IEEE CSC & ESAS SUPERCONDUCTIVITY NEWS FORUM (global edition), No. 49, January 2021.
Invited presentation Wk1MOr3B-01 given at the virtual ASC 2020, October 29, 2020.

# Development of iron-based wires and tapes with improved properties for magnet applications

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# Outline

1. Background on iron-based superconductors (IBS)
2. Results of High-$J_c$ IBS wires by PIT method
3. Long-length wire & coil fabrication
4. Conclusions

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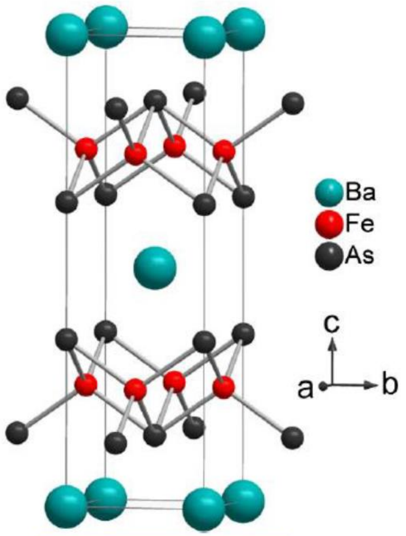
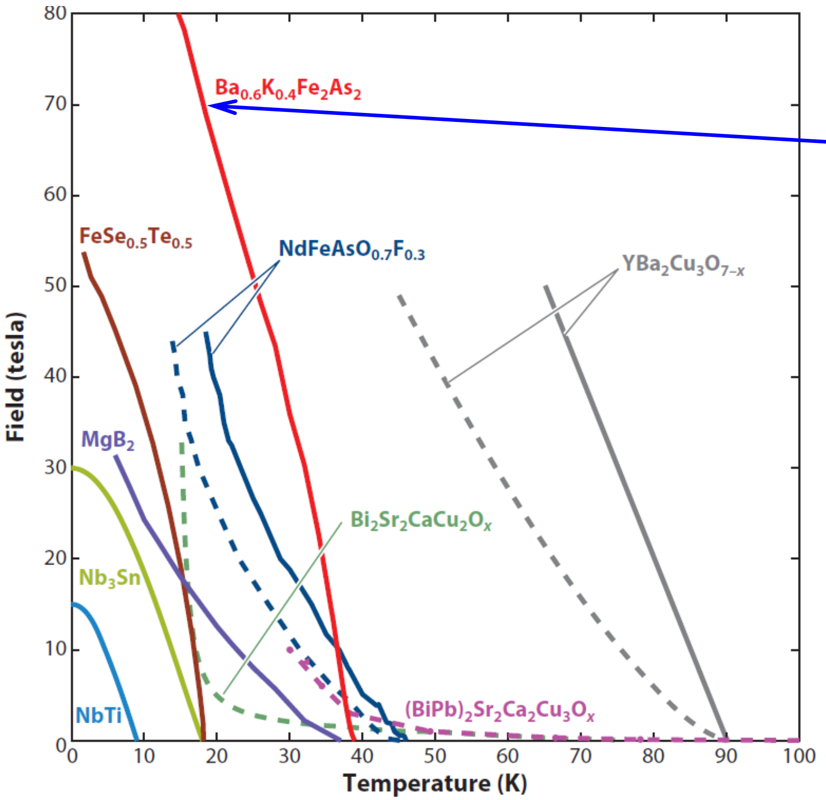
# The extremely high $H_{c2}$ in 122 IBS

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




***$T_c$* ~38 K**




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 $MgB_2$.**

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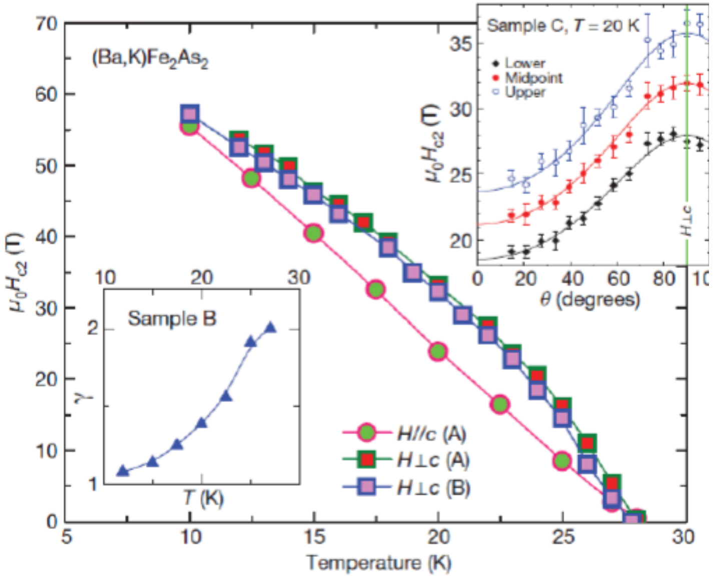
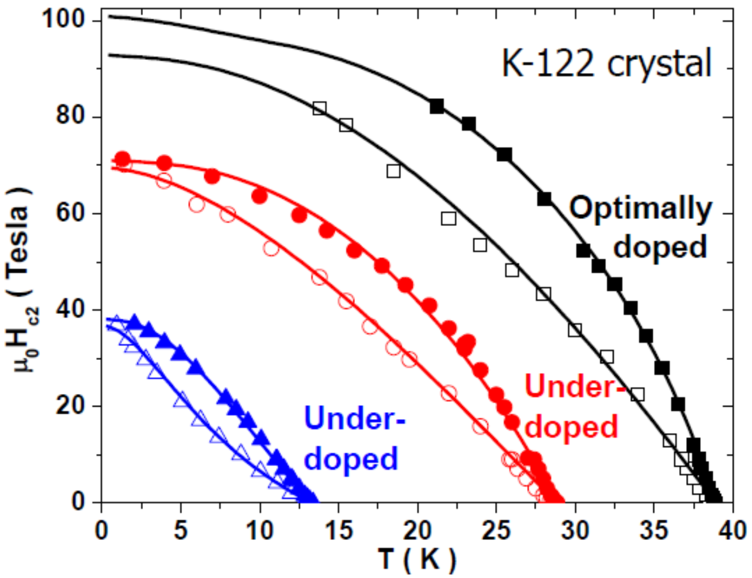
# 122 IBS - small anisotropy γ

## $H_c$ anisotropy




Yuan et al. Nature 457, 565 (2009)




Tarantini et al. PRB 86, 214504 (2012)

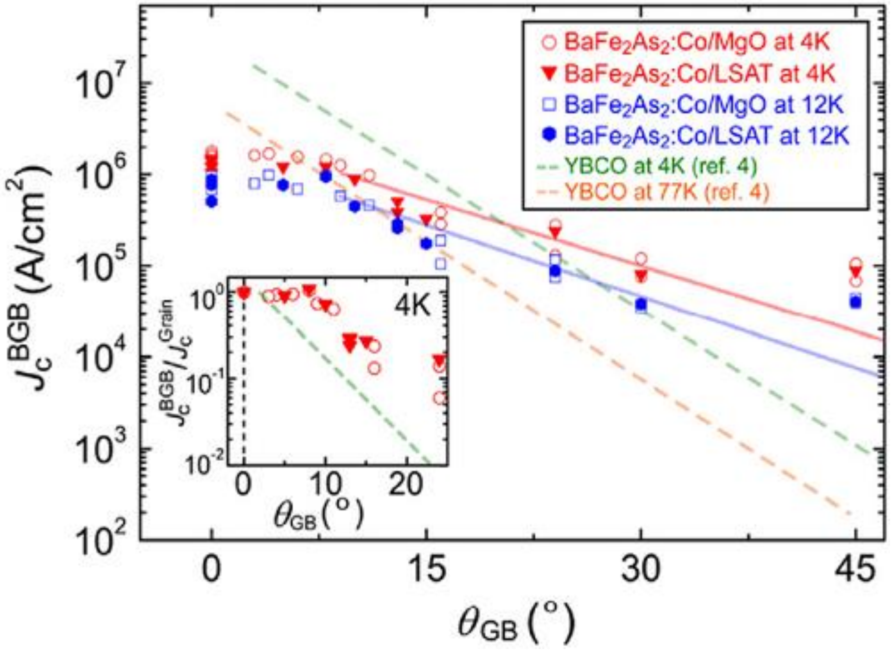
## $J_c$ anisotropy

| Materials | anisotropy $\gamma$ |
|---|---|
| $Bi_2Sr_2CaCu_2O_{8+\delta}$ | ~100 |
| $YBa_2Cu_3O_7$ | ~7 |
| $Ba_{0.6}K_{0.4}Fe_2As_2$ | < 2 |
| $MgB_2$ | ~3.5 |

Smaller than HTS and $MgB_2$

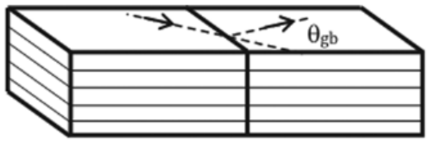
- γ ~1.1 for K-122, nearly isotropic
- γ is almost 1, clearly, vortices are much more rigid than in any cuprate-much easier to prevent depinning of any GB segment

# Another merit: Grain boundary nature of 122 IBSs




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

Co doped Ba-122 thin films on bicrystals




122 bicrystals

- **Drawback: $J_c$ decreases exponentially with increasing GB angle**
- **Advantage: the critical angle $\theta_c$ of IBS GBs is 9º, larger than YBCO ($\theta_c$3~5º)**

**Advantageous GB nature over cuprates!**

- Compared to cuprates, three dimensional grain orientation is not necessary for IBS.
- This feature is highly beneficial for the fabrication of **PIT 122 IBS wires**.
- ➲ 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.

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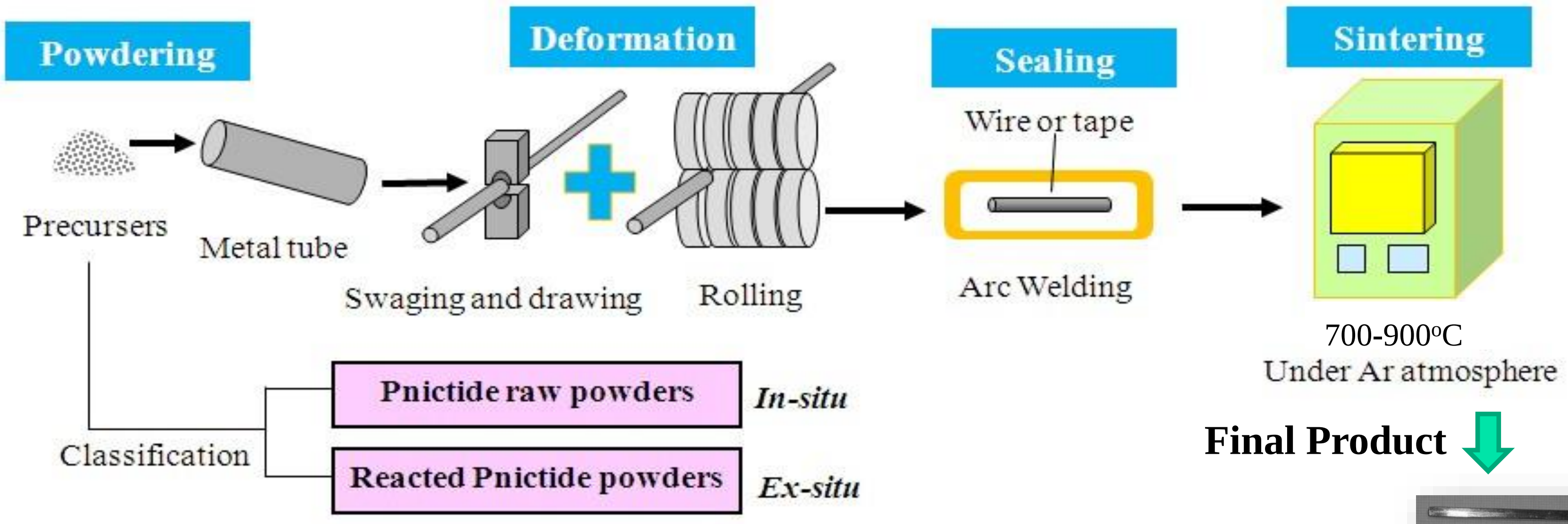
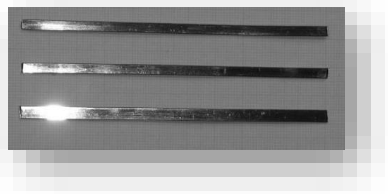
# Fabrication of 122 IBS wires by *Powder-in-tube method*

—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.

# IBS are considered as “Cheap conductor for high fields”

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

**Jan Jaroszynski**
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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 magnetic field above a critical value $H_c$, or a current density above a critical limit, $J_c$. For all known superconductors of the time, these critical values were low, making fabrication of strong magnets impossible.

It took half a century, and the investigation of thousands of different superconducting metals, compounds, and alloys [2], until the useful superconductors $Nb_3Sn$ [3] and NbTi [4], with a high $H_c$ and $J_c$, were found. Within a short time, kilometer lengths of $Nb_3Sn$ wire were fabricated and the first 6 T ‘supermagnet’ was tested the same year. During the following decades, these low temperature superconductors (LTS) entered their industrial phase. NbTi magnets are the most widely used, taking ~80% of the market, while NbTi + $Nb_3Sn$ magnets are used where fields above 10 T are needed. The record magnetic field generated by LTS is 23.5 T [5].

Meanwhile, a microscopic theory of superconductivity (Bardeen–Cooper–Schriffer) in 1957 [6] made it possible to understand the phenomenon of LTS, however, this new theory had only a minor impact on the search for new superconducting materials.

After the discovery of high-temperature superconductors (HTS) in 1986 [7], it took around 30 years to construct prototypes of 32 T [8], and more [9], only partially HTS magnets. Despite intensive efforts by the HTS community, high-temperature superconductivity still lacks a widely accepted microscopic model.

At present, long superconducting wires are only produced from six superconductors: NbTi, $Nb_3Sb$, $MgB_2$, Bi2223, Bi2212 and REBCO. Only wires of Nb compounds are used industrially, with intensive work on $Nb_3Sn$ optimization still under way. The other materials are still considered in the research and development phase.

Thus, the discovery of a new class of iron based superconductors (IBS) in 2008 [10] opened the doors to a new perspective for microscopic models. Intensive studies show that IBS phenomenology and superconducting parameters bridge the gap between conventional superconductors and cuprates and may be 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.

--Jan Jaroszynski, ***Supercond. Sci. Technol.*** 32 (2019) 070501

**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 $Nb_3Sn$.**

**From a practical point of view, IBS are ideal candidates for applications.**

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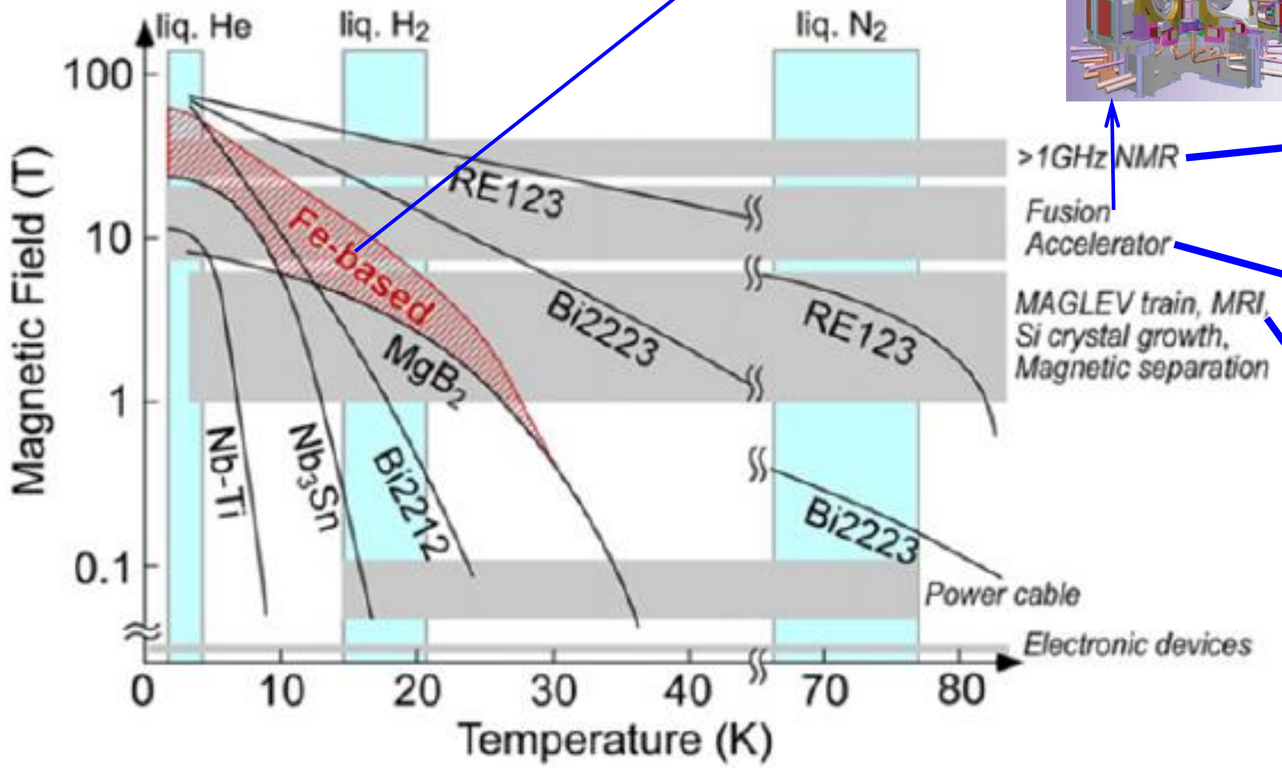
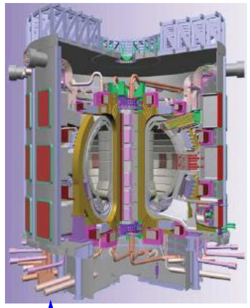
# IBS potential for high-field applications

**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***

# Outline

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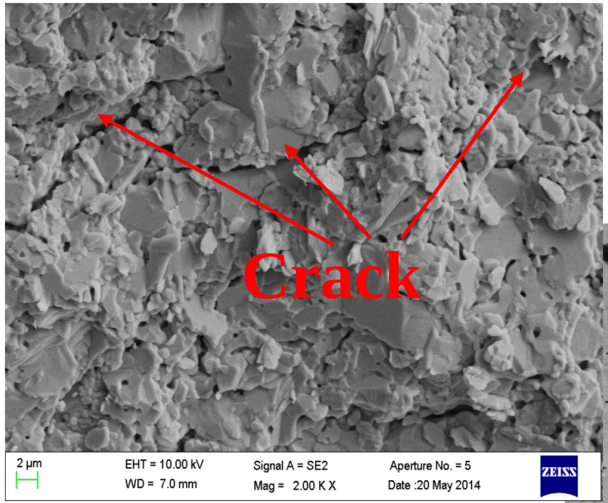
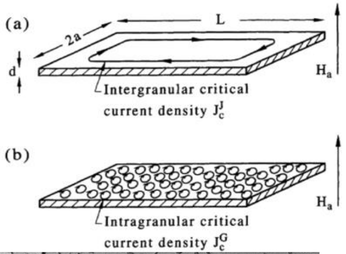
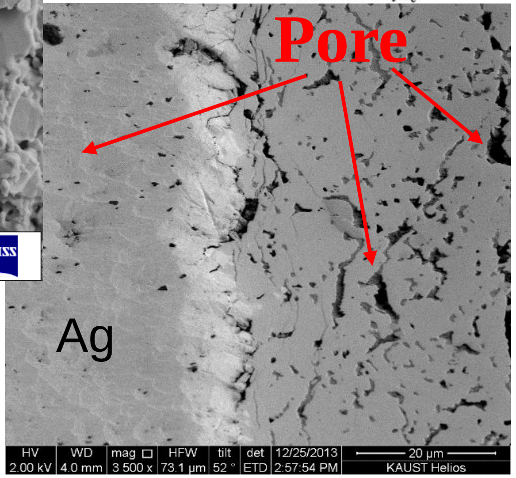
# Key problems for PIT wires ➡ Low density and Weak-link behavior

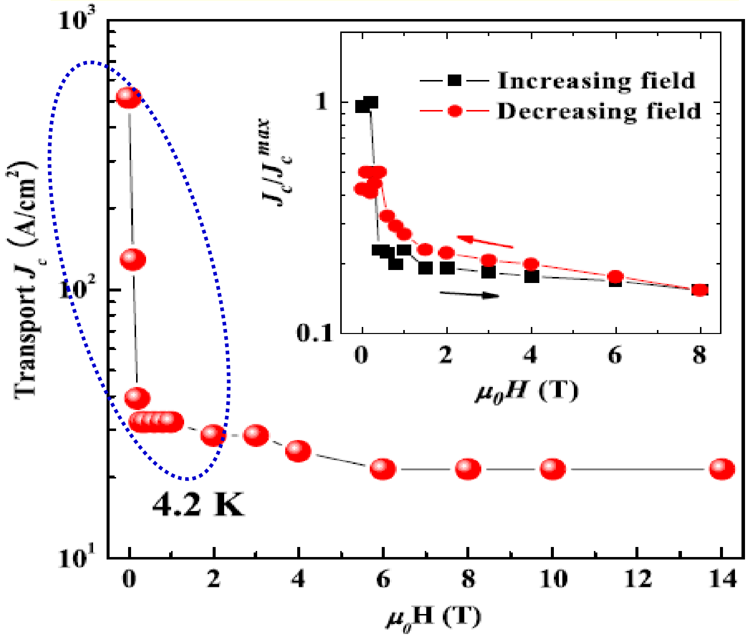



Low density: cracks and porosity

**_Good connectivity is desirable!_**

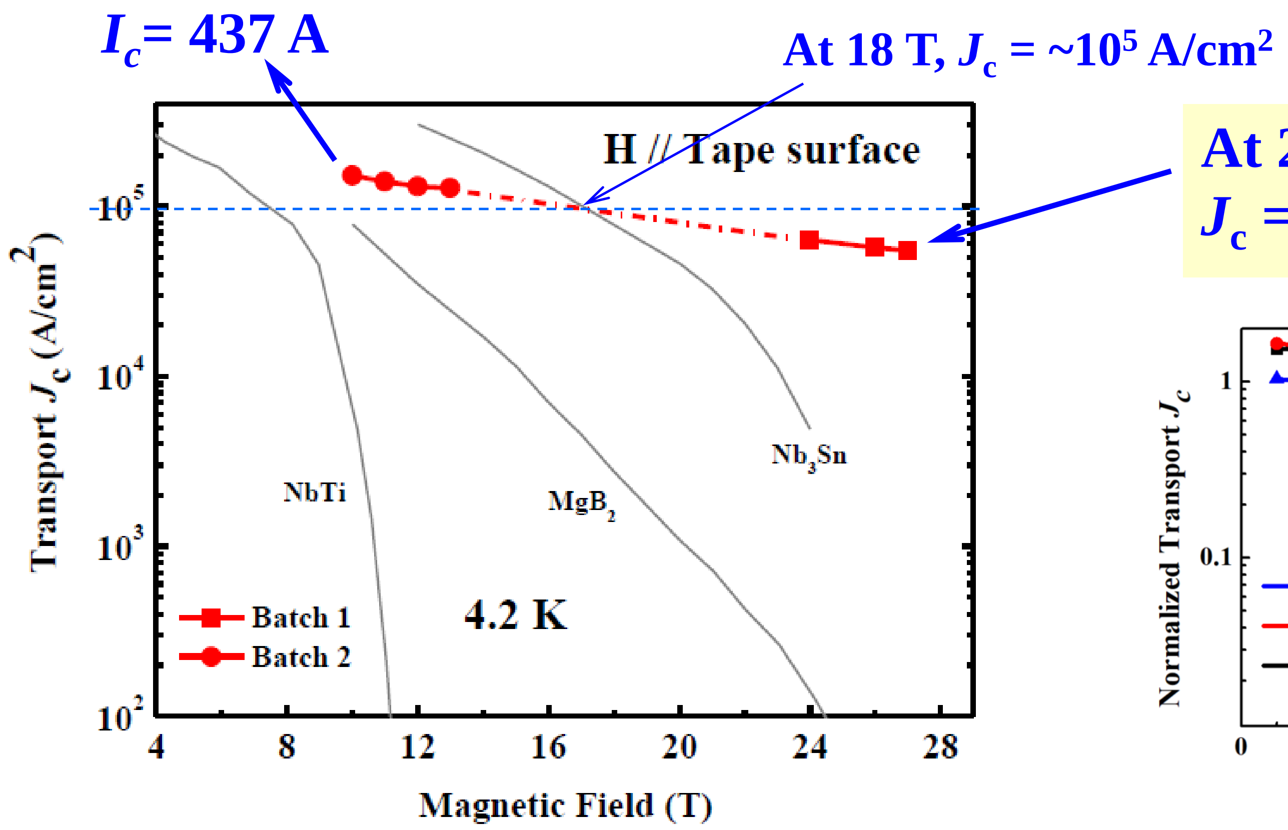


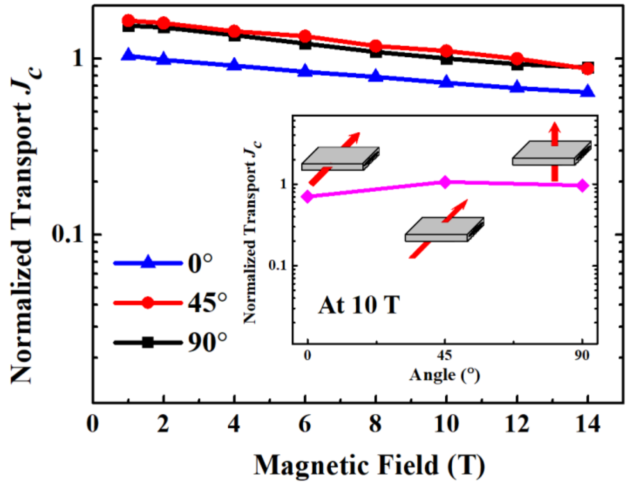

Hysteresis in transport $J_c$: signature of weak links

- **Low density (porosity)** always leads 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.

# Record $J_c$ up to $1.5\times10^5$ A/cm$^2$ @ 4.2 K, 10 T achieved in Ba-122/Ag tapes by hot pressing

--Measured at HFLSM at *Sendai*



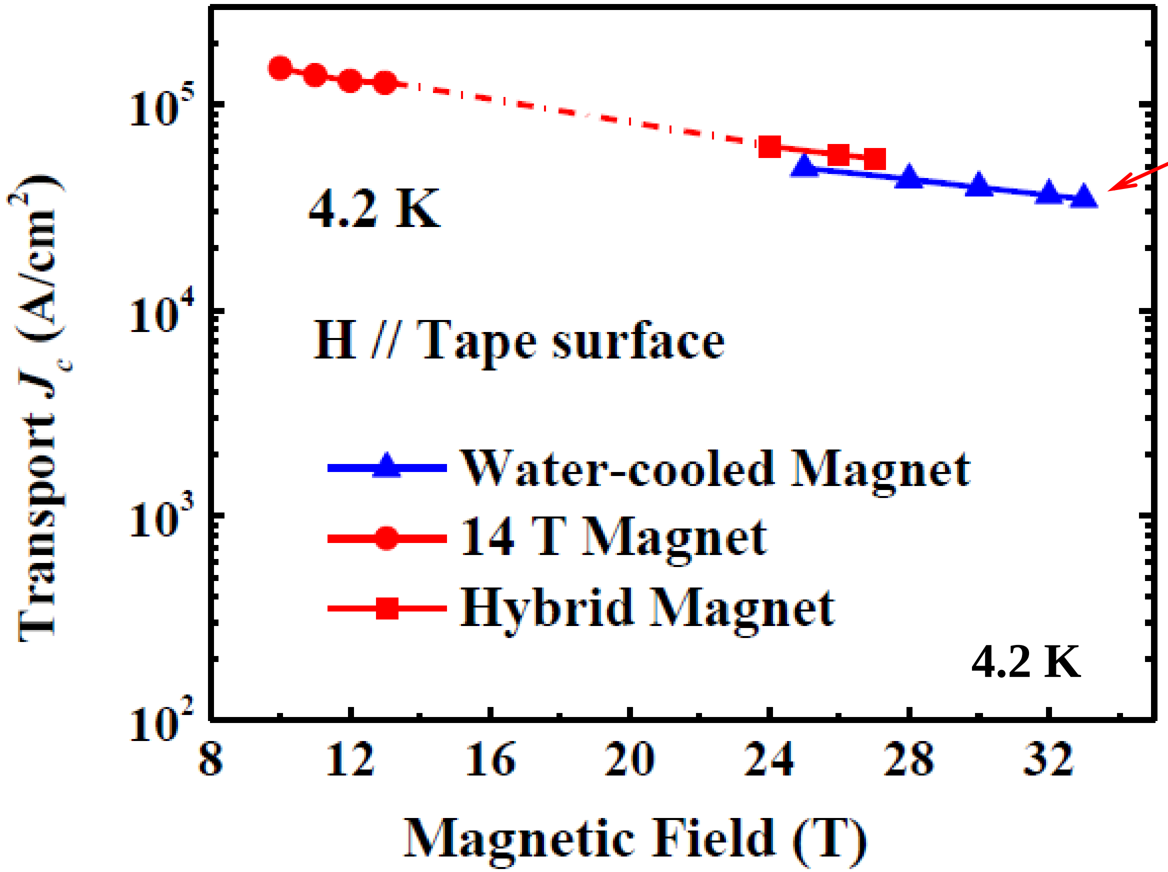

**Huang et al., *SuST* 31 (2018) 015017**

**$\gamma$ = 1.37 at 10 T**

# 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*



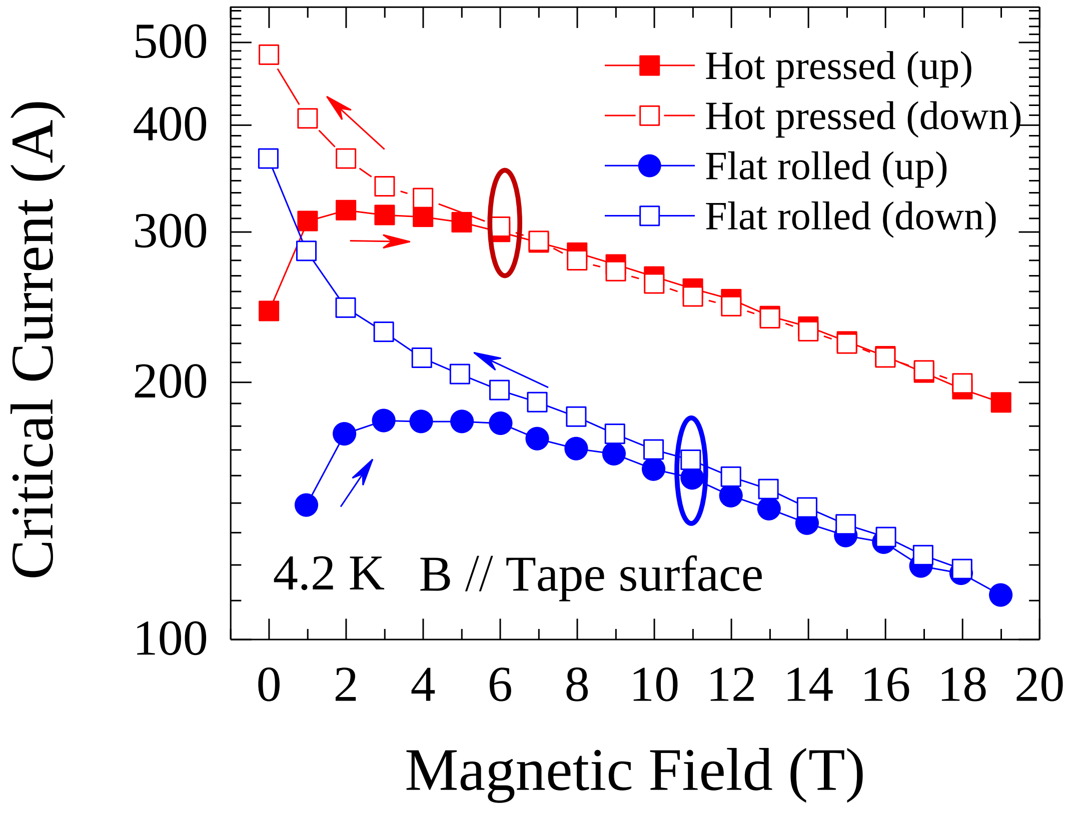

@ 33 T, $J_c$= 3.5×10$^4$ A/cm$^2$


35 T water-cooled magnet
(Heifei, China)

# The weak-link problem is effectively suppressed in HP tapes

A hysteresis phenomenon observed for transport $I_c$ in an increasing and a decreasing field indicated a **weak-linked behavior**, similar to that of the cuprates.

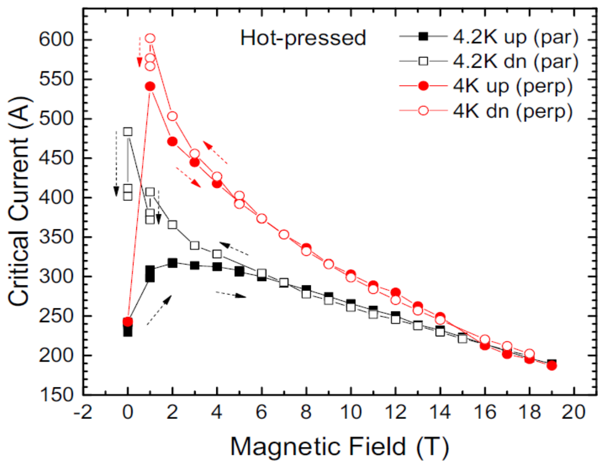
**--Measured at *Univ. Geneva***




Bonura & Senatore, ***SuST*** 33 (2020) 095008.

**The loop of HP tapes was quite smaller than that of rolled ones**

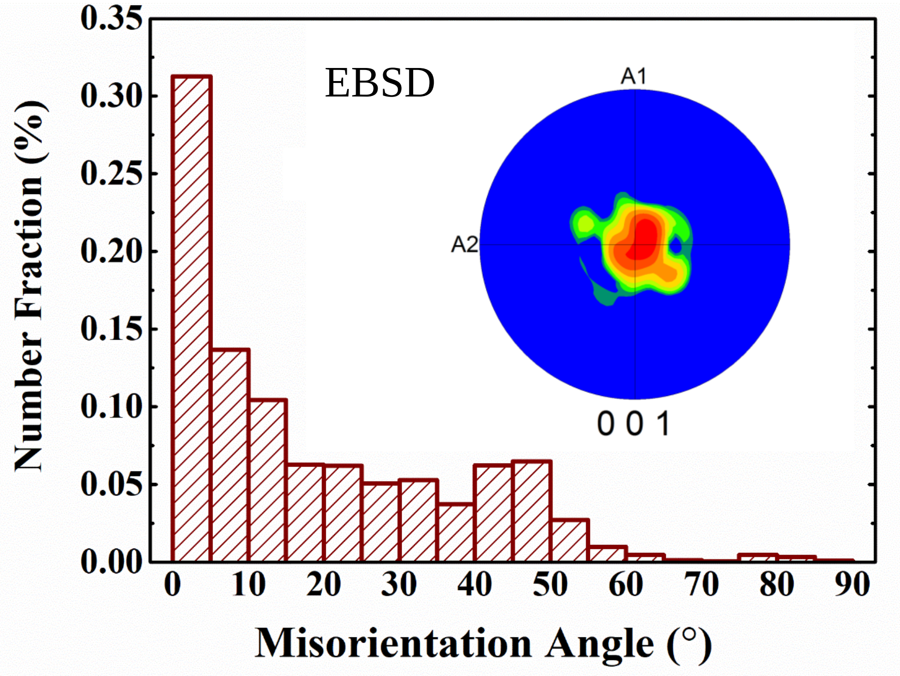
**HP much improved the *c*-axis texture**



# EBSD: Misorientation angle distribution

## HP Ba-122 tapes

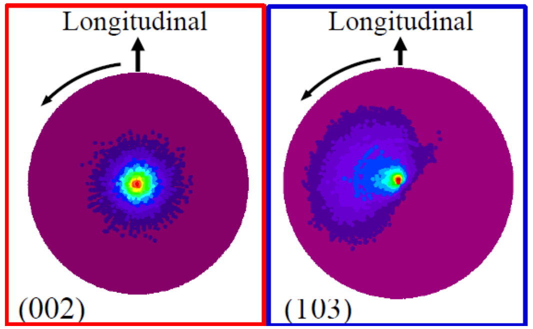
- ✓ Well-connected microstructure
- ✓ The *c*-axis texture is much improved,
- ✓ The fraction of misorientation angle <9º is up to 42.8%.
- ✓ Rolled tapes: ~10% <9º




**Further increase *c*-axis texture -- 100 % ??**

**Nearly no in-plane texture**

### Pole figure

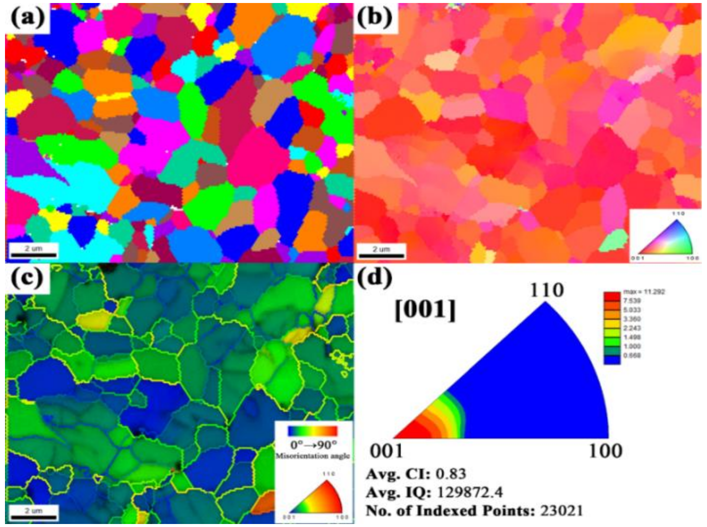



Courtesy of S. Awaji

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

**--State-of-the-art HP tapes**

**Fine grains, ~3 μm**




**Highly textured microstructure!**
**(well-connected grains, no porosity )**

**Hot press**

**The core of HP Ba122 tape**

**Vickers hardness: ~132**

Rolled: ~90

**High core density**

**Good connectivity !**

**High $J_c$**

**Both are indispensable!**

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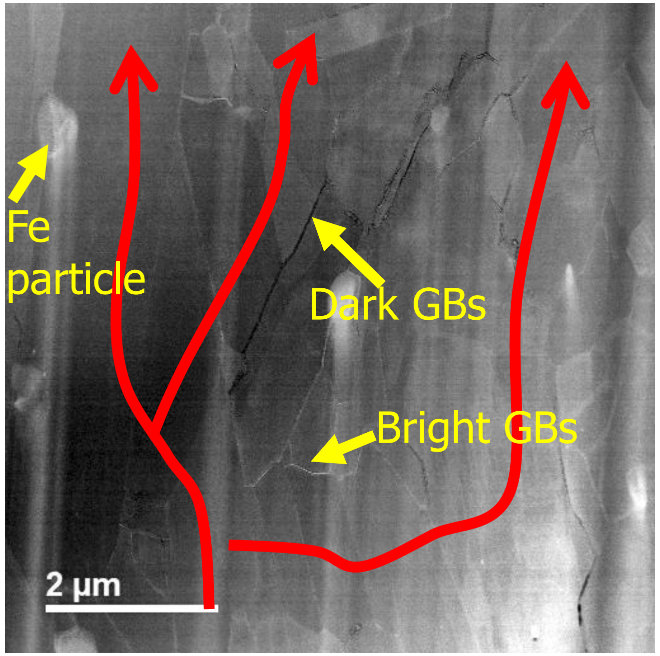
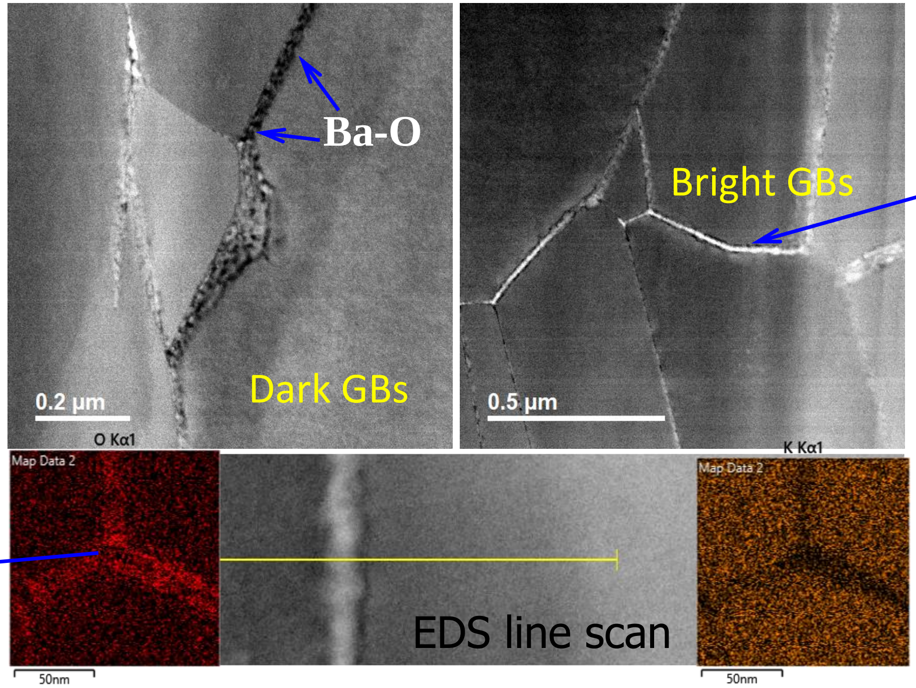
# Bright field STEM for state-of- the art HP 122 tapes: Second phases at GB

HAADF

F. Kametani, NHMFL, Florida State University




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 $J_c$.

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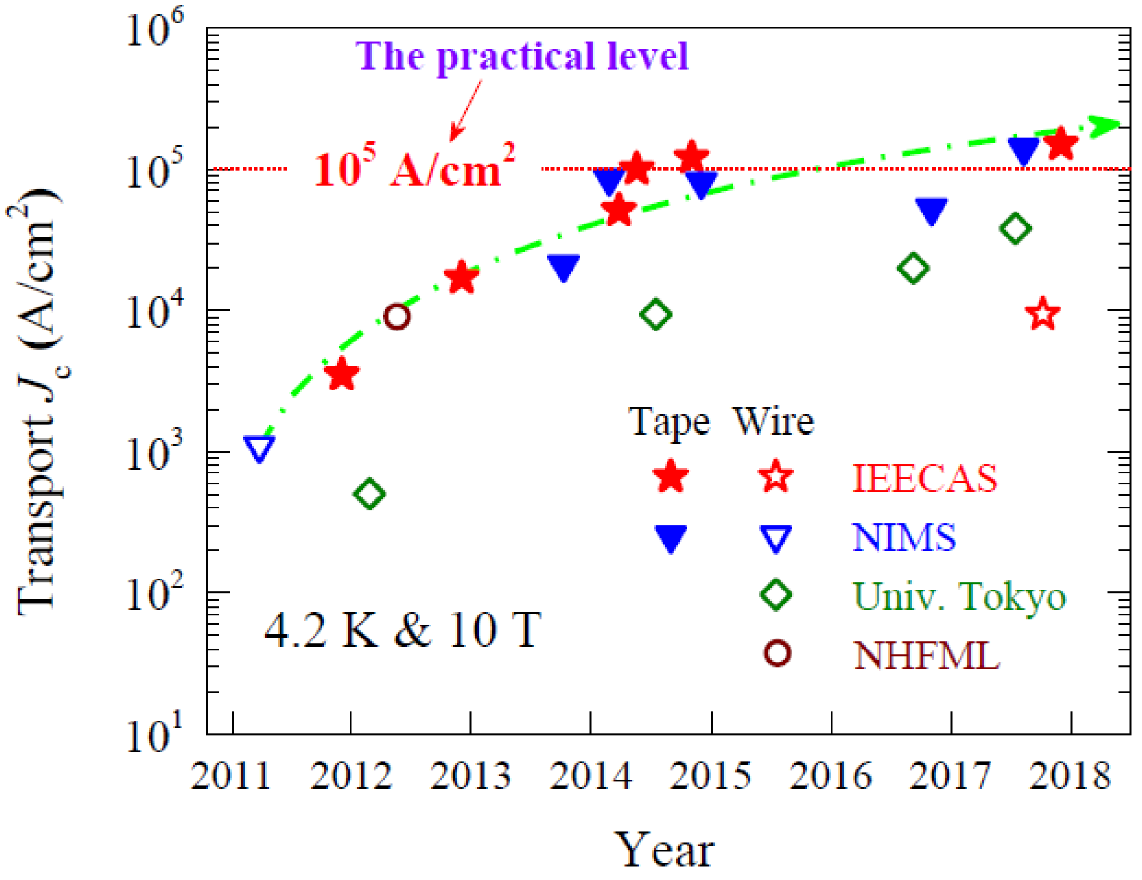
# Recent advances in transport $J_c$ of PIT processed 122 wires and tapes




**2018**

**$1.5 \times 10^5$ A/cm$^2$**

***$10^5$A/cm$^2$ at 18 T***

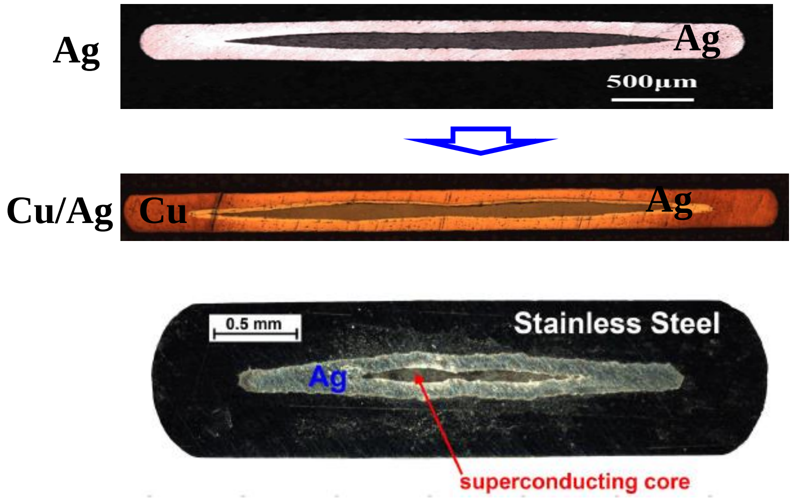
**Next target: $10^5$ A/cm$^2$ at 30 T**

# So far, high-$J_c$ 122 IBS tapes were almost made by using Ag as sheath material

**Ag is very expensive,**
**and also mechanically not strong enough for high-field applications**

**To solve this problem we tried the following methods:**

1. **Ag/Cu double sheath-** *modest mechanical*
2. **Ag/Stainless steel double sheath-** *high*




- ✓ Bi-based wires: Ag/Ag-alloy sheath
- ✓ IBS wires: Ag/various metal **composite sheath** is possible

**inner sheath:**
chemical stability

+

**outer sheath:**
mechanical strength & reduce Ag ratio

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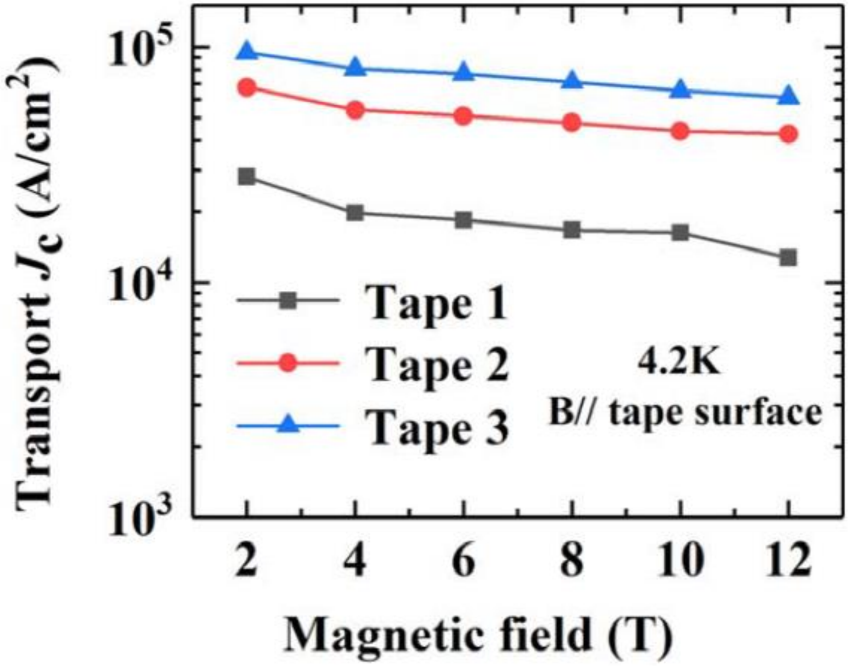
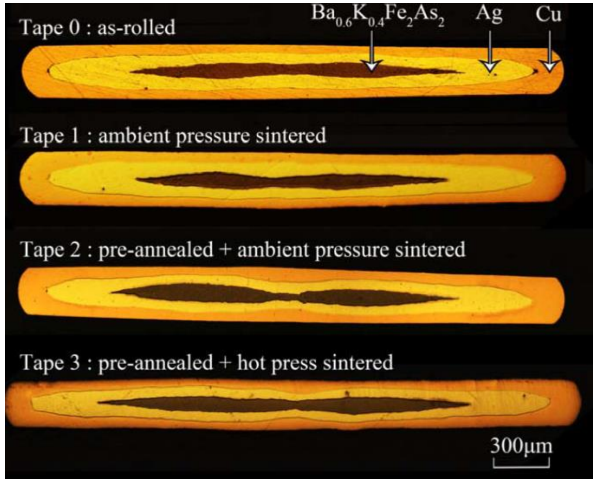
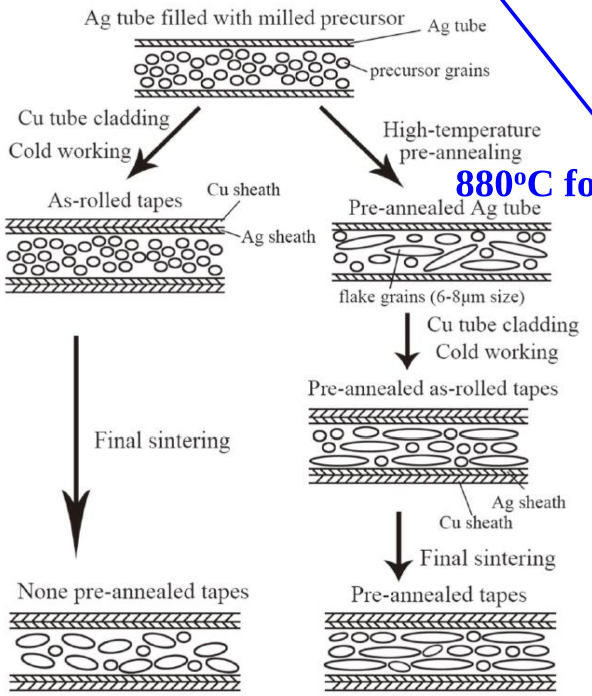
# High $J_c$ in Ba-122/Cu/Ag tapes by pre-annealing process

Cu/Ag double sheath seemed good choice!




880°C for 0.5h

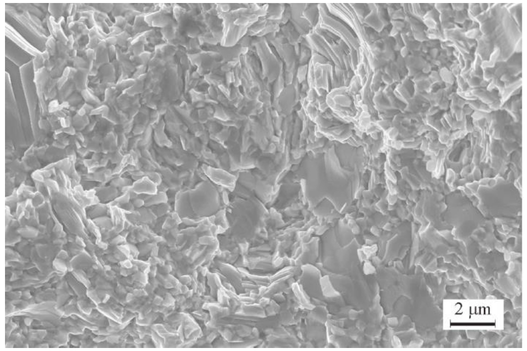
heated at 740°C

- **Rolled tapes sintered at 740°C/3h under ambient pressure showed a $J_c$ up to $4.9 \times 10^4$ A/cm$^2$ (10 T).**
- **The well-constructed crystallization and good grain connectivity obtained in pre-annealed tapes are considered as the major causes of the high $J_c$ .**

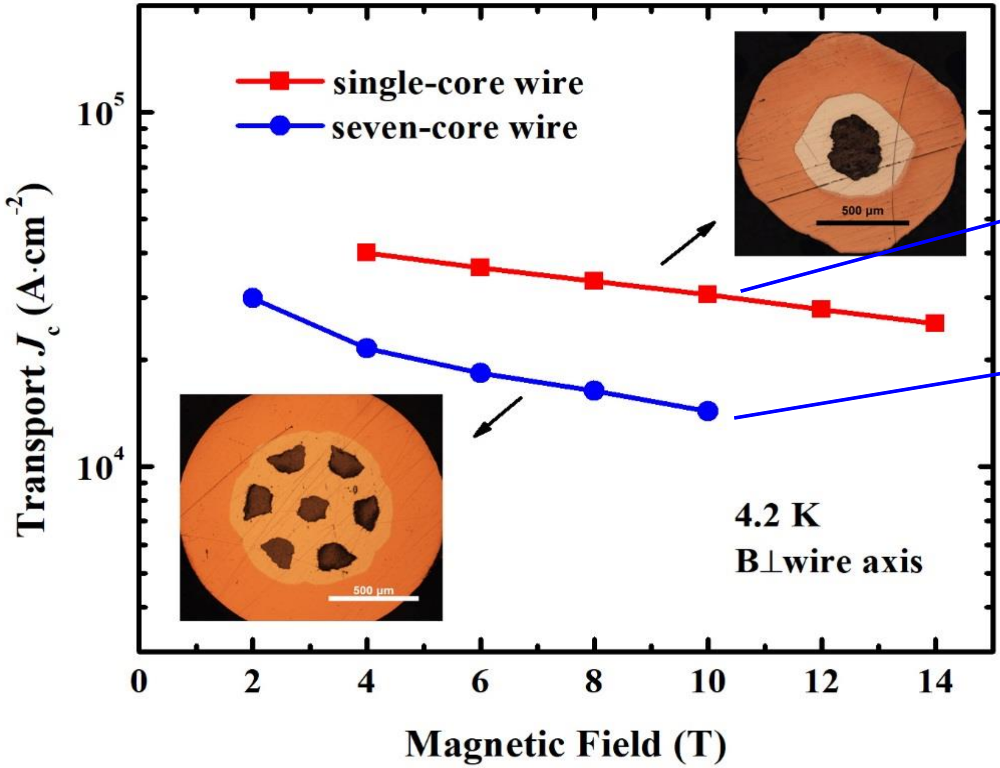
Li et al., ***Mater. Res. Express*** 6 (2019) 096003

# $J_c$ at 4.2 K of HIP-processed Ba-122/Cu/Ag round wire at IEE

**Ba-122/Ag/Cu round wires HIPed at 740°C**




The grains are well connected with few pores, less textured.




Liu et al., ***SuST*** 30 (2017) 115007

**Single-core**

$J_c$ (10 T) = 3.1×10$^4$ A/cm$^2$

**Seven-core**

$J_c$ (10 T) = 1.6×10$^4$ A/cm$^2$

**Challenge:**

*How to further enhance $J_c$ ?*

*Introduce the texture!*

# Fabrication of Cu/Ag sheathed Ba-122 tapes by HIP process

The method combines flat rolling to induce grain texture and a subsequent HIP densification process

**at 740ºC**

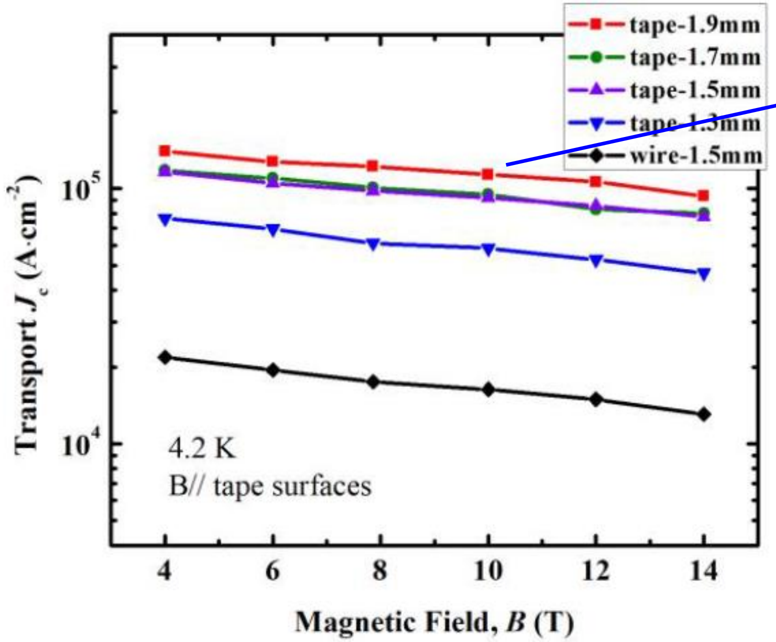
HIP + Flat Rolling

High core density + Grain texture

High $J_c$ tapes

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

**Grain texture by flat rolling**
**High density by HIP**




Tape-1.9 mm

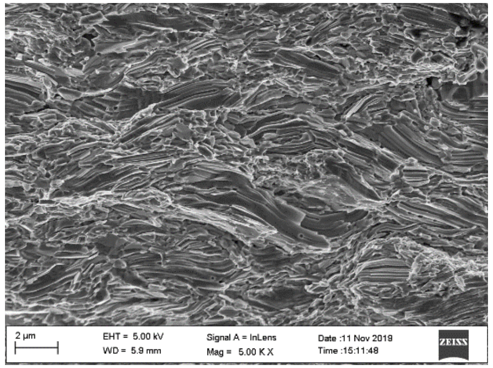
**Merits:**

1. Low annealing Temp. (740°C)
2. Good for long length production!

## Latest results

$J_c$ (4.2 K, 10 T) $= 1.1\times10^5$ A/cm$^2$

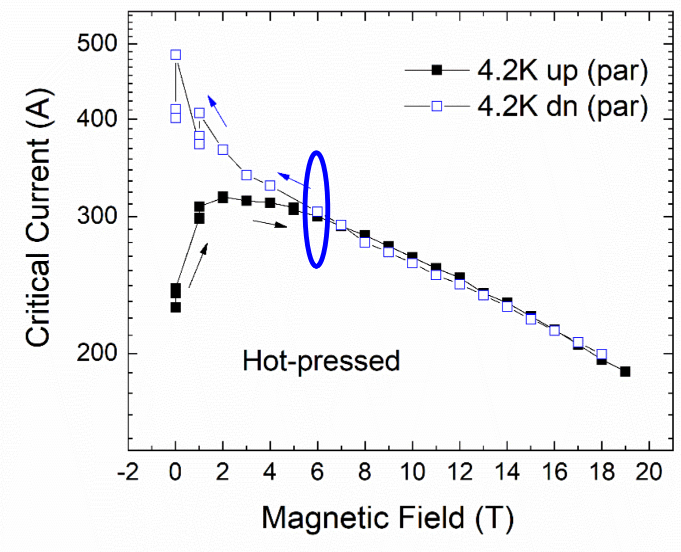
well-connected, $c$-axis textured grains



Liu et al., ***submitted***

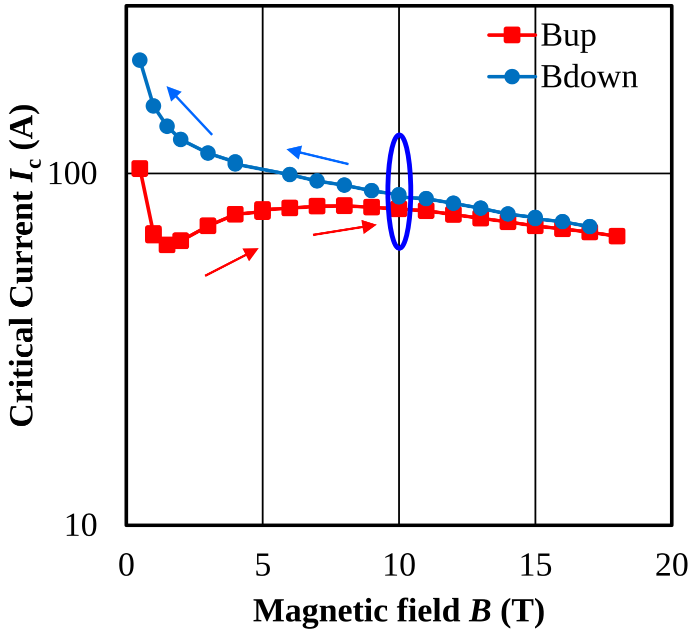
# Comparison of hysteresis loops for HP and HIP-processed Ba-122 tapes

## Hot Pressing




Courtesy: M. Bonura & C. Senatore

## Hot Isostatic Pressing




Courtesy: T. Suzuki & S. Awaji

**HP Temperature (880°C)**
**Grain size: ~3 μm**
**Lotgering orientation factor F: 0.87**

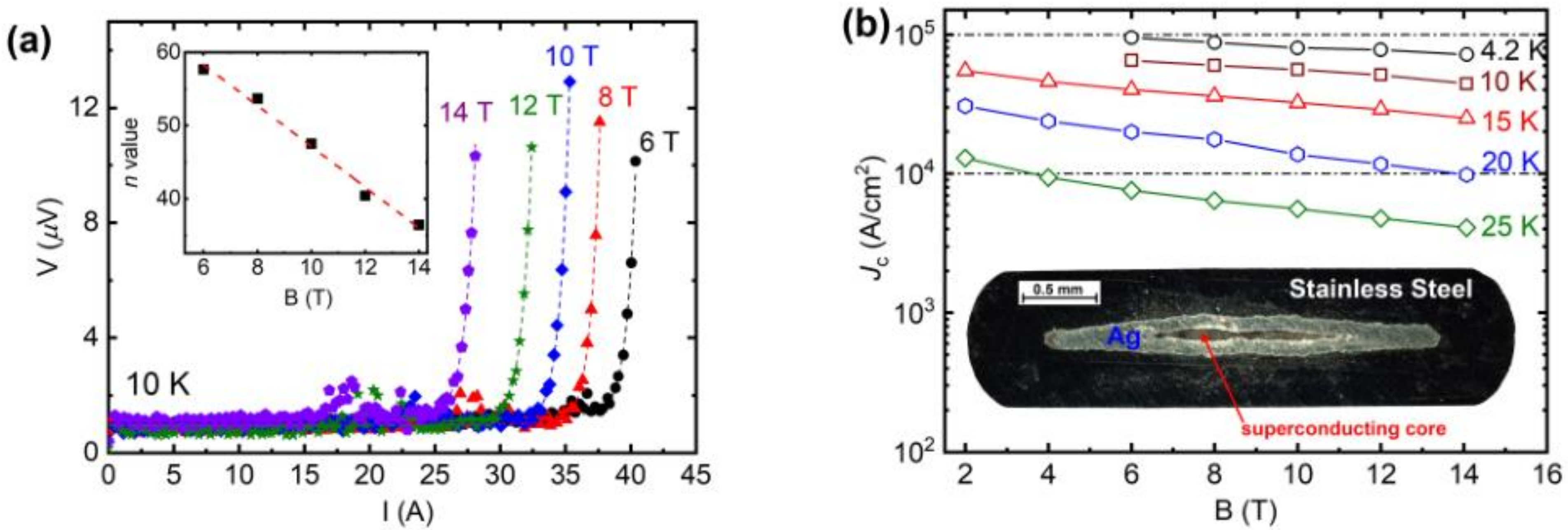
**HIP Temperature (740°C)**
**Grain size: ~1 μm**
**Lotgering orientation factor F: 0.46**

→ **Much room for the $J_c$ improvement**

# $J_c$-B properties of SS/Ag/Ba-122 tapes by rolling

--Heated at 750°C for 0.5 h

-- **SS means Stainless Steel**

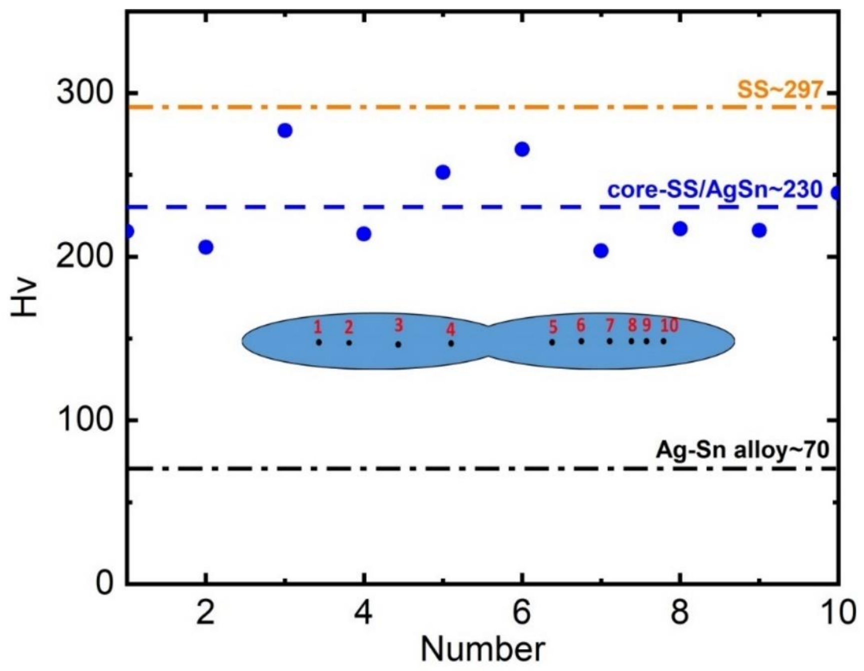


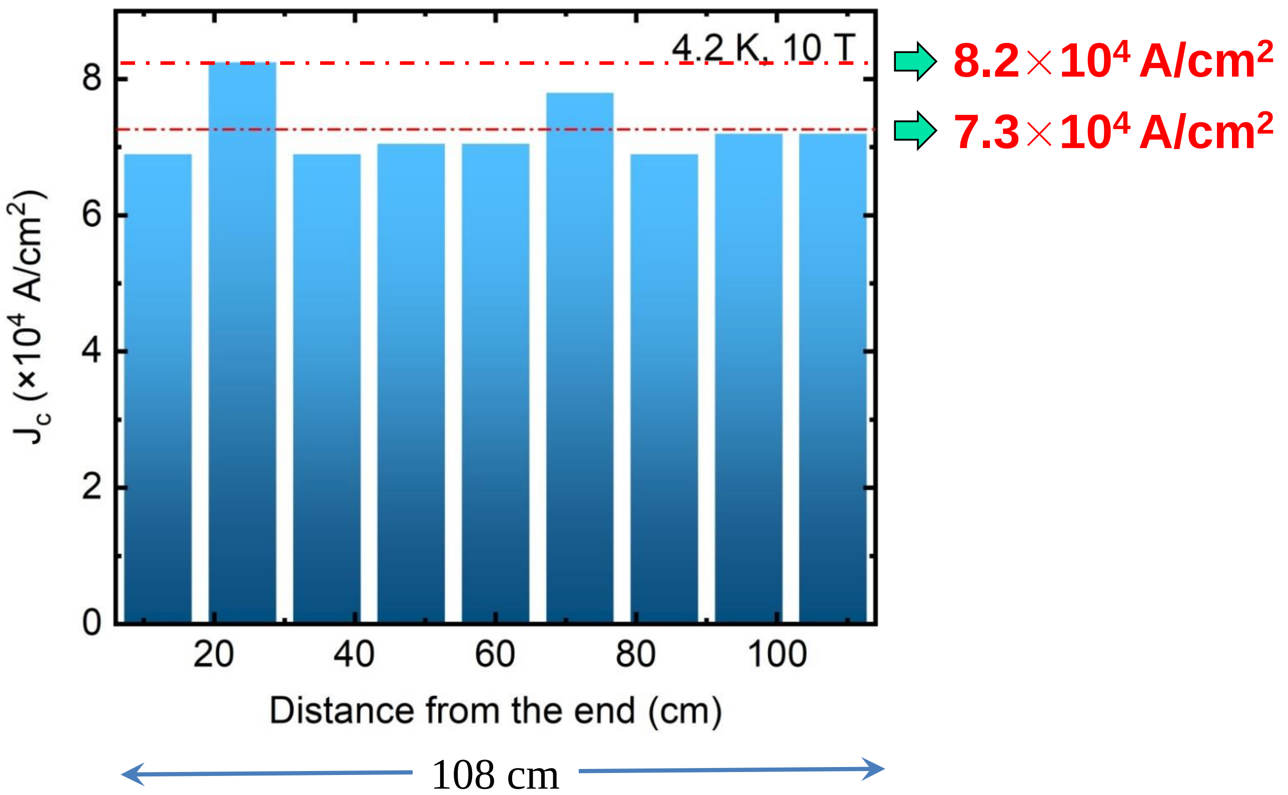

- SS/Ag double sheathed tapes were prepared, which have much improved core density and texture.
- At 4.2 K and 10 T, the $J_c$ is $8\times10^4$ A/cm$^2$. The $J_c$ decreases with the increasing temperature, but shows a weak field dependence. At 20 K, the $J_c$ is still higher than $10^4$ A/cm$^2$ at 14 T.
- I-V curves are very sharp, having large n values > 36 at 14T.

Dong et al., ***IEEE TAS.*** 29 (2019) 7300504

# $J_c$ distribution of a rolled 1.08 m SS/Ag/Ba-122 tape

Vickers Hardness (Hv)



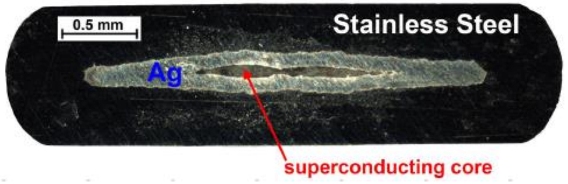

- The tape shows good $J_c$ uniformity. The highest $J_c$ is 8.2×$10^4$ A/cm$^2$, the lowest $J_c$ is 7×$10^4$ A/cm$^2$.
- High strength of stainless steel leads to high Hv value, ~230, higher than Hot-Pressed tapes.

Dong et al., ***IEEE TAS.*** 29 (2019) 7300504

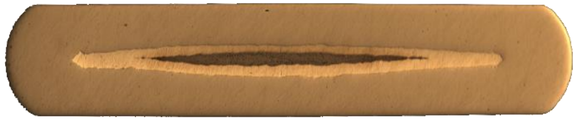
IEEE CSC & ESAS SUPERCONDUCTIVITY NEWS FORUM (global edition), No. 49, January 2021.
Invited presentation Wk1MOr3B-01 given at the virtual ASC 2020, October 29, 2020.

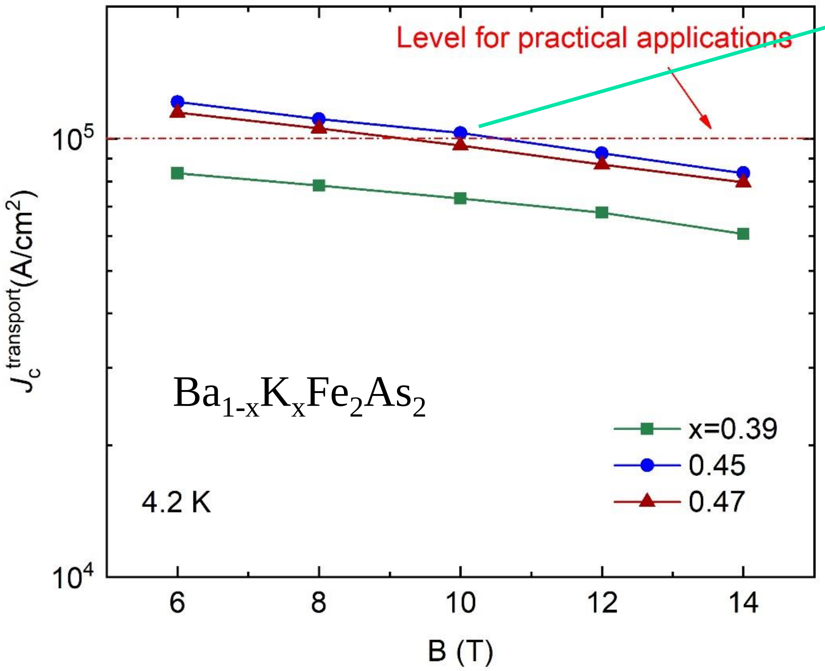
# Latest $J_c$ of SS/Ag/Ba-122 tapes >$10^5$ A/cm$^2$ at 10T

**Structure of SS/Ag Ba-122 tape**




After optimization






**$1.03 \times 10^5$ A/cm$^2$ at 10 T for rolled SS/Ag tape**

***Good for reproduction*!**

Over-doped K partially suppresses the formation of the FeAs grains and ameliorates the K deficiency in the grain boundaries.

***Challenging to longer length!***

Cheng et al., ***in preparation***

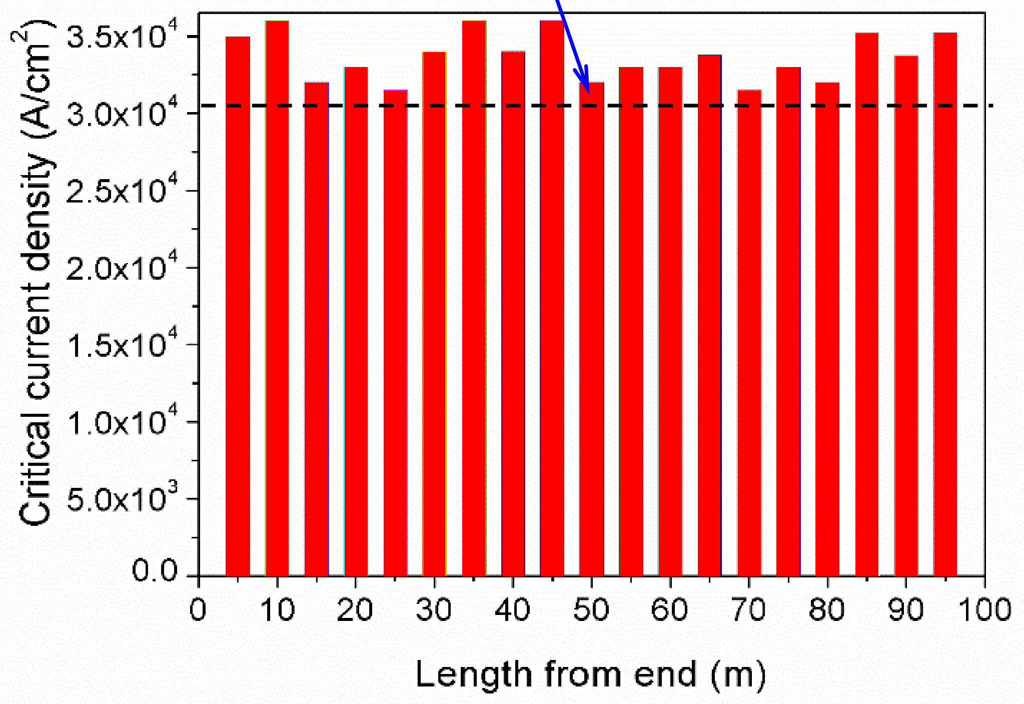
# Outline

# Recently, transport $J_c$ 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

@4.2K, 10T, transport $J_c$ >30000 A/cm²




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

# Performance of the first IBS solenoid Coil

## *Fabrication and test of IBS solenoid coil at 24T*

**-- Cooperated with Qingjin Xu group at IHEP-CAS**

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

Letter D. Wang et al 2019 ***SuST*** 32 04LT01

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

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]

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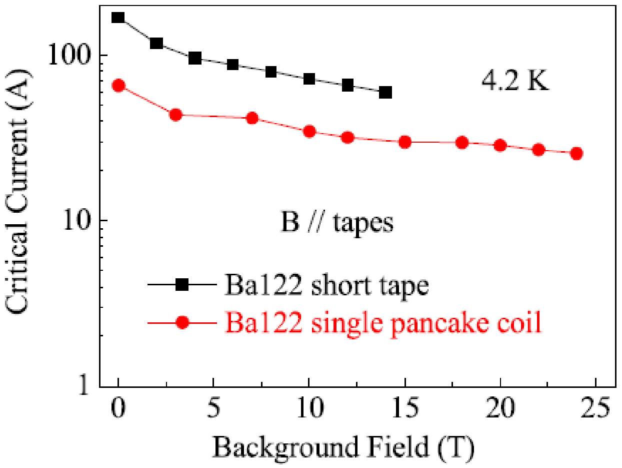
[4] High Magnetic Field Laboratory, Chinese Academy of Sciences, Hefei 230031, People's Republic of China

**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 |


25T-HM, RT bore Φ38 mm




The $I_c$ of the Ba122 coil showed weakly dependent on the field, like the short tape.

**These results suggest that IBSs are very promising for high-field magnet applications**

## Viewpoint by NHMFL

'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 $Nb_3Sn$**……

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

Jan Jaroszynski
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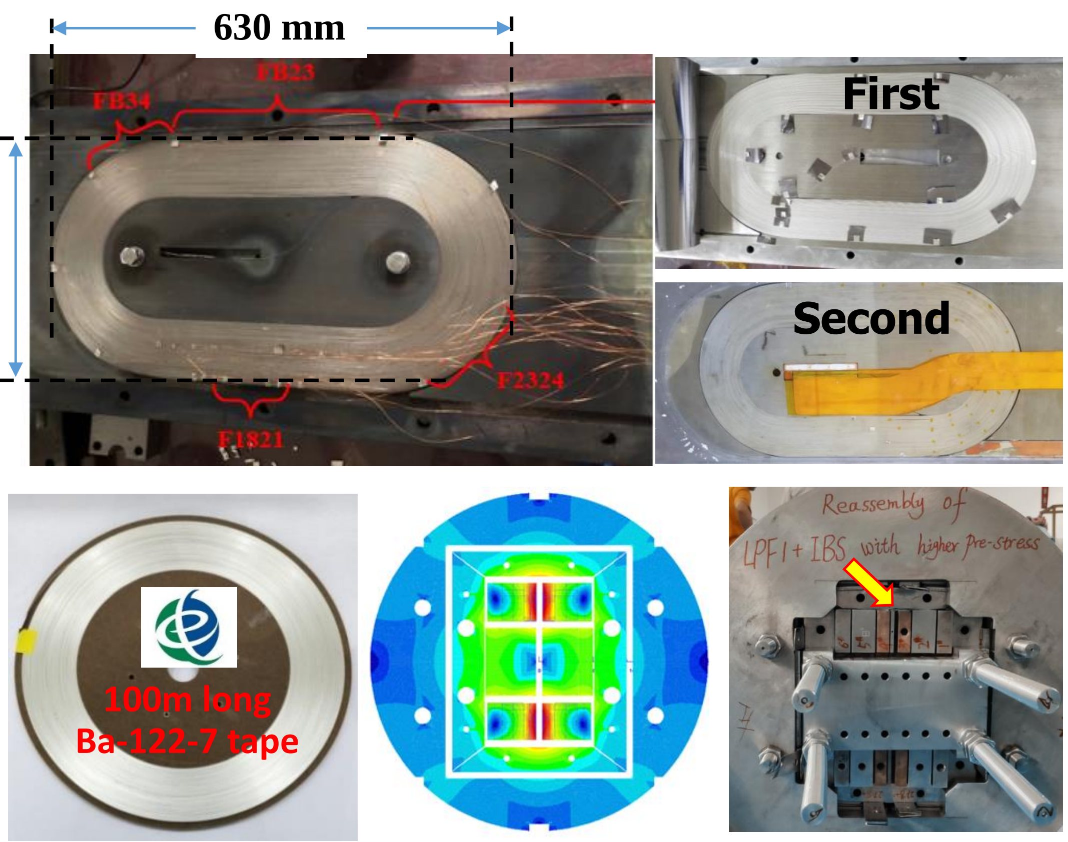
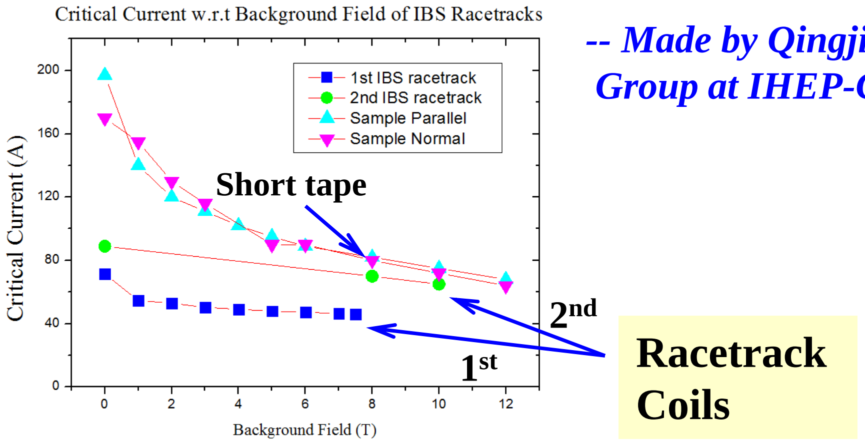
*E-mail: jaroszy@magnet.fsu.edu*

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

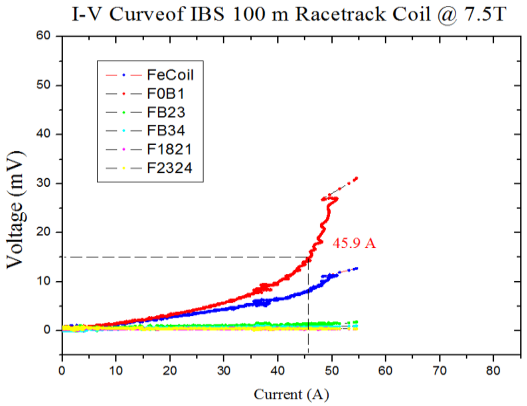
Following the discovery of superconductivity in 1911, Heike Kamerlingh Onnes foresaw the generation of strong magnetic fields as its possible application. He designed a 10 T electromagnet made of lead–tin wire, citing only the difficulty

# Test of the 1st IBS racetrack coil at 10T




*-- Made by Qingjin Xu Group at IHEP-CAS*




**Very good performance!**

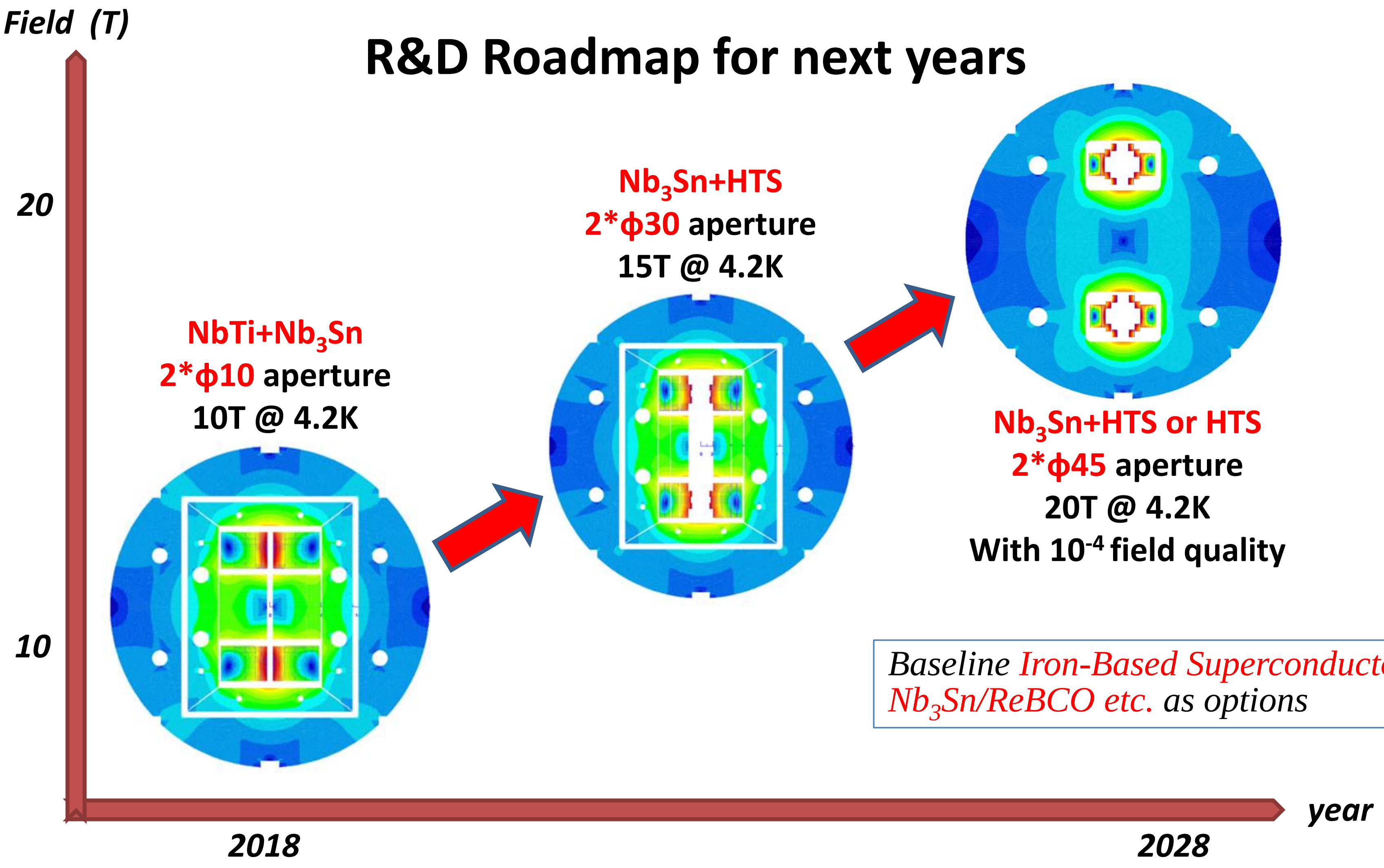
- ***Two racetrack coils with 100m long IBS tapes have been fabricated and tested at 10T background field.***
- ***The $I_c$ in the 2nd coil reached 86.7% of the short sample at 10T.***

*Supercond. Sci. Technol.* 2020, in press

IEEE CSC & ESAS SUPERCONDUCTIVITY NEWS FORUM (global edition), No. 49, January 2021.
Invited presentation Wk1MOr3B-01 given at the virtual ASC 2020, October 29, 2020.

# Status and Plan of the High Field Magnet R&D for Future Accelerators -- CEPC-SPPC Project

## R&D Roadmap for next years




*Baseline Iron-Based Superconductor (IBS), $Nb_3Sn$/ReBCO etc. as options*

IEEE CSC & ESAS SUPERCONDUCTIVITY NEWS FORUM (global edition), No. 49, January 2021.
Invited presentation Wk1MOr3B-01 given at the virtual ASC 2020, October 29, 2020.

# Conclusions

- ✓ 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 $1.5\times10^5$ A/cm$^2$.
- ✓ Both densification of Ba-122 core and high degree of grain orientation are very important to obtain high $J_c$ values.
- ✓ High performance Ag/Cu and Ag/SS double sheathed Ba-122 tapes were fabricated with transport $J_c > 10^5$ A/cm$^2$ (10 T, 4.2 K).
- ✓ Transport $J_c$ of 100-m-class Ba-122 *IBS* wires was further improved to $> 3\times10^4$ A/cm$^2$ at 10 T & 4.2 K.
- ✓ Very good performance of the first *IBS* solenoid coil tested at 24 T and *IBS* racetrack coil tested at 10 T.
- ✓ 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 K.

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**IHEP-CAS**

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# Thank you for your attention!