Mini-workshop on Accelerator, IAS Program on High Energy Physics 2018

Recent Progress on the Development of Iron-based Superconducting Wires for High-field Applications

C. Yao, H. Huang, C. Dong, D. Wang, X. Zhang, Y. Ma

Institute of Electrical Engineering, Chinese Academy of Sciences, Beijing, China

Main collaborators: S. Awaji

Institute for Materials Research, Tohoku University, Sendai, Japan

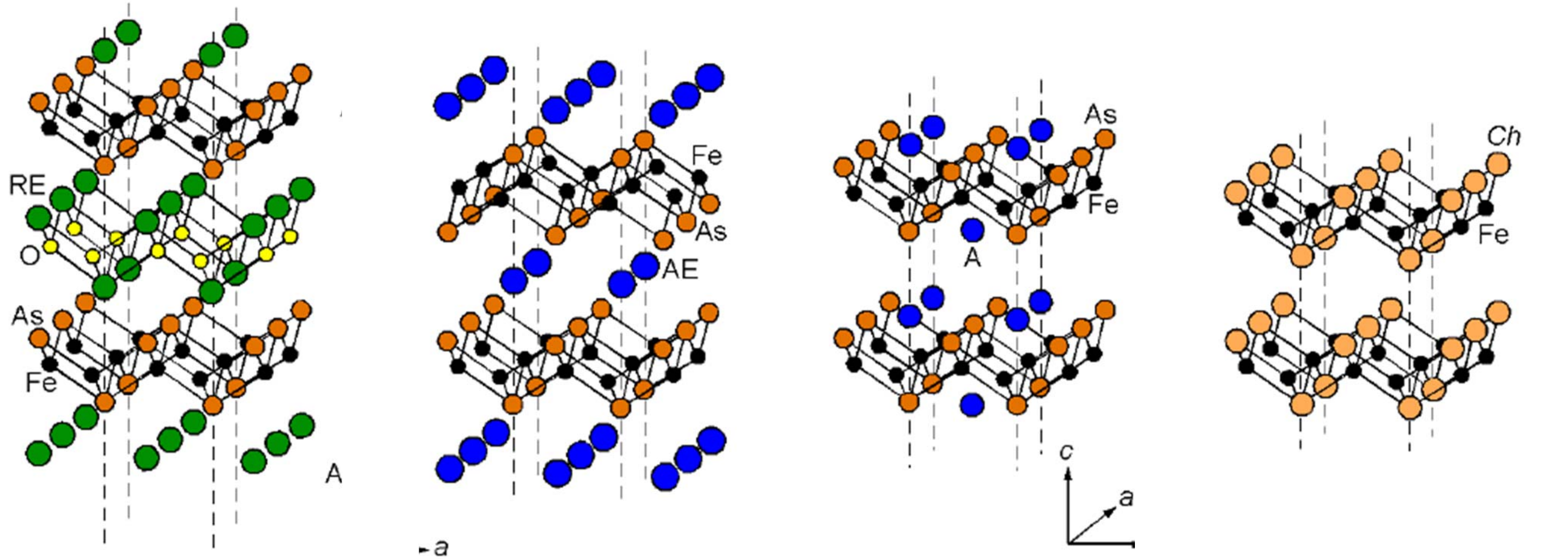
Jan 18, 2018

HKUST Jockey Club Institute for Advanced Study

Outline

1. Properties & application potential of iron-based superconductors
2. Microstructural defects & weak-link GBs in polycrystalline IBS
3. Improving the J_c-performance of IBS wires and tapes
4. Progress on practical wires for high-field applications
5. Summary & prospects

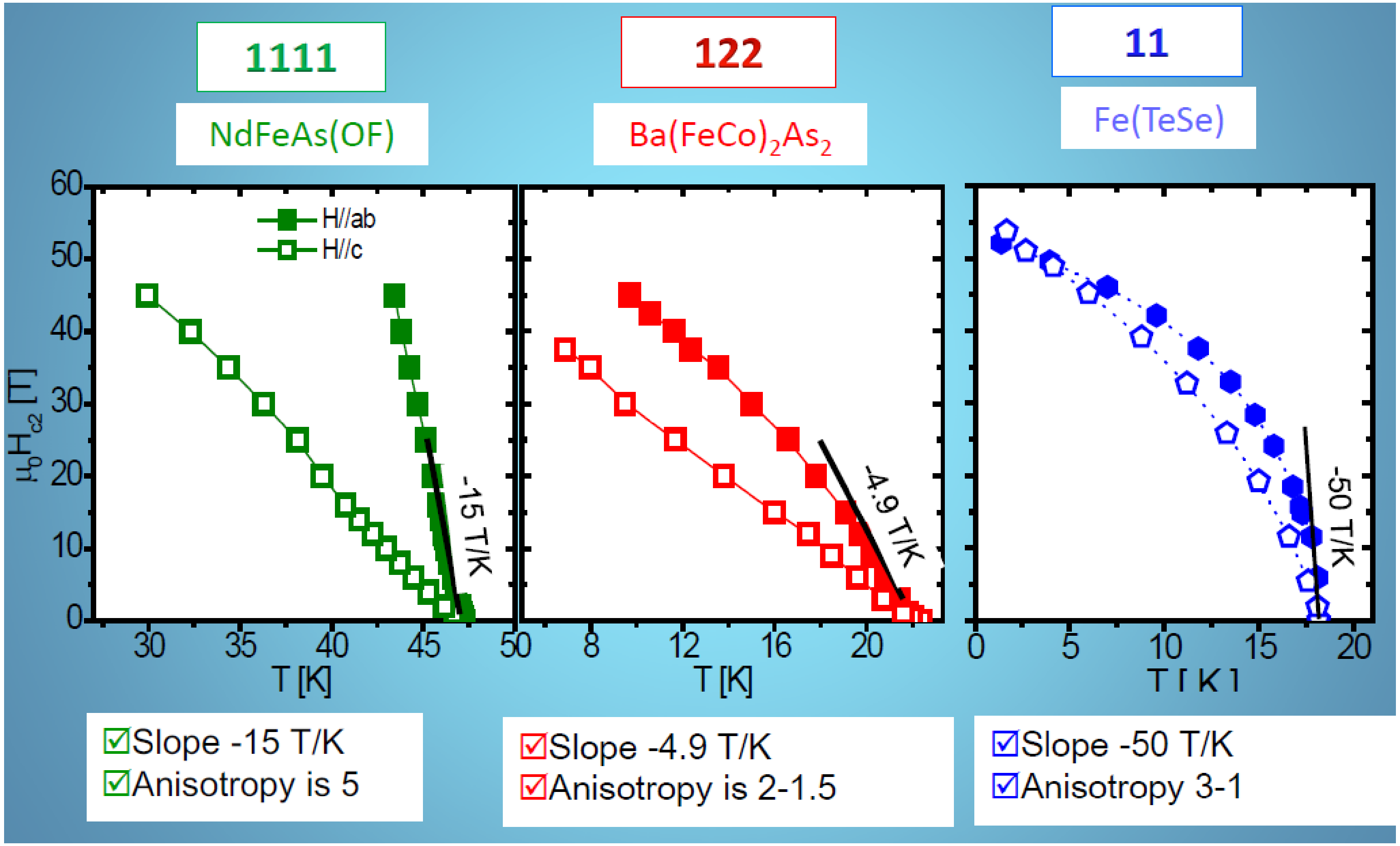
Crystal structures of iron-based superconductors



REFeAsO	$AEFe_2As_2$	AFeAs	Fe*Ch*
[1111]	**[122]**	**[111]**	**[11]**
RE: rare earth	AE: Ba, Sr	A: Li, Na	*Ch*: Se, Te, S
Kamihara, ***J. Am. Chem. Soc***, 130 3296 (2008).	M. Rotter ***Phys. Rev. Lett.*** 101,107006 (2008）	Wang ***Solid State Commun.*** 148,11 (2008)	Hsu ***Proc. Nat. Acad. Sci.*** 105 14262. (2008)
$SmFeAsO_{1-x}F_x$	$Ba_{1-x}K_xFe_2As_2$	LiFeAs	Fe(Se,Te)
T_c = 55 K	T_c = 38 K	T_c = 18 K	T_c = 16 K

- basically tetragonal with long *c*-axes including a Fe plane (*ab*-direction)
- large structural variation at blocking layer

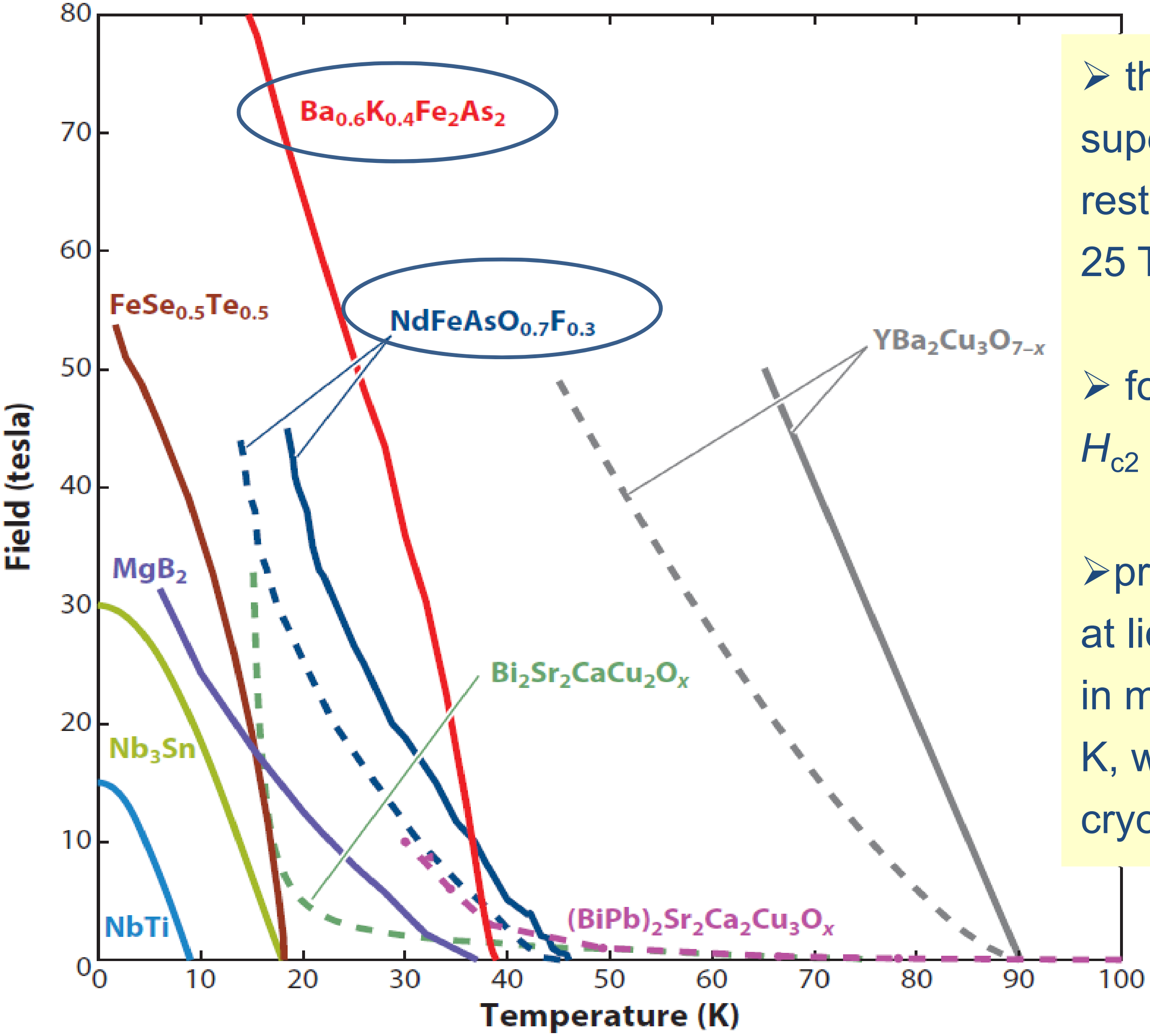
Upper critical fields of iron-based superconductors



Putti et al. 2010 *SuST* 23 034003

- exceptionally high H_{c2} for 1111- and 122-type iron-based superconductors
- small anisotropy gives high vortex stiffness

Upper critical fields of iron-based superconductors

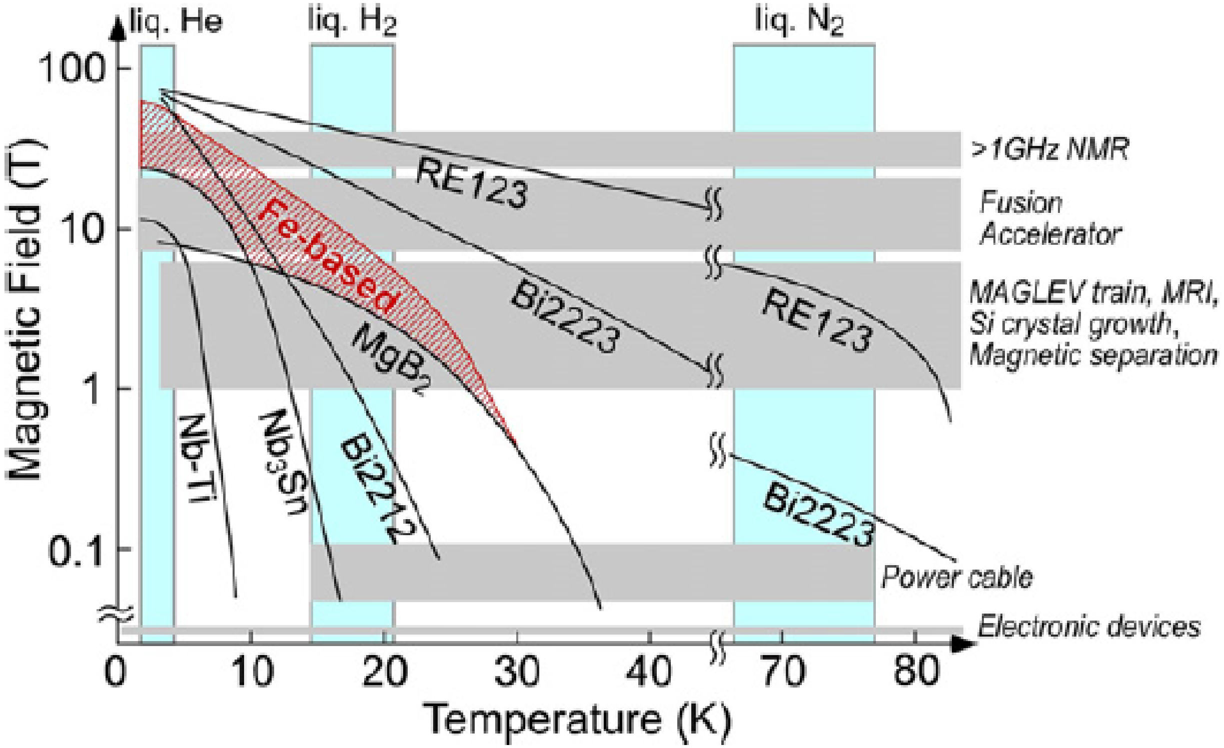


Comparative T-H phase diagram for different superconducting materials

Gurevich 2014 *Annu. Rev. Condens. Matter Phys.* 5 35

- the conventional low-*Tc* superconductors (NbTi & Nb_3Sn) restrict the magnets with field below 25 T at liquid helium temperature.
- for 1111- and 122-type IBS, the H_{c2} is still **above 40 T at 20 K**
- promising for applications operated at liquid helium temperature and also in moderate temperature around 20 K, which can be obtained by cryocoolers

Application potential of iron-based superconductors



Shimoyama 2014 *SuST* 27 044002

- T_c = 38 and 56 K in 122 & 1111 system
- ultrahigh H_{c2} > 80 T
- very small anisotropy γ= 1.5~2
- strong vortex pinning

promising candidate for:

Application potential of iron-based superconductors

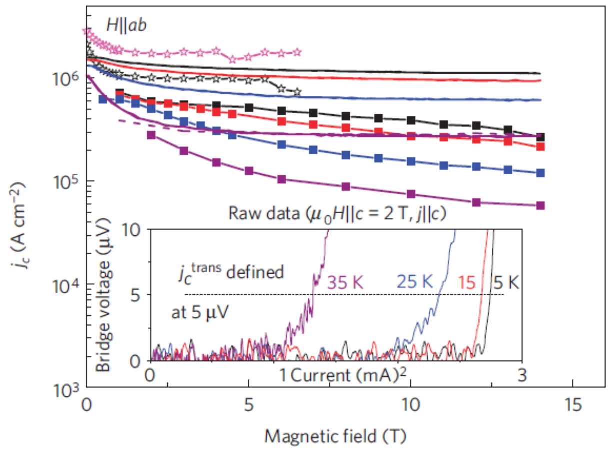
Superconductivity parameters for practical superconductors

Material	T_c (K)	$H_{c2, 4.2 K}$ (T)	Coherence length ε_{ab} (nm)	Anisotropy γ_H
Nb47wt%Ti	9	11.5	4	Negligible
Nb_3Sn	18	25	3	Negligible
MgB_2	39	25	6.5	2~2.7
YBCO	92	>100	1.5	7
Bi-2223	110	>100	1.5	50~100
Bi-2212	90	>100		50~100
Sm-1111	**55**	**>100**	**1.8~2.3**	**5~10**
Ba-122	**38**	**>80**	**1.5~2.4**	**1.5~2**
Fe(Se,Te)	**16**	**>40**	**1.2**	**1.1~1.9**

Outline

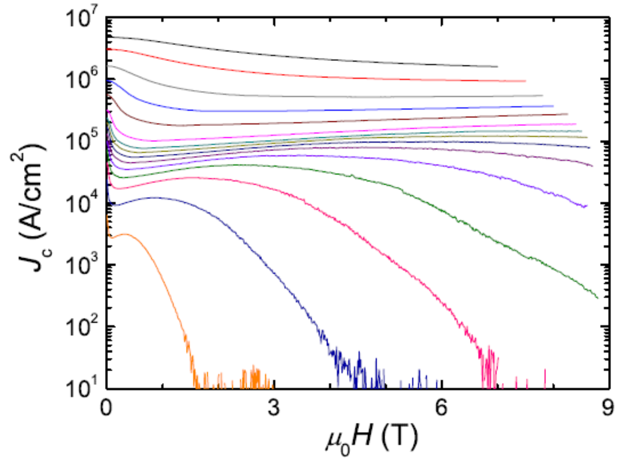
1. Properties & application potential of iron-based superconductors
2. Microstructural defects & weak-link GBs in polycrystalline IBS
3. Improving the J_c-performance of IBS wires and tapes
4. Progress on practical wires for high-field applications
5. Summary & prospects

J_c in IBS single crystals and films



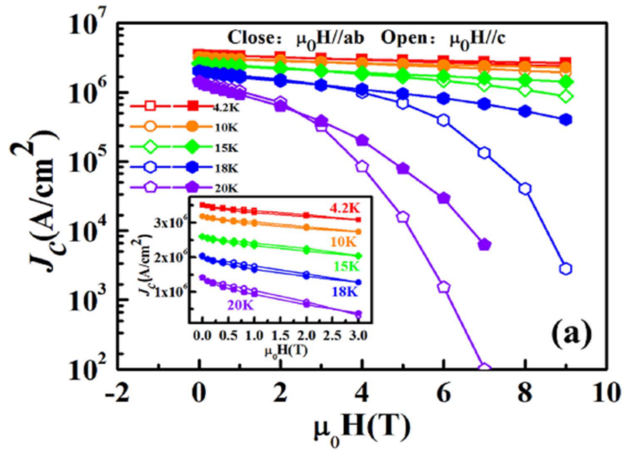
Sm-1111 single crystal

Moll 2010 *Nature Mater.* 9 628



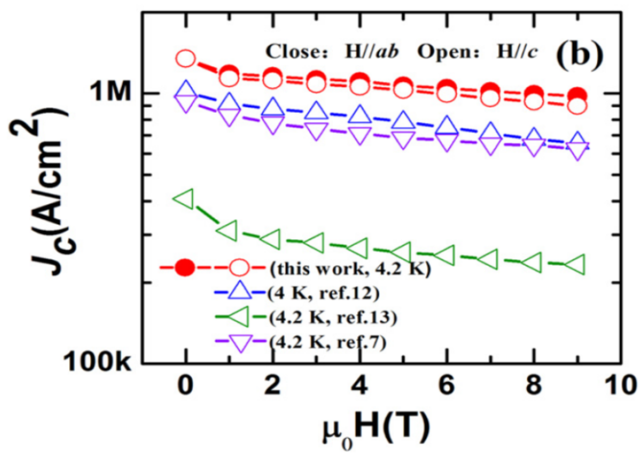
Ba-122:K single crystal

Yang 2008 *APL* 93 142506



Ba-122:Co films 2.6 MA (9 T, 4.2 K)

Yuan 2017 *SuST* 30 025001

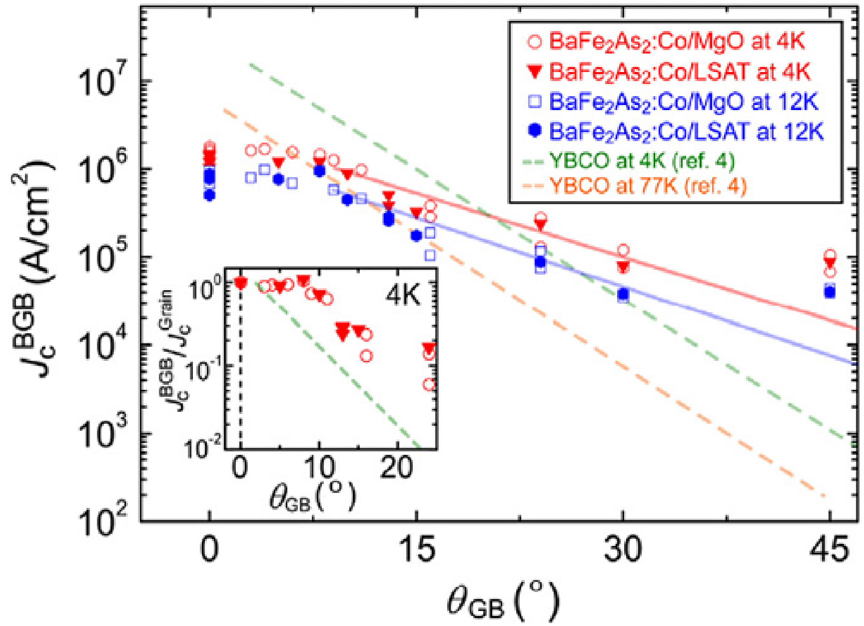


FeSeTe films 0.97 MA (9 T, 4.2 K)

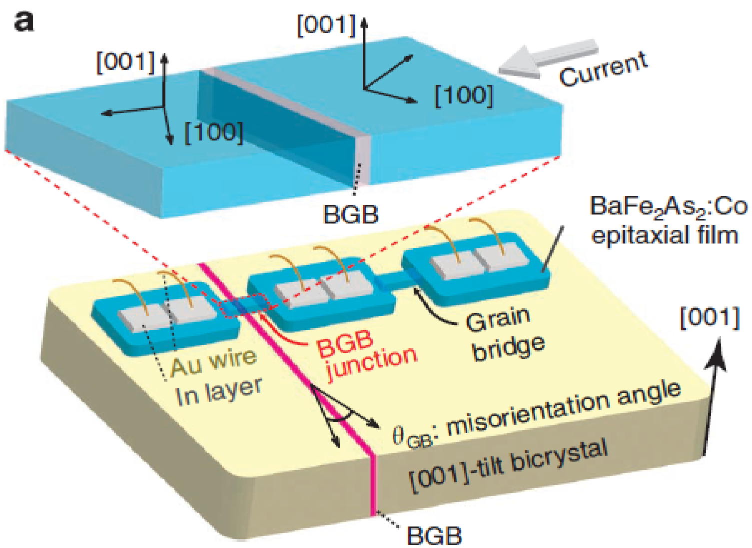
Yuan 2015 *SuST* 28 065009

- IBS single crystals and films show high in-field J_c above 1 MA
- very weak field dependence of J_c

Grain boundary nature of 122 pnictides



Katase T et al. 2011 *Nat. Commun.* 2 409

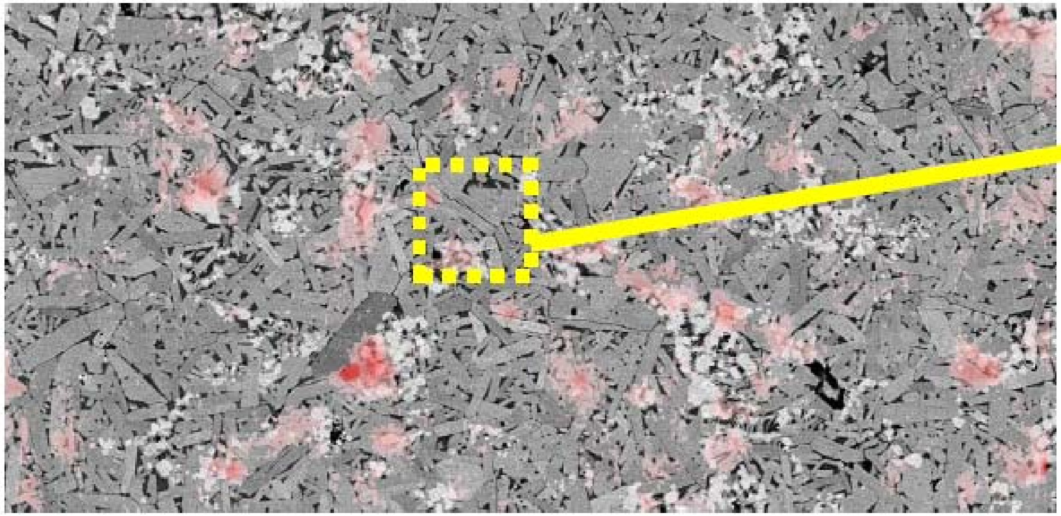


Co doped Ba-122 IBS thin films on bicrystals

- J_c decreases exponentially with increasing GB angle
- **the critical angle θ_c of Ba-122 GBs is 9°, larger than YBCO (θ_c~5°)**

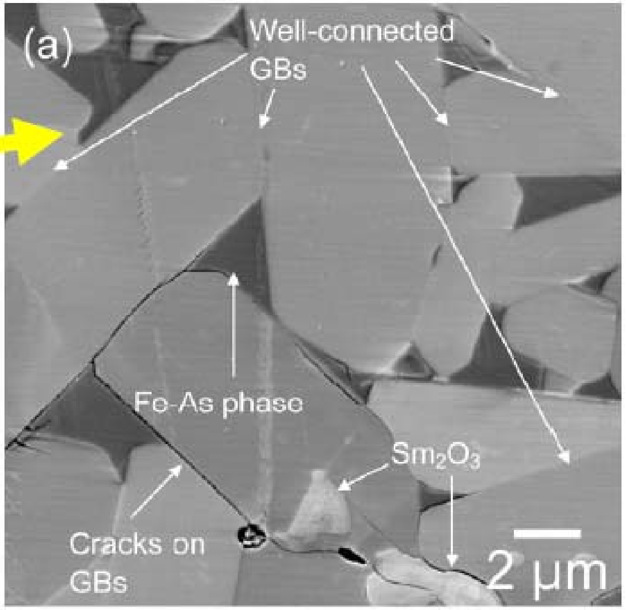
the traditional **powder-in-tube (PIT) method**, which has been utilized in commercial Nb_3Sn, Bi-2223 and MgB_2 wires, is promising for the large-scale manufacture of IBS conductors

Structural defects in polycrystal pnictides



Low Temperature Laser Scanning Microscopy (LTLSM) + SEM

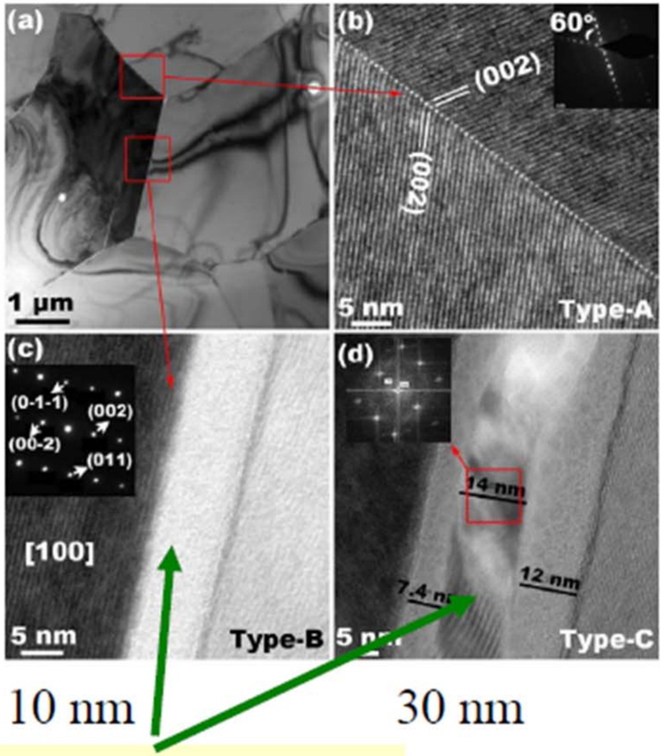
Katase T et al. 2009 *APL* 95 142502



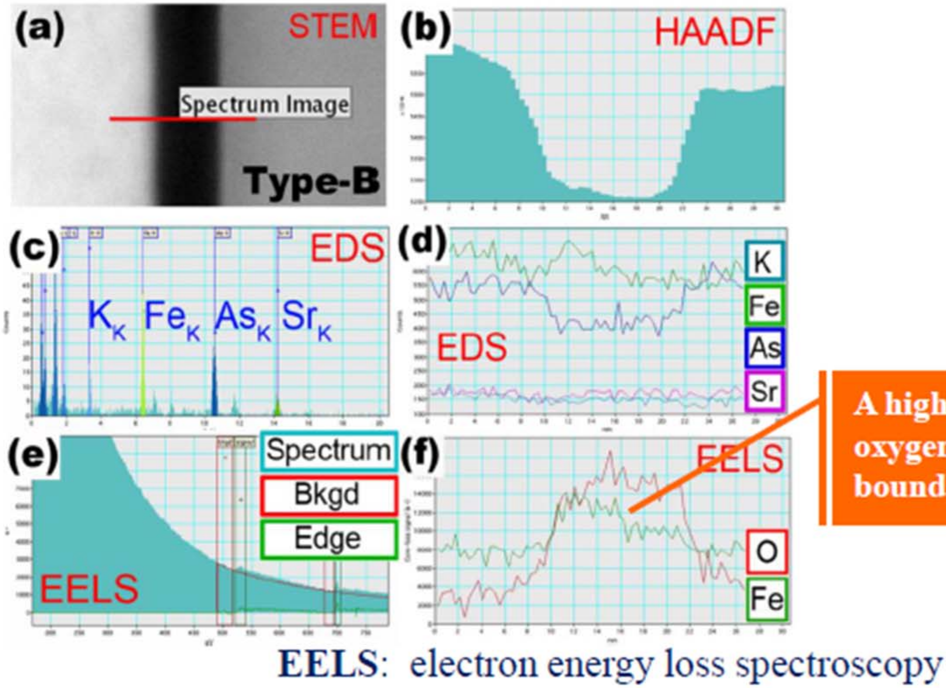
1111-type polycrystal IBS bulks

- **cracks** and low density (**porosity**) always lead to poor grain connection
- **impurity phases** (such as Fe-As) that wet the grain boundaries
- inter-grain J_c in polycrystalline IBS was largely suppressed

Structural defects in polycrystal pnictides



An amorphous layer



EELS: electron energy loss spectroscopy

STEM-EELS study of 122-type polycrystal IBS bulks

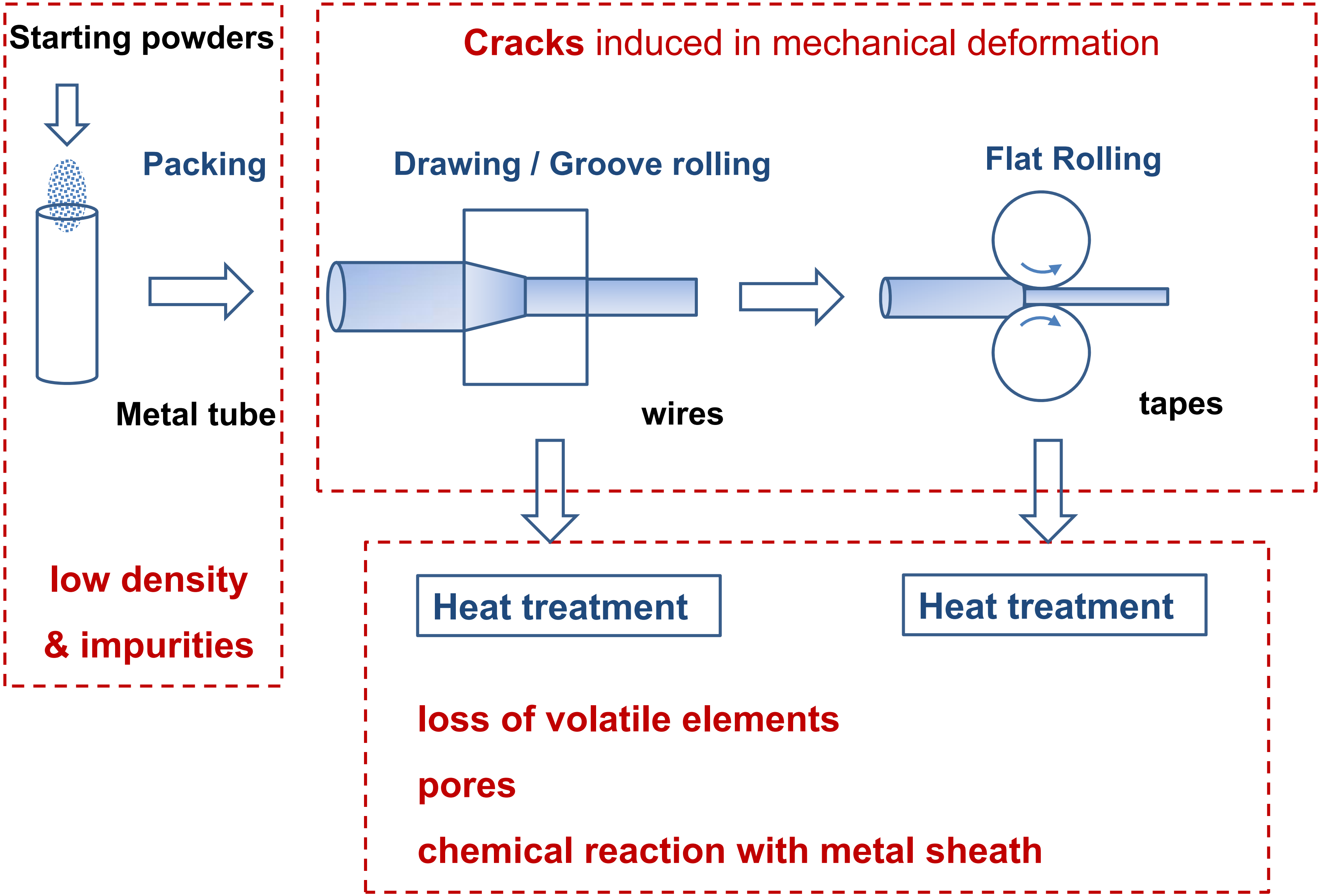
Wang et al. 2011 *APL* 98 222504

- Grain boundaries in the Sr122 polycrystals are usually coated by impurity amorphous layers (10-30 nm), which show significant oxygen enrichment
- These oxygen-rich layers undoubtedly obstructed many grain boundaries, consequently resulting in a poor grain connection.

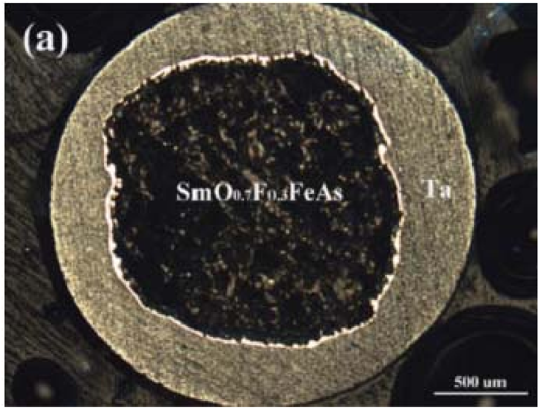
Outline

1. Properties & application potential of iron-based superconductors
2. Microstructural defects & weak-link GBs in polycrystalline IBS
3. Improving the J_c-performance of IBS wires and tapes
4. Progress on practical wires for high-field applications
5. Summary & prospects

Powder-in-tube method for IBS wires and tapes



The first IBS wire developed in IEECAS



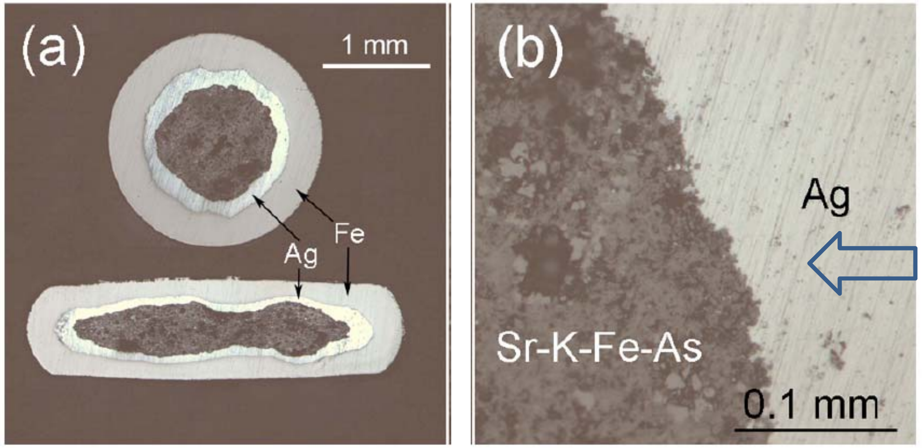
The first 1111-IBS wire in 2008

$SmFeAsO_{1-x}F_x$ wire sheathed with Ta

T_c = 52 K， H_{c2} = 120 T

But the transport current can not be measured

Gao 2008 *Sust* 21 112001



The 122-IBS wire and tape in 2010

$Sr_xK_{1-x}Fe_2As_2$ wire sheath with Ag/Fe

$J_{c,self\ field}$ = 1200 A/cm^2

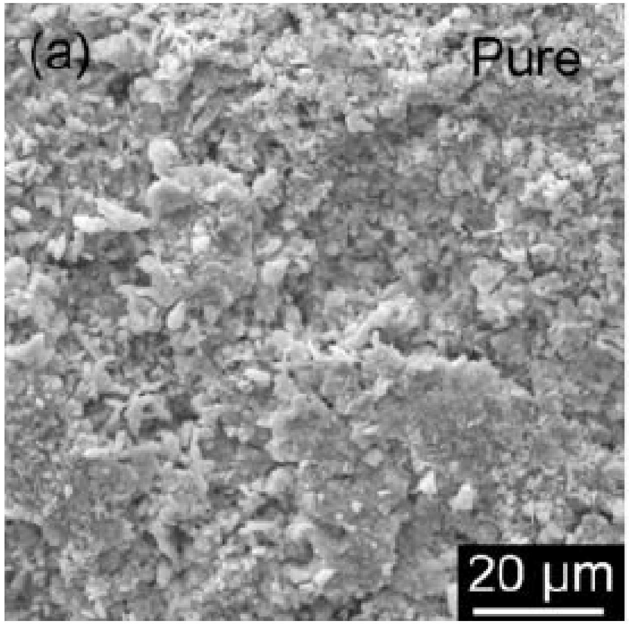
Using silver sheath, we obtained transport current for the first time.

Wang 2010 *Physica C* 470 183

- At present, Ag is the most widely used sheath materials for high-J_c IBS wires and tapes since it does not react with IBS cores during heat treatment

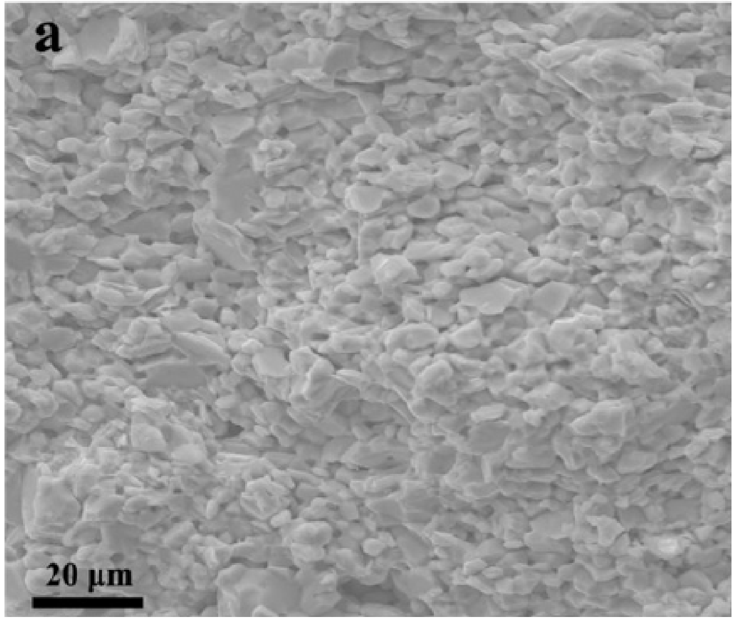
Improve the microstructure of 122-IBS wires and tapes

in-situ **VS** ***ex-situ***



Wang 2010 *Physica C* 470 183

J_c (4.2 K, 0 T) = **1200** A/cm^2



Qi 2010 *SuST* 23 055009

J_c (4.2 K, 0 T) = **3750** A/cm^2

Sr-122 wires

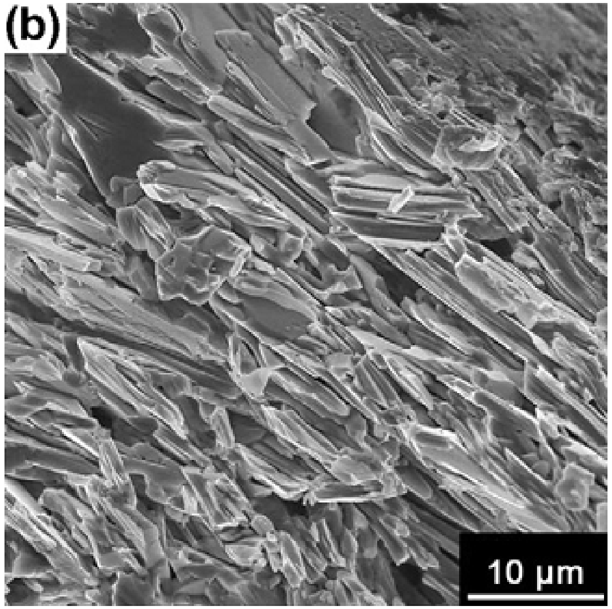
- fewer impurity phases
- higher mass density
- better crystallinity

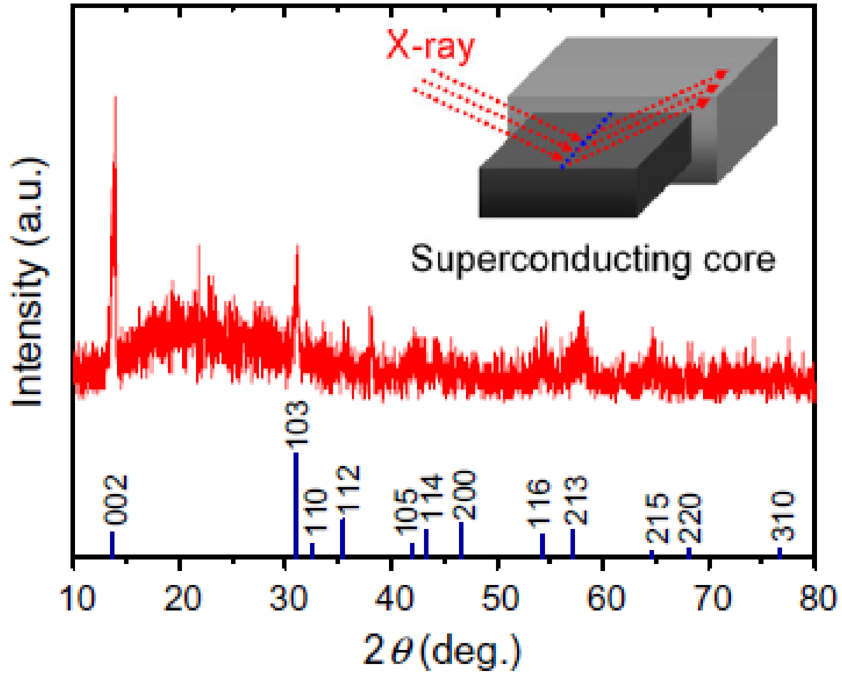
after the *ex-situ* synthesis was proposed, the transport J_c of 122-IBS increased much more rapidly than 1111-IBS, which still suffers from low purity precursor.

Improve the microstructure of 122-IBS wires and tapes

rolling induced c-axis texture

Sr-122 tape





J_c (4.2 K, 0 T) = **5400** A/cm^2

Wang L 2011 *Physica C* 471 1689

rolling texture + Sn addtion

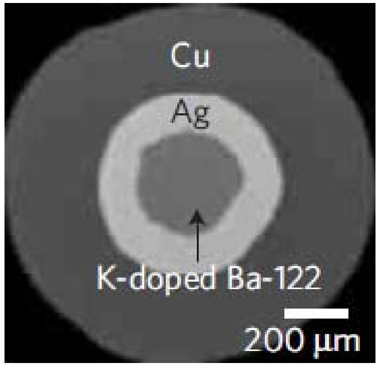
J_c (4.2 K, 10 T) = **1.7×10^4** A/cm^2

Gao 2012 *Sci.Rep.* 2 998

➢ grain texture can reduce the high-angle GBs, and suppress the influence of weak-link effect for inter-grain currents

Improve the microstructure of 122-IBS wires and tapes

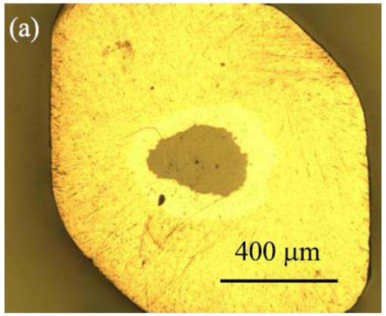
hot isostatic press (HIP)



Ba-122 round wire made in National High Magnetic Field Laboratory, Florida State University

Weiss 2012 *Nature Mater.* 11 682

J_c (4.2 K, 10 T) = **~1×10⁴** A/cm² **192 MPa, 600 °C**

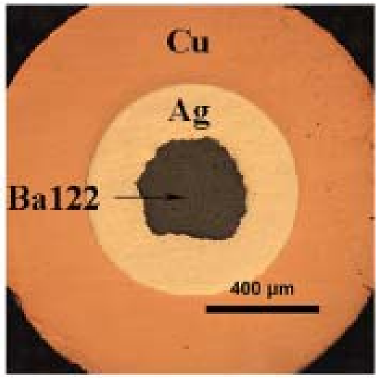


Ba-122 wire made in the University of Tokyo

Pyon 2016 *SuST 29* 115002

J_c (4.2 K, 10 T) = **2×10⁴** A/cm²

175 MPa, 700 °C



Ba-122 wire made in IEECAS

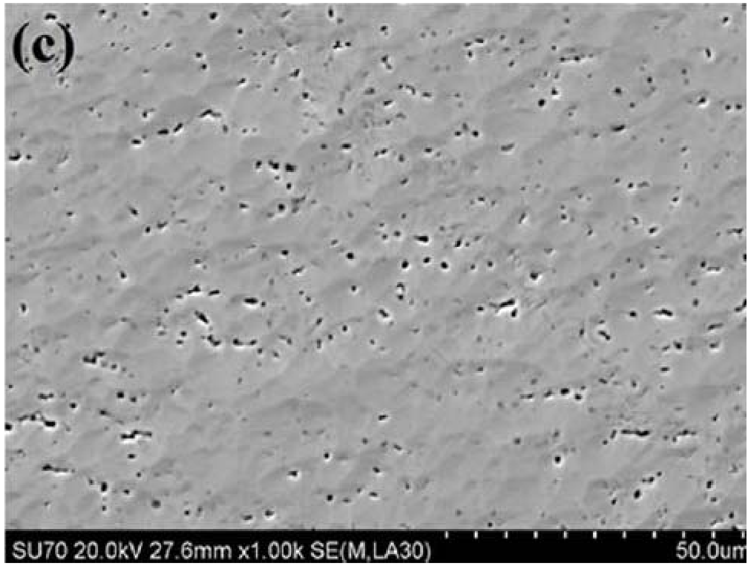
Liu 2017 *SuST* 30 115007

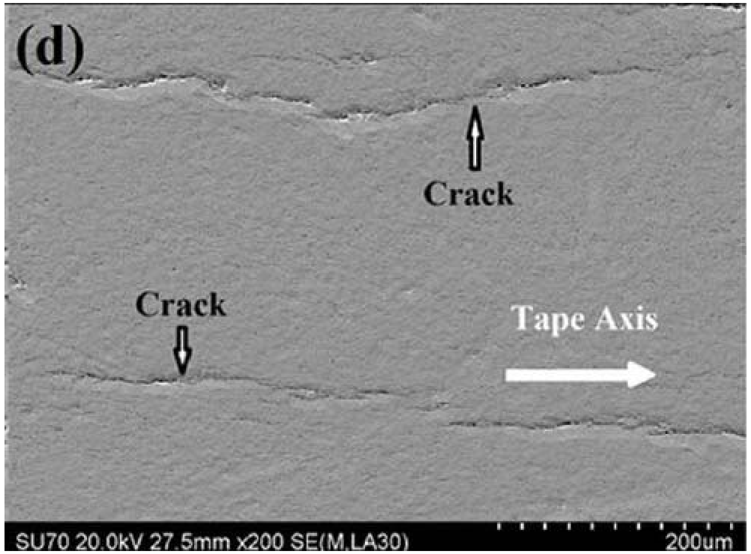
J_c (4.2 K, 10 T) = **~1×10⁴** A/cm²

200 MPa, 700 °C

- Highly dense superconducting core with mass density near 100%
- almost no grain orientation (texture)

Improve the microstructure of 122-IBS wires and tapes

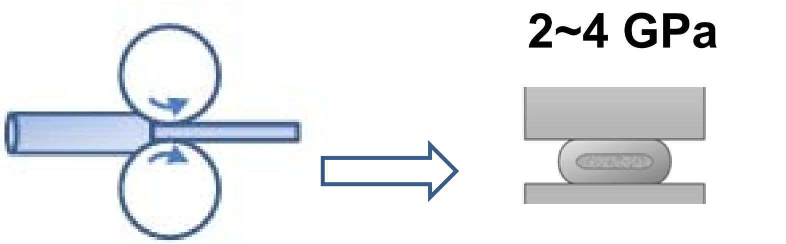




Gao 2014 *Sci. Rep.* 4 4465

cold press process

2~4 GPa



rolling

uniaxial pressing

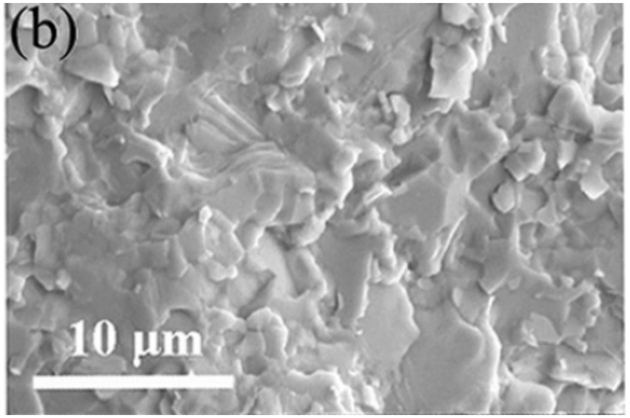
Ba-122 tapes made by NIMS, Japan

J_c (4.2 K, 10 T) = **8.6×10^4** A/cm^2

- Cold pressing can largely increase the mass density of 122-IBS phase
- cracks cannot be completely healed by subsequent heat treatment.

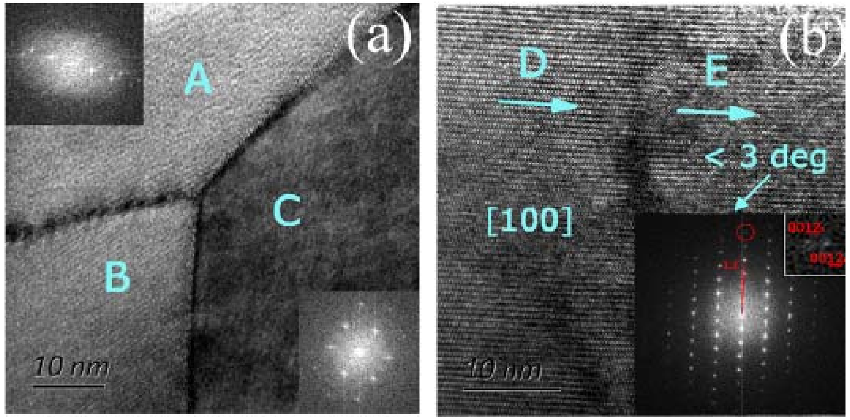
Improve the microstructure of 122-IBS wires and tapes

hot press process (Sr-122 tapes by IEECAS)



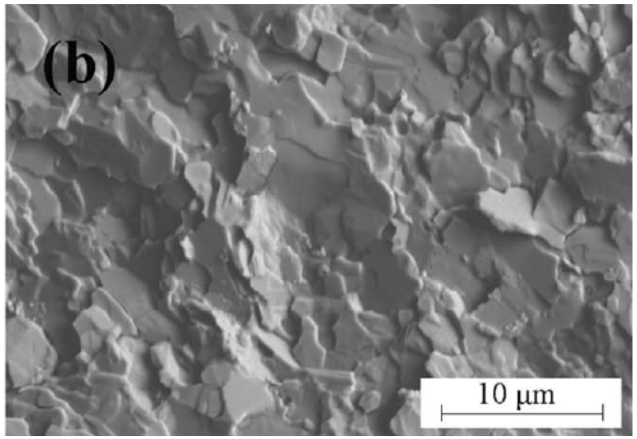
SEM (*ab* plane)

Zhang 2014 *APL* 104 202601

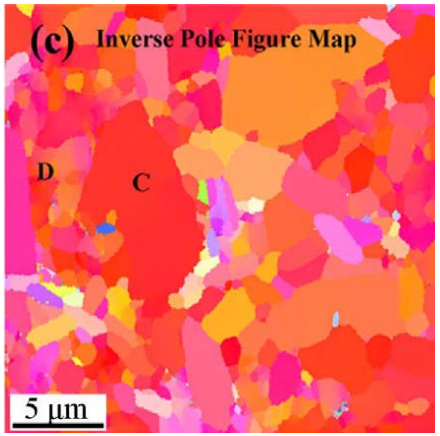


HRTEM

J_c (4.2 K, 10 T) = **1.0×10⁵** A/cm²



SEM (*ab* plane)



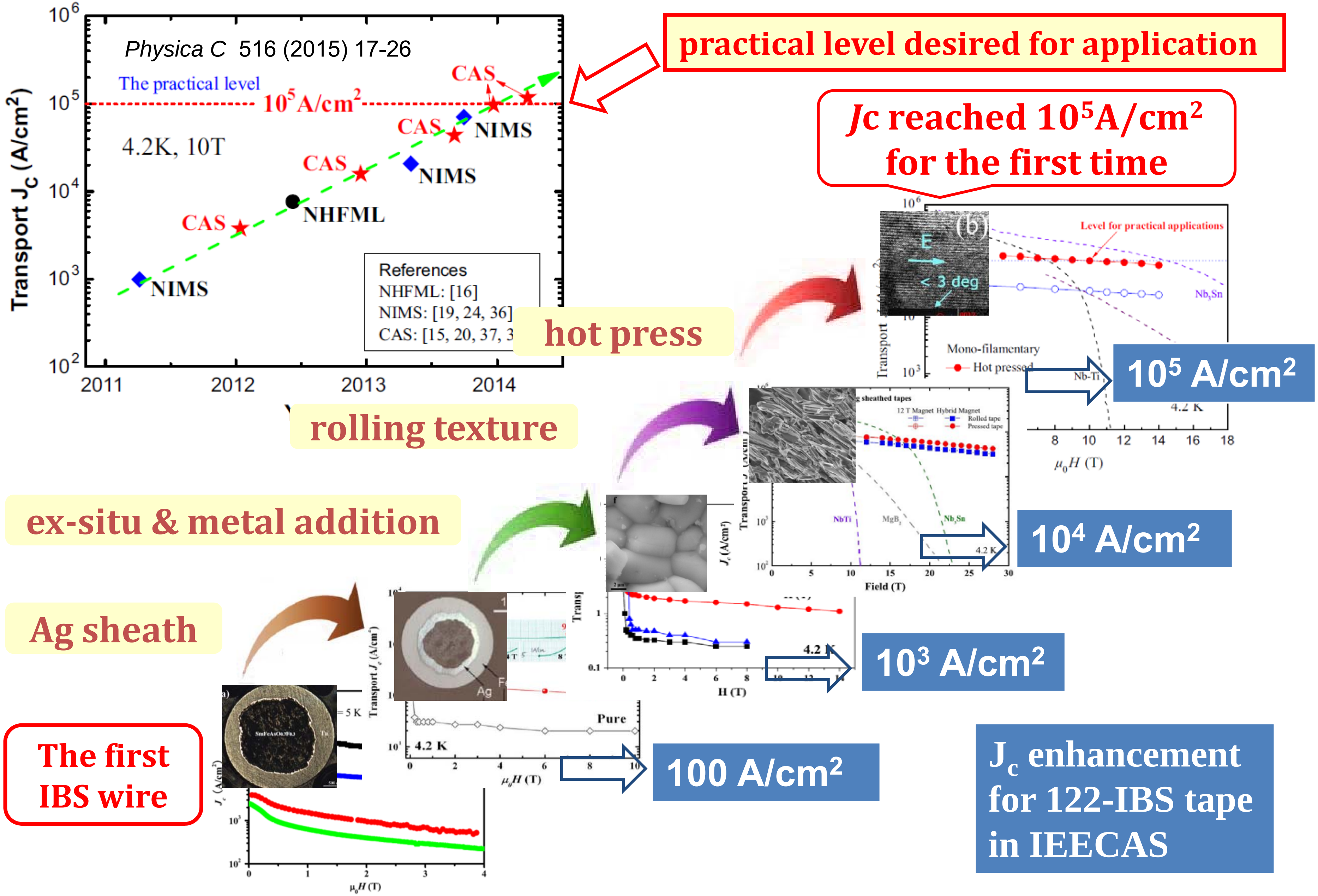
EBSD

strongly improved c-axis texture and core density, thus greatly improving transport J_c

30 MPa, 850~900 °C

Lin 2014 *Sci. Rep. 4* 6944 J_c (4.2 K, 10 T) = **1.2×10^5** A/cm²

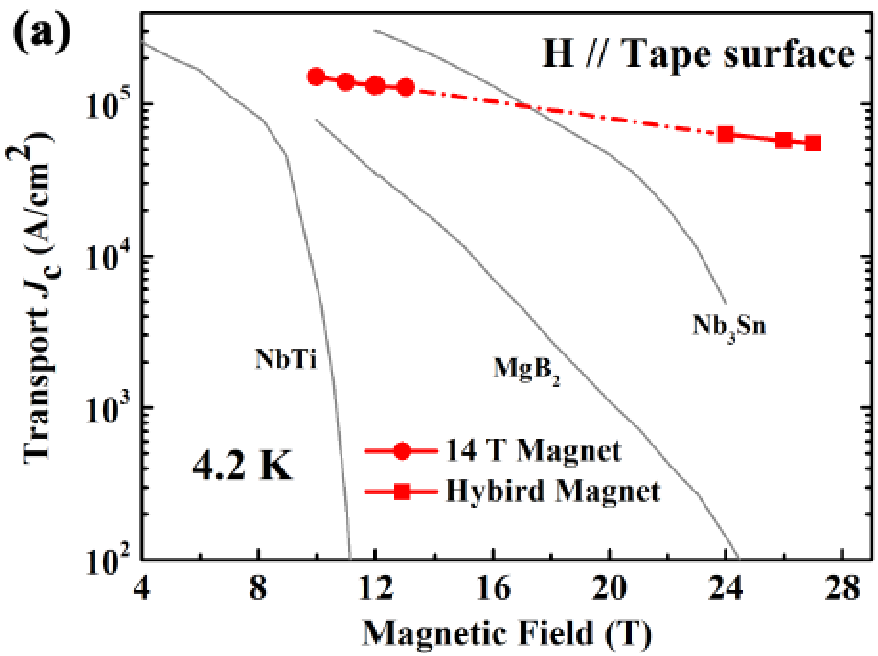
Continuously increased J_c for 122-IBS wires and tapes



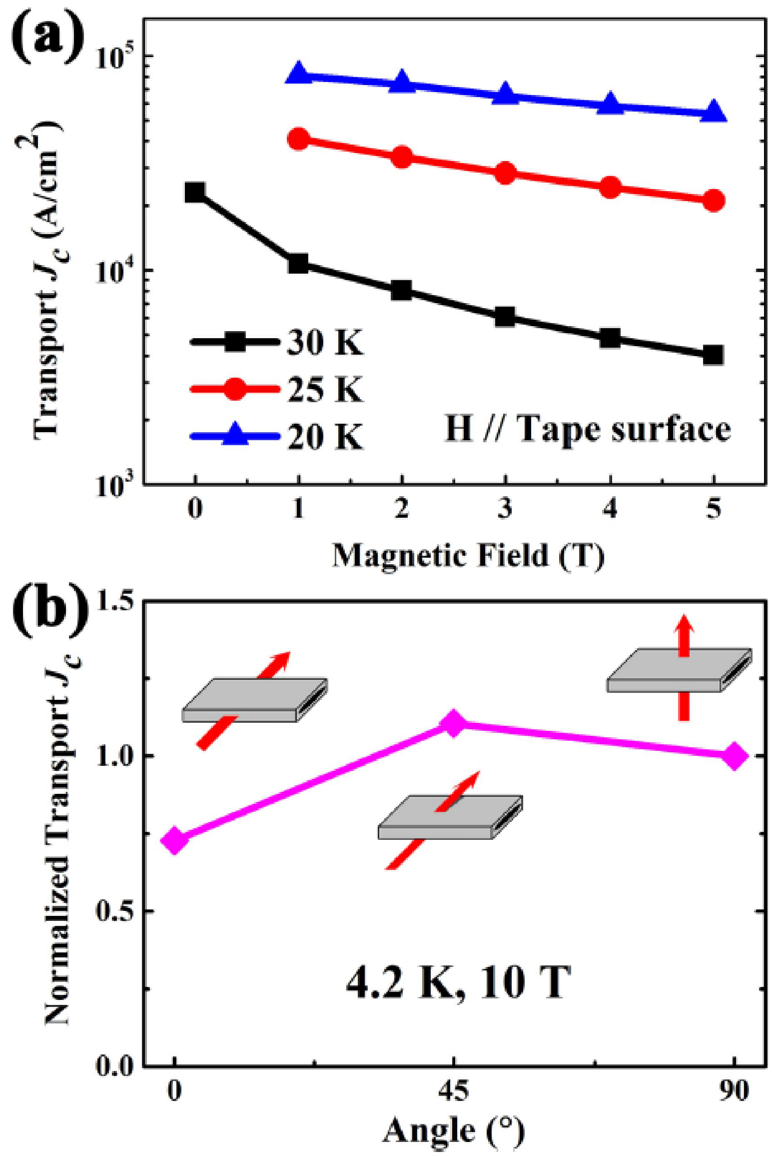
J_c enhancement for 122-IBS tape in IEECAS

Continuously increased J_c for 122-IBS wires and tapes

Recently in IEECAS, a new J_c record was achieved in Ba-122 tapes



Huang 2017 SuST 31 015017



- I_c (4.2 K, 10 T) = 437 A
- J_c (4.2 K, 10 T) = **1.5×10^5** A/cm^2
- J_c (4.2 K, **27 T**) = **5.5×10^4** A/cm^2
- J_c (**20 K**, 5 T) = **5.4×10^4** A/cm^2
- J_c anisotropy (4.2 K, 10 T) = **1.37**

Outline

1. Properties & application potential of iron-based superconductors
2. Microstructural defects & weak-link GBs in polycrystalline IBS
3. Improving the J_c-performance of IBS wires and tapes
4. Progress on practical wires for high-field applications
5. Summary & prospects

Challenges in practical applications

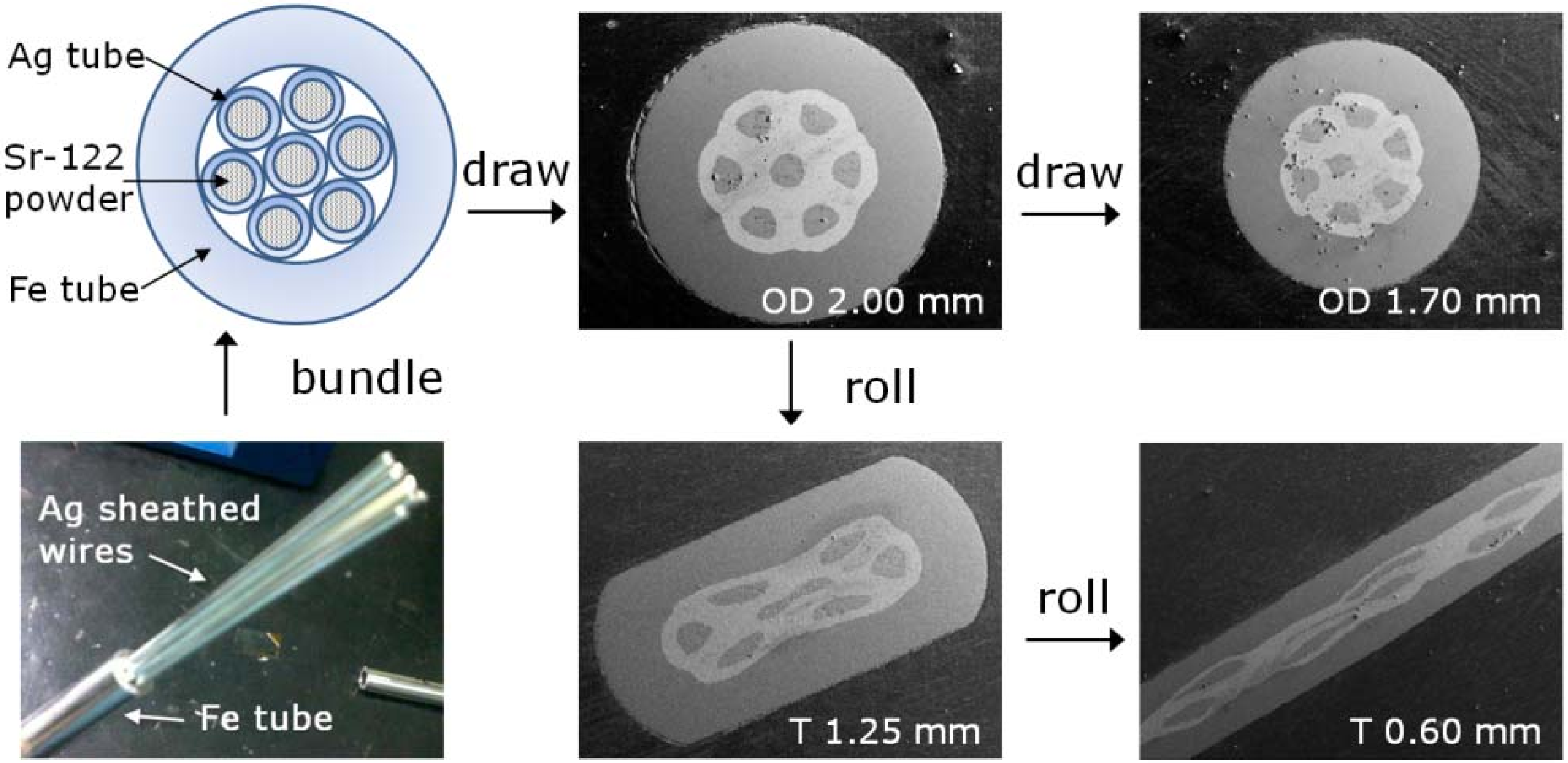
challenges		strategies
➢ magnetic flux jumps ➢ thermal quenching ➢ AC loss	⇨	✓ Multifilament structure
➢ device winding damage ➢ thermal stress ➢ electromagnetic stress ➢ material cost	⇨	✓ Composite sheath instead of silver single sheath
➢ large-scale production	⇨	✓ PIT method

Bi-based wires: Ag/Ag-alloy sheath

IBS wires: Ag/various metal composite sheath is possible

- Ag → inner sheath: chemical stability
- various metal → outer sheath: mechanical strength & reduce Ag ratio

Fabrication process for multifilament wires and tapes

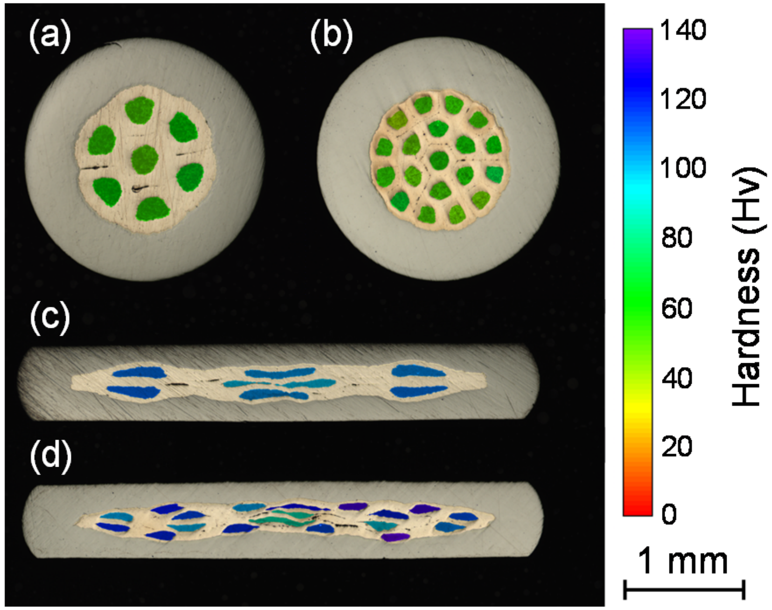


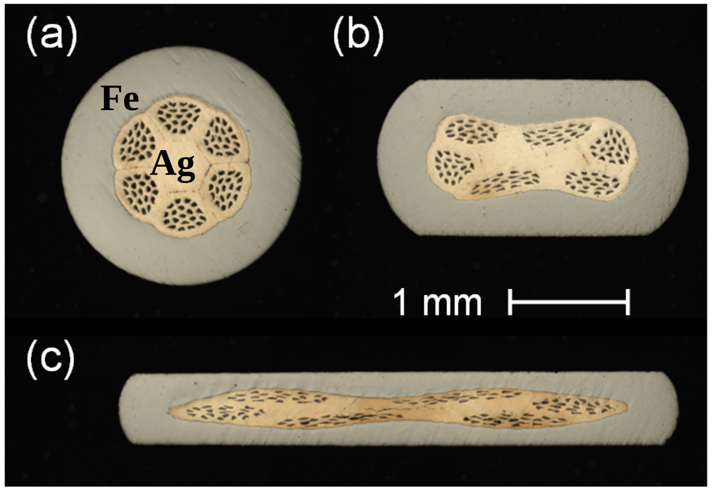
The first 122 iron-pnictide multifilamentary wire

Yao et al. 2013 *APL* 102 082602

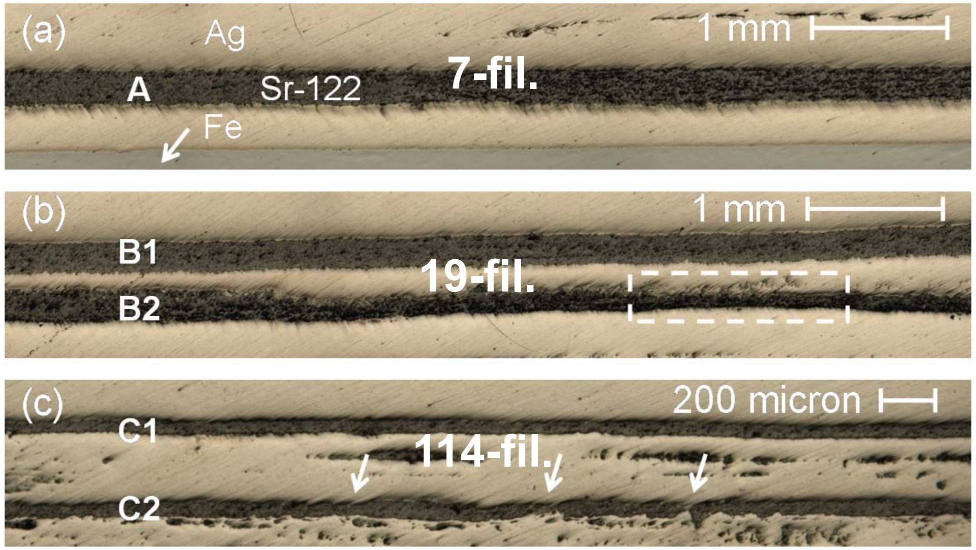
7-, 19- & 114-filament Sr-122 wires with Ag/Fe sheath

transverse cross-sections





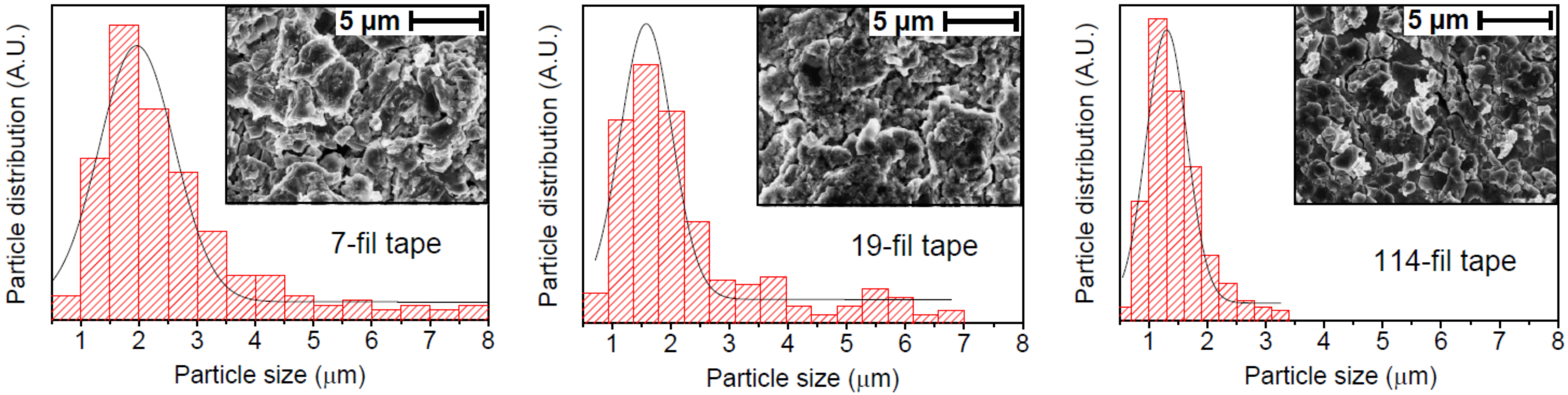
longitudinal cross-sections



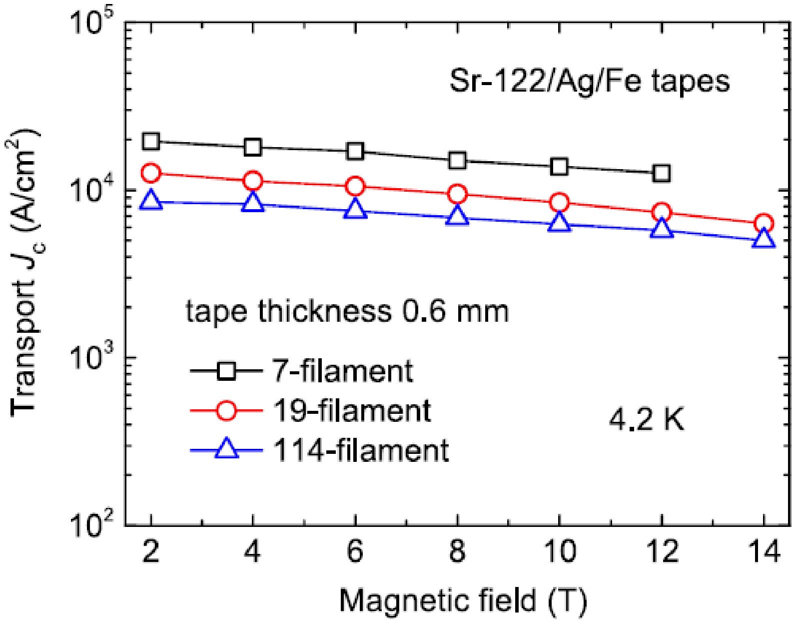
When increasing the number of filaments and reducing the filament diameter:

- ◆ degraded uniformity of mass density for Sr-122 filaments;
- ◆ degraded uniformity of interface between Sr-122 filaments and Ag sheath;

7-, 19- & 114-filament Sr-122 wires with Ag/Fe sheath



Gauss fits of particle size inside the Sr-122 filaments



J_c (4.2 K, 10 T): 7-fil: 1.4×10^4 A/cm^2

19-fil: 8.4×10^3 A/cm^2 114-fil: 6.3×10^3 A/cm^2

The refined grains can increase the density of grain boundaries and reduce the degree of grain texture, which are not beneficial to the J_c improvement

Yao et al. 2015 *JAP* 118 203909

Advantages of Ag/Monel composite sheath

Monel, any of a group of nickel-copper alloys, first developed in 1905, containing about 66 % nickel and 31.5 % copper, with small amounts of iron, manganese, carbon, and silicon.

Advantages :

- ✓ a melting range of 1300-1350 °C;
- ✓ It also has good ductility and thermal conductivity.
- ✓ excellent mechanical properties at subzero temperatures,

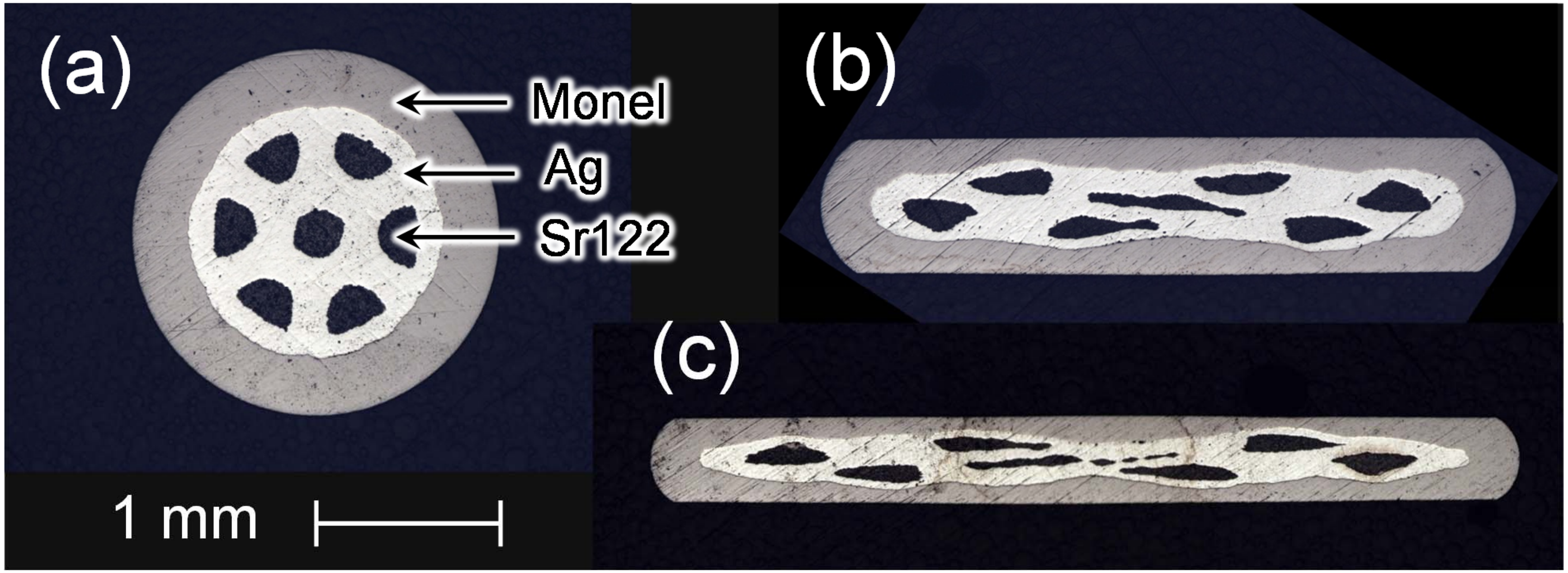
  does not undergo a ductile-to-brittle transition even when cooled to the temperature of liquid hydrogen. This is in marked contrast to many ferrous materials which are brittle at low temperatures despite their increased strength

typical values of Vickers hardness after annealed at 800~900 °C:

pure silver: 30~40; iron: 90~100; Monel: 150~180

Yao et al. 2015 *JAP* 118 203909; Yao et al. 2017 *SuST* 30 075010

7-filament Sr-122 wires with Ag/Monel composite sheath

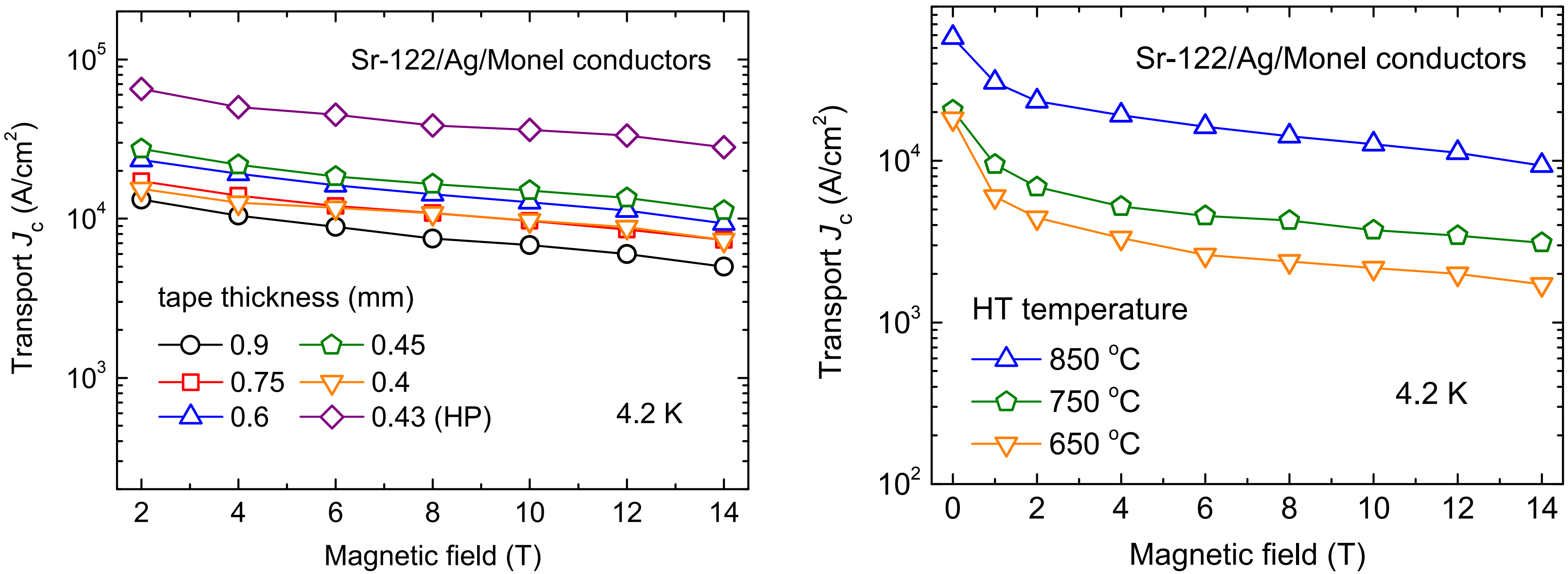


Transverse cross-sections for 7-filament Sr-122/Ag/Monel wires 2.0 mm in diameter and tapes 0.75 and 0.45 mm in thickness

- Heat treatment temperature up to 850 ^{o}C is safe for Ag/Monel sheath, higher than 770 ^{o}C for Ag/Cu sheath
- flat rolled tapes with a thickness down to 0.4 mm can be made

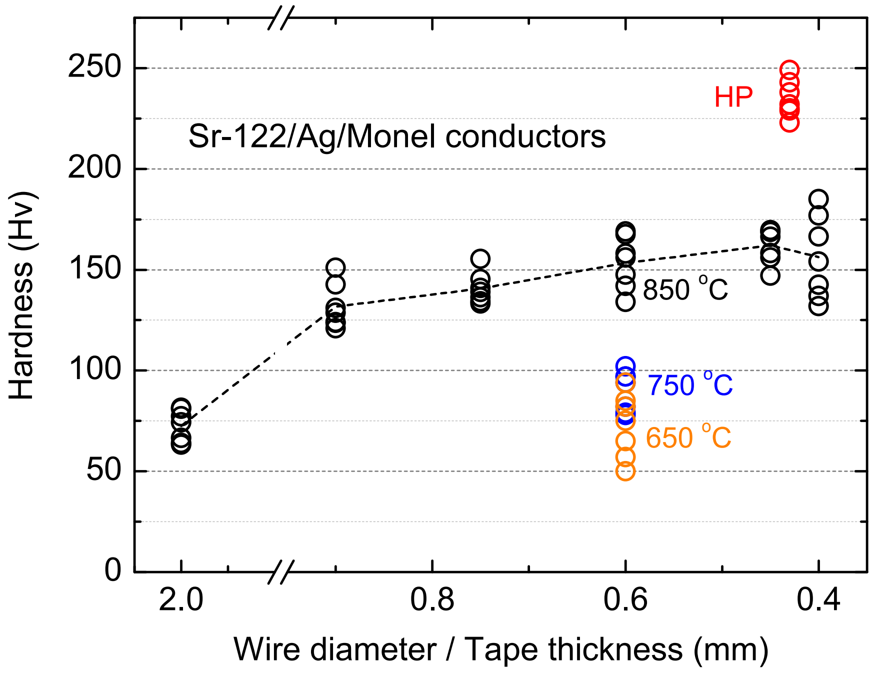
Yao et al. 2017 *SuST* 30 075010

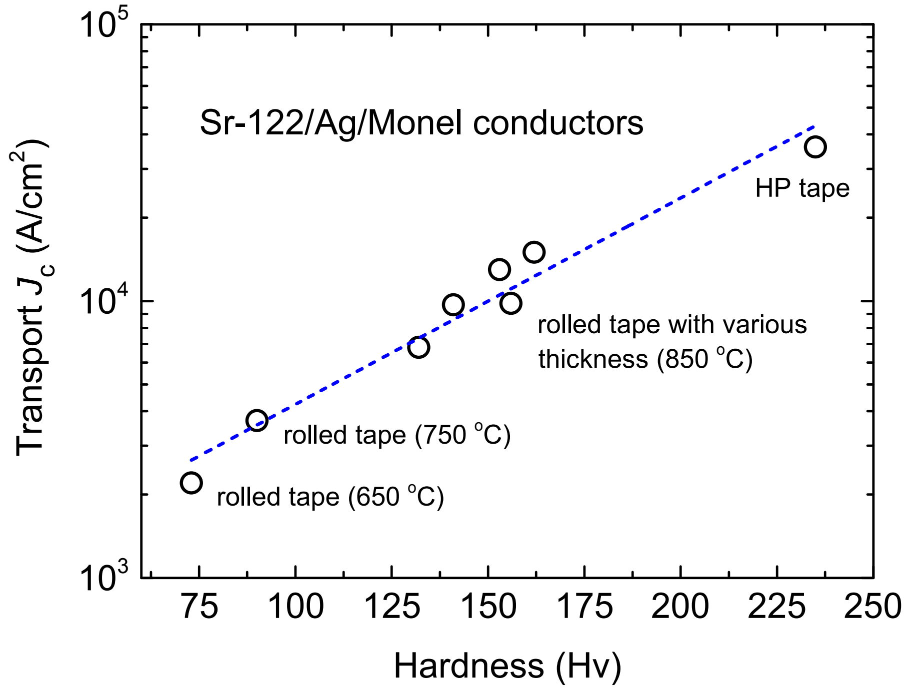
Transport J_c of 7-filament Sr-122/Ag/Monel tapes



- For the rolled tapes, the transport J_c gradually grows with the reduction of tape thickness from 0.9 to 0.45 mm.
- For the hot-pressed tapes, a high transport J_c of **3.6×10^4 A cm^{-2}** was achieved at 4.2 K and10 T.
- For the 0.6 mm thick tapes, the transport J_c decreases with the decline of heat treatment temperature.

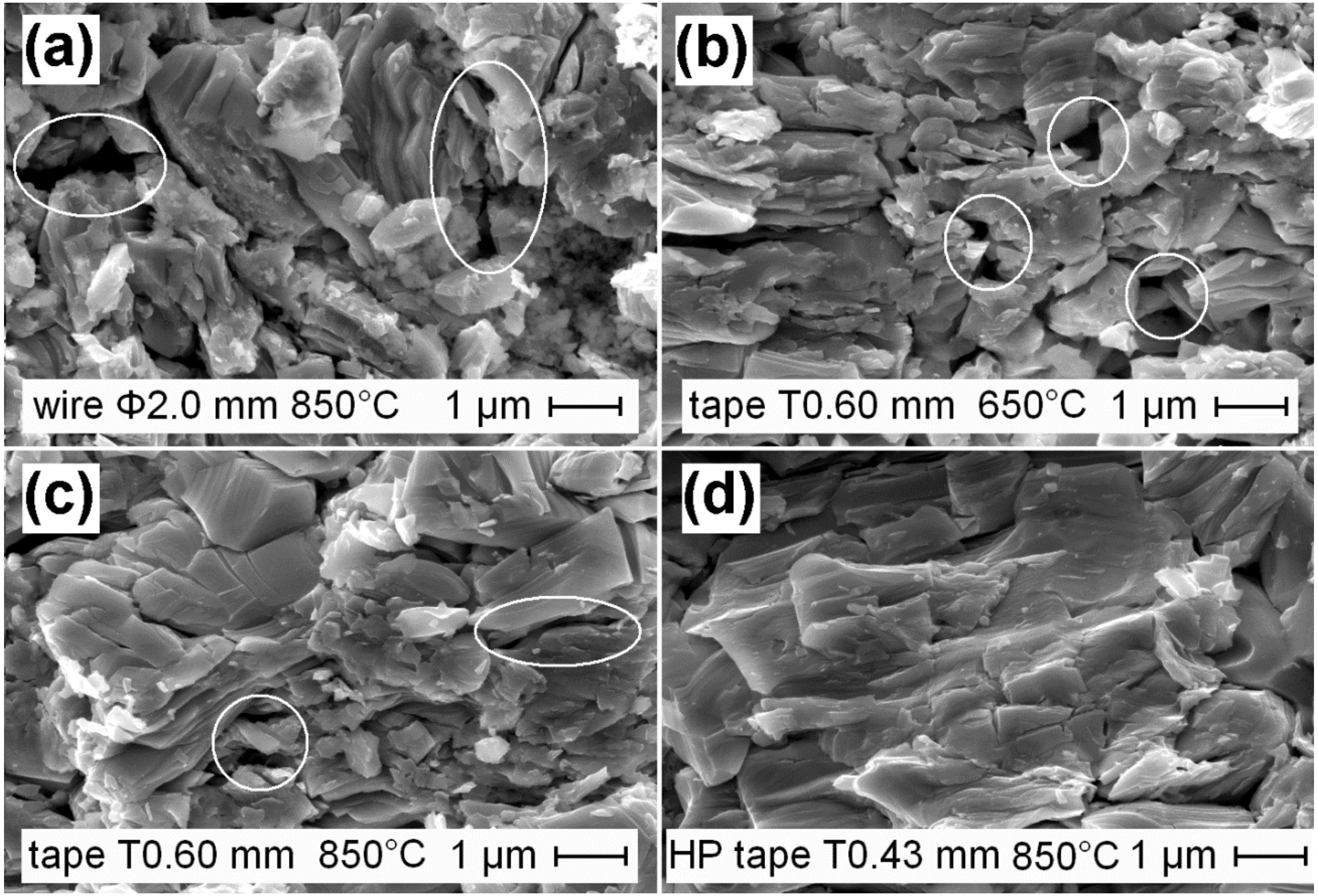
Vickers hardness of 7-filament Sr-122/Ag/Monel tapes





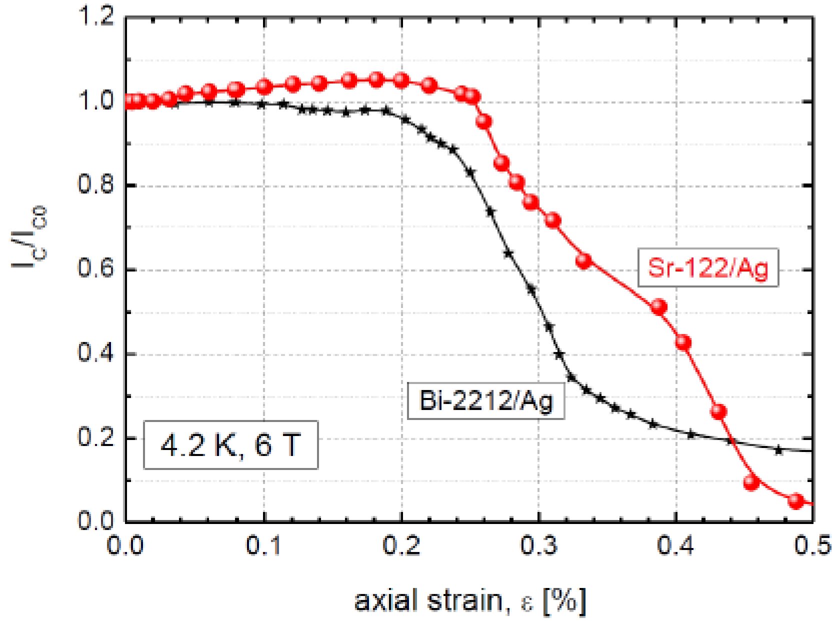
- low annealing temperature or large deforming ratio is possible to cause inhomogeneous microstructure for the Sr-122 filaments
- a well-fitted positive semi-logarithmic correlation between the Sr-122 hardness and transport J_c

Microstructure of 7-filament Sr-122/Ag/Monel tapes



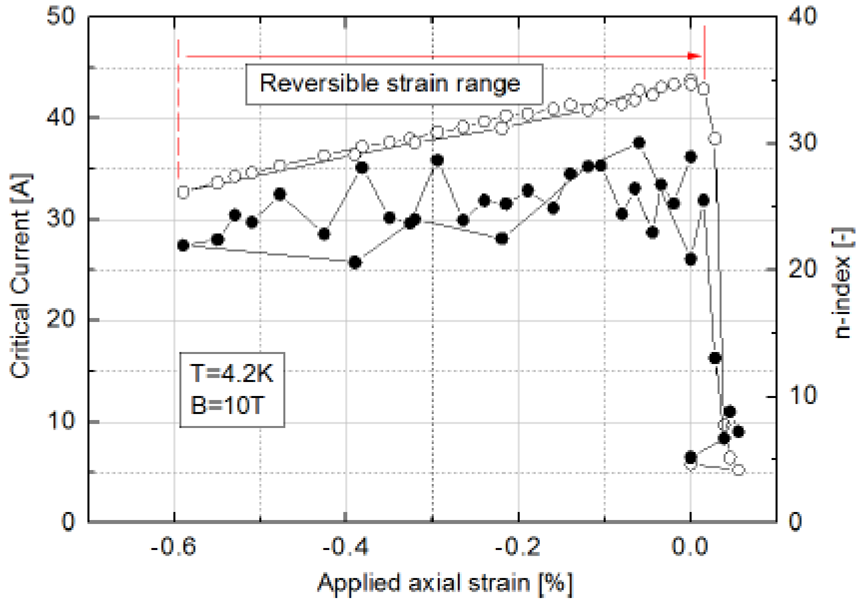
the microstructure of the Sr-122 filaments is well in accordance with their J_c performance

J_c-strain relationship of Sr-122/Ag tapes



I_c - tensile strain measurement

Kovac 2015 *SuST* 28 035007



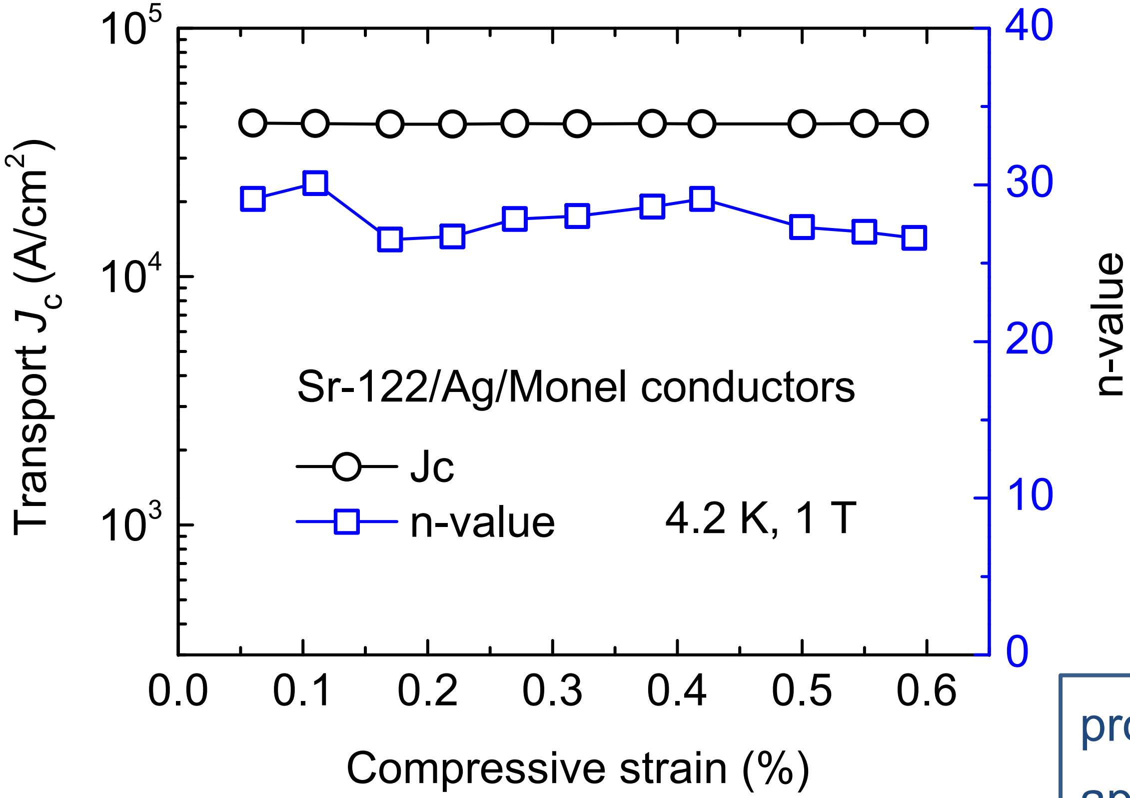
I_c –strain measurement

Liu 2017 *SuST* 30 07LT01

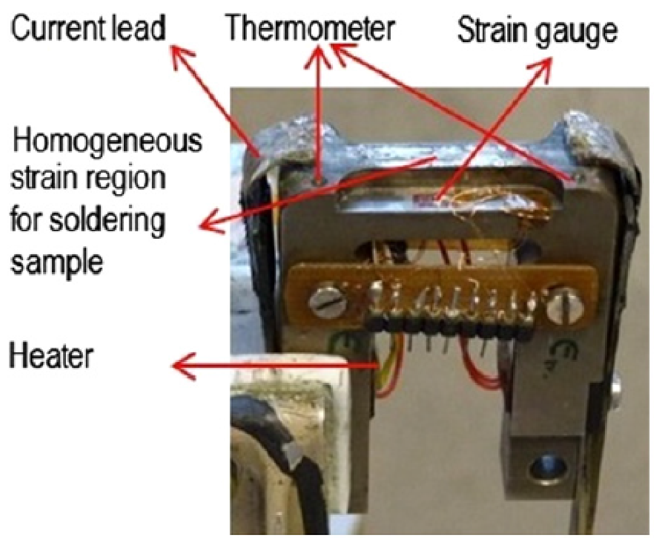
- the irreversible strain ε= 0.25% under tensile stress, comparable to Bi-2212 wire
- Reversible critical currents under a large compressive strain of ε = –0.6 % observed for Sr-122/Ag wire; when the applied strain exceeds the irreversible tensile strain limit, the critical current drops rapidly, and a significant crack is found along the sample width.

J_c-strain relationship of 7-filament Sr-122/Ag/Monel tapes

Yao et al. 2017 *SuST* 30 075010



Compressive strain dependence of transport J_c and *n*-values for the 0.75 mm tapes



The U-spring instrument

Zhou et al. 2014 *SuST* 27 0750002

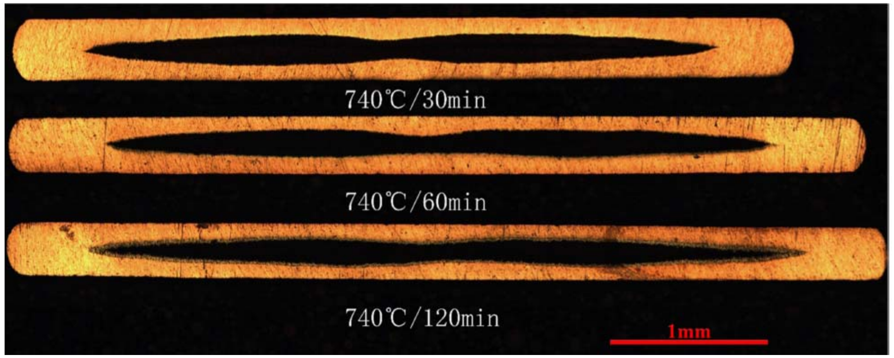
promising for large-scale applications in which conductors are usually designed to work under compressive state for safety

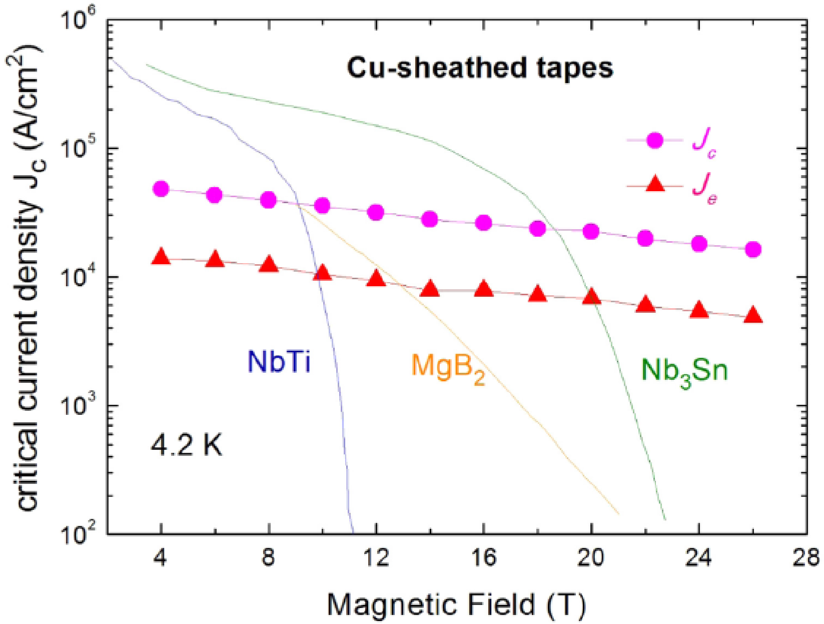
almost no J_c degradation under a large compressive strain of 0.6%

cooperate with Prof. Huajun Liu group in Institute of Plasma Physics, CAS

low-cost copper as sheath for 122-IBS tapes

single copper sheath



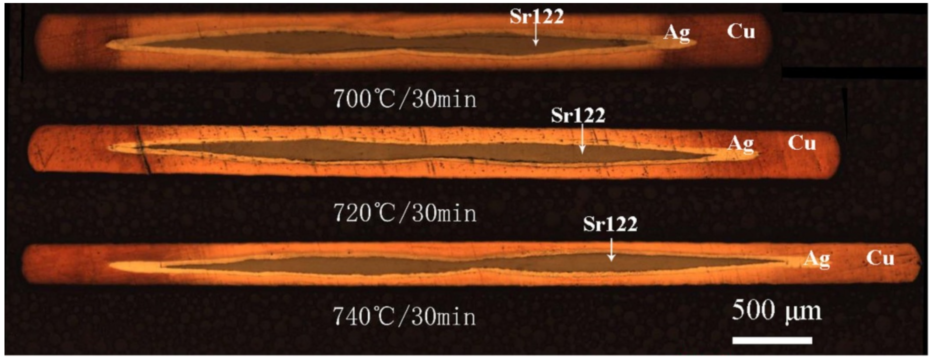


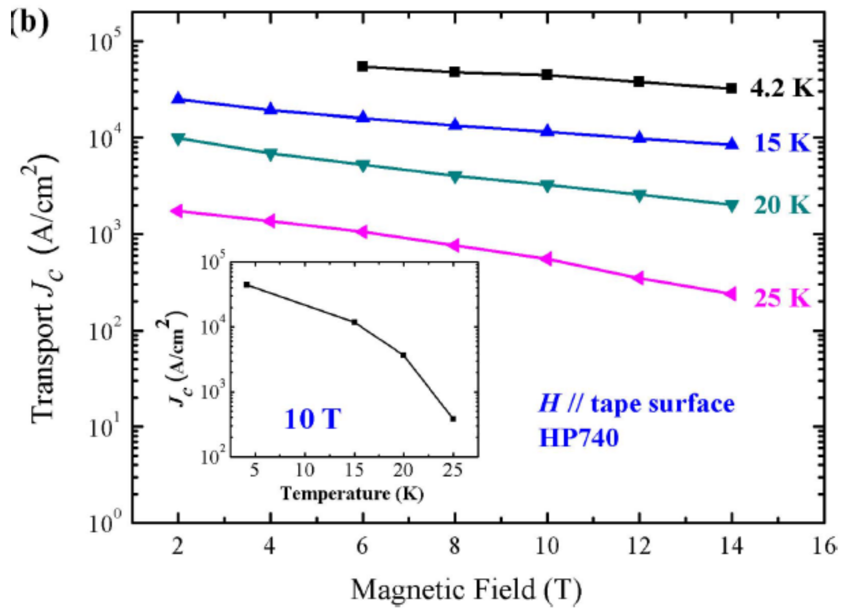
J_c (4.2 K, 10 T) = **3.5×10⁴** A/cm²

J_e (4.2 K, 10 T) = **> 10⁴** A/cm²

Lin 2016 *SuST* 29 095006

copper and thin silver double sheath



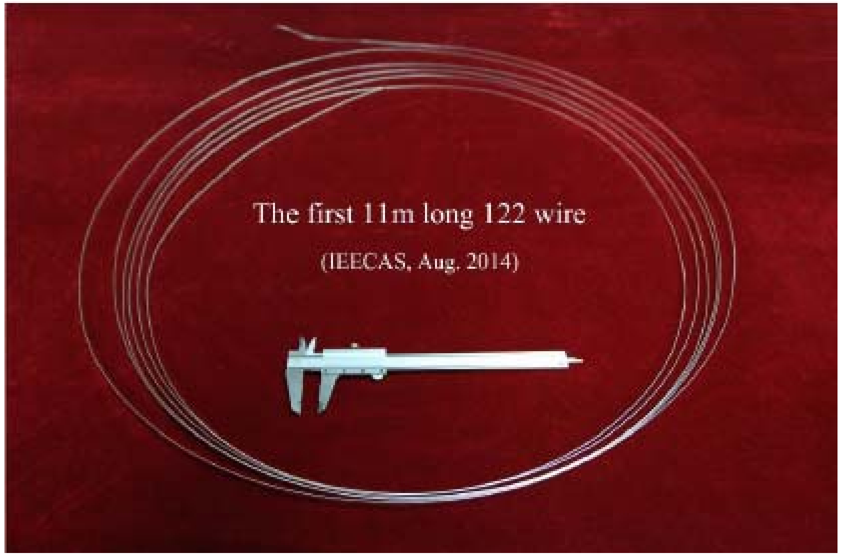


J_c (4.2 K, 10 T) = **4.4×10⁴** A/cm²

J_c (20 K, 10 T) = **3.6×10³** A/cm²

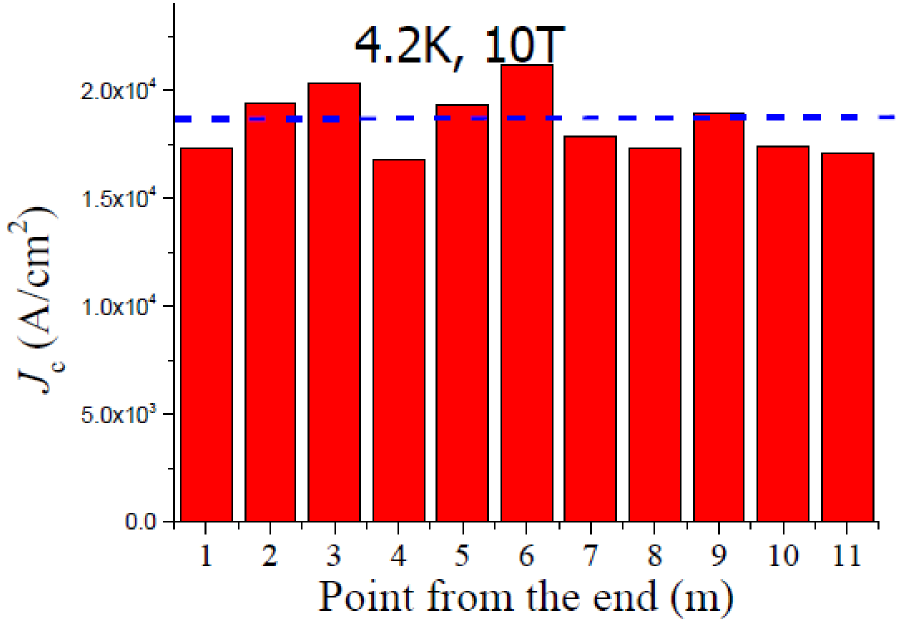
Liu 2017 *SuST* 30 115007

The first 10-meter class iron-based superconducting wire



by scalable rolling process in IEECAS

Ma 2016 Physica C17 516



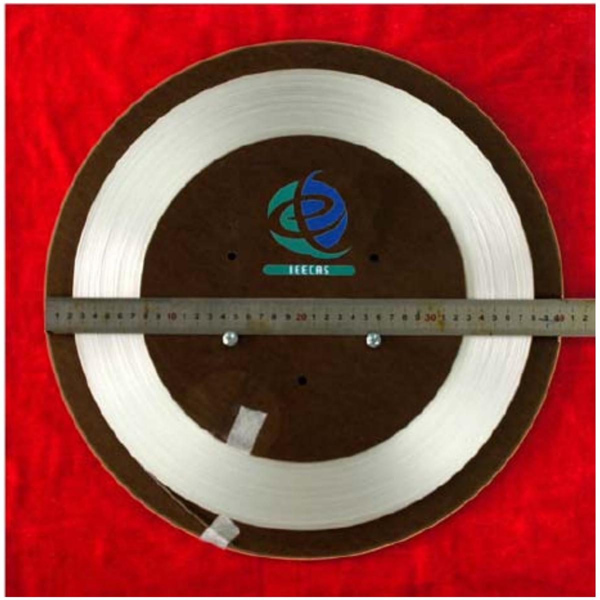
The minimum J_c ~1.7×10^4A/cm^2

The average J_c is 1.84×10^4 A/cm^2 for the 11 m long Sr122/Ag wire

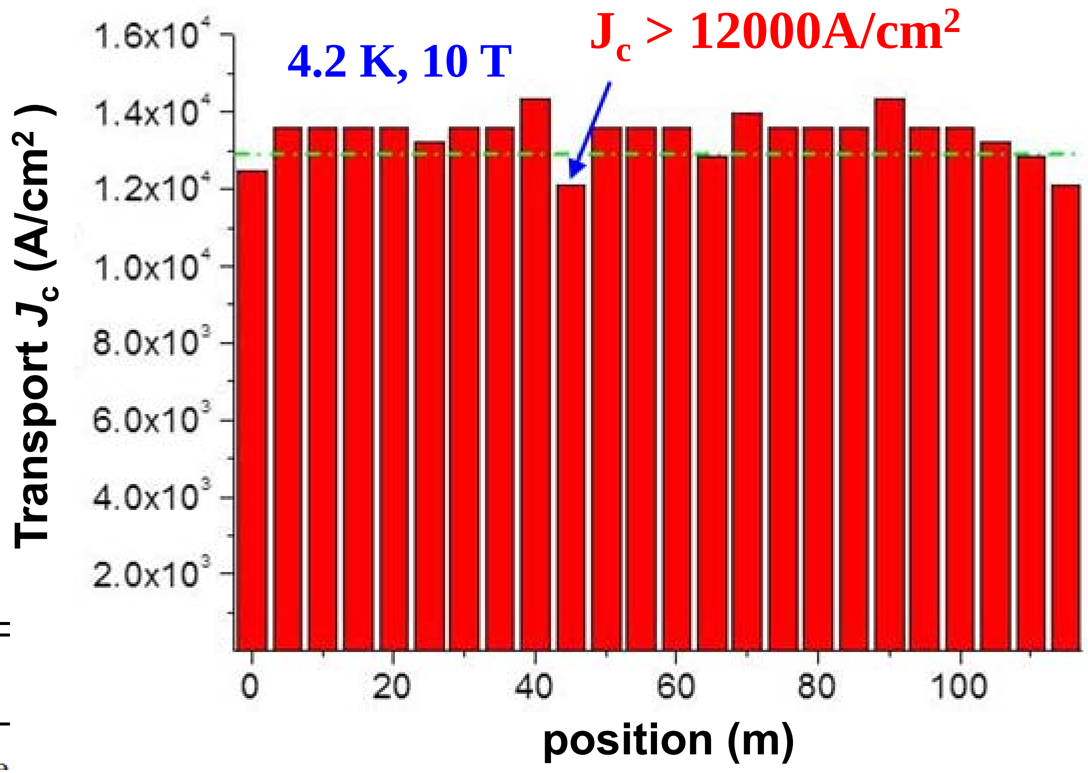
The fluctuations of the J_c is ~5%

The first 100-meter class iron-based superconducting wire

made in IEECAS



Items	Parameters
Structure	Ag-sheathed Sr122 tape
Length	10 m
Width	5 mm
Thickness	0.35 mm
Matrix	Ag
Number of filament	1
Insulation	Mica tape
Ic @ 4.2 K, 10 T	>100 A



showing a high property and good uniformity

Zhang et al. 2016 *IEEE Trans. Appl. Supercond.* 27 7300705

Outline

1. Properties & application potential of iron-based superconductors
2. Microstructural defects & weak-link GBs in polycrystalline IBS
3. Improving the J_c-performance of IBS wires and tapes
4. Progress on practical wires for high-field applications
5. Summary & prospects

Prospects for iron-based superconducting wires

- **further improving transport J_c for multifilamentary 122 IBS wires**

  find optimized conditions for cold work process and heat treatment

  improve the interface uniformity between IBS filaments and sheath

  improve the microstructure of IBS phase inside filaments

- **improving the architecture of multifilamentary 122 IBS wires**

  increase the filament number for high-field applications

  increase the engineering critical current density J_E

- **developing long-length 122 IBS wires with composite sheath**

  employ intermediate annealing in the cold-work process to alleviating the deformation hardening effect of sheath

Summary

- The transport J_c of 122-type iron-based superconducting wire is rapidly increasing, and has surpassed the practical level at 4.2 K and 10 T with a maximum of 1.5×10^5 A/cm^2
- Composite sheath is quite promising for developing high-strength, high-J_c performance and low cost multifilamentary iron-based superconducting wires, which can be strong candidates for high-field application such as IMR, NMR and accelerator.
- The world's first 100-meter class iron-based superconducting wire was achieved in IEECAS, demonstrating the great potential for large-scale manufacture.

Thank you for your attention !