



中国科学院  
CHINESE ACADEMY OF SCIENCES



# Recent progress of iron-based wire development for high-field applications

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Superconductivity  
1<sup>st</sup>-5<sup>th</sup> September 2019, Glasgow*

# Acknowledgments

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## Financial support:

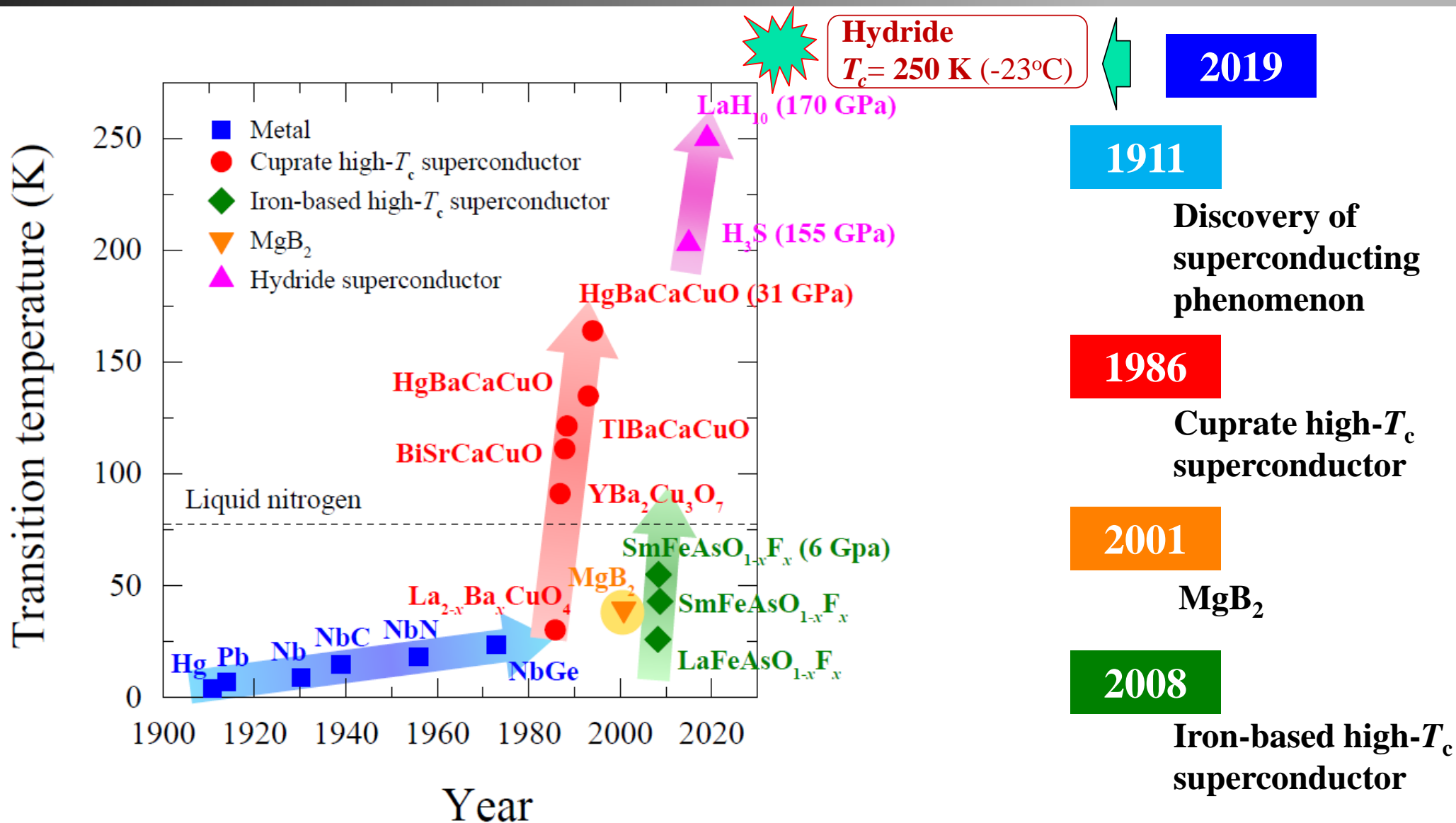


# Outline

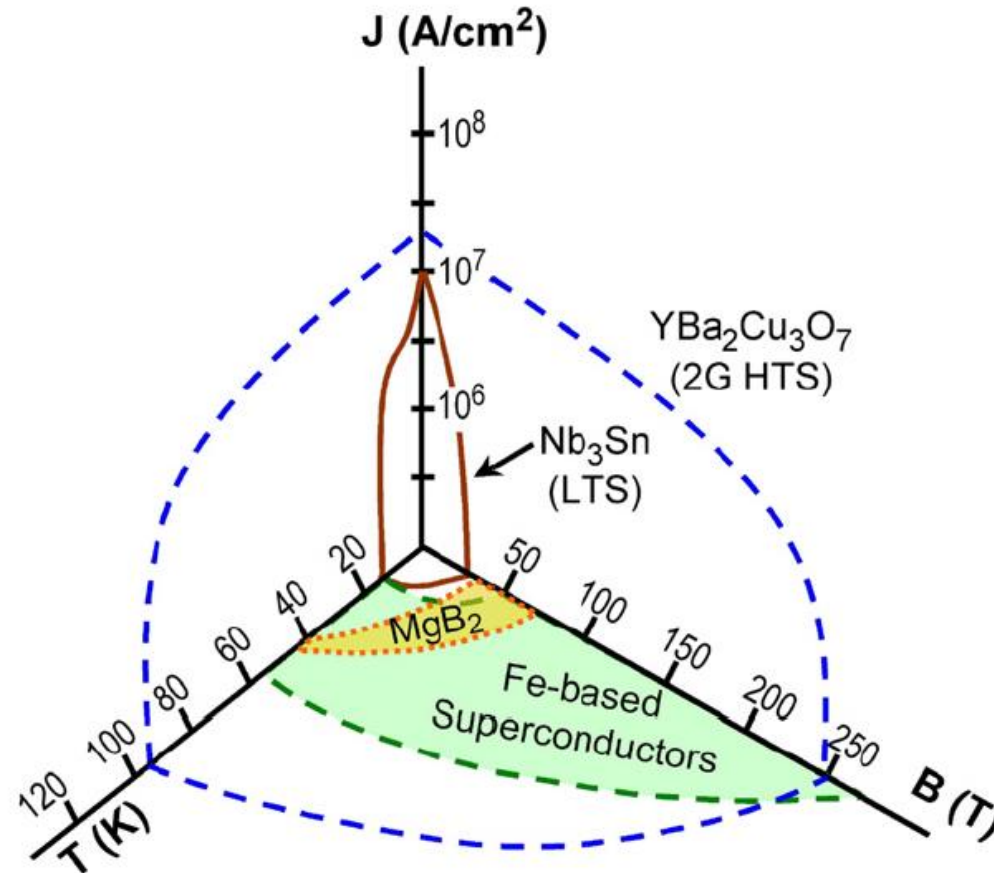
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- 1 Background on iron-based superconductors (IBS)**
- 2 High- $J_c$  IBS films and Coated Conductors (CC)**
- 3 Fabrication of PIT IBS wires**
  - i) Strategies to improve  $J_c$  in 122 wires**
  - ii) Practical properties of 122 IBS wires**
  - iii) Long-length wire & inserted coils**
- 4 Conclusions**

# History of Superconductivity



# So far, over 1000 superconductors have been discovered



Li et al., *Rep. Prog. Phys.* 74 (2011) 124510

## Three key properties for applications

- ◆ Transition temperature,  $T_c$
- ◆ Upper critical field,  $H_{c2}$
- ◆ Critical current density,  $J_c$

For applications, besides high  $T_c$ , large  $J_c$  and high  $H_{c2}$  are required.



**Practical superconductors**

**LTS, cuprate HTS, MgB<sub>2</sub>, Fe-base**

# Practical Materials

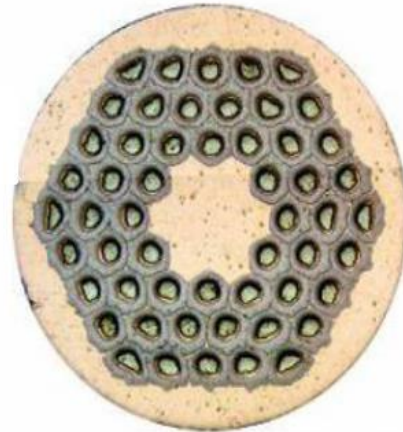
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- **Commercial production:**
  - Niobium alloys (NbTi, Nb<sub>3</sub>Sn etc)
  - **Bi2223, Bi2212** / silver tape - 1<sup>st</sup> Generation HTS
  - **MgB<sub>2</sub>**
- **Pre-commercial: (Ready for commercialization)**
  - **YBCO** 2<sup>nd</sup> Generation HTS “coated conductor”
- **Laboratory: (in rapid development)**
  - **Fe-based superconducting wires**

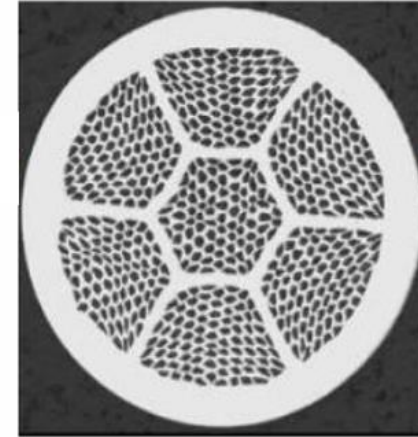
# Conductor forms of practical superconductors



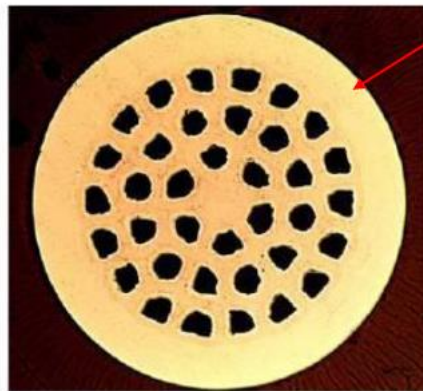
Nb47Ti (OST)



Internal Sn Nb<sub>3</sub>Sn



Bi-2212 (OST) – R&D

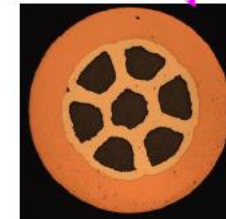
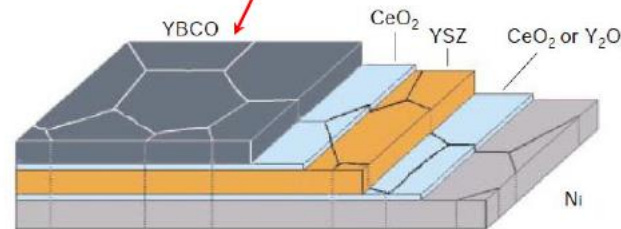


MgB<sub>2</sub>

YBCO

Bi2223

IBS



# Iron-Based Superconductors (IBS)

*J. Am. Chem. Soc.*, **130** (11), 3296 -3297, 2008. 10.1021/ja800073m  
Web Release Date: February 23, 2008  
Copyright © 2008 American Chemical Society

$T_c = 26 \text{ K}$

February, 2008

## Iron-Based Layered Superconductor $\text{La}[\text{O}_{1-x}\text{F}_x]\text{FeAs}$ ( $x = 0.05\text{-}0.12$ ) with $T_c = 26 \text{ K}$

Yoichi Kamihara,<sup>†</sup> Takumi Watanabe,<sup>‡</sup> Masahiro Hirano,<sup>†§</sup> and Hideo Hosono<sup>†§</sup>

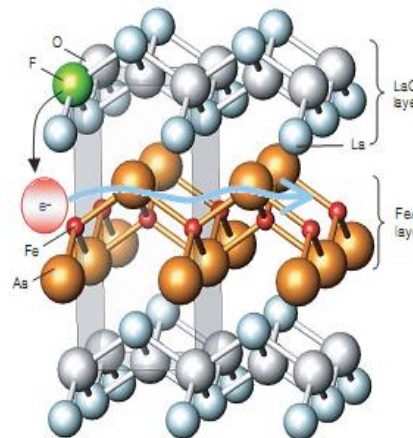
*ERATO-SORST, JST, Frontier Research Center, Tokyo Institute of Technology, Mail Box S2-13, Materials and Structures Laboratory, Tokyo Institute of Technology, Mail Box R3-1, and Frontier Research Center, Tokyo Institute of Technology, Mail Box S2-13, 4259 Nagatsuta, Midori-ku, Yokohama 226-8503, Japan*

hosono@msl.titech.ac.jp

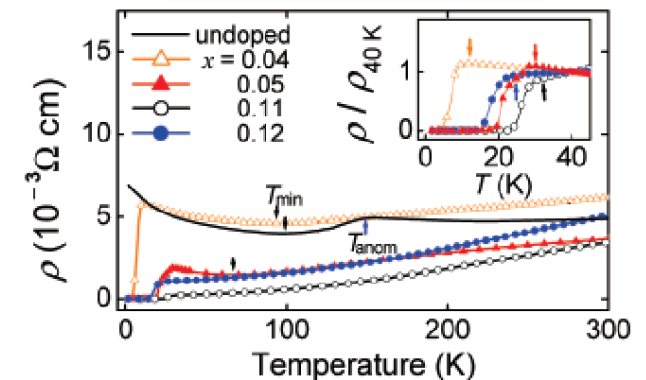
Received January 9, 2008

### Abstract:

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



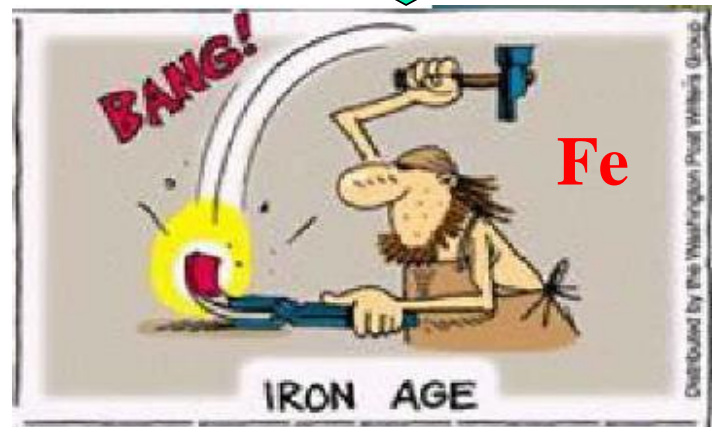
细野秀雄  
Hideo Hosono



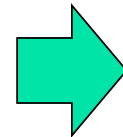
# In 2008 it started the iron age!



Cuprates

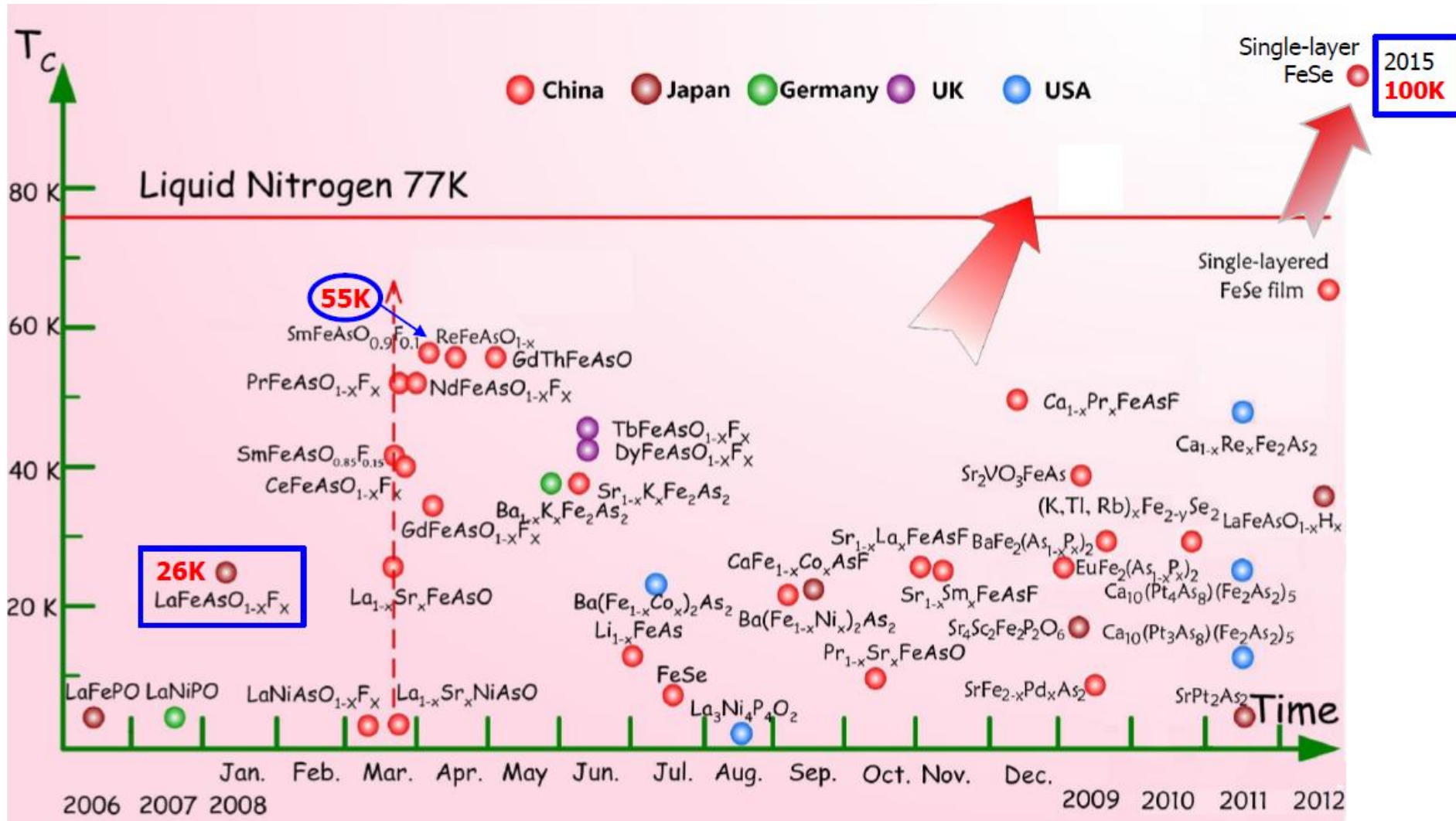


Pnictides



**Iron Man** : In cinemas from Paramount Pictures and Marvel Entertainment

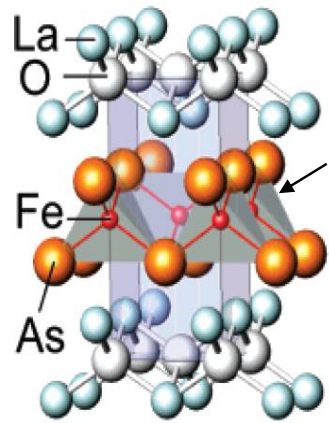
# IBS families -- $T_c$ is quite high



# Major classes of IBS families

Like the case of cuprates (**CuO<sub>2</sub> layer**), IBS has the **FeAs layered** structure alternating with spacer or charge reservoir block.

## 1111 Phase LnOFeAs

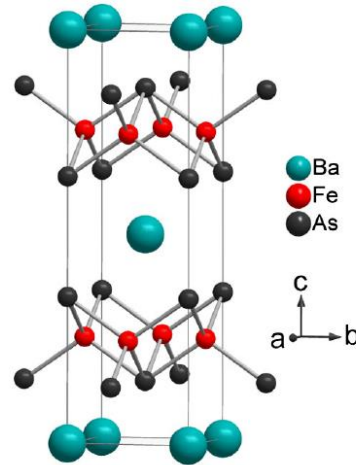


FeAs layer

$T_c \sim 55$  K

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

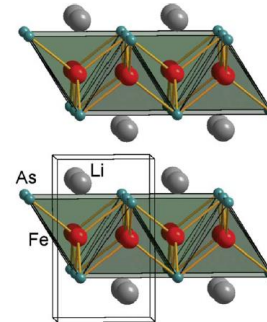
## 122 phase AFe<sub>2</sub>As<sub>2</sub> (A=Ba, Sr, Ca)



$T_c \sim 38$  K

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

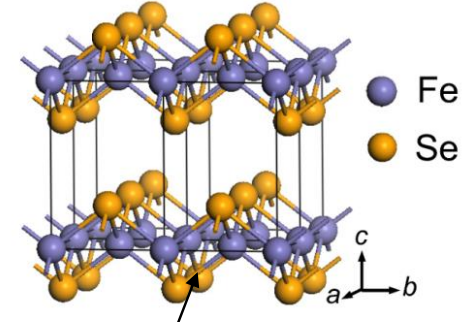
## 111 phase LiFeAs



$T_c \sim 18$  K

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

## 11 phase FeSe

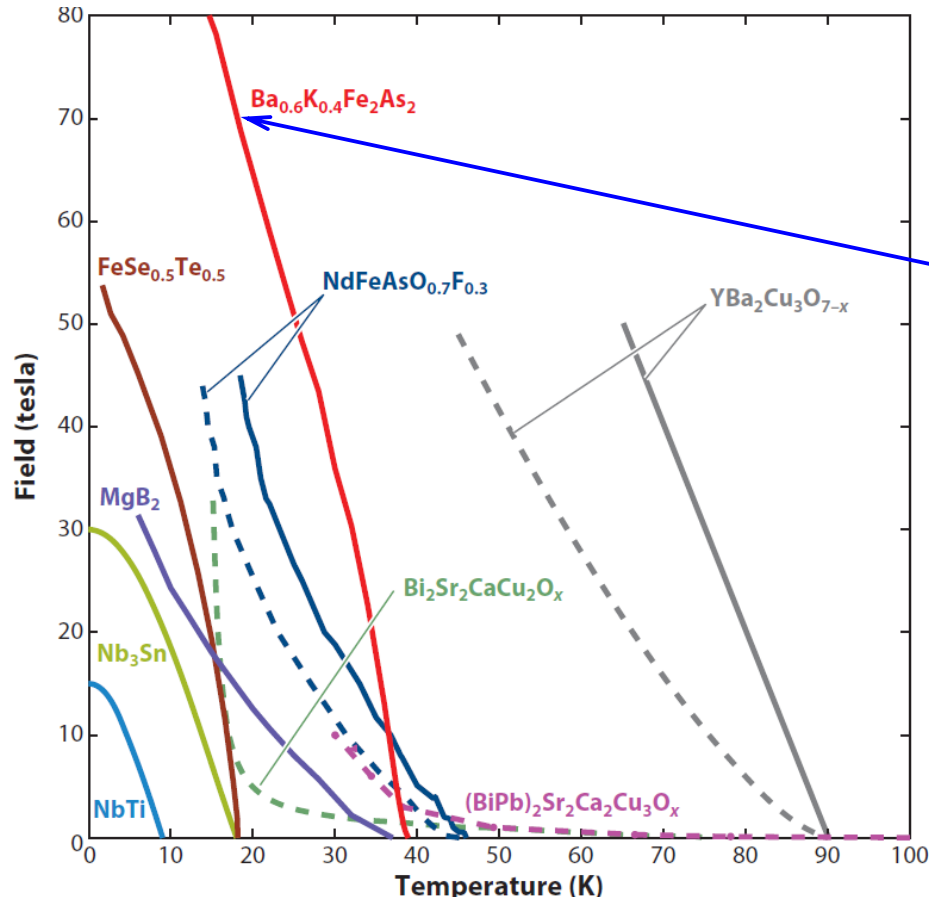


FeSe layer

$T_c \sim 8$  K

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

# The extremely high $H_{c2}$ in IBS



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

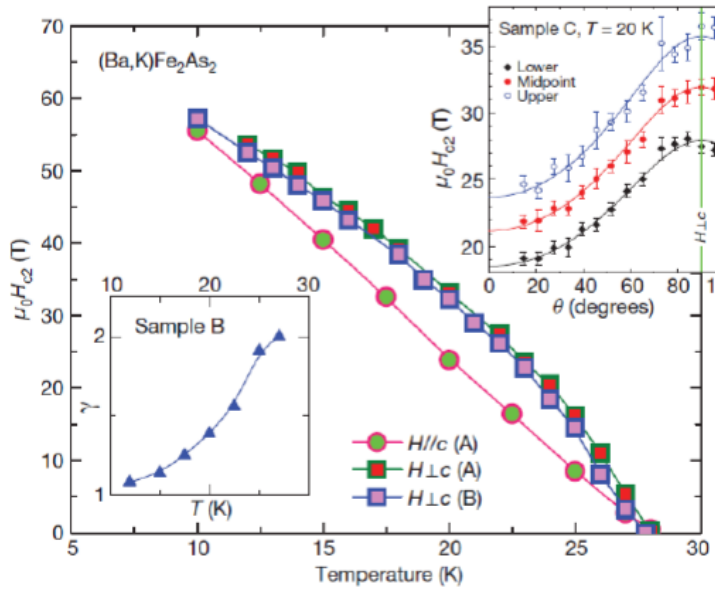
At 20 K, the  $H_{c2}$  can be >70 T where IBS outperform both MgB<sub>2</sub> and Bi-2223.

- Interesting FBS have  $T_c$ : 38-55 K >> Nb-Ti and Nb<sub>3</sub>Sn
- Operation at 4K >20T or 10-30 K at >10 T would be very valuable

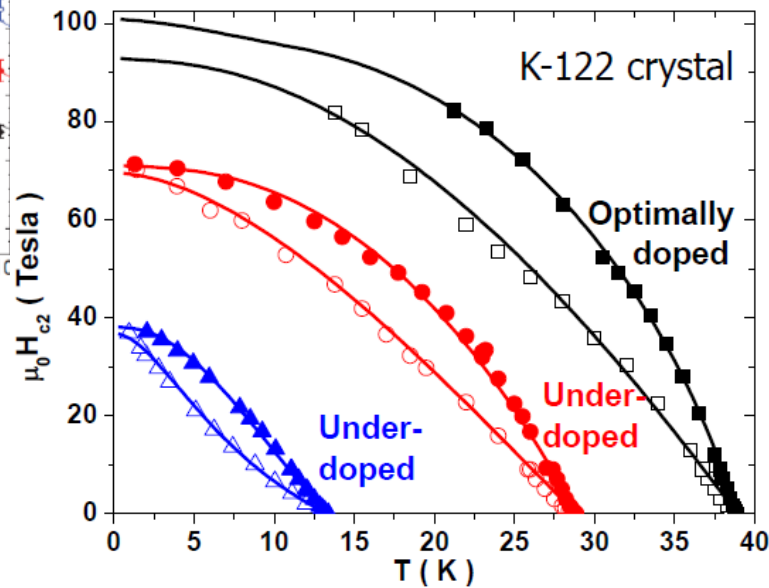
The extremely high  $H_{c2}$  in IBS shows a great potential for applications in high field magnets, e.g.,  $H > 20$  T, which cannot be achieved via LTS and MgB<sub>2</sub>.

# 122 IBS - small anisotropy $\gamma$

## $H_c$ anisotropy



Yuan et al. Nature 457, 565 (2009)



Tarantini et al. PRB 86, 214504 (2012)

## $J_c$ anisotropy

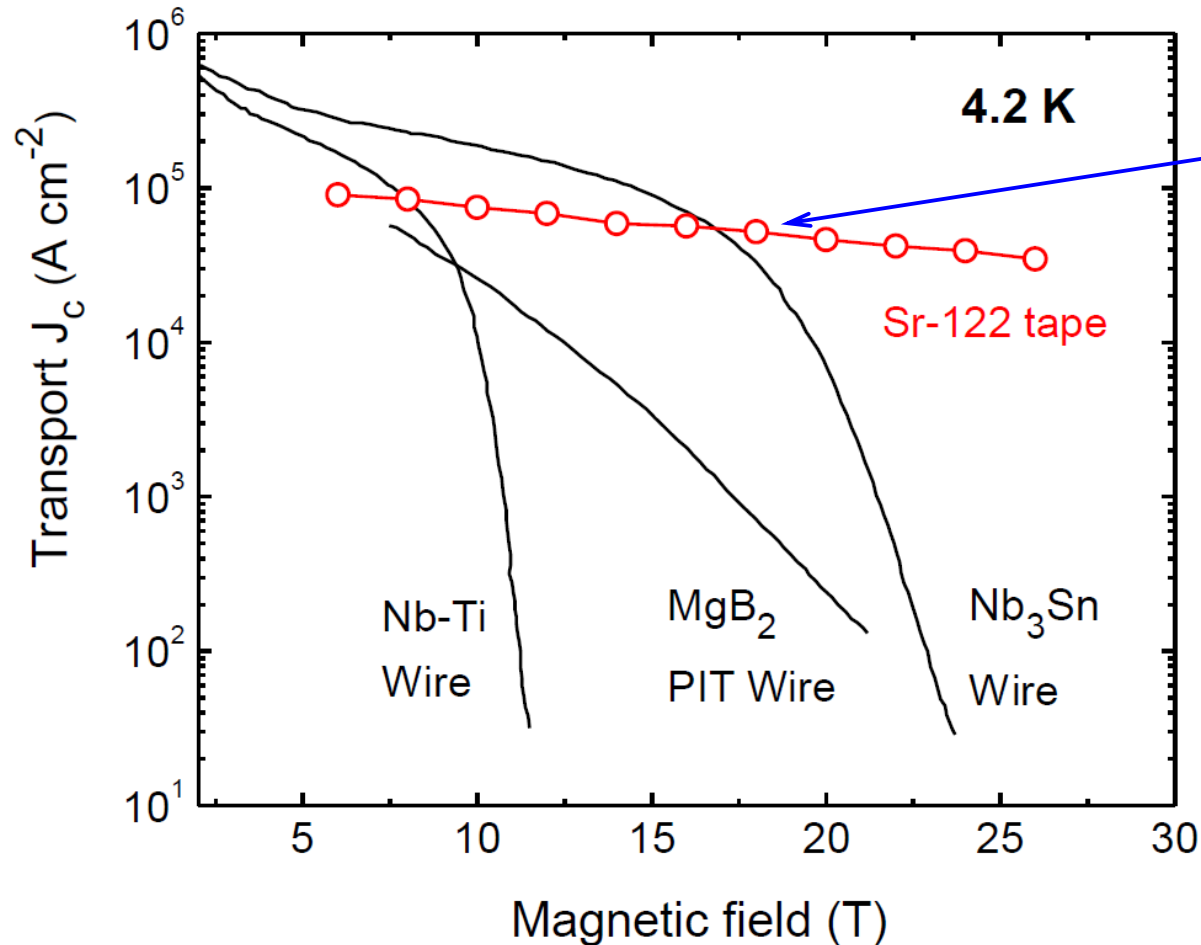
Materials	anisotropy $\gamma$
$\text{Bi}_2\text{Sr}_2\text{CaCu}_2\text{O}_{8+\delta}$	$\sim 100$
$\text{YBa}_2\text{Cu}_3\text{O}_7$	$\sim 7$
$\text{Ba}_{0.6}\text{K}_{0.4}\text{Fe}_2\text{As}_2$	$< 2$
$\text{MgB}_2$	$\sim 3.5$



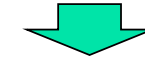
**Smaller than HTS and  $\text{MgB}_2$**

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

# High $J_c$ of IBS wires: Very weak field dependence in high field region



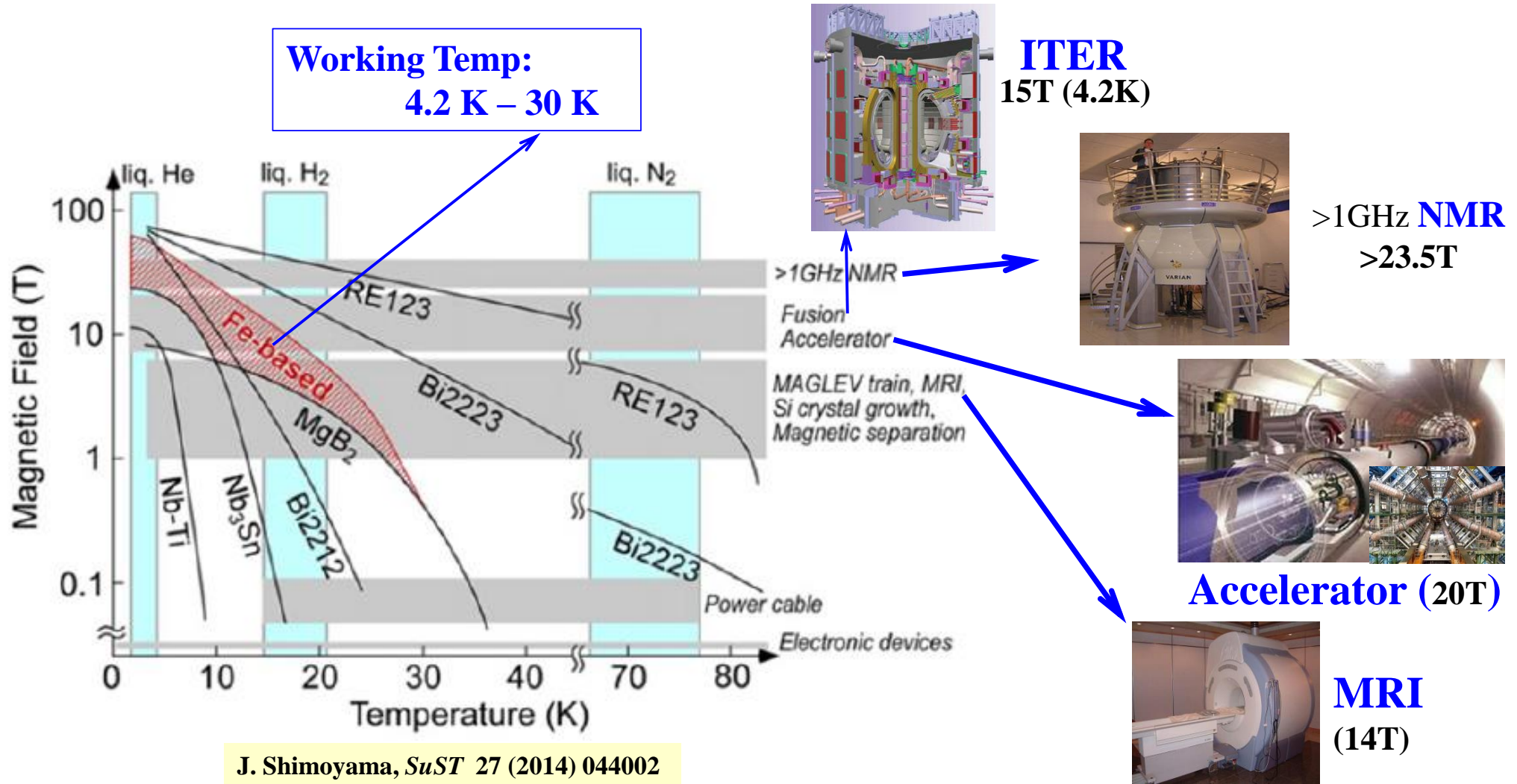
122 IBS wire:  
Large  $J_c$ , at  $H > 20\text{T}$



$J_c$  shows very weak field dependence in high fields

$I_c$  data of Sr-122 tape,  
measured in 2013 at HFLSM, Sendai

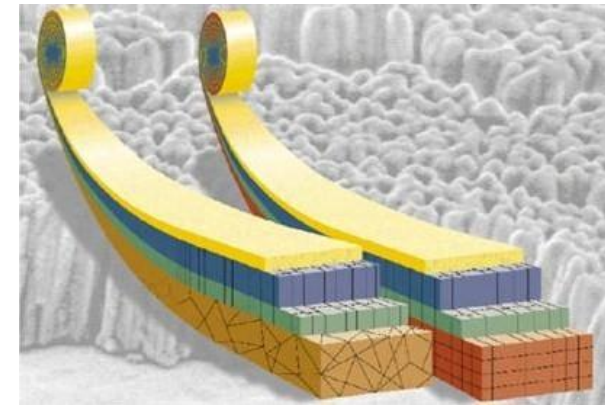
# IBS potential for high-field applications



*Development of high-performance conductors is essential*

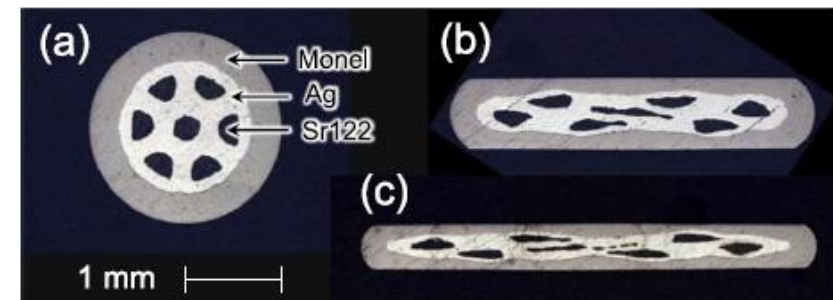
# Two routes to develop High- $J_c$ IBS conductors

1. IBS thin films on technical metallic substrates (IBAD or RABiTS), namely, Coated Conductors (CC)

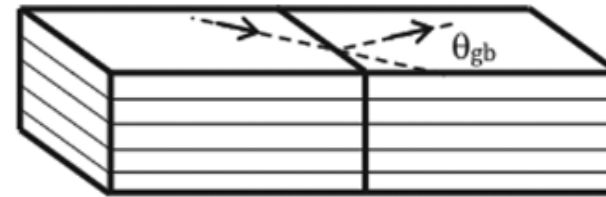
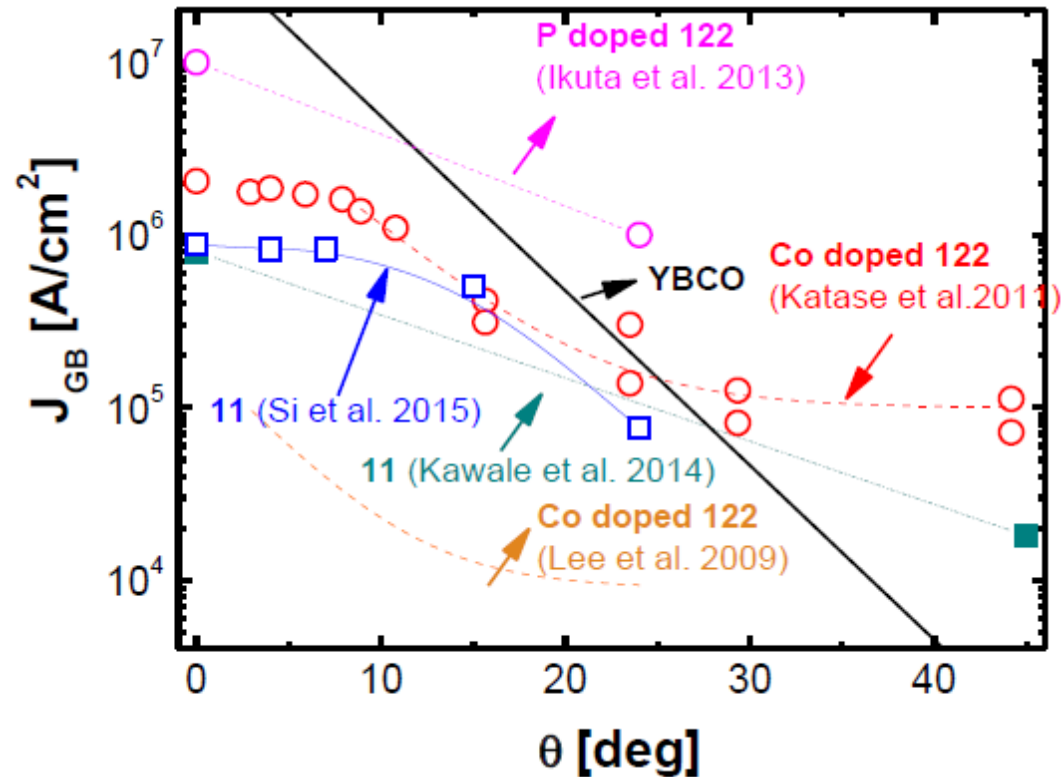


Courtesy of C. Ferdeghini

2. Powder-in-tube processed IBS wires and tapes



# Grain boundary nature of 122 and 11 IBSs



122 bicrystals  
11 bicrystals

- **Drawback:**  $J_c$  decreases exponentially with increasing GB angle
- **Advantage:** the critical angle  $\theta_c$  of IBS GBs is  $9^\circ$ , larger than YBCO ( $\theta_c \sim 5^\circ$ )

M. Putti presented at EUCAS-2015

- ◆ Compared to cuprates, high and three dimensional grain orientation is not necessary for IBS.
- ◆ This feature is highly beneficial for the the realization of **cheaper conductors** and **PIT wires** for high-field magnets at low temperature.

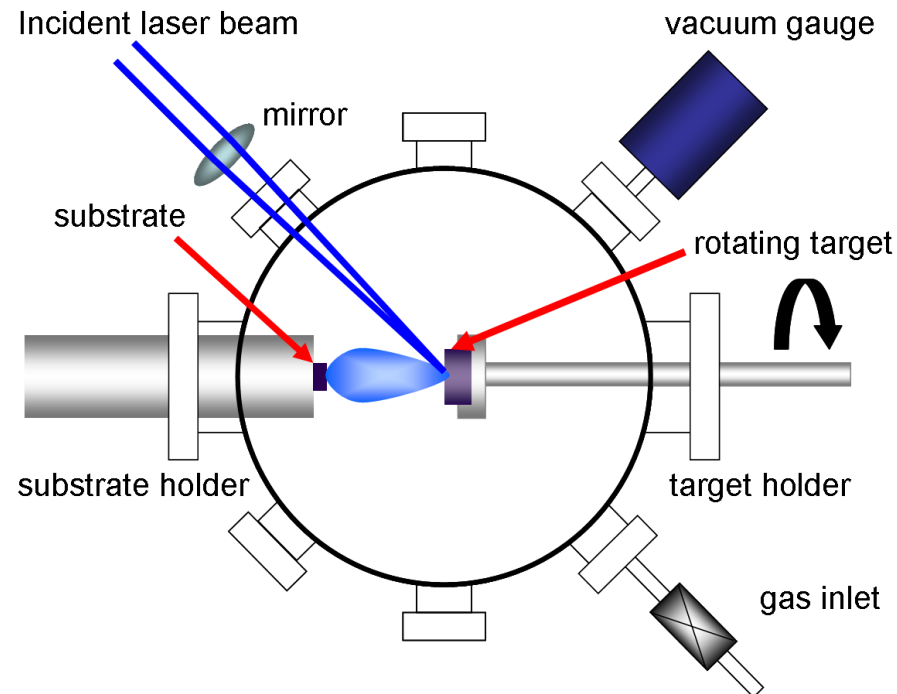
# Outline

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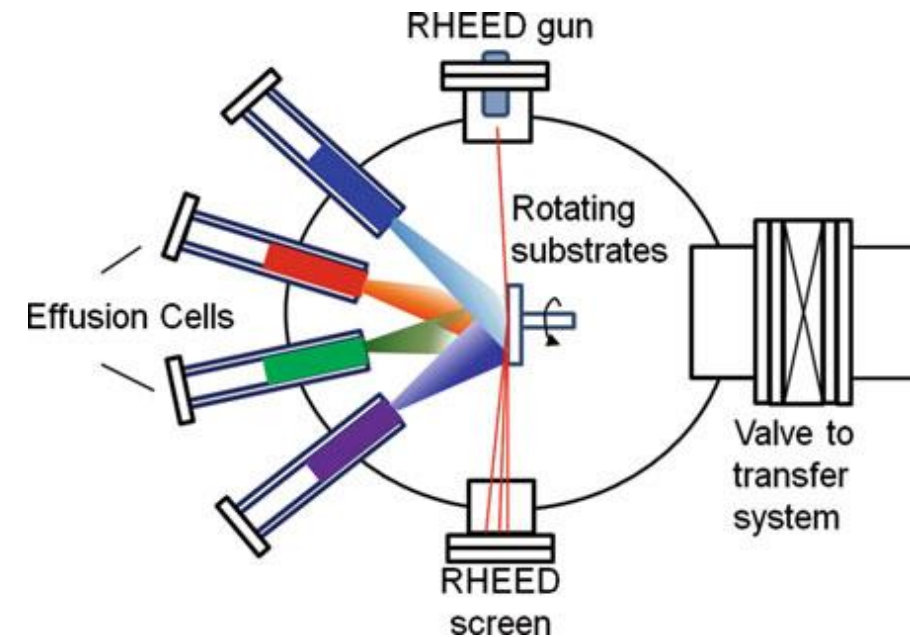
- 1** Background on iron-based superconductors (IBS)
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# Deposition techniques for IBS thin films and CCs

- ◆ **PLD** is mainly used for 11 and 122 compounds.
- ◆ **MBE** is mainly used for 1111 compounds containing high vapor pressure elements, such as F.

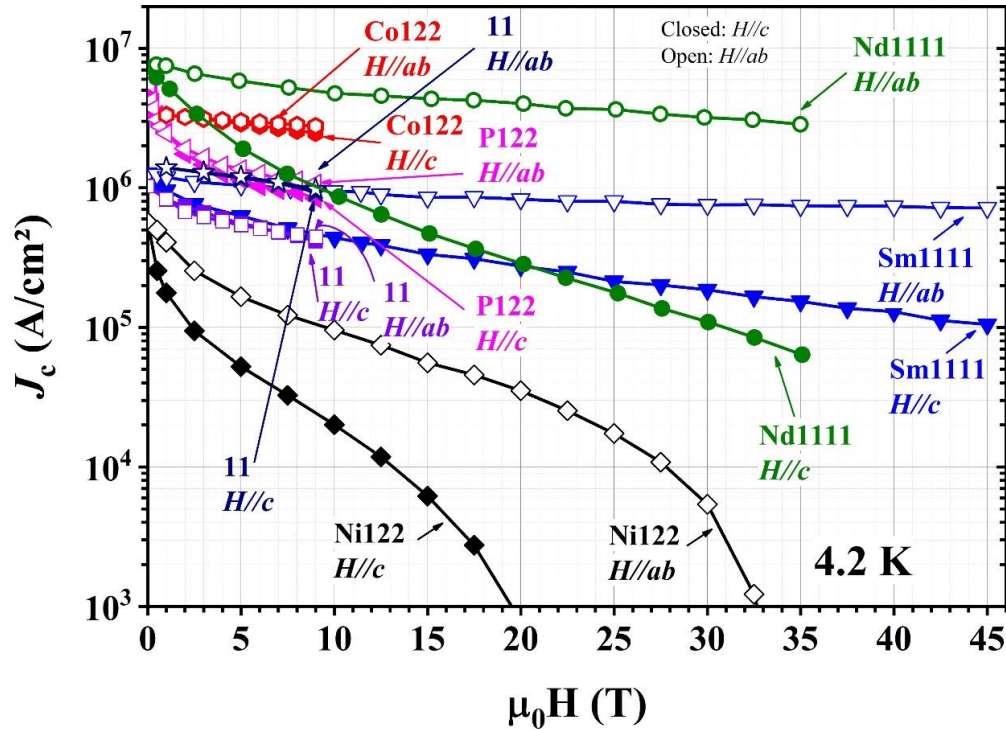


**PLD - Pulsed Laser Deposition**

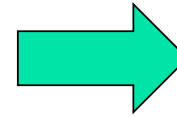


**MBE - Molecular Beam Epitaxy**

# High $J_c$ in IBS films on single crystal substrates



S. Kauffmann-Weiss *et al. Nanoscale Adv.* **1**, 3036 (2019)  
 K. Iida *et al. Sci. Rep.* **3**, 2139 (2013)  
 H. Sato *et al. APL* **104**, 182603 (2014)  
 P. S. Yuan *et al. SuST* **30**, 025001 (2017)  
 P. S. Yuan *et al. SuST* **29**, 035013 (2016)  
 V. Braccini *et al. APL* **103**, 172601 (2013)  
 S. Richter *et al. APL* **110**, 022601 (2017)  
 Some data referenced from at [nationalmaglab.org](http://nationalmaglab.org).



	$J_c$ @ 4.2K, 0T	$J_{c//ab}/J_{c//c}$
1111	$7.6 \times 10^6$ A/cm <sup>2</sup>	5-30
122	$6.3 \times 10^6$ A/cm <sup>2</sup>	< 2
11	$> 10^6$ A/cm <sup>2</sup>	< 1.5

FeSe<sub>0.5</sub>Te<sub>0.5</sub> films on CaF<sub>2</sub>: (PLD)

$J_c = 0.95$  MA/cm<sup>2</sup> (4.2 K, 9 T)

Ba122:Co films on CaF<sub>2</sub>: (PLD)

$J_c > 2.6$  MA/cm<sup>2</sup> at 9 T, 4.2 K

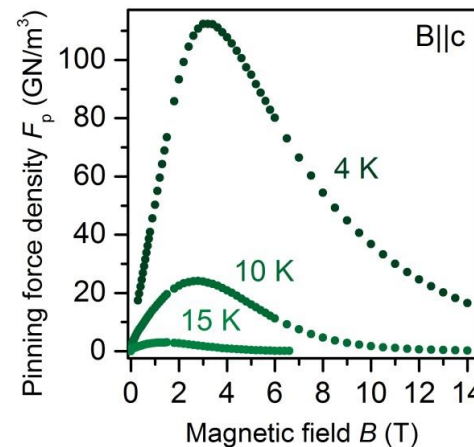
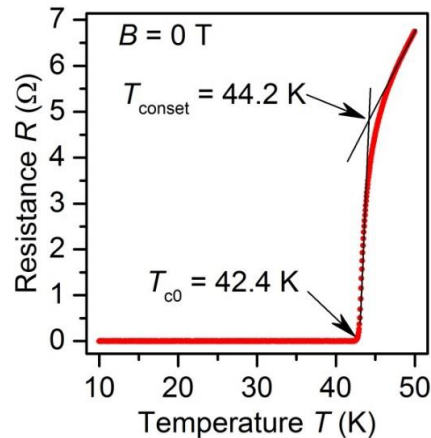
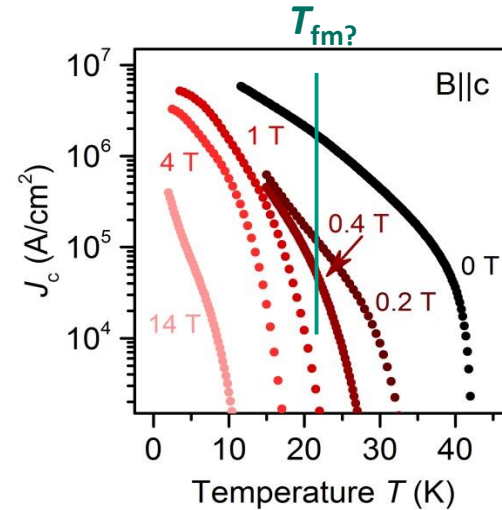
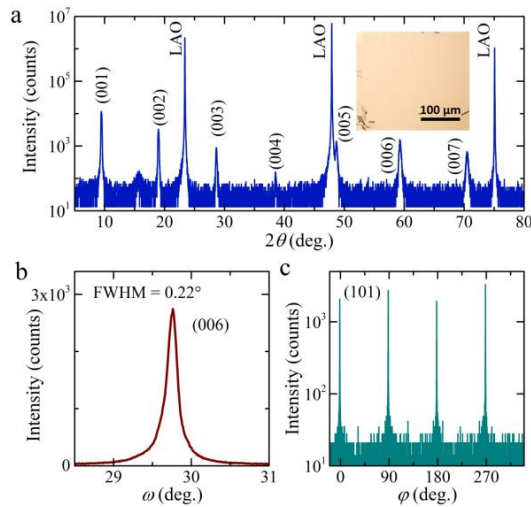
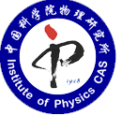
Nd-1111 films (22 nm) on MgO: (MBE)  
 @4.2 K, 35 T

$J_{c//ab} = 2.2$  MA/cm<sup>2</sup>,  
 $J_{c//c} = 70$  kA/cm<sup>2</sup>,  $\Rightarrow \gamma = \sim 30$

# (Li,Fe)OHFeSe films: growth, $J_c$ and flux pinning

FeSe-1111 on LAO substrate by a hydrothermal method

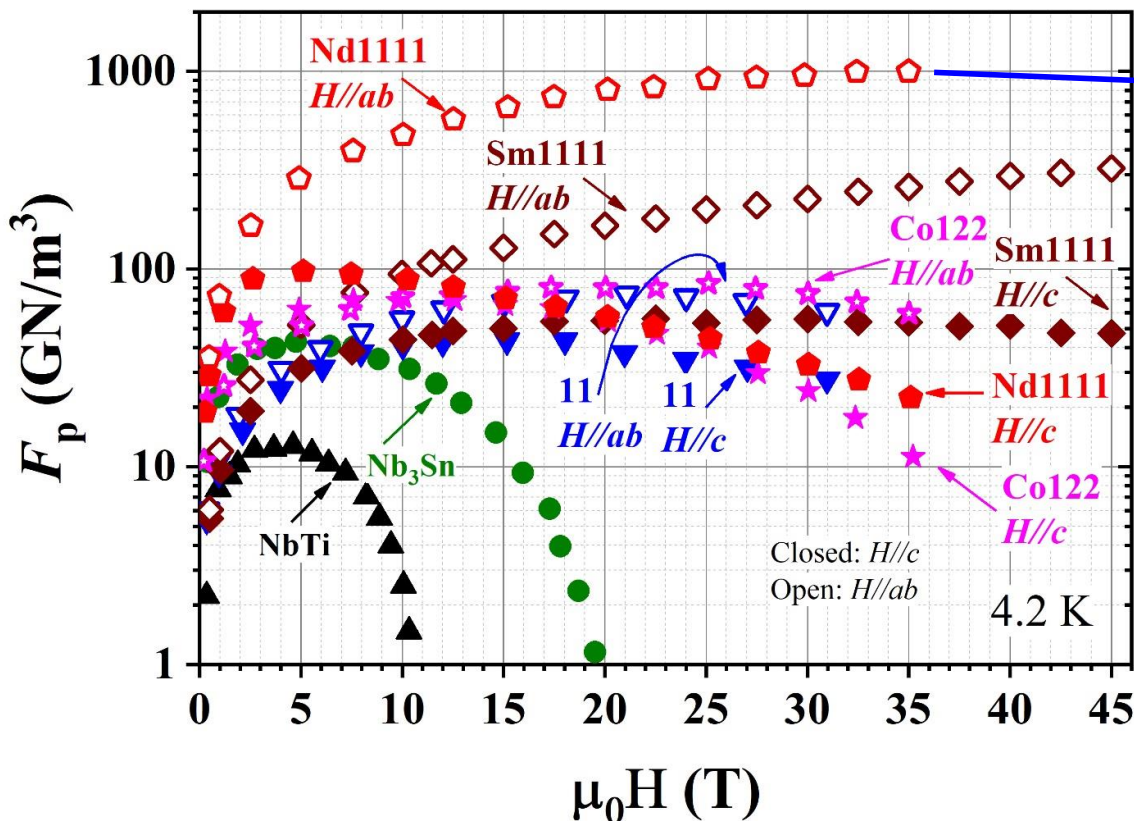
--grown by X L Dong group  
 -- Measured by Holzapfel group



- ◆ These films are highly epitaxial with  $T_{c,zero}=42.4$  K, anisotropy near  $T_c$  of  $\sim 5.6$ .
- ◆ Strong temperature and field dependencies of  $J_c$
- ◆ Self-field  $J_c$  values well above 1 MA/cm<sup>2</sup> below 20 K
- ◆ Maximum pinning force density:  $\sim 100$  GN/m<sup>3</sup> at 4 K (comparable to highest values in Nd1111)

# Large pinning force in IBS thin films

Extraordinary future for high field applications



**1111 (4.2 K, 35 T)**  
 $F_{p,max} = 992 \text{ GN/m}^3$

2019

**122 (4.2 K, 25 T)**  
 $F_{p,max} = 85 \text{ GN/m}^3$

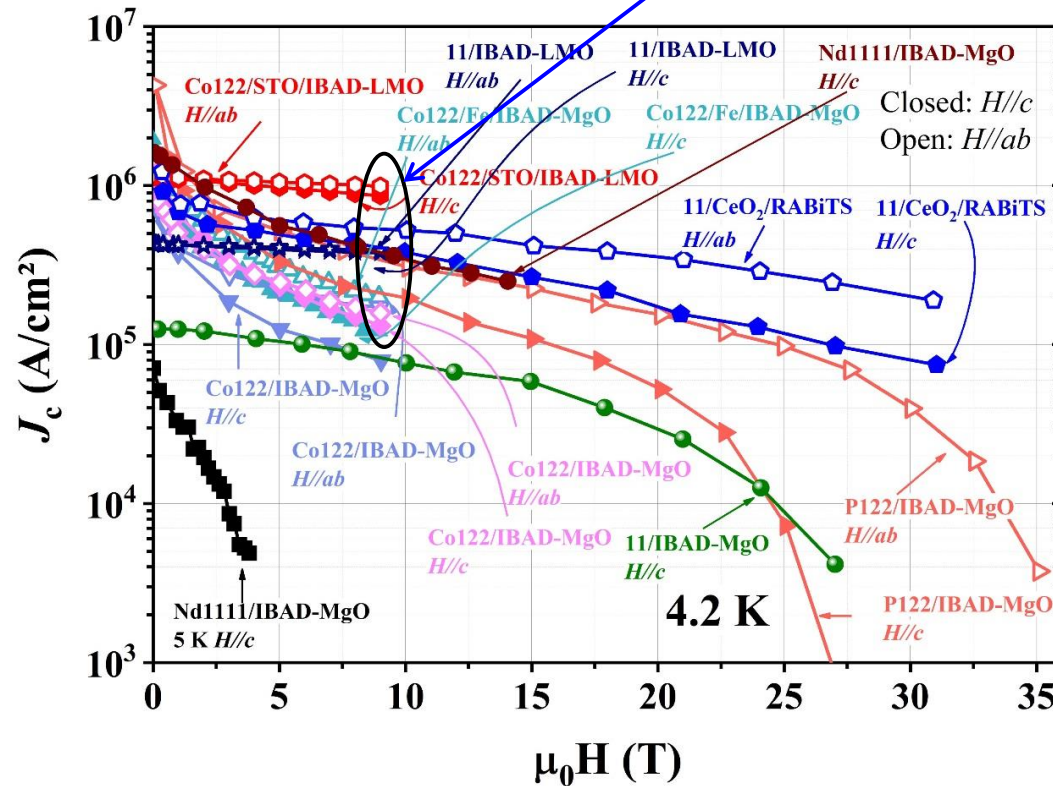
**11 (4.2 K, 21T)**  
 $F_{p,max} = 75 \text{ GN/m}^3$

**Nb<sub>3</sub>Sn(4.2K, 5T)**  
 $F_{p,max} = 42 \text{ GN/m}^3$   
**Nb-Ti (4.2K, 5T),**  
 $F_{p,max} = 16.5 \text{ GN/m}^3$

W. Si *et al. Nat. Commun.* **4**, 1347 (2017)  
 K. Iida *et al. Sci. Rep.* **3**, 2139 (2013)  
 C. Tarantini *et al. Sci. Rep.* **4**, 7305 (2014)  
 S. Kauffmann-Weiss *et al. Nanoscale Adv.* **1**, 3036 (2019)

## Summary: $J_c$ of different IBS coated conductors

- ◆ From the point of view of possible applications, many groups tried film deposition on technical substrates.
- ◆ Three main systems (11, 122, and 1111) with superior  $J_c$  have already been realized on technical substrates, e.g., **most of  $J_c$  at  $\sim 10$ T are  $> 10^5$  A/cm $^2$ , from  $10^5$  to  $10^6$  A/cm $^2$ .**



The  $J_c$  anisotropy of 11 and 122 was quite small

*To further improve  $J_c$ , the introduction of APC is necessary.*

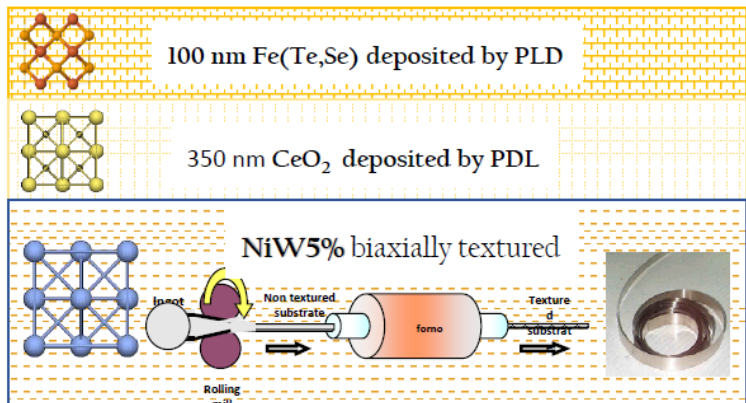
K. Iida *et al.* APL 105, 172602 (2014)  
 Courtesy of K. Iida  
 S. Trommler *et al.* SuST 25, 084019(2012)  
 T. Katase *et al.* APL 98, 242510 (2011)  
 H. Hiramatsu *et al.* SuST 30, 044003(2017)  
 K. Iida *et al.* Sci. Rep. 7, 3995 (2017)  
 Z. T. Xu *et al.* SuST 31, 055001 (2018)  
 Z. T. Xu *et al.* SuST 30, 035003 (2017)  
 W. Si *et al.* Nat. Commun. 4, 1347 (2017)  
 W. Si *et al.* APL 98, 262509 (2011)

**Task: to develop simpler and scalable techniques for making long coated conductors**

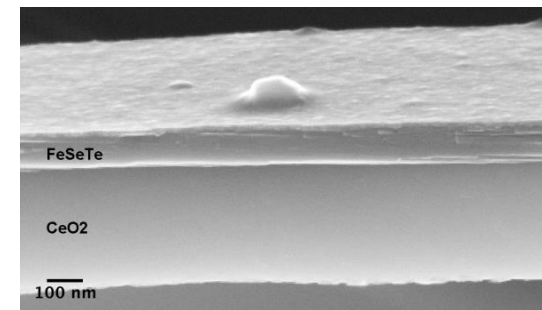
# IBS CC--towards simpler template: NiW5%+CeO<sub>2</sub>

Now trying to develop simpler and cheaper metallic templates for coated conductors reducing or eliminating the number of buffer layers.

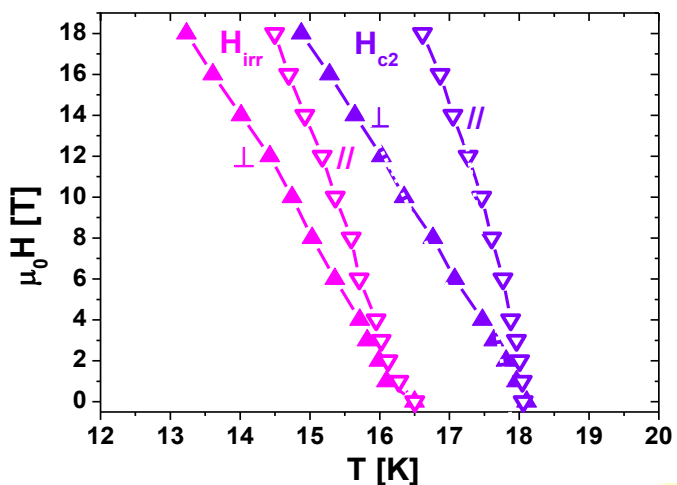
-- by C. Ferdeghini group



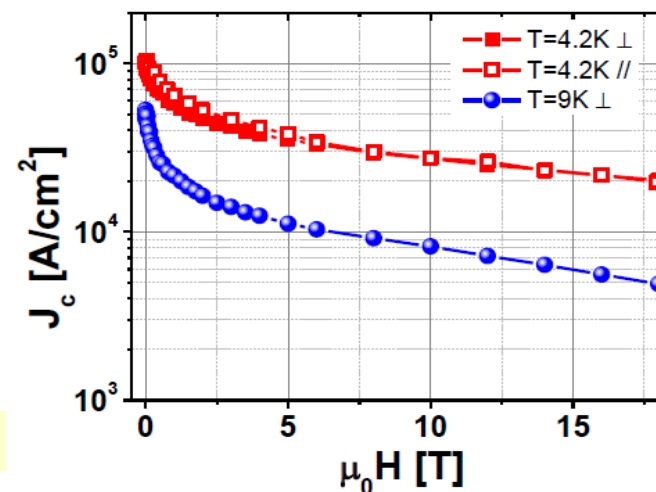
Fe(Se,Te) on  
NiW5%+CeO<sub>2</sub>



- ✓  $J_c = 10^5 \text{ A/cm}^2 @ 4.2\text{K self field}$
- ✓  $J_c = 3 \times 10^4 \text{ A/cm}^2 @ 4.2\text{K}, 10\text{T}$
- ✓  $J_c$  is isotropic



- ✓  $T_{c0} \approx 18\text{K}$
- ✓  $H_{c2}$  slopes are very sharp



G. Sylva et al., *SuST* 32 (2019) 084006

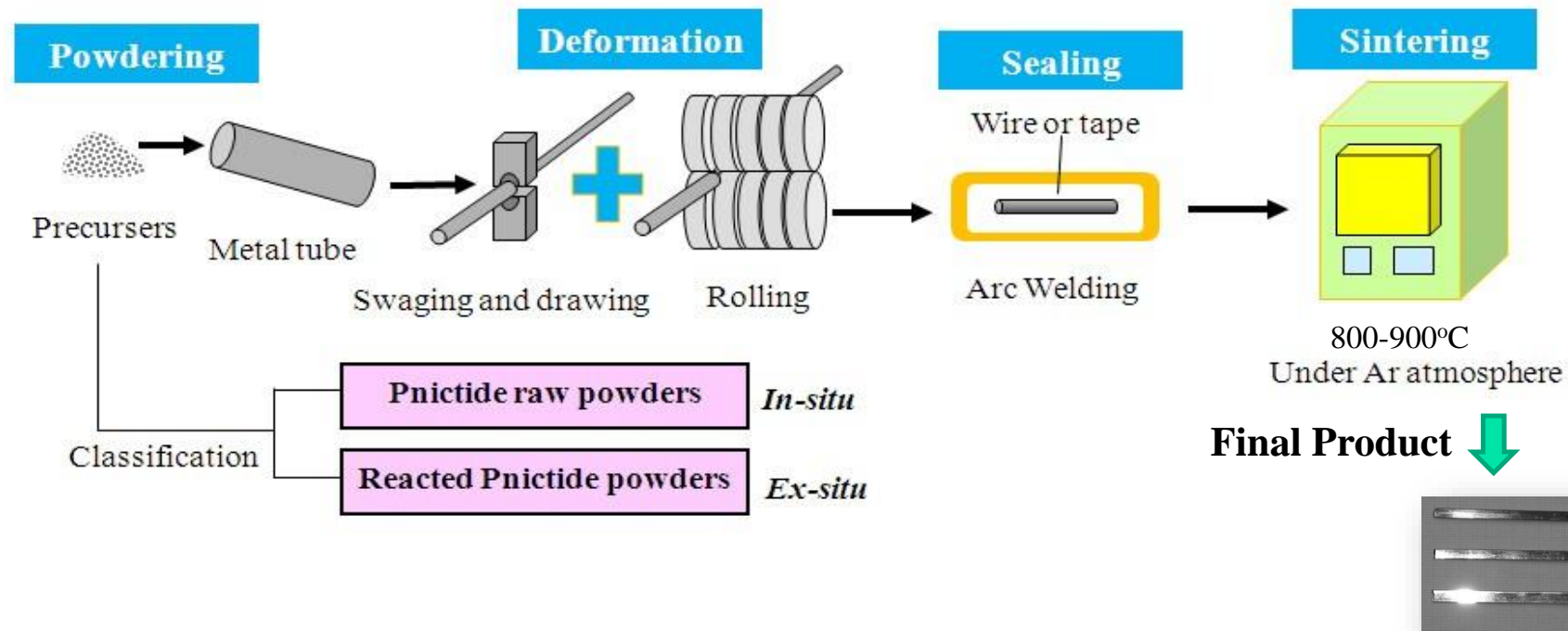
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# Fabrication process for IBS wires and tapes (*Powder-in-tube method*)

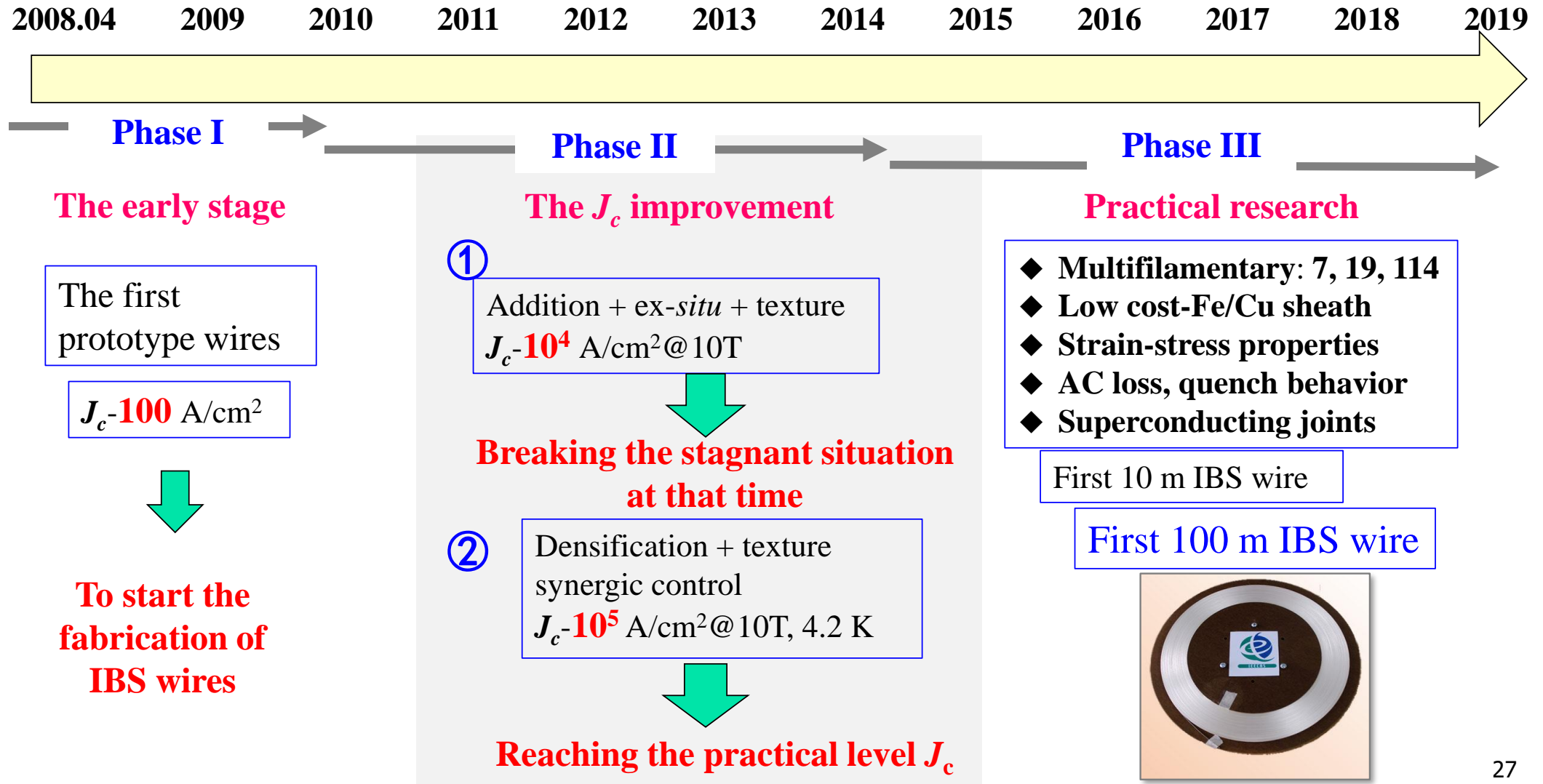
— Low cost, simple deformation process



➔ **122 PIT wires are expected to be much cheaper than BSCCO conductors:**

1. Many types of sheaths of Ag, Cu, Fe, and Ag-based composites (Ag/Fe, Ag/Cu, Ag/stainless steel) can be employed.
2. For BSCCO, Ag is the only material that is inert to the BSCCO superconductor and permeable to oxygen at the annealing temperature.

# Development of IBS wires and tapes

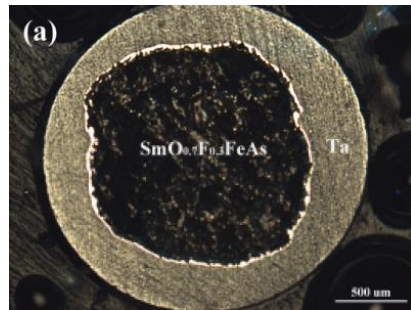
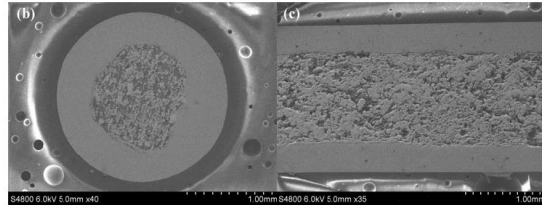
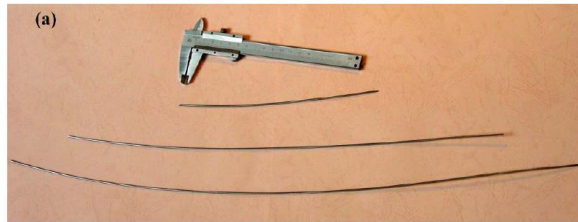


# In April 2008, the first pnictide wire was fabricated by the powder-in-tube method

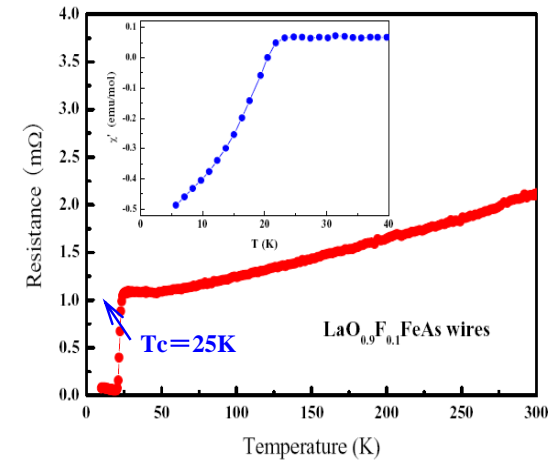
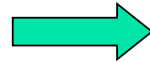
The early wires



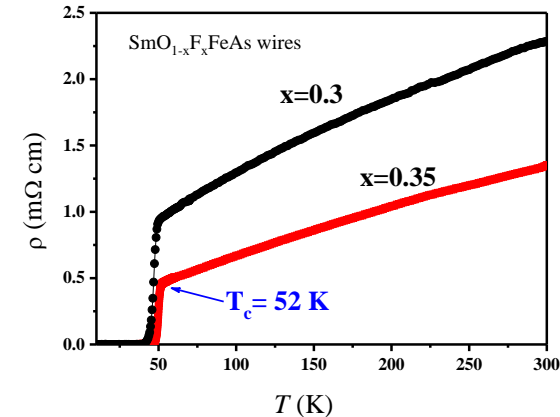
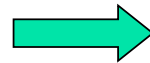
- ◆ Much low critical current density  $J_c$ !
- ◆ Due to thick reaction layer, many impurities, and cracks.



LaOFeAs

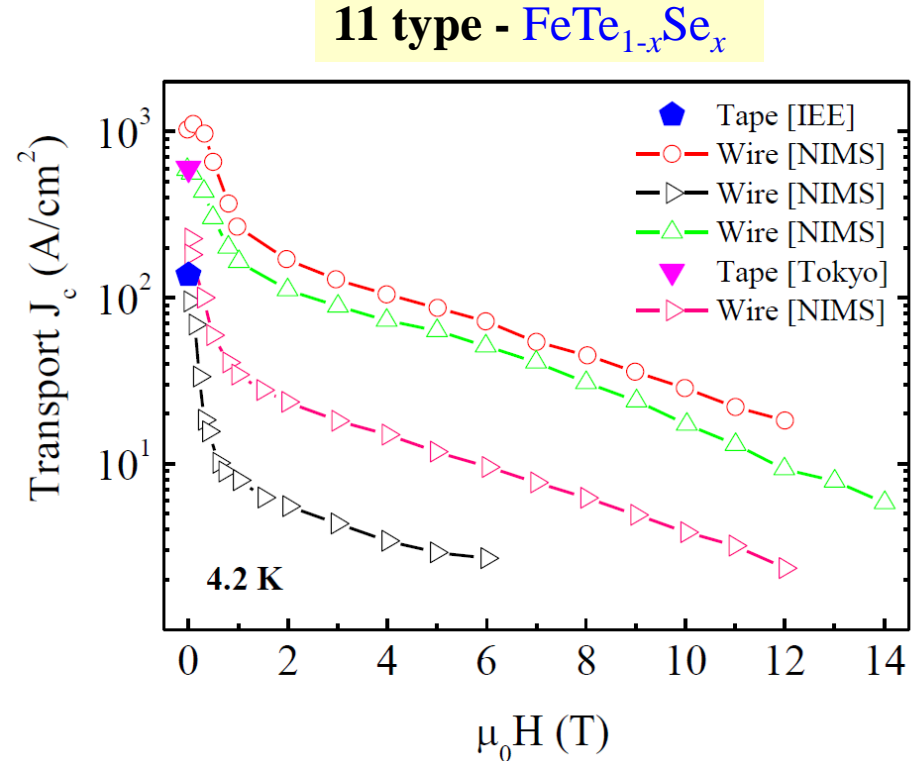
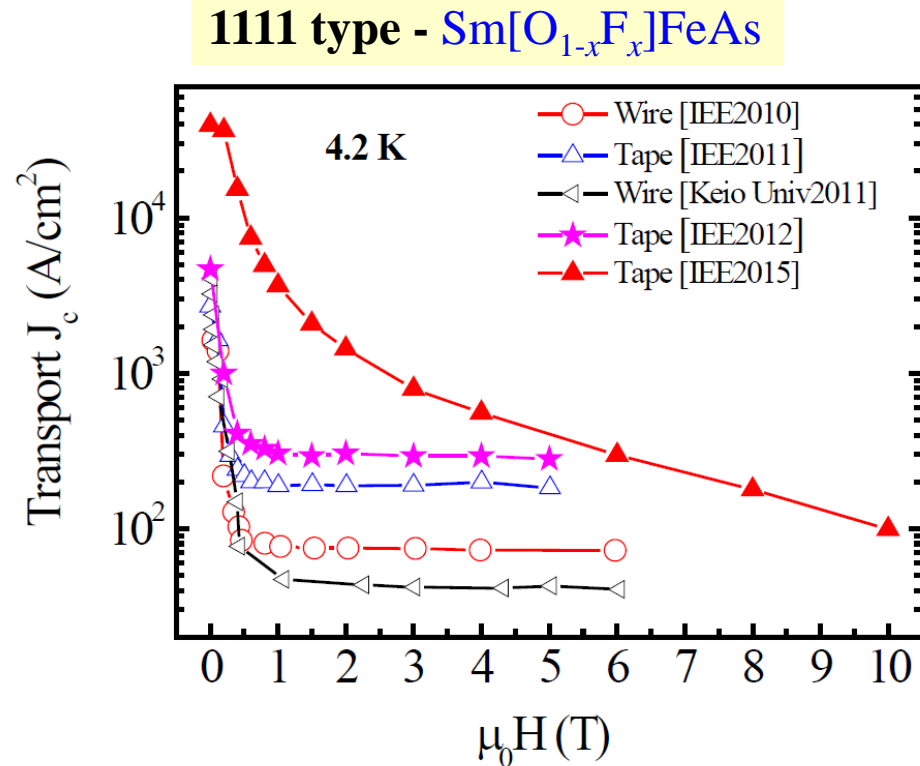


SmOFeAs



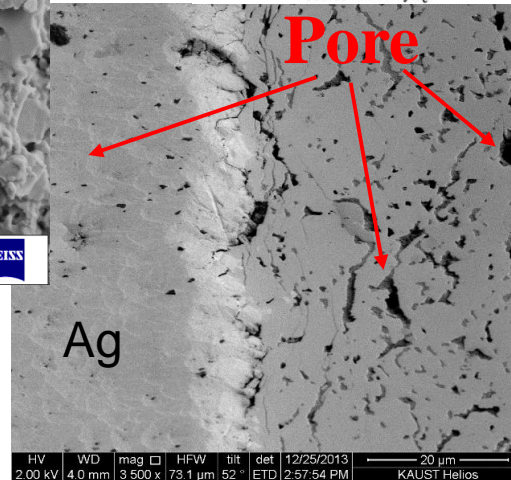
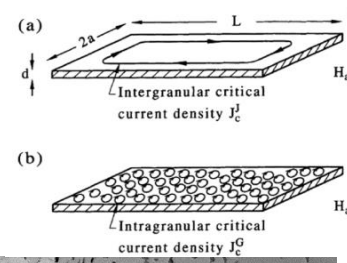
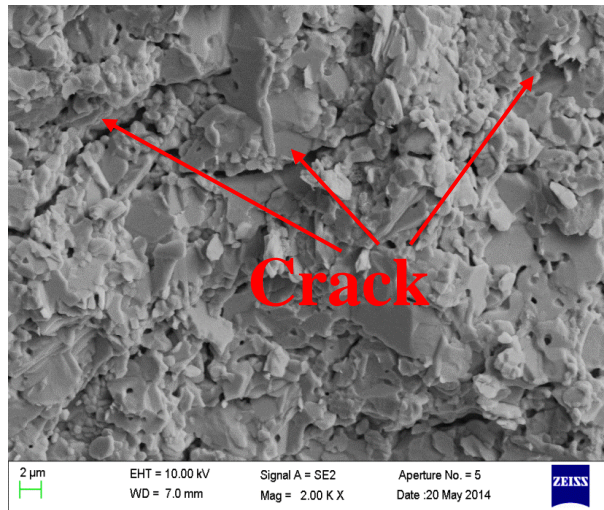
Compared to 122 tapes with  $J_c$  of  $10^5$  A/cm<sup>2</sup> @ 10 T

## 1111 and 11 wire and tapes: $J_c \sim 200$ A/cm<sup>2</sup> in high fields



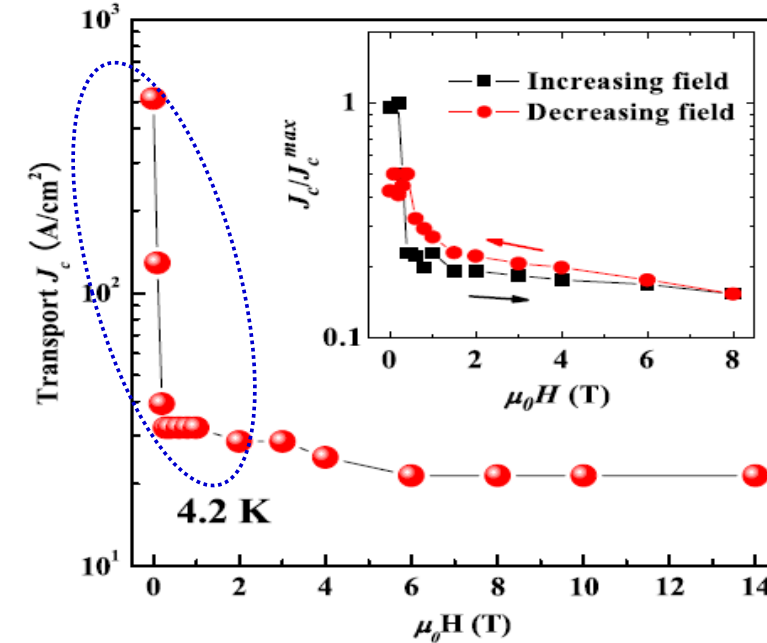
- ◆ The  $J_c$  values obtained are still two to three orders of magnitude lower than for the 122 tapes.
- ◆ **1111 wires:** how to control fluorine content during sintering.
- ◆ **11 wires:** hard to remove excess Fe.

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



Low density: cracks and porosity

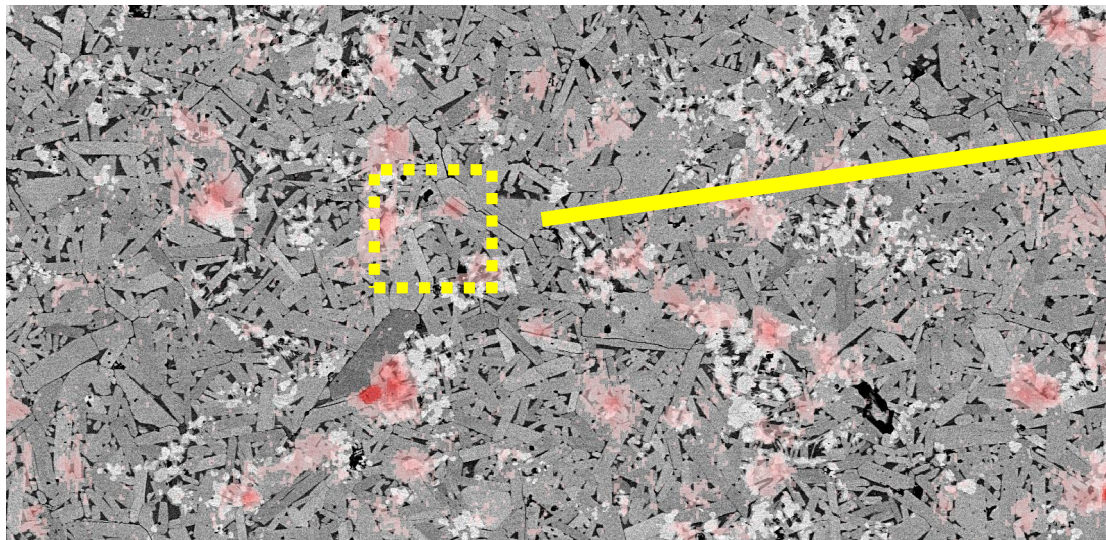
*Good connectivity is desirable!*



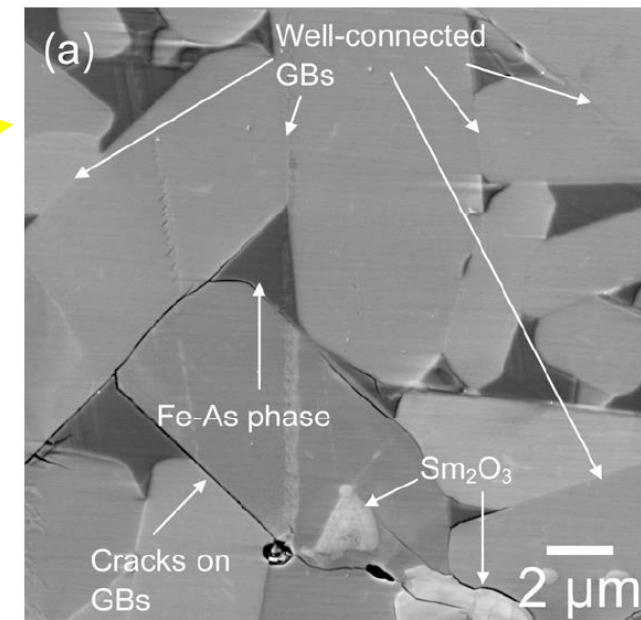
Hysteresis in transport  $J_c$ : signature of weak links

- ➡ **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  $J_c$



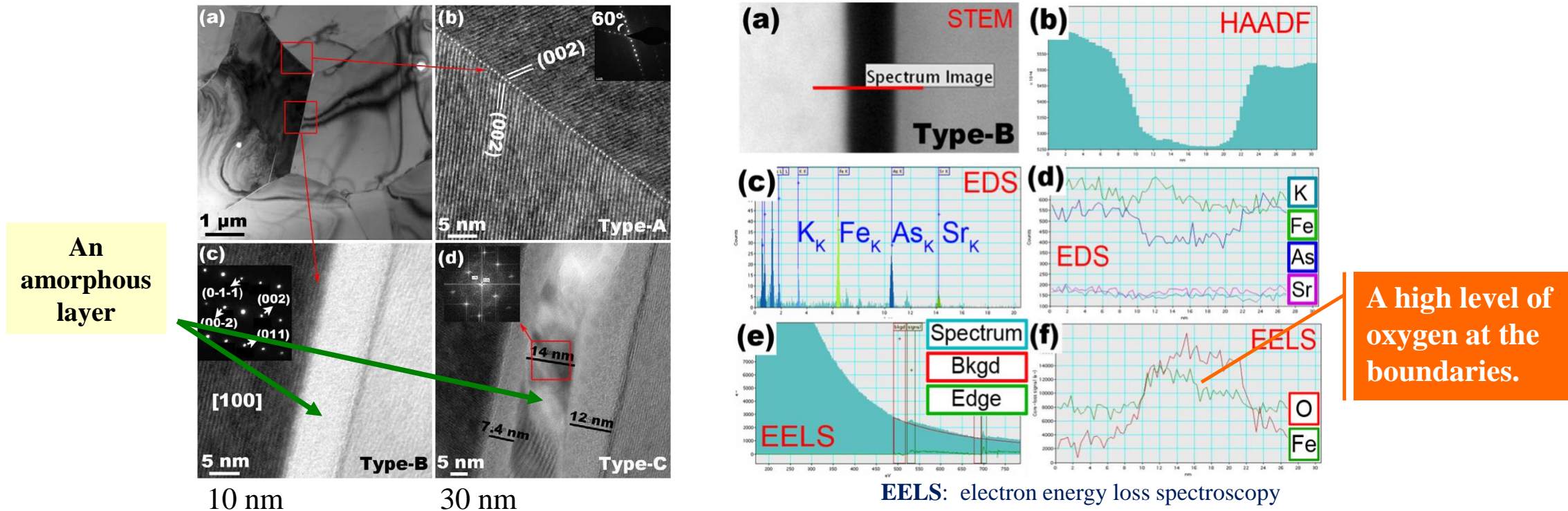
Low Temperature Laser Scanning Microscopy (LTLSM) + SEM



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

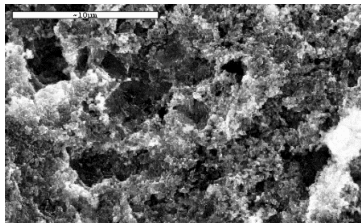
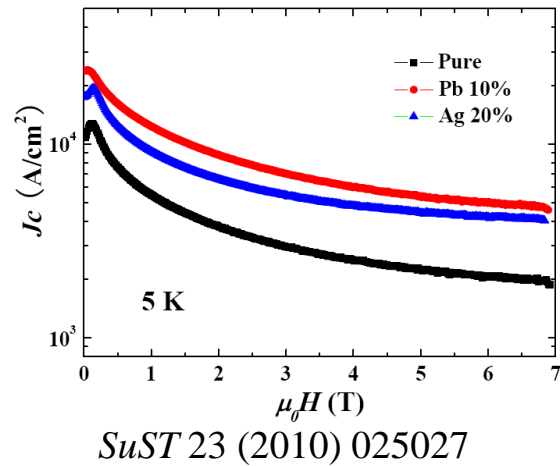


L. Wang, *et al.*, *APL* 98, 222504 (2011)

- ◆ Obviously, these **O-rich** amorphous layers are related to the introduction of O<sub>2</sub> 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

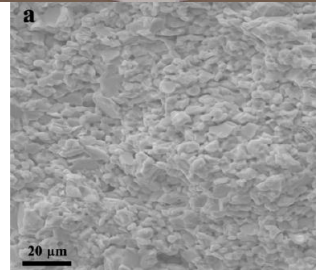
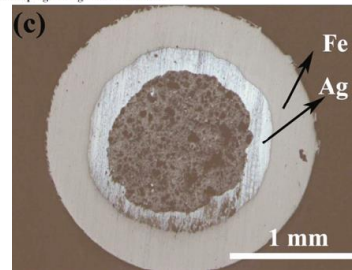
- ◆ *Ex-situ* PIT method: fewer impurity phases as well as a high density of the superconducting core for the final wires.
- ◆ Ag or Pb addition to improve the grain connectivity, hence the enhanced  $J_c$ .



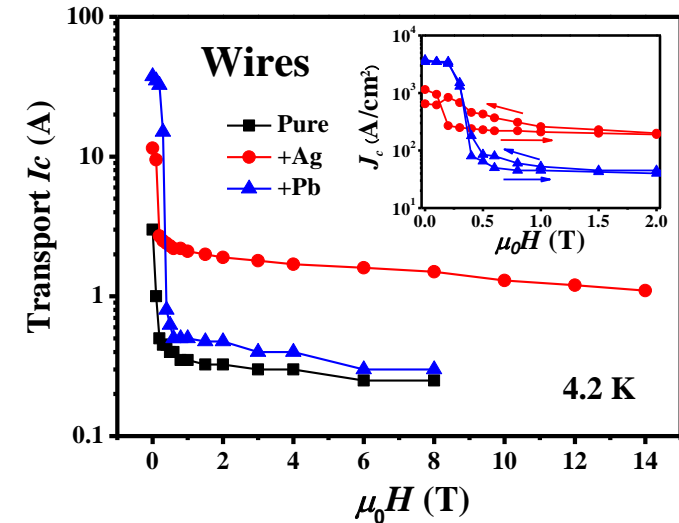
*In Situ*: loose, more second phases

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<sup>1</sup>



*Ex Situ*: Dense & more 122



At 0 T, 4.2 K,  $I_c$  reached 37.5 A, correspondingly,  $J_c = 3750$  A/cm<sup>2</sup>.

***Lessons*** learned during the preparation of high quality 122 precursor

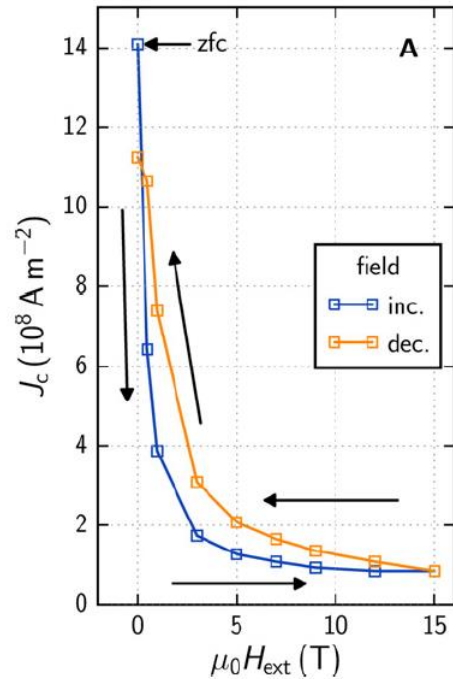
## **Less O<sub>2</sub> & rich K process**

---

- ✓ **Phase purity of the wire samples is an important factor.**
- ✓ **For the 122 compounds, K loss and the formation of oxygen-rich amorphous layers are the main causes for the inhomogeneities and impurities.**
- ✓ **Since the element K is highly volatile and has a strong affinity to oxygen during the fabrication.**

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

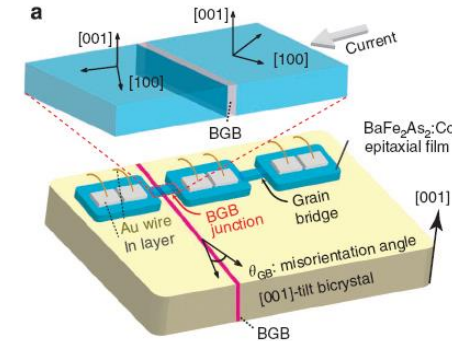
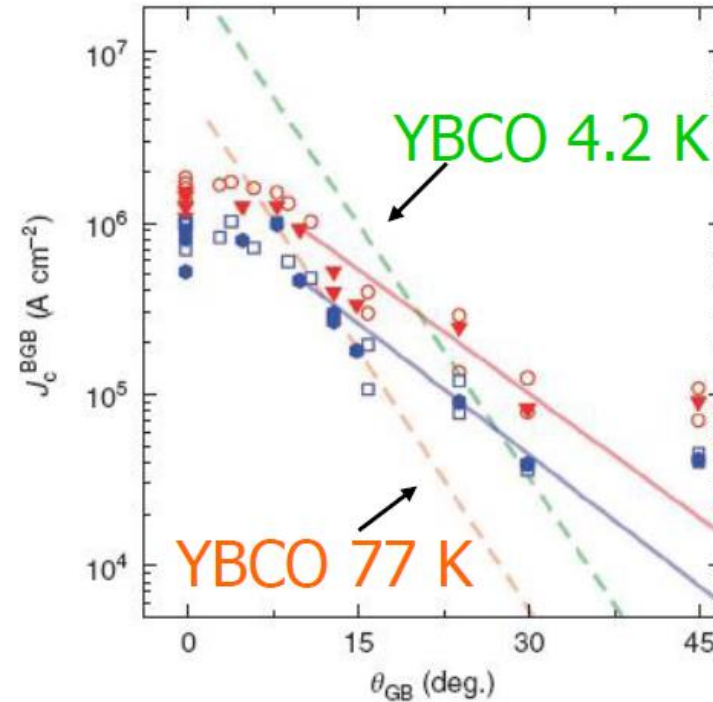
Hecher et al., *SuST* 29 (2016) 025004



**Weak link effect**

Co doped Ba-122 thin films on bicrystals

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



**Critical GB angle**

**YBCO : 3-5°**

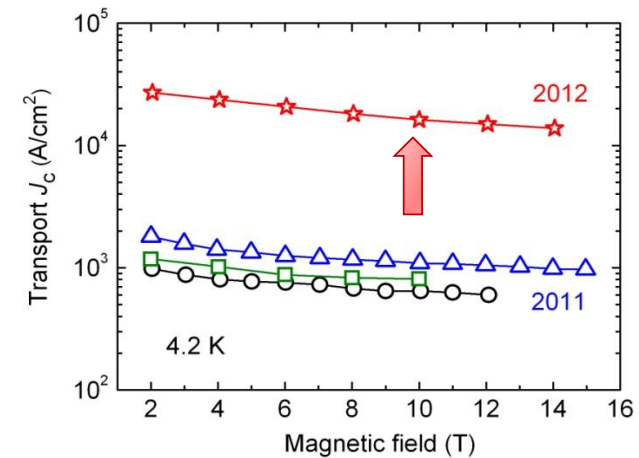
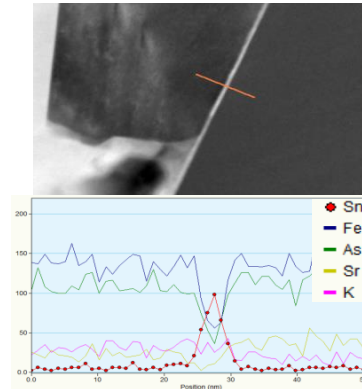
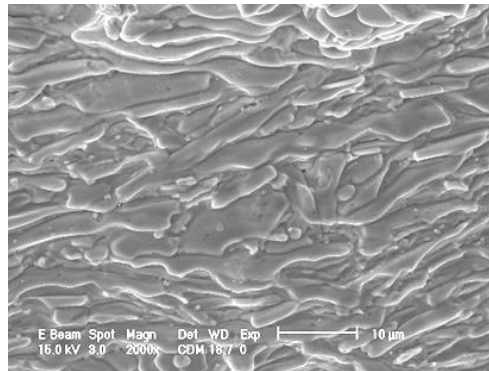
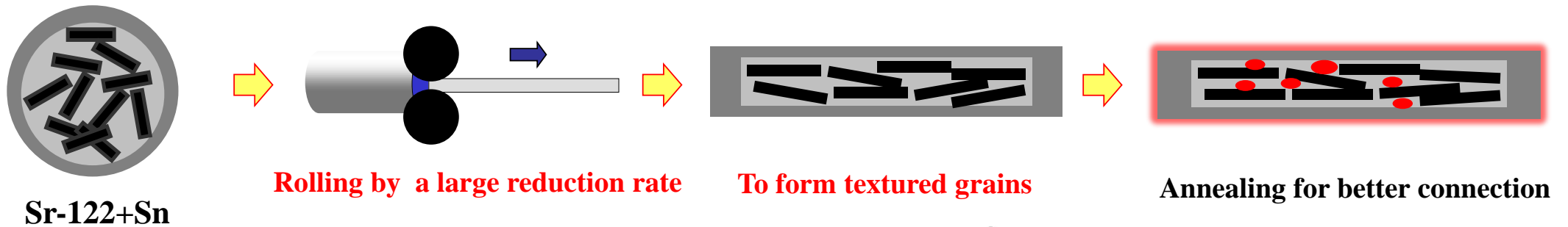
**Ba-122: 9°**

**Different fabrication techniques!**

- For 122 IBS, the GBs do not degrade the  $J_c$  as heavily as YBCO.
- **122 IBS advantageous GB over cuprates!** This is the reason why we can use the PIT method to make high- $J_c$  122-pnictide wires, but PIT can not work for YBCO.

# Texturing process of PIT Sr-122 tapes

- ◆ One effective method is to engineering textured grains to minimize degradation of  $J_c$  across high-angle grain boundaries, like the Bi2223.

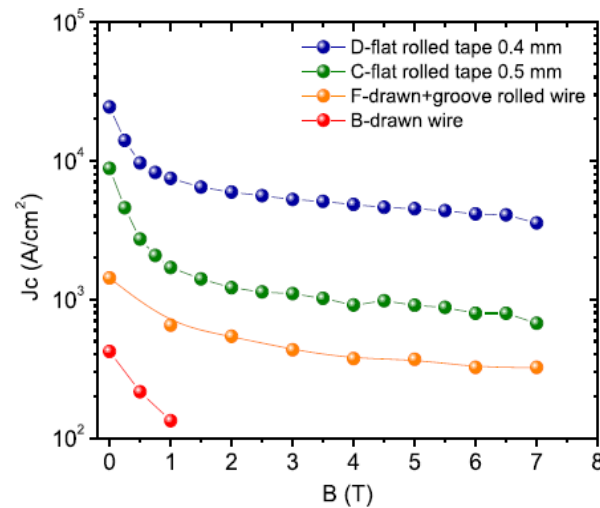
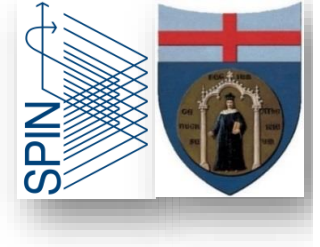
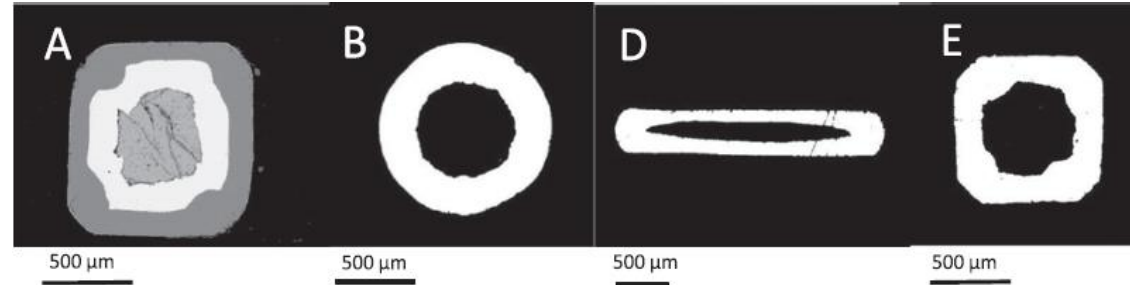


The above rolling strongly improved c-axis texturing, and effectively reduce the large angle GBs, thus  $J_c$  was enhanced by **an order of magnitude, from  $10^3$  to  $10^4$  A/cm<sup>2</sup>.**

# Optimization of mechanical-thermal treatments for PIT Ba-122 tapes



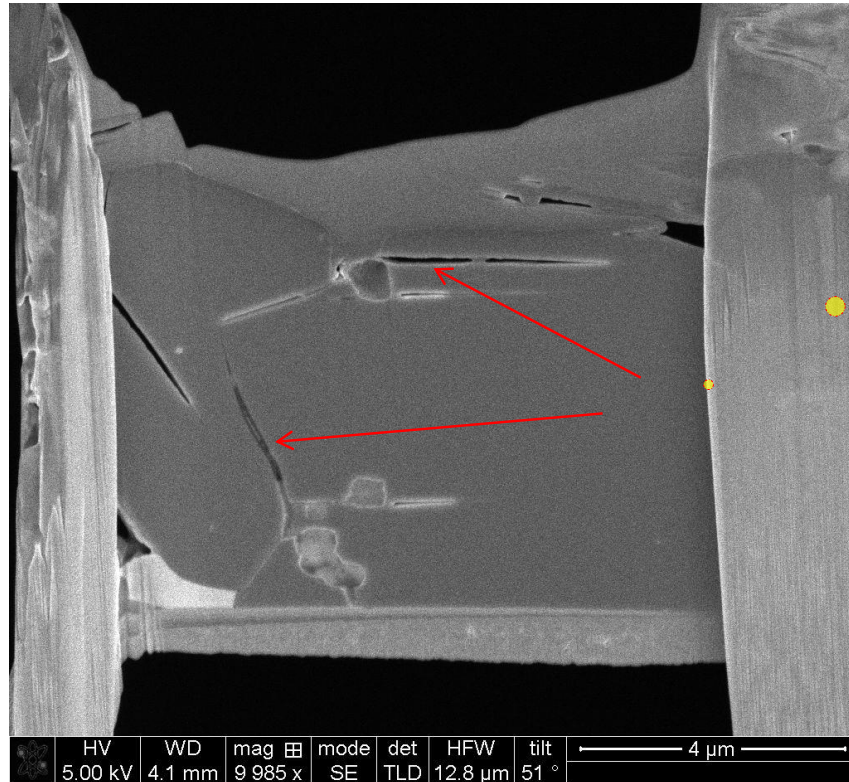
4-5 grams



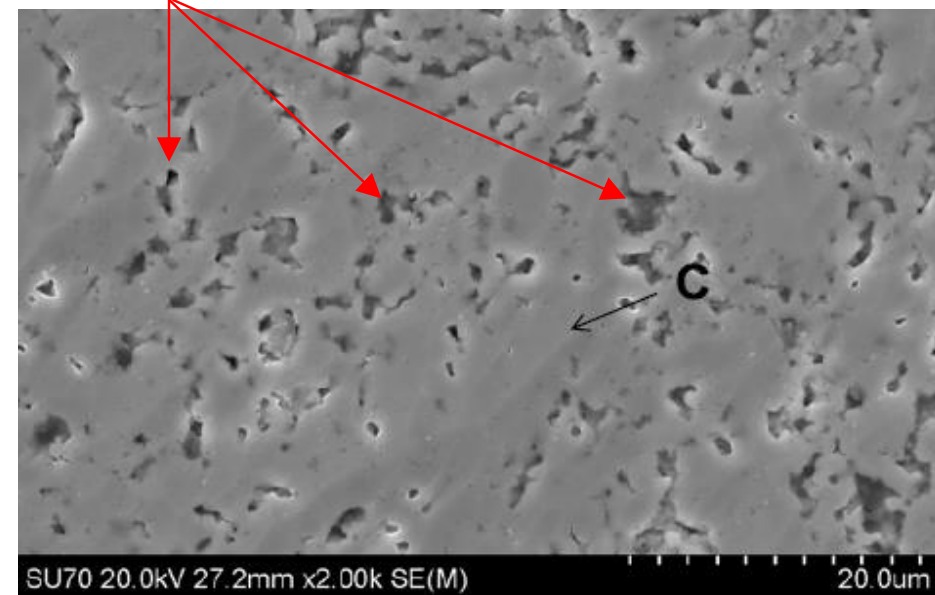
Sample (sheat)	Working	Size
A (Ni/Ag)	groove rolled wire	1 × 1 mm <sup>2</sup>
B (Ag)	drawn wire	∅ 0.9 mm
C (Ag)	drawn + flat rolled tape	0.5 mm
D (Ag)	drawn + flat rolled tape	0.4 mm
E (Ag)	groove rolled wire	0.9 × 0.9 mm <sup>2</sup>
F (Ag)	drawn + groove rolled wire	0.9 × 0.9 mm <sup>2</sup>
G (Ag)	groove rolled + flat rolled tape	0.4 mm

**Flat rolling process is more effective rather than groove rolling to achieve high  $J_c$ !**

## **Q3:** Densification is another dominant factor that determines the $J_c$ of PIT pnictide wire



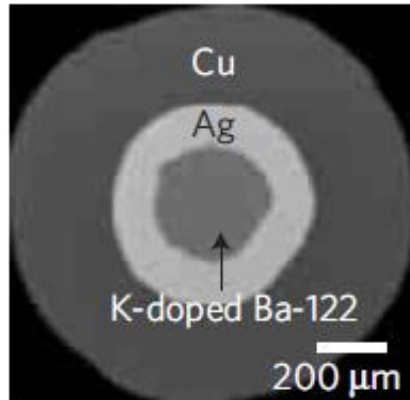
**Porosity**



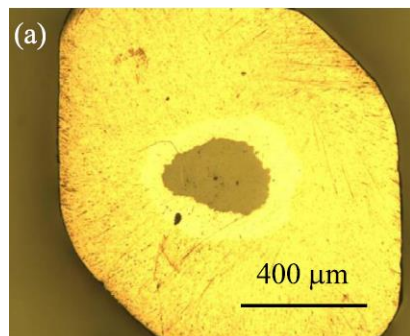
Cracks and voids are one of the important reasons for low critical current density values

## Application of High Pressures on IBS wires

# Hot isostatic pressing (HIP)--Ba-122 round wire



**HIP**  
(during reaction)



**First Ba-122 round wire** made in Florida State University

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

$$J_c (4.2 \text{ K}, 10 \text{ T}) = \sim 1 \times 10^4 \text{ A/cm}^2 \quad @0\text{T}, J_c > 10^5 \text{ A/cm}^2$$

192 MPa, 600 °C

- The core density nearly 100%
- Almost no grain orientation (texture)

**Later Ba-122 wire** made in the University of Tokyo

Pyon et al., *SuST* 31 (2018) 055016

$$J_c (4.2 \text{ K}, 10 \text{ T}) = 3.8 \times 10^4 \text{ A/cm}^2 \quad @0\text{T}, J_c > 1.7 \times 10^5 \text{ A/cm}^2$$

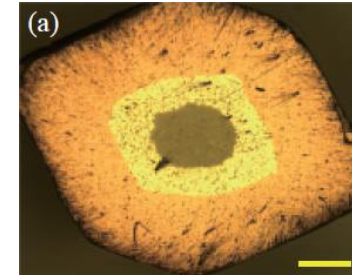
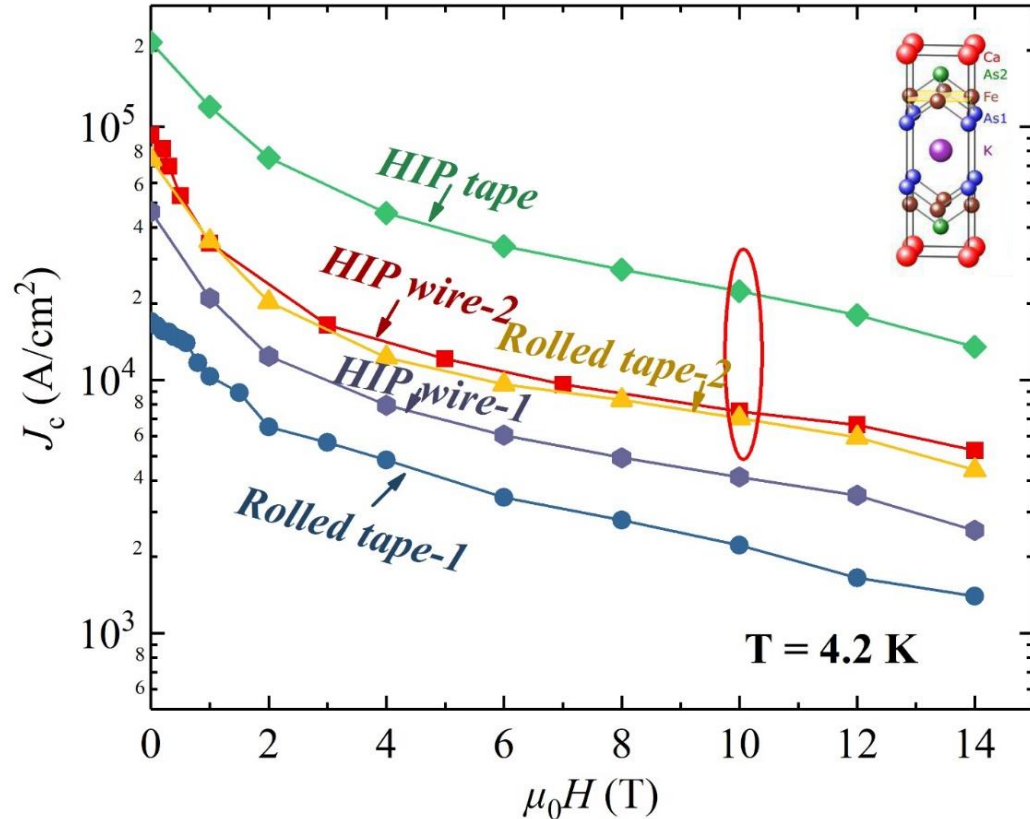
175 MPa, 700 °C

**Latest:** For BaNa-122 HIP wire,  $J_c (10\text{T}) = 4 \times 10^4 \text{ A/cm}^2$ . →

Courtesy of T. Tamegai

# Hot isostatic pressing (HIP)--CaKFe<sub>4</sub>As<sub>4</sub> (1144) wires & tapes

1144 single crystal showed promising high  $J_c$  values in high magnetic fields.



The highest  $J_c$  at 10 T

CaKFe <sub>4</sub> As <sub>4</sub>	$J_c$ (4.2 K, 10 T)
<b>HIP tape</b>	<b>22000 A/cm<sup>2</sup></b>
<b>HIP wire</b>	<b>7600 A/cm<sup>2</sup></b>

- ◆ Cheng *et al. SuST* (accepted)
- ◆ Pyon *et al. APEX* 11 123101 (2018)
- ◆ Cheng *et al. SuST* 32 015008 (2019)
- ◆ (unpublished)

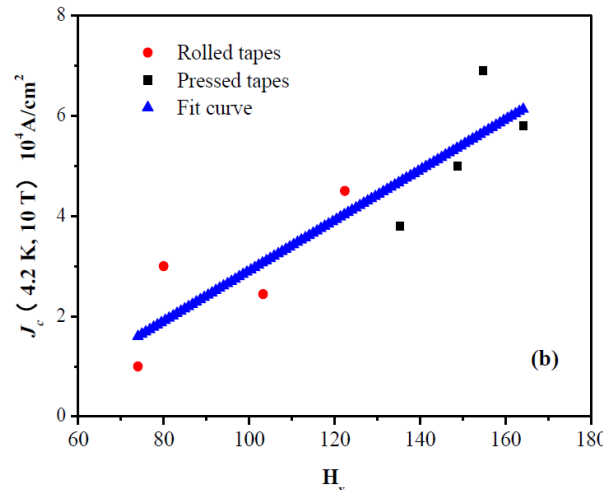
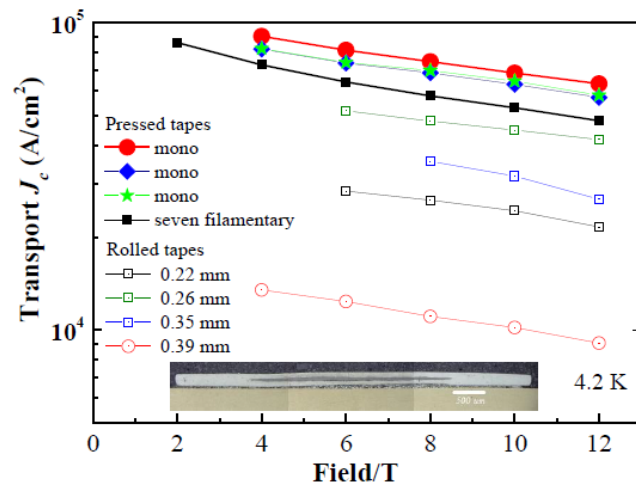
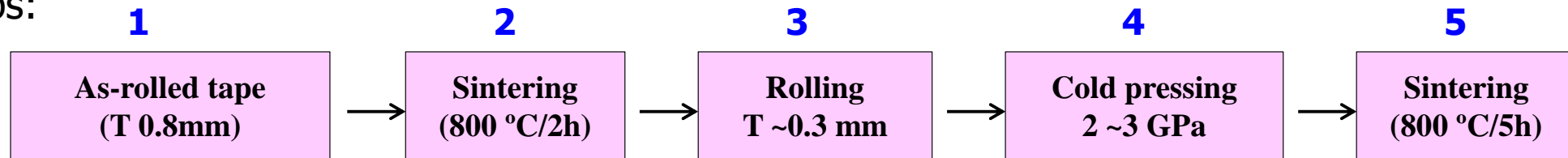
- ◆ For Ca1144, the transport  $J_c$  of wires and tapes is still low.
- ◆ When sintering temperature exceeds 500°C, Ca1144 phase is not stable with Ag sheath.

**Cold pressing (before reaction)**

**Ba-122 tapes by combined the rolling, cold pressing and sintering process-- Denser core yields higher  $J_c$**

--Ag-sheathed Ba122 tapes

Steps:



The higher the core density, the higher the  $J_c$



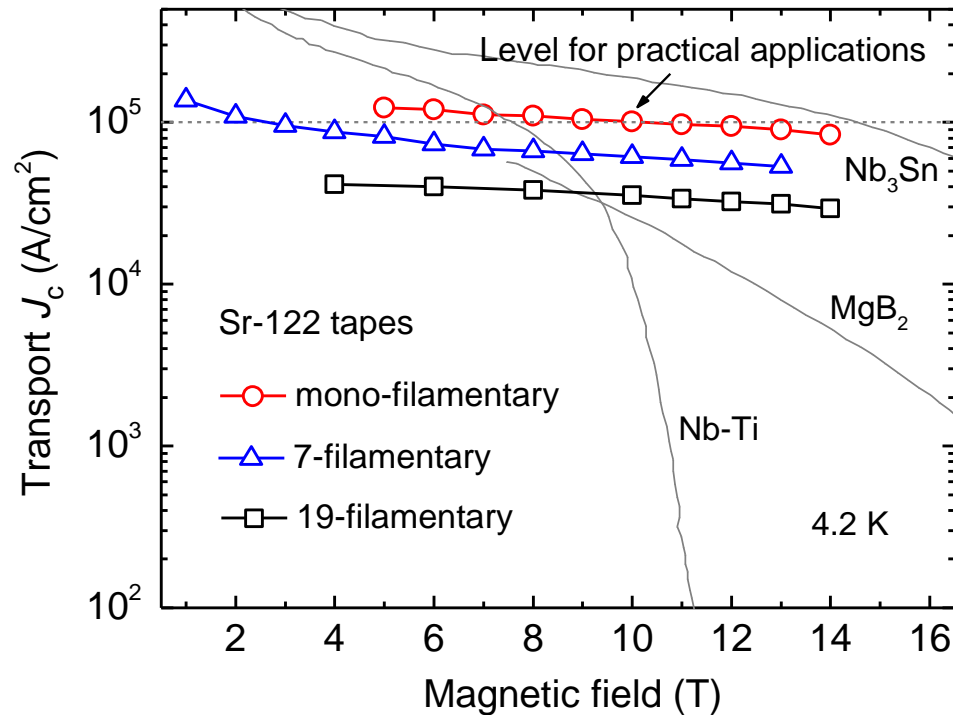
**4.2 K, 10T:**  
 $J_c = \sim 86000 \text{ A/cm}^2$

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

## Hot pressing (during reaction)

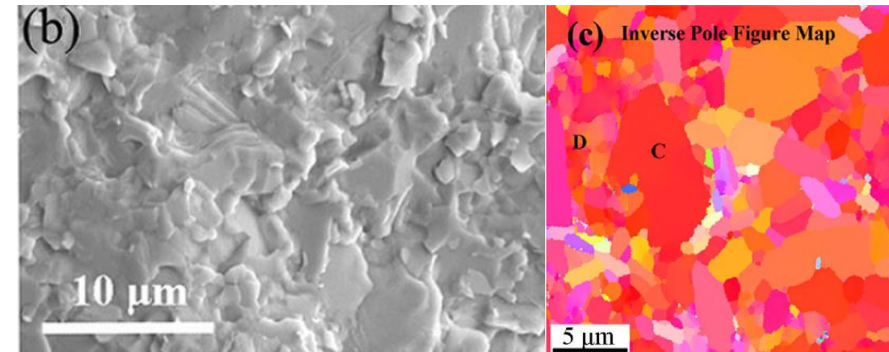
# Very high transport $J_c$ were achieved in Sr122/Ag tapes: $J_c > 10^5$ A/cm<sup>2</sup> (4.2 K, 10 T) - by hot pressing

First to reach practical level  $J_c$ !



30 MPa, 850~900 °C

The threshold for practical application:  
 $J_c = 10^5$  A/cm<sup>2</sup> @ 10 T

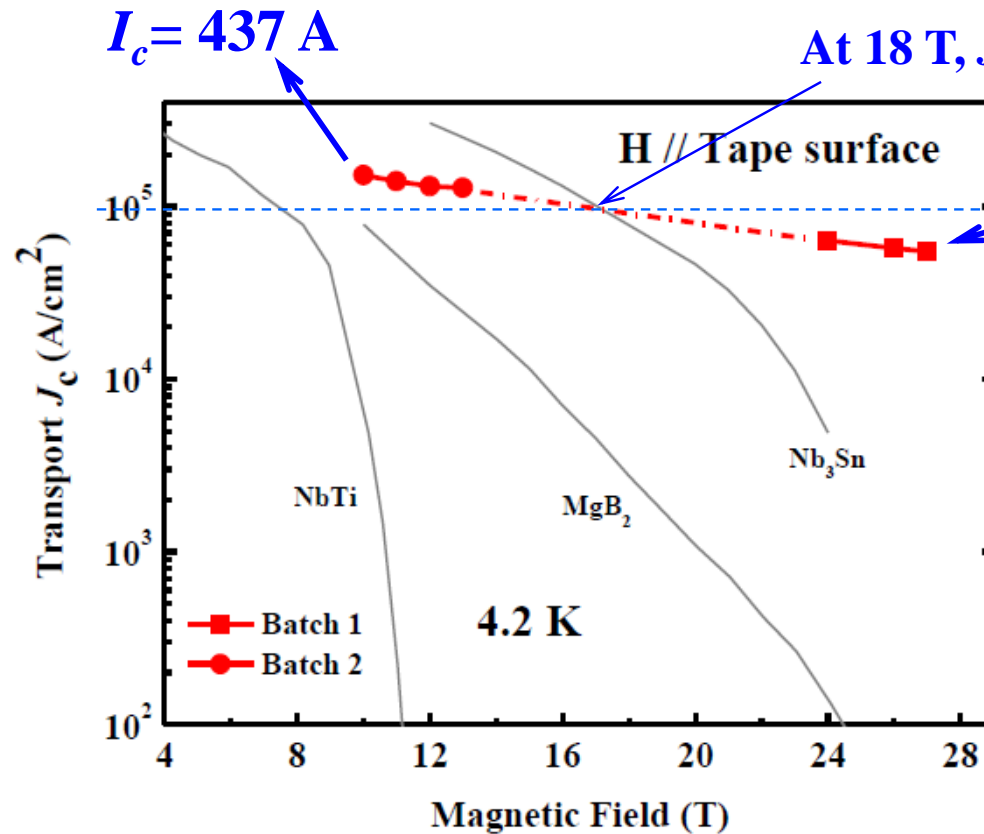


- almost no crack !
- high core density
- strong c-axis texture

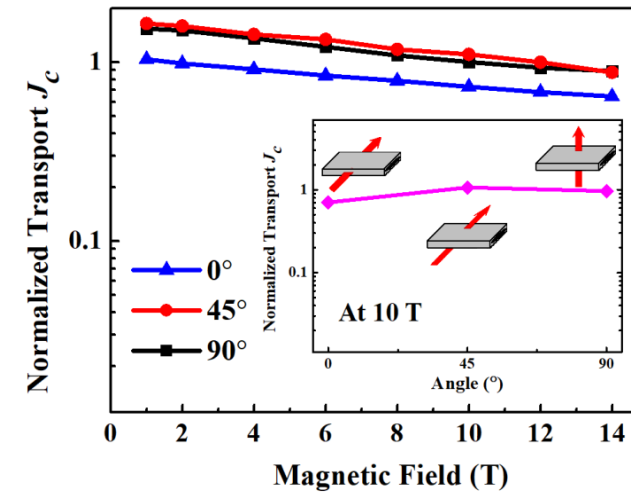
Recently

--Ba<sub>0.6</sub>K<sub>0.4</sub>Fe<sub>2</sub>As<sub>2</sub>/Ag tapes

**New record transport  $J_c$  up to  $1.5 \times 10^5$  A/cm<sup>2</sup> @ 4.2 K, 10 T  
was obtained by Hot Pressing**



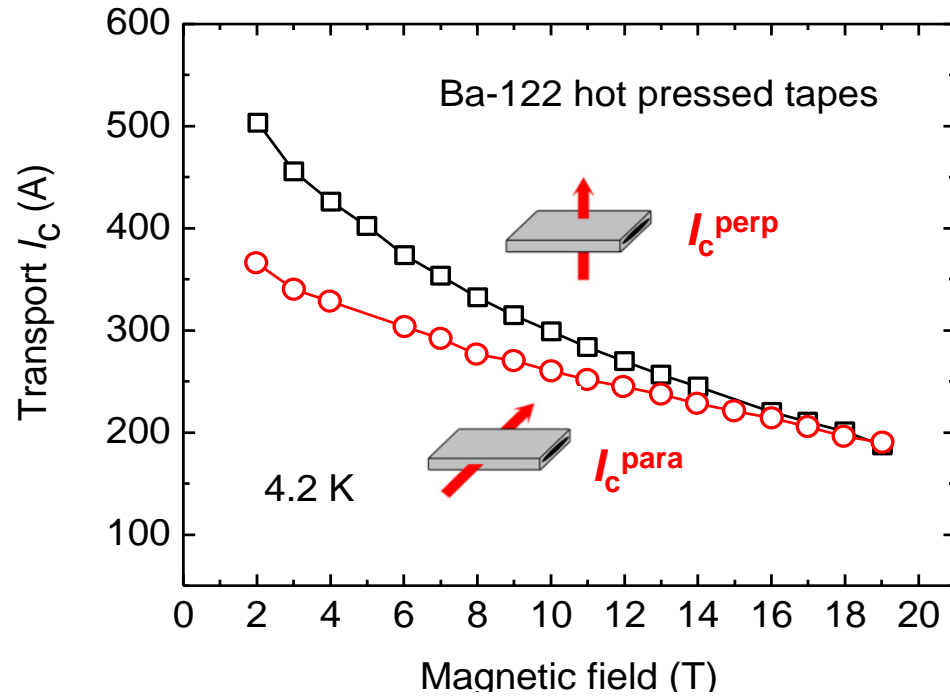
At 27 T,  
 $J_c = 5.5 \times 10^4$  A/cm<sup>2</sup>



Huang et al., *SuST* 31 (2018) 015017

$\gamma = 1.37$  at 10 T

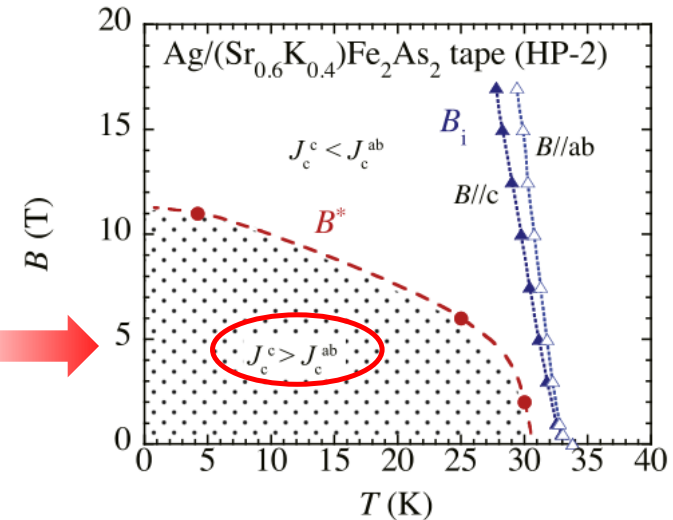
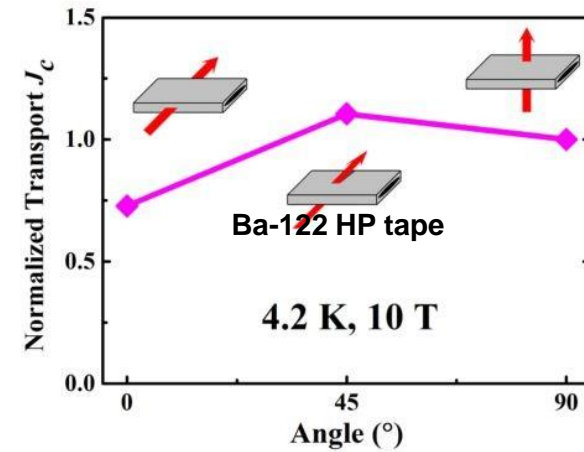
# Anomalous anisotropy of $J_c$ for HP Ba-122 tapes



Courtesy: M. Bonura & C. Senatore (Univ. Genève)

- At 4.2 K and low-field regions,  $J_c$  (perp) >  $J_c$  (para).
- Anomalous  $J_c$  anisotropy, different from that in cuprates.

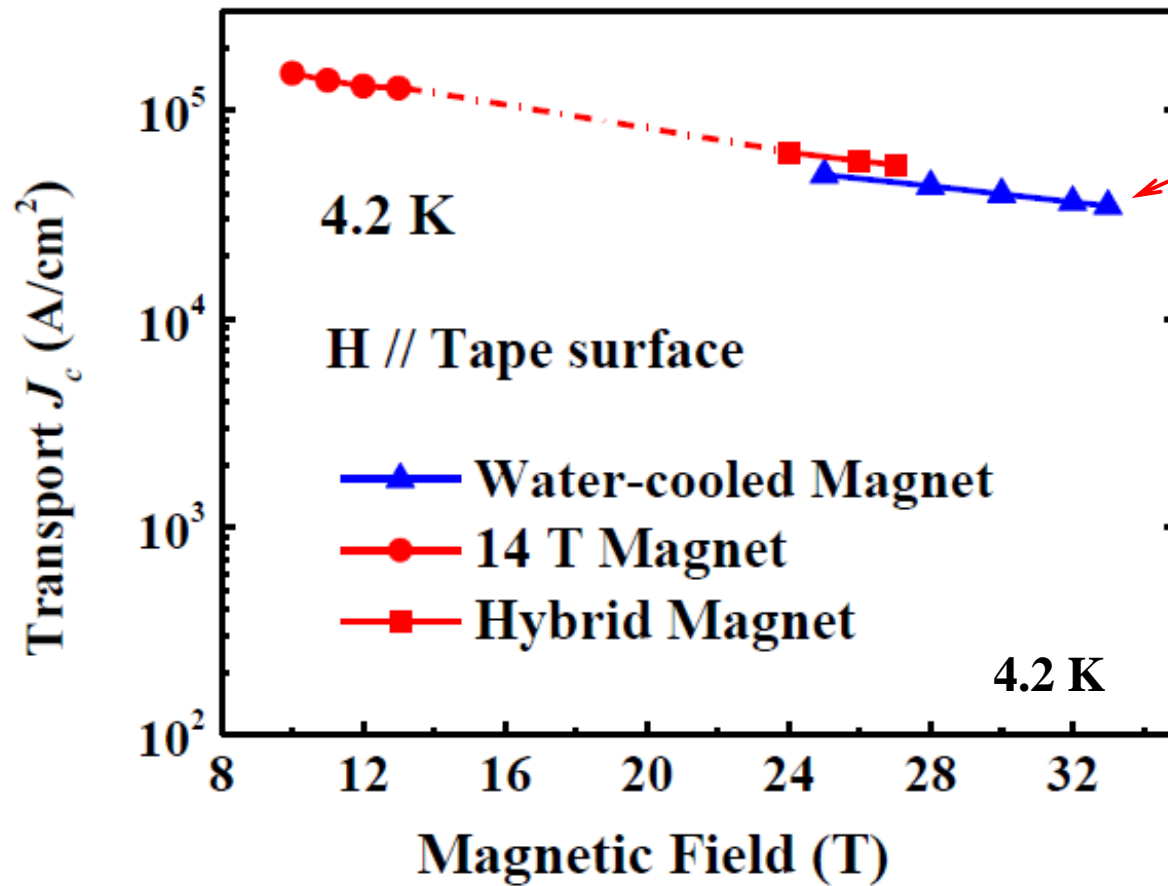
Consistent with literature data



# The state-of-art high $J_c$ Ba-122 tape:

## $I_c$ measured in high fields up to 33 T

--by High Magnetic Field Laboratory at *Heifei*



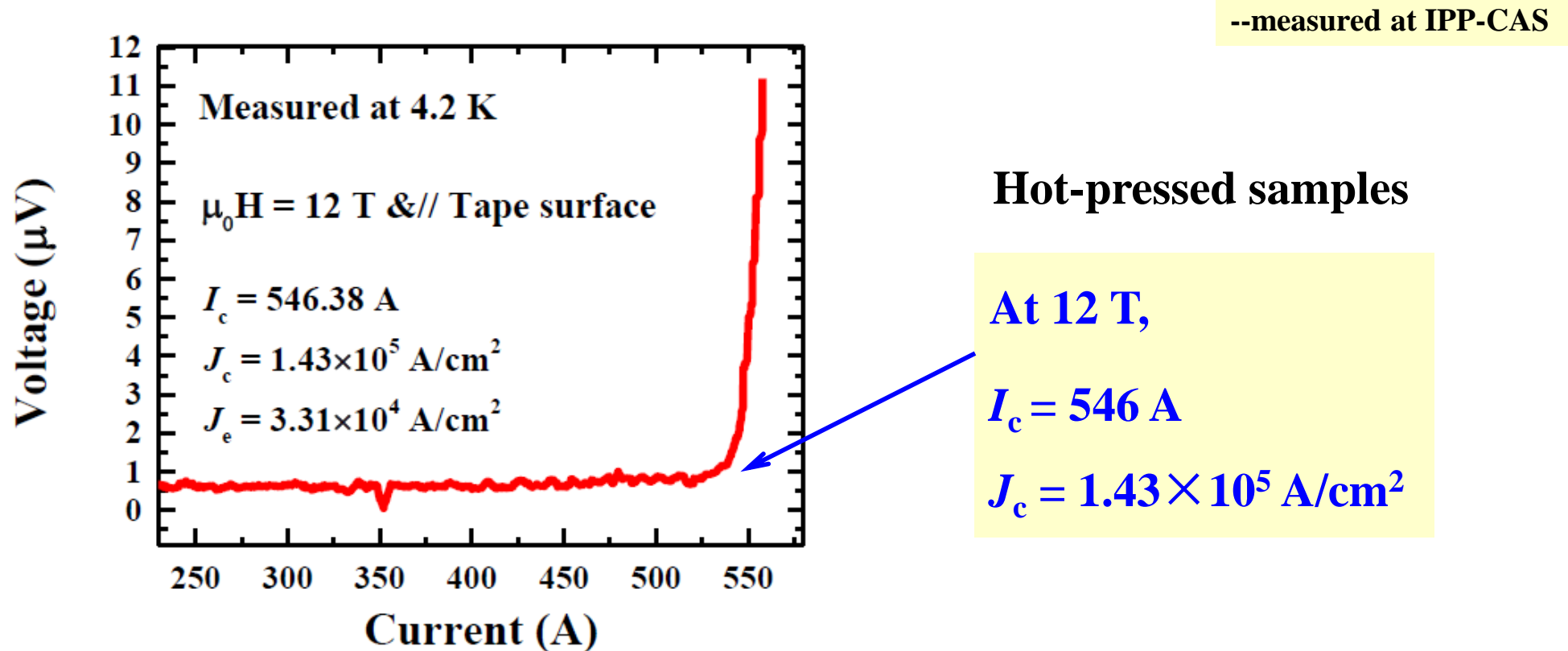
@ 33 T,  $J_c = 3.5 \times 10^4$  A/cm<sup>2</sup>



35 T water-cooled magnet  
(Heifei, China)

Latest result

## Ba-122 tapes showed even higher $J_c$ - $B$ value

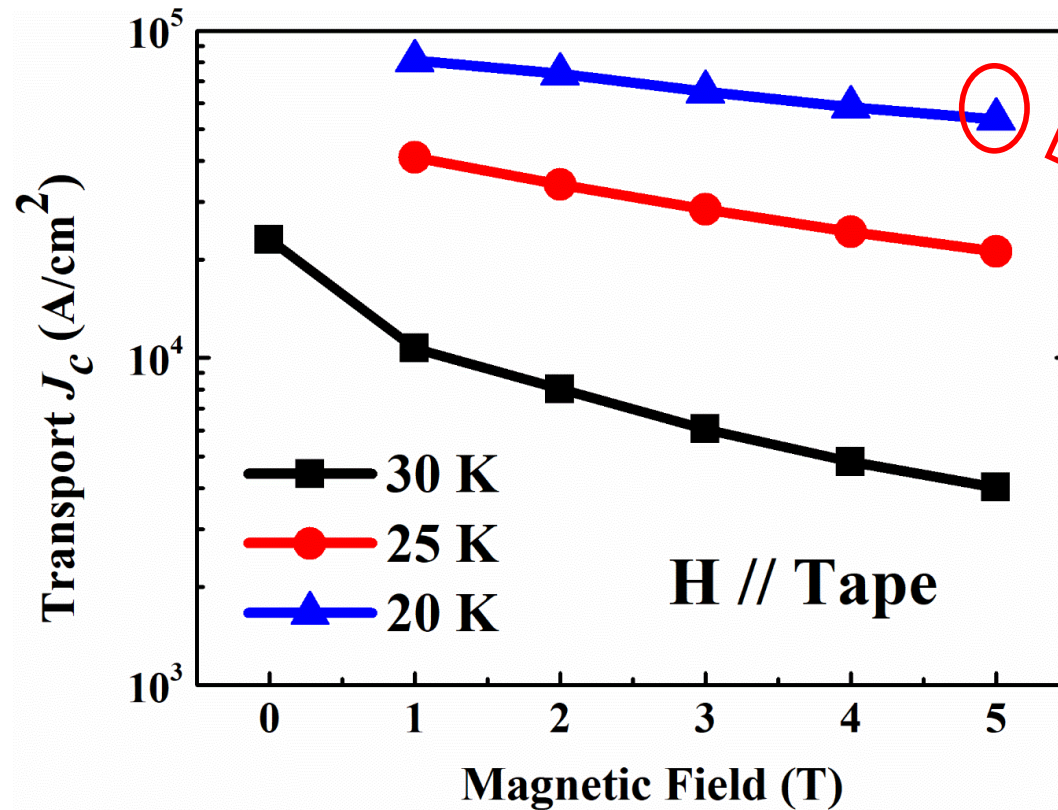


- ◆ For hot-pressed tapes, at 12 T, 4.2 K,  $I_c = 546.38$  A,  $J_c = 1.43 \times 10^5$  A/cm<sup>2</sup>, correspondingly,  $J_c \sim 1.6 \times 10^5$  A/cm<sup>2</sup> in the field of 10 T.

# Transport $J_c$ at medium temperatures

-- HPed  $\text{Ba}_{0.6}\text{K}_{0.4}\text{Fe}_2\text{As}_2/\text{Ag}$  tapes

Measured at Northeastern University in China



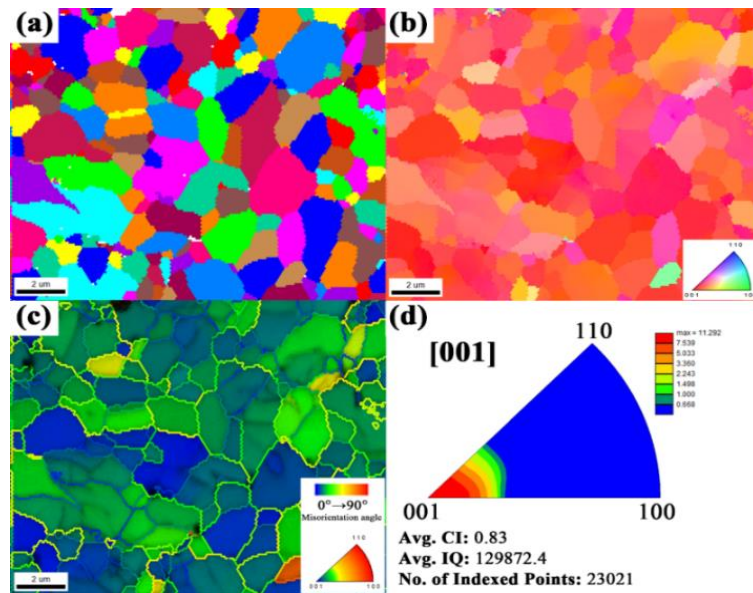
$5.4 \times 10^4 \text{ A}/\text{cm}^2$   
@ 5 T & 20 K

Huang et al., *SuST* 31 (2018) 015017

Strong potential for applications working at medium temperature region by cryogenic cooling systems.

# High core density and High degree of texture are the key to achieving excellent $J_c$

Fine grains,  $\sim 3 \mu\text{m}$



Highly textured microstructure!

(well-connected grains, no porosity )

--State-of-the-art HP tapes

The core of HP Ba122 tape

Hot press

Vickers hardness:  $\sim 132$

Rolled:  $\sim 90$

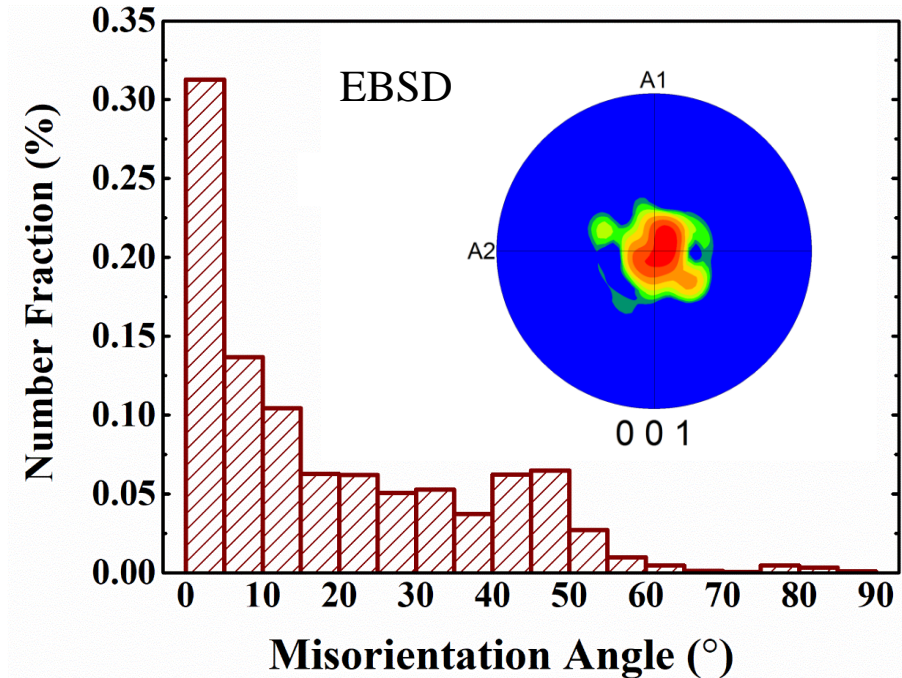
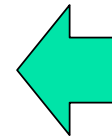
High core density

Good connectivity !

# EBSD: Misorientation angle distribution

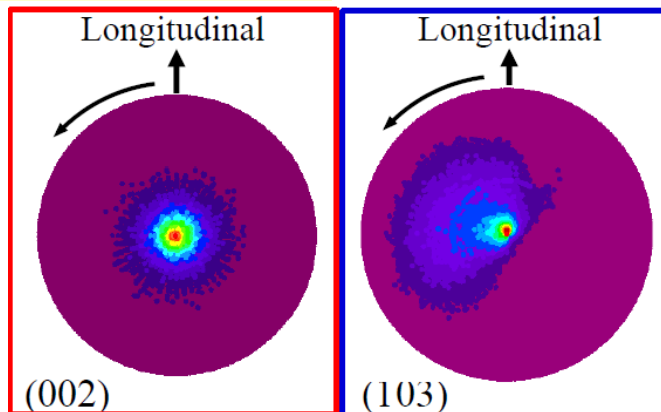
## HP Ba-122 tapes

- ✓ Well-connected microstructure
- ✓ The *c*-axis texture is much improved,
- ✓ The fraction of misorientation angle  $<9^\circ$  is up to 42.8%.
- ✓ Nearly no in-plane texture

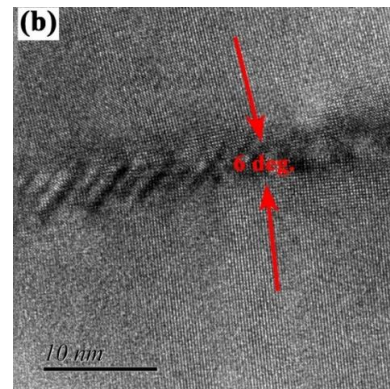


Courtesy of S. Awaji

## Pole figure



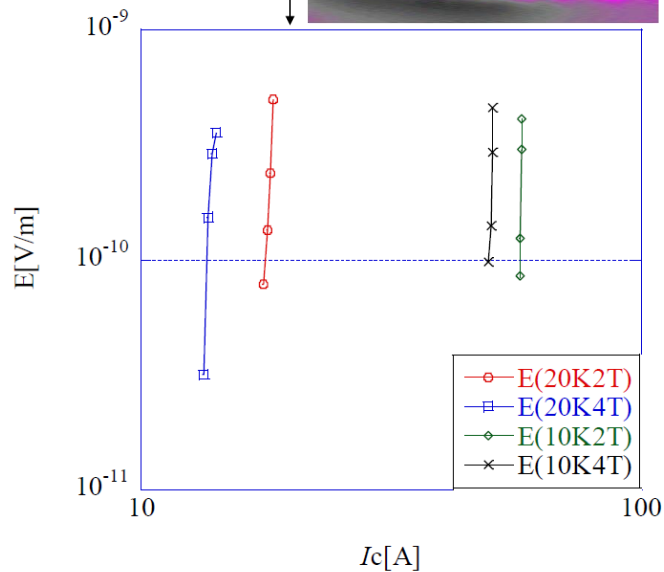
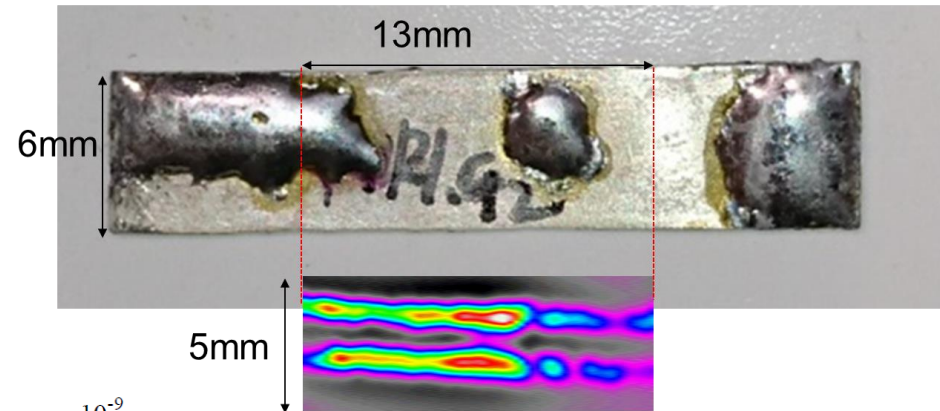
## TEM



**A large amount of grain boundaries below  $10^\circ$  are also detected, indicating that the weak-link problem is effectively suppressed in HP tapes.**

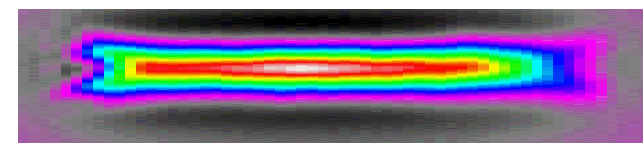
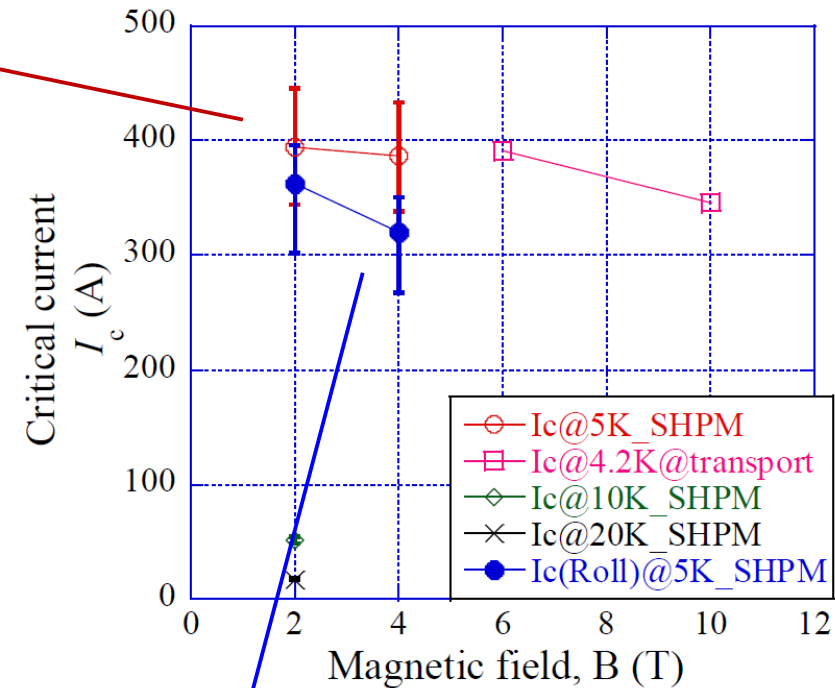
# Scanning Hall Probe Microscopy: Calculated $I_c$ and $n$ value (HP Ba-122)

Hot pressed Ba-122 tape



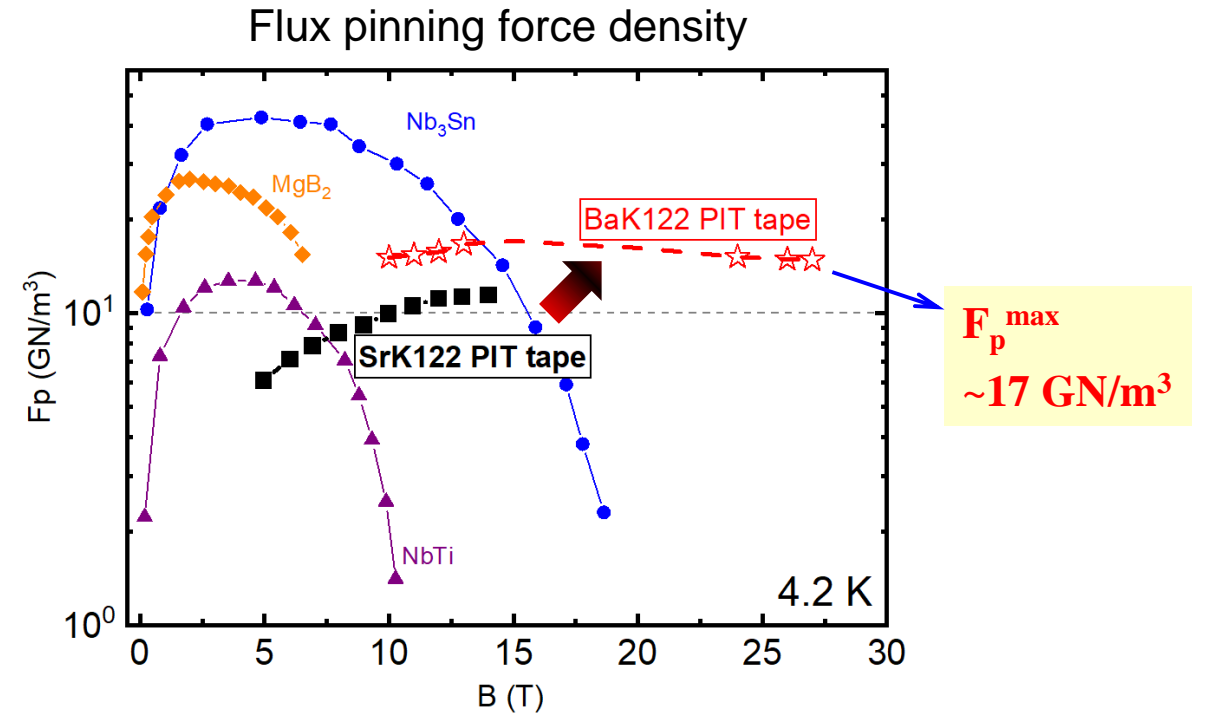
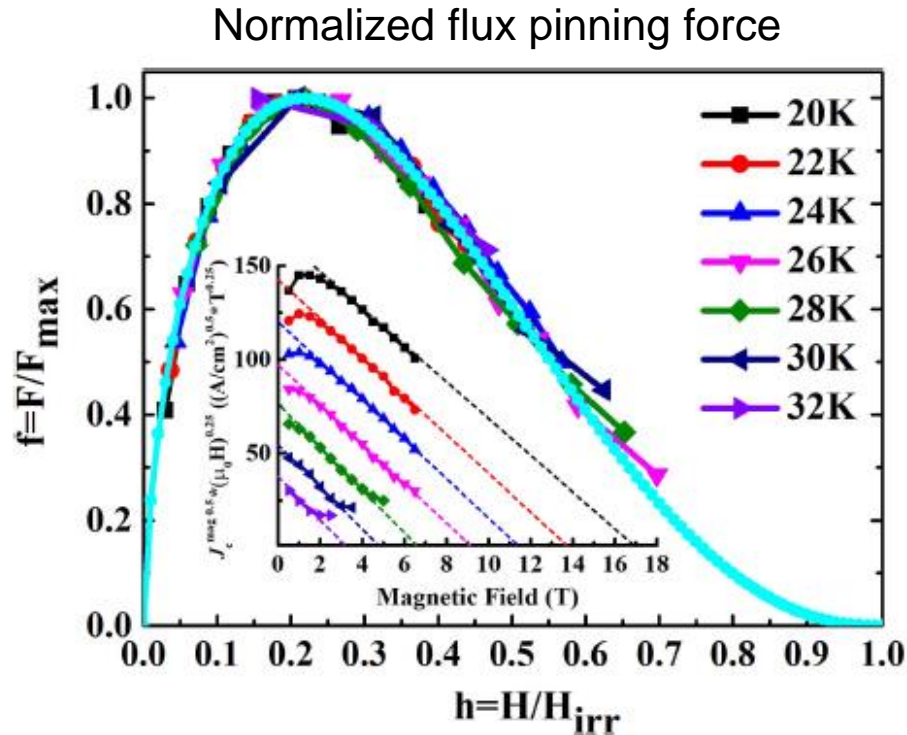
Temperature & Field	$n$ value
10 K & 2 T	143.4
10 K & 4 T	77.9
20 K & 2 T	43.9
20 K & 4 T	39.4

-- Measured by Kiss group  
 Kyushu Univ.



Rolled tape

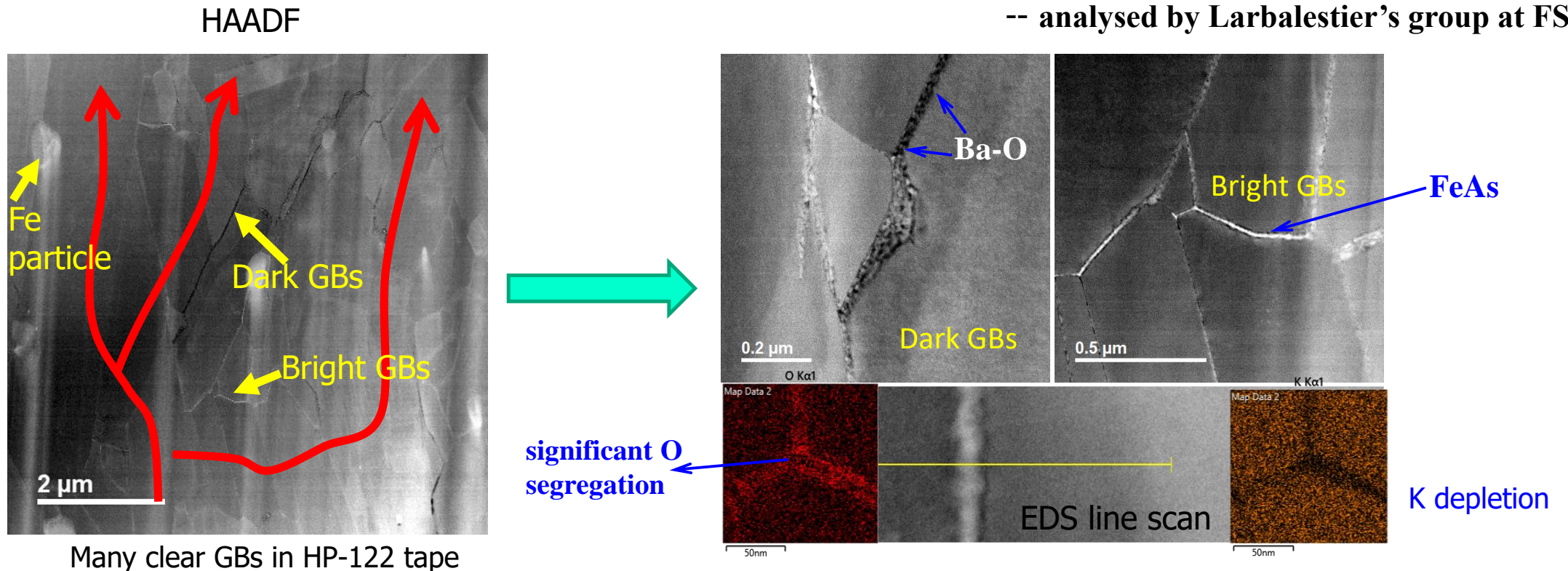
# Flux pinning mechanism in HP Ba-122 tapes



- Normalized flux pinning force  $f$  vs. normalized magnetic field  $h$  curves are well fitted by the formula:  $f = h^p(1-h)^q$ ,  $h_{max} \sim 0.22$ , indicate the surface pinning.
- Two sources: i) dislocations, ii) grain boundaries.
- There are still much room for  $J_c$  improvement, *e.g.*, decreasing grain size seems to be a good way to increase  $F_p$ .

# Bright field STEM for state-of- the art HP 122 tapes: Second phases at GB

-- analysed by Larbalestier's group at FSU

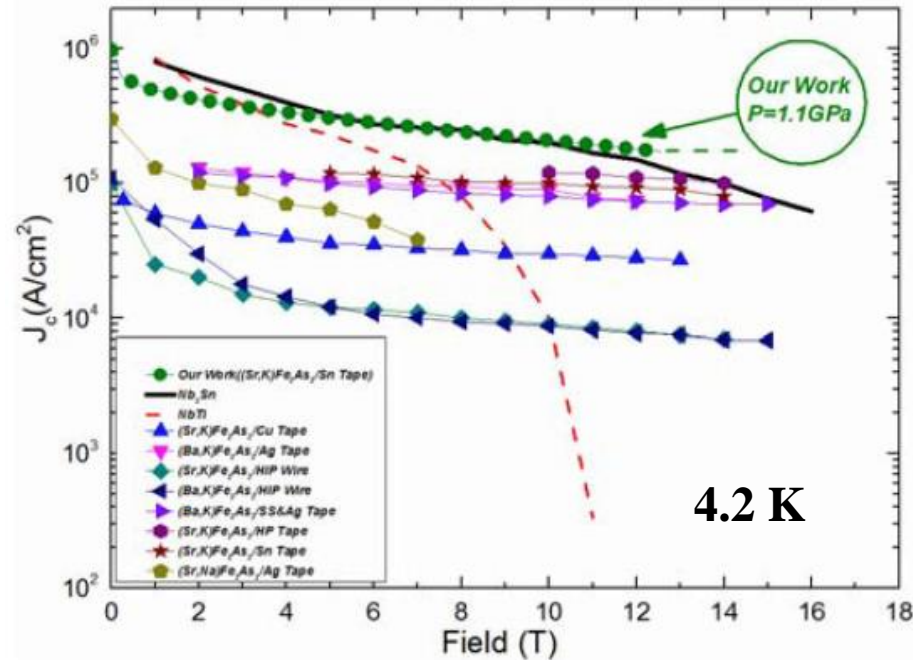


Many clear GBs in HP-122 tape

- ◆ The state-of-art high  $J_c$  tapes still contain many contaminated GBs which disconnect the Ba122 grains. The  $J_c$  can be largely improved if we can eliminate these secondary phases.
- ◆ Avoid oxidation of starting materials and LT sintering are important to further improve  $J_c$ .

Courtesy of F. Kametani

# Magnetic $J_c$ up to $3 \times 10^5$ A/cm<sup>2</sup> @ 4.2 K, 10 T can be achieved under Hydrostatic Pressure on 122 tapes

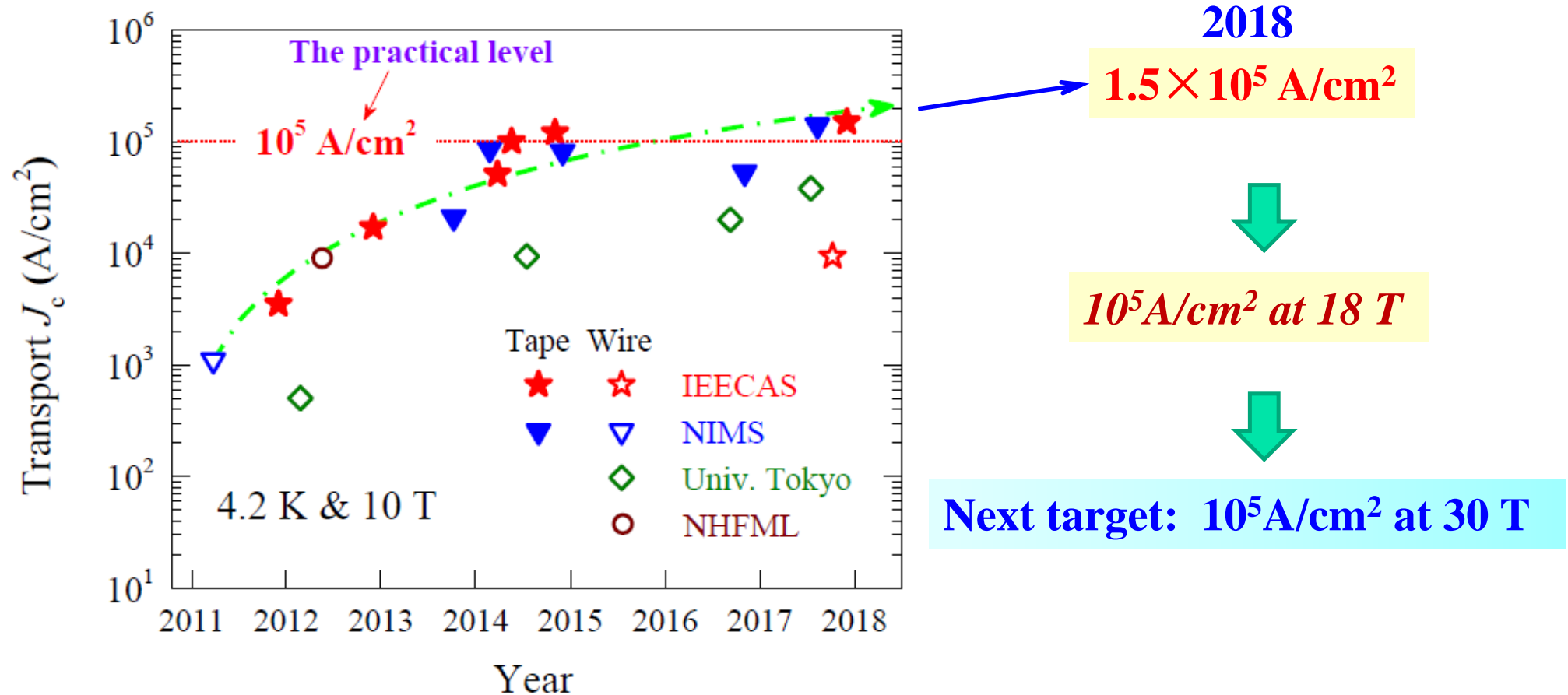


-- Collaborated with Prof. Xiaolin Wang,  
S. X. Dou, Wollongong Univ.

- ✓ 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  $\text{Sr}_{0.6}\text{K}_{0.4}\text{Fe}_2\text{As}_2$  tapes at different temperatures, e.g.,  $\sim 2 \times 10^5$  A/cm<sup>2</sup> at 13T, 4.2 K.
- ➡ Pressure can improve the grain connectivity and increase the pinning number density.
- ➡ The result demonstrated that the current IBS tapes/wires should have plenty of room for the  $J_c$  improvement.

# Recent advances in transport $J_c$ 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)...*

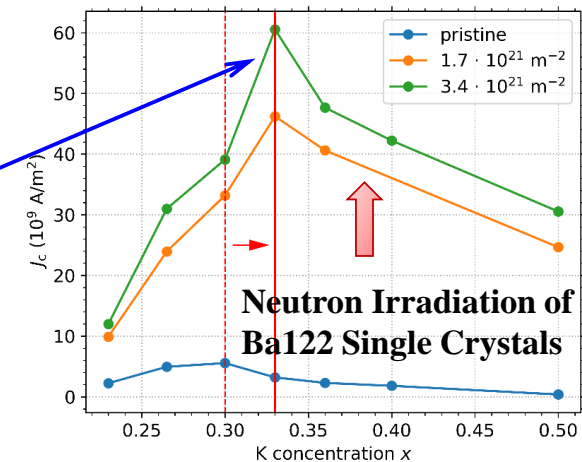
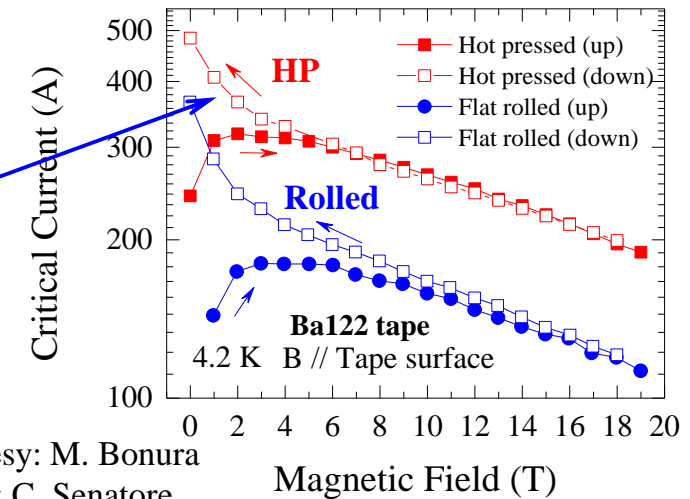
# Strategies to further improve $J_c$ in 122 PIT wires

◆ Reduction of secondary phases at GBs.

◆ To improve the texture degree,  
especially increase the fraction of misorientation  
angle  $< 9^\circ$ .

◆ To further increase flux pinning force:

- (1) decrease grain size to make more GBs,
- (2) increase point pinning sites, *e.g.* irradiation  
or the introduction of nano-particle inclusion.



# Outline

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- 1** Background on iron-based superconductors (IBS)
- 2** High- $J_c$  IBS films and Coated Conductors (CC)
- 3** Fabrication of PIT IBS wires
  - i) Strategies to improve  $J_c$  in 122 wires
  - ii) Practical properties of 122 IBS wires**
  - iii) Long-length wire & inserted coils
- 4** Conclusions

# For applications, many other problems to be solved

## Challenge



## Strategy

- 1、 Low AC loss/Quenching,
- 2、 Large EMF/thermal stress,
- 3、 Market requirement,
- 4、 Scalability of fabrication,

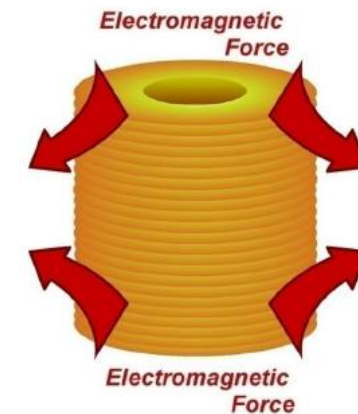
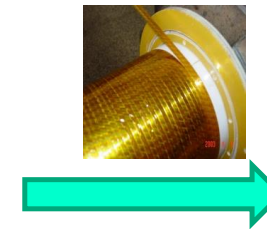
- Multifilamentary**
- High strength**
- Low cost**
- Long length**



Short sample: 1m



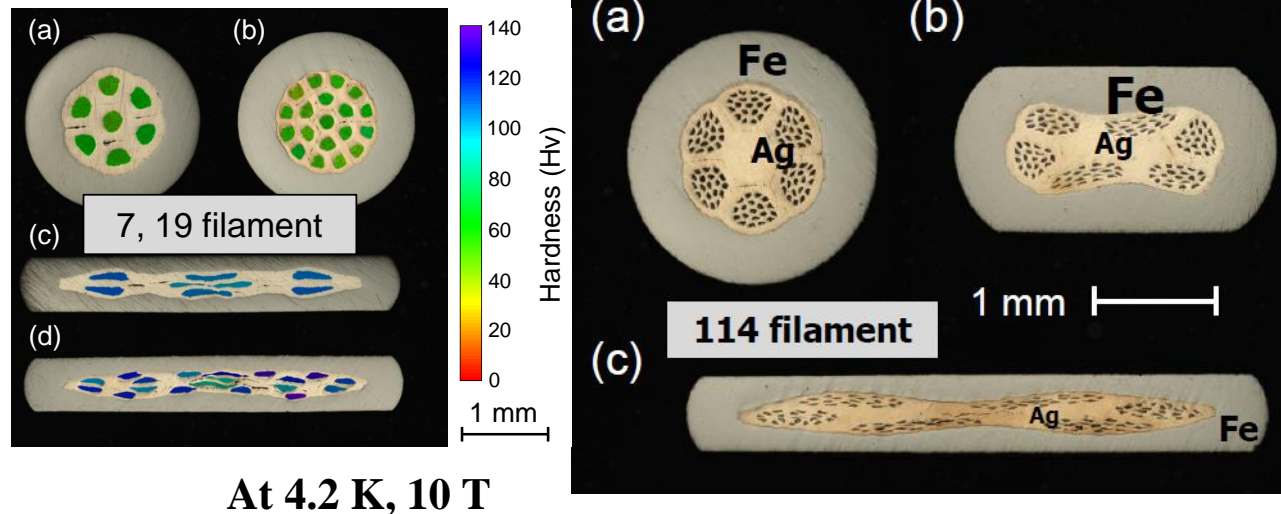
Long wire



Magnet

# Fabrication of 7-, 19- & 114-filament 122 IBS wires

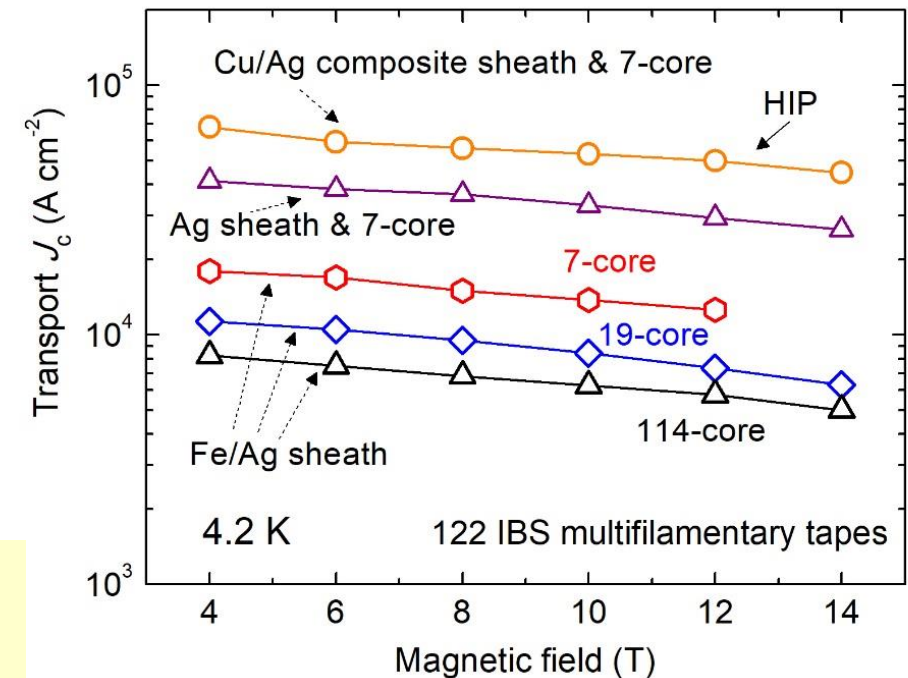
➤ The fabrication of multifilamentary wires and tapes is an indispensable step, to reduce the AC loss and avoid the flux jump.



At 4.2 K, 10 T

- ◆ 114-core round wires:  $J_c = 800 \text{ A/cm}^2$ .
- ◆ 114-core tapes (0.6 mm):  $J_c = 6.3 \times 10^3 \text{ A/cm}^2$ .
- ◆ 7-core rolled tapes:  $J_c = 3.2 \times 10^4 \text{ A/cm}^2$ .
- ◆ Latest: 7-core HIP tapes:  $J_c = 5.3 \times 10^4 \text{ A/cm}^2$
- ◆ This  $J_c$  degradation can be ascribed to the sausage effect.

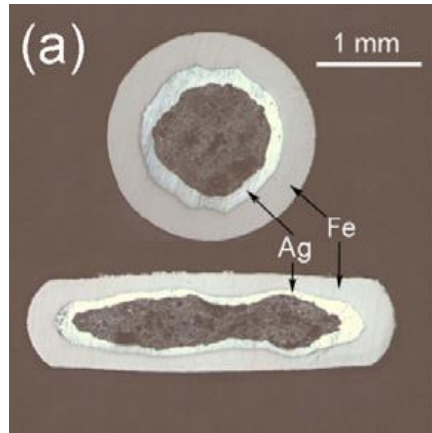
$J_c$ , the very weak field dependence



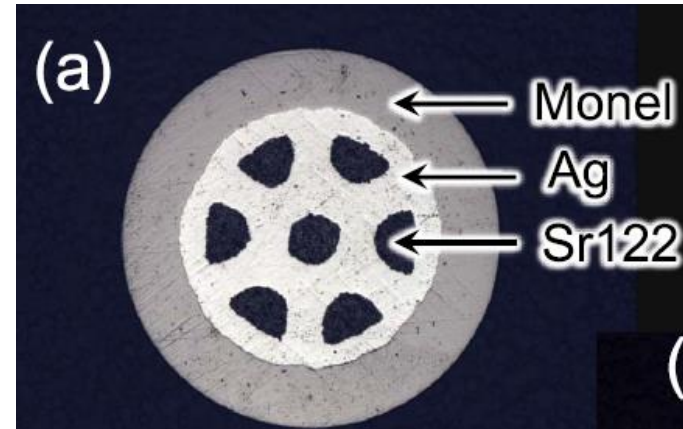
$J_c$  needs to be further improved

# Fabrication of high-strength IBS wires

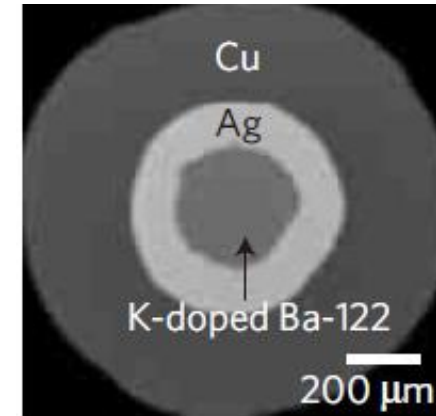
Ag may be also used in combination with an additional outer sheath made of Fe, Cu, and stainless steel to **reduce costs and improve the mechanical strength.**



**Fe/Ag, IEECAS**



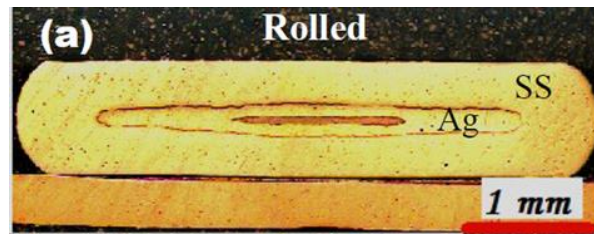
**Monel/Ag, IEECAS**



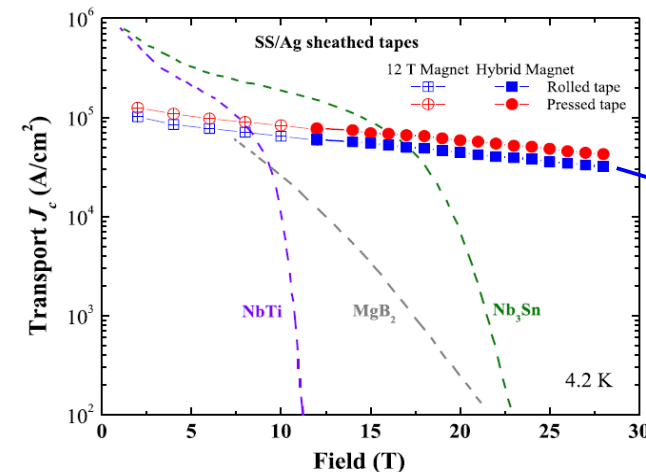
**Cu/Ag, Florida**



**Cu/Ag, IEECAS**



**SS/Ag, NIMS, SuST 30 (2017) 095012**



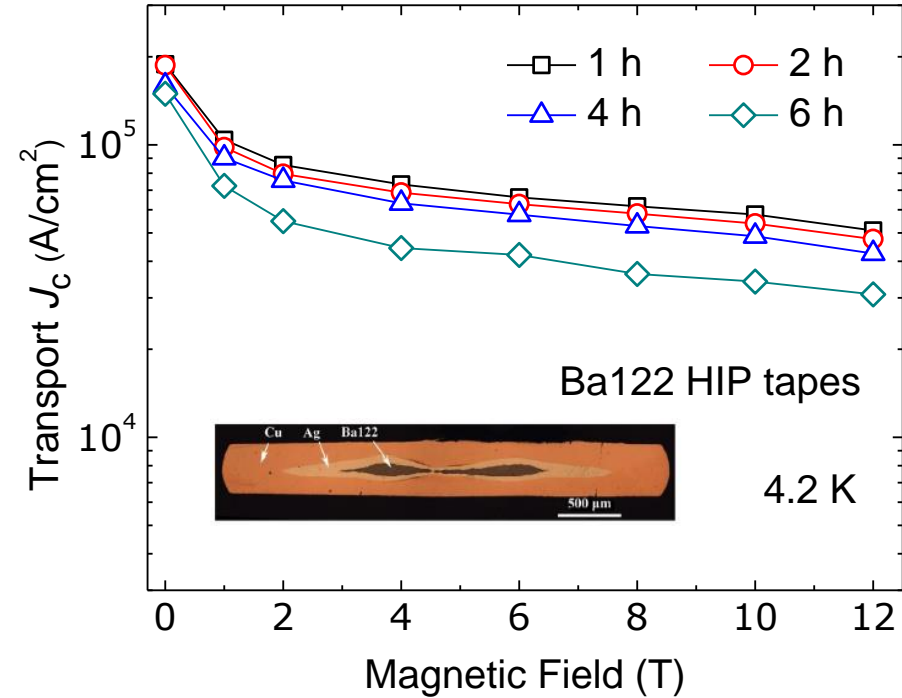
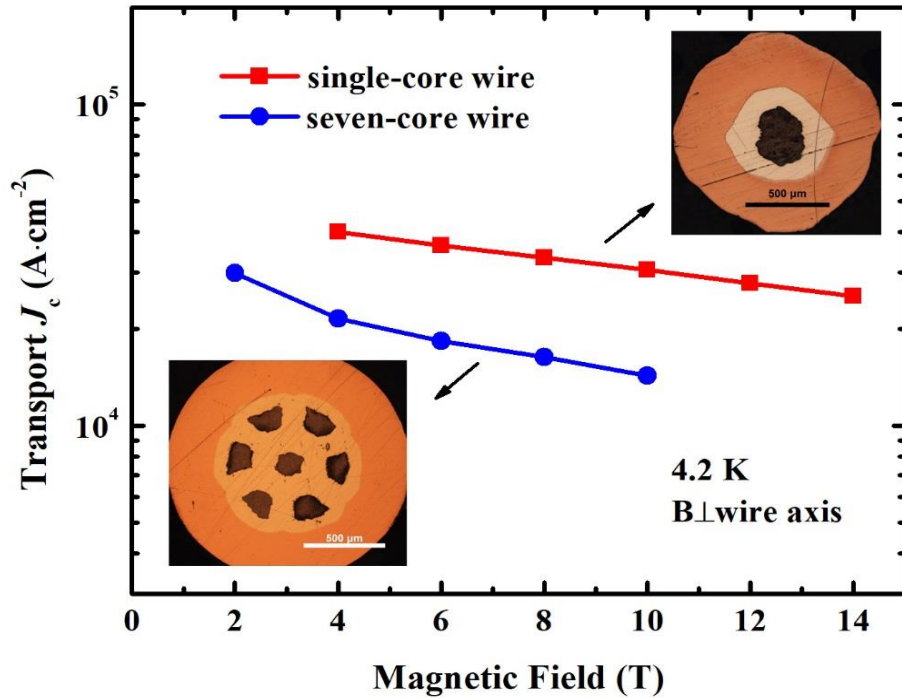
**28T,  $J_c = 3 \times 10^4$  A/cm<sup>2</sup>**

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

Ba-122/Ag/Cu round wires

at 740°C

Ba-122/Ag/Cu tapes



$$J_c (4.2 \text{ K}, 10 \text{ T}) = 3.1 \times 10^4 \text{ A/cm}^2$$

$$7\text{-core } J_c (4.2 \text{ K}, 10 \text{ T}) = 1.6 \times 10^4 \text{ A/cm}^2$$

$$J_c (4.2 \text{ K}, 10 \text{ T}) = \sim 6 \times 10^4 \text{ A/cm}^2$$

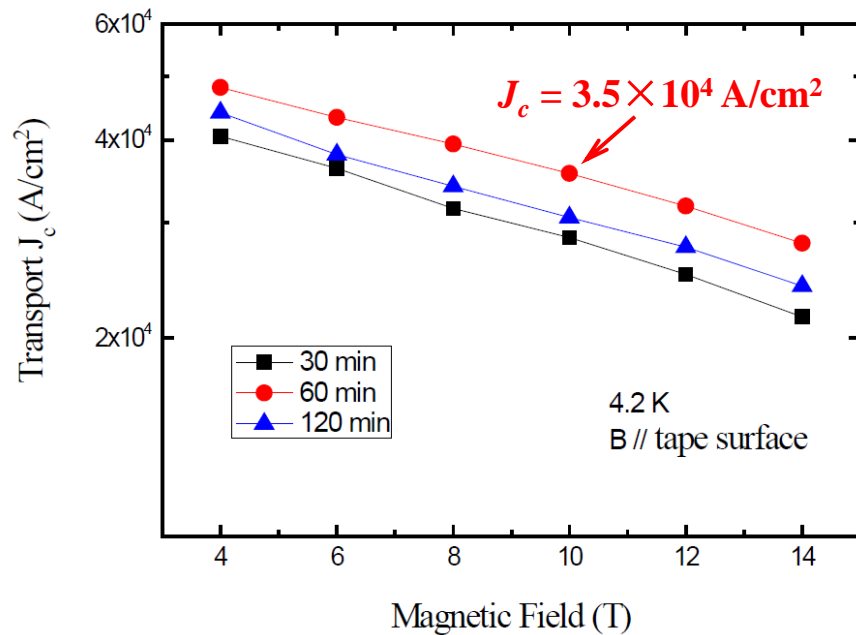
**A scalable process  
(Rolling+HIP)**

⇒ { grain texture by flat rolling  
high density by HIP

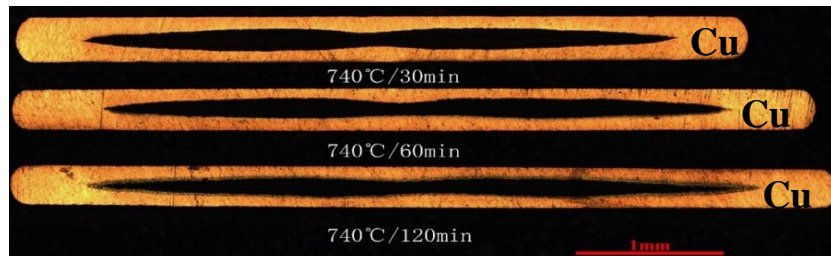
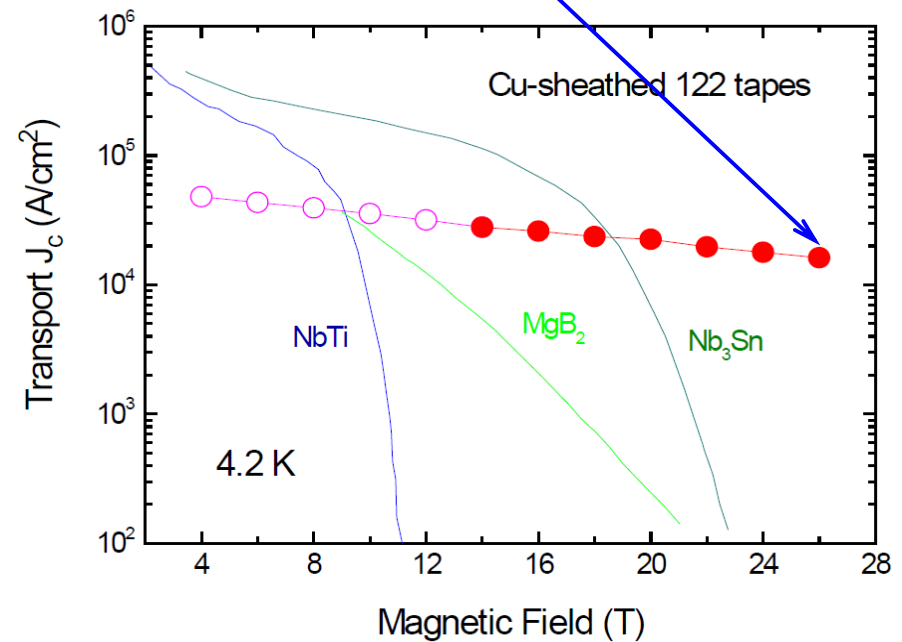
## Low-cost copper as sheath

# High $J_c$ in Cu-sheathed Sr-122 tapes at 740°C

At 4.2 K, 10 T,  $J_c > 10^4$  A/cm<sup>2</sup>



At 26 T:  $J_c = 1.6 \times 10^4$  A/cm<sup>2</sup>

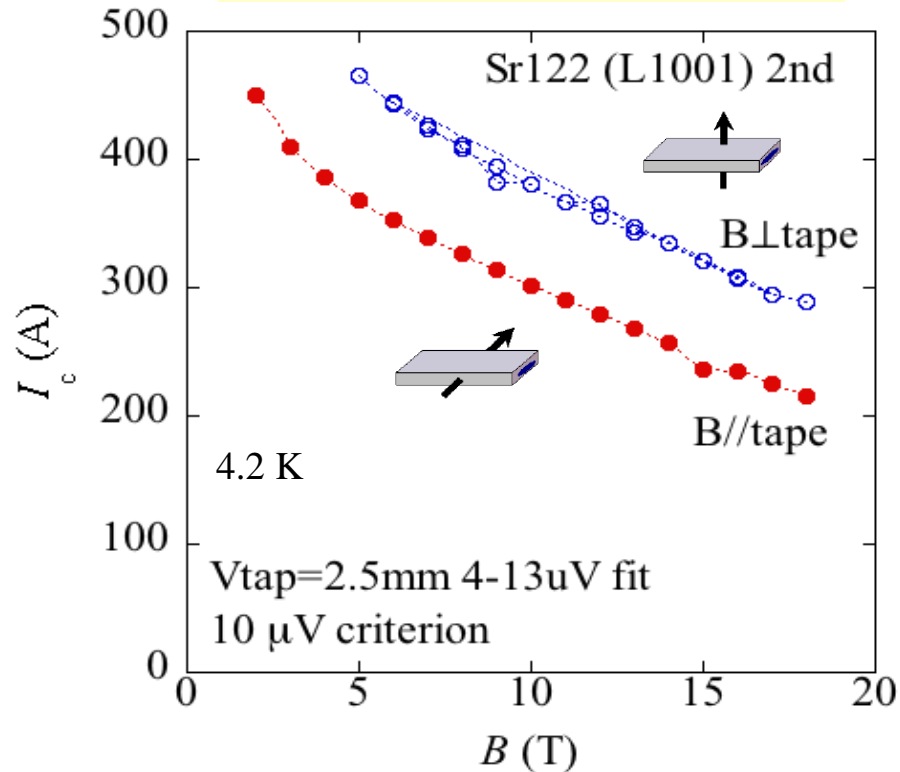


- ◆ The rapid fabrication method (HP740C/60 min) can effectively thwart the diffusion of Cu into Sr-122 core.
- ◆ The best transport  $J_c$  reaches  $3.5 \times 10^4$  A/cm<sup>2</sup> at 10 T and keeps  $1.6 \times 10^4$  A/cm<sup>2</sup> at 26 T.

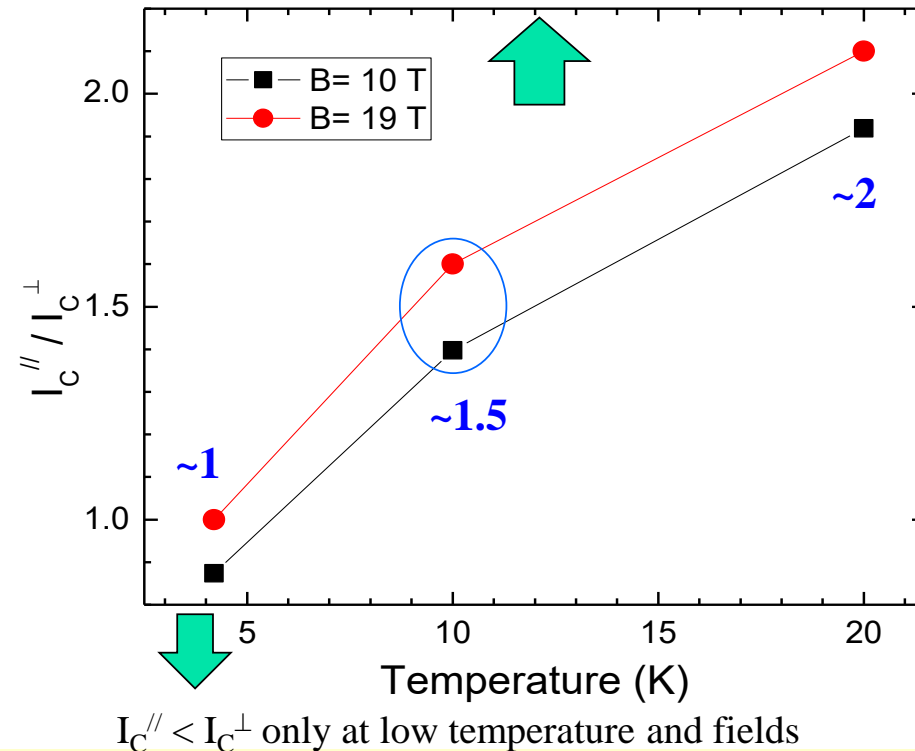
## Small anisotropy

# $I_c$ properties at various fields for 122/Ag tapes

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



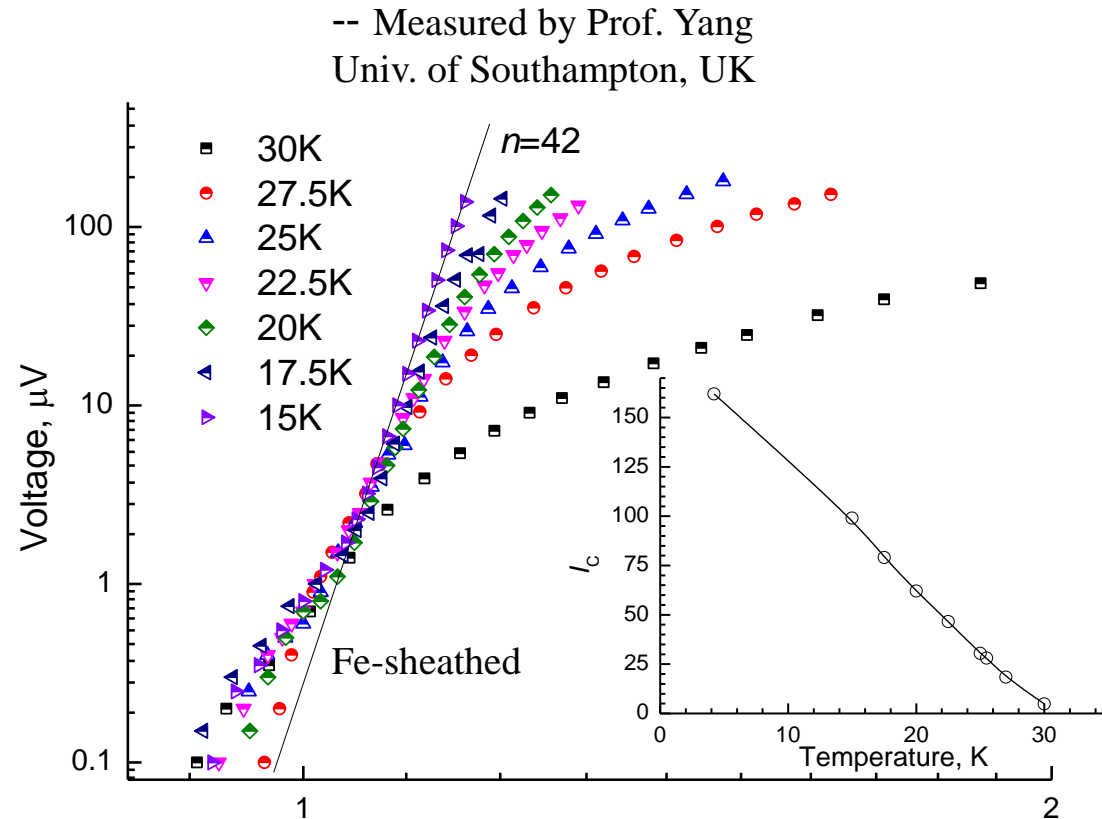
Measured by *C. Senatore* group  
 at Geneva Univ.



- ◆ 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 ( $\Gamma = I_c^\perp / I_c^//$ ) is quite low, less than **2**, very good for applications.

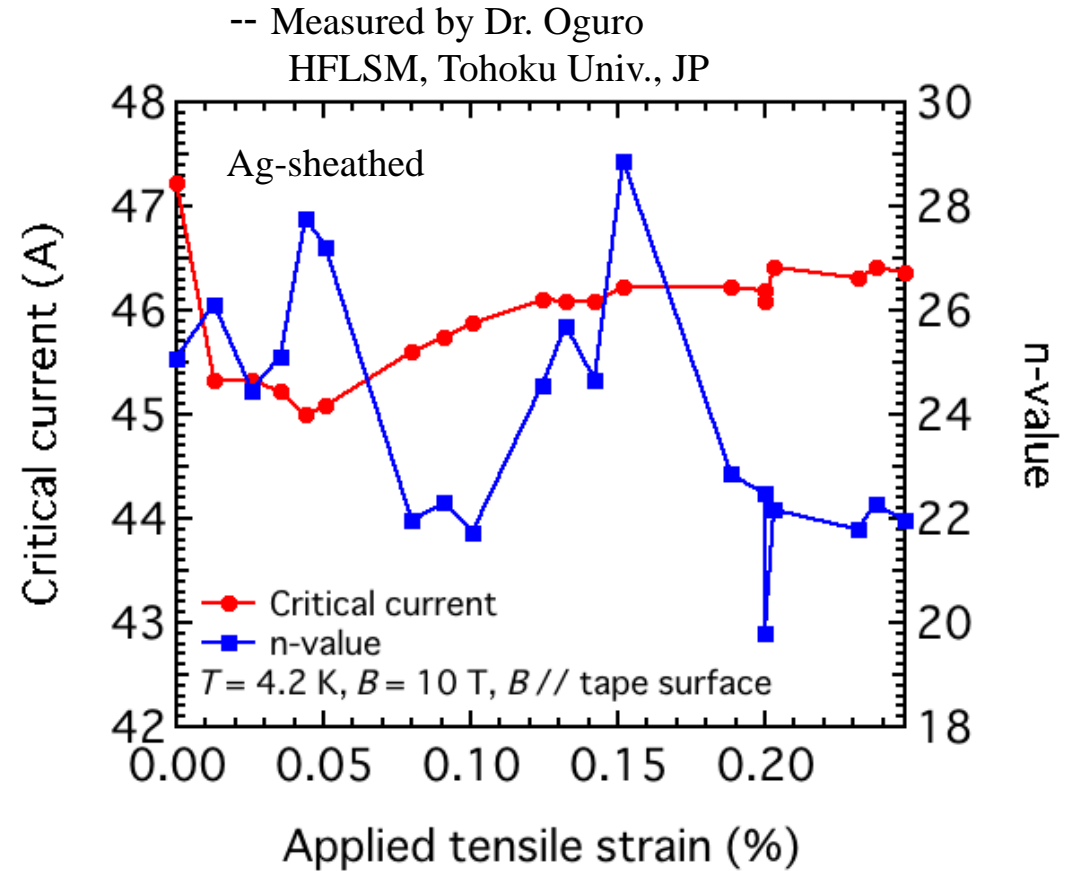
***n* value**

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



Courtesy of Yifeng Yang

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

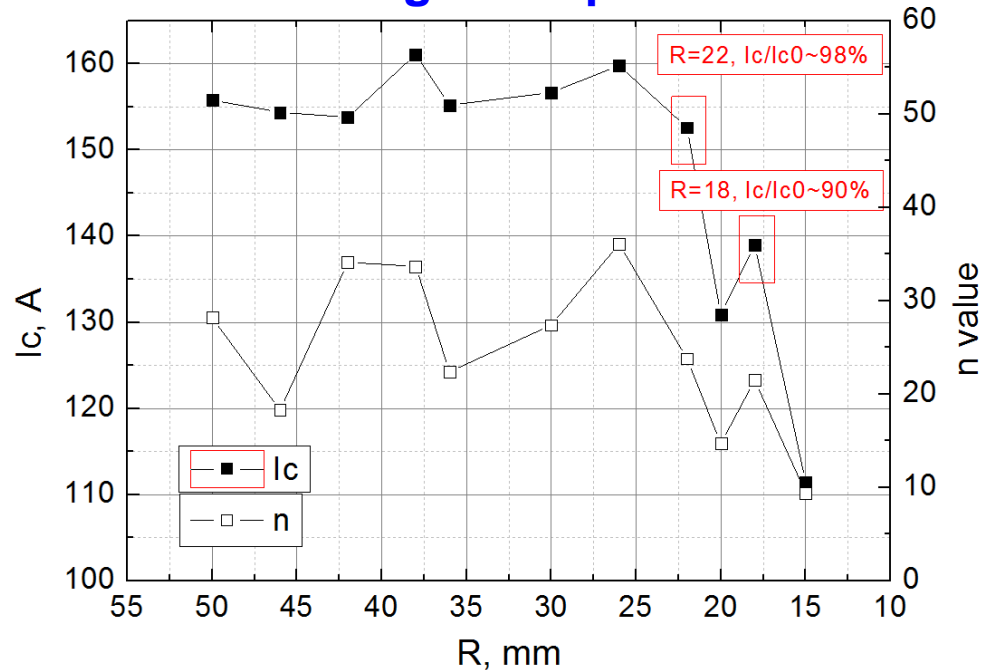


**At 4.2 K, the *n* value was over 20**



# Bending test of 122 IBS tapes

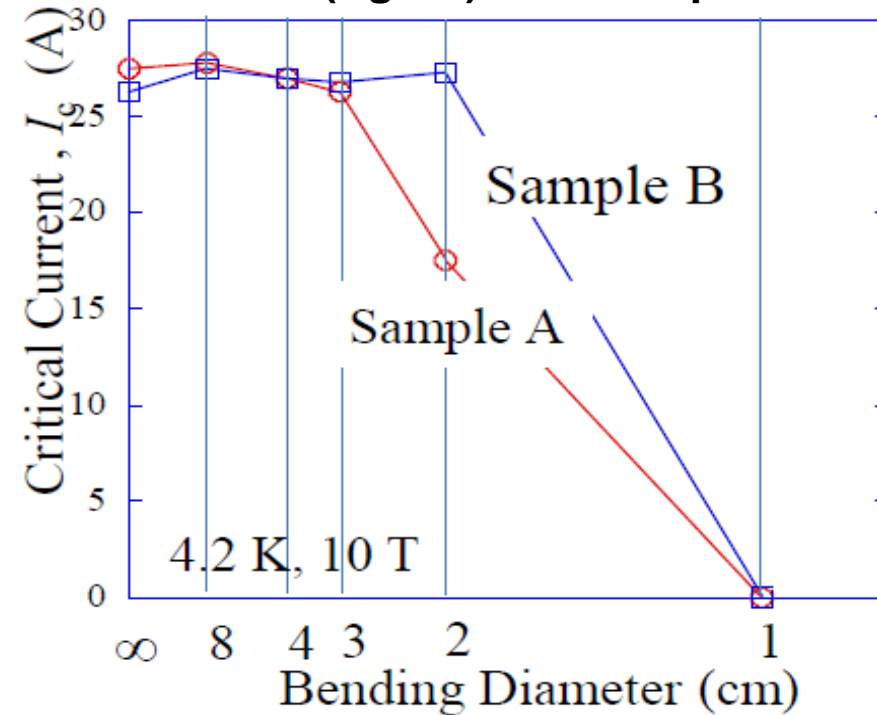
122/Ag IBS tapes



width ~ 4.5 mm, thickness = 0.3 mm

Cooperated with Prof. Huajun Liu in IPP-CAS

SUS/(Ag-Sn)/Ba-122 tapes

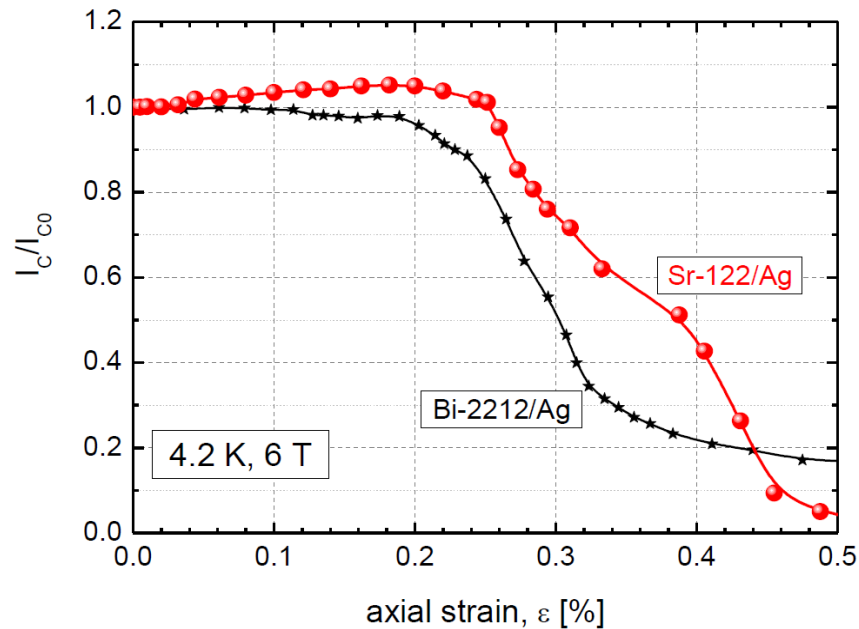


Courtesy of H. Kumakura

- The critical bending diameter is **4.4 cm** for Sr-122/Ag tapes in thickness of 0.3 mm.
- For **high strength Ba-122 tapes**, the bending diameter is even smaller, **only of 2~3 cm**.

# 122/Ag tape – Strain-stress properties

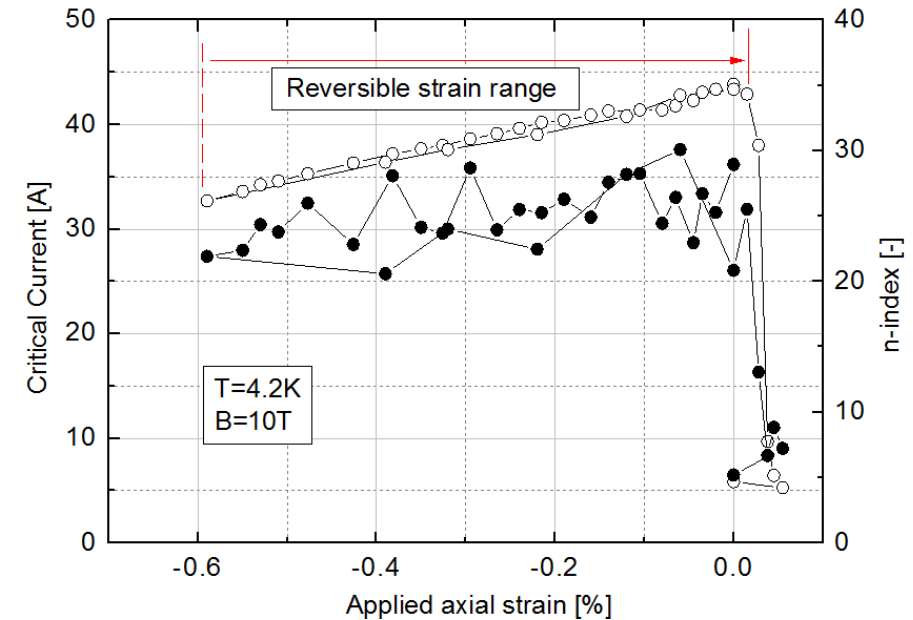
The first strain measurement  
under **tensile stress**



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

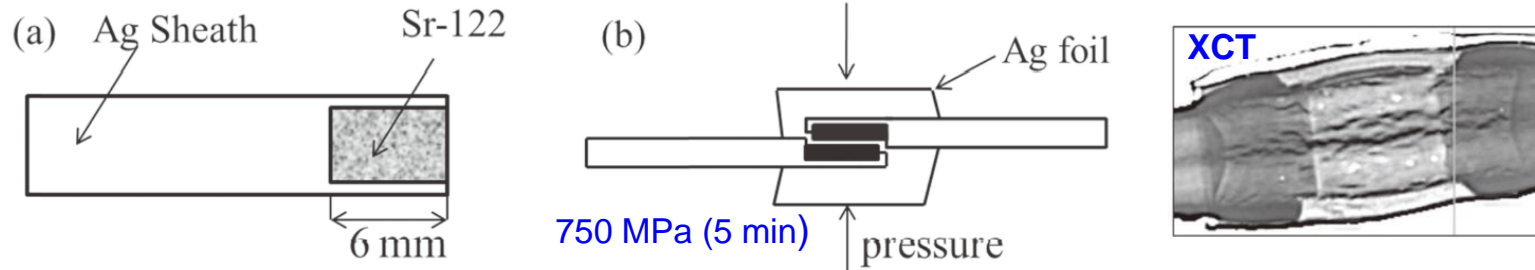
Comparable to Bi2212

Reversible critical currents under a large  
**compressive strain** of  $\epsilon = -0.6\%$

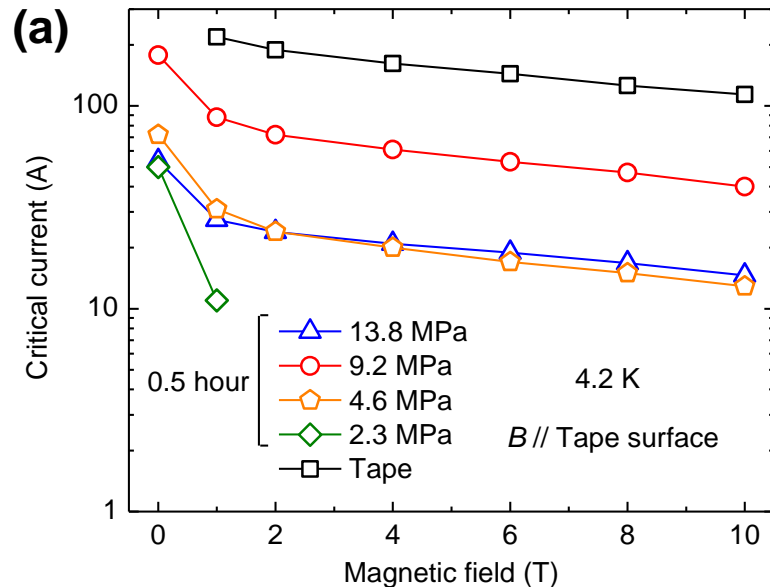


The  $I_c$  of **Sr-122** tape exhibits **less strain sensitivity** than that of the **Nb<sub>3</sub>Sn**, which is an important for ITER application.

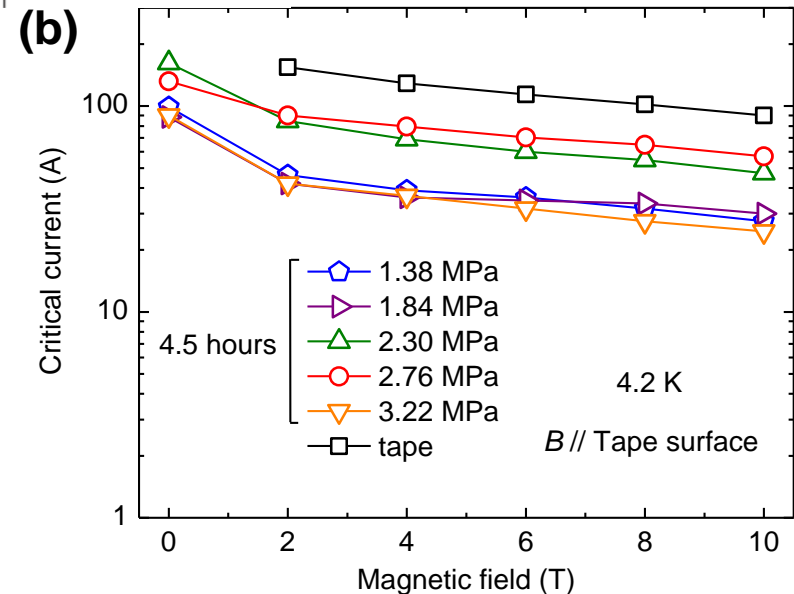
# Development of superconducting joints between iron-based superconductor tapes



for persistent current operation



Zhu et al., *SuST* 31 (2018) 06LT02



Zhu et al., *SuST* 32 (2019) 024002

CCR =  $I_c^{\text{joint}} / I_c^{\text{tape}}$  of **63.3%**  
 at 10 T, 4.2K  
 $dV/dI < 1 \text{ n}\Omega$

critical current ratio (CCR) = 35.3% → Optimizing the HP pressure

# Outline

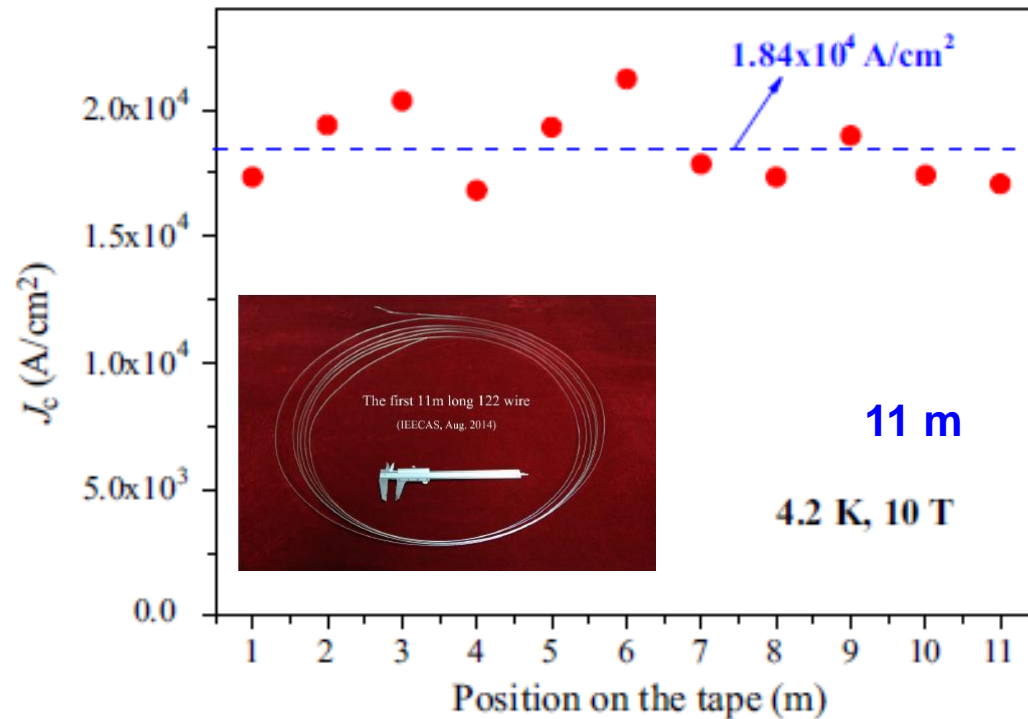
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- 1 Background on iron-based superconductors (IBS)**
- 2 High- $J_c$  IBS films and Coated Conductors (CC)**
- 3 Fabrication of PIT IBS wires**
  - i) Strategies to improve  $J_c$  in 122 wires**
  - ii) Practical properties of 122 IBS wires**
  - iii) Long-length wire & inserted coils**
- 4 Conclusions**

# Fabrication of the meter long 122 IBS wire

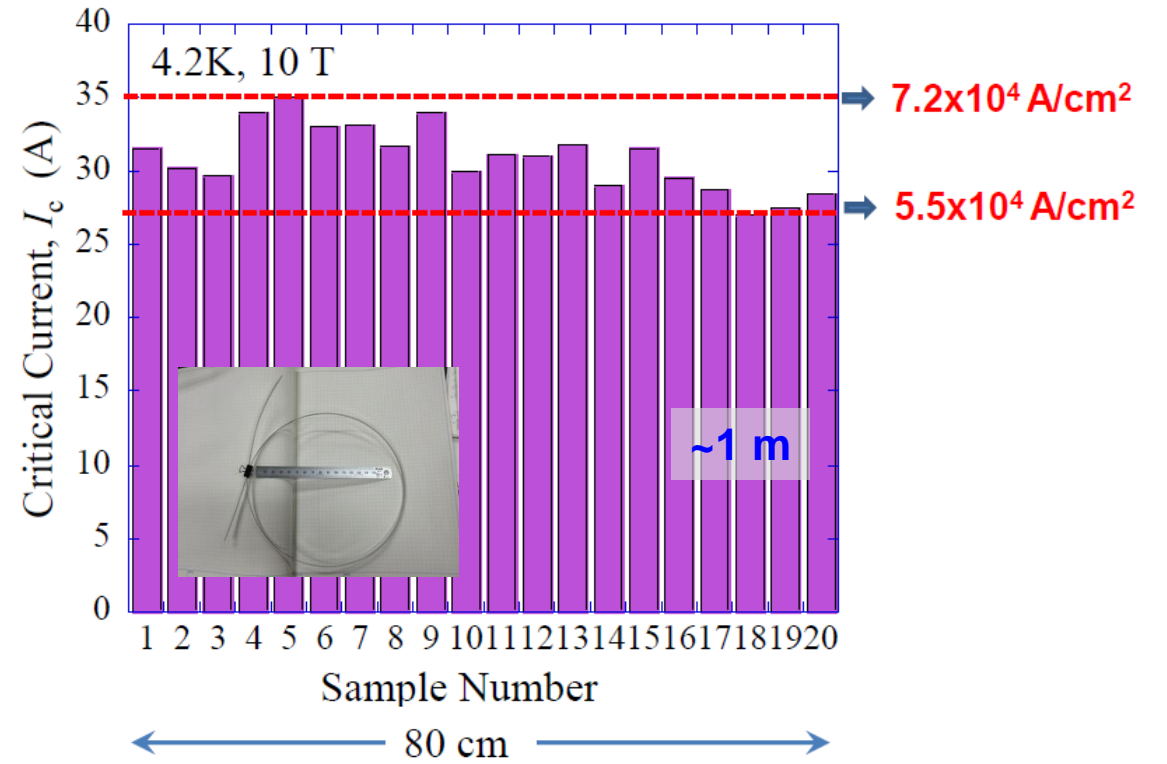
---by scalable rolling process

The fluctuations of the  $J_c$  is ~5% for  
11 m long Sr-122/Ag tape



Ma, Physica C 516 (2015) 17-26

$I_c$  distribution of a ~1 m long  
SUS316/(Ag-Sn)/Ba-122 tape



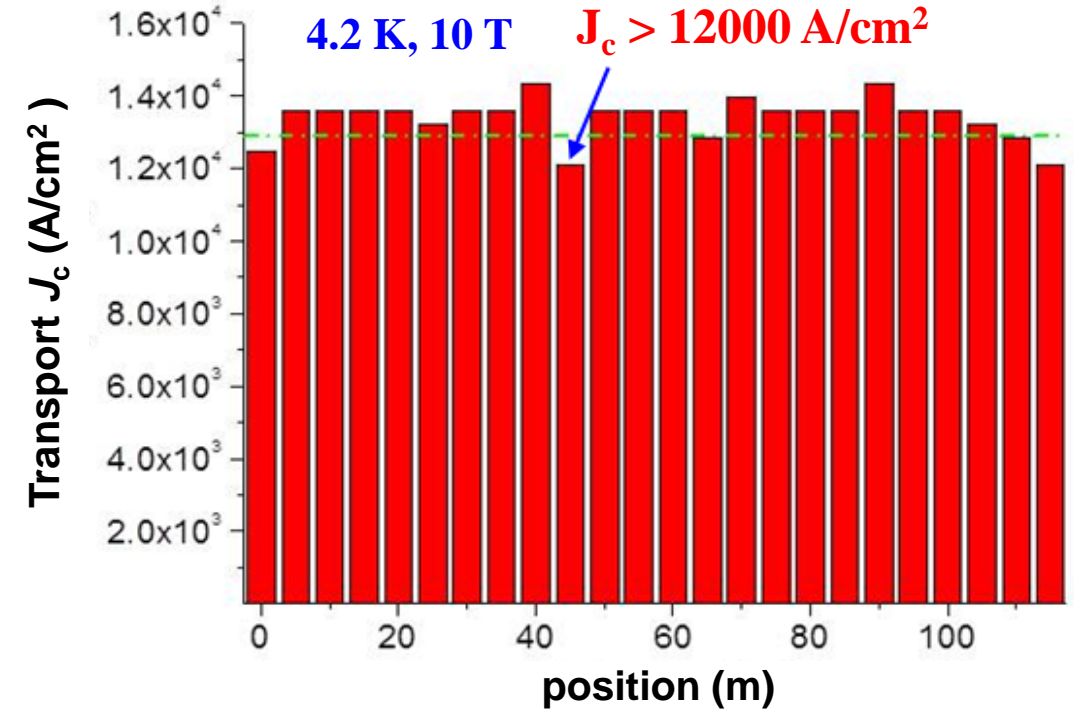
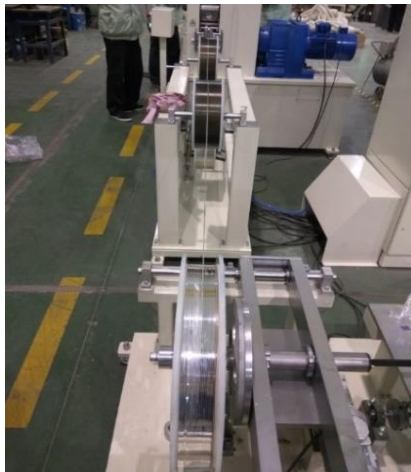
*Challenging to longer length!*

By courtesy of H. Kumakura

In 08/2016

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

115 m long  
7-filamentary  
122 tape



showing a good uniformity

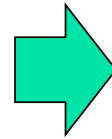
Zhang et al., *IEEE Trans. Appl. Supercond.* 27 (2017) 7300705

# Recently, $J_c$ of 100 m long tapes was further enhanced: $>30000 \text{ A/cm}^2$ (4.2 K, 10 T)

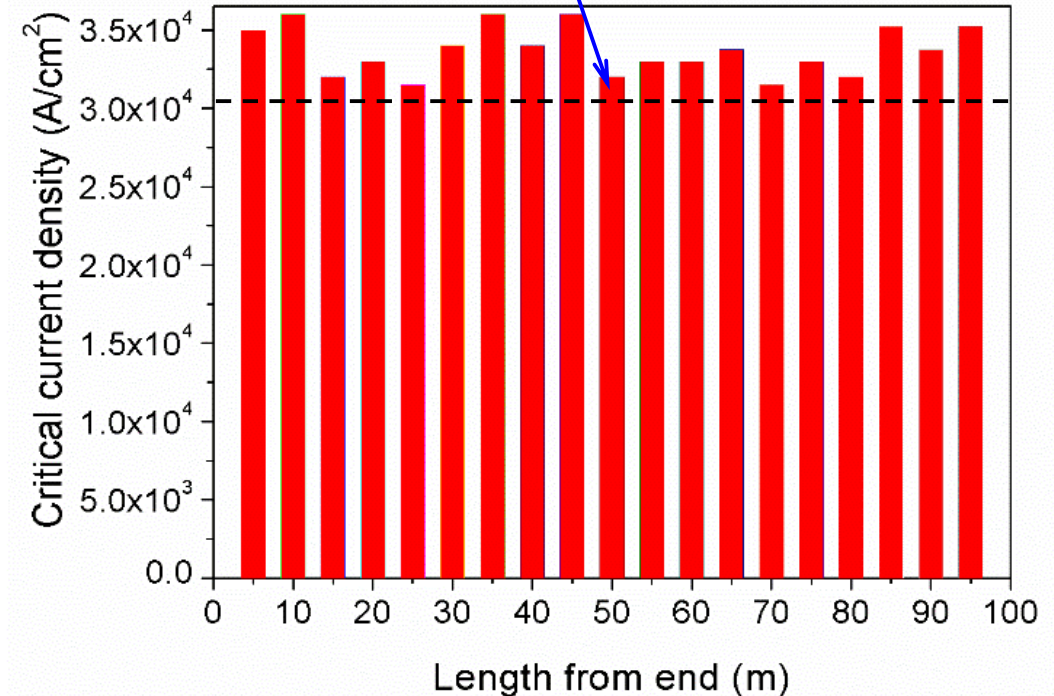
3 times larger than the first!



Key steps  
to the  
application



@4.2K, 10T, transport  $J_c >30000 \text{ A/cm}^2$



Supported by the Strategic Priority Research Program of Chinese Academy of Sciences (Grant No. XDB25000000).



## Letter

# First performance test of a 30mm iron-based superconductor single pancake coil under a 24T background field

-- Cooperated with Qingjin Xu group at IHEP-CAS

Dongliang Wang<sup>1,2,5</sup>, Zhan Zhang<sup>3,5</sup>, Xianping Zhang<sup>1,2</sup>, Donghui Jiang<sup>4</sup>, Chiheng Dong<sup>1</sup>, He Huang<sup>1,2</sup>, Wenge Chen<sup>4</sup>, Qingjin Xu<sup>3,6</sup> and Yanwei Ma<sup>1,2,6</sup>

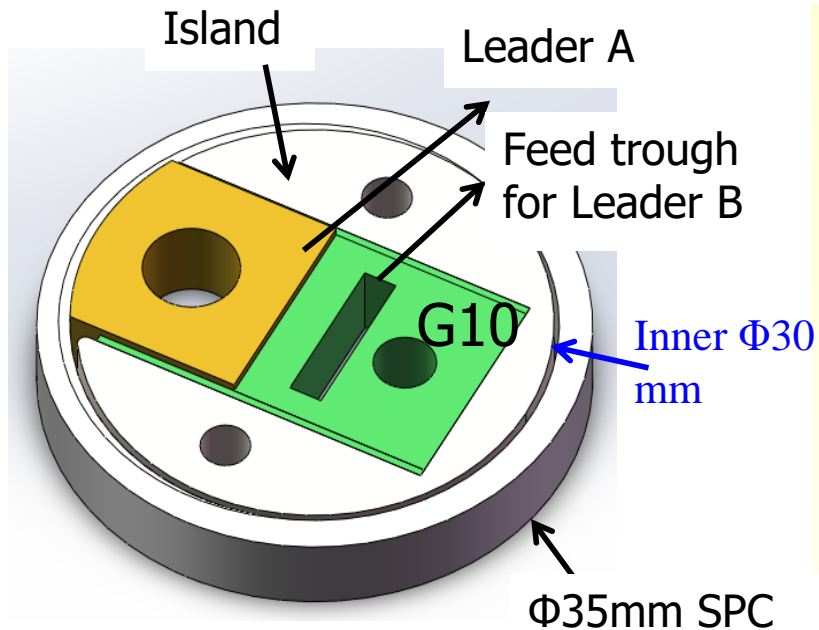


Table 2. Specification of single pancake coil

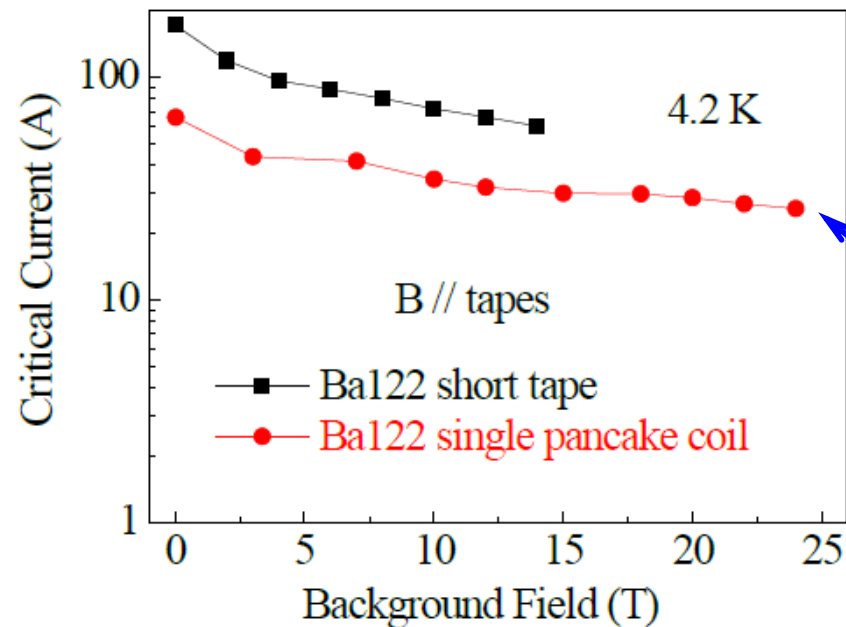
Parameter	Unit	Value
Inner diameter	mm	30
Outer diameter	mm	34.8
Height	mm	4.62
Thickness of stainless steel tape	mm	0.1
Turns		4.5
Total length of IBS wire	mm	450



# Transport $I_c$ -B curve for inserted coils

--Measured at HMFL in Hefei

25T-HM, RT bore  $\Phi 38$  mm




- ➡ The  $I_c$  of the Ba122 coil showed weakly dependent on the magnetic field, like the short tape. ( $I_c=26$  A in a field of 24 T)
- ➡ These results suggest that IBSs are very promising for high-field magnet applications.



CrossMark

## Viewpoint

# Constructing high field magnets is a real tour de force

Jan Jaroszynski 

National High Magnetic Field,  
Laboratory, Tallahassee, FL,  
32310, United States of America  
E-mail: [jaroszy@magnet.fsu.edu](mailto:jaroszy@magnet.fsu.edu)

This is a viewpoint on the letter by Dongliang Wang *et al* (2019 *Supercond. Sci. Technol.* **32** 04LT01).

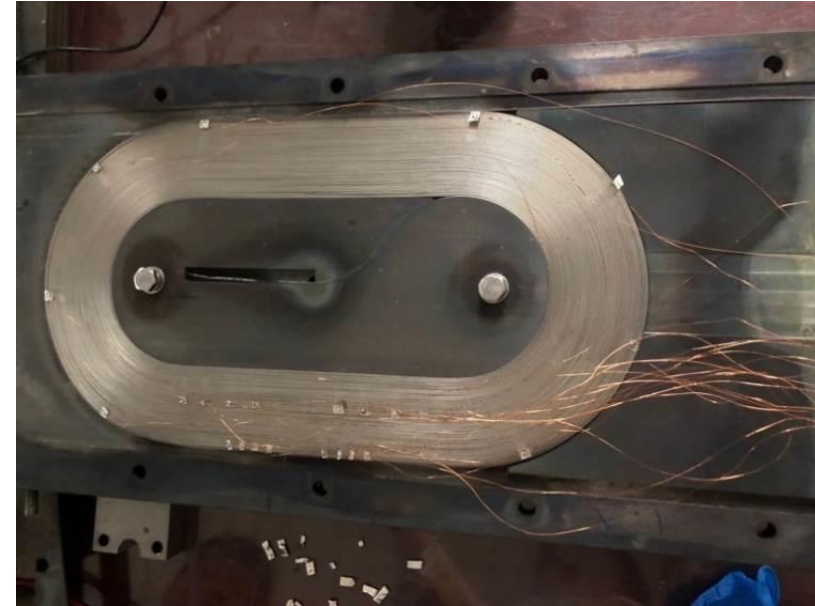
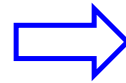
Following the discovery of superconductivity in 1911, Heike Kamerlingh Onnes foresaw the generation of strong magnetic fields as its possible application. He designed a 10 T electromagnet made of lead–tin wire, citing only the difficulty in obtaining ‘relatively modest financial support’ for his laboratory in Leiden.

helpful in explaining the latter. From a practical point of view, IBS are ideal candidates for applications. Indeed, some of them have quite a high critical current density, even in strong magnetic fields, and a low superconducting anisotropy. Moreover, the cost of IBS wire can be four to five times lower than that of Nb<sub>3</sub>Sn, making it more expensive than NbTi, but with much higher critical parameters than Nb<sub>3</sub>Sn. Attempts to make a superconducting wire started immediately, using either the powder-in-tube (PIT) [11–13] or coated conductor [14, 15] methods.

However, this is an important result, because at such high fields, coiled wires suffer from high tensile hoop stress that pushes them to the limits of their mechanical strength. In this high stress regime, critical current densities and critical fields are not what limit the generation of very high fields, these are forces exerted to the superconducting wires. Here, the Ba122/Ag/AgMn tape coil survived these forces.

# IBS Racetrack coil made from a 100 m 122/Ag tape

Recently...



**IBS Racetrack coil**

Tested data will be reported soon

**Made by Qingjin Xu group:**



Institute of High Energy Physics  
Chinese Academy of Sciences

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

# Domestic Collaboration on HTS

**“Applied High Temperature Superconductor Collaboration (AHTSC)” formed in Oct. 2016.**

**with >18 related institutions and companies and >70 scientists and engineers to advance HTS R& D and industrialization in China..**

**➤ Goal :**

- 1) To increase the  $J_c$  of **IBS** by 10 times, reduce the cost to 20 Rmb/kAm @ 12T & 4.2K in 10 years, and realize the industrialization of the conductor;
- 2) To reduce the cost of **ReBCO** and **Bi-2212** conductors to 20 Rmb/kAm @ 12T & 4.2K in 10 years;

***Make IBS the high-field “NbTi” Conductor in 10 years!***

**Now we have 5-Year Program first, starting in 2018!**



# Conclusions

---

- ✓ **Currently, iron-based wires and tapes are in the rapid development stage of research and development.**
- ✓ **Transport  $J_c$  of 122-type IBS wires has been significantly improved, and has surpassed the practical level at 4.2K & 10T with a maximum of  $1.5 \times 10^5$  A/cm<sup>2</sup>.**
- ✓ **Transport  $J_c$  of 100-m-class Ba-122 IBS tapes was further improved to  $> 3 \times 10^4$  A/cm<sup>2</sup> at 10 T & 4.2 K.**
- ✓ **Highlights some remarkable advances of IBS relevant to practical applications, including strain-stress behavior, superconducting joints, and the first IBS inserted coils.**
- ✓ **We believe that Fe-based wires are very promising for applications in high magnetic fields, e.g.  $>20$  T at 4.2 K or  $>10$  T at 20-30 K.**

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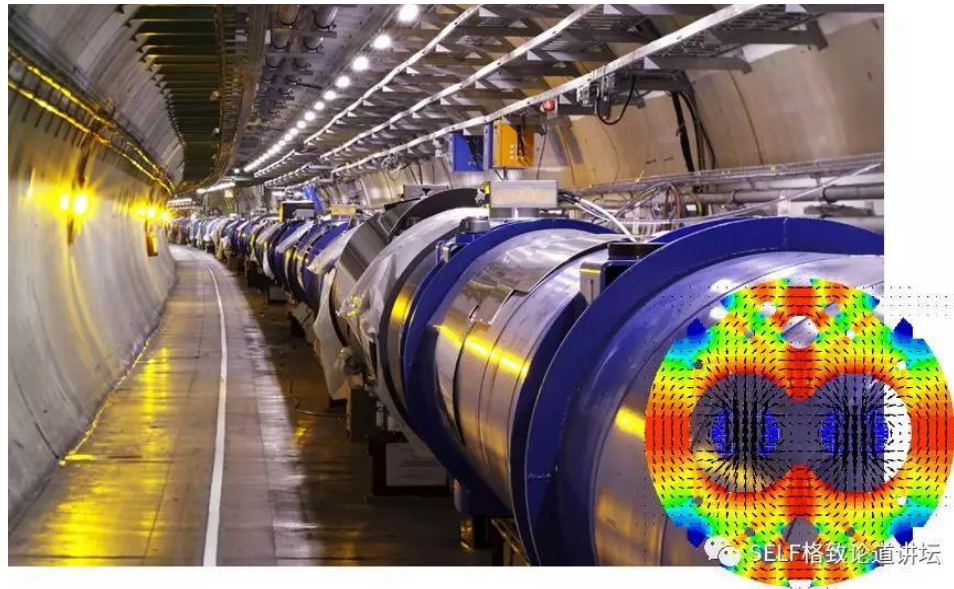
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***Thank you for your attention!***



From a movie: Avatar