IEEE CSC & ESAS SUPERCONDUCTIVITY NEWS FORUM (global edition), No. 49, March 2021.
Young Scientist Vision plenary presentation Wk2P3-2 given at the virtual ASC 2020, November 5, 2020.

APPLIED SUPERCONDUCTIVITY CONFERENCE ASC 2020 VIRTUAL CONFERENCE Oct 24 – Nov 7 2020

Young scientists plenary

Challenges and opportunities in the development of high-performance, low-cost iron-based superconducting wires and tapes

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IPP-CAS

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Proposal for
Strategic Priority Research Program
of Chinese Academy of Sciences (CAS)
Science and Technology Frontier Research
for High Field Applications of High Temperature Superconductors

Ranked No. 1 in 7 candidates
by Academic Committee of CAS
$ 53.8 M **for 2018-2023**

The National Key Research and Development Program of China


科学技术部
高技术研究发展中心
$ 6.4 M **for 2019-2024**
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2018年度项目立项的通知

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Long wires
- Iron-based
- 2212 & YBCO
- LTSC

→

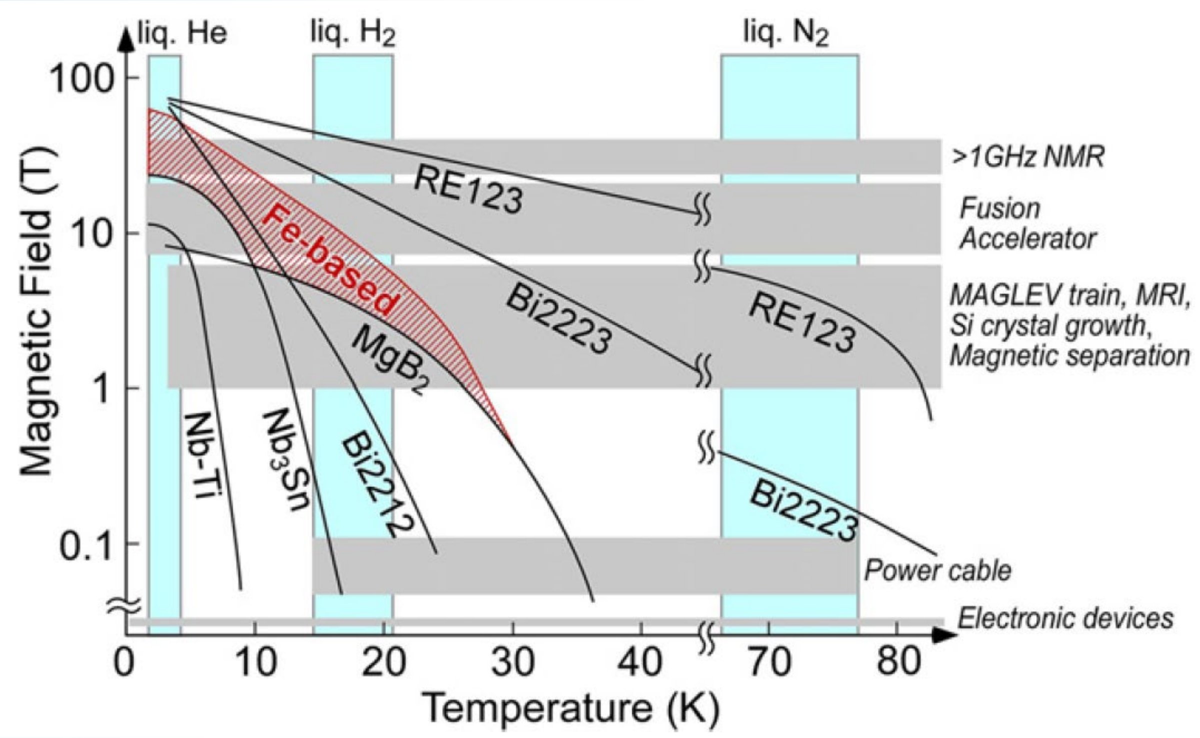
- ☐ Accelerator magnets
- ☐ Fusion magnets
- ☐ High-field MRI

Contents

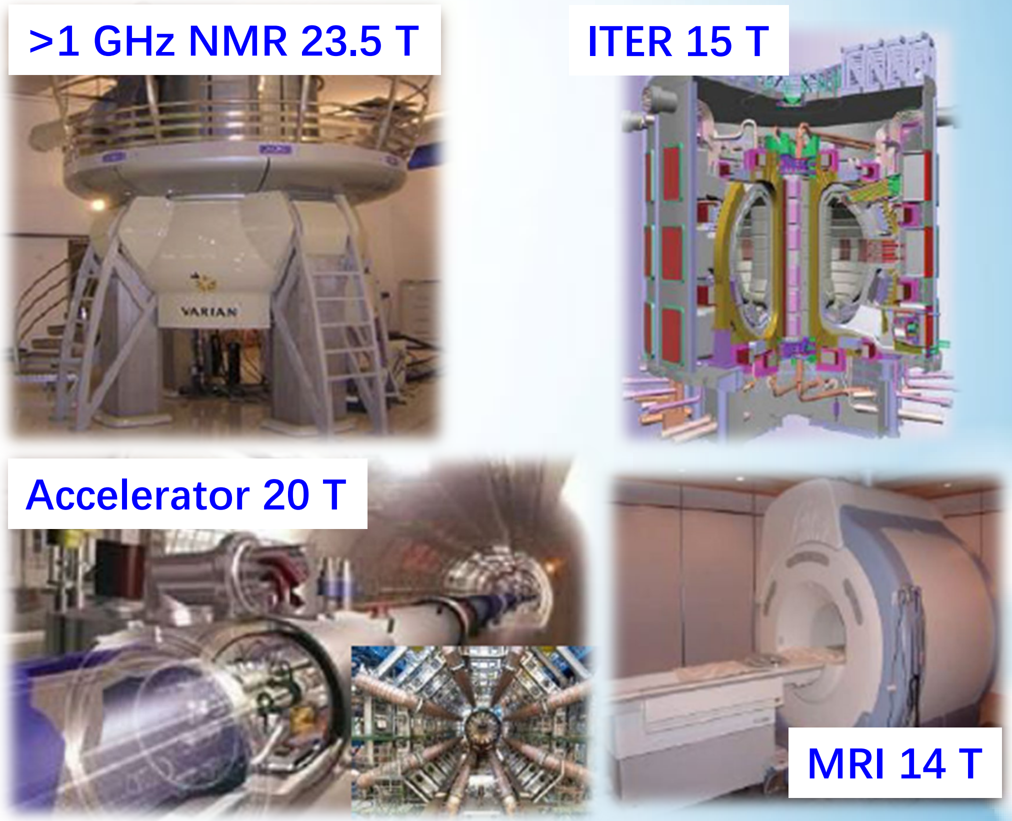
- Why we choose iron-based superconductor (IBS)?
- Development status
- Challenges & prospects
- Conclusions

Why we choose IBS?

Basic properties of IBS



J. Shimoyama, *Supercond. Sci. Technol.* **27**, 044002 (2014)



	Bi-system	YBCO	IBS 122	MgB_2
γ	50-90	5-7	1-2	2
ξ_{ab}	2.3	2.1	2.4	8
Gi	1	10^{-2}	10^{-4}	10^{-5}

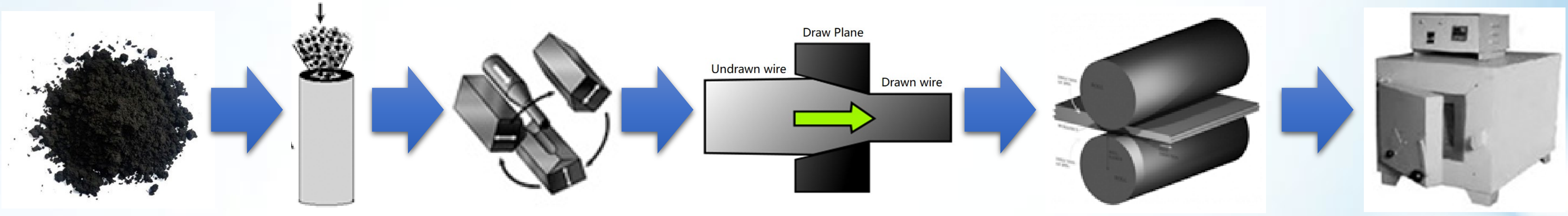
- High T_c~100 K (Single layer FeSe)
- High H_{c2}~100 T, H_{irr} very close to H_{c2}
- Small anisotropy, γ<2
- High J_c~6 MA/cm^2 & J_c-depairing~160 MA/cm^2

PIT (Powder in tube) wires and tapes

Fabrication procedures

Cost-effective & High yield

Ex-situ → Filling → Swaging → Drawing → Rolling → Annealing



Precursors

- ☐ $SmFeAsO_{1-x}F_x$
- ☐ $FeTe_{1-x}Se_x$
- ☐ **$Ba_{1-x}K_xFe_2As_2$**
- ☐ $BaFe_{2-x}Co_xAs_2$
- ☐ $CaKFe_4As_4$

BEST!

Sheath

- ☐ Fe
- ☐ Cu
- ☐ **Ag & Ag alloy**
- ☐ Monel
- ☐ Stainless steel

Deformation

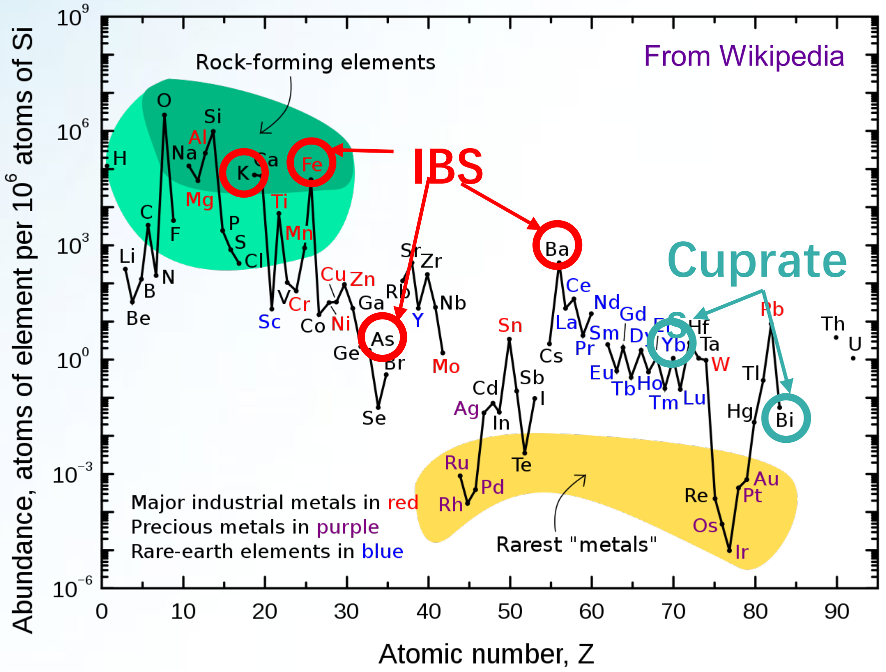
- ☐ Swaging
- ☐ Drawing
- ☐ Flat & grooved rolling
- ☐ Uniaxial pressing
- ☐ Extrusion

Sintering

- ☐ **Large window: 600-900 ^{o}C**
- ☐ No oxygen needed
- ☐ Ambient pressure
- ☐ HIP
- ☐ Wind & react

Low material cost

Raw materials

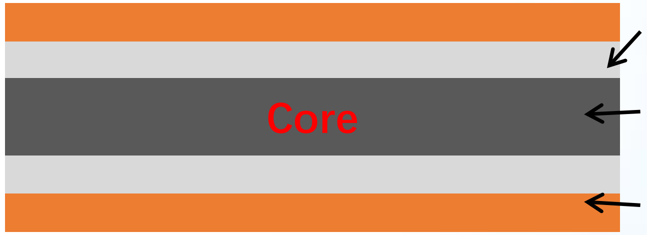


Rich abundance & cheap raw materials

Metal sheath

No need for annealing in oxygen

Architecture



Ag only acts as a block layer !

Cu/Ag tapes

Thickness of Ag ~**20 μm; Area of Ag: ~15 %**

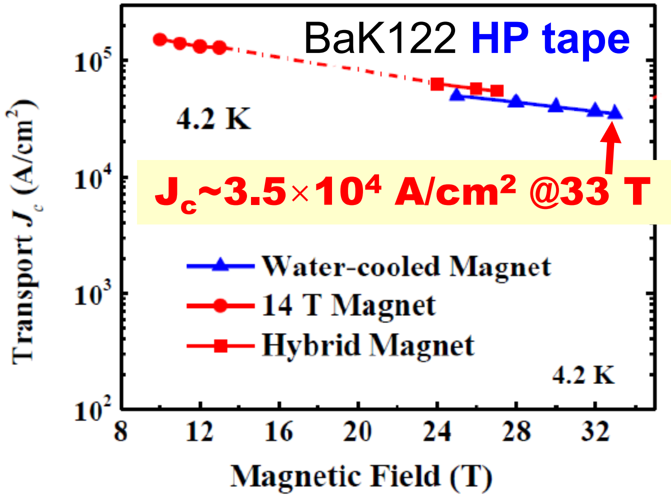
The cost of IBS wire can be four to five times lower than that of Nb_3Sn

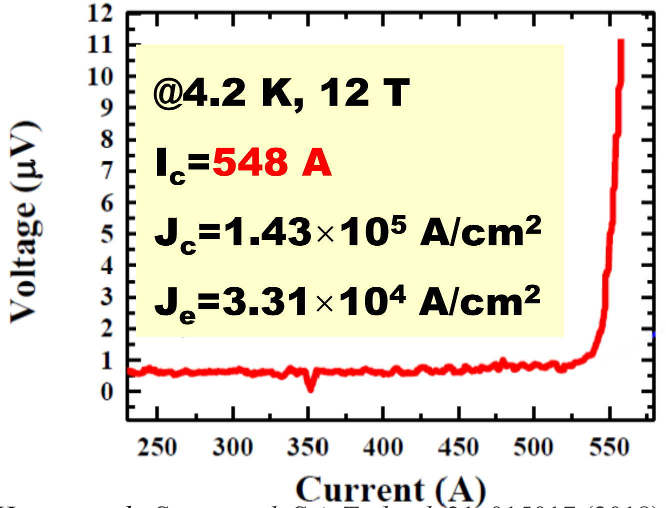
Jan Jaroszynski *et al.*, *Supercond. Sci. Technol.* **32,** 070501 (2019)

Development status

High J_c achieved in short wires and tapes (@4.2 K)

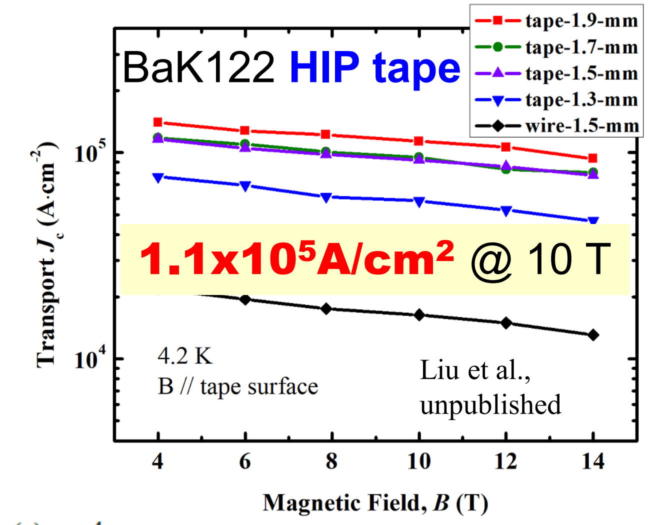
Hot pressing (HP)

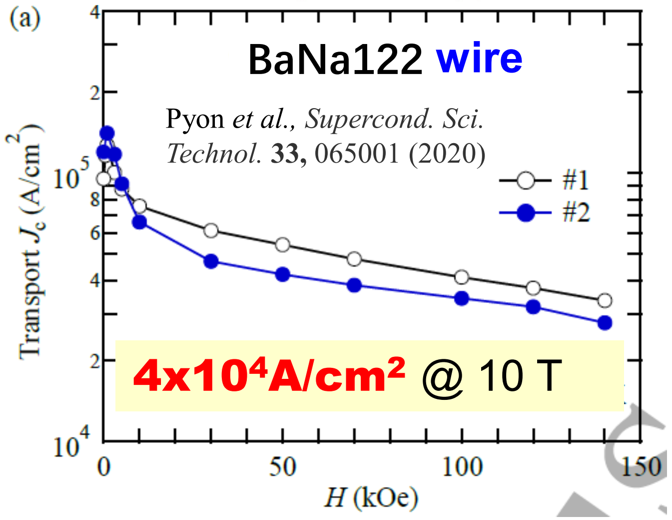




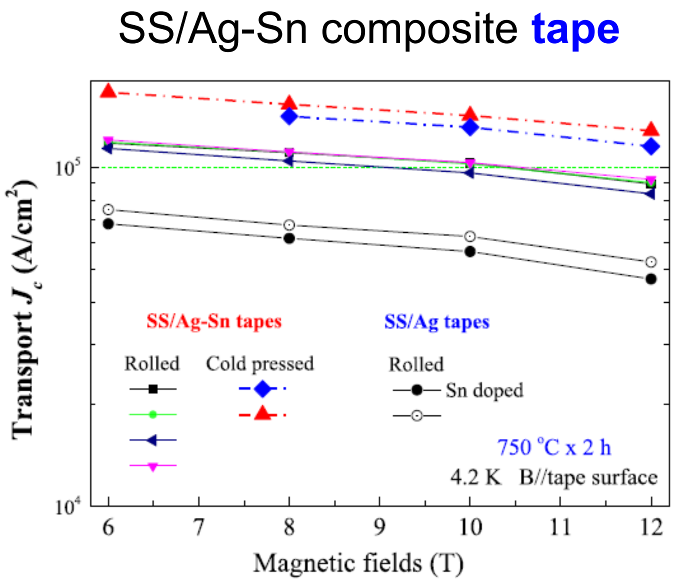
Huang *et al.*, *Supercond. Sci. Technol.* **31**, 015017 (2018)

Hot isostatic pressing (HIP)





Composite architecture



Gao, et al., *Supercond. Sci. Technol.* **30**, 095012 (2017)

Rolled Tape

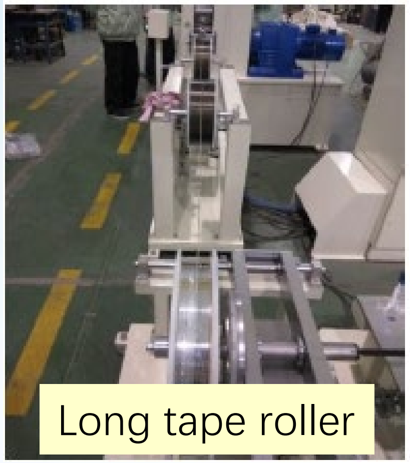
1.0x10⁵A/cm² @ 10 T

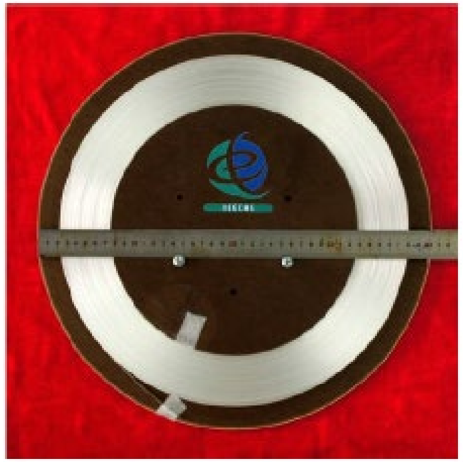
Cold pressed tape

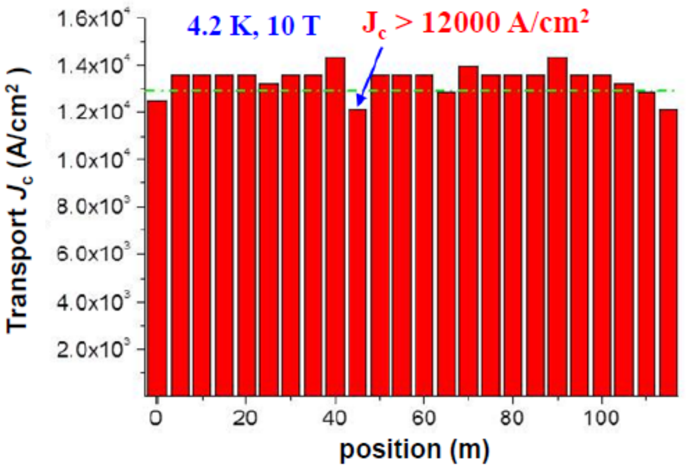
1.4x10⁵A/cm² @ 10 T

J_c development of 100-m long tapes

World's 1st 100-m class iron-based superconducting tapes



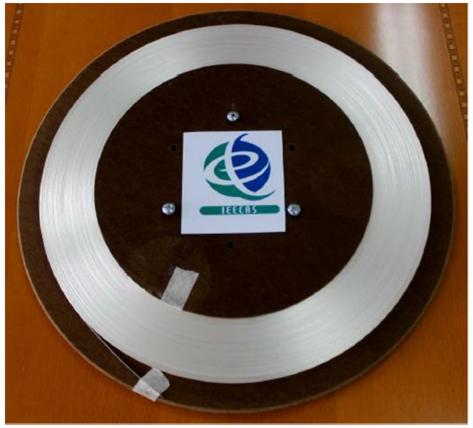


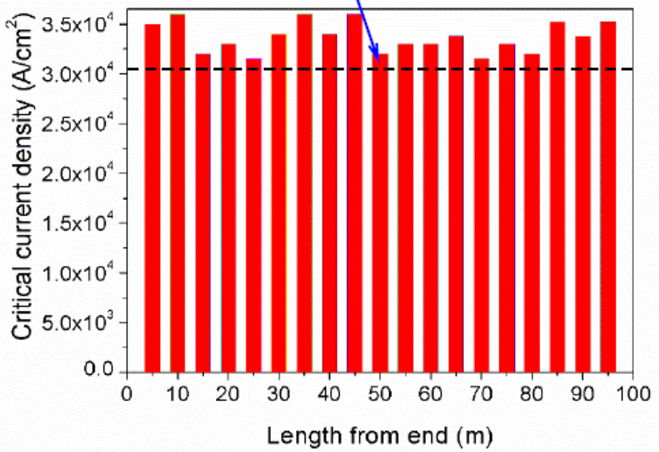


Ag/Ag tape

<5 % fluctuation
Good homogeneity

Key step to practical applications



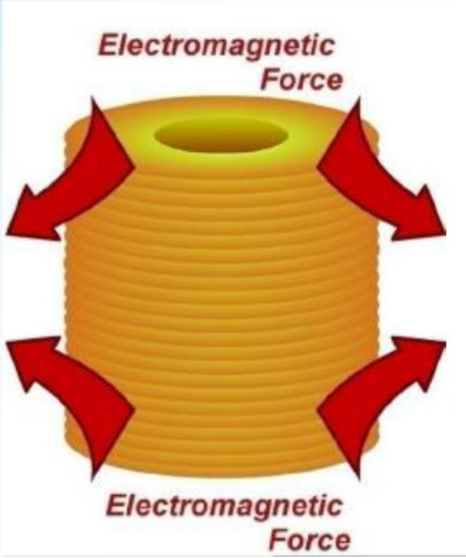


Increased by three times!

Ag/AgSn tape

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

Electromechanical properties



Equivalent stress:

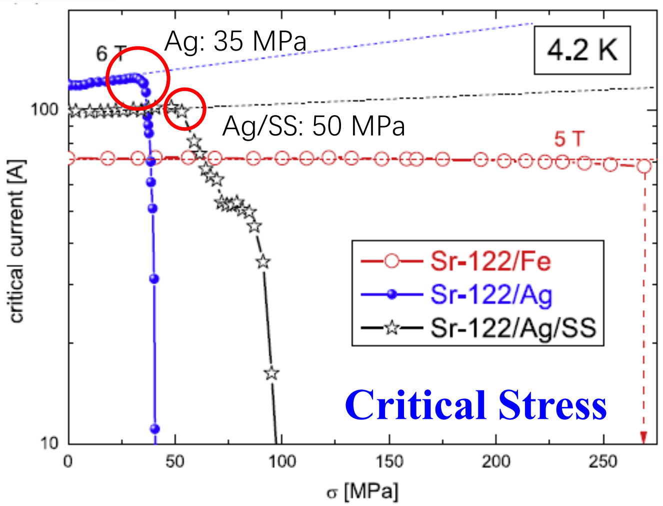
$P_m = \delta = B^2/2\mu_0$

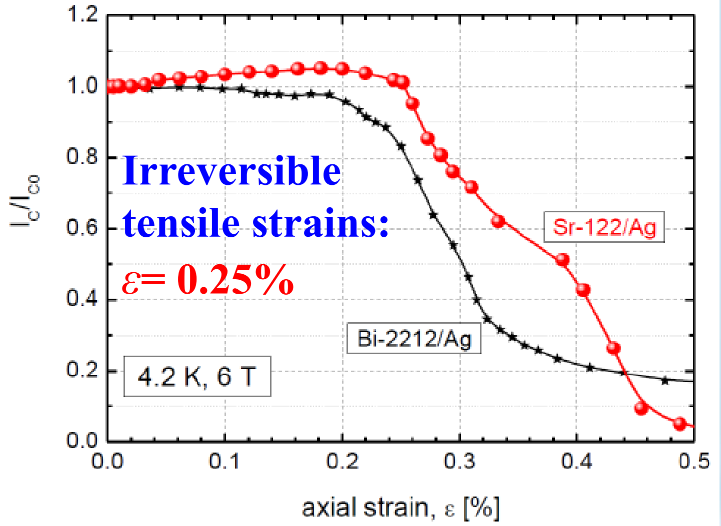
160 MPa @ 20 T

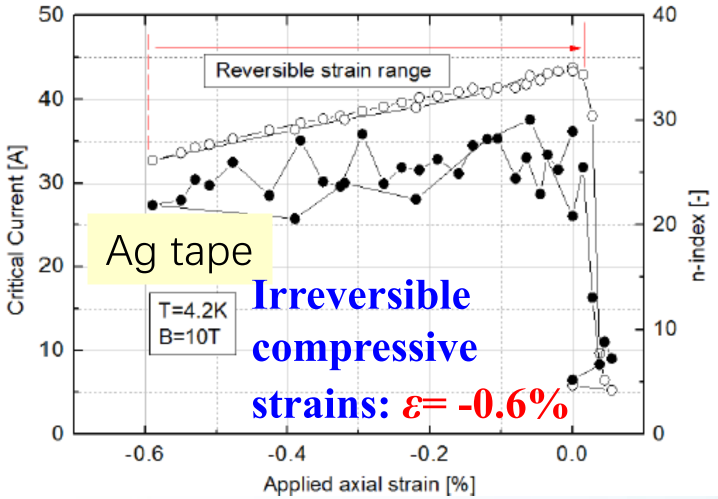
350 MPa @ 30 T

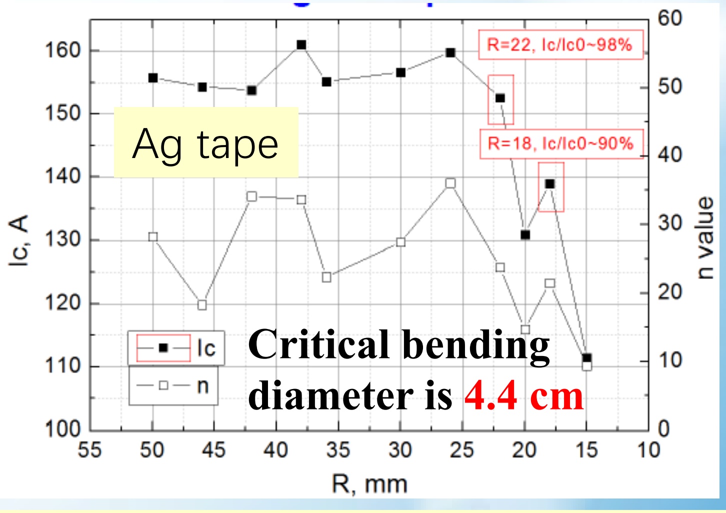
Tapes with high strength outer sheath need to be measured!

Kováč *et al.*, *Supercond. Sci. Technol.* **28,** 035007 (2015)







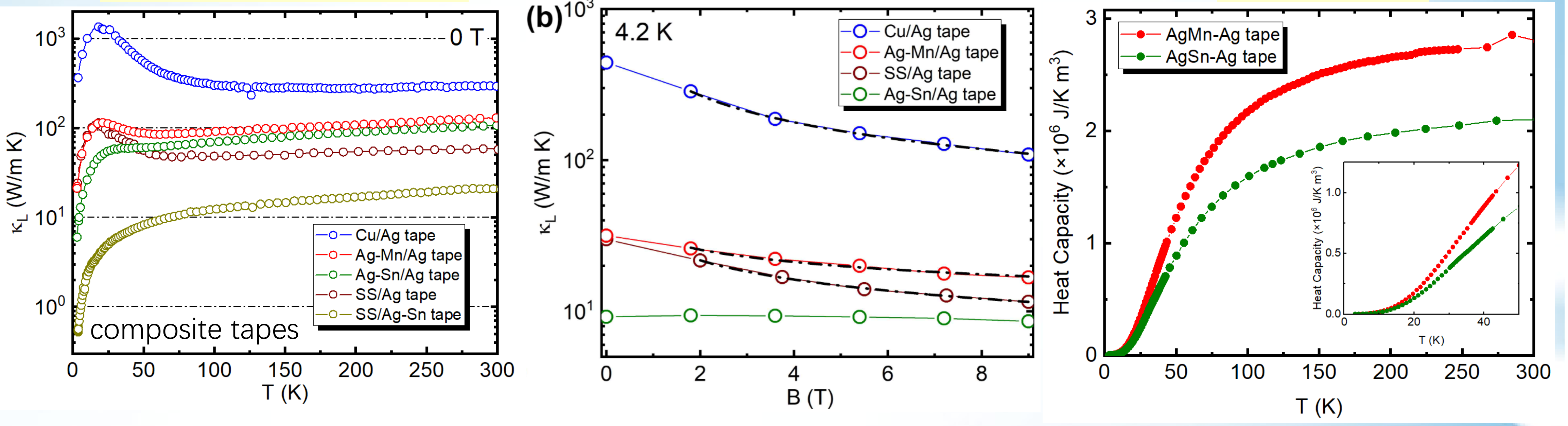


Cooperated with *Prof.* Huajun Liu from IPP-CAS

Thermal properties of composite tapes

Dong *et al.*, *Supercond. Sci. Technol.* **33,** 075010 (2015)

Thermal conductivity, κ | *κ vs. magnetic field* | Specific heat



- The thermal conductivity ranges from **1 to 1000 W/m K** by adjusting the sheath materials

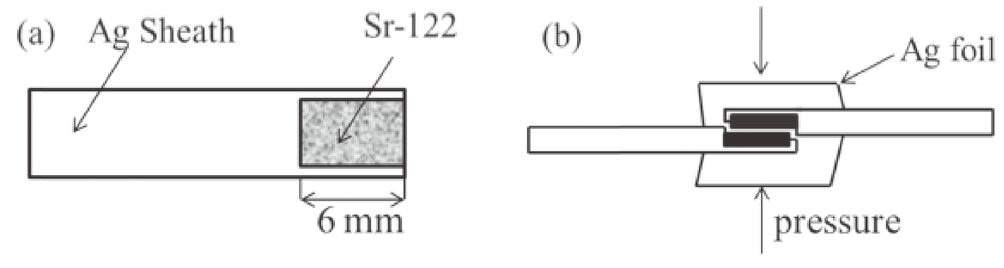
@4.2 K: **Cu/Ag**: **400 W/m K at 0 T; >100 W/m K at 9 T**——*magnets*

SS/AgSn: ~10 W/m K——*current leads*

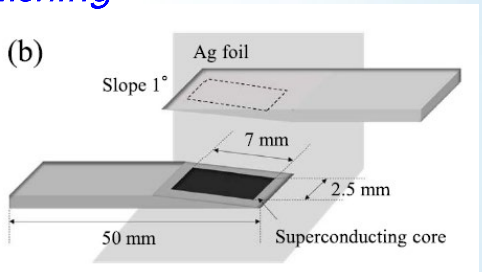
Thermal properties are dominated by the sheath materials and **it can be easily modulated by applying different sheaths and conductor architectures**

Applications at present—— Superconducting joints

Peeling-off



Angle polishing



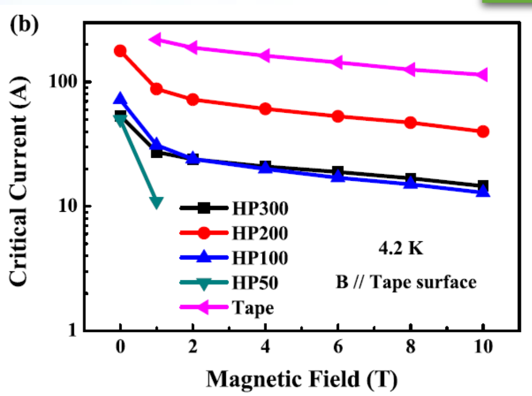
CCR: Critical current ratio=I_c^{joint}/I_c^{tape}

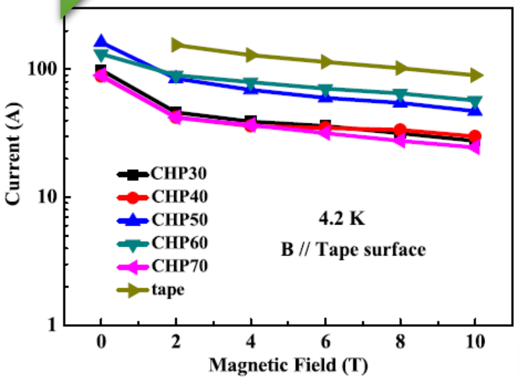
Hot pressing

35.3 % @ 4.2 K, 10 T

Optimization

63.3 %





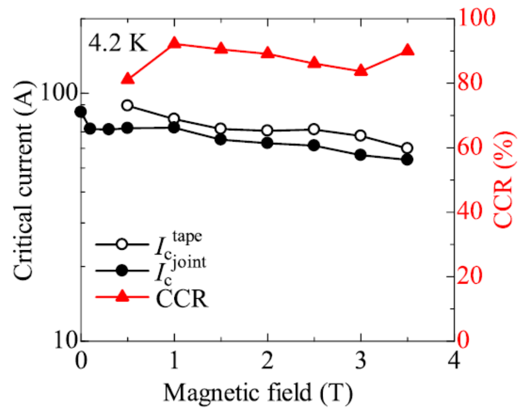
Zhu *et al.*, Supercond. Sci. Technol. **31**, 06LT02 (2018)
Zhu *et al.*, Supercond. Sci. Technol. **32**, 024002 (2019)

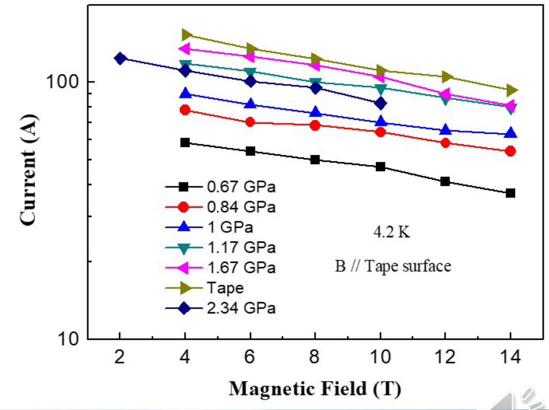
Cold pressing

More suitable for applications

80-90 % up to 3.5 T

95 % @ 4.2 K, 10 T





Imai *et al.*, Supercond. Sci. Technol. **33**, 084011 (2020)

Zhu *et al.*, unpublished

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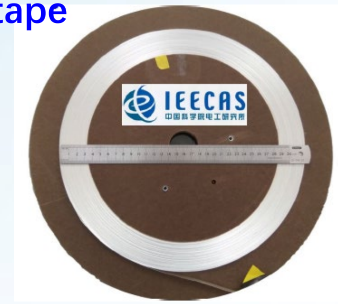
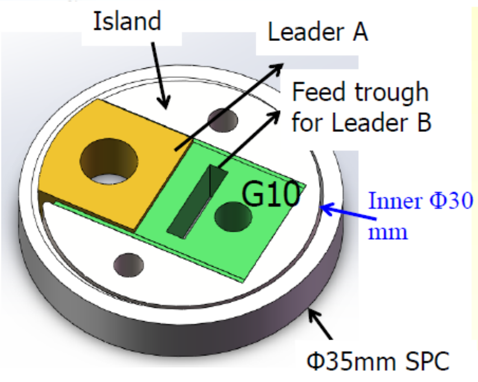
Applications at present—— Superconducting coils

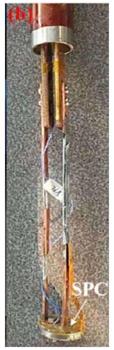
World's 1st Pancake coils

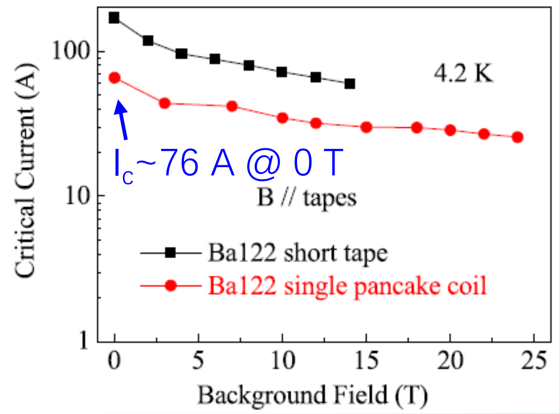
Wang *et al.*, Supercond. Sci. Technol. 32 (2019) 04LT01

7-core Ag/AgMn(Sn) tape

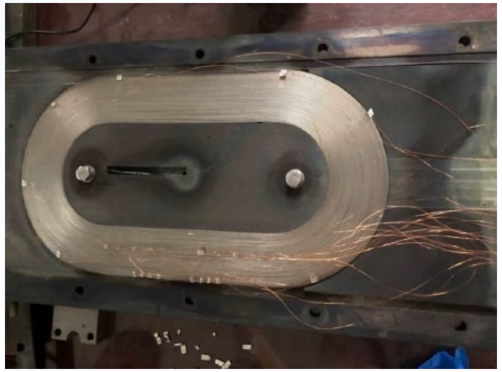


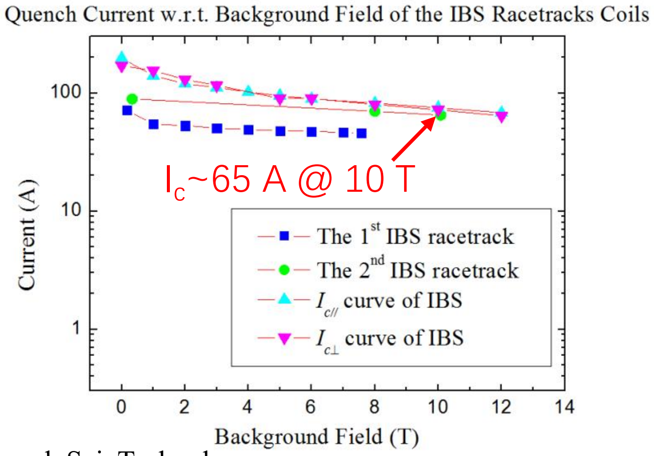






World's 1st Racetrack coils





- Metal-as-insulation technique, SS
- Wind & react > 800 °C
- Pancake coil:
  $I_c(24T)=26$ A——**40 %** of $I_c(0T)$
- Racetrack coil:
  $I_c(10T)\sim$**81 %** of $I_c(0\ T)$
  87 % of the short samples

Institute of High Energy Physics
Chinese Academy of Sciences

Zhang *et al.*, Accepted by Supercond. Sci. Technol.

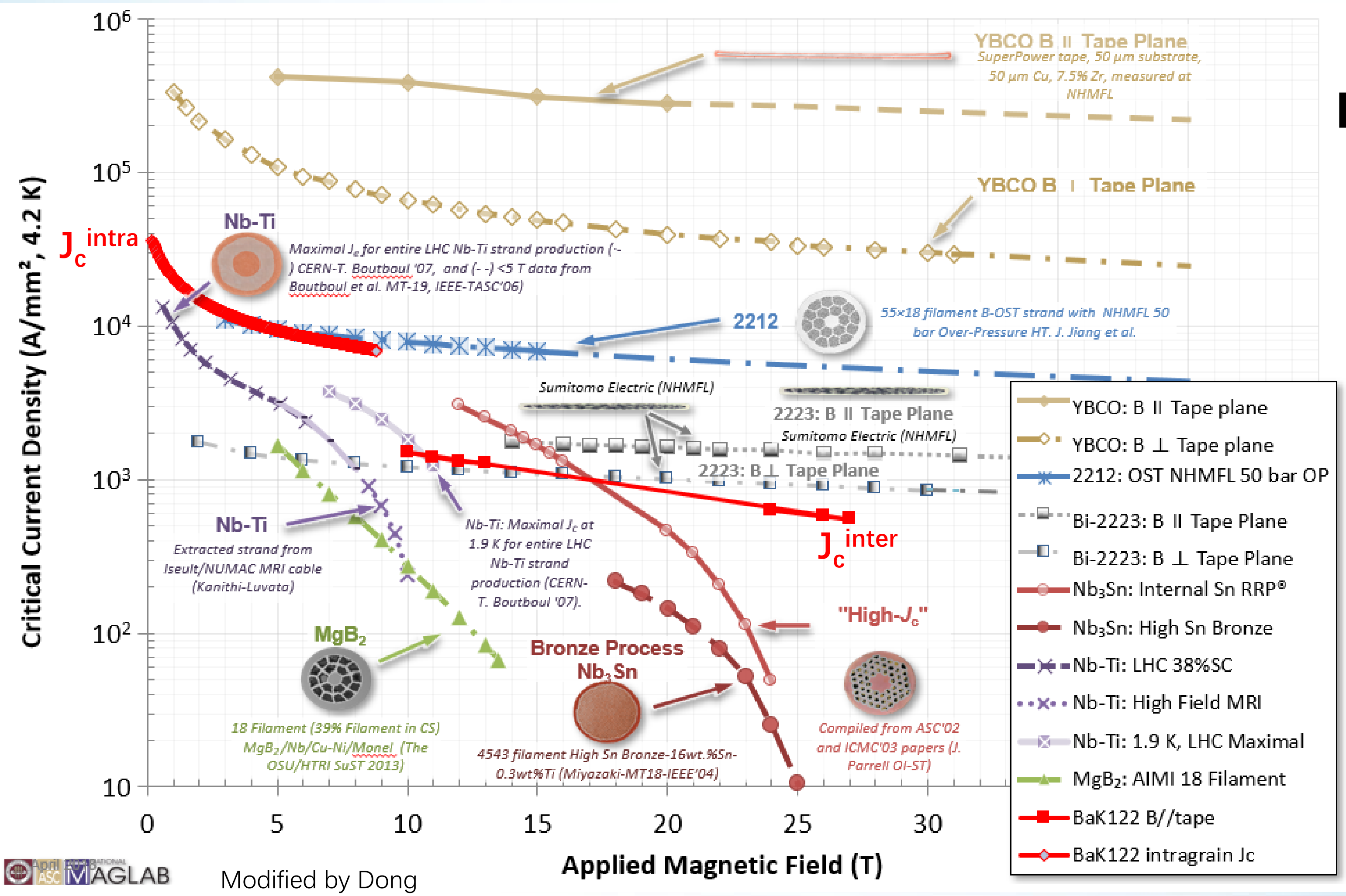
Cooperate with *Prof.* Qingjin Xu's group, IHEP

Very promising for high filed magnets !

Challenges & Prospects

Primary challenge——increase J_c

Non-stabilizer Critical Current Density vs. Applied Field



MAGLAB Modified by Dong

- ☐ Very promising to be enhanced to 2223 level
- ☐ Large gap from the 2212 and YBCO

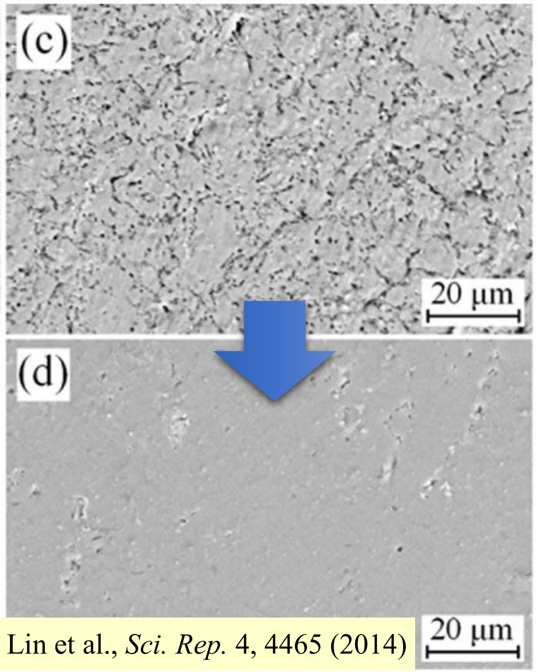
J_c^{inter}/J_c^{intra} ~ 20 %

Key: increase intergrain current

- ☐ Porosity
- ☐ Texture
- ☐ Secondary phases at GBs

Porosity is no more a problem !

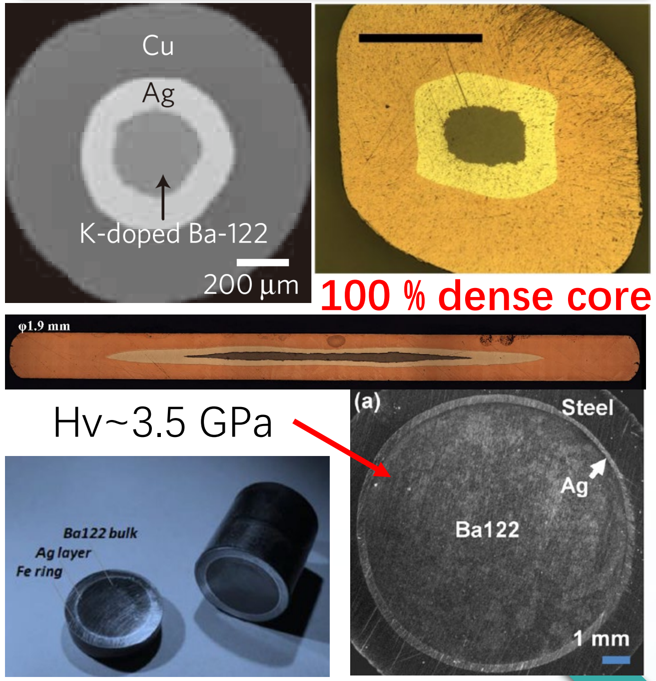
Hot pressing (HP)



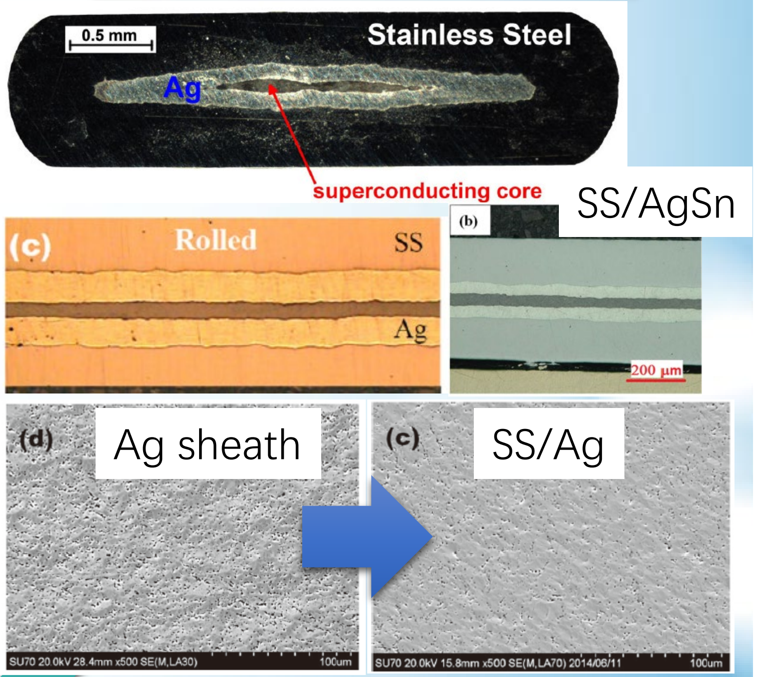
Lin et al., *Sci. Rep.* 4, 4465 (2014)

Only for short samples

Hot isostatic pressing (HIP)



Composite architecture



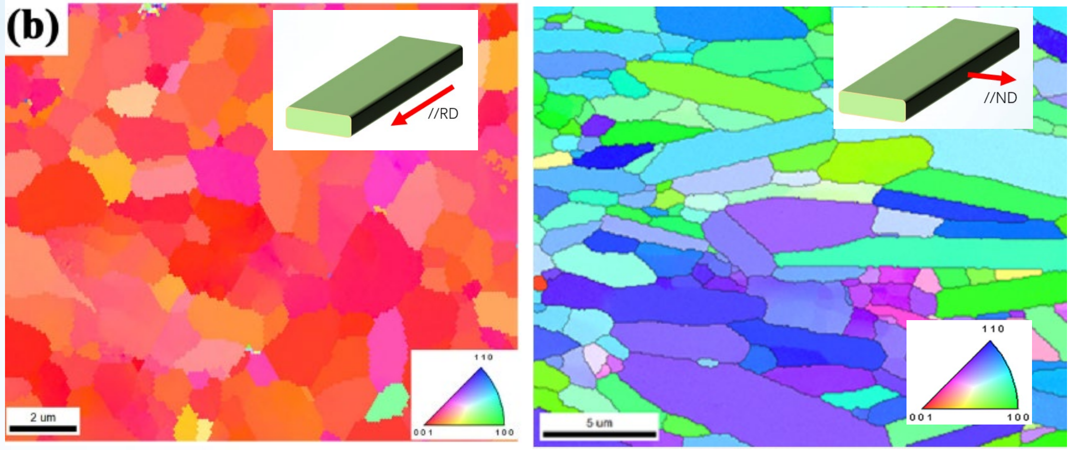
Applicable for long wires production !

Weiss *et al.*, *Nat. Mater.* 11, 683 (2012);
Hosono *et al.*, Mater. Today 21, 278 (2018);
Weiss *et al.*, *Supercond. Sci. Technol.* **28,** 112001 (2015)
Pyon *et al.*,*Supercond. Sci. Technol.* **33,** 065001 (2020)

Gao et al., *Supercond. Sci. Technol.* **28,** 012001 (2015)
Gao et al., *Supercond. Sci. Technol.* **30,** 095012 (2017)
Dong *et al.*, IEEE Trans. Appl. Supercond. 29, 7300504 (2019)

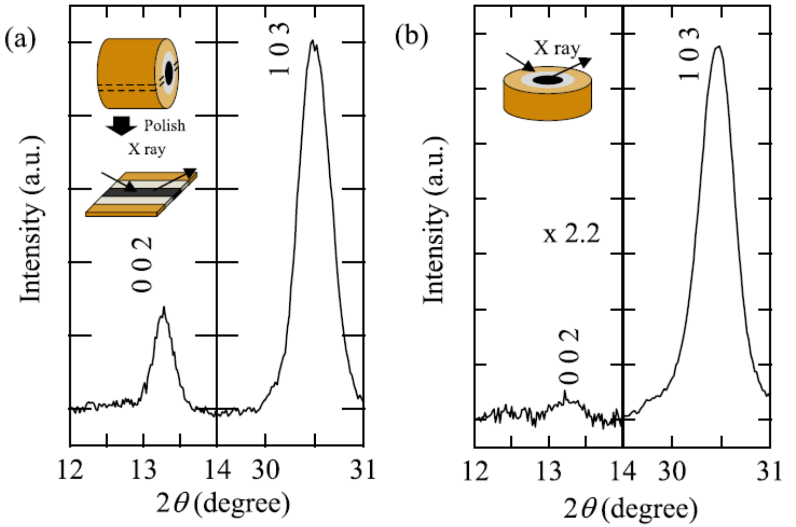
Texture is hard to improve

TAPE EBSD



WIRE XRD

Pyon *et al.*, *Supercond. Sci. Technol.* **31,** 055016 (2018)



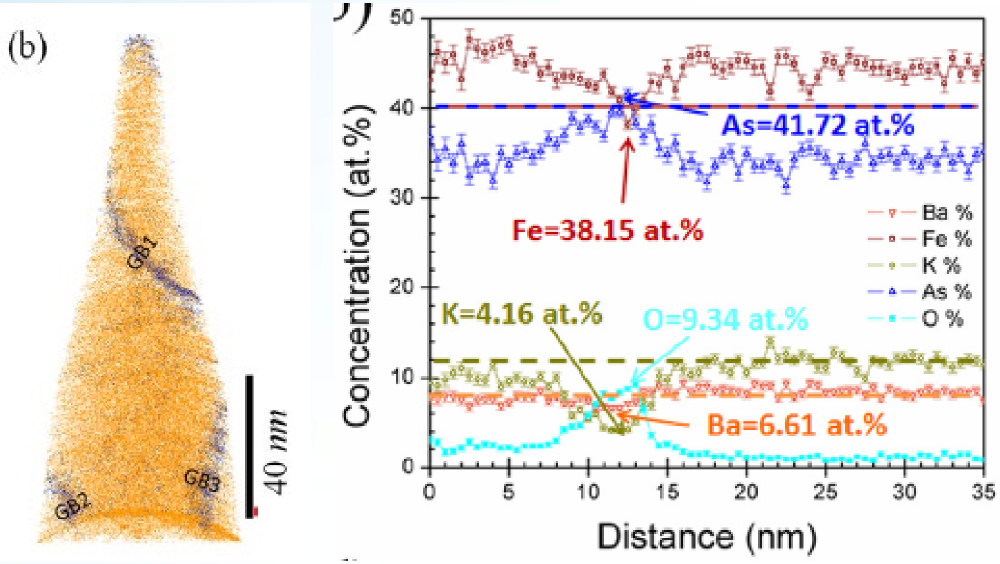
- Critical misorientation angle: θ_c~9º
- **No in-plane texture** in tapes or wires
- Rolling or pressing induced **partial *c*-axis texture**

  BEST: 43% of GBs with out-of-plane θ_c< 9º

- Optimized deformation process
- Controlled directional solidification
- Melting texture (T_m>1100 ºC)

Dirty grain boundaries (GBs)——probable breakthrough

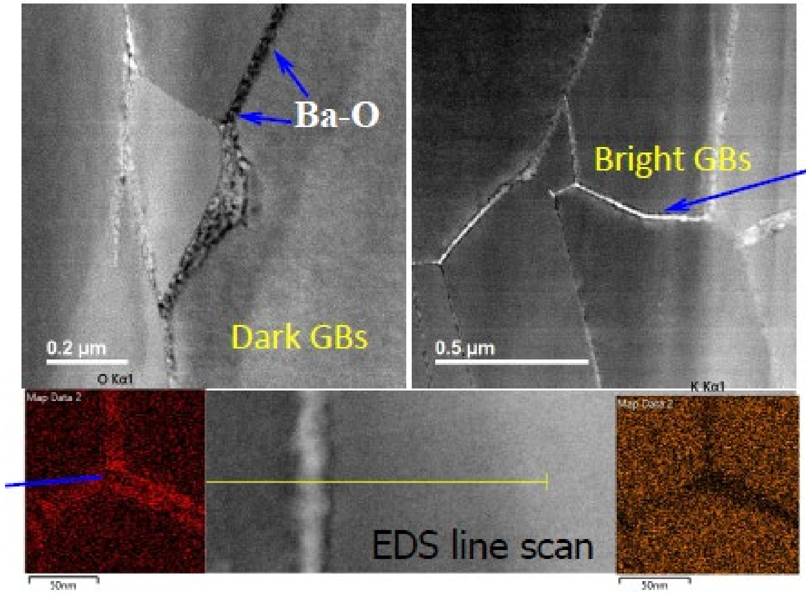
Atom-probe tomography (APT)



$Ba_{1-x}K_xFe_2As_2$ bulk

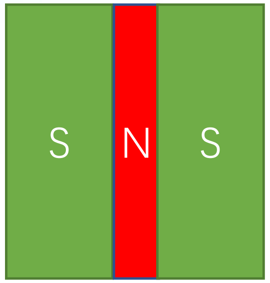
Kim *et al.*, Appl. Phys. Lett. **105**, 162604 (2014)

Tunneling electron microscope (TEM)



Our best tapes

By courtesy of *Prof.* Kametani



SNS Josephson junction

Tunneling current $I_T \sim \exp(-t/\xi)$

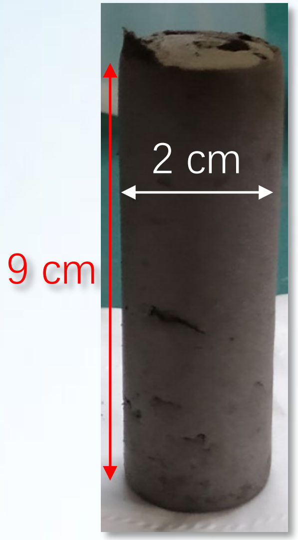
$\xi \sim 2.4$ nm

Secondary phase at GB thicker than 2.4 nm is a current blocker!

- Large amounts of **FeAs wetting phase** **is still the major problem**
  New synthesis tech. *e.g.* Low-T HIP
- Oxides——high purity raw materials & high performance glove box

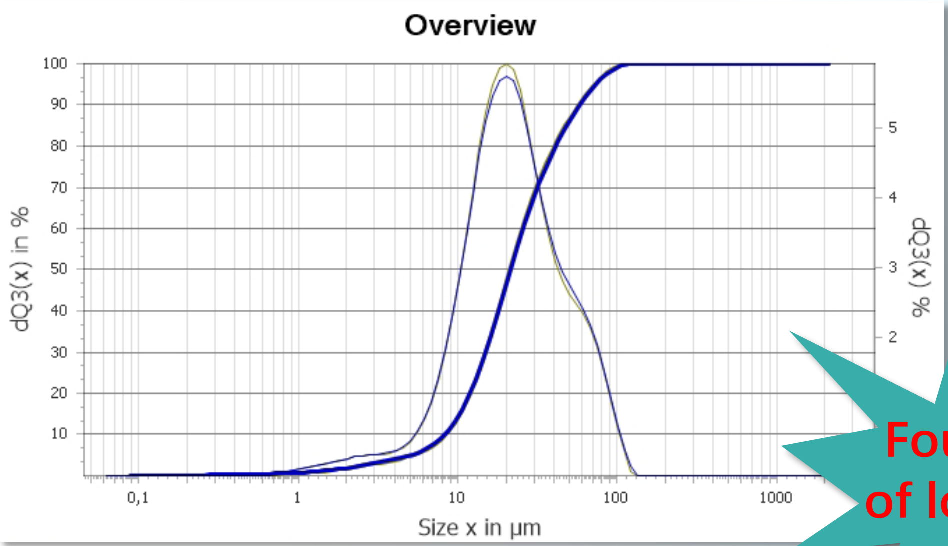
Challenge Ⅱ——Massive production of precursor powders

Billets 200 g



Powders

Particle size distribution



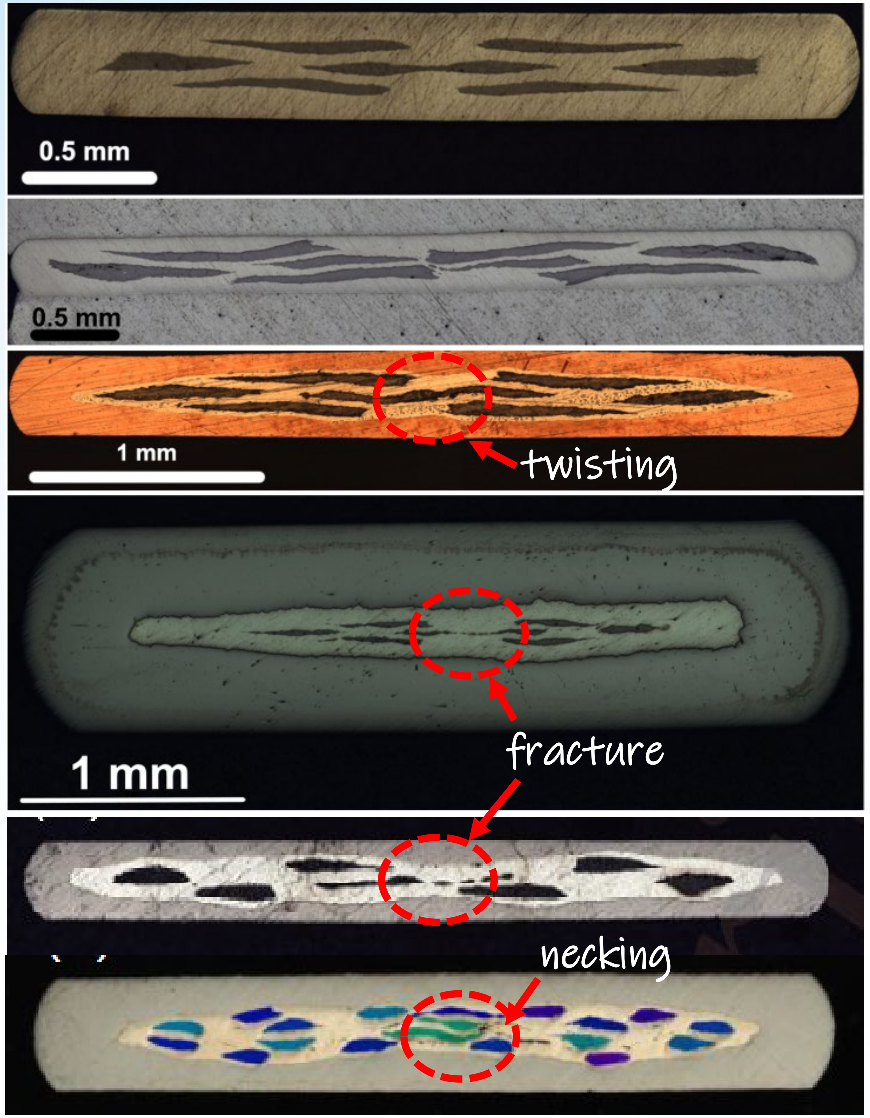
Foundation of long wires!

100-m 7-filaments tapes	⟷	0.5 kg precursor powders
1 km 7-filaments tapes	⟷	4-5 kg precursor powders

New synthesis strategy is required!

- ☐ **Massive production**
- ☐ Impurity phase, especially FeAs and oxides
- ☐ Composition control
  - ✓ K content & homogeneity
- ☐ Particle size distribution

Challenge Ⅲ——Homogeneous deformation process



Ag/AgMn tape

Ag/AgSn tape

Ag/Cu tape

Ag/SS tape

Ag/Monel tape

Ag/Fe tape

Ag must be reduced!

Composite structure must be applied!

Now be used in 100-m long tapes

Only for short samples

- Ag must be used as the inner sheath
- Large difference in mechanical strength between outer- and Ag-sheaths !
  - Necking in the middle
  - Filaments twisting, fracture
  - Wire breaking
- **Work-hardening** must be removed !

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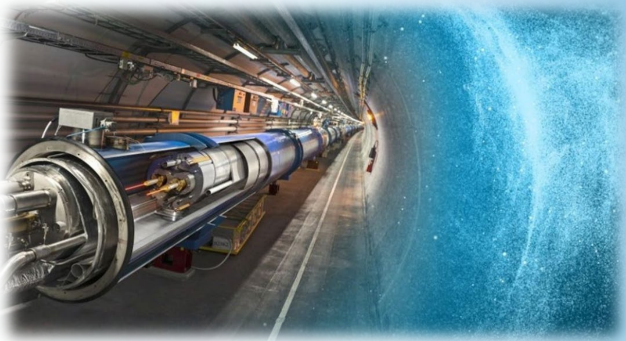
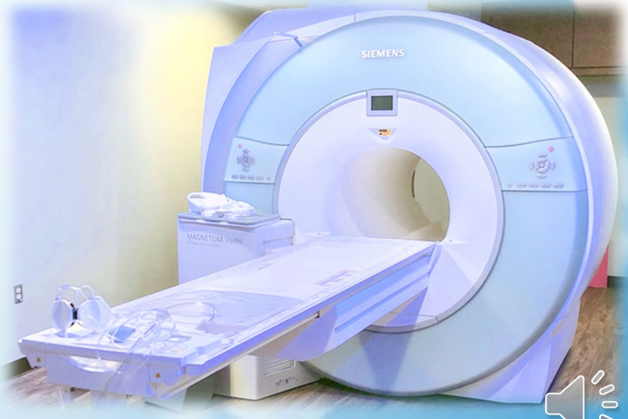
Conclusions

- Opportunities:
  - High T_c, H_{c2} and J_c^{intra}
  - Small γ
  - Low material cost
- Present status (@ 4.2 K, 10 T):
  - 1.5×10^5 A/cm^2 for short tapes, 4×10^4 A/cm^2 for short wires
  - >3×10^4 A/cm^2 for 100-m long tapes
  - Up to 20 % of J_c^{intra} —— a long way to go
- Challenges:
  - **Enhance J_c**: core density, texture, **secondary phases at GBs**
  - Massive production of high quality precursor powders
  - Homogeneous deformation of composite wires and tapes





Thank you for your attention!