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

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Outline

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

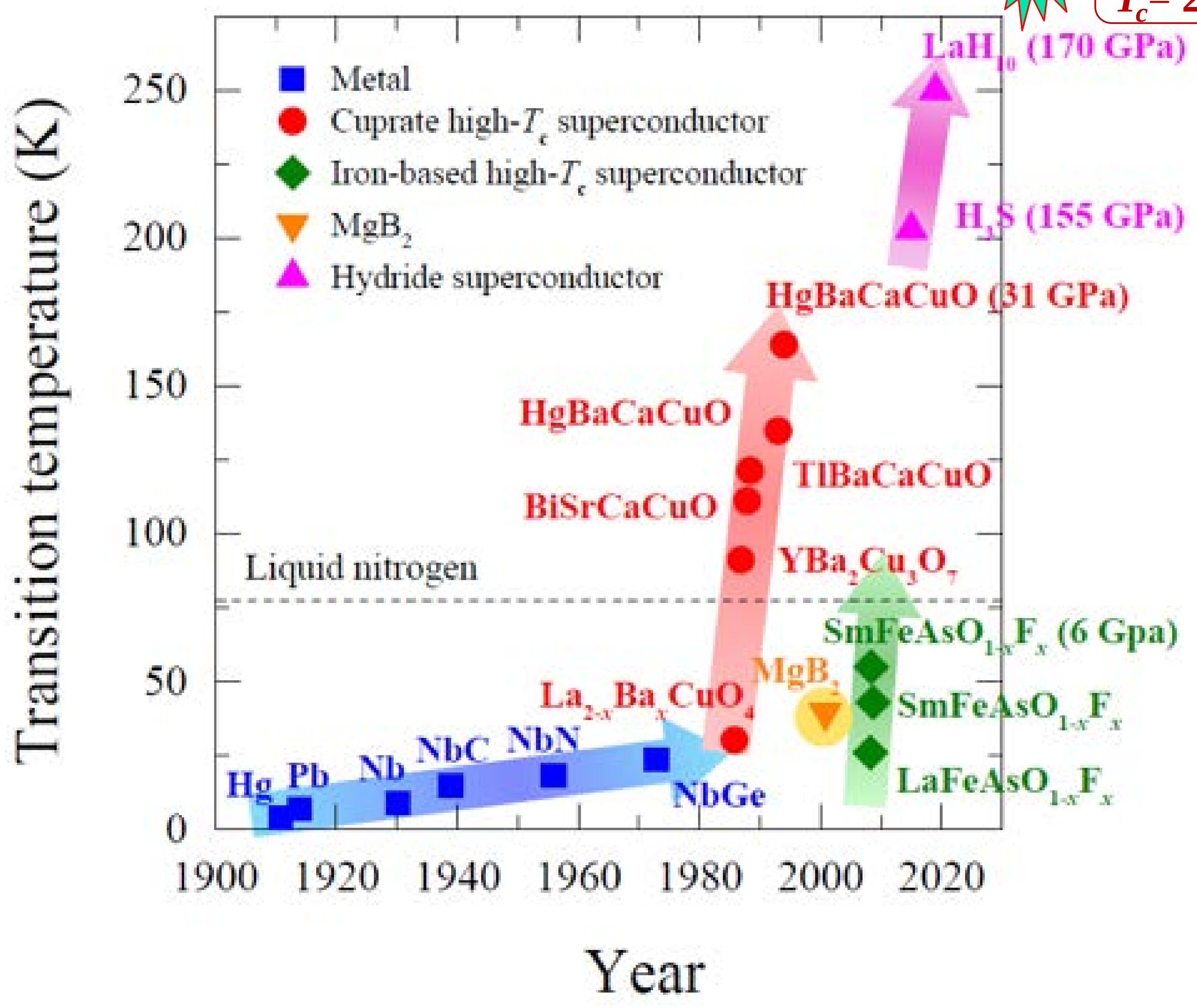
iii) Long-length wire & inserted coils

4 Conclusions

History of Superconductivity

Hydride
T_c= 250 K (-23°C)

2019



1911

Discovery of superconducting phenomenon

1986

Cuprate high-T_c superconductor

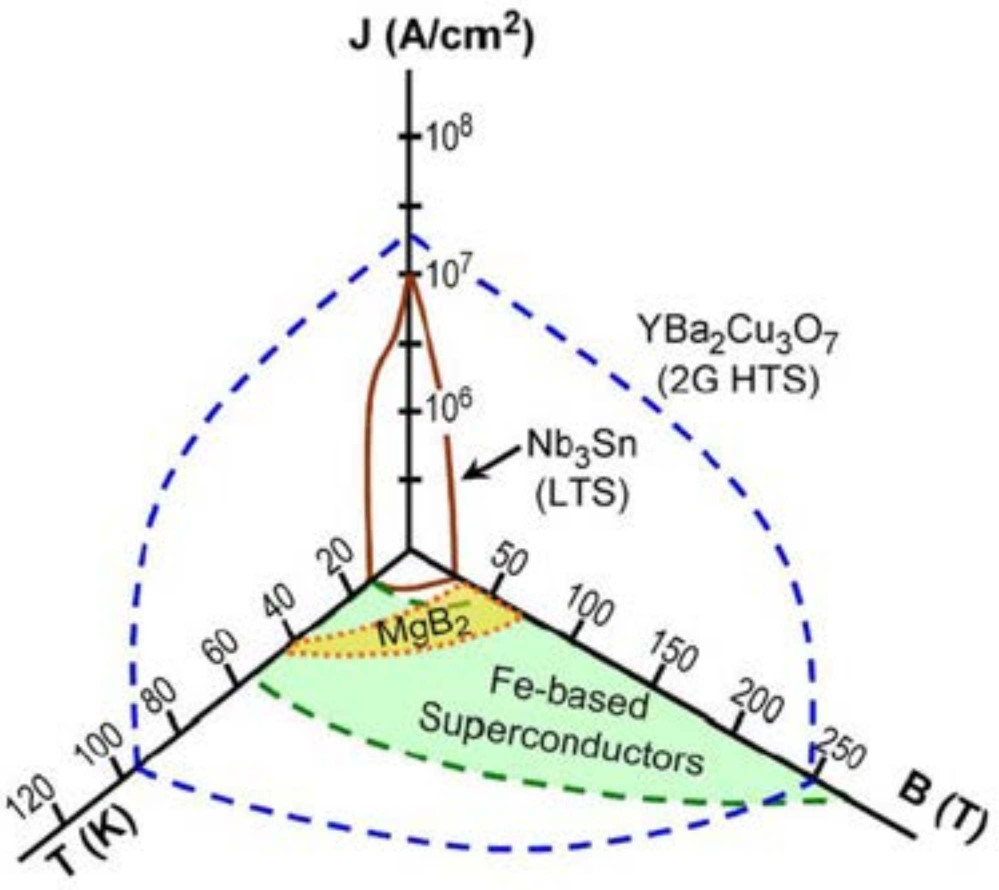
2001

MgB_2

2008

Iron-based high-T_c superconductor

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.

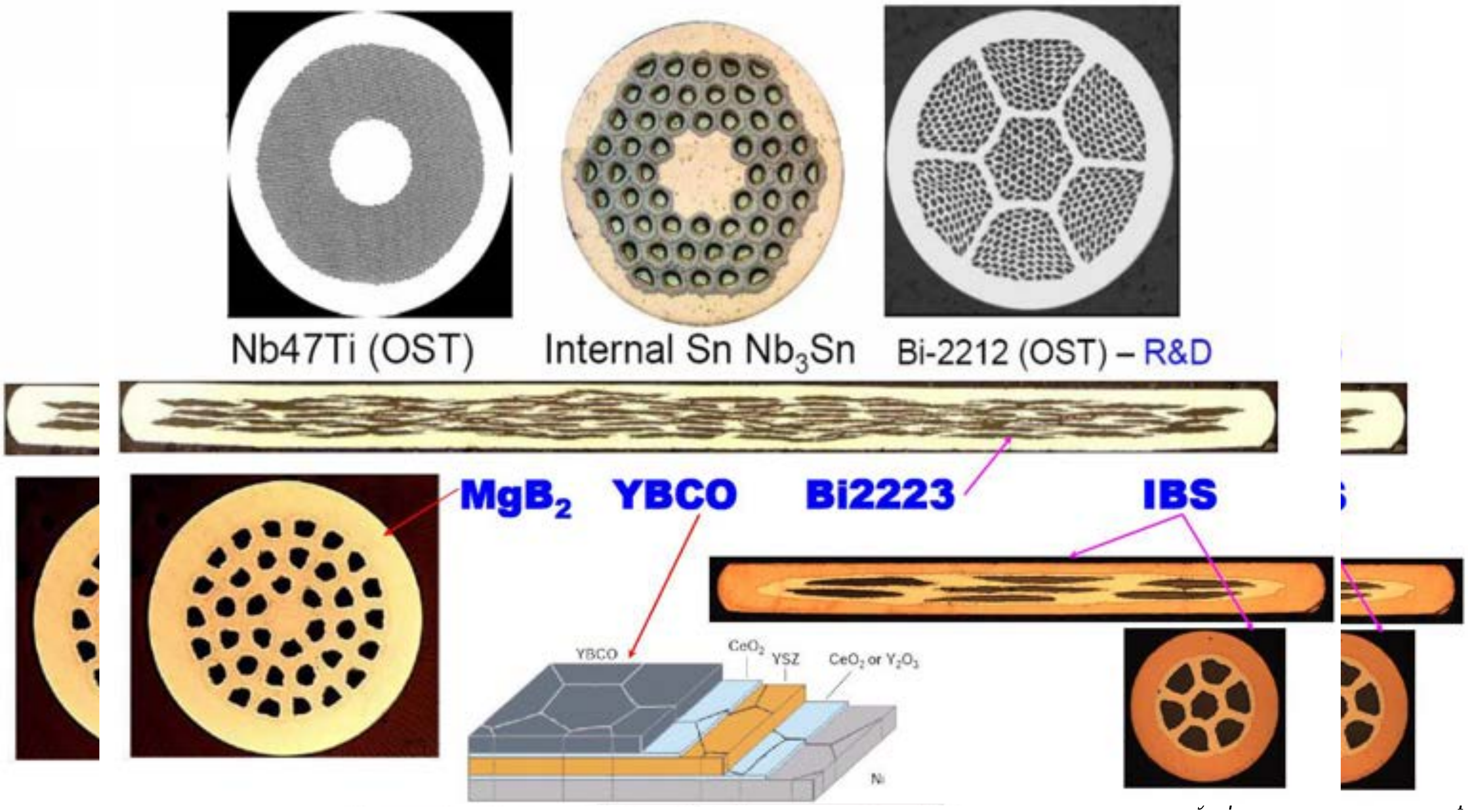
Practical superconductors

LTS, cuprate HTS, MgB_2, Fe-base

Practical Materials

- **Commercial production:**
  - Niobium alloys (NbTi, Nb_3Sn etc)
  - **Bi2223, Bi2212** / silver tape - 1st Generation HTS
  - **MgB_2**
- **Pre-commercial: (Ready for commercialization)**
  - **YBCO** 2nd Generation HTS "coated conductor"
- **Laboratory: (in rapid development)**
  - **Fe-based superconducting wires**

Conductor forms of practical superconductors



Iron-Based Superconductors (IBS)

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

T_c= 26 K

February, 2008

Iron-Based Layered Superconductor $La[O_{1-x}F_x]FeAs$ (x = 0.05-0.12) with T_c = 26 K

Yoichi Kamihara,*† Takumi Watanabe,‡ Masahiro Hirano,†§ and Hideo Hosono†‡§

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

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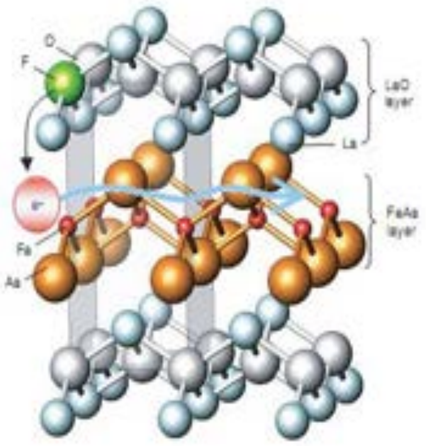
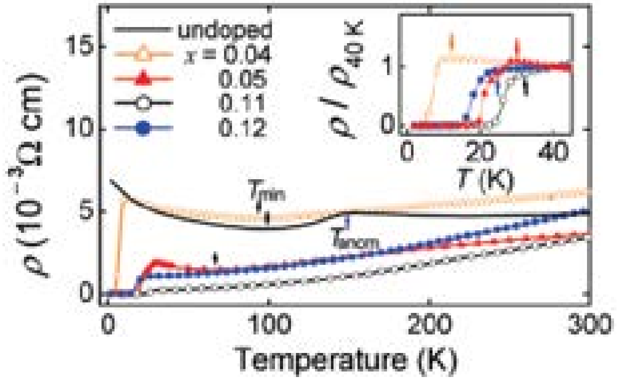
Received January 9, 2008

Abstract:

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



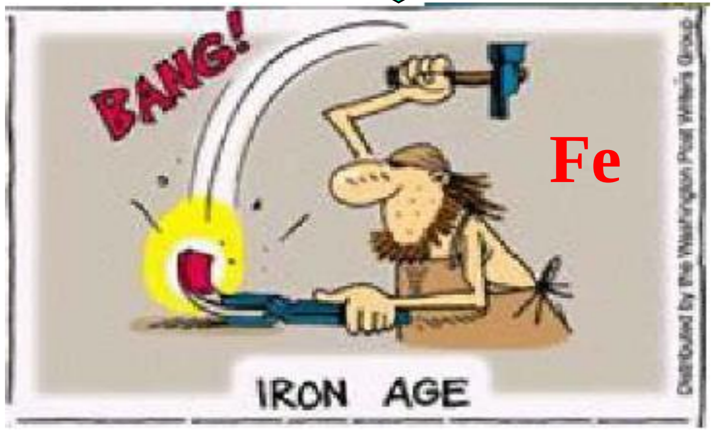
細野秀雄
Hideo Hosono



In 2008 it started the iron age!

Cu

Cuprates

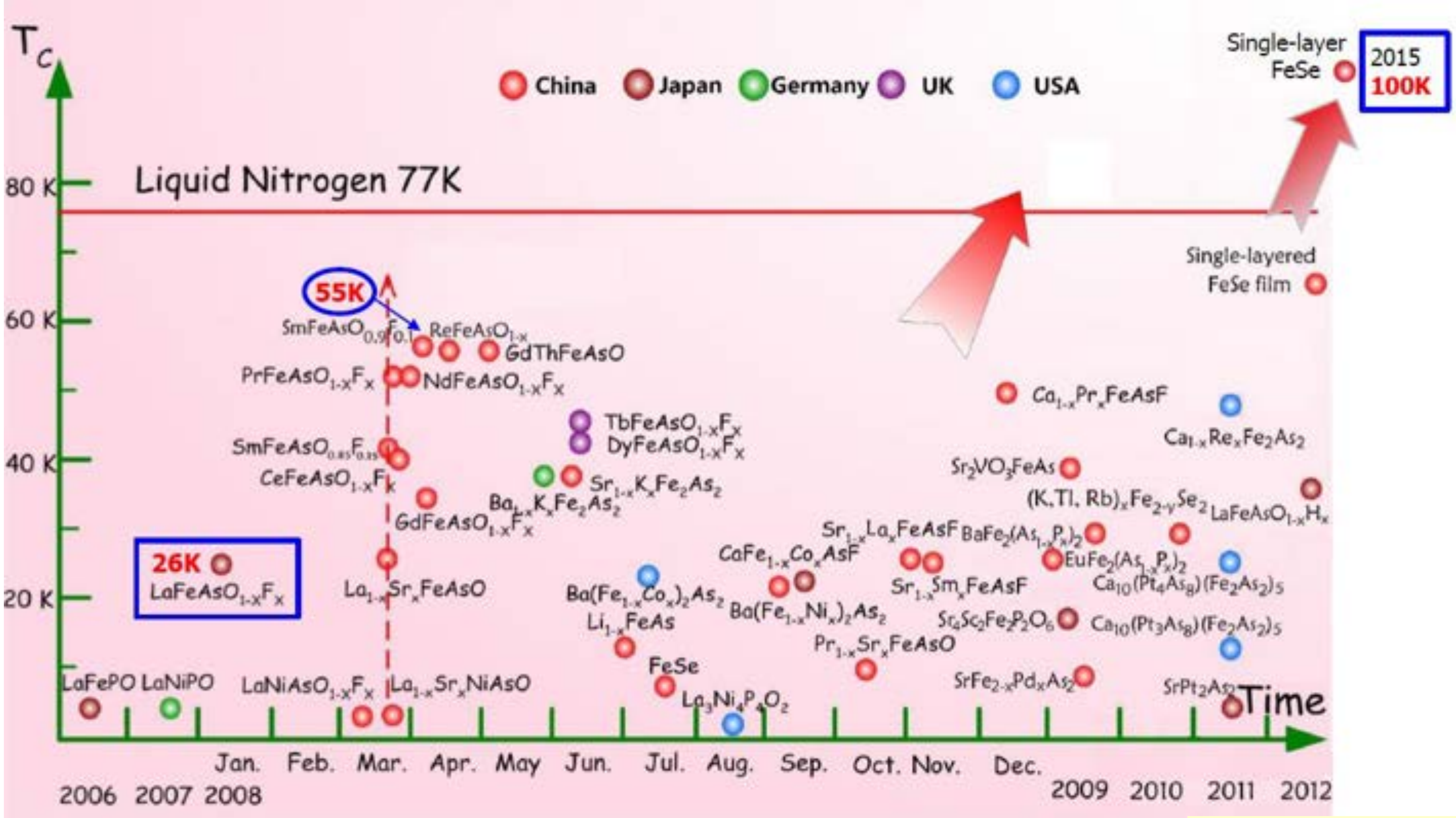


Fe

Pnictides

Iron Man : In cinemas from Paramount Pictures and Marvel Entertainment

IBS families -- T_c is quite high

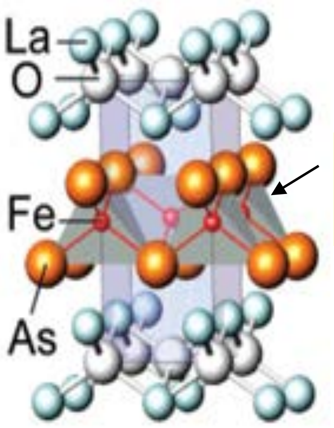


Courtesy: Huiqian Luo, IOP-CAS

Major classes of IBS families

Like the case of cuprates (**CuO_2 layer**), **IBS** has the **FeAs layered** structure alternating with spacer or charge reservoir block.

1111 Phase LnOFeAs

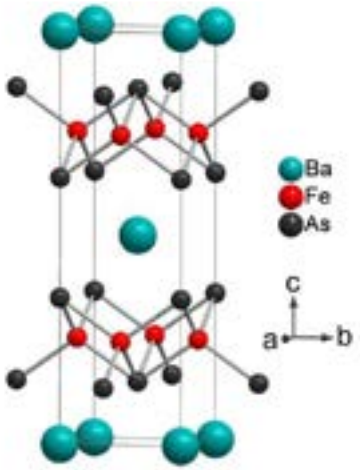


FeAs layer

***T_c* ~55 K**

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

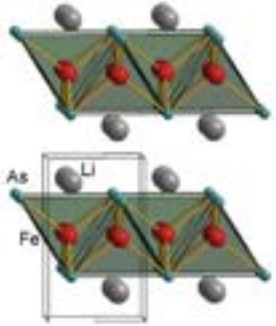
122 phase AFe_2As_2 (A=Ba, Sr, Ca)



***T_c* ~38 K**

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

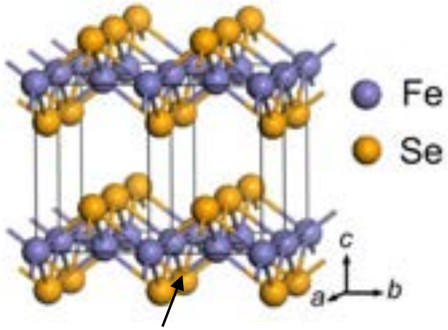
111 phase LiFeAs



***T_c* ~18 K**

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

11 phase FeSe

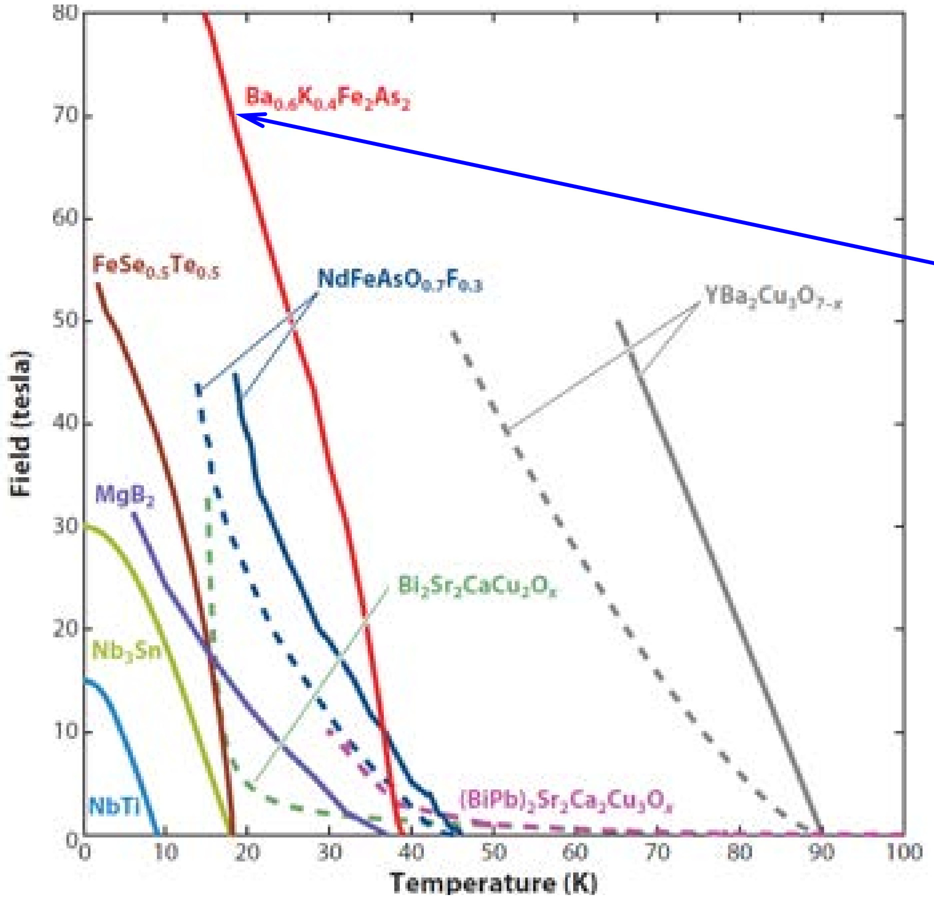


FeSe layer

***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 IBS



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

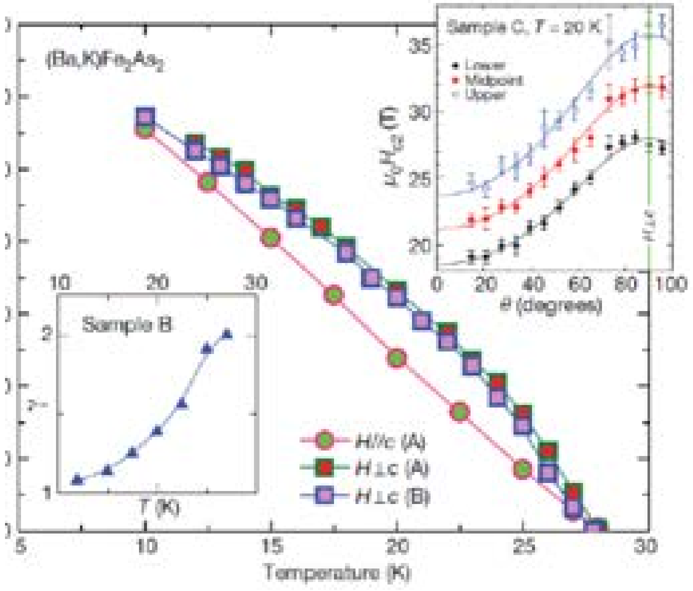
At 20 K, the H_{c2} can be >70 T where IBS outperform both MgB_2 and Bi-2223.

- **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**

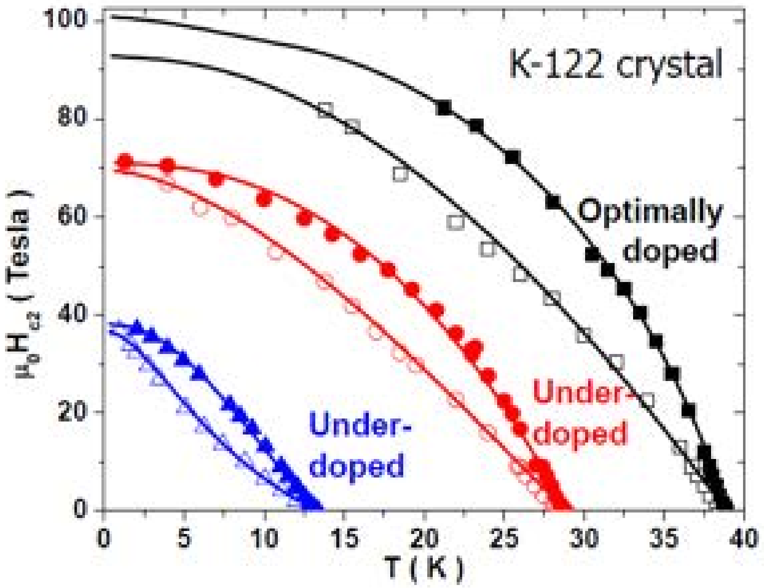
The extremely high H_{c2} in IBS shows a great potential for applications in high field magnets, e.g., H > 20 T, which cannot be achieved via LTS and MgB_2.

122 IBS - small anisotropy γ

H_c anisotropy



uan et al. Nature 457, 565 (2009)



Tarantini et al. PRB 86, 214504 (2012) 2)

J_c anisotropy

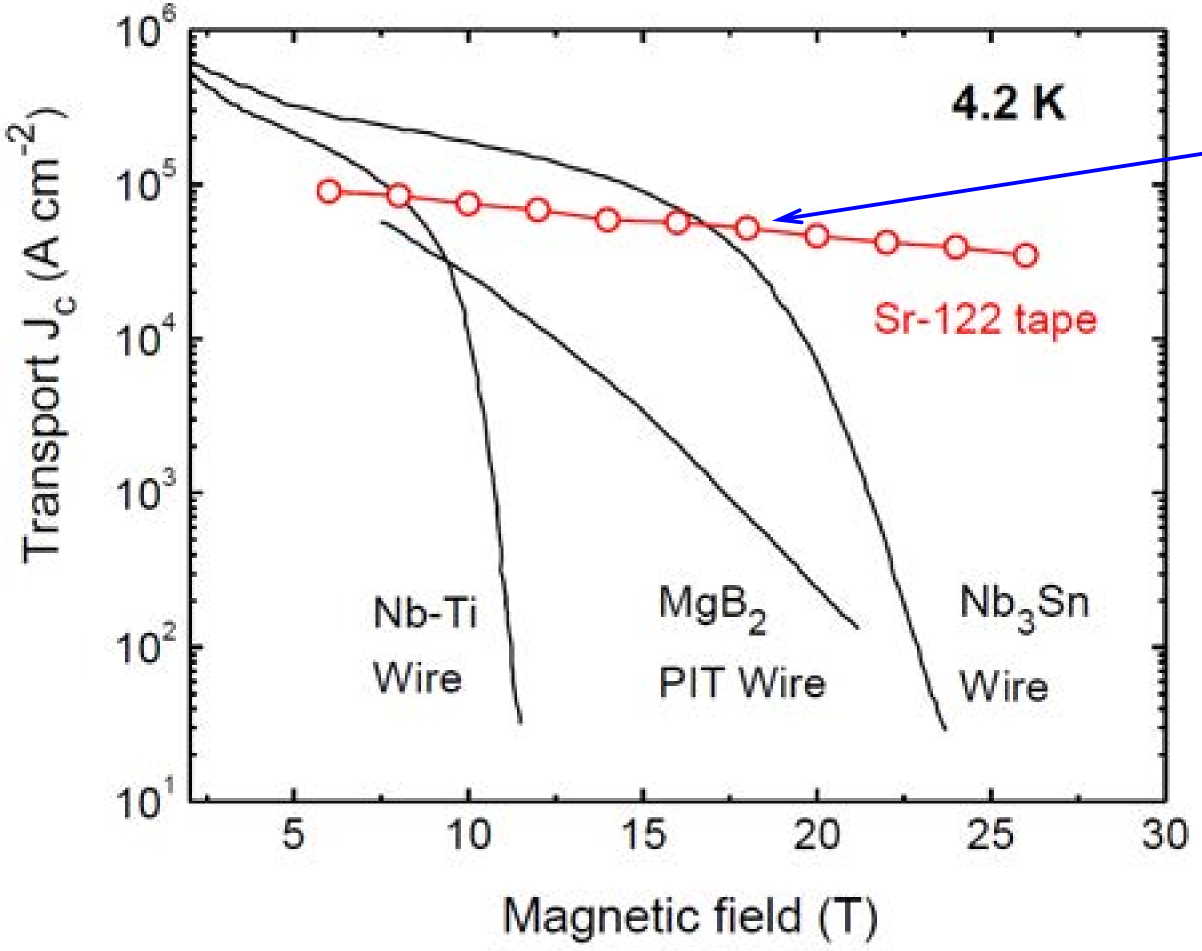
Materials	anisotropy γ
$Bi_2Sr_2CaCu_2O_{8+\delta}$	∼100
$YBa_2Cu_3O_7$	∼7
$Ba_{0.6}K_{0.4}Fe_2As_2$	**< 2**
MgB_2	∼3.5

40

maller than HTS and MgB_2

- **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**

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



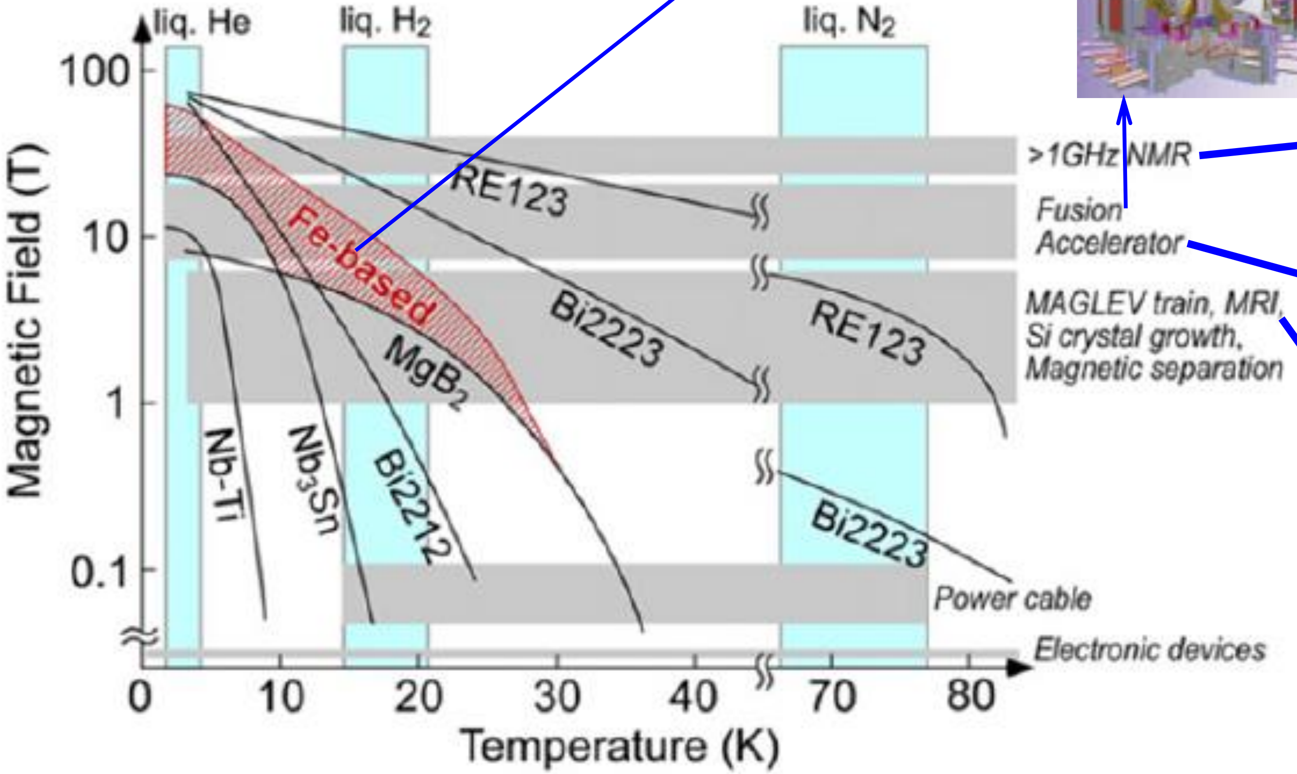
122 IBS wire:
Large J_c, at H > 20T

J_c shows very weak field dependence in high fields

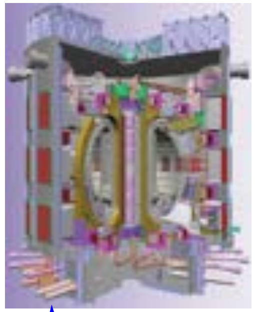
I_c data of Sr-122 tape,
measured in 2013 at HFLSM, Sendai

IBS potential for high-field applications

Working Temp:
4.2 K – 30 K



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



ITER
15T (4.2K)

>1GHz **NMR**
>23.5T

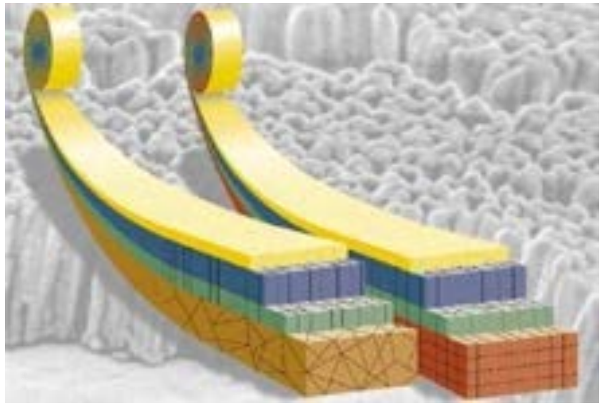
Accelerator (20T)

MRI
(14T)

Development of high-performance conductors is essential

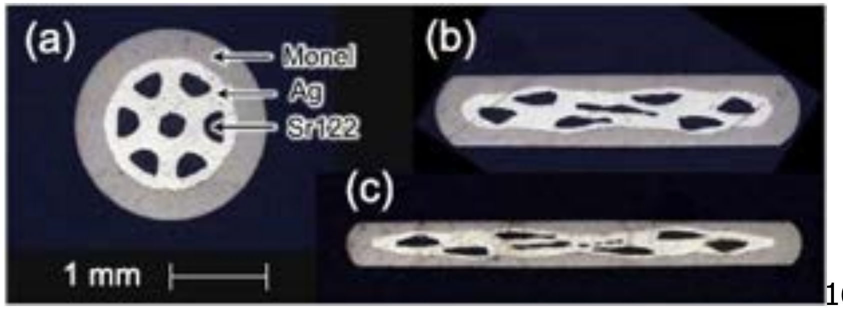
Two routes to develop High-J_c IBS conductors

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

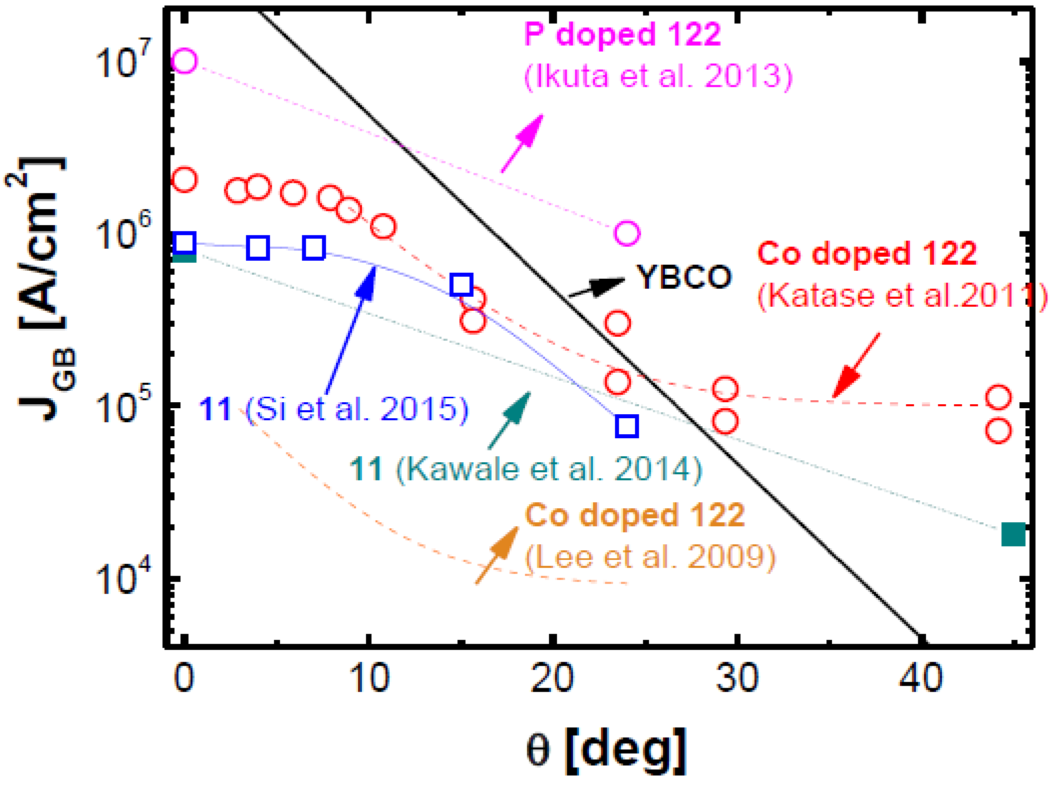


Courtesy of C. Ferdeghini

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



Grain boundary nature of 122 and 11 IBSs



M. Putti presented at EUCAS-2015

122 bicrystals
11 bicrystals

- **Drawback:** J_c **decreases exponentially with increasing GB angle**
- **Advantage: the critical angle θ_c of IBS GBs is 9º, larger than YBCO (θ_c~5º)**

- 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.

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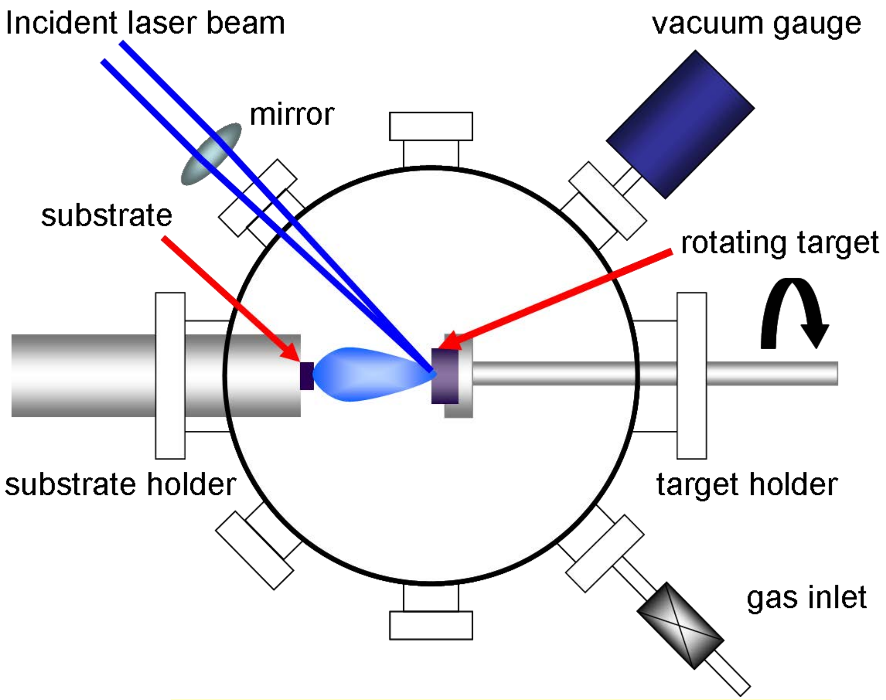
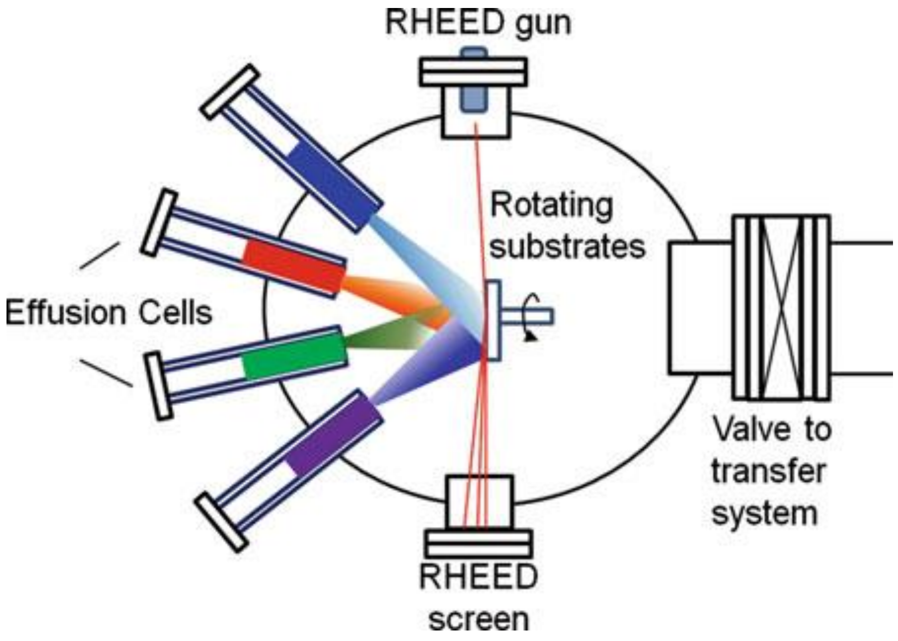
4 Conclusions

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.**

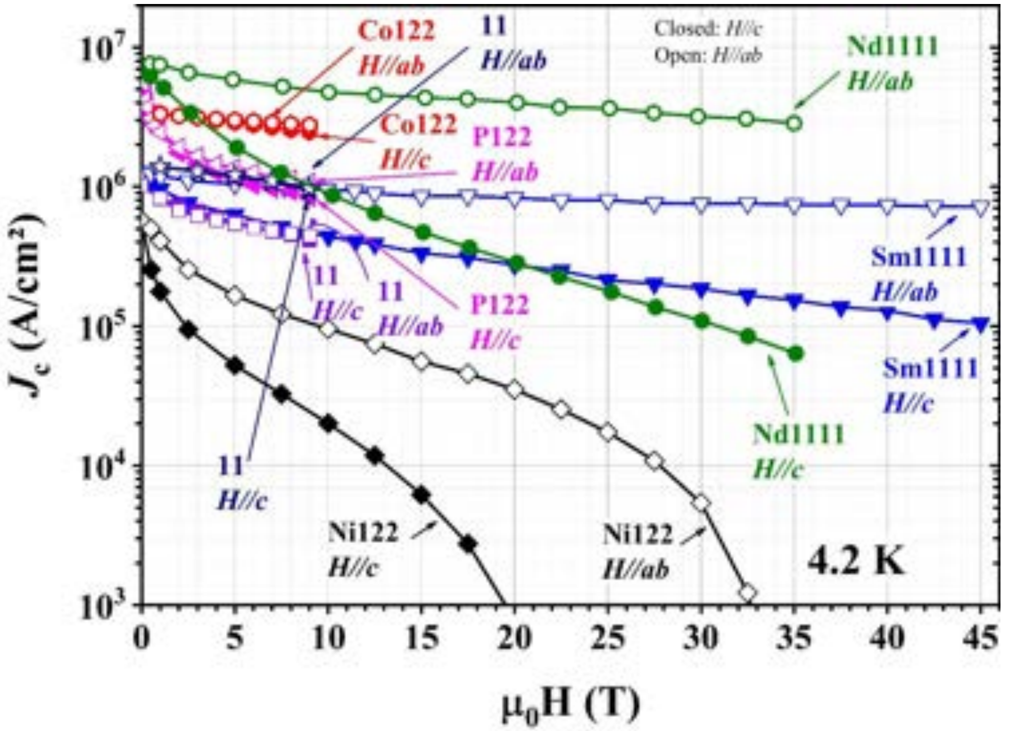


PLD - Pulsed Laser Deposition



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.

	J_c @ 4.2K , 0T	$J_{c//ab}/J_{c//c}$
1111	7.6×10^6 A/cm²	5-30
122	6.3×10^6 A/cm²	< 2
11	>10^6 A/cm²	< 1.5

$FeSe_{0.5}Te_{0.5}$ films on CaF_2: (PLD)

J_c = 0.95 MA/cm² (4.2 K, 9 T)

Ba122:Co films on CaF_2: (PLD)

J_c > 2.6 MA/cm² at 9 T, 4.2 K

Nd-1111 films (22 nm) on MgO: (MBE)

@4.2 K, 35 T

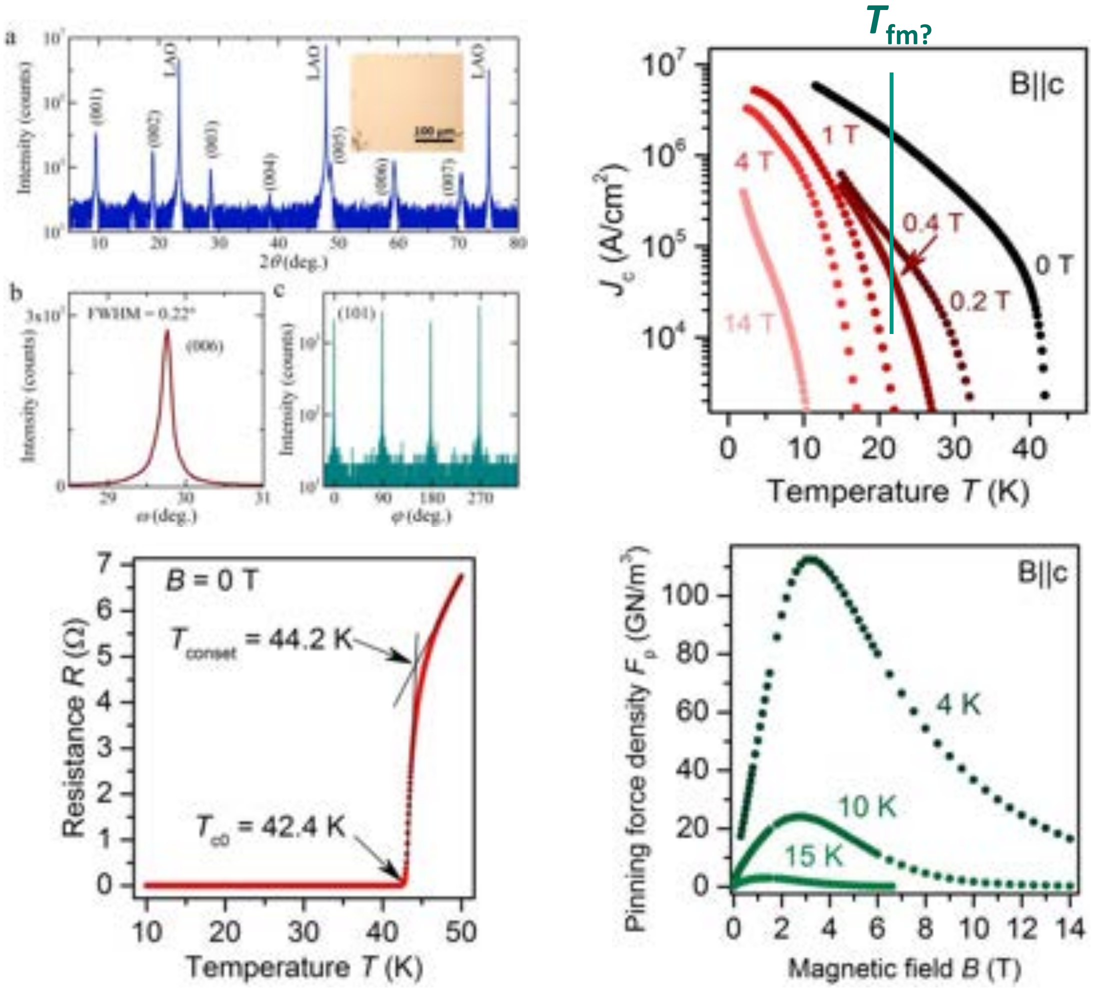
$J_{c//ab}$ = 2.2 MA/cm², $J_{c//c}$ = 70 kA/cm², ⇒ γ = ~30

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

FeSe-11111 on LAO substrate by a hydrothermal method

--grown by X L Dong group

-- Measured by Holzapfel group

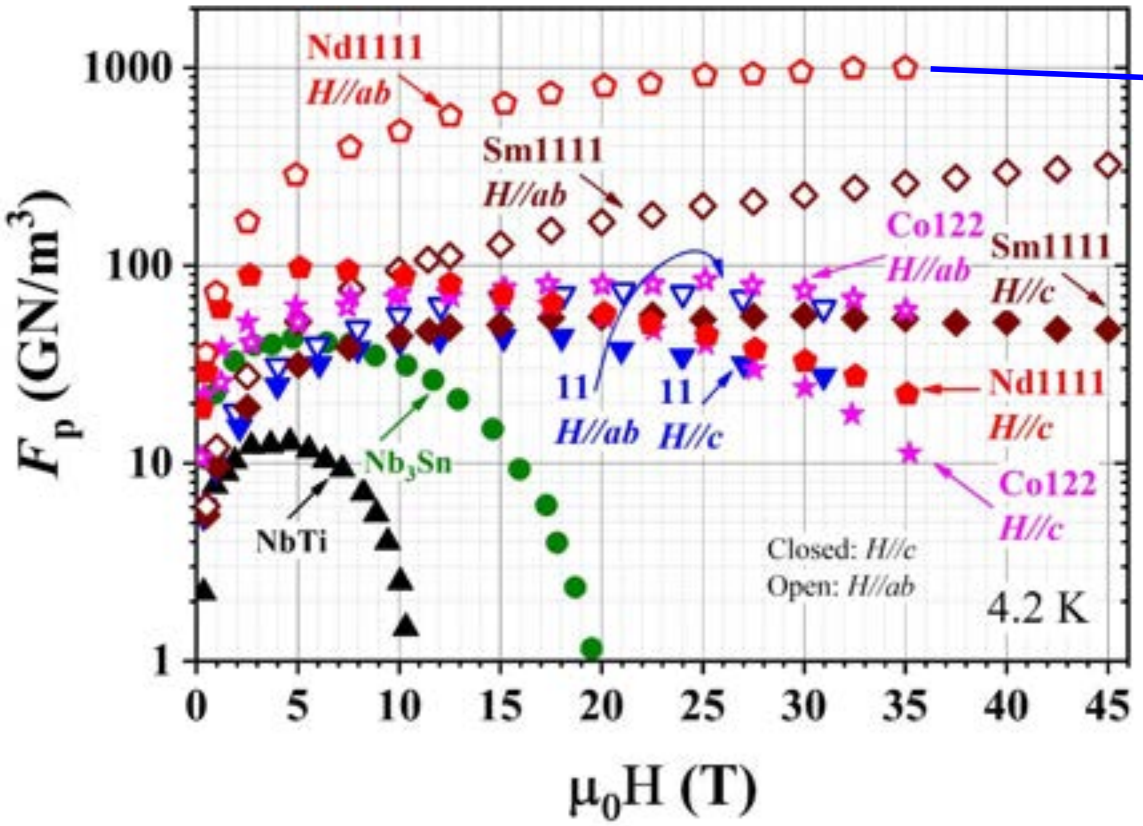


- These films are highly epitaxial with $T_{c,zero}$=42.4 K, anisotropy near T_c of ~5.6.
- Strong temperature and field dependencies of J_c
- Self-field J_c values well above 1 MA/cm² below 20 K
- Maximum pinning force density: ~100 GN/m³ at 4 K (comparable to highest values in Nd1111)

Y.L. Huang et al. ***CPL*** 34 (2017) 077404
J. Hänisch, Y. Huang, XL Dong, B. Holzapfel, ZX Zhao, unpublished

Large pinning force in IBS thin films

Extraordinary future for high field applications



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)

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

2019

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

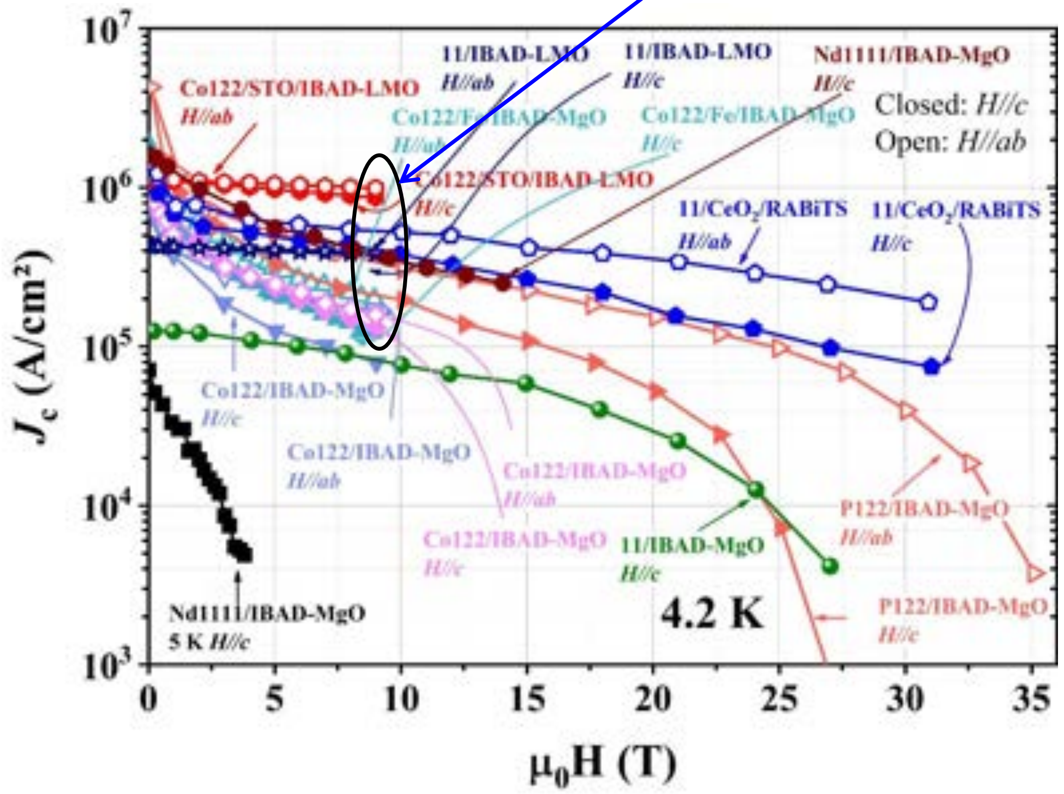
11 (4.2 K, 21T)
$F_{p,max}$= 75 GN/m^3

Nb_3Sn(4.2K, 5T)
F_p,max= 42 GN/m^3

Nb-Ti (4.2K, 5T),
F_p,max= 16.5 GN/m^3

Sumary: 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 ~10T 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.

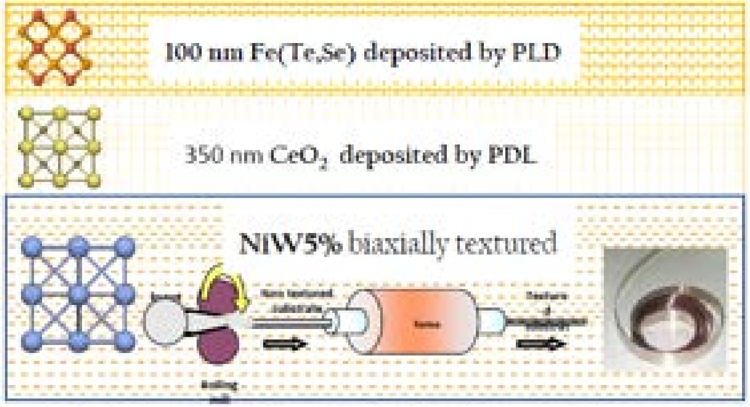
K. Iida *et al*. APL 105, 172602 (2014)
Courtesy of K. Iida
S. Trommler *et al*. *SuST* 25, 084019(2012)
T. Katase *et al*. *APL* 98, 242510 (2011)
H. Hiramatsu *et al*. *SuST* 30, 044003(2017)
K. Iida *et al*. *Sci. Rep.* 7, 3995 (2017)
Z. T. Xu *et al*. *SuST* 31, 055001 (2018)
Z. T. Xu *et al*. *SuST*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

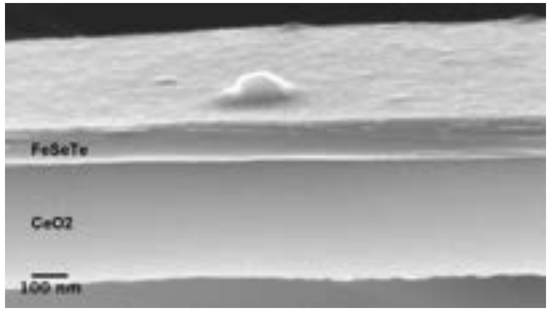
IBS CC--towards simpler template: $NiW5\%+CeO_2$

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

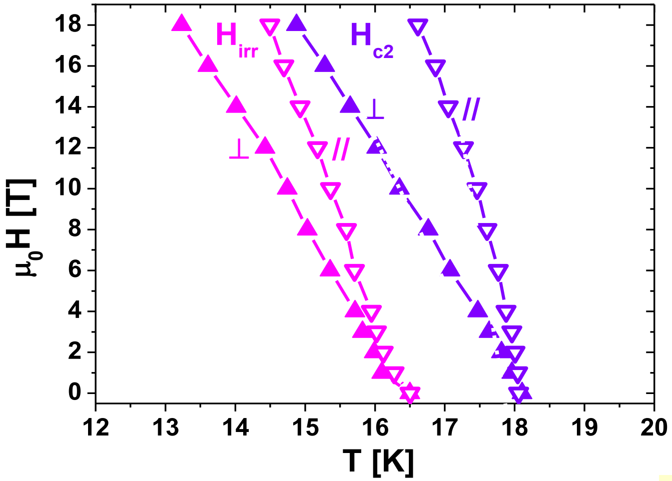
-- by C. Ferdeghini group



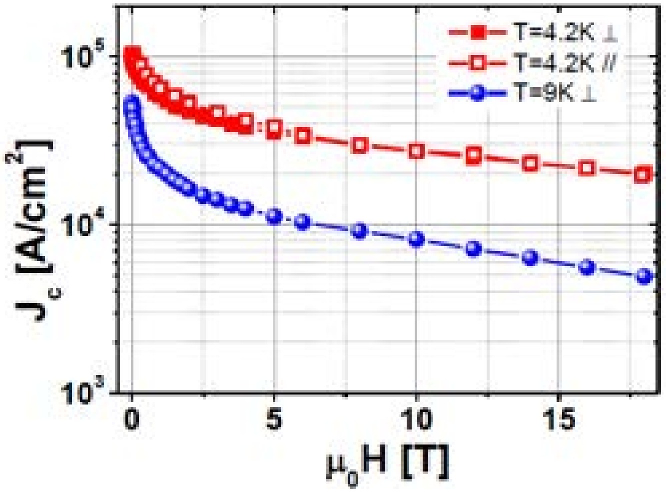
Fe(Se,Te) on $NiW5\%+CeO_2$



- ✓ $J_c = 10^5$ A/cm² @ 4.2K self field
- ✓ $J_c = 3\times10^4$ A/cm² @ 4.2K , 10 T
- ✓ J_c is isotropic



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



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

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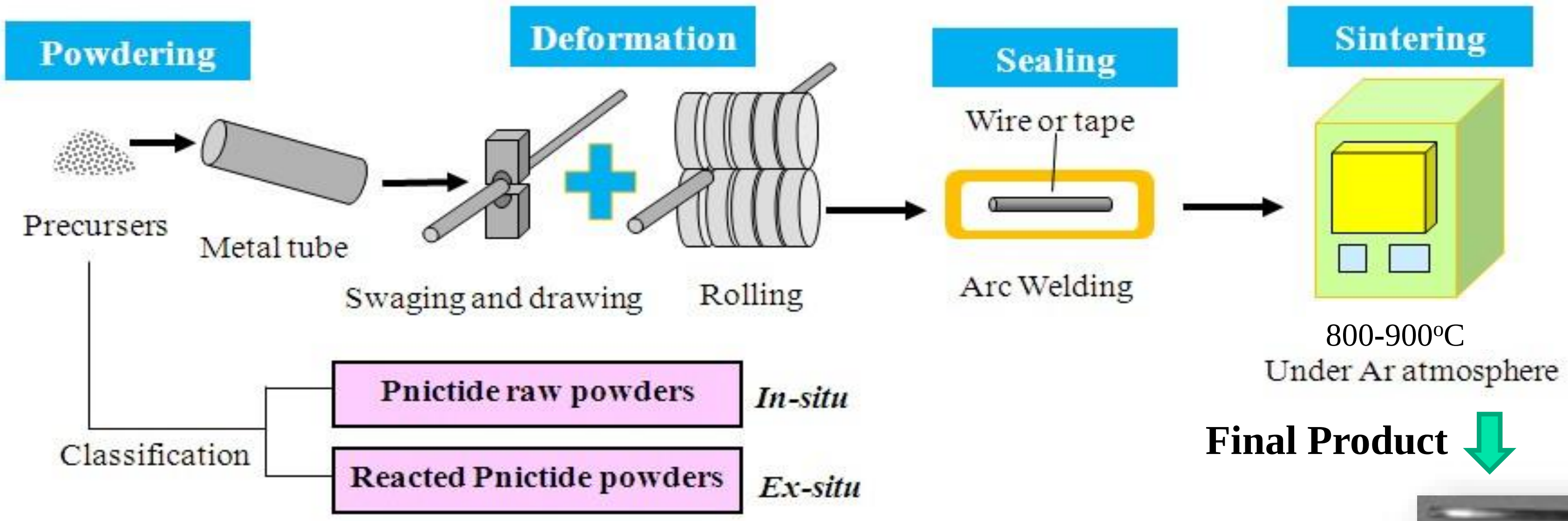
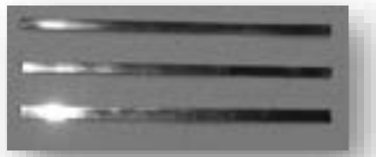
4 Conclusions

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

–Low cost, simple deformation process



Final Product



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

2008.04 | 2009 | 2010 | 2011 | 2012 | 2013 | 2014 | 2015 | 2016 | 2017 | 2018 | 2019

Phase I

The early stage

The first prototype wires

J_c-100 A/cm^2

To start the fabrication of IBS wires

Phase II

The J_c improvement

① Addition + ex-*situ* + texture
J_c-10^4 A/cm^2@10T

Breaking the stagnant situation at that time

② Densification + texture synergic control
J_c-10^5 A/cm^2@10T, 4.2 K

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**
- **Superconducting joints**

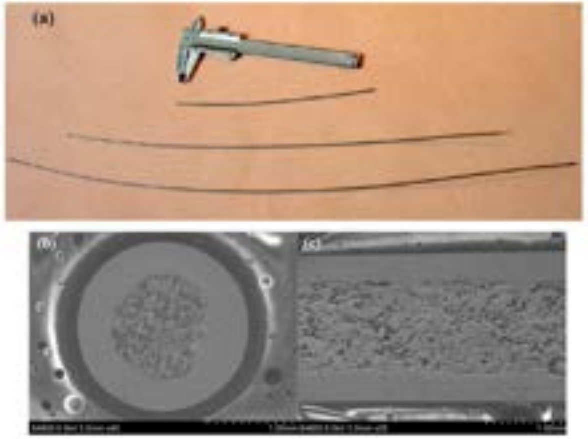
First 10 m IBS wire

First 100 m IBS wire

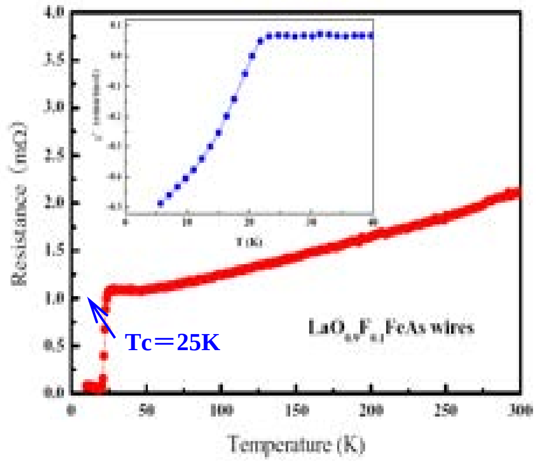
In April 2008, the first pnictide wire was fabricated by the powder-in-tube method

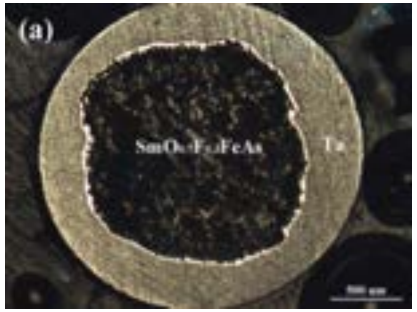
The early wires

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

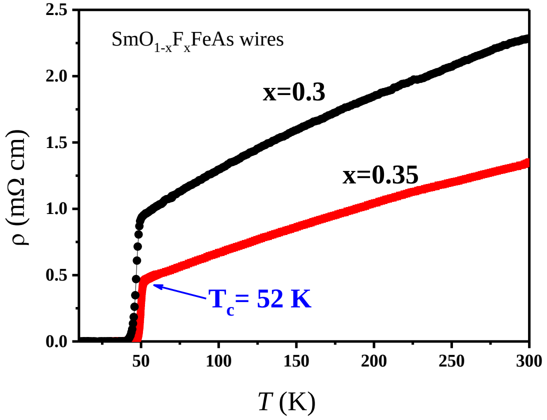


LaOFeAs





SmOFeAs

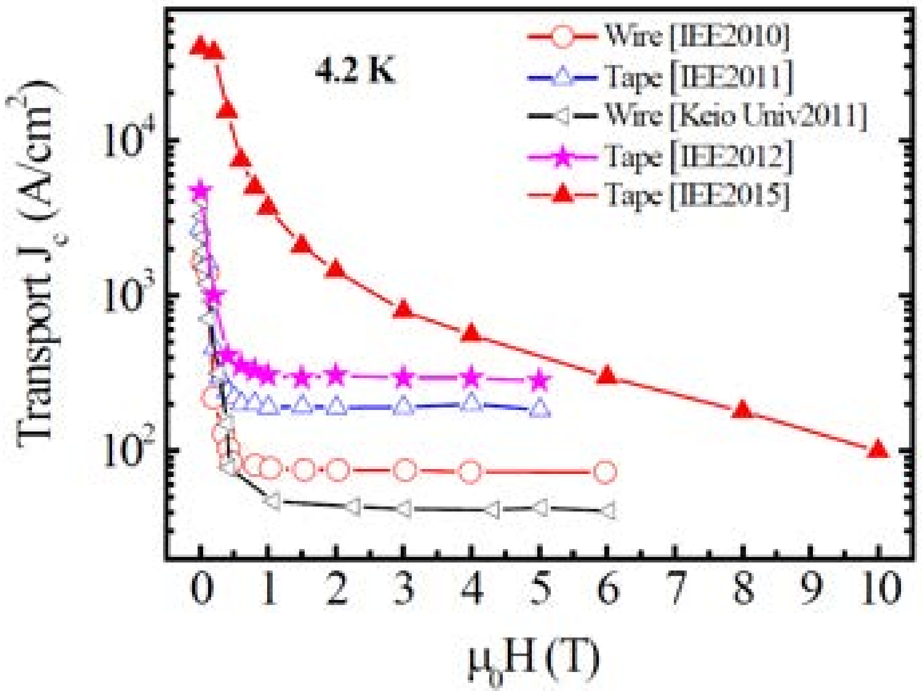


Our group: ***Supercond. Sci. Technol.*** 21 (2008) 105024

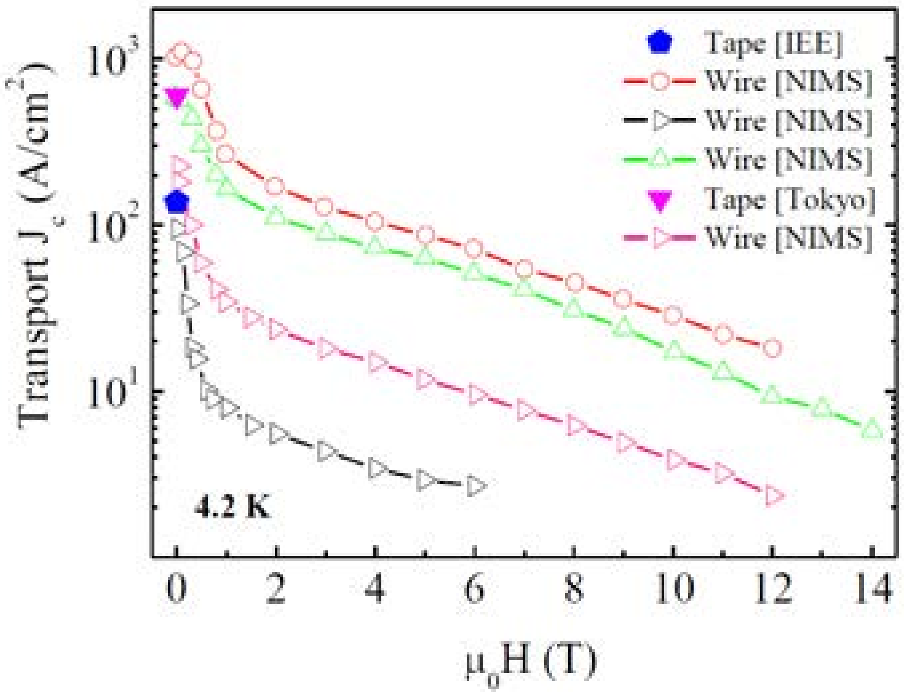
Compared to 122 tapes with J_c of 10^5 A/cm² @ 10 T

1111 and 11 wire and tapes: J_c ~ 200 A/cm² in high fields

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

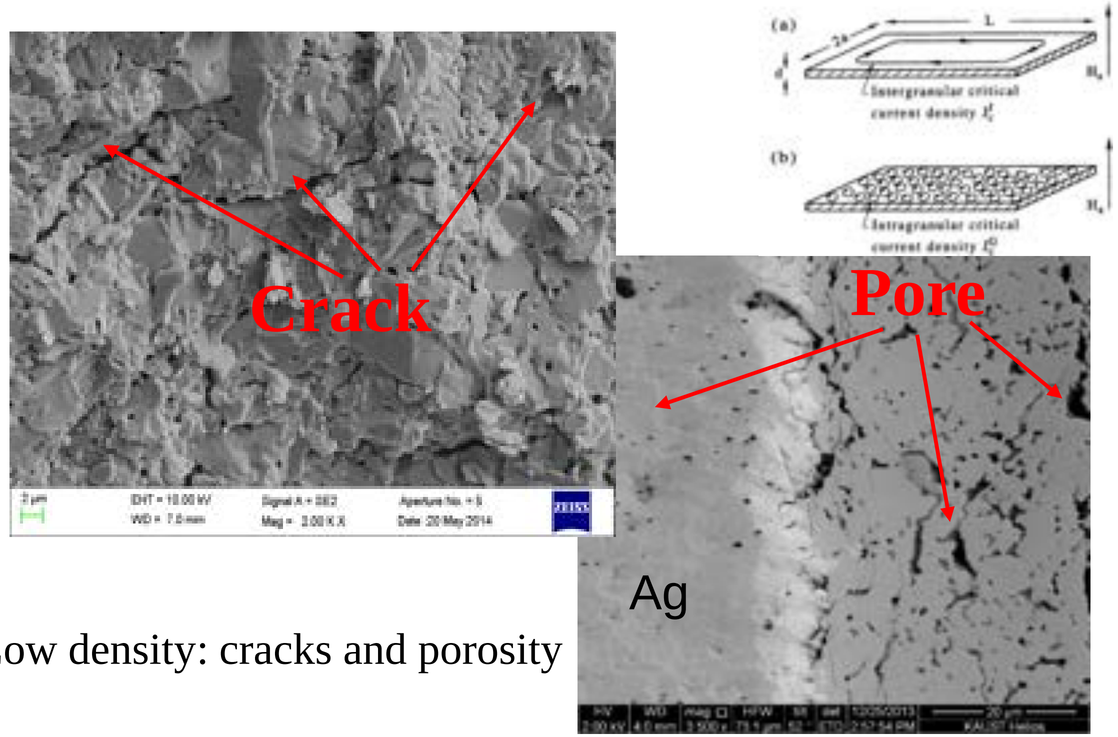


11 type - $FeTe_{1-x}Se_x$



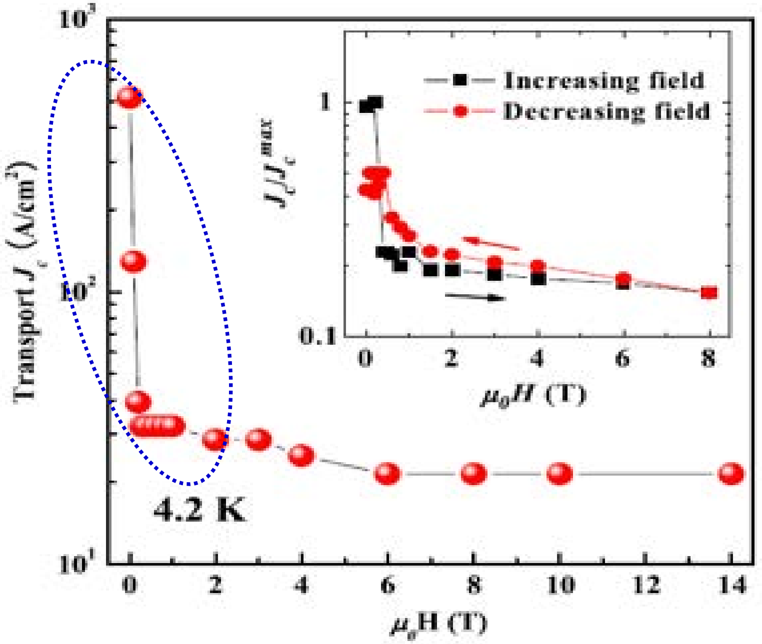
- **The J_c values obtained are still two to three orders of magnitude lower than for the 122 tapes.**
- **1111 wires:** how to control fluorine content during sintering.
- **11 wires:** hard to remove excess Fe.

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



Low density: cracks and porosity

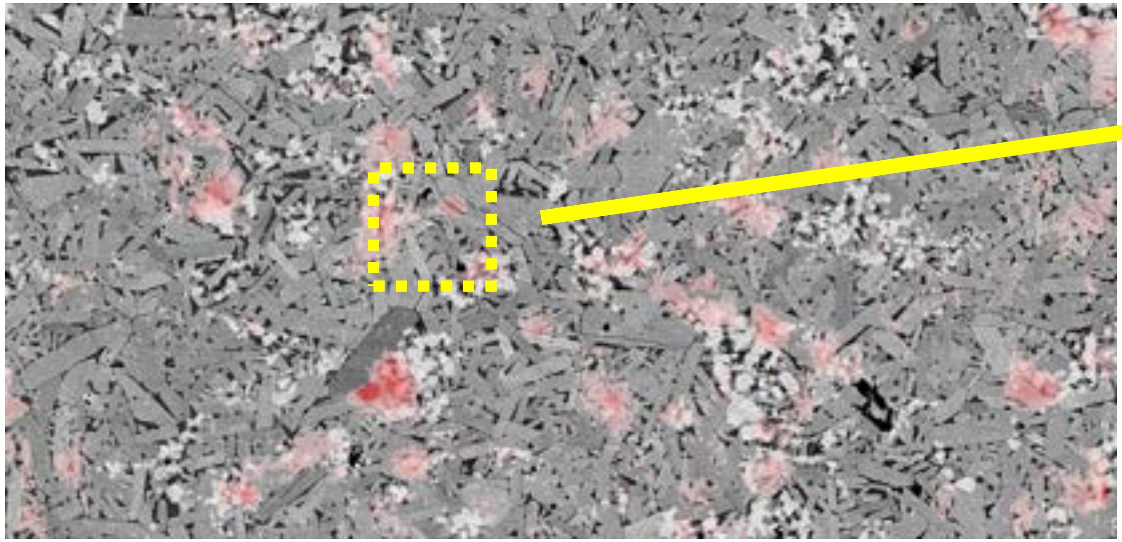
Good connectivity is desirable!



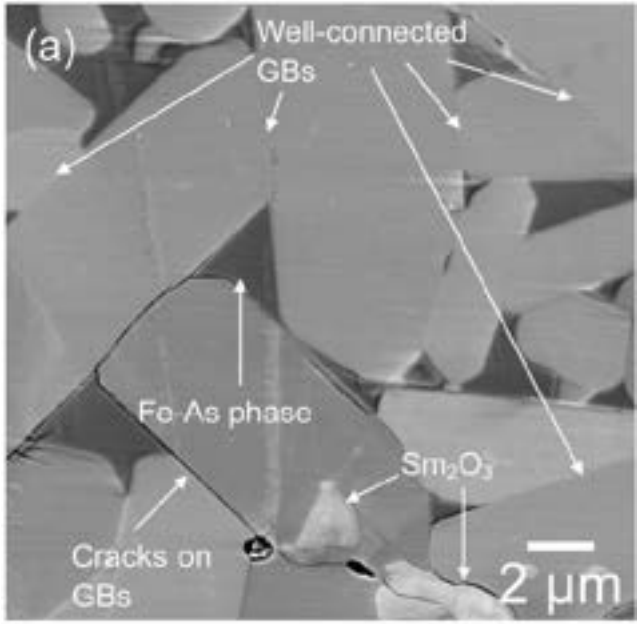
Hysteresis in transport J_c: signature of weak links

- **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



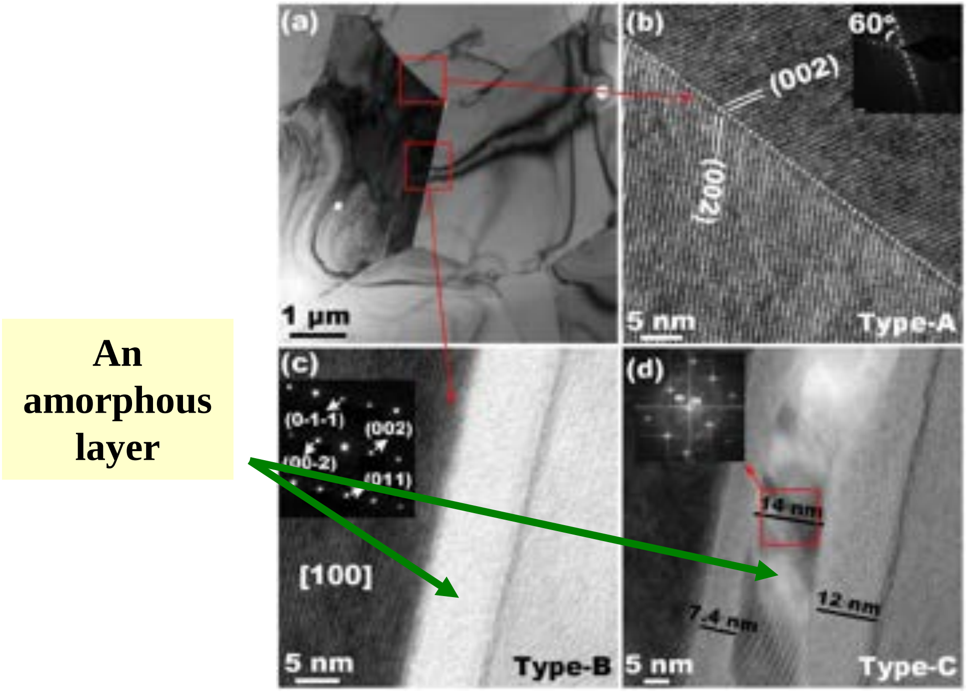
Low Temperature Laser Scanning Microscopy (LTLSM) + SEM



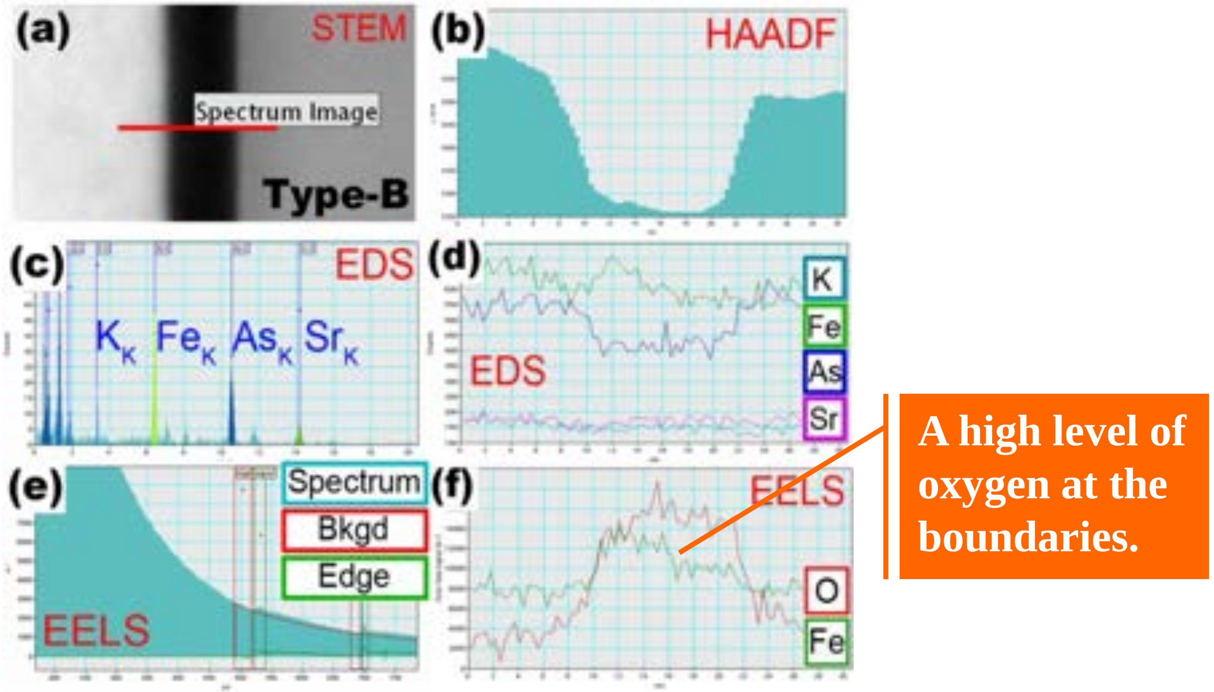
Kametani et al., ***APL***. 95, 142502 (2009)

- **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



10 nm 30 nm



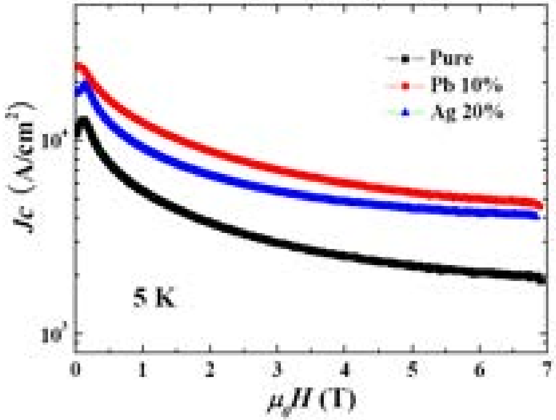
EELS: electron energy loss spectroscopy

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

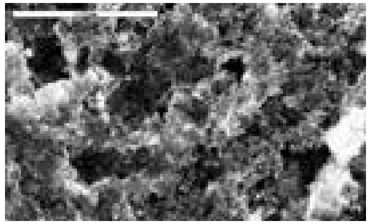
- Obviously, these **O-rich** amorphous layers are related to the introduction of O_2 during fabrication.
- These oxygen-rich layers undoubtedly obstructed many grain boundaries, consequently resulting in a poor grain connection.

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

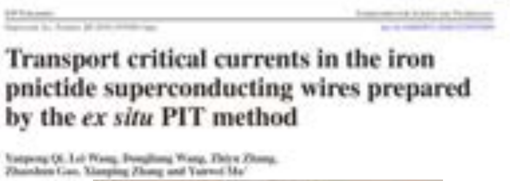
- ***Ex-situ* PIT method:** fewer impurity phases as well as a high density of the superconducting core for the final wires.
- **Ag or Pb** addition to improve the grain connectivity, hence the enhanced J_c.

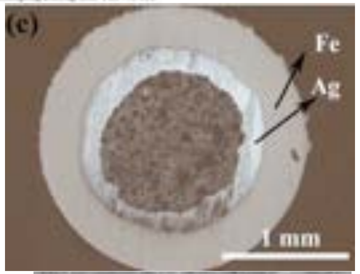


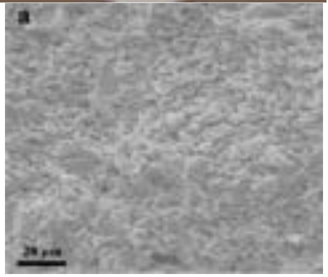
SuST 23 (2010) 025027



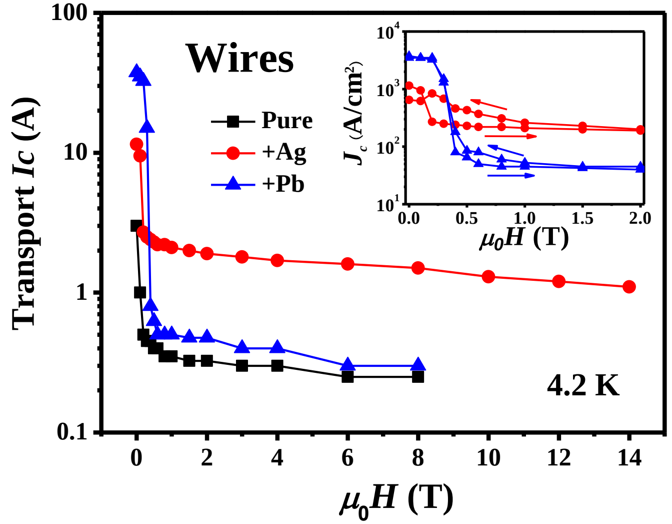
In Situ：loose，more second phases


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





Ex Situ：Dense & more 122



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

SuST 23 (2010) 055009

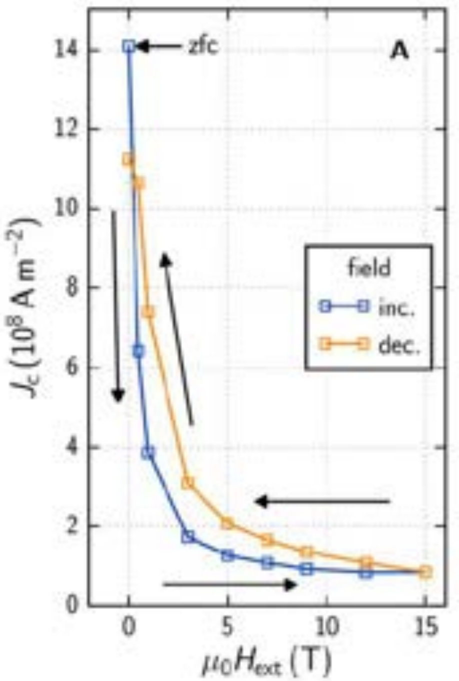
Lessons **learned during the preparation of high quality 122 precursor**

Less O_2 & 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.**

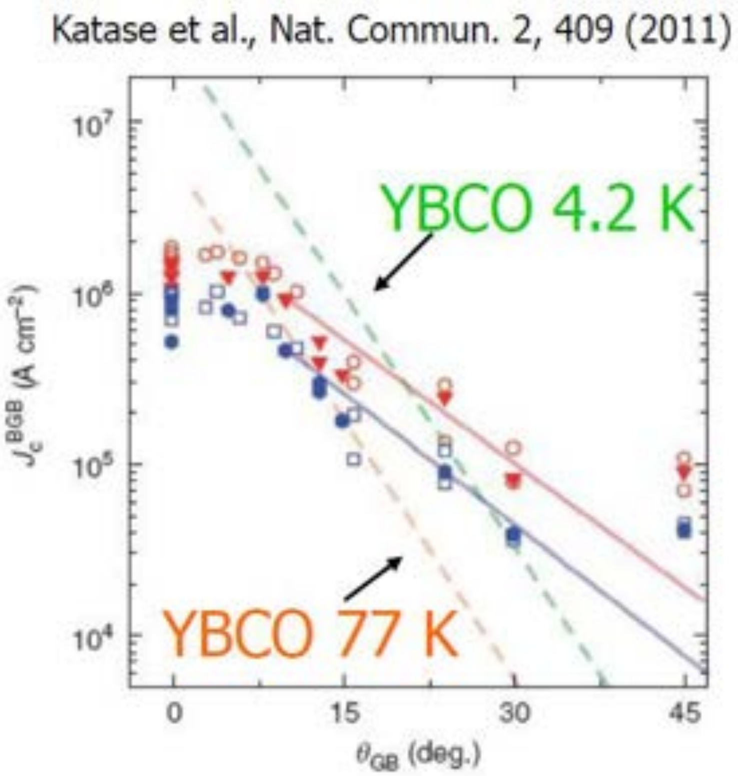
Q2: Weak-link problem - *Intrinsic nature of dissipation*

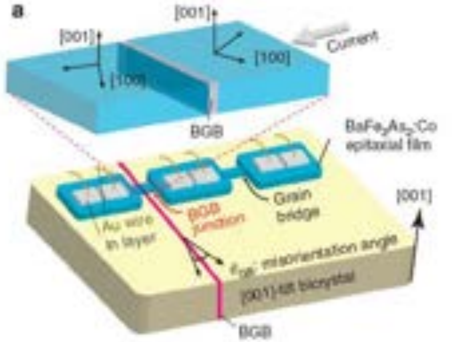
Hecher et al., *SuST* 29 (2016) 025004



Weak link effect

Co doped Ba-122 thin films on bicrystals





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

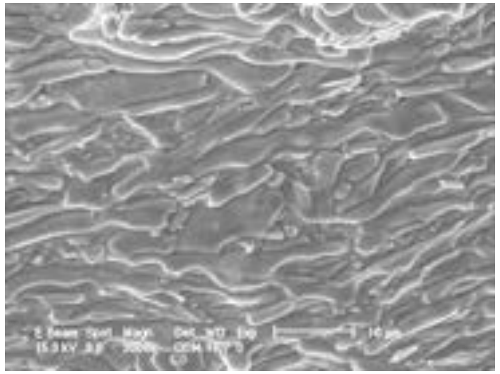
- **One effective method is to engineering textured grains to minimize degradation of J_c across high-angle grain boundaries, like the Bi2223.**

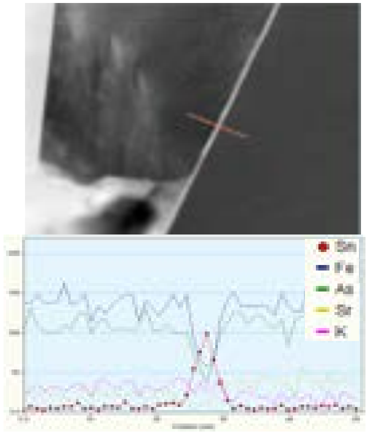
Sr-122+Sn

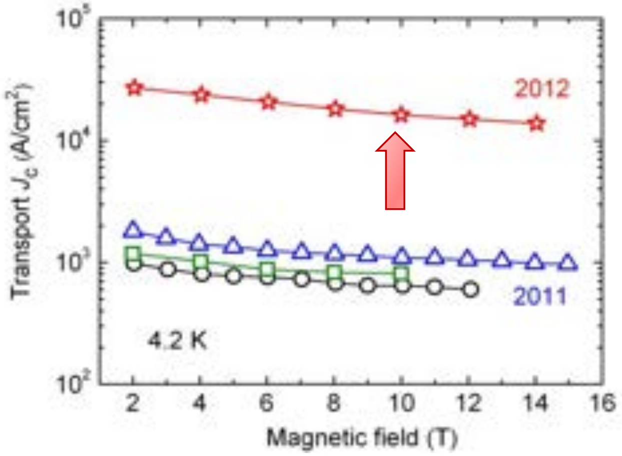
Rolling by a large reduction rate

To form textured grains

Annealing for better connection



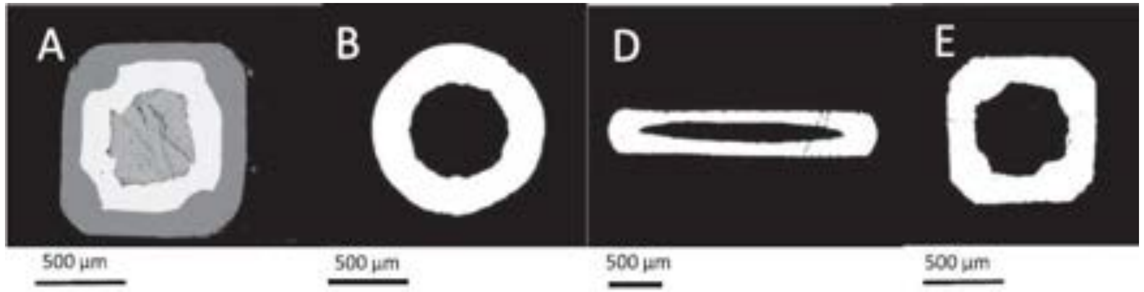


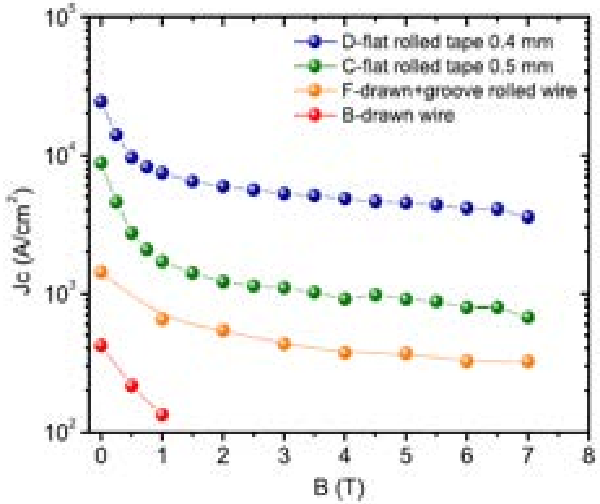


The above rolling strongly improved c-axis texturing, and effectively reduce the large angle GBs, thus J_c was enhanced by **an order of magnitude, from 10^3 to 10^4 A/cm^2**.

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

Optimization of mechanichal-thermal treatments for PIT Ba-122 tapes



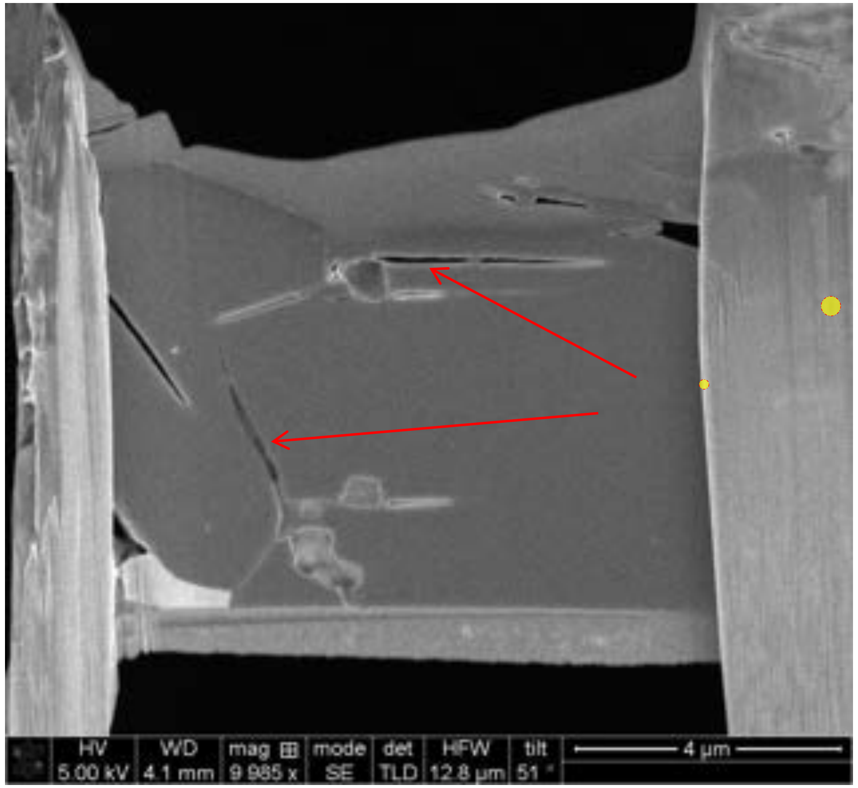


Sample (sheat)	Working	Size
A (Ni/Ag)	groove rolled wire	1×1 mm^2
B (Ag)	drawn wire	Ø 0.9 mm
C (Ag)	drawn + flat rolled tape	0.5 mm
D (Ag)	drawn + flat rolled tape	0.4 mm
E (Ag)	groove rolled wire	0.9×0.9 mm^2
F (Ag)	drawn + groove rolled wire	0.9×0.9 mm^2
G (Ag)	groove rolled + flat rolled tape	0.4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

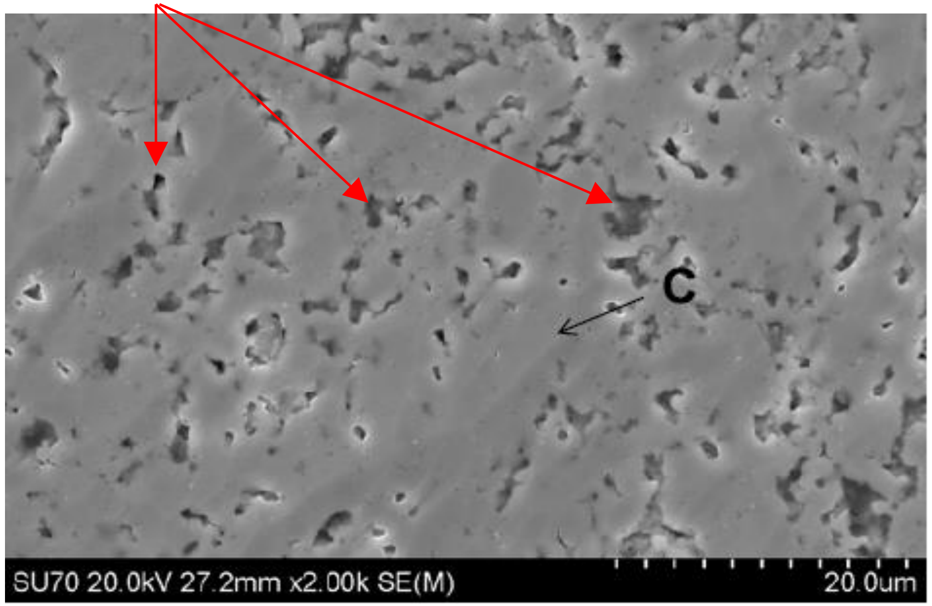
Flat rolling process is more effective rather than groove rolling to achieve high J_c!

A. Malagoli et al., ***SuST*** 28 (2015) 095015

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



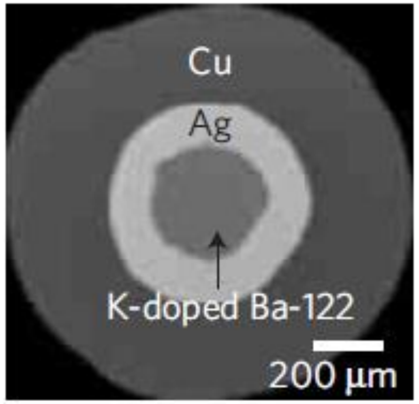
Porosity



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



First Ba-122 round wire made in Florida State University

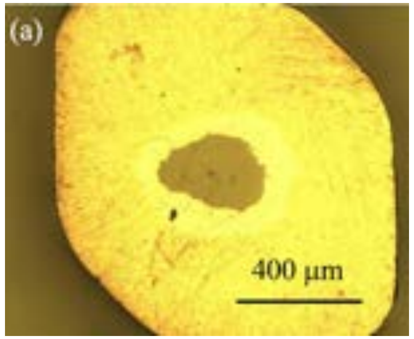
Weiss et al., ***Nature Mater.*** 11 (2012) 682

J_c (4.2 K, 10 T) = ~1×10^4 A/cm^2 @0T, J_c >10^5 A/cm^2

192 MPa, 600 °C

HIP
(during reaction)

- 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

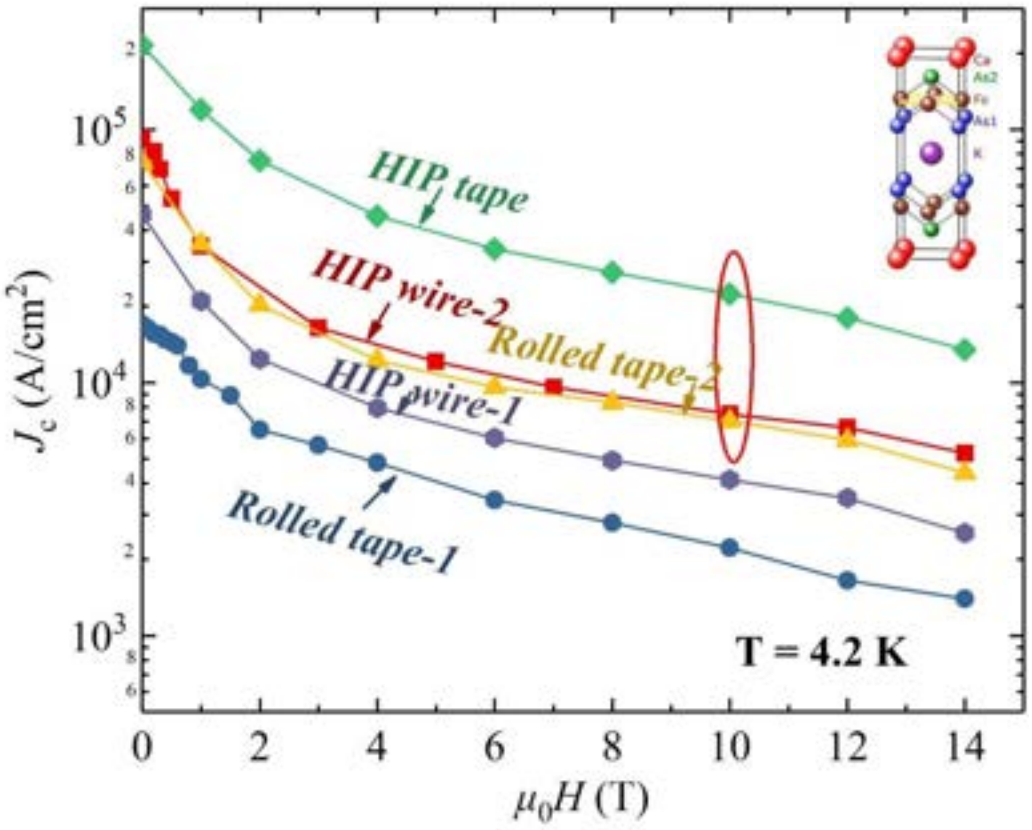
J_c (4.2 K, 10 T) = 3.8×10^4 A/cm^2 @0T, J_c >1.7×10^5 A/cm^2

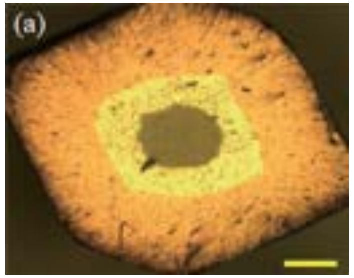
175 MPa, 700 °C

Latest: For BaNa-122 HIP wire, J_c **(10T) = 4×10^4** A/cm^2. → Courtesy of T. Tamegai

Hot isostatic pressing (HIP)--$CaKFe_4As_4$ (1144) wires & tapes

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





The highest J_c at 10 T

$CaKFe_4As_4$	J_c (4.2 K, 10 T)
HIP tape	22000 A/cm²
HIP wire	7600 A/cm²

- **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.**

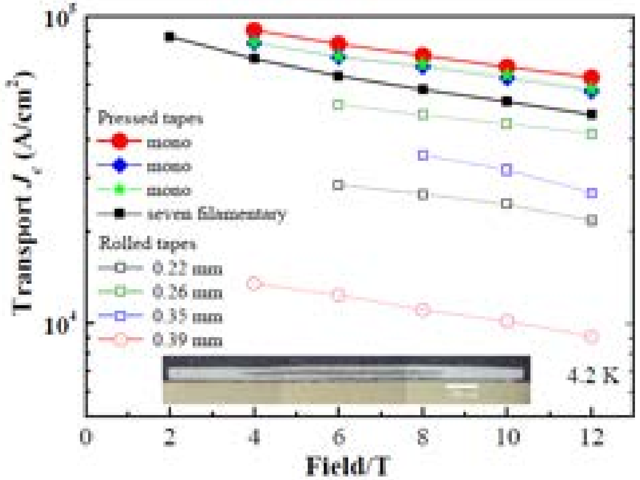
Cold pressing (before reaction)

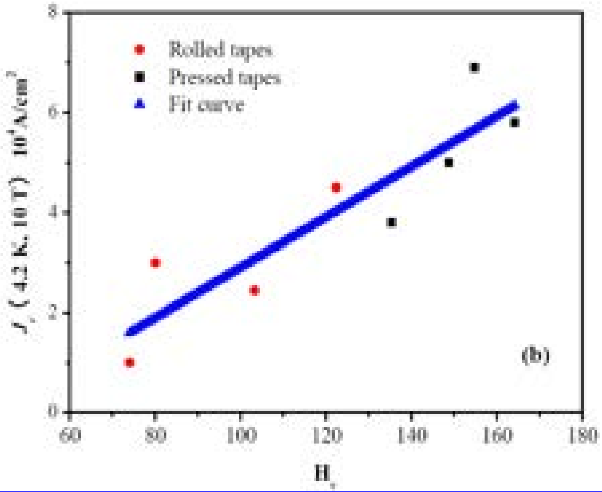
Ba-122 tapes by combined the rolling, cold pressing and sintering process-- Denser core yields higher J_c

--Ag-sheathed Ba122 tapes

Steps:

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/cm²

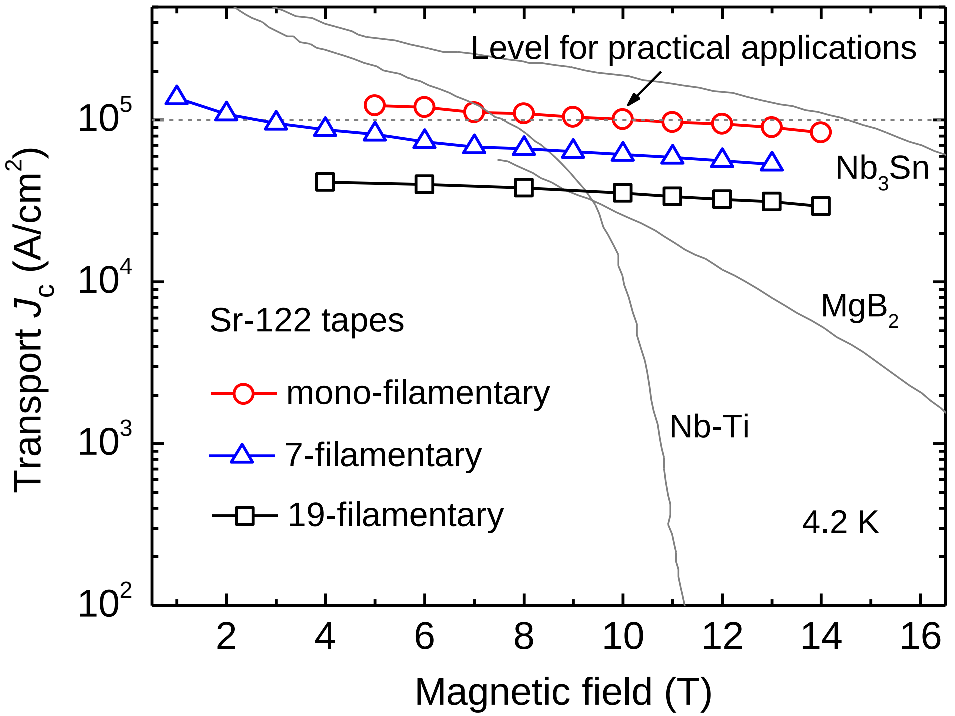
Cold pressing always results in fatal micro-cracks, which cannot be healed by subsequent heat treatment.

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

Hot pressing (during reaction)

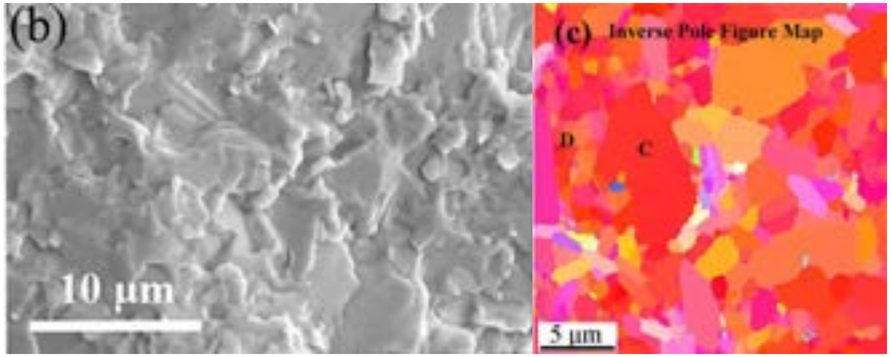
Very high transport J_c were achieved in Sr122/Ag tapes: $J_c > 10^5$ A/cm² (4.2 K, 10 T) - by hot pressing

First to reach practical level J_c!



30 MPa, 850~900 °C

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



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

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

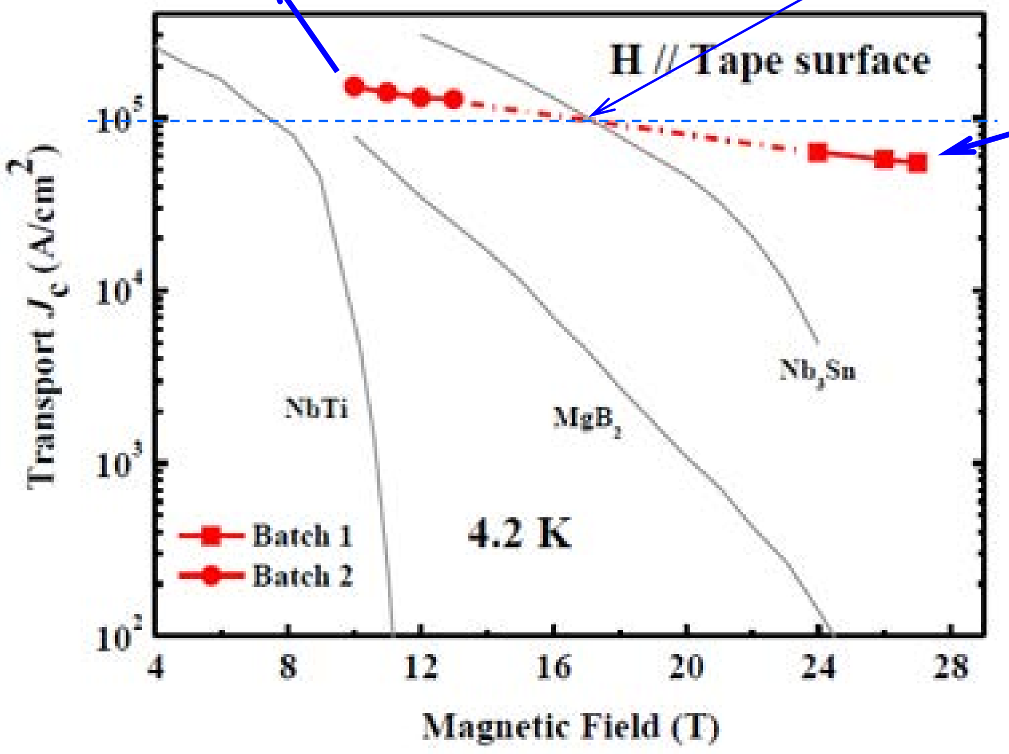
Recently

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

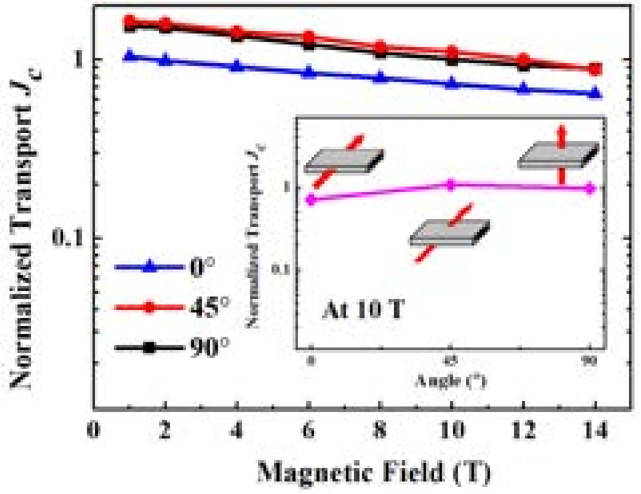
New record transport J_c up to 1.5×10^5 A/cm^2 @ 4.2 K, 10 T was obtained by Hot Pressing

I_c = 437 A

At 18 T, J_c = ~10^5 A/cm^2



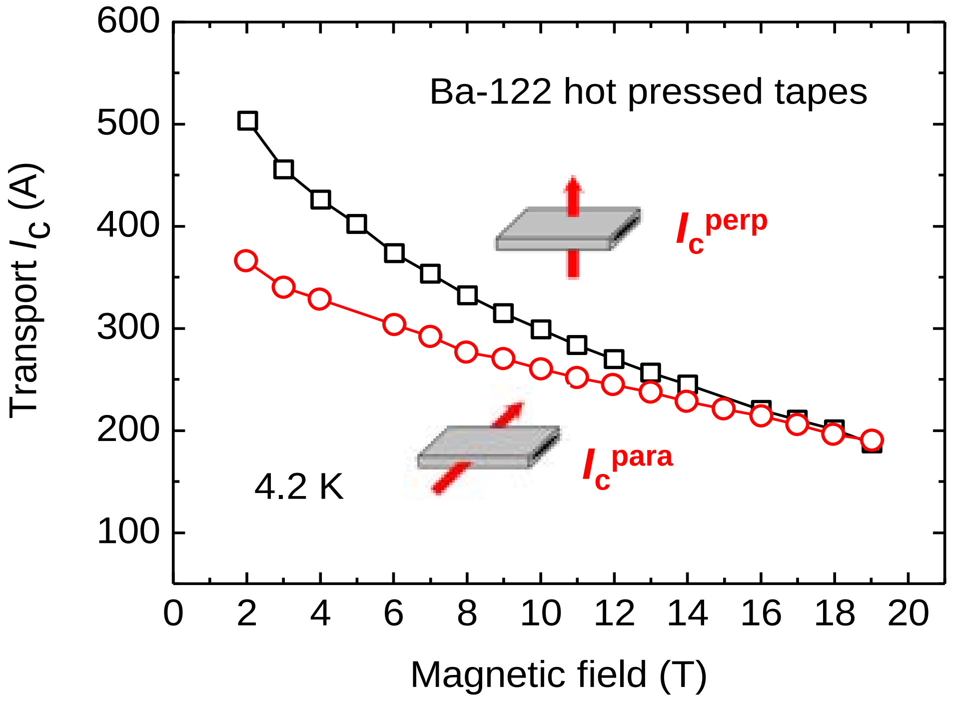
At 27 T,
J_c = 5.5×10^4 A/cm^2



γ = 1.37 at 10 T

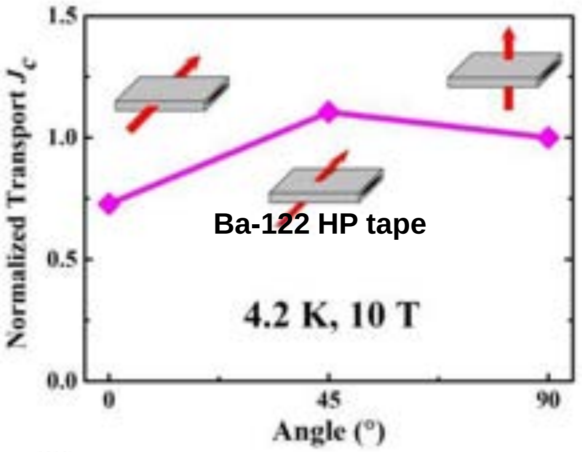
Huang et al., *SuST* 31 (2018) 015017

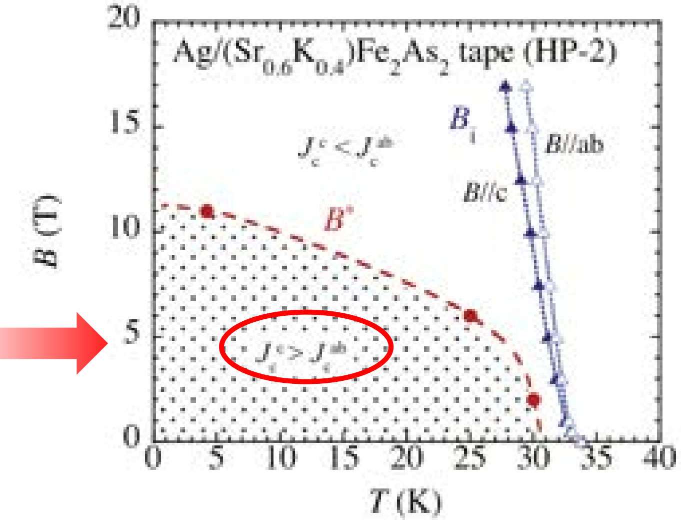
Anomalous anisotropy of J_c for HP Ba-122 tapes



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

Consistent with literature data





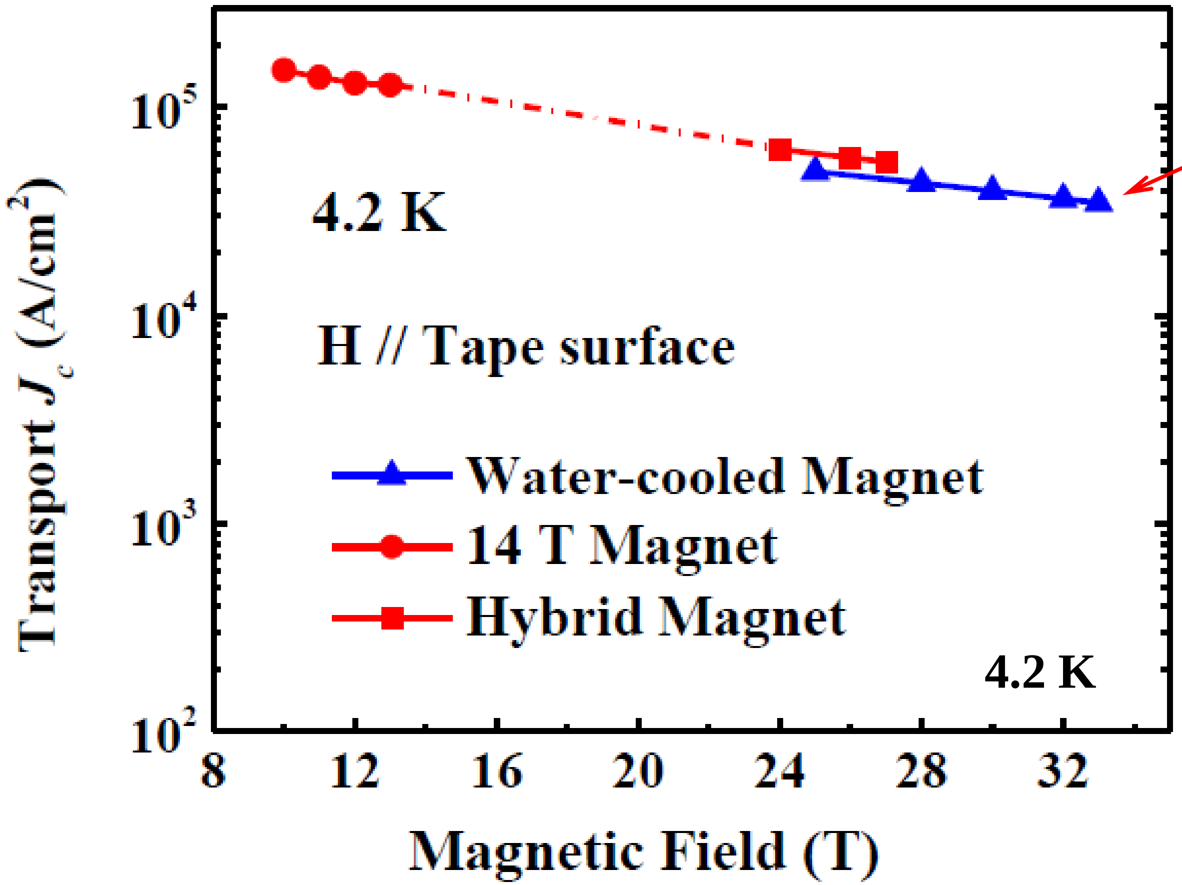
Awaji *et al.* ***SuST*** 30 (2017) 035018

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

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*



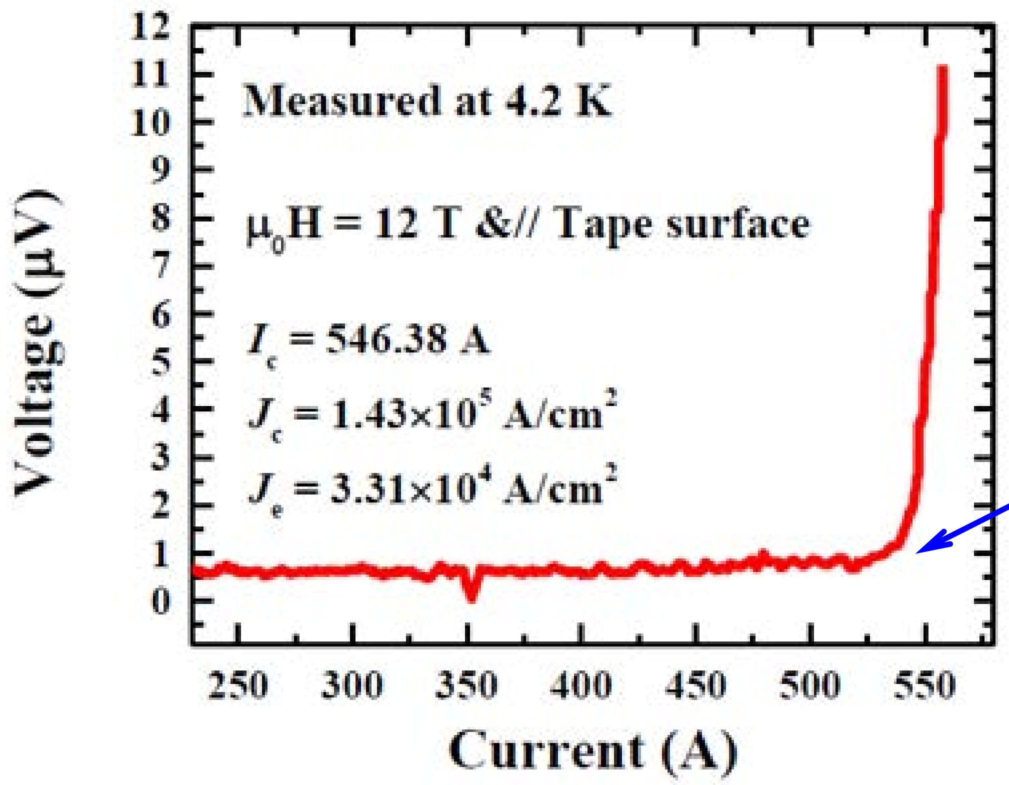
@ 33 T, J_c= 3.5×10^4 A/cm^2

35 T water-cooled magnet (Heifei, China)

Latest result

Ba-122 tapes showed even higher J_c-B value

--measured at IPP-CAS



Hot-pressed samples

At 12 T,

I_c = 546 A

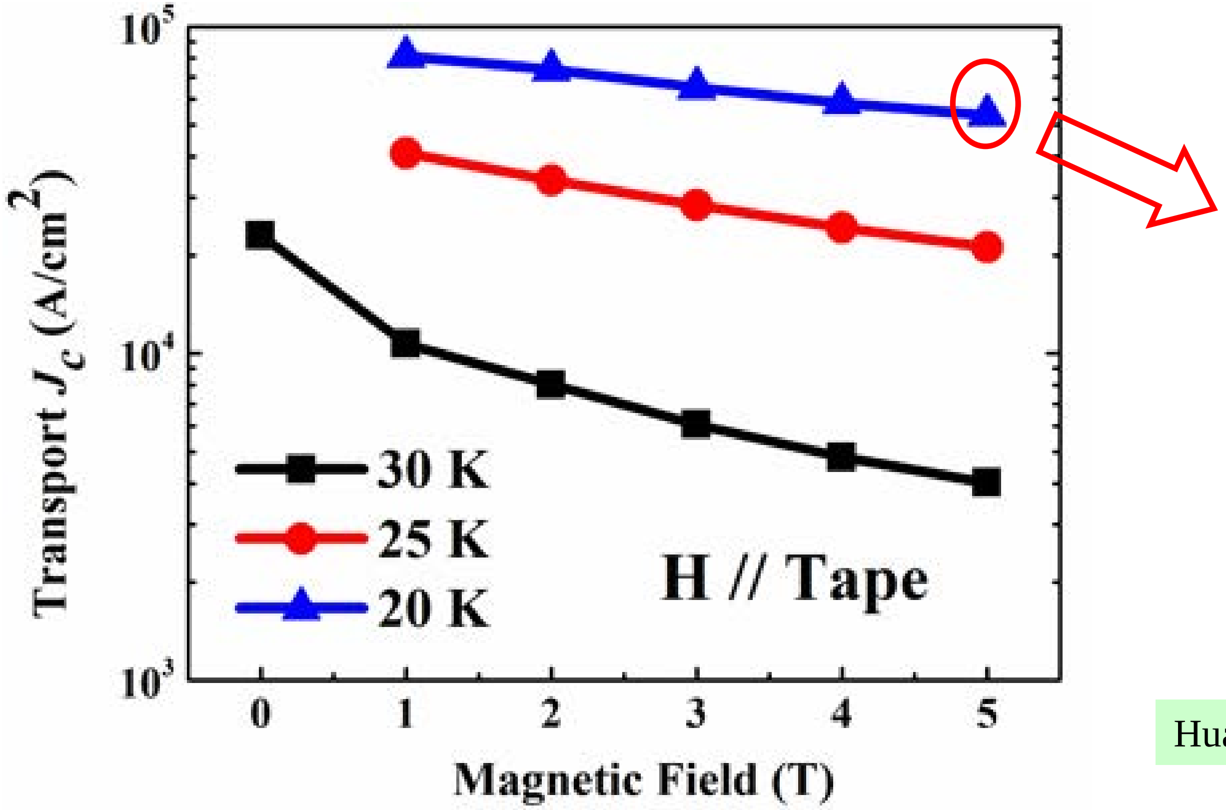
$J_c = 1.43\times10^5$ A/cm²

◆ **For hot-pressed tapes, at 12 T, 4.2 K, I_c= 546.38 A, J_c= 1.43×10^5 A/cm², correspondingly, J_c~ 1.6×10^5 A/cm² in the field of 10 T.**

Transport J_c at medium temperatures

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

Measured at Northeastern University in China



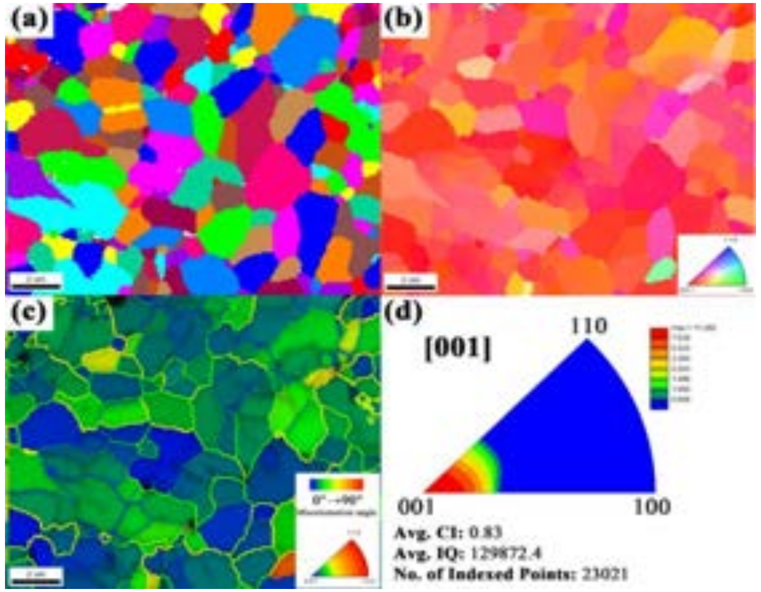
5.4×10^4 A/cm^2
@ 5 T & 20 K

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, ~3 µm



Highly textured microstructure!

(well-connected grains, no porosity)

Hot press

--State-of-the-art HP tapes

The core of HP Ba122 tape

Vickers hardness: ~132

Rolled: ~90

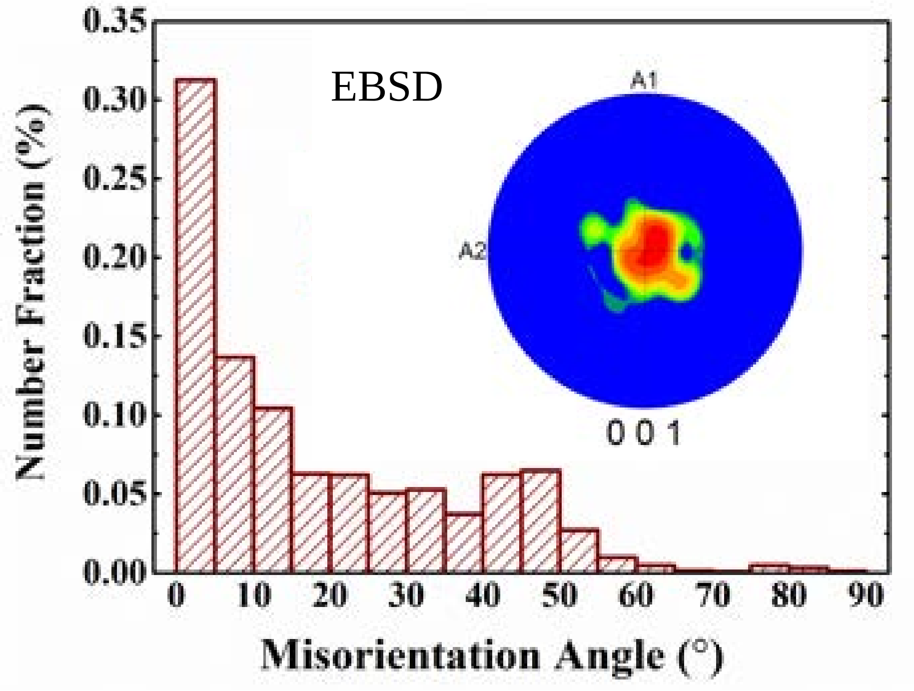
High core density

Good connectivity !

EBSD: Misorientation angle distribution

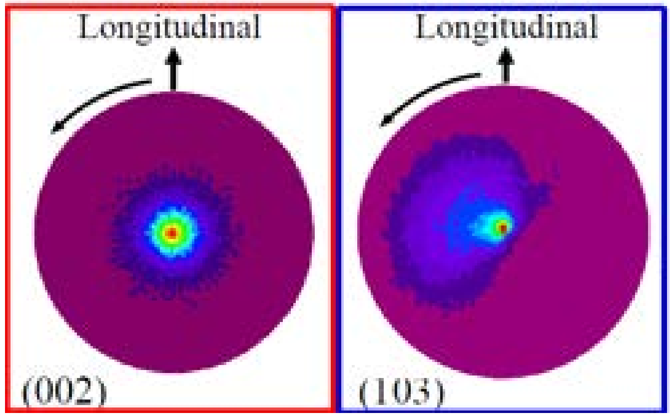
HP Ba-122 tapes

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

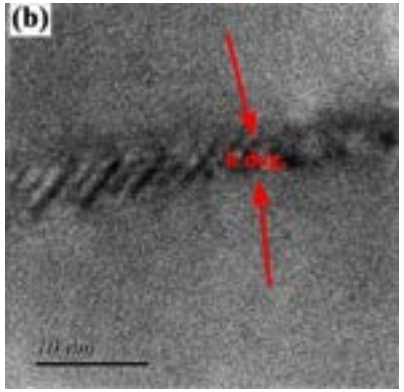


Courtesy of S. Awaji

Pole figure



TEM

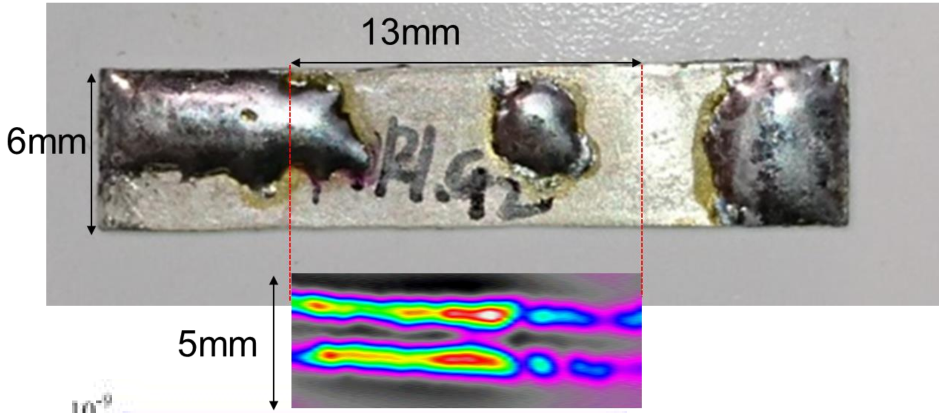


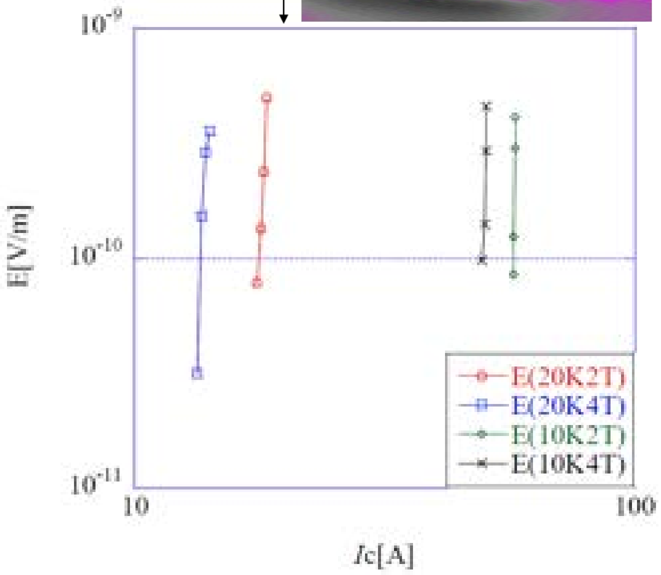
A large amount of grain boundaries below 10º are also detected, indicating that the weak-link problem is effectively suppressed in HP tapes.

Scanning Hall Probe Microscopy:
Calculated Ic and n value (HP Ba-122)

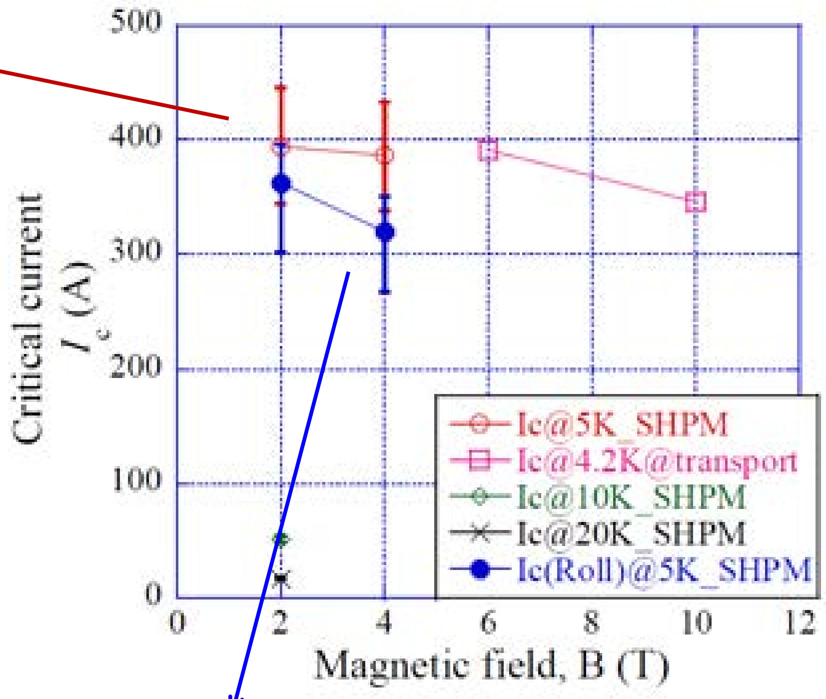
-- Measured by Kiss group
Kyushu Univ.

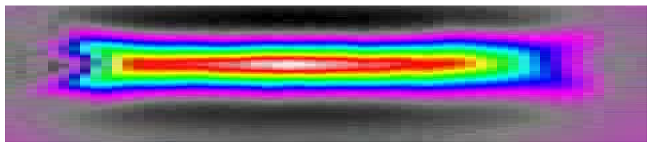
Hot pressed Ba-122 tape





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

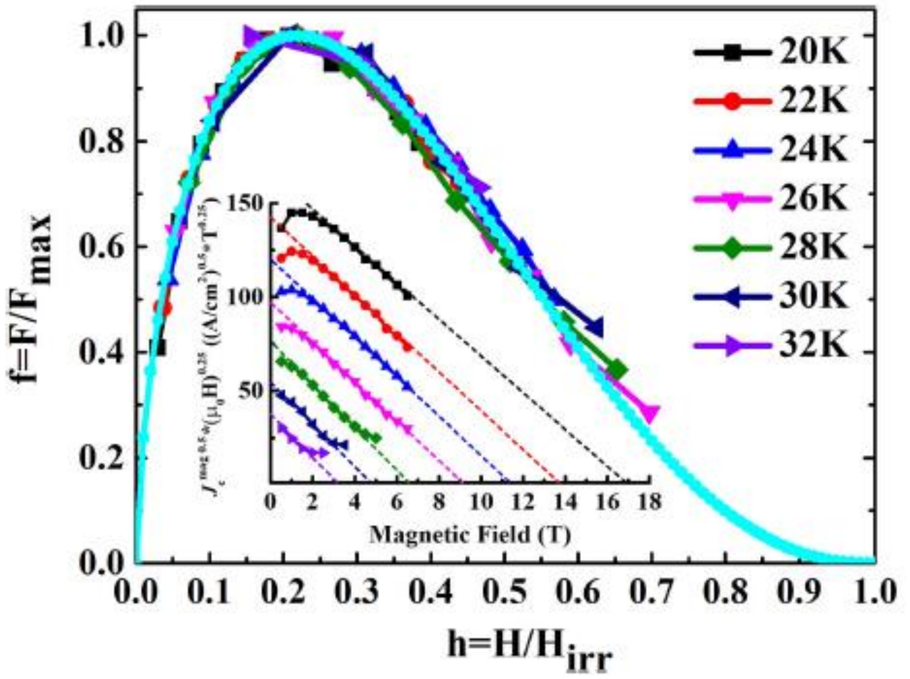




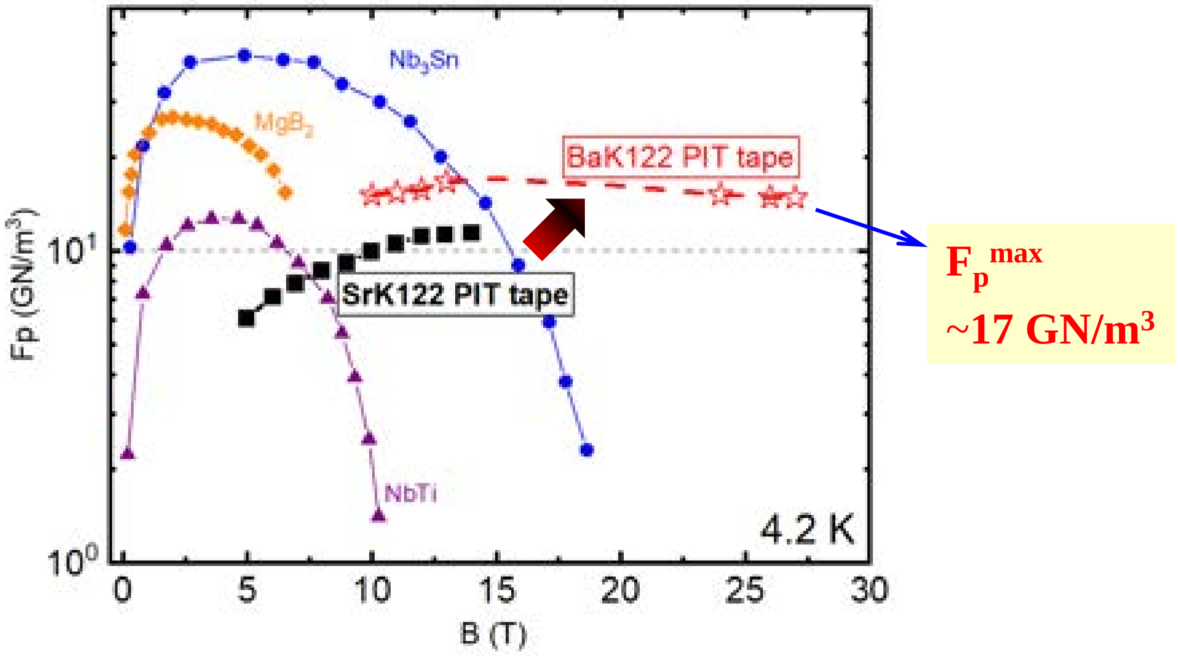
Rolled tape

Flux pinning mechanism in HP Ba-122 tapes

Normalized flux pinning force



Flux pinning force density

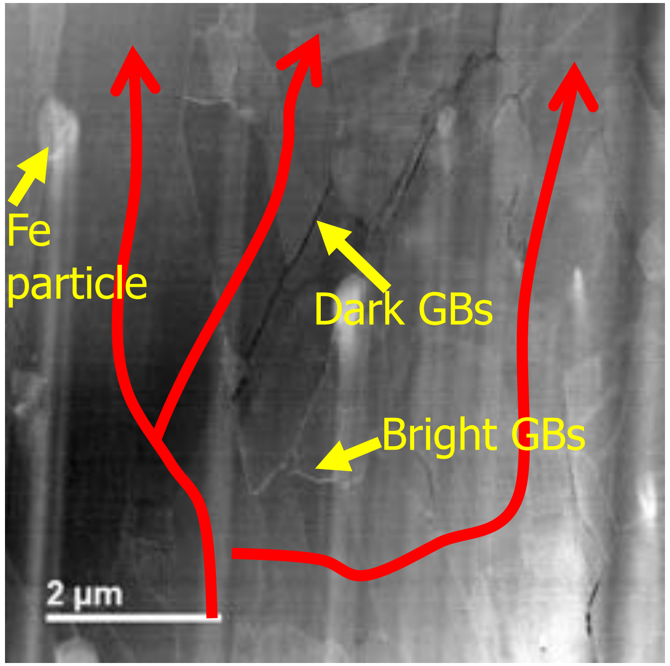


- **Normalized flux pinning force f *vs.* normalized magnetic field h curves are well fitted by the formula: $f=h^p(1-h)^q$, h_{max} ~ 0.22, indicate the surface pinning.**
- **Two sources: i)** dislocations**, ii) grain boundaries.**
- **There are still much room for J_c improvement, *e.g.*, decreasing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

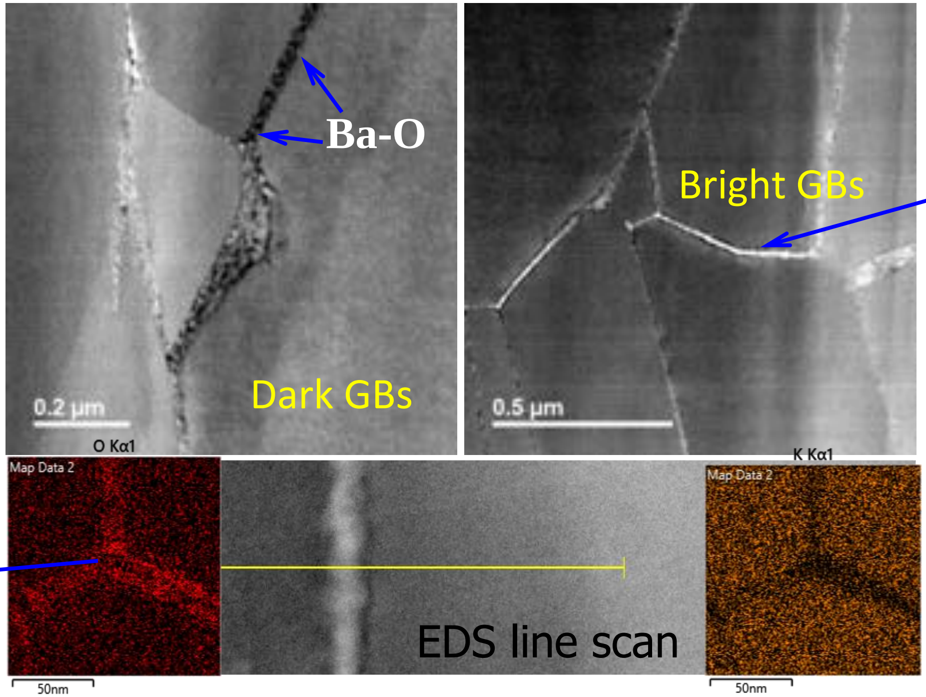
Bright field STEM for state-of- the art HP 122 tapes: Second phases at GB

HAADF

-- **analysed by Larbalestier's group at FSU**



Many clear GBs in HP-122 tape



FeAs

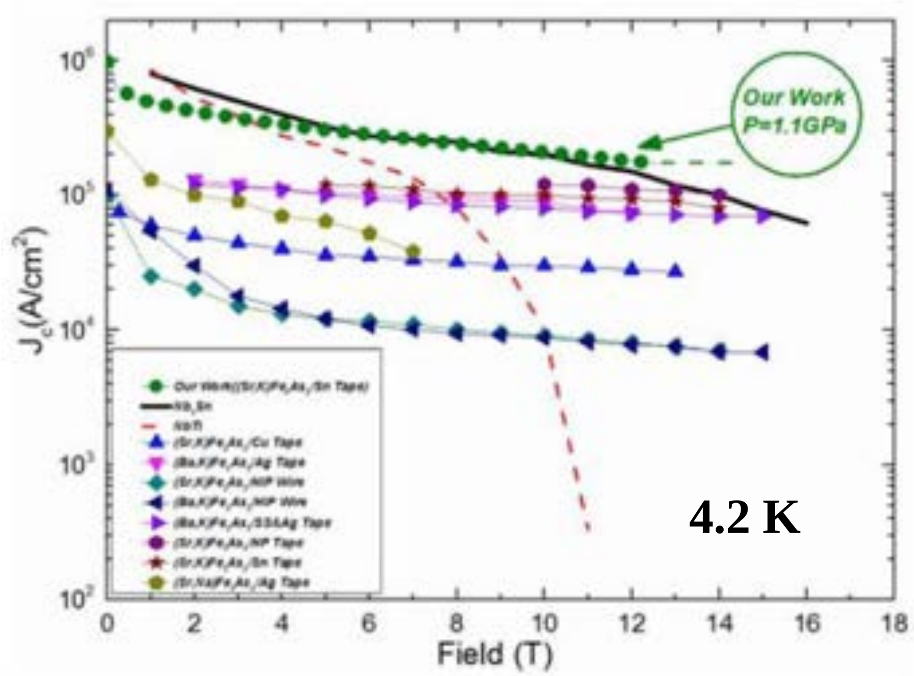
significant O segregation

K depletion

- **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 3×10^5 A/cm^2 @ 4.2 K, 10 T can be achieved under Hydrostatic Pressure on 122 tapes



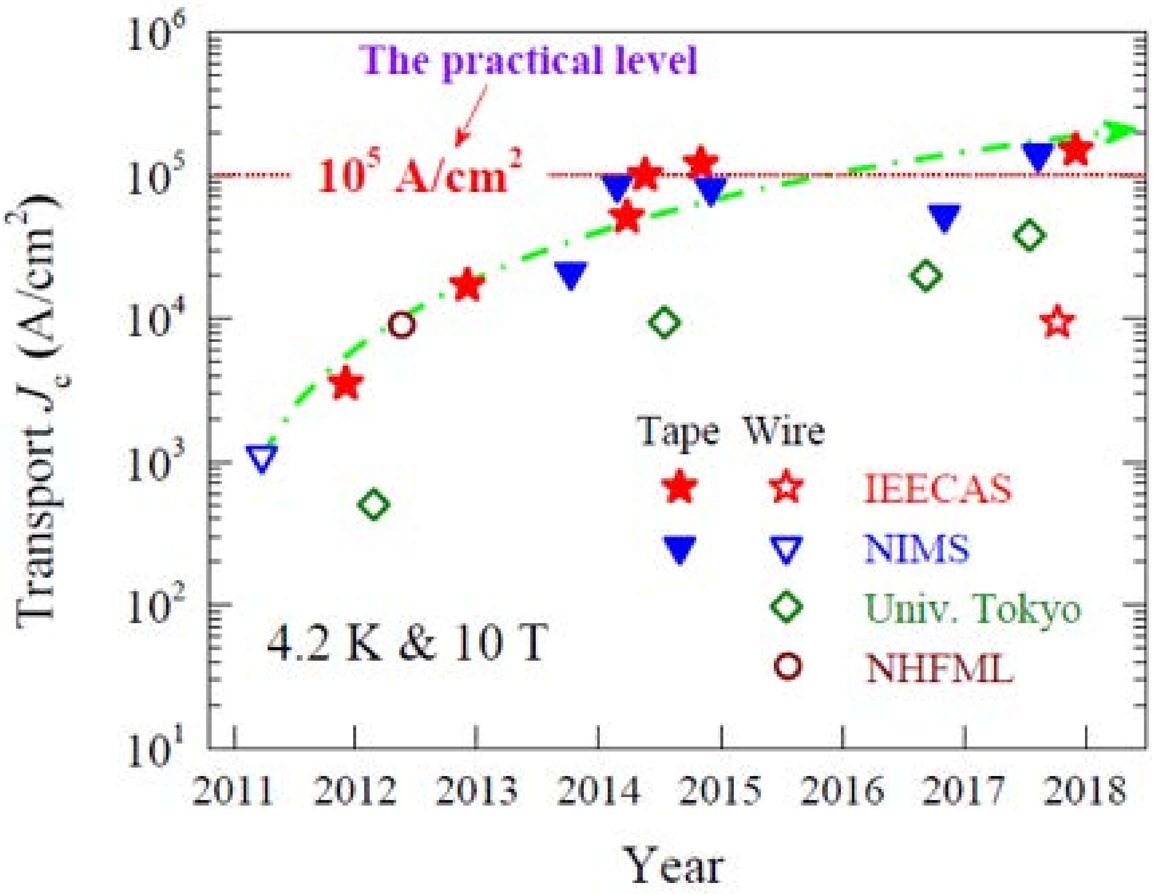
-- Collaborated with Prof. Xiaolin Wang, S. X. Dou, Wollongong Univ.

- ✓ 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 $Sr_{0.6}K_{0.4}Fe_2As_2$ 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 demonstrated that the current IBS tapes/wires should have plenty of room for the J_c improvement.**

Shabbir et al., ***Phys. Rev. Mater.*** 1 (2017) 044805

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



2018

1.5×10^5 A/cm^2

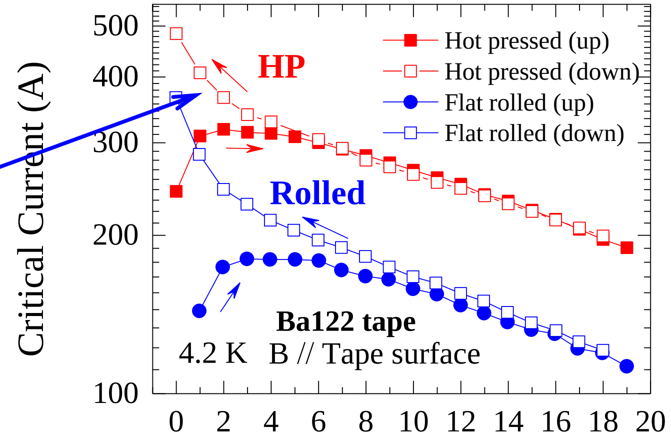
10^5A/cm^2 at 18 T

Next target: 10^5A/cm^2 at 30 T

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

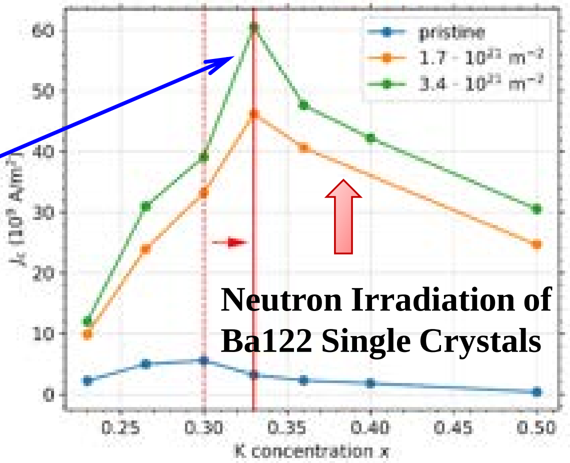
Strategies to further improve J_c in 122 PIT wires

- **Reduction of secondary phases at GBs.**
- **To improve the texture degree,** especially increase the fraction of misorientation angle <9°.



Courtesy: M. Bonura & C. Senatore

- **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.



Courtesy: M. Eisterer

Outline

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

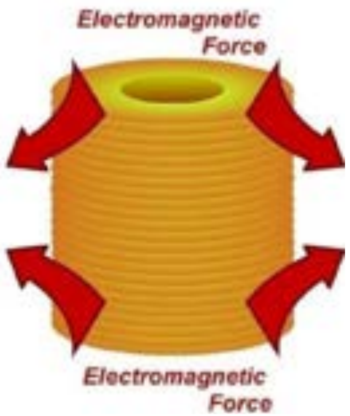
4 Conclusions

For applications, many other problems to be solved

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

Short sample:1m

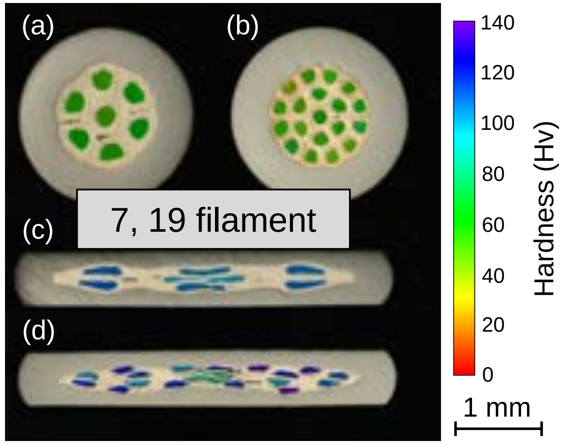
Long wire



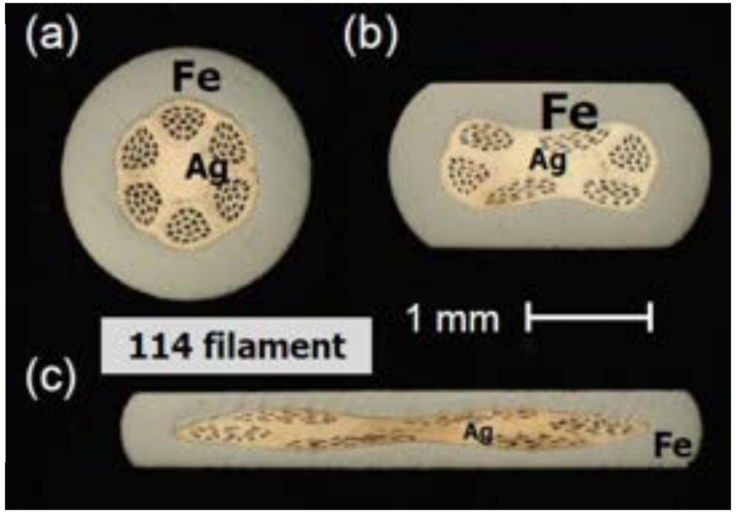
Magnet

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

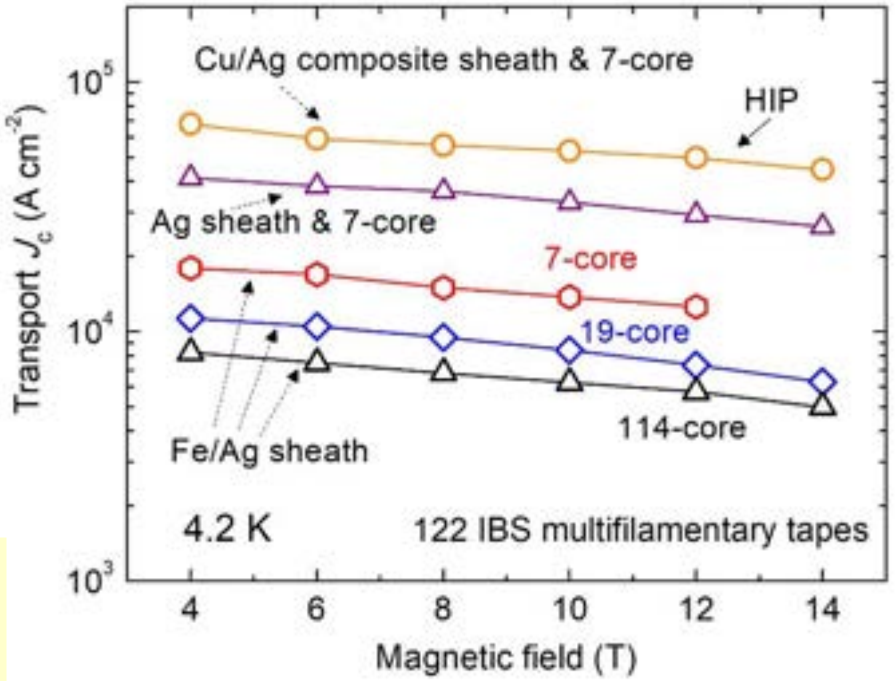
➢ **The fabrication of multifilamentary wires and tapes is an indispensable step, to reduce the AC loss and avoid the flux jump.**



At 4.2 K, 10 T



J_c, the very weak field dependence



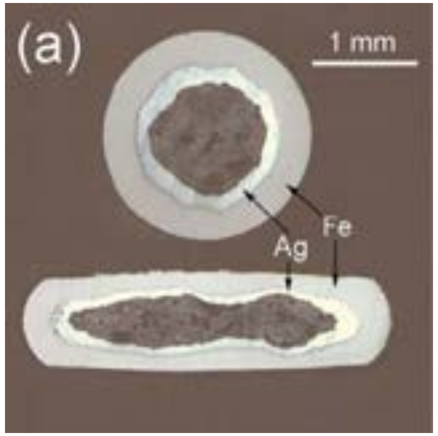
J_c needs to be further improved

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

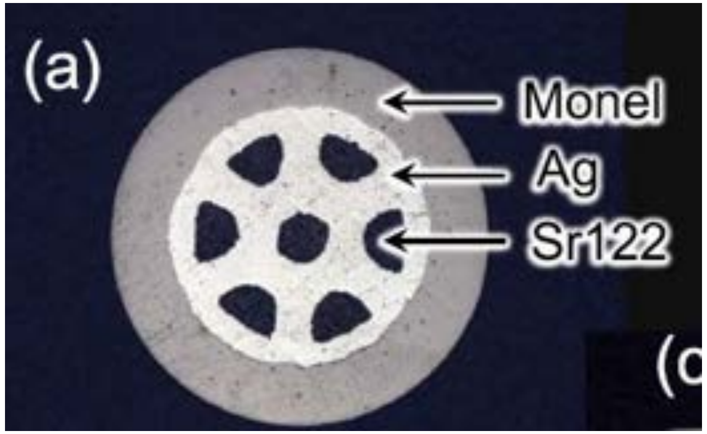
Yao et al., ***JAP*** 118 (2015) 203909

Fabrication of high-strength IBS wires

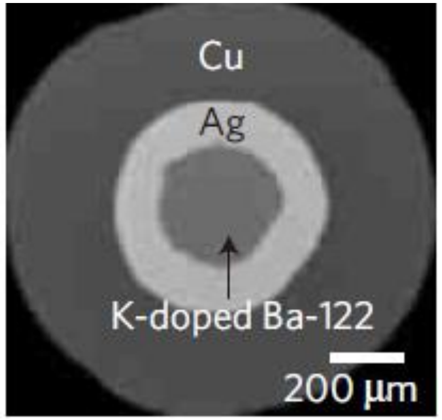
Ag may be also used in combination with an additional outer sheath made of Fe, Cu, and stainless steel to **reduce costs and improve the mechanical strength.**



Fe/Ag, IEECAS

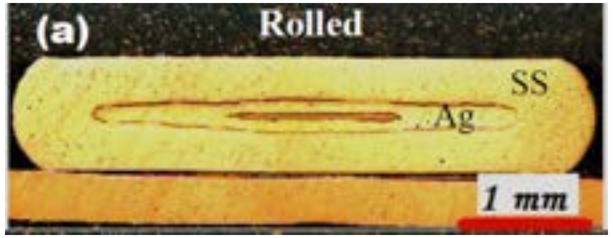


Monel/Ag, IEECAS

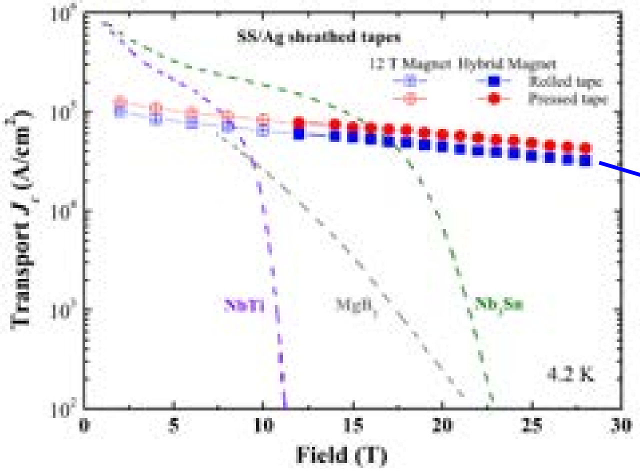


Cu/Ag, Florida

Cu/Ag, IEECAS



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

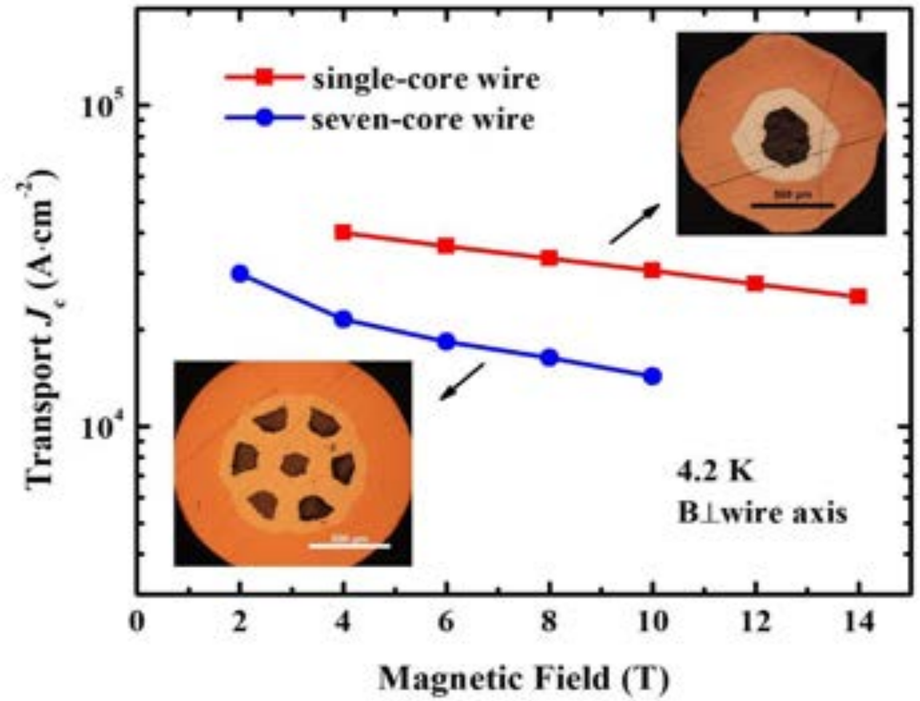


28T, J_c=3×10^4 A/cm^2

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

at 740ºC

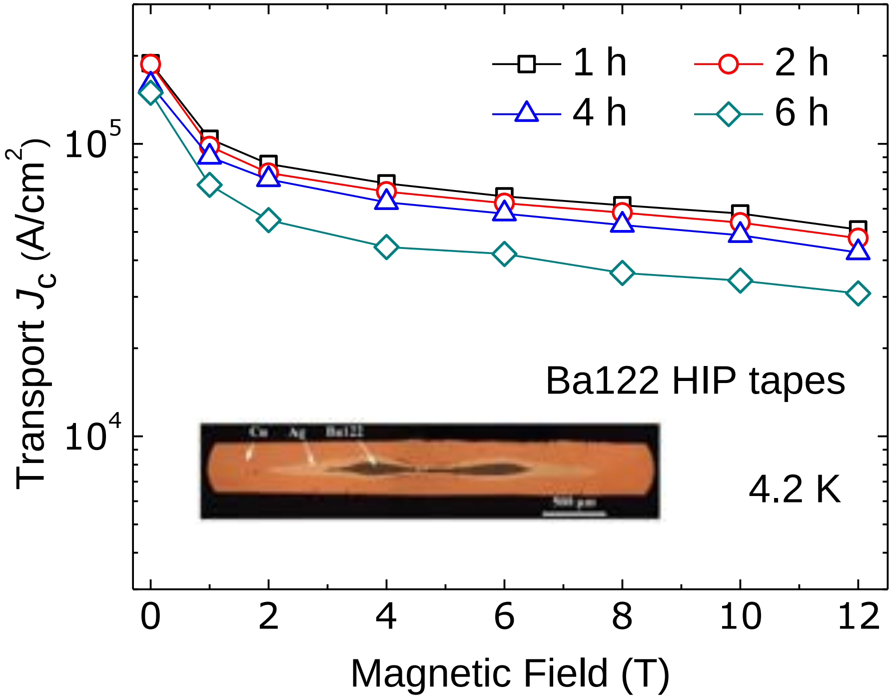
Ba-122/Ag/Cu round wires



J_c (4.2 K, 10 T) = 3.1×10^4 A/cm^2

7-core J_c (4.2 K, 10 T) = 1.6×10^4 A/cm^2

Ba-122/Ag/Cu tapes



J_c (4.2 K, 10 T) = ~6×10^4 A/cm^2

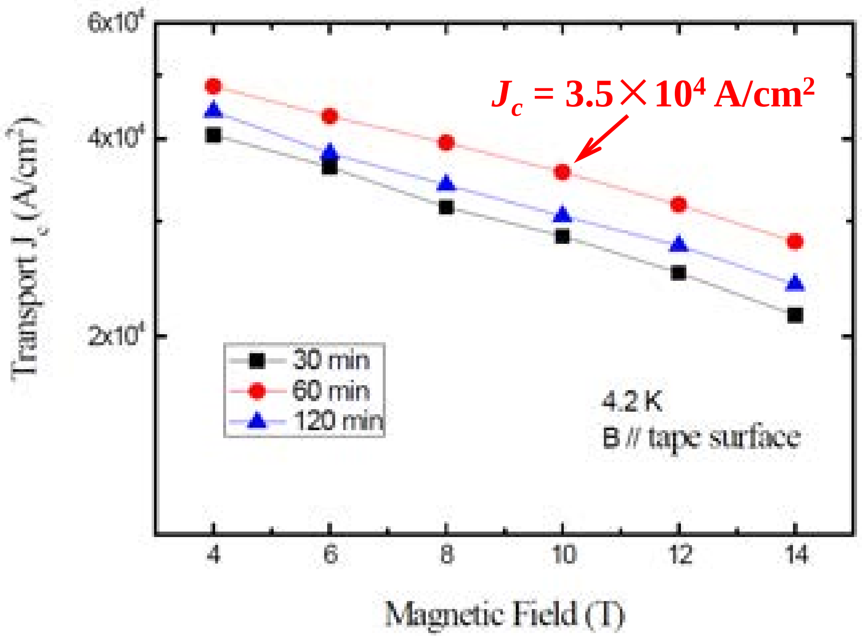
A scalable process (Rolling+HIP) ⇒
- grain texture by flat rolling
- high density by HIP

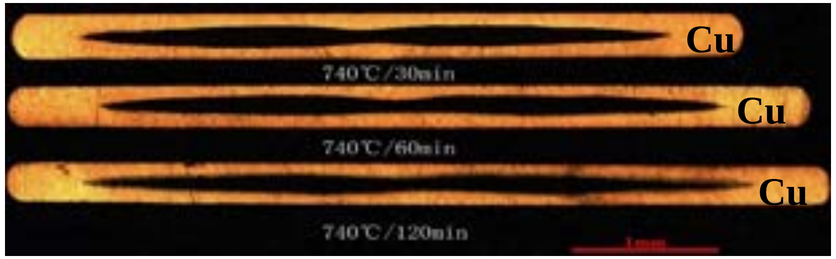
Liu et al., ***SuST*** 32 (2019) 044007

Low-cost copper as sheath

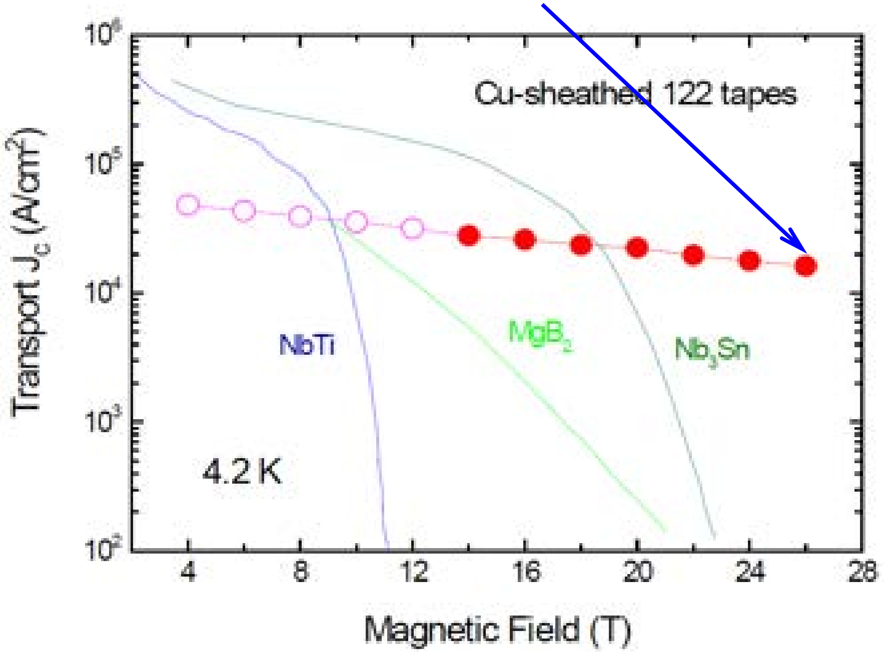
High J_c in Cu-sheathed Sr-122 tapes at 740ºC

At 4.2 K, 10 T, J_e >10^4 A/cm^2





At **26 T**: $J_c = 1.6\times10^4$ A/cm^2



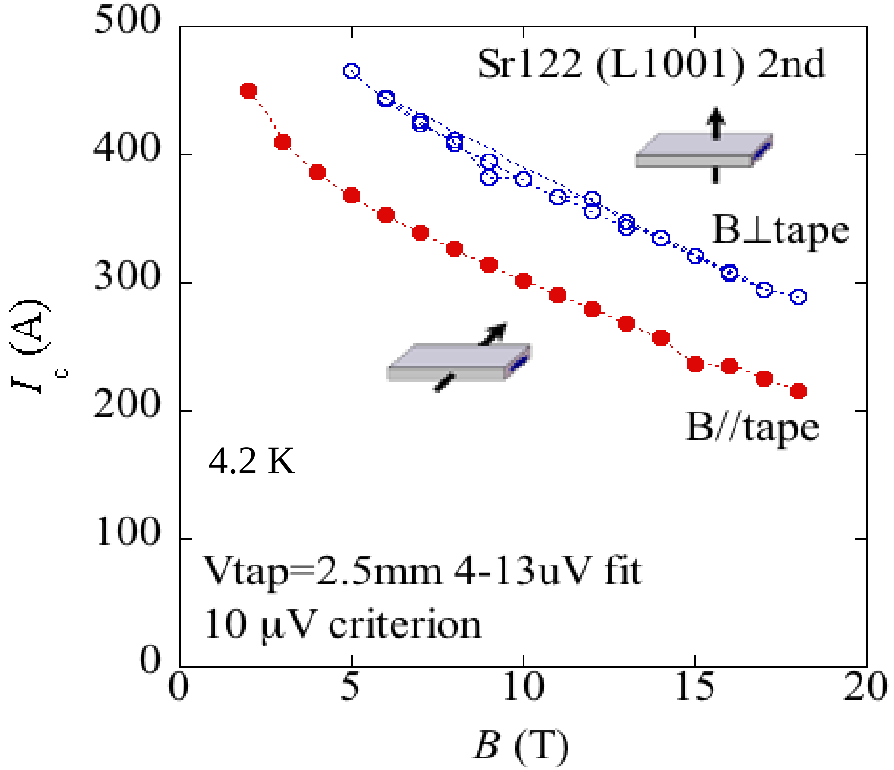
- The rapid fabrication method (HP740C/60 min) can effectively thwart the diffusion of Cu into Sr-122 core.
- The best transport J_c reaches 3.5×10^4 A/cm^2 at 10 T and keeps 1.6×10^4 A/cm^2 at 26 T.

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

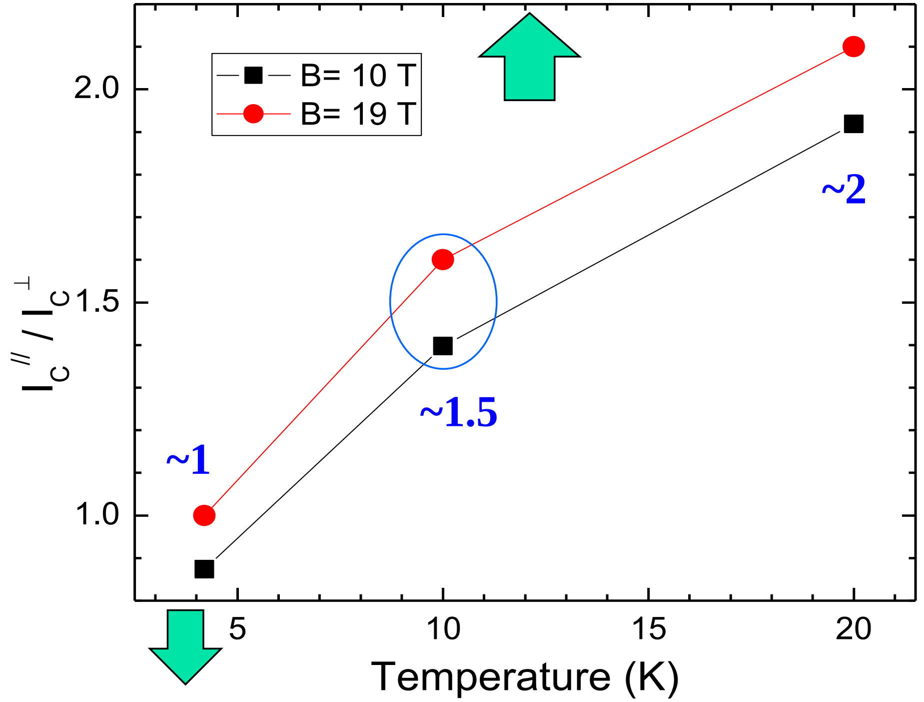
Small anisotropy

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.



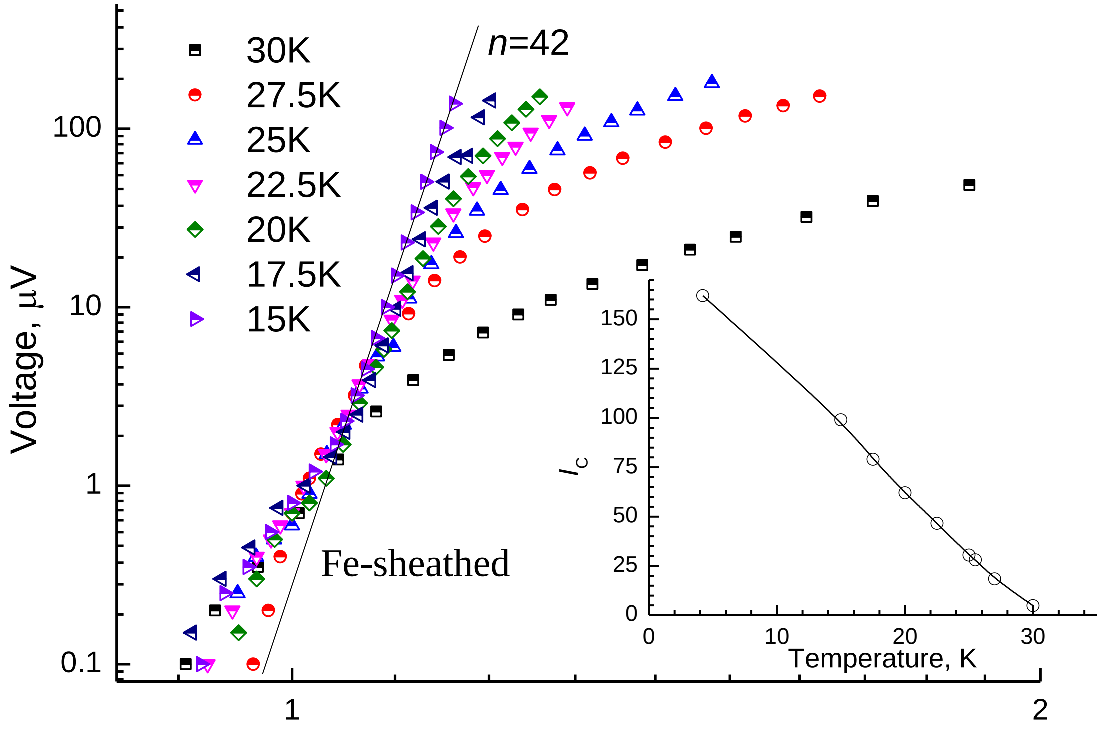
$I_C^{//} < I_C^{\perp}$ only at low temperature and fields

- **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**

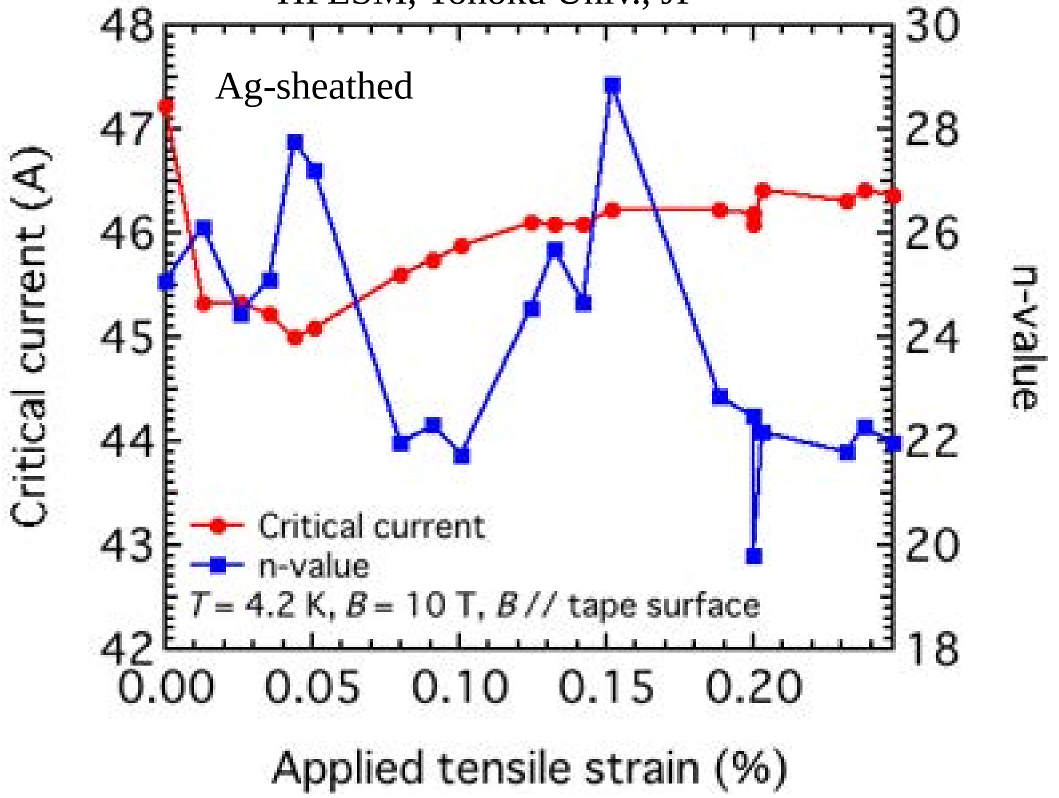
Temperature dependence of *n value* for Sr-122 tapes

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



Courtesy of Yifeng Yang

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



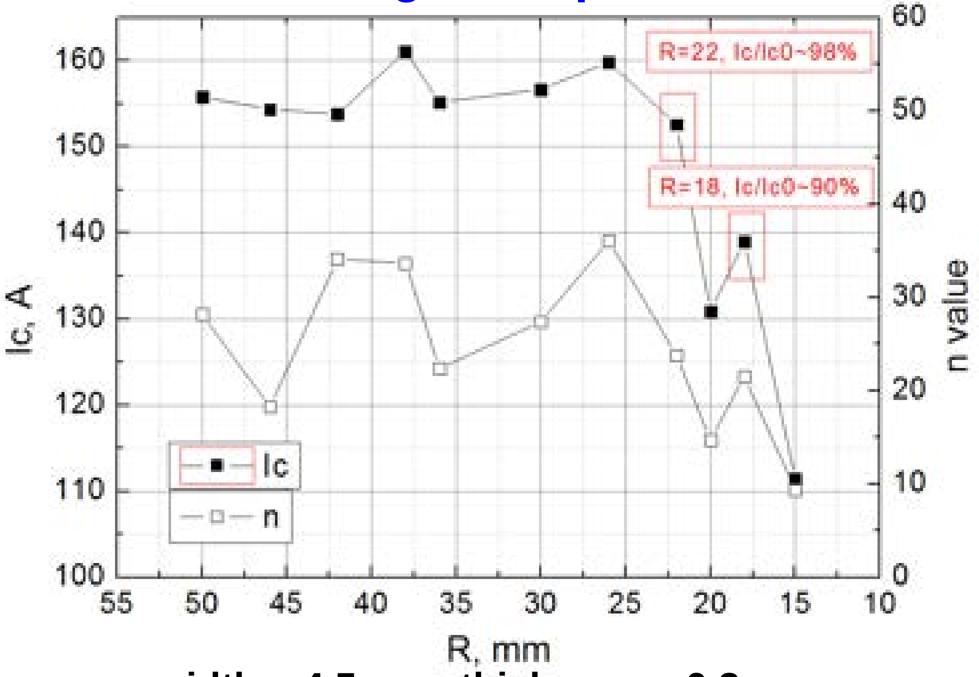
At 20 K, the *n value* was over 30

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

Straight → Bent → Straighten

Bending test of 122 IBS tapes

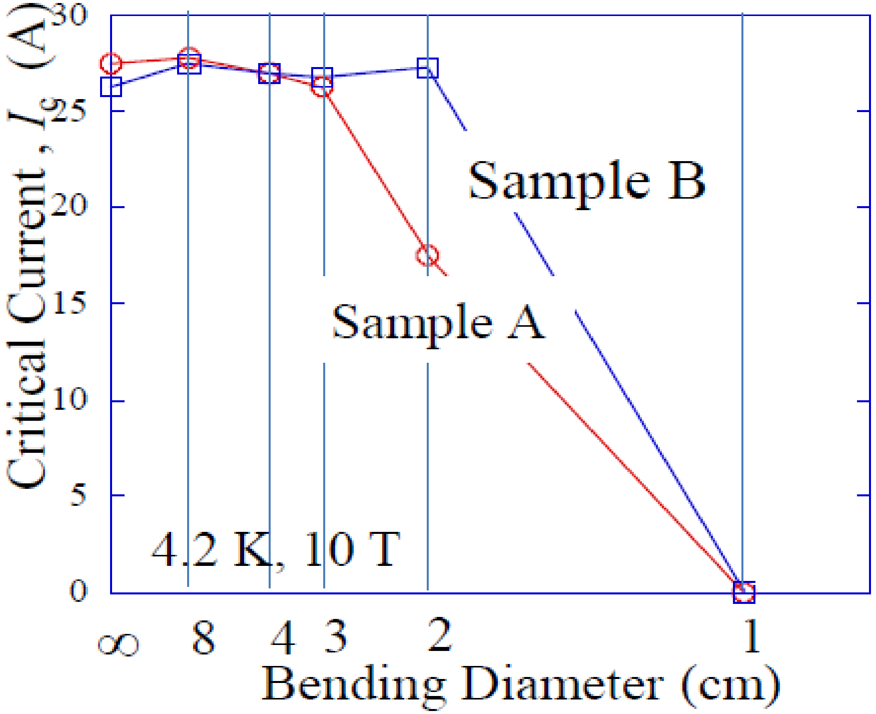
122/Ag IBS tapes



width ~ 4.5 mm, thickness = 0.3 mm

Cooperated with Prof. Huajun Liu in IPP-CAS

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

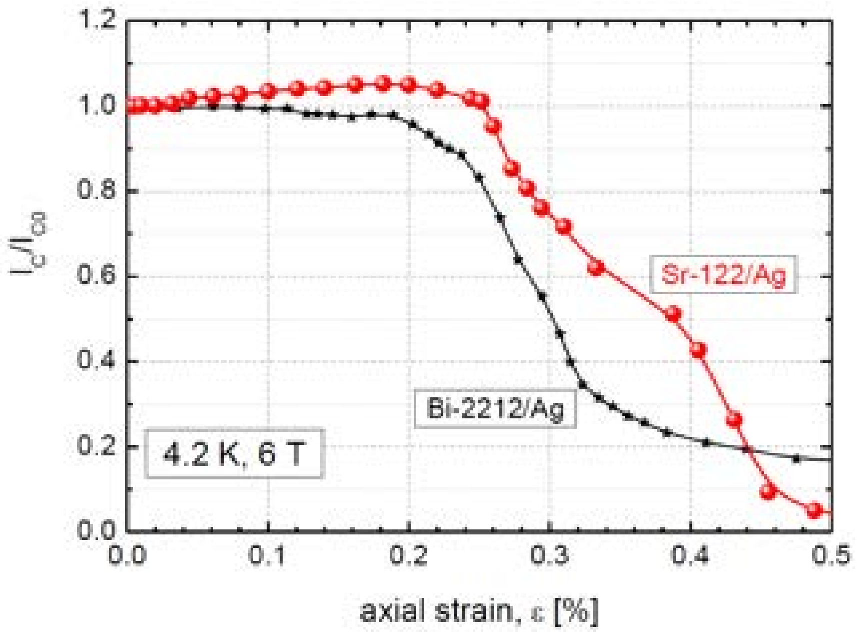


Courtesy of H. Kumakura

- **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

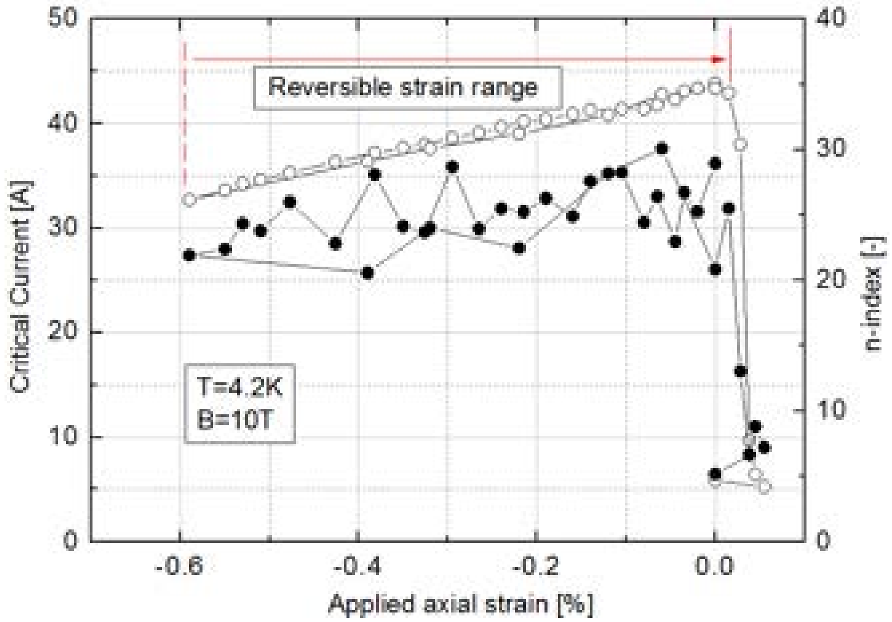


At 4.2 K, 10 T: I_c >125A
Irreversible strains: ε = 0.25%

Comparable to Bi2212

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

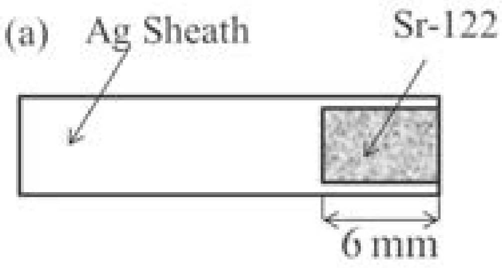
Reversible critical currents under a large compressive strain of ε = –0.6 %

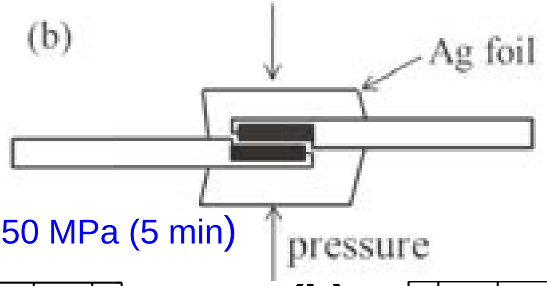


The I_c of Sr-122 tape exhibits less strain sensitivity than that of the Nb_3Sn, which is an important for ITER application.

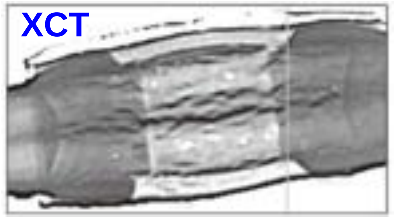
Liu et al., ***SuST*** 30 (2017) 07LT01

Development of superconducting joints between iron-based superconductor tapes

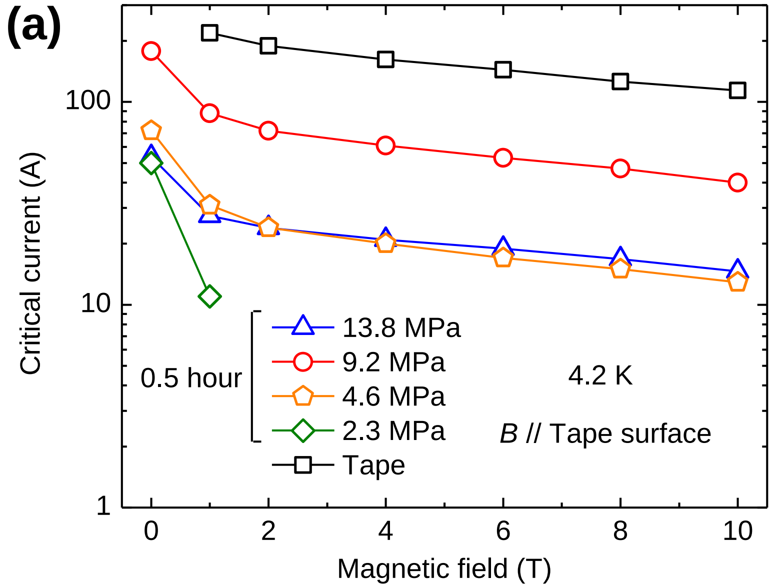




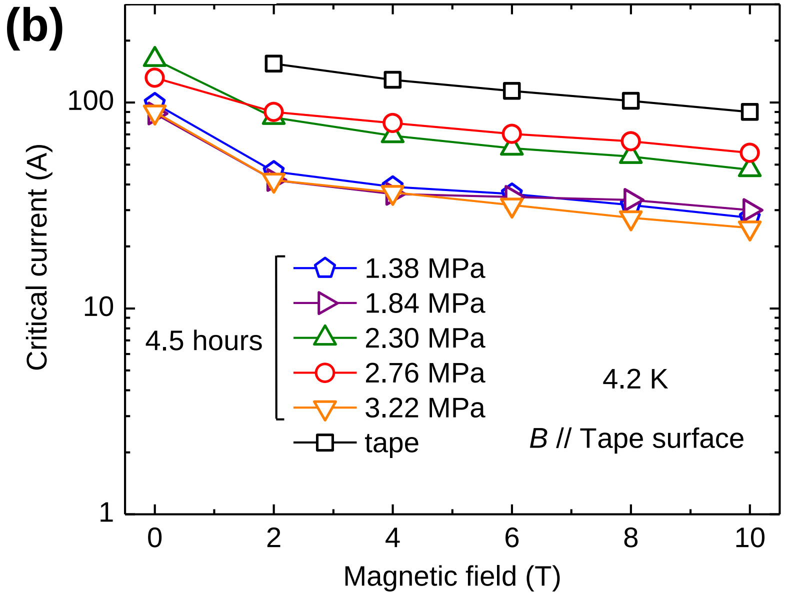
750 MPa (5 min)



for persistent current operation



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



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

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

critical current ratio (CCR) = 35.3%

Optimizing the HP pressure

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1 Background on iron-based superconductors (IBS)

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3 Fabrication of PIT IBS wires

i) Strategies to improve J_c in 122 wires

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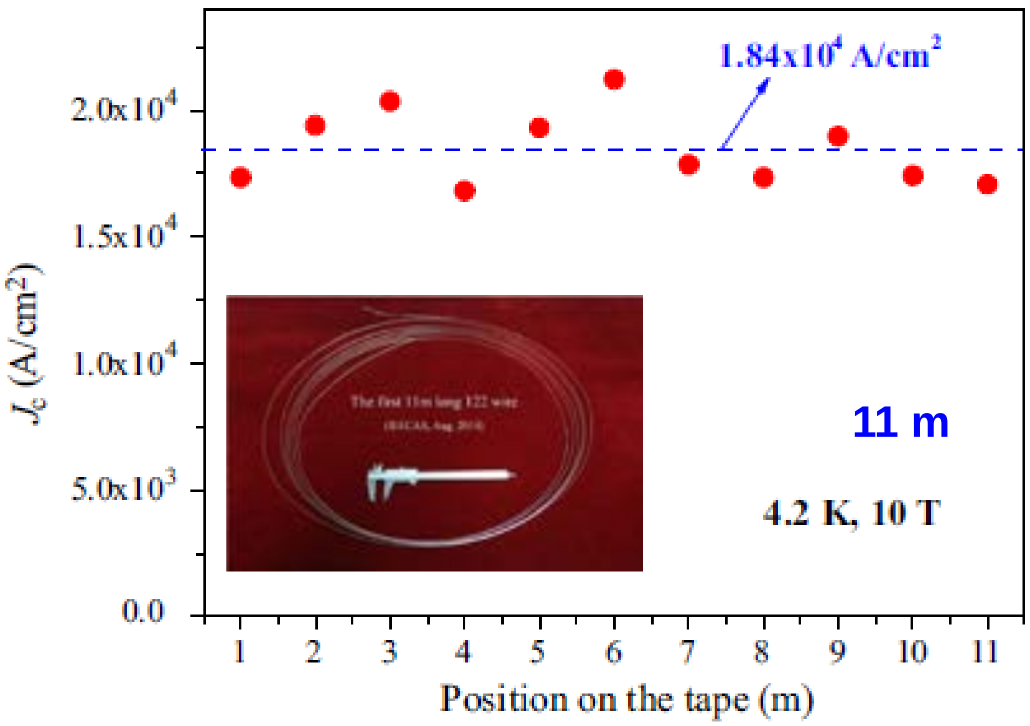
iii) Long-length wire & inserted coils

4 Conclusions

Fabrication of the meter long 122 IBS wire

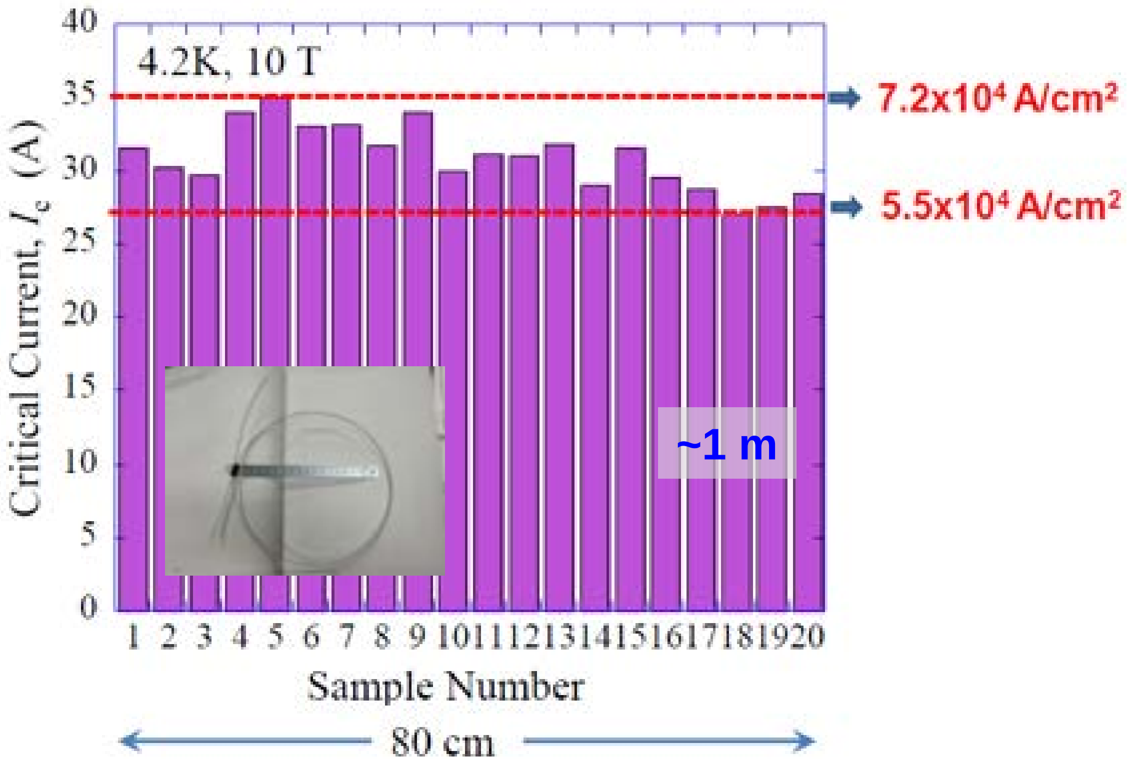
---by scalable rolling process

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



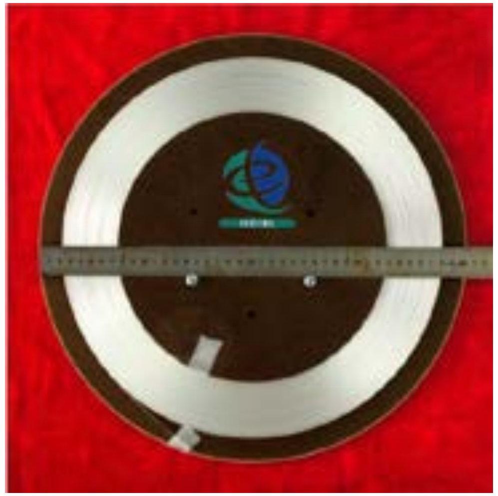
Challenging to longer length!

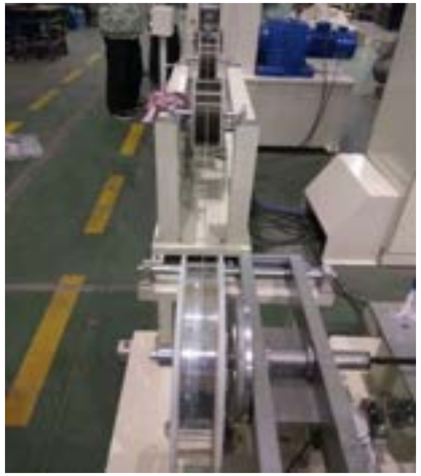
By courtesy of H. Kumakura

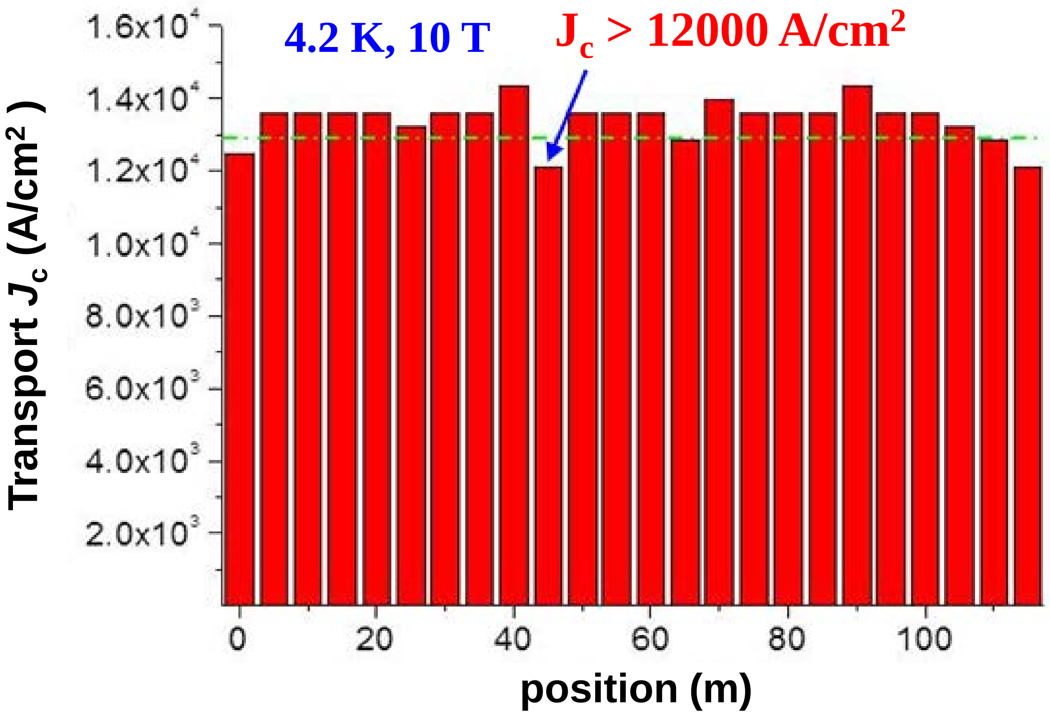
In 08/2016

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

115 m long
7-filamentary
122 tape





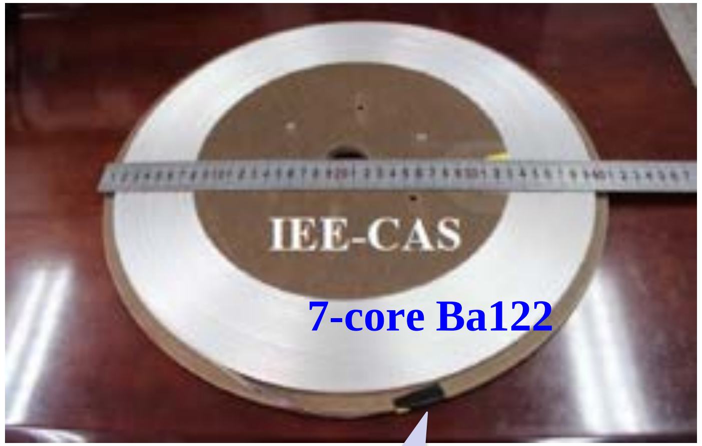


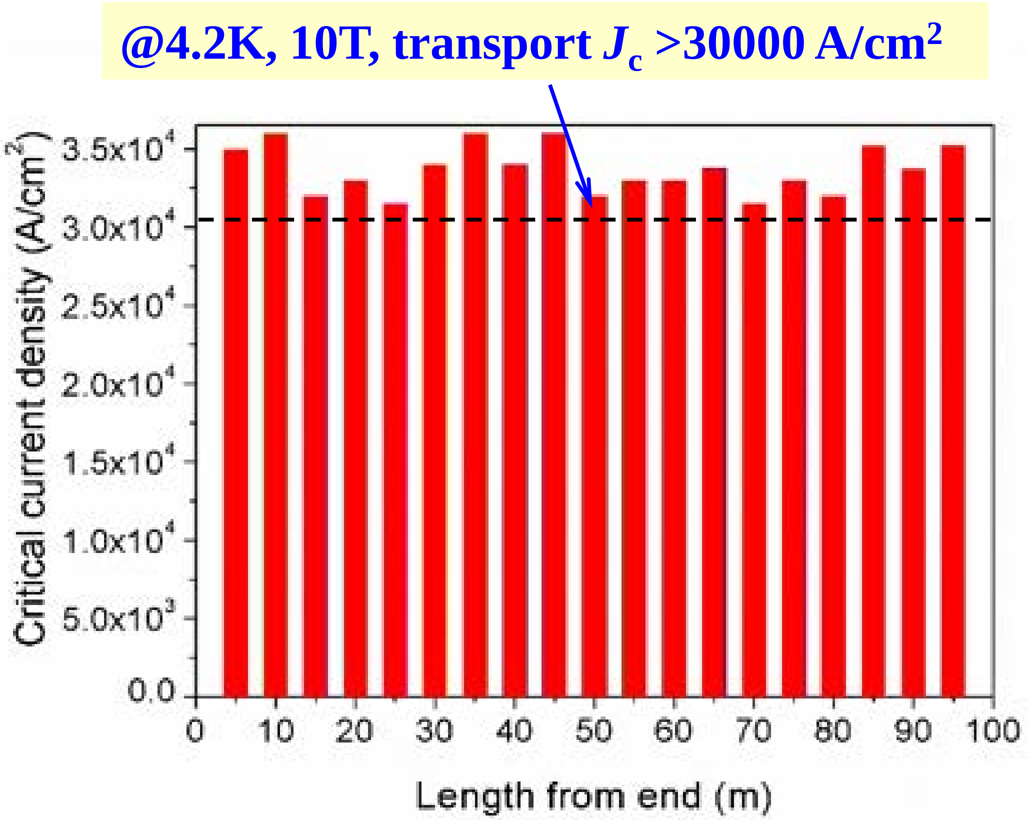
showing a good uniformity

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

Recently, J_c of 100 m long tapes was further enhanced: >30000 A/cm² (4.2 K, 10 T)

3 times larger than the first!





Key steps to the application

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

Letters
IOP Publishing Superconductor Science and Technology
Supercond. Sci. Technol. 32 (2019) 04LT01 (5pp) https://doi.org/10.1088/1361-6668/ab09a4

Letter

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

-- Cooperated with Qingjin Xu group at IHEP-CAS

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

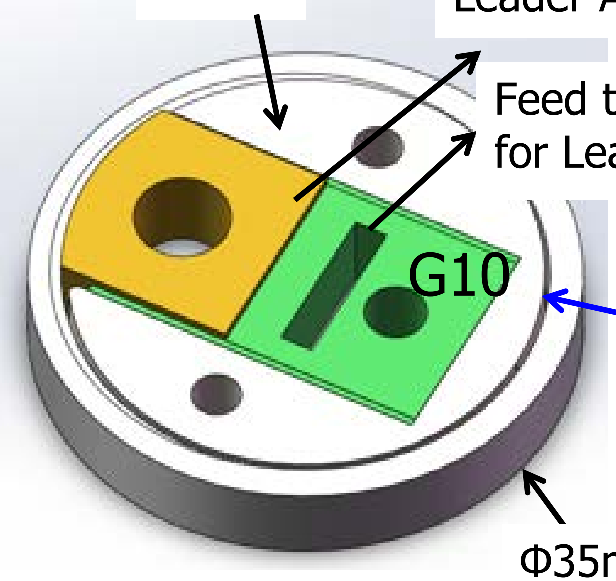


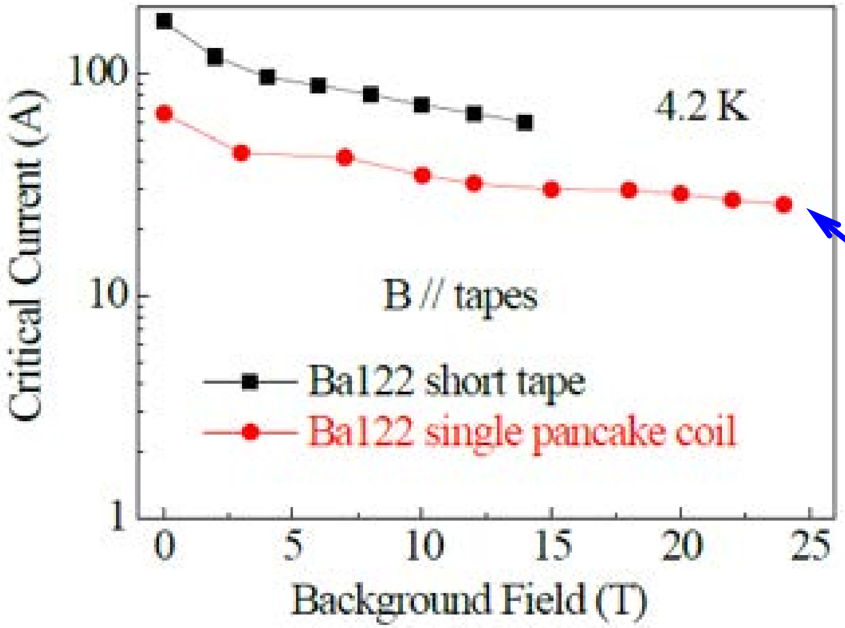
Table 2. Specification of single pancake coil

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 Φ38 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.

Wang et al., *SuST* 32 (2019) 04LT01

IOP Publishing Superconductor Science and Technology
Supercond. Sci. Technol. 32 (2019) 070501 (3pp) https://doi.org/10.1088/1361-6668/ab1fc9

Viewpoint

Constructing high field magnets is a real tour de force

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E-mail: 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. However, he soon found [1] that superconductivity disappears in the presence of a

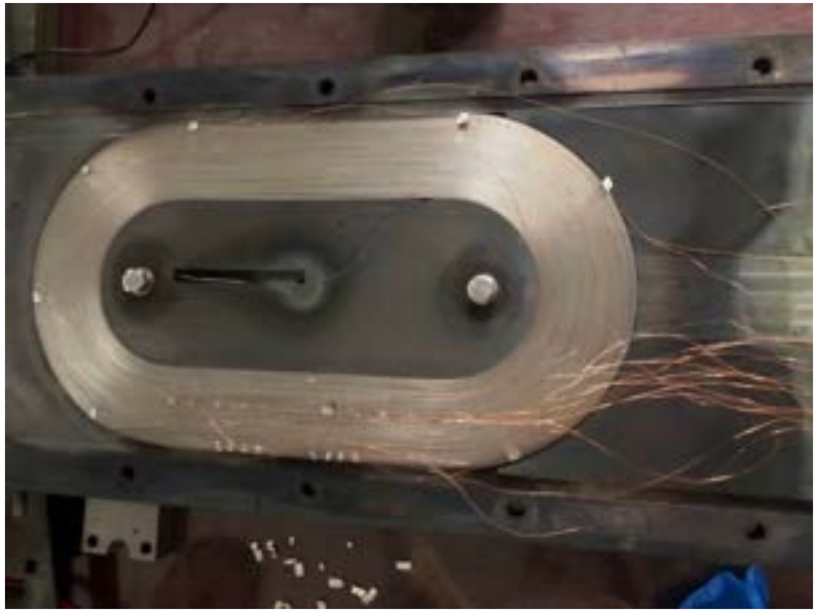
helpful in explaining the latter. From a practical point of view, IBS are ideal candidates for applications. Indeed, some of them have quite a high critical current density, even in strong magnetic fields, and a low superconducting anisotropy. Moreover, the cost of IBS wire can be four to five times lower than that of Nb_3Sn, making it more expensive than NbTi, but with much higher critical parameters than Nb_3Sn. 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…

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



IBS Racetrack coil

Tested data will be reported soon

Made by Qingjin Xu group:

Institute of High Energy Physics
Chinese Academy of Sciences

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 1.5×10^5 A/cm^2.**
- ✓ **Transport J_c of 100-m-class Ba-122 IBS tapes was further improved to > 3×10^4 A/cm^2 at 10 T & 4.2 K.**
- ✓ **Highlights some remarkable advances of IBS relevant to practical applications, incuding strain-stress behaivior, 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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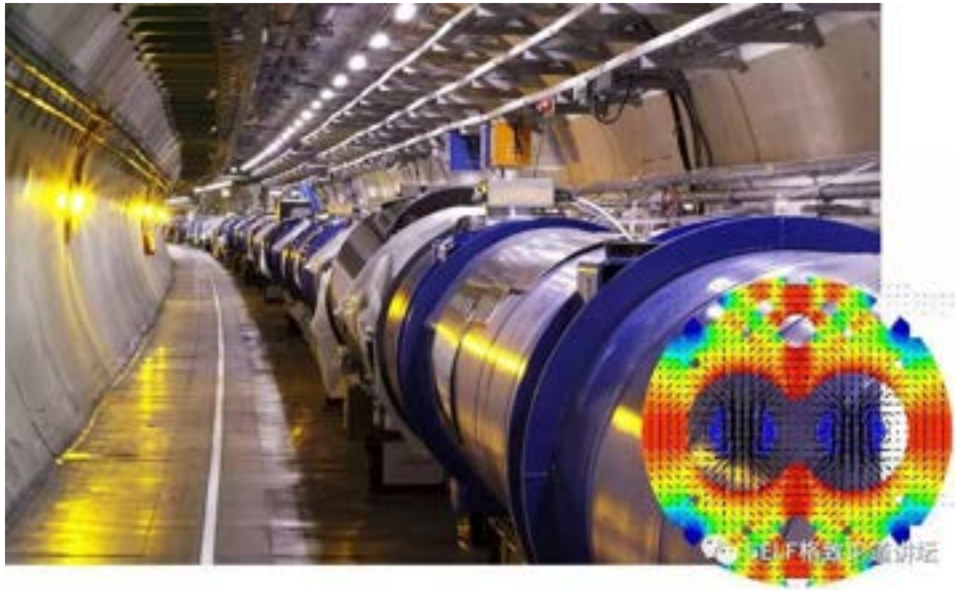
Thank you for your attention!



From a movie：Avatar