univ. Geneva

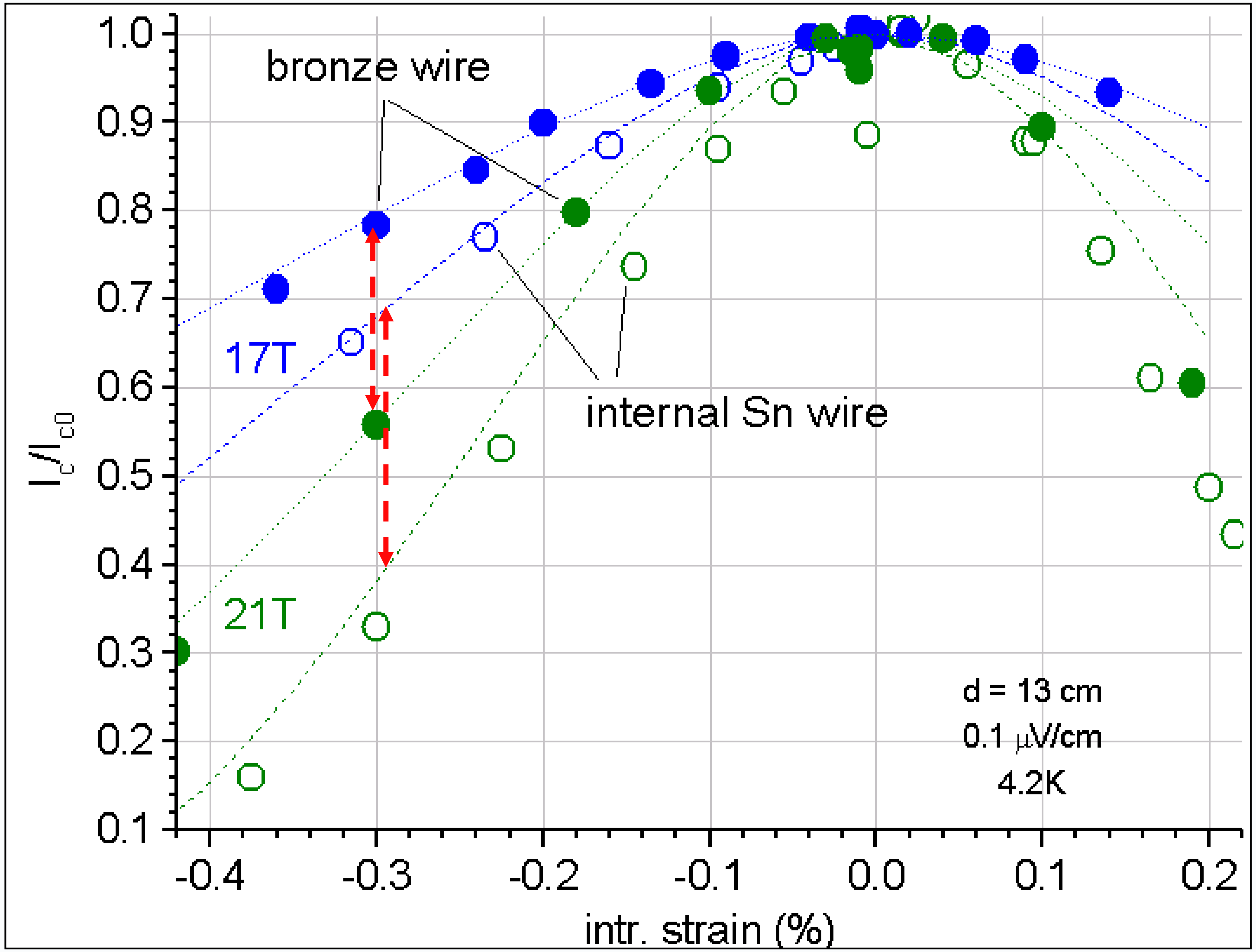


Rotation of the spiral is transformed into uniaxial force

Uniaxial tensile and compressive forces possible

Max. current 1’000 A
Wire length up to 0.8 m
I_c criterion 0.01μV/cm
Magnetic field up to 21T

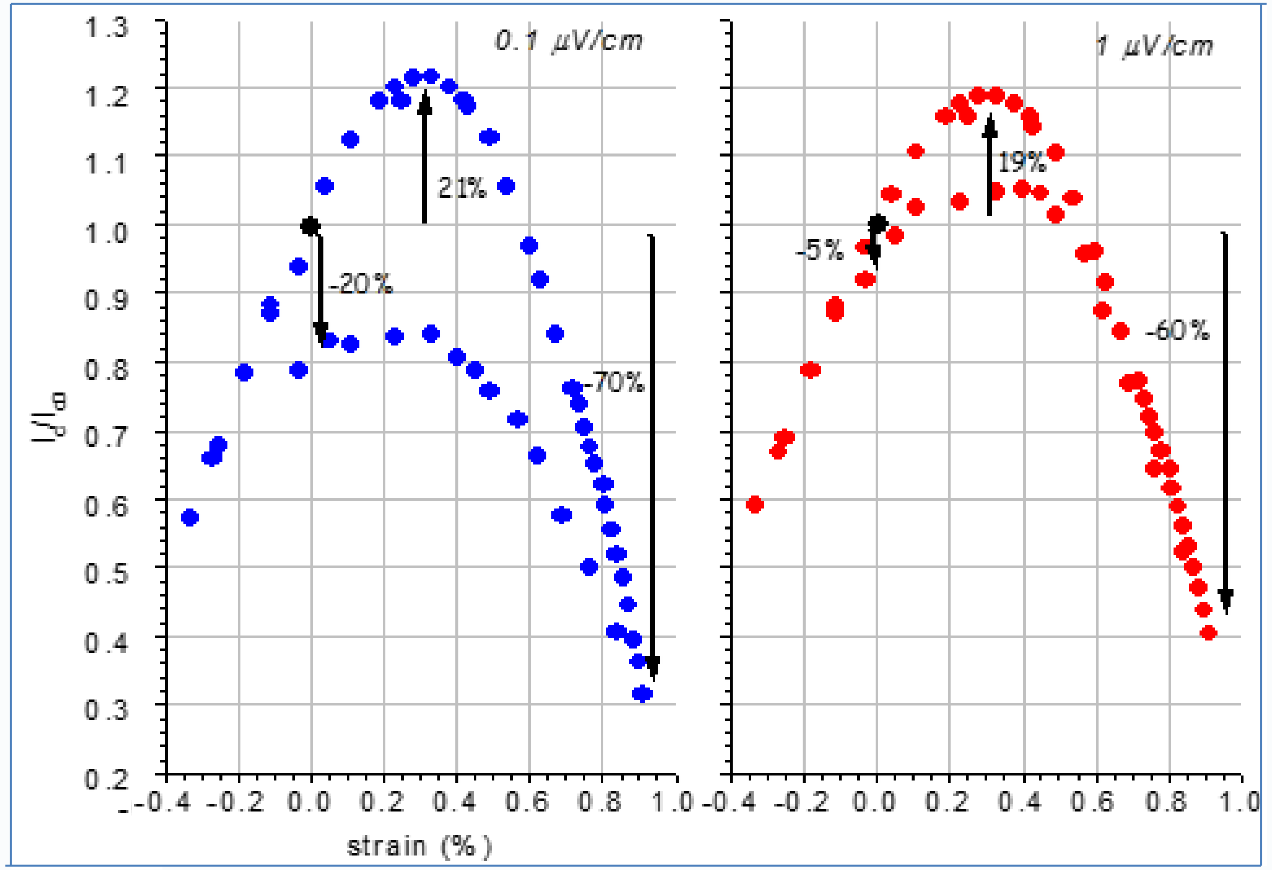
Effectof uniaxial stress on J_c at various fields



The difference increases with applied field

D.Uglietti, B.Seeber, R. Flükiger, SuST, in press

St iterion (0.01 mV/cm) leads to early Detection of I acks



Furukawa bronze Nb_3Sn wire for ITER,
dia. 0.8 mm; 4.2K/13T

I_c does not depend on strain criterion up to 0.6%/0.7%

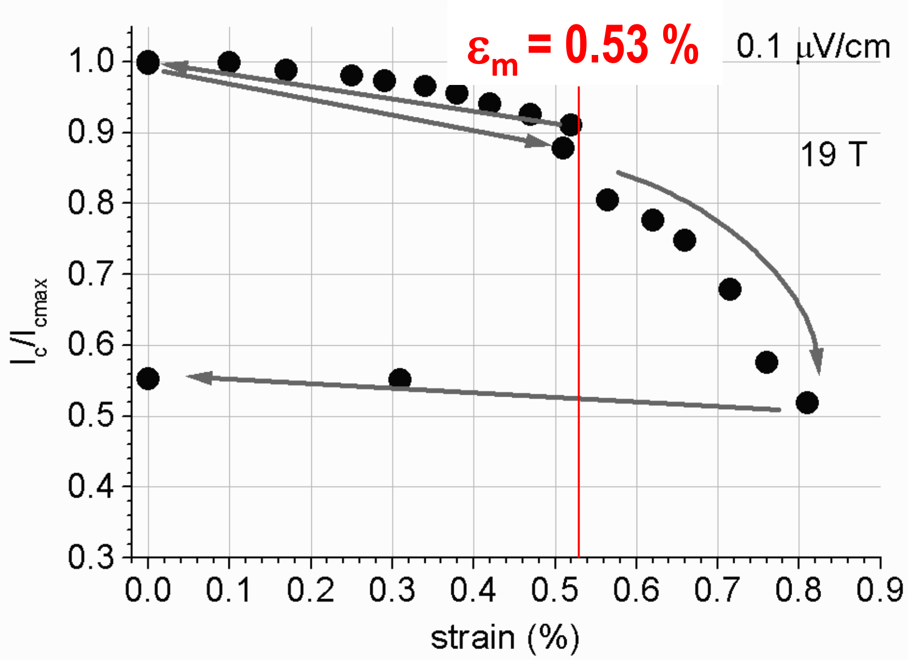
After releasing the strain, I_c depends strongly on the criterion

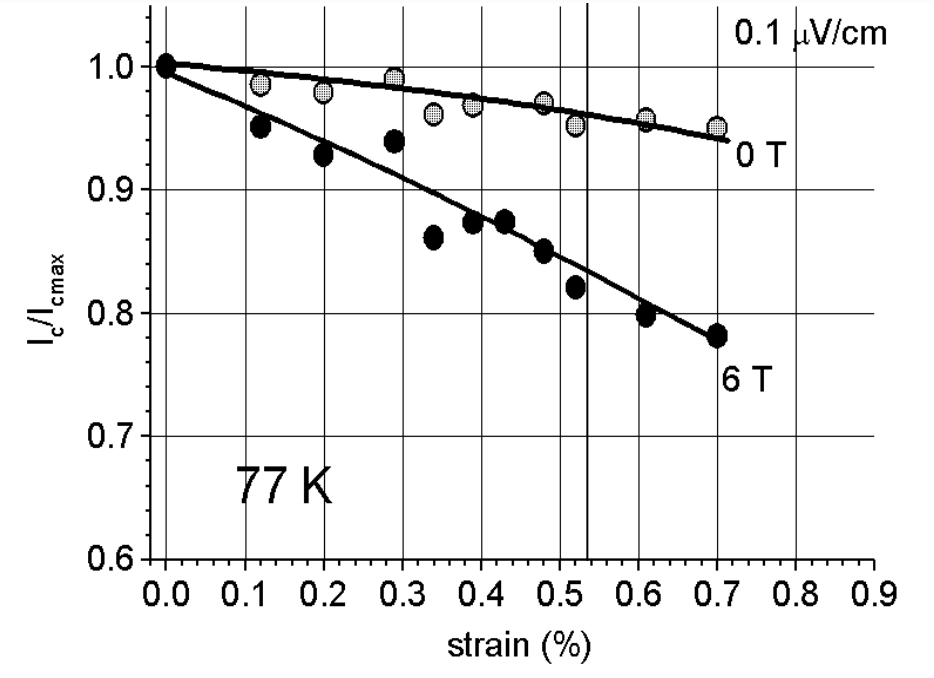
The irreversible strain limit (begin of nanocracks) depends on the I_c criterion: Advantage for the Walters spiral

D. Uglietti, V. Abächerli, R.Flükiger, 2004

Tensile stress on Coated Conductor Tapes (AMSC 344 type)

Tape length: 0.8 m

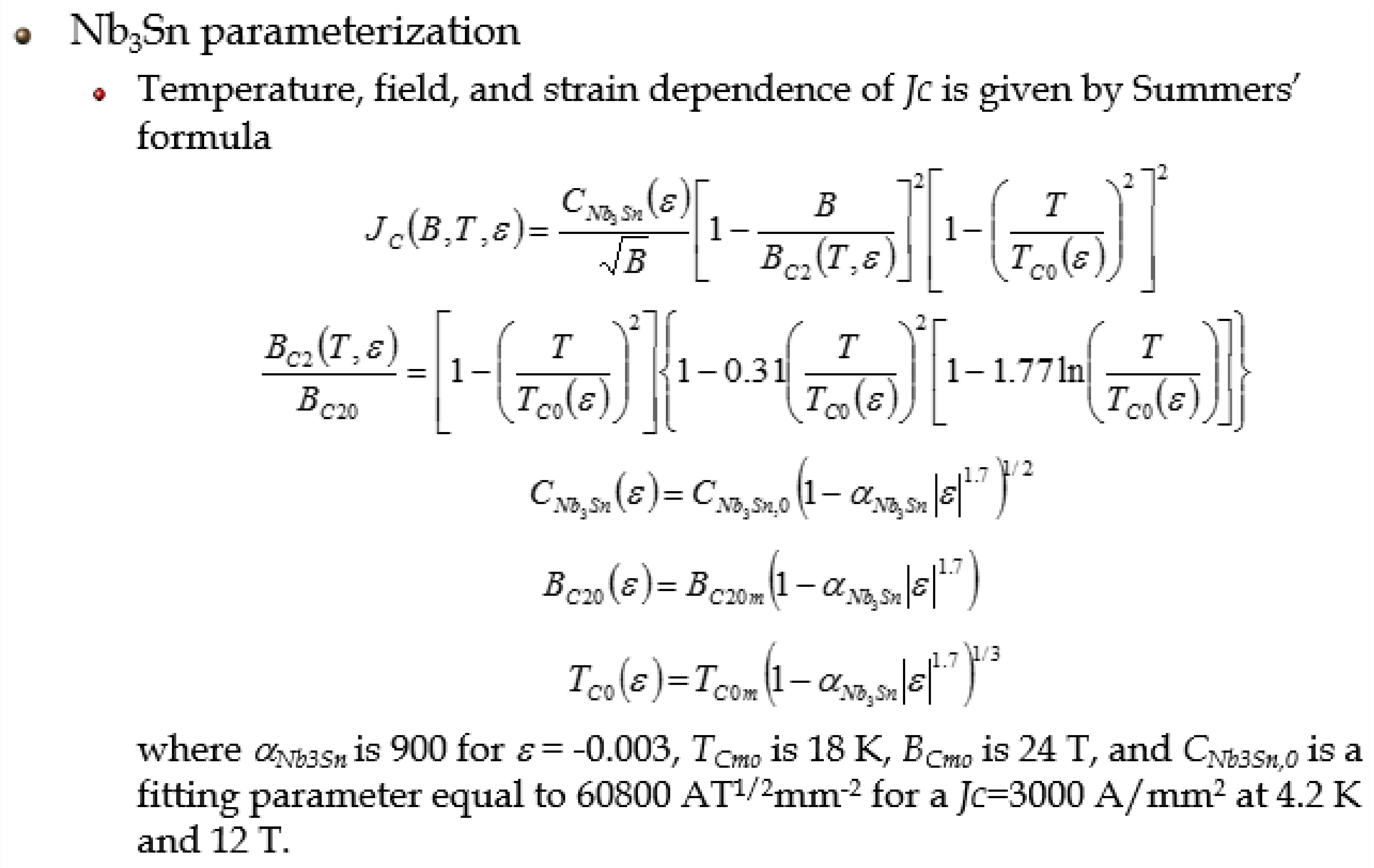




Uniaxial stress effects are also effective in HTS superconductors!

D. Uglietti, B. Seeber, R. Flükiger, SuST, in press

Case study 1 solution
Margins (Summers formula)



- Nb$_3$Sn parameterization
  - Temperature, field, and strain dependence of *Jc* is given by Summers' formula

$$J_C(B,T,\varepsilon)=\frac{C_{Nb_3Sn}(\varepsilon)}{\sqrt{B}}\left[1-\frac{B}{B_{C2}(T,\varepsilon)}\right]^2\left[1-\left(\frac{T}{T_{C0}(\varepsilon)}\right)^2\right]^2$$

$$\frac{B_{C2}(T,\varepsilon)}{B_{C20}}=\left[1-\left(\frac{T}{T_{C0}(\varepsilon)}\right)^2\right]\left\{1-0.31\left(\frac{T}{T_{C0}(\varepsilon)}\right)^2\left[1-1.77\ln\left(\frac{T}{T_{C0}(\varepsilon)}\right)\right]\right\}$$

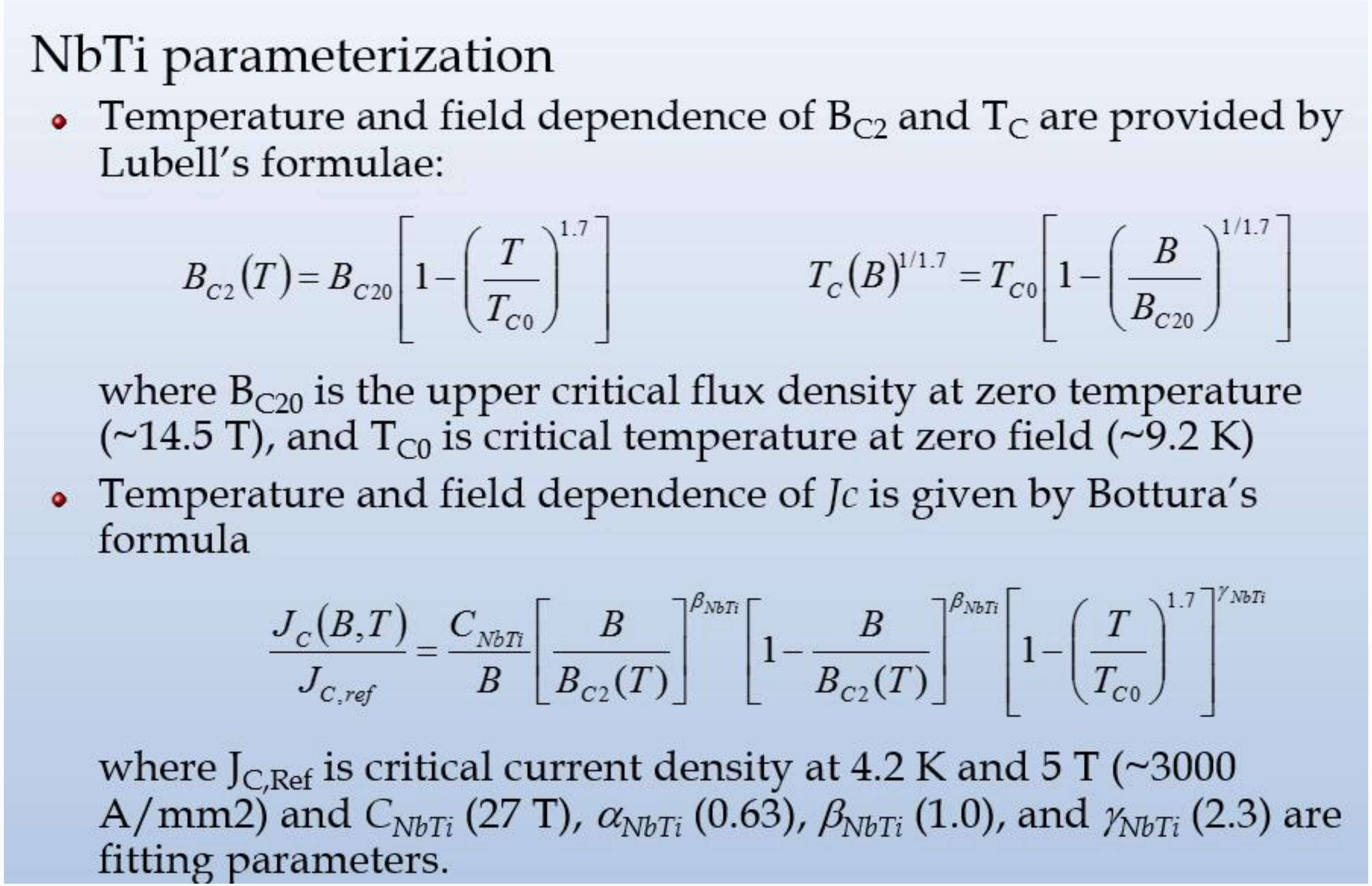
$$C_{Nb_3Sn}(\varepsilon)=C_{Nb_3Sn,0}\left(1-\alpha_{Nb_3Sn}|\varepsilon|^{1.7}\right)^{1/2}$$

$$B_{C20}(\varepsilon)=B_{C20m}\left(1-\alpha_{Nb_3Sn}|\varepsilon|^{1.7}\right)$$

$$T_{C0}(\varepsilon)=T_{C0m}\left(1-\alpha_{Nb_3Sn}|\varepsilon|^{1.7}\right)^{1/3}$$

where α_{Nb3Sn} is 900 for ε = -0.003, T_{Cmo} is 18 K, B_{Cmo} is 24 T, and $C_{Nb3Sn,0}$ is a fitting parameter equal to 60800 AT$^{1/2}$mm^{-2} for a *Jc*=3000 A/mm^2 at 4.2 K and 12 T.

Case study 1 solution
Margins (Bottura's formula)



NbTi parameterization

- Temperature and field dependence of B_{C2} and T_C are provided by Lubell's formulae:

$$B_{C2}(T) = B_{C20}\left[1-\left(\frac{T}{T_{C0}}\right)^{1.7}\right] \qquad T_C(B)^{1/1.7} = T_{C0}\left[1-\left(\frac{B}{B_{C20}}\right)^{1/1.7}\right]$$

where B_{C20} is the upper critical flux density at zero temperature (~14.5 T), and T_{C0} is critical temperature at zero field (~9.2 K)

- Temperature and field dependence of Jc is given by Bottura's formula

$$\frac{J_C(B,T)}{J_{C,ref}} = \frac{C_{NbTi}}{B}\left[\frac{B}{B_{C2}(T)}\right]^{\beta_{NbTi}}\left[1-\frac{B}{B_{C2}(T)}\right]^{\beta_{NbTi}}\left[1-\left(\frac{T}{T_{C0}}\right)^{1.7}\right]^{\gamma_{NbTi}}$$

where $J_{C,Ref}$ is critical current density at 4.2 K and 5 T (~3000 A/mm2) and C_{NbTi} (27 T), α_{NbTi} (0.63), β_{NbTi} (1.0), and γ_{NbTi} (2.3) are fitting parameters.

Transverse compressive stresses, i.e. in cables

Knowledge about the effect of transverse compressive stresses: Important for the safe design of

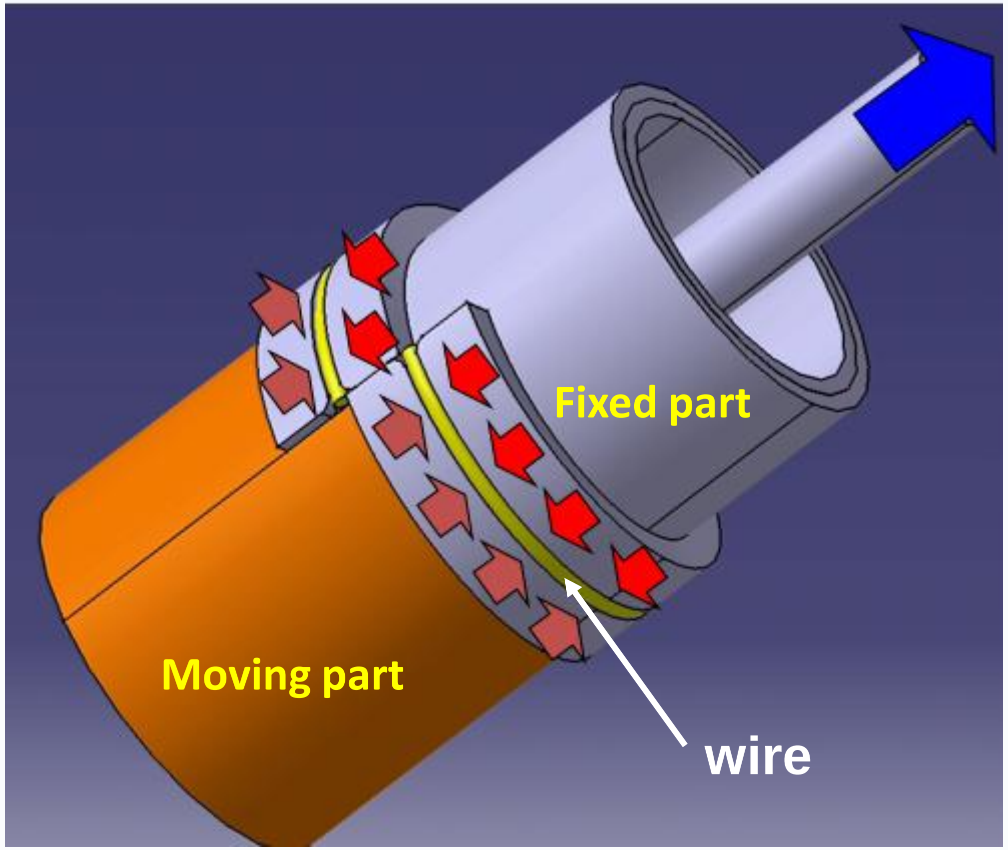
* High field magnets (B > 20 T)
* Large magnets, for
    Fusion magnets (Tokamak)
    Accelerators (LHC, LHC Upgrade)

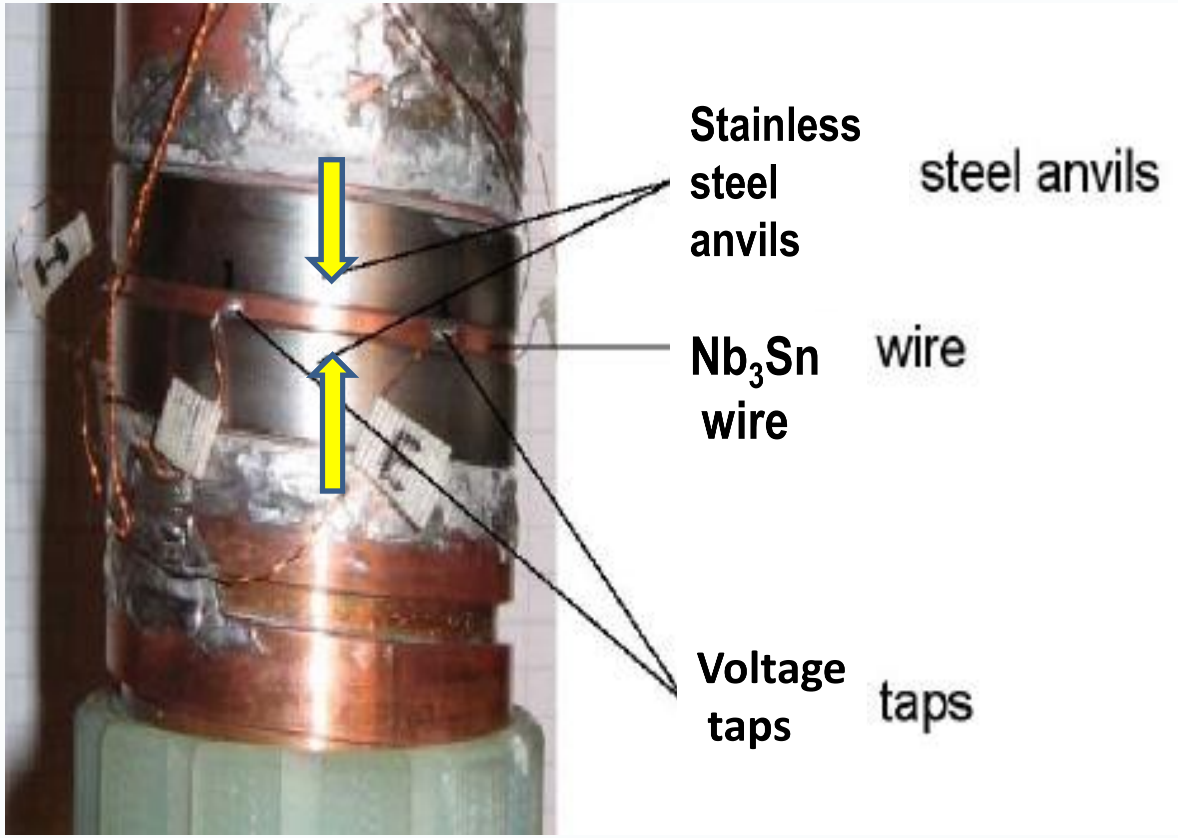
Measuring devices:
* Pacman, Univ. Twente
* Inverse Walters Spiral (Univ. Geneva)

ITER TF model coil: cable

Ø 40 mm, 1.5 mm thick steel
Conduit rated current:
70 kA/11.8 T/4,6 K
~1028 strands:Nb_3Sn + 1/3 Cu

Inverse Walters spiral (Univ. Geneva)

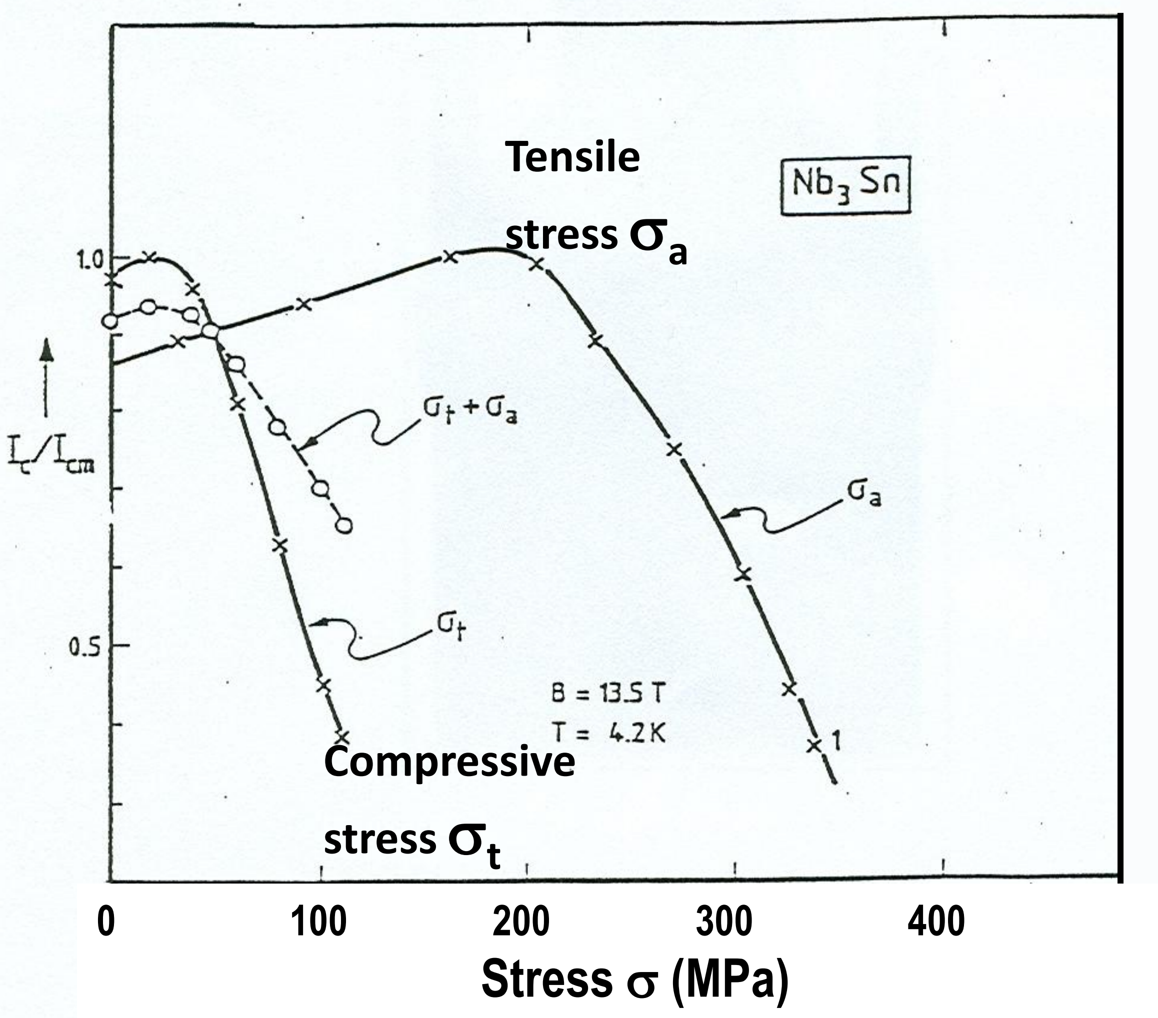




Specifications: - F = 5KN

- I = 1000 A
- Field: 21 T

J_c vs. transverse compressive stress σ_t



$\sigma_t(I_{cm}) << \sigma_a(I_{cm})$

J. Ekin (1986)

W. Specking, R.Flükiger, (1987)

Conclusions : Nb_3Sn wires

- Low and intermediate fields: J_c determined by flux pinning (grain size)
- At high fields, J_c is determined by the value of B_{c2}

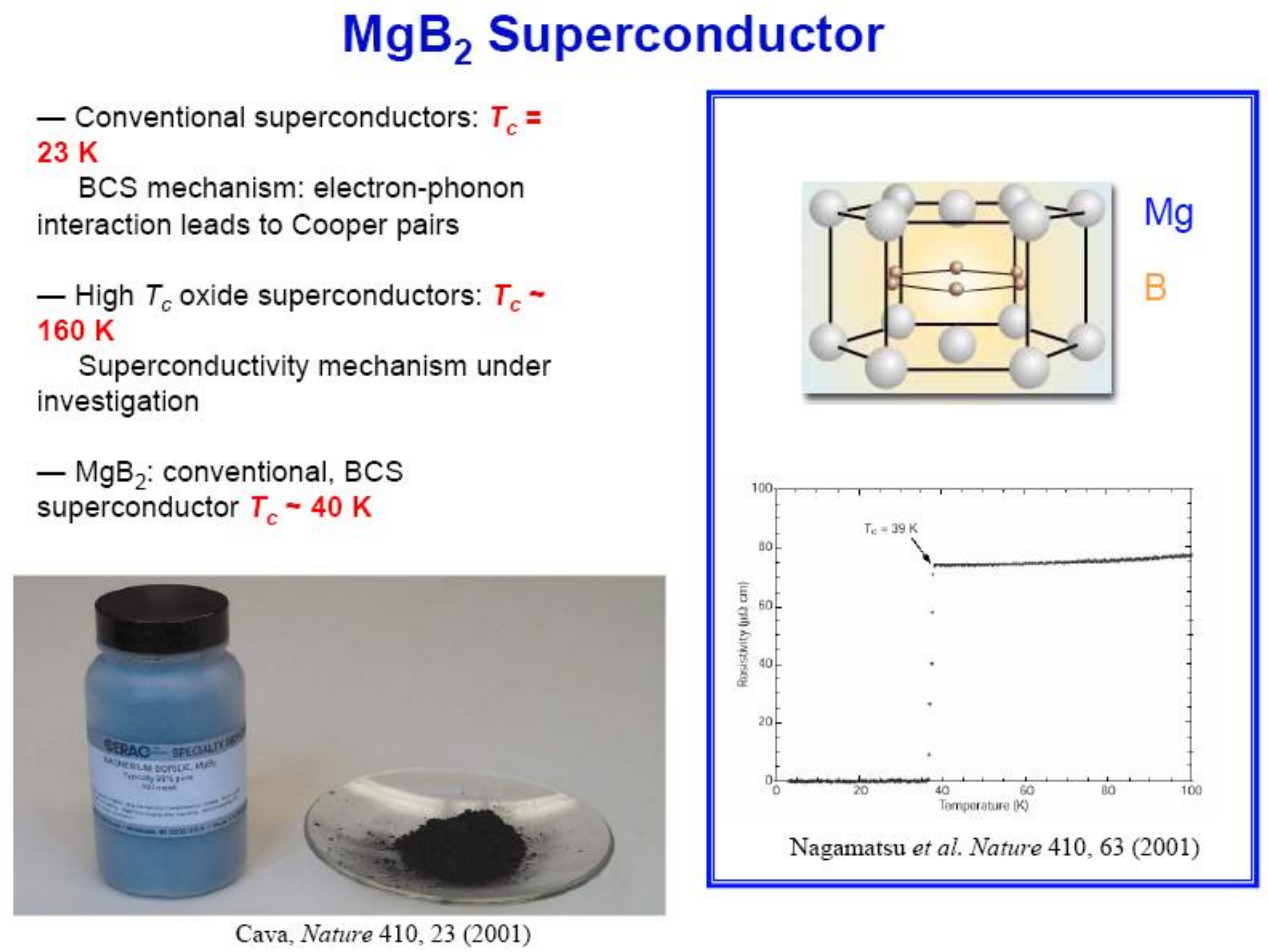
- Industrial round wires for magnets up to 23.5 T (1 GHz): Nb_3Sn
- The amount of Nb_3Sn wire in a magnet increases strongly with the produced field: at 20T, 5 times more Nb_3Sn than for 12 T.

- Bronze route wires: best suited for *«persistent mode»* operation of NMR magnets, in spite of their lower J_c value with respect to Internal Sn wires

- **Internal Sn (RRP) and Powder-in-Tube (PIT) wires satisfy the conditions for *LHC Upgrade accelerator* magnet: 1’500 A/mm^2 at 4.2K/15T.**

2. MgB_2 wires

The MgB_2 system



MgB_2 Superconductor

— Conventional superconductors: T_c = 23 K
BCS mechanism: electron-phonon interaction leads to Cooper pairs

— High T_c oxide superconductors: T_c ~ 160 K
Superconductivity mechanism under investigation

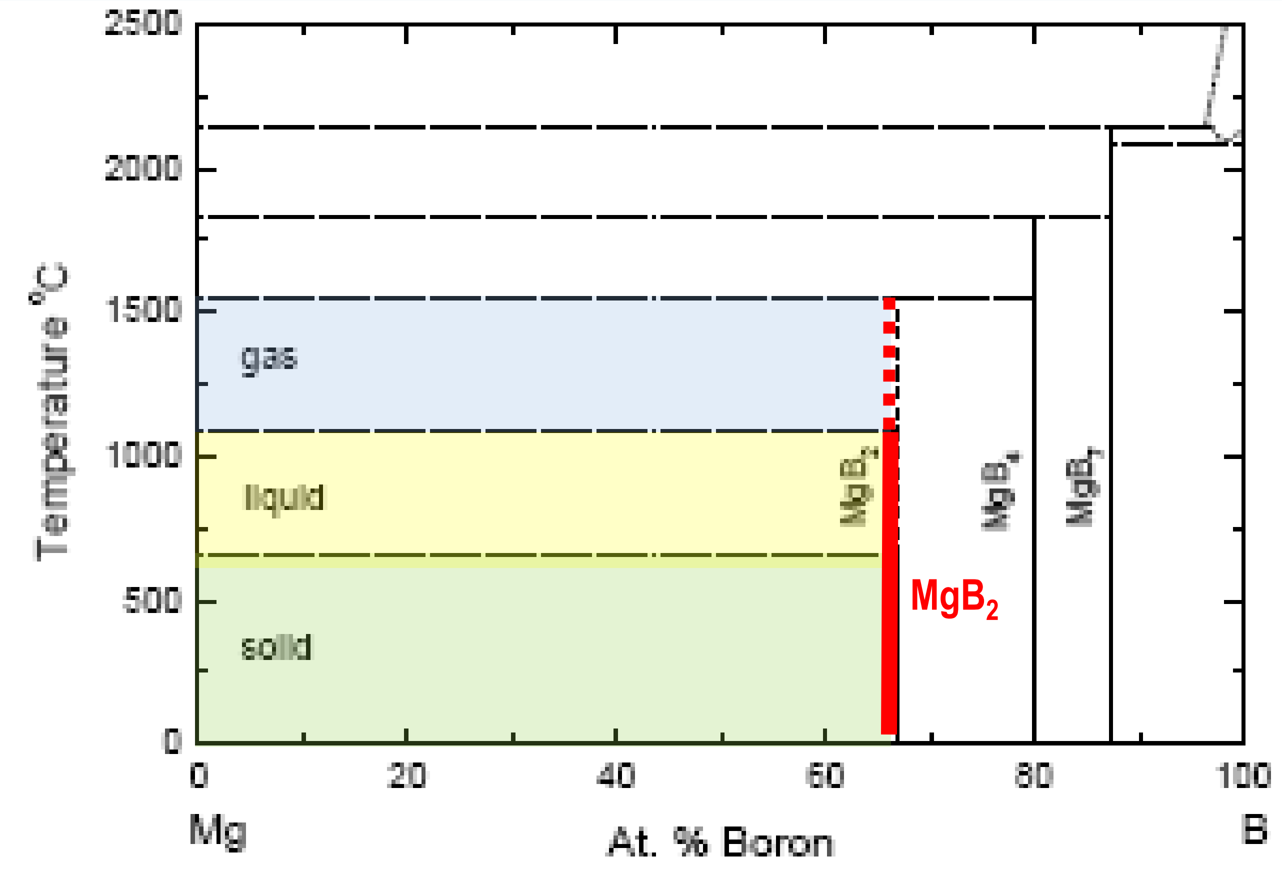
— MgB_2: conventional, BCS superconductor T_c ~ 40 K

Nagamatsu *et al. Nature* 410, 63 (2001)

Cava, *Nature* 410, 23 (2001)

Hexagonal lattice
a = 0.30834 nm
c = 0.35213 nm

The binary Mg-B Phase Diagram



Binary Alloys Phase Diagrams, 2nd Edition, Ed. T. Massalski (A.S.M.International, 1990)

MgB_2 applications

Possible applications:

* Level measurement of Liquid H_2 containers

* Hydrogen cooled current leads at T ≈ 20K (Kostyuk et al.)

* LINK project (CERN): 13’000A current leads at ≈10K

(> 10’000 km of MgB_2 wire): under investigation

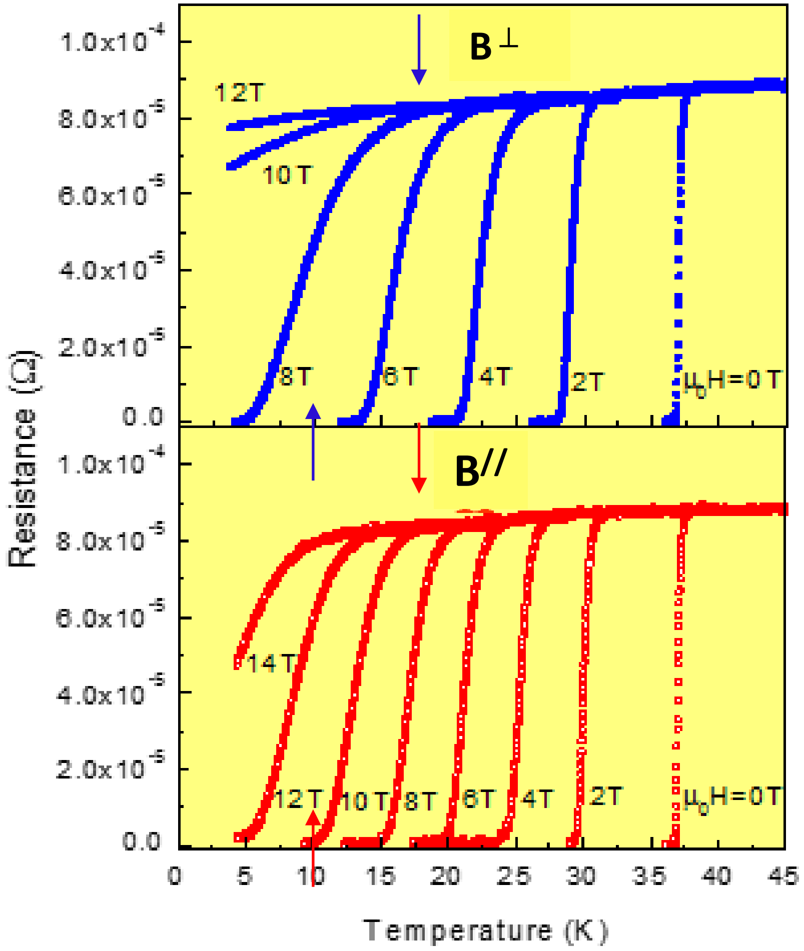
(talk at CAS, last day: Amalia Ballarino)

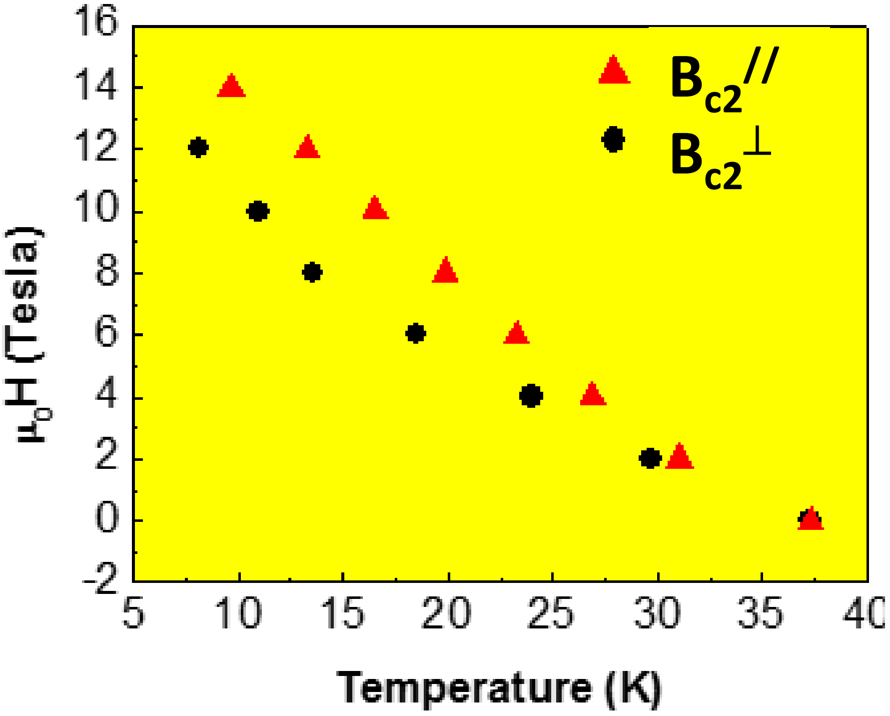
* Ignitor (under construction (Russia/Italy)

* Wind generators ? First device under study

* Poloidal field coils ? The question is discussed

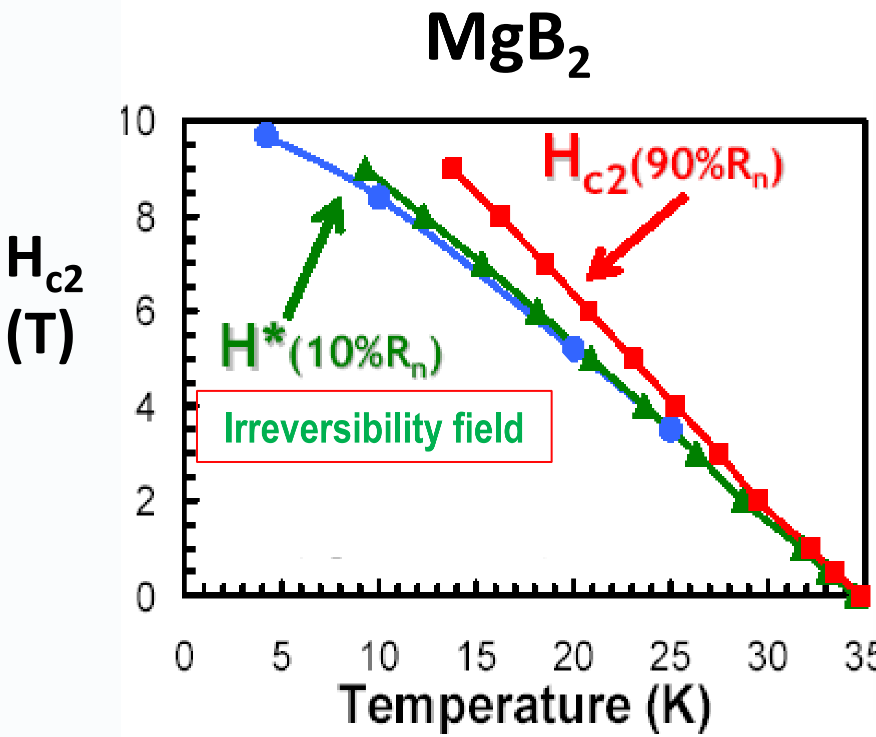
Determination of B_{c2}// and $B_{c2}^{\perp}$ in *ex situ* MgB_2 wires



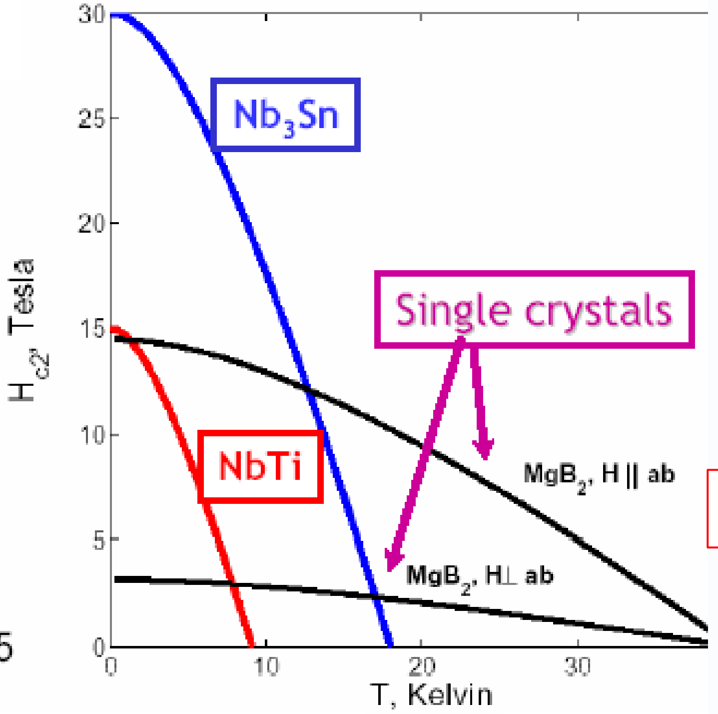


- Field-induced decrease of T_c : larger for $H^{\perp}$ than for $H^{\parallel}$
- Transition width for $H^{\parallel}$: narrower than that for $H^{\perp}$

Upper critical field and irreversibility field of MgB_2



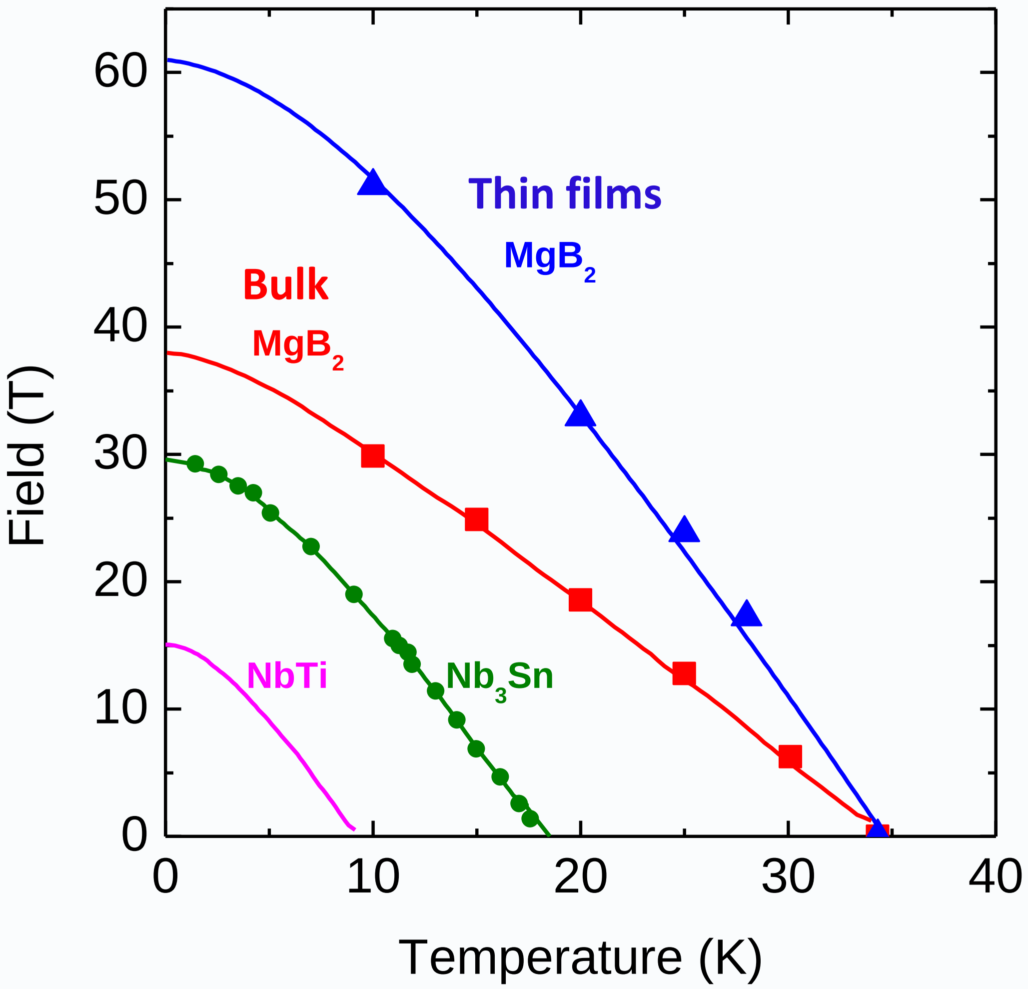
Larbalestier et al., 2002



anisotropy

Alloying required to raise H_{c2} above Nb-base superconductors

Upper critical field of MgB_2: films and wires



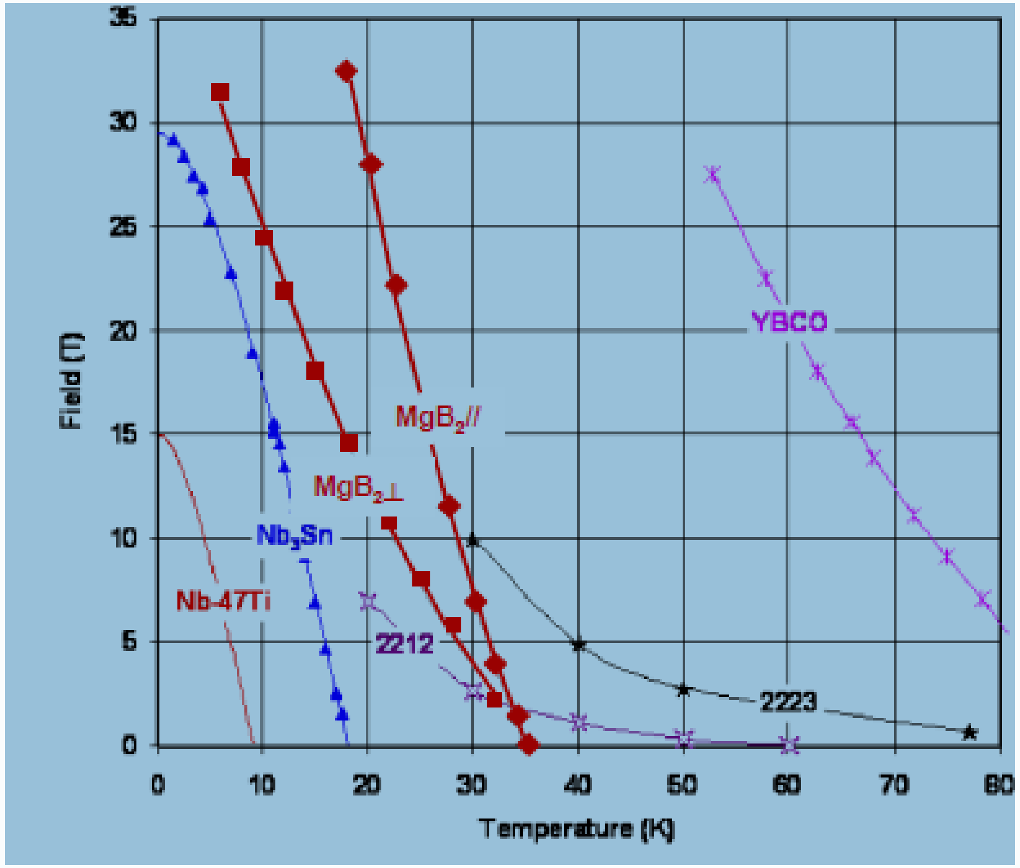
Films: B_{c2} = 60 T

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

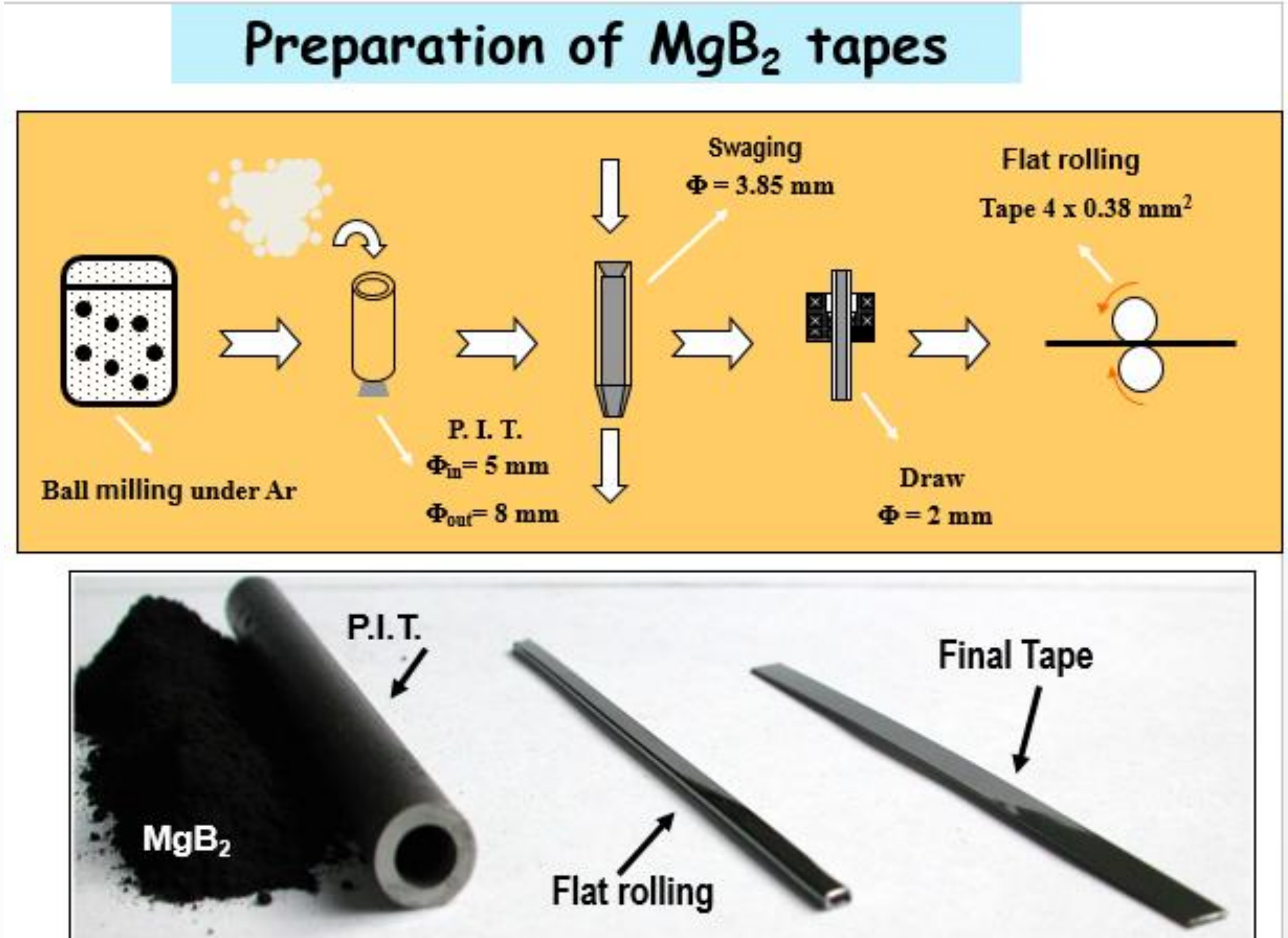
The reason for this difference is still unknown

Upper critical fields of various superconductors

Comparison of B_{c2} for various superconductors

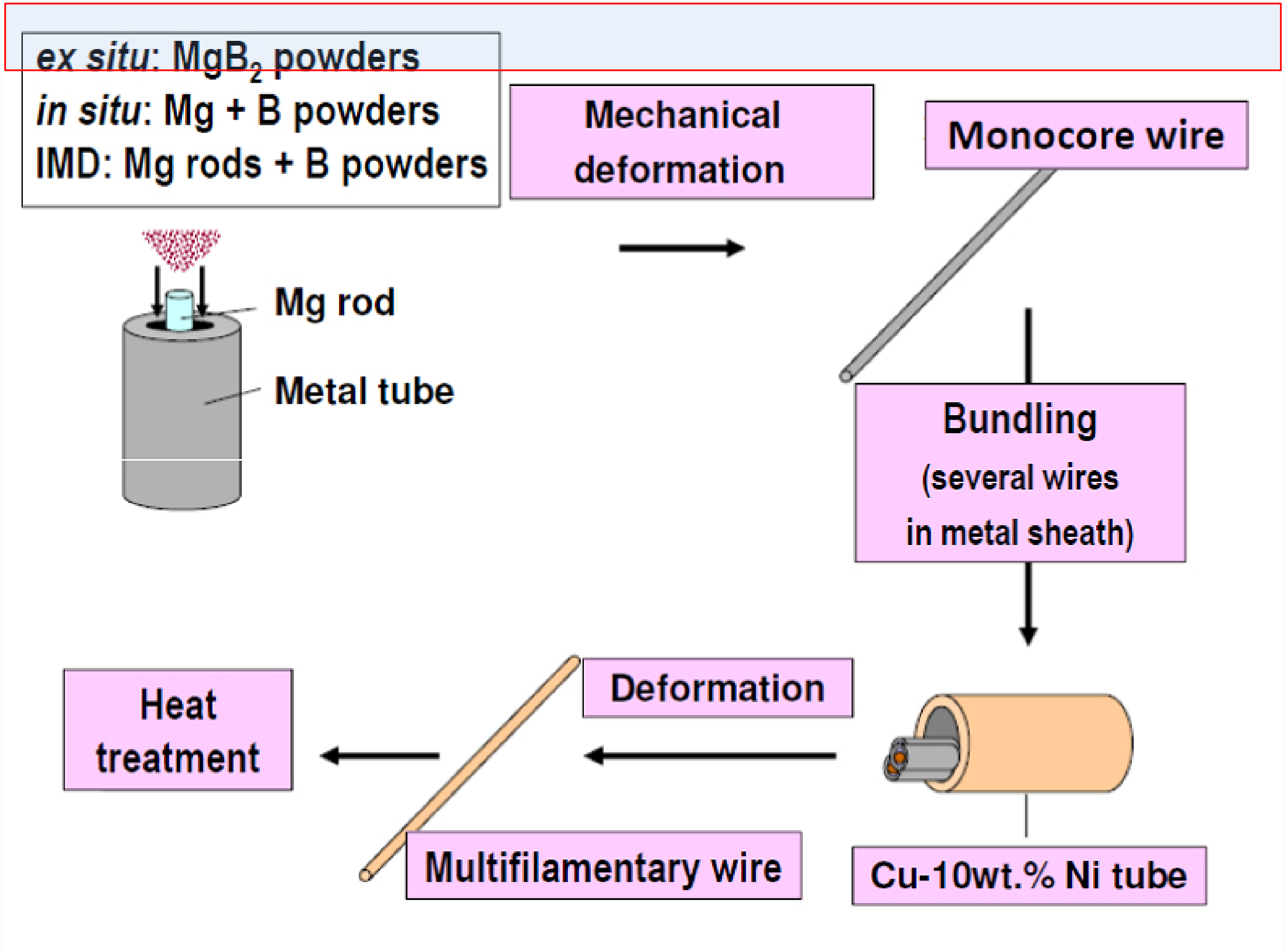


MgB$_2$ wires, *ex situ* processing



Preparation of MgB$_2$ tapes

MgB_2 wires: 3 preparation methods



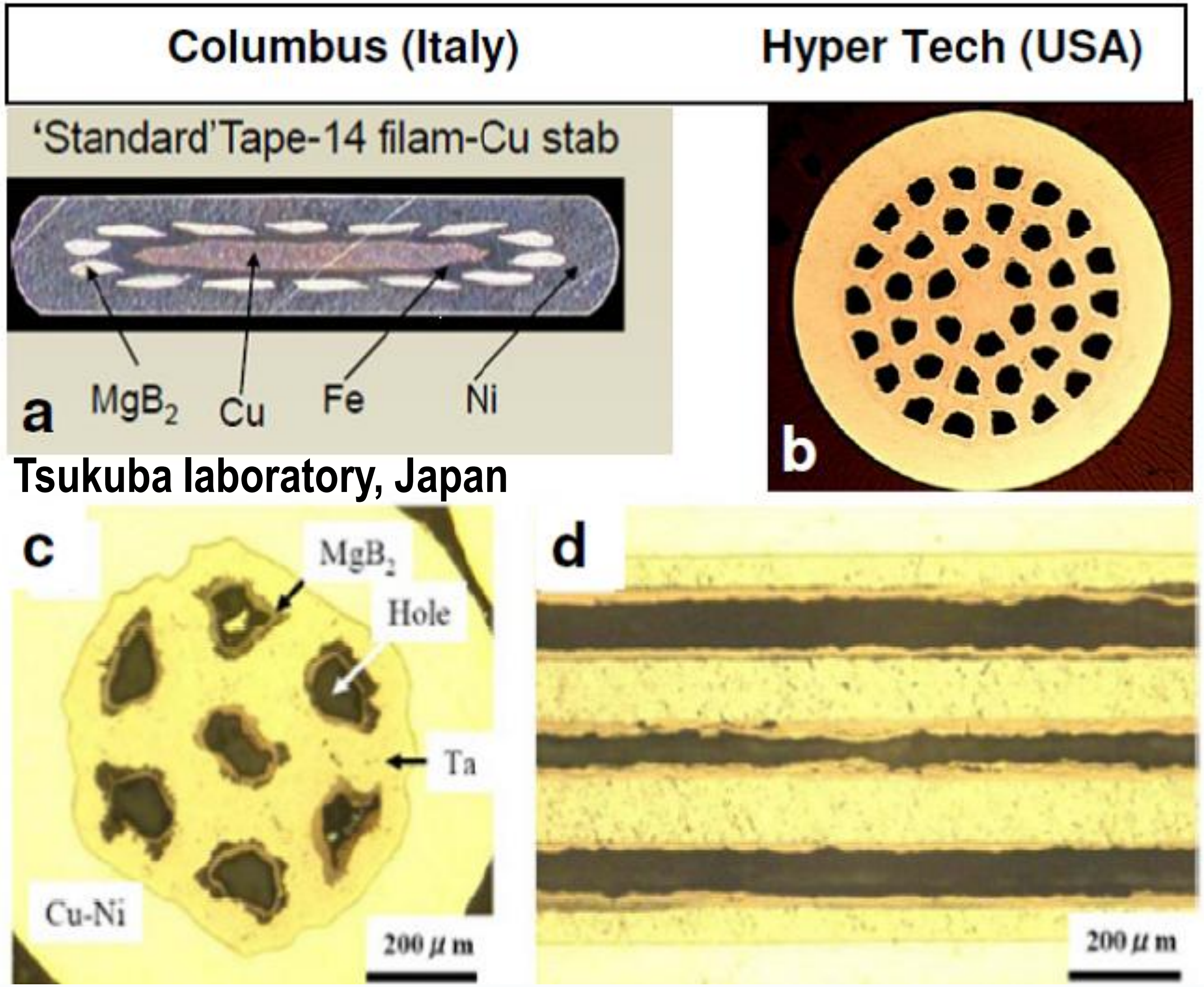
ex situ: MgB_2 powders
in situ: Mg + B powders
IMD: Mg rods + B powders

Mechanical deformation → Monocore wire → Bundling (several wires in metal sheath) → Cu-10wt.% Ni tube → Deformation → Multifilamentary wire → Heat treatment

Known MgB$_2$ wire configurations

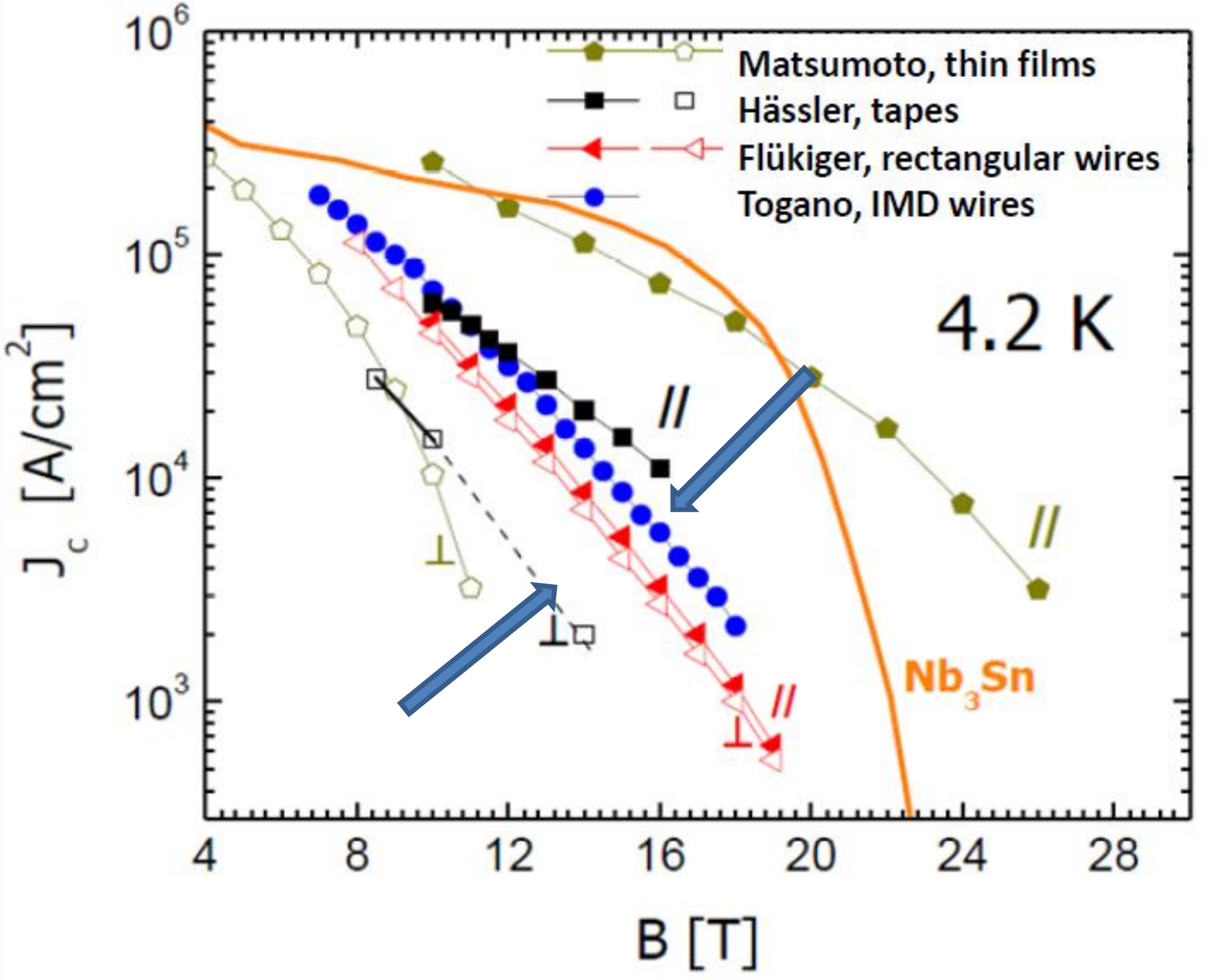
Ex situ

In situ



IMD

The limitation of J_c in MgB_2 due to anisotropy



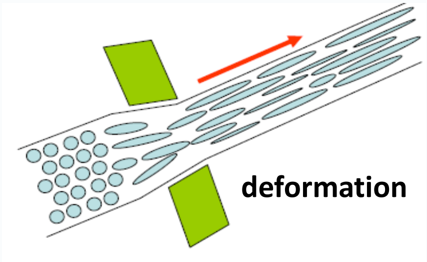
MgB_2 wires

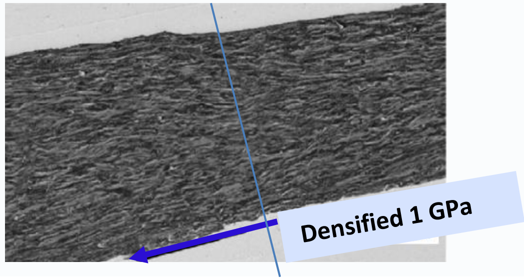
Strong anisotropy

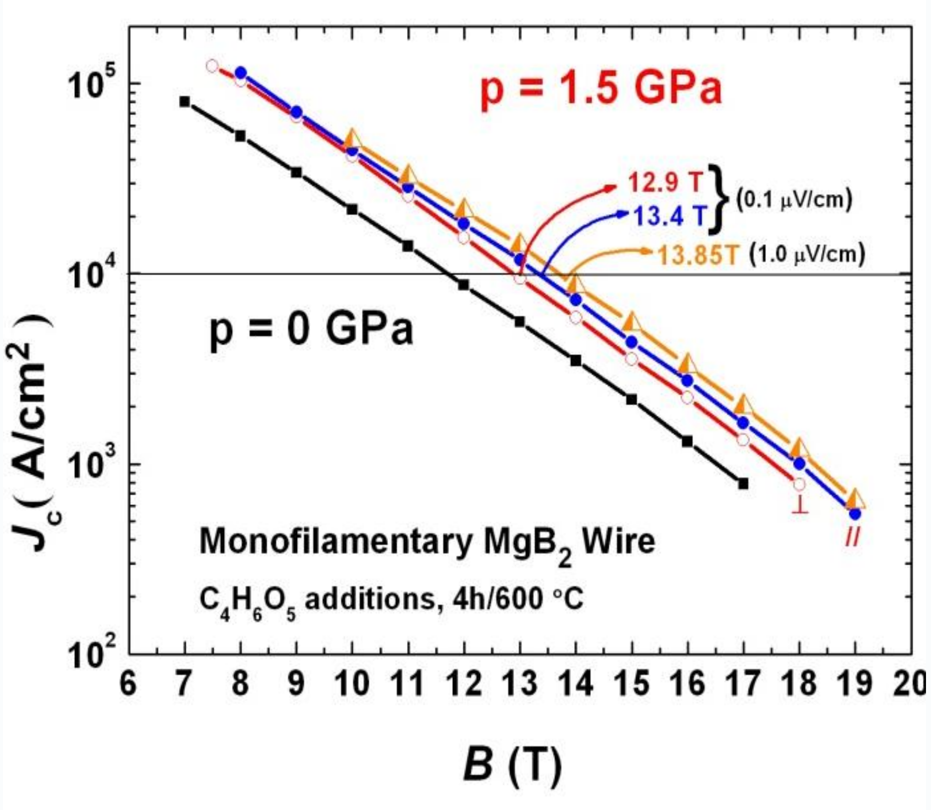
B // surface: J_c comparable to that of Nb_3Sn

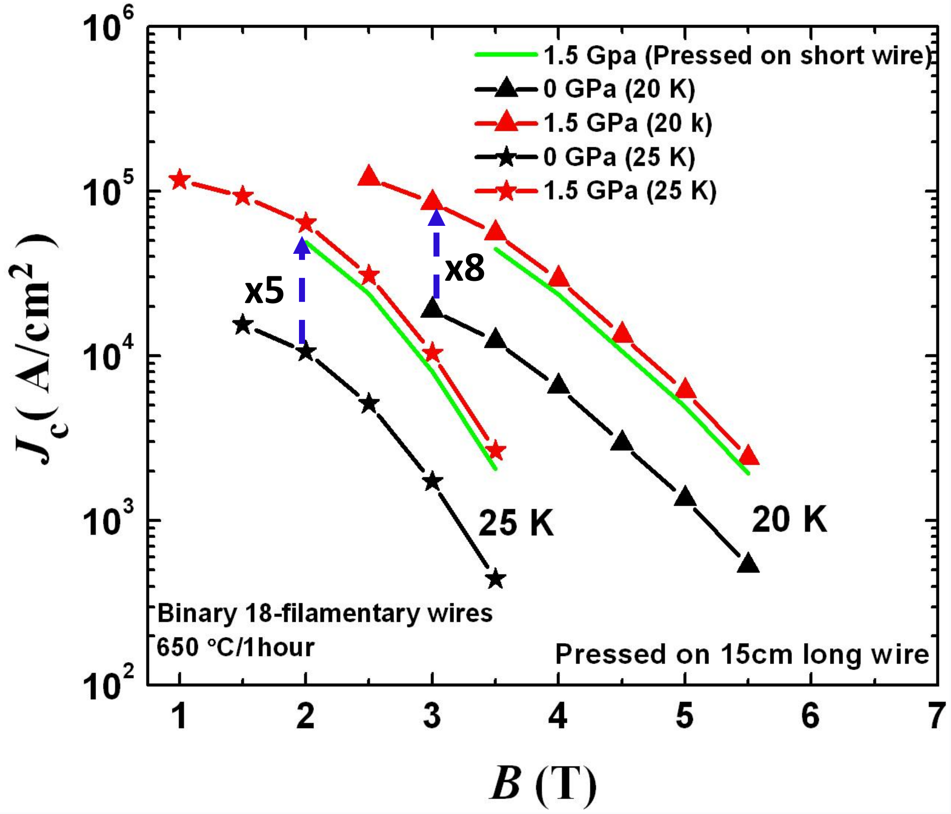
B ⊥ surface: J_c much smaller than Nb3Sn.
It is the limiting factor.

J_c of densified MgB_2 wires after densification

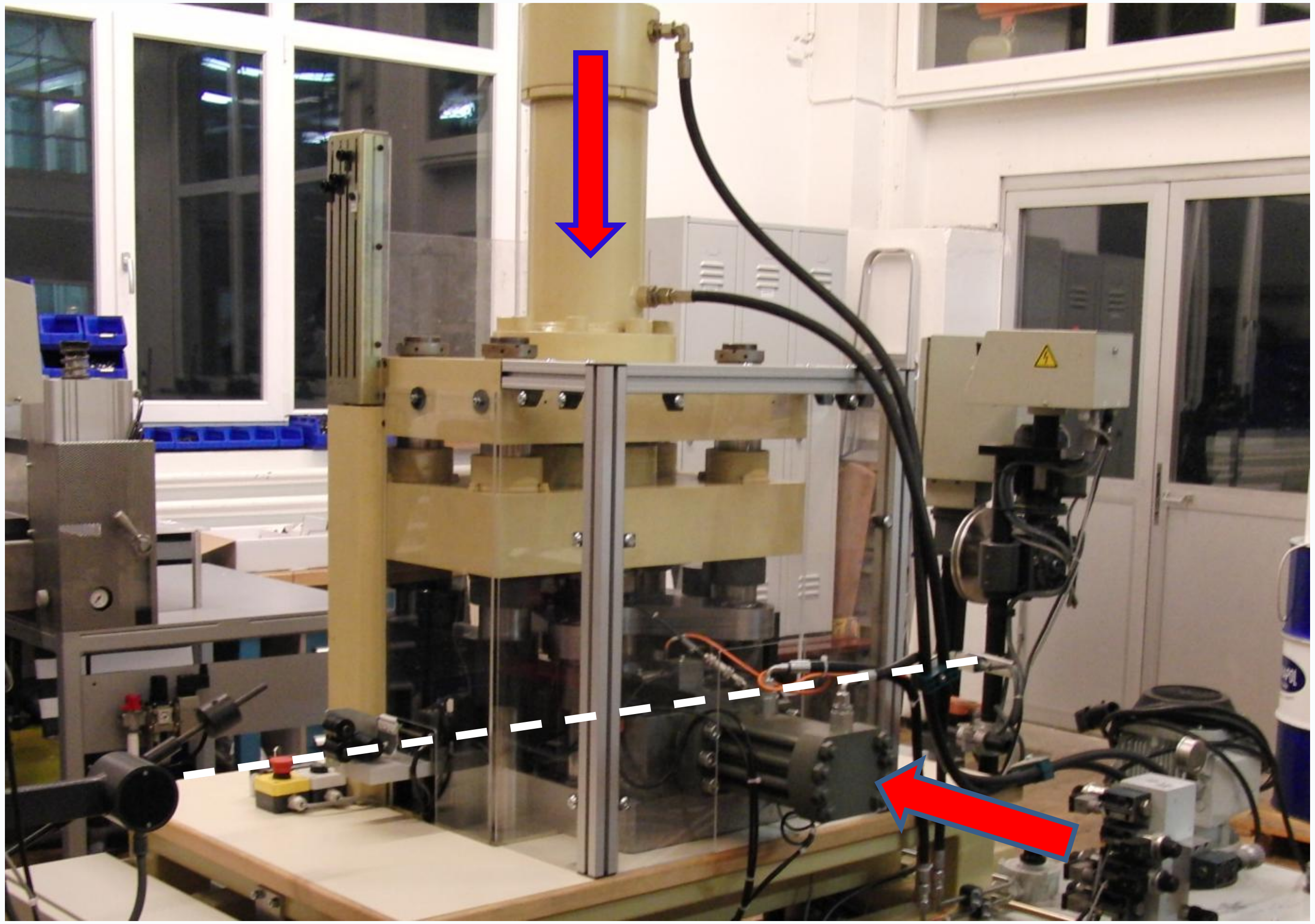






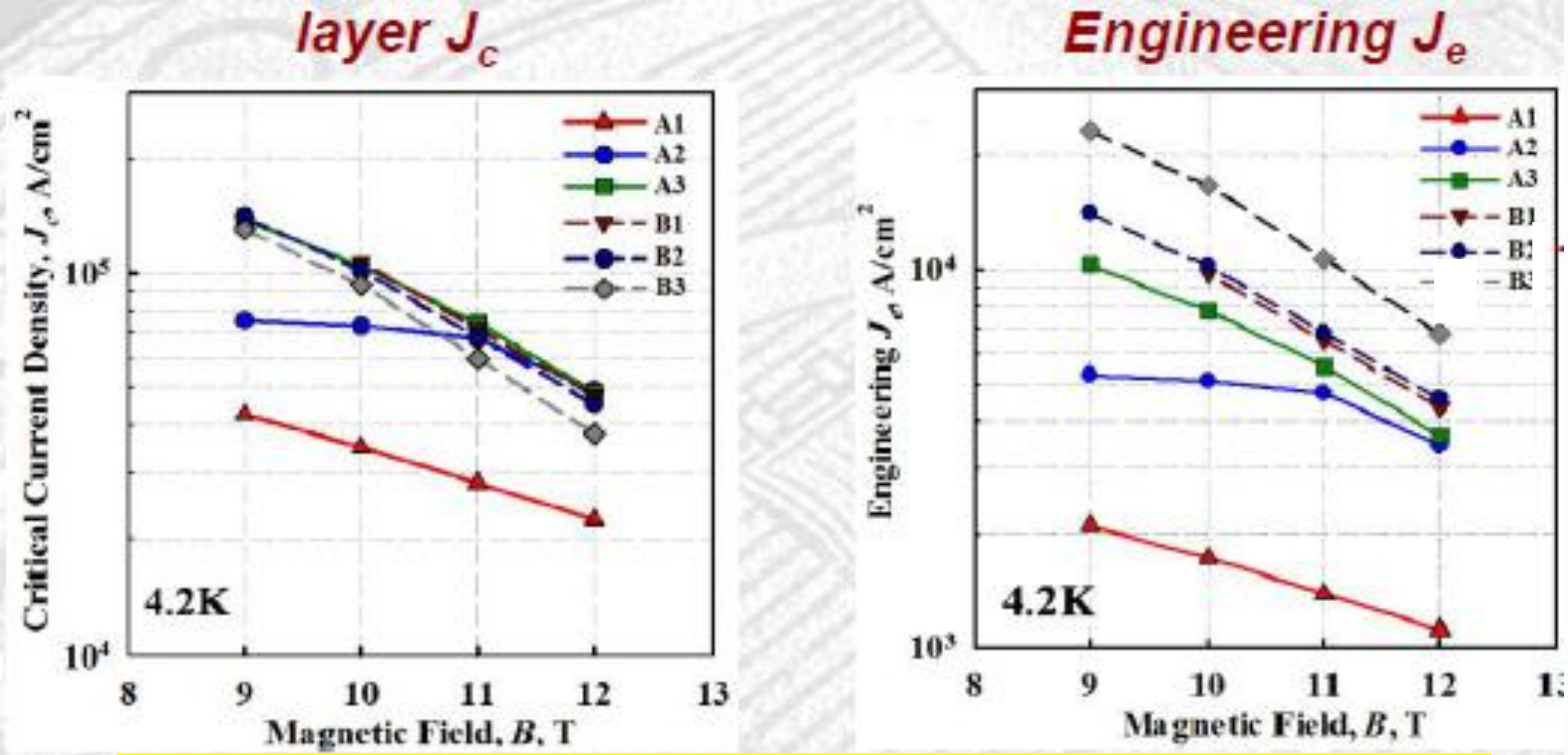


Densification machine for long s.c. wires



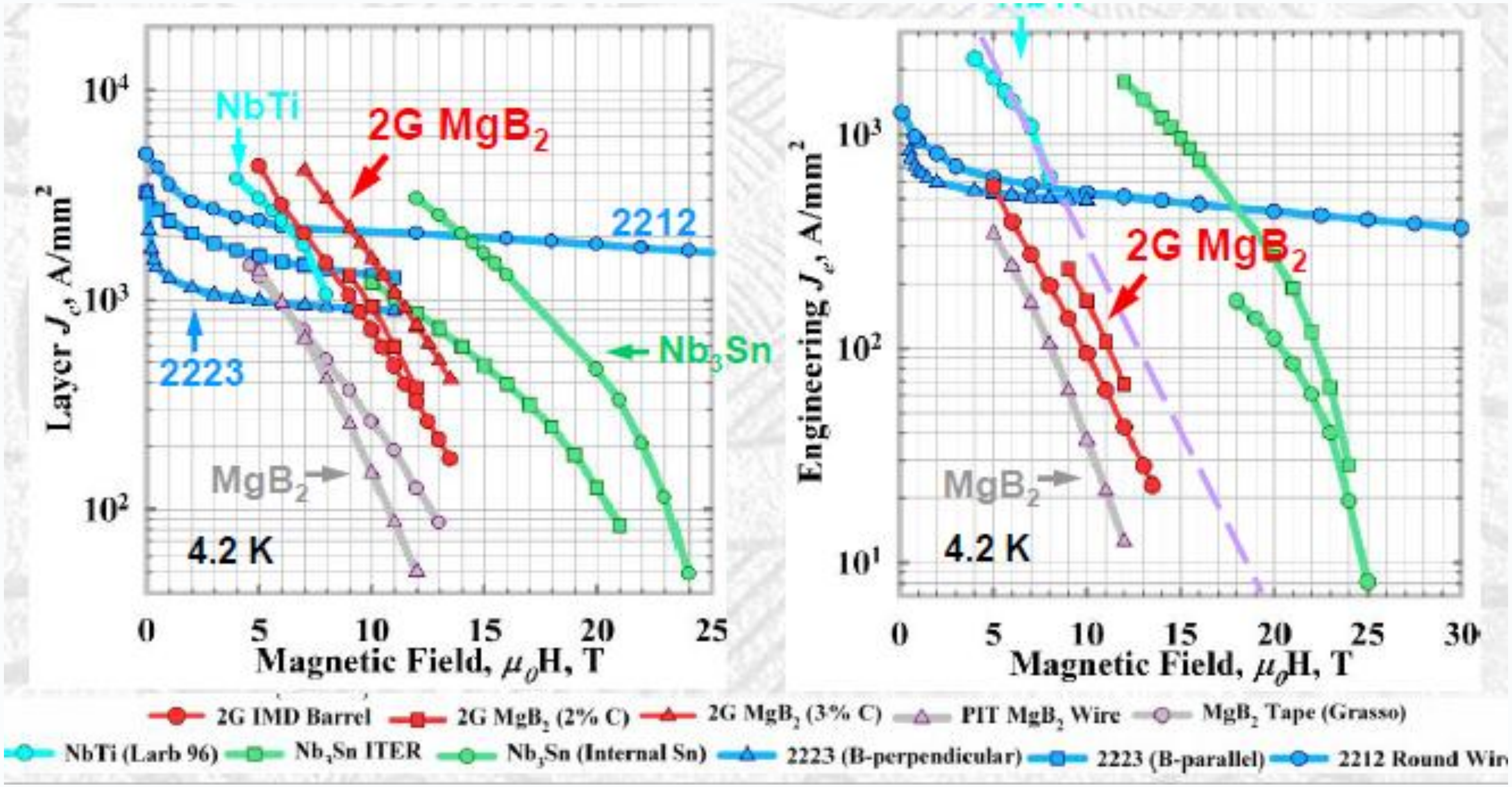
Possible application of densification: Bi-2212, pnictides,....

MgB_2 wire: highest Jc at high fields



Wire B3 (highest value): J_c (eng.) = 1.67 x 10^4 A/cm^2 at 10 T

Comparison between various superconductors



The system MgB_2

Advantages:
- Abundant constituents Mg and B
- No chemical toxicity
- **Low cost material** (comparable or lower to NbTi)
- Applicable at $4.3 \leq T \leq 25K$
- Mechanically stable

Disadvantages
- At 4.2K, only applicable up to ~11 T
- At 25K, only applicable up to ~ 5 T
- Thermal stability: should be increased

Bi-2212 round wires

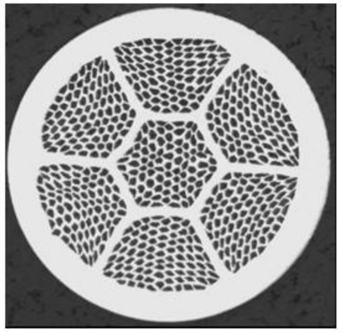
3. Other round wires for high field accelerators

3A. The HTS system Bi-2212

The system Bi-2212

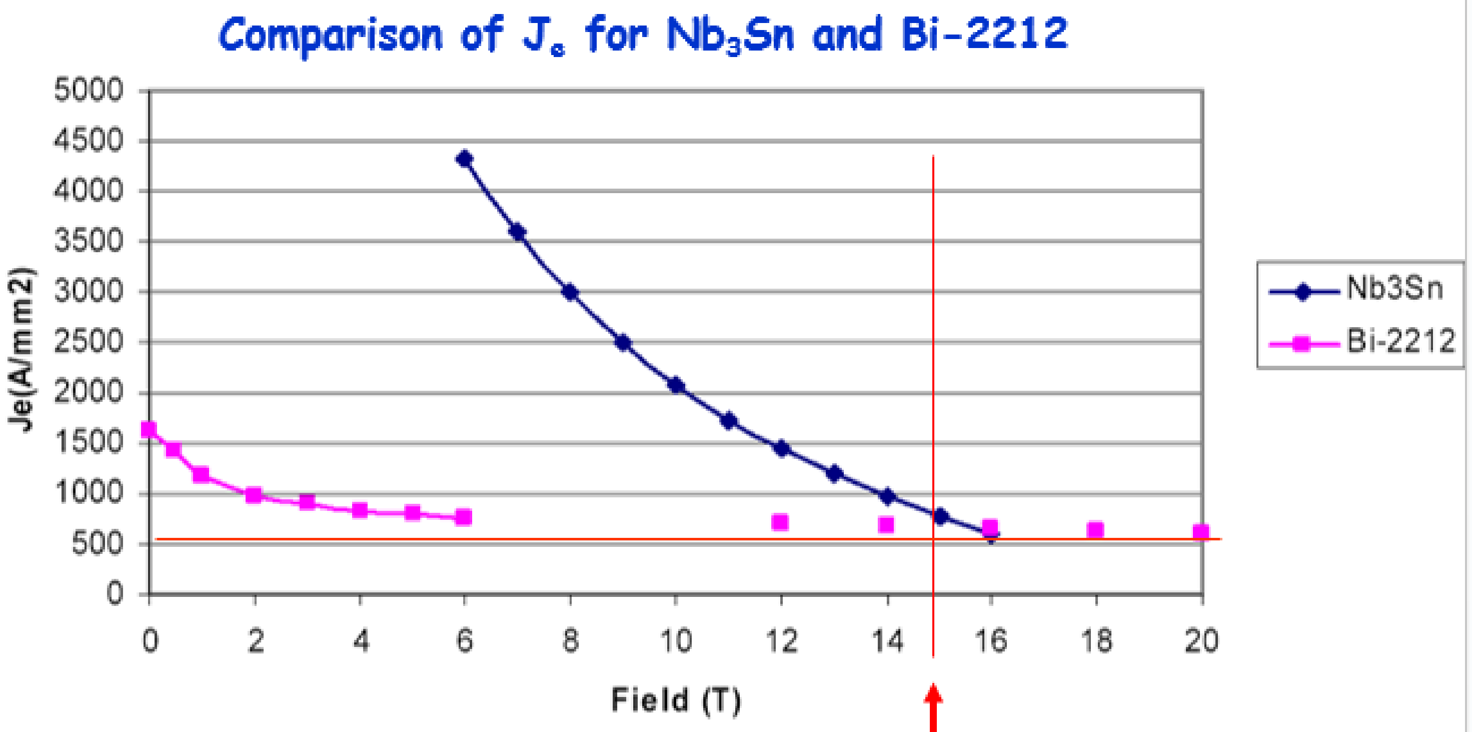
Possible applications	**High field magnets 22.5T (20T+2.5T insert)** **Accelerator magnets??**
	Advantage: Round wire, but * I_c still low *** mechanically weak**
Main research efforts:	**D. Larbalestier et al., Florida State University** **Oxford Instruments**

Round Bi-2212 wires



Is Bi-2212 an alternative for high field dipoles?

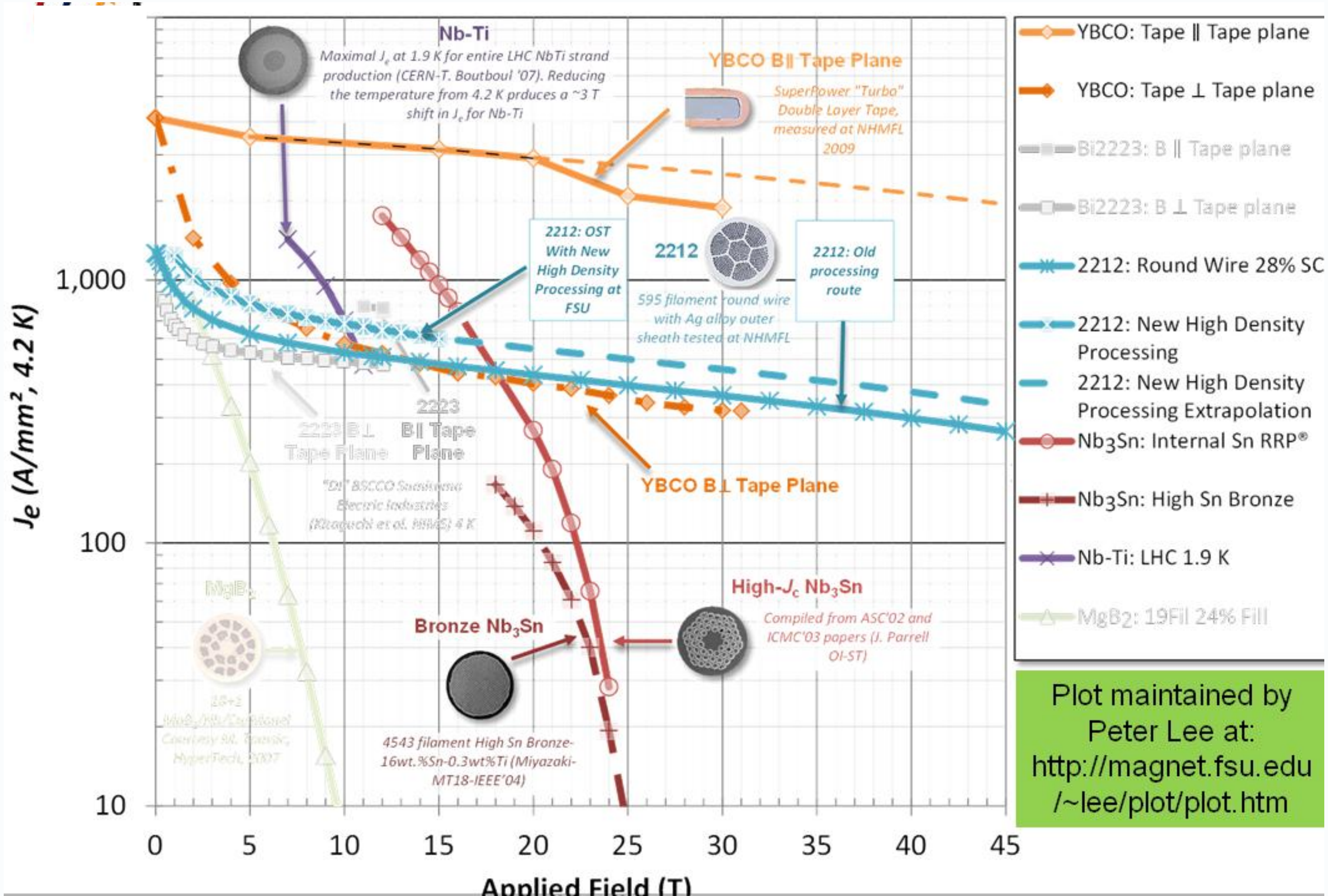
Bi(2212): an alternative to Nb_3Sn for high field dipoles?


Comparison of J_e for Nb_3Sn and Bi-2212

J_e: overall critical current densities

15 T

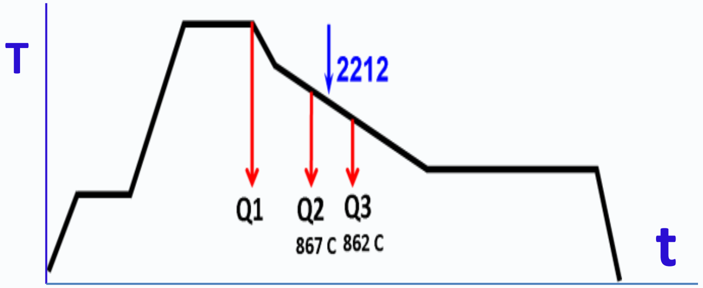
Peter Lee’s plot about J_c values

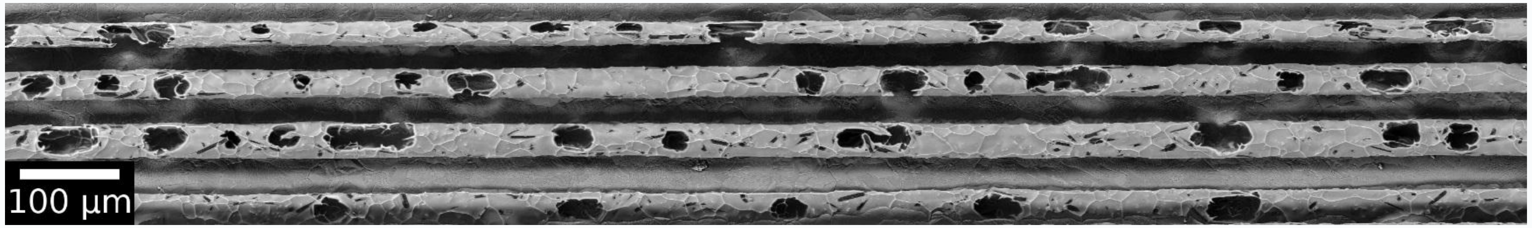


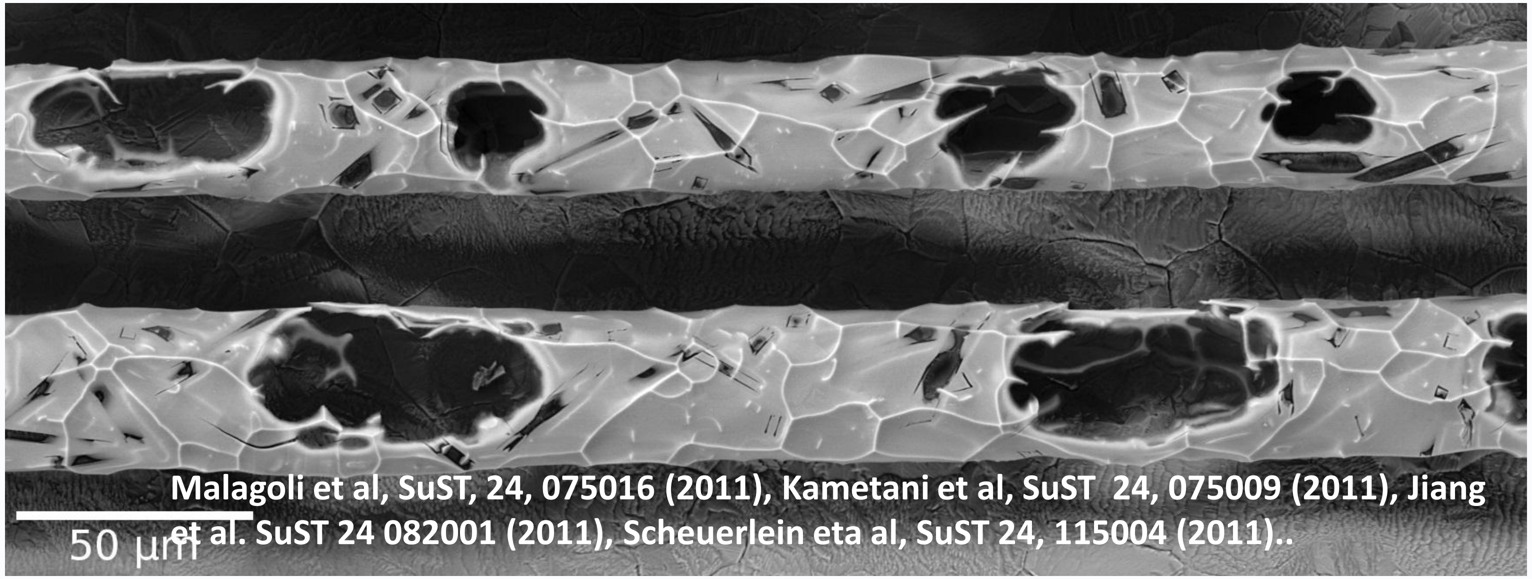
Plot maintained by Peter Lee at: http://magnet.fsu.edu/~lee/plot/plot.htm

Large bubbles form on melting and holding at T_{max}

Bi-2212 Reaction scheme

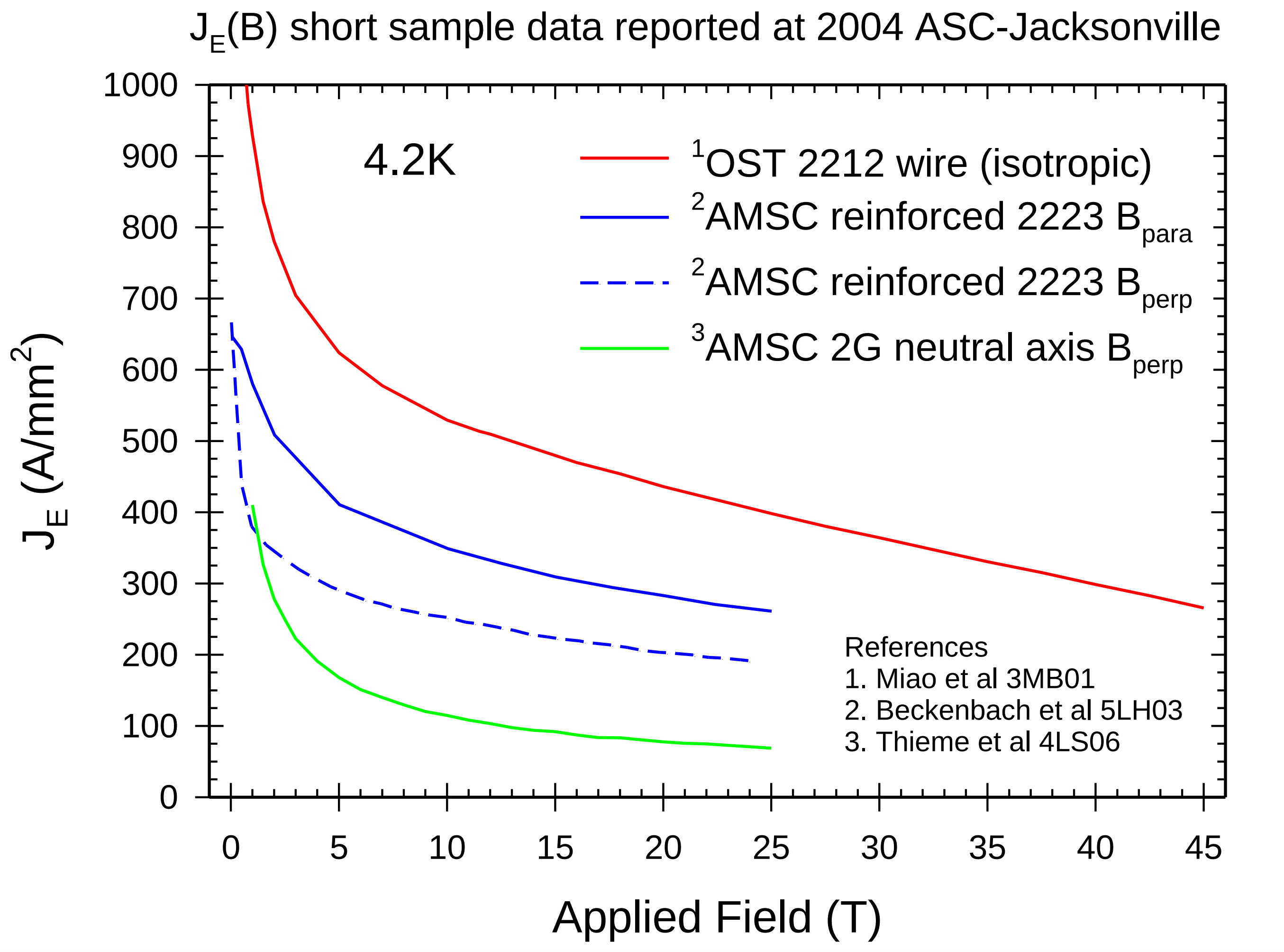




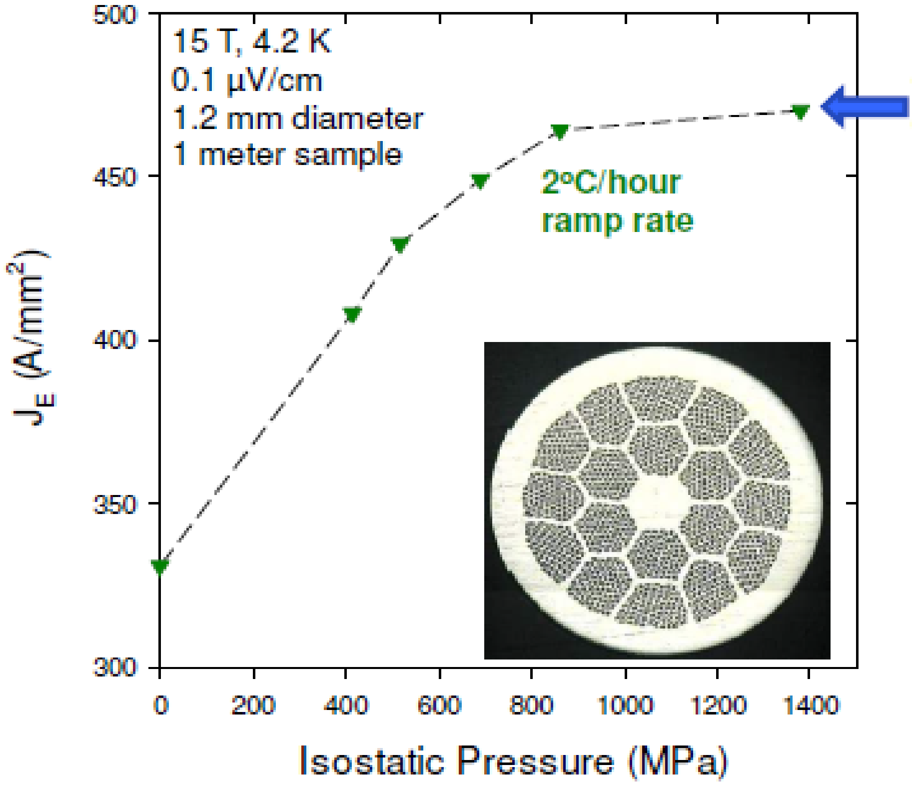


Malagoli et al, SuST, 24, 075016 (2011), Kametani et al, SuST 24, 075009 (2011), Jiang et al. SuST 24 082001 (2011), Scheuerlein eta al, SuST 24, 115004 (2011)..

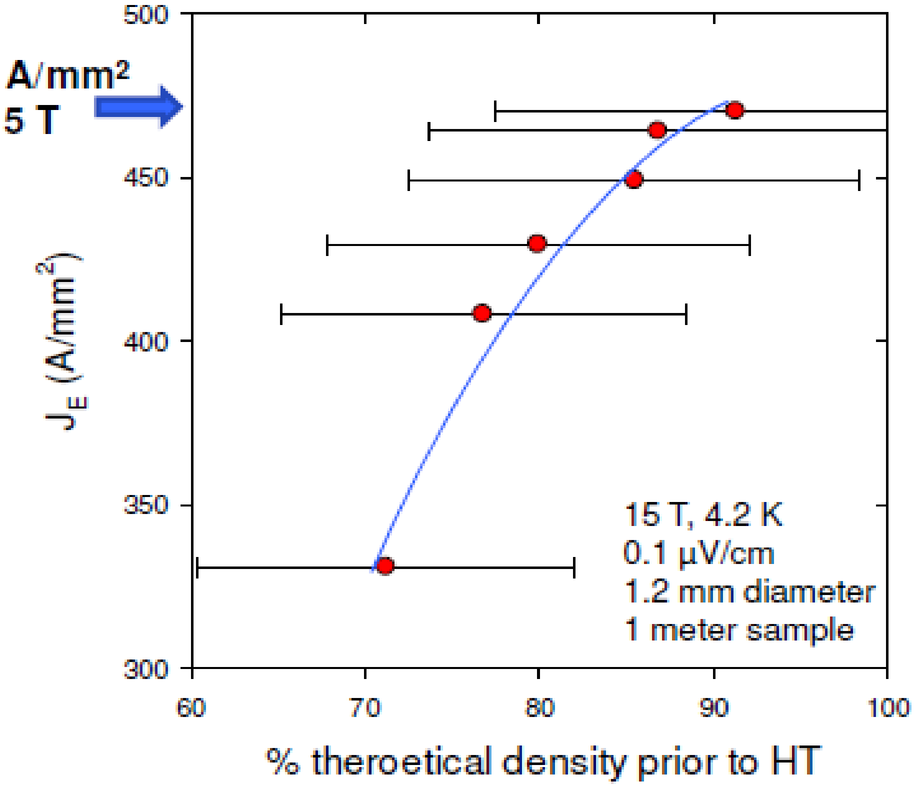
J_c of Bi-2212: progress



Enhancement of J_c by compaction and slow heating



470 A/mm²
@ 15 T



- Combined “best process” result in 15 T J_E values >450 A/mm²

→ Values match the best we’ve ever obtained, seem reproducible

Further enhancements are possible!

The system Bi-2212

Advantages: It is the only HTS materials available in round wires
Multifilamentary configuration: OK
Excellent thermal stability
At 4.2K, very high J_c values up to fields > 25 T
J_c values: close to level required by LHC Upgrade

Disadvantages: Important costs due to processing and Ag sheath
Poor mechanical stability: no solution yet for enhancing the mechanical reinforcement

Pnictides

3B. Pnictides

FeAs based superconductors

J_c in Pnictide wires and tapes

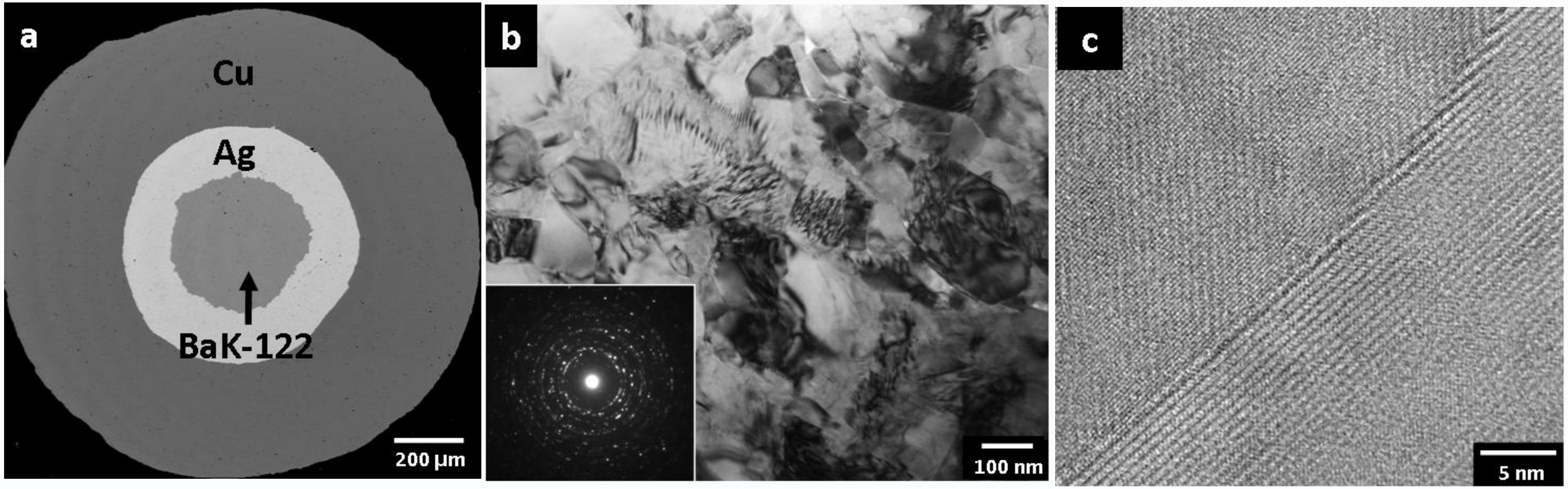
Examples: 122 Wires based on $(Ba,K)Fe_2As_2$ and $(Sr,K)Fe_2As_2$

Very recent data obtained from

- * J. Weiss, M. Hannion, E. Hellstrom, J. Jiang, F. Kametani, D. Larbalestier, A. Polyanskii, and C. Tarantini, FSU, 2012
- * Z. Gao, L. Wang, C. Yao, Y. Qi, C. Wang, X. Zhang, C. Wang, YW. Ma, ArXiv:1110.5784
- * YW. Ma, ICSM2012
- * I. Pallecchi, M. Tropeano, G. Lamura, M. Pani, M. Palombo, A. Palenzona, M. Putti, to be published in Physica C

TEM of 122 pnictides

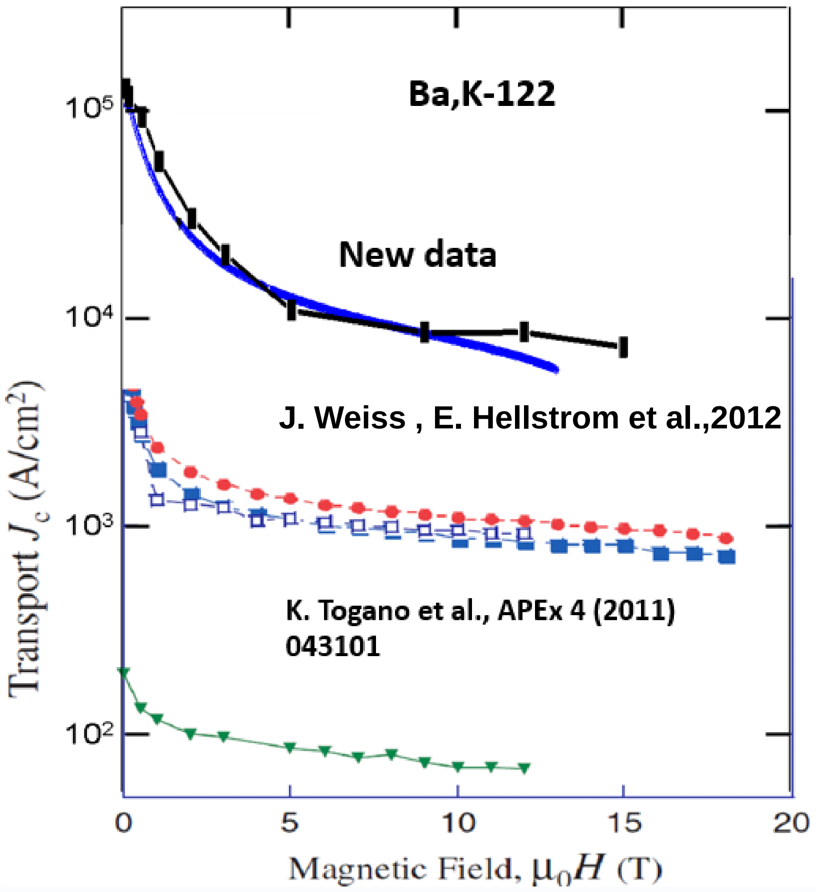
TEM shows K-doped 122 has small grains, contains only little amounts of nonsuperconducting material, and has many clean GBs



F. Kametani et al., FSU, ASC 2012

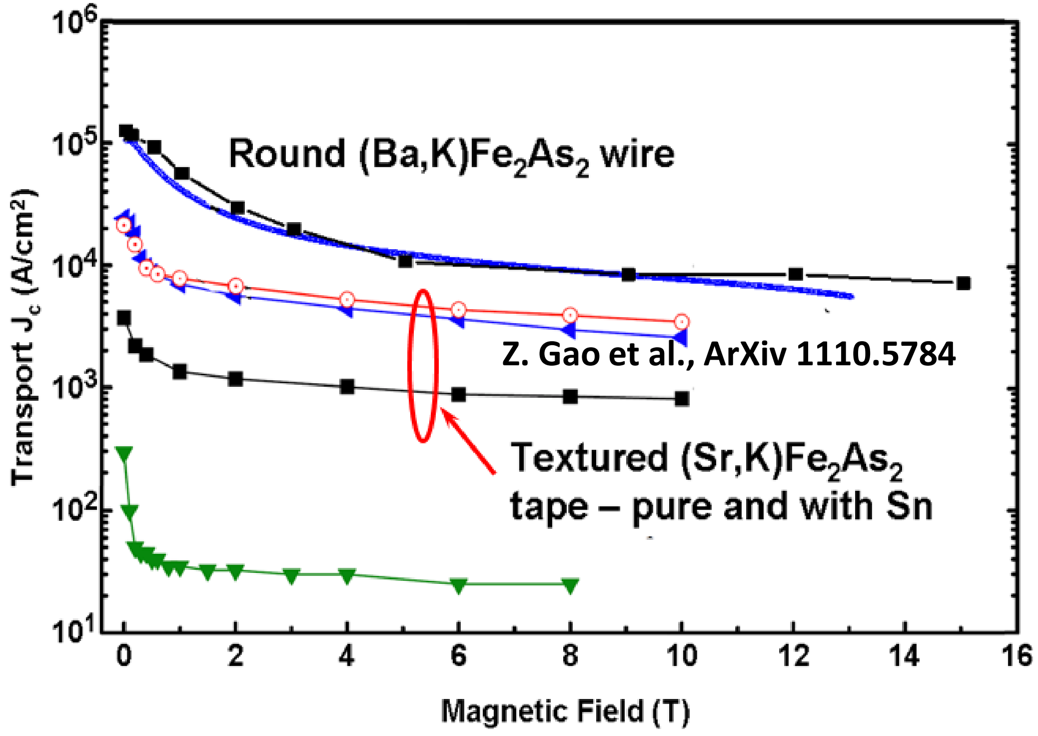
J. Weiss, M. Hannion, E. Hellstrom, J. Jiang, F. Kametani, D. Larbalestier, A. Polyanskii, and C. Tarantini, Arkhiv, 2012

New synthesis method for 122 wires



J. Weiss , E. Hellstrom et al.,2012

K. Togano et al., APEx 4 (2011) 043101



Z. Gao et al., ArXiv 1110.5784

Textured (Sr,K)Fe_2As_2 tape – pure and with Sn

Comparison of HTS and pnictides

What can we learn comparing HTS and pnictides (from the current carrying point of view)?

- Very low coherence lengths → very high H_{c2} values lengths in both, HTS and pnictides.
- Considerably lower anisotropy in pnictides reduces the effect of the field orientation in the wrong direction (perp. to the wire surface) (K. Tanabe, H. Hosono, Jap. J. Appl. Phys. 51 (2012) 010005).

→ it is possible to produce round pnictide wires with considerable J_c values: 2×10^4 A/cm^2 at 4.2K/ 10T (Y.W. Ma, 2011).

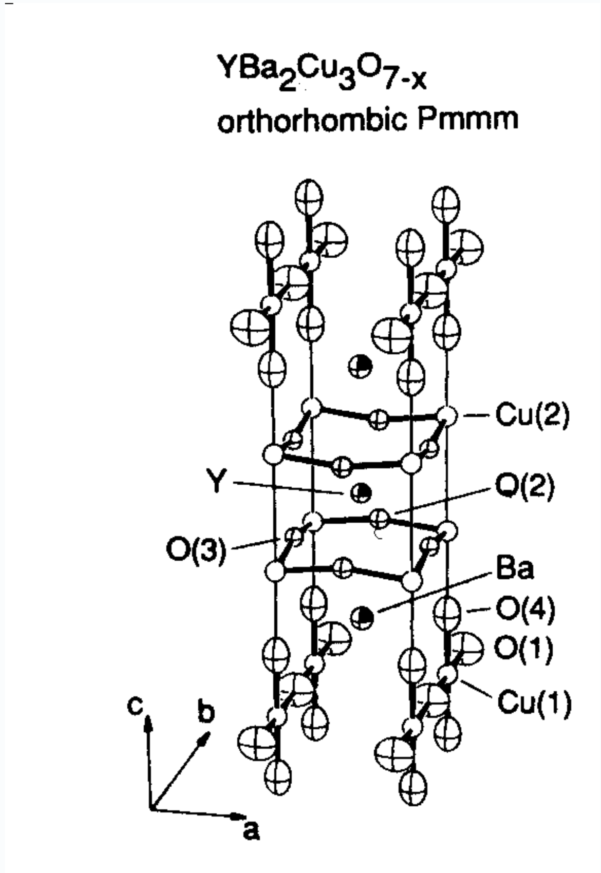
This behavior, only 4 years after the discovery of pnictides, is encouraging for further research

Pnictides

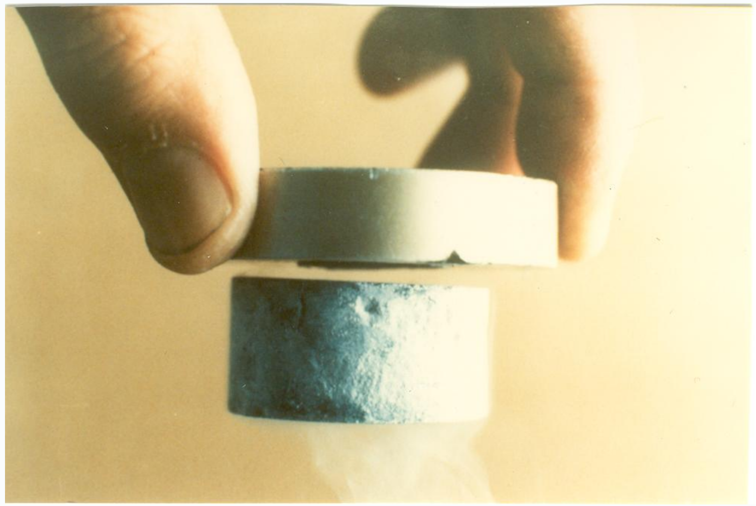
Advantages	Abundant basis materials
	Low costs of constituents and wires
	Possibility to fabricate round wires
	Applicable up to very high magnetic fields (30 T and more)
Disadvantages	Toxicity of As and Se
	Strong metallurgical problems to get homogeneity
	Thermal stability: no data yet

HTS Coated Conductors

4. The systems Y-123 or R.E.-123 («Coated Conductors»)



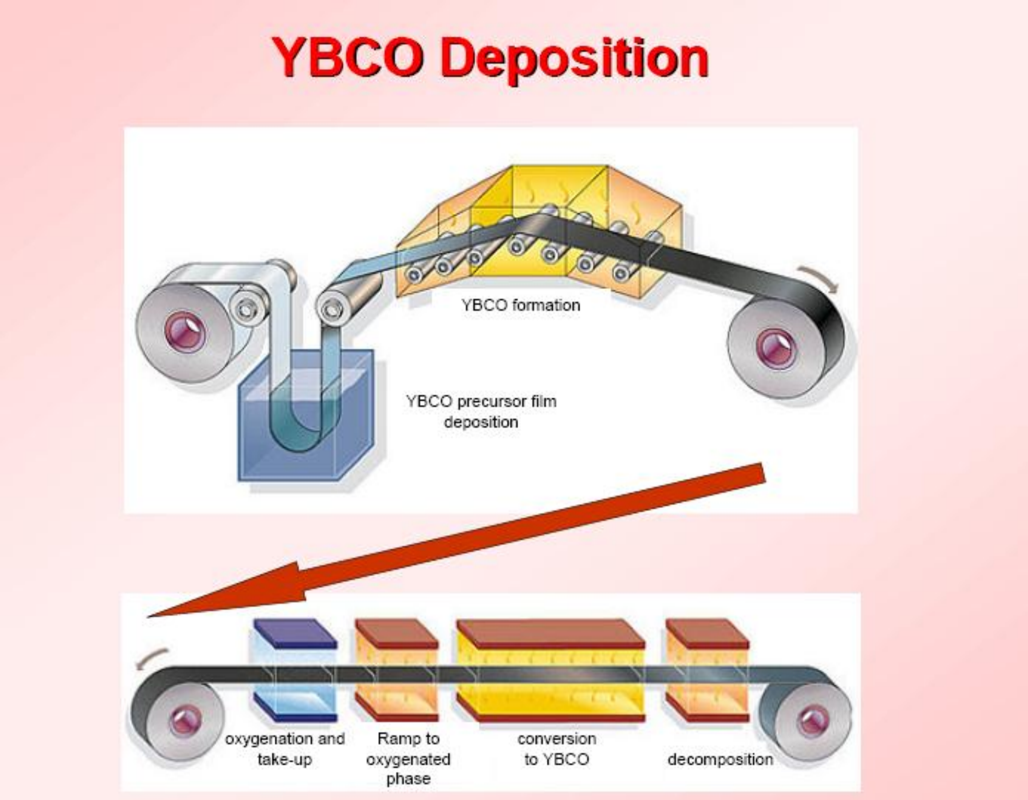
$YBa_2Cu_3O_{7-d}$
Superconductor of the Future?



Levitating YBaCuO sample at 77K

HTS Coated Conductors

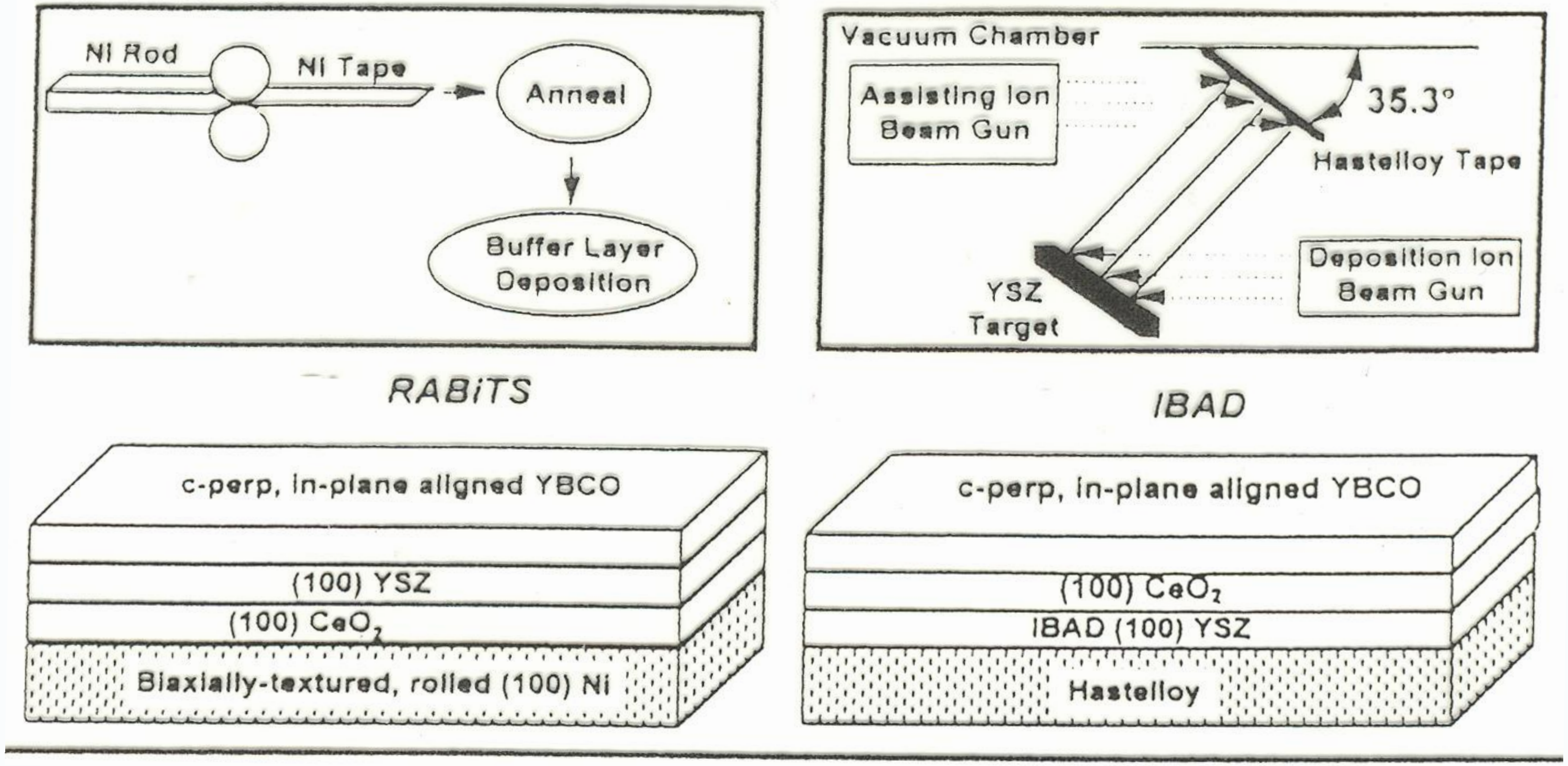
The layered oxide structure causes a strong anisotropy in B_{c2}, J_c,…….
this induces a layered conductor configuration: Tapes
(also called «Coated Conductors»)



Typical shaping of a HTS Coated Conductor with the structure $YBa_2Cu_3O_7$.

Two main deposition techniques
(many variations used by various manufaturers)

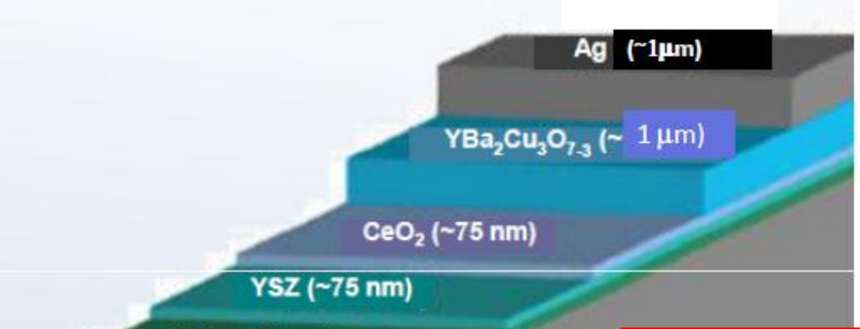
Rolling Assisted, Biaxially Textured Substrate **RABITS**	IonBeam Assisted Deposition **IBAD**



Typical «Coated Conductor» tape architectures

REBaCuO tape of AMSC

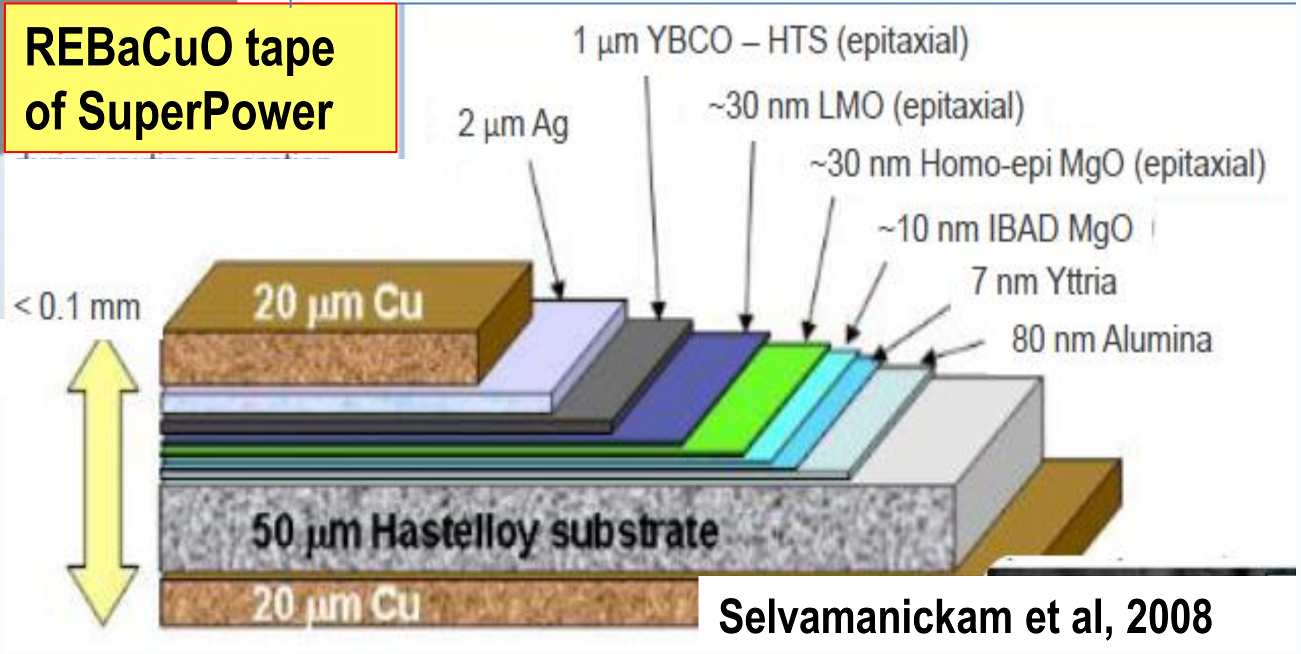
Reel-to reel PLD process, 40 mm wide
Substrats: RABITS (Rolling Assisted Biaxial Texturing



M. Rupich et al., AMSC, 2008

Other manufacturers:
Fujikura, Japan
Sunam, S. Corea
Sumitomo, Japan
BEST), Germany
....

REBaCuO tape of SuperPower



Selvamanickam et al, 2008

Summary: Fabrication width, production rate

SEI: Fabrication width 30 mm,
No indication about production rate

AMSC: Fabrication width 40 mm, Goal: 100 mm width, **lengths: > 500 m**
> 1’000 km/year of 4 mm tape

SuperPower: Fabrication width 12 mm, Lengths: 1’400 m
July 2010: > 150 km/year (?)

Fujikura: Fabrication width 10 mm, lengths: > 1’000 m
2009: PLD/CeO_2 (60 m/h), IBAD MgO (≤1,000 m/h), Y_2O_3 (500m/h), Al_2O_3 (150 m/h), GdBaCuO (15 m/h)

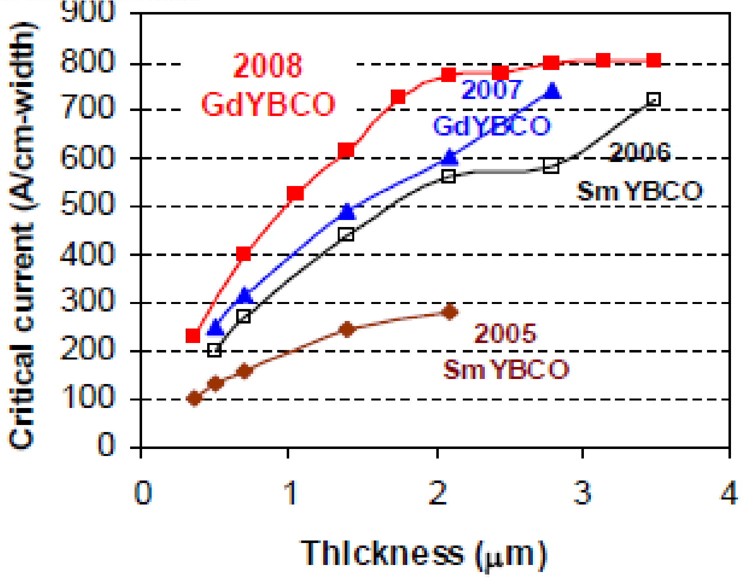
SuNAM: Fabrication width 12 mm, lengths: > 100 m (planned: 2’000 m)
Nov. 2009: Homoepitactic (70m/h),LMO buffer (50 m/h)
Goal: 2,000 km/year (assuming 100% yield)

Bruker: Fabrication width 40 mm, lengths: ≤ 100 m (planned: > 1’000 m)
Goal: line speed (ABAD) 30 m/h and PLD (70 m/h)

Requirements to a REBaCuO tape

Current density	* Carry optimized current in REBaCuO (dopants)
Mechanical	* Substrate strong enough at high temperature to stand the formation of REBaCuO * Tape as a whole strong and flexible enough to be wound into cable and coils at 300 K * Tape must withstand longitudinal and transverse stresses during operation
Electrical stability	* Carry excess current in Ag layer and in in Al, Cu,……. outer layers
Thermal stability	* Enable heat transfer to the coolant
AC losses	* Modify architecture to minimize AC losses (Roebel, striations)

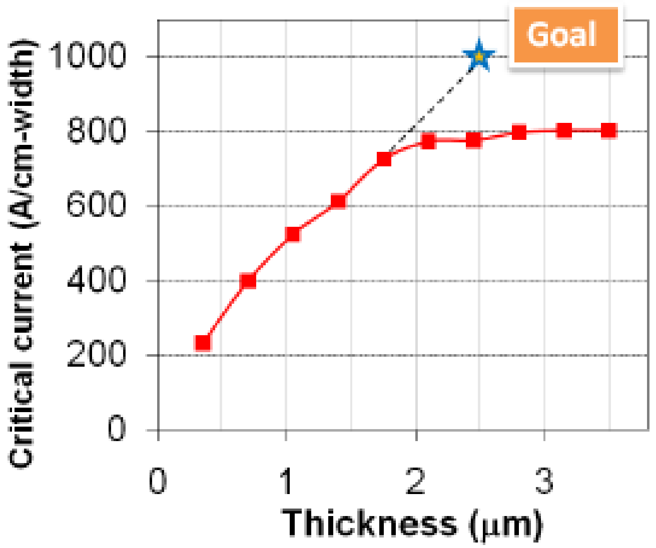
Towards higher J_{cw} values

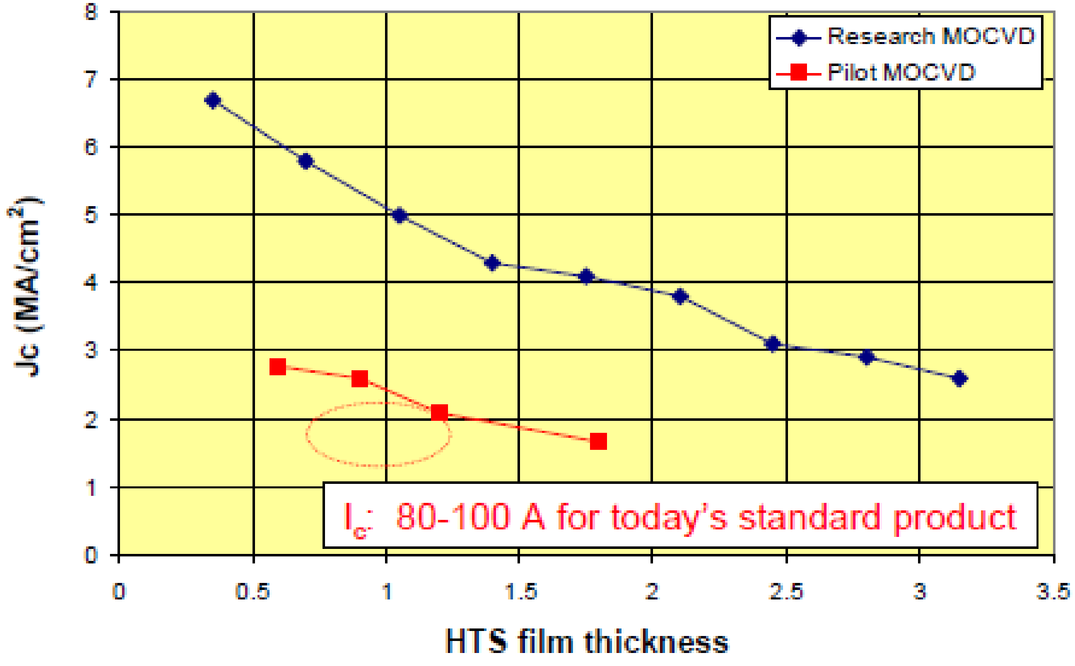


Over 1 m length,

I_c = 976 A = 813 A/cm = 320 A/4 mm

Using production buffer tapes





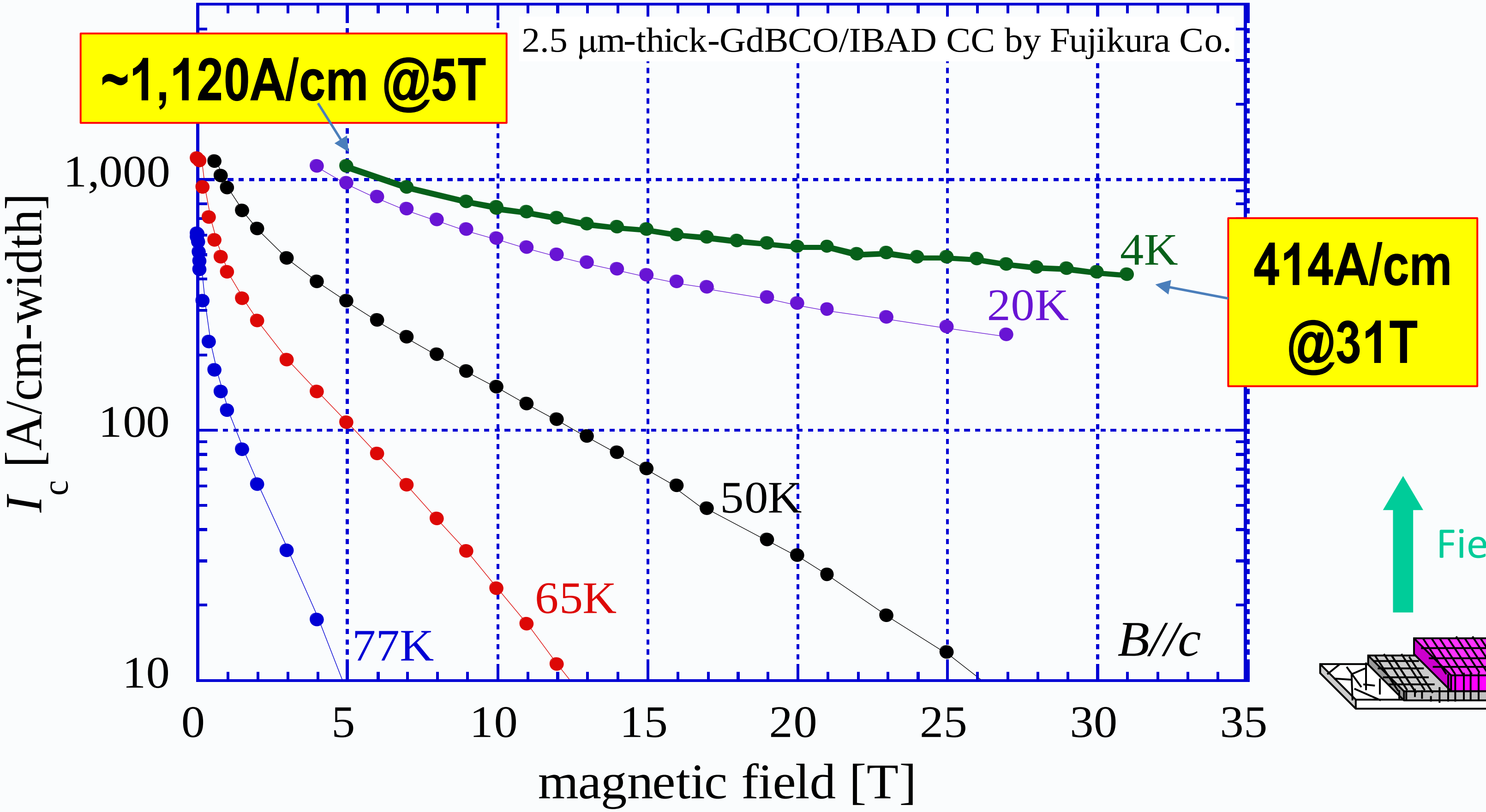
I_c: 80-100 A for today's standard product

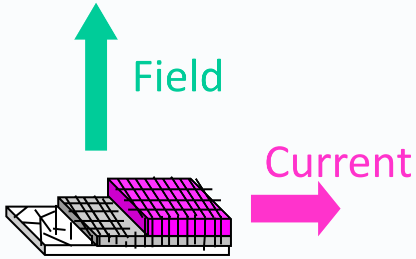
uper

CERN Visit 4 May, 2010

I_c-B-T property for 600A class C.C.

Measured by Prof. Kiss group of Kyushu University,
In collaboration with Florida State Univ. & Tohoku Univ.

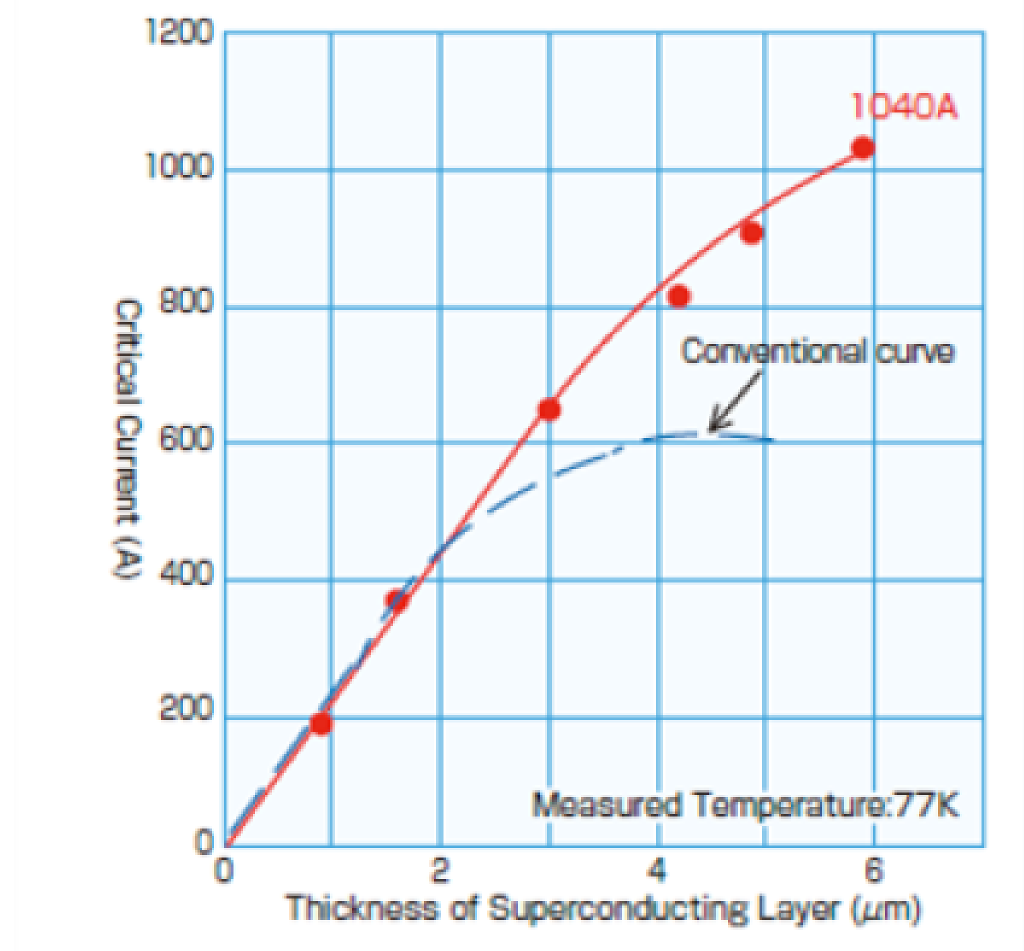




Higher critical current density

Enhanced layer thickness:

Fujikura reports
6 mm thick layer with 1’040 A/cm-w
(Deposition time not reported)



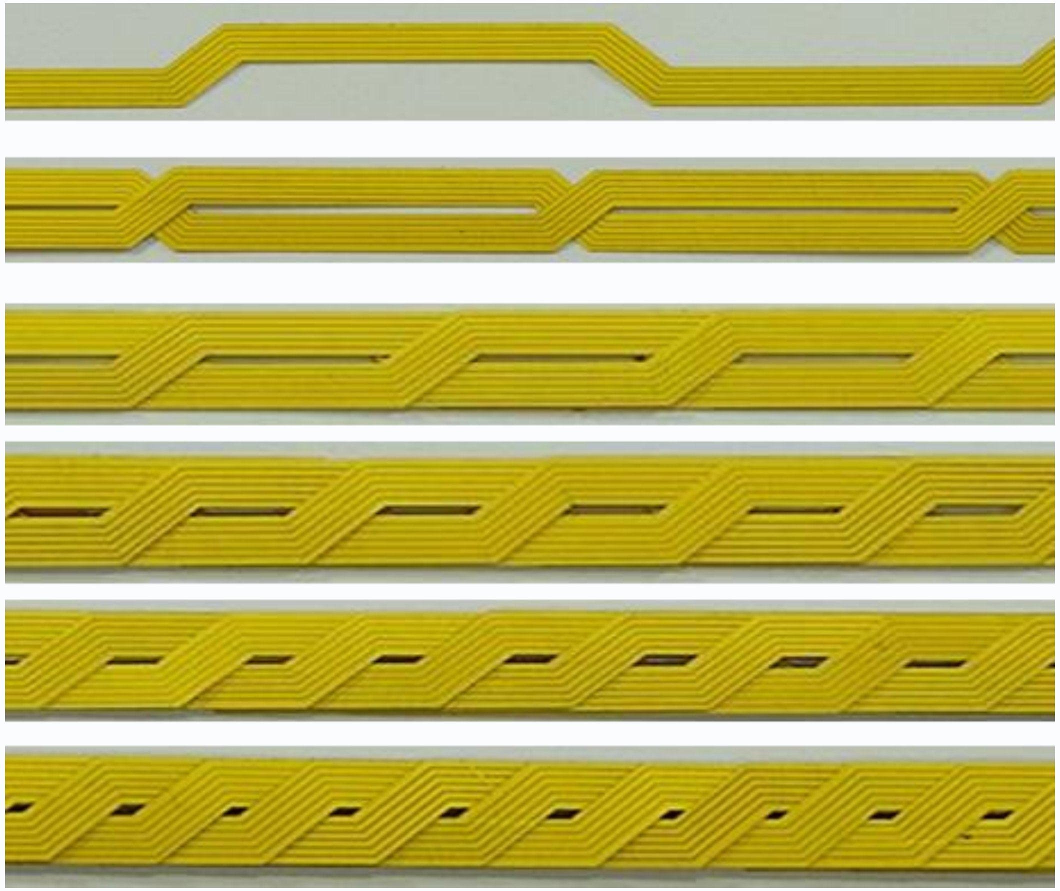
M. Igarishi et al., EUCAS 2009 (Fujikura)

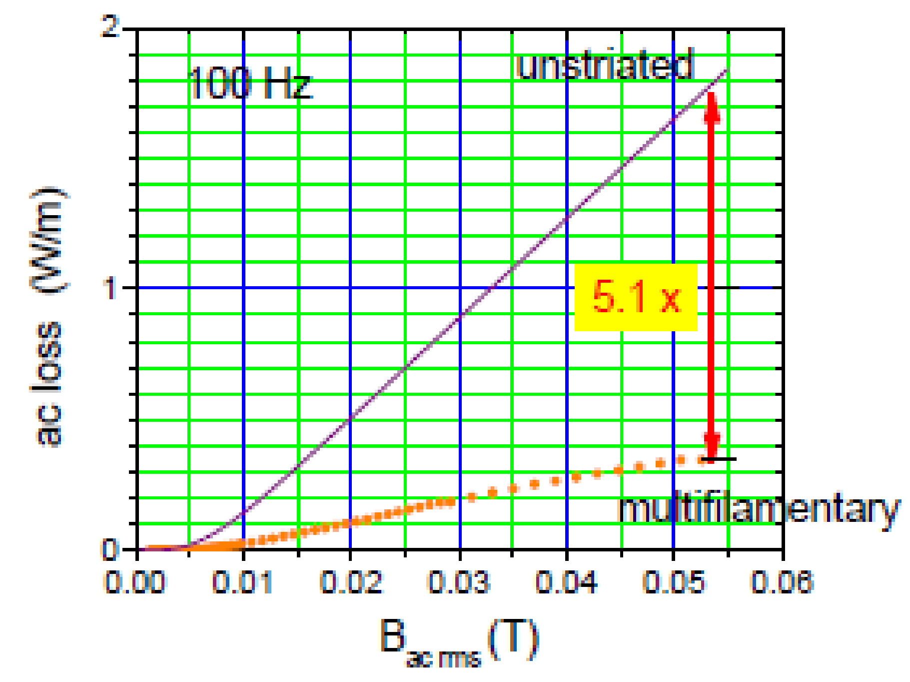
Reduction of AC losses

* Roebel technique,

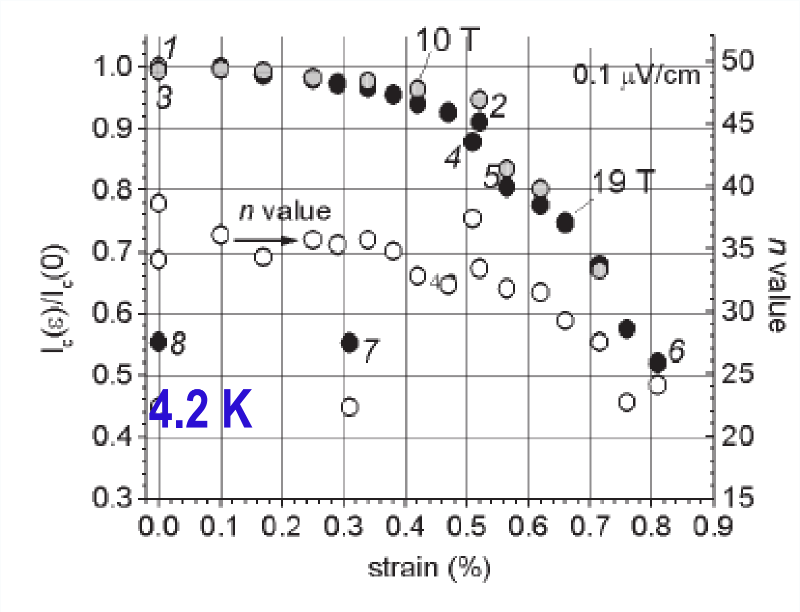
* Striations,

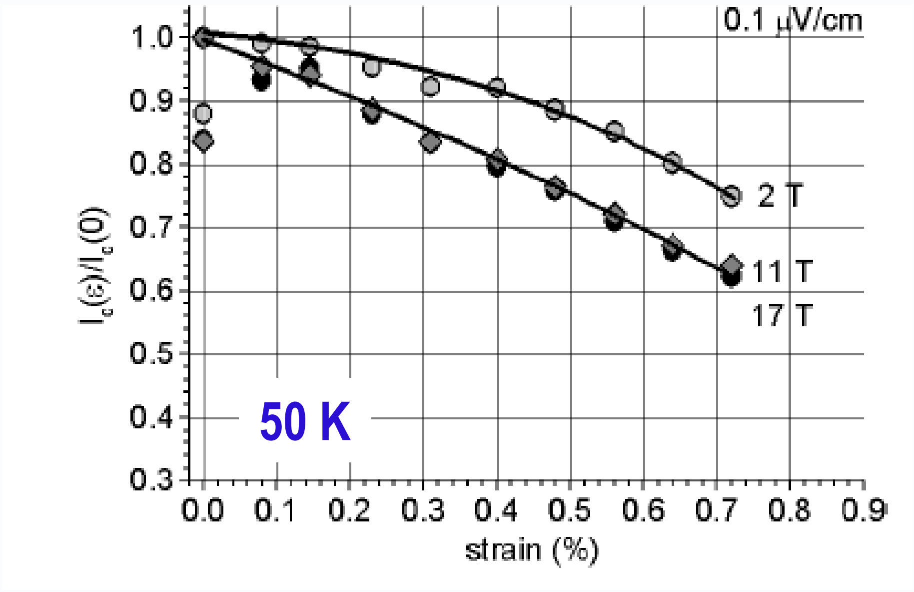
* Roebel + striations





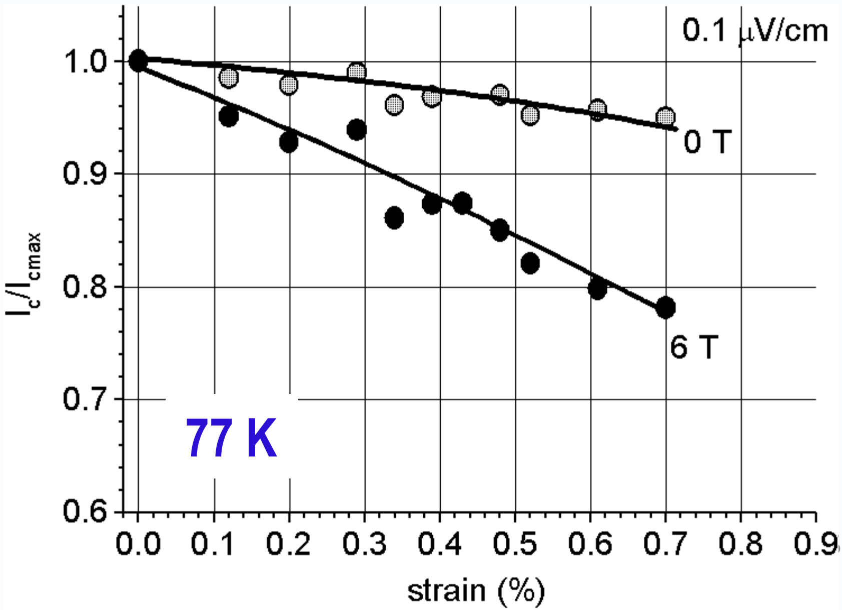
Coated Conductors: Effect of tensile stress on J_c





AMSC tape; measured with a Walters spiral

ε_{irr} = 0.51 %



Effect of transverse stress: unknown

D. Uglietti, B. Seeber, V. Abächerli, W.L. Carter, R. Flükiger, SuST, 19(2006)869

What remains to be done in Coated Conductors ?

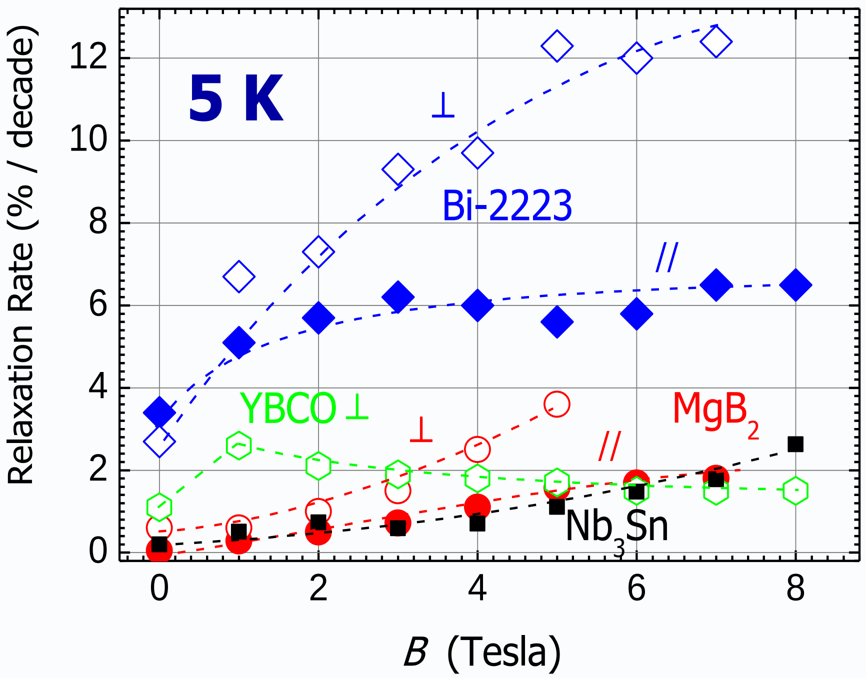
- Higher homogeneity of J_c over whole tape length
- Thicker layers
- Reproducible production of > 1 km lengths
- Enhanced pinning by nano-additives
- Reduced anisotropy by nano-additives
- Reduced costs

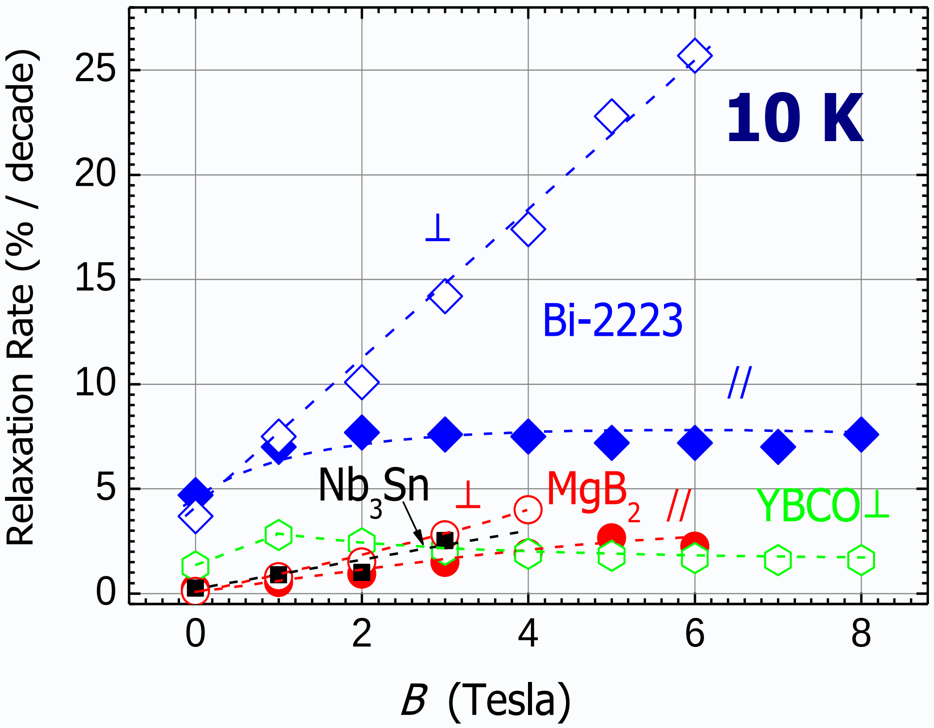
Annex II: Relaxation rates

Annex I:
Relaxation rates of various superconductors

Relaxation rates at 5 and 10 K

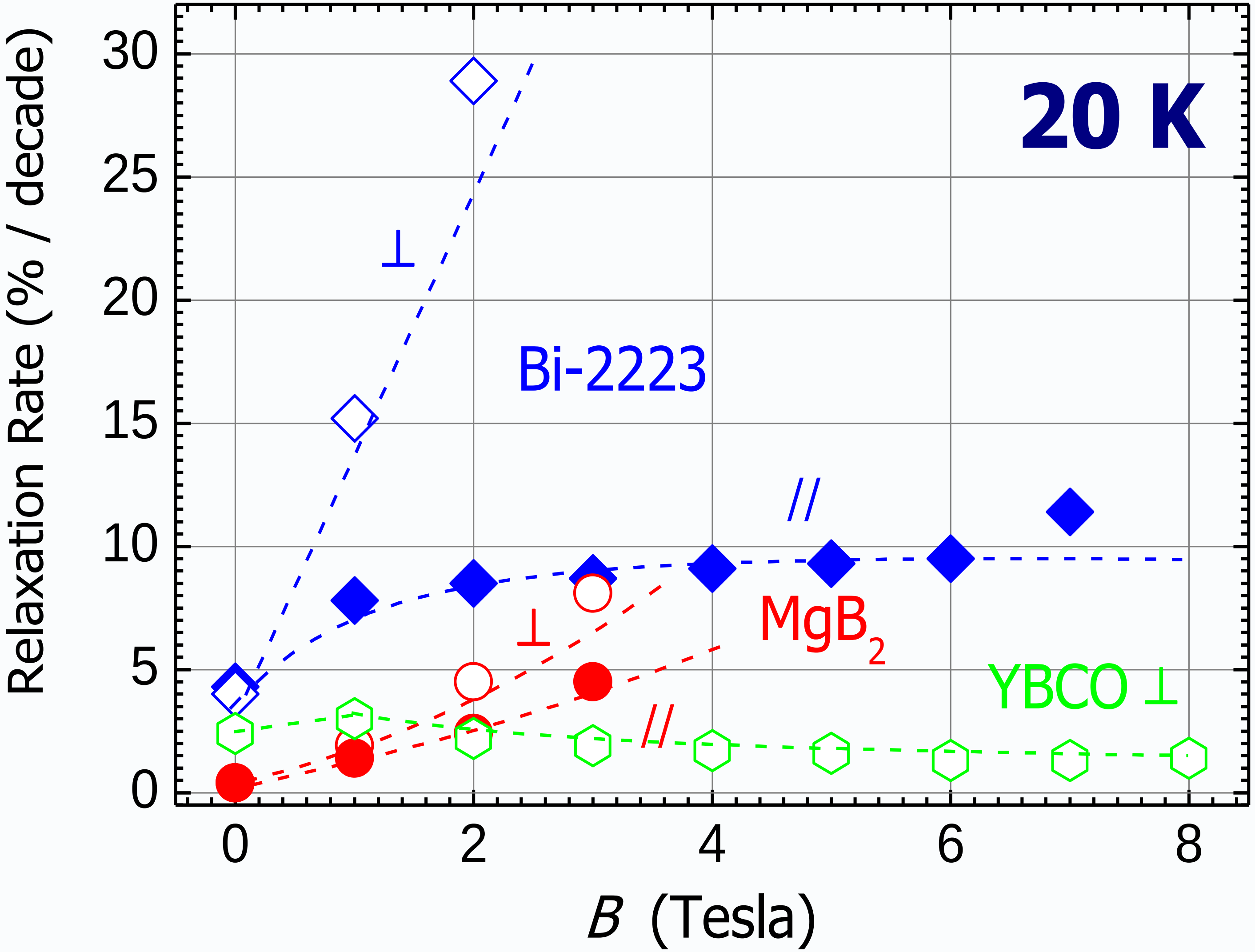
Persistent mode operation for NMR and IRM technology for a series of superconductors





C. Senatore, P. Lezza, R. Flükiger, to be published

Relaxation rates at 20K



At 20K, the relaxation rates are sufficiently low for persistent mode operation of

*** Coated Conductors (for B >> 8T)**
*** MgB_2 (B ≤ 5T)**