



AFF, Journées thématiques, 6./7.6.2013, CERN

Les supraconducteurs du futur

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Que veut dire «Supraconducteurs du futur?»

- Nouveaux matériaux avec des propriétés supraconductrices nouvelles
mais aussi
- Supraconducteurs connus, avec des propriétés fortement améliorées.

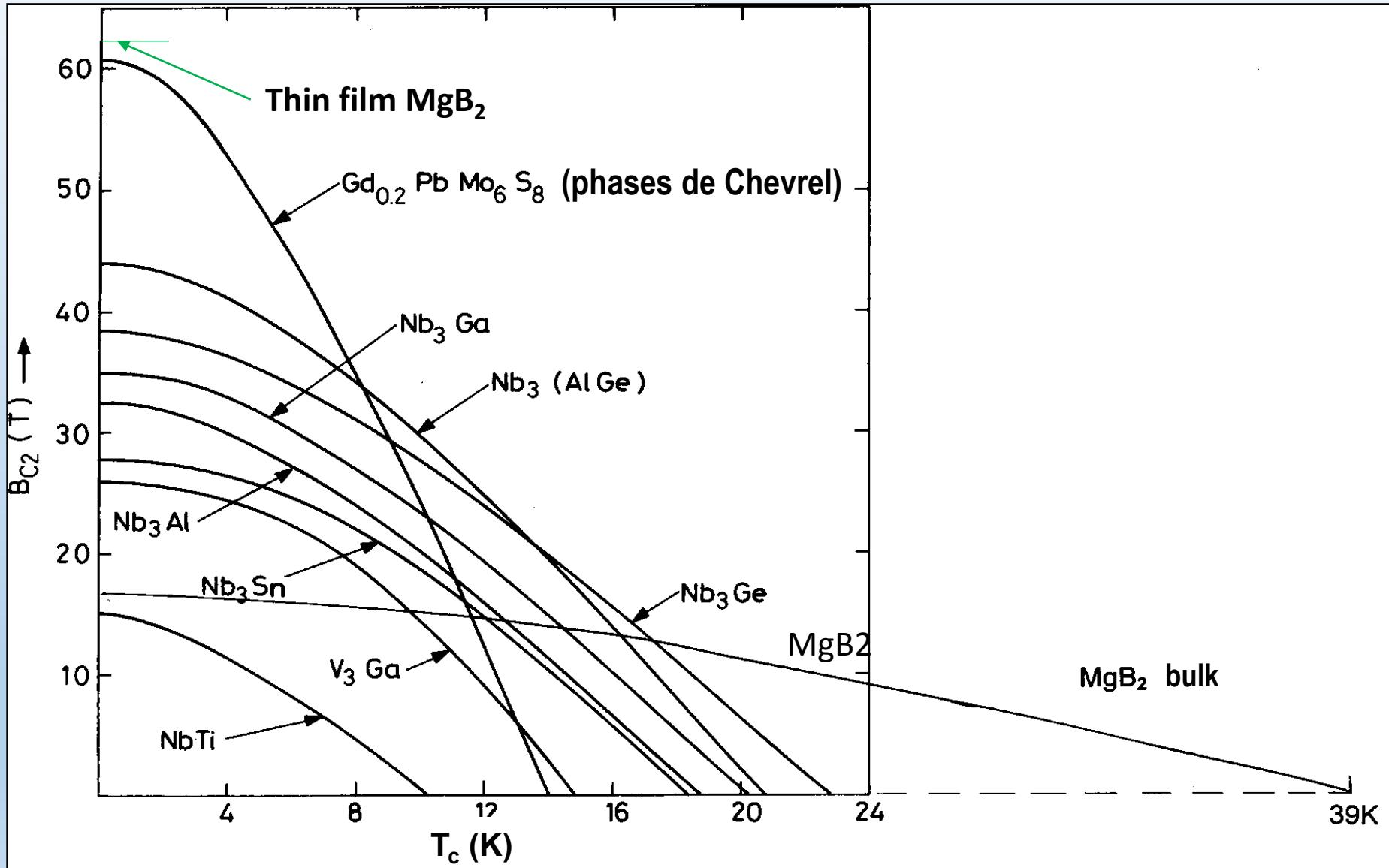
Dans cet exposé:
Considérations en vue des applications à très hauts champs magnétiques.



Challenges for future technical superconductors

- Accelerators:
 - LHC Upgrade ($B = 12\text{T}$, 4.2K): Nb_3Sn
 - HF LHC ($B \geq 15\text{T}$, 4.2K): (Nb_3Sn), (Bi-2212, Coated Conductors)
 - HHF LHC ($B \geq 20\text{T}$, 4.2K): (Coated Conductors)
- Fusion:
 - ITER ($B = 12\text{T}$, 4.2K): Nb_3Sn (Nb_3Al)
 - DEMO ($B > 13\text{T}$, 4.2K): (Nb_3Sn , Nb_3Al , Bi-2212, Coated Conductors)
- High field magnets: ($B > 25\text{T}$, 4.2K): Bi-2212, Coated Conductors, (Bi2223),
- NMR magnets: ($B > 25\text{T}$, 4.2K): Coated conductors (no persistent mode at HTS/LTS joints)
- Motors: ($B \leq 4\text{T}$, 77K): Coated Conductors
- Wind generators: ($B \leq 4\text{T}$, 20K): MgB_2
 ($B \leq 4\text{T}$, 30K): Coated Conductors

Upper critical fields of metallic (LTS) superconductors





MgB₂ and PbMo₆S₈ : mysteries in two-band superconductors

Limitations for J_c of LTS superconductors

MgB₂:

Limitation due to low Irreversibility field B_{irr}

B_{c2(0)}= 38 T > 2 x B_{irr} (bulk, wires)

B_{c2(0)}= 65 T > 3 x B_{irr} (thin films)

The difference in B_{c2} is not yet understood

PbMo₆S₈:

B_{c2(0)}= 60T > B_p(Pauli): B_{c2} / B_p = 2.3 !

Reason of B_{c2} > B_p is not yet understood

Practical limitations for Chevrel phase wires:

- * Limitation due to Sulfur deficiency at grain boundaries
- * Small prestress of Mo (low α_{Mo}) must be compensated by 70% stainless steel —→ strong lowering of J_c(eng.)



What can be improved in a known superconductor ?

Properties which are not subject to relevant changes

T_c :

$T_c = T_c(\text{max})$ for maximum atomic order parameter in the structure

$T_c \leq T_{co}$ for any change of external conditions: stresses, irradiation,....

ξ_o :

$\xi \sim \xi_o$: Coherence length ξ_o remains essentially unchanged

Properties subject to improvements

J_c (low fields)

Enhanced pinning force $F_p = J_c \times B$

J_c (high fields)

Enhancement of B_{c2} : ternary and quaternary additions, with lowering of the normal state electrical resistivity \rightarrow higher J_c at the same field

J_c (stress)

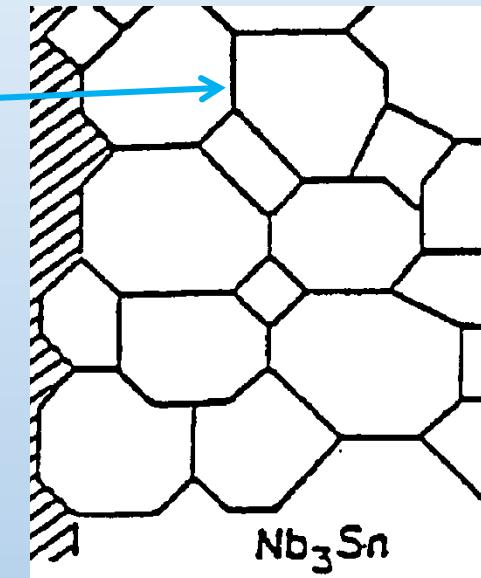
Depends on the configuration of the conductor and of the magnet system

Possible pinning mechanisms

J_c in a wire is **zero**, unless vortices can be «pinned» !

Microscopic defects provide pinning sites:

- Grain boundaries
- Irradiation tracks, defect clusters (point defects)
- Precipitates
- Dislocations
- Twin boundaries, stacking faults



LTS: Grain boundaries are main contribution to pinning
HTS: Dislocations, nano-precipitates



Enhancement of J_c by various mechanisms:

1: Grain boundary pinning: Dominant in LTS and MgB₂, complex in HTS!

2: Artificial pinning:

A. LTS Superconductors: * **NbTi wires** (α phase)

* **not achieved in: Nb₃Sn or MgB₂ wires**

Reason: the “artificial” element must be plastically deformed to nanosize; in addition, it must withstand reaction during the high temperature heat treatment.

B. HTS Superconductors: * **Coated conductors** (+ BaZrO₃)

* **Pnictide tapes** (+ BaZrO₃)

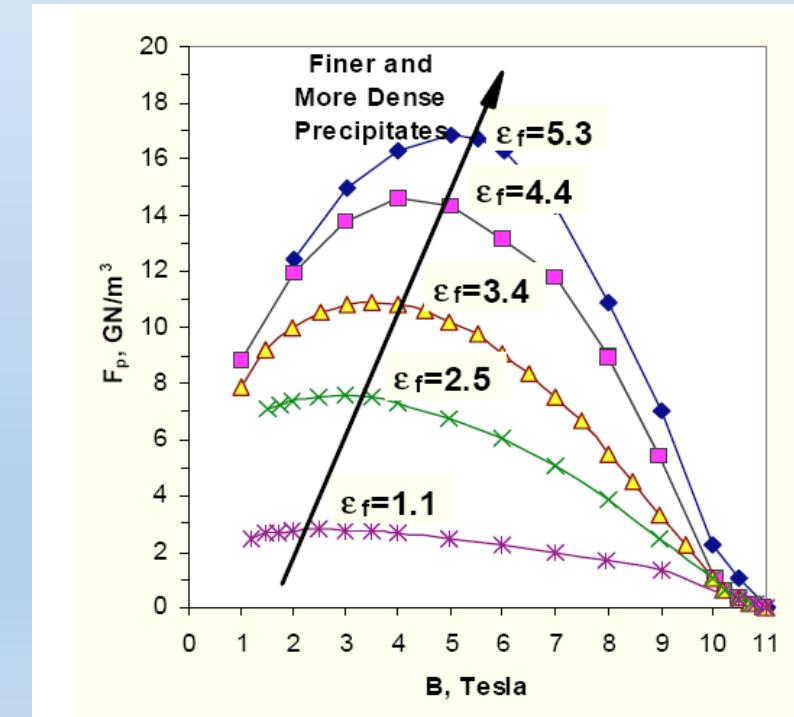
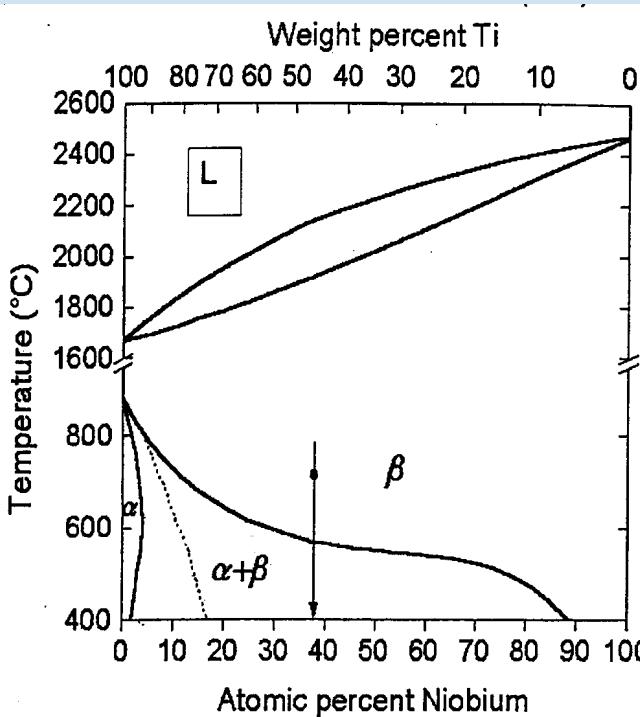
* **not achieved in: Bi-2212 wires or Bi-2223 tapes**

Reason: incorporation of nanosize BaZrO₃ only possible by deposition processes

Artificial pinning centers in NbTi

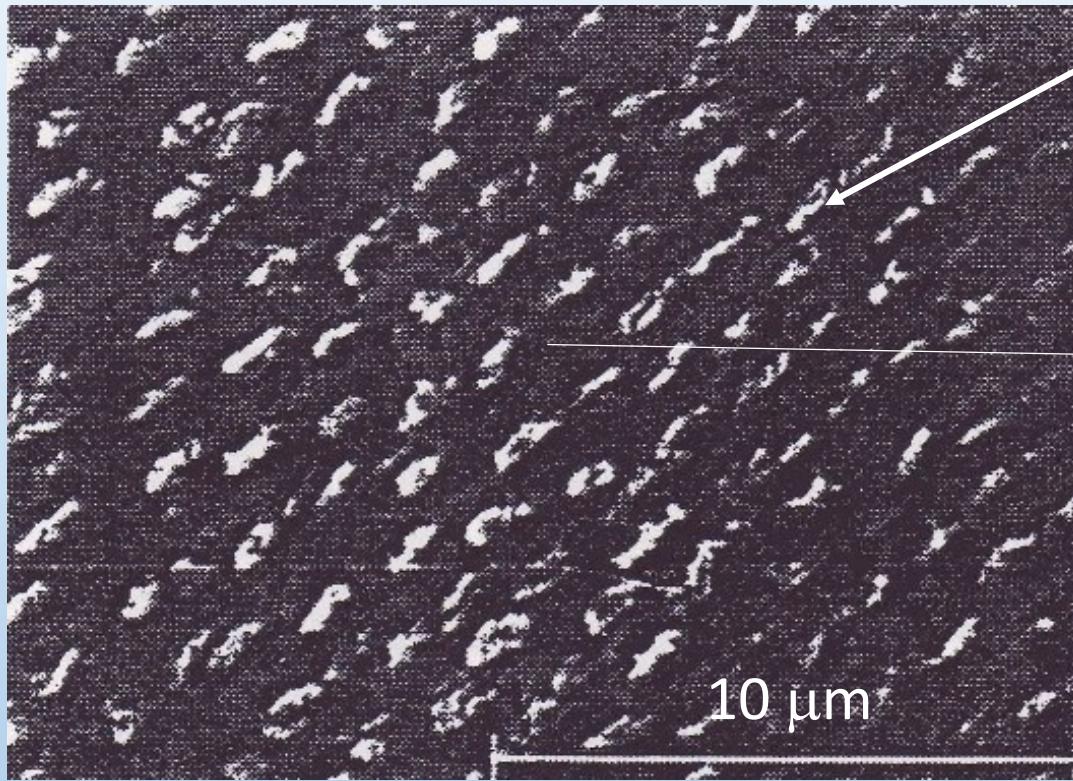
Artificial pinning: Introducing defects having sizes comparable or smaller than ξ_0

At the interface between the α – Ti precipitations and the NbTi matrix: periodicity of NbTi matrix is broken:
 * creation of defects
 * creation of normal conducting centers: **new vortices** —————> Enhancement of J_c



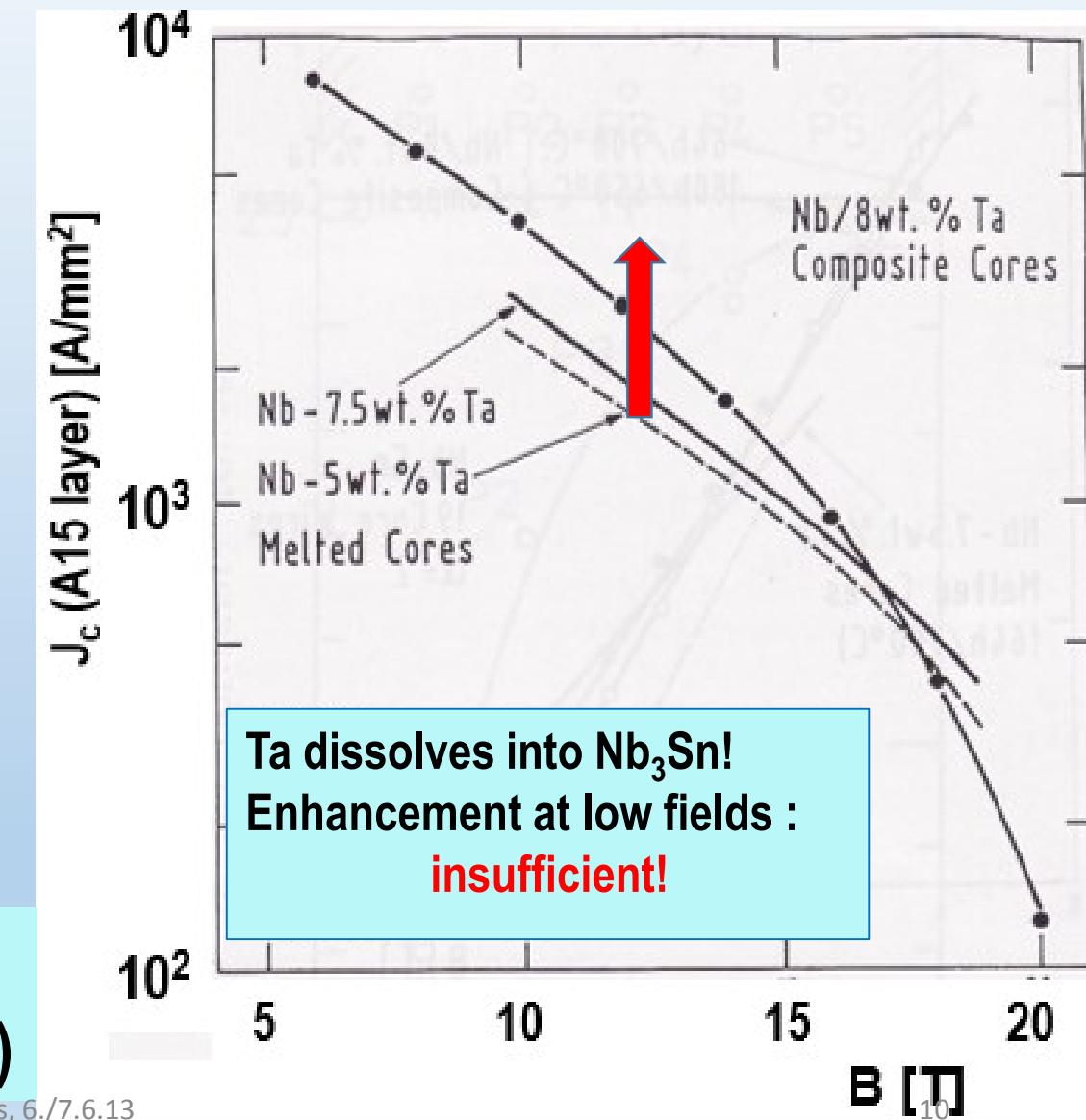
Attempt for artificial pinning in Nb_3Sn : Ta nano-inclusions

M. Klemm and R. Flükiger, SuST, 3,249(1990)



Ta size at the end of deformation: ~ 20 nm

The attempt was **unsuccessful** (as any other attempt in Nb_3Sn ; no spinodal transformation)





«Artificial pinning» in HTS Superconductors

The case of BaZrO₃ nanoparticles

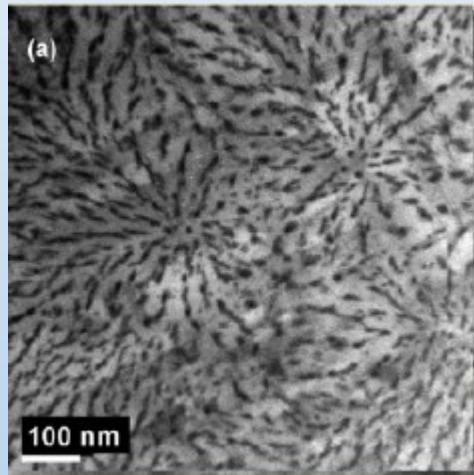
Why BaZrO₃?

This material was found as the best crucible material:
No reaction between YBaCuO and BaZrO₃ crucible during single crystal growth at >1'000°C

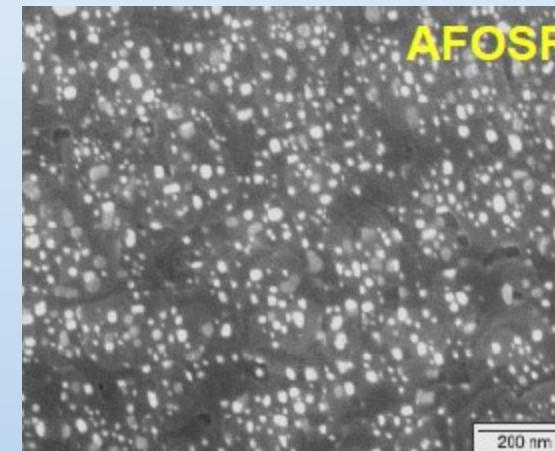
A. Erb, E. Walker, R. Flükiger, Physica C 245 (1995) 245-251)

BaZrO₃ in Coated Conductors: Combination of nanoparticles and columnar pins

Self-assembled chains of
BaZrO₃ nanoparticles



8 nm BaZrO₃ nanoparticles



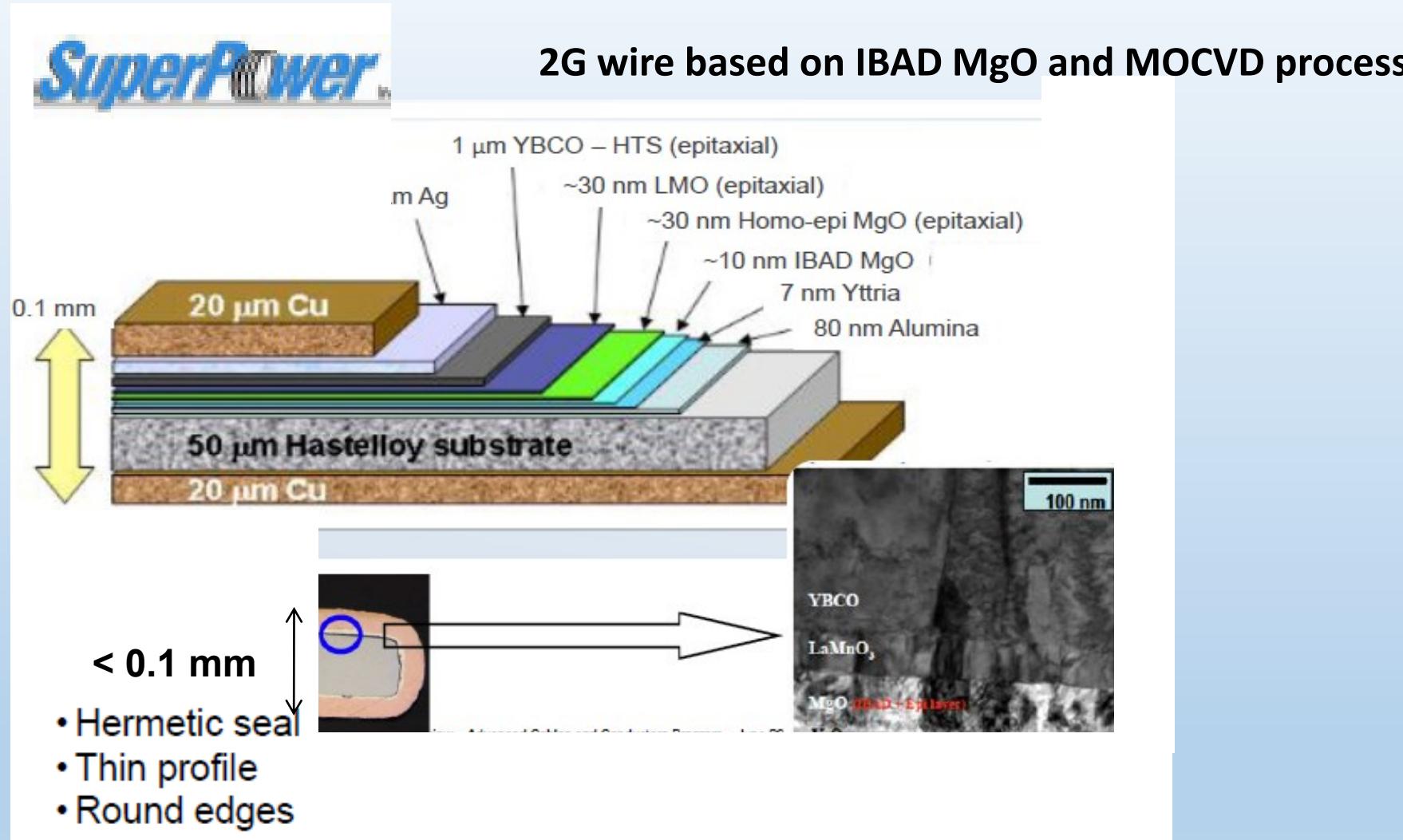
Optimum distance
between BaZrO₃
nanoparticles, 30 nm

J.L. McManus-Driscoll, Nature Materials, 3,439(2004)

P. Mele, K. Matsumoto, T. Horide, A. Ichinose, M. Mukaida, Y. Yoshida, R. Kita, SuST 21, 032002 (2008)

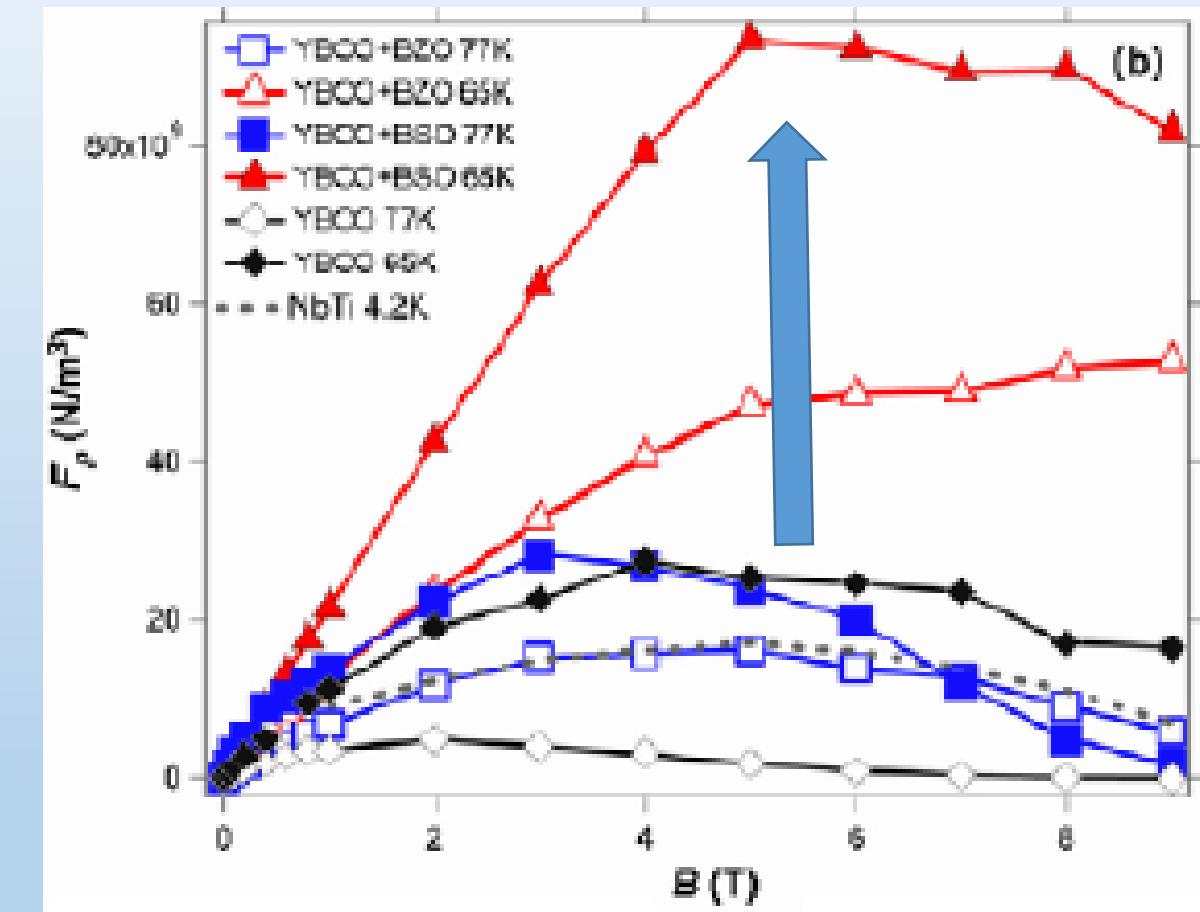
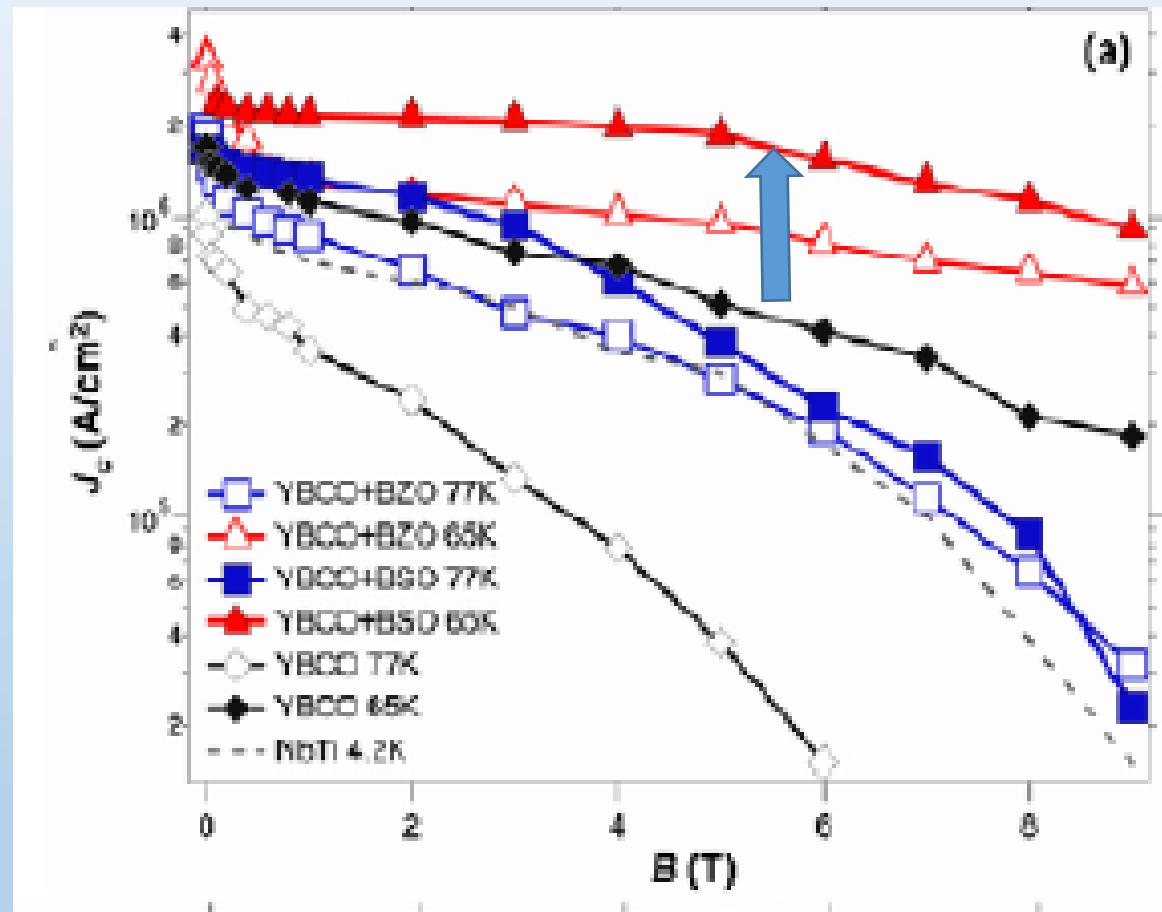
B. Majorov et al., Nature Materials, 8, 398(2008)

REBaCuO tape of SuperPower



D. Hazelton et al. (SuperPower), ASC 2010

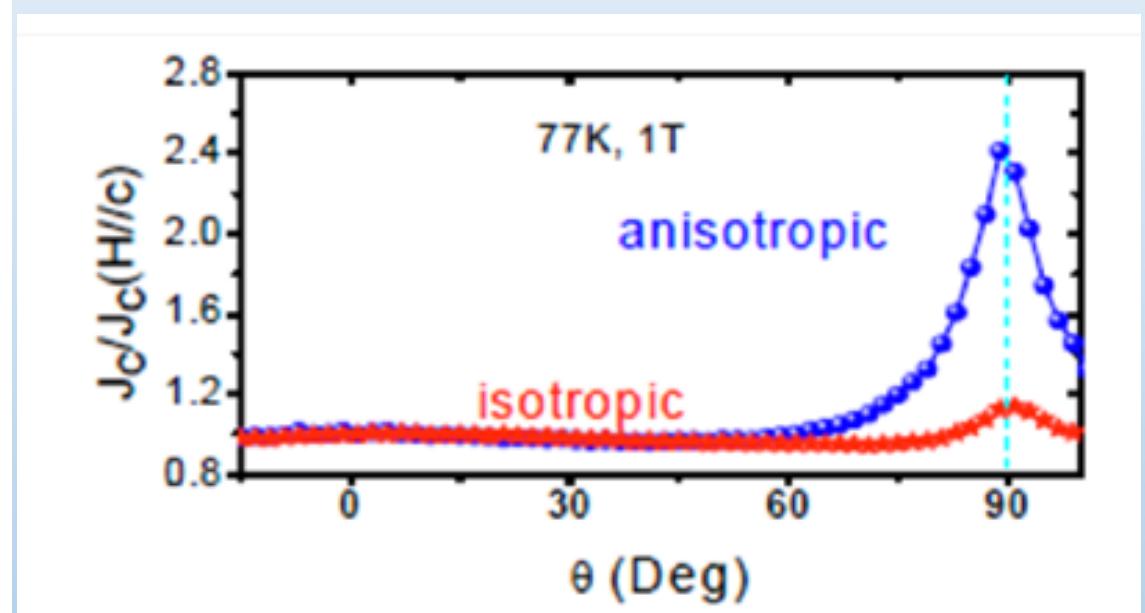
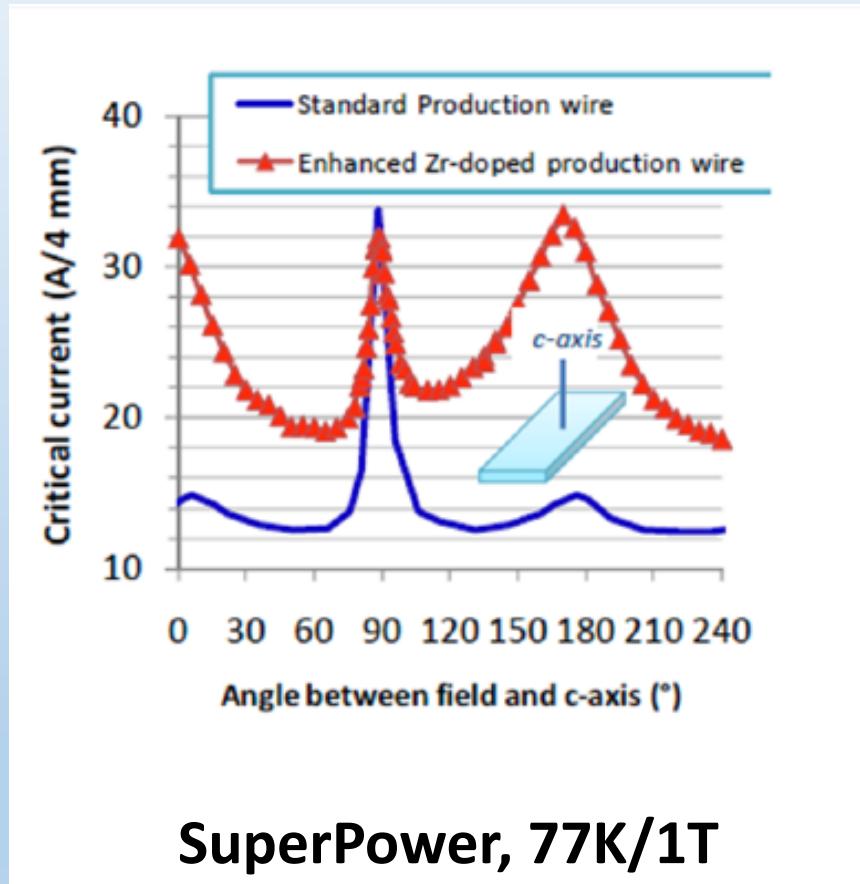
Enhancement of J_c and F_p by BaZrO_3 nanoparticles in Coated Conductors



P. Mele, K. Matsumoto, T. Horide, A. Ichinose, M. Mukaida, Y. Yoshida, R. Kita, SuST 21, 032002 (2008)

Enhancement of J_c and Reduction of anisotropy in Coated Conductors

Enhancement of J_c for fields **out-of plane**: the minimum J_c is the decisive one for applications
Further progress still to expect





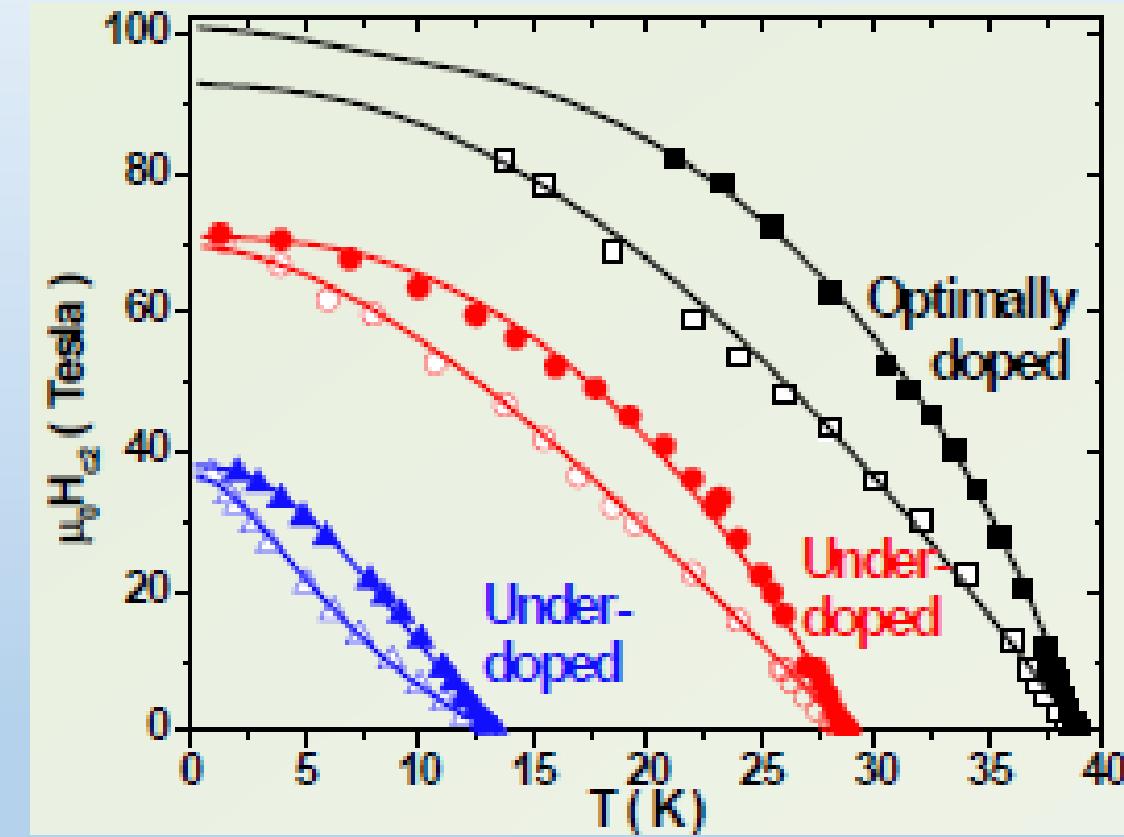
Artificial Pinning in Pnictides

122 phase in Wires based on $(\text{Ba},\text{K})\text{Fe}_2\text{As}_2$ and $(\text{Sr},\text{K})\text{Fe}_2\text{As}_2$

Upper critical fields of K doped 122 phases

- Pnictides:**
- * K doped Ba 122 phase
 - * $B_{c2} \sim 100T$
 - * Almost no anisotropy

Tarantini et al., Phys. Rev. Lett., 84, 184522(2011)

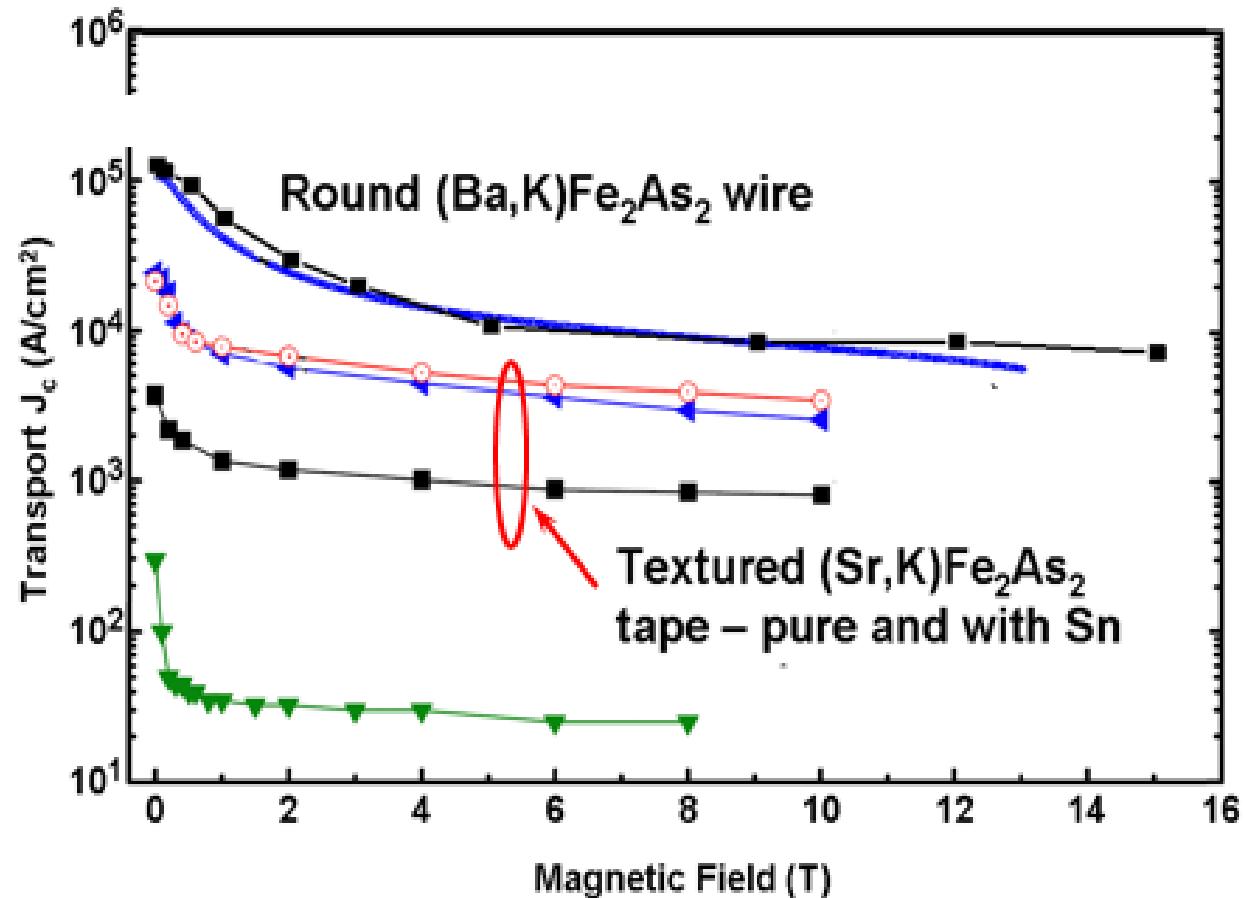
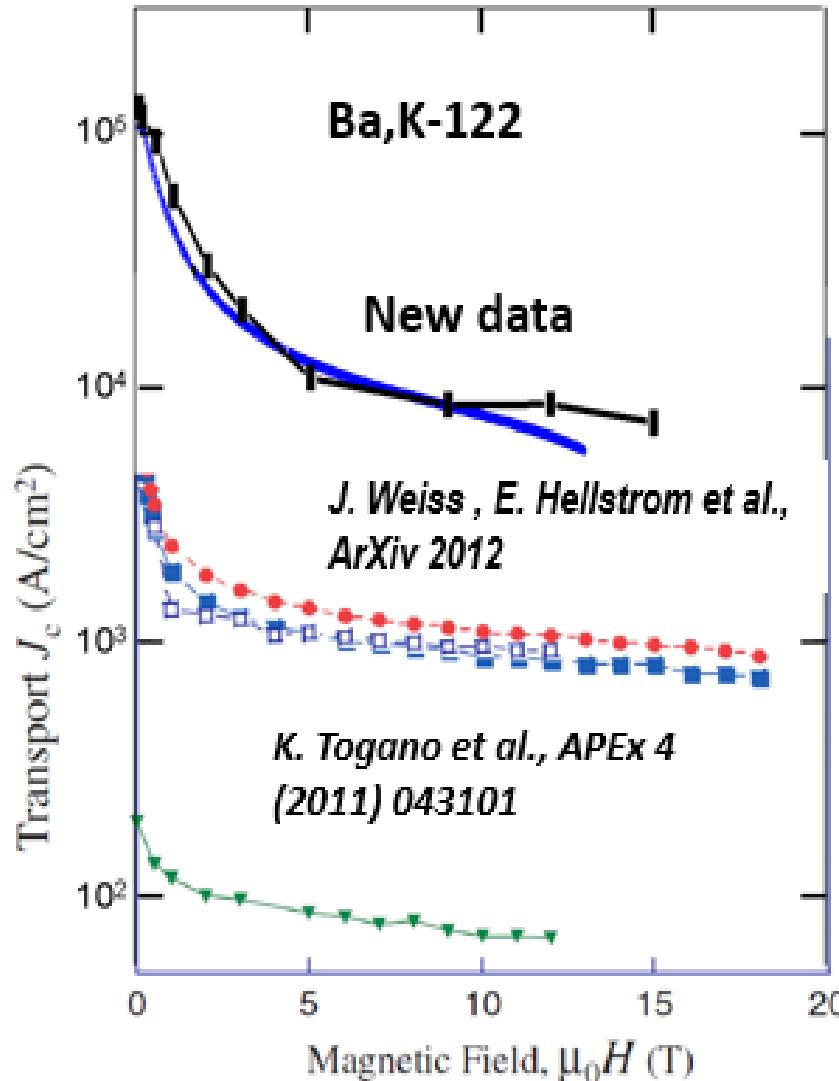


Question: how do these promising values reflect into J_c ?

New synthesis method increased J_c by 5x in K-doped 122 round wire

Round wires: highest value $J_c = 10^4 \text{ A/cm}^2$ at 15T (probably also at > 20T)

Tapes: much higher values!



Z. Gao et al., ArXiv 1110.5784

Another kind of artificial pinning: defect clusters in irradiated superconductors

Ongoing research at CERN

R.F., T. Spina, C. Scheuerlein, D. Richter, A. Ballarino, L. Bottura, Presented at RESMM'13, Tsukuba, 2013

Collaboration with ATI Vienna (A), KTI Kurchatov (Ru), Cyclotron at Louvain-la- Neuve Be)

Amorphous «defect clusters» at nanosize: similar effect on pinning as BaZrO_3 nanoparticles

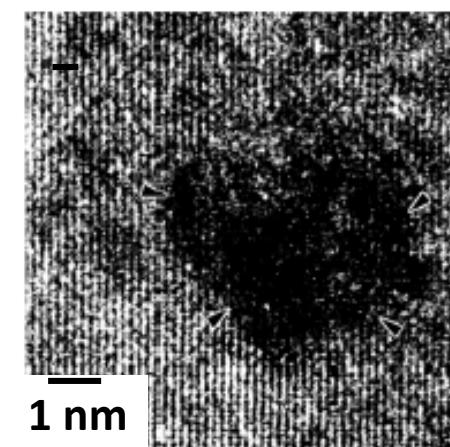
Direct collisions (high energy neutrons)

Defect cascades

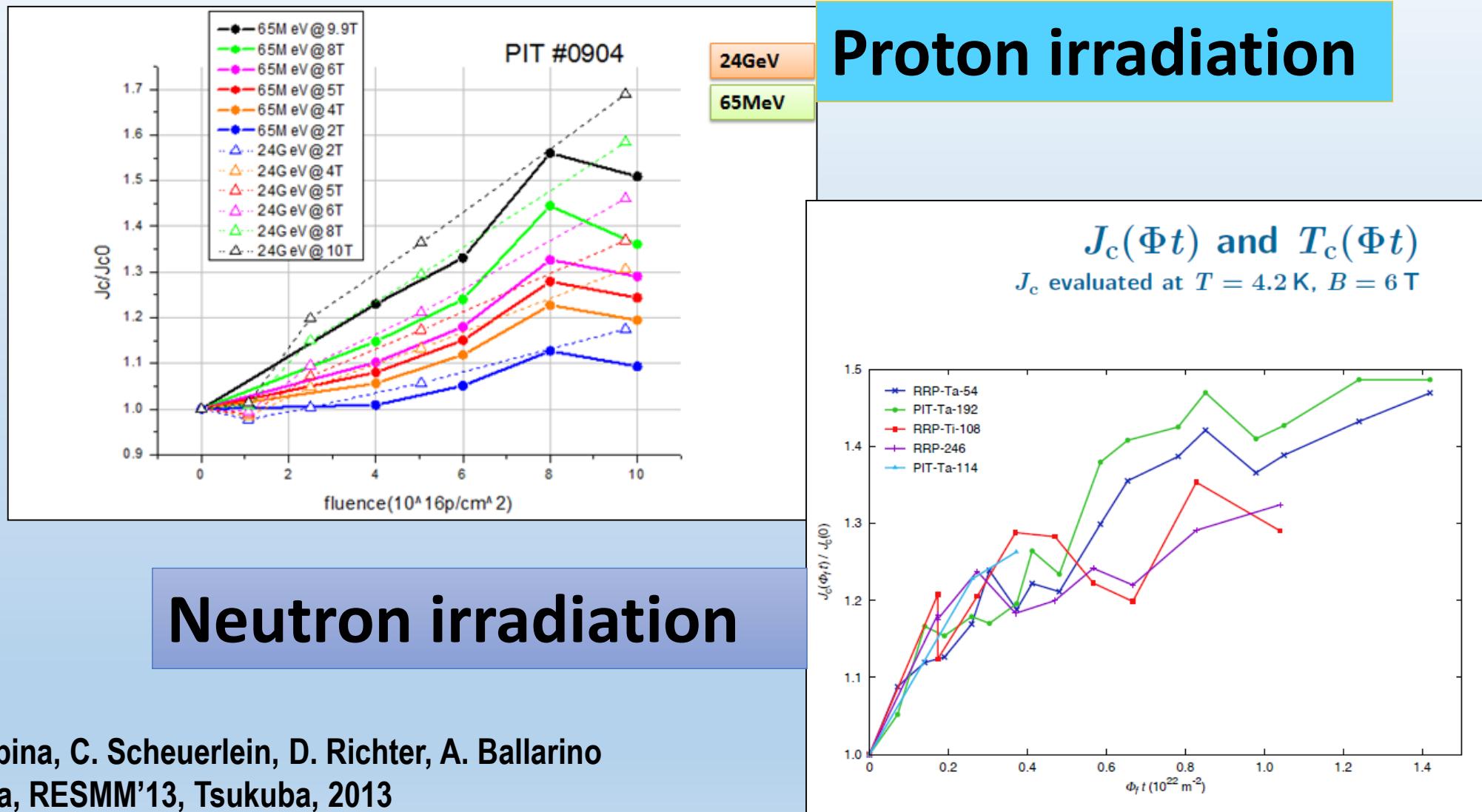
$\varnothing \sim 5 \text{ nm}$, density: $3 \cdot 10^{22} \text{ m}^{-3}$ ($d_{av} \sim 40 \text{ nm}$)

Smaller defects

Single displaced atoms, clusters of point defects....

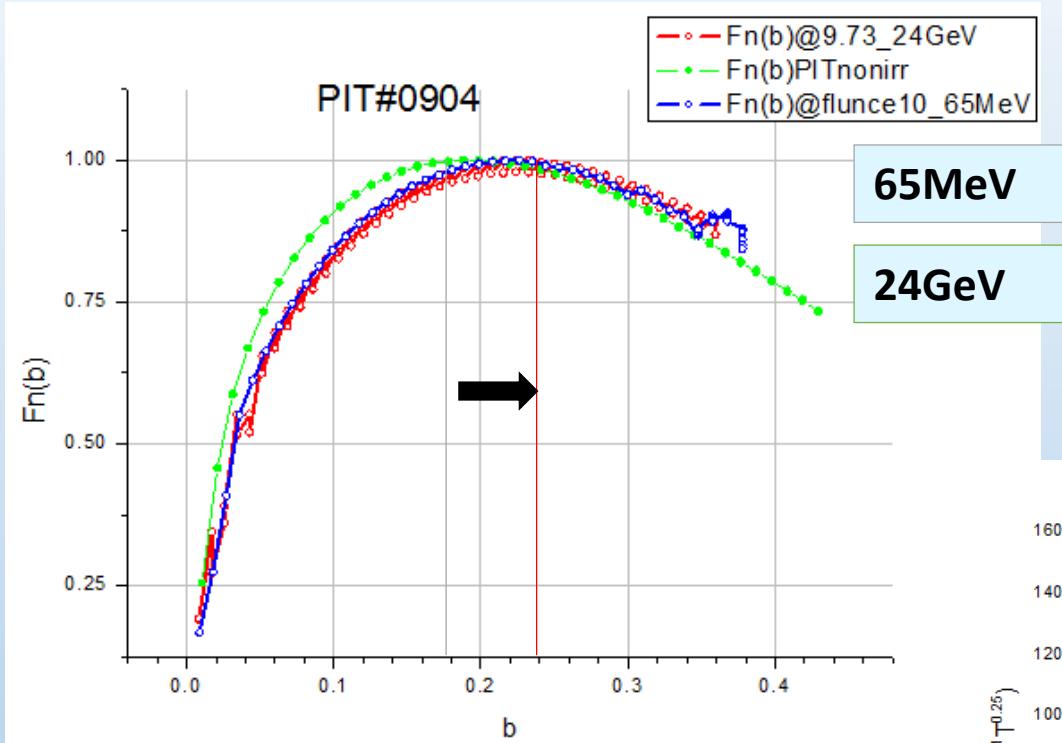


Results of ongoing neutron and proton irradiation (CERN)



R.F., T. Spina, C. Scheuerlein, D. Richter, A. Ballarino
L. Bottura, RESMM'13, Tsukuba, 2013

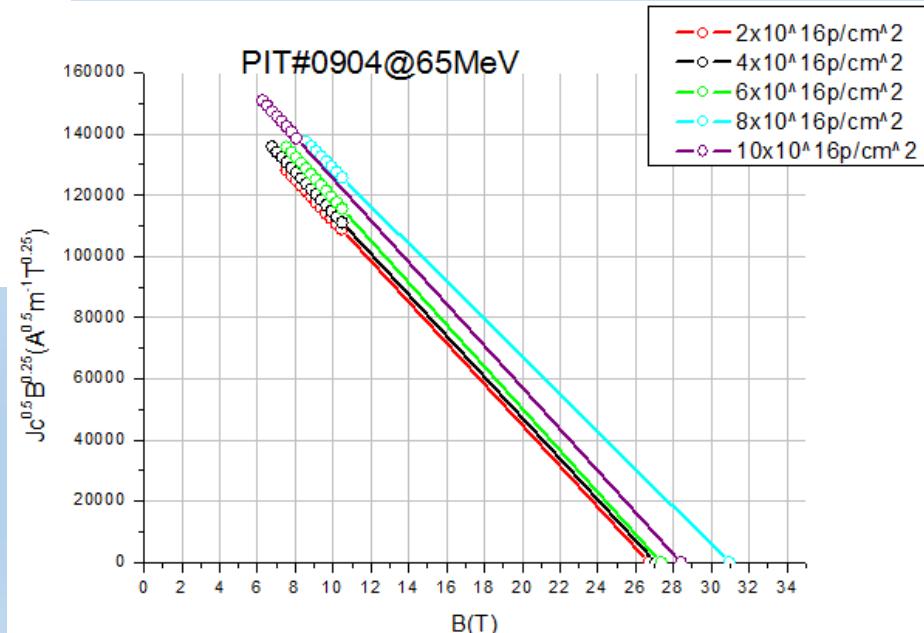
Nb₃Sn: Stronger Pinning force after irradiation



Normalized pinning force

$$F_n \left(b = \frac{B}{B_{c2} *} \right) = \frac{F_p}{F_{pmax}}$$

Kramer plot



R.F., T. Spina, C. Scheuerlein, D. Richter, A. Ballarino,
L. Bottura, RESMM'13, Tsukuba, 2013

Radiation-induced pinning: Two-mechanism field scaling model

Pinning mechanism after neutron irradiation (T. Baumgartner, ATI):

$$f(b) = \alpha * b^{p_1} (1 - b)^{q_1} + \beta * b^{p_2} (1 - b)^{q_2}$$

$$\alpha + \beta = 1$$

Grain boundary pinning

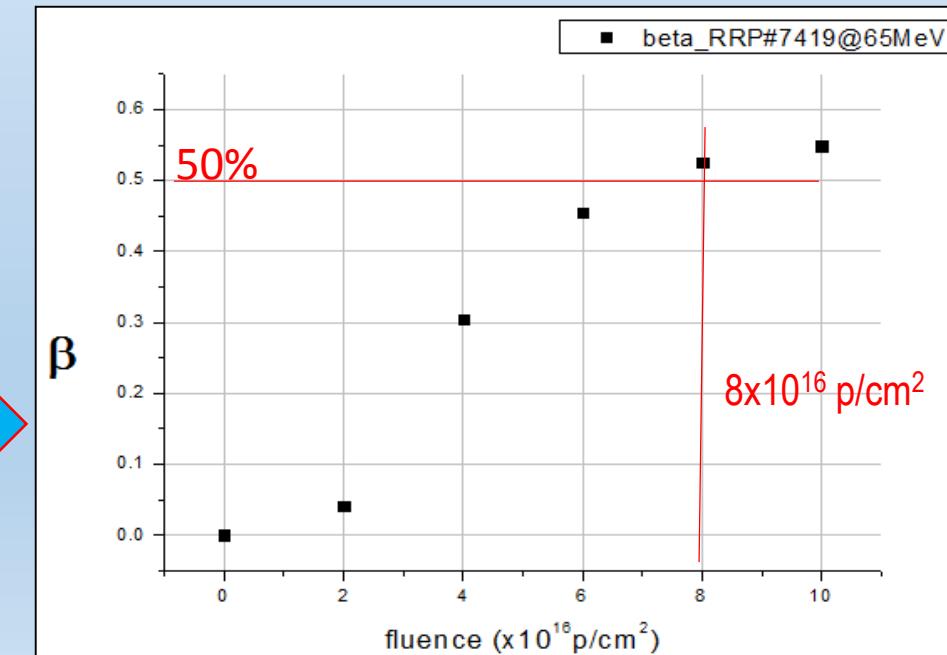
p₁, q₁ equal to the values **p** and **q** of non irradiated wires

Grain boundaries: do not change after irradiation

β: Increase of radiation induced pinning with fluence

Defect cluster pinning

α, β, p₂, q₂: fit parameters



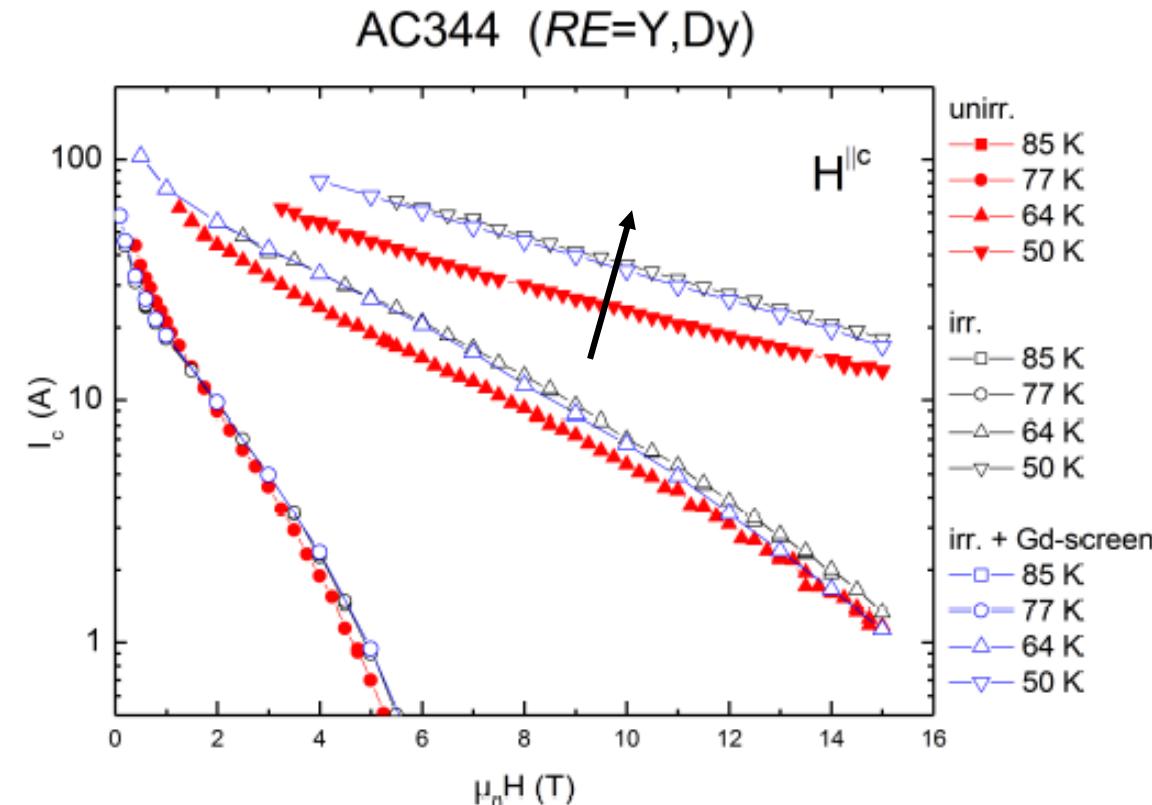


Neutron irradiation on YBaCuO Coated Conductors

M. Eisterer, H. Weber,
RESMM'13, Tsukuba, 2013



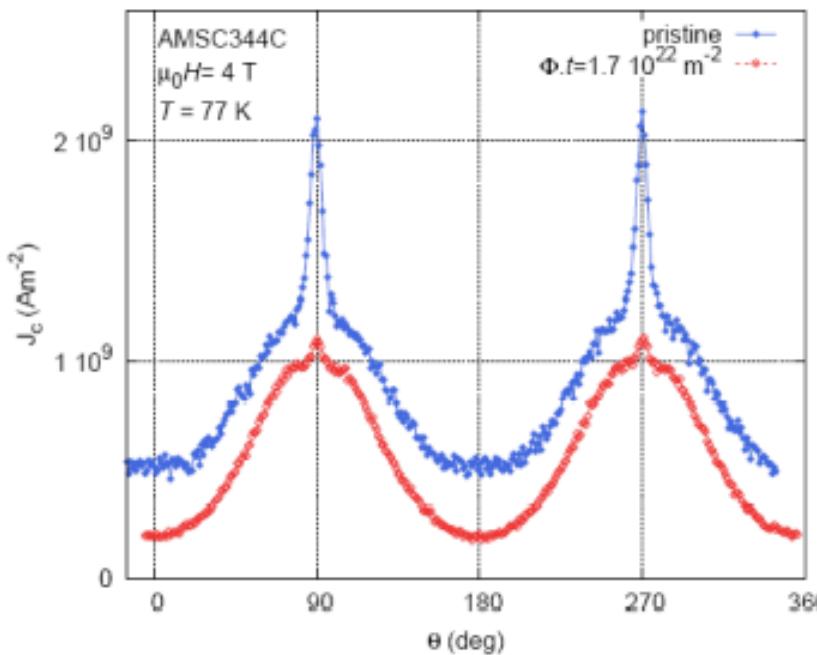
Increase of J_c after irradiation



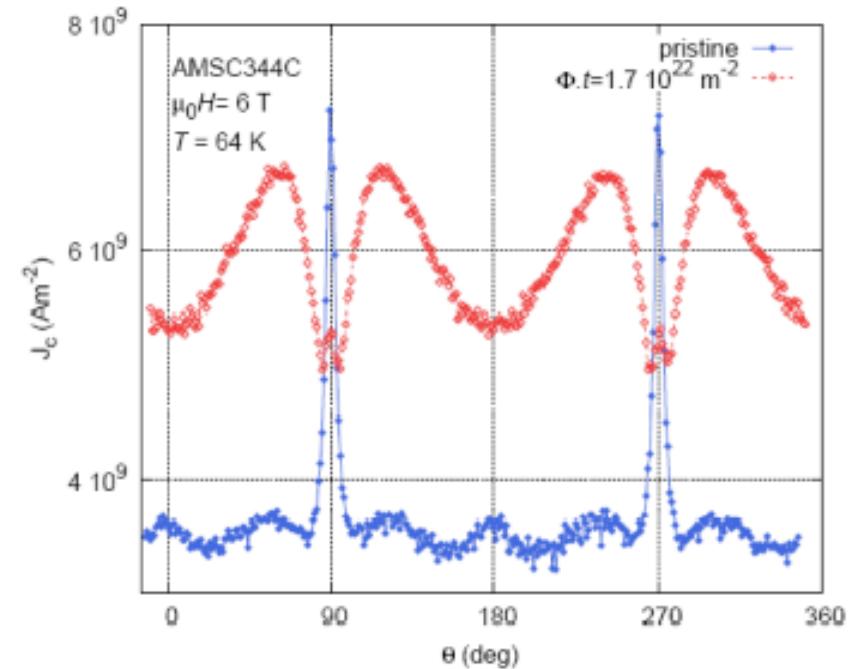
Fast neutron fluence: $6 \cdot 10^{21} \text{ m}^{-2}$

Angular dependence of I_c decreases after neutron irradiation

YBCO/RaBiTS



Similar angular dependence,
reduced ab peak

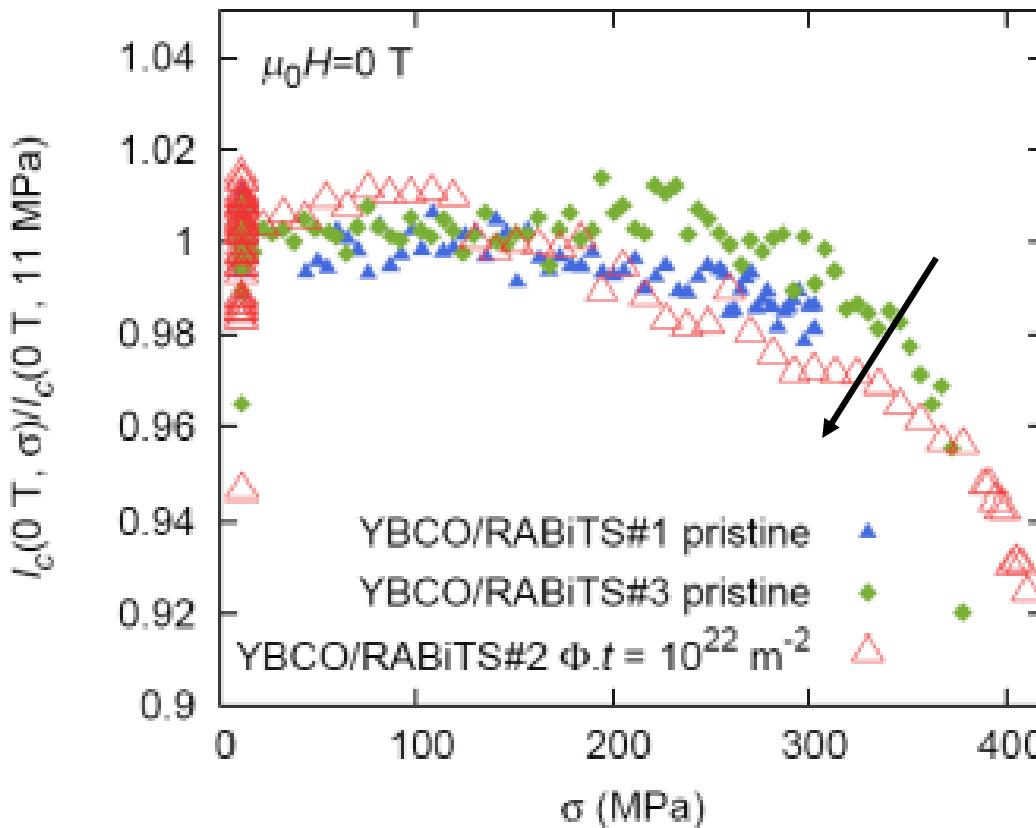


Angular dependence changes
qualitatively, reduced ab peak

M. Eisterer, H. Weber, RESMM'13,
Tsukuba, 2013

I_c at self field

$$I_c^{\text{irr}} = 0.76 I_c^{\text{unirr}}$$



REBaCuO:
Tensile strain dependence
slightly increases after
neutron irradiation

M. Eisterer, H. Weber, RESMM'13, Tsukuba, 2013



Comparison between various conductors in view of future LHC upgrades



The system Bi-2212

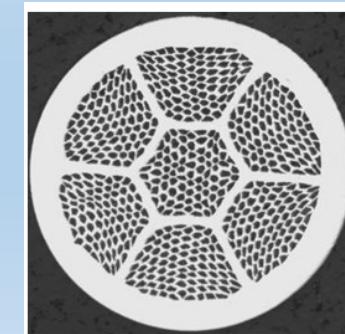
Possible applications High field magnets at 4.2K 34 T (31 + 2.5T insert)
Accelerator magnets at $B \leq 20$ T ?

Unique behavior for LHC superconductors: Current transport through grain boundaries

Consequence: Round wire are now possible, but * I_c still low
* mechanically weak

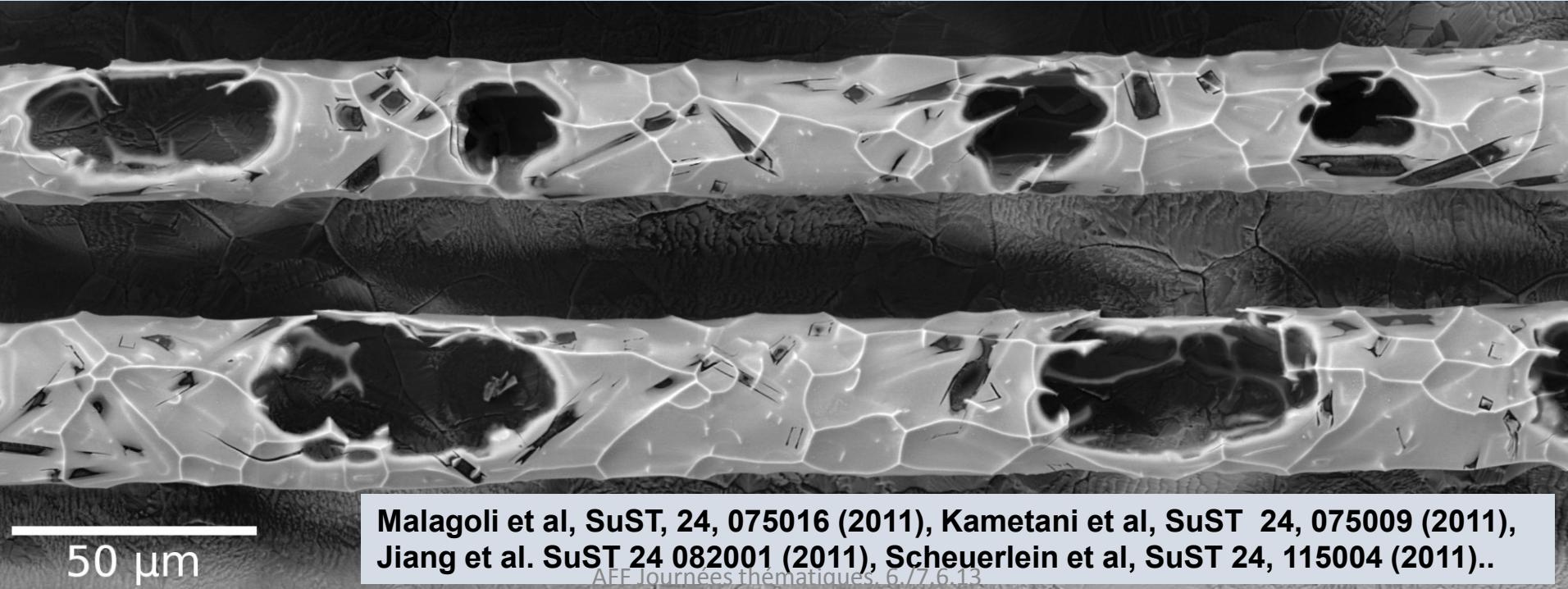
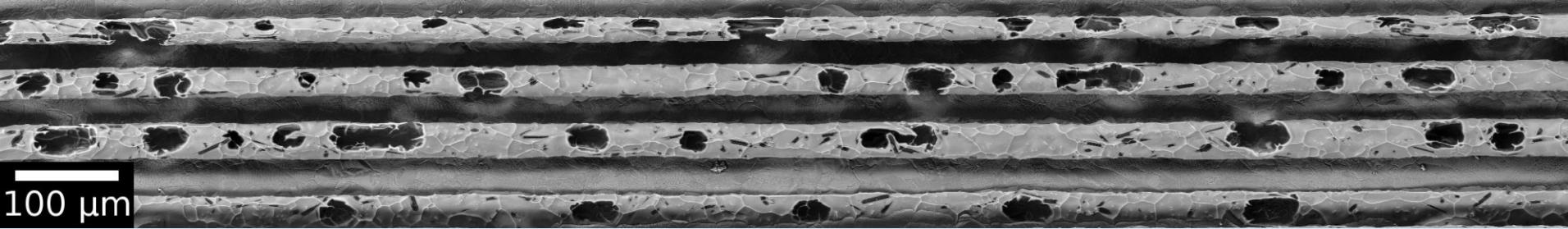
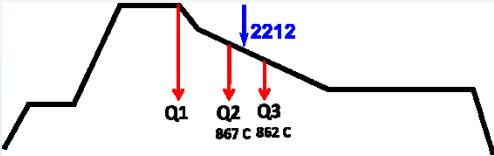
Main research efforts: D. Larbalestier, Florida State University
Oxford Instruments

Round Bi-2212 wires





Quench1: Large bubbles form on melting and holding at T_{\max}

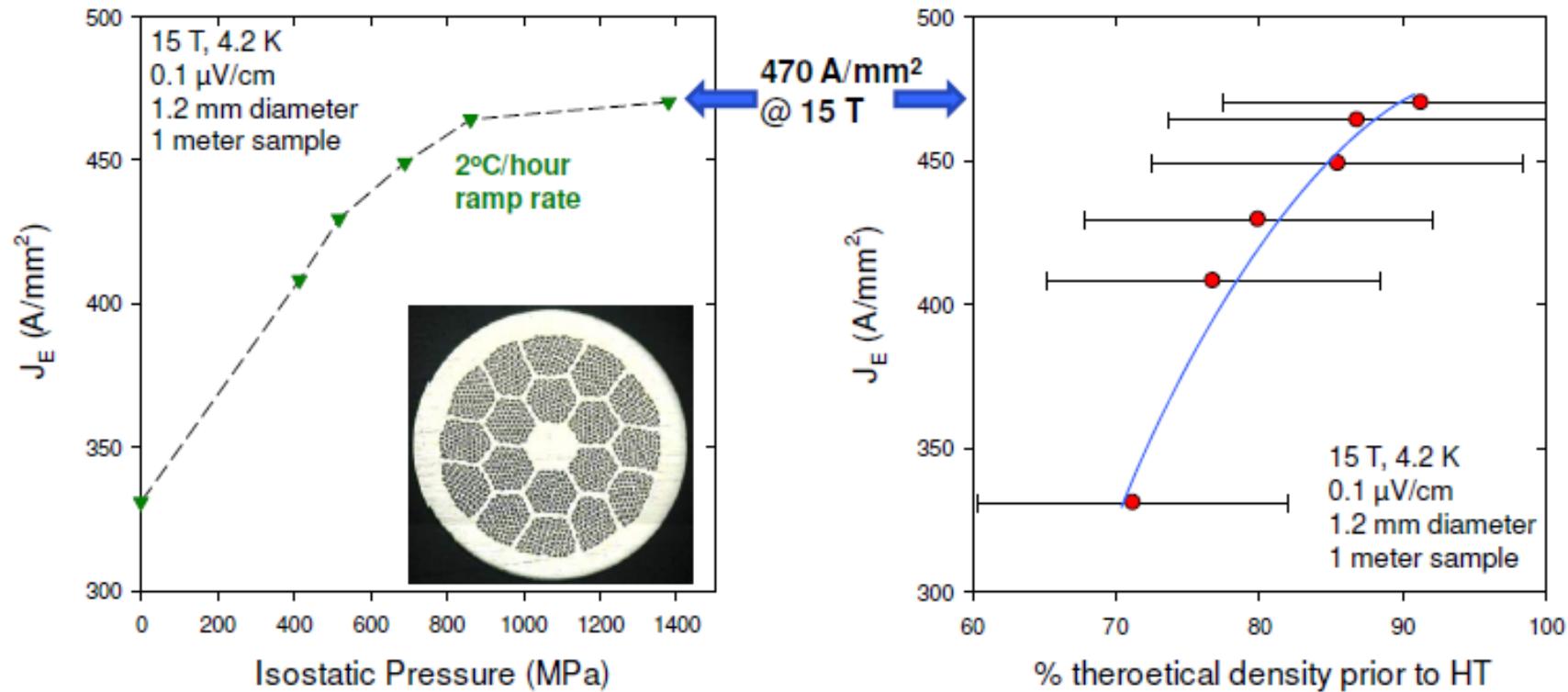


Courtesy:
D. Larbalestier

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

AFF Journées thématiques, 6./7.6.13

Compaction + slow heating → improved J_E



- Combined “best process” result in 15 T J_E values $>450 \text{ A/mm}^2$
→ Values match the best we’ve ever obtained, seem reproducible

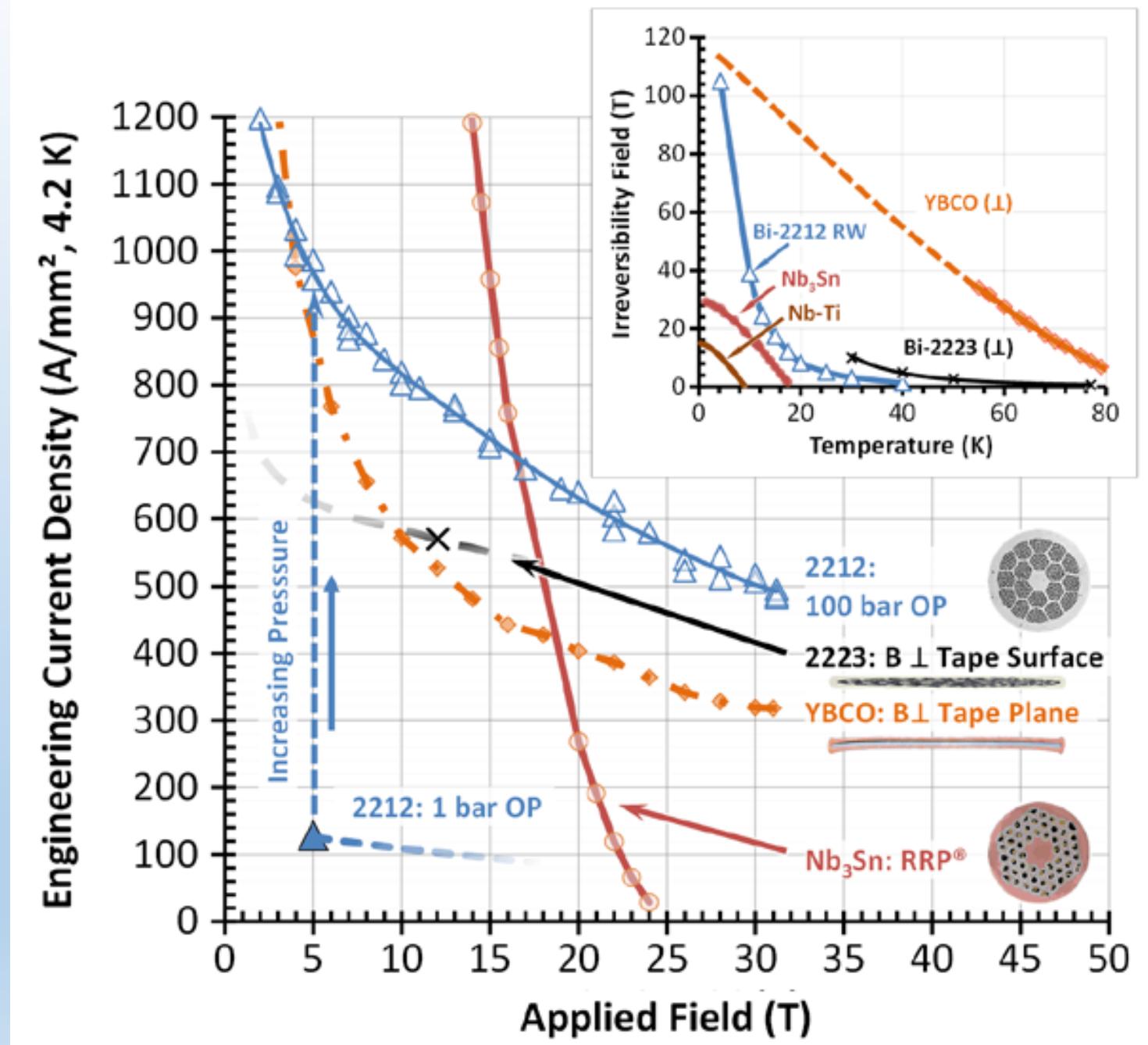
Further enhancements are possible!



Requires ~100 bar 890°C processing
High J_c , high J_e and high J_w has been demonstrated in a coil already (2.4T in 31T)

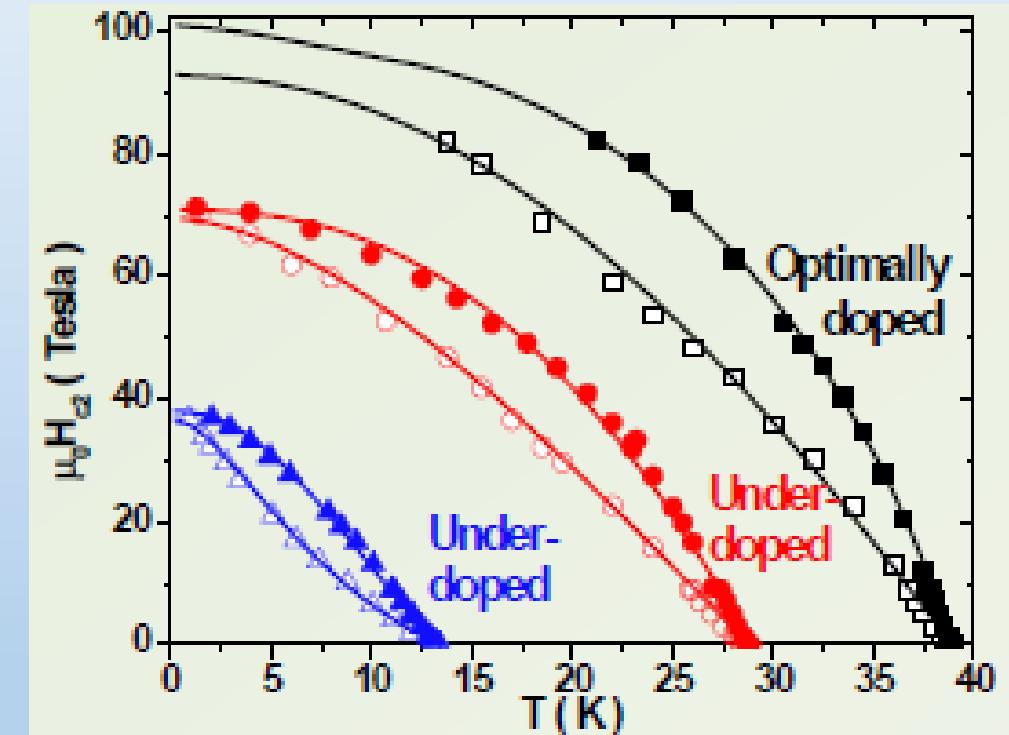
Much less field distortion from 2212 than from coated conductors – better for high homogeneity coils 7 times increase in long length J_e by removing bubbles

Data from D. Larbalestier, CAS, Erice 2013

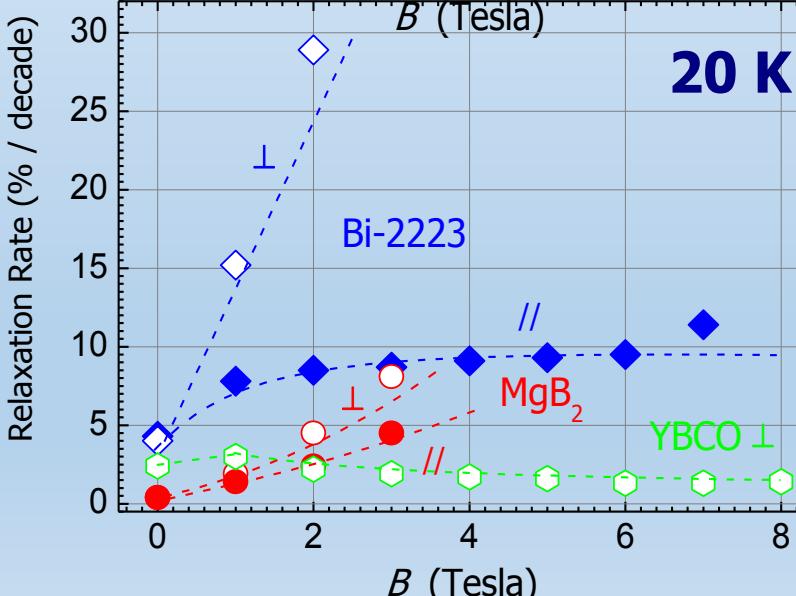
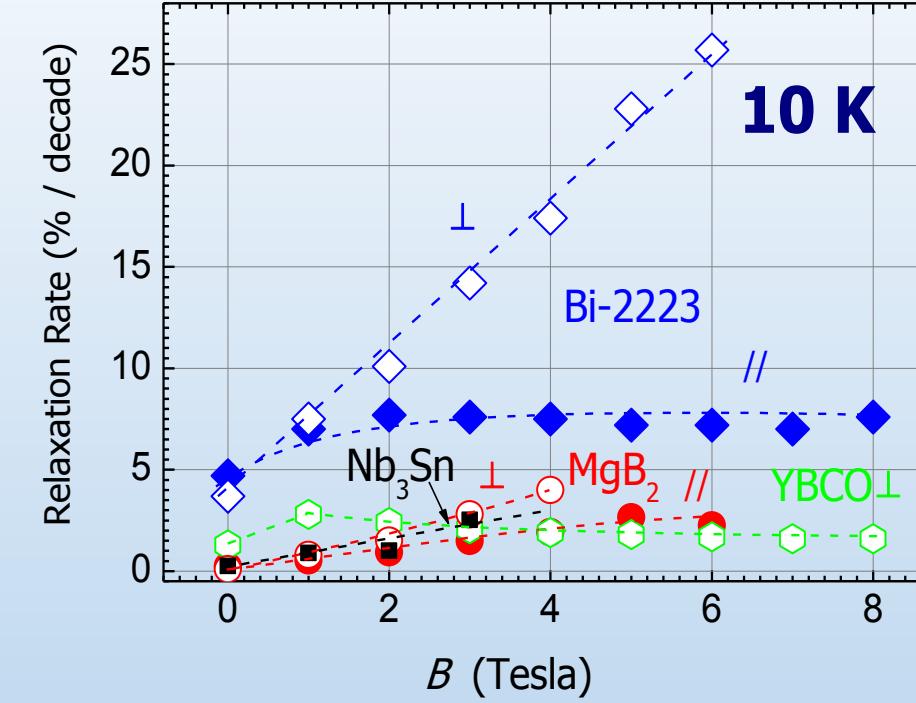
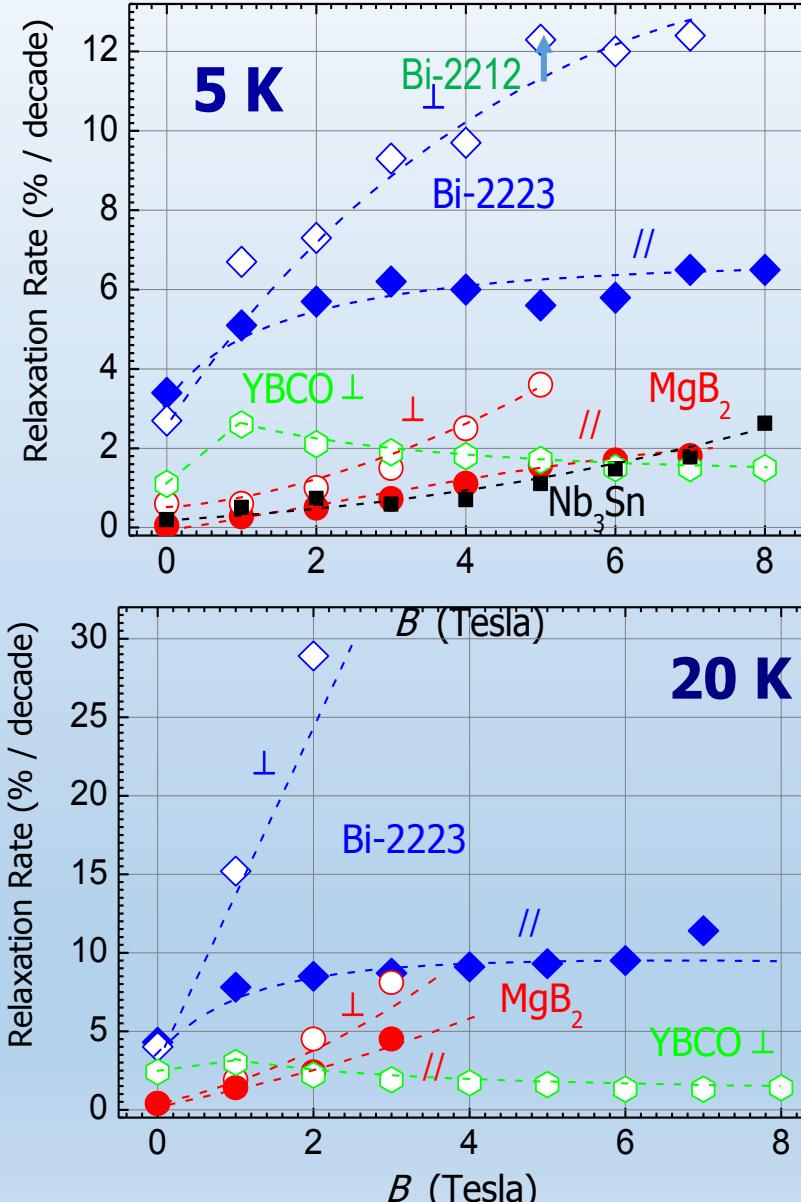


- Pnictides:**
- * K doped Ba 122 phase
 - * $B_{c2} \sim 100T$
 - * Almost no anisotropy

Tarantini et al., Phys. Rev. Lett., 84, 184522(2011)



Relaxation Rates: MgB_2 , Nb_3Sn , YBCO and Bi-2223



Relaxation rates sufficiently low for NMR:
NbTi, Nb_3Sn , MgB_2 and YBCO

Persistent mode operation: only in NbTi, Nb_3Sn , MgB_2
 YBCO/YBCO: yes
 YBCO/ Nb_3Sn : no (power supply!)

Conclusions (for accelerators)

Magnetic fields up to 15T: Nb₃Sn

Nb₃Al To improve: * prestress

Magnetic fields > 15 T: Bi-2212

To improve: * J_{eng} .
* Mechanical properties
* Proof for long length fabrication (100 bar)

YBCO To improve: * Reduced anisotropy (BaZrO₃)

* New configurations for Rutherford cables
* Longer lengths, lower costs

Pnictides So far only tapes with high J_c

High energy irradiation: So far, only increase of J_c within reasonable fluences

(The problem resides rather in the Cu stabilizer and in the insulator)

Mechanical properties under irradiation:

* Improved for Nb₃Sn
* Slightly influenced for YBCO
* Strongly decreased for GdBCO !