KEK

Workshop on Advanced Superconducting Materials and Magnets

Development of high-strength 122-type iron-based superconducting wires and tapes for high-field applications

IEECAS 中国科学院电工研究所

中国科学院 CHINESE ACADEMY OF SCIENCES

Z. Cheng, C. Yao, Y. Ma

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

Session 5

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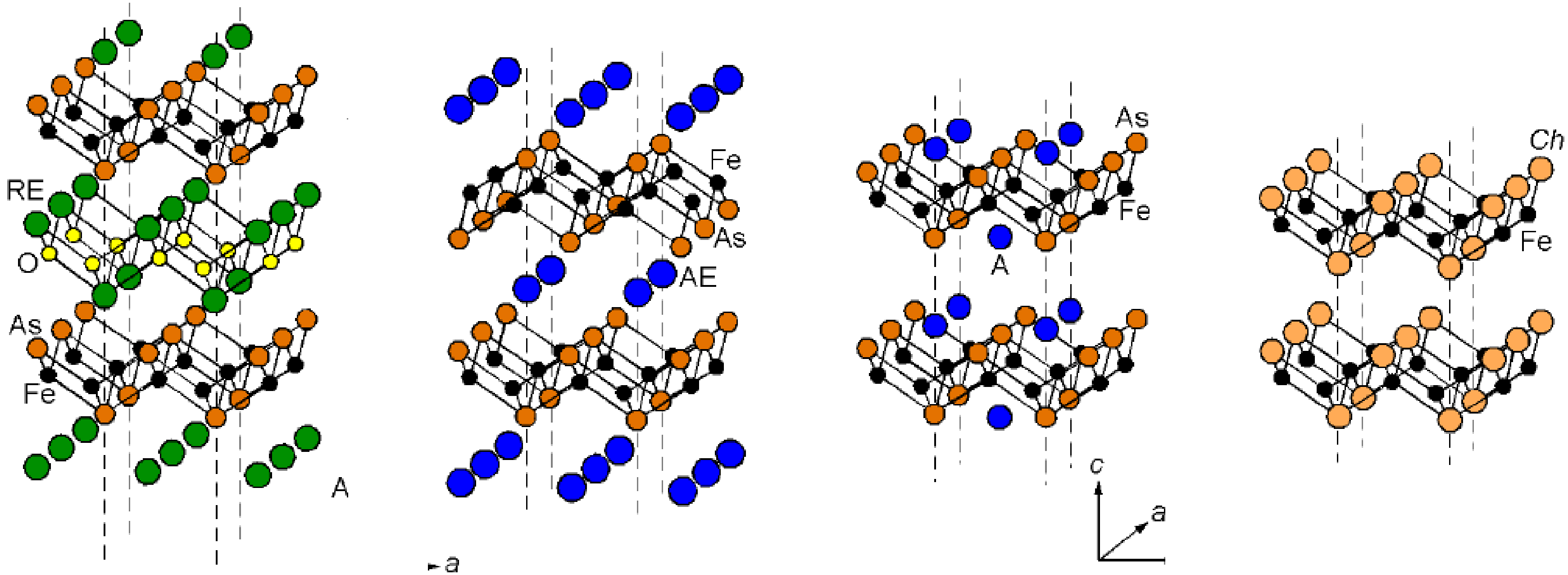
Outline

1. Properties & application potential of iron-based superconductors
2. Improving the J_c-performance of IBS wires and tapes
3. Long-length fabrications and superconducting joints
4. IBS wires and tapes with composite sheaths
5. Mechanical properties of IBS tapes

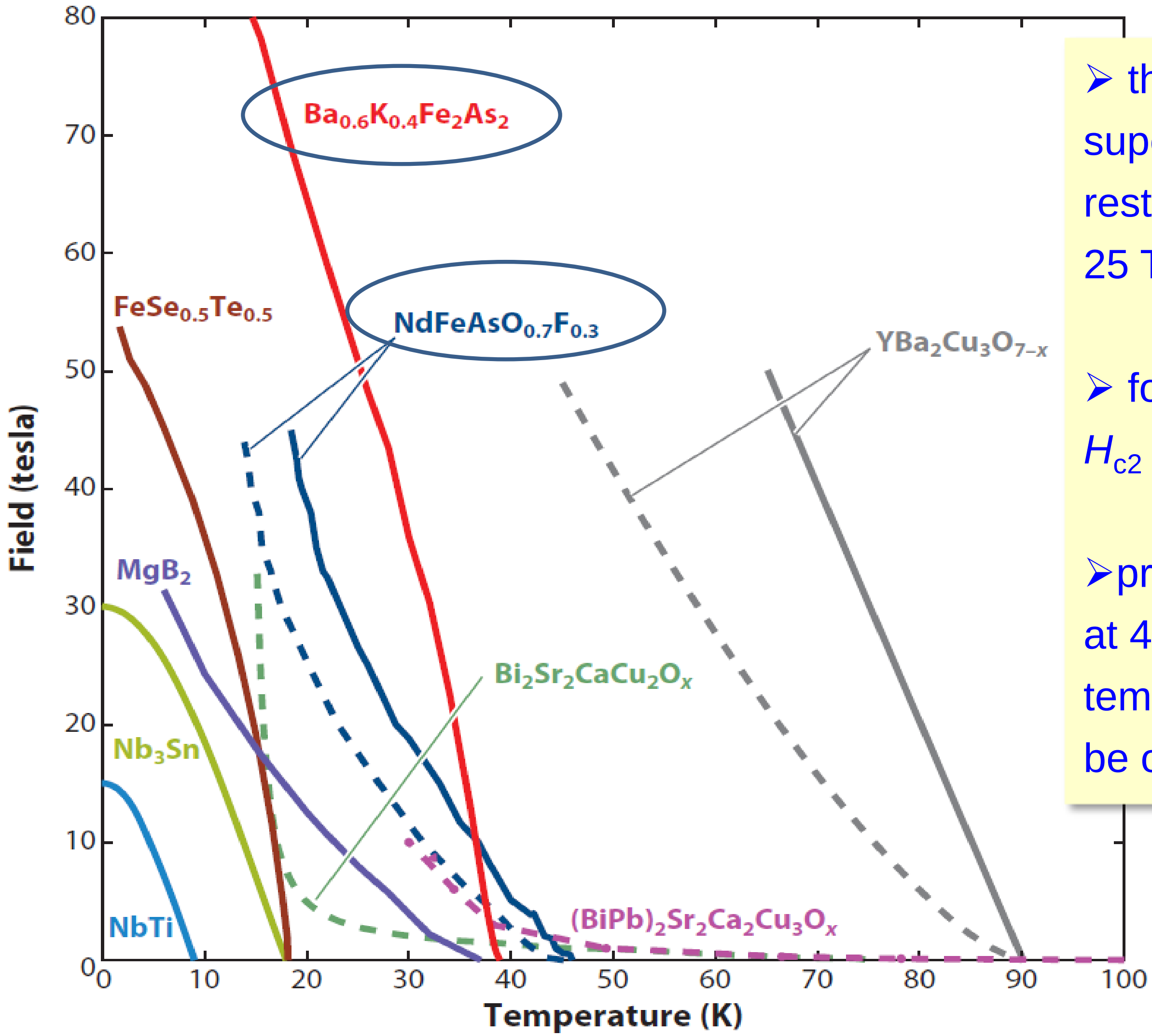
Crystal structures of iron-based superconductors (IBSs)



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 IBSs



Comparative T-H phase diagram for different superconducting materials

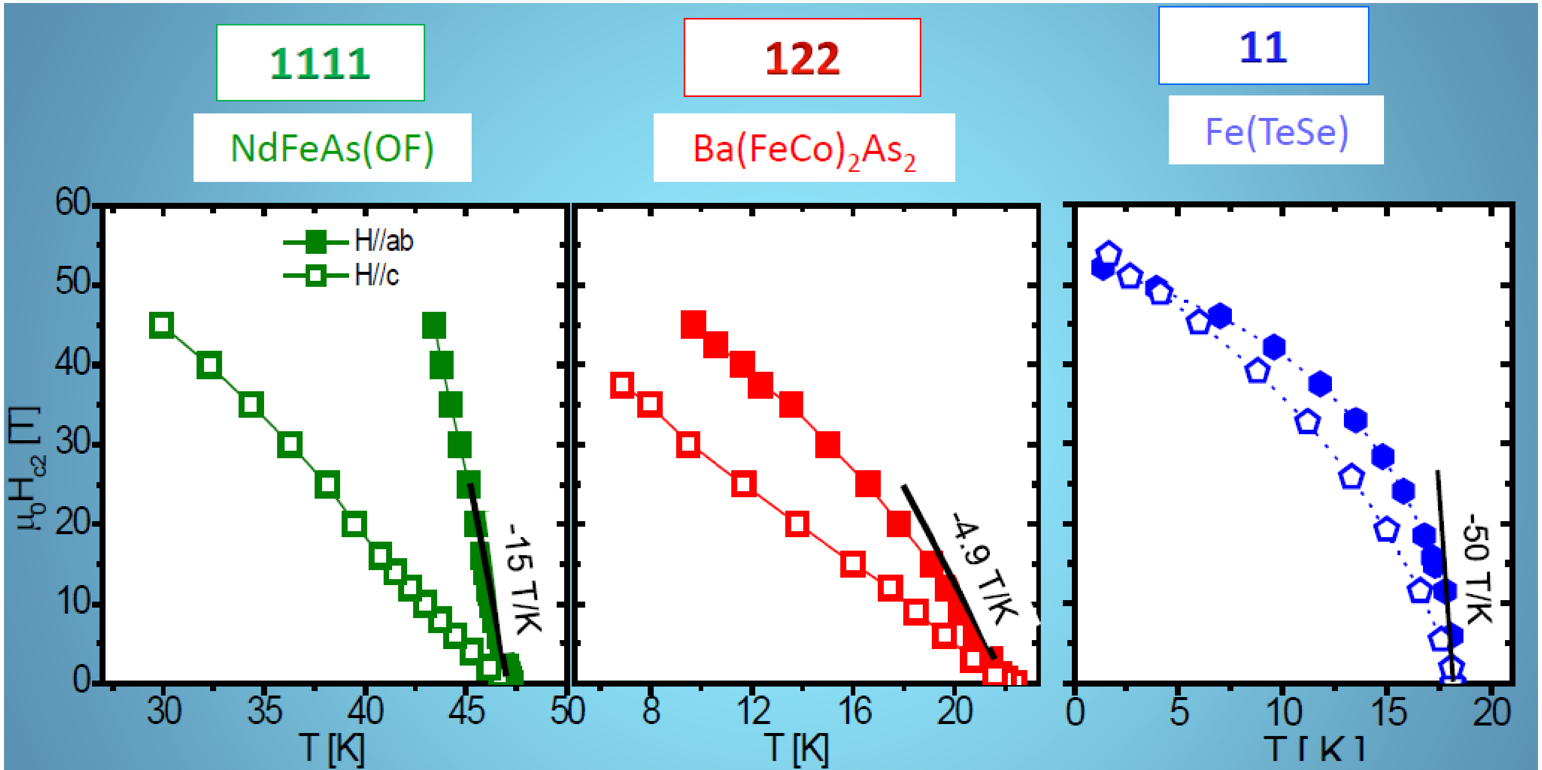
Gurevich 2014 *Annu. Rev. Condens. Matter Phys.* 5 35

- the conventional low-*T*c 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 4.2 K and also in moderate temperature around 20 K, which can be obtained by cryocoolers

Small anisotropy of IBSs



☑Slope -15 T/K
☑Anisotropy is 5

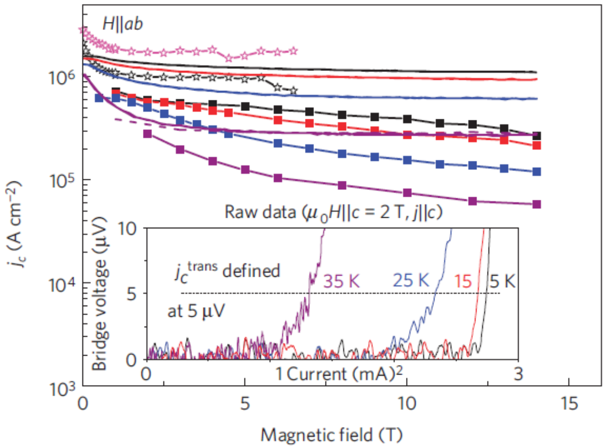
☑Slope -4.9 T/K
☑Anisotropy is 2-1.5

☑Slope -50 T/K
☑Anisotropy 3-1

Putti et al. 2010 *SuST* 23 034003

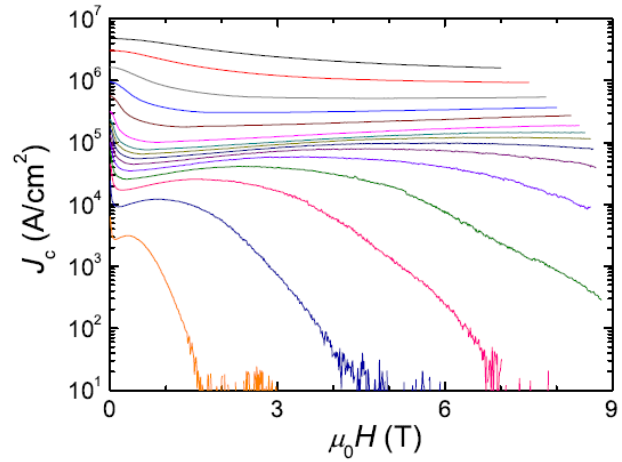
- small anisotropy gives high vortex stiffness, high H_{irr} close to H_{c2}
- advantageous for the design and construction of high-field magnets

J_c in IBSs single crystals and films



Sm-1111 single crystal

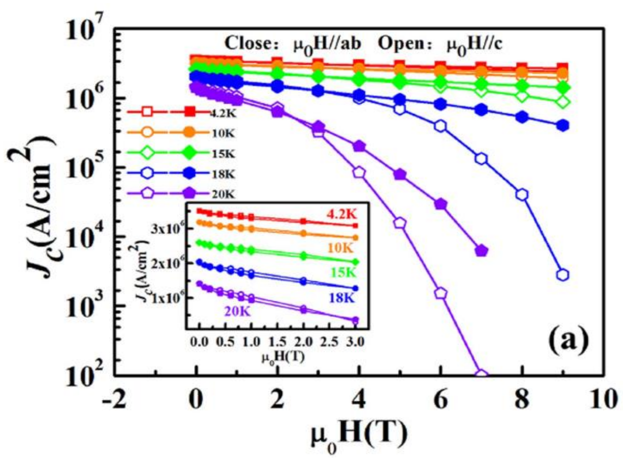
Moll 2010 *Nature Mater.* 9 628



Ba-122:K single crystal

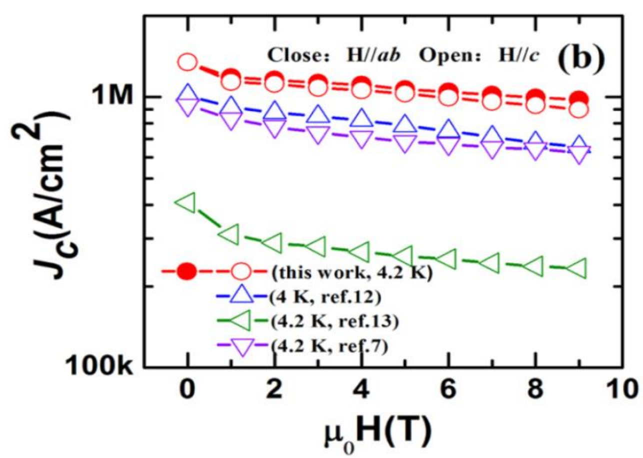
Yang 2008 *APL* 93 142506

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



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

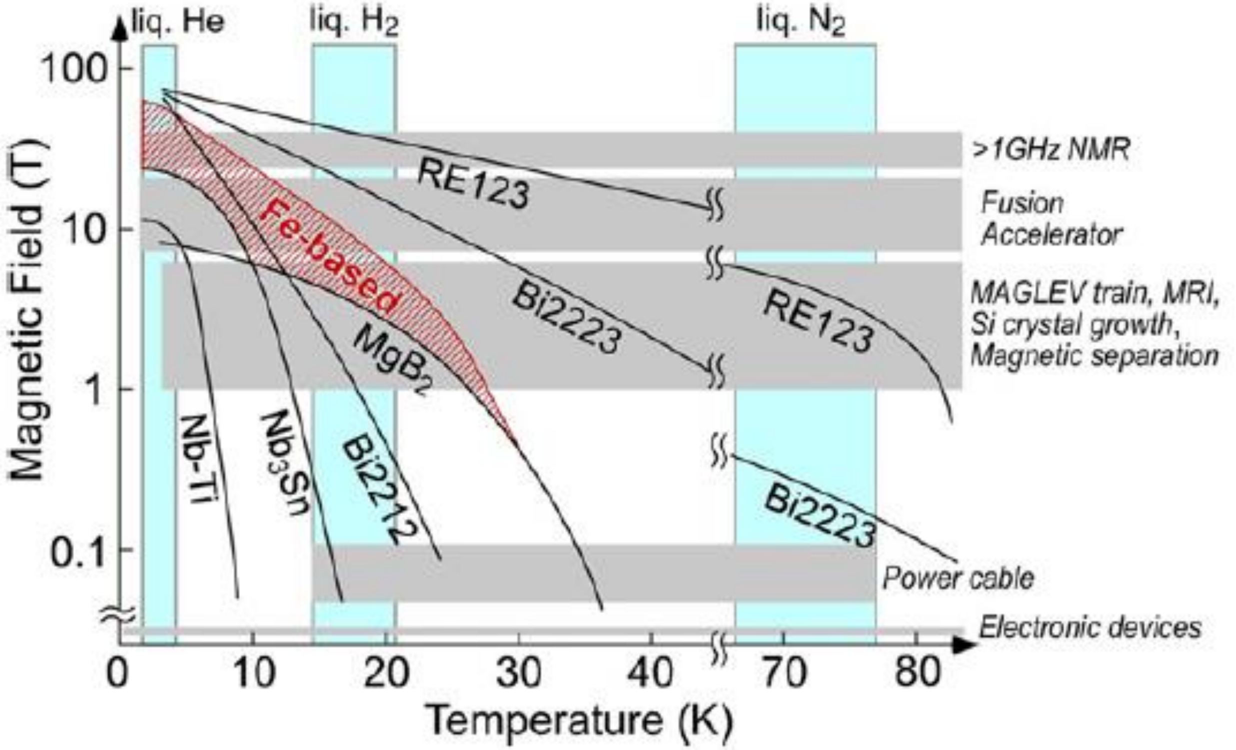
Yuan 2017 *SuST* 30 025001



FeSeTe films 0.97 MA (9 T, 4.2 K)

Yuan 2015 *SuST* 28 065009

Application potential of iron-based superconductors

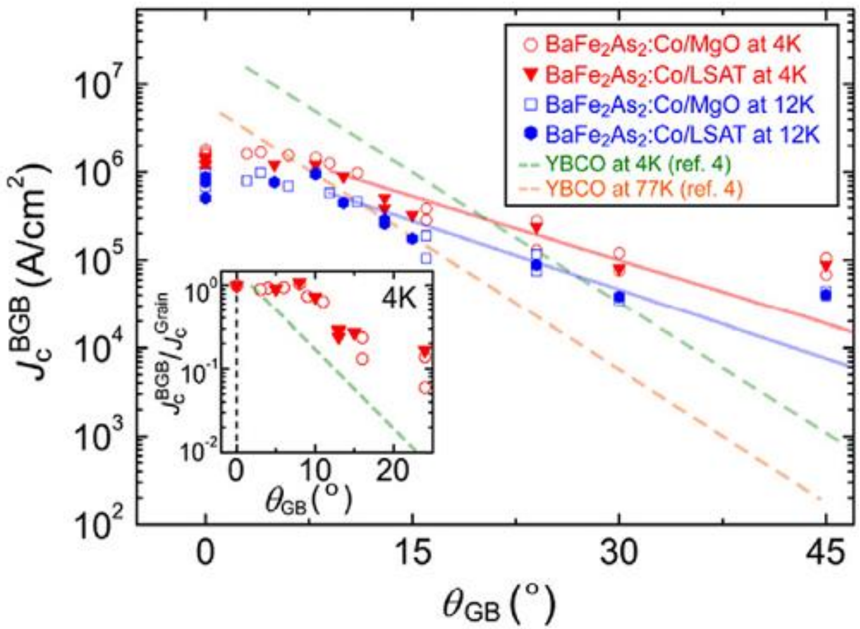


Shimoyama 2014 *SuST* 27 044002

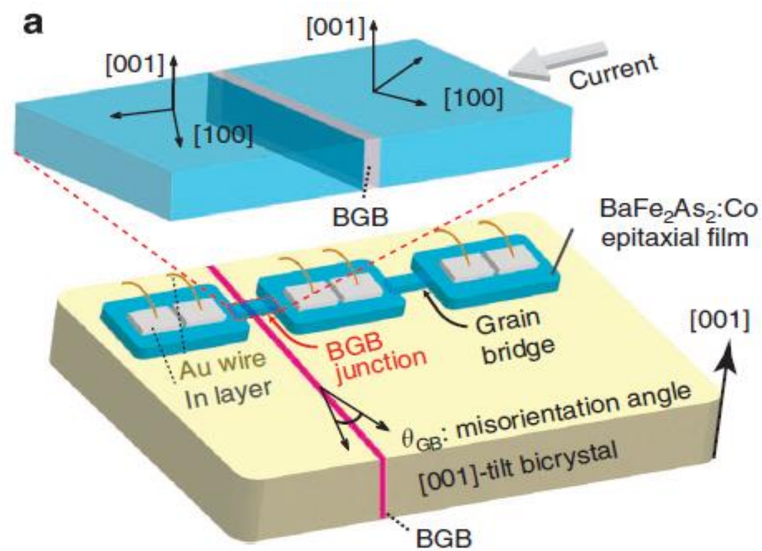
- T_c = 38 and 56 K in 122 & 1111 system
- ultrahigh H_{c2} > 80 T
- very small anisotropy γ= 1.5~2
- strong vortex pinning

promising candidate for:

Grain boundary nature of 122-type IBSs



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 9º, larger than YBCO (θ_c~5º)**

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

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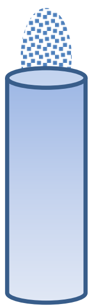
Typical PIT process & induced defects

Starting powders

Packing



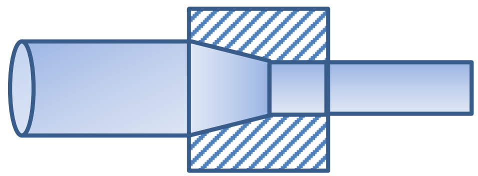
Metal tube

low density, oxidization, & impurities

Mechanical deformations

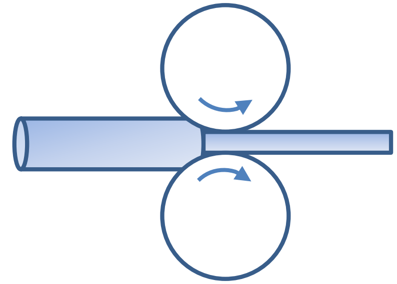
cracks and strains induced in IBS phase

Drawing



wires

Flat Rolling

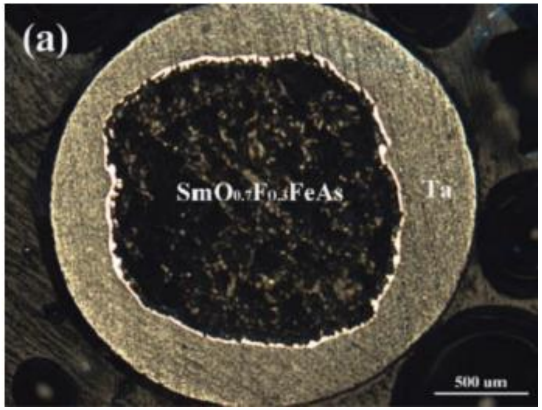


tapes

Heat treatment in furnace under vacuum or argon gas atmosphere

loss of volatile elements, pores, second phase, chemical reaction with metal sheath

Why using silver as sheath material ?



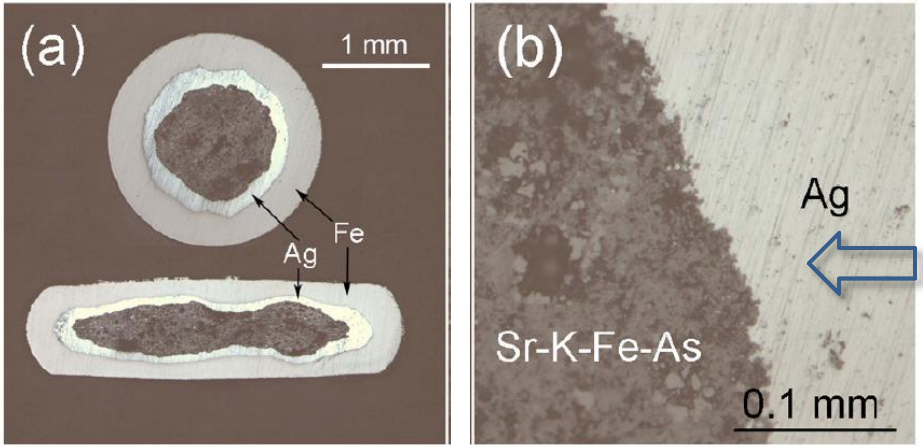
The first 1111-IBS wire in 2008

$SmFeAsO_{1-x}F_x$ 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

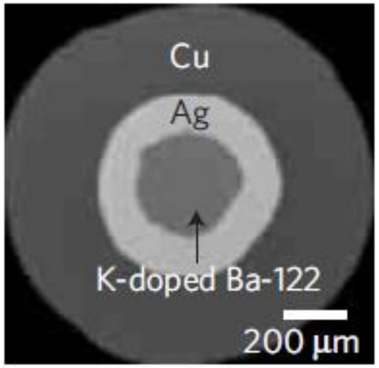
Using silver sheath, we obtained transport current for the first time.

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

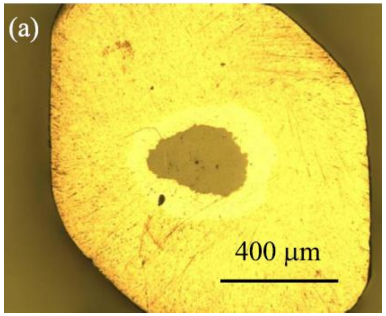
hot isostatic press (HIP)



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**

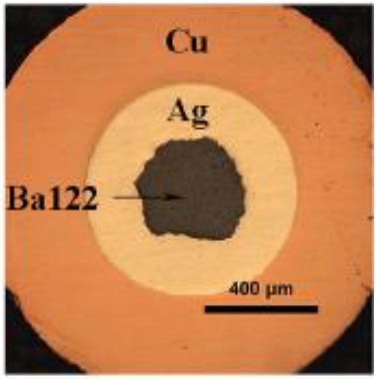


Ba-122 wire made in the University of Tokyo

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 IEE, CAS

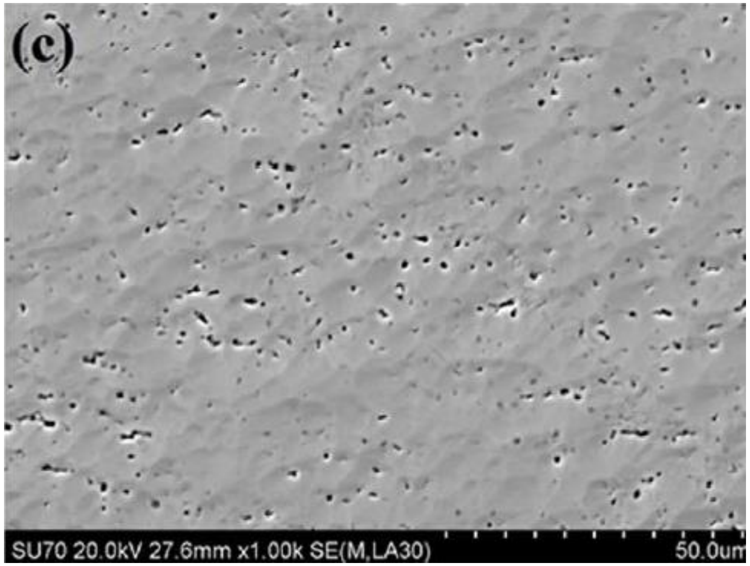
Liu 2017 *SuST* 30 115007

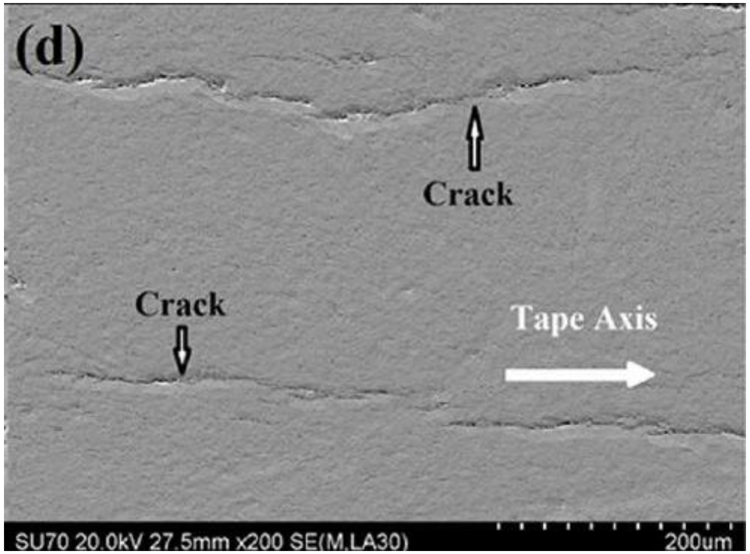
J_c (4.2 K, 10 T) = **~1×10⁴** A/cm²

200 MPa, 700 °C

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

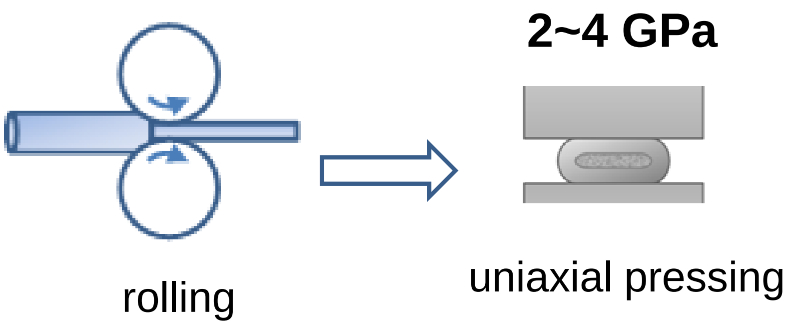
Improve the microstructure of 122-IBS wires and tapes





Gao 2014 *Sci. Rep.* 4 4465

cold press process



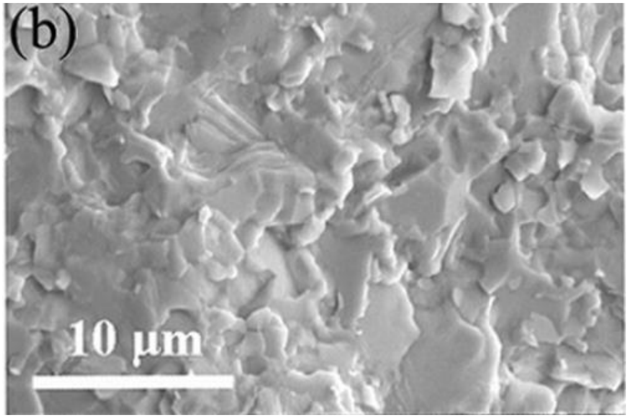
Ba-122 tapes made by NIMS, Japan

J_c (4.2 K, 10 T) = $\mathbf{8.6\times10^4}$ A/cm^2

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

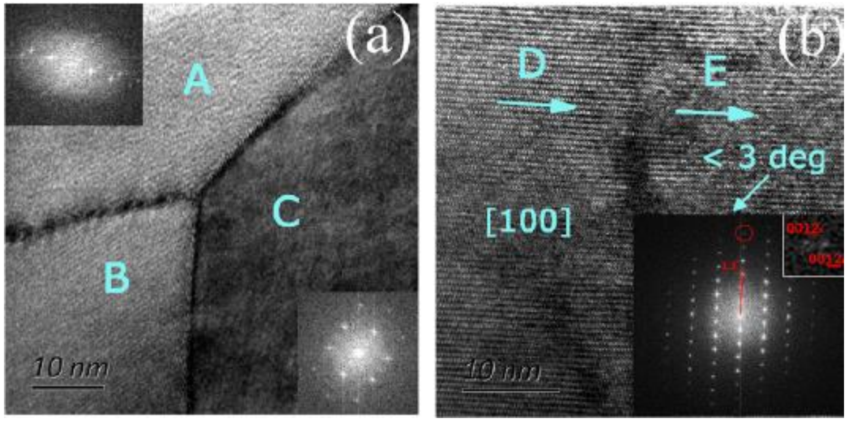
Improve the microstructure of 122-IBS wires and tapes

hot press process (Sr-122 tapes by IEECAS)



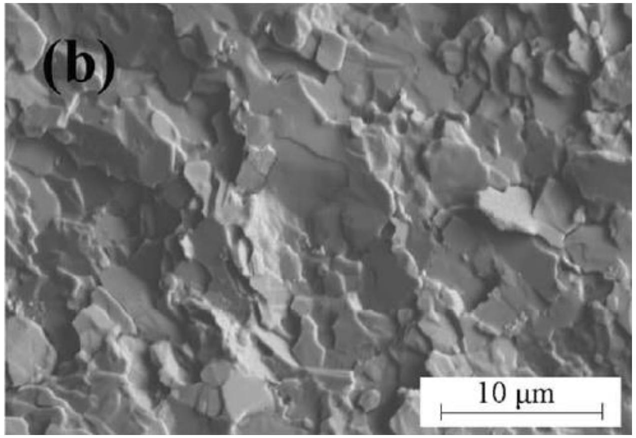
SEM (*ab* plane)

Zhang 2014 *APL* 104 202601

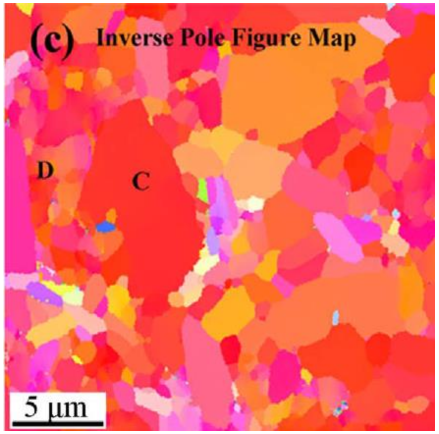


HRTEM

J_c (4.2 K, 10 T) = **1.0×10⁵** A/cm²



SEM (*ab* plane)



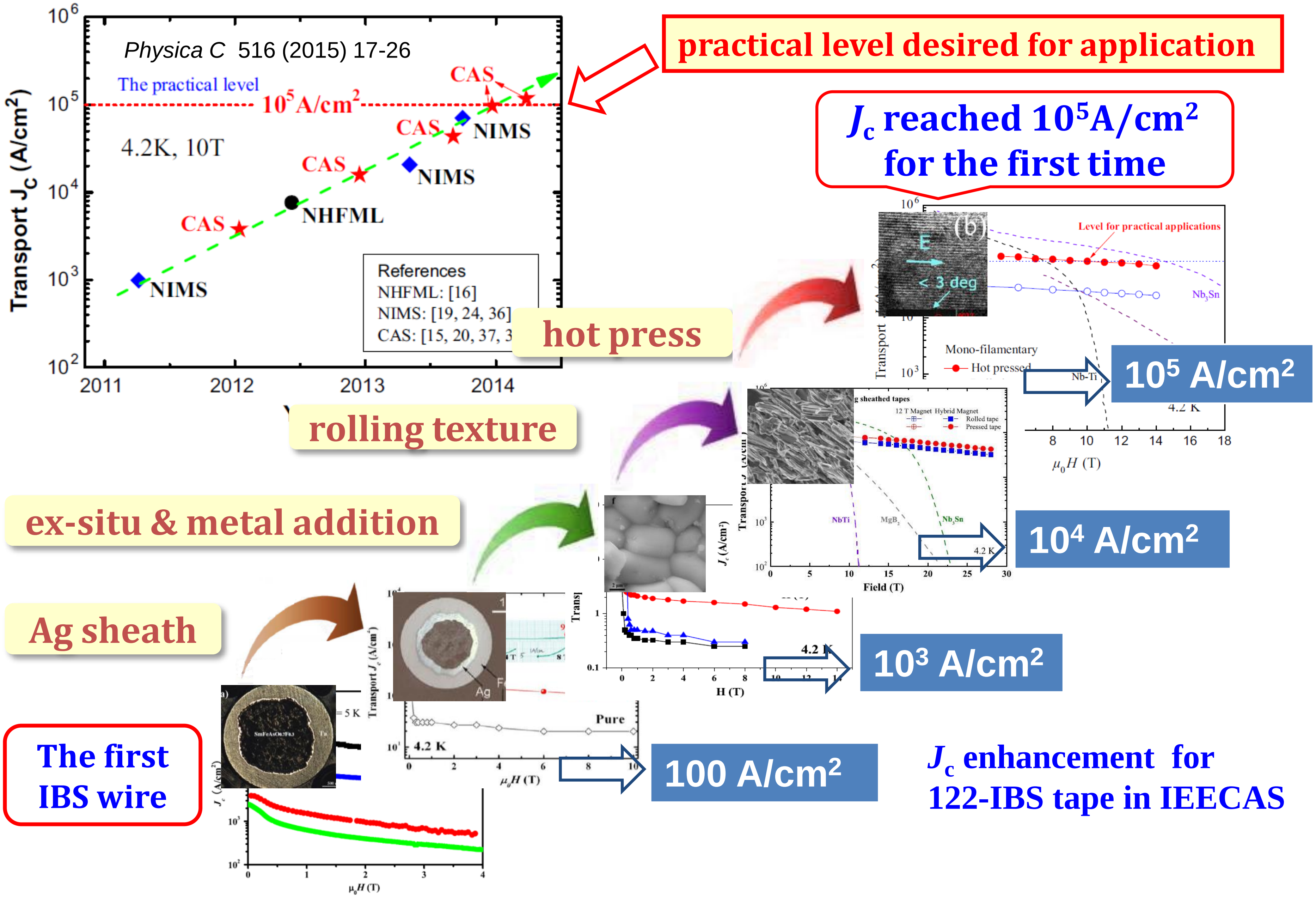
EBSD

- **strong c-axis texture**
- **very high core density**
- **almost no crack !**

30 MPa, 850~900 ^{o}C

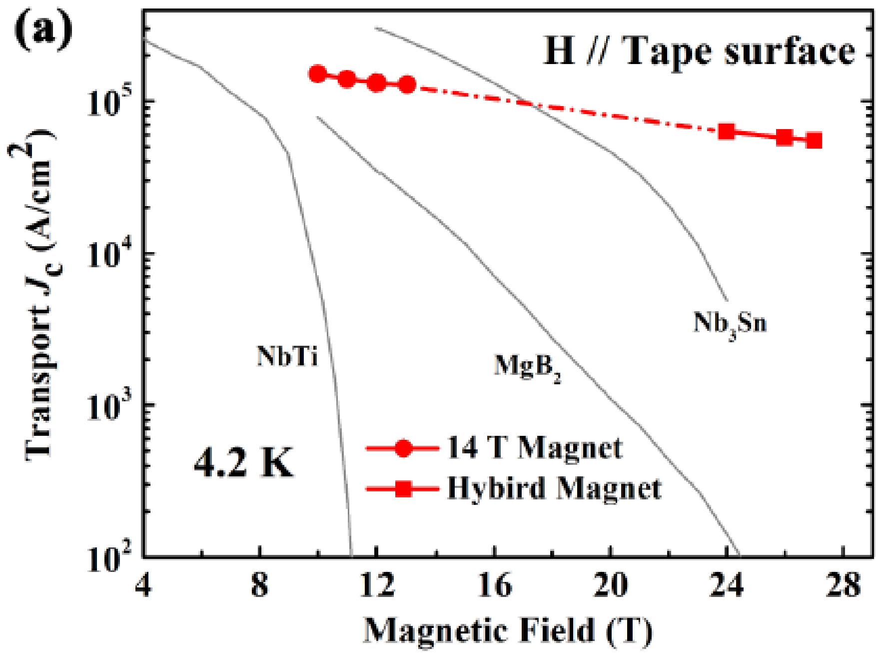
Lin 2014 *Sci. Rep. 4* 6944 J_c (4.2 K, 10 T) = **1.2×10^5** A/cm^2

Continuously increased J_c for 122-IBS wires and tapes

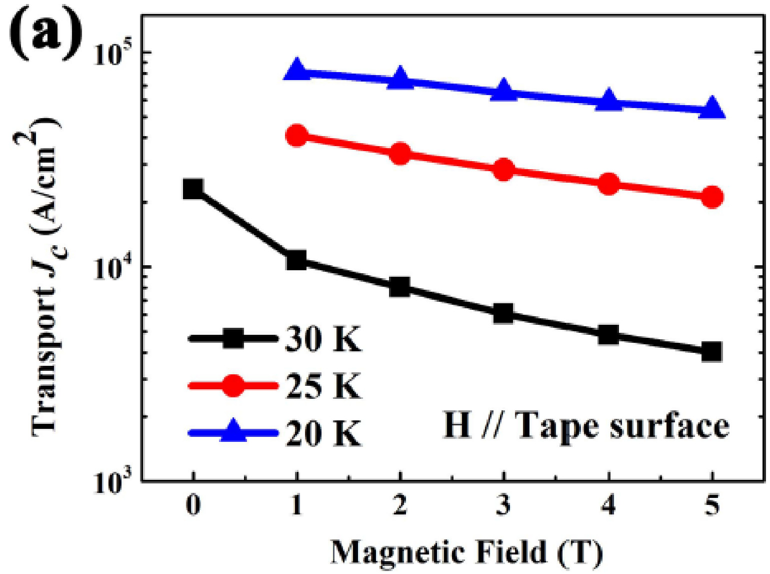


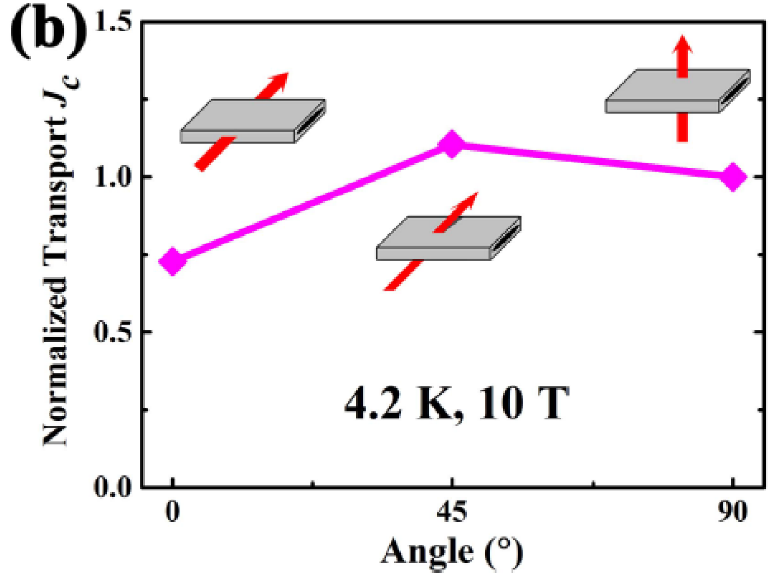
Continuously increased J_c for 122-IBS wires and tapes

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



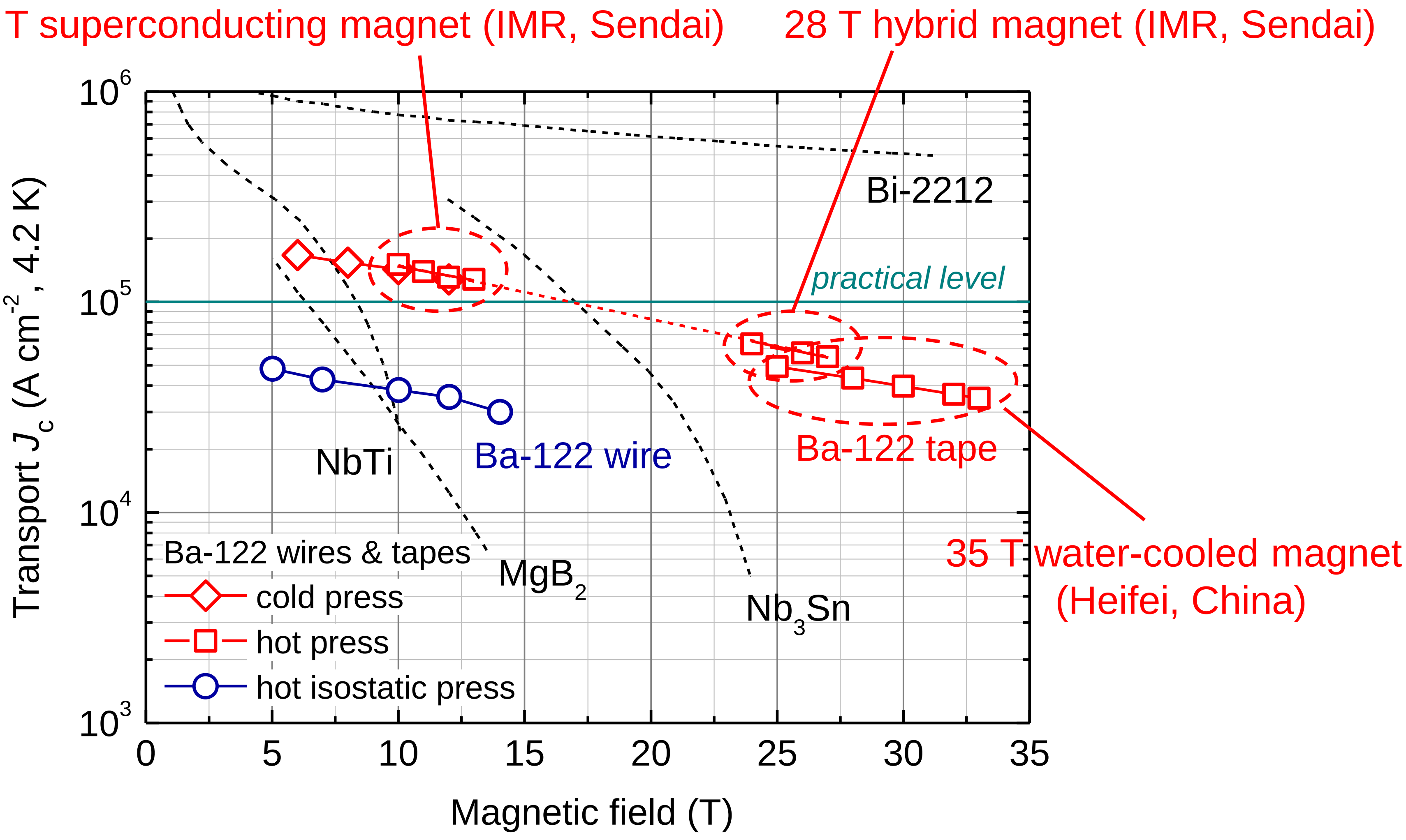
Huang 2018 SuST 31 015017





- I_c (4.2 K, 10 T) = 437 A
- J_c (4.2 K, 10 T) = **1.5×10⁵** A/cm²
- J_c (4.2 K, **27 T**) = **5.5×10⁴** A/cm²
- J_c (**20 K**, 5 T) = **5.4×10⁴** A/cm²
- J_c anisotropy (4.2 K, 10 T) = **1.37**

State-of-the-art J_c for practical superconductors



Yao 2018 *Supercond. Sci. Technol.* (https://doi.org/10.1088/1361-6668/aaf351)

Data for Nb-Ti, Nb3Sn, MgB2 and Bi-2212 are collected from P. Lee (nationalmaglab.org)
https://nationalmaglab.org/magnet-development/applied-superconductivity-center/plots

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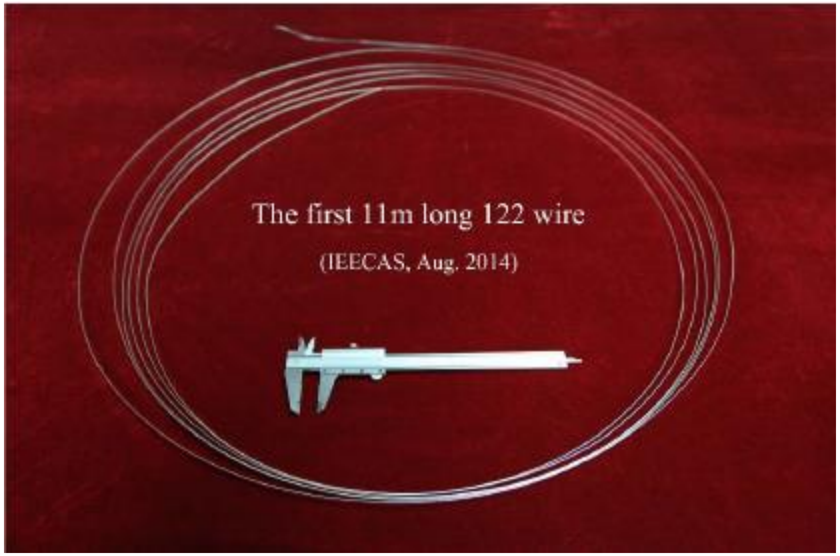
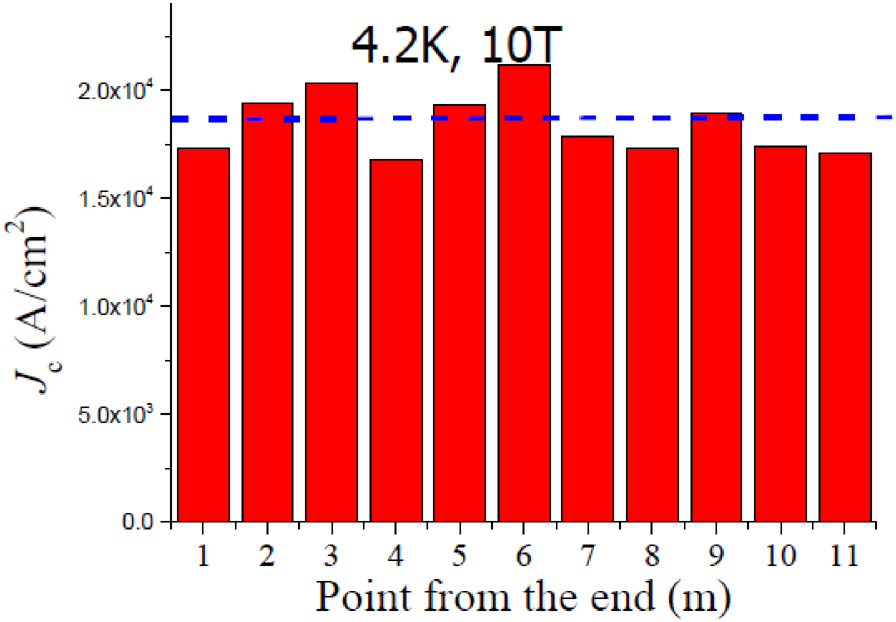
The first 10-meter class IBS wire





by scalable rolling process in IEECAS

Ma 2016 Physica C17 516

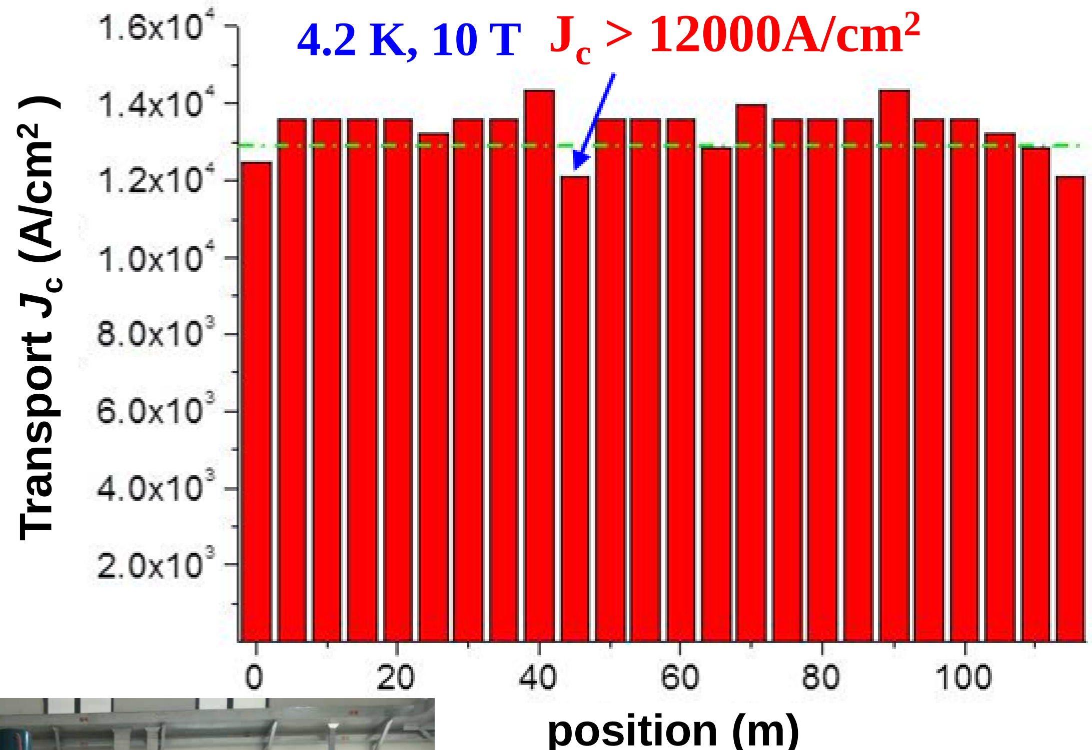
The minimum J_c ~1.7×10^4 A/cm^2

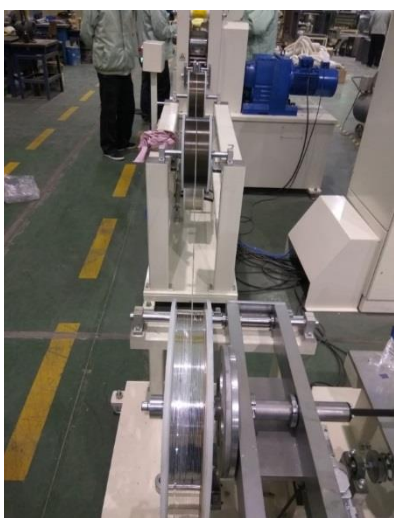
The average J_c is 1.84×10^4 A/cm^2 for the 11 m long Sr122/Ag wire

The fluctuations of the J_c is ~5%

The first 100-meter class IBS wire

made in IEECAS



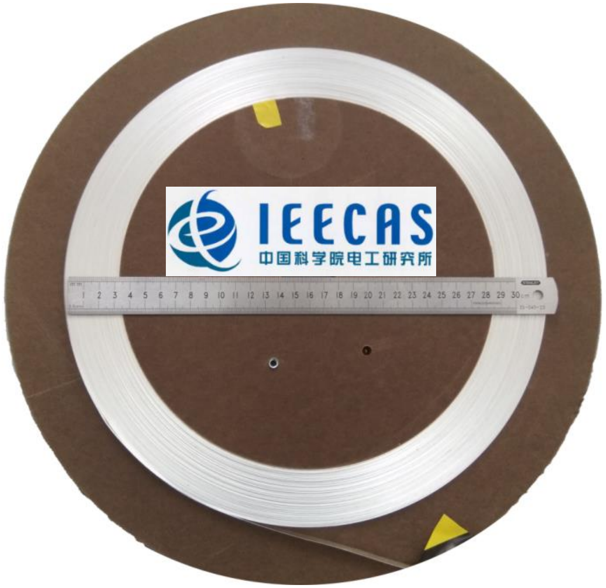


showing a good uniformity

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

IBS Racetrack coil made from a 100 m tape

Recently…



$J_c > 20000\ A/cm^2$ (4.2 K, 10 T)

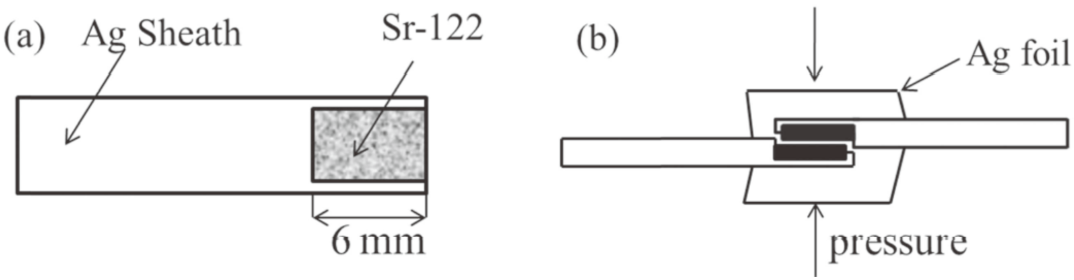
Parameter	Unit	Value
Width	mm	4.5
Thickness	mm	0.33
Number of filament		7
Non-SC/SC ratio		5.0

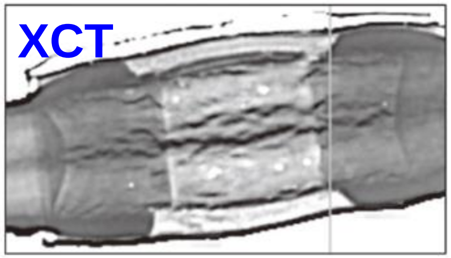
IBS Racetrack coil

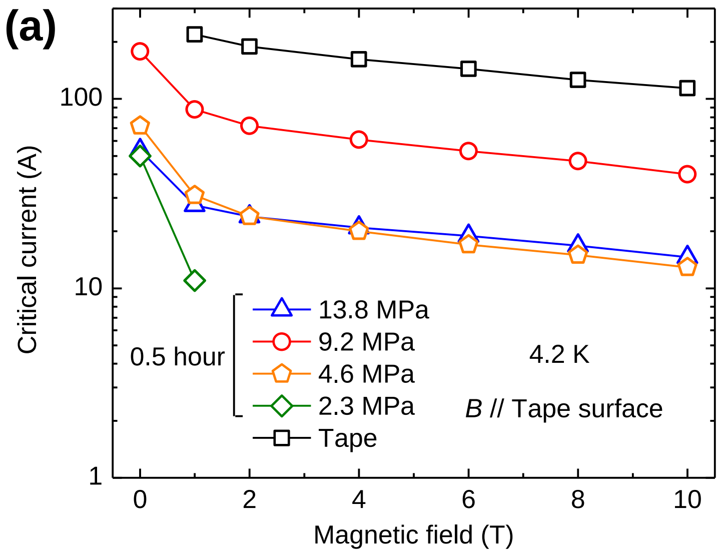
made by :

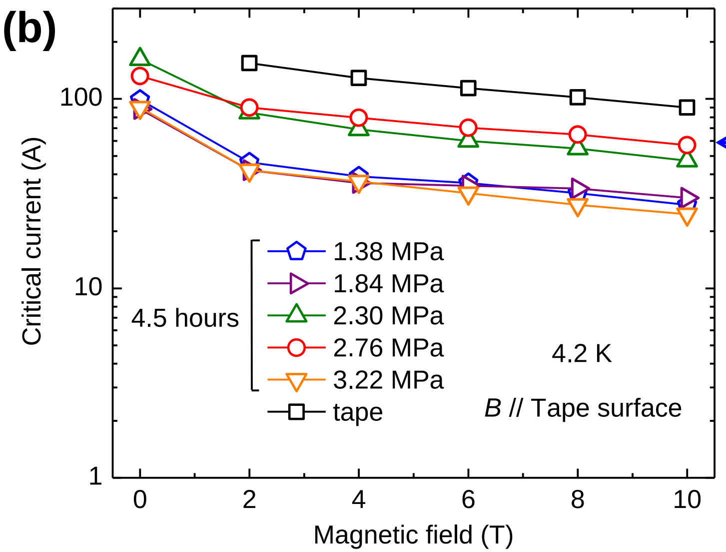
Institute of High Energy Physics
Chinese Academy of Sciences

IBS joints by hot press









Zhu 2018 SuST 31 06LT02

Zhu 2019 SuST 32 024002

critical current ratio
CCR = 35.3%

optimize the pressure of HP process

CCR=I_c^{joint}/I_c^{tape} of
63.3% at 10 T, 4.2K
dV/dI < 1 nΩ

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Challenges in practical applications

challenges

- 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

⇒ ✓ Long wires by PIT method

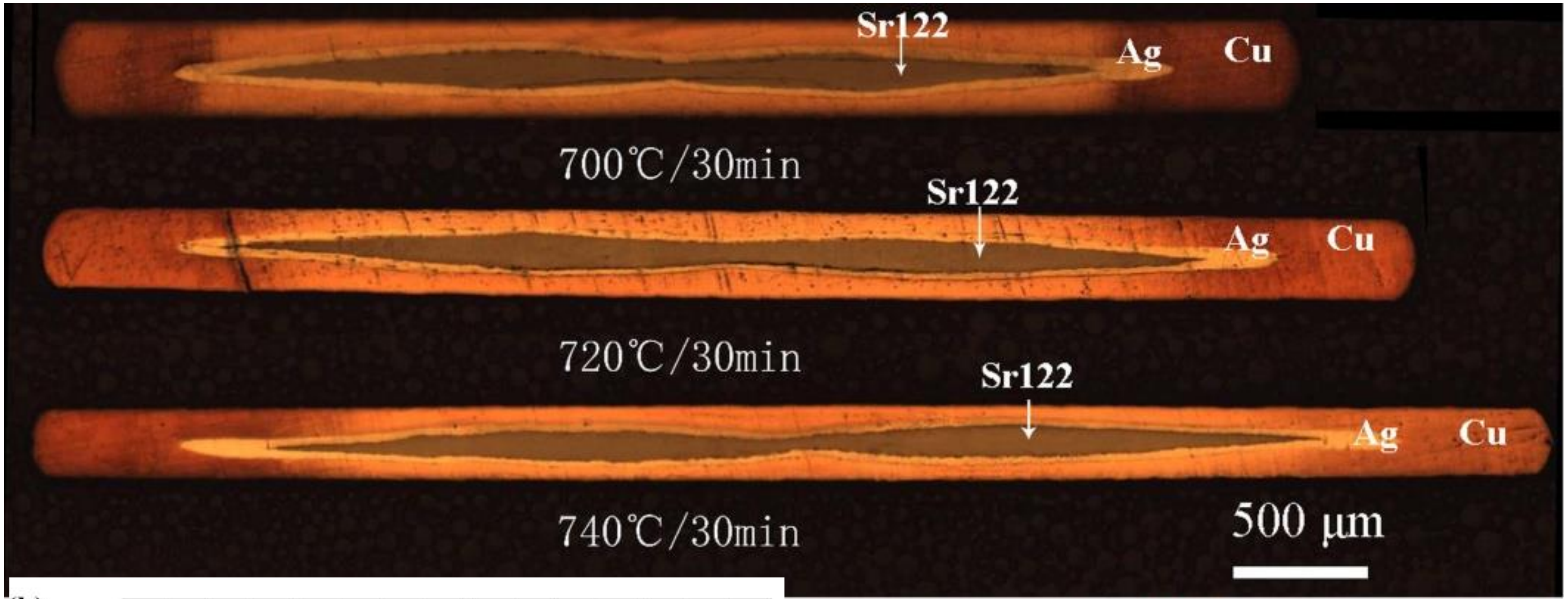
strategies

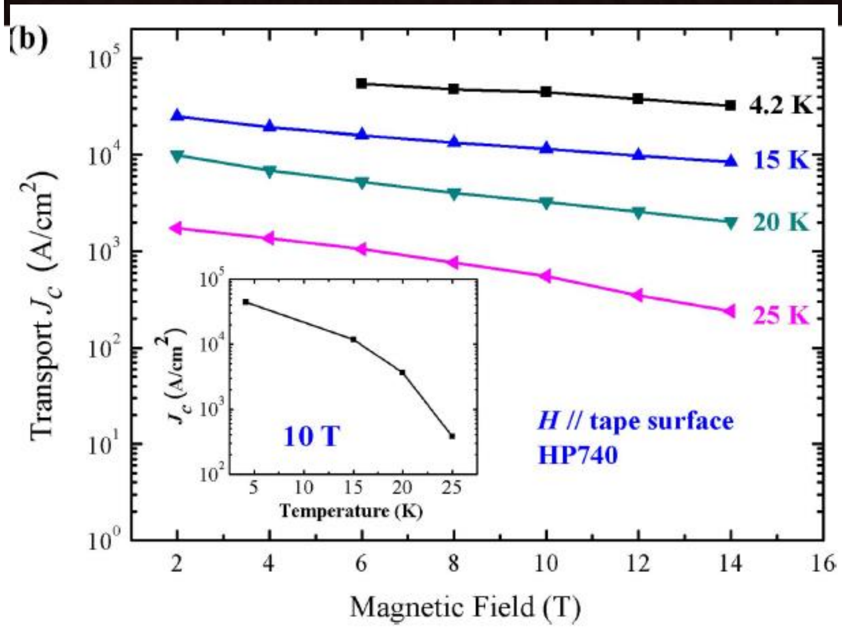
Bi-based wires: Ag/Ag-alloy sheath

IBS wires: Ag/various metal **composite sheath** is possible

inner sheath: chemical stability + **outer sheath:** mechanical strength & reduce Ag ratio

Cu/Ag sheathed 122-IBS tapes (hot press)





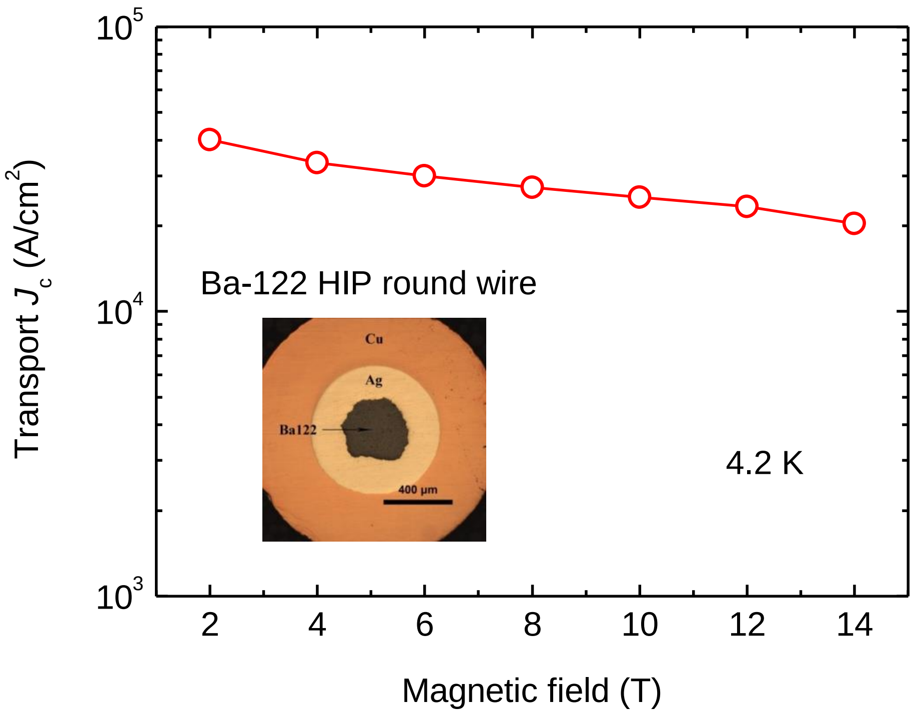
copper and thin silver double sheath

J_c (4.2 K, 10 T) = **4.4×10^4** A/cm^2

J_c (20 K, 10 T) = **3.6×10^3** A/cm^2

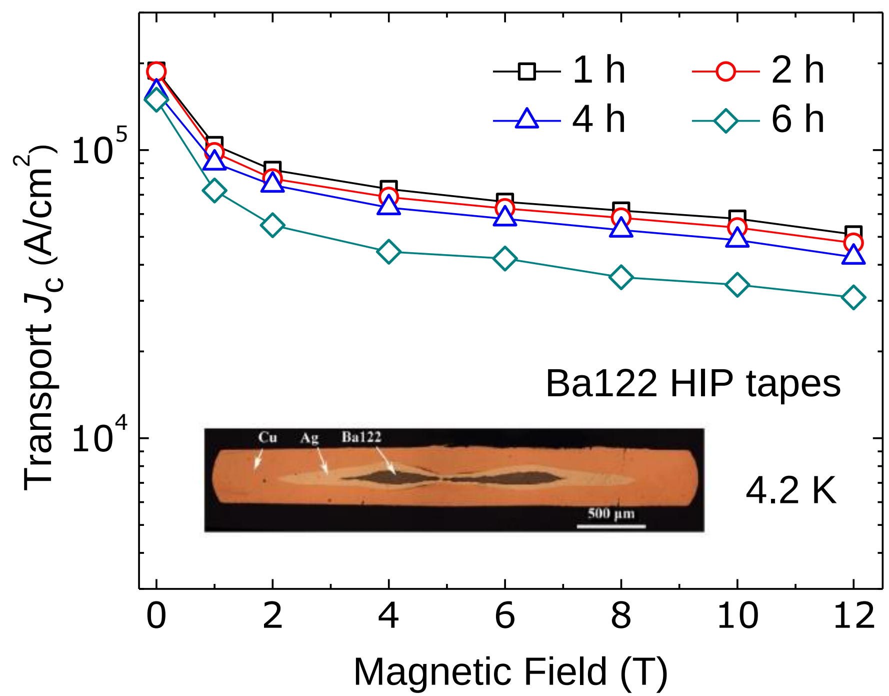
Cu/Ag sheathed 122-IBS wires & tapes (HIP)

Ba-122/Ag/Cu round wires



J_c **(4.2 K, 10 T) = 2.5×10^4 A/cm^2**

Ba-122/Ag/Cu tapes

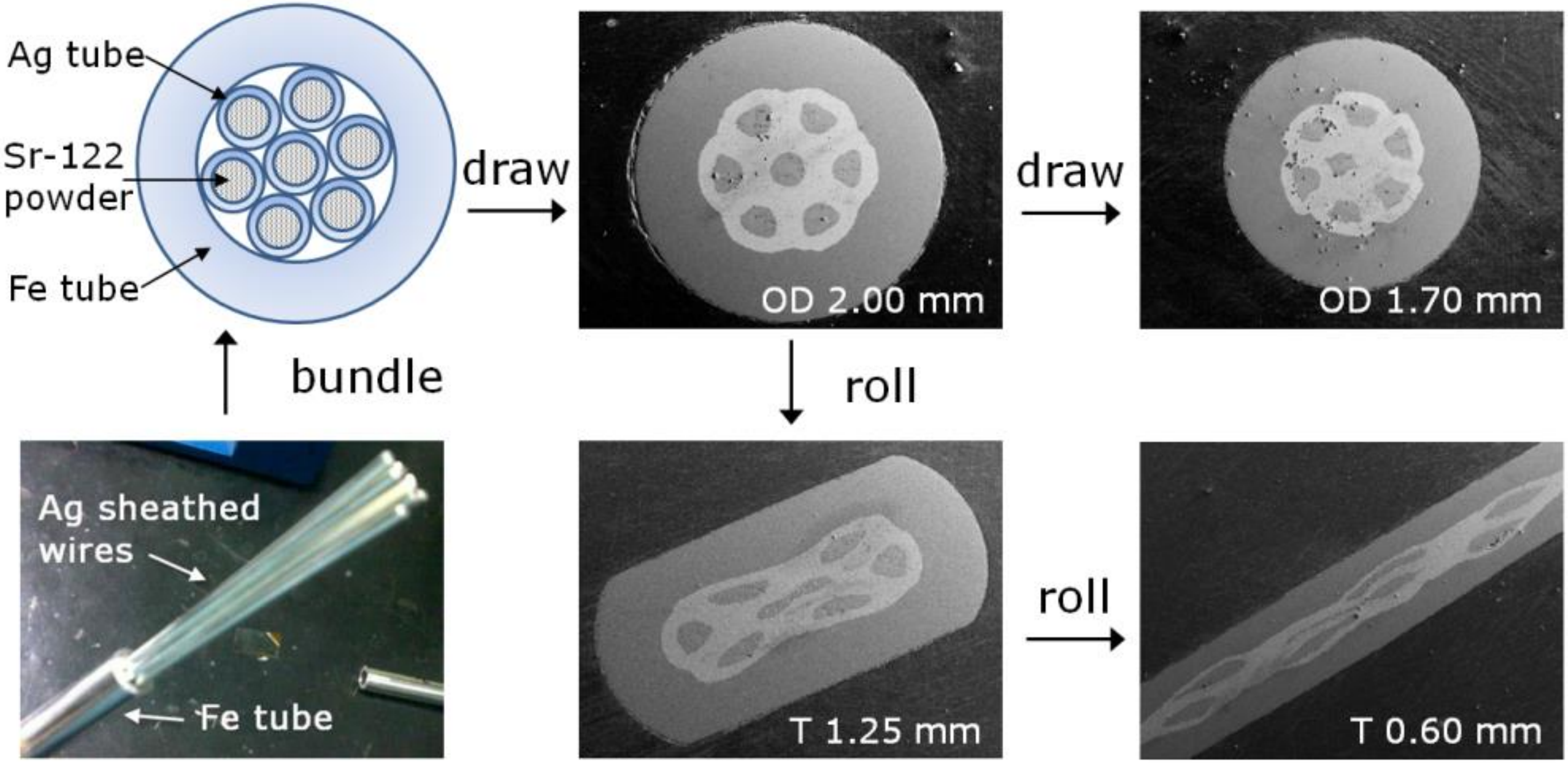


J_c **(4.2 K, 10 T) = 5.8×10^4 A/cm^2**

A scalable process ⇨
- grain texture by flat rolling
- high density by HIP

Liu 2019 *SuST* accepted

Fe/Ag sheathed multifilament IBS wires and tapes

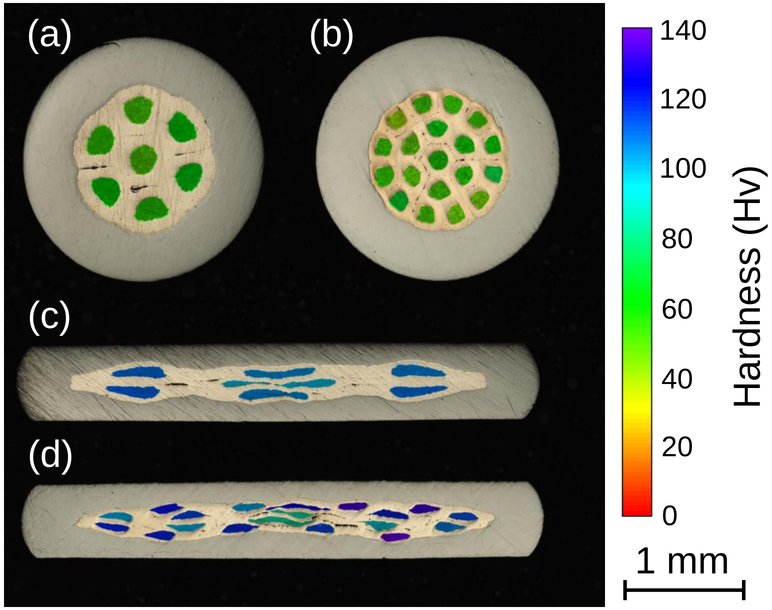


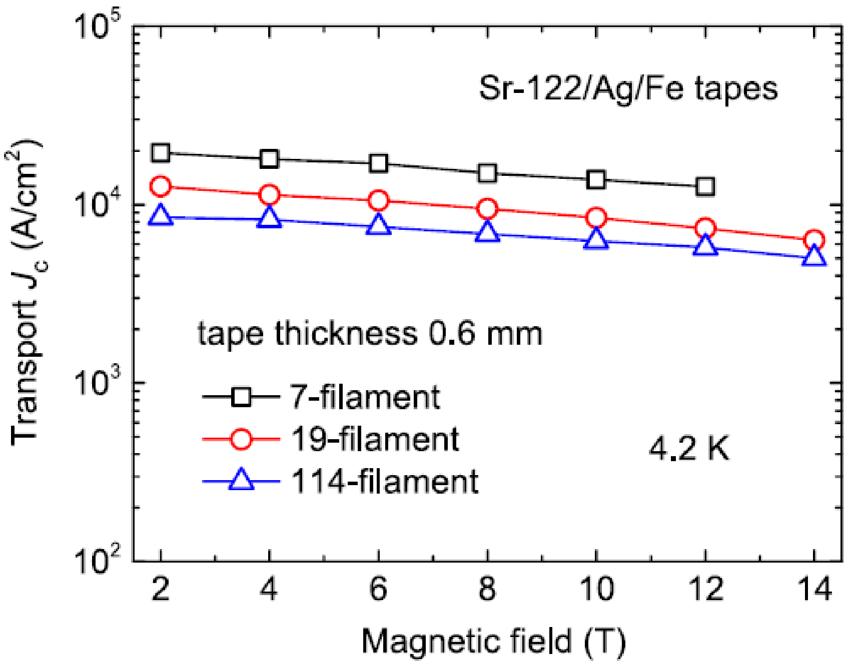
The first 122 iron-pnictide multifilamentary wire

Yao et al. 2013 *APL* 102 082602

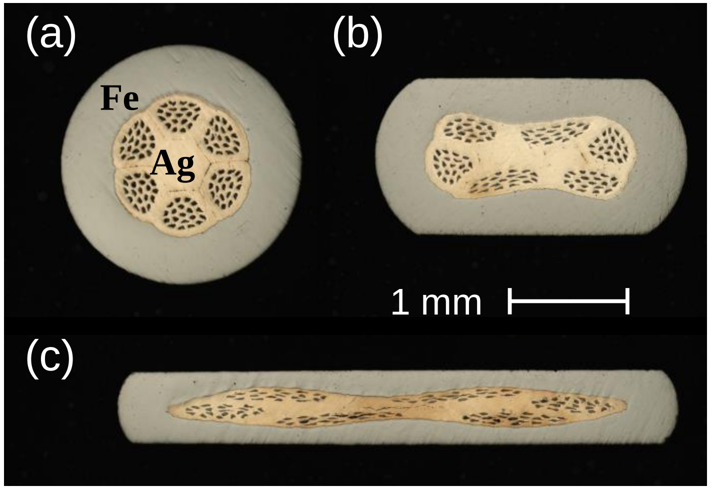
7-, 19- & 114-filament Sr-122 wires with Ag/Fe sheath

transverse cross-sections





Yao et al. 2015 *JAP* 118 203909



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;

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 ^{o}C;
- ✓ It also has good ductility and thermal conductivity.
- ✓ excellent mechanical properties at subzero temperatures

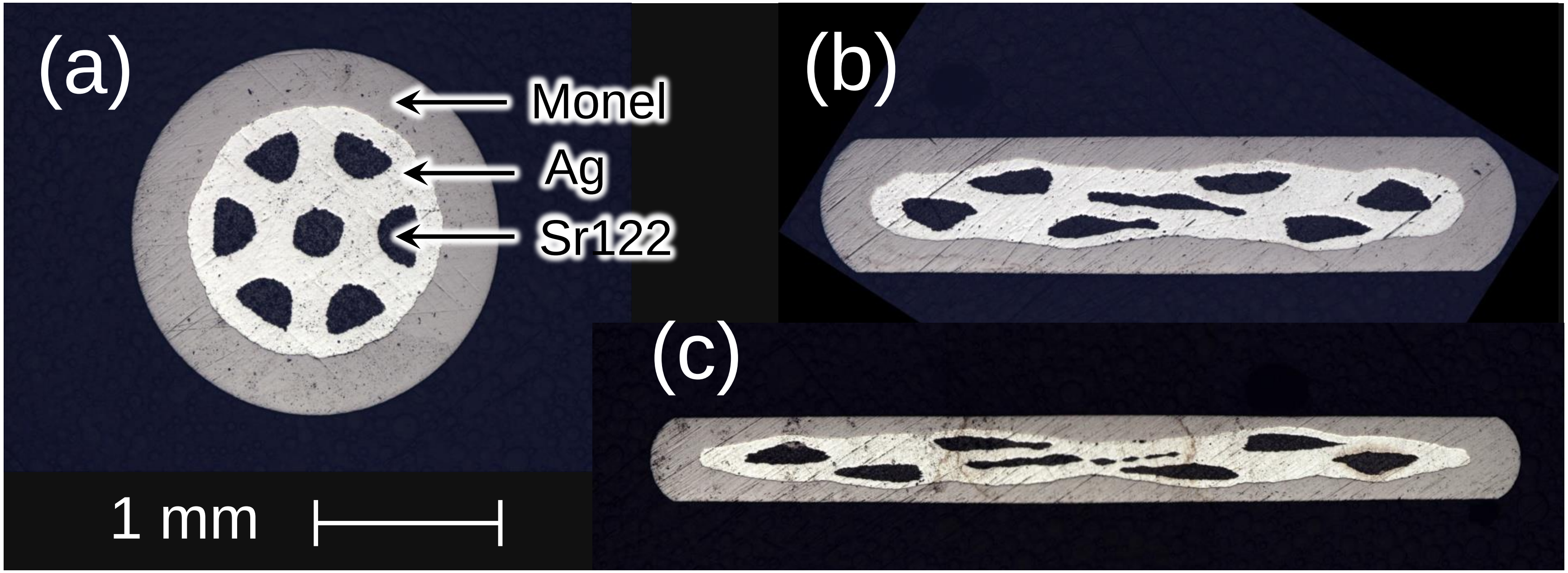
  does not undergo a ductile-to-brittle transition even when cooled to the temperature of liquid hydrogen. This is in marked contrast to many ferrous materials which are brittle at low temperatures despite their increased strength

typical values of Vickers hardness after annealed at 800~900 ^{o}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 sheath

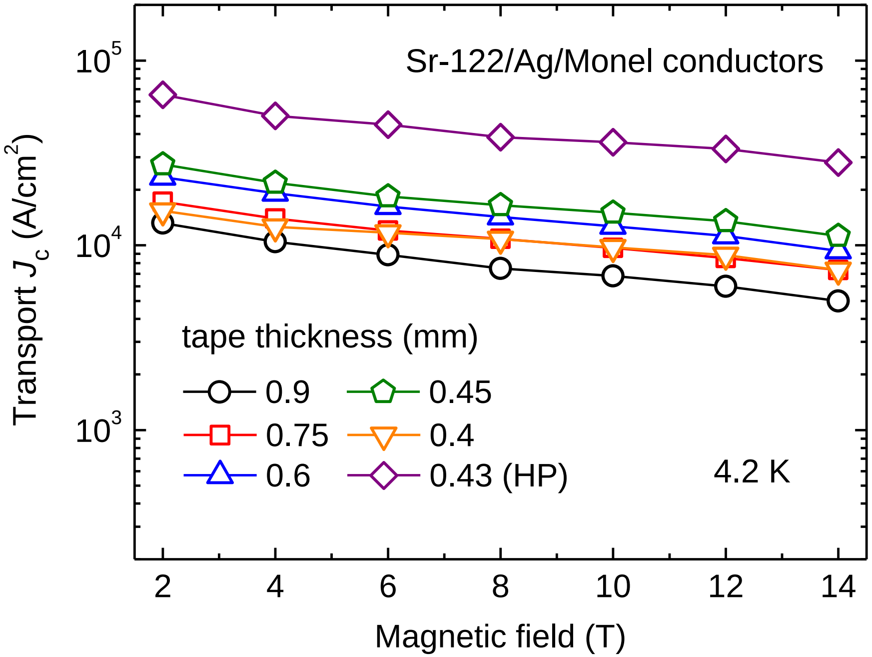


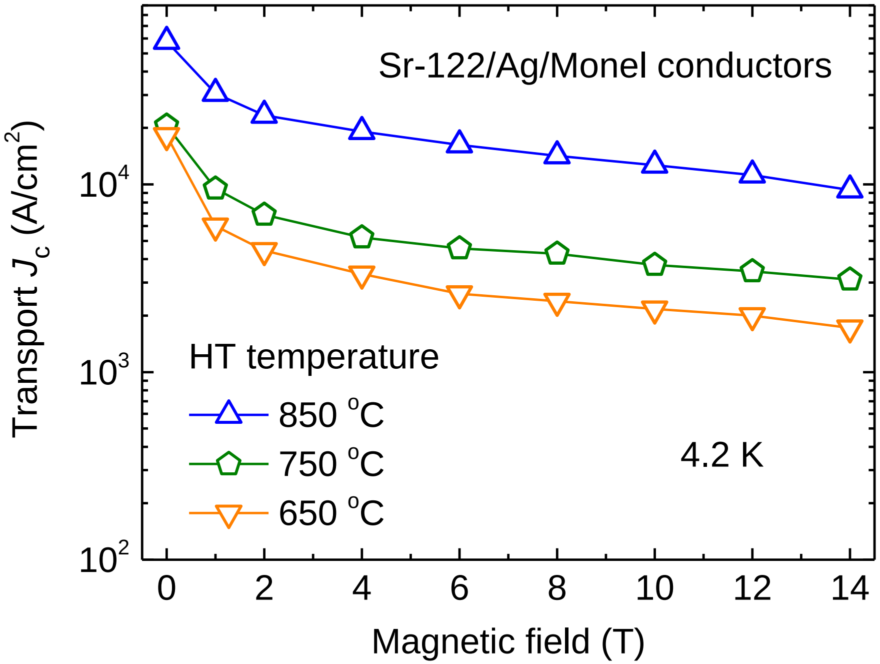
Transverse cross-sections for 7-filament Sr-122/Ag/Monel wires 2.0 mm in diameter and tapes 0.75 and 0.45 mm in thickness

- 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 0.6 mm thick tapes, the transport J_c decreases with the decline of heat treatment temperature.
- 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.

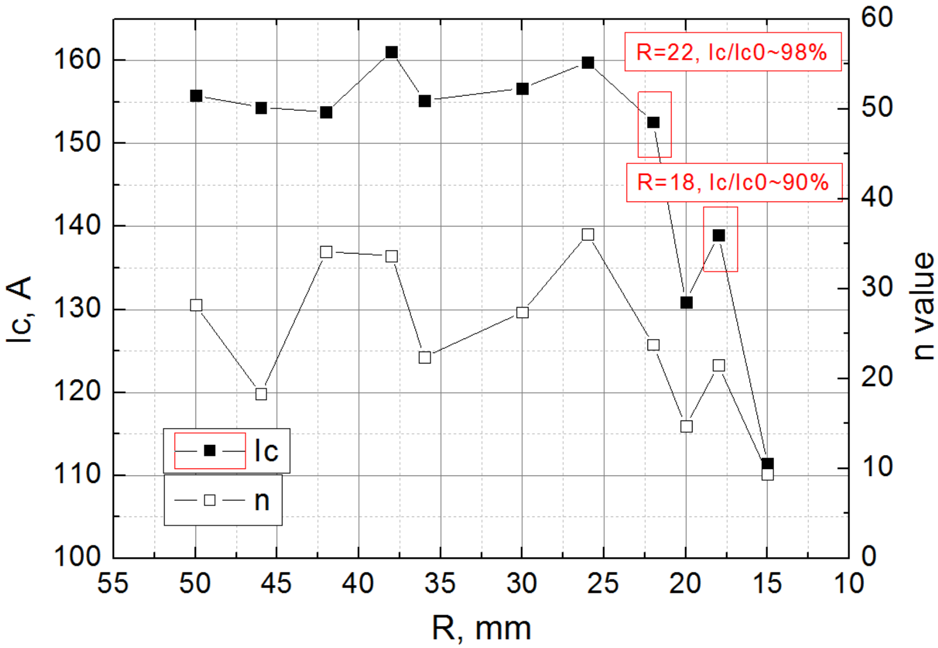
Yao et al. 2017 *SuST* 30 075010

Outline

1. Properties & application potential of iron-based superconductors
2. Improving the J_c-performance of IBS wires and tapes
3. Long-length fabrications and superconducting joints
4. IBS wires and tapes with composite sheaths
5. **Mechanical properties of IBS tapes**

Bending test of Sr-122/Ag tapes

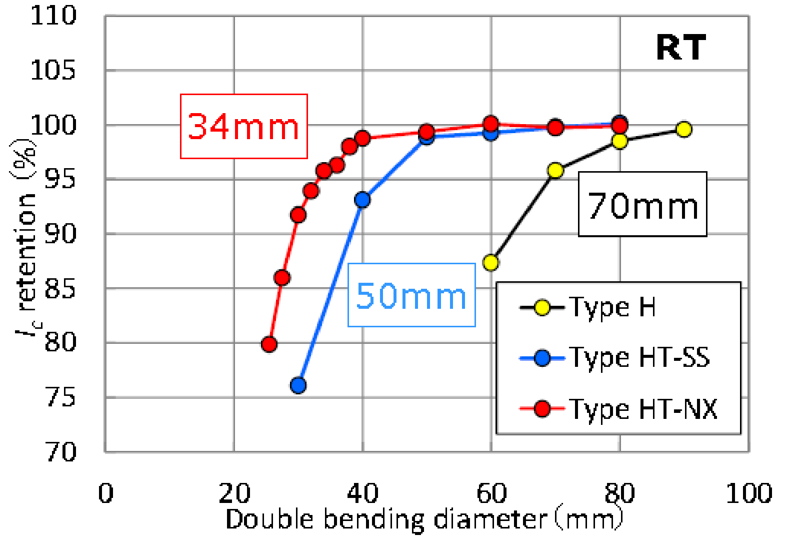
Sr-122/Ag IBS tapes



width ~ 4.5 mm, thickness = 0.3 mm

cooperate with Prof. Huajun Liu in Institute of Plasma Physics, Chinese Academy of Sciences

SUMITOMO ELECTRIC

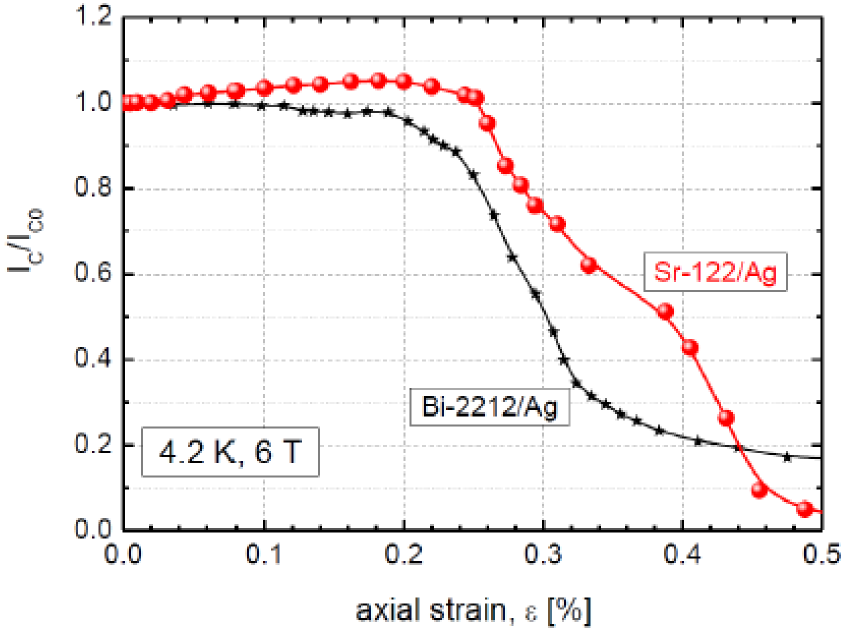


Wire Type	Type H Type G	TypeHT	*Type HT-NX*
Status	Commercial	Commercial	Commercial (100-200m)
Reinforcement tape	-	CA/SS	Ni-alloy
Width	4.3 mm	4.5 mm	*4.5* mm
Thickness	0.23 mm	0.34/0.29 mm	*0.31* mm

Kagiyama et al. The 8th Asian Conference on Applied Superconductivity and Cryogenics

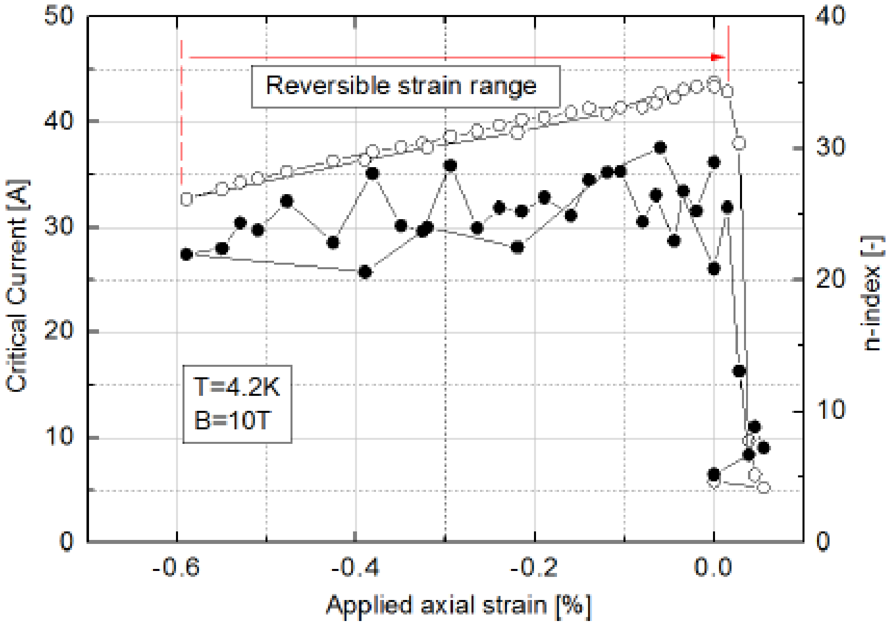
- the critical bending diameter **is 44 mm** for Sr-122/Ag tapes in thickness of 0.3 mm
- smaller than the **70 mm** of Bi-2223 tapes with no reinforcement tape

J_c-strain relationship of Sr-122/Ag tapes



I_c - tensile strain measurement

Kovac 2015 *SuST* 28 035007



I_c –strain measurement

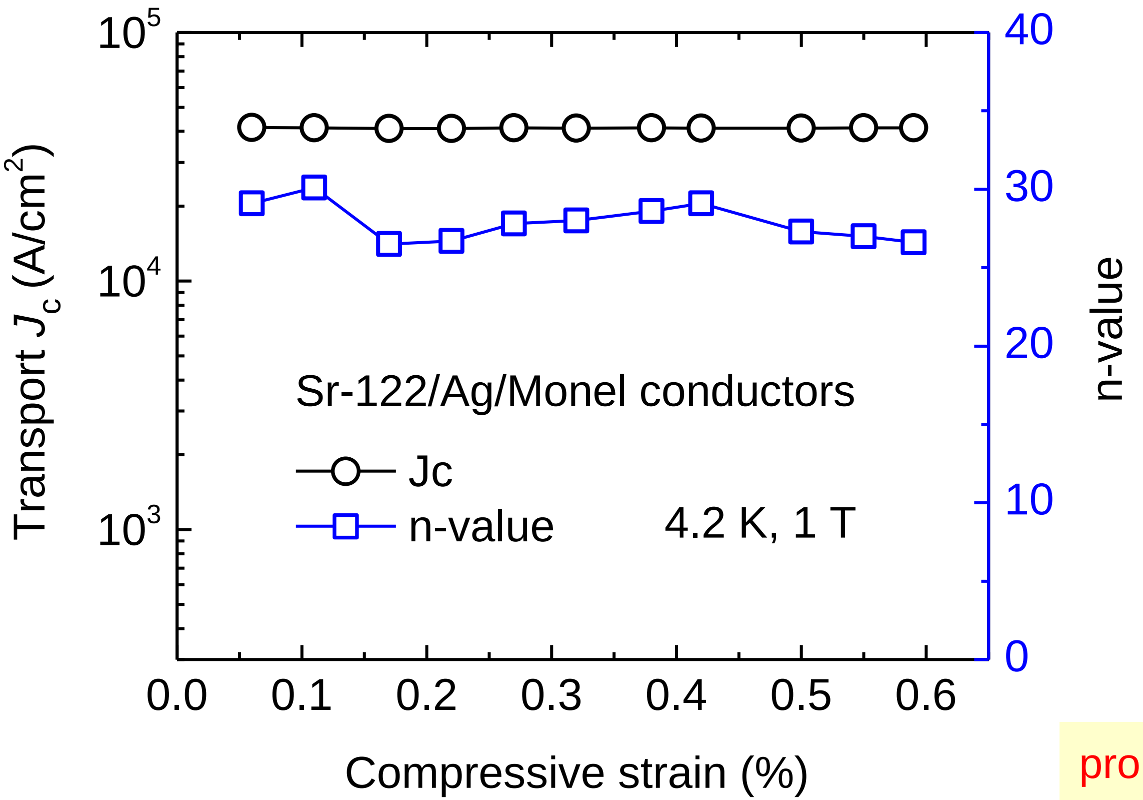
Liu 2017 *SuST* 30 07LT01

- 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 % were observed
- 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.

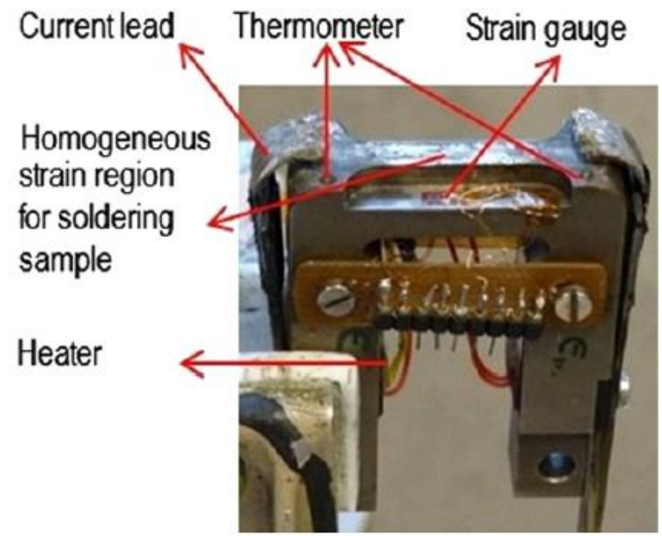
cooperate with Prof. Kovac in Institute of Electrical Engineering, Slovak Academy of Sciences
& Prof. Huajun Liu group in Institute of Plasma Physics, Chinese Academy of Sciences

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

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
- The world's first 100-meter class iron-based superconducting wire was achieved in IEECAS, demonstrating the great potential for large-scale manufacture.
- 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.

Thank you for your attention !
Thanks our collaborators !

Prof. Satoshi Awaji (I_c measurements)

Institute for Materials Research, Tohoku University

Prof. Yifang Wang, Prof. Qinjin Xu (coils)

Institute of High Energy Physics, Chinese Academy of Sciences

Prof. Huajun Liu (mechanical test)

Institute of Plasma Physics, Chinese Academy of Sciences

Prof. Wenge Chen, Prof. Li Pi (I_c measurements)

High Magnetic Field Laboratory of the Chinese Academy of Sciences

Prof. Pavol Kovac (mechanical test)

Institute of Electrical Engineering, Slovak Academy of Sciences

Prof. Jianqi Li (HR-TEM)

Beijing National Laboratory for Condensed Matter Physics
Institute of Physics, Chinese Academy ofSciences