EEE/CSC & ESAS SUPERCONDUCTIVITY NEWS FORUM (global edition), No. 42, October 2017.
Invited presentation M4OrB-02 given at CEC-ICMC 2017, July 09-13, 2017, Madison, WI (USA).


# Progress in the development of high performance pnictide wires

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# Outline

- Good superconducting property of pnictide
- Two main problems existing in the PIT wires
- Hot pressing effects on $Sr_{0.6}K_{0.4}Fe_2As_2$ tapes
- Progress in the multifilament wire /Cu sheathed tapes

# Iron superconductor

*J. Am. Chem. Soc.*, **130** (11), 3296 -3297, 2008. 10.1021/ja800073m
**Web Release Date:** February 23, 2008
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## Iron-Based Layered Superconductor La[$O_{1-x}F_x$]FeAs ($x$ = 0.05-0.12) with $T_c$ = 26 K

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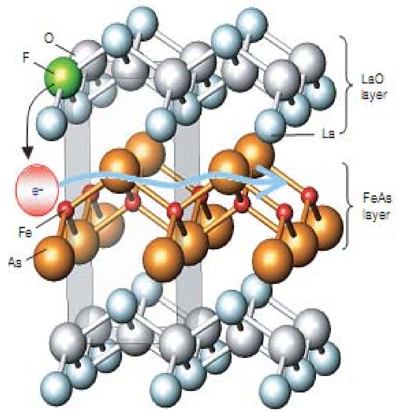
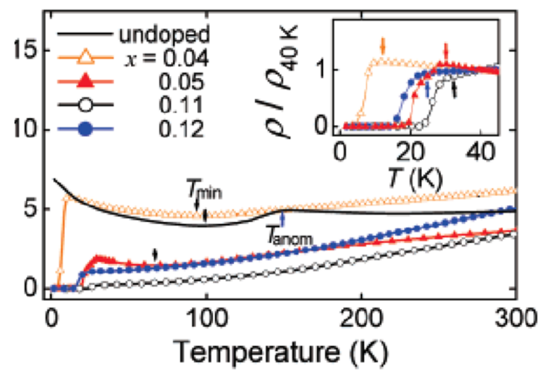
*Received January 9, 2008*

**Abstract:**

We report that a layered iron-based compound LaOFeAs undergoes superconducting transition under doping with $F^-$ ions at the $O^{2-}$ site. The transition temperature ($T_c$) exhibits a trapezoid shape dependence on the $F^-$ content, with the highest $T_c$ of ~26 K at ~11 atom %.

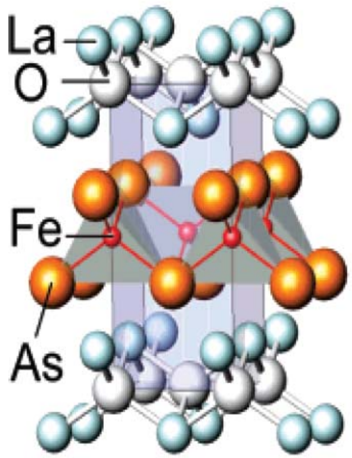


# Main known Fe-based superconductors

Among them, the three phases most relevant for wire applications are 1111, 122, and 11 types with a $T_c$ *of 55, 38 and 8 K, respectively.*

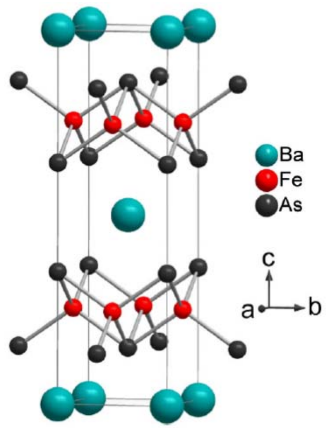
**1111 Phase LnOFeAs**




**$T_c$ ~55 K**

Z. A. Ren et al., ***Chin. Phys. Lett.*** 25, 2215 (2008)

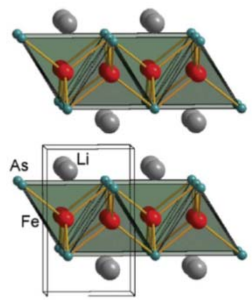
**122 phase $AFe_2As_2$ (A=Ba, Sr, Ca)**




**$T_c$ ~38 K**

M. Rotter, et al., ***Phys. Rev. Lett.*** **101**, 107006 (2008)

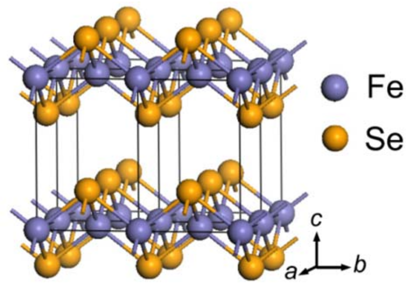
**111 phase LiFeAs**




**$T_c$ ~18 K**

X. C. Wang, et al., ***Solid State Commun***. **148**, 538 (2008).

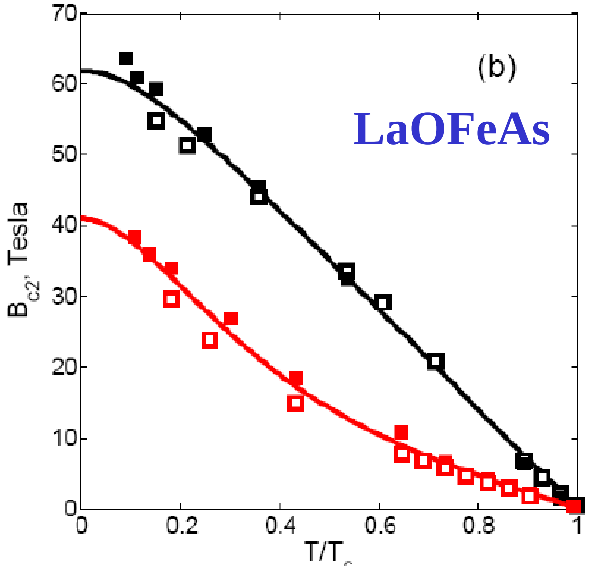
**11 phase FeSe**



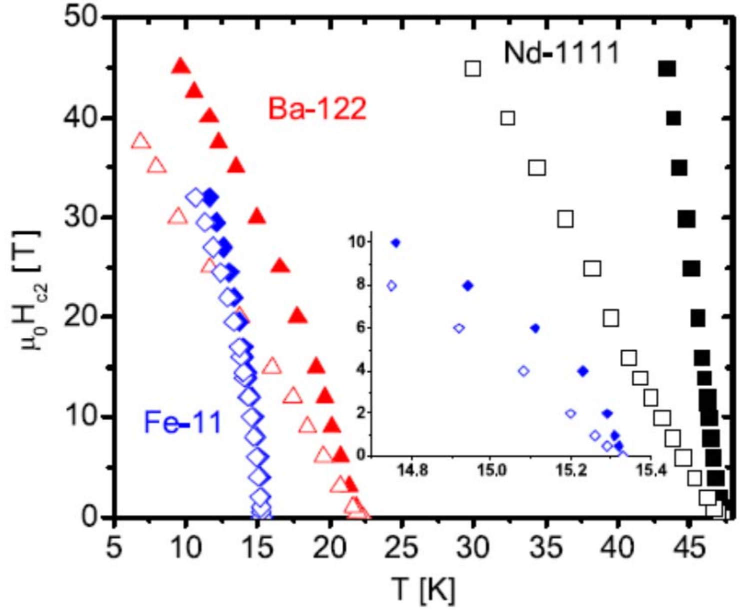

**$T_c$ ~8 K**

F. C. Hsu, et al., ***Proc. Natl. Acad. Sci. U.S.A.*** **105**, 14262 (2008).

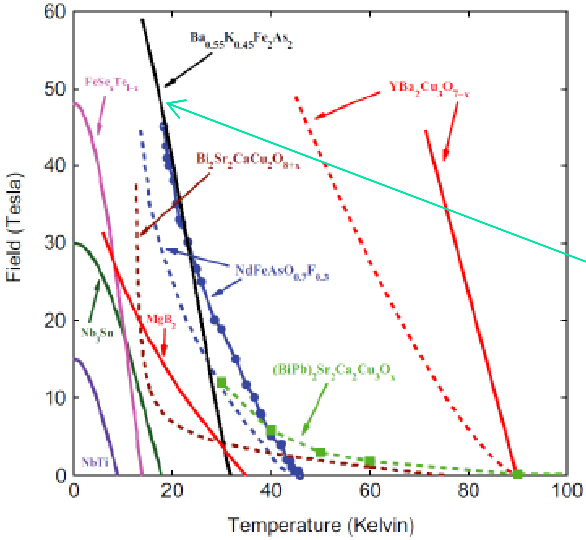
# Very high upper critical fields in iron pnictides




**Hunte et al., *Nature* 453, 903 (2008)**




**Putti et al., *SUST* 23, 034003 (2010)**




**An extrapolated $B_{c2}$( 0 K) can exceed 200 T, especially *at 20 K, the $B_{c2}$ can be 40-50 T*, suggesting a very encouraging application in high field magnets.**

- **Pnictides, e.g. 122 and 1111, could in principle provide fields up to 40-50 T at 20K.**

Gurevich, ***Nature Mater.*** 10 (2011) 255

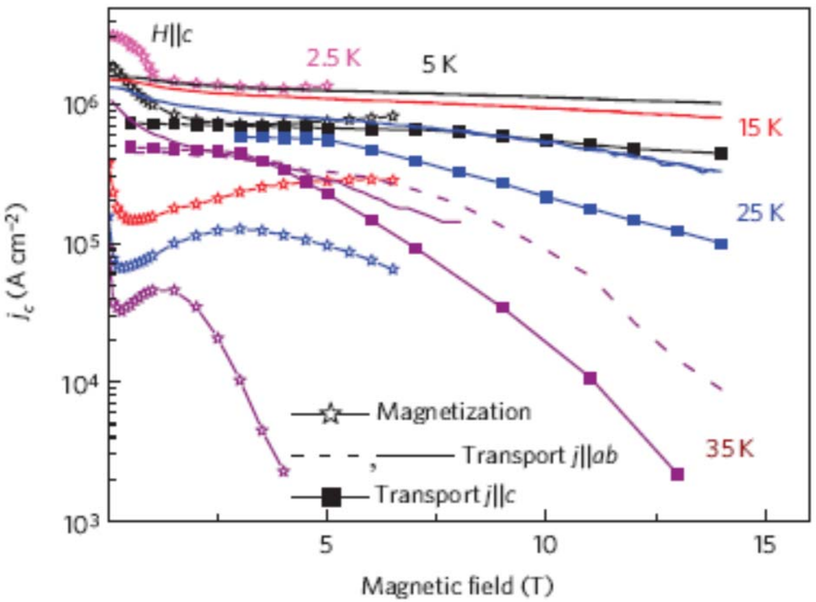
# High critical current densities in iron pnictides

**The single crystal of both the 1111 and 122 type pnictides show high $J_c$ values.**

**The anisotropy of the pnictides is relatively small.**

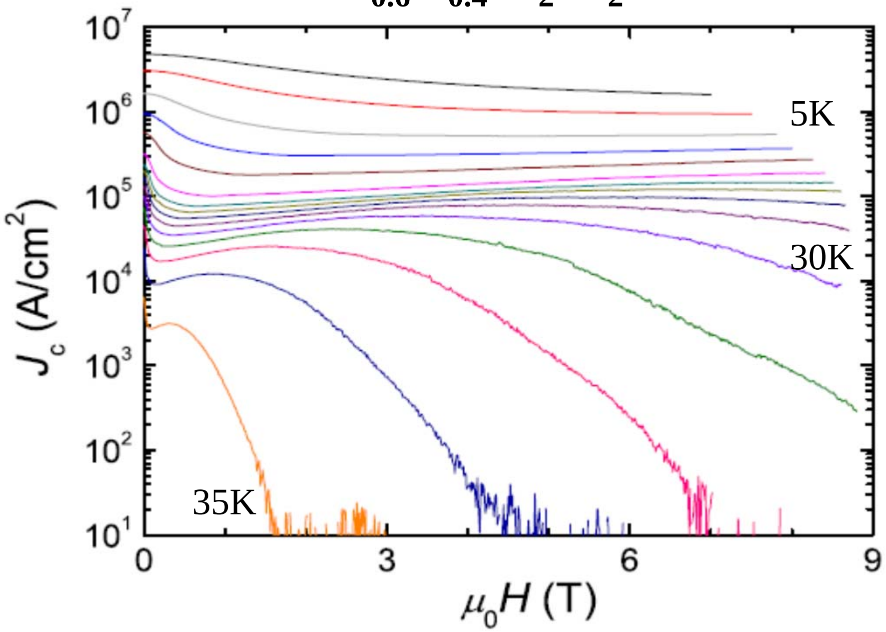
| | $J_c$ @ 5K @ 0 T | $J_{c\,//a}$/ $J_{c\,//c}$ |
|---|---|---|
| 1111 | ~3 × $10^6$ A/cm$^2$ | 2.5 |
| 122 | ~3 × $10^6$ A/cm$^2$ | 2 |
| 11 | ~$10^6$ A/cm$^2$ | |

**$SmFeAsO_{1-x}F_x$**




Moll et al., ***Nature Mater.*** 9, 628 (2010)

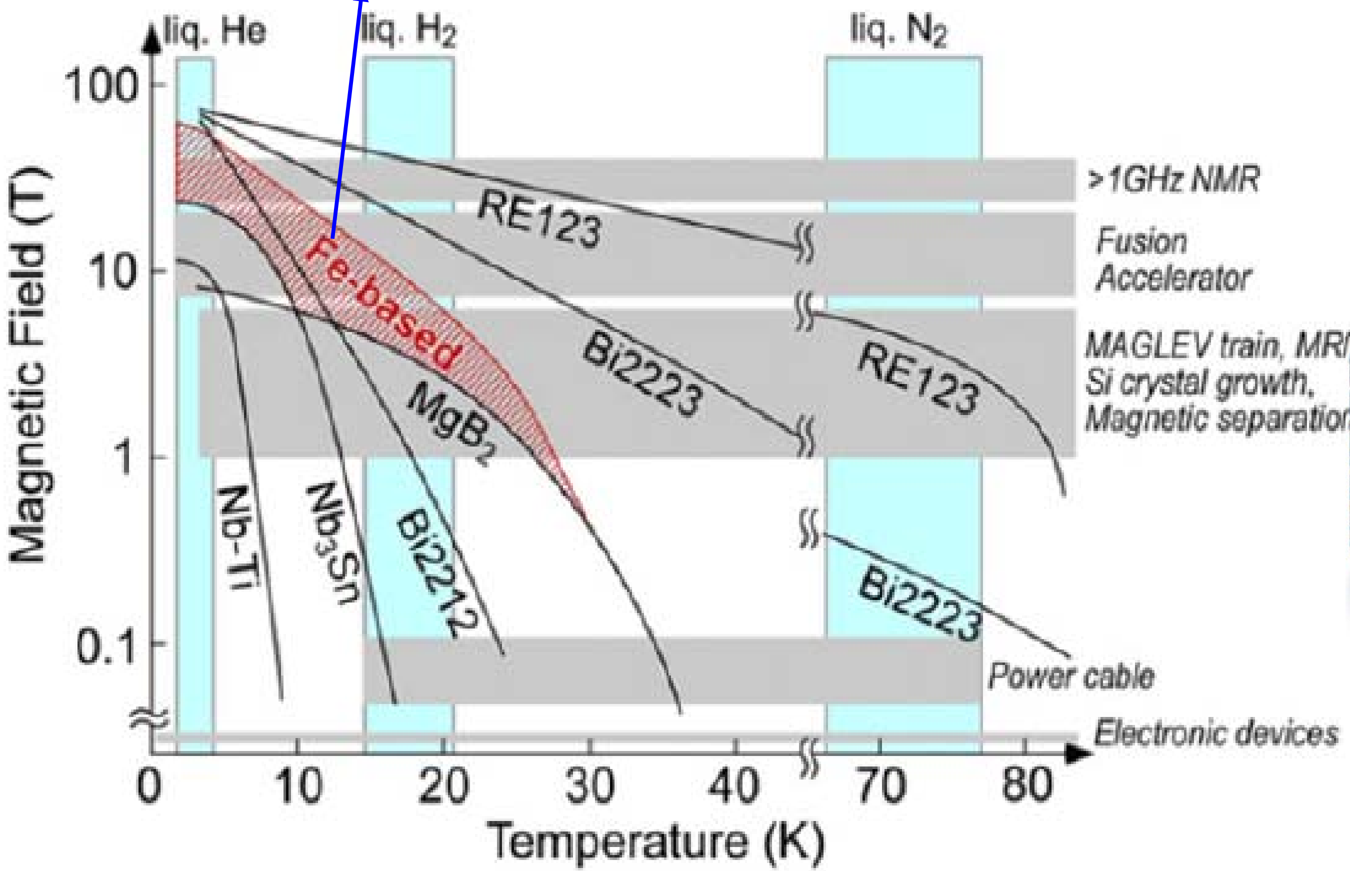
**$Ba_{0.6}K_{0.4}Fe_2As_2$**



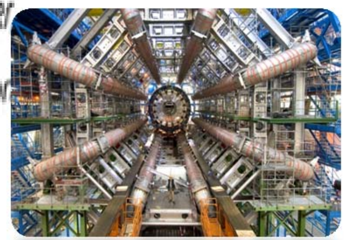

Yang, et al, ***APL*** 93 (2008) 142506

# IBS: high-field applications

**Possible application area**




**NMR**



Accelerator

**MRI**

Shimoyama, *SuST* 27 (2014) 044002

# Outline

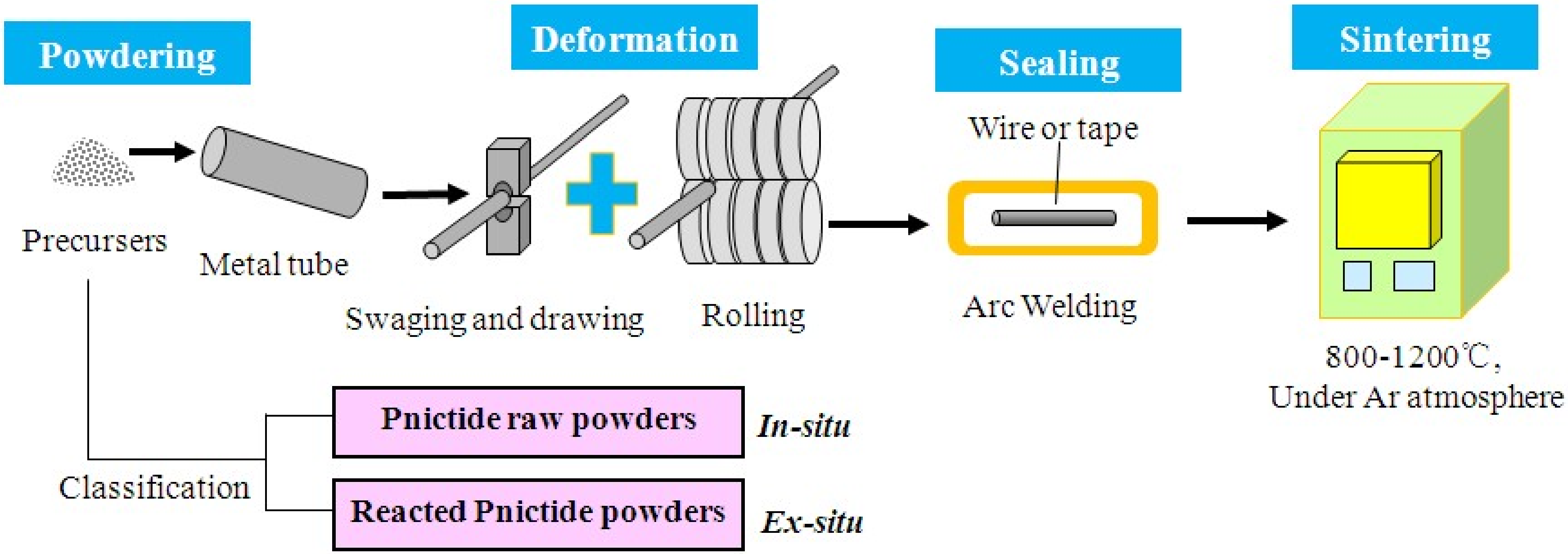
- Good superconducting property of pnictide
- **Two main problems existing in the PIT wires**
- Hot press effects on $Sr_{0.6}K_{0.4}Fe_2As_2$ tapes
- Progress in the Cu sheath and multifilament wire

# Fabrication technique for pnictide wires

**Powder-in-tube method:**

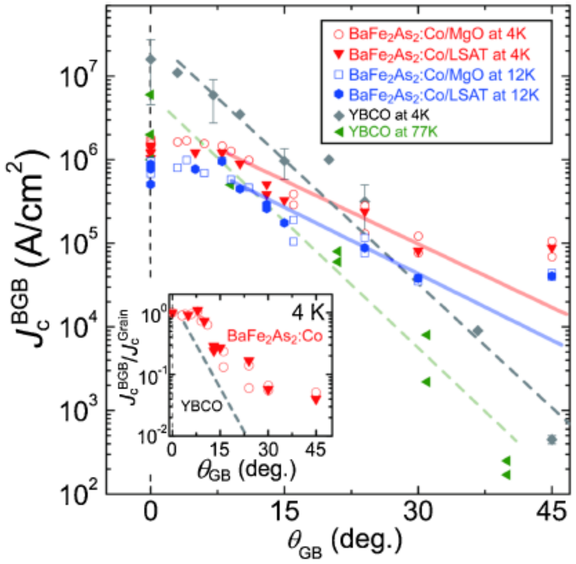
**Simple, easy for fabrication**

**Has been used for Bi2223 superconductor**



# Challenges for high-$J_c$ pnictide wire

## 1) How to solve weak-linked problem




Katase et al., *Nat. Commun.* 2, 409 (2011)

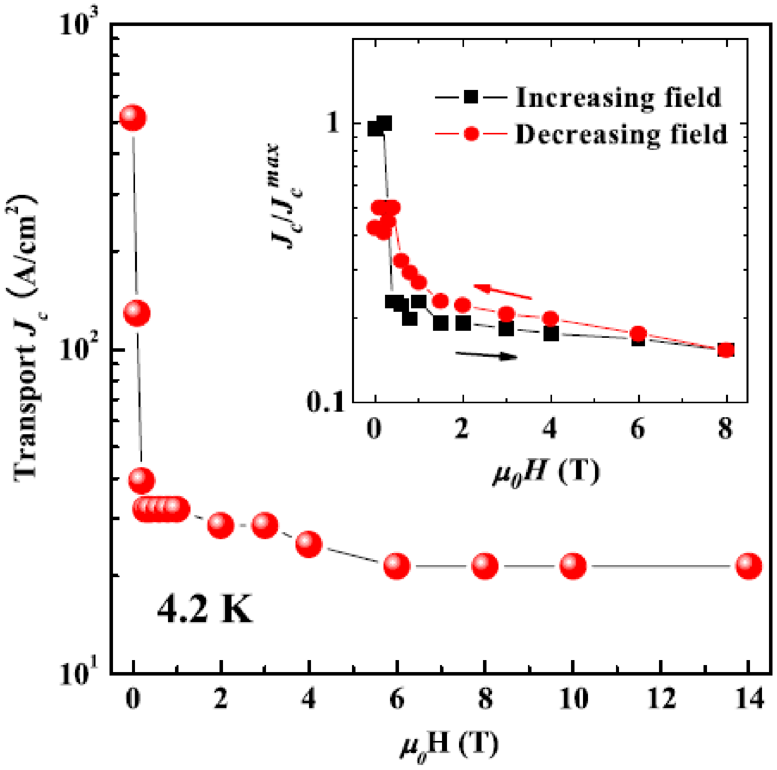
**Critical misorientation angle**

**YBCO : 3-5º**

**Pnictide 122: 9º**

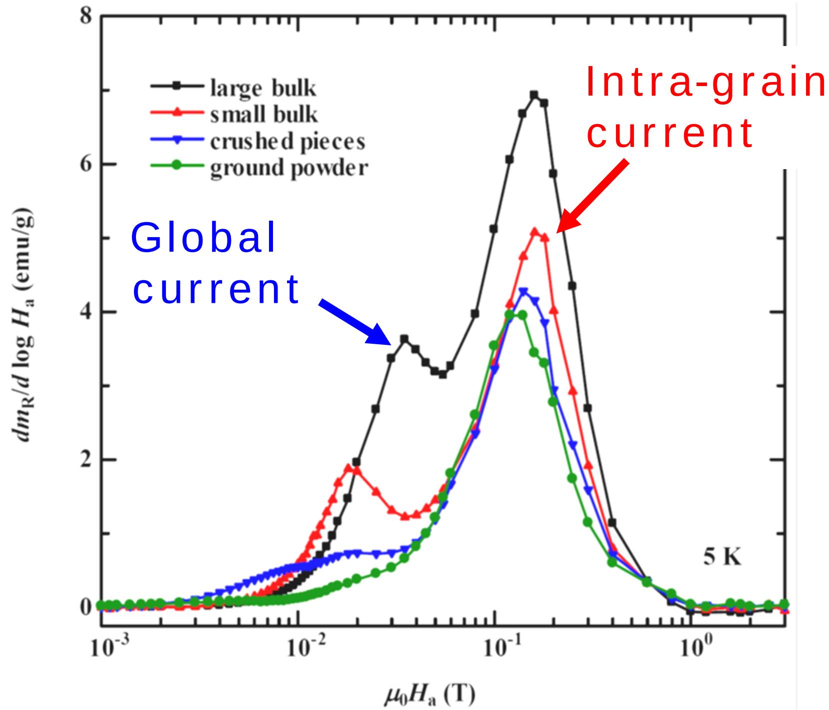
## 2） How to achieve high density core

# Hysteresis in transport $J_c$: signature of weak links




*Physica C* 470 (2010) 183

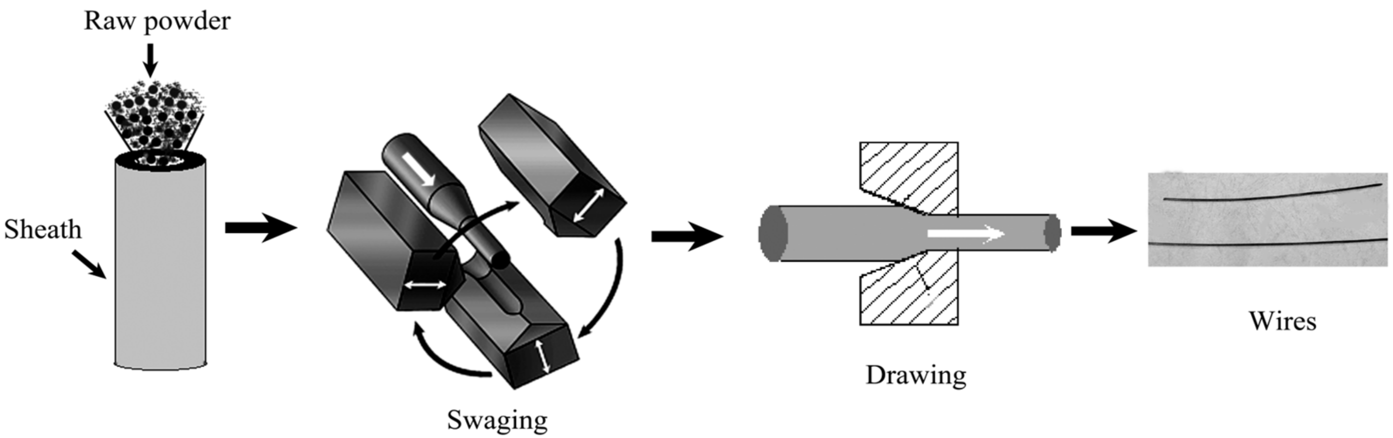
**Remanent magnetization**

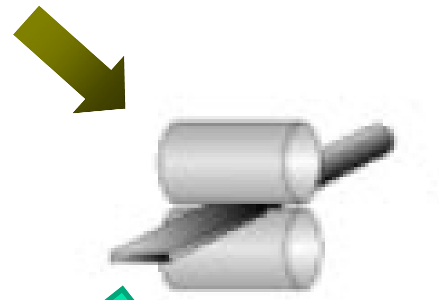



***Physica C 470 (2010) 1216–1218***

- **A hysteretic phenomenon observed for $J_c$ in an increasing and a decreasing field indicated a weak-link behavior, similar to that of the cuprates.**
- **To overcome the weak-link problem, one effective method is to engineer textured grains to minimize deterioration of Jc across high-angle grain boundaries, like the Bi2223.**

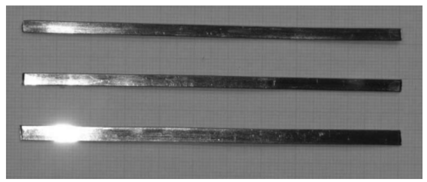
# Texturing process of PIT Sr122 tapes



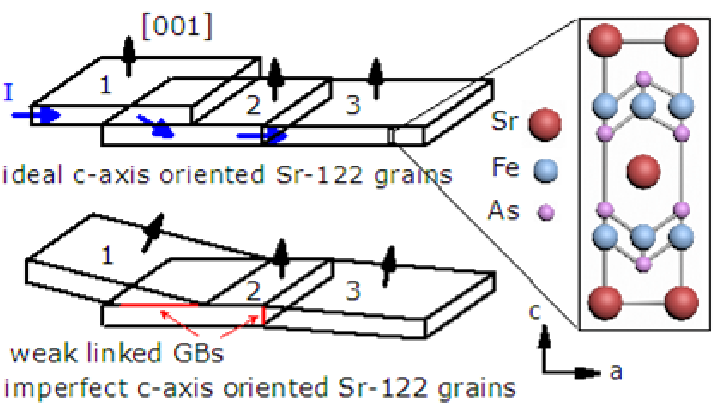



**Fe or Ag tube used sheath material**

**Large deformation ratio**

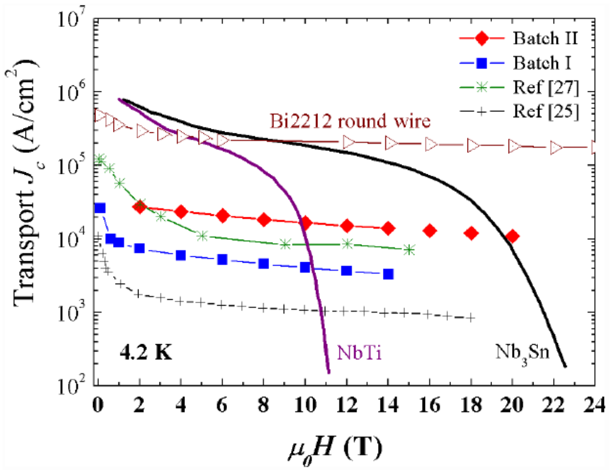


**Photograph of the final 122 tapes**




*Physica C* 471 (2011) 1689; ***APL*** 99 (2011) 242506

# Transport $J_c$ of flat-rolled 122 tapes




**Fe-sheathed Sr-122 tape**

**At 4.2 K/10 T, $J_c$= 1.7×10$^4$ A/cm$^2$**

**The degree of texturing F: ~0.4**

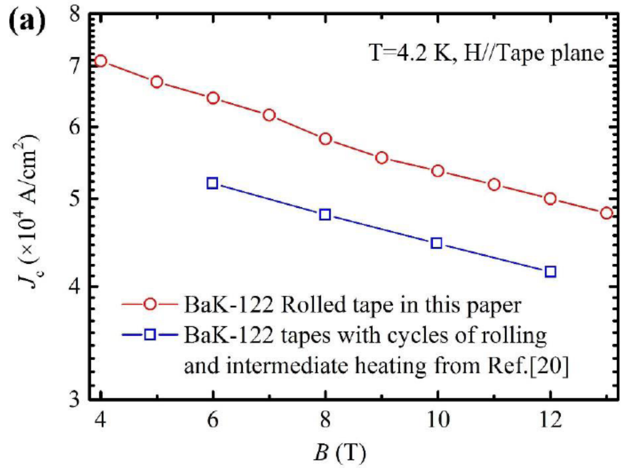
***Sci. Rep.* 2, 998 (2012)**

**Ag-sheathed Ba-122 tape**

**At 4.2 K and 10 T: $J_c$ = 5.4×10$^4$ A/cm$^2$**

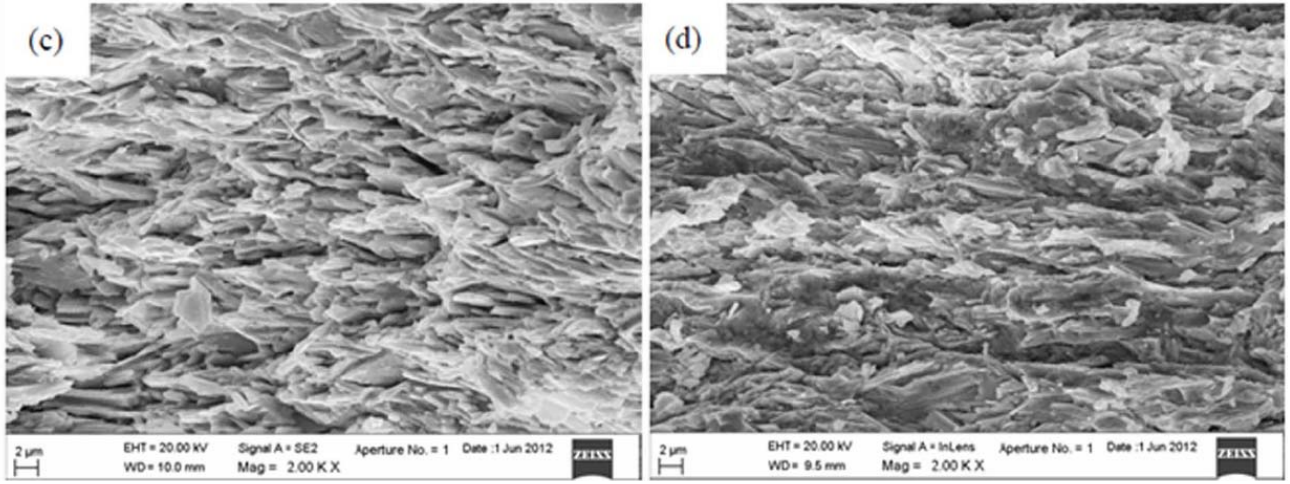
**The degree of texturing F: ~0.69**

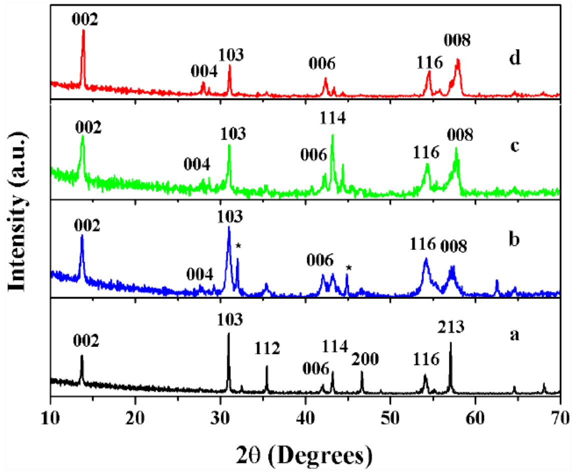
**Average Hv: ~135**




***Scripta Mater.* 99 (2015) 33**

# The textured PIT seems an effective method to overcome the weak-link problem in pnictide wires, but···




texture of the $Sr_{1-x}K_xFe_2As_2$ phase, we have evaluated the *c* axis orientation factor F by the Lotgering method as follows[29].

$$F = (\rho - \rho_0)/(1 - \rho_0),$$

Where $\rho = \sum I(00l)/\sum I(hkl)$, $\rho_0 = \sum I_0(00l)/\sum I_0(hkl)$, $I$ and $I_0$ are the intensities of each reflection peak (*hkl*) for the oriented and random samples, respectively. The value of F for the as-rolled tape,

The c axis orientation factor **F=~0.4**

**-- Fe sheath**

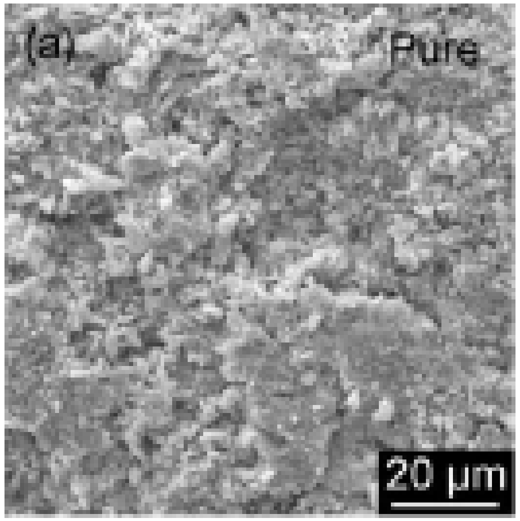
- **There are still existed some impurity phases and pores, and the degree of texture is still low, e.g. only about 0.4.**
- **Suggesting that there is more room for improvement.**

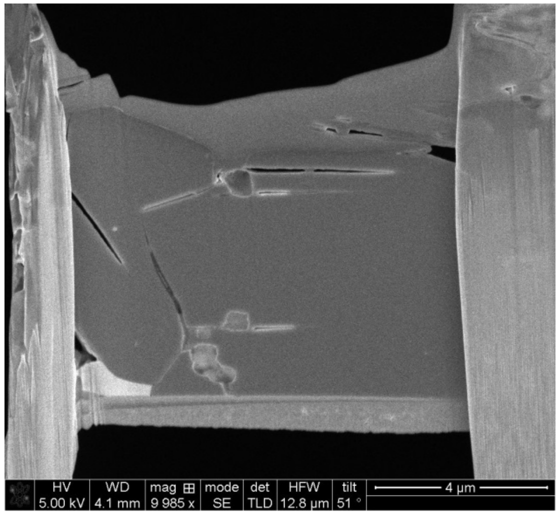
# Challenges for high-$J_c$ pnictide wire

1) How to solve the weak-link problem

2）How to achieve high density core

Cracks and voids are important reasons for low critical current density values



# Hot pressing of Ag-sheathed Sr122 tapes

Mixed powders (10% excess K) /(900℃, 35 h)

**Ag tube used sheath material**

Wire of 1.9 mm in diameter

Rolled into tapes (0.44 mm)

Sintering (850℃, 10-60 min) → "Sintered"

Hot pressing 850℃, 10-60 min → "HP"

Suppress the voids and cracks

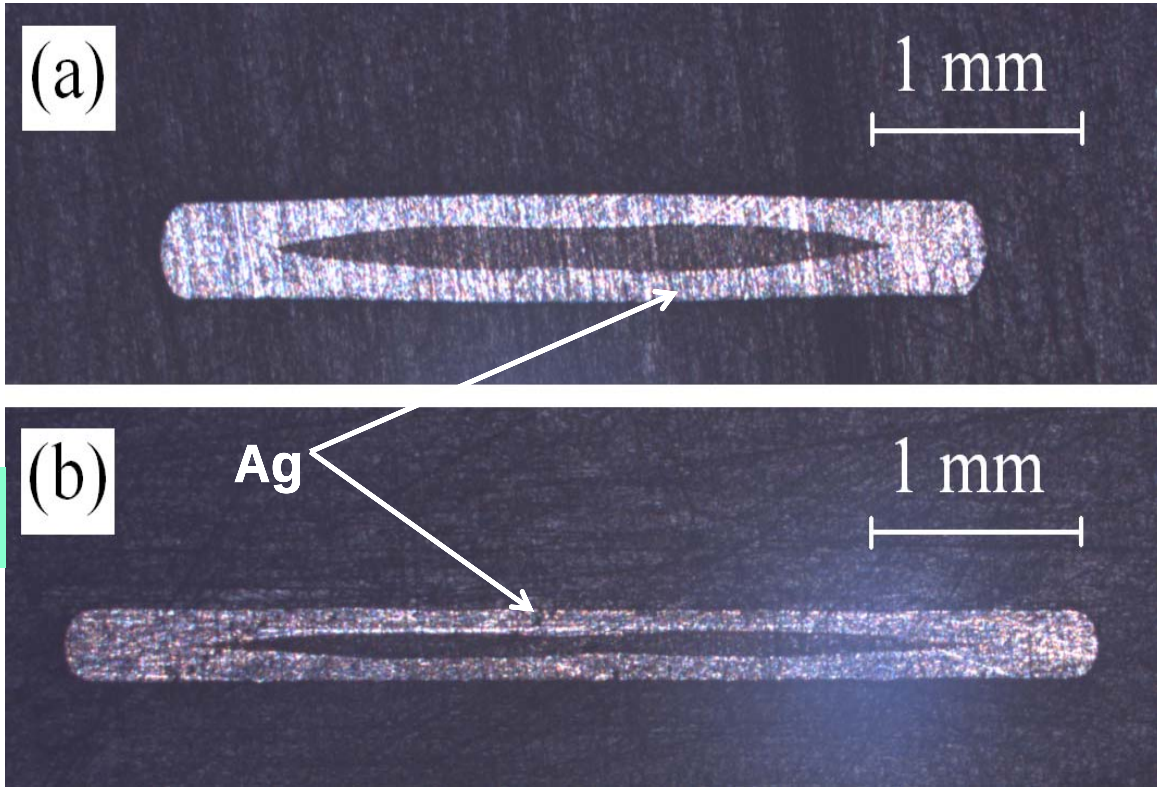
XRD, SEM, R(H), PPMS, V-I

# Cross section of 122/Ag tapes by Hot Pressing

**Sintering**

↓

**Hot pressing**



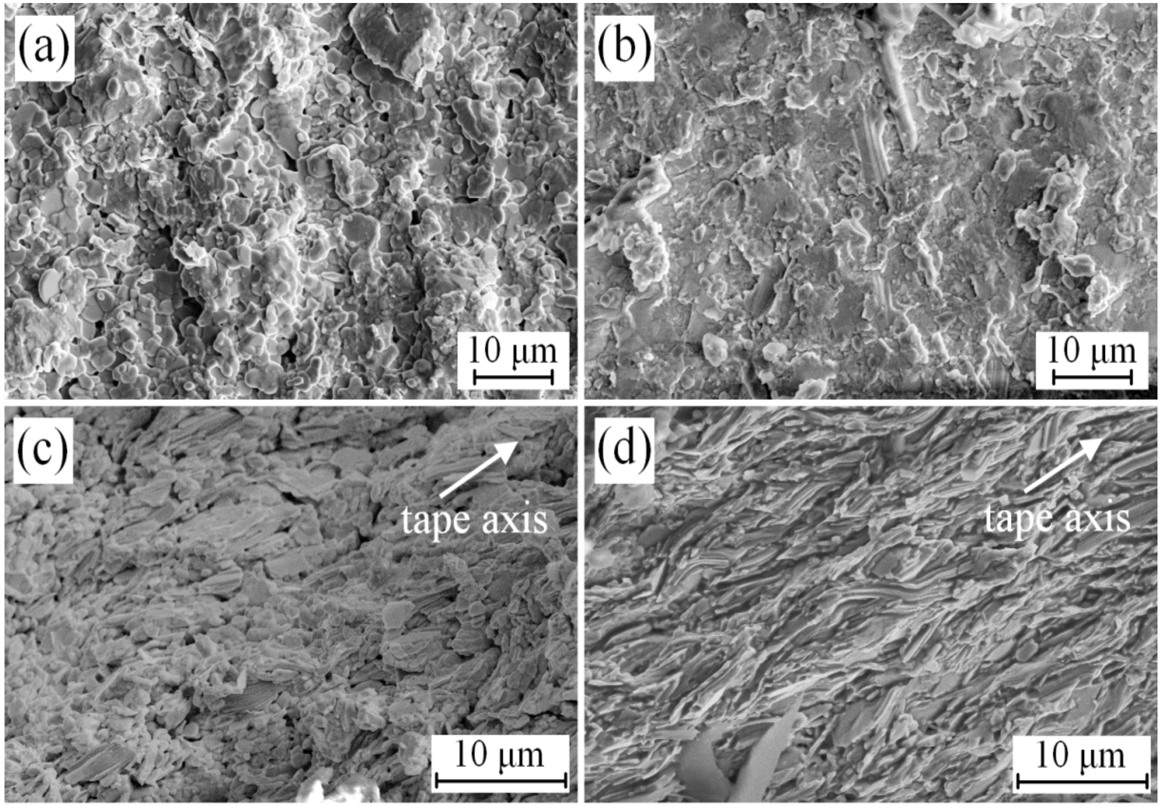

**Hot pressing significantly decreased the tape thickness, *ie*. from 0.44 mm to 0.3 mm.**

# Evolution of microstructure

**Sintering** **Hot pressing**

**Planar view**

**Longitudinal Cross-section**




**No microcracks**

**Sintered tapes: loose microstructure from more voids, and/or cracks**

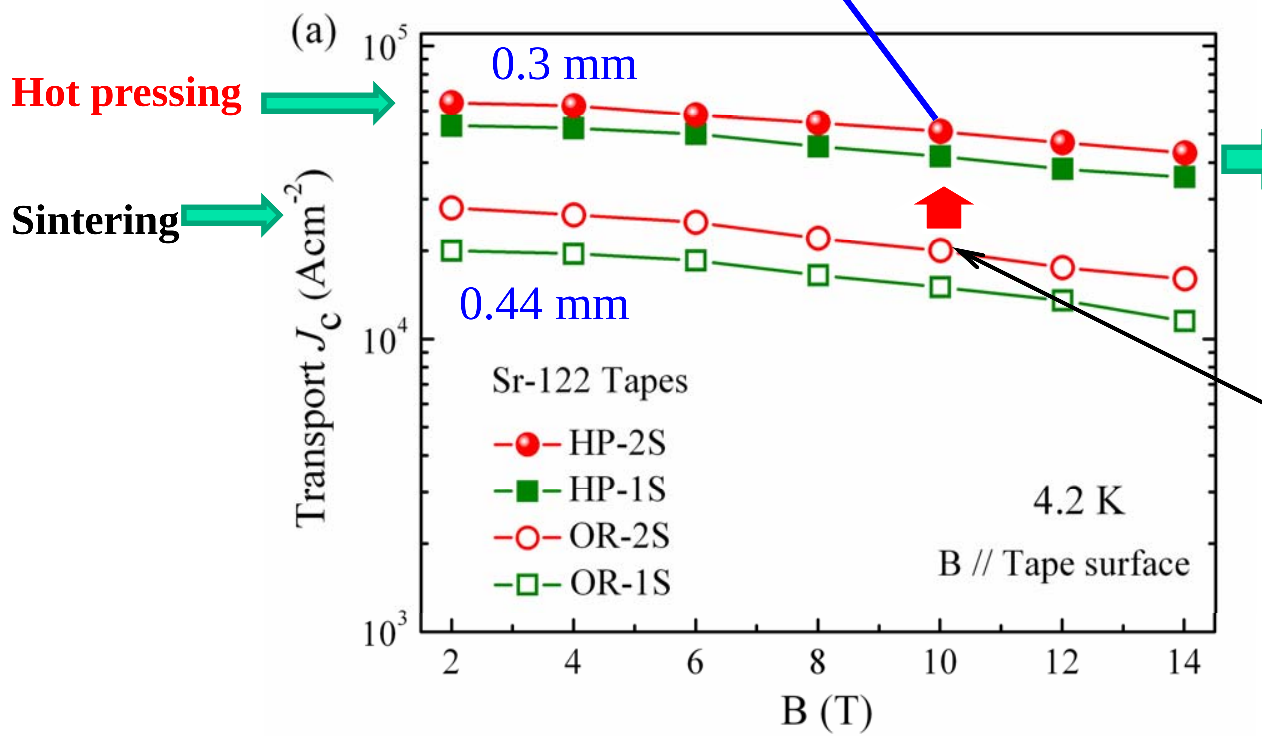
**HP tapes: higher density with fewer voids**

# High transport $J_c$ in HP 122/Ag tapes

## $J_c = 5.1 \times 10^4$ A/cm$^2$ (4.2 K, 10 T)

-- **Ag sheath**

**Strong enhancement**




**At 14T:**
**$J_c = 4.3 \times 10^4$ A/cm$^2$**

Sintering tapes:
$J_c = 2.0 \times 10^4$ A/cm$^2$

**Hot pressing is very effective to achieve high density core, thus significant increase in $J_c$-$B$.**

Lin, et al., ***Sci. Rep.*** 4, 4465 (2014)

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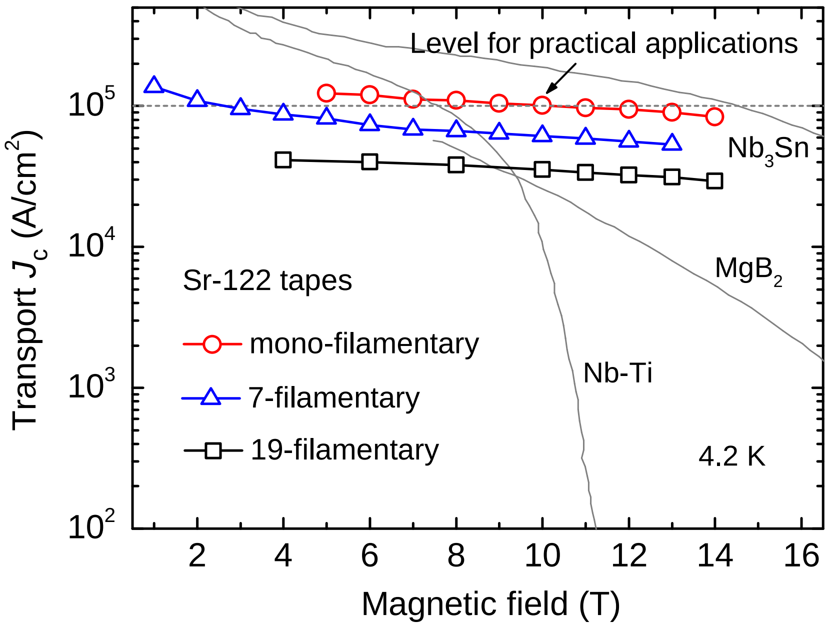
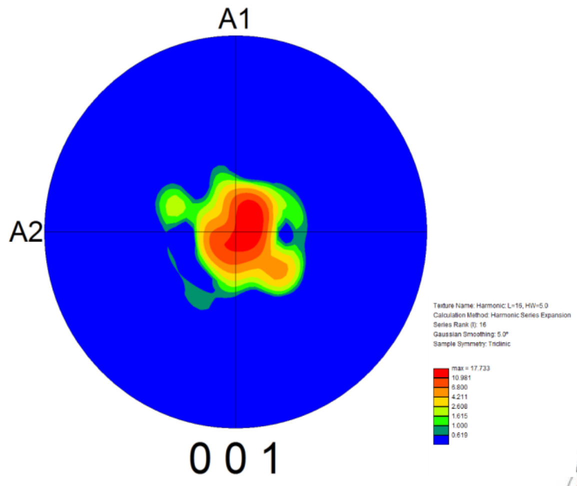
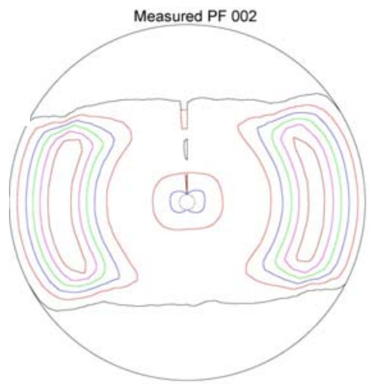
## By pressure optimization

Record transport $J_c$ values were achieved in 122/Ag tapes: $J_c > 10^5$ A/cm$^2$ (4.2 K, 10 T)



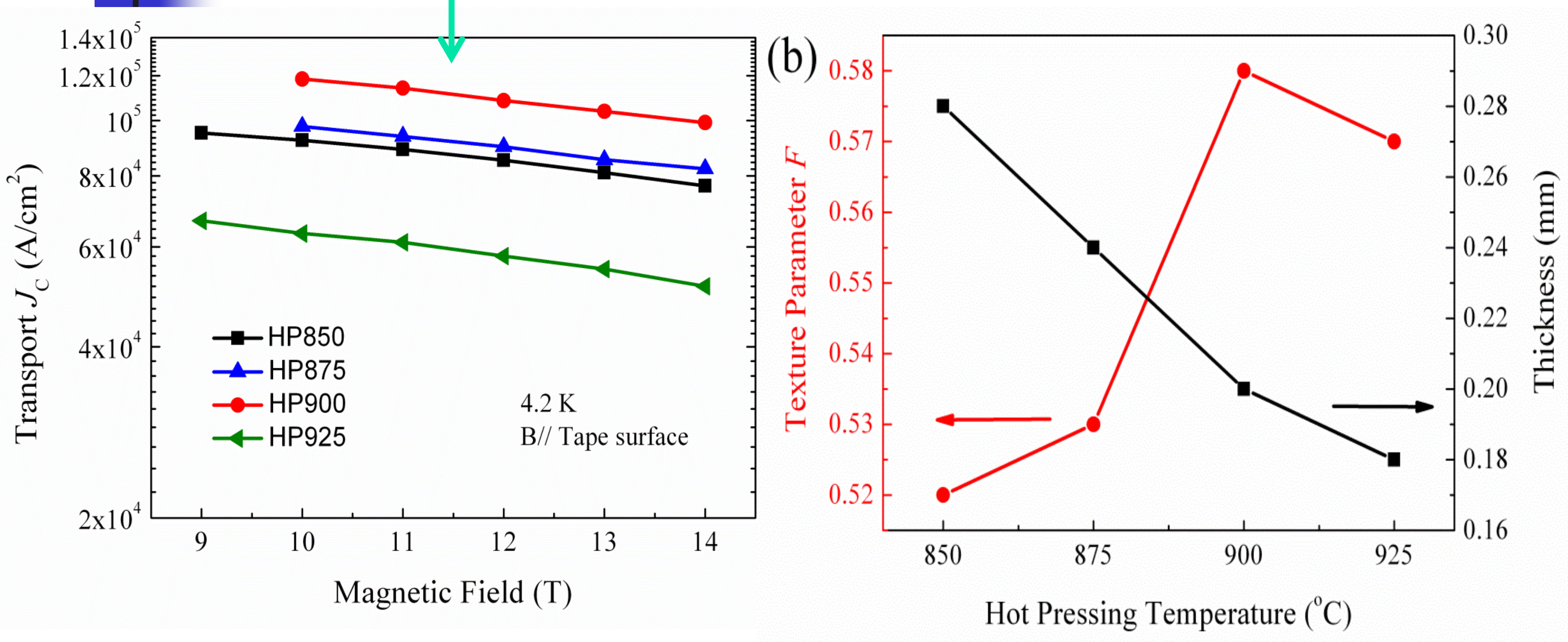




**The superior $J_c$ can be attributed to higher grain texture and improved densification.**

**Zhang et al., *APL* 104 (2014) 202601**

## By temperature optimization

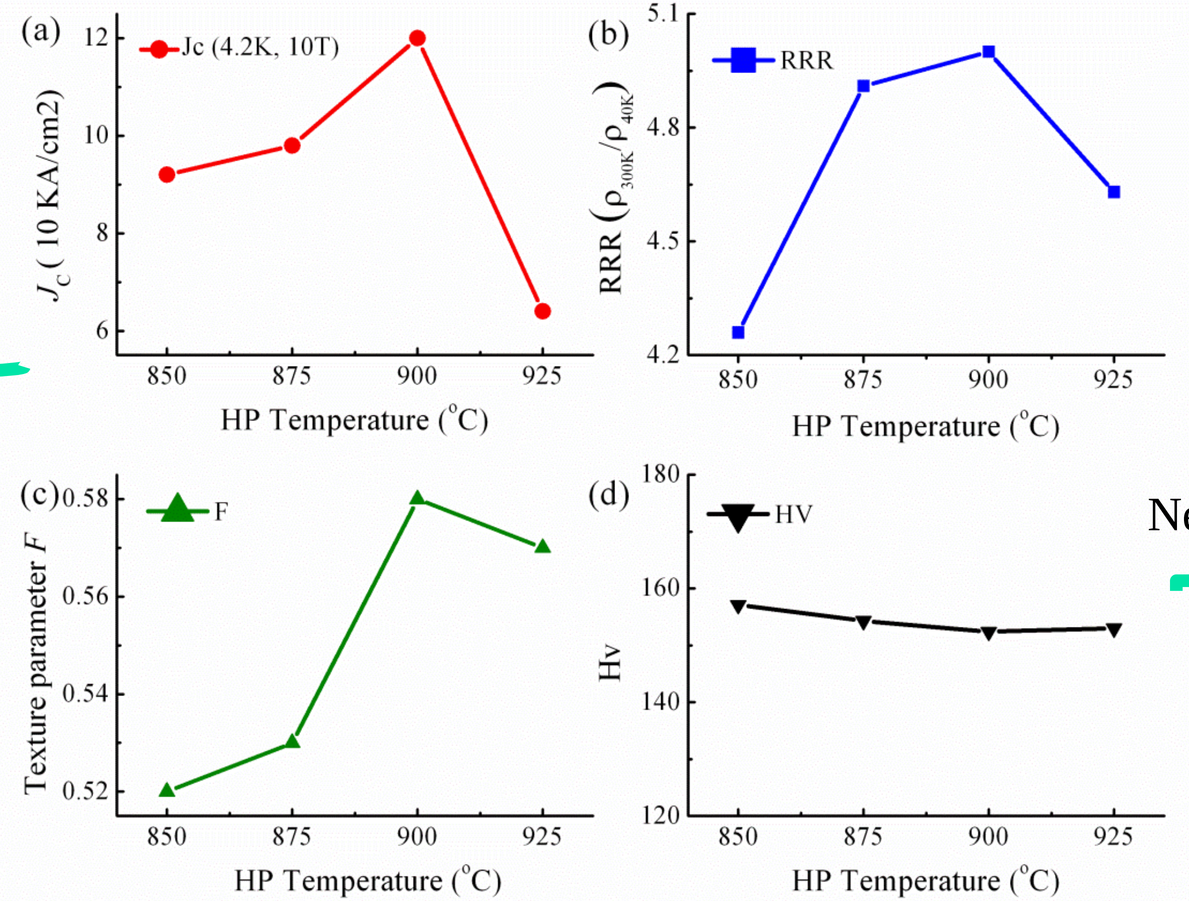
The new record transport $J_c$ values were achieved in 122/Ag tapes: $J_c \sim 1.2\times10^5$ A/cm$^2$ (4.2 K, 10 T)




1. **The $J_c$ was over $10^5$ A/cm$^2$ at 13 T;**
2. **The $J_e$ was about $2.6\times10^4$ A/cm$^2$ at 10T.**

*Sci. Rep.* 4(2014)4964

# Texture and hardness: which is dominant ?



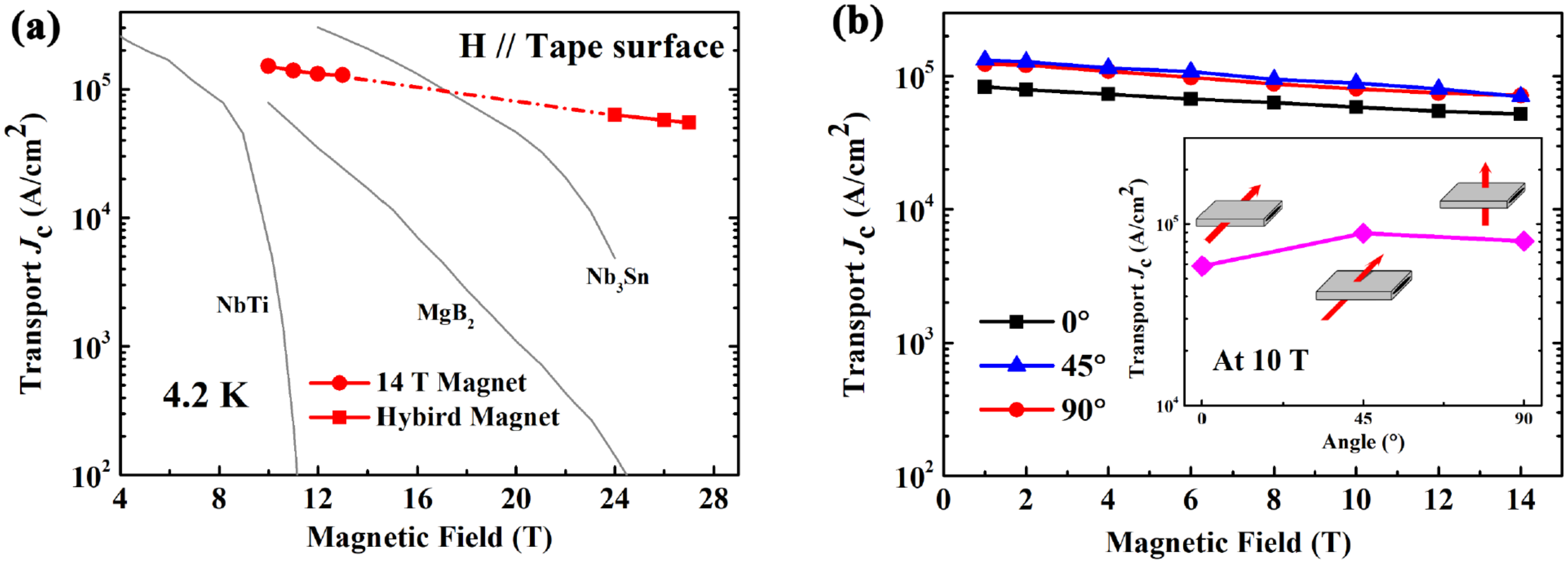

Nearly constant !

**Similar tendency appeared in the $J_c$ and texture parameter.**

**The hardness was almost saturated as soon as the hot press was applied.**

HP processed Ba122 tape

# At 4.2K, 10 T, Ic=437 A, $J_c$~150000A/cm$^2$




**At 4.2K, 14 T, $J_c$~140000A/cm$^2$**

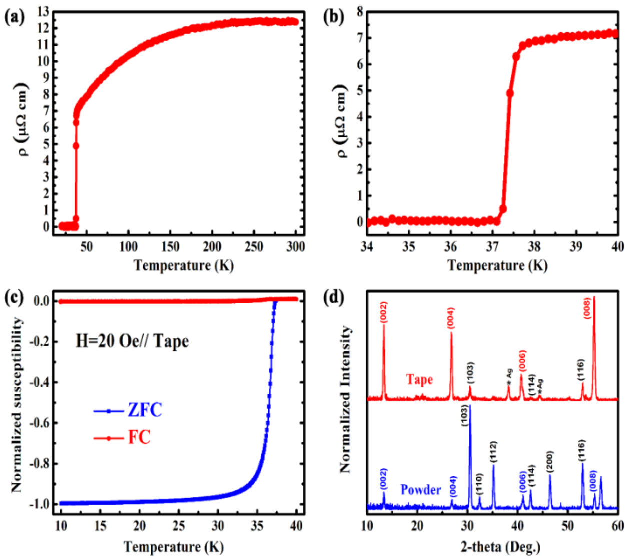
**At 4.2K, 27 T, $J_c$~55000A/cm$^2$**

**The anisotropy of Jc at 10T is 1.37**

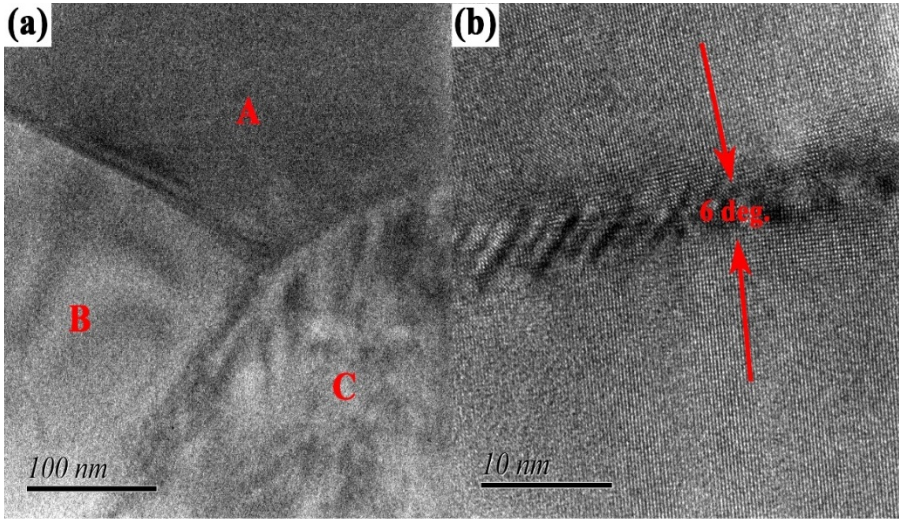
He Huang, et al., arXiv:1705.09788

# Analysis on the superconducting core

## Good crystallinity




## Clean grain boundary




Vickers hardness ~132

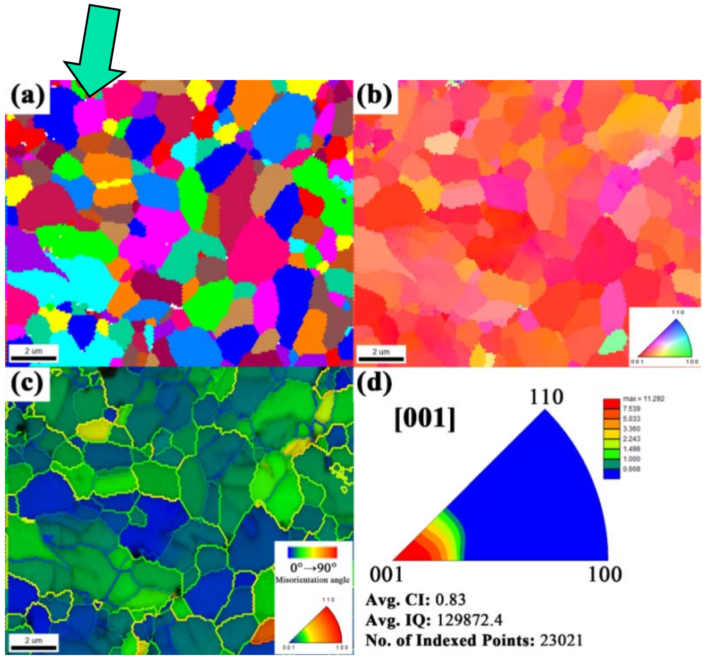
**RT: Homogeneous**
**MT: high quality superconducting phase**
**XRD: Good crystallinity, texture**

**Good connectivity !**

# Microstructure analysis: EBSD

Neighboring grains marked with different color

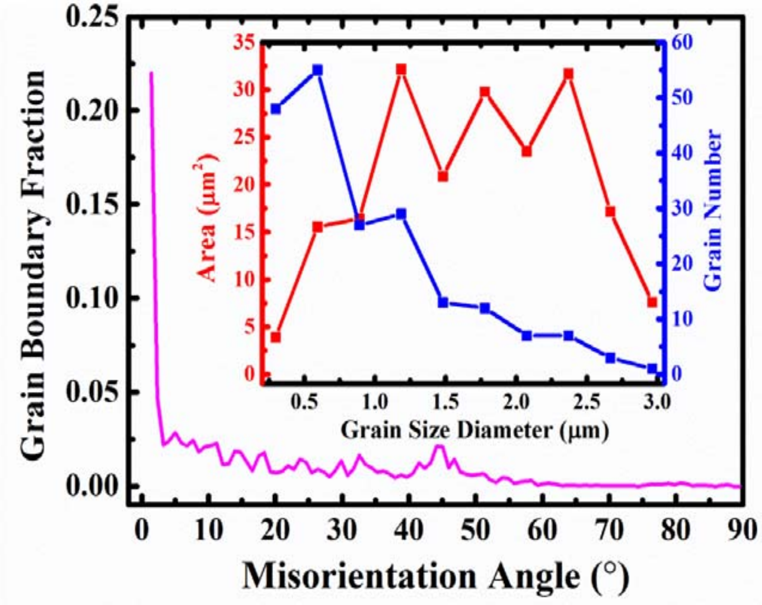
EBSD




**High texture degree !**

F value ~0.87

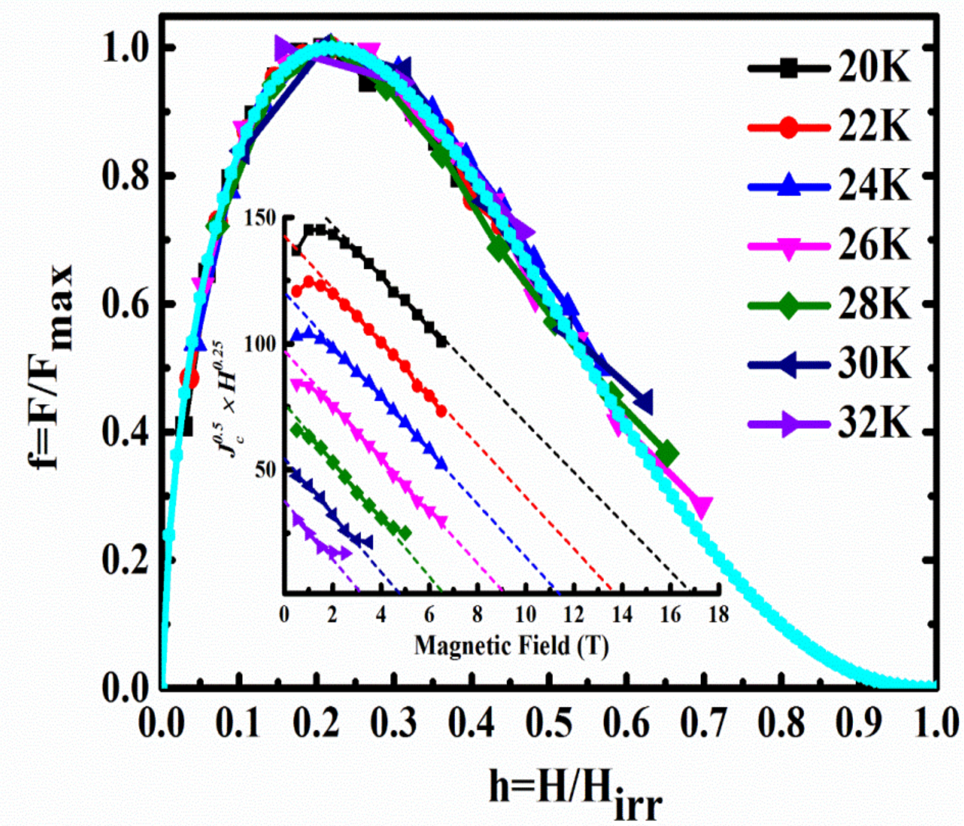
Most grains smaller than 2μm




**Small misorientation angle**

**42.8% number fraction of misorientation angle <9°**

# Pinning property




function $f = Ah^p(1-h)^q$

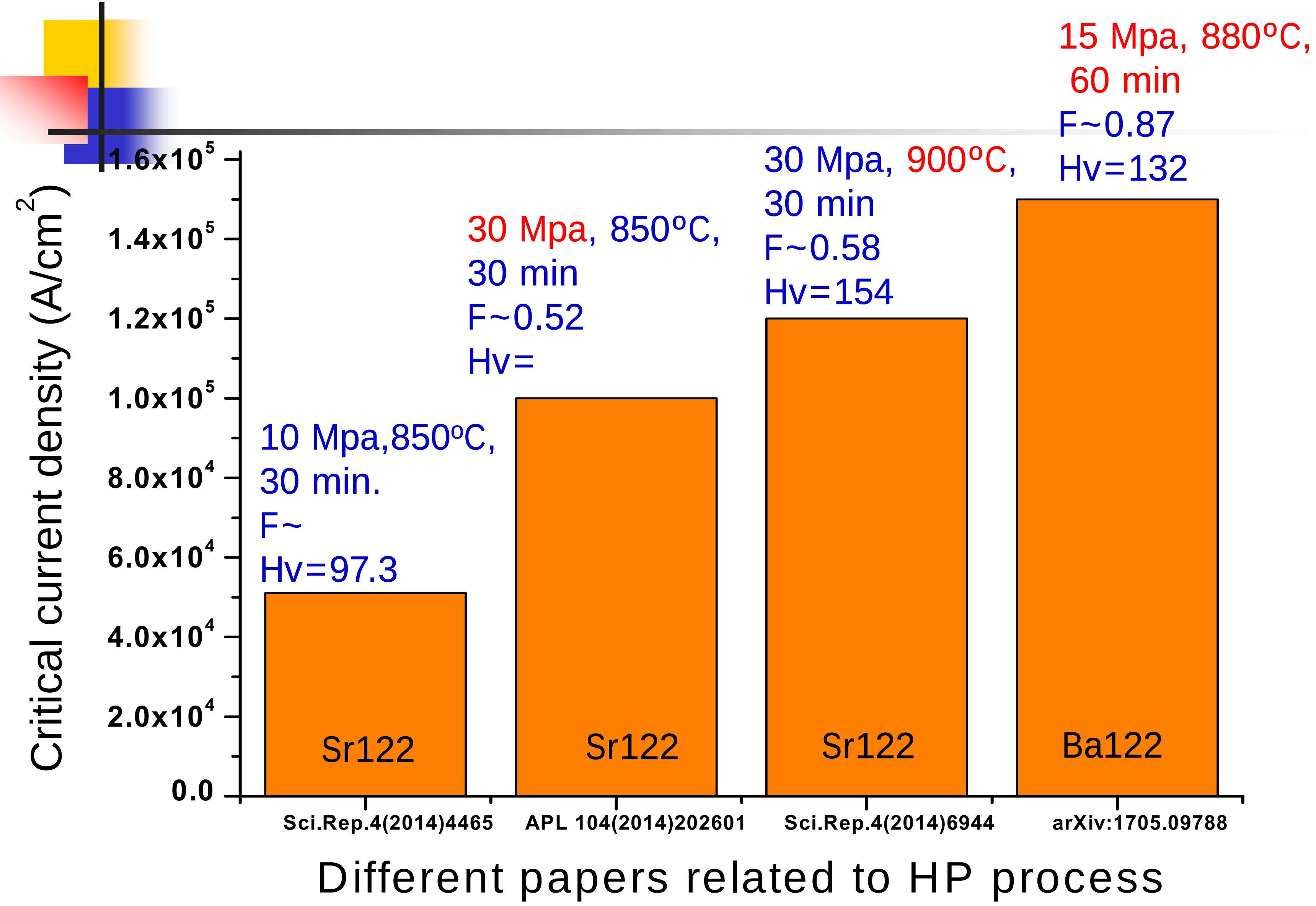
The $h_{max}$ value is close to 0.2

**The dominant pinning is Grain boundary pinning**

**The Small grain size is beneficial to the improvement of vortex pinning property.**

**Similar with the HP Sr-122, $Nb_3Sn$ and $MgB_2$ superconducting wires**

# Optimization of hot pressing parameter



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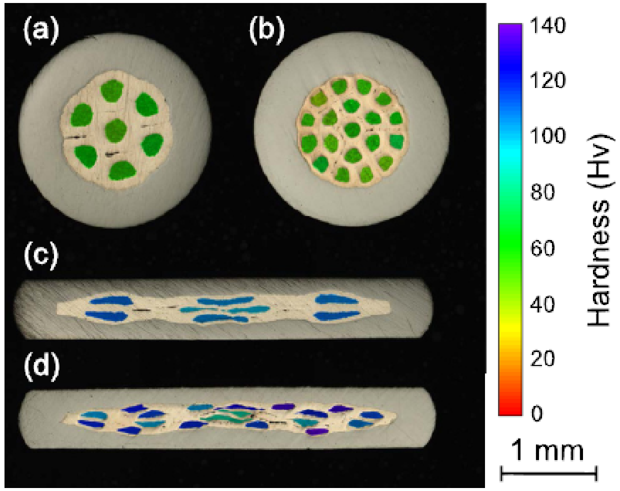
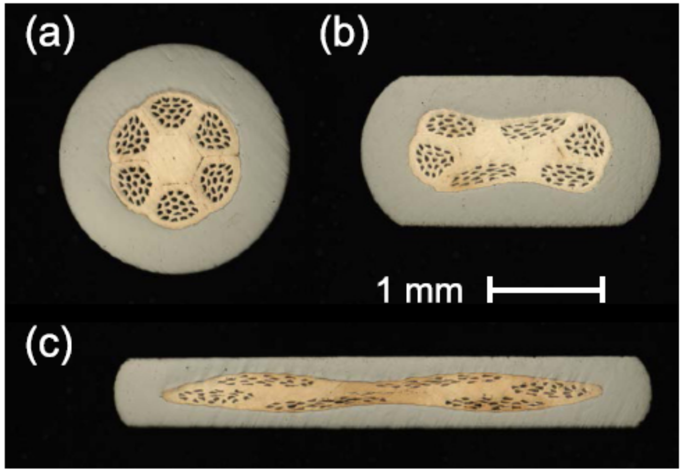
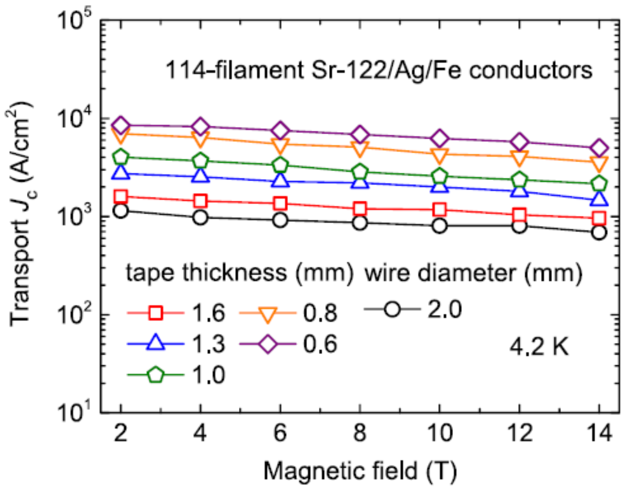
# Sr-122/Ag-Fe multifilamentary wires



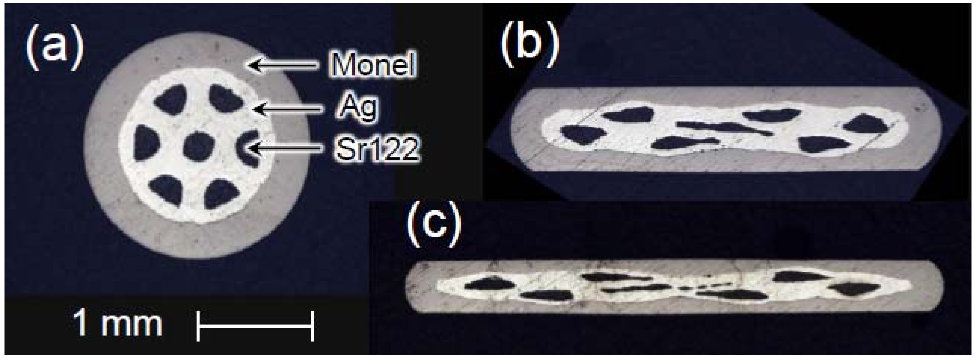




**7/ 114 filamentary Sr122 tapes**

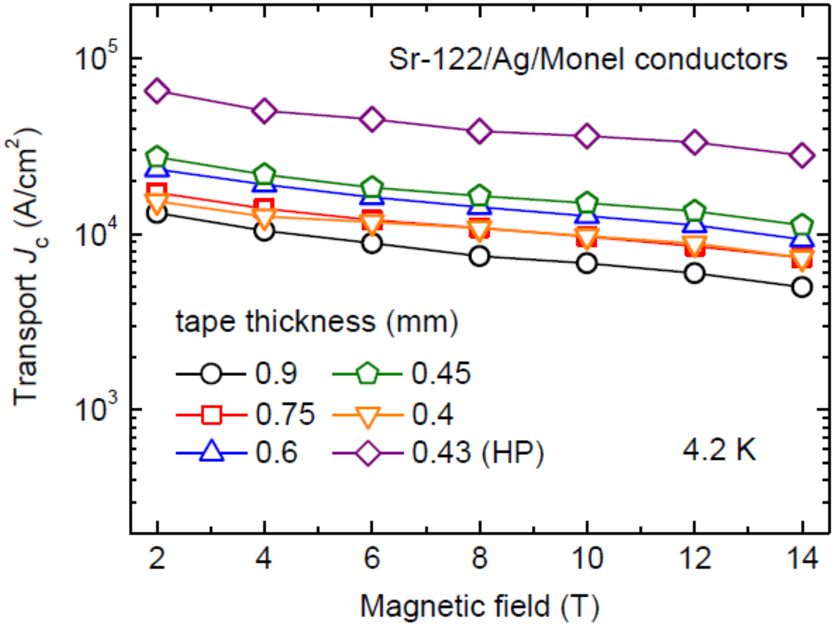
**Weak field dependence of Jc**

Yao et al., *JAP* 1118, 203909 (2015)

# Fabrication and transport properties of Sr-122/Ag-Monel multifilamentary wires by rolling process



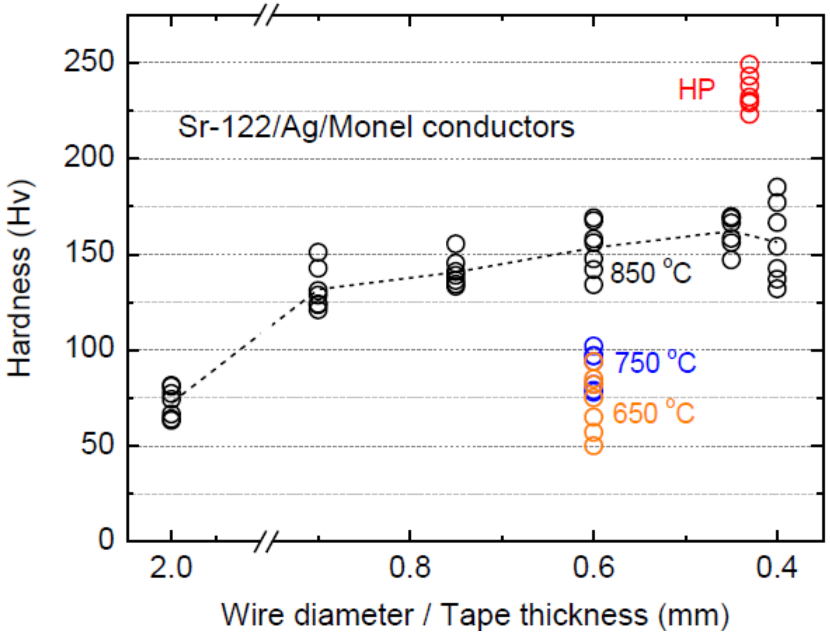

$3.6 \times 10^4 A/cm^2$

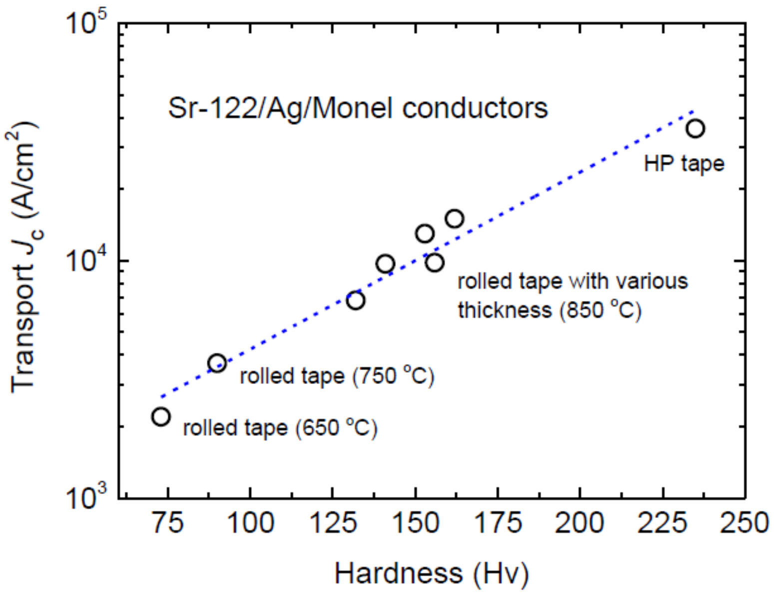


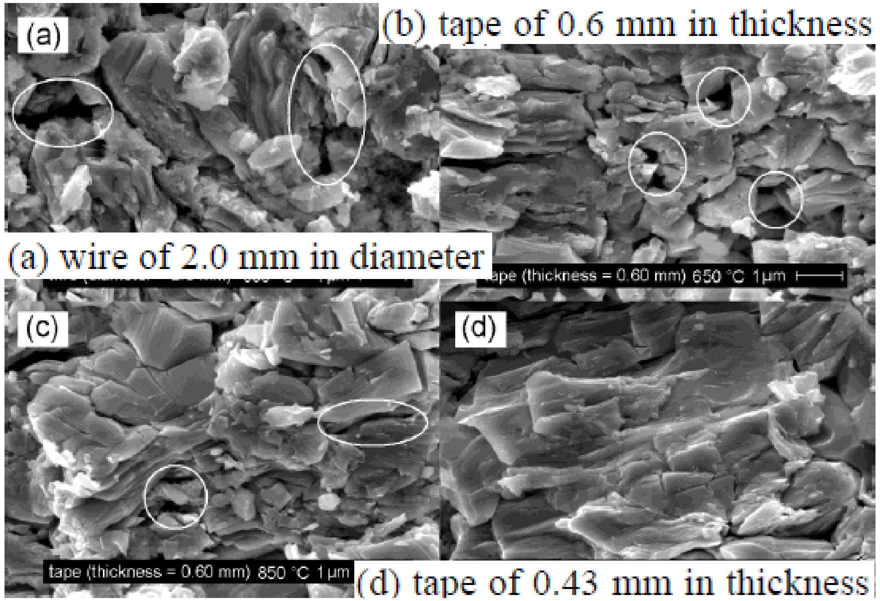

- The transport $J_c$ achieved 36 kA/cm$^2$ at 4.2 K/10T
- Very weak magnetic field dependence at high fields.

Yao et al., *SuST*, 30, 075010 (2017)

# Density is an important factor in the Jc improvement



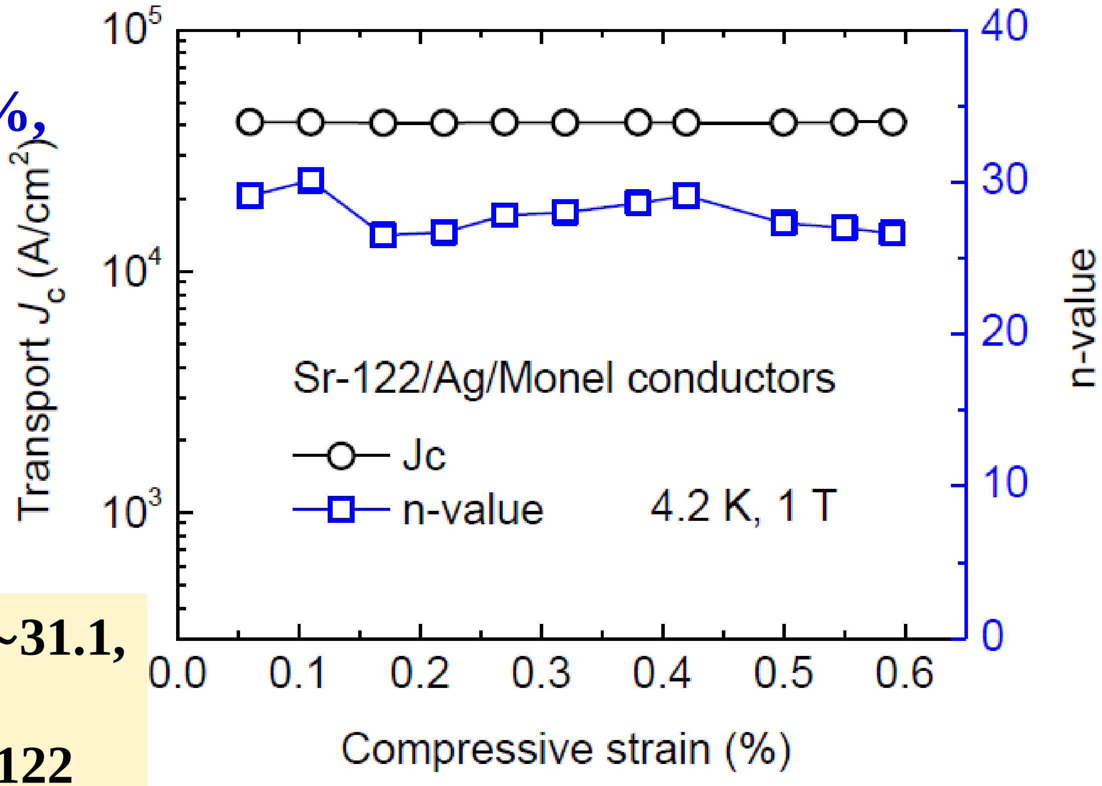




(a) wire of 2.0 mm in diameter
(b) tape of 0.6 mm in thickness
(d) tape of 0.43 mm in thickness

**Hardness of the Sr-122 phase decreases with the decrease of annealing temperature**

# Good compressive strain property of the Sr-122/Ag/Monel tape

**Axial compressive strain increases from 0.06% to 0.6%, Jc exhibits almost no degradation.**



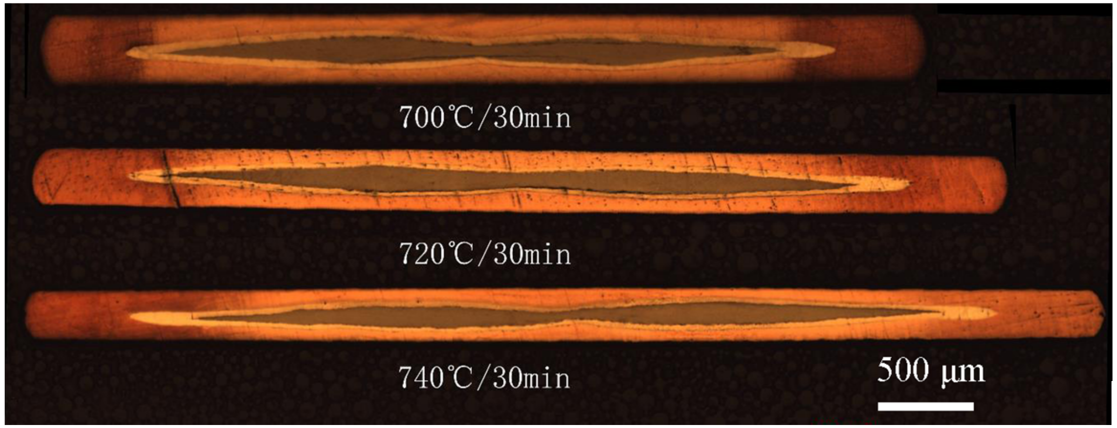

Ti-6Al-4V U-shaped bending spring (U-spring)

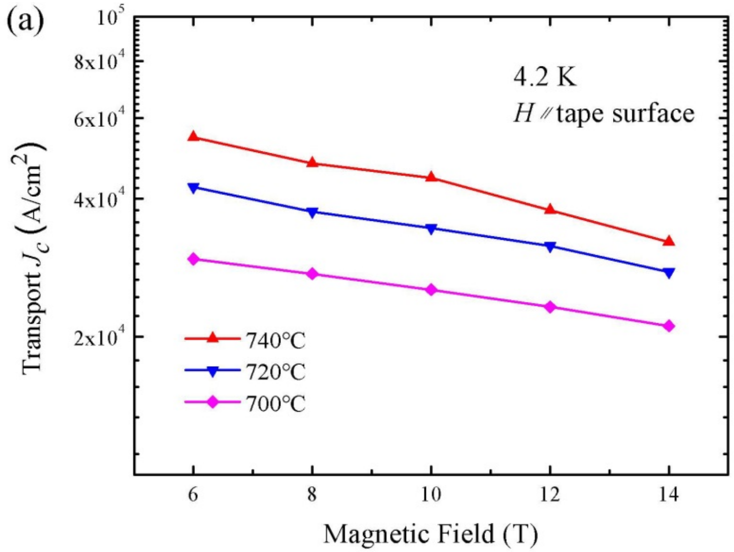
**n-values are in the range of 26.5~31.1, indicating:**

- **Good homogeneity of the Sr-122 filaments;**
- **Weak dependence on compressive strain.**

# Copper as the sheath material

Good property of copper: Low cost, high thermal stability

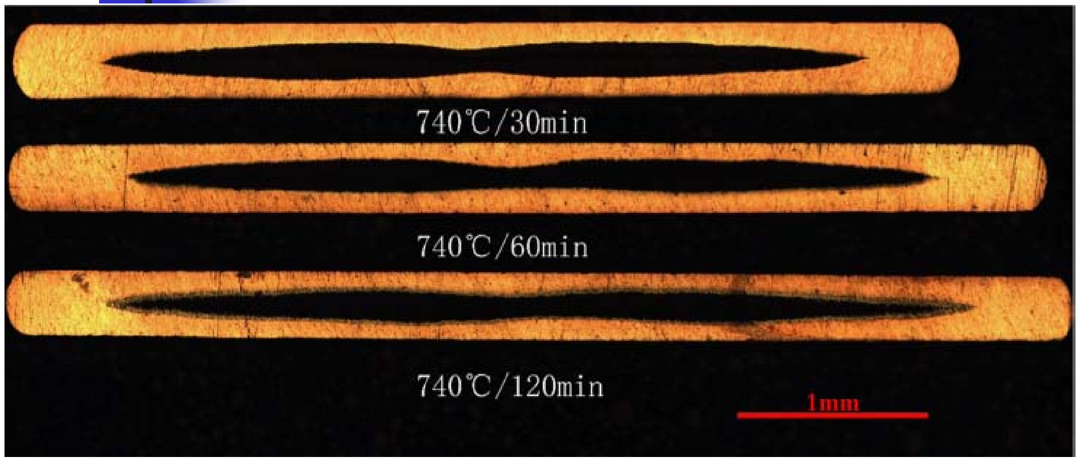


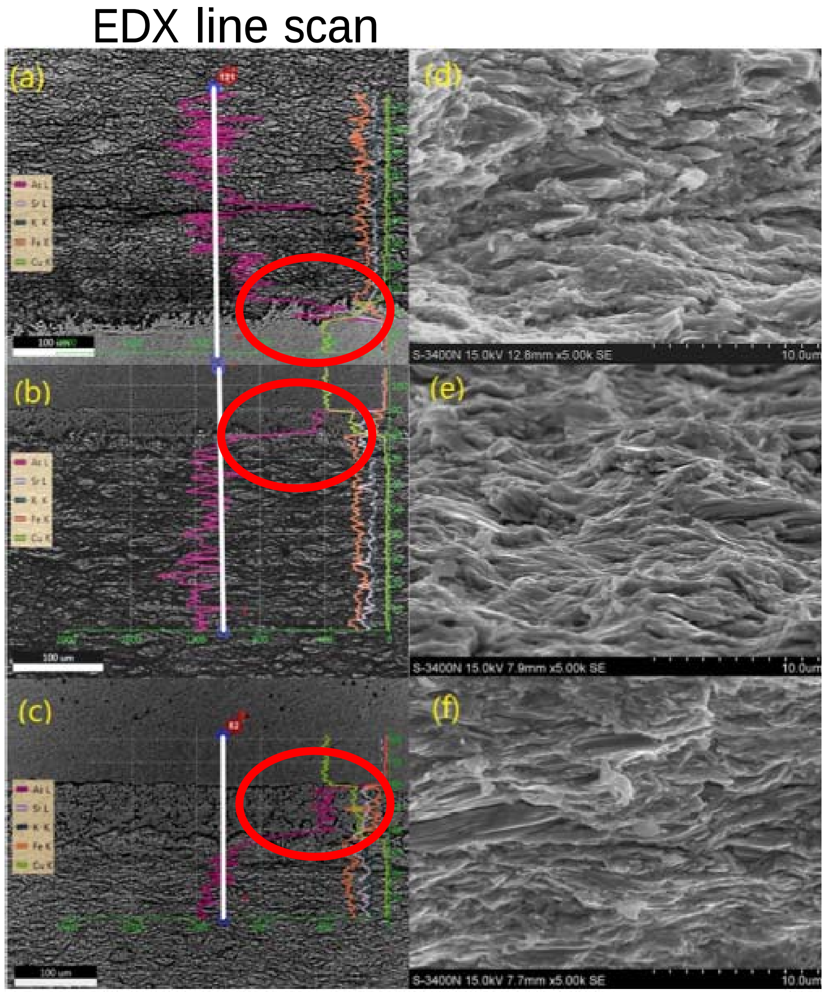

**Reaction layer is the main problem**

**Low sintering temperature is one way**

# Copper as the sheath material



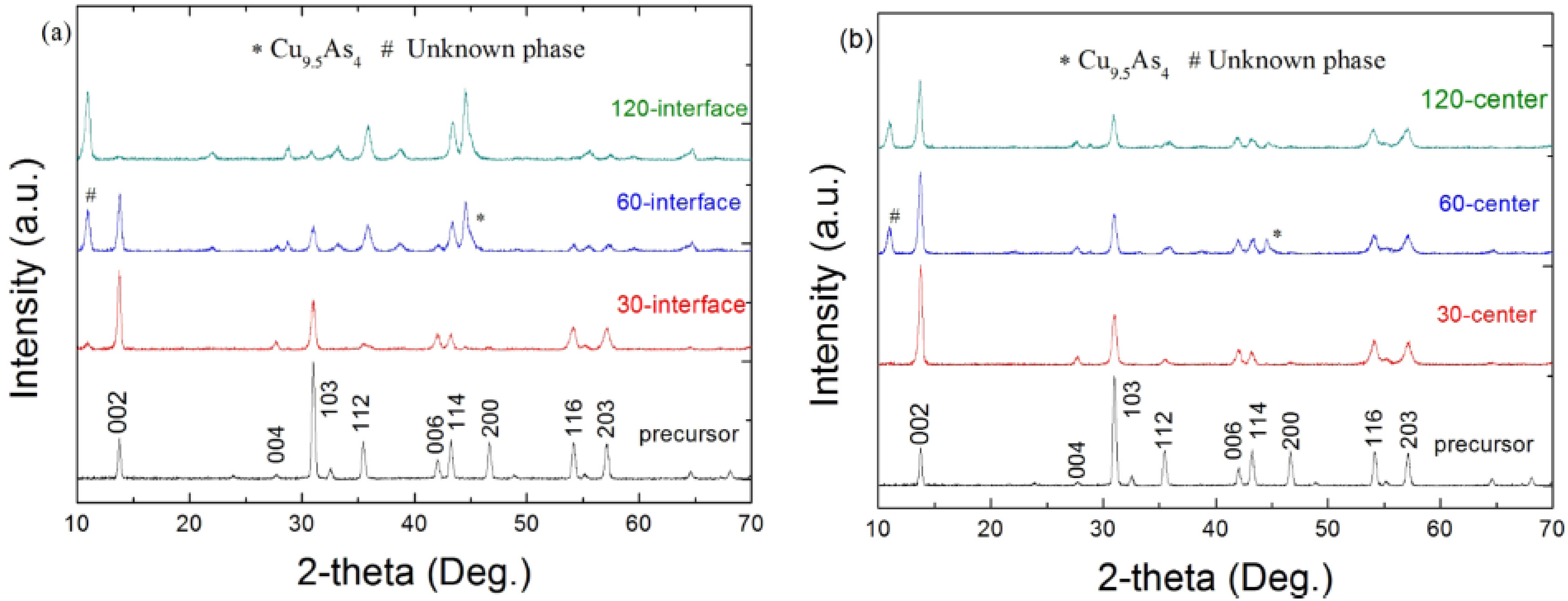

Supercond. Sci. Technol. **29** (2016) 095006




**The thickness of the reaction layer increased with heat temperature increasing.**

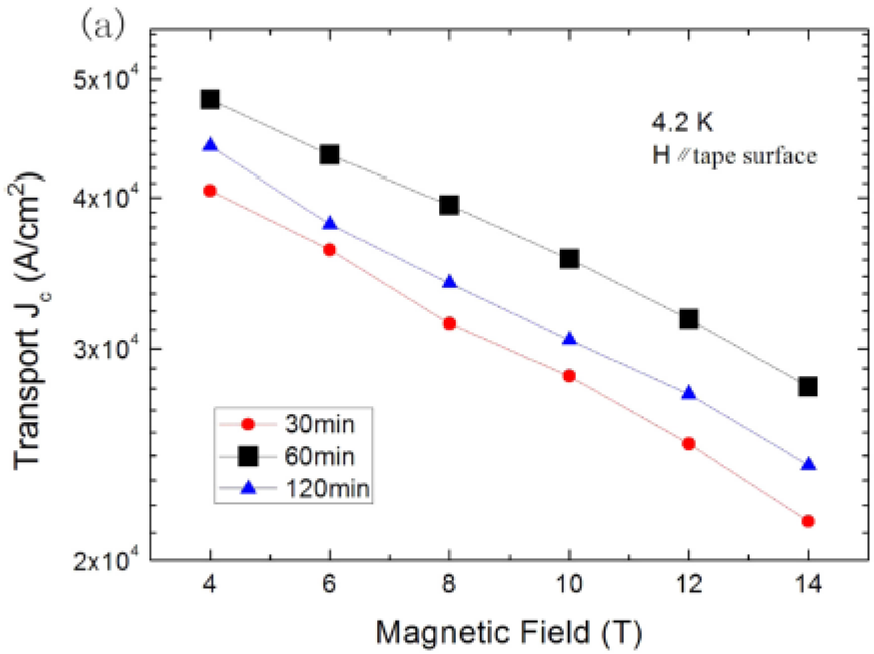
**From several micron to 25 micron**

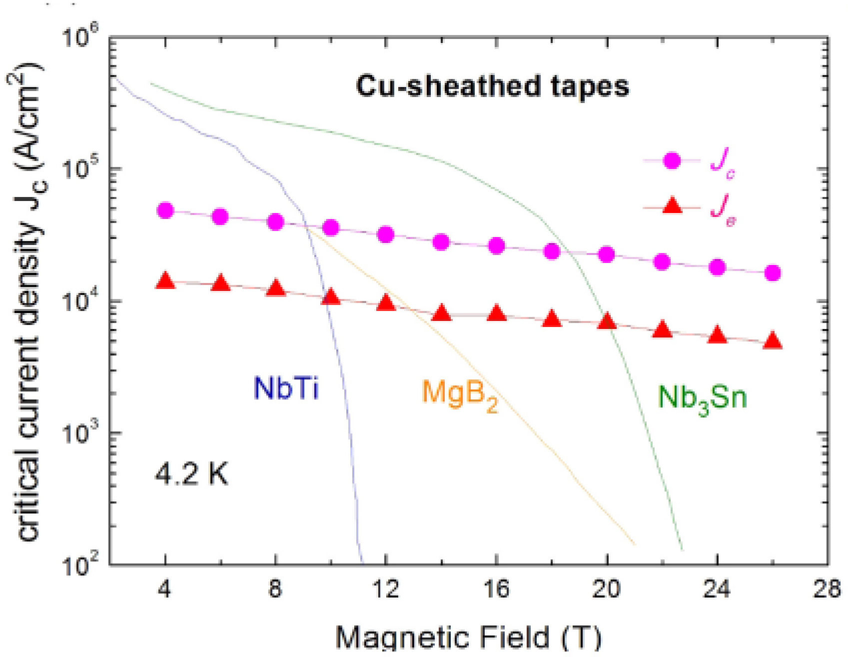
# Reaction layer




**Even at 740$^{o}$C, an impurity phase is produced when the sintering time is longer than 30 min.**

# $J_c$ property




**4.2K,10T, Jc~3.5×$10^4$A/$cm^2$**

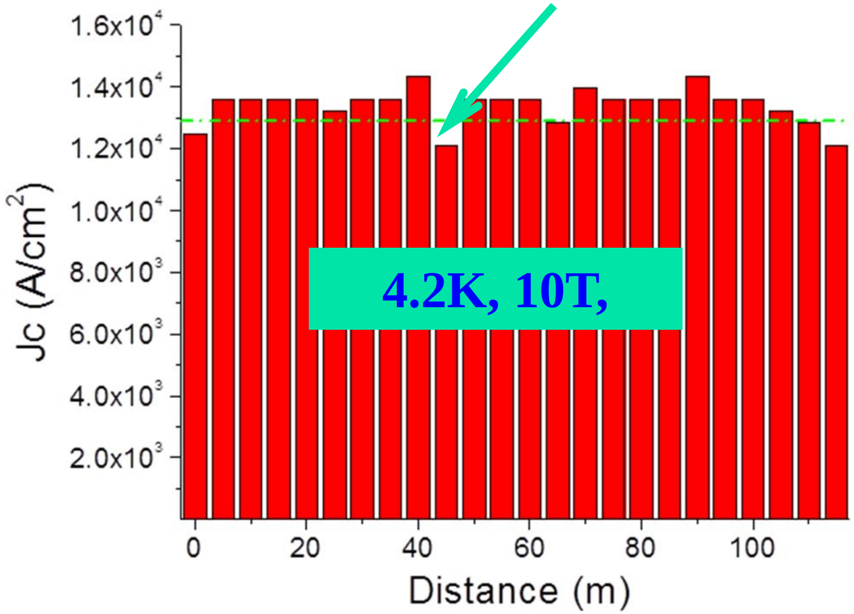
**Je~$10^4$A/$cm^2$**

**At 4.2K, 26T, Jc~ 1.6×$10^4$A/$cm^2$**

**Copper is a promising sheath material for Pnictide superconductor**

# 100m long Sr-122 tapes by rolling process

Minimum $J_c$ >12000A/cm$^2$

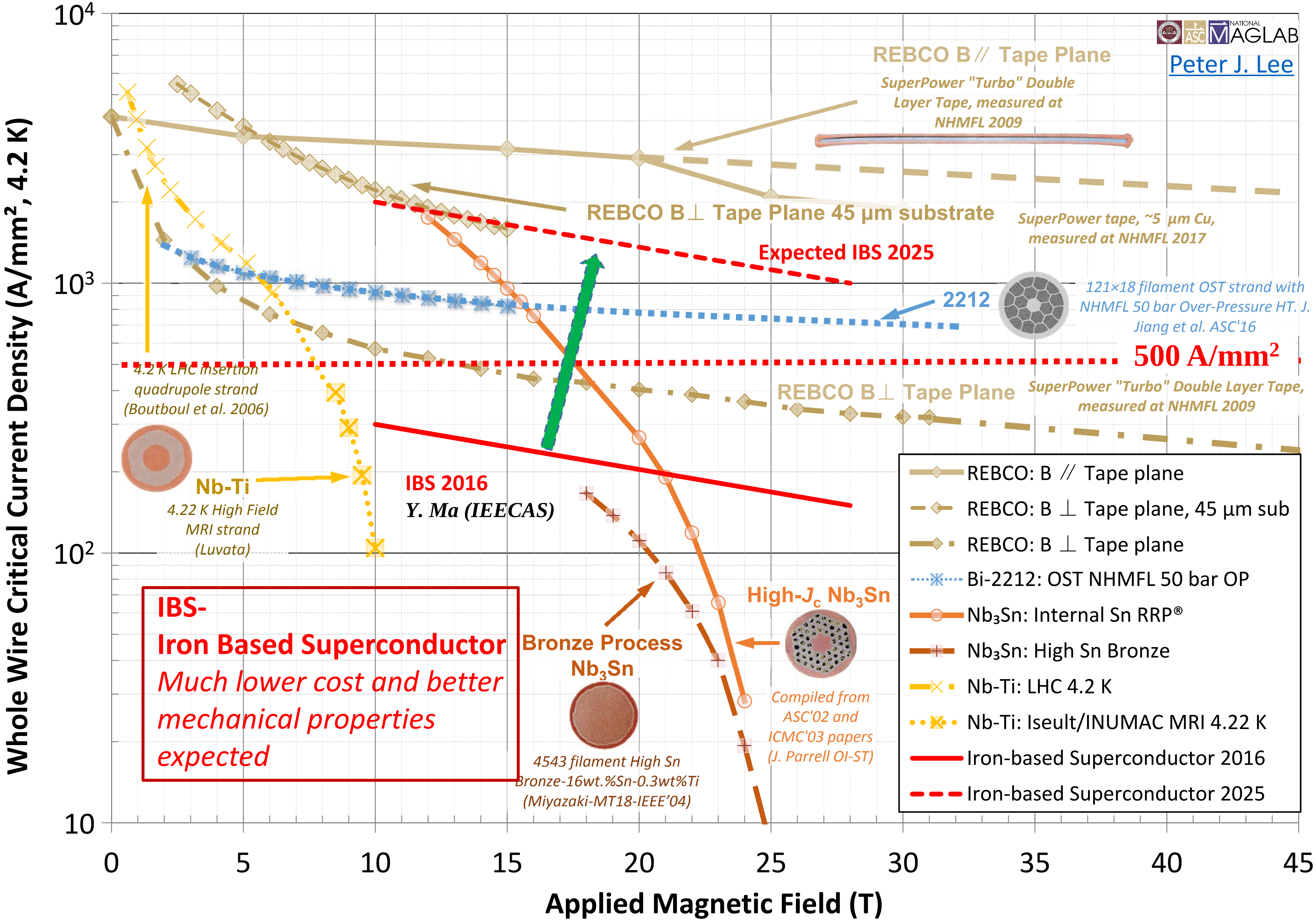



Transport Jc distribution along the length of the first 100 m long 7-filament Sr122 tape

Wire


Tape

# Prospects


Peter J. Lee
MAGLAB
REBCO B // Tape Plane
SuperPower "Turbo" Double Layer Tape, measured at NHMFL 2009
REBCO B ⊥ Tape Plane 45 µm substrate
SuperPower tape, ~5 µm Cu, measured at NHMFL 2017
Expected IBS 2025
2212
121×18 filament OST strand with NHMFL 50 bar Over-Pressure HT. J. Jiang et al. ASC'16
500 A/mm²
4.2 K LHC insertion quadrupole strand (Boutboul et al. 2006)
REBCO B ⊥ Tape Plane
SuperPower "Turbo" Double Layer Tape, measured at NHMFL 2009
Nb-Ti
4.22 K High Field MRI strand (Luvata)
IBS 2016
Y. Ma (IEECAS)
High-$J_c$ $Nb_3Sn$
Bronze Process $Nb_3Sn$
4543 filament High Sn Bronze-16wt.%Sn-0.3wt%Ti (Miyazaki-MT18-IEEE'04)
Compiled from ASC'02 and ICMC'03 papers (J. Parrell OI-ST)
IBS-
Iron Based Superconductor
Much lower cost and better mechanical properties expected
REBCO: B // Tape plane
REBCO: B ⊥ Tape plane, 45 µm sub
REBCO: B ⊥ Tape plane
Bi-2212: OST NHMFL 50 bar OP
$Nb_3Sn$: Internal Sn RRP®
$Nb_3Sn$: High Sn Bronze
Nb-Ti: LHC 4.2 K
Nb-Ti: Iseult/INUMAC MRI 4.22 K
Iron-based Superconductor 2016
Iron-based Superconductor 2025
Whole Wire Critical Current Density (A/mm², 4.2 K)
Applied Magnetic Field (T)
$10^4$
$10^3$
$10^2$
10
0
5
10
15
20
25
30
35
40
45


# Thank you for your attention！