Recent advances of iron-based superconducting wires and tapes

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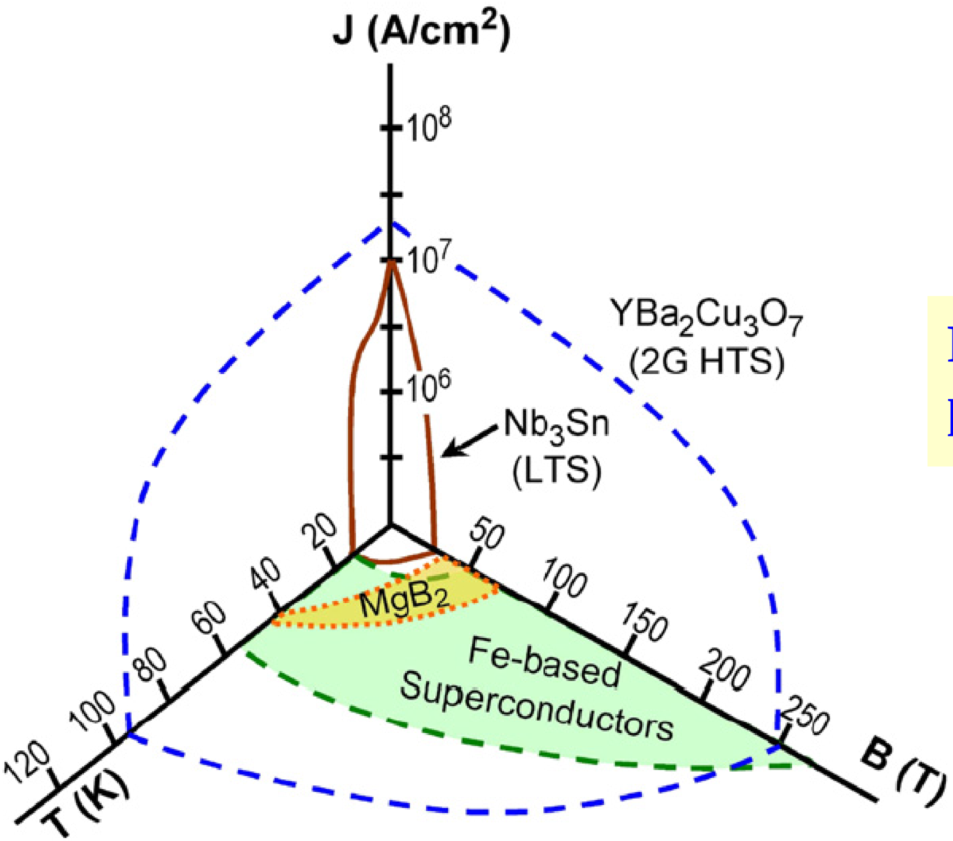
Outline

1. Background on Fe-based superconductor
2. Fabrication techniques to achieve high-J_c in 122 wires and tapes
3. Recent results about practical properties of 122 tapes
4. Conclusions

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 superconductor

LTS, cuprate HTS, MgB_2, Fe-base

Practical Wires & Tapes

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

Iron-Based Superconductors (IBS)

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

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

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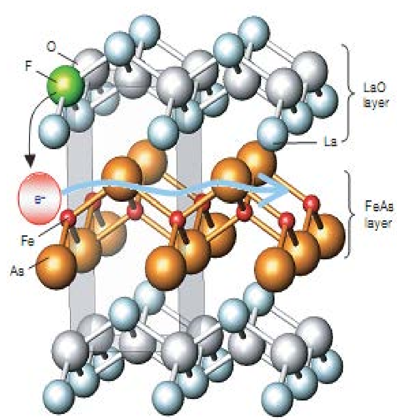
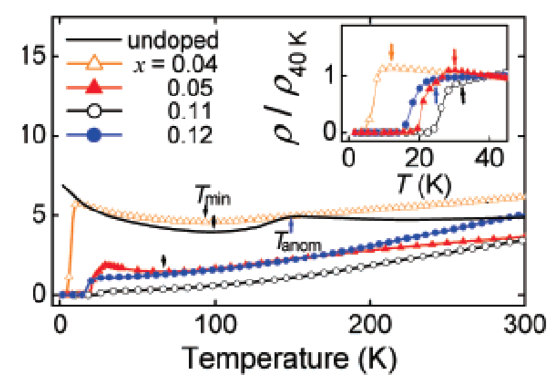
Received January 9, 2008

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 %.

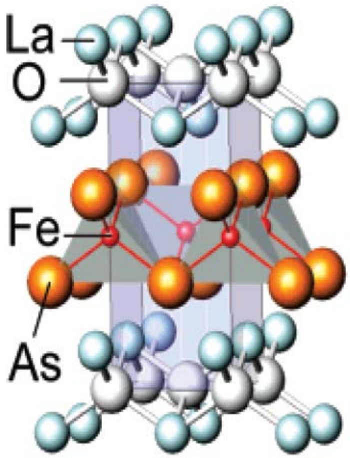




Main known IBS families

Among them, the three phases most relevant for wire applications are 1111, 122, and 11 types with a T_c *of 55, 38 and 8 K, respectively.*

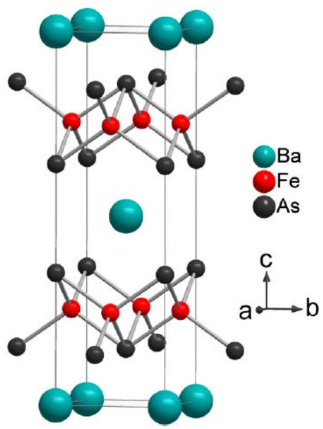
1111 Phase LnOFeAs



T_c ~55 K

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

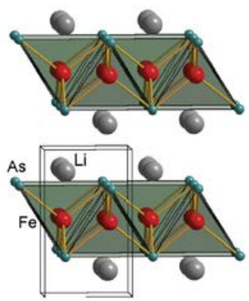
122 phase AFe_2As_2 (A=Ba, Sr, Ca)



T_c ~38 K

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

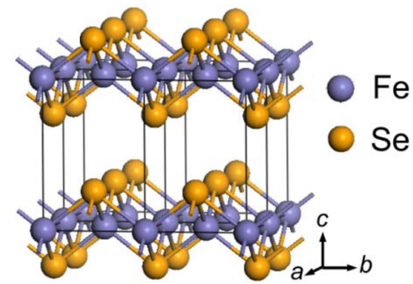
111 phase LiFeAs



T_c ~18 K

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

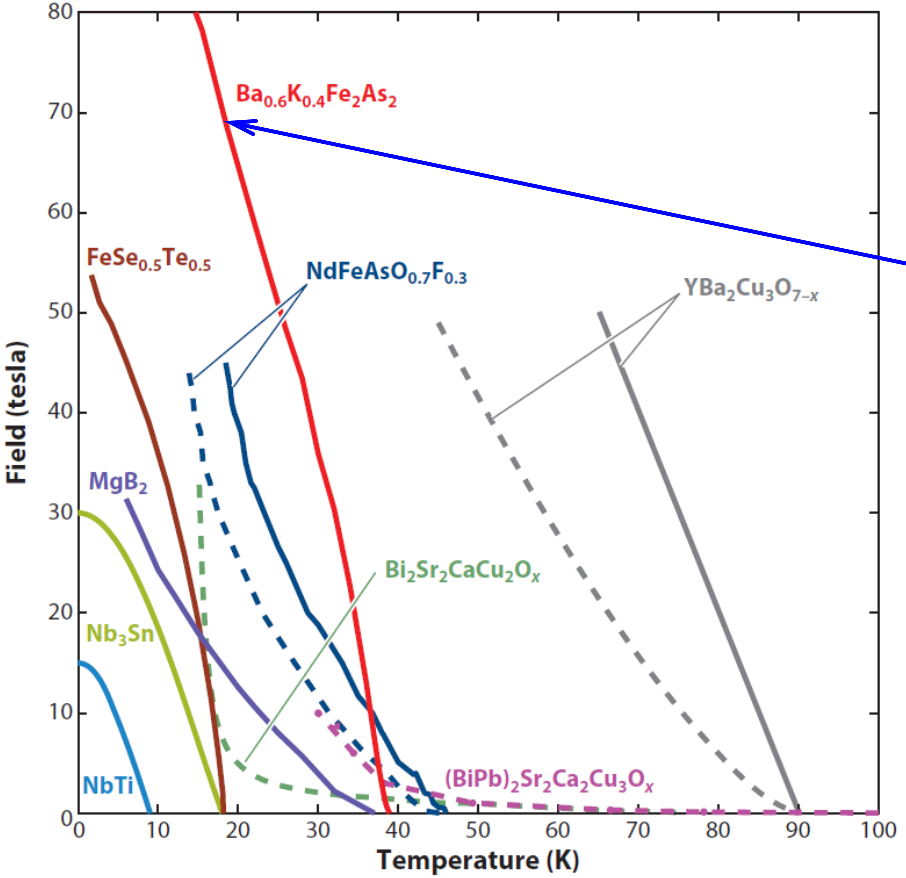
11 phase FeSe



T_c ~8 K

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

The extremely high H_{c2} in IBS



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

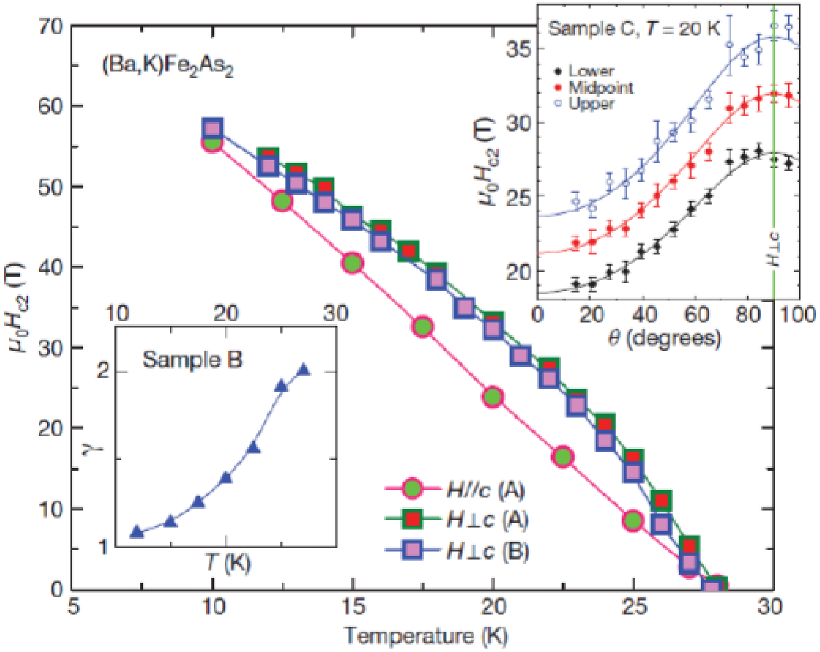
At 20 K, the H_{c2} can be >70 T

where IBS outperform both MgB_2 and Bi-2223.

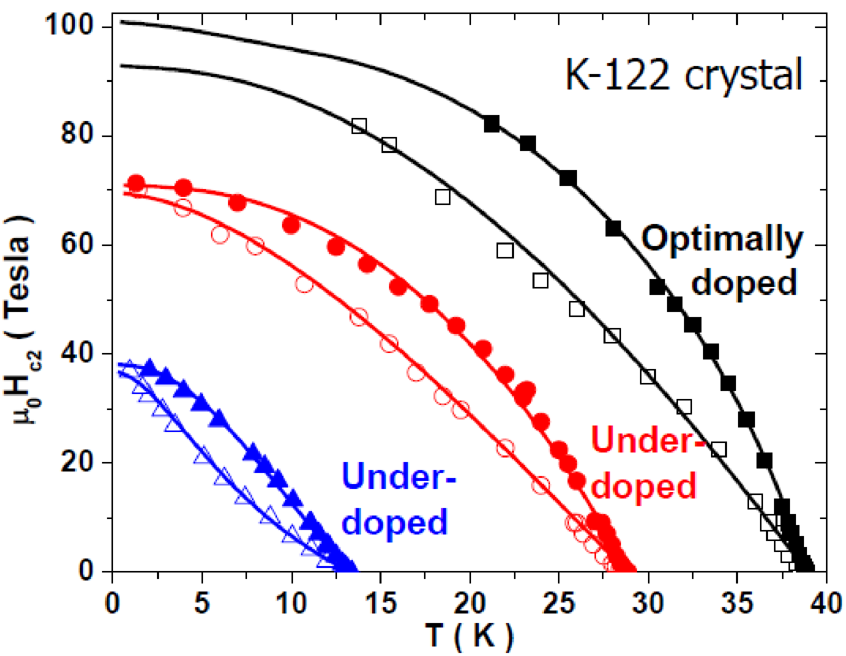
- **Interesting FBS have T_c: 38-55 K >> Nb-Ti and Nb_3Sn**
- **Operation at 4K >20T or 10-30 K at >10 T would be very valuable**

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

122 IBS - small anisotropy γ



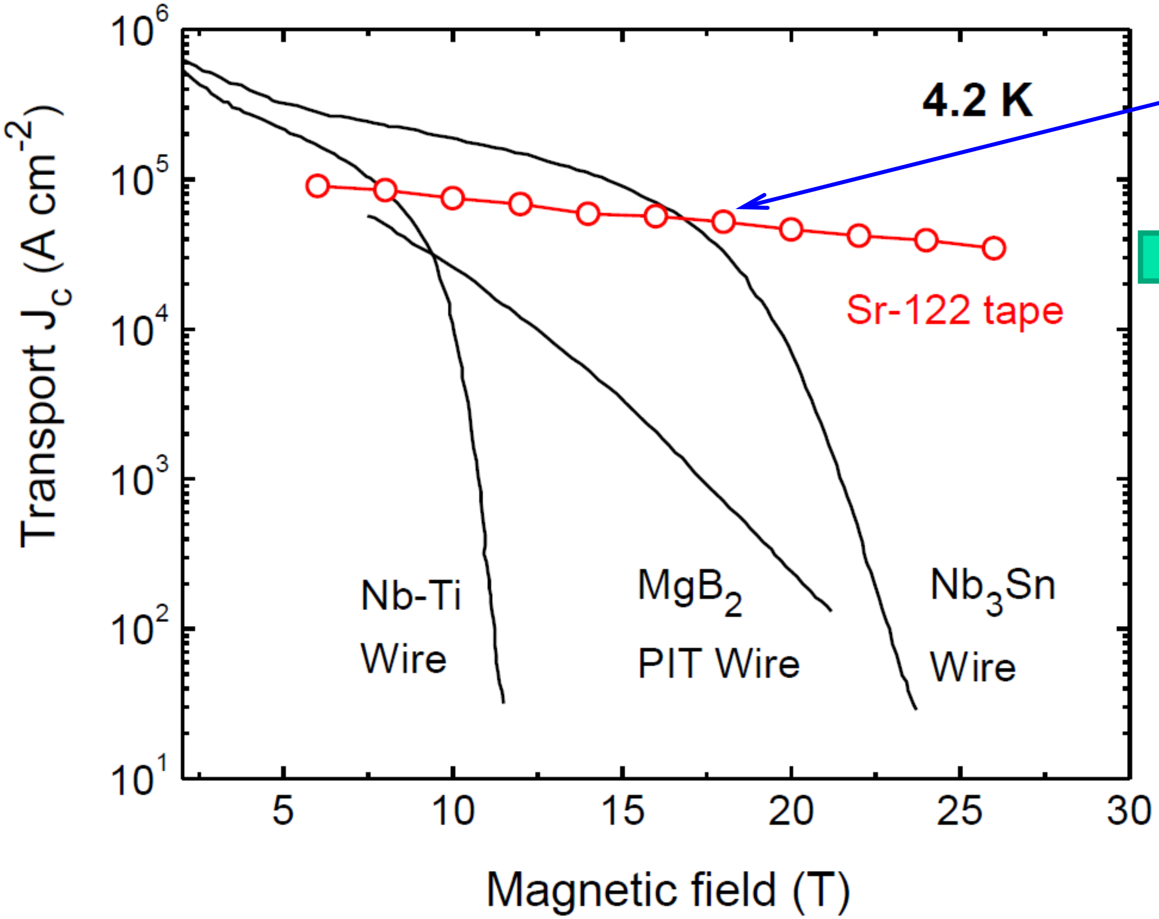
Yuan et al. Nature 457, 565 (2009)



Tarantini et al. PRB 86, 214504 (2012)

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

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

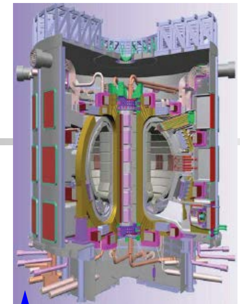


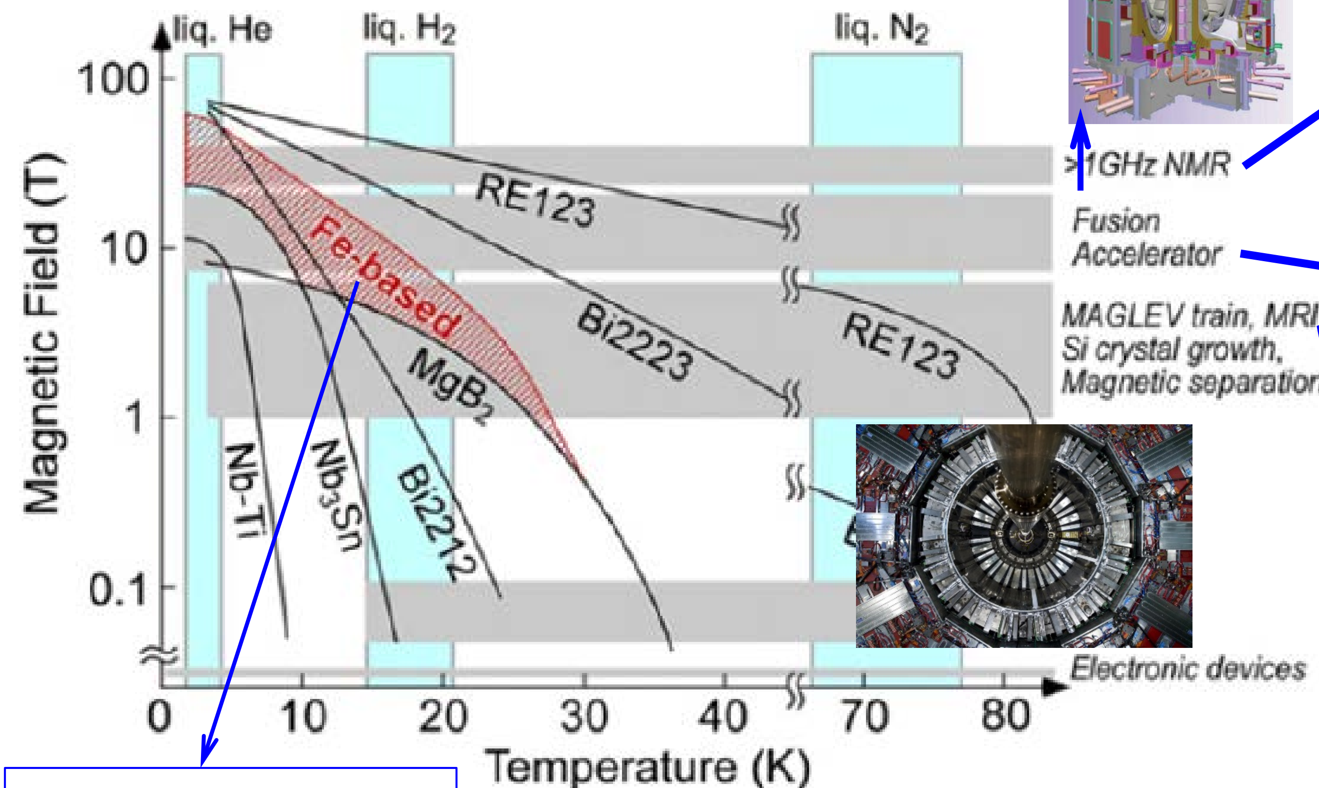
122 IBS wire:
Large J_c, at H > 20T

J_c shows very weak field dependence in high fields

IBS potential for high-field applications

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





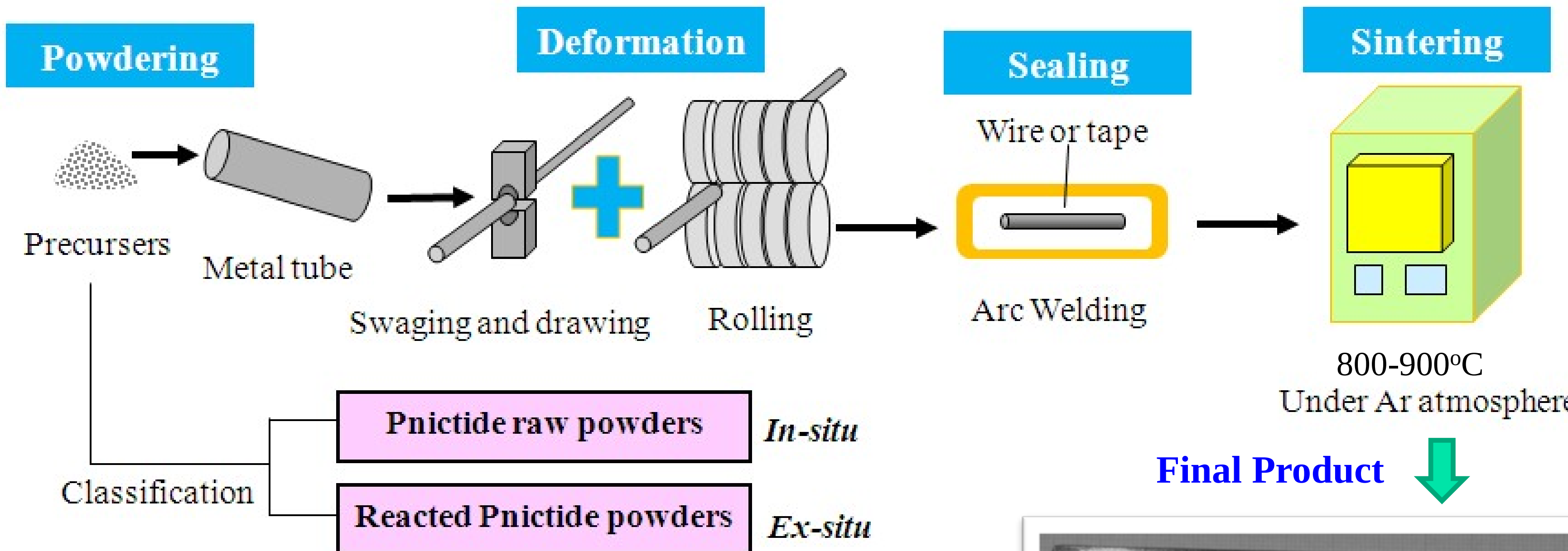
Working Temp:
4.2 K – 30 K

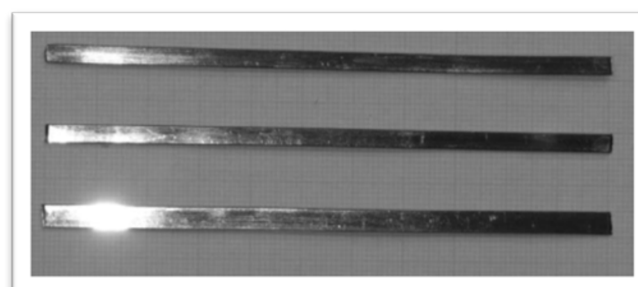
Shimoyama, ***SuST*** 27 (2014) 044002

Development of high-performance wire conductors is essential

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

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





Iron-based superconducting tapes

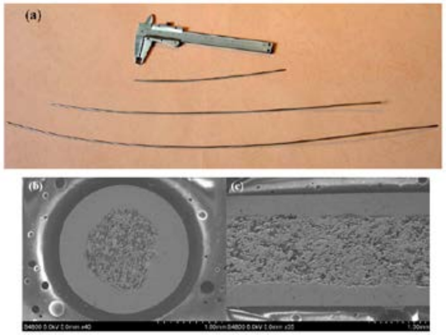
122 PIT wires:

1. The single phase can easily be obtained.
2. The sintering temperature is low.

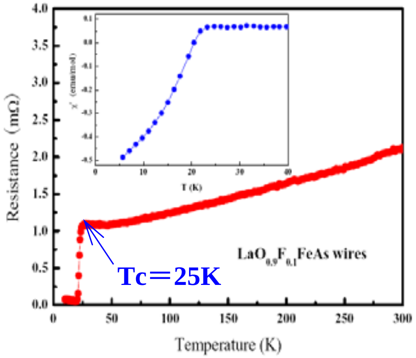
In April 2008, the first pnictide wire was fabricated by the powder-in-tube method

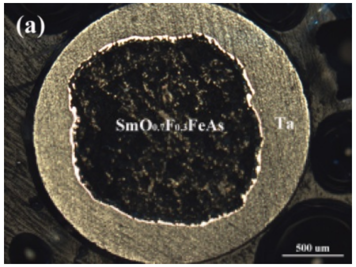
The early wires

- **much low critical current density Jc!**
- **due to thick reaction layer, many impurities, and cracks.**

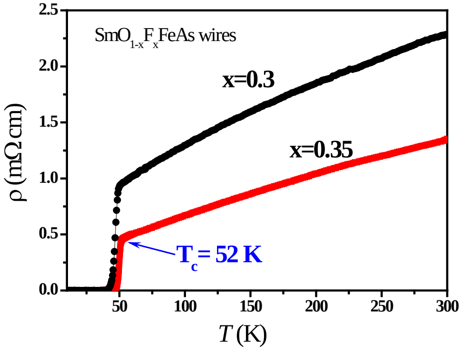


LaOFeAs



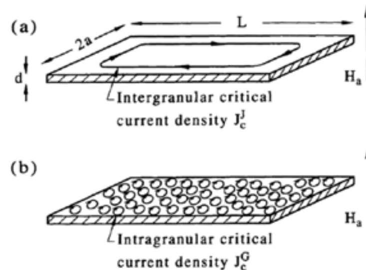


SmOFeAs

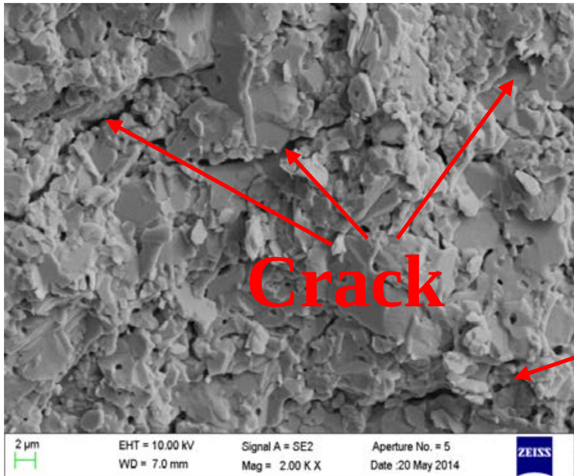


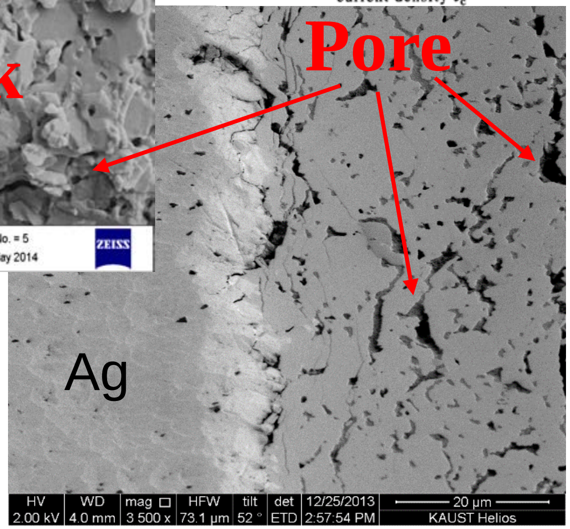
Our group: ***Supercond. Sci. Technol.*** *21 (2008) 105024*

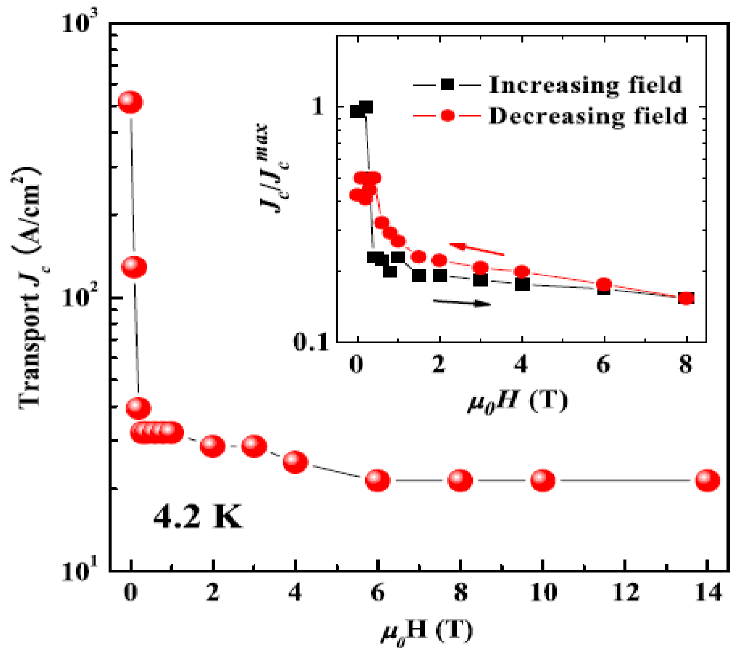
Key problems for PIT wires: Low density and weak link



Good connectivity is desirable!







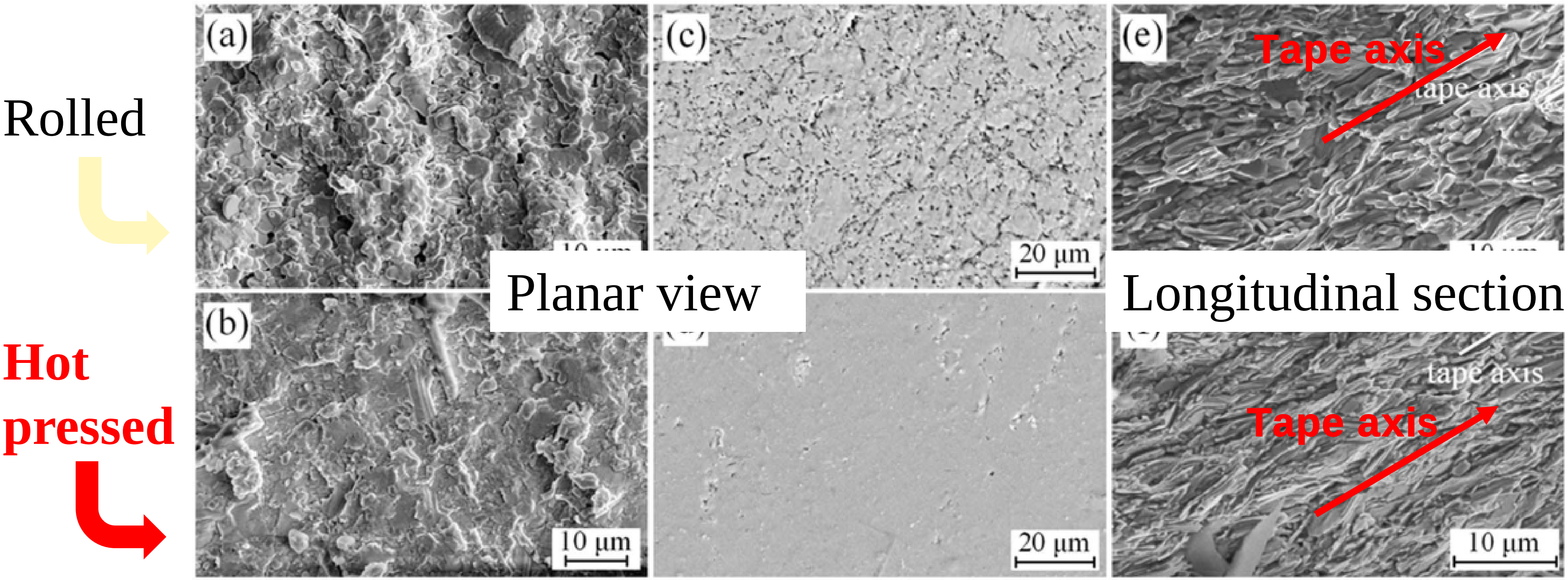
Low density: cracks and porosity

Hysteresis in transport J_c: signature of weak links

- Residual cracks and 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.

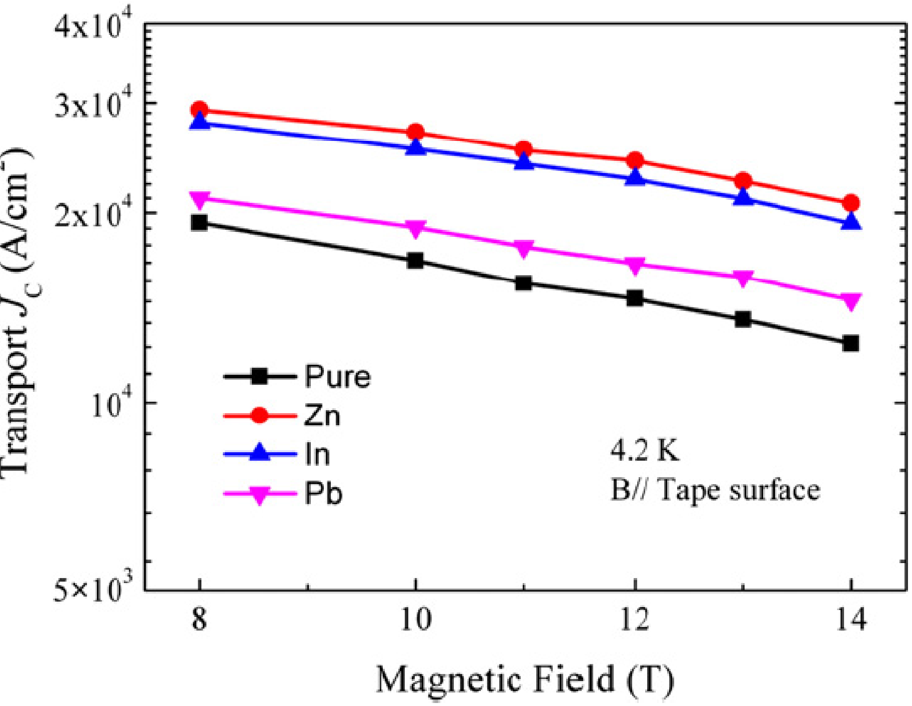
Solutions

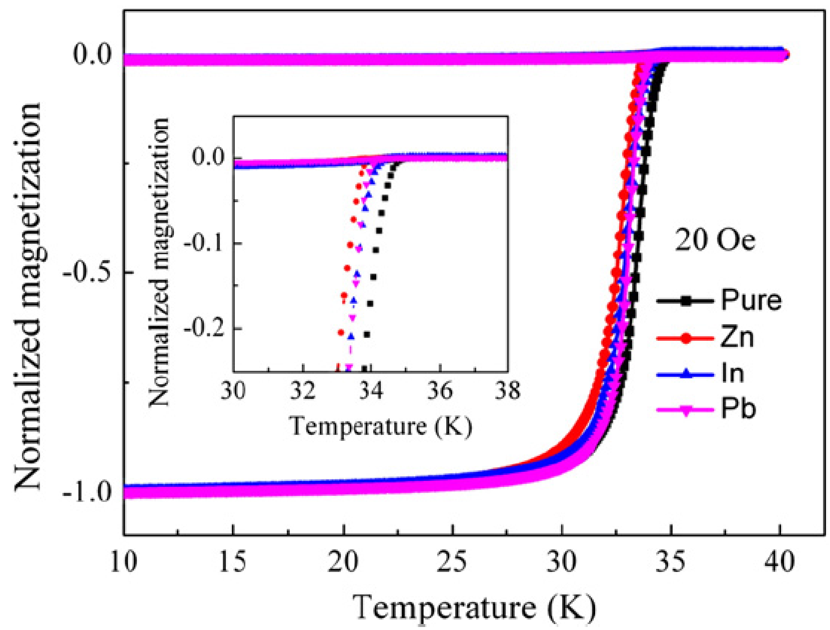
- ✓ **Add Sn** to improve the grain connectivity. (APL2011)
- ✓ **Large reduction rolling** to increase texture. (*Physica C* 2011, *APL* 2011)
- ✓ **Hot pressing** is effective to enhance the superconducting core density as well as grain alignment. (*APL*2014)



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

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

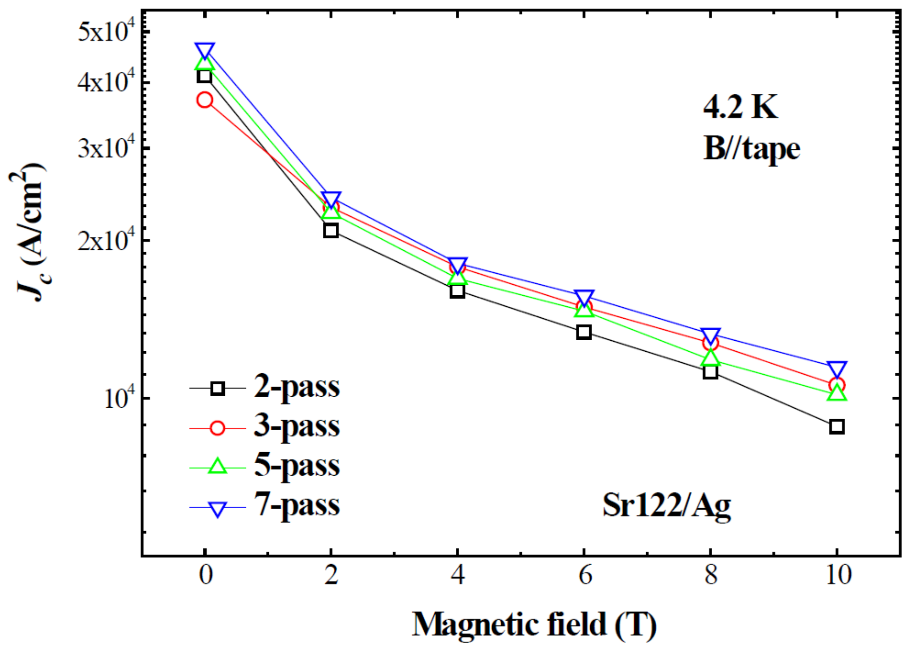


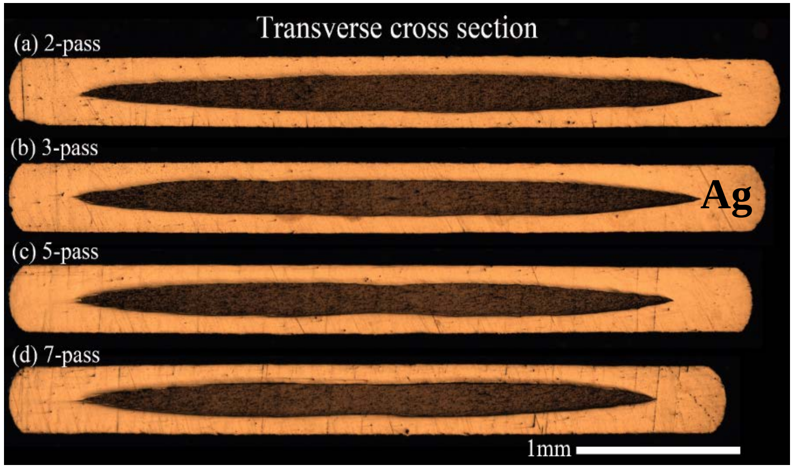


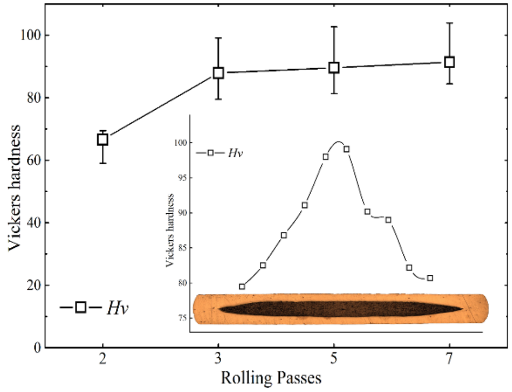
- The additions do not significantly affect the temperature transition Tc, and the Tc decreased only 0.4 K.
- the Jc enhancement in In or Zn-added samples may be attributed to the improved phase uniformity as well as the good grain connectivity

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

Optimized rolling process for 122/Ag tapes: 3-pass deformation is best





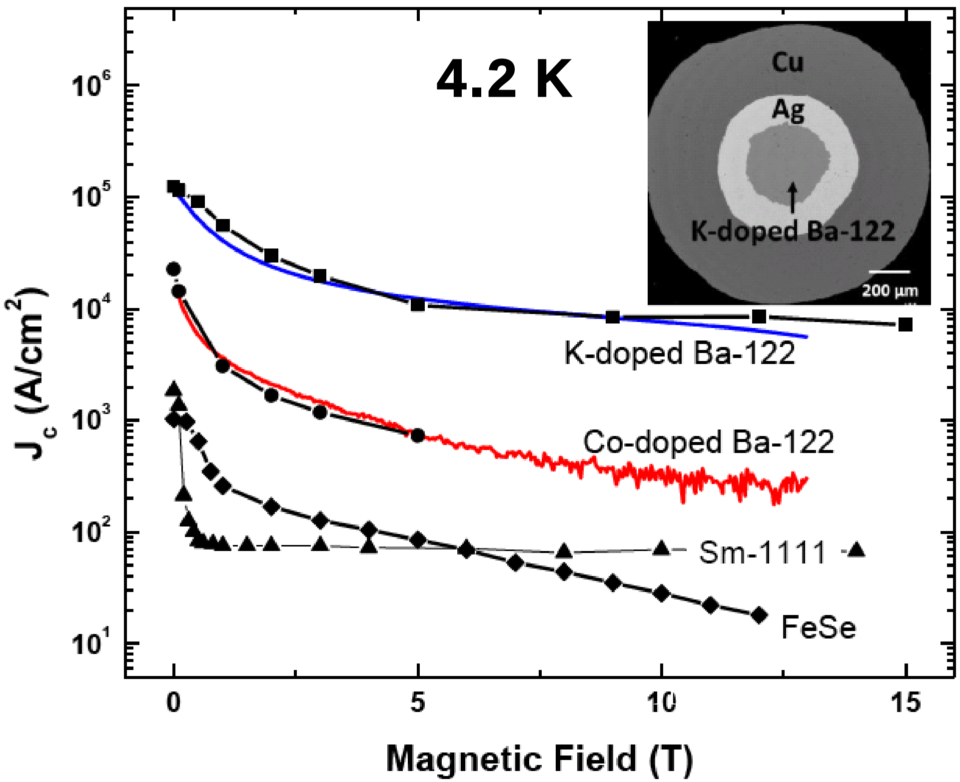


- The width of the tapes and the area of superconducting cores increase with decreasing the rolling pass, but the transport J_c seems close.
- We can fabricate tapes with 3 rolling passes to get the uniform and high-J_c 122 tapes.

Huang, ***Physica C***, 2016

NHMFL, USA

New synthesis method (HIP) increased J_c in Ba-122 round wire



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

Hot isostatic press (HIP) under 192 MPa of pressure at 600 ° C for 20 hours

HIP

Nearly 100% dense core

4.2 K

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

10 T, J_c = ~10000 A/cm^2

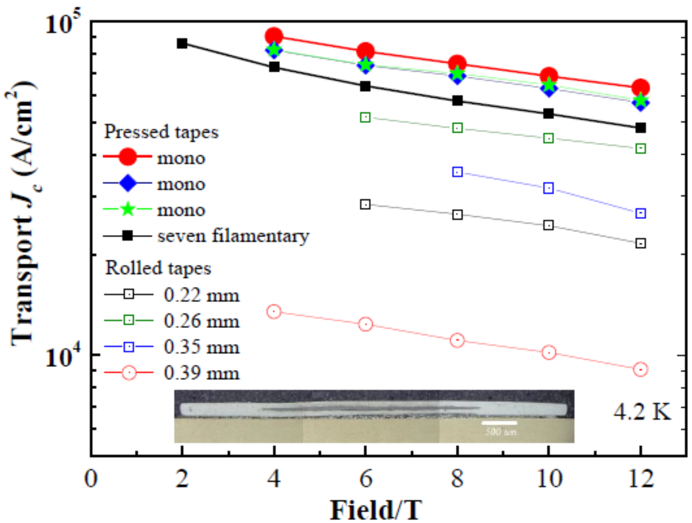
NIMS, Japan

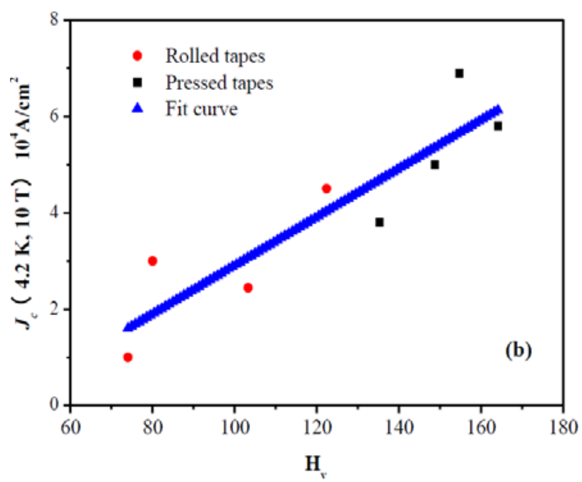
Thin tapes by combined the rolling, cold pressing and sintering process-- Denser core yields higher J_c

--Ag-sheathed Ba122 tapes

Steps:

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





The higher the core density, the higher the J_c

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

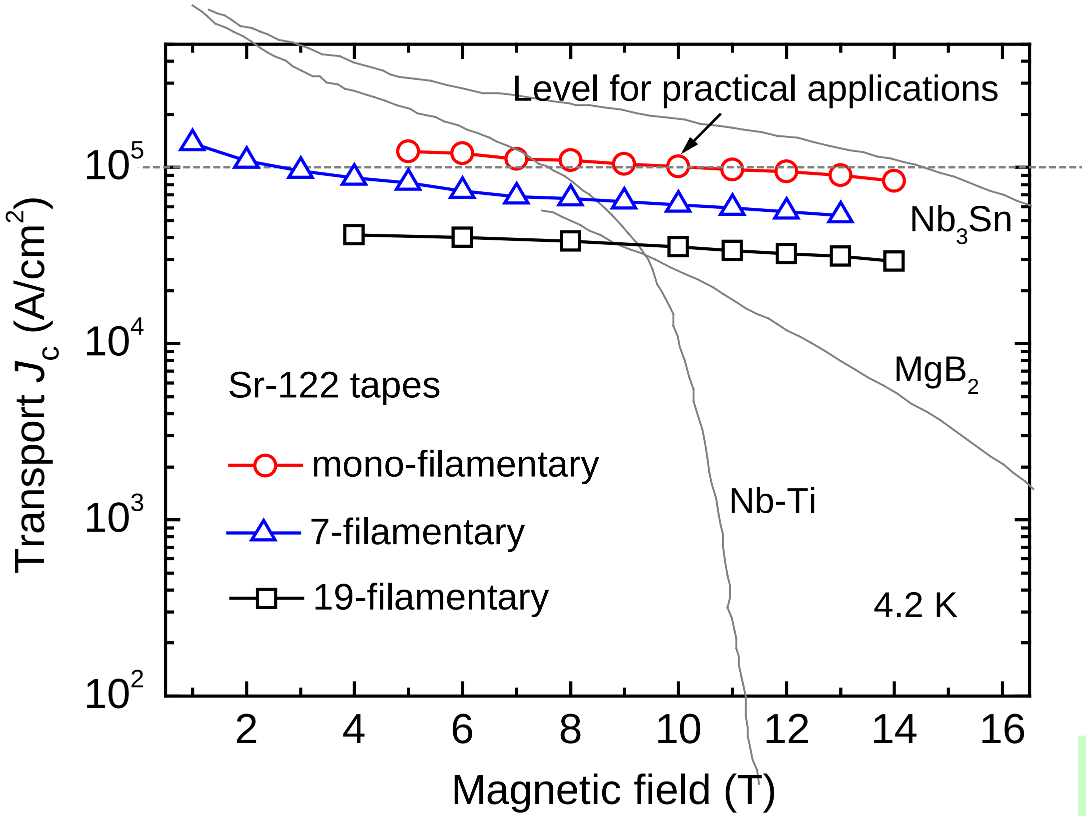
NIMS group, *Sci. Rep.* 4, 4465 (2014)

Breakthrough work

Very High transport J_c were achieved in 122/Ag tapes: $J_c > 10^5$ A/cm^2 (4.2 K, 10 T) - by hot pressing

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

First to reach practical level J_c!



Later achieved

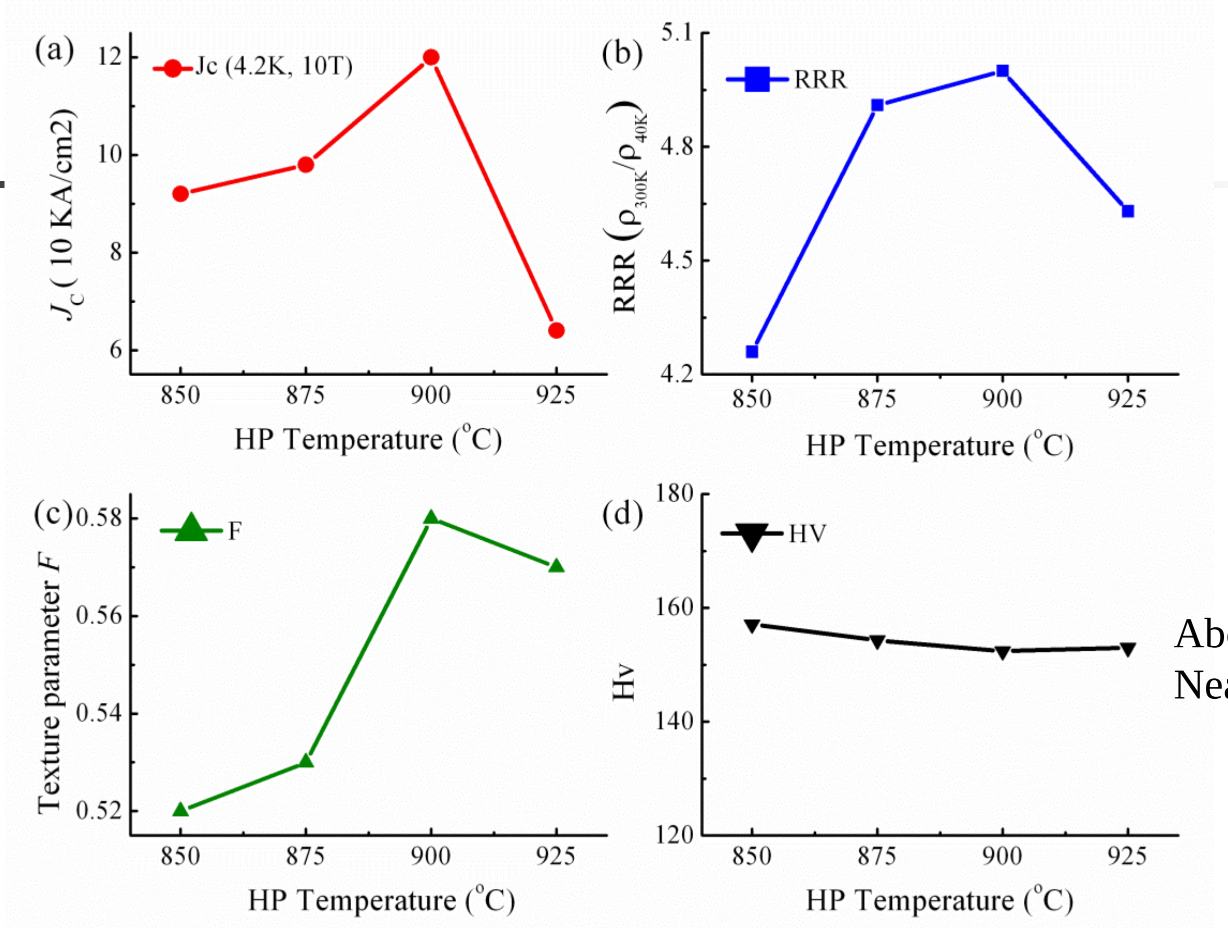
At 10 T, $J_c = 1.2\times10^5$ A/cm^2

even in 14 T, J_c = ~10^5 A/cm^2

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

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

Reasons for high transport J_c in HP900 tapes



About 154.0
Nearly constant !

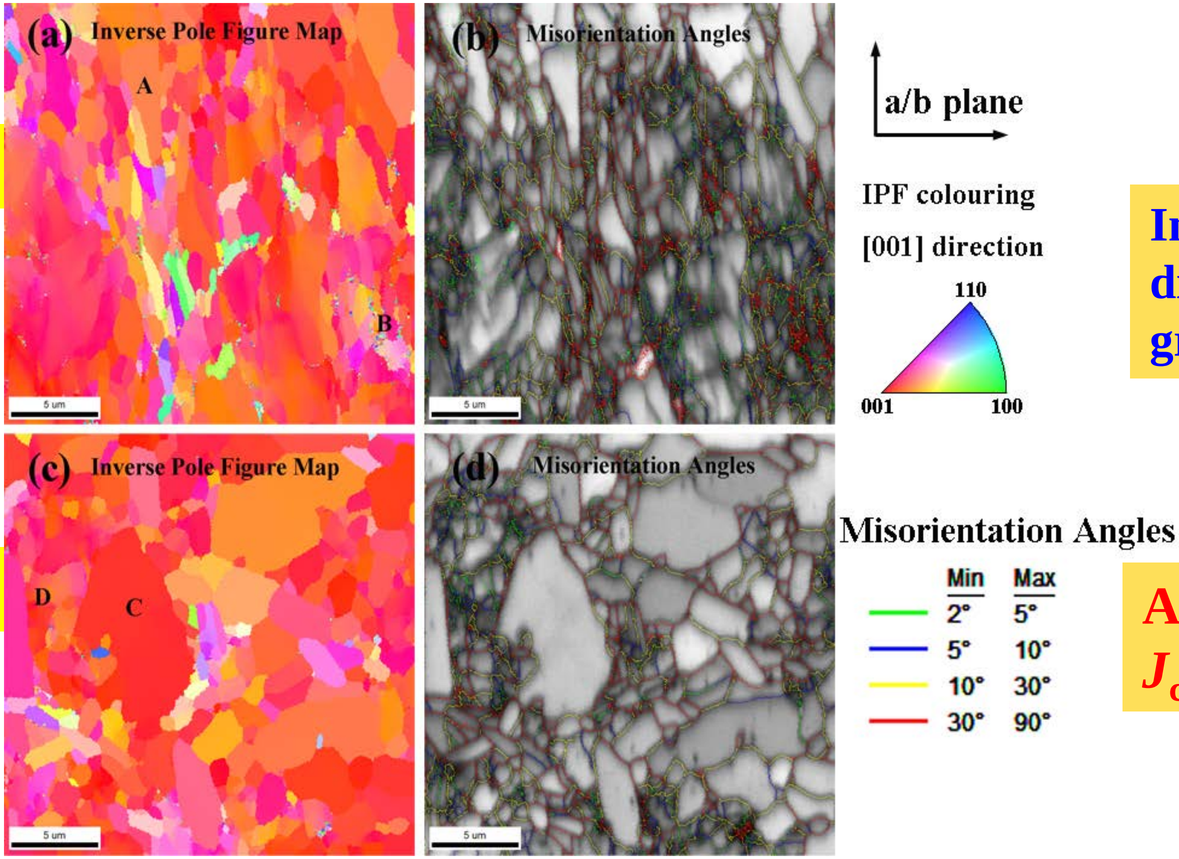
- **The variation tendency of J_c values was qualitatively similar to those of F and RRR values.**
- **The hardness was almost saturated as soon as the hot pressing was applied.**
- **The J_c increase for HP900 tapes was mainly attributed to higher degree of c-axis texture and enhanced grain connectivity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

EBSD images: the orientation mapping of grains

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

Upper: HP850

Lower: HP900

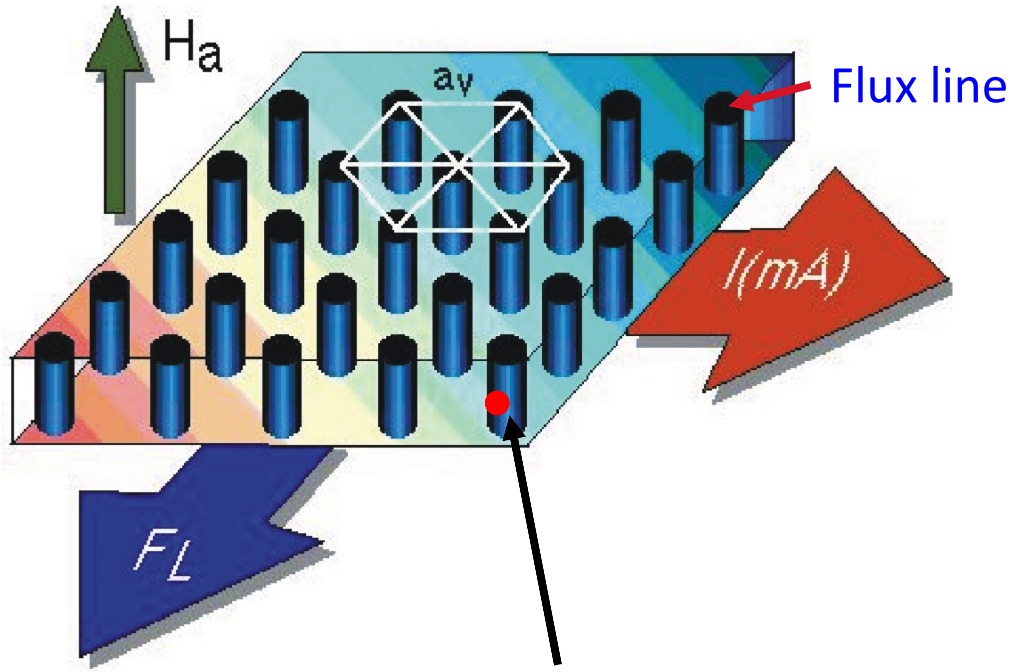


Inhomogeneous distribution of grain size

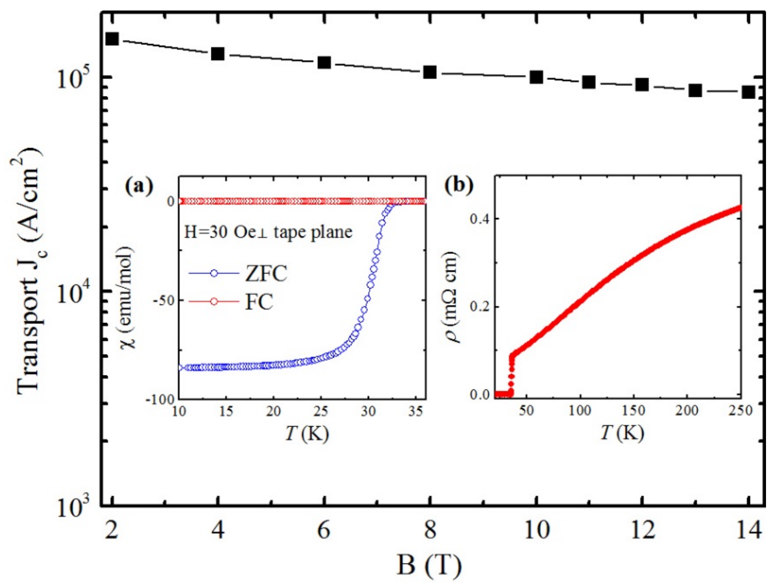
A room for the J_c improvement

- **The dominant orientation is (001) as the expected red color for both tapes, but there is a small (100) orientation for HP850 tapes as the green color.**
- **The large fraction of small misorientation angles between 2–10°C (HP850 tapes 23.3%, HP900 tapes 26.2%).**

Flux pinning and dynamics in hot-pressed high J_c Sr122 tapes



Pinning sites: crystal defects, dislocations, nano-particles *et al.*

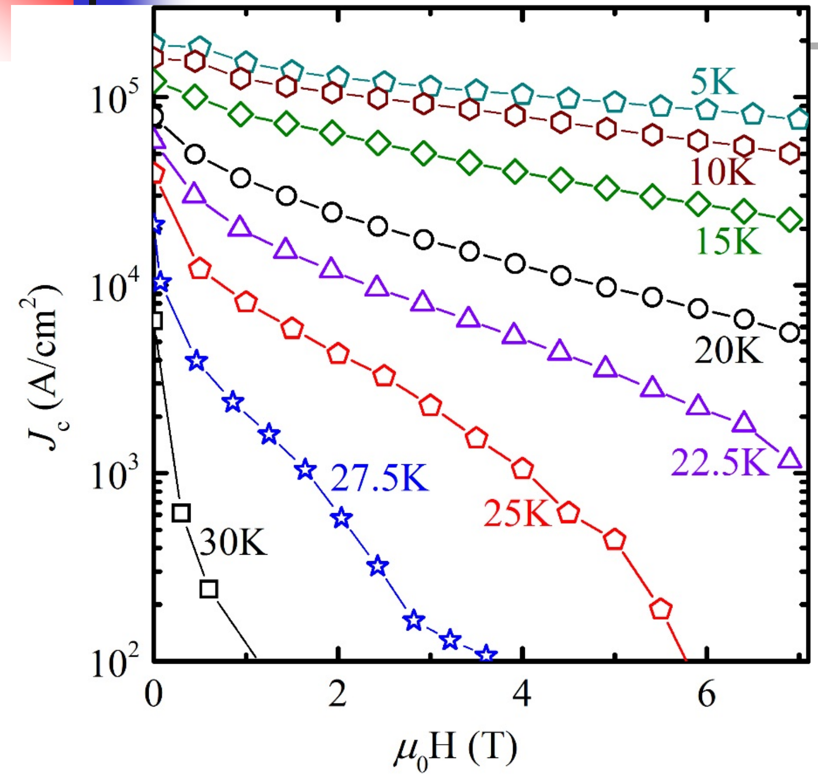


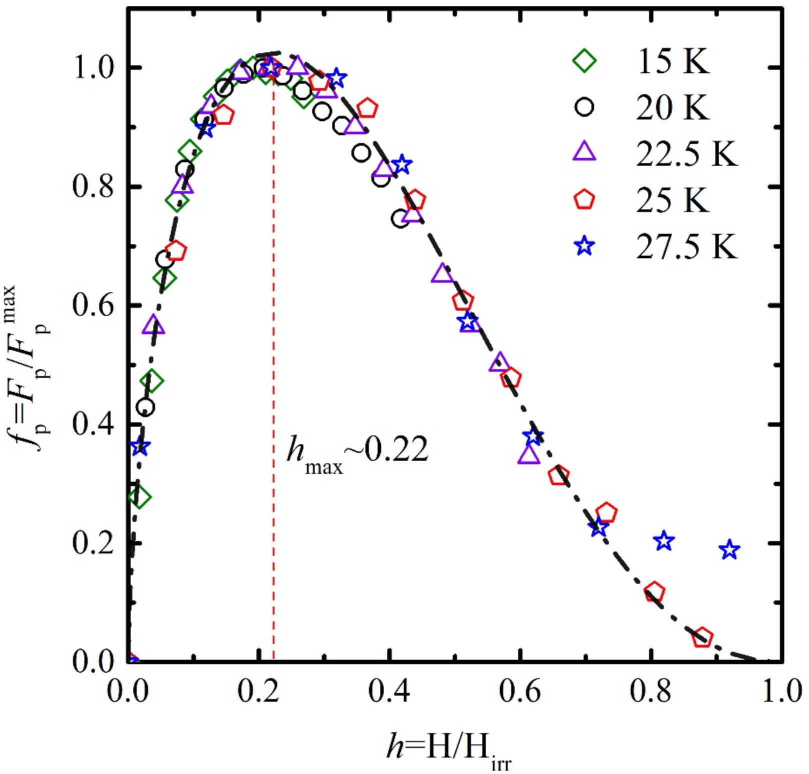
- J_c (4.2 K, 10 T)~**10^5 A/cm^2**, I_c(4.2 K, 10 T)~300 A.
- T_c~35 K, sharp superconducting transition.
- Residual resistivity ratio: RRR=ρ(250 K)/ρ(37 K)=4.81, indicating good connectivity between grains.

- No pinning, no Jc.
- Thermal excitation, quantum tunneling and mechanical vibration will lead to redistribution of flux and hence relax of magnetization.

Flux pinning and motion are important factors that control J_c

Flux pinning mechanism





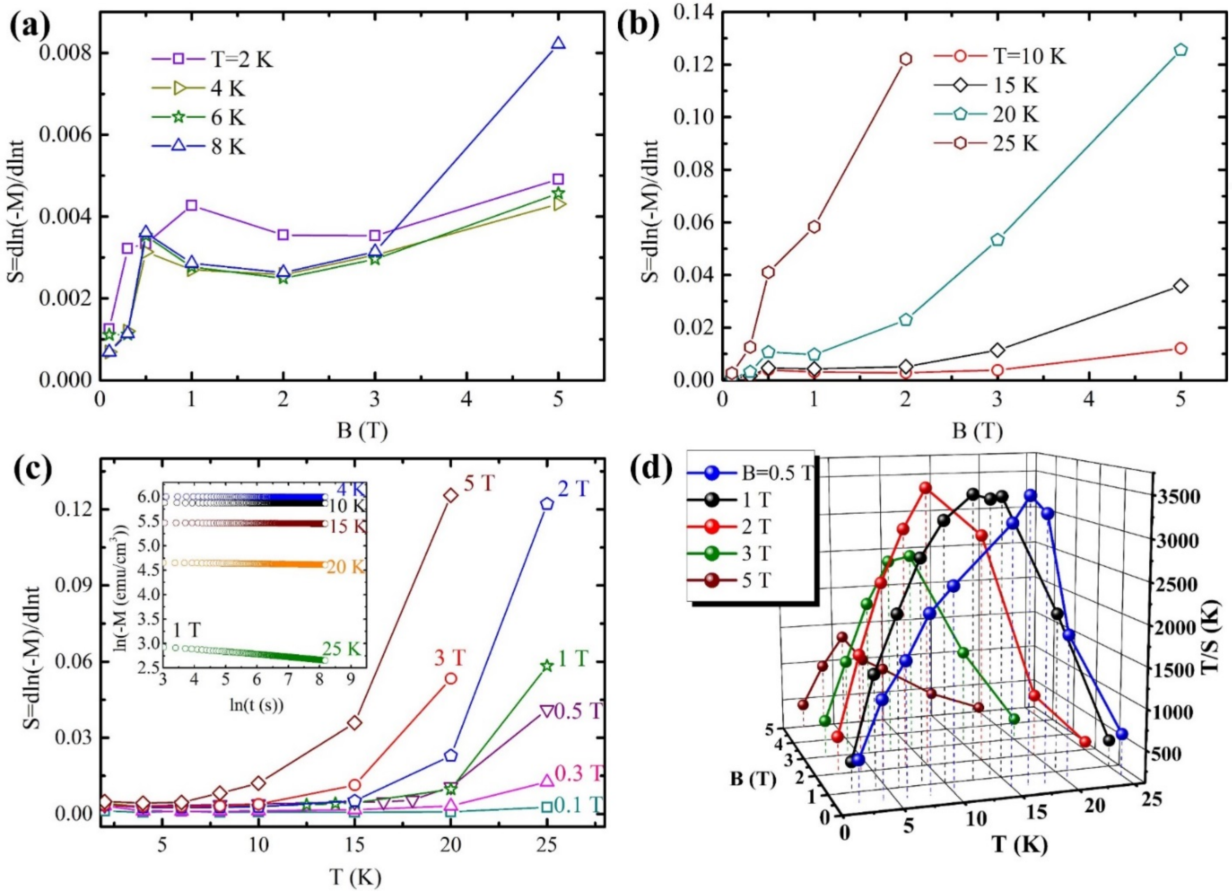
- Magnetic J_c is very close to the transport J_c, confirming that granularity is negligible.
- Dew-Hughes model: $f_p=Ah^p(1-h)^q$, $H_{max}=p/(p+q)=$**0.22**

  Grain boundaries and *dislocations* are dominant, *point pinning* also plays a role.
- **δ*l* pinning**, flux is pinned via spatial fluctuation of charge carrier mean free path.

Magnetization relaxation - flux creep study

Relaxation rate:

$$S = d\ln(-M)/d\ln(t)$$



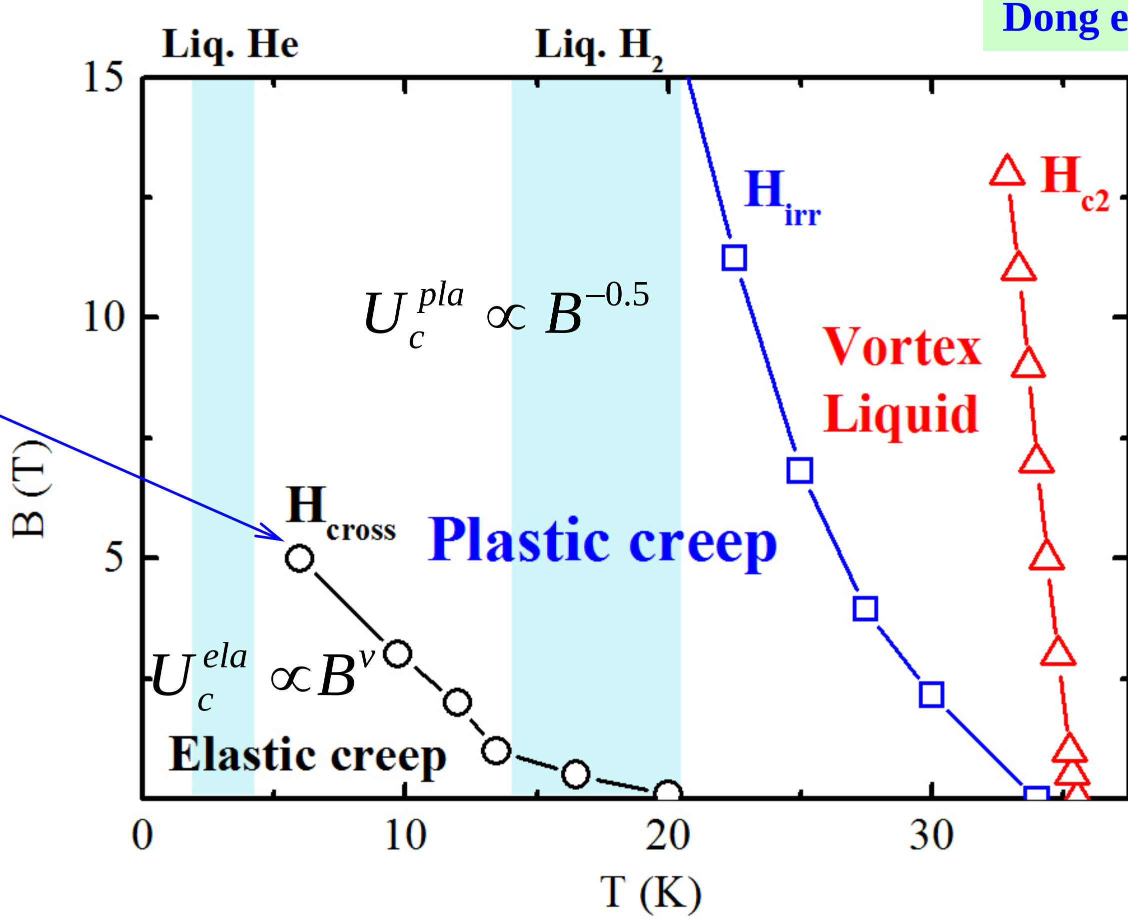
- Magnetic relaxation data indicates a logarithmic dependence of magnetization on time, *thermal activated flux creep.*
- Very small relaxation rate with weak temperature and field dependence, indicating strong flux pinning and weak field dependence of J_c.
- Crossover from elastic creep to plastic creep.

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

Vortex phase diagram of high-J_c HP-122 tapes

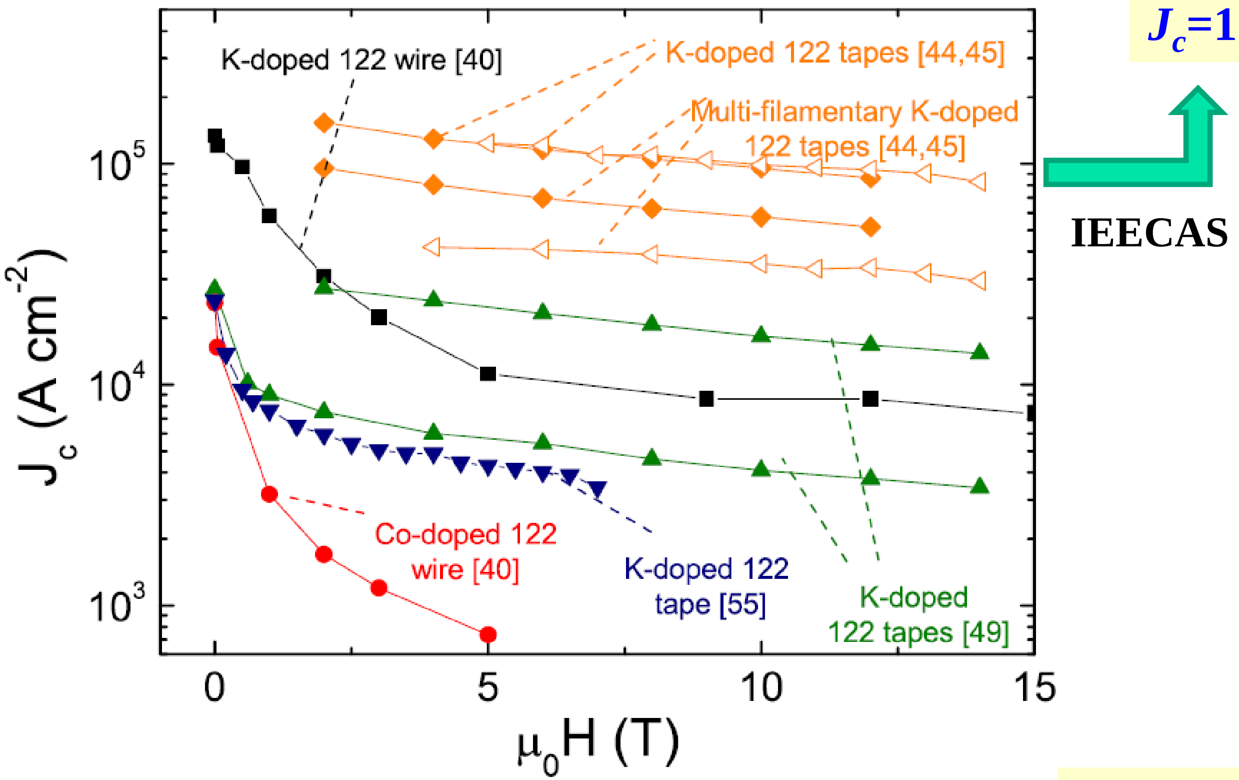
Dong et al., *JAP*, 2016

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



- More robust field dependence of J_c in the elastic creep regime.
- Weak field dependence of J_c in the liquid helium region, but J_c quickly decrease in the liquid hydrogen region.
- **To further increase flux pinning force: i)** decrease grain size to make more grain boundaries, ii) increase point pinning sites, *e.g.* radiation or nano-particle inclusion.

Progress of J_c values in 122 wires and tapes



4.2K, 10 T
J_c=1.2×10^5 A/cm^2

Highest J_c value reported in literature!

Putti, ***SuST*** 28 (2015) 114005

Next target: 10^{5}A/cm^2 at 20-30T

Conductor requirements for practical applications

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

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

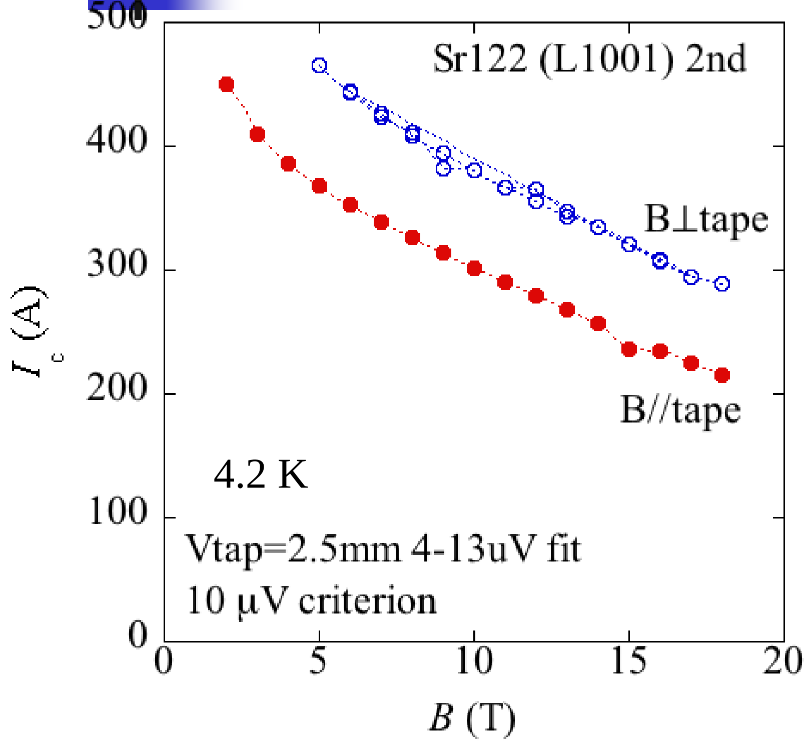
Larbalestier, ***Nature*** 414 (2001) 368

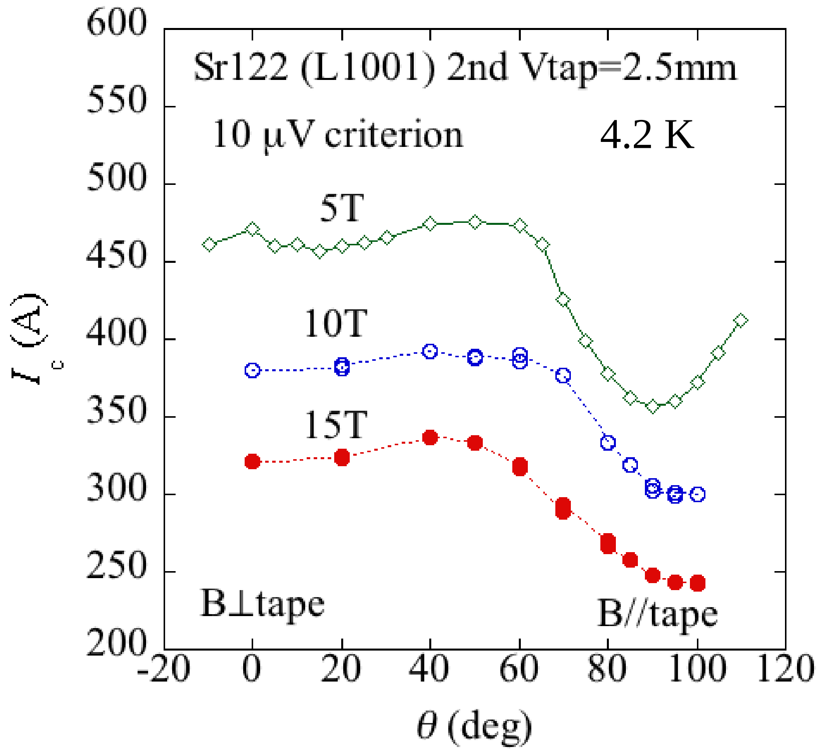
Small anisotropy

Awaji et al., *SuST*, 2017

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

-- Measured by Dr. S. Awaji
HFLSM, Tohoku Univ.

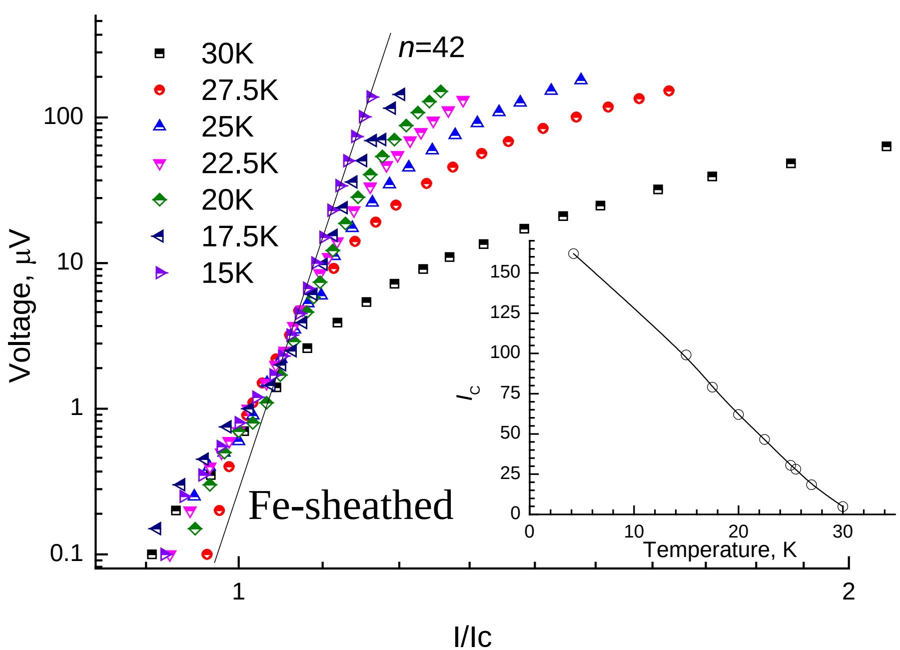




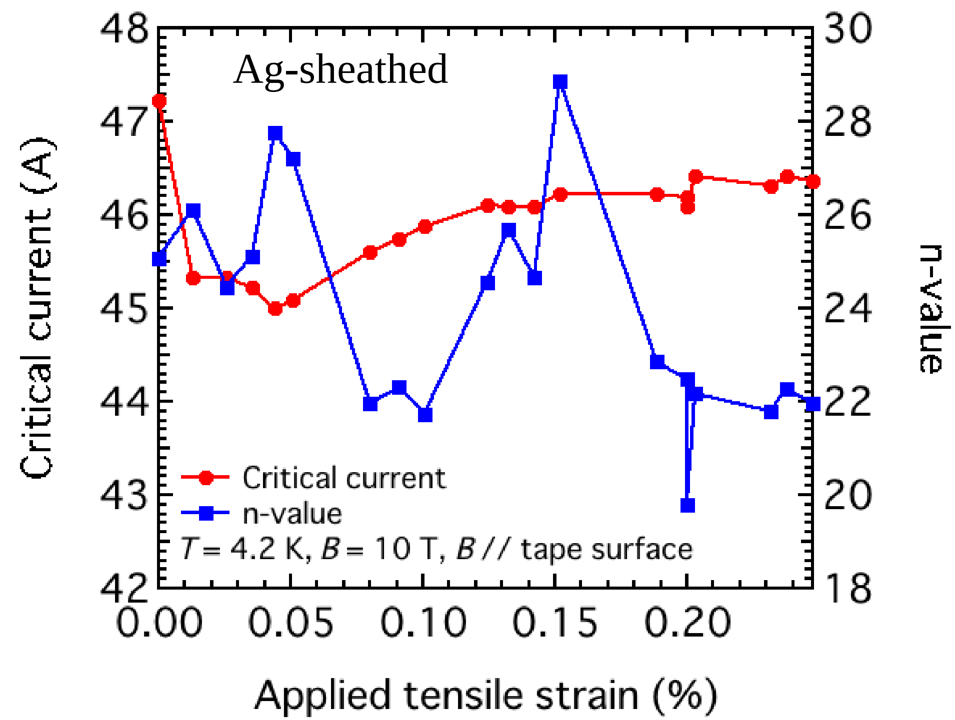
- **The I_c in applied magnetic fields is slightly higher in the perpendicular field ($I_c^{\perp}$) than in the parallel field ($I_c^{//}$).**
- **The anisotropy ratio ($\Gamma = I_c^{\perp}/I_c^{\parallel}$) is less than *1.5*, quite small, very promising for applications.**

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

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



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



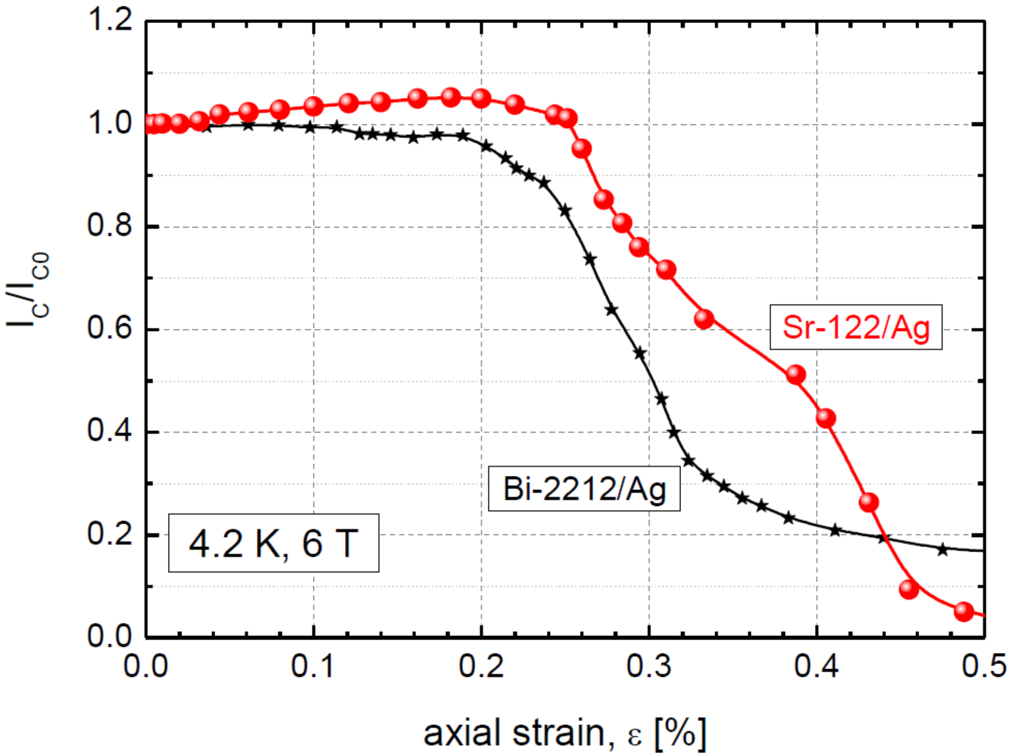
At 20 K, the *n value* was over 30

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

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

The first strain measurements of Sr-122/Ag tapes

-- Measured by Dr. Kovac
Slovak Academy of Sciences



At 4.2 K, 10 T: I_c >125A

Irreversible strains:

ε = 0.25%

which seems better than that of Bi-2212/Ag

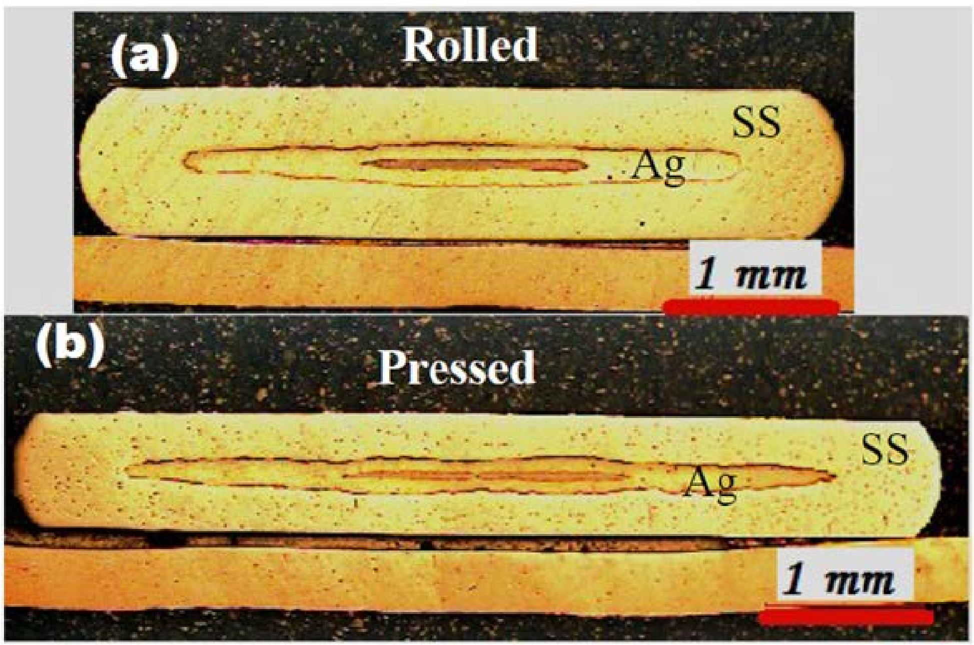
The first observation of strain effects on the critical current of 122 wires

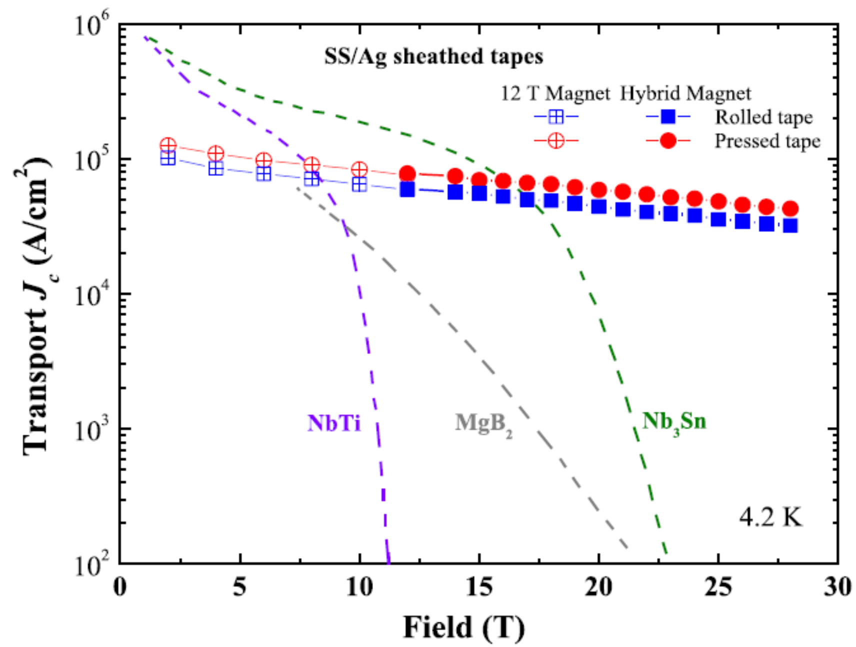
Next step:

Improvement of mechanical property of pnictide wires will be one of the major challenges for high field applications

Fabrication of stainless steel/Ag double sheathed Ba122 tapes

Highly mechanical property is expected!





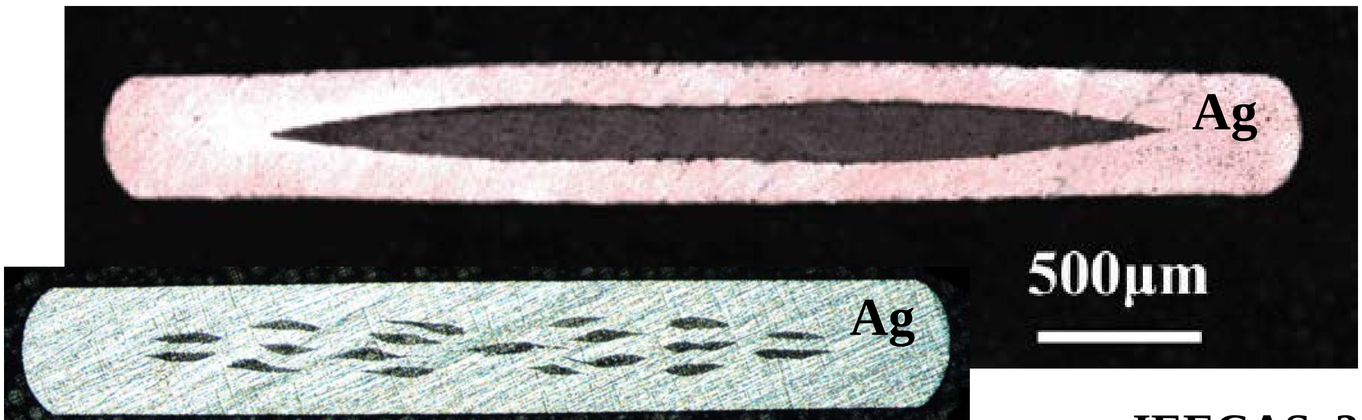
High J_c, but show lower $\boldsymbol{J_e}$

NIMS group, ***Supercond. Sci. Technol.*** 28 (2015) 012001

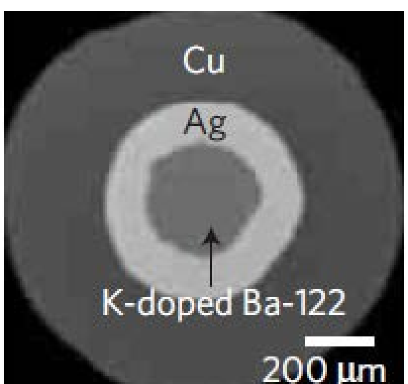
So far, all high-J_c pnictide wires and tapes were made by using Ag as sheath material

Ag is very expensive

We should find other cheap materials, in order to reduce the cost!



IEECAS, 2014



Florida, 2012

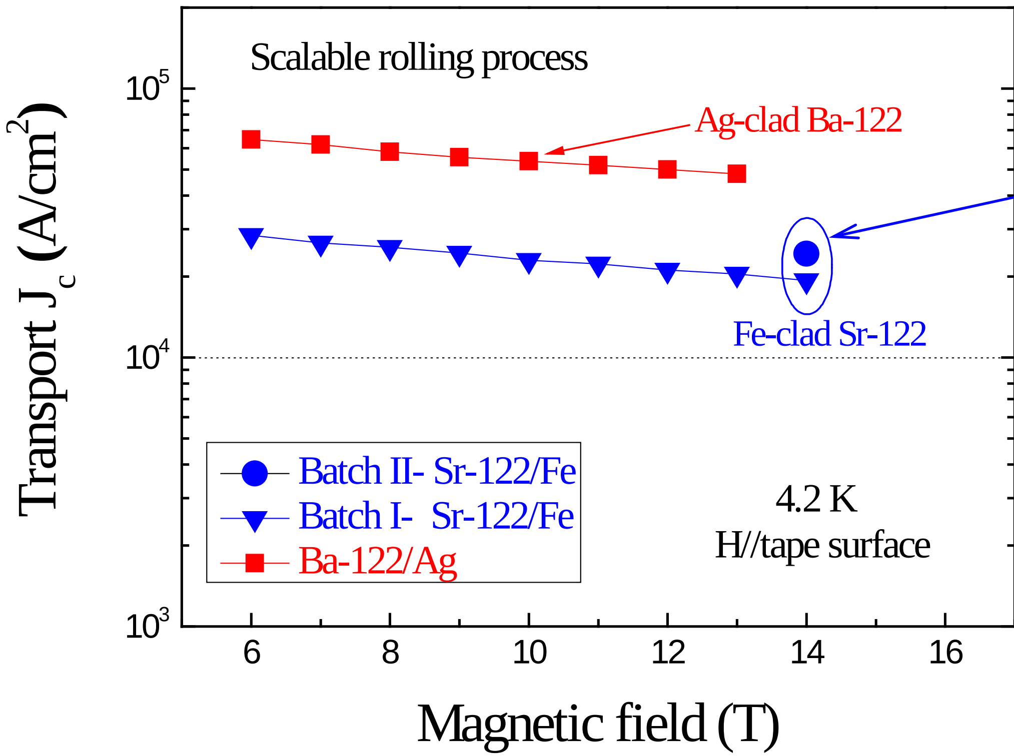
NIMS, 2014

Fe sheath material

Ma , *Physica C* 516 (2015) 17

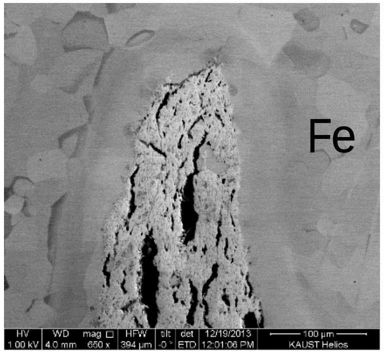
Fabrication of Fe-cladded 122 tapes

-- tape thickness=0.6 mm -- by the scalable rolling



At 4.2 K and 14 T:

J_c = 2.4×10^4 A/cm^2

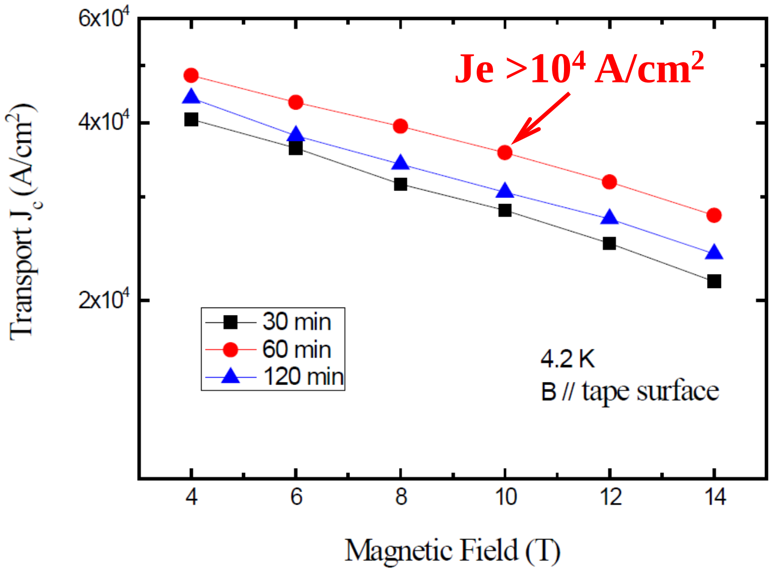


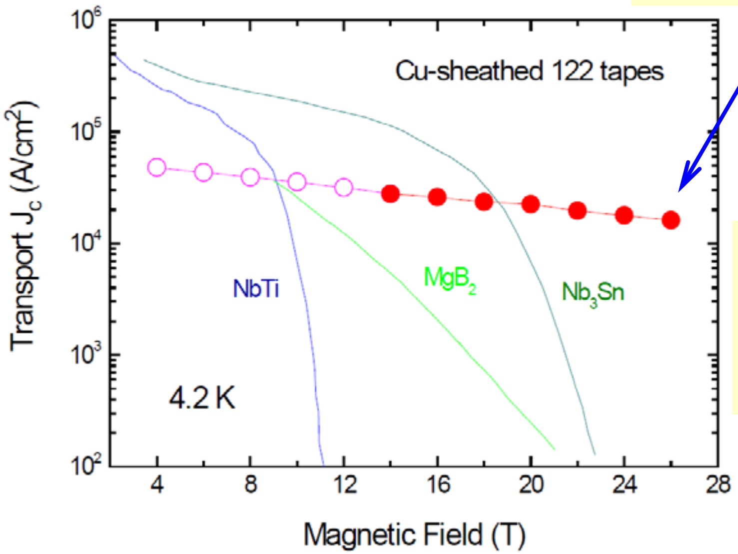
From an economic point of view, the Fe sheath is more attractive than the Ag sheath in fabricating Sr122/Ba122 tapes for practical applications.

Copper sheath material

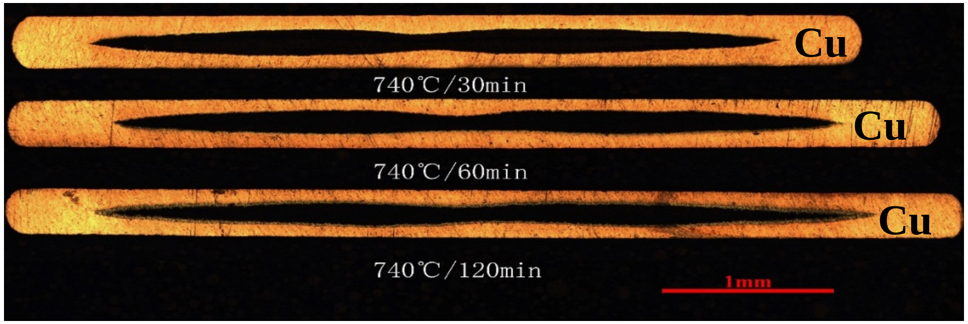
High J_c in Cu-sheathed Sr-122 tapes at low temperature 740°C

At **26 T**:
$J_c = 1.6 \times 10^4$ A/cm²





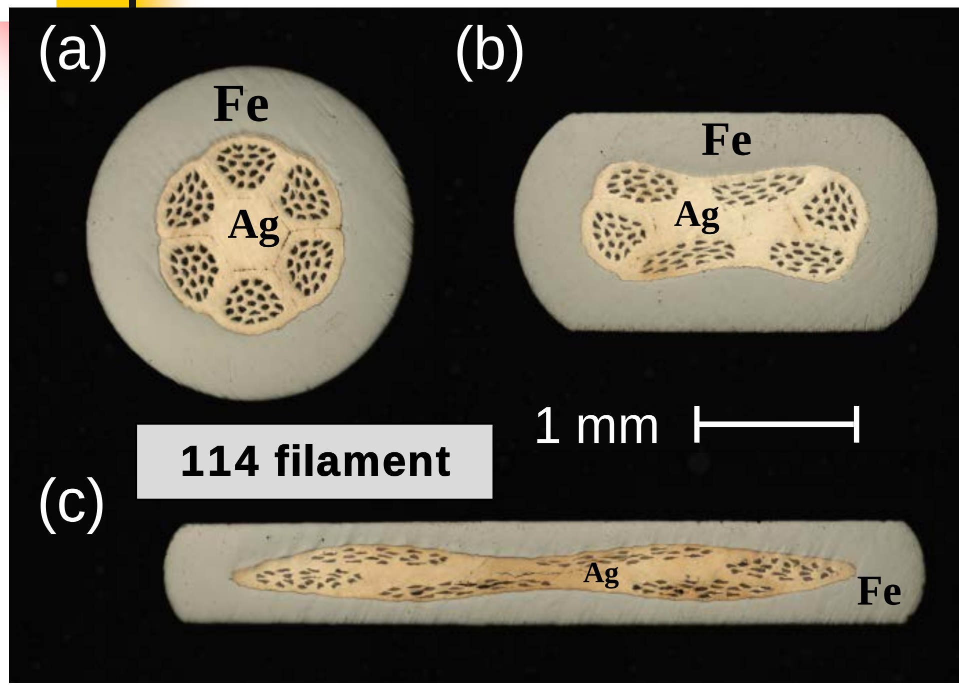
At 4.2 K, 10 T
Engineering J_e: $>10^4$ A/cm²

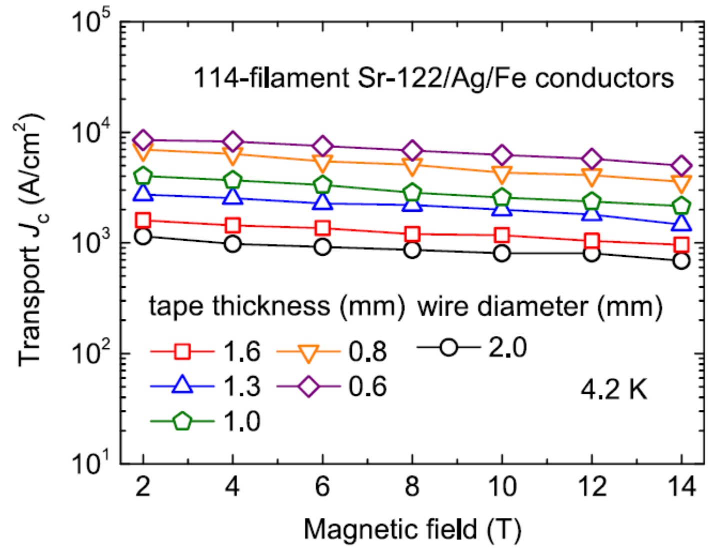


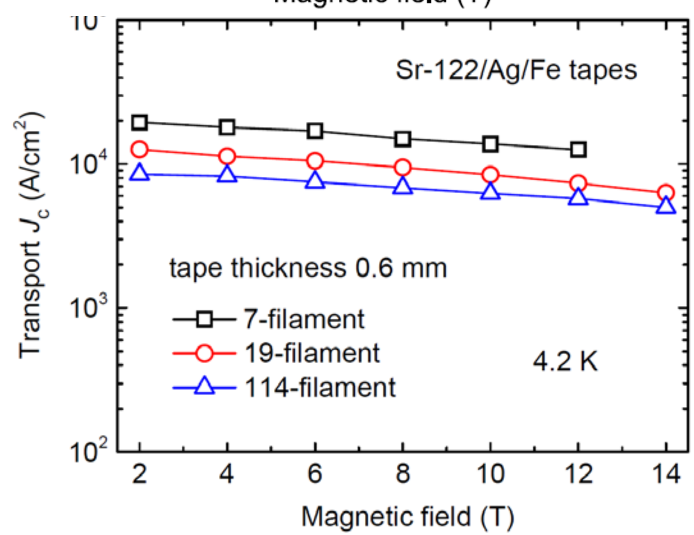
- The HP740/60 tape has a uniform and well connective superconducting phase and only a small amount of diffusion of Cu.
- The best transport J_c reaches 3.5×10^4 A/cm² at 10 T and keeps 1.6×10^4 A/cm² at 26 T.

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

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







At 4.2 K, 10 T:

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

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

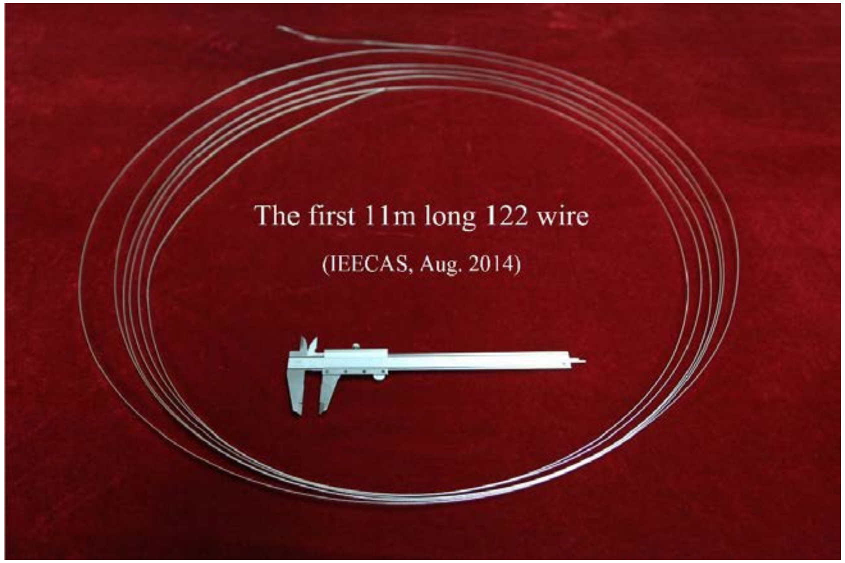
IEE-CAS

Ma , *Physica C* 516 (2015) 17

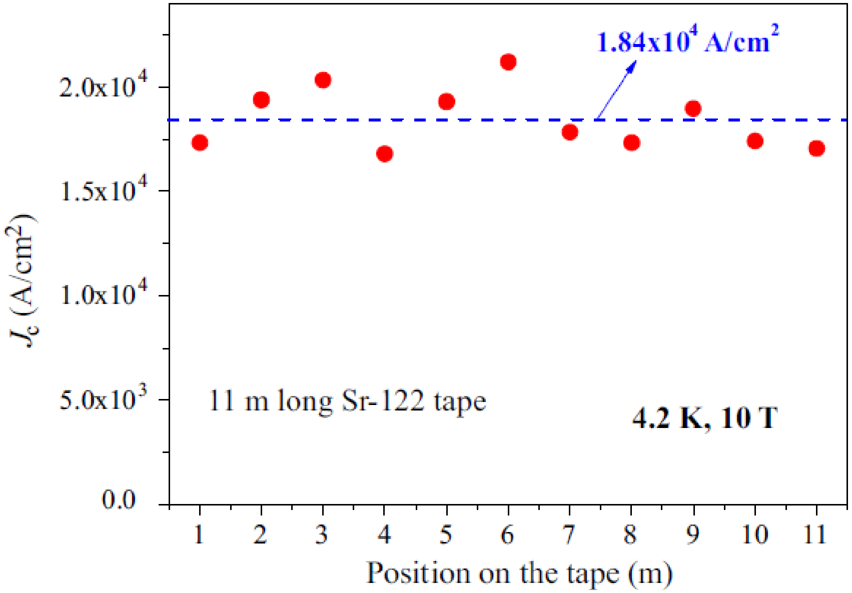
The first 11m long Sr-122 tape

-- by the scalable rolling process

The first long wire-- 11 m



Uniform wires can be fabricated



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

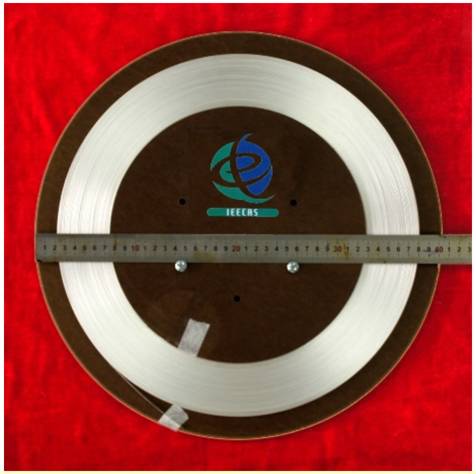
The fluctuations of the J_c is ~5%

Significant breakthrough!

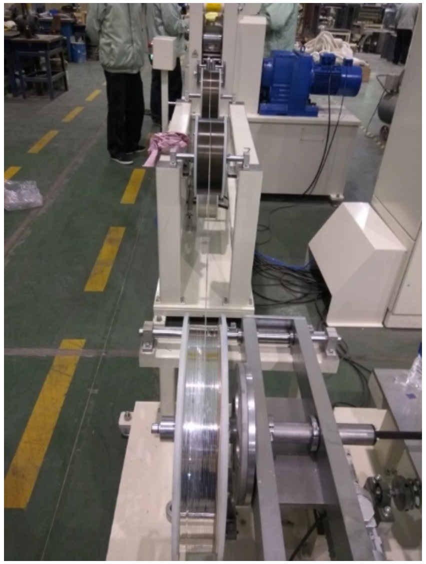
In Aug., 2016

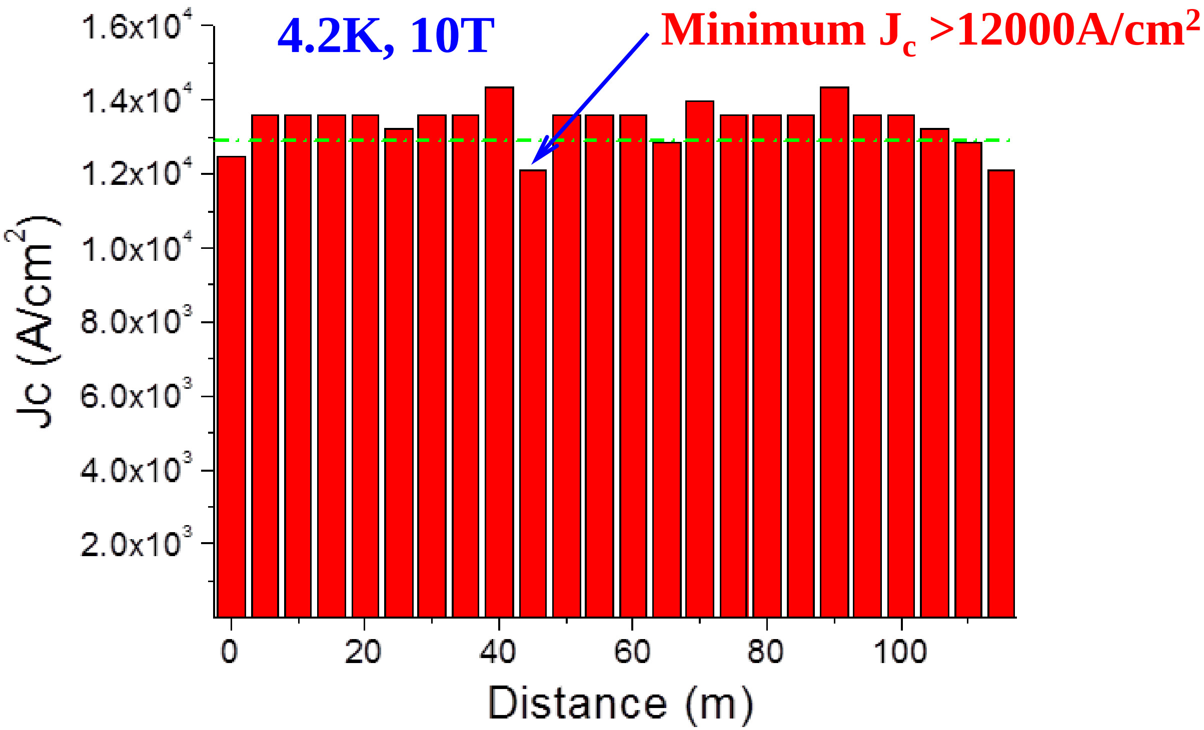
The world's first 100 meter-class iron-based superconducting wire

-- Presented at ASC2016, Denver



115 m long **7-filamentary** wire





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

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

X. P. Zhang et al., *IEEE TAS*, 2017

Challenges for the next stage R&D

- ✓ **Ultra High In-Field Critical Currents: I_c– B**

  → e.g. engineering current density J_e > 500 A/mm^2 **@** 4.2 K, 20 T

- ✓ ***Homogeneous long length wires:***

  → High performance, high productivity, length up to 1 km level

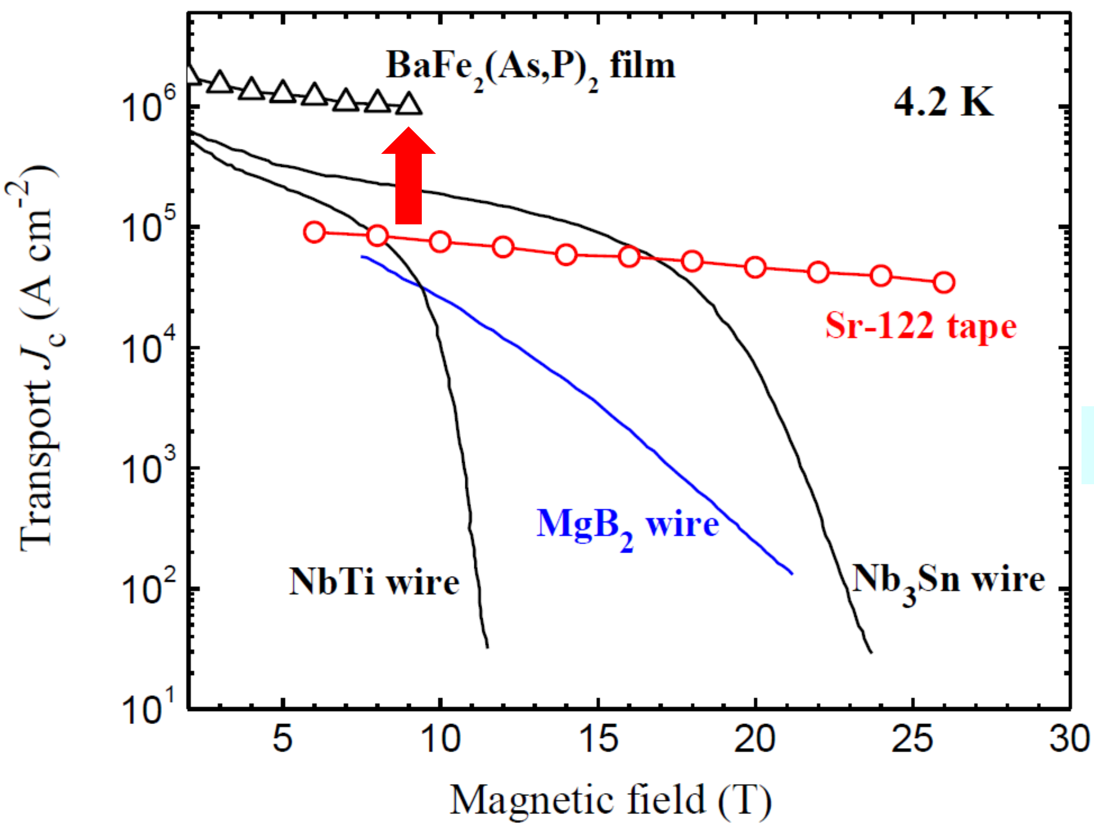
- ✓ ***Low Cost Wires:***

  → e.g. Cu- or Fe-sheathed wire fabrication, instead of using Ag

- ✓ ***High Mechanical Strength Wires:***

  → *Tensile, Bending*

Prospects



At present

J_c >10^5 A/cm^2 at 10 T, 4.2 K

The J_c is much lower than the pair breaking current density >10^8 A/cm^2.

Much room to further improve J_c!

Strong promising for high-field applications !

- We believe that iron-based wires would be possible to operate at 4.2 K >20T or 20-30 K at >10 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)*…

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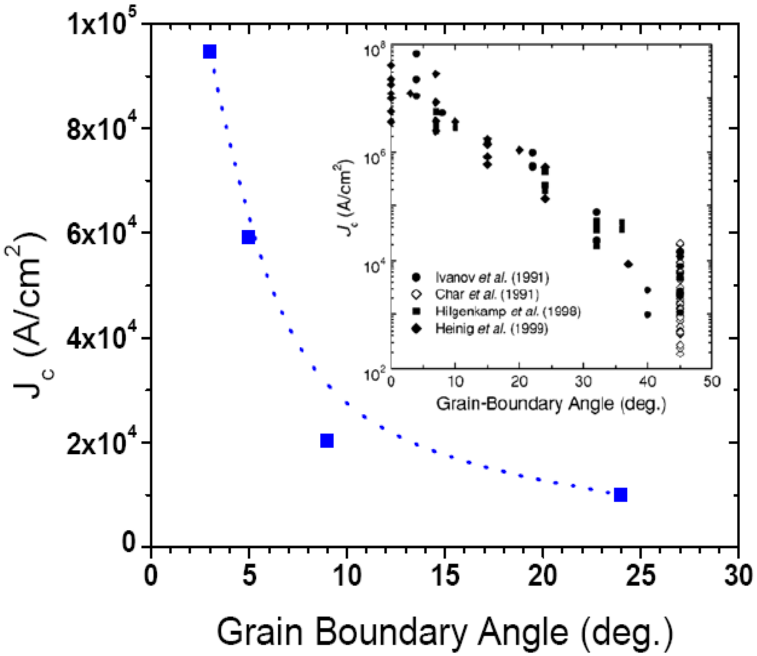
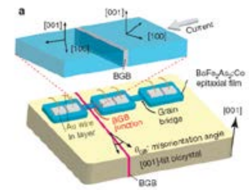
Thank you for your attention

Grain boundary behavior in 122-type pnictides

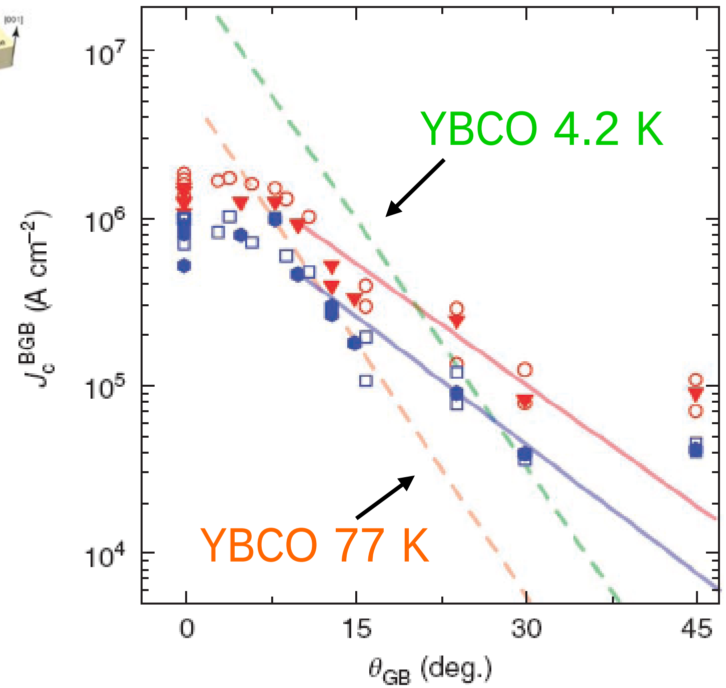
Co doped Ba-122 thin films on bicrystals

Lee et al., *APL* 95, 212505 (2009).





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

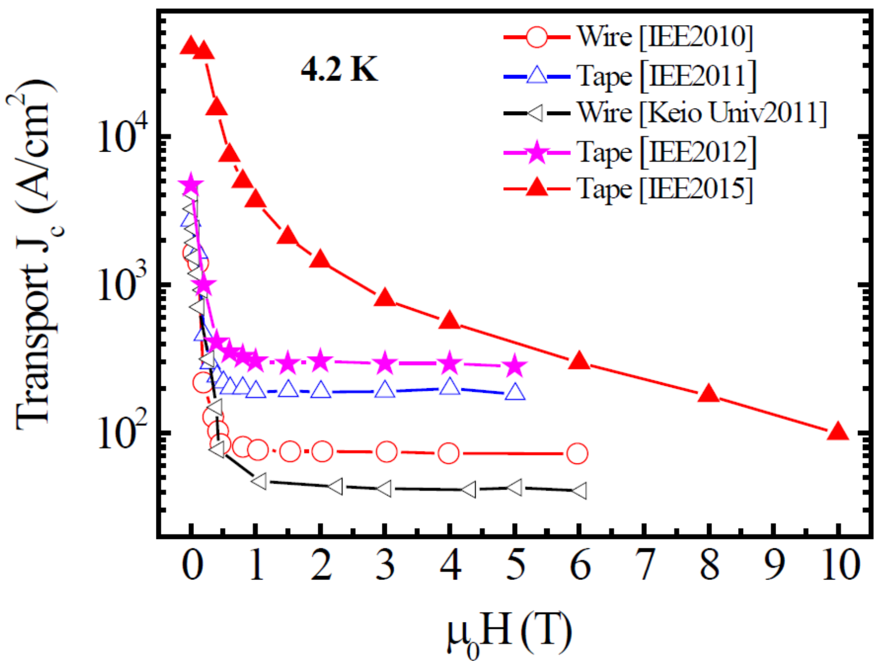


- **J_c decreases exponentially with GB angle, however, the critical angle GBs of pnictides is θ_c = 9°, larger than YBCO (θ_c~5°) .**
- **Weak link effect, the GBs do not degrade the J_c as heavily as YBCO.**
- **Advantageous GB over cuprates!** This is the reason why we can use the PIT method to make the pnictide wire and tapes, but PIT can not work for YBCO.

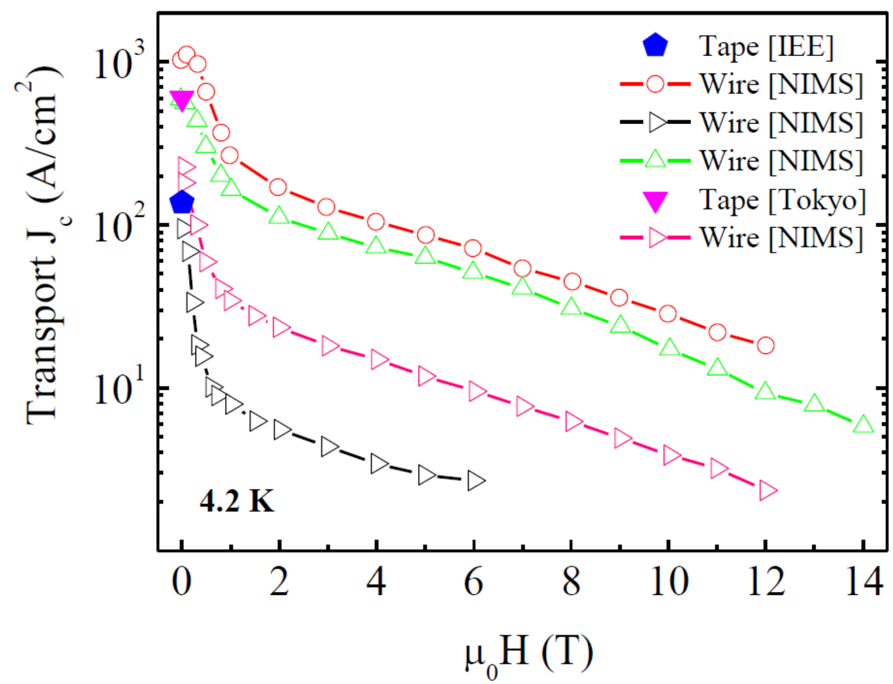
122 tapes showed the highest J_c: 10^5 A/cm^2 @ 10 T, 4.2 K

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

1111 type - Sm[O$_{1-x}$F$_x$]FeAs



11 type - FeTe$_{1-x}$Se$_x$



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