Practical Superconductors for Accelerator Magnets

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Outline

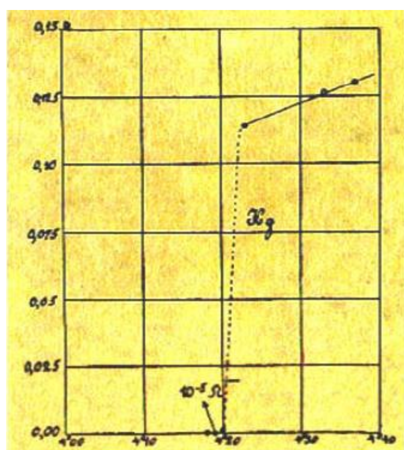
Overview: recent progress on conductors

1. LTS
2. HTS conductors
   - Bi-2223 tapes
   - Bi-2212 round wires
   - Y or R.E. based coated conductor tapes
3. MgB_2 wires
4. Iron-based superconducting wires and tapes
5. Conclusions

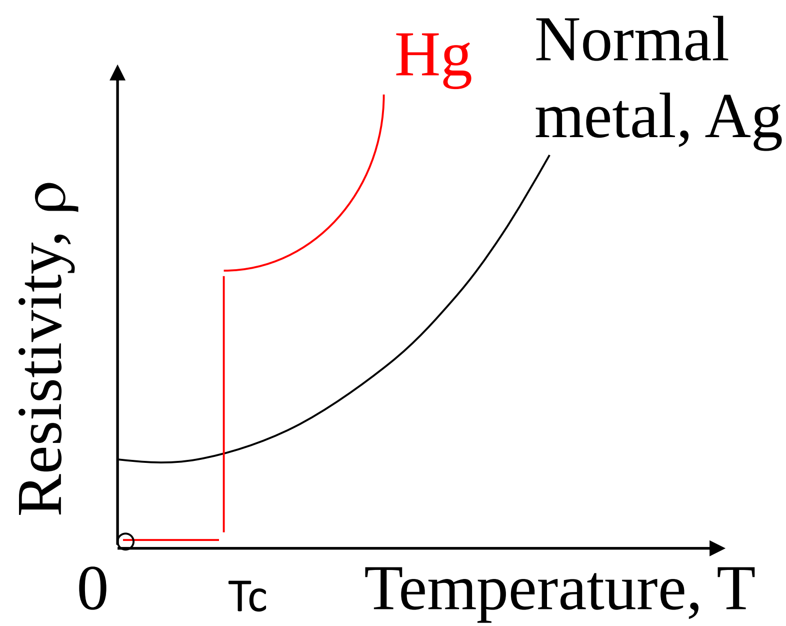
History of the Superconductor

- Superconductivity was discovered in 1911 by Heike Kamerling Onnes.
- He first observed conductivity in an experiment with mercury.
- In 1913, won the Nobel prize for liquifying helium (1908).

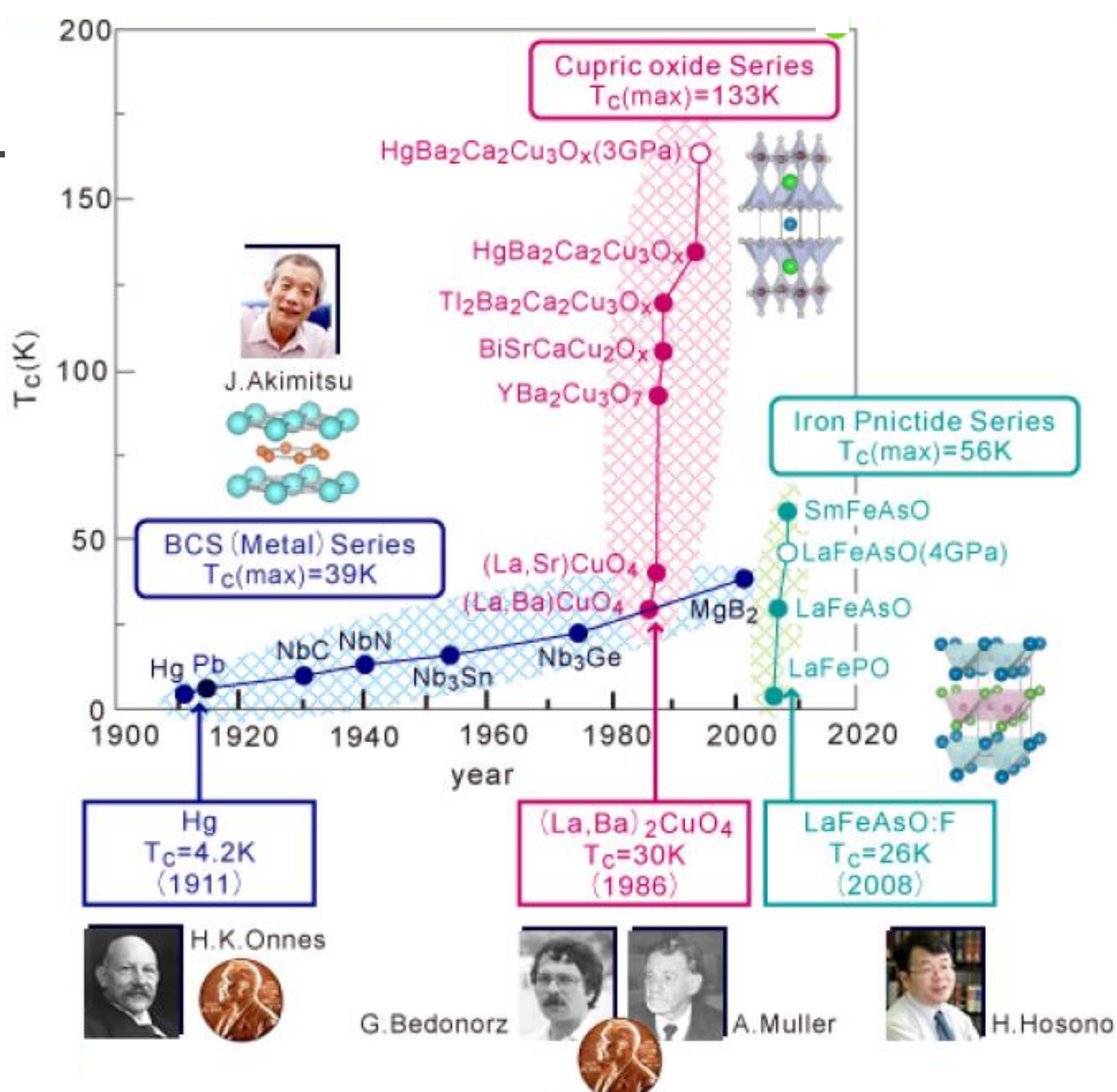
1911年，荷兰莱顿大学的卡末林—昂内斯意外地发现，将汞冷却到-268.98℃时，汞的电阻突然消失。



Resistance vs temperature curve of mercury (Onnes, 1911)



Timeline of Superconductivity from 1900 to 2015



So far, over 1000 superconductors have been discovered

Metallic materials
(pure metal, alloy & intermetallic compound)

Pure metals	<10K
Ca	29K(216GPa)
Nb- Ti	9.7K
Nb- Zr	11K
Nb_3Sn	18K
Nb_3Ge	23.2K
V_3Ga	16K
HfV_2	9.2K
$LuRh_4B_4$	11.5K
UPt_3	0.54K
MgB_2	39K

Organic(molecular) material

Cs_3C_{60}	38K
$RbCs_2C_{60}$	33K
$K_xC_{22}H_{14}$	18K
$(TMTSF)_2CiO_4$	1.2K
K-(BEDT-TTF)$_2$-Cu(SCN)$_2$	10.4K

Ceramic

$YB_2Cu_3O_X$	93K
$Bi_2Sr_2CaCu_2O_y$	110K
$Bi_2Sr_2CaCu_3O_z$	110K
$HgSr_2Ca_2Cu_3O_8$	135K
$SmFeAsO_xF_{1-x}$	55K
$(Ba_{1-x}K_x)Fe_2As_2$	38K
$(Ba_yK)BiO_3$	30K
$LiTi_2O_4$	13.7K
NbC	11.5K
$PbMo_6O_8$	15K
YPd_2B_2C	23.2K

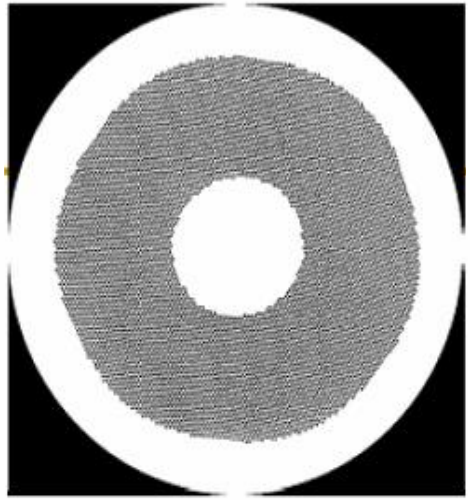
Semiconductor, Semi-metal & insulator

Si	0.34K
Ge	0.5K?
SiC	1.4K
GeTe	0.3K
PbTe	0.6K
C(diamond)	~11K
C(graphite)	11.5K

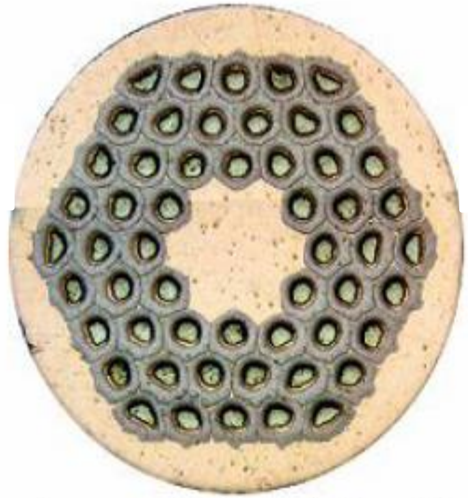
Practical Wires & Tapes

- **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**

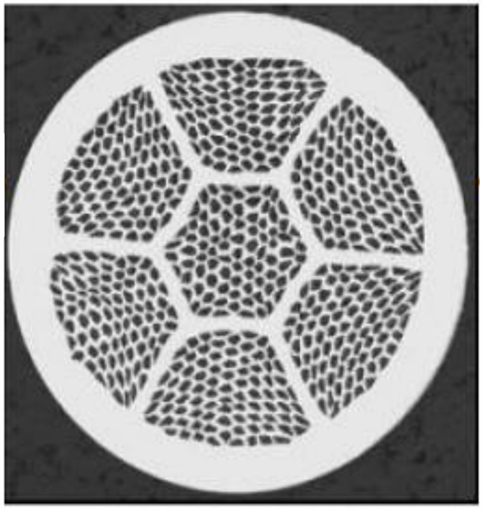
Basic structure of practical SM



Nb47Ti (OST)

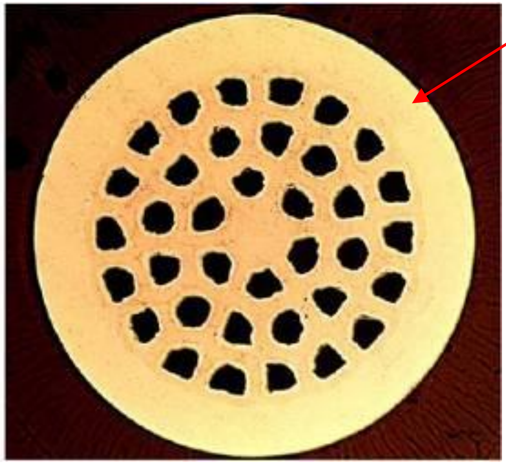


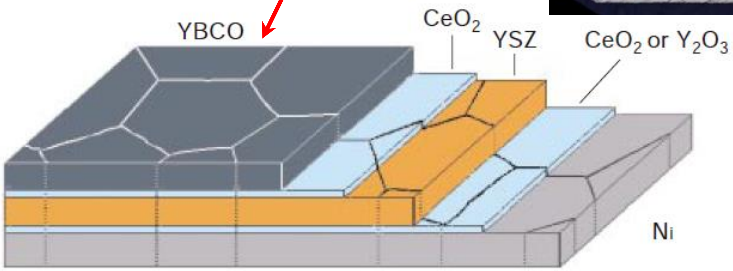
Internal Sn Nb_3Sn

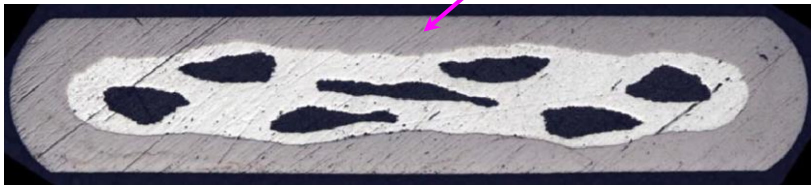


Bi-2212 (OST) – R&D

MgB_2 YBCO Bi2223 FBS







The key factor limiting the widespread use of superconducting materials

1. Properties

2. Price

$\Big\}$ **cost performance**

Fabrication cost

Operating cost － LHe, LN_2

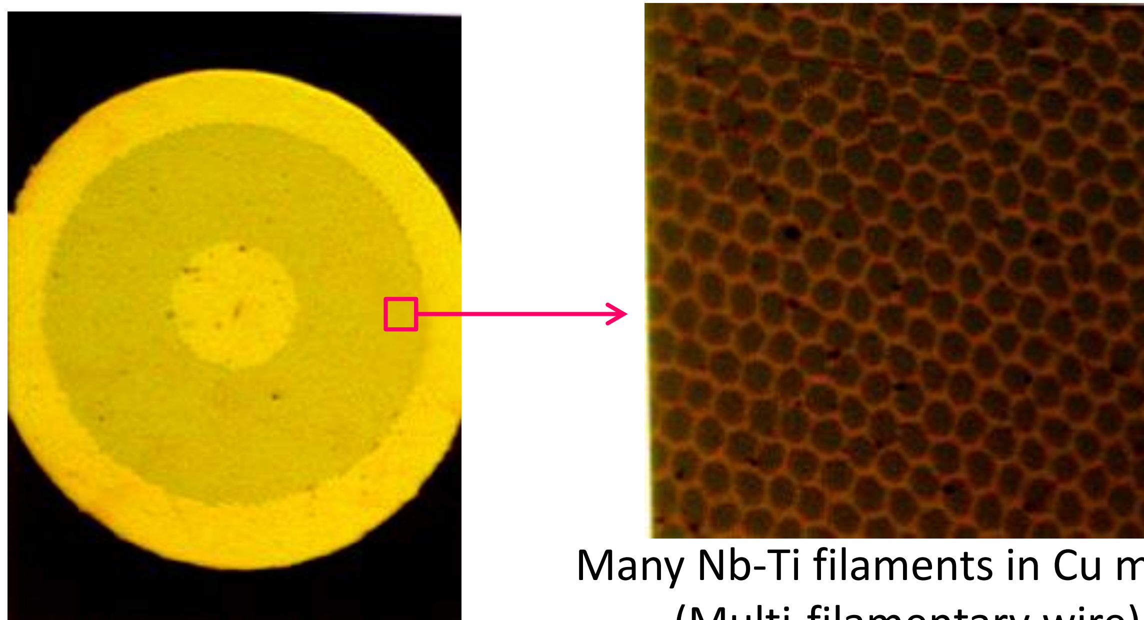
Recent progress in practical superconducting materials

Commercial superconductor – I Nb-Ti alloy

Commercialization: 1960s

Tc = 9.7 K, Hc2= 12 T

NbTi
for high field up to 9 T and 4 K and 11T at 1.8 K



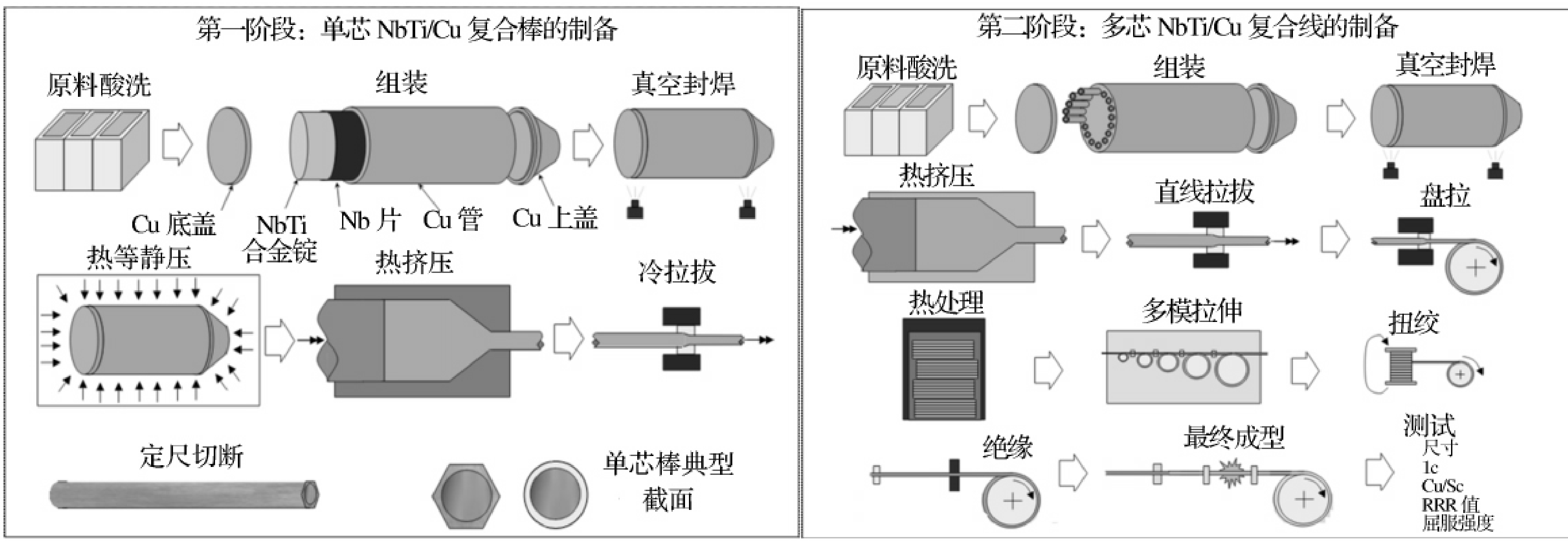
Many Nb-Ti filaments in Cu matrix
(Multi-filamentary wire)

Application of Nb-Ti

- Easily processing, high strength
- Low cost: ~2 US$/m
- MRI， 2500 Ton/year

Fabrication process of NbTi wires

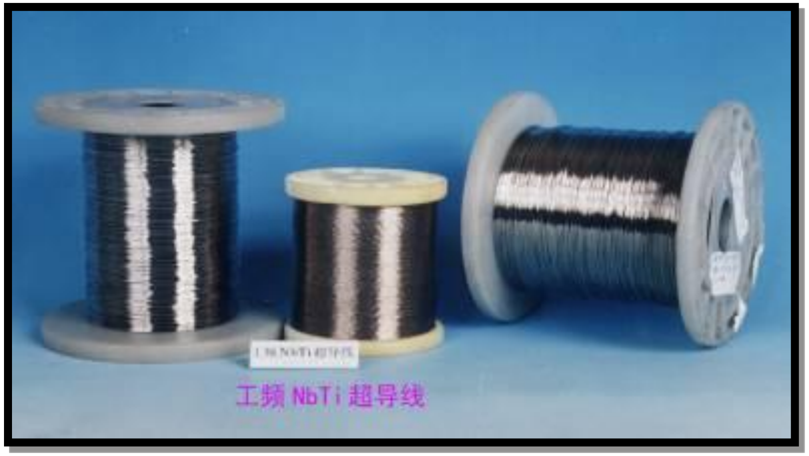
-- Western Superconducting Technologies

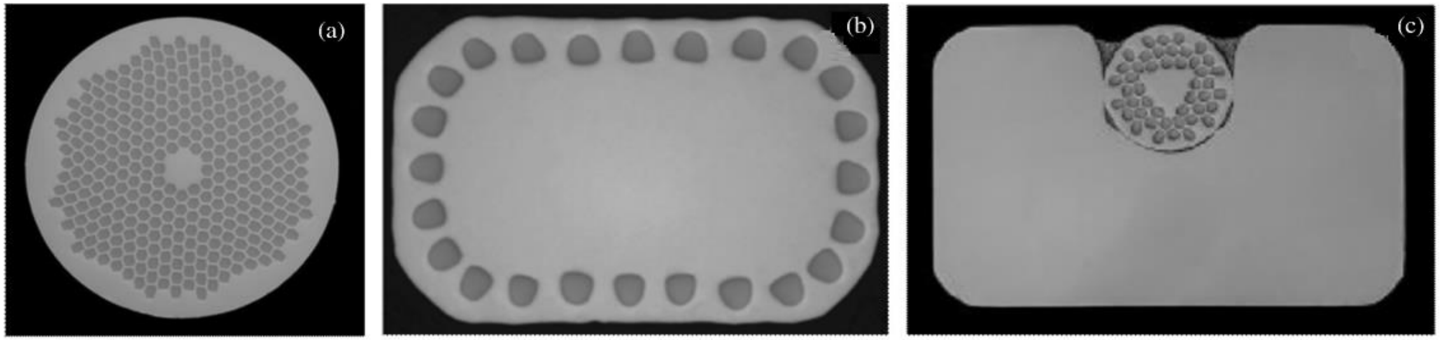


NbTi alloys are the most successful, practical and commercial superconducting materials because of their easy processing, low cost and good mechanical properties.

An example of NbTi wire

NbTi composite wire with 0.46 μm thin filament and 24,462 filaments.





用途： **NMR** **MRI** **MagLev**

Commercial superconductor – II Nb_3Sn

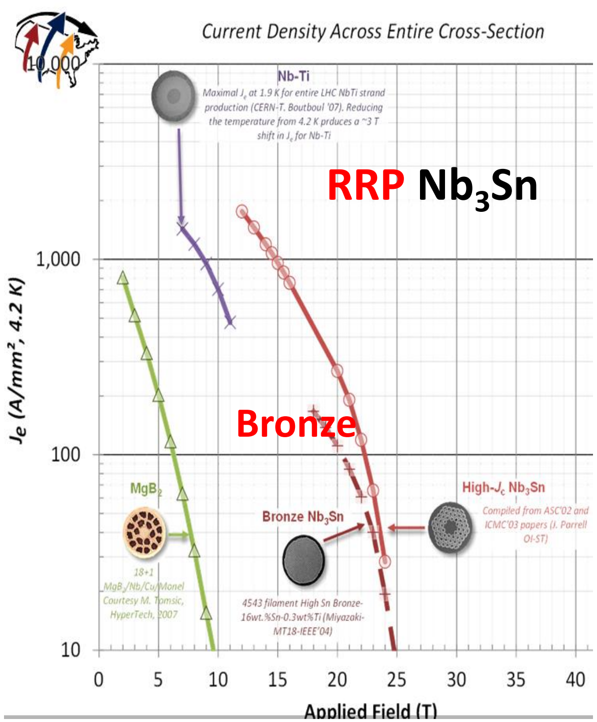
(Application of Nb_3Sn wires at very high fields (NMR))

Commercialization: 1970s

$T_c \approx 18K$, $H_{c2}(4.2K) \approx 24\text{-}25T$

Grain boundaries as pinning sites

Features: Very brittle, high hardness, poor mechanical properties



Critical current density across wire cross section (extracted from Peter Lee plots)

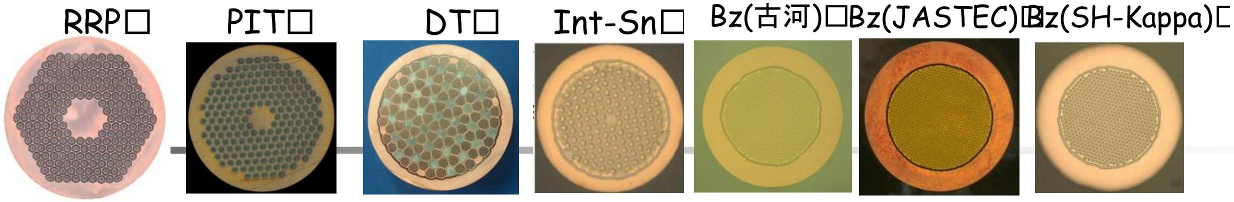
Typical A15 type superconductors

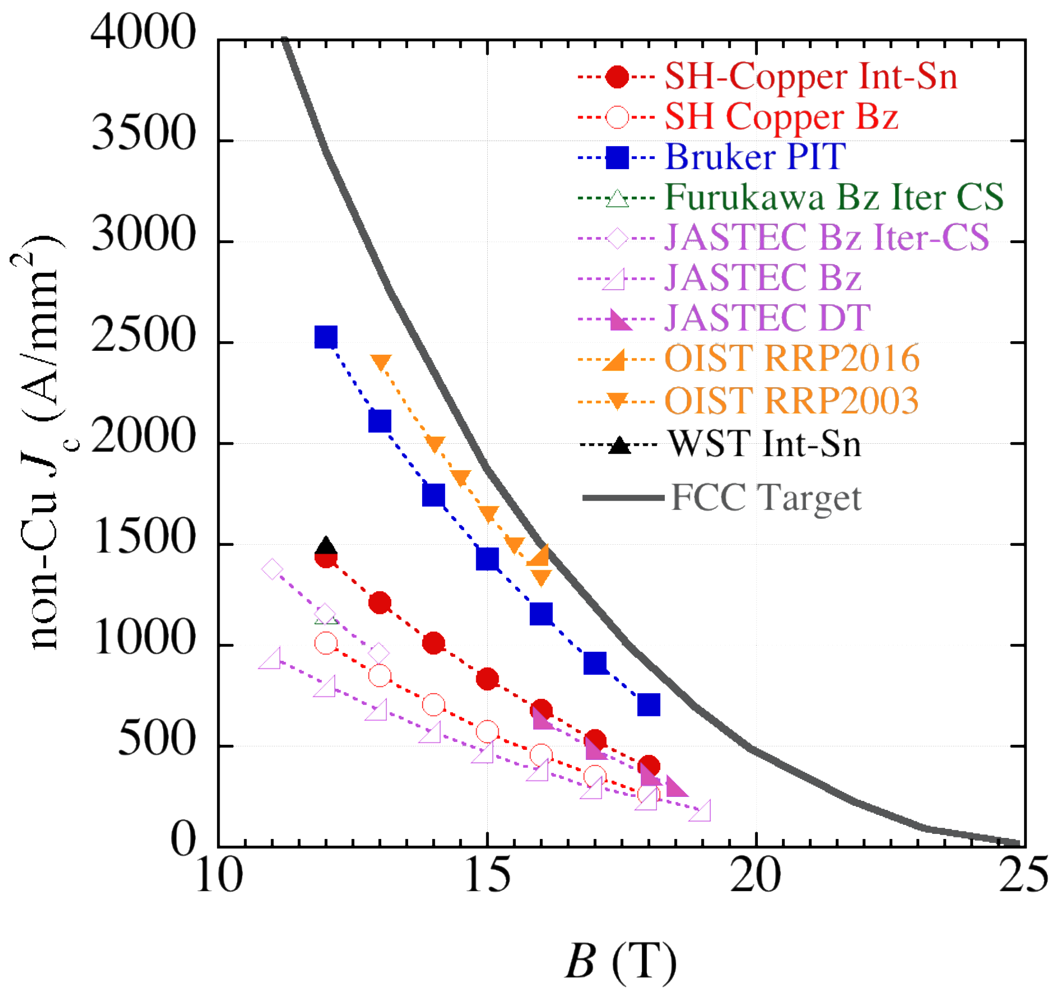
Material	T_c(K)	$H_{c2}(0)$(T)
V_3Al	14	
V_3Ga	16.5	23.1
V_3Si	17.1	34.0
Nb_3Al	19.1	32.4
Nb_3Ga	20.7	34.1
Nb_3Si	18.2	15.3
Nb_3Ge	23.2	37.1
Nb_3Sn	18	27
$Nb_3(Al, Ge)$	21.0	42.0
$Nb_3(Al, Si)$	19.5	30.0

Bronze Nb_3Sn, Kobe Steel, Bruker
NMR at 23.5 T (2011)

18Toroidal coils(Nb_3Sn)

Non-Cu J_c of Nb_3Sn wires





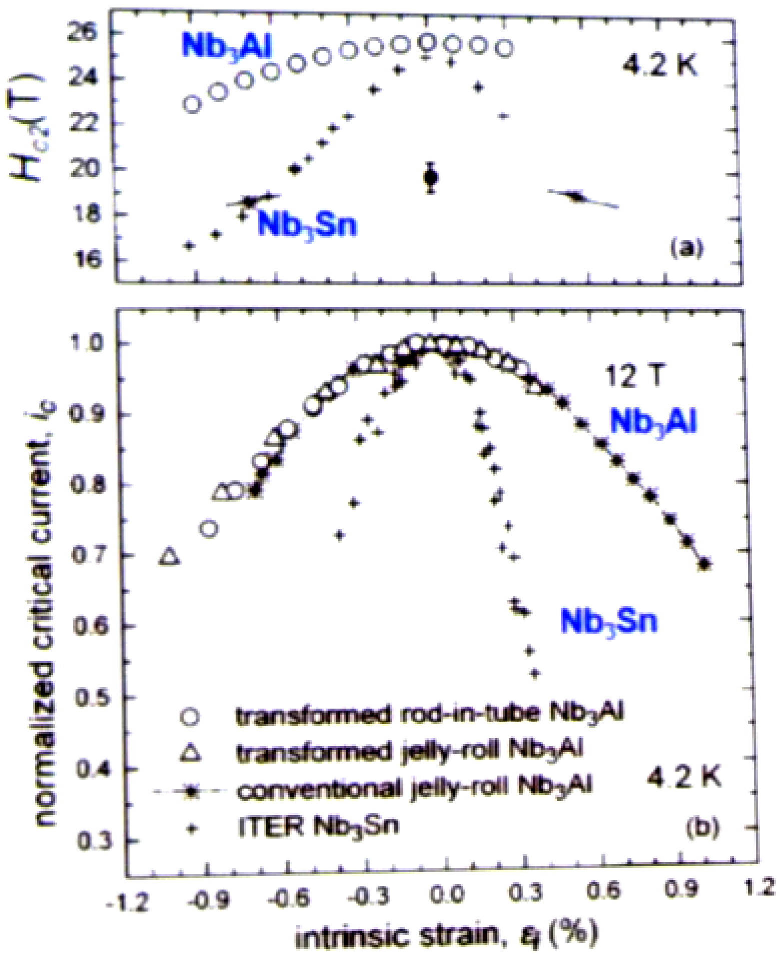
Motivation for higher Jc

from FCC Accelerator project

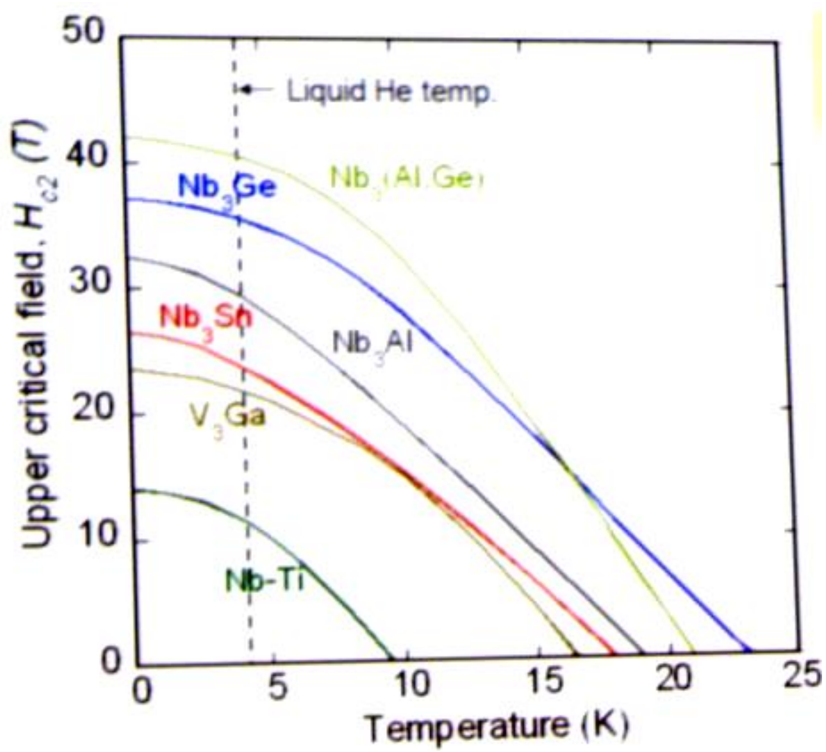
Nb_3Al superconductor- Research hotspot

Advantage of Nb_3Al over Nb_3Sn

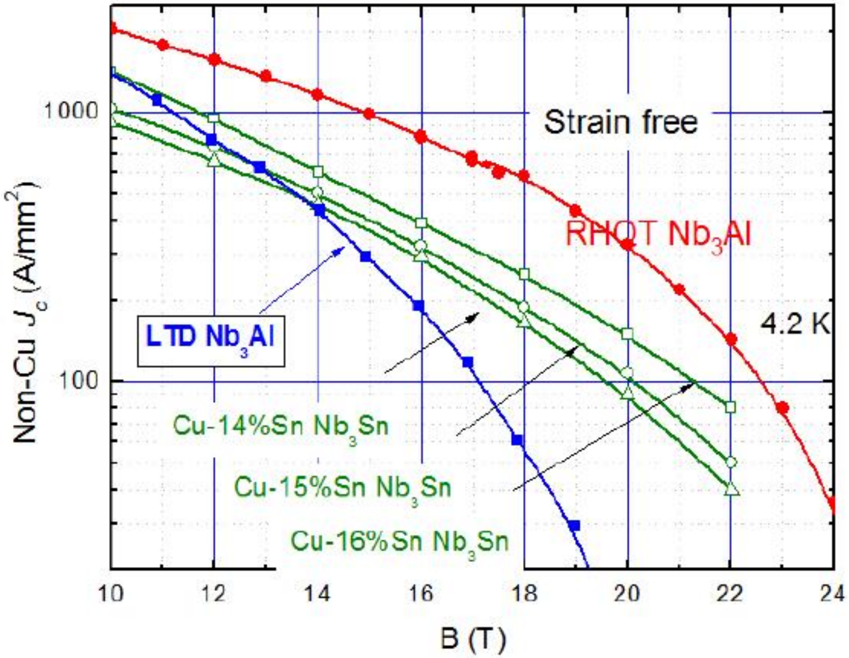
Good strain tolerance, higher H_{c2}



	T_c(K)	H_{c2}(0K)
Nb_3Al	19.1	32.4
Nb_3Sn	18	27



Japan has fabrication of kilometer-long Nb_3Al wires



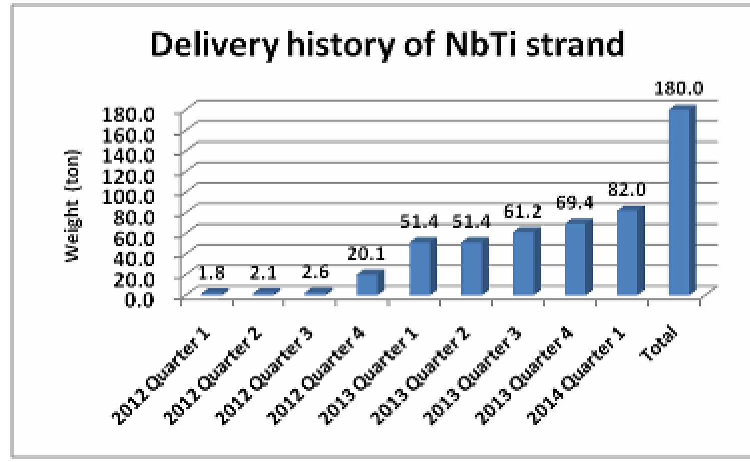
In 2011, NIMS successfully made insert-coils with Nb_3Al wires.

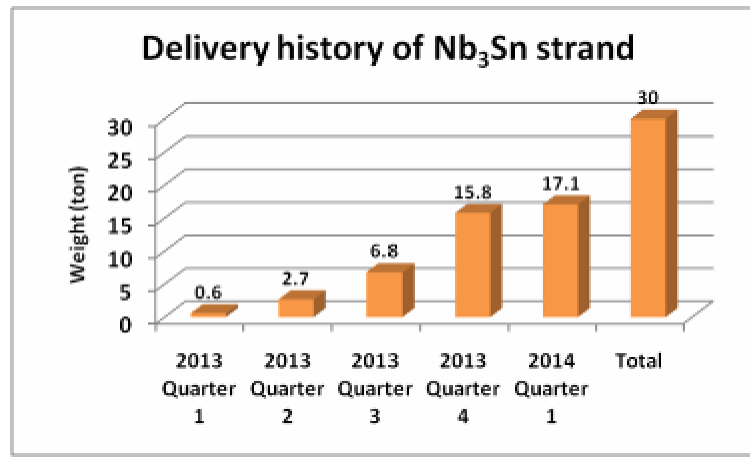
LTS Materials at Western Superconductor (WST)

Western Superconductor company in Xi'an now is the only institution to develop low Tc superconducting materials that are supplied for ITER project.

Capability of advanced Ti alloy and superconductor production lines: 6000 ton ingots of Ti alloy, 3000 ton rods of Ti alloy and 400 ton superconductor per year

Overview of NbTi and Nb_3Sn Strands for ITER

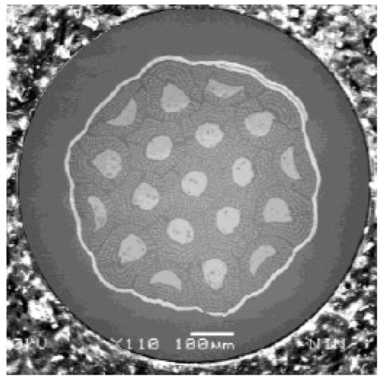
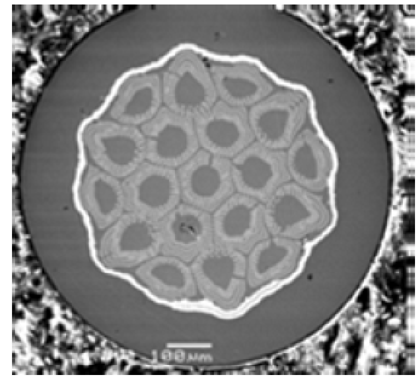
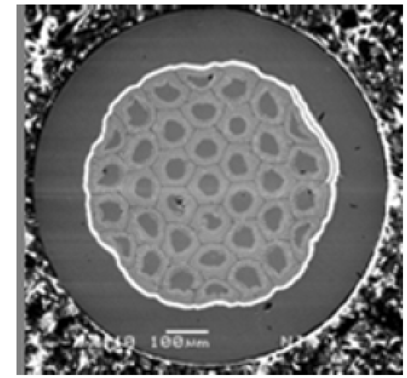




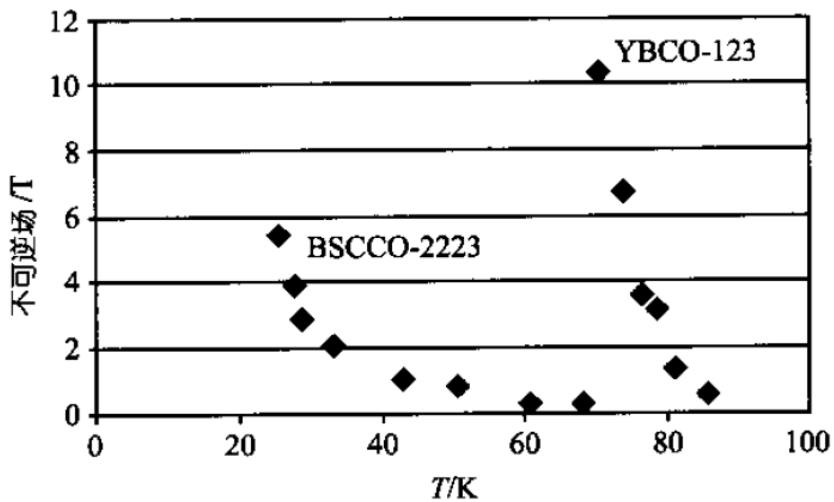
WST and NIN launched mass production of NbTi and Nb_3Sn strands for ITER in 2009 and delivered 180t NbTi and 30t Nb_3Sn strands until the end of 2015.

ITER project pushed the R&D and production of LTS in China

WST: Internal-tin Nb_3Sn Strand for ITER

Strand type	Type 1	Type 2	Type 3
Cross section			
Structure feature	Cu split	Cu split	Cu split
	--	Tin spacer	--
	--	--	37 sub-elements
I_c (A) @4.2K,12T	>250	>280	>270
n value @4.2K,12T	>20	>20	>20
RRR(273K/20K)	>100	>100	>100
Q_h (mJ/cm^3) @4.2K, ± 3T	<300	<340	<320

The system Bi-2223



Bi-2223

H*(77 K) ~ 0.2 T

Application:

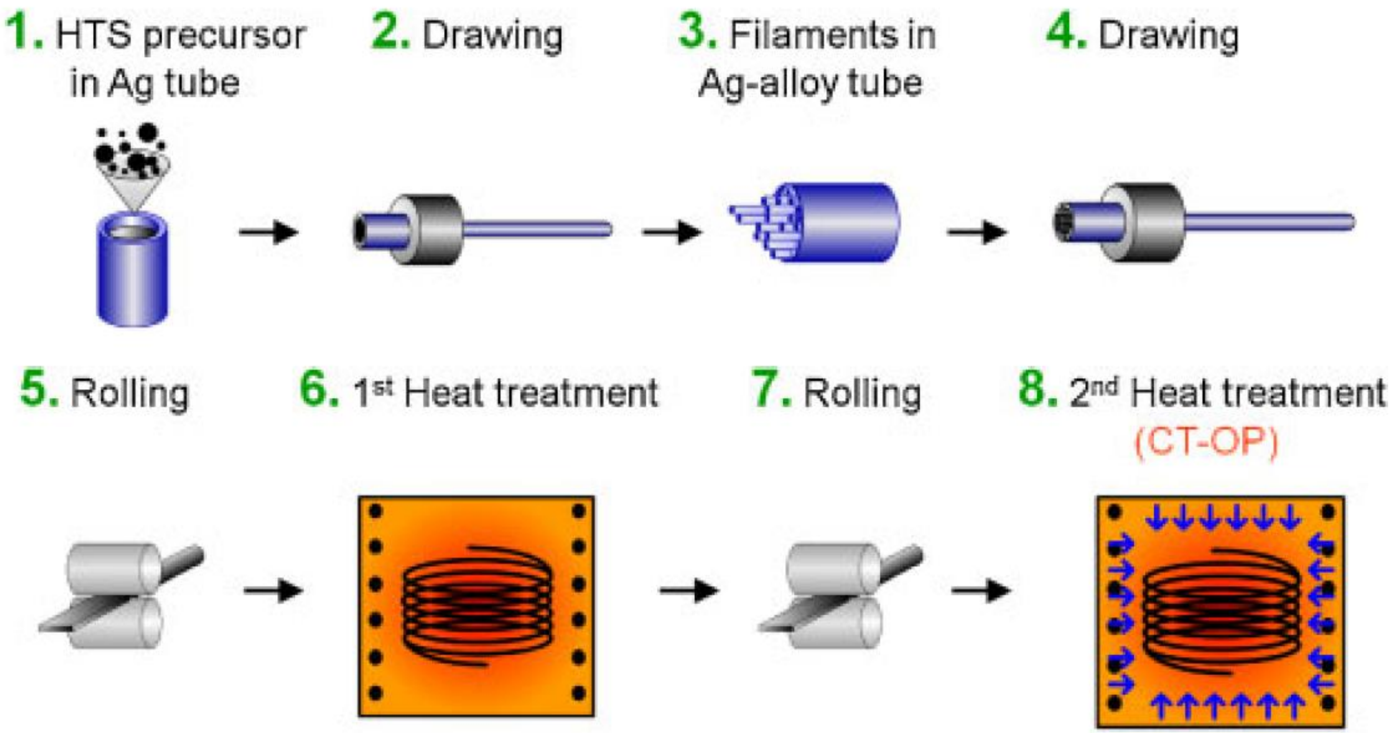
Mainly for cable

Well established PIT fabrication process by Sumitomo, Japan

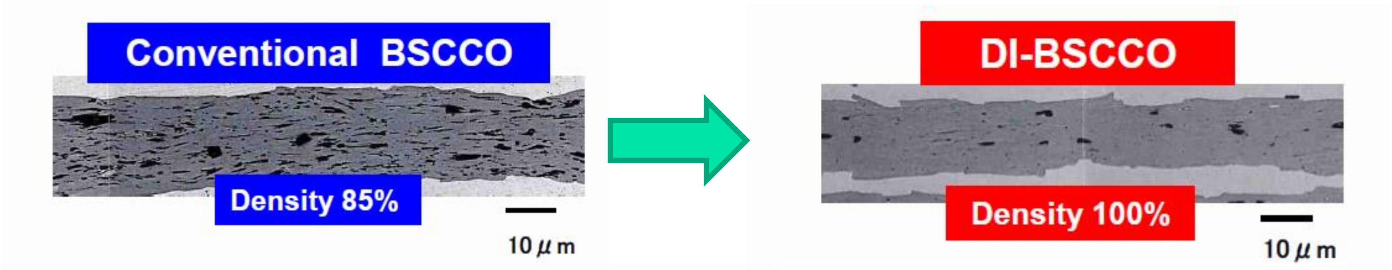
In china:

1. Innova Superconductor;
2. Northwest Institute for Nonferrous Metal Research (NIN)

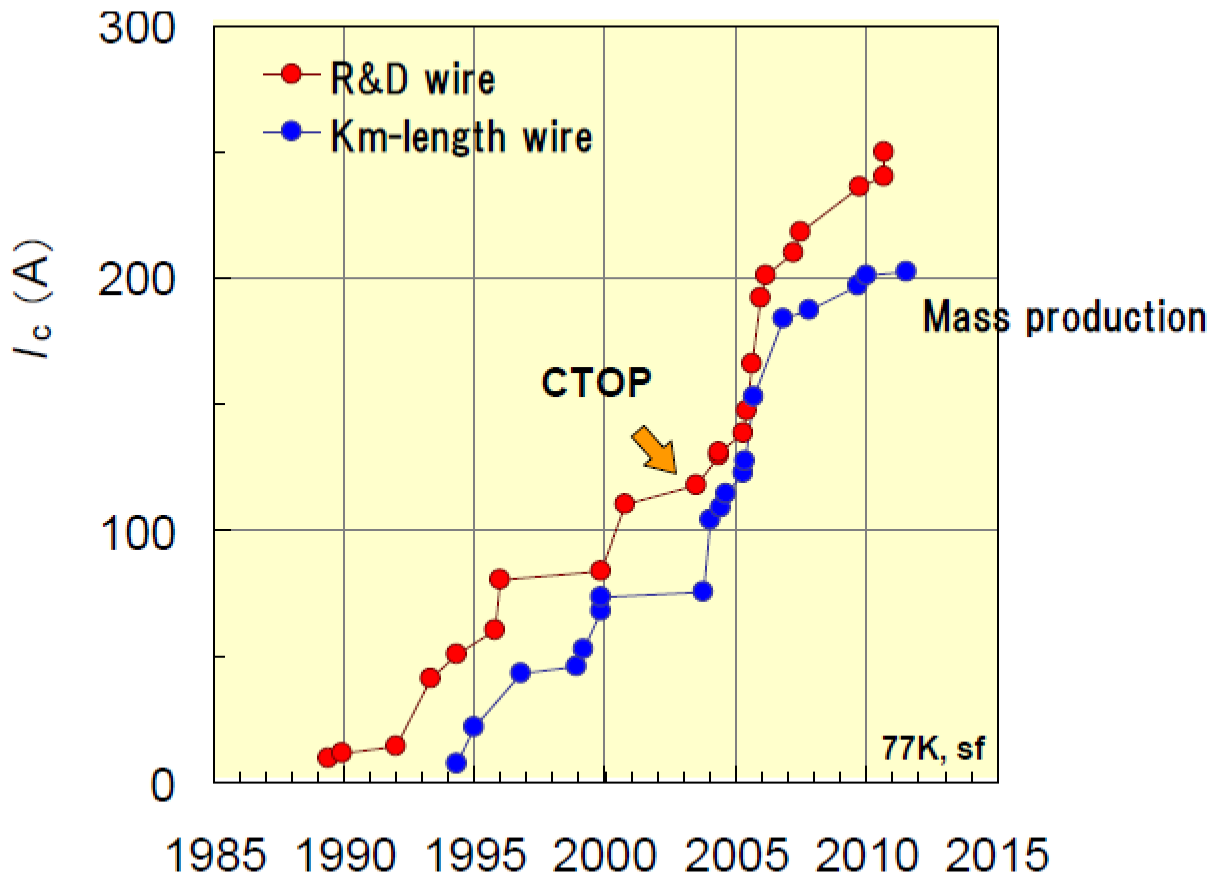
Schematic of powder-in-tube (PIT) method for fabricating Bi-2223 wires



Ag sheathed Bi2223 tapes produced with CT-OP (Over Pressure) ~30MPa



Bi-2223 Tapes (Sumitomo)



CTOP: Controlled Over Pressure Process

200 A over 1000 m tape has been attained

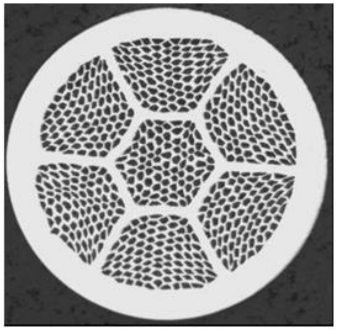
The system Bi-2212

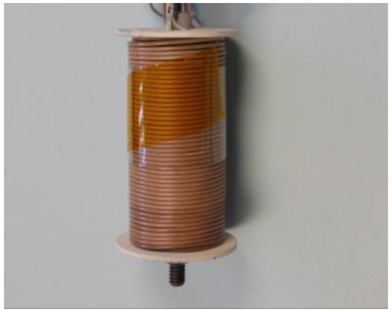
Possible applications	High field magnets	34 T (31T+3T insert)
	Accelerator magnets??	

Advantage: Round wire, but * I_c still low
* mechanically weak

Main research units: Oxford Instruments
Northwest Institute for Nonferrous Metal Research (NIN)

Round Bi-2212 wires

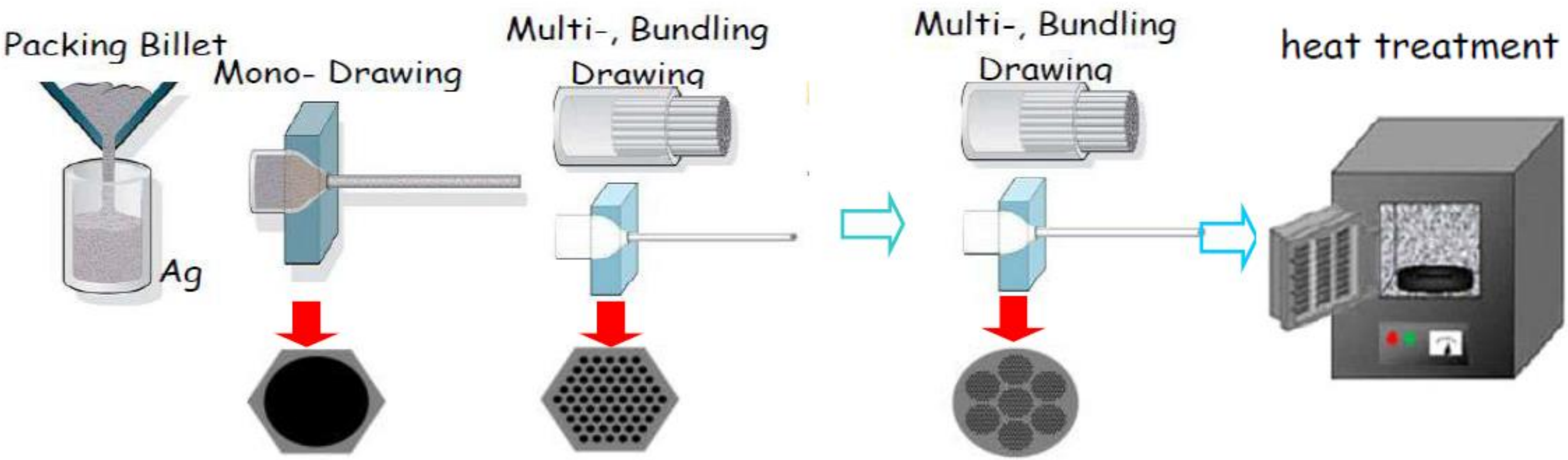


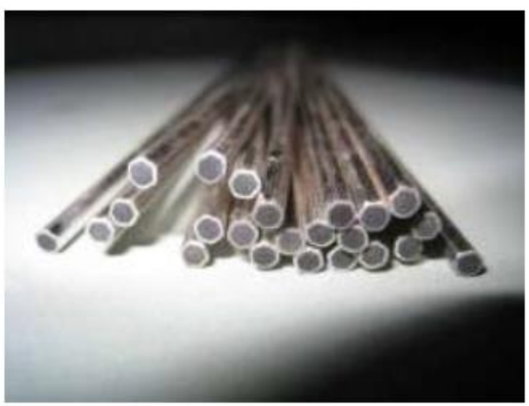


Larbalestier et al. Nature Mater., 2014, 13: 375

34T (in 31T)

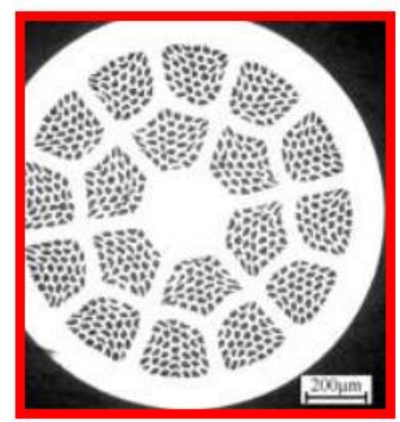
Fabrication of Bi-2212 with PIT





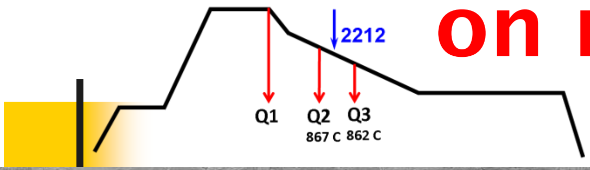
Single filament

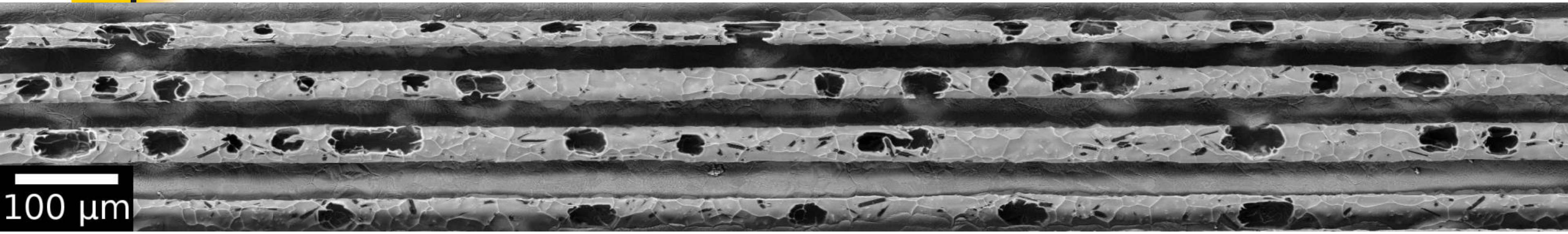
Bundling of
multifilament wire

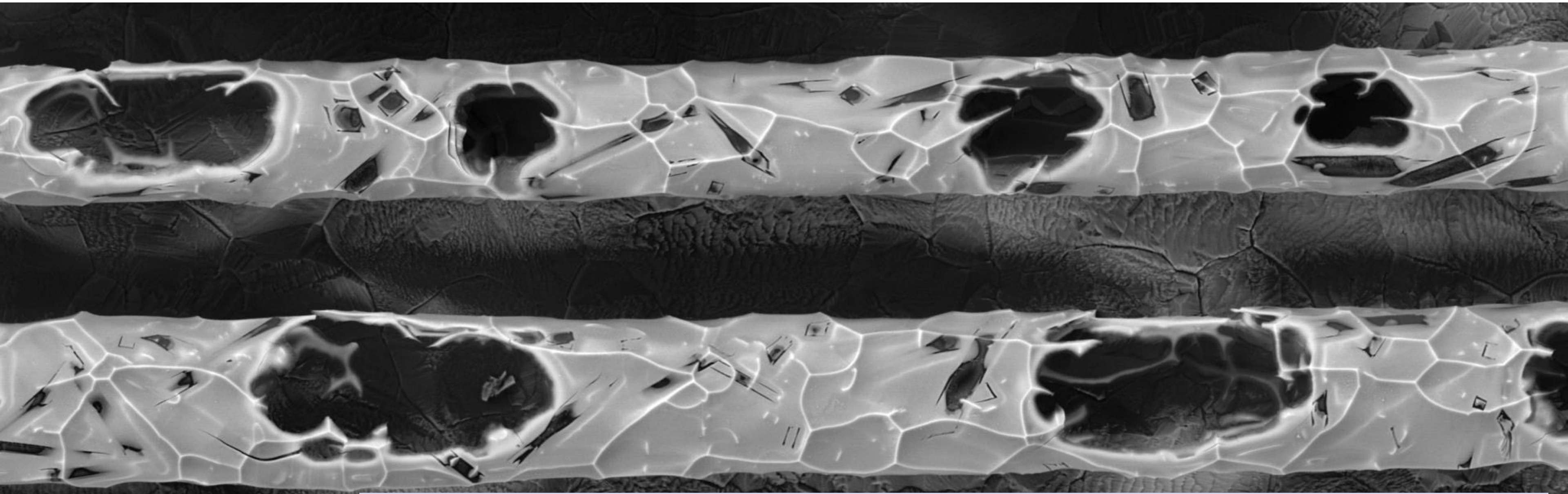


Microstructure
of Final wires

Quench1: Large bubbles form on melting and holding at T_{max}

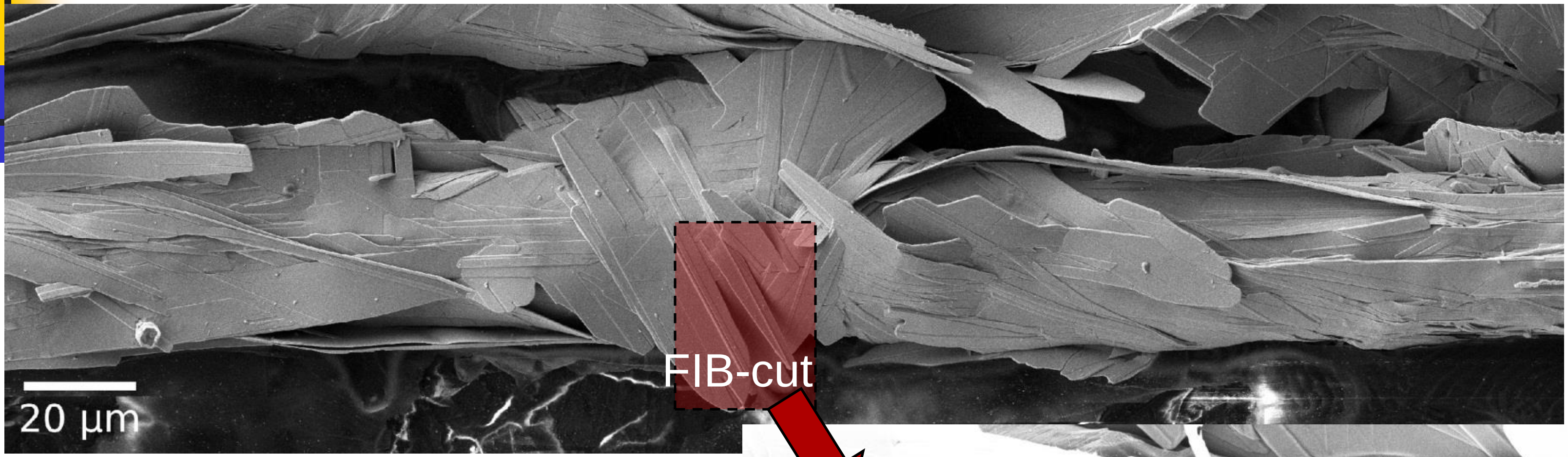


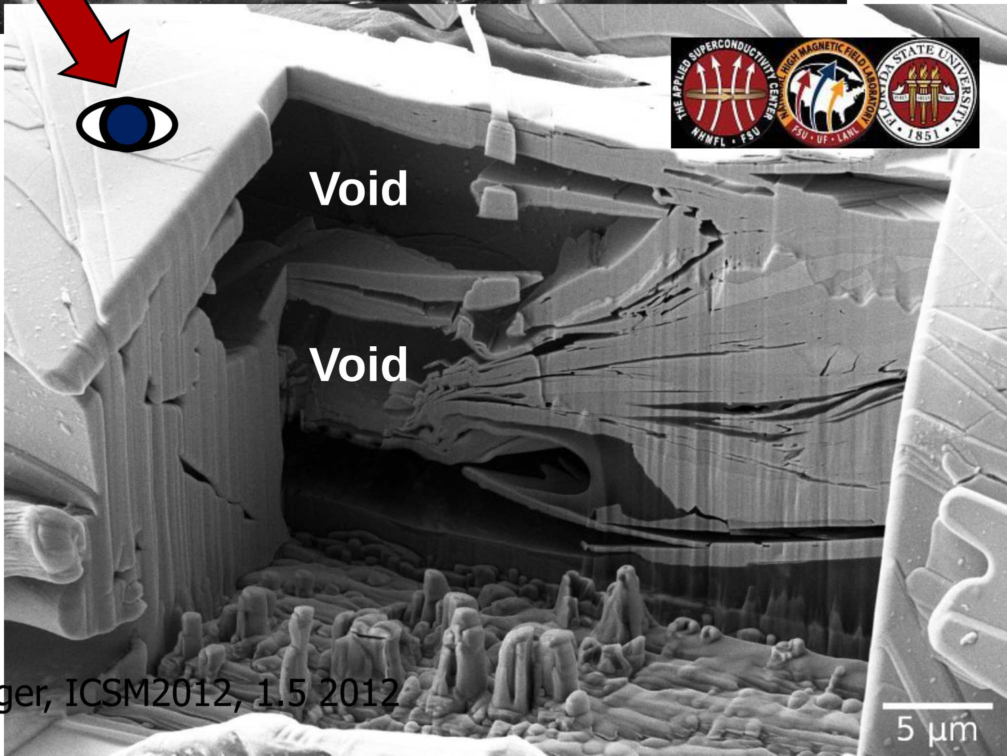




Malagoli et al, SuST, 24, 075016 (2011), Kametani et al, SuST 24, 075009 (2011), Jiang et al. SuST 24 082001 (2011), Scheuerlein eta al, SuST 24, 115004 (2011)..

Large voids in filaments block current in fully-processed wire





Bubbles can be partially filled on resolidification and 2212 reformation – but many voids remain

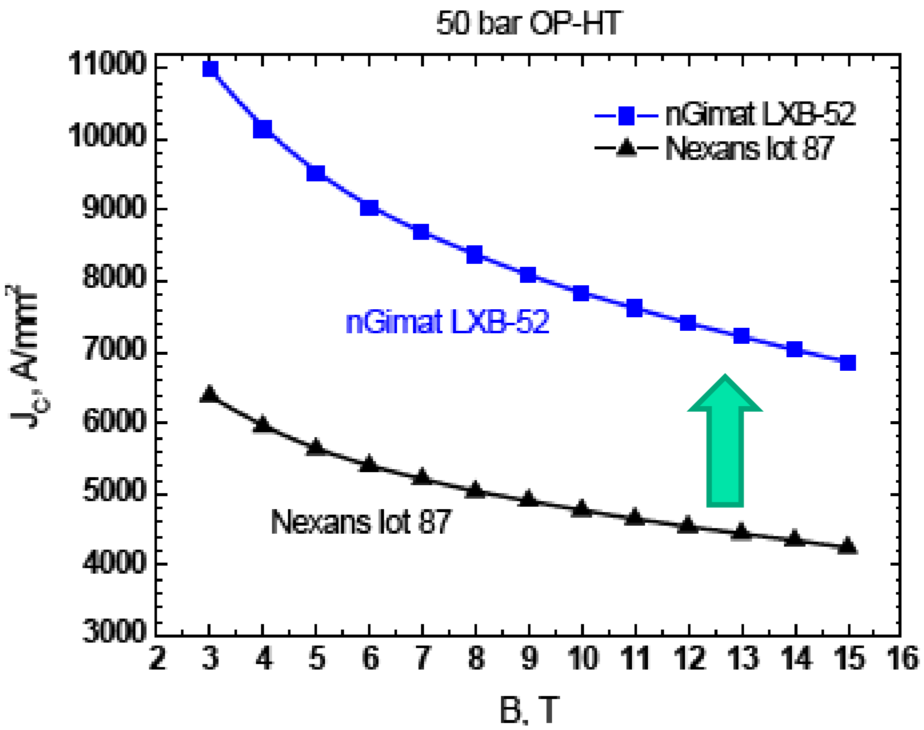
Variation of void density is a major part of the wire Jc variation

Kametani et al, SuST 24, 075009 (2011).

Flükiger, ICSM2012, 1.5 2012

Bi2212 research in NHMFL

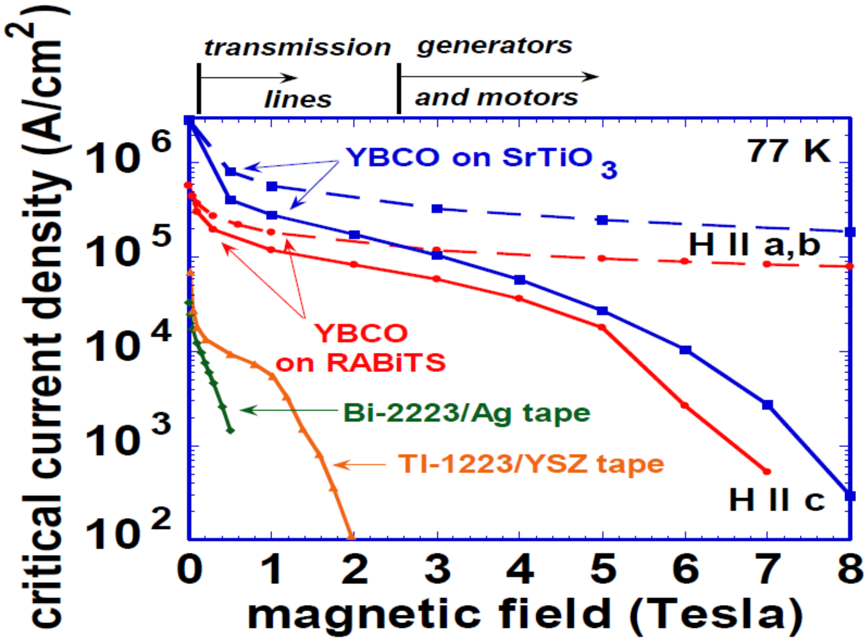
nGimat: Spray pyrolysis→ high quality powder→ improved Je



Short wire: I_C(4.2K, 15T) = 658 A, J_E(4.2K, 15T) = 1365A/mm^2, J_C(4.2K, 15T) = 6860 A/mm^2

The system YBCO
-- coated conductors (SG)

Excellent performance in magnetic fields at 77K (liquid nitrogen), and has broad prospects for power application



Applications at 77 K:

Cables

Generators

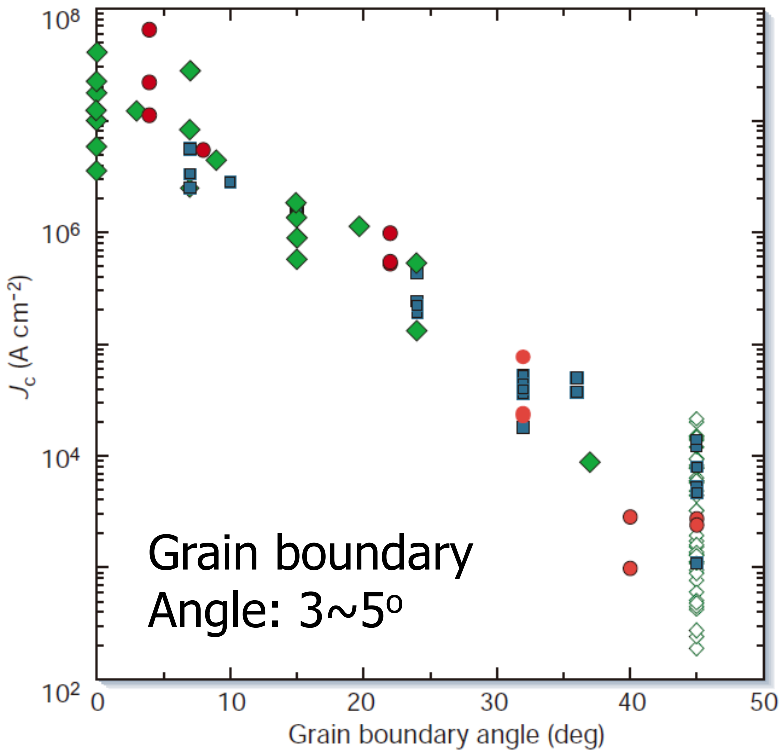
Motors

Transformers

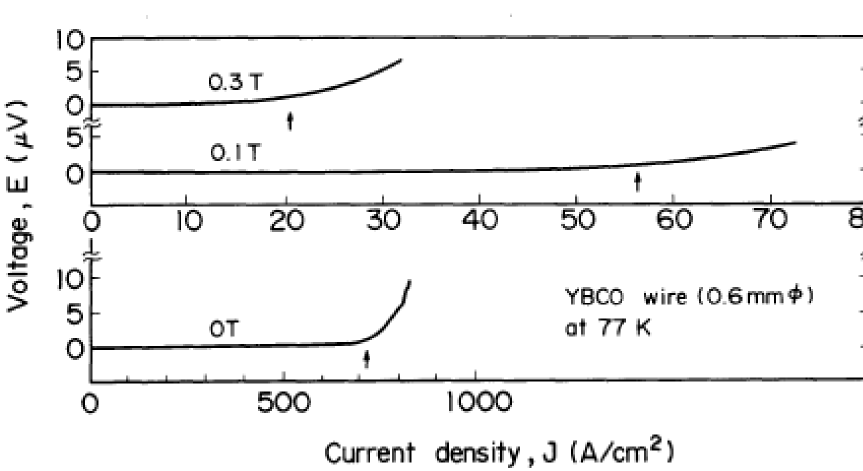
Wind generators

YBCO conductors must contain GBs, having serious weak-linked behavior

GB (Grain Boundary) angle vs Jc



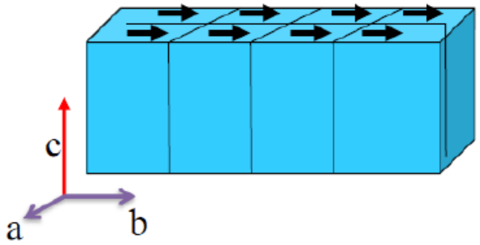
Dimos et al., PRB 41 (1991) 4038



Yamada et al., JJAP 26 (1987) L865

The J_c of ***PIT*** YBCO/Ag wires and tapes:
<1000 A/cm^2 (77 K, s.f.)

Many ways lead to REBaCuO coated conductor tapes

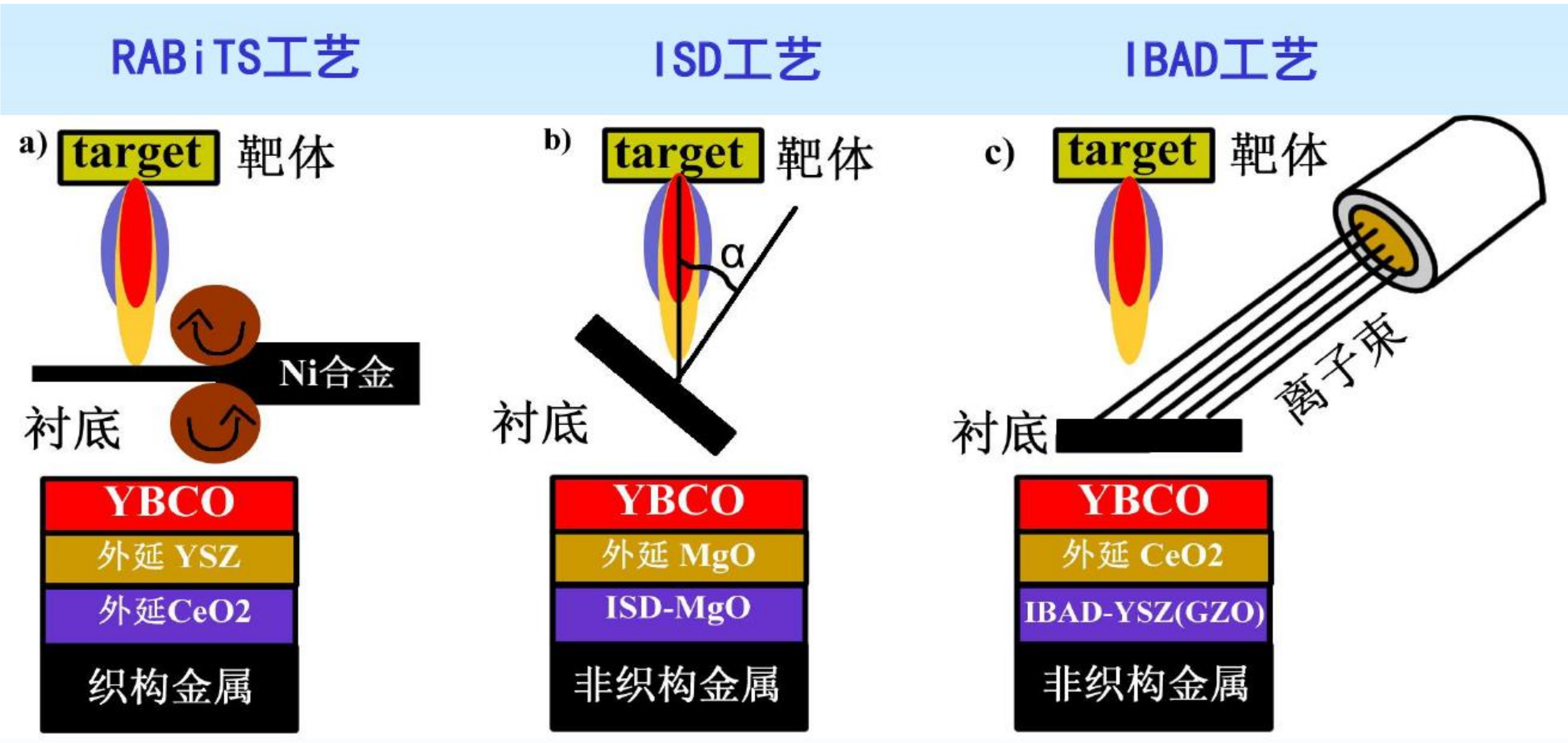


Key technology issues:
biaxial texture and epitaxial growth

Coating with liquid (metal organic deposition,	MOD	(AMSC)
Adsorb vapors (metal organic chemical vapor deposition,	MOCVD	(SuperPower)
Adsorb metal atoms from vacuum (pulsed laser deposition),	PLD	(Bruker, SEI)
(electron beam evaporation):	RCE	(SuNAM)

The main technical route of the second generation YBCO

Biaxial Textured Buffer + Epitaxial YBCO Film

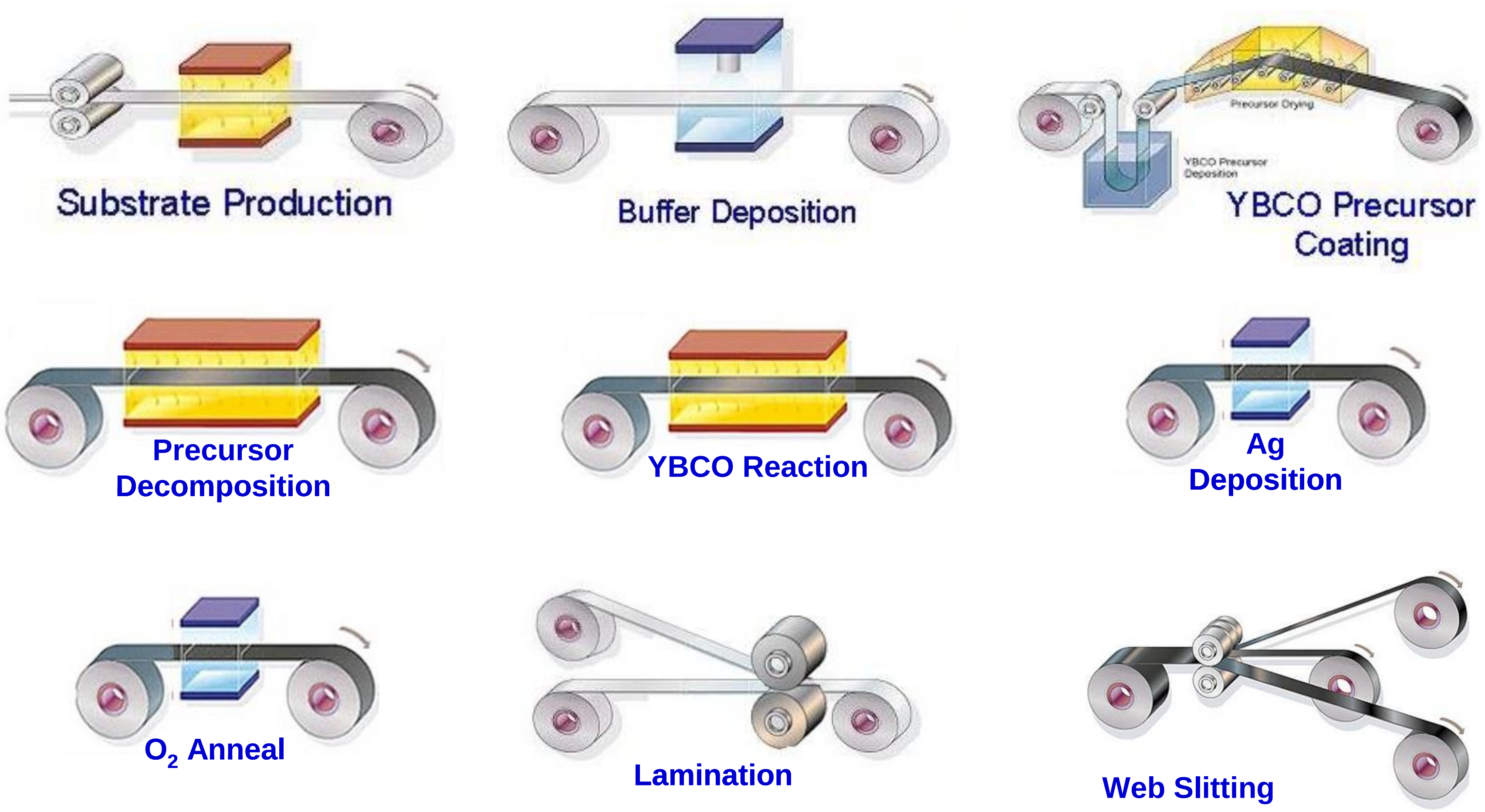


ONL

Fujikura, LANL

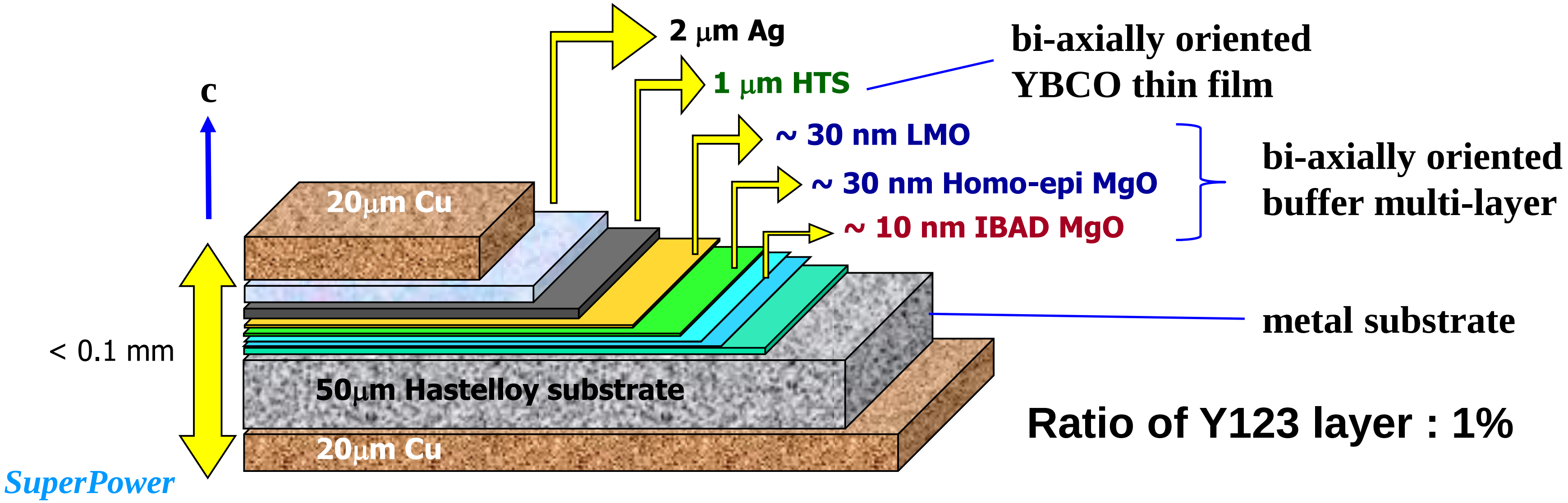
Sumitomo

AMSC YBCO coated conductor MOD Process (RABiTS+MOD)



3 main wok： Substrate + Buffer layer + YBCO → coated conductor

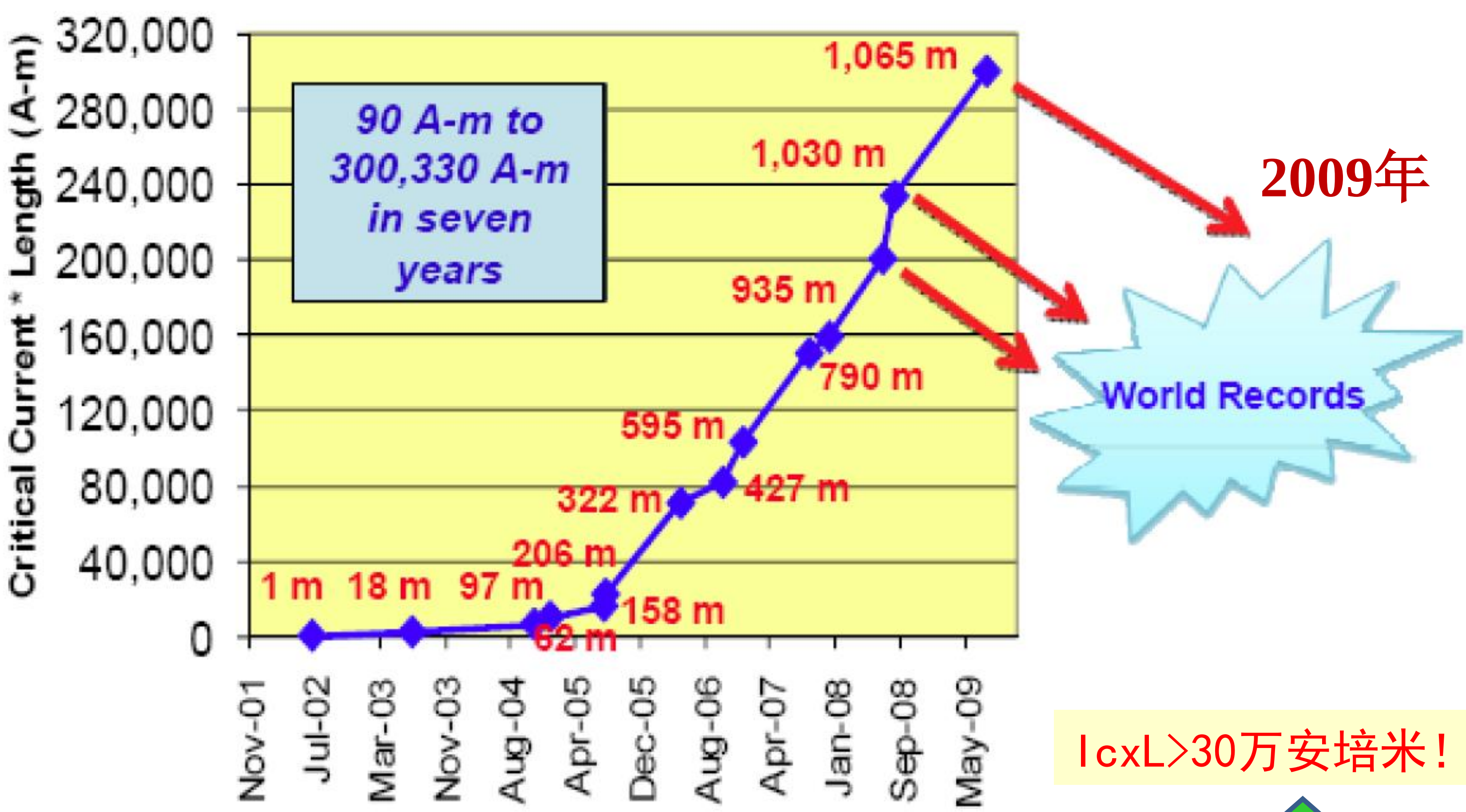
Structure of YBCO tapes



Ratio of Y123 layer : 1%

Increase in thickness and J_c of SC layer

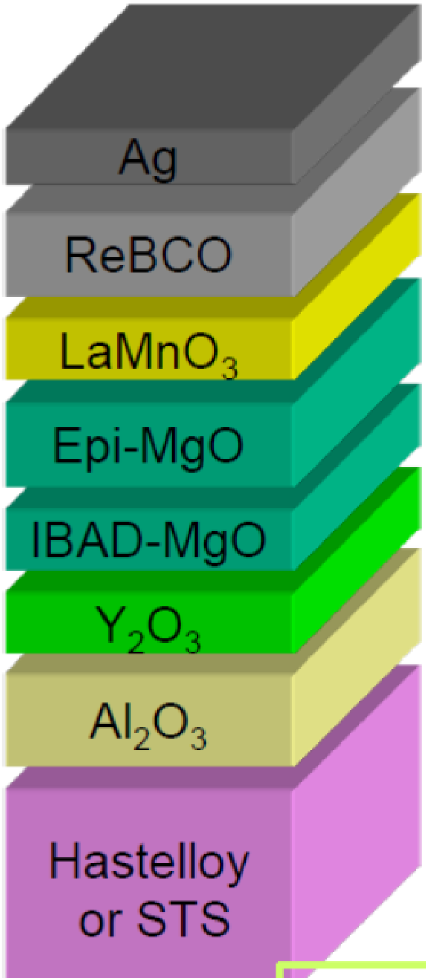
Superpower’s milestone work：1000 m



IcxL>30万安培米！

282A×1065m = 300,330 A-m

SuNAM's 2G Wire Architecture



Protecting layer (0.6 μm) — DC sputter

Superconducting layer (1.2 ~ 1.8 μm) — RCE-DR

Buffer layer ~20 nm — sputter

Homoepi-MgO layer ~ 20 nm

IBAD-MgO layer ~ 10 nm

Seed layer (Y_2O_3)
~ 7 nm

Diffusion barrier (Al_2O_3)
~ 40 nm

IBAD
(sputter &
E-beam)

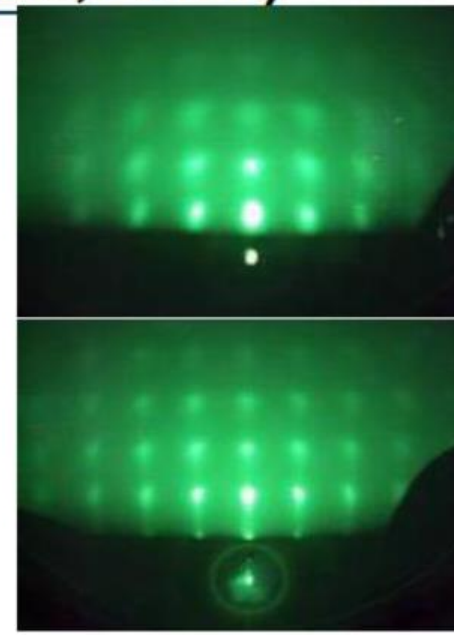
Hastelloy C276 (Ni-alloy tape)
or
SUS-tape

Electro
-polishing

(Not to scale)

- Typical I_c ~ 600 A/12 mm at 77 K self-field (J_c ~ > 4 MA/cm²)

Barrier, Seed, IBAD& Buffer (D&M, 2009)

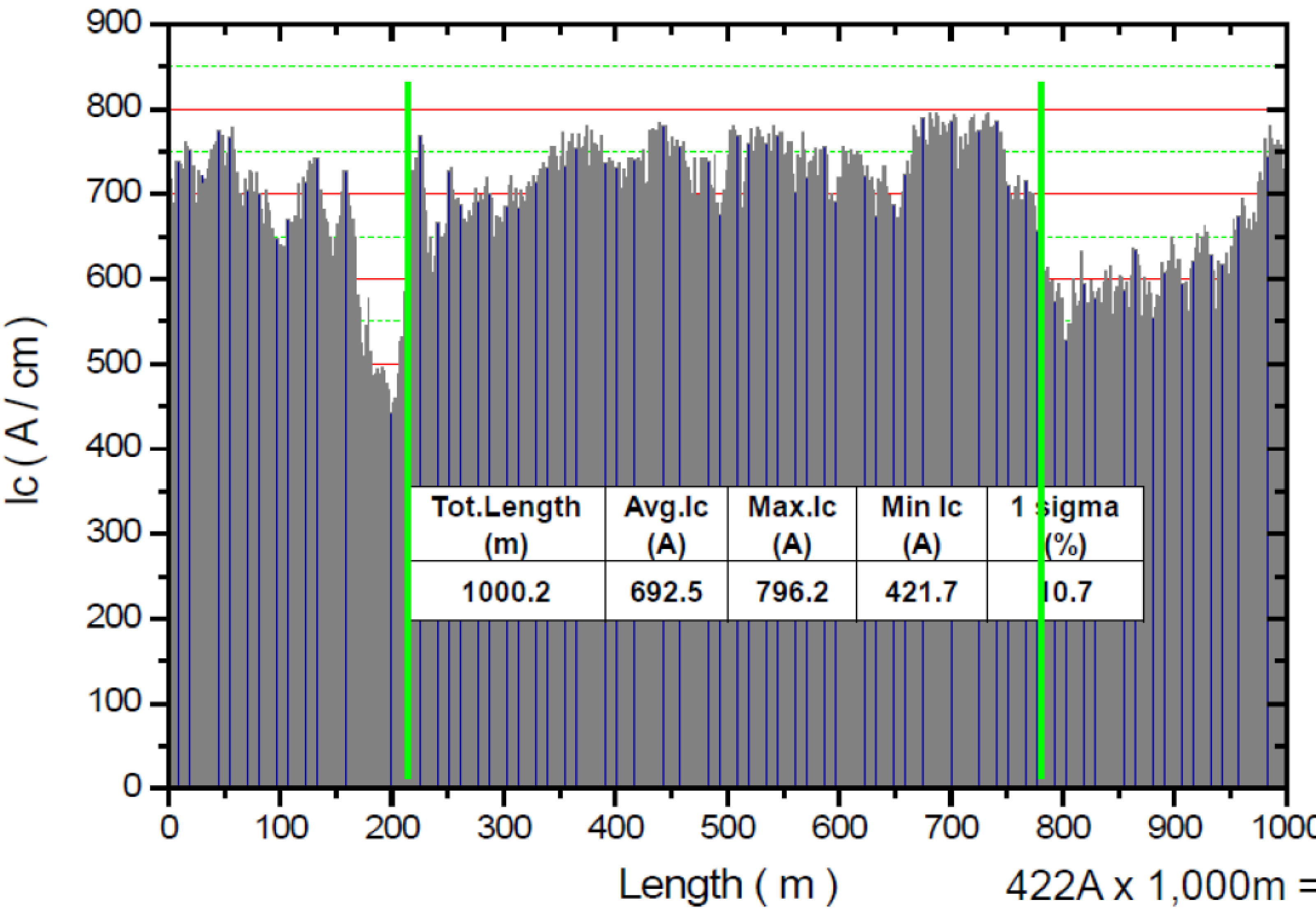


Process Speed

Each Step	R&D system ('08)	Pilot system('09)
Al_2O_3	210 m/hr	600 m/hr (1 system)
Y_2O_3	500 m/hr	
IBAD-MgO	600 m/hr	360 m/hr (1 system) Buffer layer limits the speed.
Homo-epi MgO	~ 70 m/hr	
LMO buffer	~50 m/hr	

* 4 mm width equivalent.

RCE – DR Results on Hastelloy substrate (2012. 01)

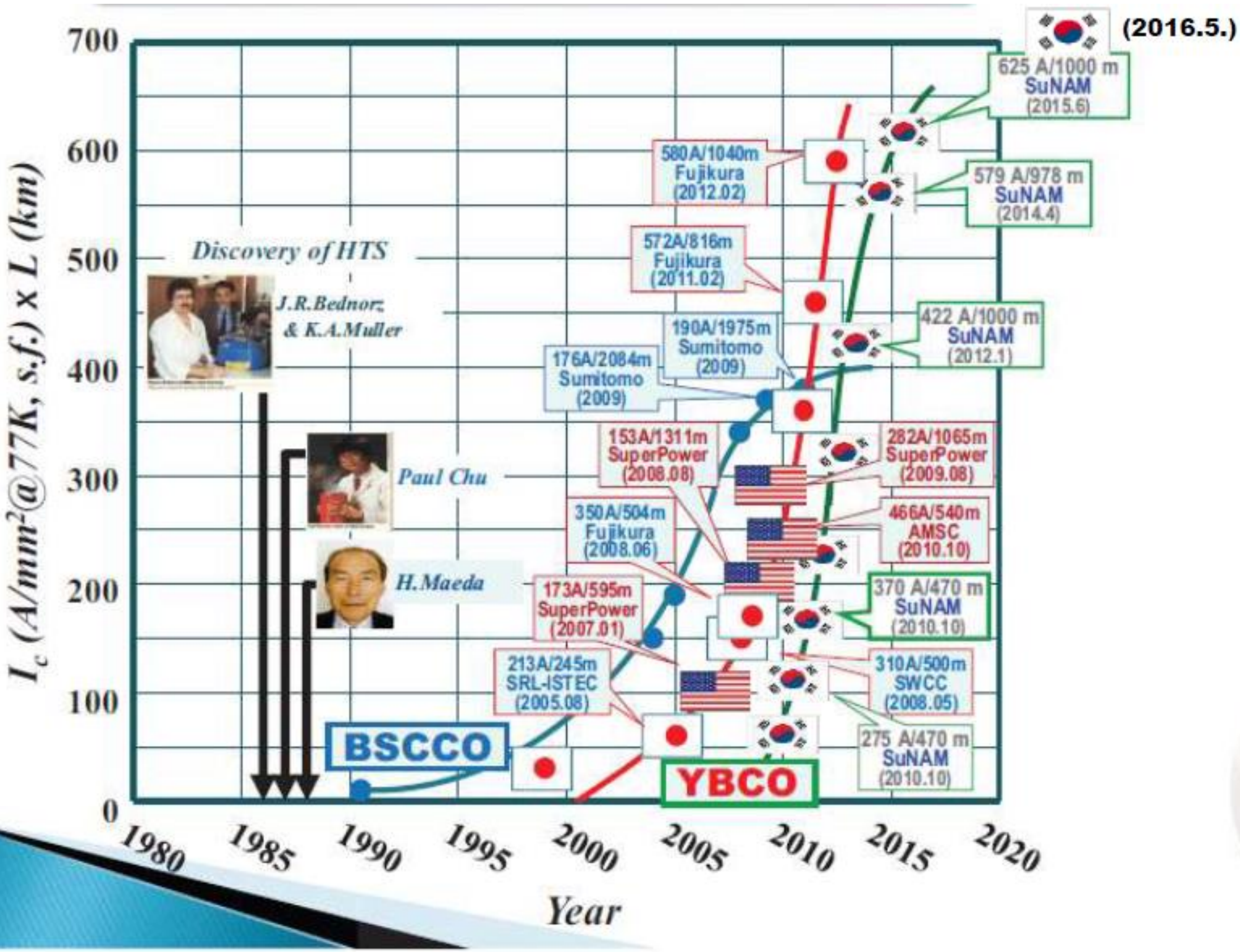


Tot.Length (m)	Avg.Ic (A)	Max.Ic (A)	Min Ic (A)	1 sigma (%)
1000.2	692.5	796.2	421.7	10.7

Ic x L :

422A x 1,000m =421,700

Progress in the development of long length manufacturing of coated conductors



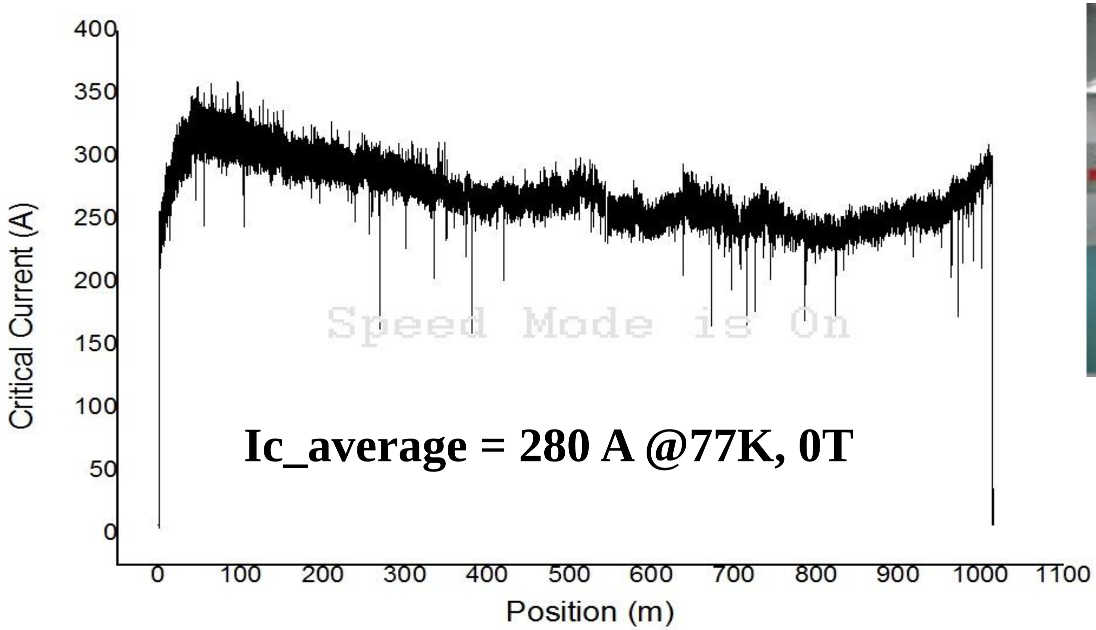
Research groups of 2G HTS tapes in China

R2R: Reel-to-reel system for the fabrication of long tape

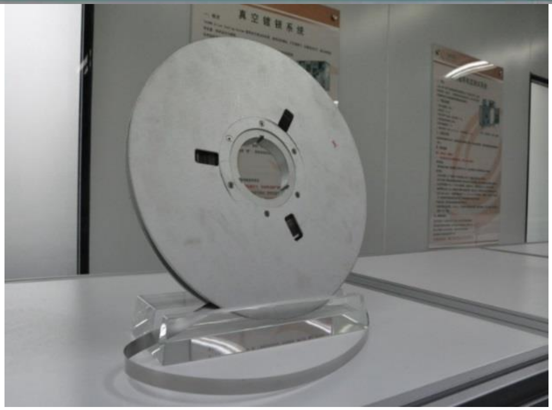
Enterprises and Institutions	Buffer layer		YBCO layer		
	On textured NiW	On untextured tape via IBAD	MOCVD	PLD	MOD
Tsinghua清华	√	√			√
BJTU北工大	R2R				√
NINM/XTU西北有色院/西安理工	√				√
SWJT西南交大	√				R2R
JLU吉林大学			√		
CAS中科院	√				√
UEST电子科大	R2R	√	√		
GRINM北京有色院	R2R			R2R	
SJTU-SC 交大-上超	R2R	R2R		R2R	
SHU-SCSC 上大-上创	R2R	R2R			R2R
SAMRI 苏州新材料-永鼎		R2R	R2R		

Long YBCO C.C. by IBAD-MOCVD

@ Suzhou SAMRI



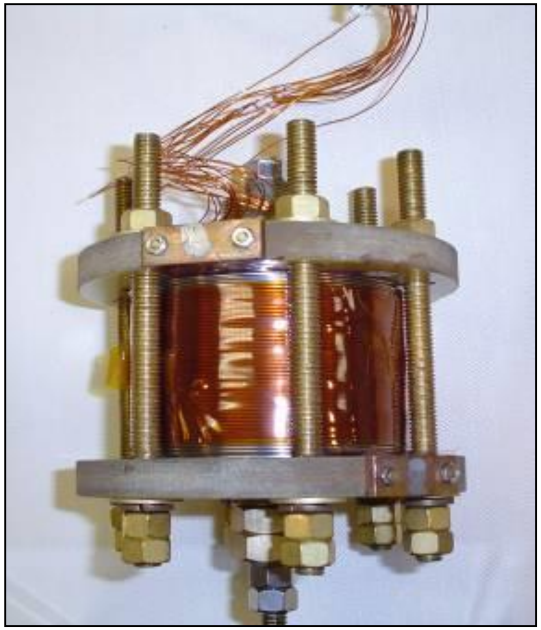
Production rate： 50 -100 m/h



- **1000 meter long YBCO tapes were fabricated by MOCVD, with the width of 12 mm and thickness of YBCO 1-3 μm.**

Applications of high-T_c Cu-oxide superconductors

Ultra high-field magnet ($YBa_2Cu_3O_x$ coil)

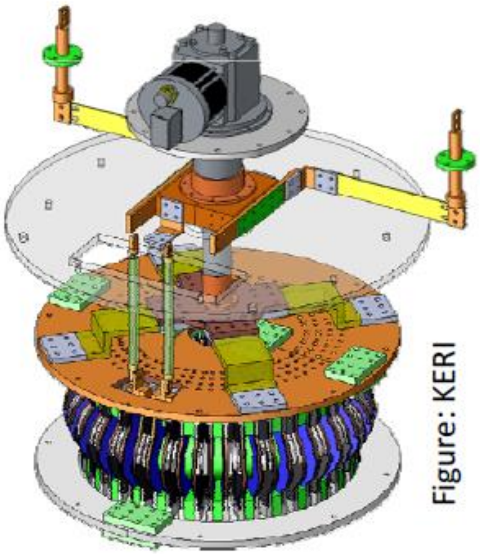


APL, 2011, 99: 202506

World record:
35.4T achieved @ 4.2K, 31 T

Utilizing 100 m of SuperPower SCS4050-AP wire, with minimum Ic value of 100A; fabricated and tested by NHMFL

SMES-YBCO



2.5 MJ
YBCO tape, 22 km
550 A
20 K conduction cooled
B_{maxII} 6.24 T
Test in 2011

Key Issues for YBCO Coated Conductors

Industrial limitation factors: * Costs

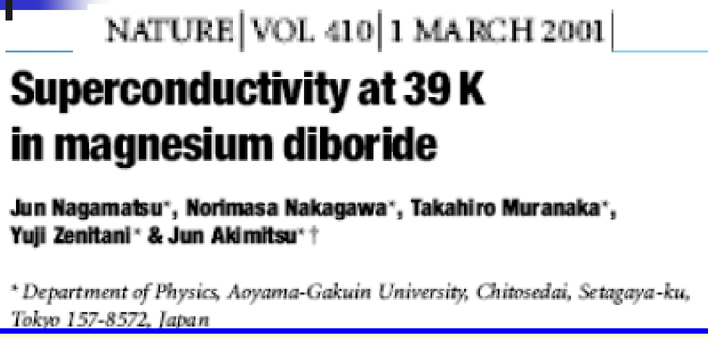
In power equipment, Cu wires typically operate in the range of $15–25/kAm. This sets a benchmark for superconducting wire.

To improve performance, and reduce cost

- **Increased thickness of YBCO layer**
- **Enhanced flux pinning via doping**

MgB_2 wires and tapes

MgB_2 – Magnesium diboride

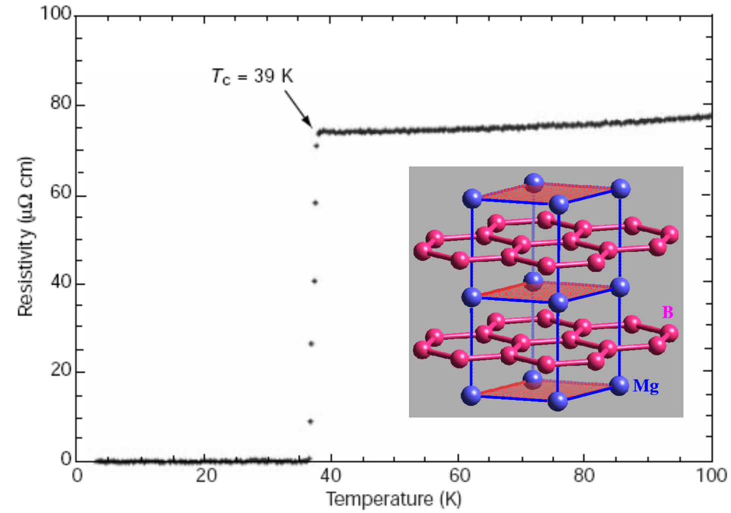

NATURE | VOL 410 | 1 MARCH 2001

Superconductivity at 39 K in magnesium diboride

Jun Nagamatsu*, Norimasa Nakagawa*, Takahiro Muranaka*, Yuji Zenitani* & Jun Akimitsu*†

* Department of Physics, Aoyama-Gakuin University, Chitosedai, Setagaya-ku, Tokyo 157-8572, Japan

MgB_2 was a well known material since the 1950s and commercially available in 2011!



J. Nagamatsu, et al. , Nature 410 (2001) 63

Advantage of MgB_2

- Highest T_c(~40K) among metallic superconductors
- No grain orientation required
  (Easy to fabricate long tape or wire)
- Low materials cost
- Good mechanical properties
- Light weight material

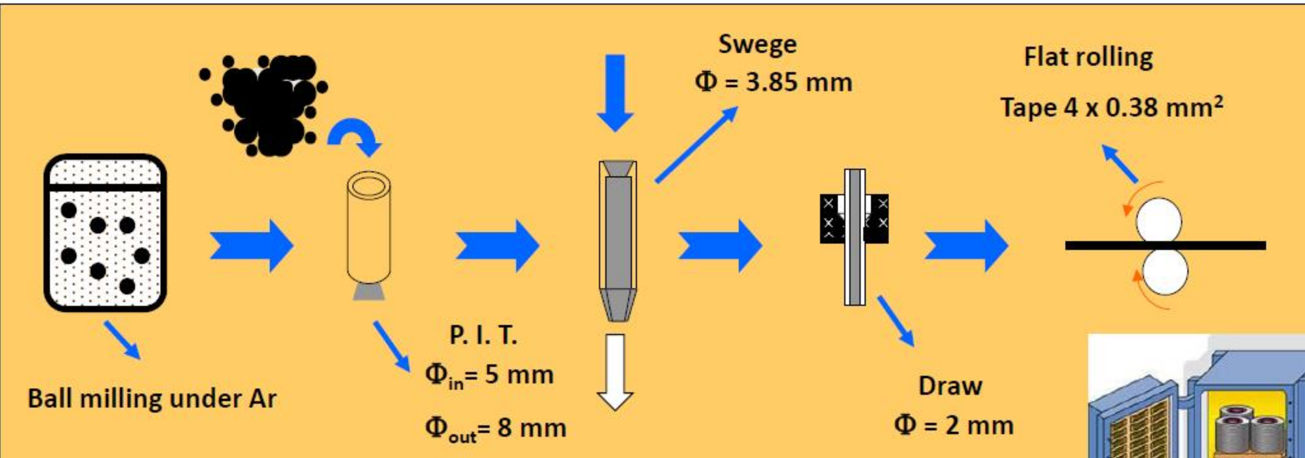
T_c=38 K

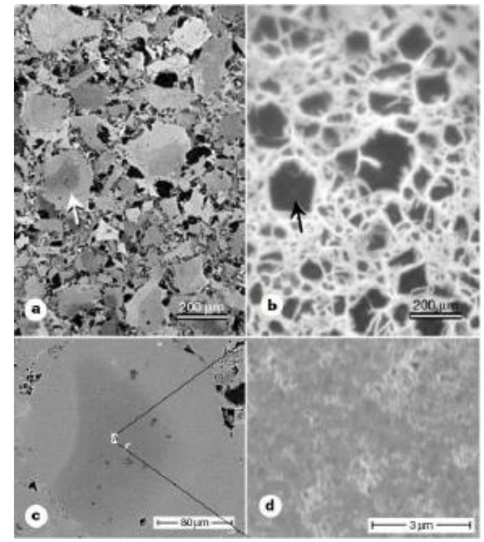
Low H_{c2}

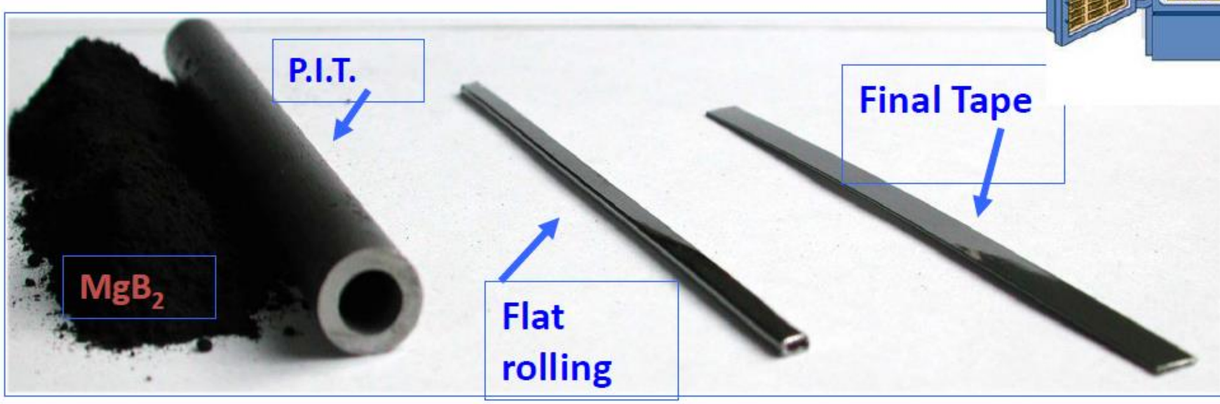
Main Application:

1-2T MRI magnets at 15-20K

Fabrication of MgB_2 wires by the powder-in-tube method (PIT)





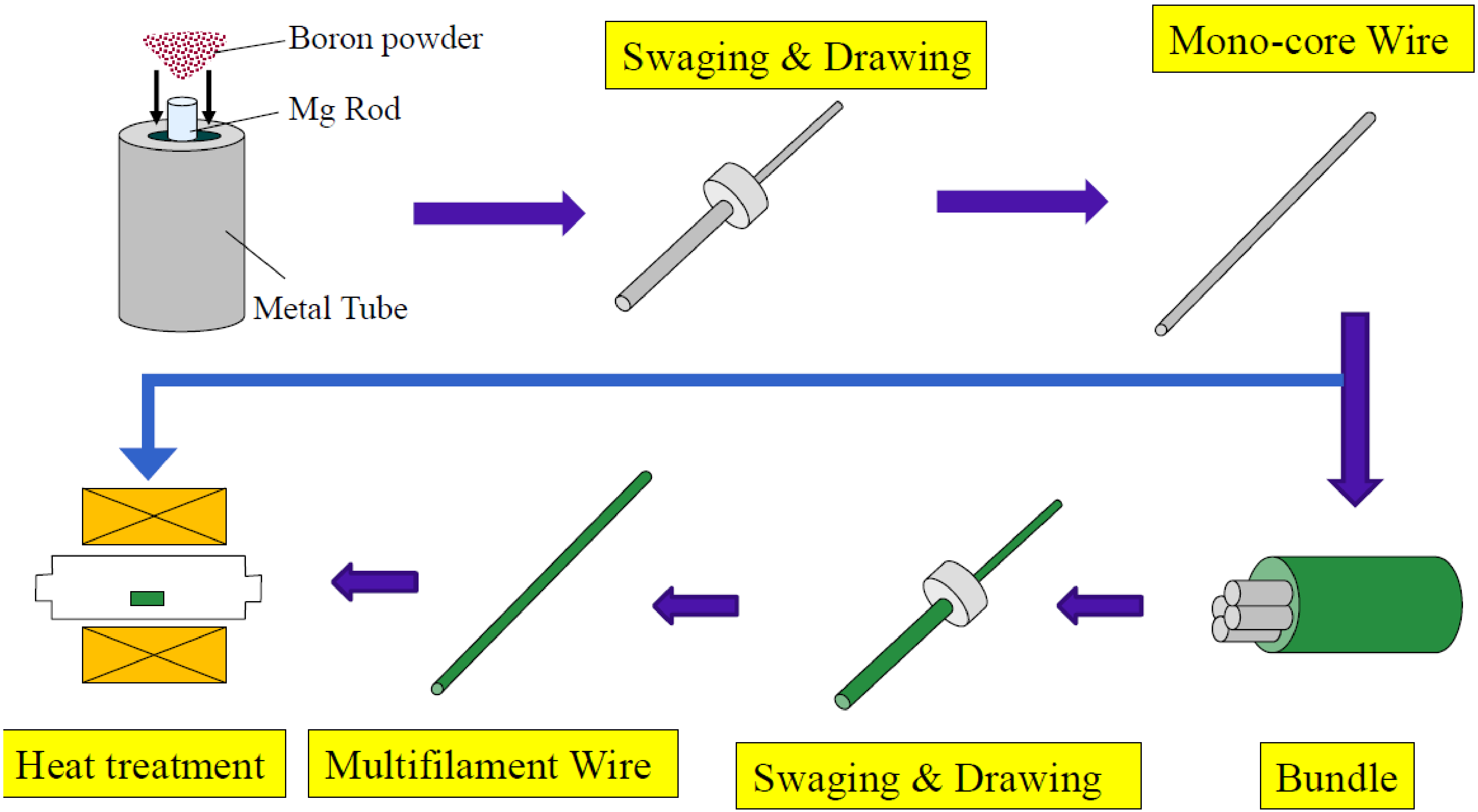


- **No evidence of "weak link"**
- **Coherence length: $\xi \sim$ 10 nm**

Larbalestier, *Nature* **410**, 186 (2001)

MgB_2 wires by internal Mg diffusion process

G. Giunchi et al (EDISON, Italy), Physcia C 401 (2004) 310



Merit: ***Less porosity and better connectivity***

MgB_2: Barrier for applications

The in-field J_c of MgB_2 tapes and wires is still lower because of low upper critical field and poor flux pinning.

How to enhance J_c in MgB_2 wires?

Chemical doping is the most effective way !

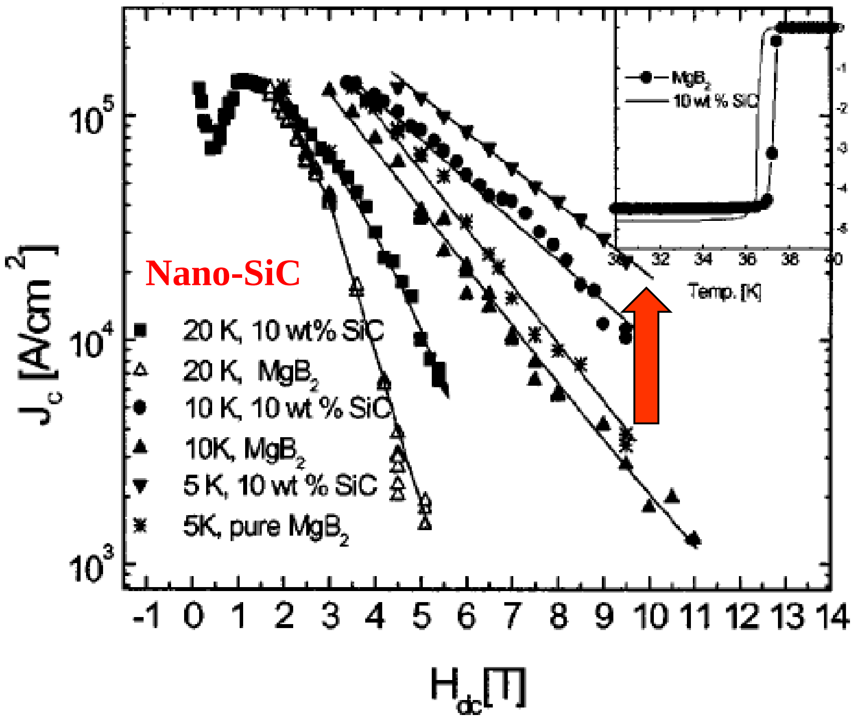
- Increasing H_{c2} with C doping
- Introducing pinning centers with nanopartical addition

Most effective additives are carbon (carbon-containing compounds): SiC, C, carbohydrates, etc.

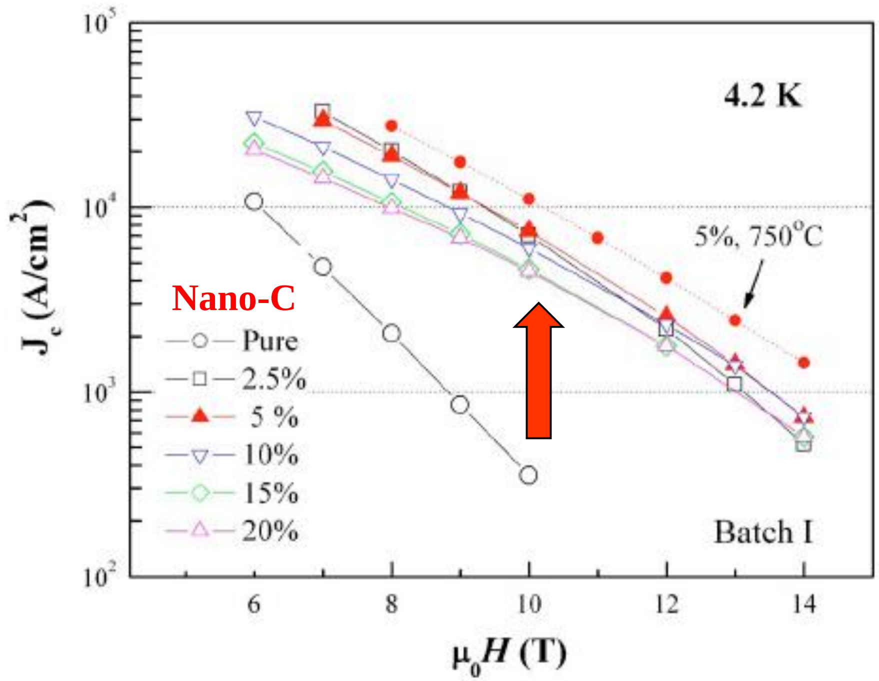
The most effective additives

Nano-SiC or nano-C doping to MgB_2 tapes

-- enhanced by more than an order of magnitude in high fields



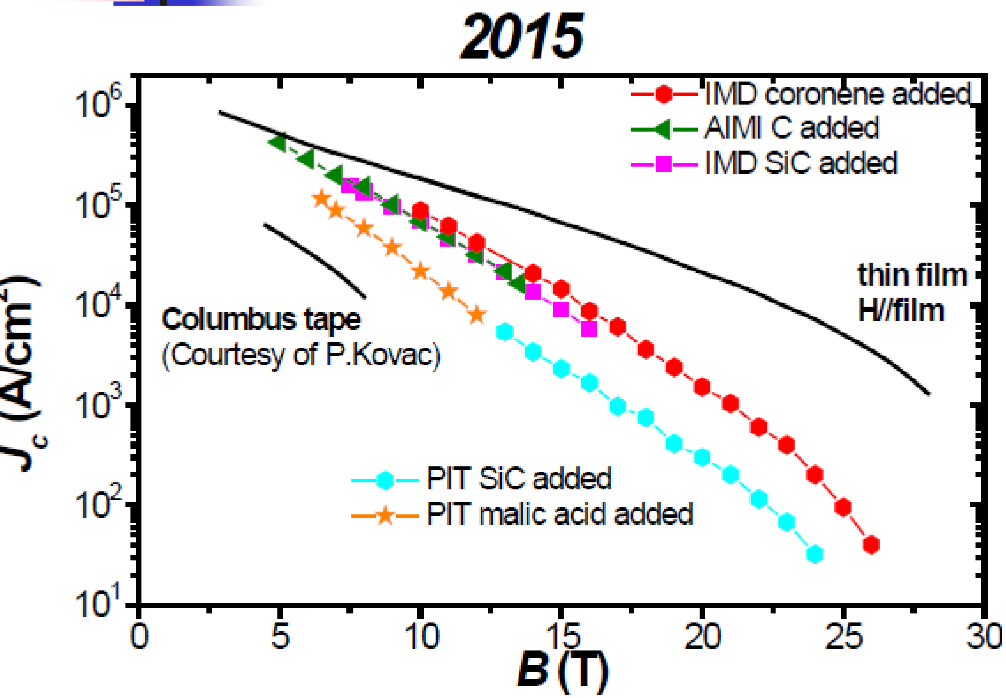
Dou et al. *APL* 81 (2002) 3419



Ma et al. *APL* 88 (2006) 072502

Fine grains in C doped MgB_2 ⟹ Large Jc

Latest critical current density J_c of MgB_2 wires



Putti presented at EUCAS2015

K Togano, et al., SUST **22** (2009) 015003
J.H. Kim , et al., SUST 23 (2010) 075014
G Z Li et al.SUST 26 (2013) 095007
Shu Jun Ye, et al., SUST 27 (2014) 085012

PIT tapes:
J_c= 6×10^4 A/cm^2 (4.2 K, 10 T)

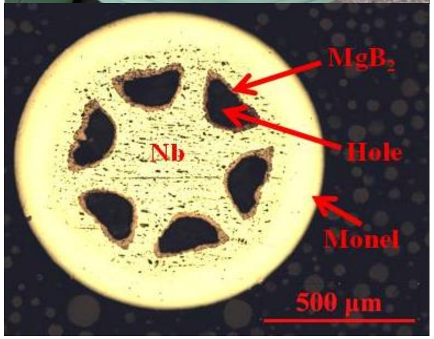
W. Hassler, ***SUST*** 21 (2008) 062001

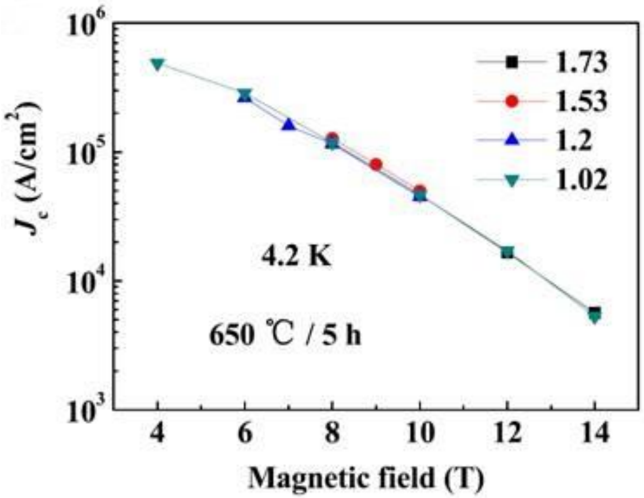
IMD wires:
J_c= 1.5×10^5 A/cm^2 (4.2 K, 10 T)

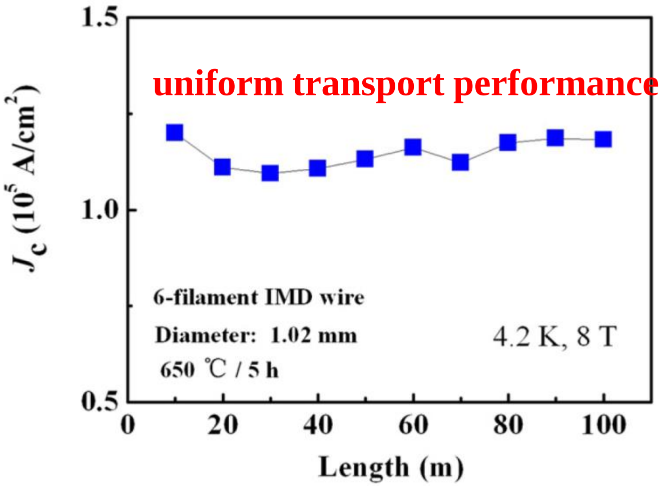
Moving from 1G (PIT) to 2G (IMD) wires

Fabrication of 100 m-class IMD-processed 6-filament MgB_2 wires

-- MgB_2/Monel/Cu





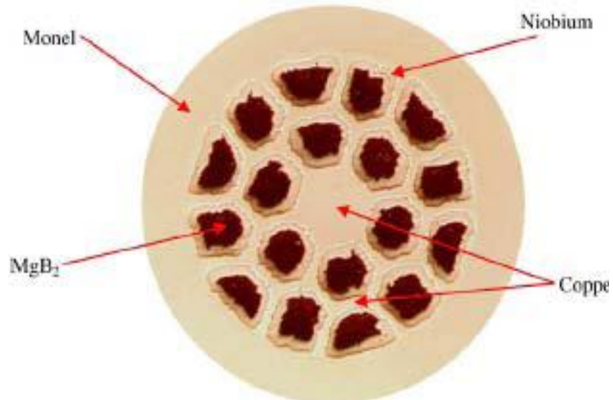


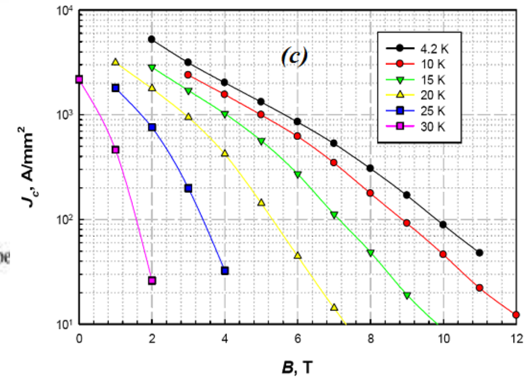
Wang et al., *SuST 29 (2016) 065003*

- A 100-m long 6-filament MgB_2 wire was successfully fabricated using internal magnesium diffusion (IMD) process.
- A layer J_c as high as 1.2×10^5 A/cm^2 at 4.2 K and 8 T was obtained, which was the highest value of the long multifilament IMD wire reported so far.
- *The J_c has a fairly uniform distribution through-out the wire.*

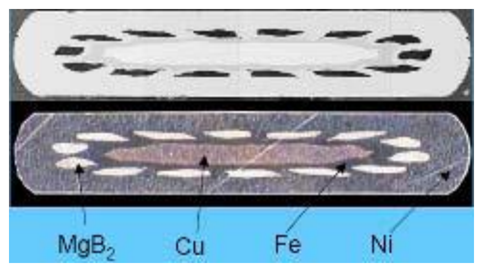
Fabrication of km-level PIT MgB_2 wires

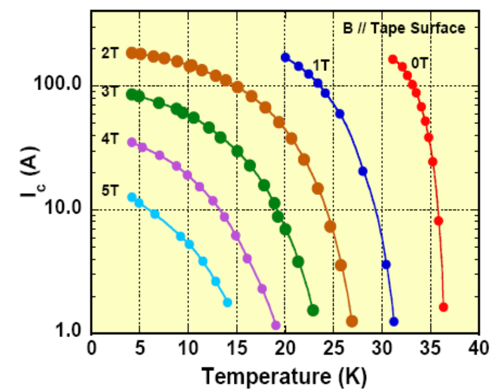
American **Hyper Tech.** Corporation



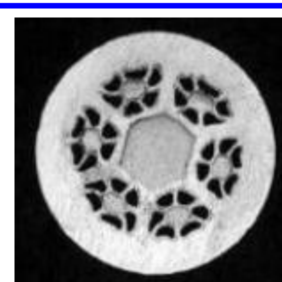


Italy **Columbus Supercon.** Corporation

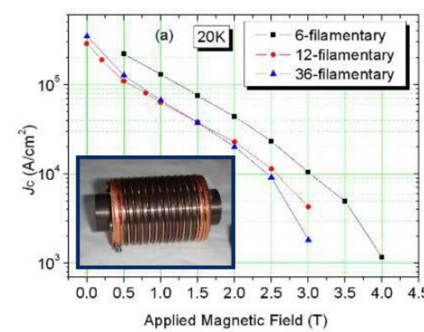




China **Western Superconducting Technologies** Corporation

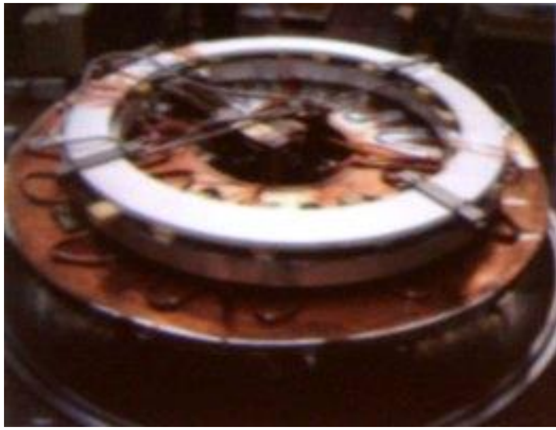


MgB_2/Nb/Cu



Applications of MgB_2 (Open MRI system)

MgB_2 coil



26 magnet systems produced so far

Columbus Superconductors
ASG Superconductors
PARAmed MEDICAL SYSTEMS

Magnetic field : 0.5 ~ 0.6T

Higher Jc of MgB_2 wire is expected!

PARAmed MEDICAL SYSTEMS

Iron-based wires and tapes

Iron-Based Superconductors (IBS)

Februry in 2008

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

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

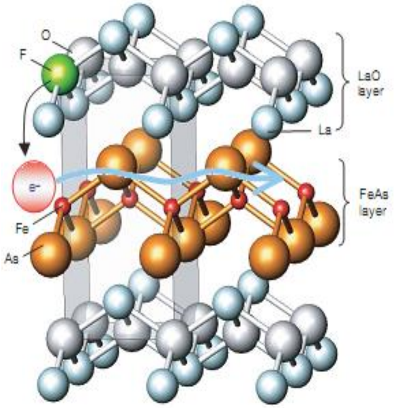
ERATO-SORST, JST, Frontier Research Center, Tokyo Institute of Technology, Mail Box S2-13, Materials and Structures Laboratory, Tokyo Institute of Technology, Mail Box R3-1, and Frontier Research Center, Tokyo Institute of Technology, Mail Box S2-13, 4259 Nagatsuta, Midori-ku, Yokohama 226-8503, Japan

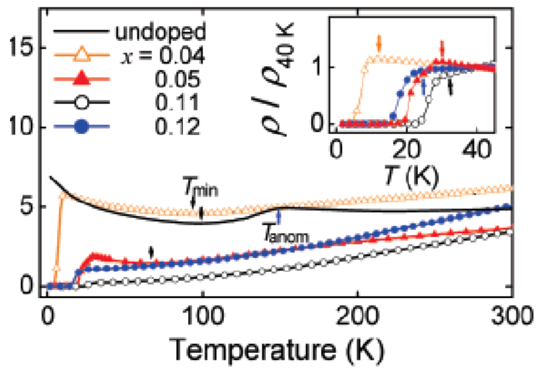
hosono@msl.titech.ac.jp

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 %.

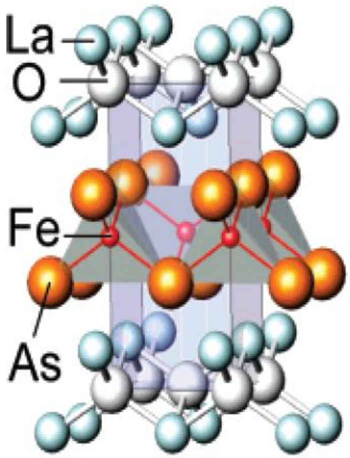




Main known IBS families

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.*

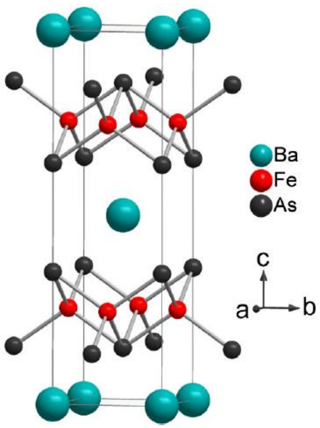
1111 Phase LnOFeAs



T_c ~55 K

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

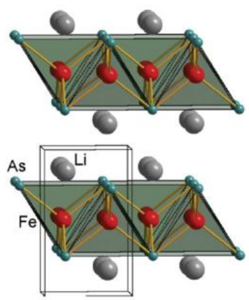
122 phase AFe_2As_2 (A=Ba, Sr, Ca)



T_c ~38 K

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

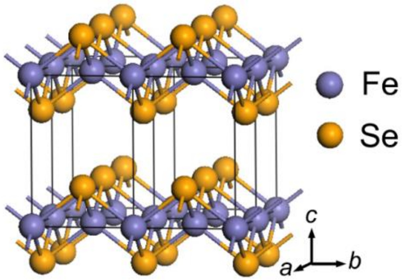
111 phase LiFeAs



T_c ~18 K

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

11 phase FeSe



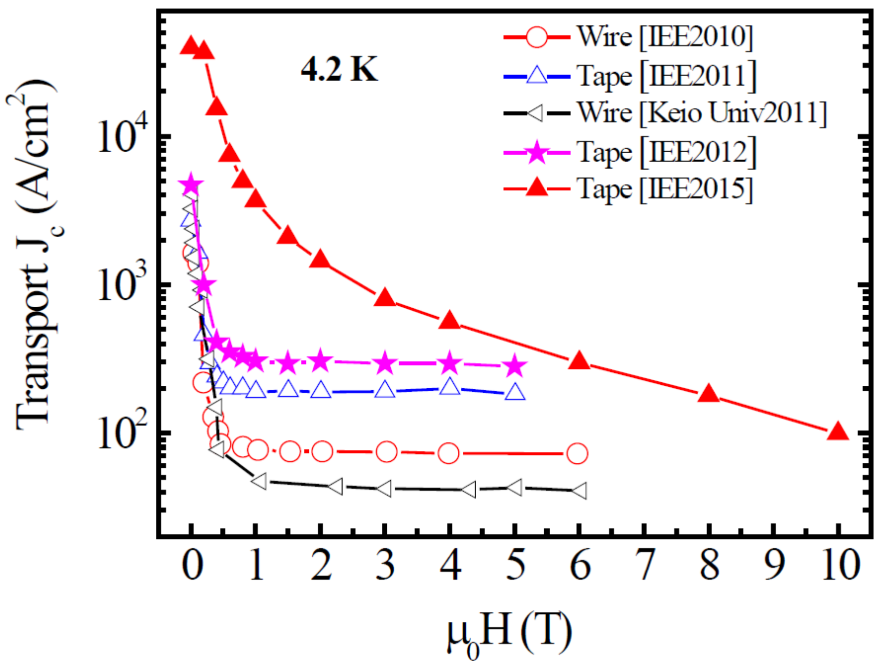
T_c ~8 K

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

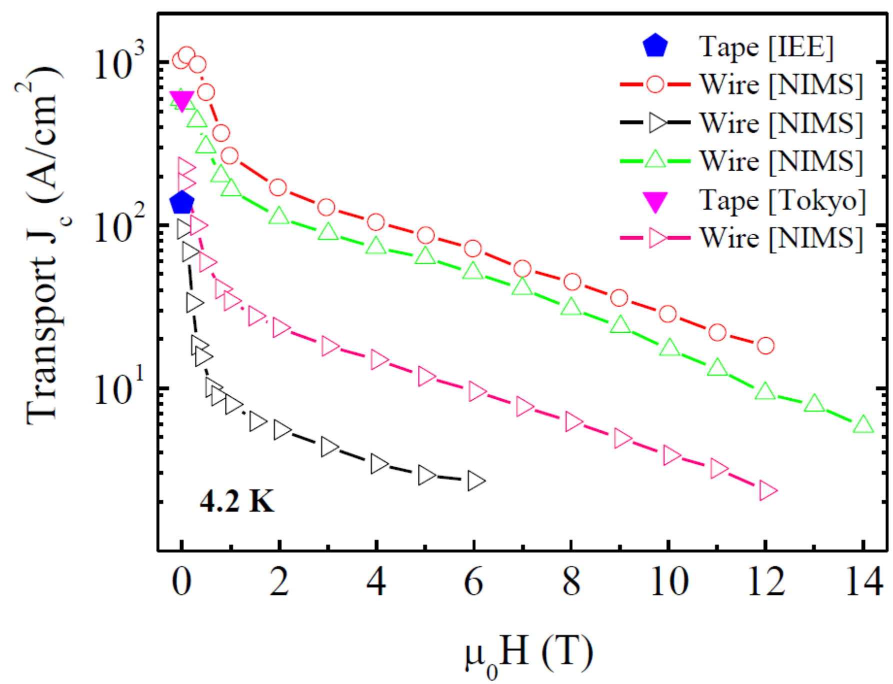
122 tapes showed the highest J_c: 10^5 A/cm^2 @ 10 T, 4.2 K

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

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

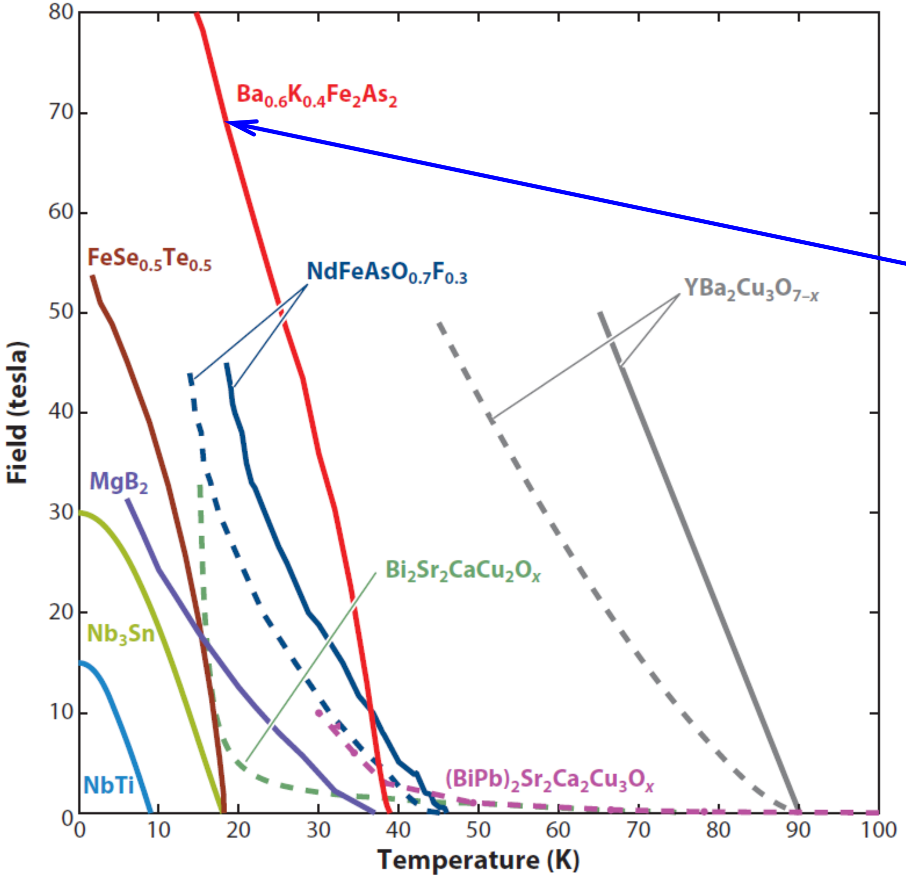


11 type - $FeTe_{1-x}Se_x$



- **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.

The extremely high H_{c2} in IBS



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

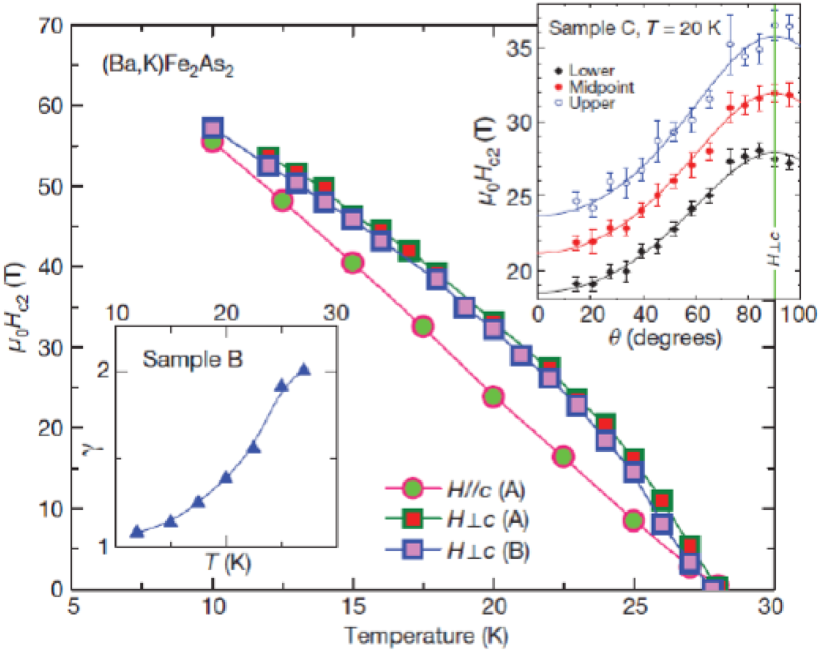
At 20 K, the H_{c2} can be >70 T where IBS outperform both MgB_2 and Bi-2223.

- **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



Yuan et al. Nature 457, 565 (2009)

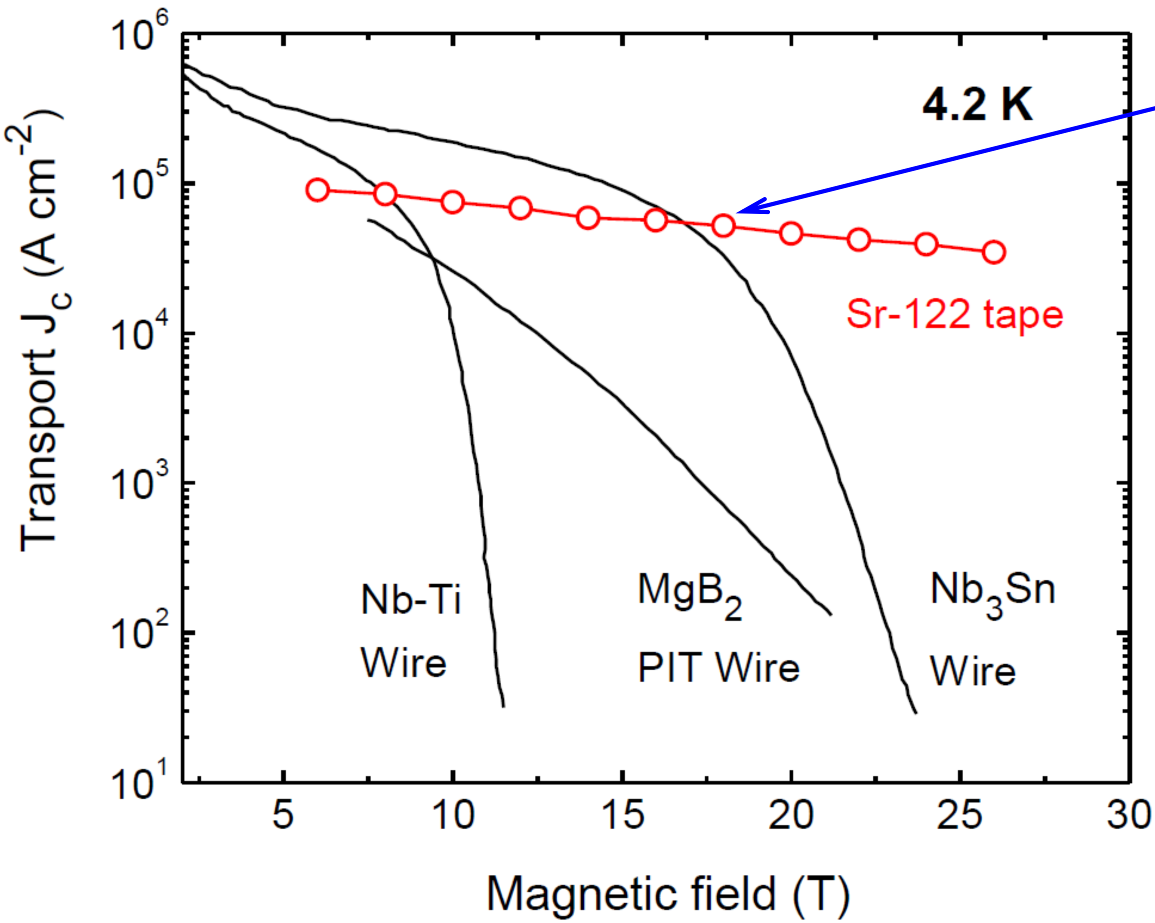
J_c anisotropy

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

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**

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

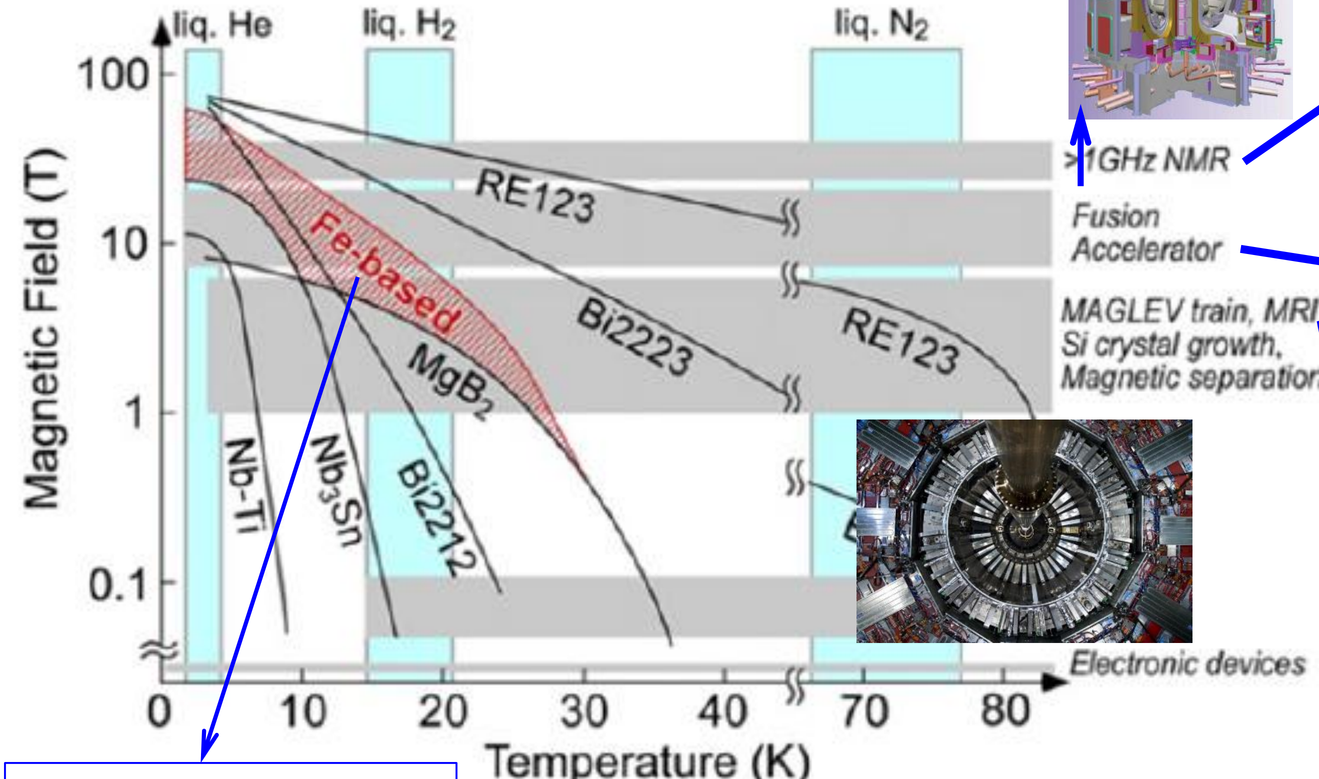


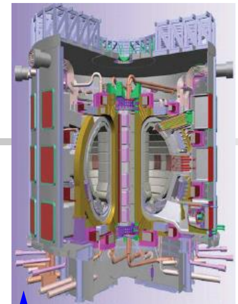
122 IBS wire:

Large J_c, at H > 20T

IBS potential for high-field applications

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





ITER

NMR

Accelerator

MRI

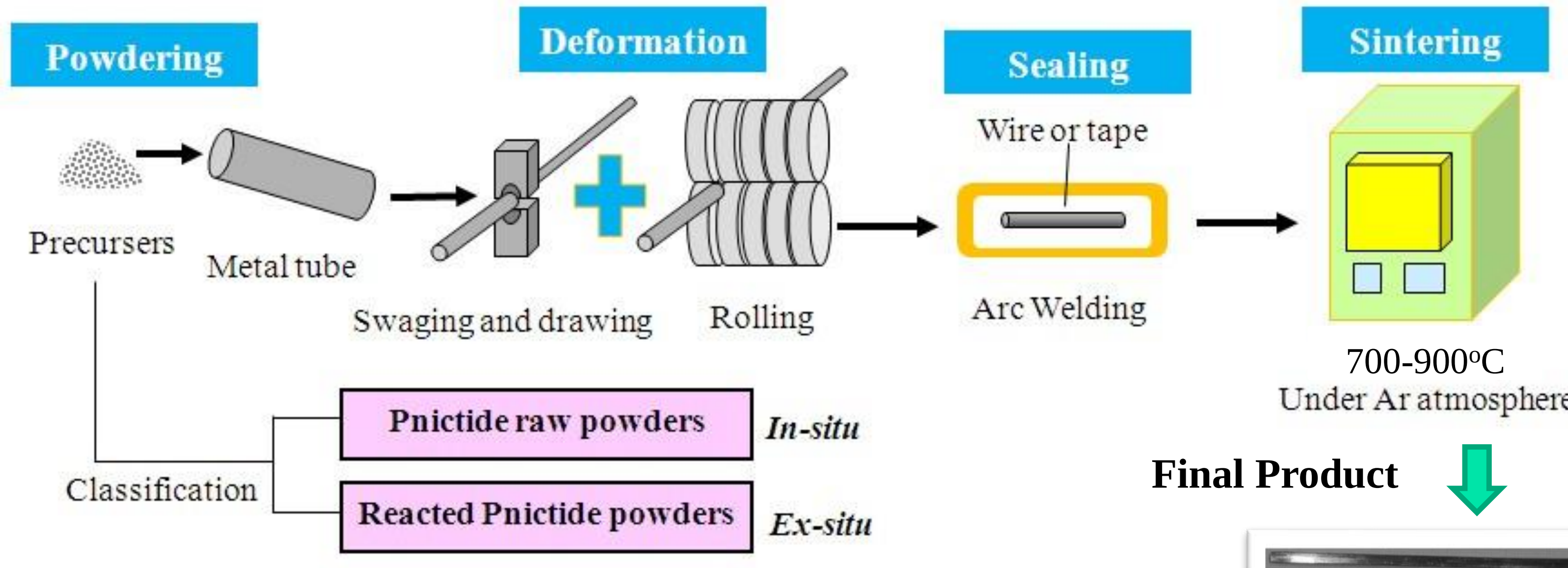
Working Temp:
4.2 K – 30 K

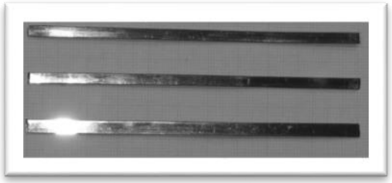
Shimoyama, ***SuST*** 27 (2014) 044002

Development of high-J_c 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





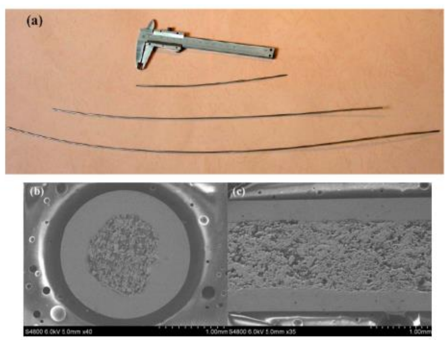
122 PIT wires are expected to be much more cost effective than Bi2223 conductors:

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 Bi2223, Ag is the only material that is inert to the BSCCO superconductor and permeable to oxygen at the annealing temperature.

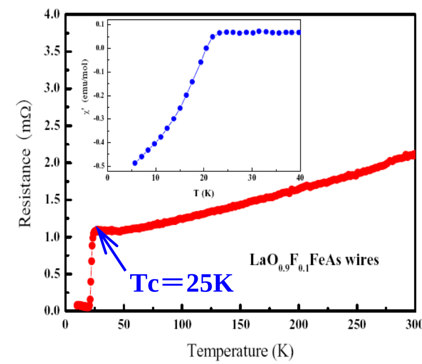
In April 2008, the first pnictide wire was fabricated by the powder-in-tube method

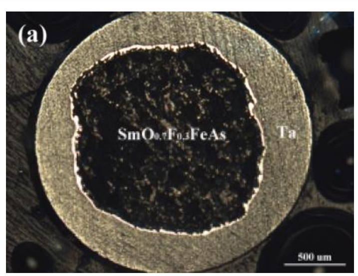
The early wires

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

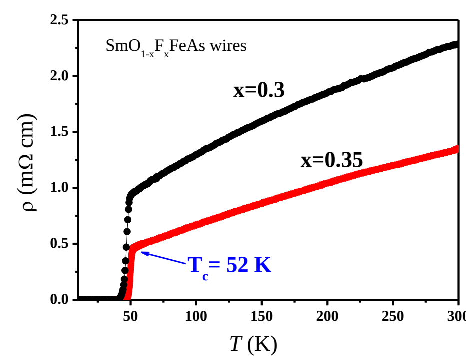


LaOFeAs



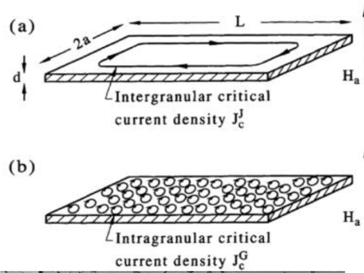


SmOFeAs

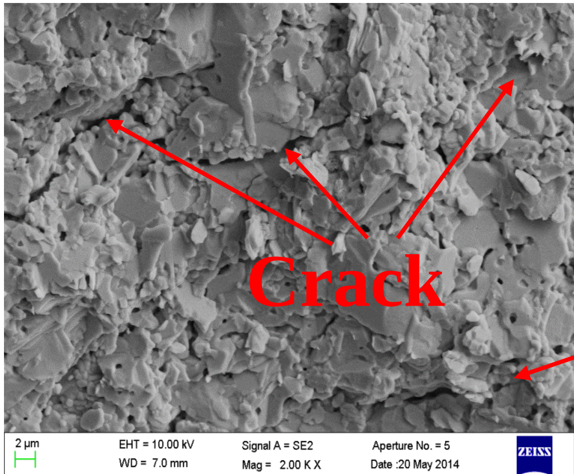


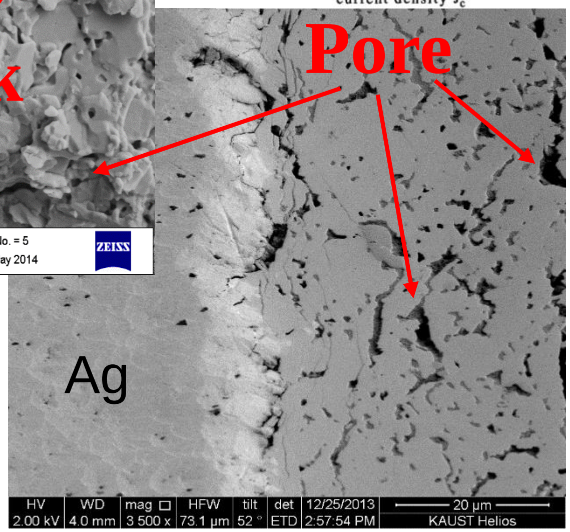
IEECAS group: ***Supercond. Sci. Technol.*** *21 (2008) 105024*

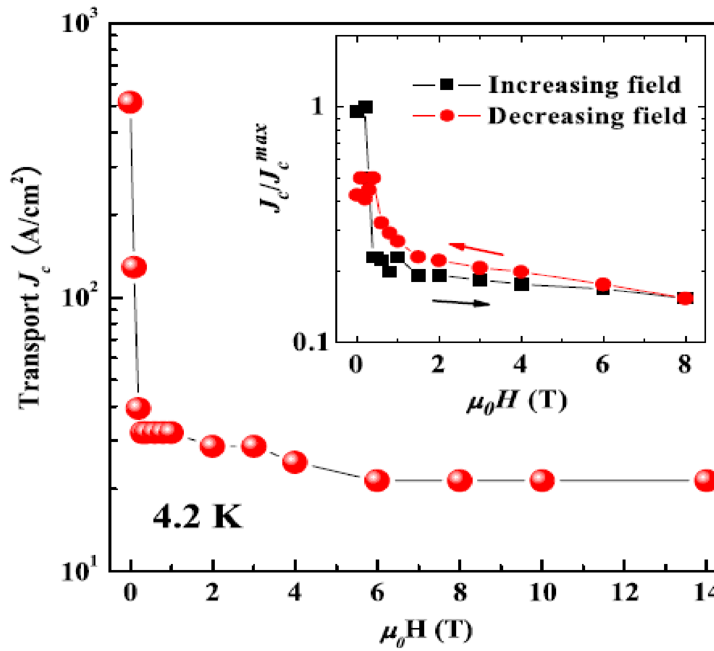
Key problems for PIT wires: Low density and weak link



Good connectivity is desirable!







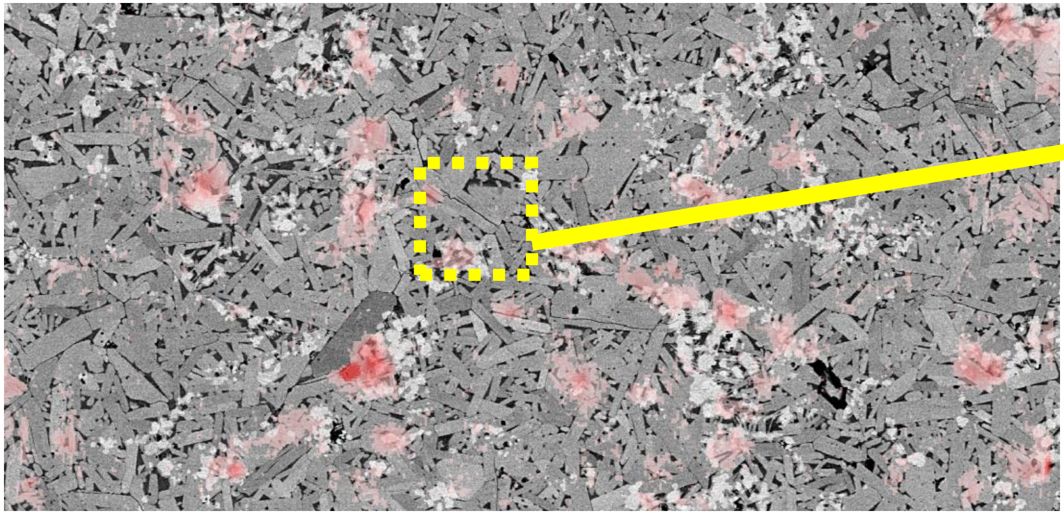
Low density: cracks and porosity

Hysteresis in transport J_c: signature of weak links

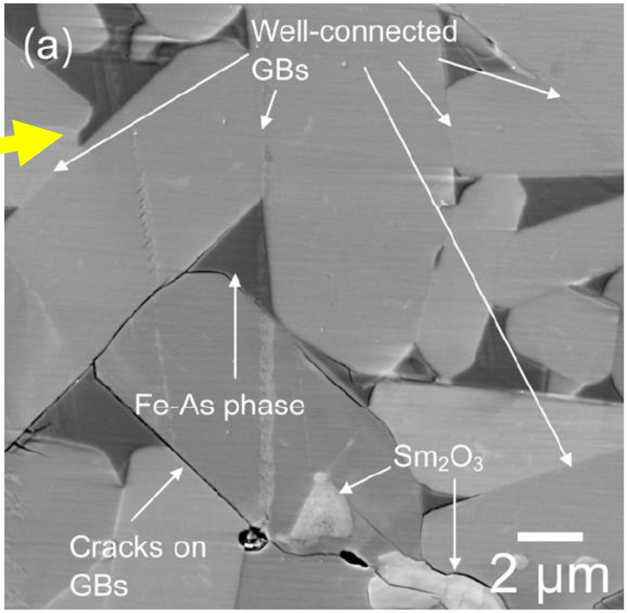
- Residual cracks and porosity always lead to poor grain connection, so suppress J_c in polycrystalline wires!
- A hysteretic phenomenon observed for transport J_c in an increasing and a decreasing field indicated a weak-linked behavior, similar to that of the cuprates.

Q1 :

Early efforts at wire development suffered from many impurity phases (such as Fe-As) that wet the grain boundaries, largely decreasing Jc



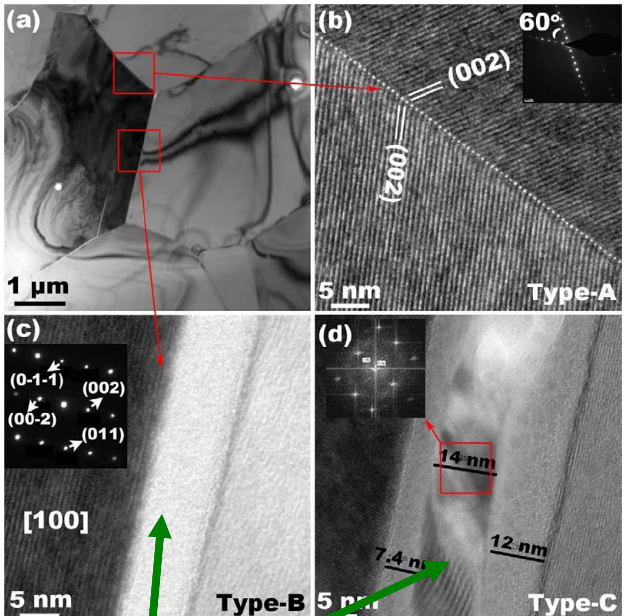
Low Temperature Laser Scanning Microscopy (LTLSM) + SEM



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

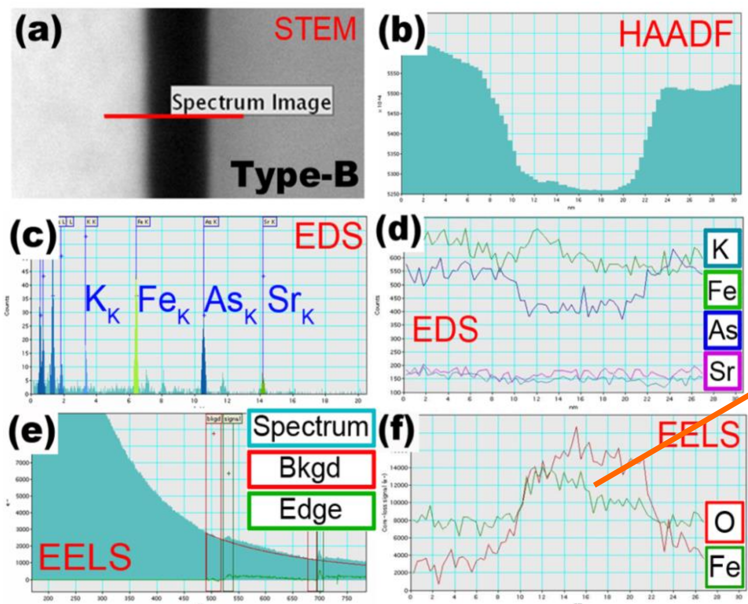
- **Dissipation is clearly localized in impurity-rich regions.**
- **Fe-As phase covers the grains causing a current blocking effect.**

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

An amorphous layer



A high level of oxygen at the boundaries.

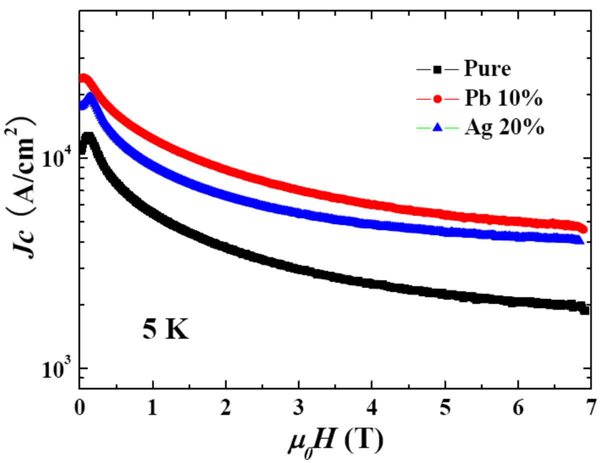
EELS: electron energy loss spectroscopy

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

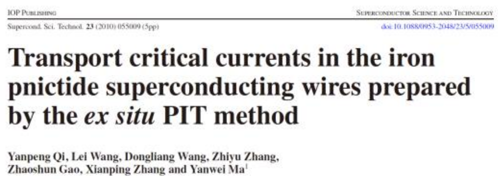
- **Obviously, these O-rich amorphous layers are strongly related to the introduction of O_2 during fabrication.**
- **These oxygen-rich layers undoubtedly obstructed many grain boundaries, consequently resulting in a poor grain connection.**

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.

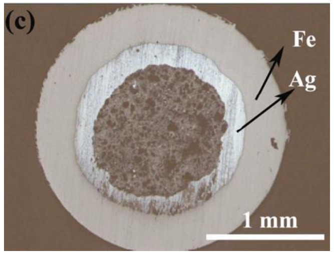


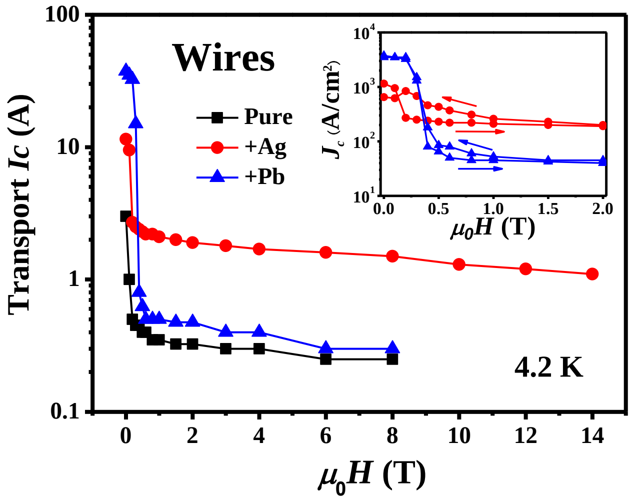
SuST 23 (2010) 025027

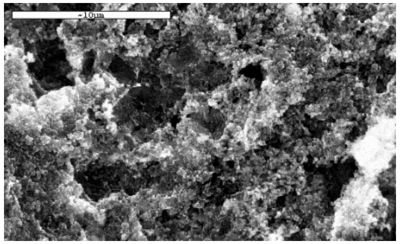

IOP Publishing
Superconductor Science and Technology

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

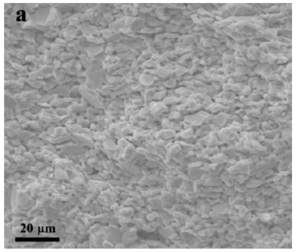
Yanpeng Qi, Lei Wang, Dongliang Wang, Zhiyu Zhang, Zhaoshun Gao, Xianping Zhang and Yanwei Ma[1]







In Situ : more impurity



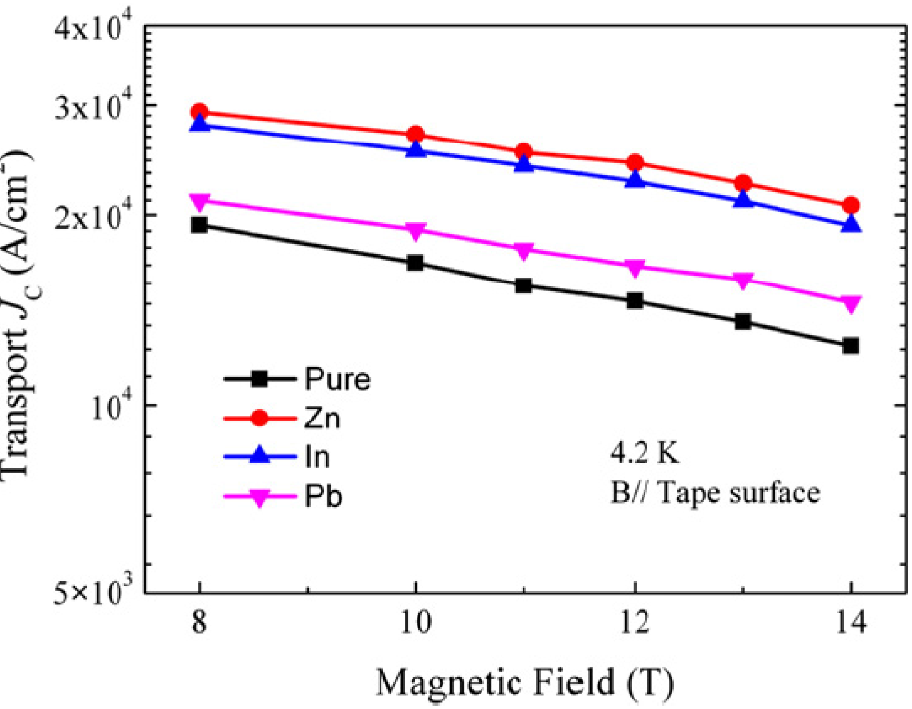
Ex Situ : high purity

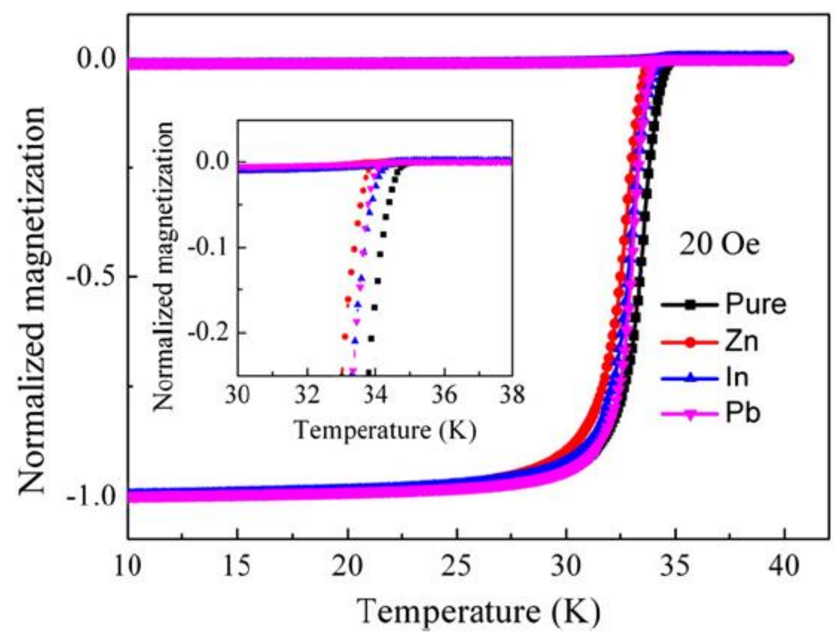
At 0 T, 4.2 K, I_c reached 37.5 A, correspondingly, J_c= 3750 A/cm².

SuST 23 (2010) 055009

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.





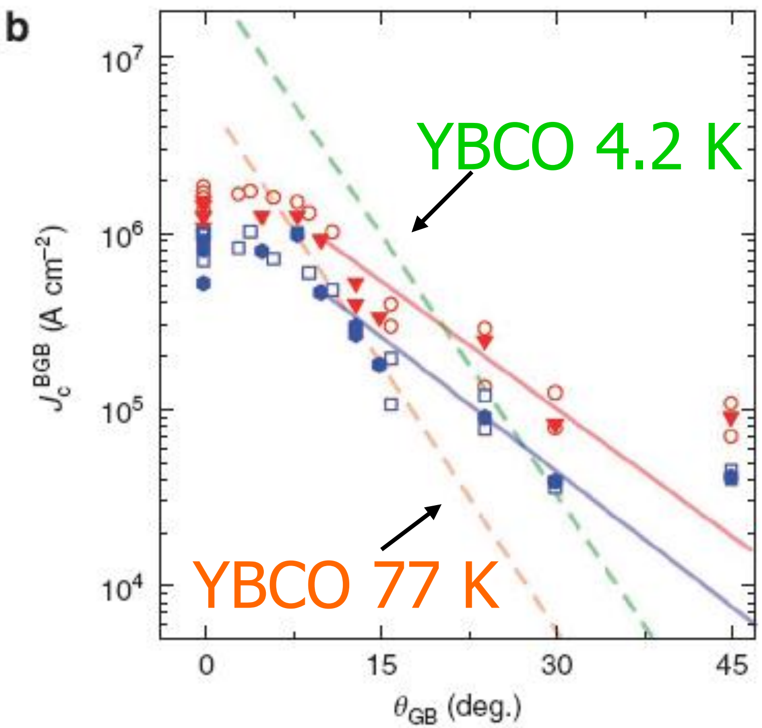
- The additions do not significantly affect the temperature transition Tc, and the Tc decreased only 0.4 K.
- the Jc enhancement in In or Zn-added samples may be attributed to the improved phase uniformity as well as the good grain connectivity

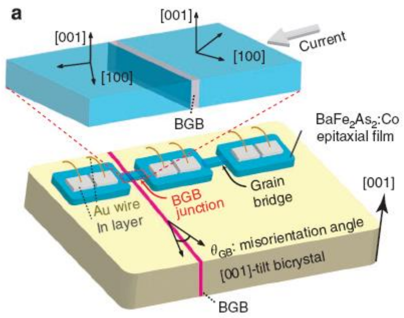
Lin et al., *Scripta Mater*. 112 (2016) 128

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

Co doped Ba-122 thin films on bicrystals

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





The critical GB angle

YBCO :	**3-5°**
Ba-122:	**9°**

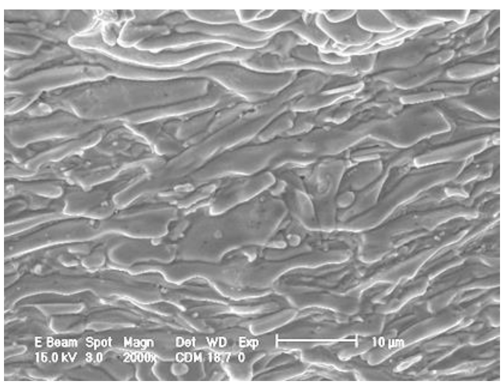
Different fabrication techniques!

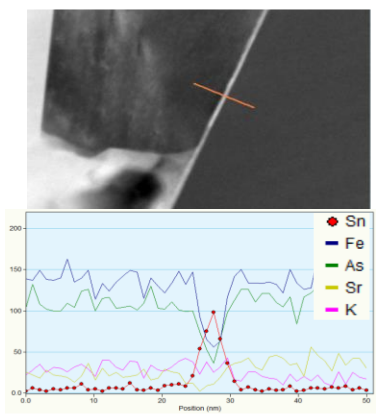
- **J_c decreases exponentially with GB angle .**
- **Weak link effect, the GBs do not degrade the J_c as heavily as YBCO.**
- **Advantageous GB over cuprates!** This is the reason why we can use the PIT method to make the pnictide wire and tapes, but PIT can not work for YBCO.

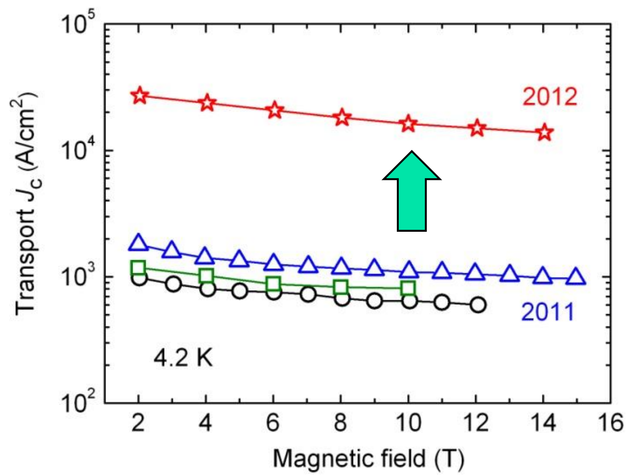
Texturing process of PIT Sr122 tapes

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

Sr122+Sn **Rolling by a large reduction rate** **To form textured grains** **Annealing for better connection**



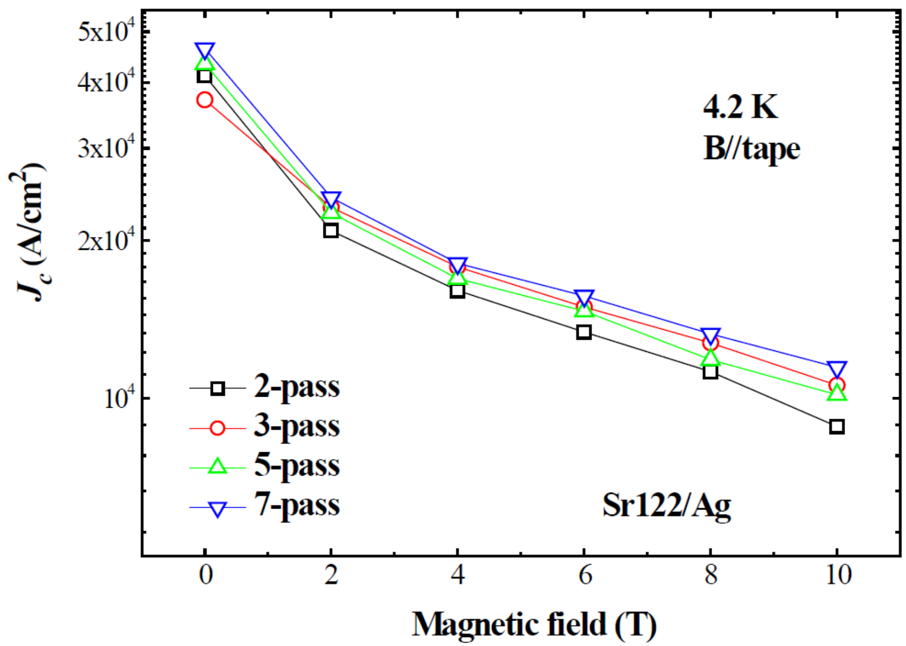


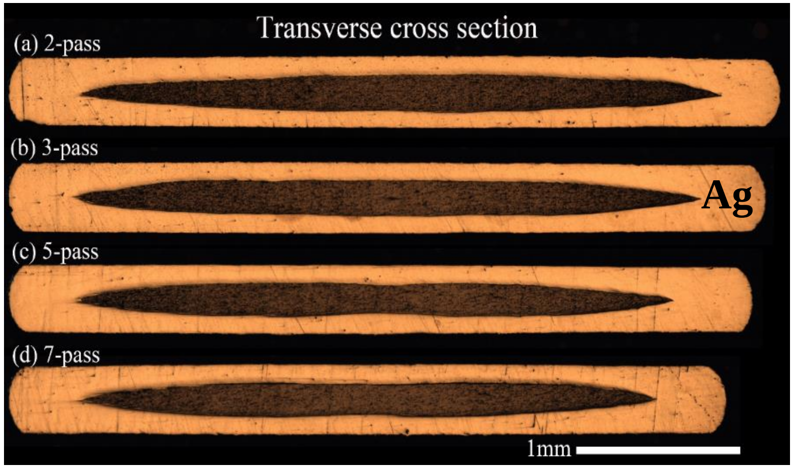


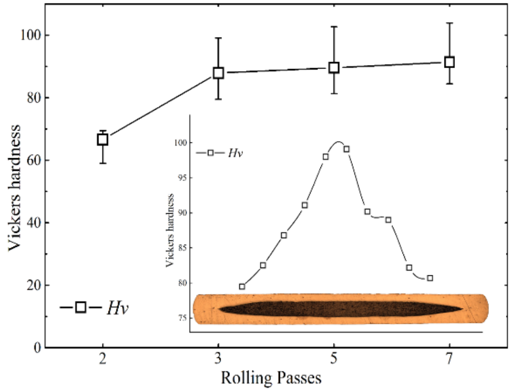
The above rolling strongly improved c-axis texturing, and effectively reduce the large angle GBs, thus Jc was enhanced by **an order of magnitude, from 10^3 to 10^4 A/cm^2**。

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

Optimized rolling process for $Sr_{0.6}K_{0.4}Fe_2As_2$ /Ag tapes: 3-pass deformation is best



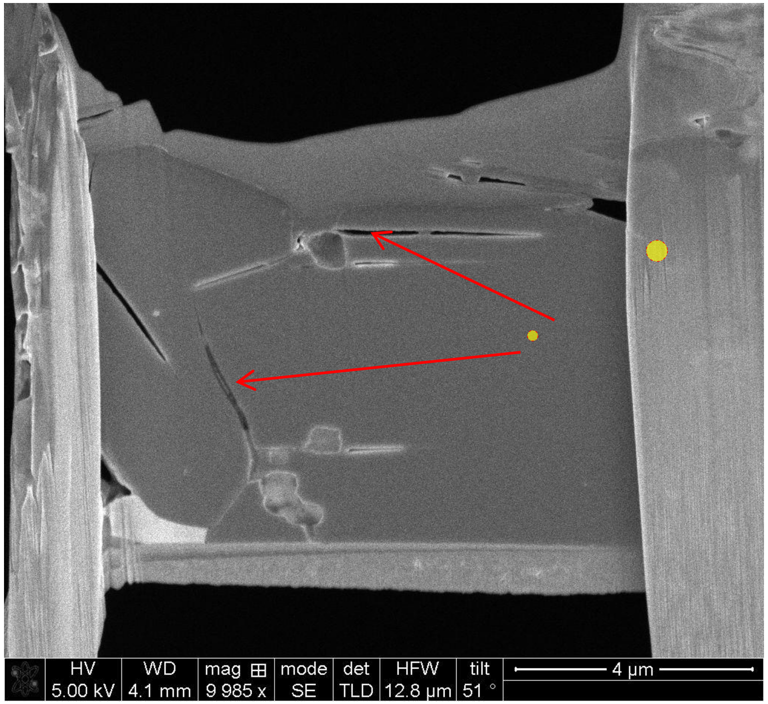


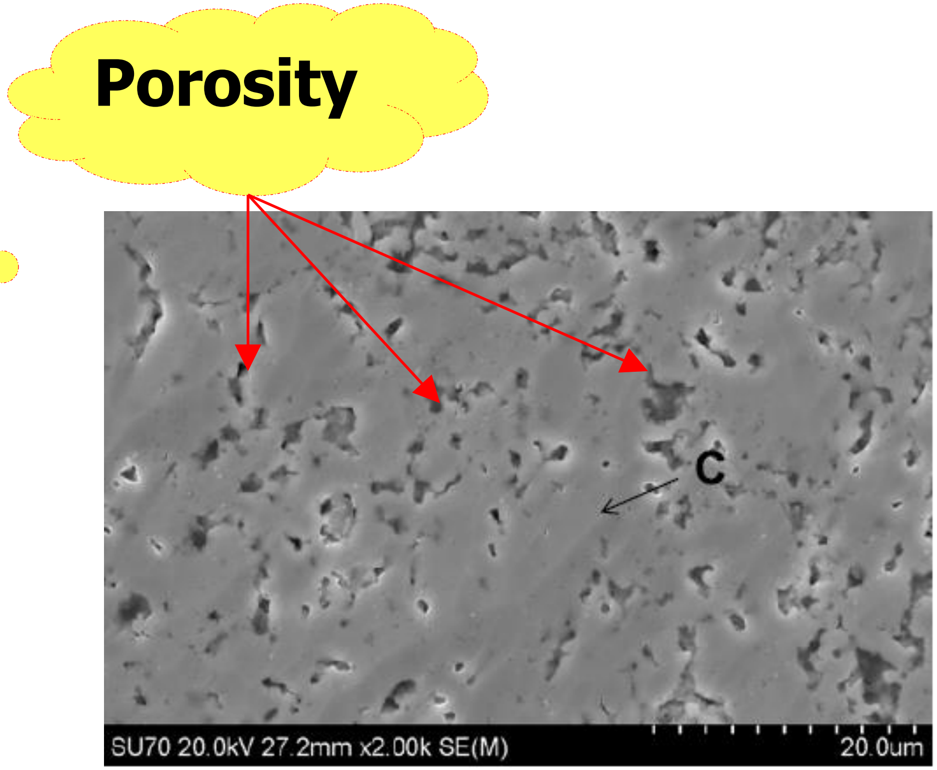


- The width of the tapes and the area of superconducting cores increase with decreasing the rolling pass, but the transport J_c seems close.
- We can fabricate tapes with 3 rolling passes to get the uniform and high-J_c 122 tapes.

Physica C 525 (2016) 94

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

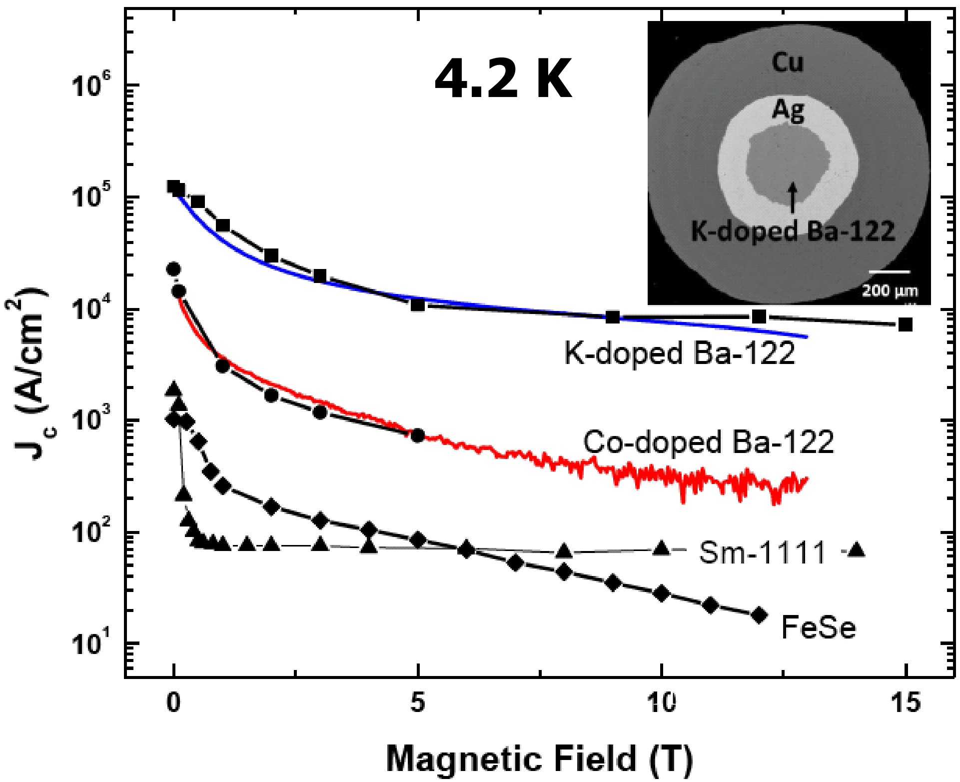




Cracks and voids are one of the important reasons for low critical current density values

NHMFL

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

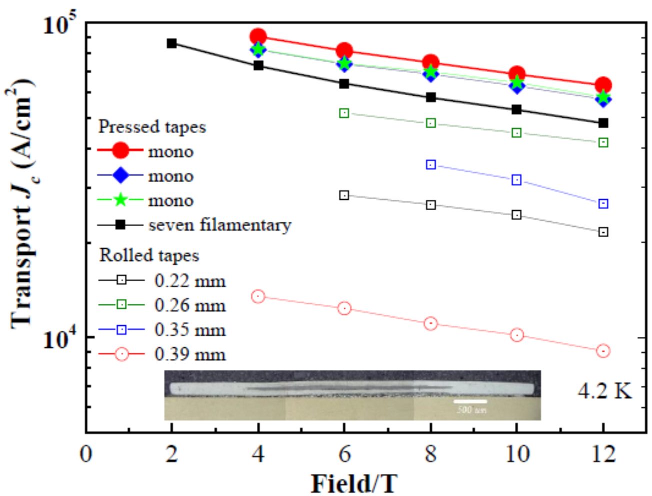
NIMS

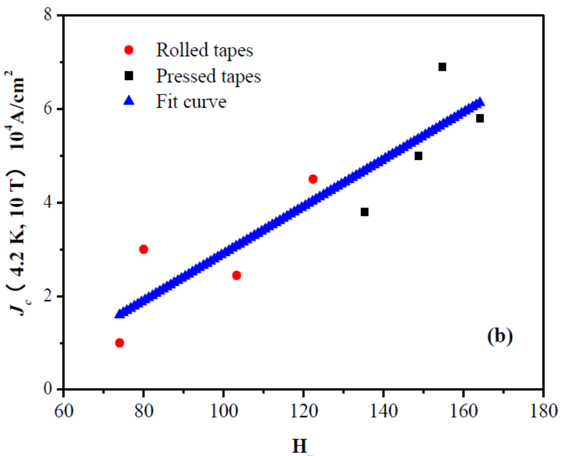
Thin tapes by combined the rolling, cold pressing and sintering process-- Denser core yields higher J_c

--Ag-sheathed Ba122 tapes

Steps:

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





The higher the core density, the higher the J_c

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

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

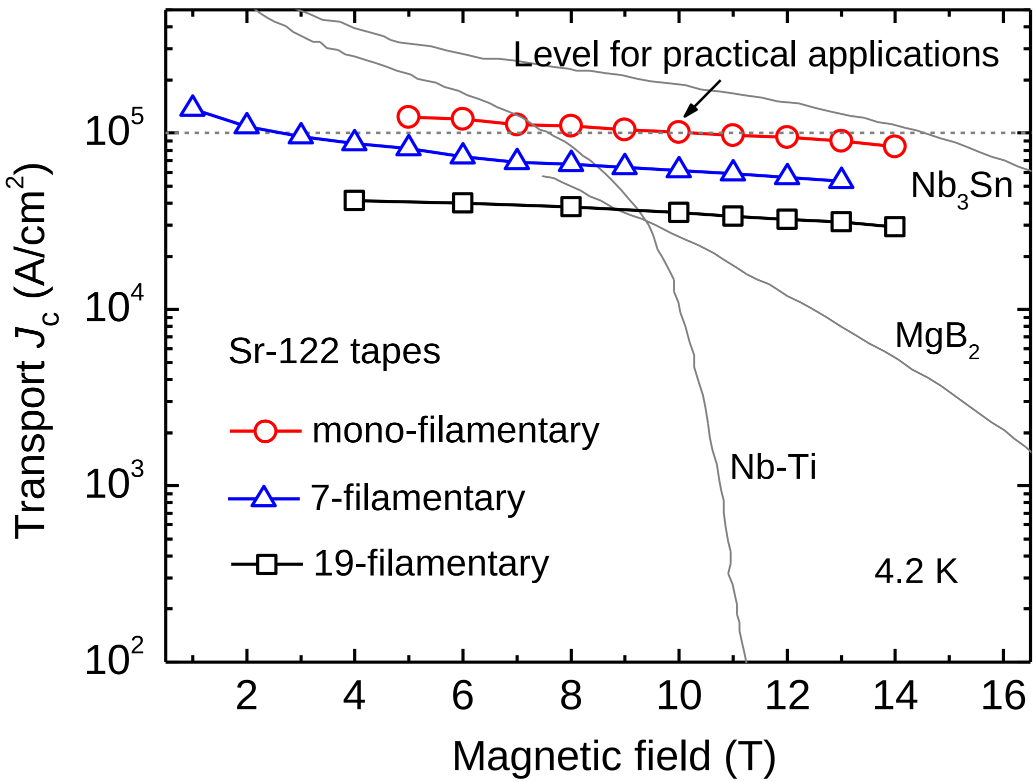
NIMS group, *Sci. Rep.* 4, 4465 (2014)

Breakthrough work --$Sr_{0.6}K_{0.4}Fe_2As_2$

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!

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



Later achieved

At 10 T, $J_c = 1.2 \times 10^5$ A/cm²

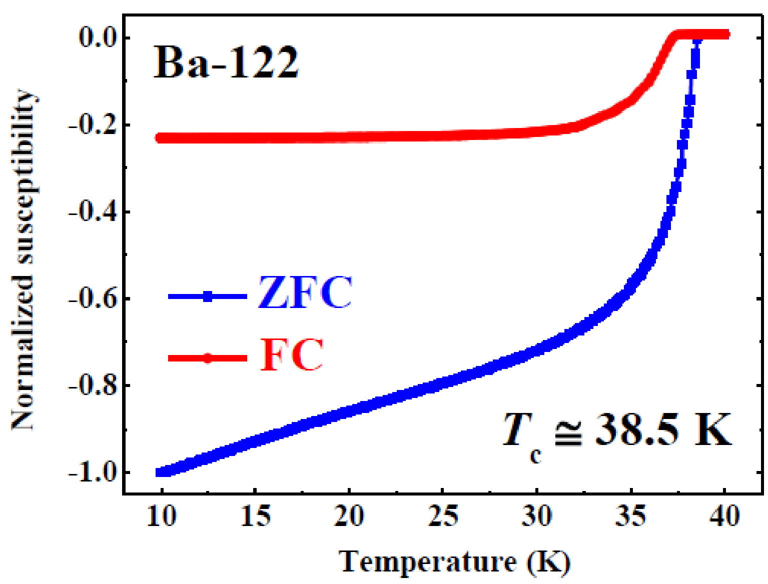
even in 14 T, $J_c = \sim 10^5$ A/cm²

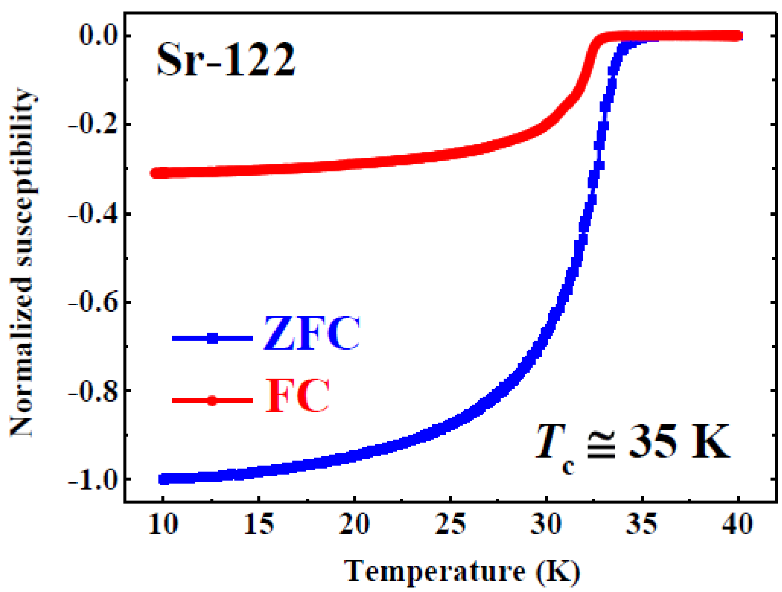
The superior J_c can be attributed to higher grain texture and improved densification.

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

Why HPressed Ba-122?

T_c comparison between reacted powders





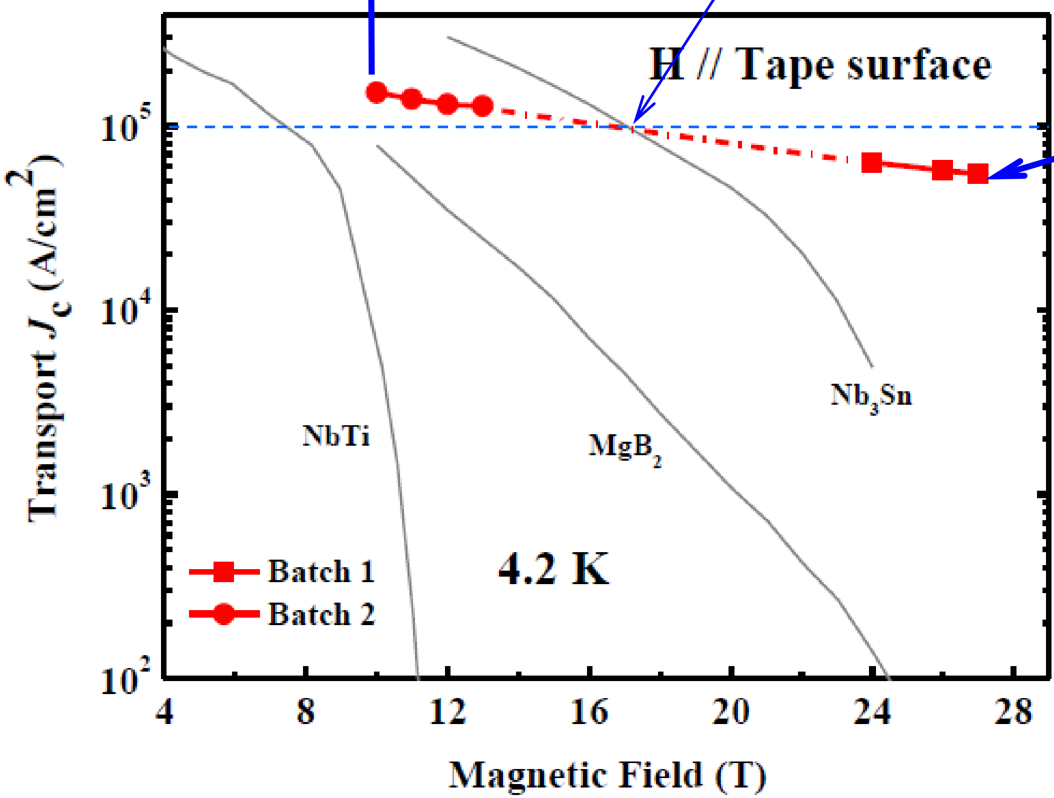
- The transition temperature of $Ba_{1-x}K_xFe_2As_2$ (38.5 K) is higher than that of the $Sr_{1-x}K_xFe_2As_2$ (35 K),
- The purity of Sr fillings is lower than that of Ba fillings.

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

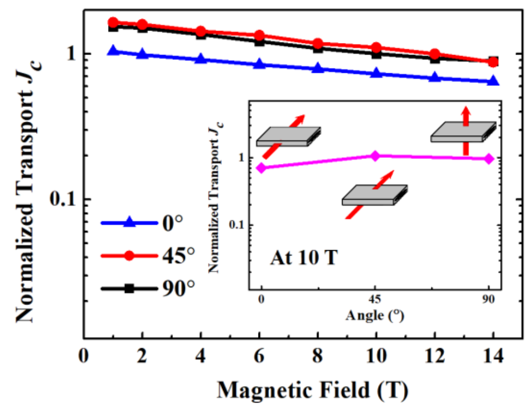
New record transport J_c up to 1.5×10^5 A/cm^2 @ 4.2 K, 10 T was obtained by Hot Pressing

I_c = 437 A

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



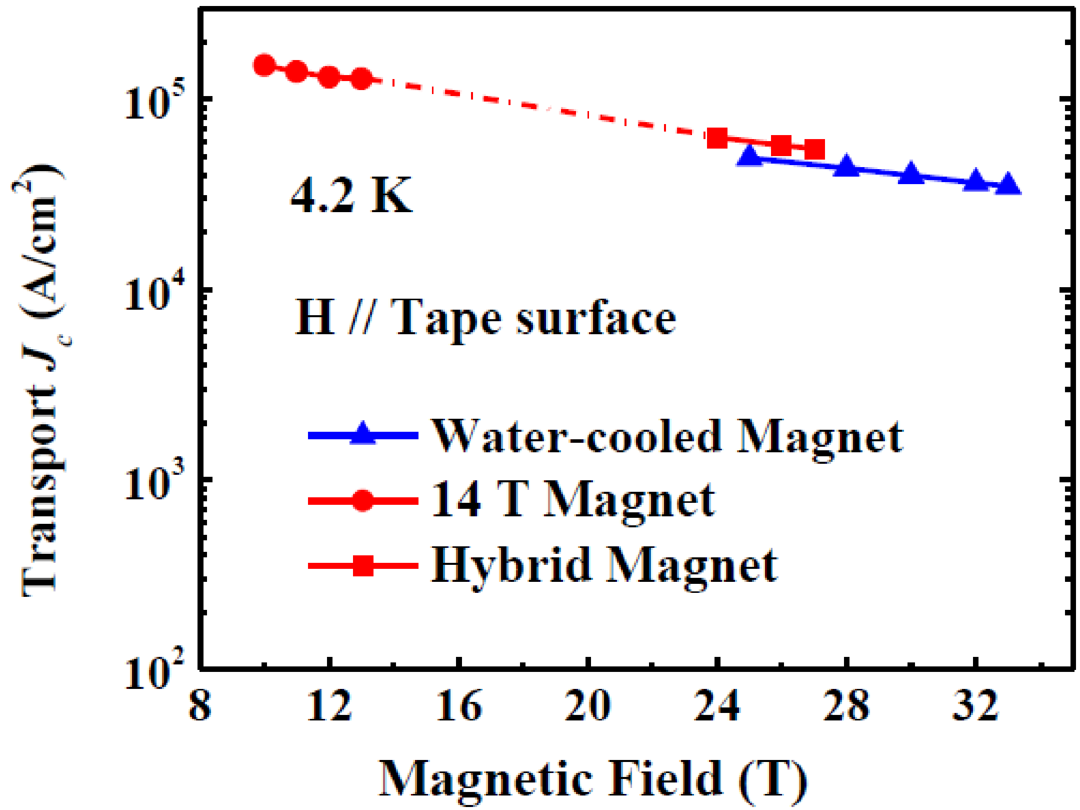
At 27 T, J_c = 5.5×10^4 A/cm^2



γ = 1.37 at 10 T

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

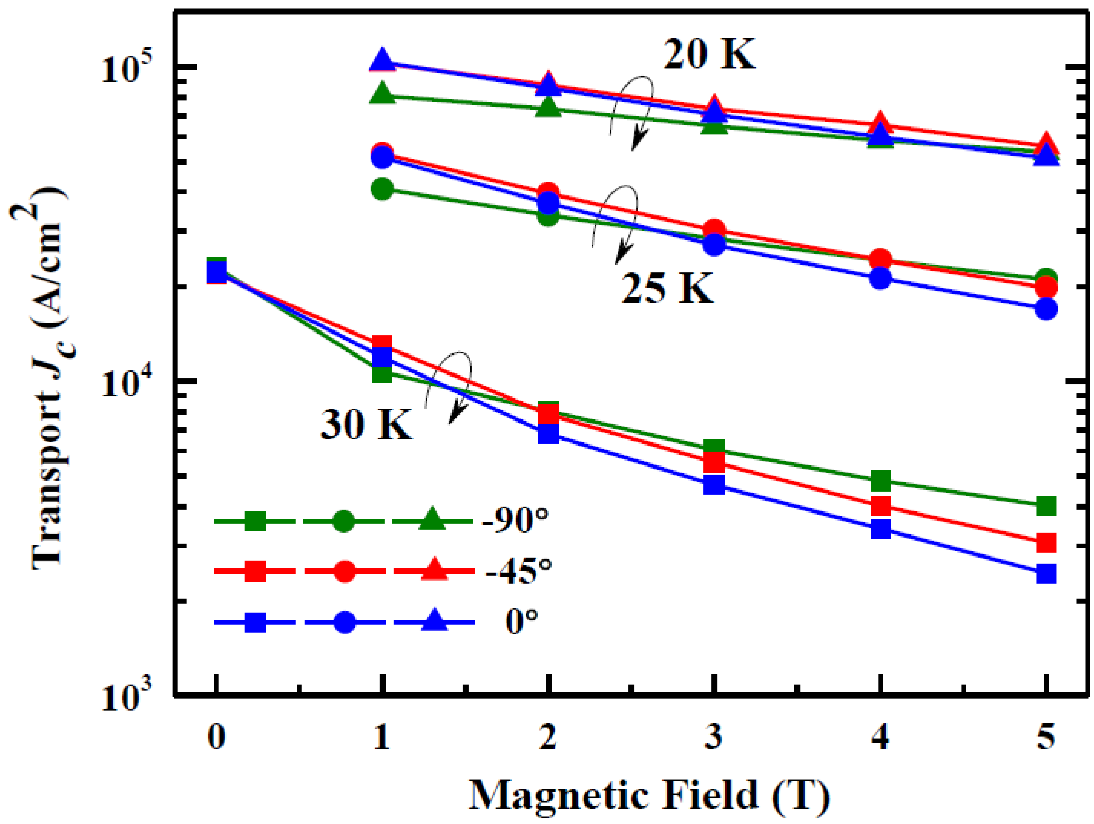
I_c measured in high fields up to 33 T



High Magnetic Field Laboratory at ***Heifei***

HP Ba-122 tapes

At 20 K, 1 T, transport $J_c > 10^5$ A/cm^2



5 T, J_c>50000 A/cm^2

5 T, J_c>20000 A/cm^2

5 T, J_c>4000 A/cm^2

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

EBSD Data: Grain size and crystal orientation

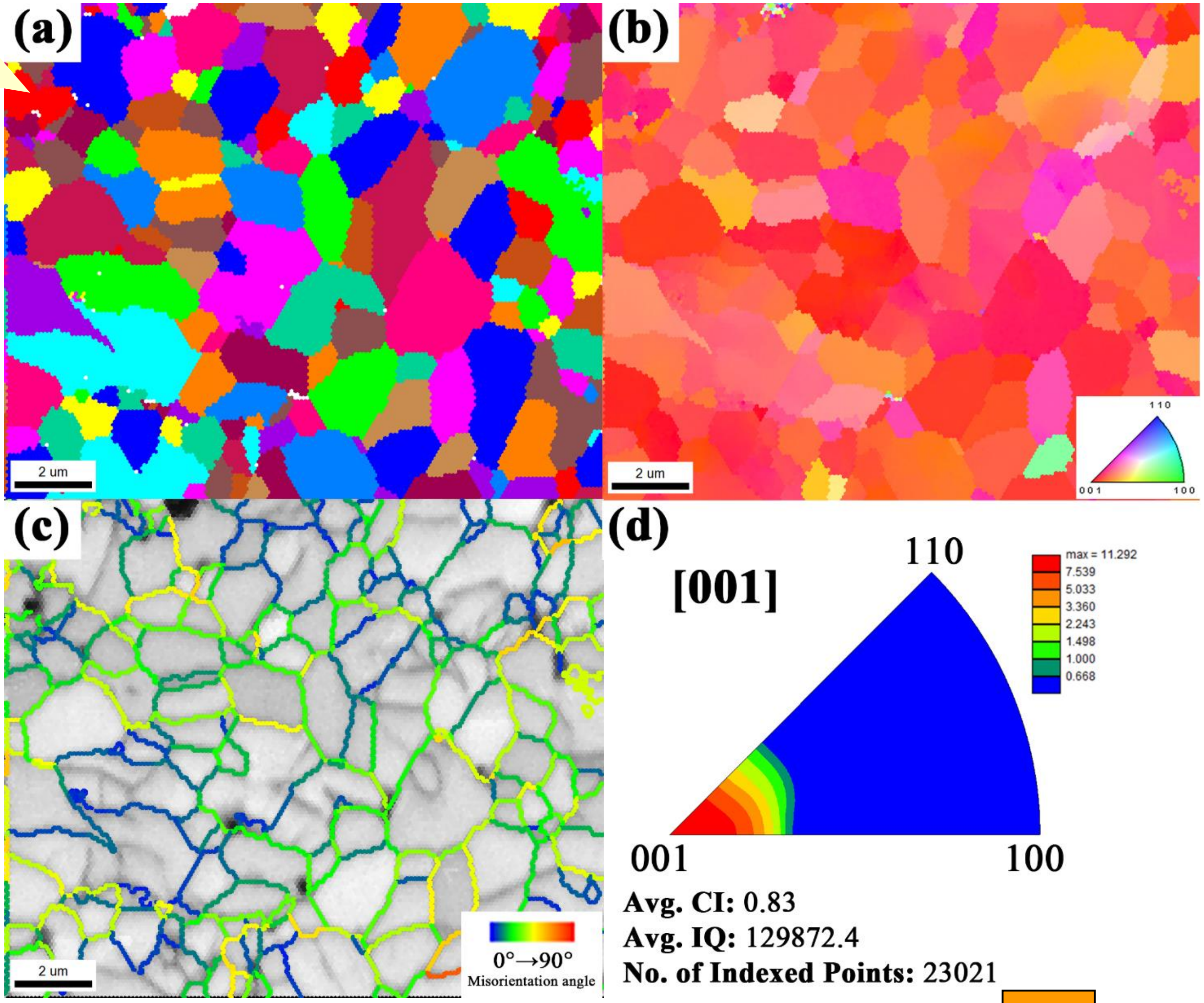
--Electron backscatter diffraction

HP Ba122

Small, uniform Grain, 1~2 μm

HP Sr122

2-8 μm



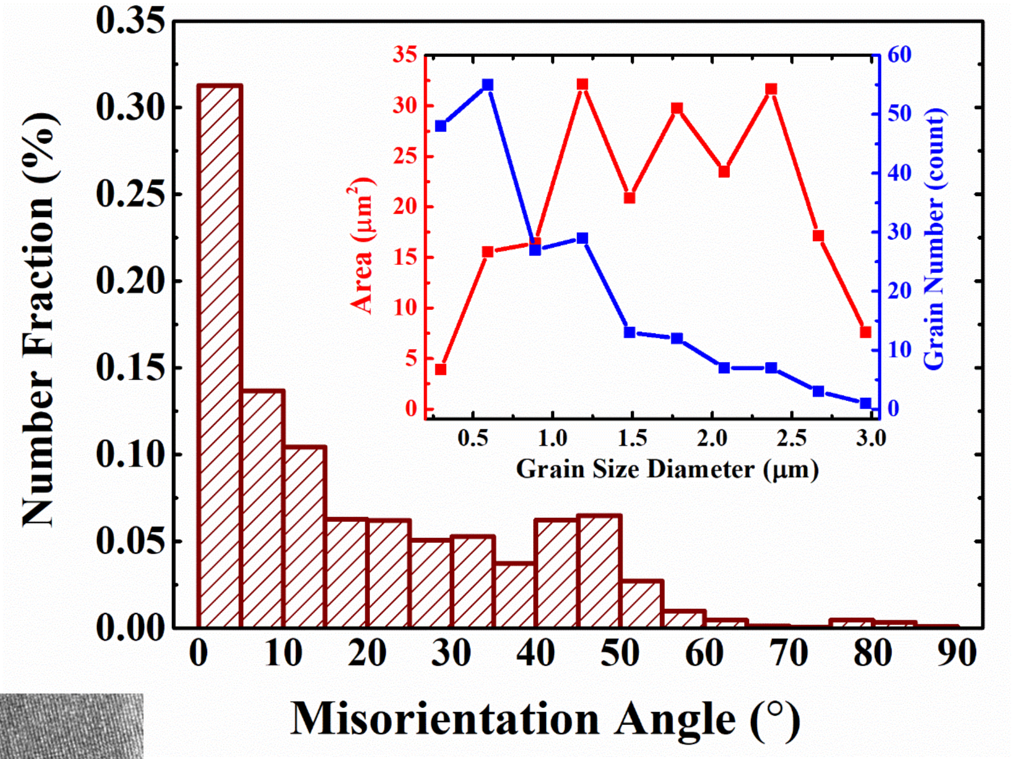
Small misorientation angle between grains

A highly textured microstructure

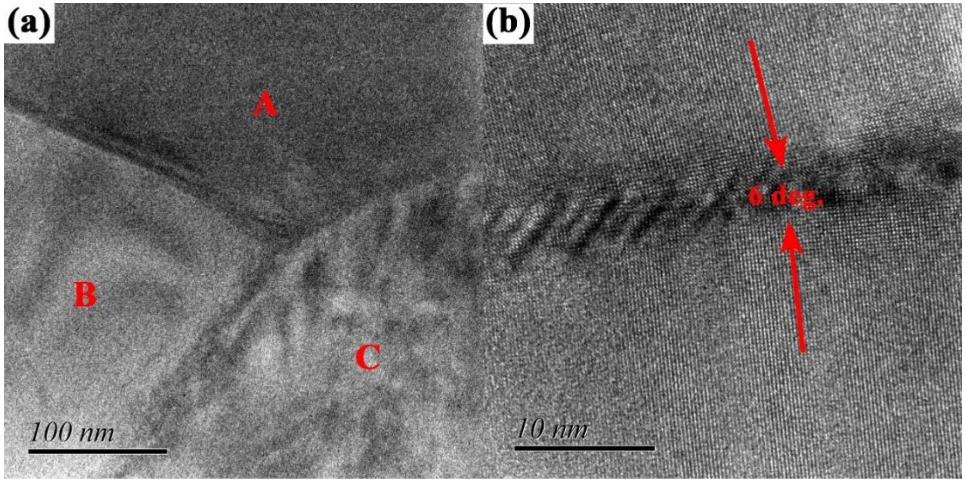
Misorientation angle distribution

EBSD measurement

- ✓ **Small grains accounted for a large percentage;**
- ✓ **The size of most grains are between 1-2 μm;**
- ✓ **42.8% number fraction of misorientation angle <9º.**



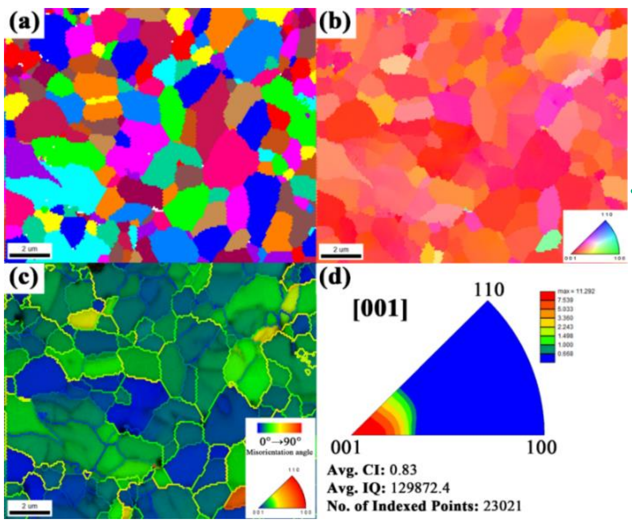
TEM observation



A large amount of grain boundaries with low angle are also detected, indicating that the weak-link behavior is suppressed in HP tapes.

The reasons for strong Jc enhancement in HP samples

Fine grains!



Highly textured microstructure!

Hot press

The core of HP Ba122 tape

Vickers hardness: ~132

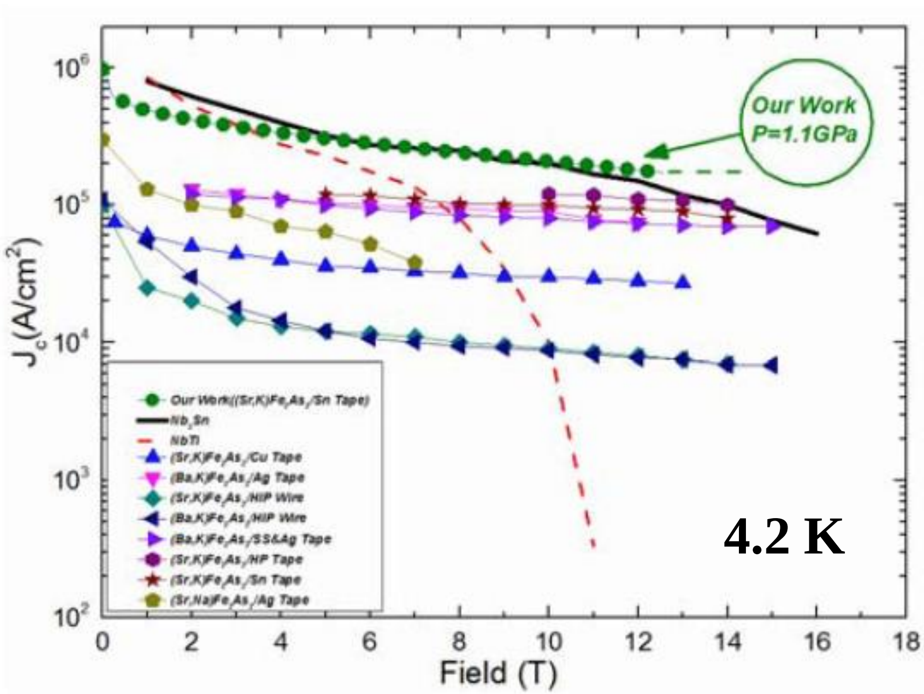
Rolled: ~65

High core density

Good connectivity !

Such excellent J_c in HP tapes is attributed to the synergy effect of small grains, high degree of texture and improved connectivity between grains!

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



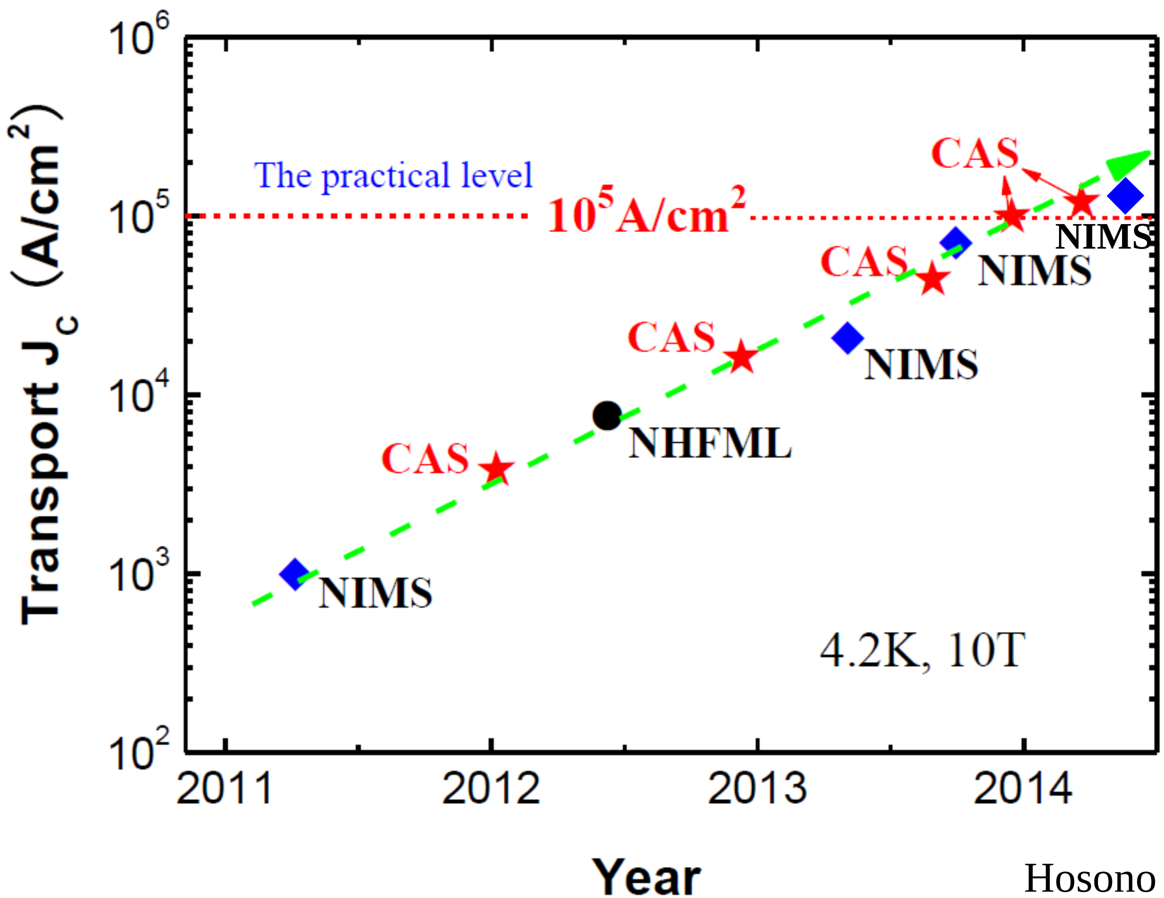
-- Collaborated with Prof. Xiaolin Wang, S. X. Dou, Wollongong Univ.

- ✓ **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 shows that the current IBS tapes/wires should have plenty of room to raise their J_c or I_c to higher levels.

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

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



2018

★ **1.5×10^5 A/cm^2**
CAS

10^{5}A/cm^2 at 18 T

Hosono et al., ***Mater. Today*** 2018

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

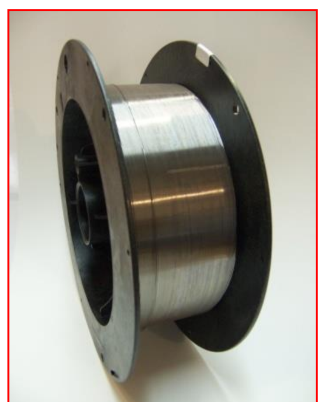
- **An scalable process is required to fabricate high performance long length tapes, e.g., *Rolling (hard sheath), Hot Rolling or Hot isostatic press (HIP)…***

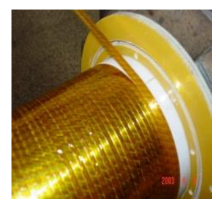
For applications, many other problems to be solved

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**

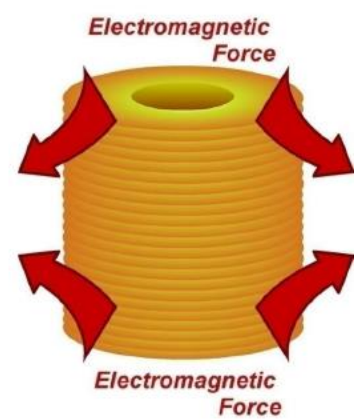
Short sample:1m

Long wire



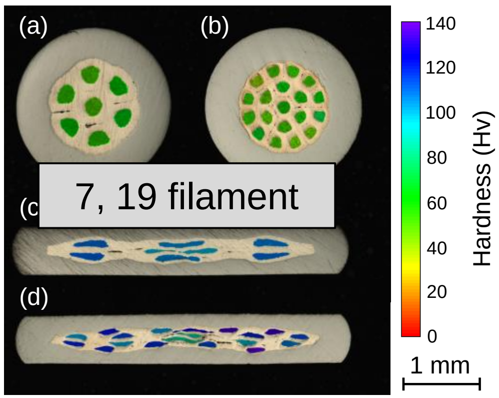


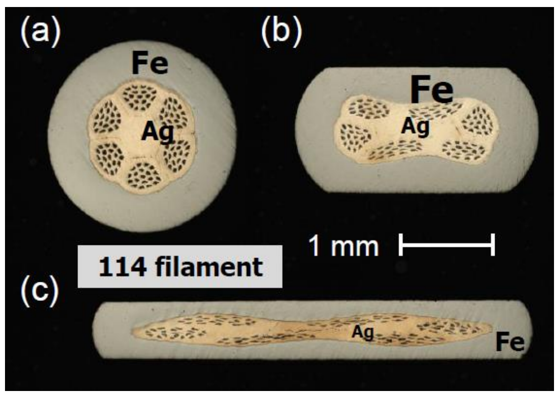
Magnet



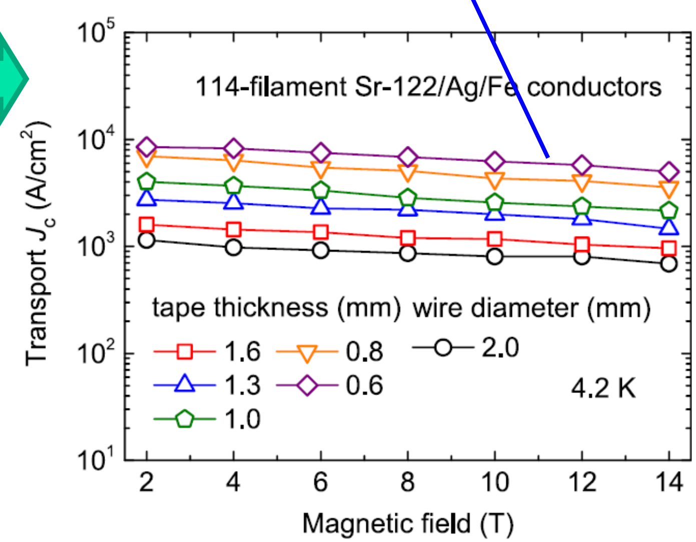
Fabrication of 114-filament Sr-122/Ag/Fe wires by the drawing and rolling

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





Jc, the very weak field dependence



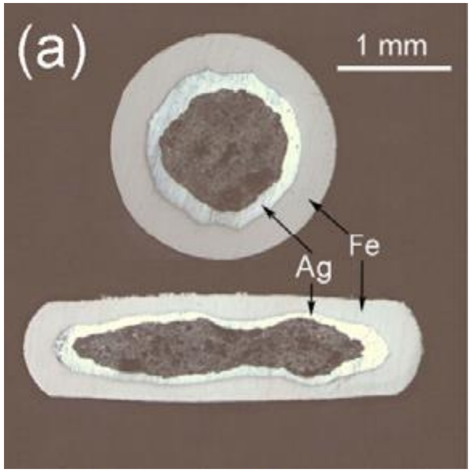
- 114-core round wires: J_c=800 A/cm^2.
- When they are flat rolled into tapes, the J_c grows with the reduction of tape thickness. the J_c =6.3×10^3 A cm^{-2} in 0.6 mm thick tapes.
- 7-core tapes: J_c= 1.5×10^4 A/cm^2.
- This J_c degradation can be ascribed to the sausage effect.

Jc needs to be further improved

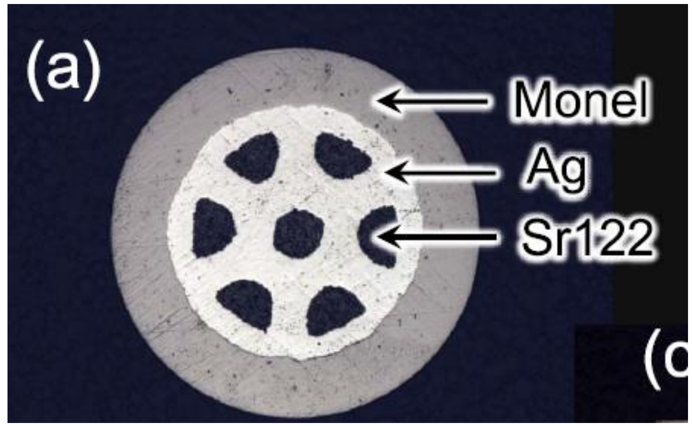
Yao et al., ***JAP*** **118 (2015) 203909**

Fabrication of high-strength IBS wires

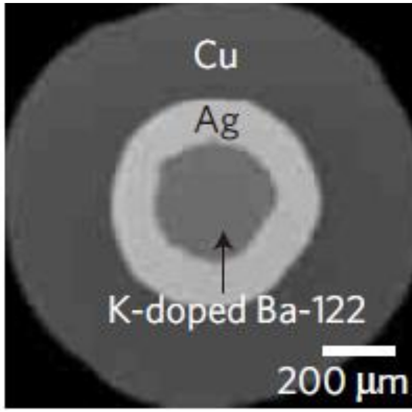
Ag may be also used in combination with an additional outer sheath made of Fe, Cu, and stainless steel to **reduce costs and improve the mechanical strength.**



Fe/Ag, **IEECAS**

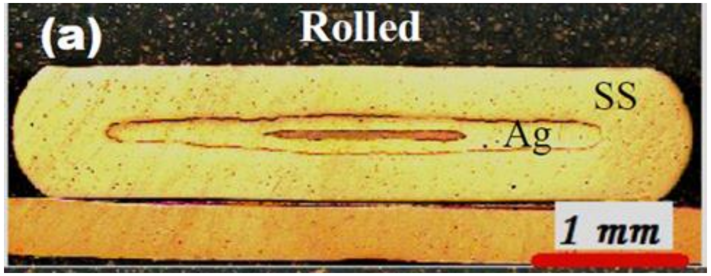


Monel/Ag, **IEECAS**

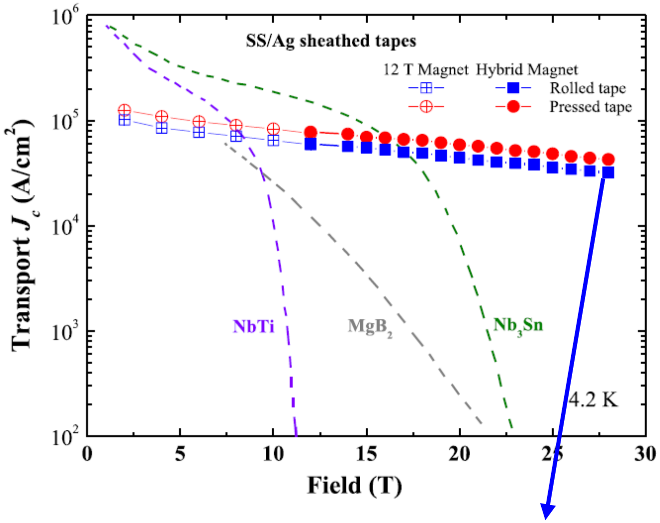


Cu/Ag, **Florida**

Cu/Ag, **IEECAS**



SS/Ag, **NIMS**

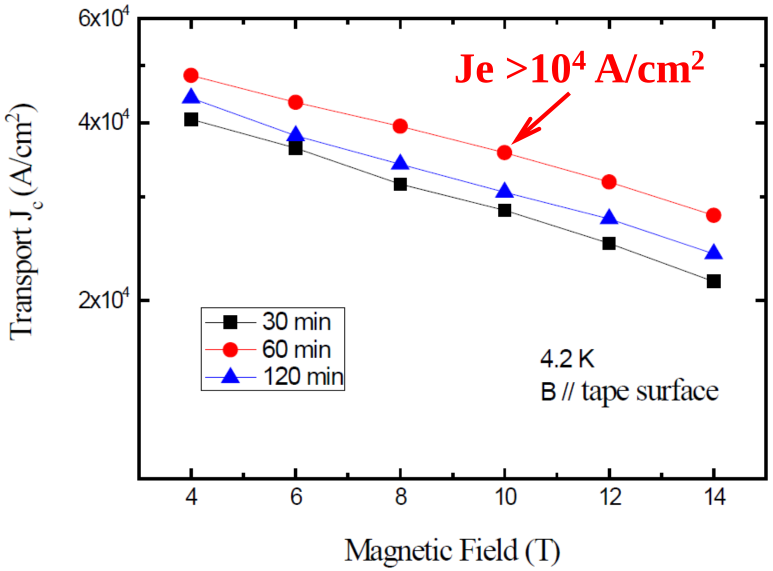


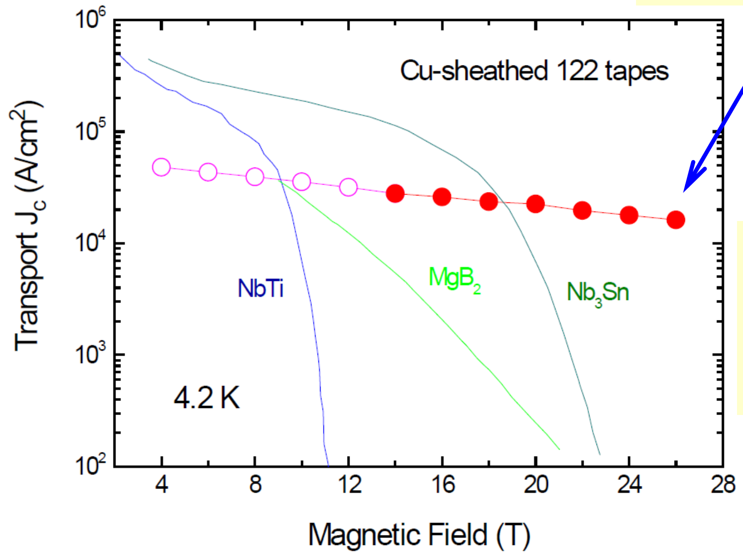
28T, $J_c = 3\times10^4$ A/cm^2

Copper sheath material

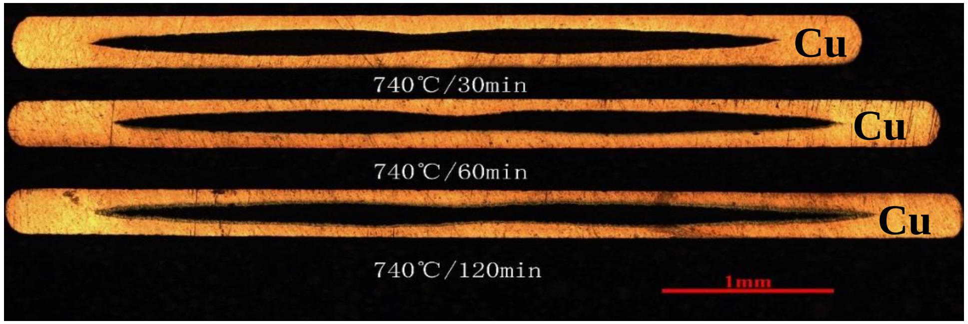
High J_c in Cu-sheathed Sr-122 tapes at low temperature 740°C

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





At 4.2 K, 10 T
Engineering J_e: >10^4 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.

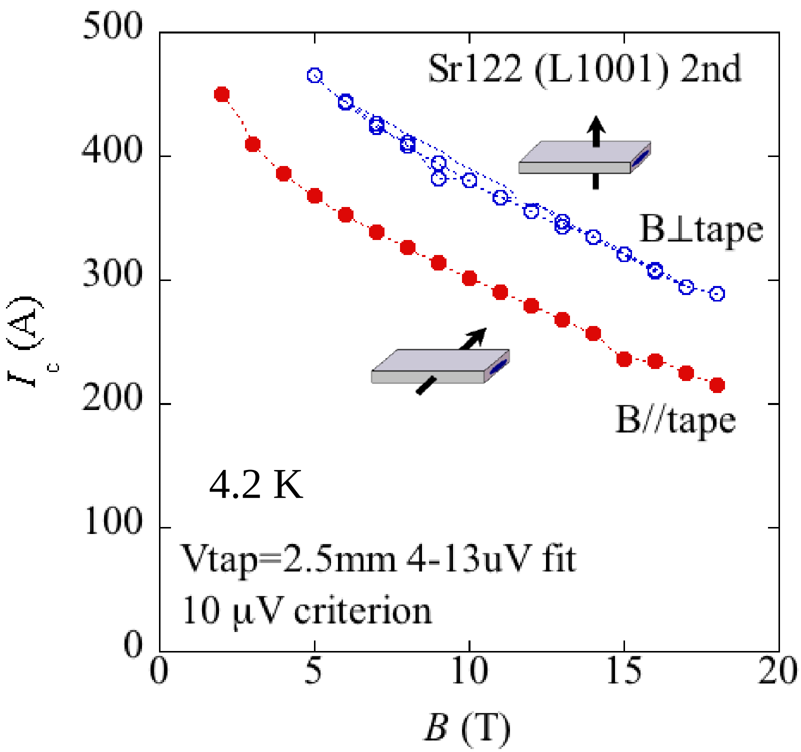
Lin et al., *SuST* 29 (2016) 095006

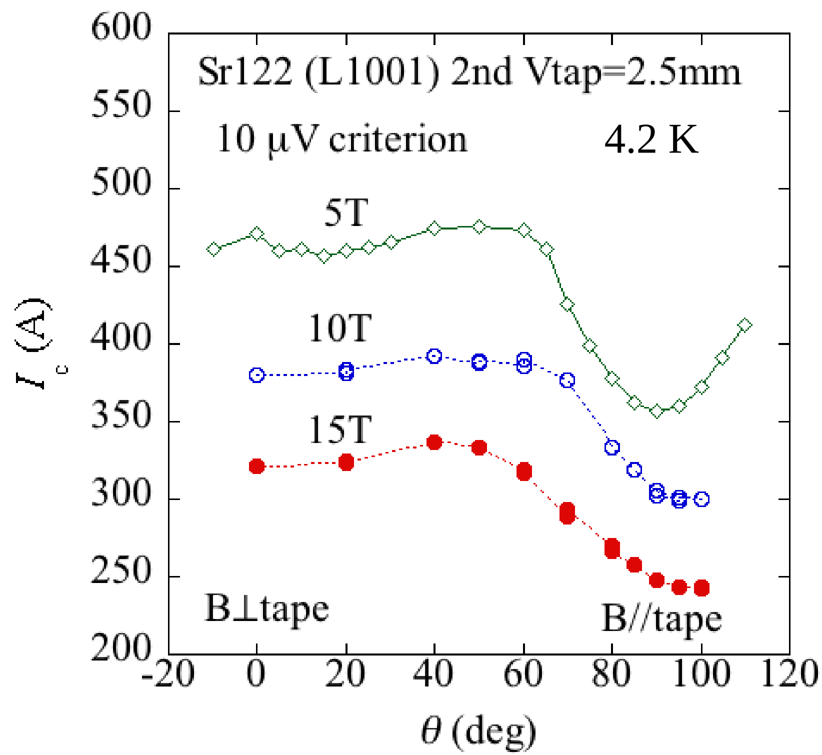
Small anisotropy

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

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

-- Measured by Prof. Awaji
HFLSM, Tohoku Univ.



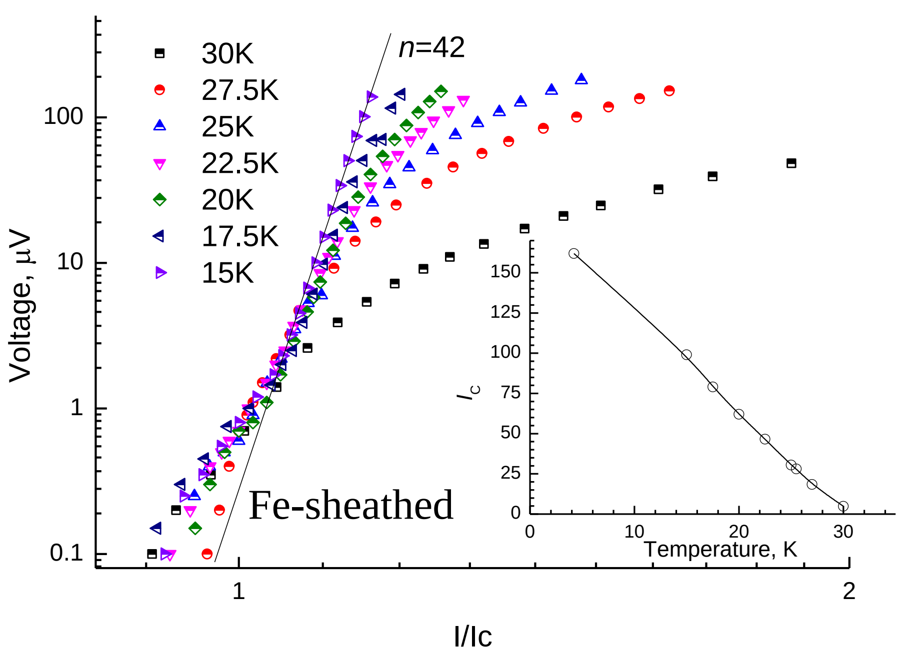


- **The I_c in applied magnetic fields is slightly higher in the perpendicular field ($I_c^{\perp}$) than in the parallel field ($I_c^{//}$).**
- **The anisotropy ratio ($\Gamma = I_c^{\perp}/I_c^{//}$) is less than *1.5*, quite small, very promising for applications.**

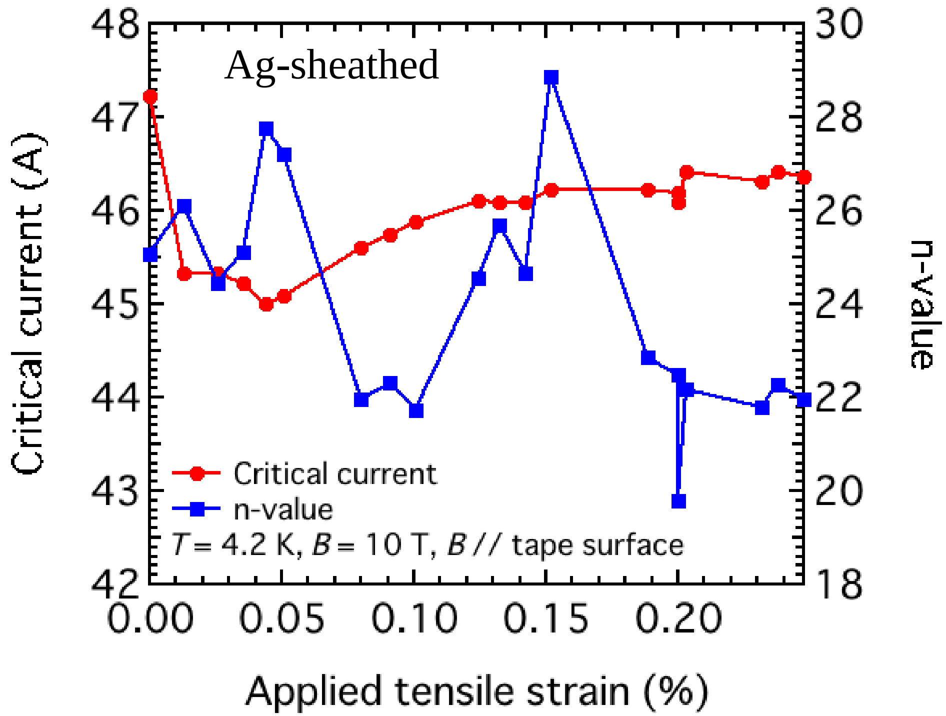
n value

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

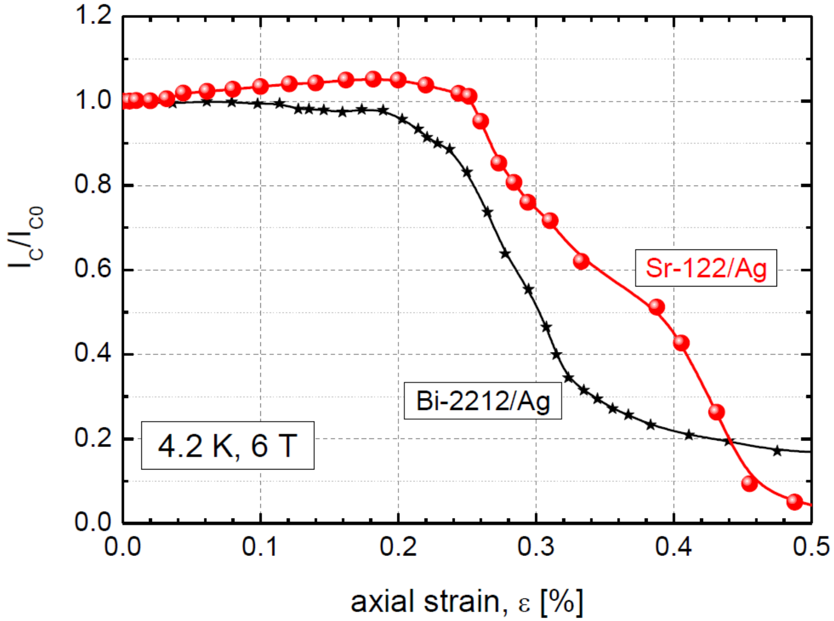


At 20 K, the *n value* was over 30

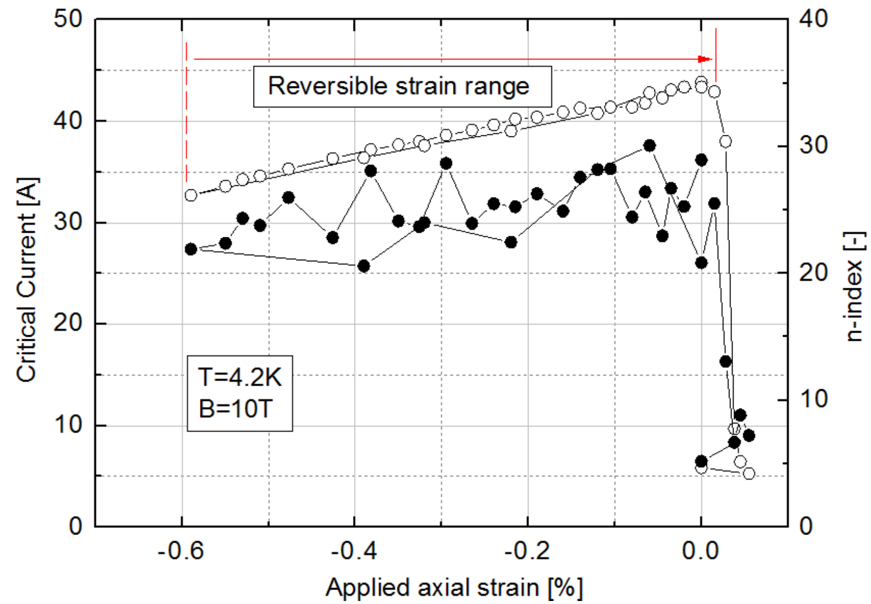
At 4.2 K, the *n value* was over 20

Sr122/Ag tape – Strain-stress properties

The first strain measurements



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



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

Comparable to Bi2212

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

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

Liu, *SuST* 30 (2017) 07LT01

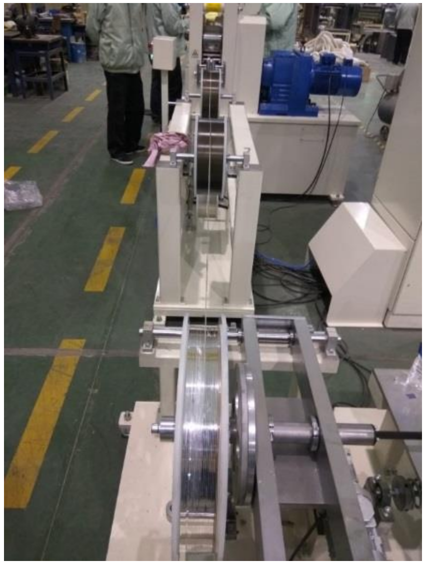
Significant breakthrough!

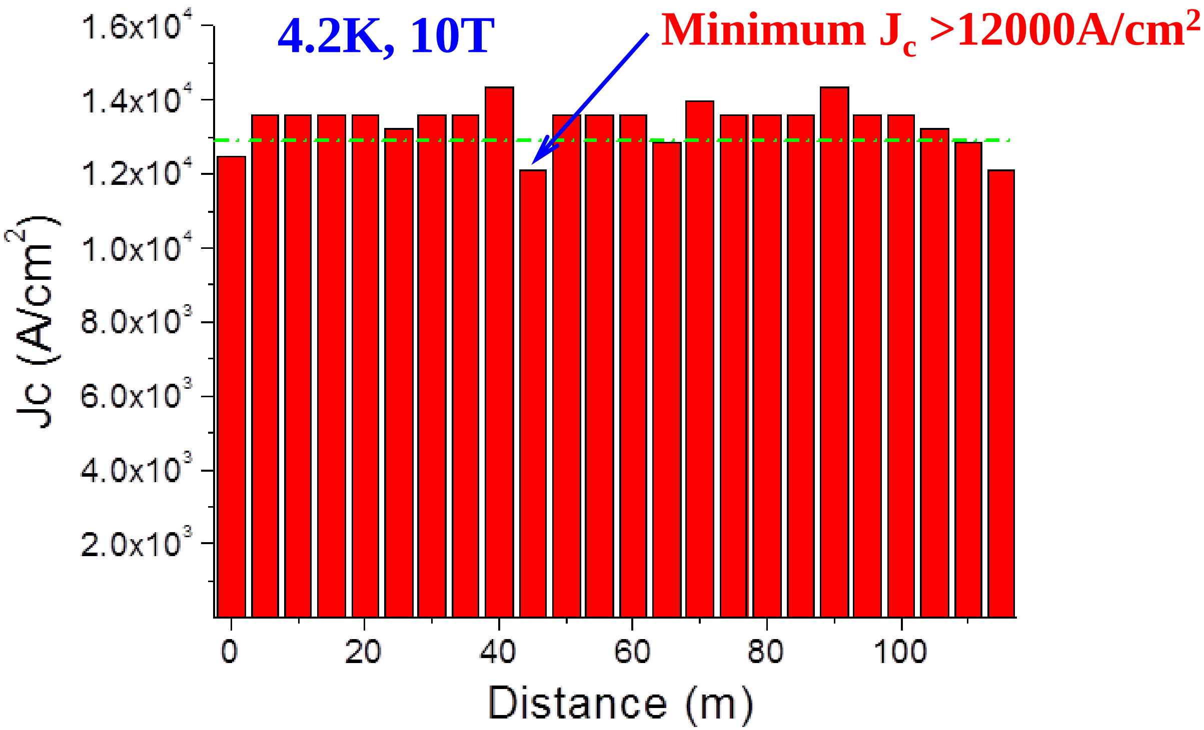
In Aug., 2016

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

-- Presented at ASC2016, Denver

115 m long **7-filamentary** wire



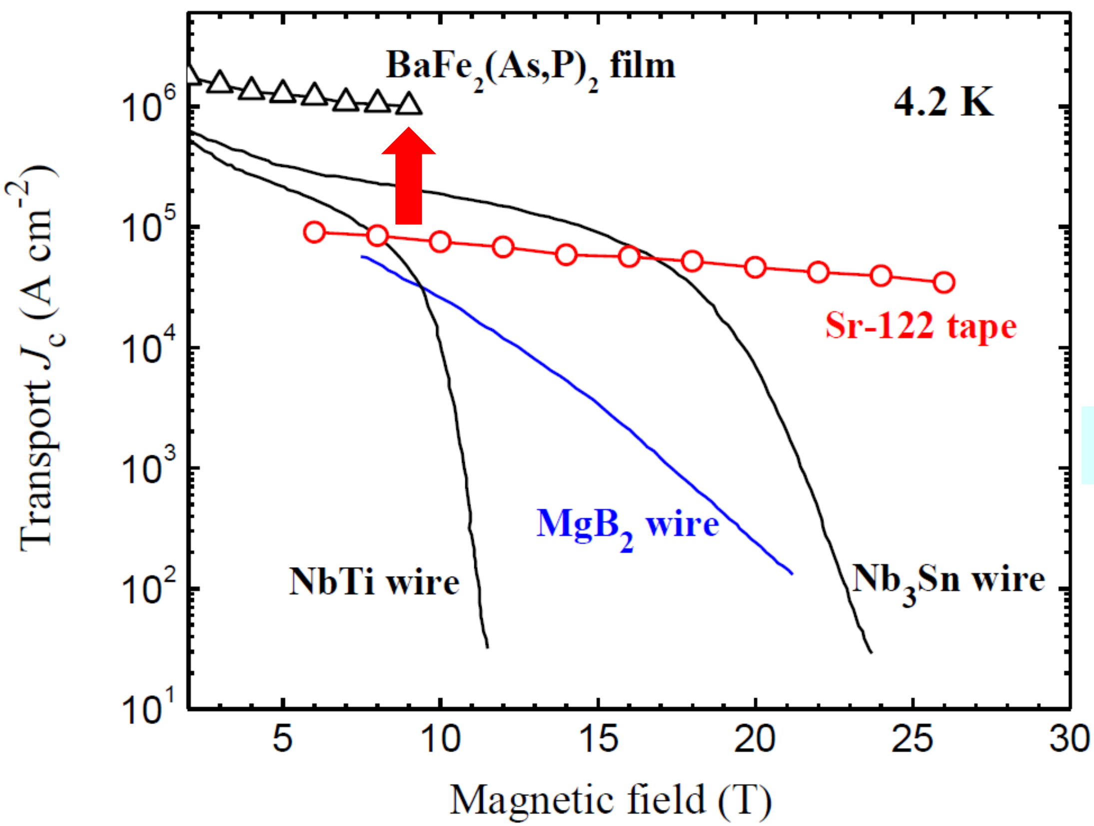


At 4.2 K, 10 T, transport Jc distribution along the length of the first 100 m long 7-filament Sr122 tape

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

X. P. Zhang et al., *IEEE TAS* 27 (2017) 7300705

Prospects



At present

J_c ~1.5×10^5 A/cm^2 at 10 T, 4.2 K

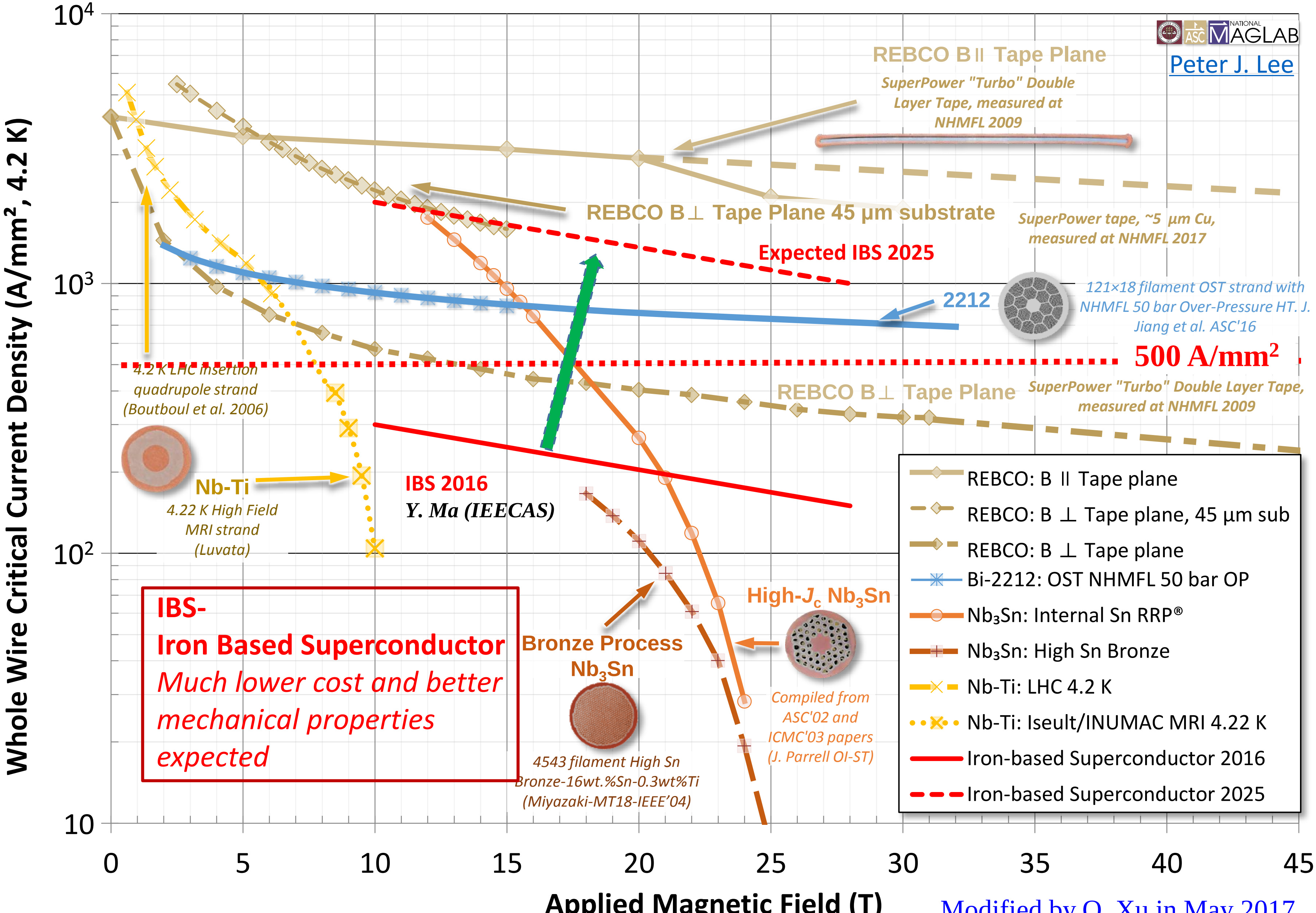
The J_c is much lower than the pair breaking current density >10^8 A/cm^2.

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.**

Prospects



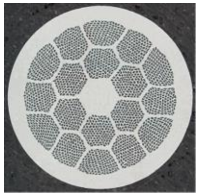
Modified by Q. Xu in May 2017

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

✓ ***High J_c Round Wires:***



→ Like Bi-2212, round wire is ideal for high homogeneity magnets – NMR

✓ ***Low Cost Wires:***

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

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

→ *Tensile, Bending*

Summary

- **In the past 5 years, significant progress in the development of LTS, YBCO C.C., Bi-2212, MgB_2 and iron-based superconducting wires and tapes has been made.**
- **Further improvement of J_c is needed, in view of the high cost of present HTS conductors.**
- **There should be a place for Fe-based superconductors such 122 type with H_{c2} values exceeding 70 T @20 K, T_c =38 K and anisotropy of <1.5.**

Thank you for your attention