中国科学院
CHINESE ACADEMY OF SCIENCES

中国科学院电工研究所
Institute of Electrical Engineering
Chinese Academy of Sciences

Recent progress in Fe-based superconducting wires and tapes

Yanwei Ma

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

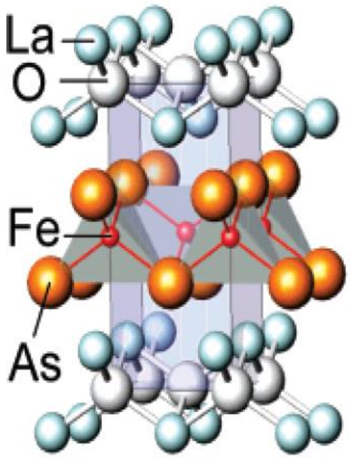
Outline

1. Background on Fe-based superconductor
2. Strategies to improve Jc in 122 wires
3. Fabrication of practical 122 pnictide wires
4. Scaling up to the first 100-m-class 122 wire
5. Conclusions

Main known Fe-based superconducting families

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.*

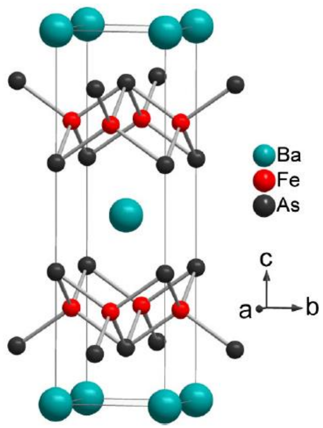
1111 Phase LnOFeAs



T_c ~55 K

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

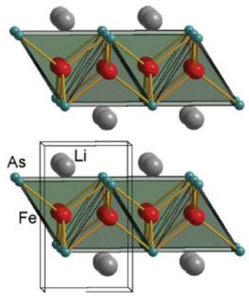
122 phase AFe_2As_2 (A=Ba, Sr, Ca)



T_c ~38 K

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

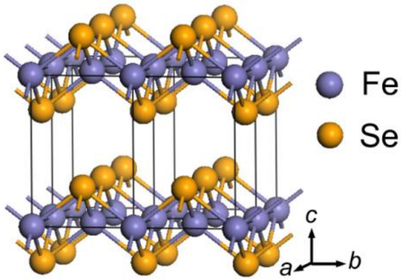
111 phase LiFeAs



T_c ~18 K

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

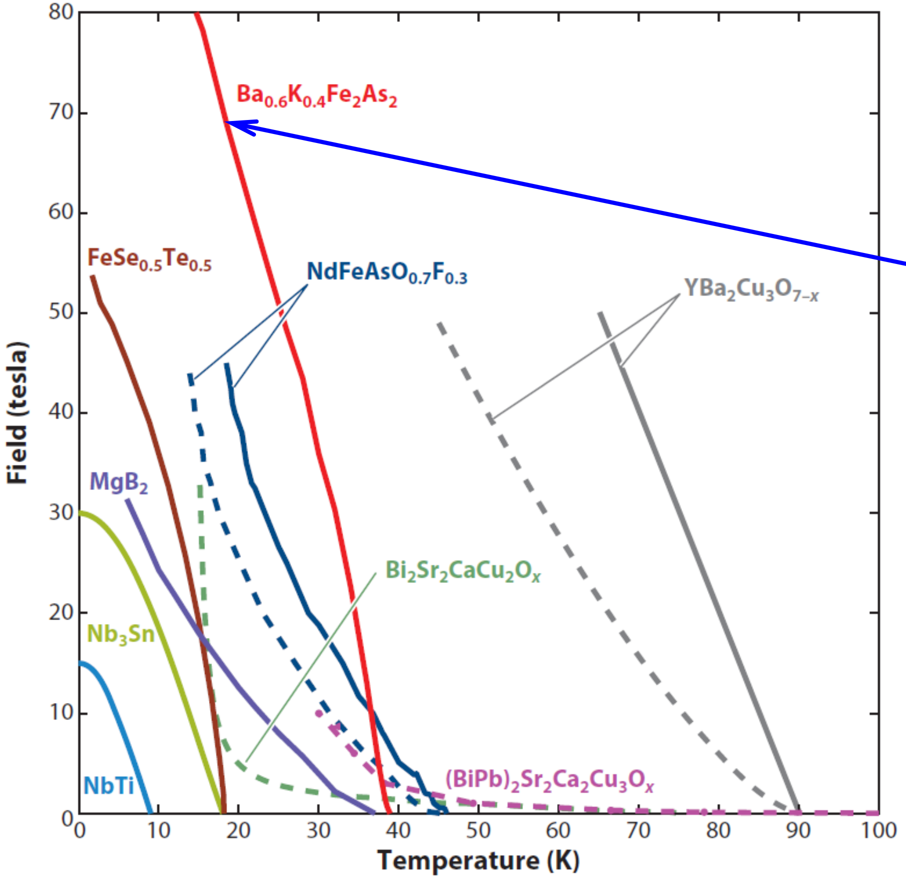
11 phase FeSe



T_c ~8 K

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

The extremely high H_{c2} in 122 IBS



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

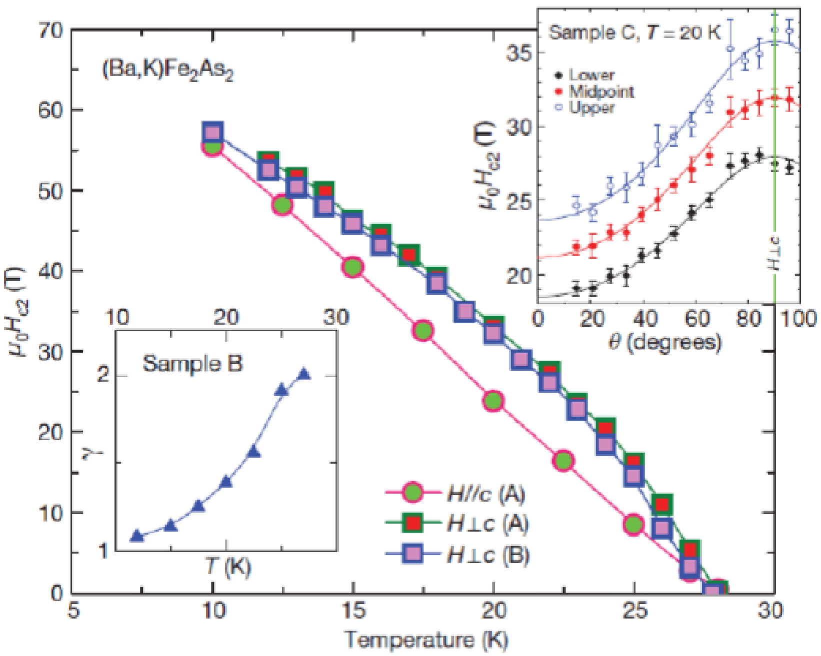
At 20 K, the H_{c2} can be >70 T

where IBS outperform both MgB_2 and Bi-2223.

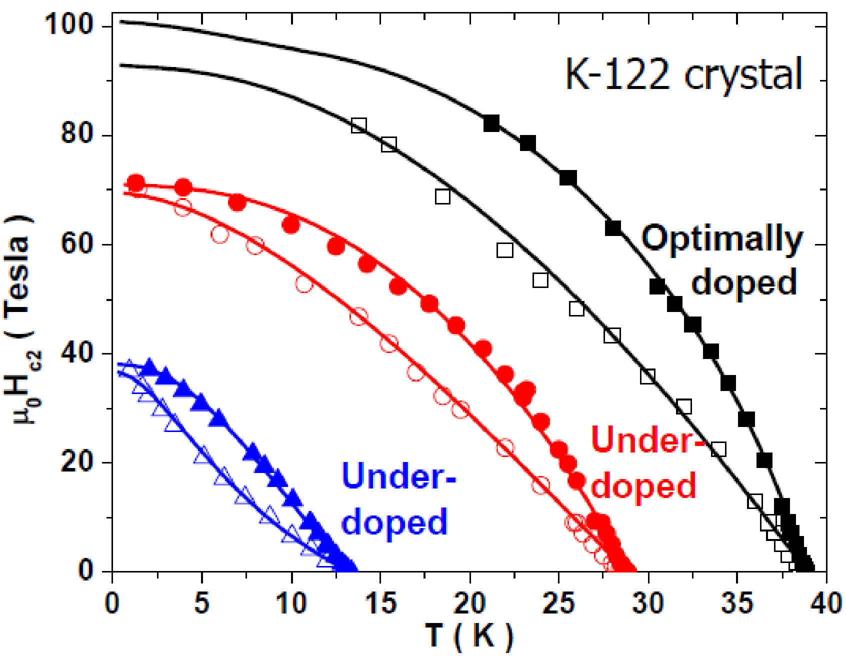
- **Interesting FBS have T_c: 38-55 K >> Nb-Ti and Nb_3Sn**
- **Operation at 4K >20T or 10-30 K at >10 T would be very valuable**

The extremely high H_{c2} in IBS shows a great potential for applications in high field magnets, e.g., H > 20 T, which cannot be achieved via LTS and MgB_2.

122 IBS - small anisotropy γ



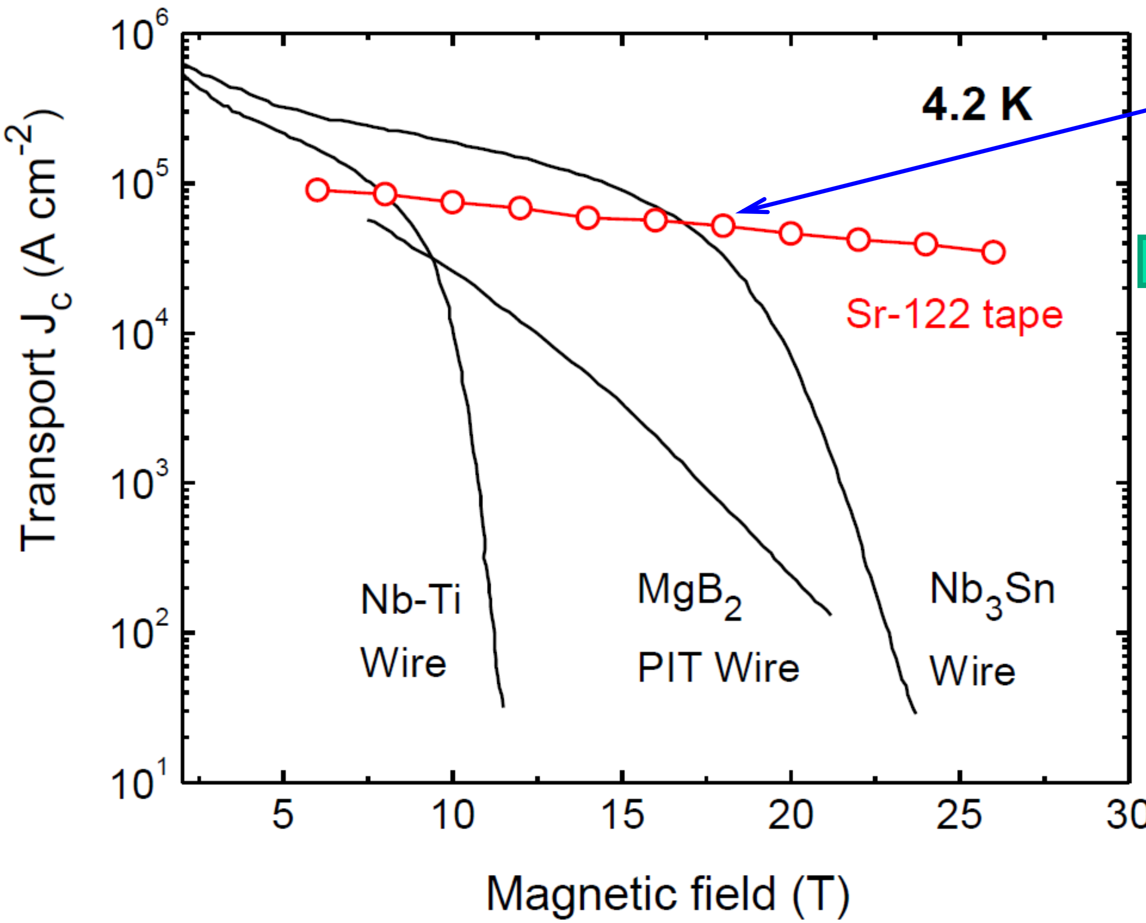
Yuan et al. Nature 457, 565 (2009)



Tarantini et al. PRB 86, 214504 (2012)

- γ ~1.1 for K-122, nearly isotropic
- γ is almost 1, clearly, vortices are much more rigid than in any cuprate-much easier to prevent depinning of any GB segment

The J_c of IBS wires: Very weak field dependence in high-field region



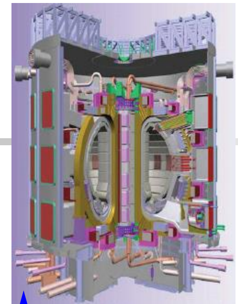
122 IBS wire:

Large J_c, at H > 20T

J_c shows very weak field dependence in high fields

IBS potential for high-field applications

To apply superconducting materials to technologies related to magnets, they must be transformed into wires

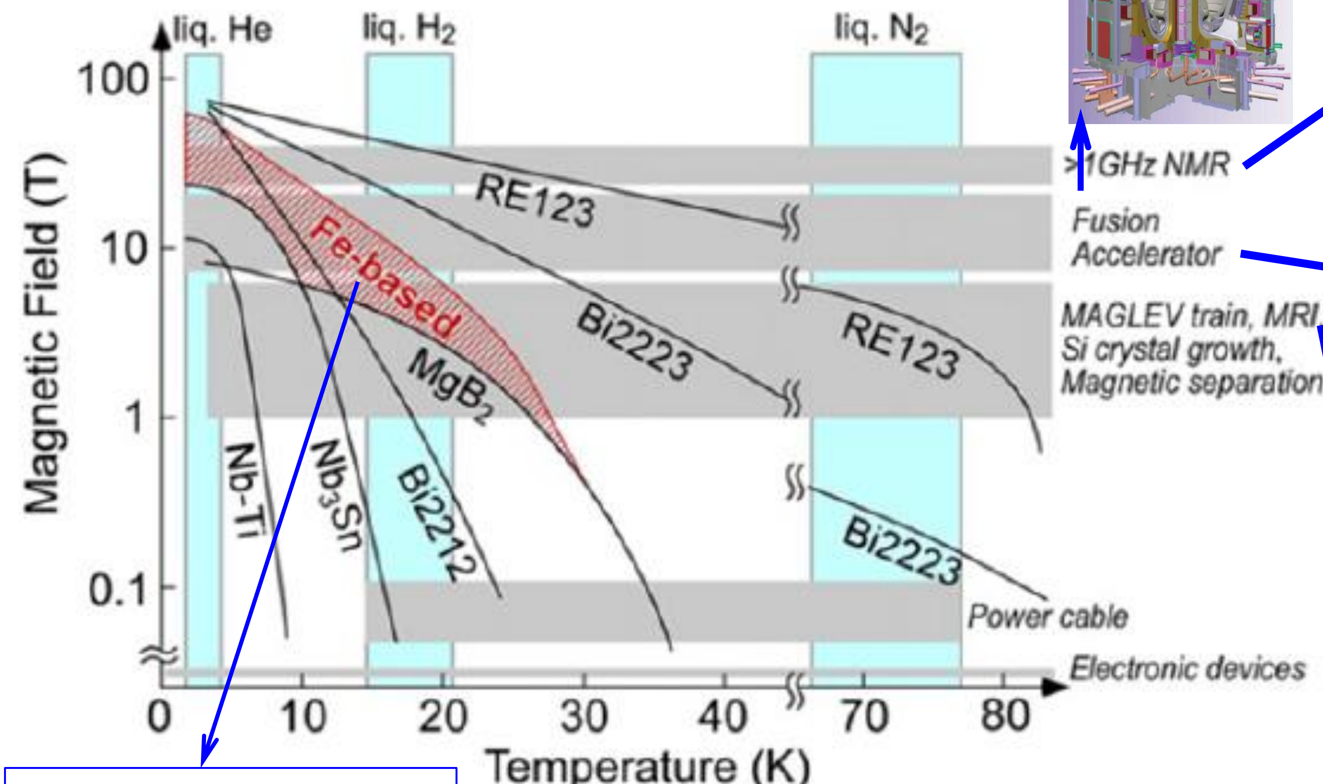


ITER

NMR

Accelerator

MRI



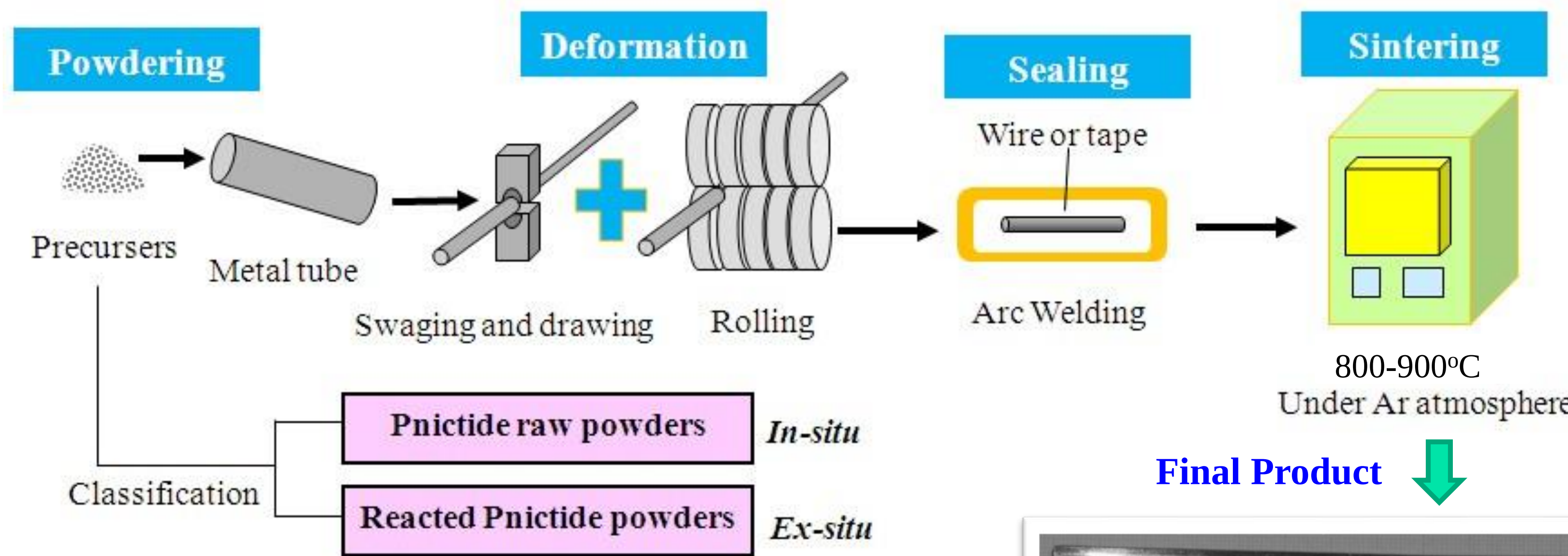
Working Temp:
4.2 K – 30 K

Shimoyama, ***SuST*** 27 (2014) 044002

Development of high-performance wire conductors is essential

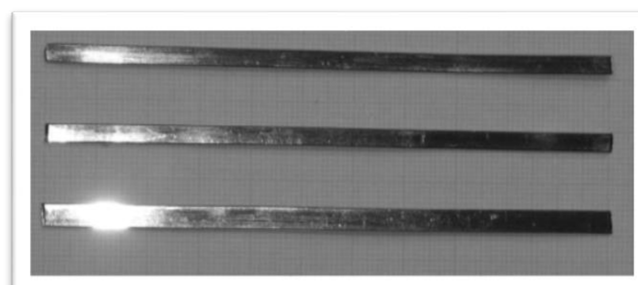
Fabrication process for $Sr(Ba)_{1-x}K_xFe_2As_2$ wires
(*Powder-in-tube method*)

– **Simple and scalable process, low cost**



Different from Bi2223 PIT wires:

BSCCO requires the use of a Ag sheath because Ag is the only material that is inert to the superconductor and permeable to oxygen at the annealing temperature.



Iron-based superconducting tapes

Development of IBS wires and tapes

2008.04 — 2009 — 2010 — 2011 — 2012 — 2013 — 2014 — 2015 — 2016 — 2017

Phase I

The early stage

The first prototype wires

Jc-**100** A/cm^2

To start the fabrication of IBS wires

Phase II

The Jc improvement

①

Addition + ex-*situ* + texture
Jc-**10^4** A/cm^2@10T

Breaking the stagnant situation at that time

②

Densification + texture synergic control
Jc-**10^5** /cm^2@10T

Reaching the practical level J_c

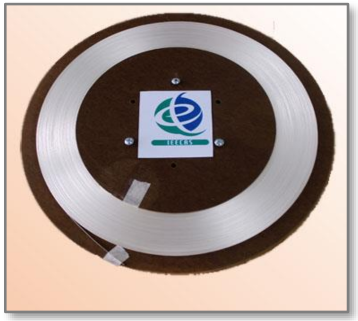
Phase III

Practical research

- **Multifilamentary**: **7, 19, 114**
- **Low cost-Fe/Cu sheath**
- **Strain-stress properties**
- **Ac loss, quench behavior**

First 10 m IBS wire

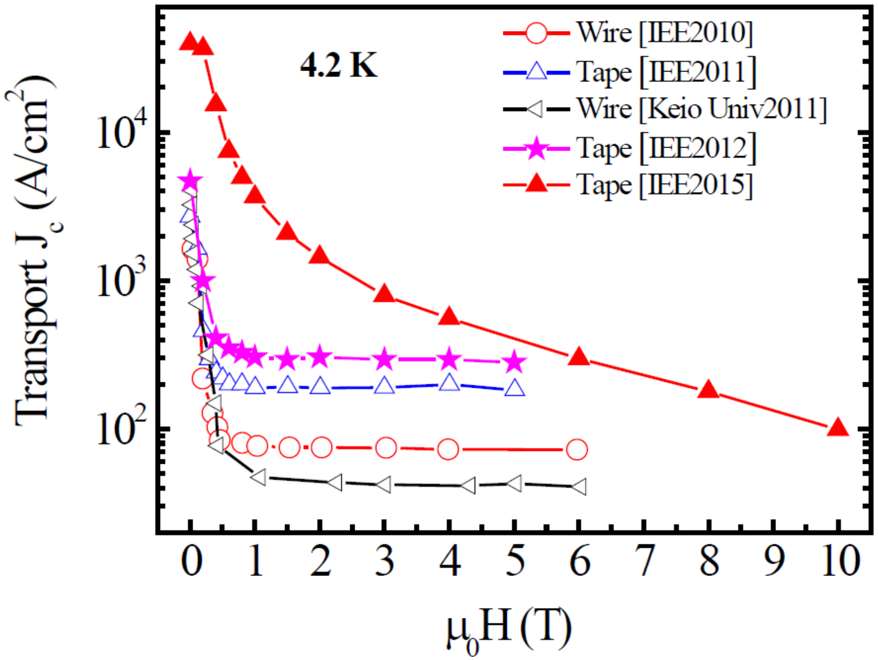
First 100 m IBS wire



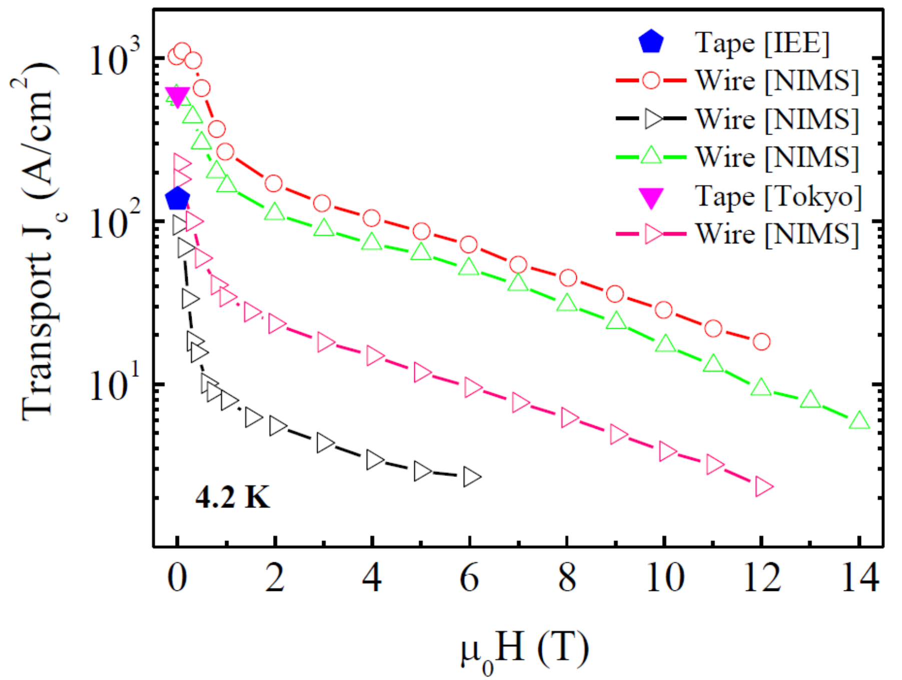
122 tapes showed the highest J_c: 10^5 A/cm^2 @ 10 T, 4.2 K

1111 and 11 wire and tapes: J_c ~ 200 A/cm^2 in high fields

1111 type - Sm[$O_{1-x}F_x$]FeAs



11 type - $FeTe_{1-x}Se_x$



- **The J_c values obtained are still two to three orders of magnitude lower than for the 122 tapes.**
- **1111 wires:** how to control fluorine content during sintering.
- **11 wires:** hard to remove excess Fe.

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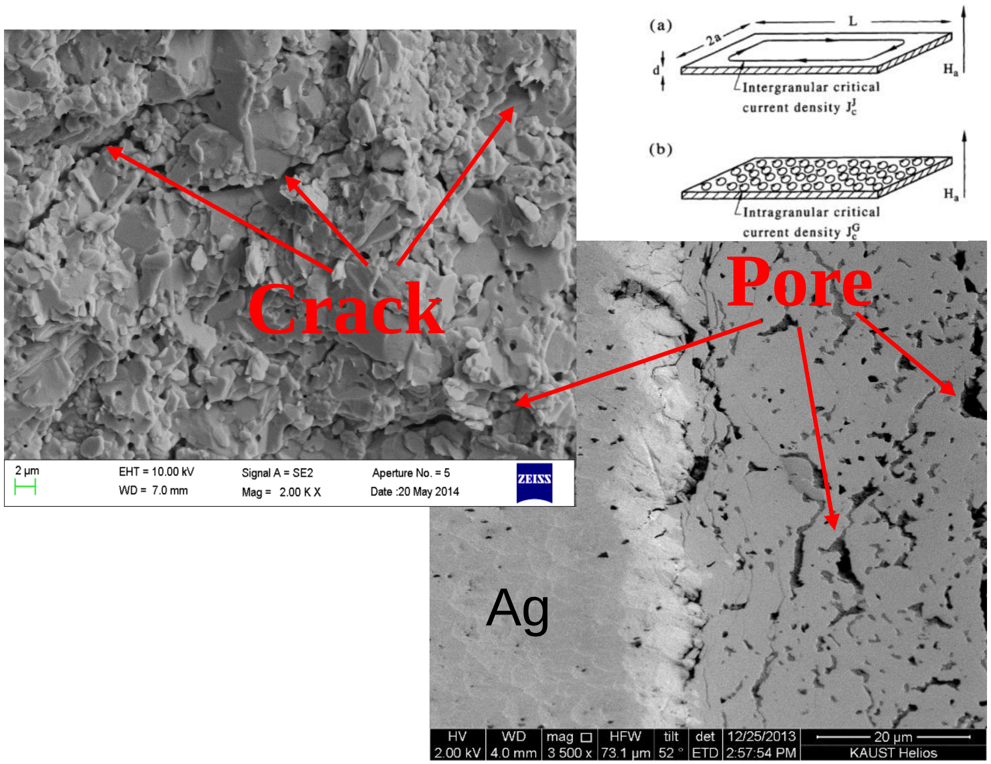
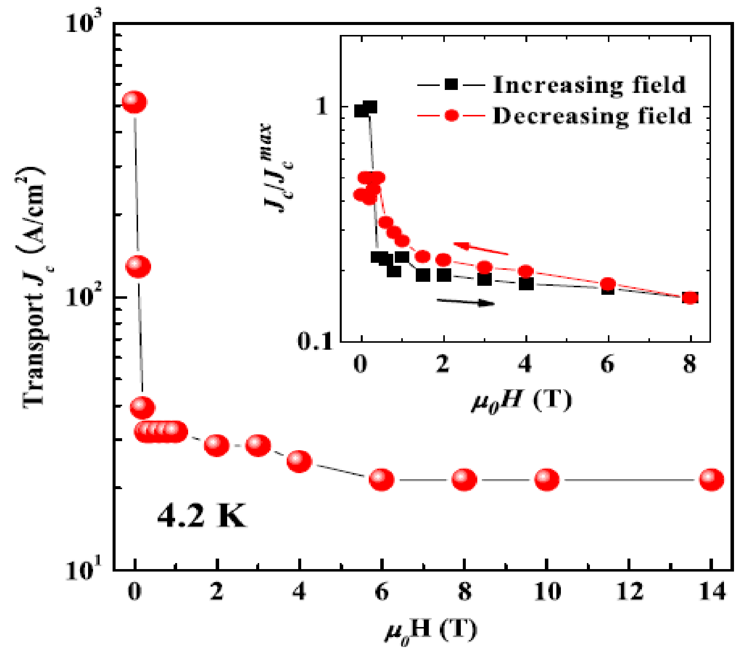
Key problems for PIT wires: Impurity, Low density and Weak-link behavior



Low density: cracks and porosity

Good connectivity is desirable!

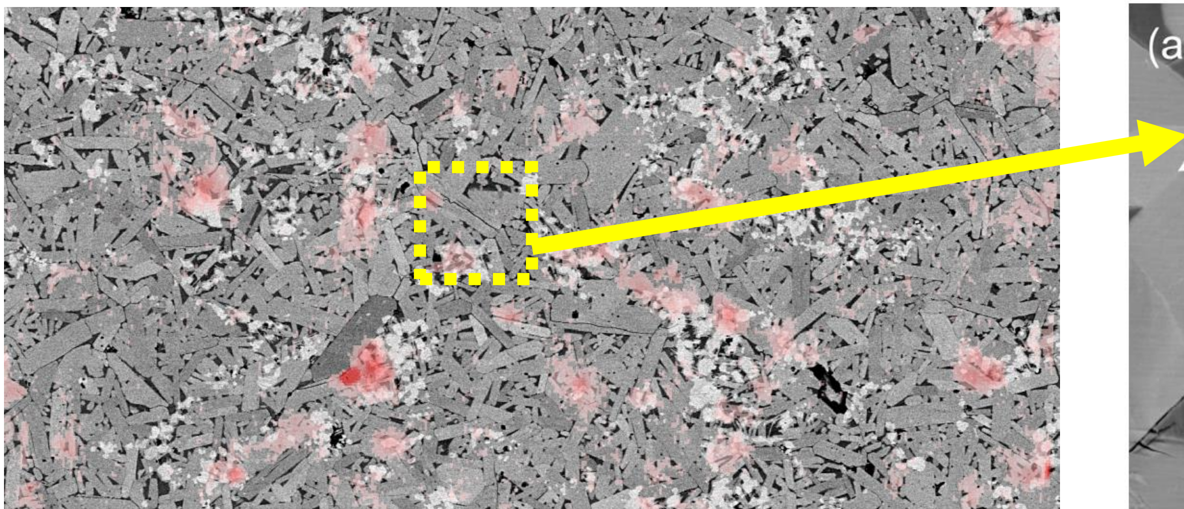


Hysteresis in transport J_c: signature of weak links

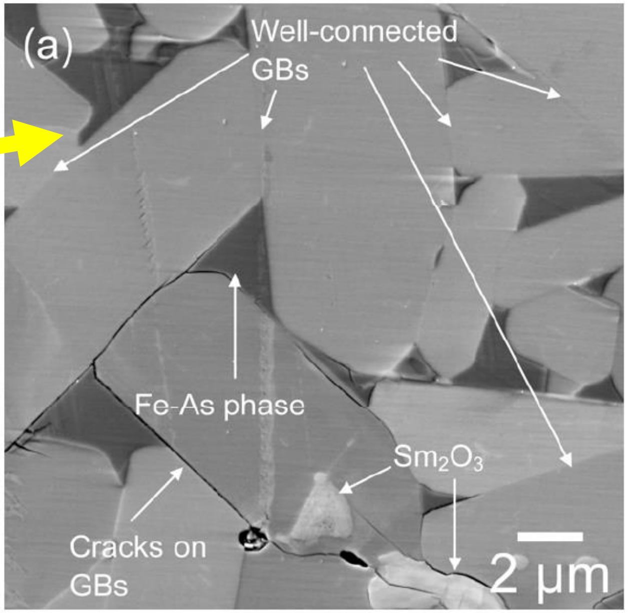
- **Impurity and low density (porosity)** always lead to poor grain connection, so suppress J_c in polycrystalline wires!
- A hysteretic phenomenon observed for transport J_c in an increasing and a decreasing field indicated a **weak-linked behavior**, similar to that of the cuprates.

Q1 :

Early efforts at wire development suffered from many impurity phases (such as Fe-As) that wet the grain boundaries, largely decreasing Jc



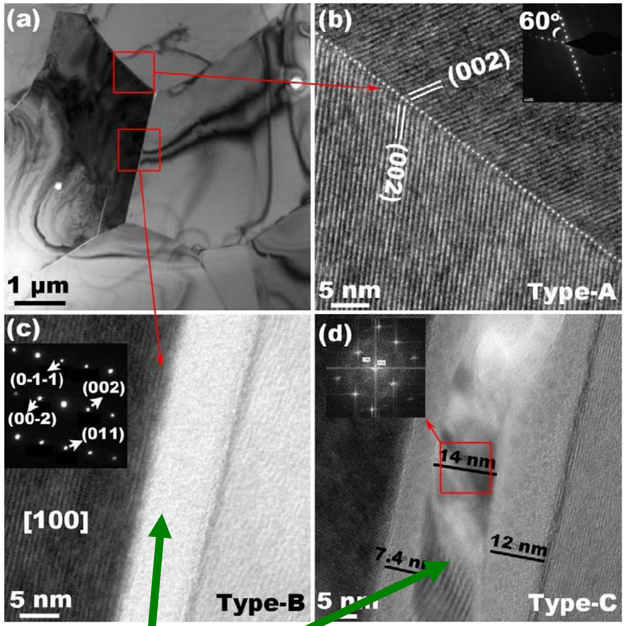
Low Temperature Laser Scanning Microscopy (LTLSM) + SEM



Kametani et al., ***APL***. 95, 142502 (2009)

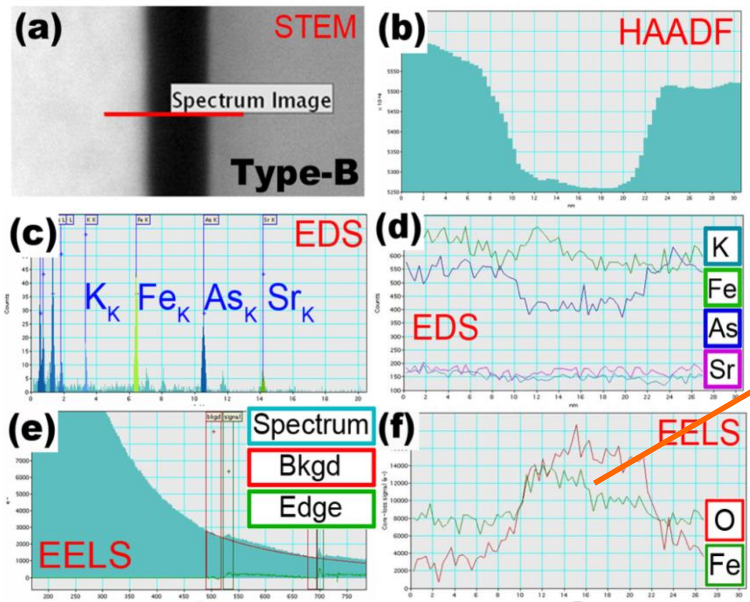
- **Dissipation is clearly localized in impurity-rich regions.**
- **Fe-As phase covers the grains causing a current blocking effect.**

TEM-EELS studies: Grain boundaries in the Sr122 polycrystals are usually coated by impurity amorphous layers (10-30 nm), which show significant oxygen enrichment



10 nm   30 nm

An amorphous layer



A high level of oxygen at the boundaries.

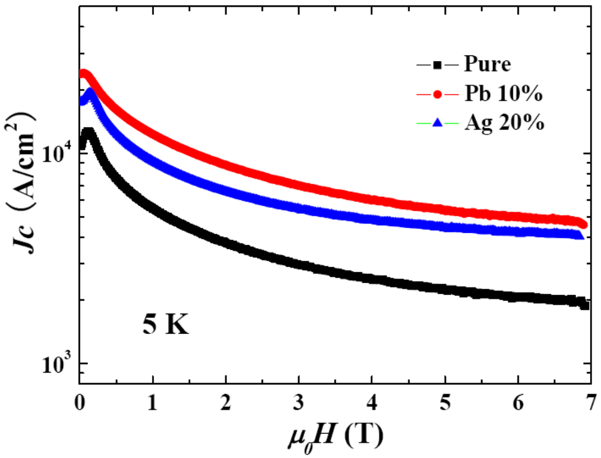
EELS: electron energy loss spectroscopy

L. Wang, *et al.*, *APL* 98, 222504 (2011)

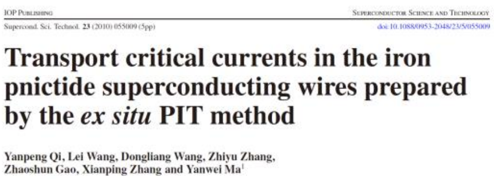
- **Obviously, these O-rich amorphous layers are strongly related to the introduction of O_2 during fabrication.**
- **These oxygen-rich layers undoubtedly obstructed many grain boundaries, consequently resulting in a poor grain connection.**

Solutions: *Ex-situ + Addition* **PIT method → removed the impurity phases in Ag-cladded 122 wires**

- ***Ex-situ* PIT method:** fewer impurity phases as well as a high density of the superconducting core for the final wires.
- **Ag or Pb** addition to improve the grain connectivity, hence the enhanced J_c.



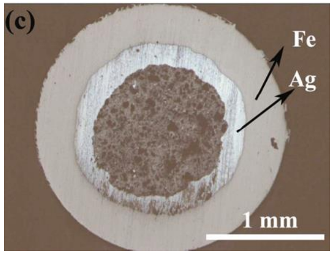
SuST 23 (2010) 025027

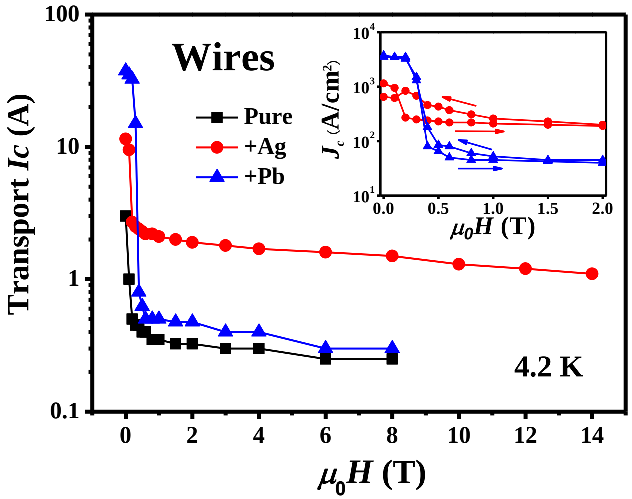

IOP Publishing — Superconductor Science and Technology

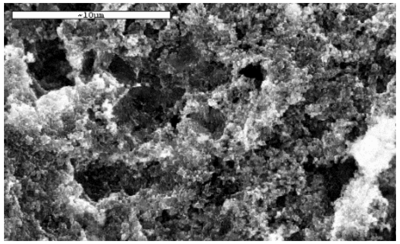
Supercond. Sci. Technol. 23 (2010) 055009 (5pp)

Transport critical currents in the iron pnictide superconducting wires prepared by the *ex situ* PIT method

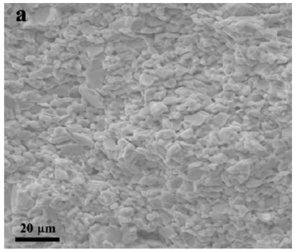
Yanpeng Qi, Lei Wang, Dongliang Wang, Zhiyu Zhang, Zhaoshun Gao, Xianping Zhang and Yanwei Ma[1]







In Situ：杂相多，疏松



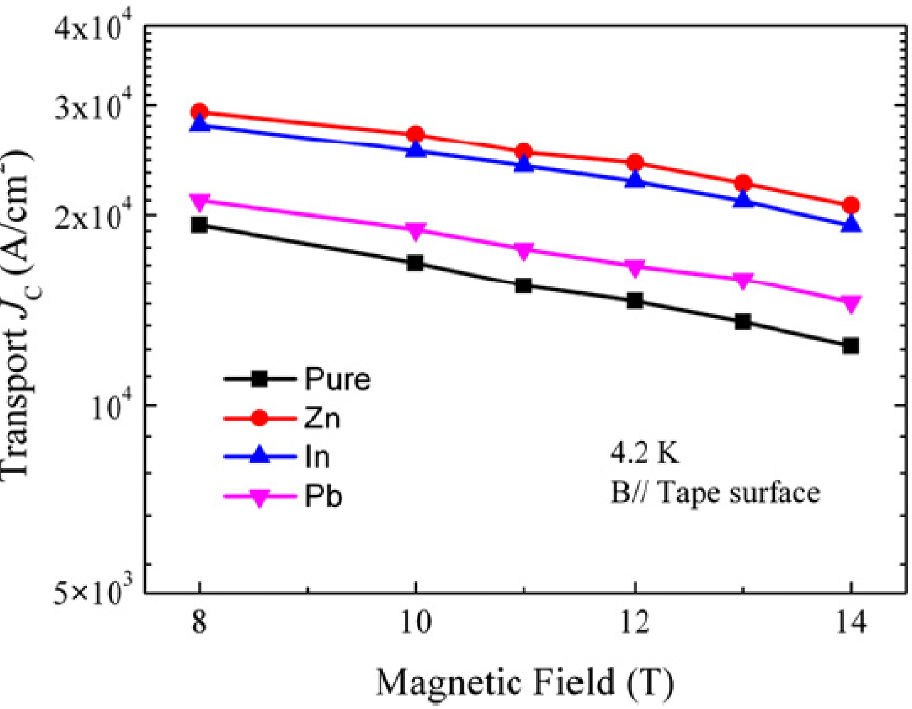
Ex Situ：相纯，密度高

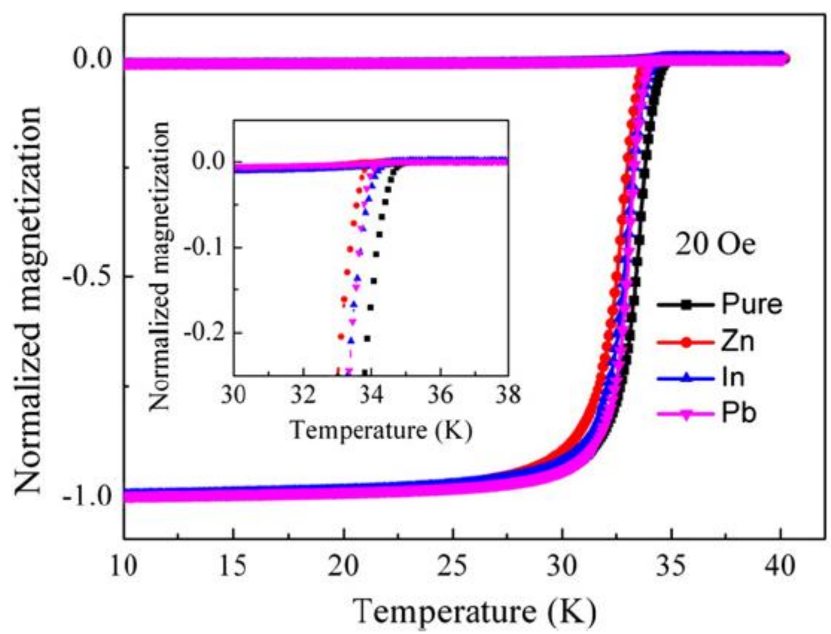
At 0 T, 4.2 K, I_c reached 37.5 A, correspondingly, J_c= 3750 A/cm².

SuST 23 (2010) 055009

Zn and In additions are effective to enhance the J_c-B of 122/Ag tapes

Chemical addition has been confirmed as a simple and readily scalable technique for enhancing Jc.





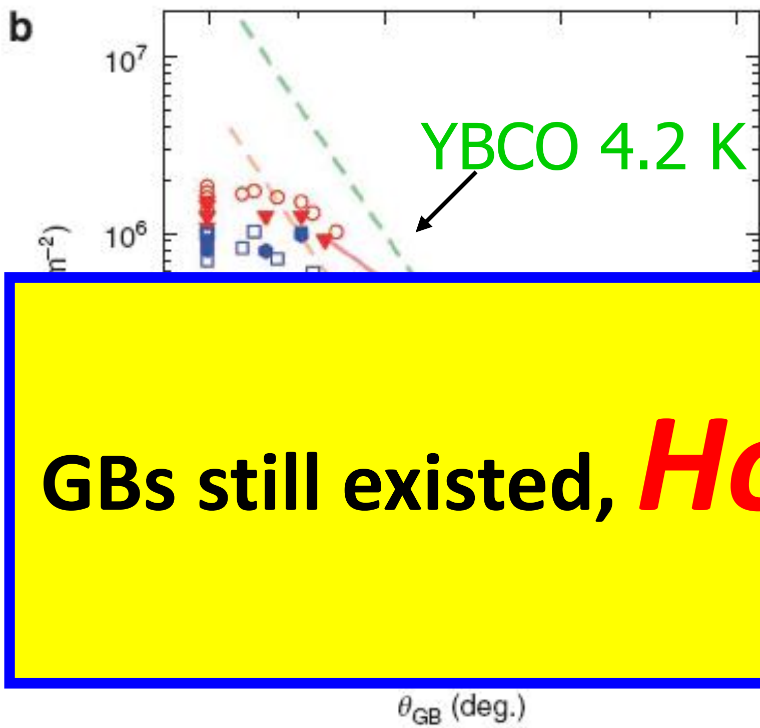
- The additions do not significantly affect the temperature transition Tc, and the Tc decreased only 0.4 K.
- the Jc enhancement in In or Zn-added samples may be attributed to the improved phase uniformity as well as the good grain connectivity

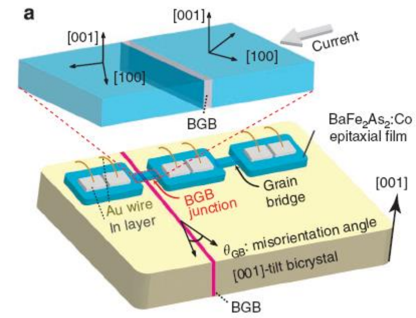
Lin et al., *Scripta Mater*. 112 (2016) 128

Q2: Weak-link problem - *Intrinsic nature of dissipation*

Co doped Ba-122 thin films on bicrystals

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





The critical GB angle

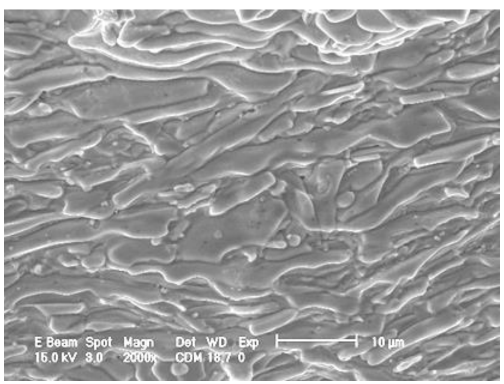
GBs still existed, ***How to overcome?***

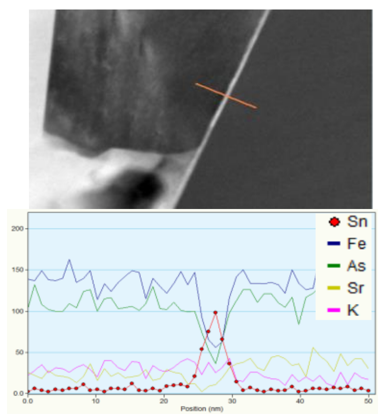
- **J_c decreases exponentially with GB angle .**
- **Weak link effect, the GBs do not degrade the J_c as heavily as YBCO.**
- **Advantageous GB over cuprates!** This is the reason why we can use the PIT method to make the pnictide wire and tapes, but PIT can not work for YBCO.

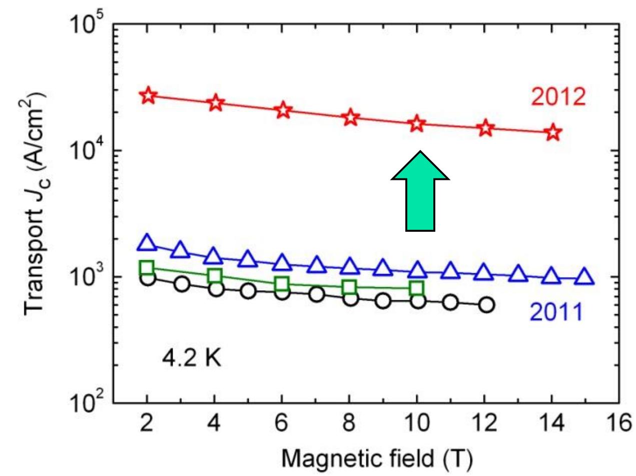
Texturing process of PIT Sr122 tapes

- **One effective method is to engineering textured grains to minimize deterioration of Jc across high-angle grain boundaries, like the Bi2223.**

Sr122+Sn | **Rolling by a large reduction rate** | **To form textured grains** | **Annealing for better connection**



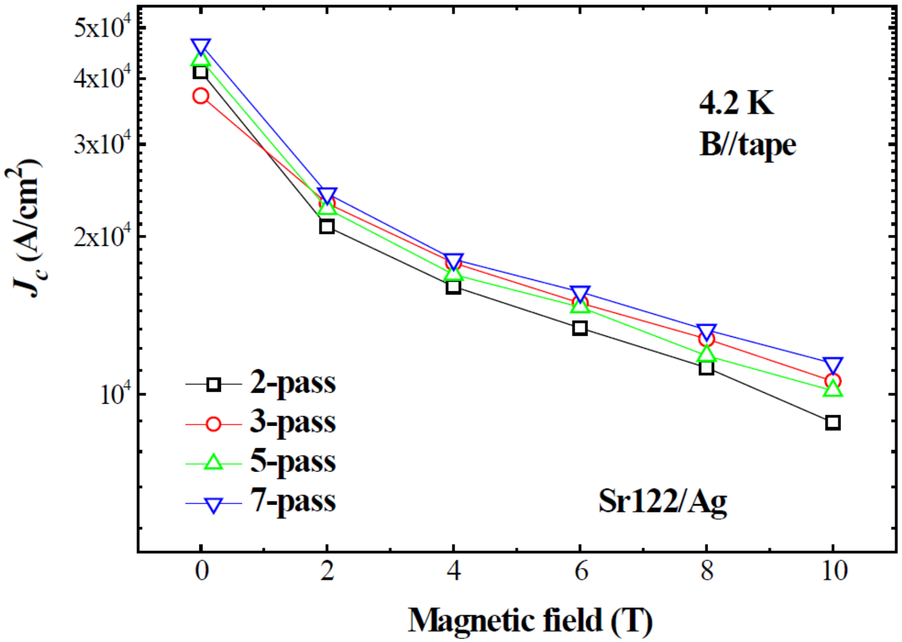


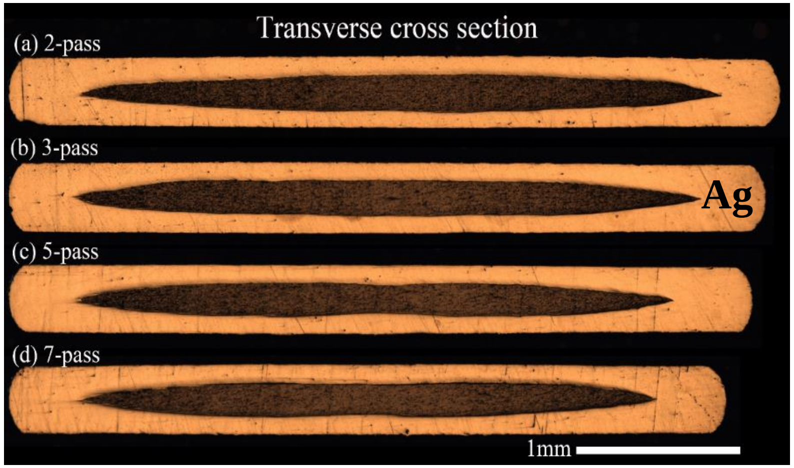


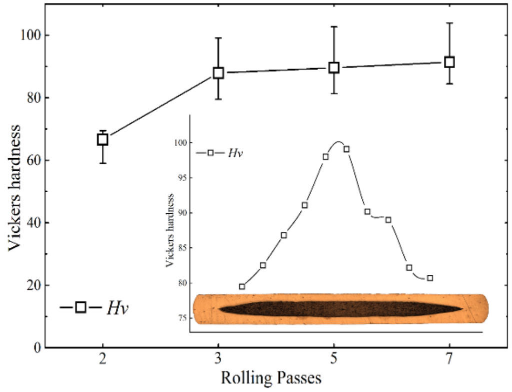
The above rolling strongly improved c-axis texturing, and effectively reduce the large angle GBs, thus Jc was enhanced by **an order of magnitude, from 10^3 to 10^4 A/cm^2**。

Physica C 471 (2011) 1689; ***Sci. Rep.*** 2 (2012) 998

Optimized rolling process for $Sr_{0.6}K_{0.4}Fe_2As_2$ /Ag tapes: 3-pass deformation is best



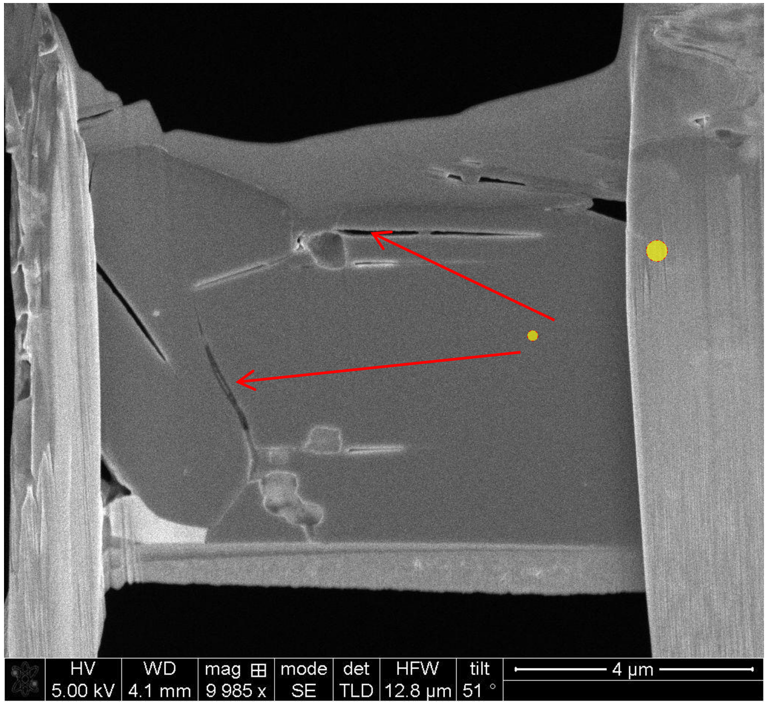


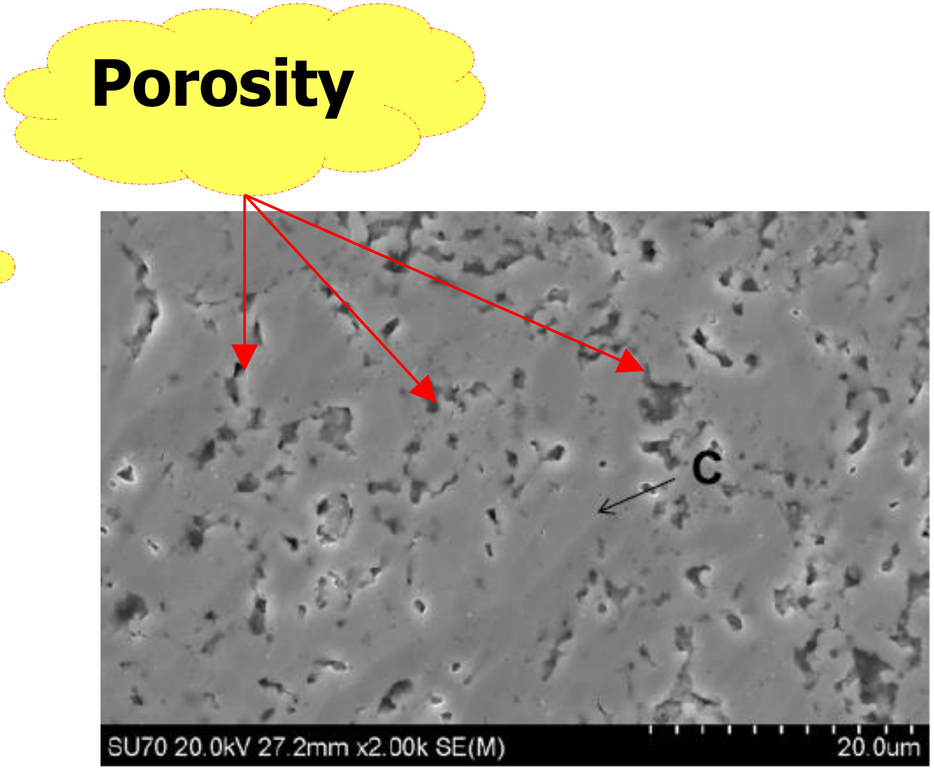


- The width of the tapes and the area of superconducting cores increase with decreasing the rolling pass, but the transport J_c seems close.
- We can fabricate tapes with 3 rolling passes to get the uniform and high-J_c 122 tapes.

Physica C 525 (2016) 94

Q3: Densification is another dominant factor that determines the J_c of PIT 122 wire





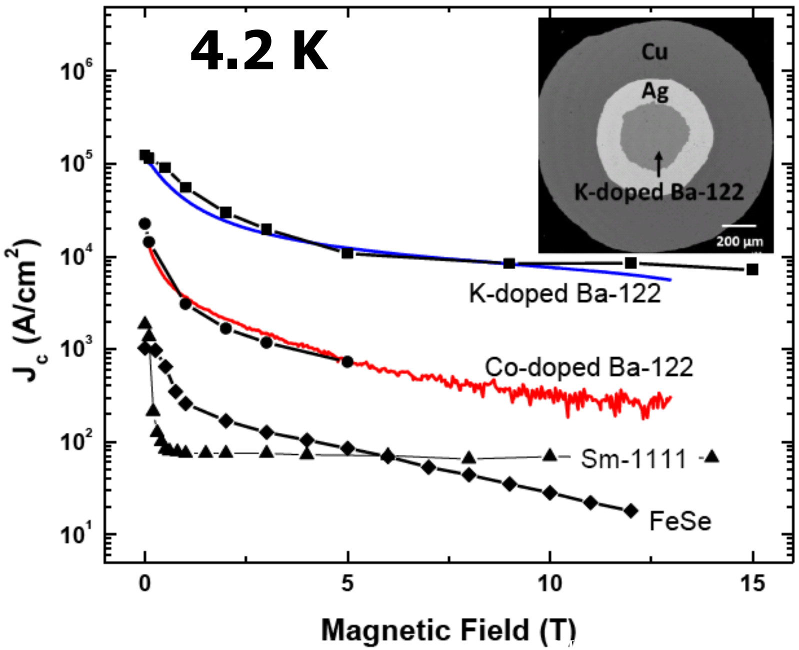
Cracks and voids are one of the important reasons for low critical current density values

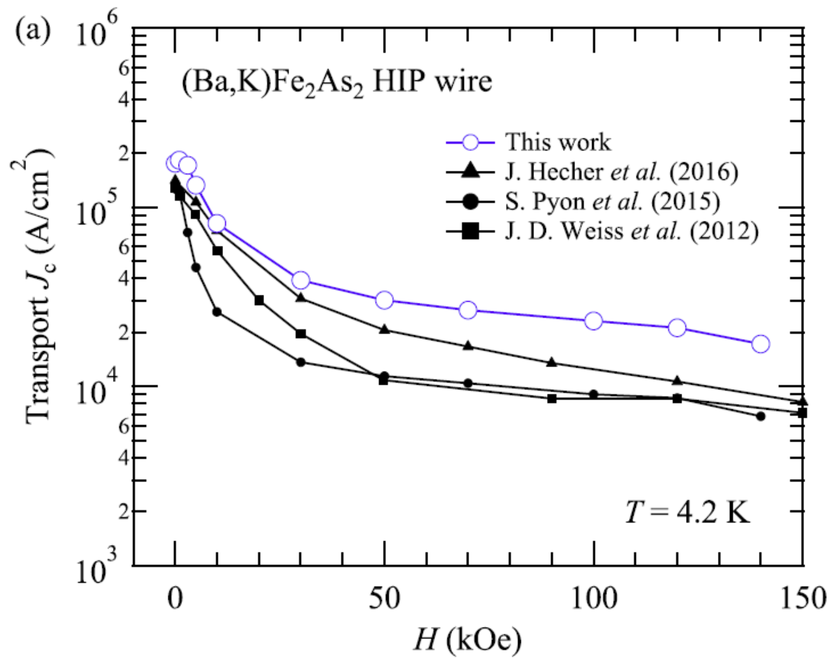
NHMFL & UT

Hot isostatic press (HIP) increased J_c in Ba-122 round wire

Nearly 100% dense core

HIP under 192 MPa at 600 ° C for 20 h





0 T, $J_c > 10^5$ A/cm^2
10 T, J_c = ~10000 A/cm^2

4.2 K, 10 T, J_c = 23000 A/cm^2

J. Weiss et al., ***Nature Mater.*** 11, 682 (2012)

Pyon et al., ***SuST*** 29, 115002 (2016)

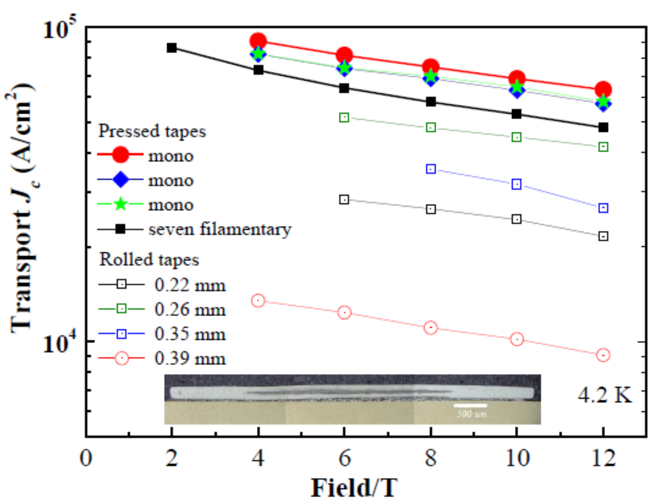
NIMS

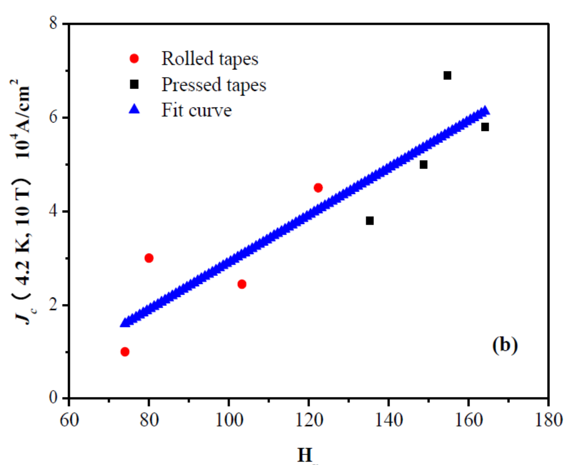
Thin tapes by combined the rolling, cold pressing and sintering process-- Denser core yields higher J_c

--Ag-sheathed Ba122 tapes

Steps:

1		2		3		4		5
As-rolled tape (T 0.8mm)	→	**Sintering (800 °C/2h)**	→	**Rolling T ~0.3 mm**	→	**Cold pressing 2 ~3 GPa**	→	**Sintering (800 °C/5h)**





The higher the core density, the higher the J_c

4.2 K, 10T:
J_c = ~86000 A/cm^2

Cold pressing always results in fatal micro-cracks, which cannot be healed by subsequent heat treatment.

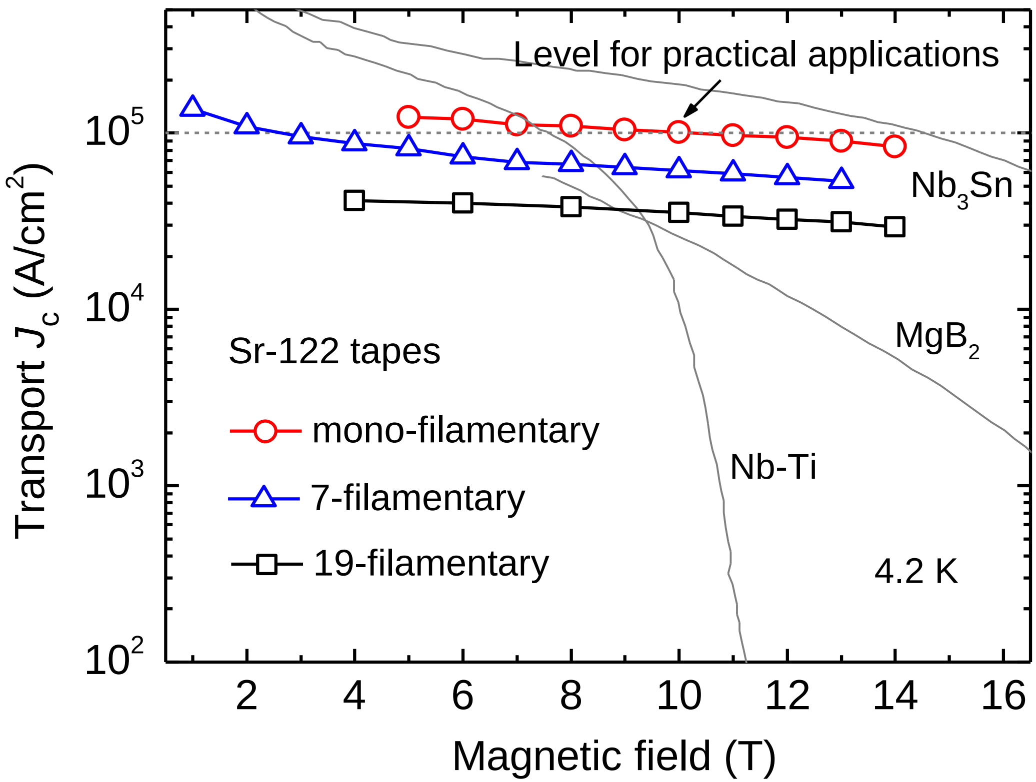
NIMS group, *Sci. Rep.* 4, 4465 (2014)

--$Sr_{0.6}K_{0.4}Fe_2As_2$

Very high transport J_c were achieved in Sr122/Ag tapes: $J_c > 10^5$ A/cm² (4.2 K, 10 T) - by hot pressing

First to reach practical level J_c!

The threshold for practical application:
$J_c = 10^5$ A/cm²@10 T



Later achieved

At 10 T, $J_c = 1.2 \times 10^5$ A/cm²

even in 14 T, $J_c = \sim 10^5$ A/cm²

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

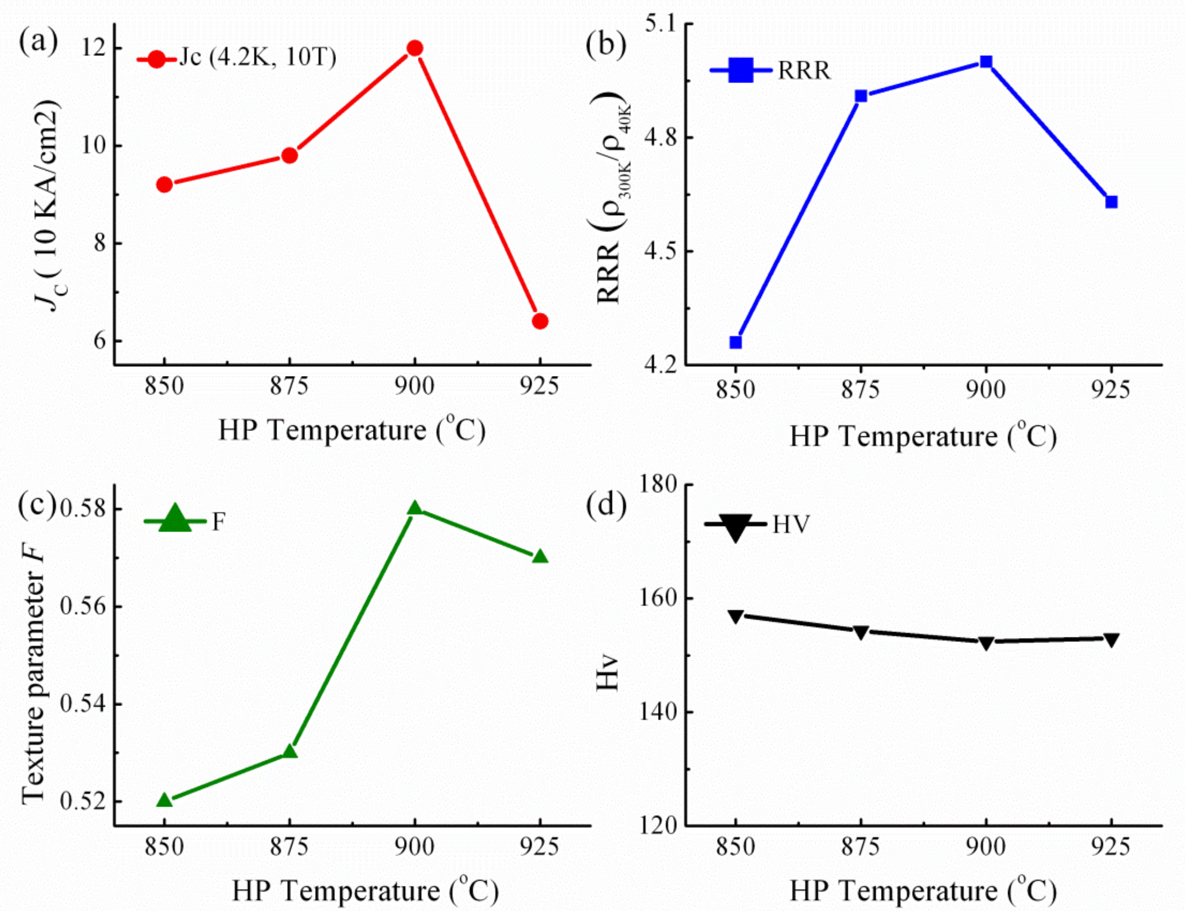
Zhang et al., *APL* 104 (2014) 202601
Lin et al., *Sci. Rep.* 4 (2014) 6944

Reasons for high transport J_c in HP900 tapes

texture of the $Sr_{1-x}K_xFe_2As_2$ phase, we have evaluated t
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
the intensities of each reflection peak (hkl) for the orie
random samples, respectively. The value of F for the as-ro



Rolled Tapes:
Hv=61.3

HP tapes:
Hv= ~154.0

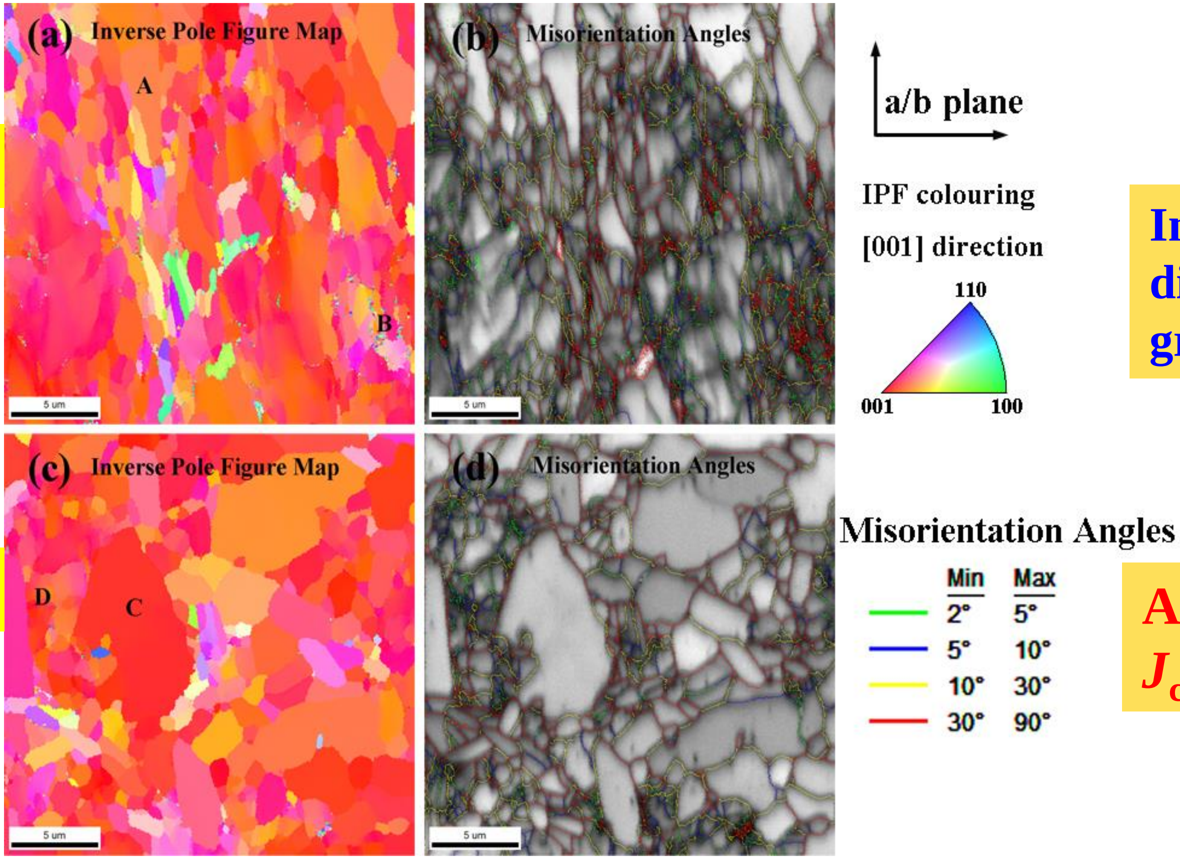
- **The variation tendency of J_c values was qualitatively similar to those of F and RRR values.**
- **The hardness was almost saturated as soon as the hot pressing was applied.**
- **The J_c increase for HP900 tapes was mainly attributed to enhanced grain connectivity (high density) and higher degree of c-axis texture.**

EBSD images: HP samples are highly textured

A useful tool to clarify the grain size, local orientation of the grains and misorientation angles between grains.

Upper: HP850

Lower: HP900



Inhomogeneous distribution of grain size

A room for the J_c improvement

- **The large fraction of small misorientation angles between 2–10°C (HP850 tapes 23.3%, HP900 tapes 26.2%).**
- **A large proportion of misorientation angles of the GBs were smaller than 9° such that the transport Jc would not be greatly reduced upon encountering these GBs.**

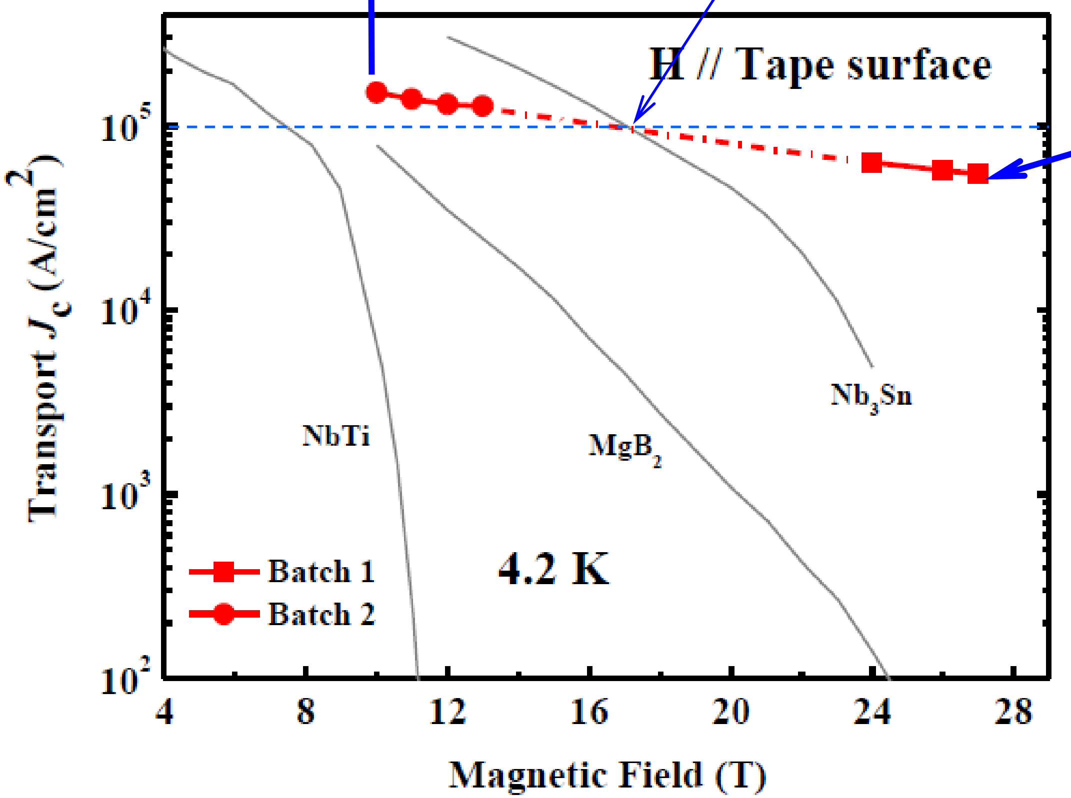
Latest result

--$Ba_{0.6}K_{0.4}Fe_2As_2$/Ag tapes

New record transport J_c up to 1.5×10⁵ A/cm² @ 4.2 K, 10 T was obtained by Hot Pressing

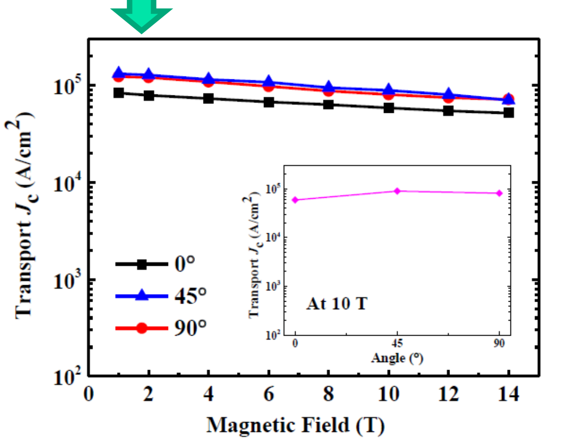
I_c= 437 A

At 18 T, J_c = ~10^5 A/cm²



At 27 T,
J_c = 5.5×10^4 A/cm²

Small anisotropy

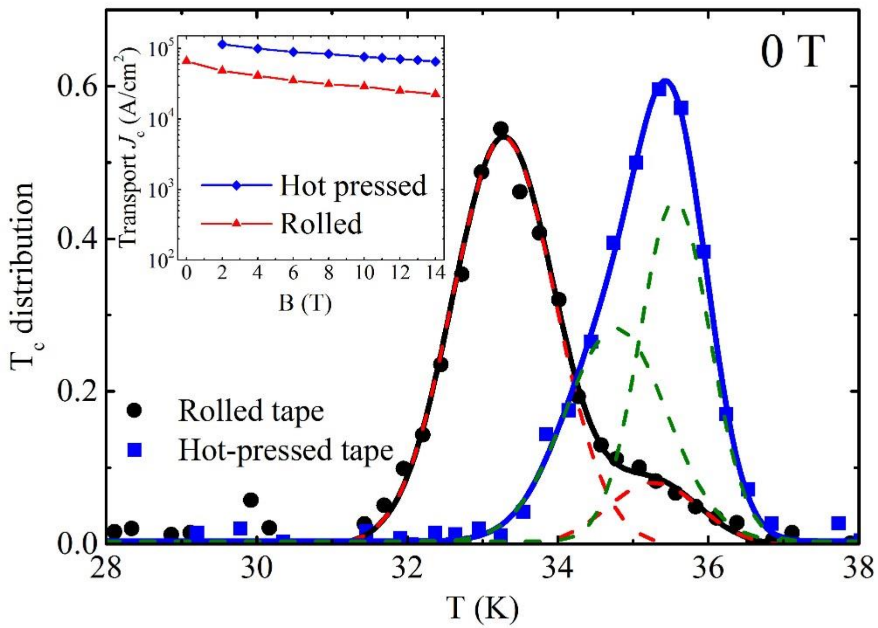


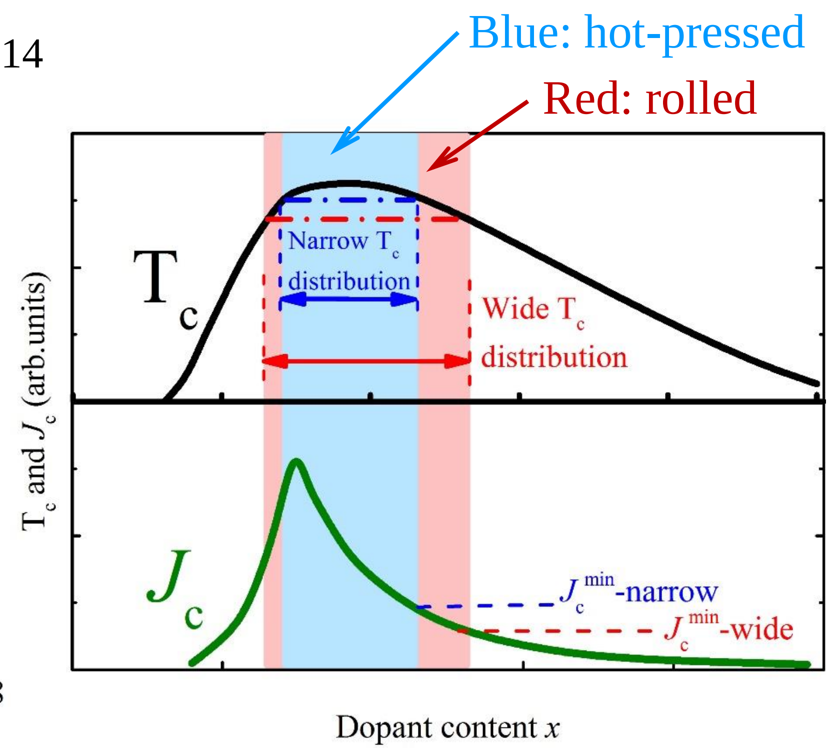
2MO3-05

Huang et al., arXiv:1705.09788

Specific heat measurement: Calorimetric evidence for enhancement of homogeneity

Dong et al., *Scripta Mater.* 138 (2017) 114

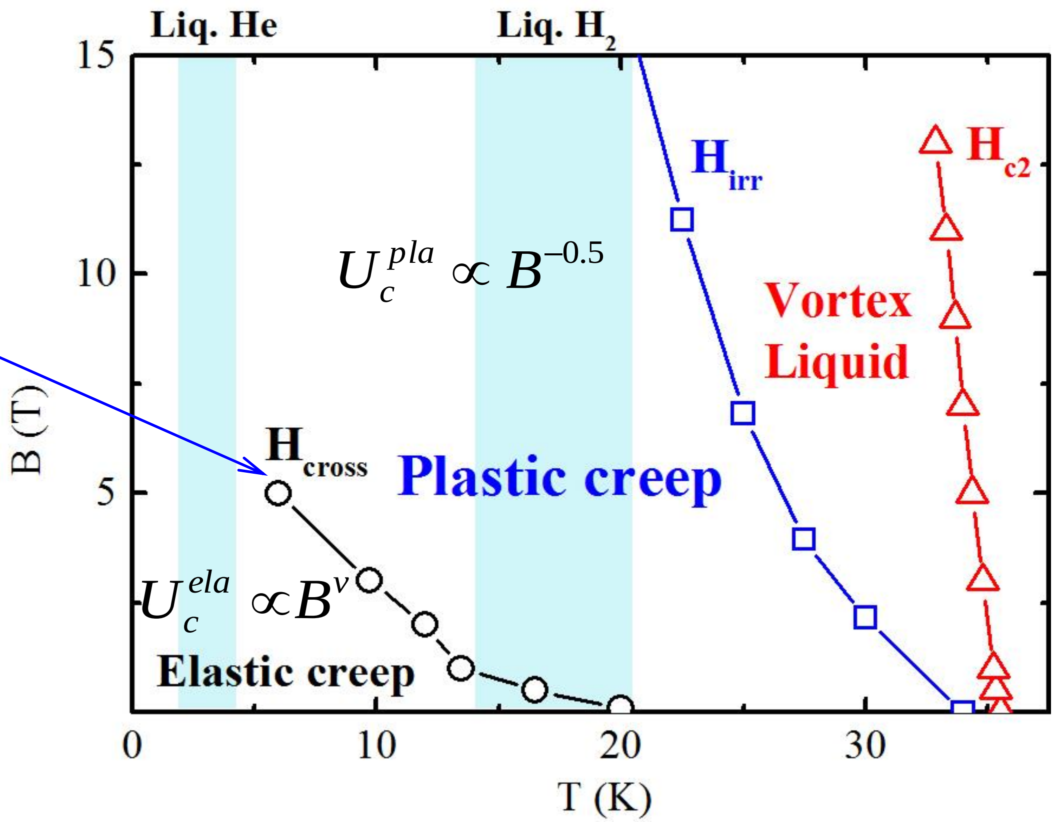




- **The Schottky anomaly that is obvious in the specific heat of the rolled Sr122 tape disappears in the hot-pressed Sr122 tape.**
- **the hot-pressed tape has a higher fraction of superconductivity and a narrower distribution of superconducting transition temperature than the rolled tape.**

Vortex phase diagram of high-J_c HP-122 tapes

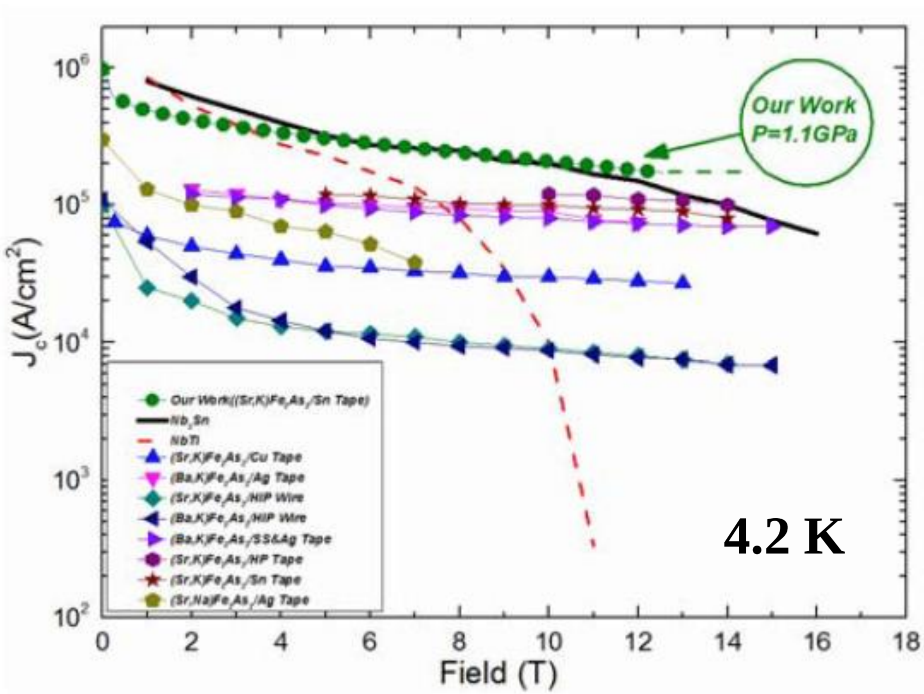
H_{cross} is defined as the crossover field from elastic to the plastic creep regime.



- More robust field dependence of J_c in the elastic creep regime.
- Weak field dependence of J_c in the liquid helium region, but J_c quickly decrease in the liquid hydrogen region.
- **To further increase flux pinning force: increase point pinning sites, *e.g.* irradiation or nano-particle inclusion.**

Dong et al., *JAP* 119 (2016) 143906

Magnetic J_c up to 3×10^5 A/cm^2 @ 4.2 K, 10 T can be achieved under Hydrostatic Pressure



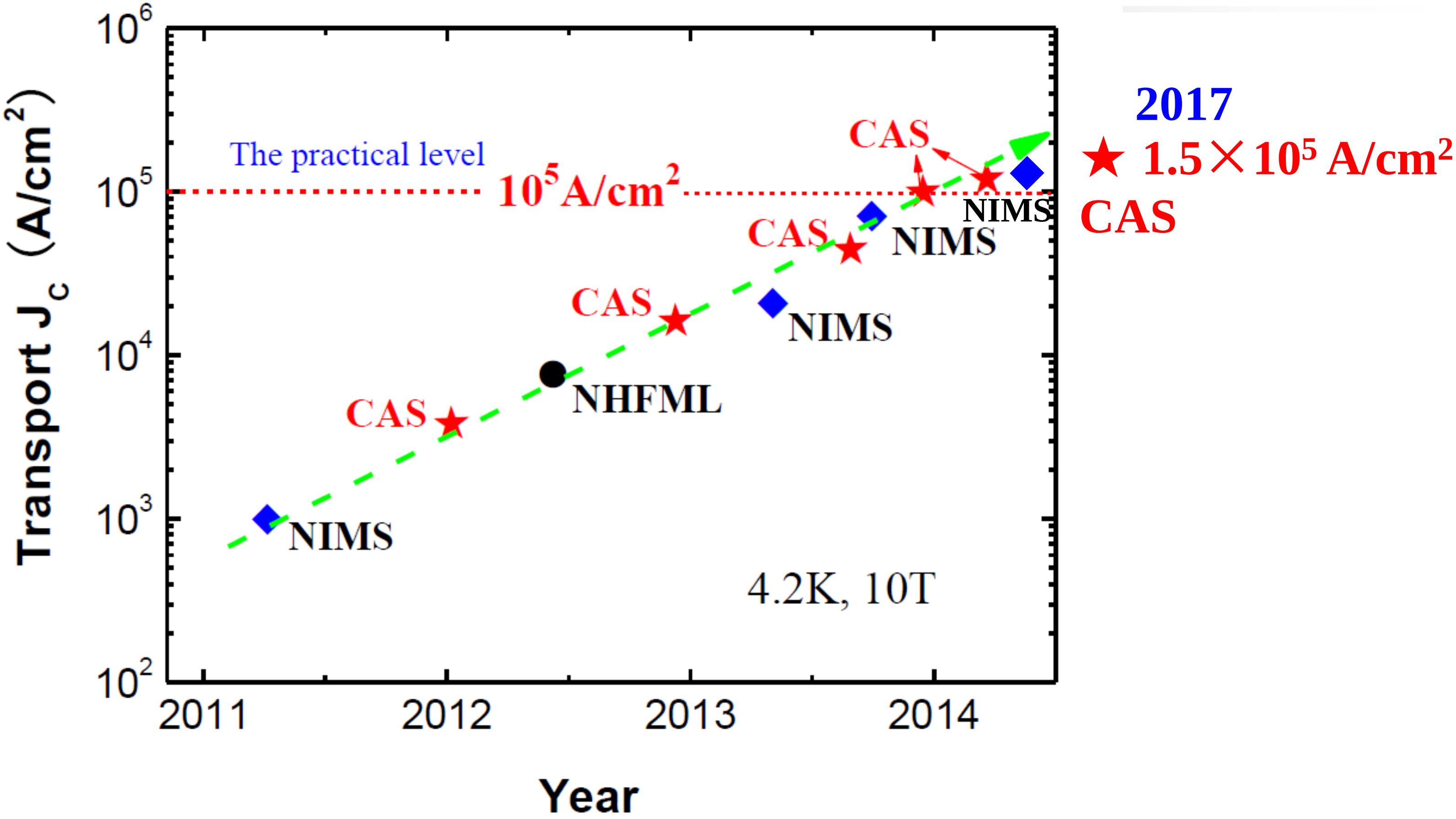
-- Collaborated with Prof. Xiaolin Wang, S. X. Dou, Wollongong Univ.

- ✓ **Using PPMS, HMD high pressure cell and Daphne 7373 oil as the medium for applying hydrostatic pressure on Sr-122/Ag tape samples.**
- ✓ **Tape samples were measured under pressure.**

- The hydrostatic pressure of 1GPa can significantly enhance J_c in Ag-clad $Sr_{0.6}K_{0.4}Fe_2As_2$ tapes at different temperatures, e.g., ~2×10^5A/cm^2 at 13T, 4.2 K.
- Pressure can improve the grain connectivity and increase the pinning number density.
- The result shows that the current IBS tapes/wires should have plenty of room to raise their J_c or I_c to higher levels.

Shabbir et al., *Phys. Rev. Mater.*, 2017

Recent advances in transport Jc of PIT processed 122 wires and tapes



- **An scalable process is required to fabricate high performance long length tapes, e.g., *Rolling (hard sheath), Hot Rolling or Hot isostatic press (HIP)*…**

Outline

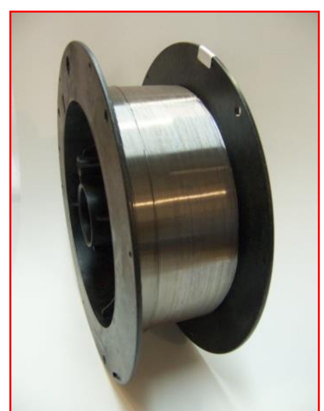
1. Background on Fe-based superconductor
2. Strategies to improve Jc in 122 wires
3. Fabrication of practical 122 pnictide wires
4. Scaling up to the first 100-m-class 122 wire
5. Conclusions

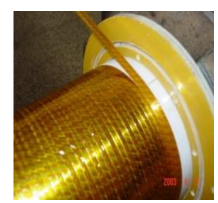
For applications, many other problems need to be solved

Challenge	Strategy
1、Low AC loss/Quenching,	**Multifilamentary**
2、Large EMF/thermal stress,	**High strength**
3、Market requirement,	**Low cost**
4、Scaleability of fabrication,	**Long length**

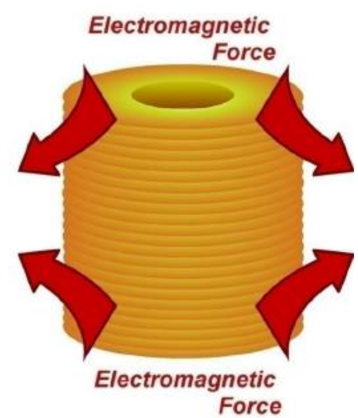
Short sample:1m

Long wire



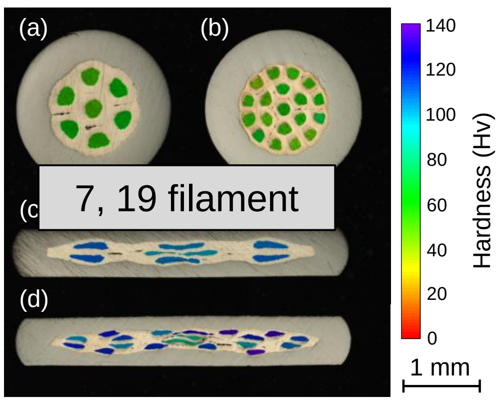


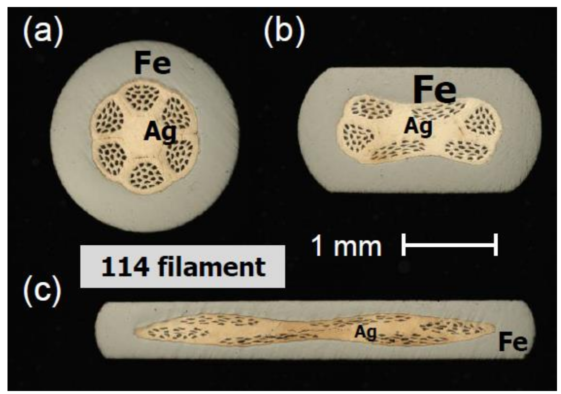
Magnet



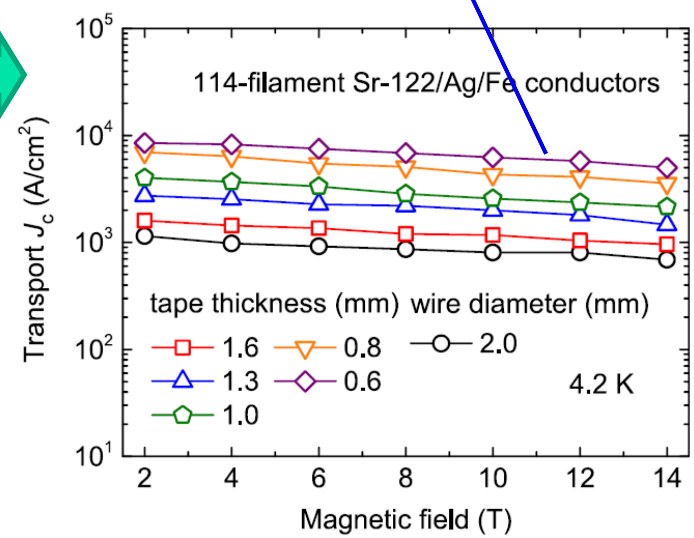
Fabrication of 114-filament Sr-122/Ag/Fe wires by the drawing and rolling

- **The fabrication of multifilamentary wires and tapes is an indispensable step, to reduce the AC loss and avoid the flux jump.**





Jc, the very weak field dependence



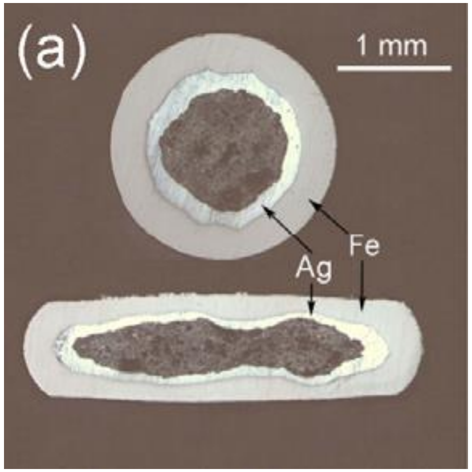
- 114-core round wires: J_c=800 A/cm^2.
- When they are flat rolled into tapes, the J_c grows with the reduction of tape thickness. the J_c =6.3×10^3 A cm^{-2} in 0.6 mm thick tapes.
- 7-core tapes: J_c= 1.5×10^4 A/cm^2.
- This J_c degradation can be ascribed to the sausage effect.

Jc needs to be further improved

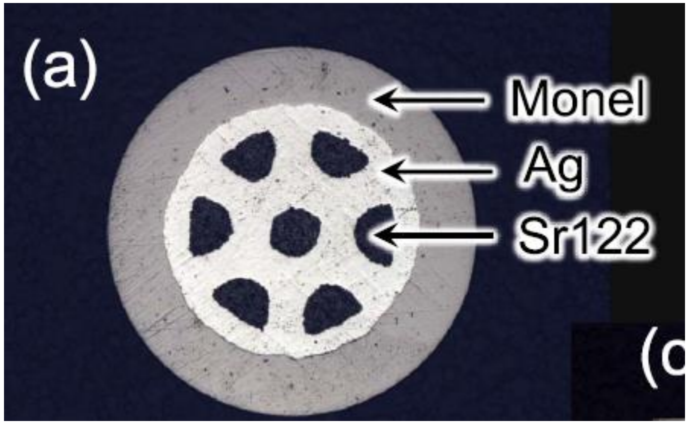
Yao et al., *JAP* 118 (2015) 203909

Fabrication of high-strength IBS wires

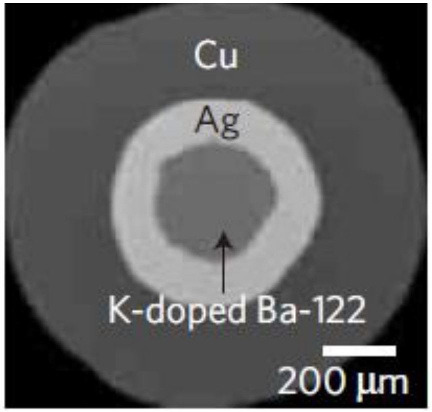
Ag may be also used in combination with an additional outer sheath made of Fe, Cu, and stainless steel to **reduce costs and improve the mechanical strength.**



Fe/Ag, **IEECAS**

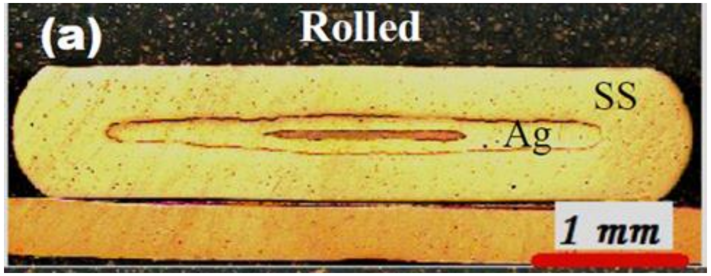


Monel/Ag, **IEECAS**

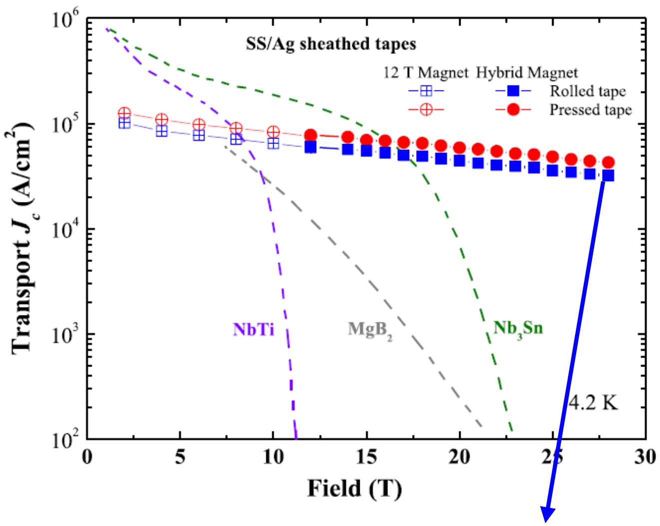


Cu/Ag, **Florida**

Cu/Ag, **IEECAS**



SS/Ag, **NIMS**

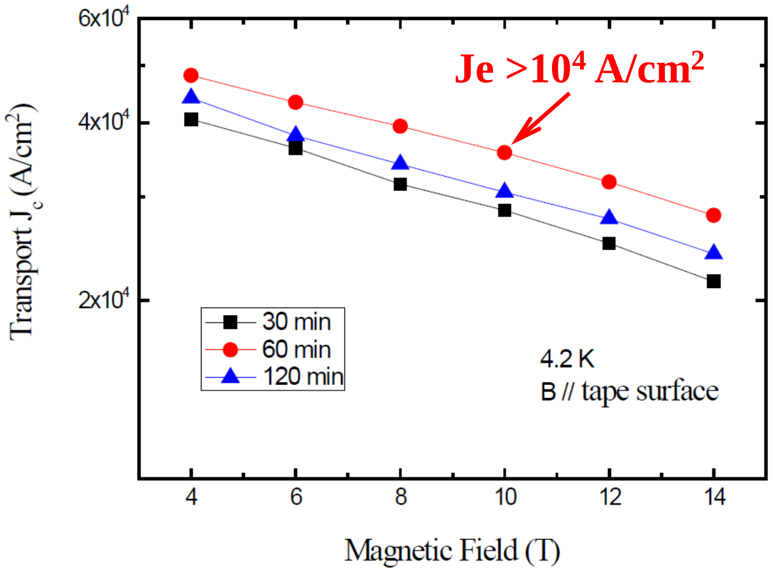


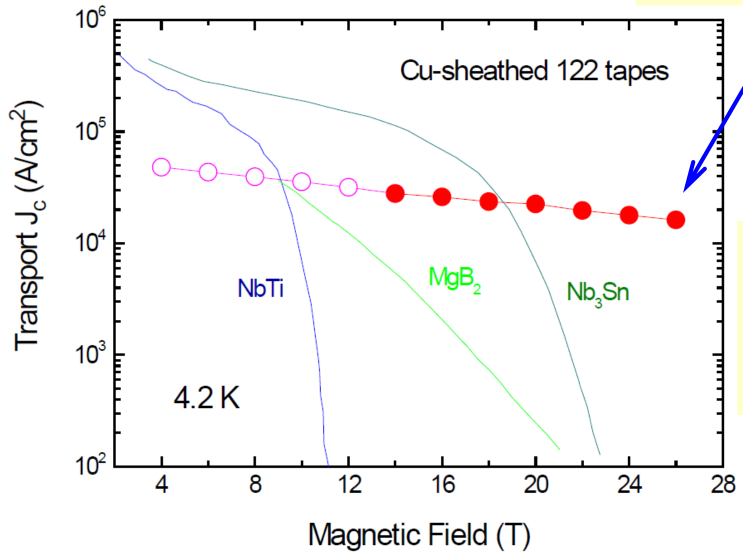
28T, **$J_c = 3\times10^4$ A/cm^2**

Copper sheath material

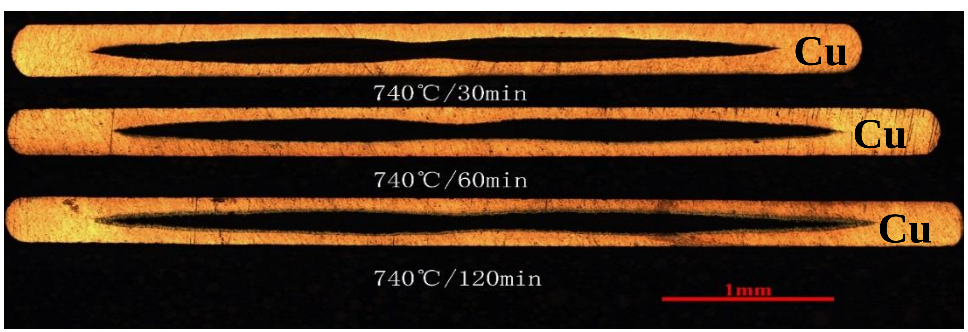
High J_c in Cu-sheathed Sr-122 tapes at low temperature 740ºC

At **26 T**:
J_c = 1.6×10⁴ A/cm²





At 4.2 K, 10 T
Engineering J_e: >10⁴ A/cm²



- The rapid fabrication method (HP740C/60 min) can effectively thwart the diffusion of Cu into Sr-122 core.
- The best transport J_c reaches 3.5×10^4 A/cm² at 10 T and keeps 1.6×10^4 A/cm² at 26 T.

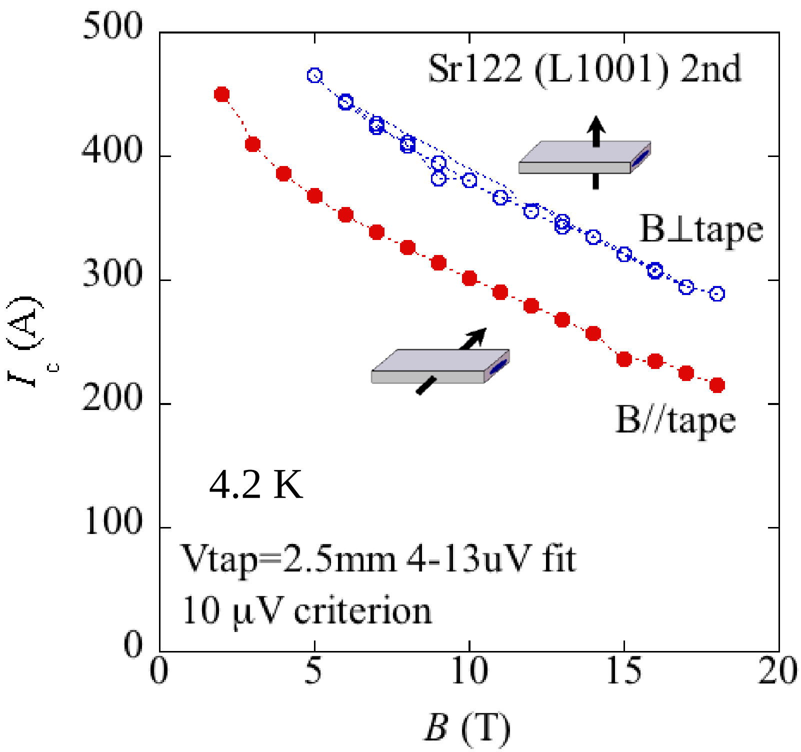
Lin et al., *SuST* 29 (2016) 095006

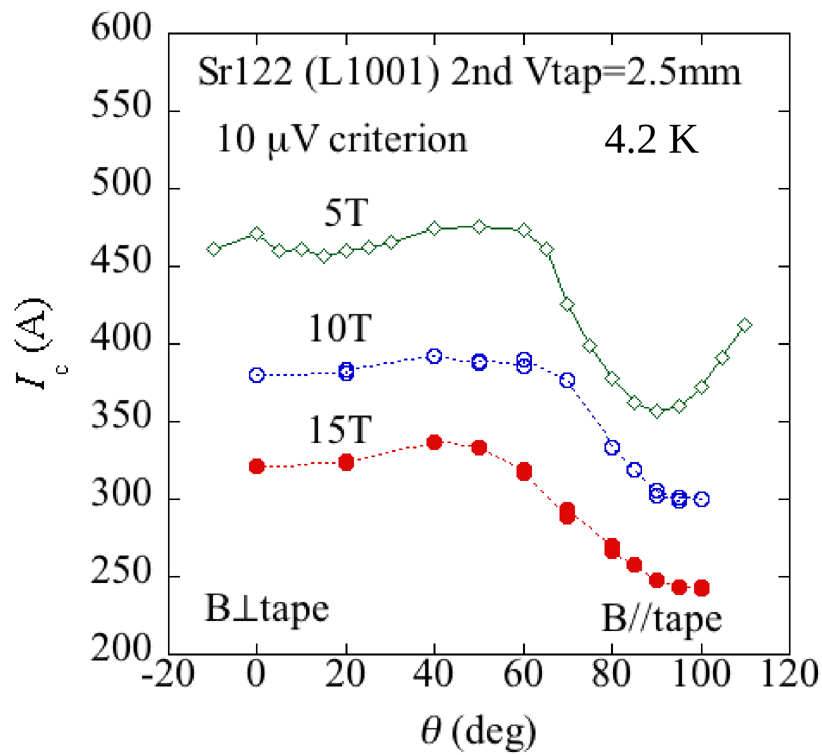
Small anisotropy

Awaji et al., ***SuST*** 30 (2017) 035018

J_c properties at 4.2 K for HP Sr-122/Ag tapes

-- Measured by Prof. Awaji
HFLSM, Tohoku Univ.



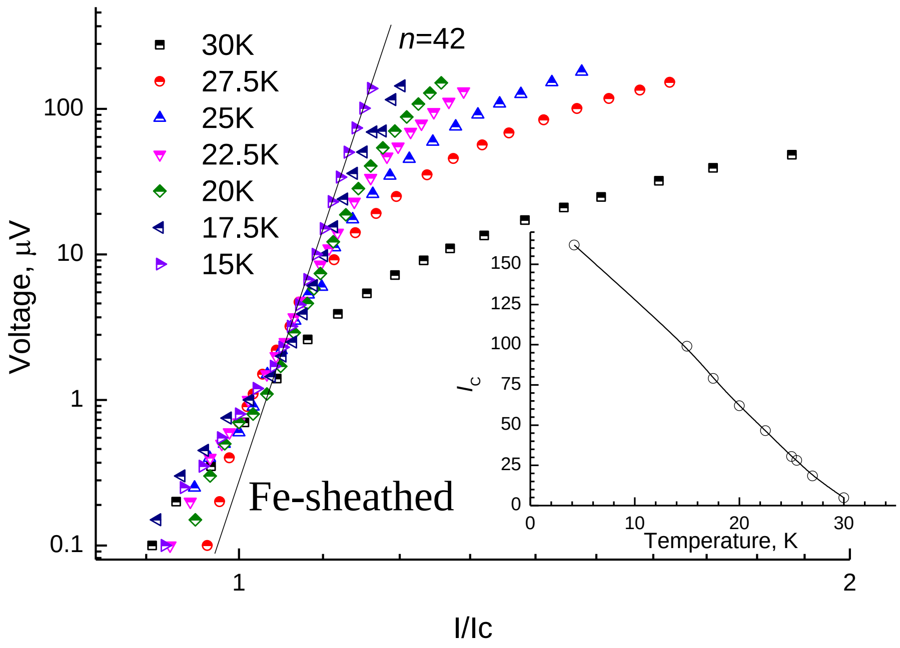


- **The I_c in applied magnetic fields is slightly higher in the perpendicular field ($I_c^{\perp}$) than in the parallel field ($I_c^{//}$).**
- **The anisotropy ratio ($\Gamma = I_c^{\perp}/I_c^{\parallel}$) is less than *1.5*, quite small, very promising for applications.**

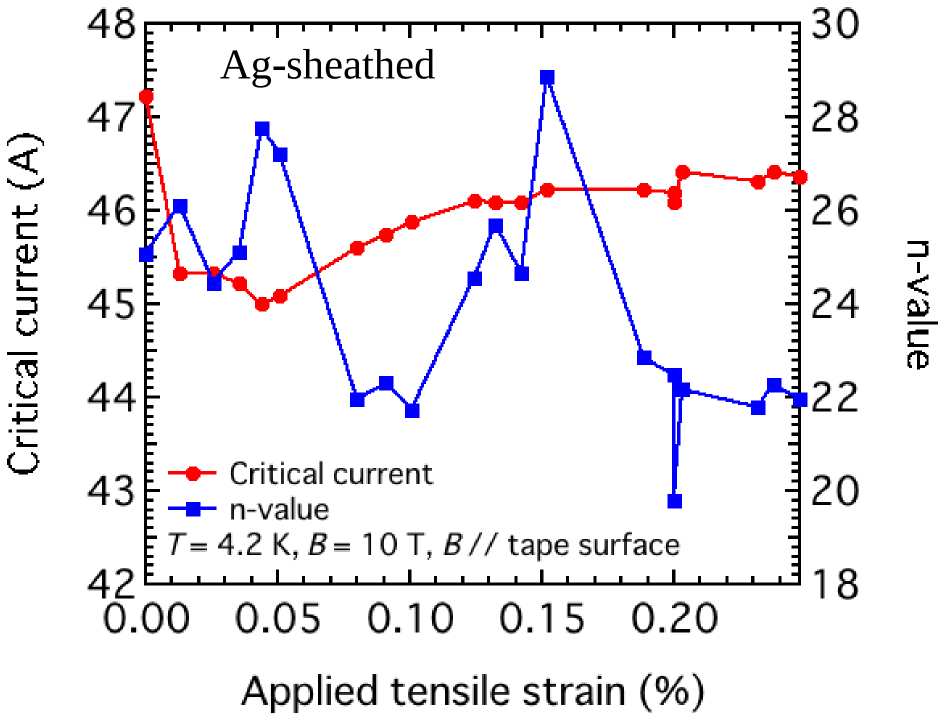
n value

Temperature dependence of *n value* for Sr-122 tapes

-- Measured by Prof. Yang
Univ. of Southampton, UK



-- Measured by Dr. Oguro
HFLSM, Tohoku Univ., JP

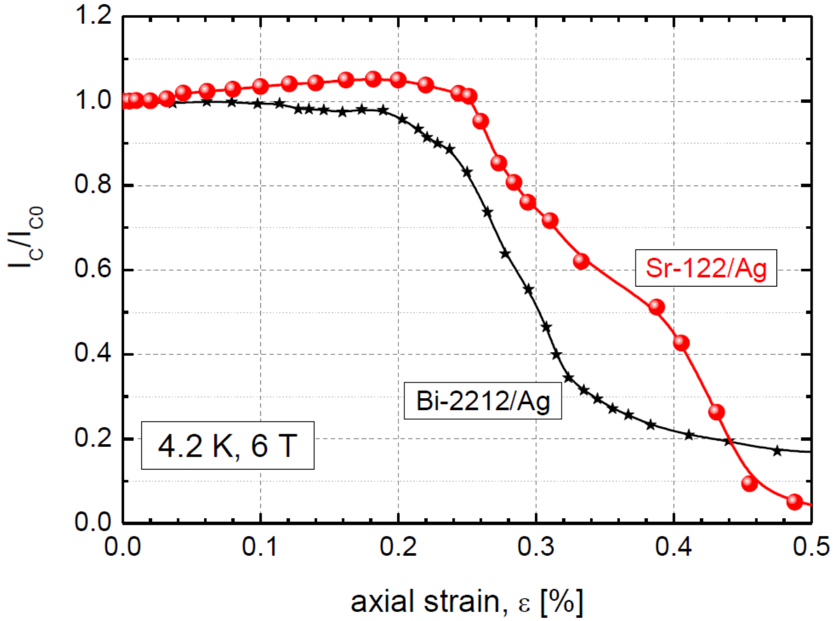


At 20 K, the *n value* was over 30

At 4.2 K, the *n value* was over 20

Sr122/Ag tape – Strain-stress properties

The first strain measurements

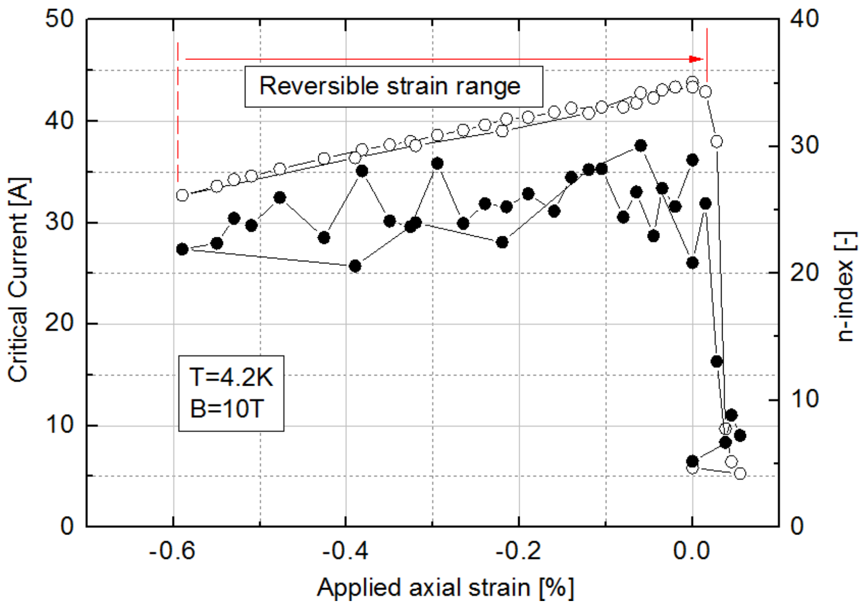


At 4.2 K, 10 T: I_c >125A
Irreversible strains: ε = 0.25%

Comparable to Bi2212

Kovac et al., *SuST* 28 (2015) 035007

Reversible critical currents under a large compressive strain of ε = –0.6 %



The critical current of Sr-122 tape exhibits less strain sensitivity than that of the Nb_3Sn, which is an important for ITER application.

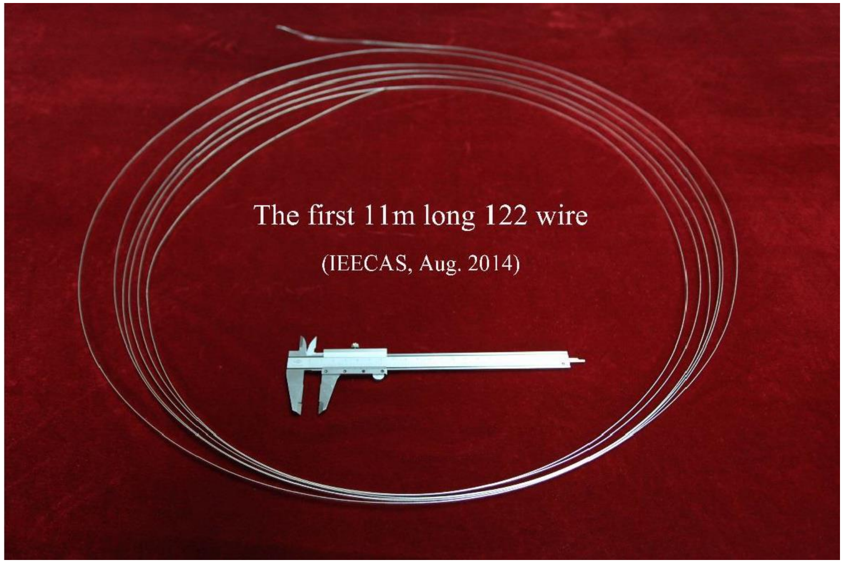
Liu, *SuST* 30 (2017) 07LT01

Ma , *Physica C* 516 (2015) 17

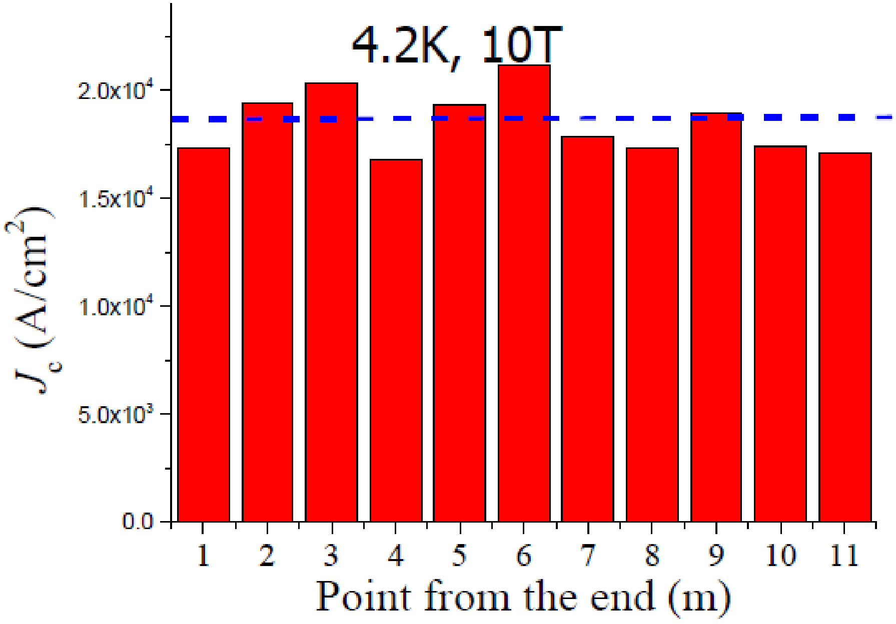
The first 11m long Sr-122 tape

-- by the scalable rolling process

The first long wire-- 11 m



Uniform wires can be fabricated



The minimum J_c ~1.7×10^4 A/cm^2

The average J_c of this long Sr122/Ag wire is ~ 18400A/cm^2

The fluctuations of the J_c is ~5%

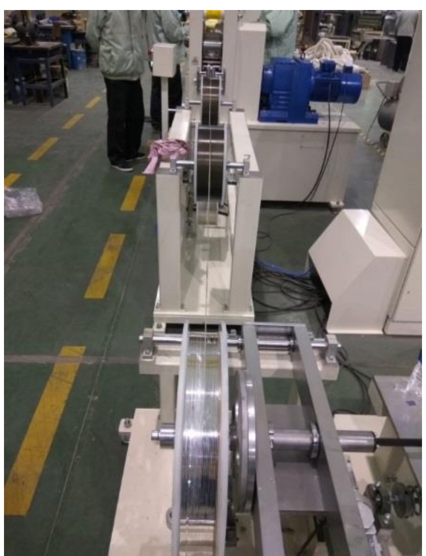
Significant breakthrough!

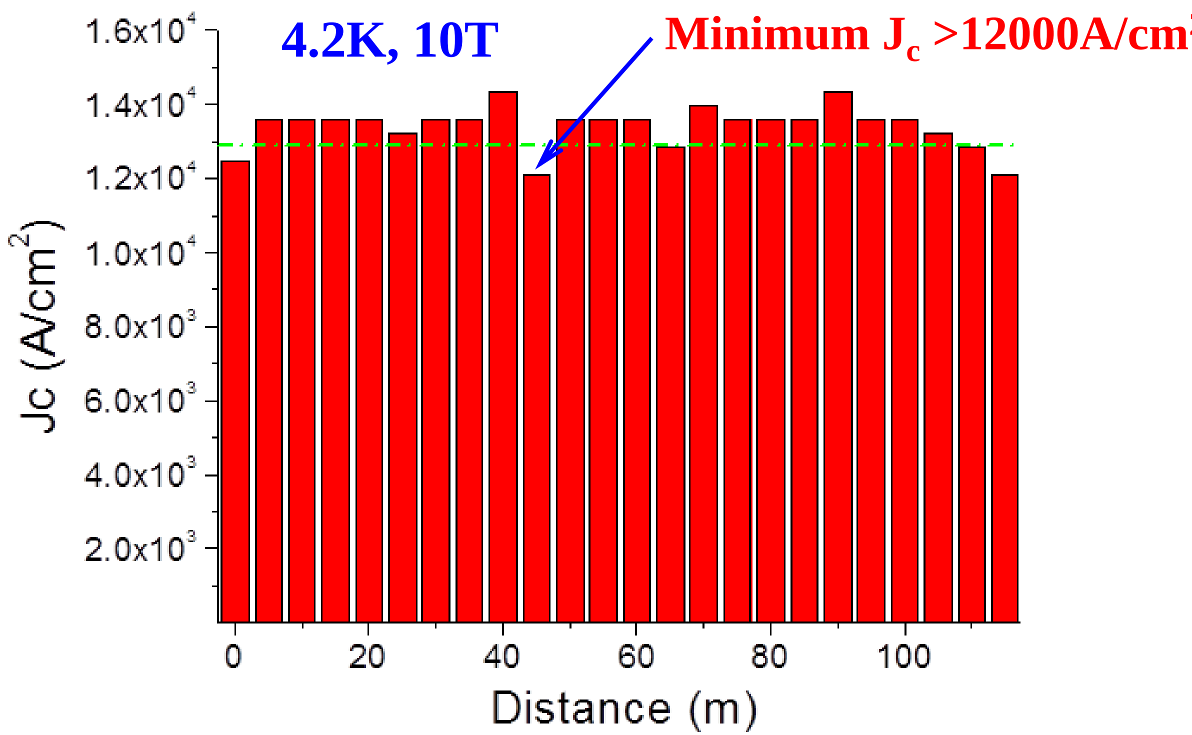
In Aug., 2016

The world's first 100 meter-class iron-based superconducting wire

-- Presented at ASC2016, Denver

115 m long **7-filamentary** wire



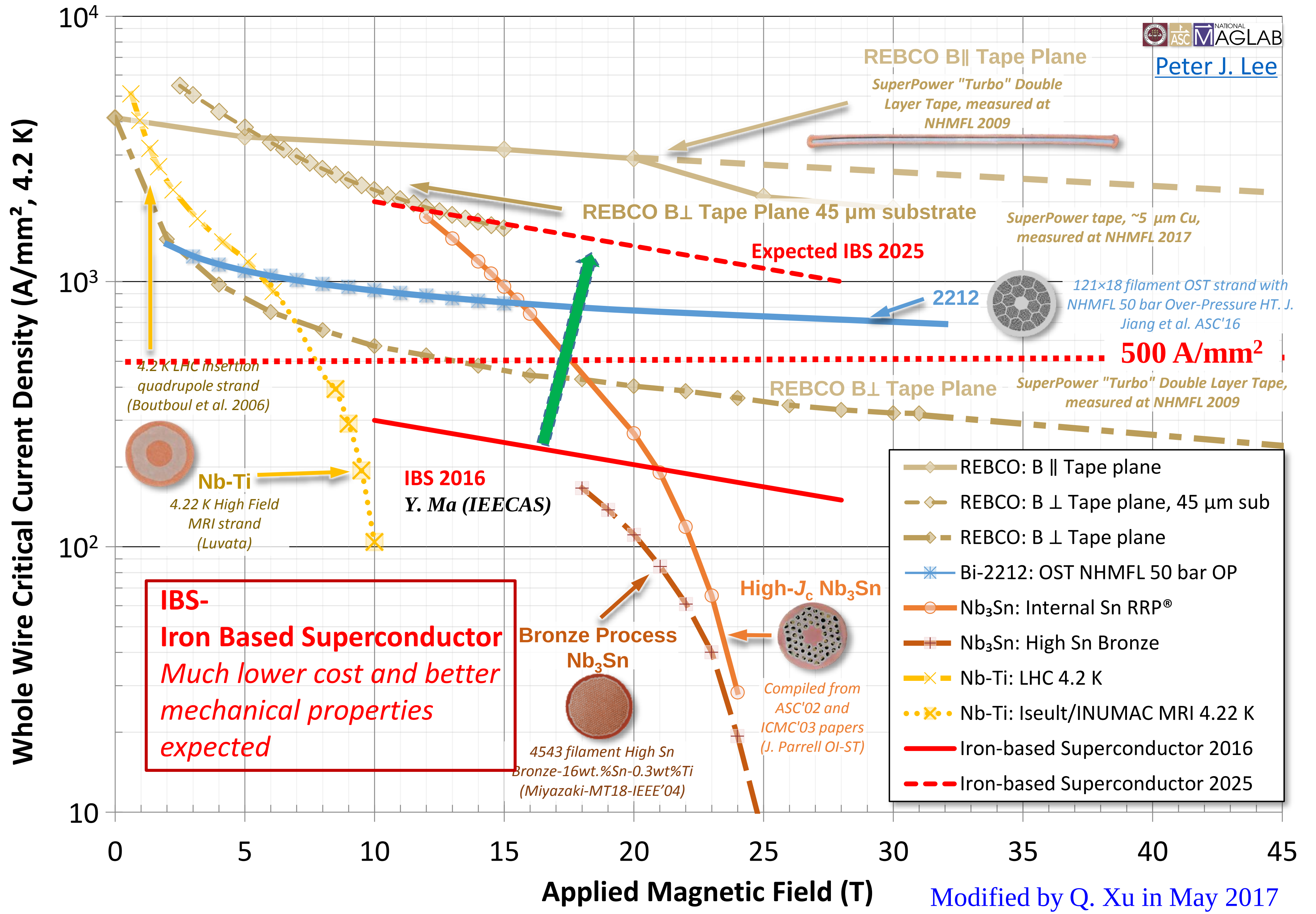


At 4.2 K, 10 T, transport Jc distribution along the length of the first 100 m long 7-filament Sr122 tape

http://snf.ieeecsc.org/pages/new-paper-and-result-highlights

X. P. Zhang et al., *IEEE TAS* 27 (2017) 7300705

Prospects



Whole Wire Critical Current Density (A/mm², 4.2 K)
Applied Magnetic Field (T)
NATIONAL MAGLAB
Peter J. Lee
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-Jc Nb3Sn
Bronze Process Nb3Sn
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)
REBCO: B || Tape plane
REBCO: B ⊥ Tape plane, 45 µm sub
REBCO: B ⊥ Tape plane
Bi-2212: OST NHMFL 50 bar OP
Nb3Sn: Internal Sn RRP®
Nb3Sn: 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
IBS-
Iron Based Superconductor
Much lower cost and better mechanical properties expected
Modified by Q. Xu in May 2017

Conclusions

- ✓ **Currently, Fe-based wires and tapes are in the rapid development stage of research and development.**
- ✓ **The transport J_c values are already extremely high, maximum J_c=1.5×10^5 A/cm^2 at 10 T and 4.2 K, surpassing the widely accepted threshold for applications.**
- ✓ **In particular, the world's first 100-m-class 122-type Fe-based wire was achieved, which demonstrates the great potential for large-scale manufacture.**
- ✓ **Further improvement in J_c can be expected upon either introducing more pinning centers, or enhancing grain texturing.**
- ✓ **We believe that Fe-based wires are very promising for applications using high magnetic fields, e.g. >20 T at 4.2 K or >10 T at 20-30 K.**

Contributors:

Xianping Zhang, Chao Yao, Chiheng Dong, Qianjun Zhang, Dongliang Wang, He Huang, Shifa Liu, Zhe Cheng

Institute of Electrical Engineering, CAS

Collaborators:

S. Awaji (Ic-B measurement**)**
Institute for Materials Research, Tohoku University, Japan

Hai-hu Wen (Pinning properties**)**
Nanjing University, China

Jianqi Li (HRTEM**)**
Institute of Physics, Chinese Academy of Sciences

Xiaolin Wang, S. X. Dou (Pinning and hydrostatic studies**)**
Wollongong University, Australia

W. K. Kwok, U. Welp (Irradiation**)**
Argonne National Laboratory, USA

T. Kiss (Characterizing local microstructure and homogeneity of wires**)**
Kyushu University, Japan

Thank you for your attention

Conductor requirements for practical applications

- Overall current density J_{cE} of conductor, not just of superconductor
- Performance in field
- Filamentary architecture essential for AC applications
- Anisotropy of J_{cE} with respect to field direction

- Cost
  - Conductor itself
  - Cooling
- Scaleability of fabrication
- Mechanical
  - Strength, bend radius, …..
- Conductor shape
  - tape or wire

Larbalestier, ***Nature*** 414 (2001) 368