铁基超导线带材研究进展

报告人：马衍伟 研究员

中国科学院电工研究所

报告内容

一、实用化超导材料简介

二、铁基超导体及其特性

三、铁基超导线材的制备与性能提高

四、铁基超导线材的实用化制备研究

五、结论与展望

超导技术—21世纪战略高新技术

超导体的奇特物理学特性：

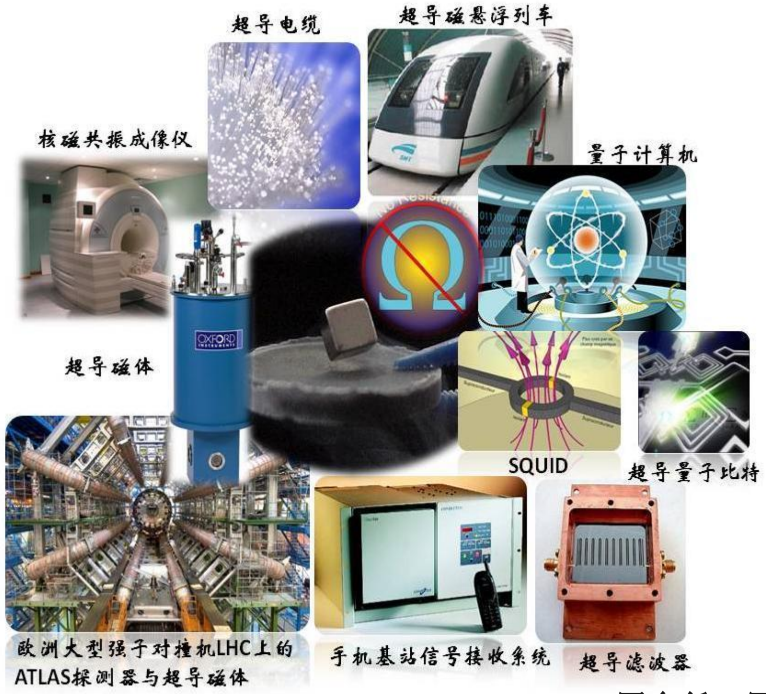
- ➢ 零电阻
- ➢ 高密度载流能力
- ➢ 完全抗磁性

可广泛应用于：医疗、能源、交通、电力、国防等领域

超导材料 ➡ **超导电力** / **超导磁体及应用**

➢ **《国家中长期科技发展规划纲要》前沿技术中的“高温超导技术”专题方向**

➢ **超导材料及应用被列入十大重点突破领域发展方向**

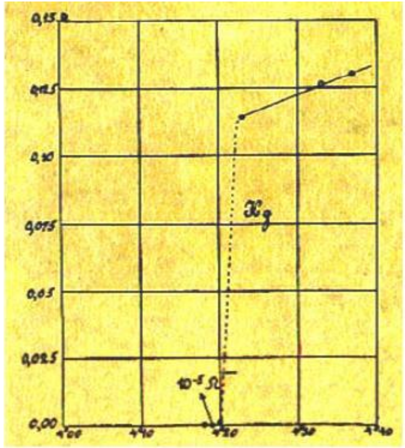


罗会仟，周兴江，神奇的超导，2012

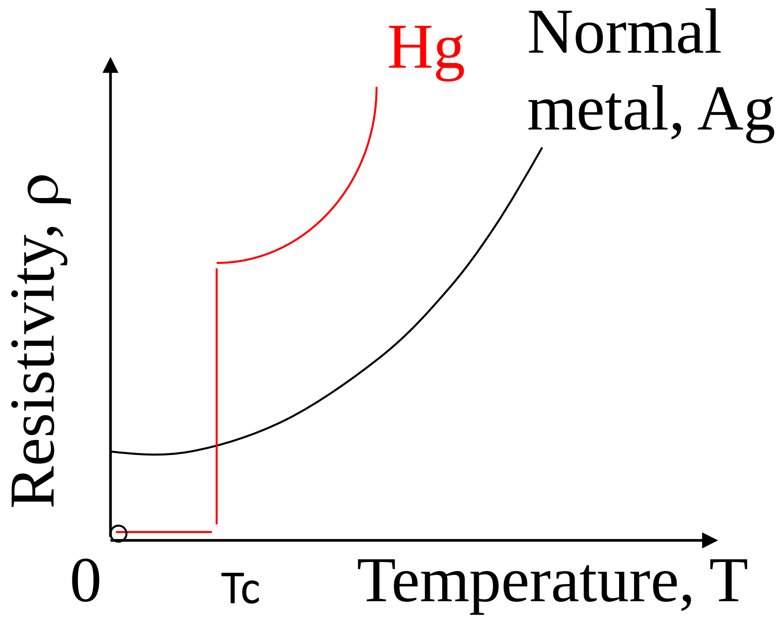
超导体的发现

- 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).

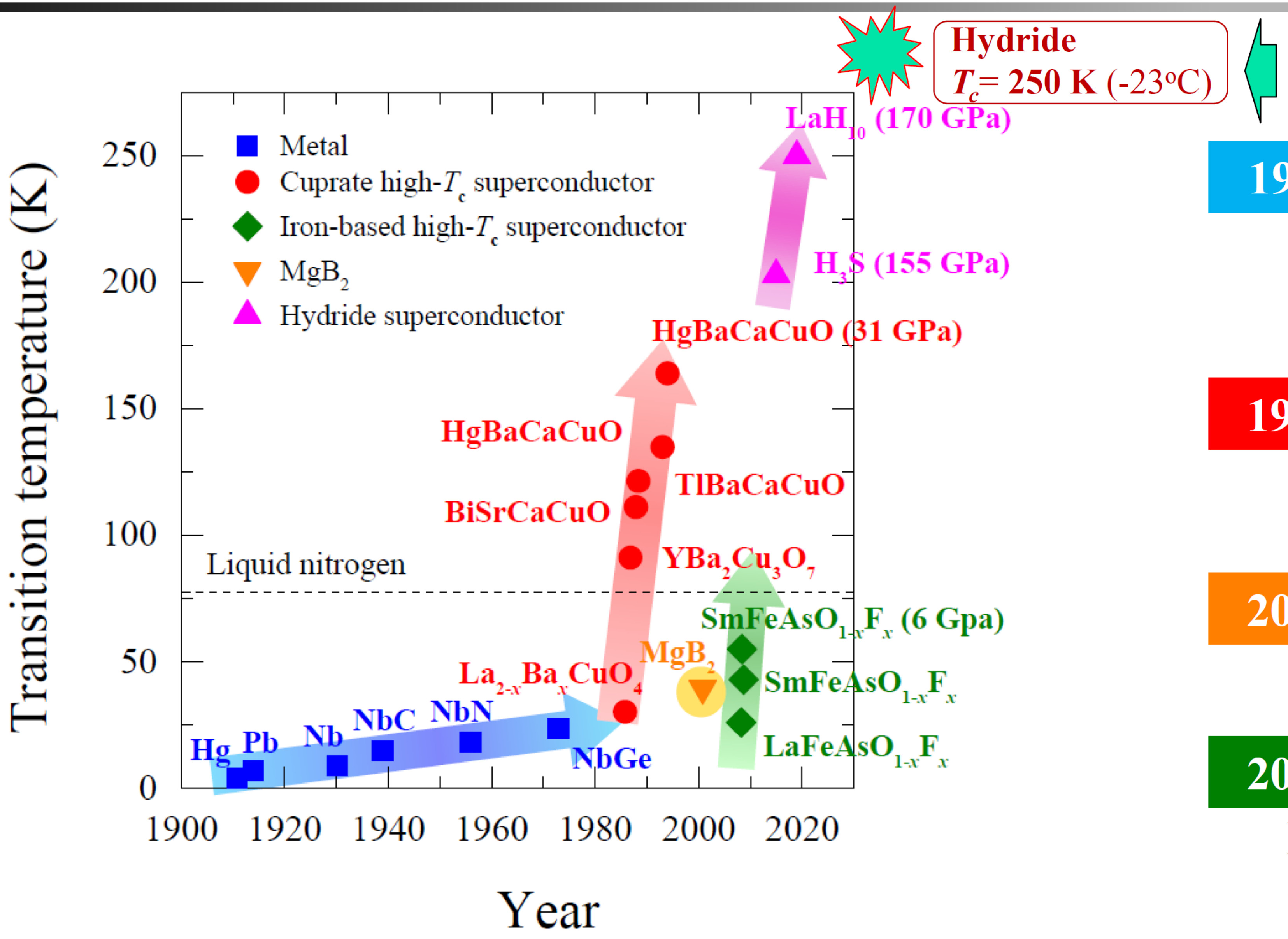
1911年，荷兰莱顿大学的卡末林—昂内斯意外地发现，将汞冷却到-268.98°C时，汞的电阻突然消失。



Resistance vs temperature curve of mercury (Onnes, 1911)



History of Superconductivity



2019

1911

Discovery of superconducting phenomenon

1986

Cuprate high-T_c superconductor

2001

MgB_2

2008

Iron-based high-T_c superconductor

发现的超导体已达上千种

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-$(BEDT\text{-}TTF)_2$-$Cu(SCN)_2$	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

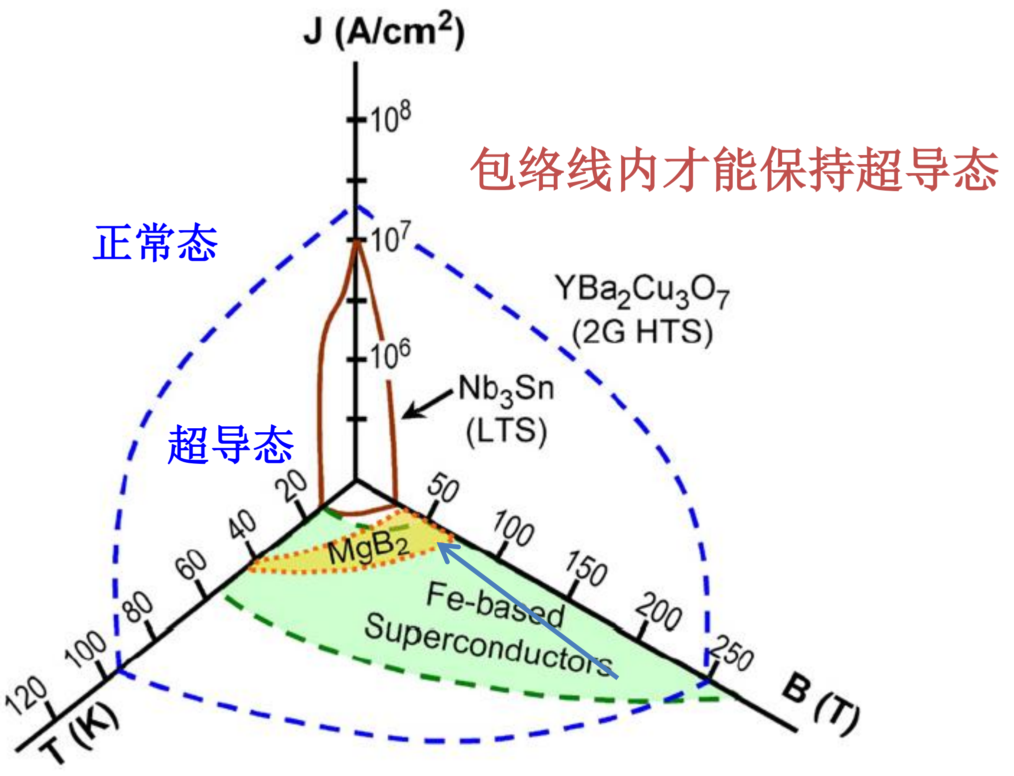
Semiconductor, Semi-metal & insulator

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

超导材料的临界参数

实用化超导材料的要求：

1. 临界温度 - T_c
2. 临界磁场 - H_{c2}
3. 临界电流 - J_c



Li et al., ***Rep. Prog. Phys.*** **74** (2011) 124510

超导线的特性：与温度、磁场、电流相关

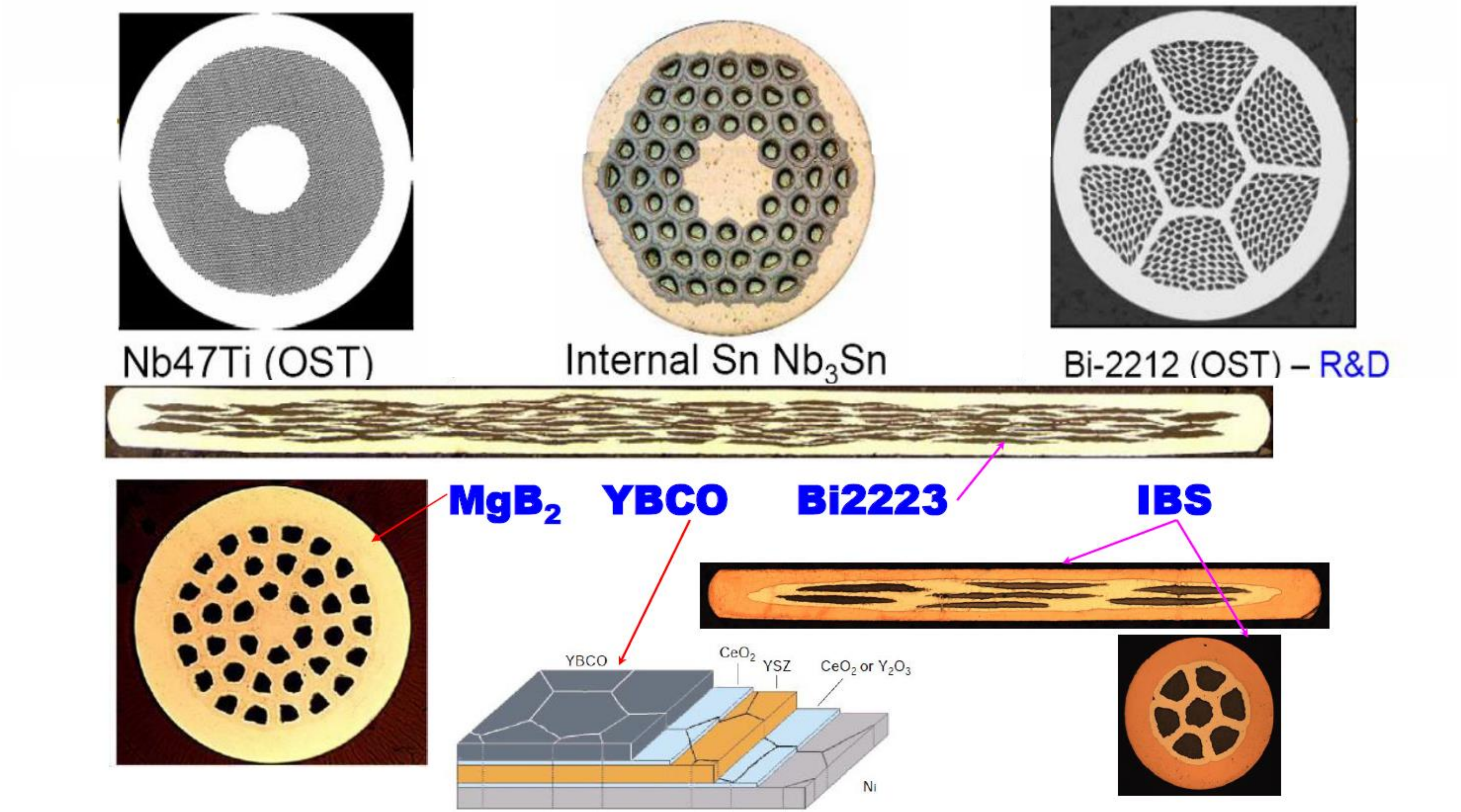
这三个值越大，其应用范围越广，不同材料有不同的值

实用化超导材料 Wire & Tape

尽管目前已有上千种超导体被发现，但是具有实用化价值的仅6种， 只有低温超导材料实现了大规模应用，高温超导尚处研发阶段。

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

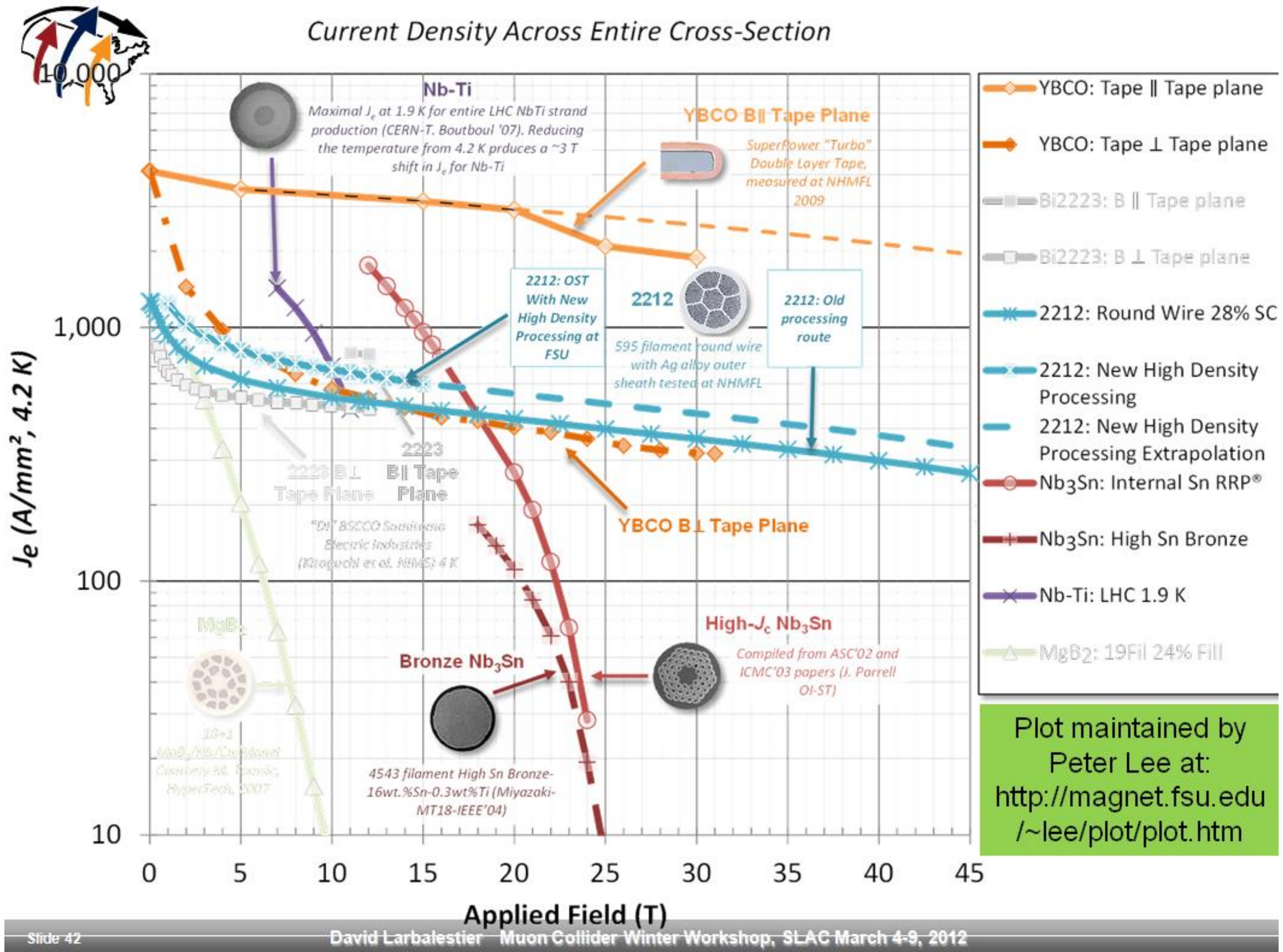
实用超导材料工艺及结构—多芯线带材



Courtesy of D. Larbalestier -- adapted

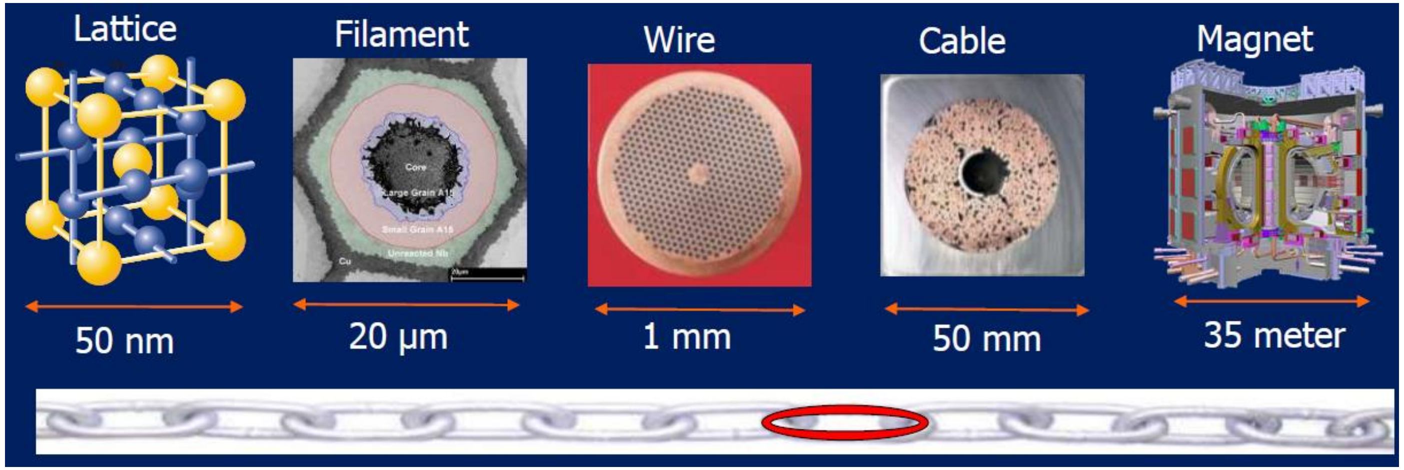
强电或强磁场下的应用

关键——如何提高磁场下的临界电流密度？



影响实用化超导材料发展的其它因素

除J_c外



材料实用化特性方面：

- 小的各向异性
- 低的交流损耗
- 良好的热稳定性
- 良好的机械特性
- 易于规模化生产
- 低成本

1.性能
2.价格

性价比

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

国家战略需求：高场超导磁体技术

大科学装置、未来能源变革性发展、先进医用设备等重大需求牵引：

高场超导磁体

磁感应强度B

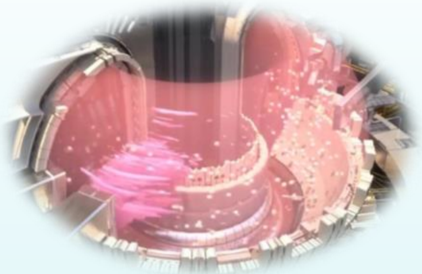
40T+/32mm混合磁体装置（CHMFL）

高能量粒子加速器

对撞能量$\propto B$

CEPC-SPPC下一代加速器 16-24T二极磁体

磁约束核聚变装置



聚变功率$\propto B^4$

CFETR要求最高磁场>15T

先进MRI成像设备

分辨率$\propto B^2$

先进核磁成像系统

- 未来高场超导应用与装置的发展与变革，对磁场强度的要求不断提高；
- 极高磁场所带来的诸多优点，使得人类对于物质世界的认识不断加深，对于生命起源以及重大疾病的防治研究具有特别重要的意义；
- 高场超导磁体技术是科学仪器、医疗、工业加工、电力装备和国防特种装备的核心技术。

新的高能量粒子加速器：更高磁场的超导磁体

科学价值

环形粒子加速器对撞能量与二极磁体场强成正比

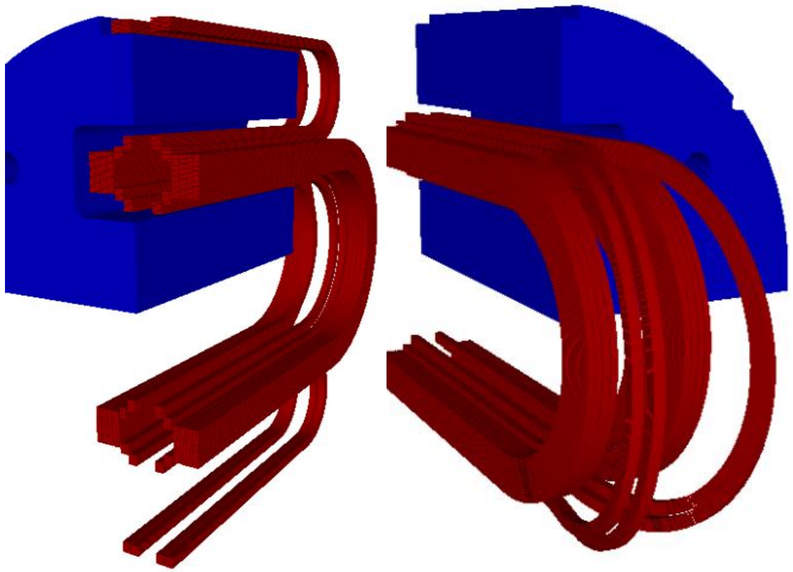
$$E[GeV]=0.3\times B[T]\times \rho[m]$$

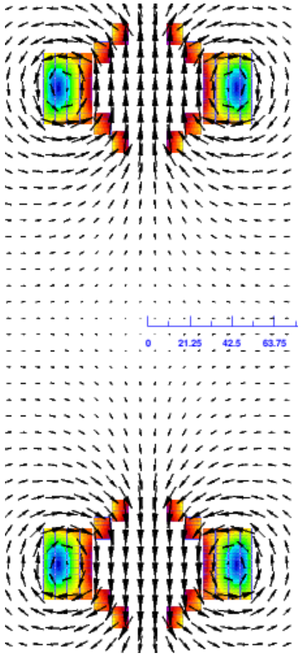
高温超导材料是进一步提高场强（16～24 T）、同时控制造价的唯一选择，高温超导材料应用前景巨大。

未来 CEPC SPPC

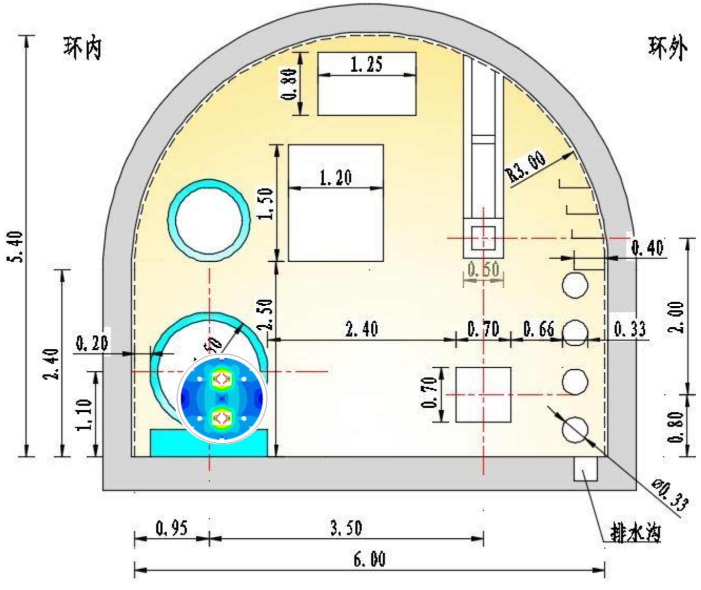
LHC 升级为 FCC

SPPC或FCC需数千个高场超导磁体





SPPC高场超导磁体概念设计

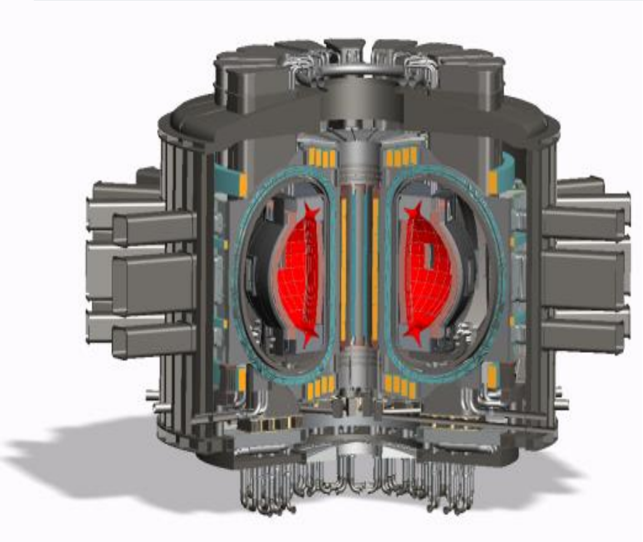


SPPC隧道截面布局

未来聚变堆需求挑战大型超导磁体极限

未来聚变堆运行环境：

- 高磁场：~15T
- 大电流：~100kA
- 大尺寸：~10m

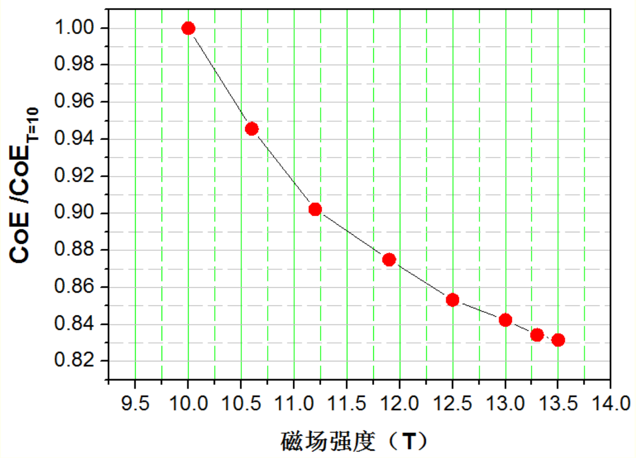


装置名称	ITER	EU-DEMO	CFETR
国家	国际	欧盟	中国
最高场 （T）	10.8	~13.5	~15

经济价值

磁体系统是聚变堆的核心

P_{fusion}=500MW



高场优势：

- □ 提高聚变功率($\propto B^4$)
- □ 增强等离子体约束能力
- □ 减小规模，提高经济性

磁场升高↑ 发电成本↓

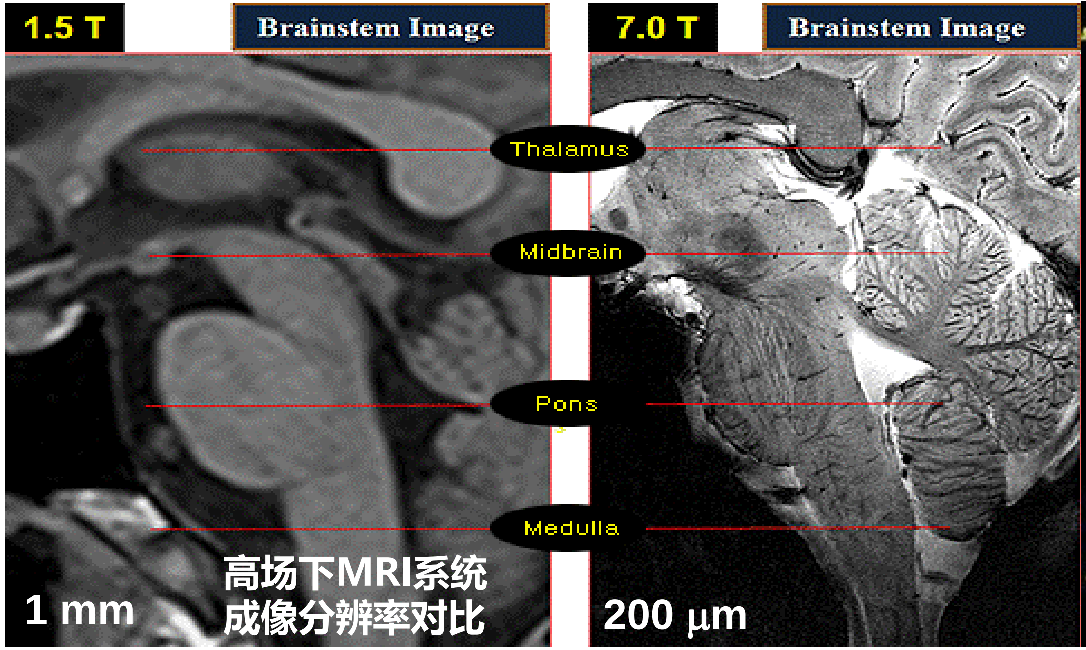
超高场磁共振成像系统

社会价值

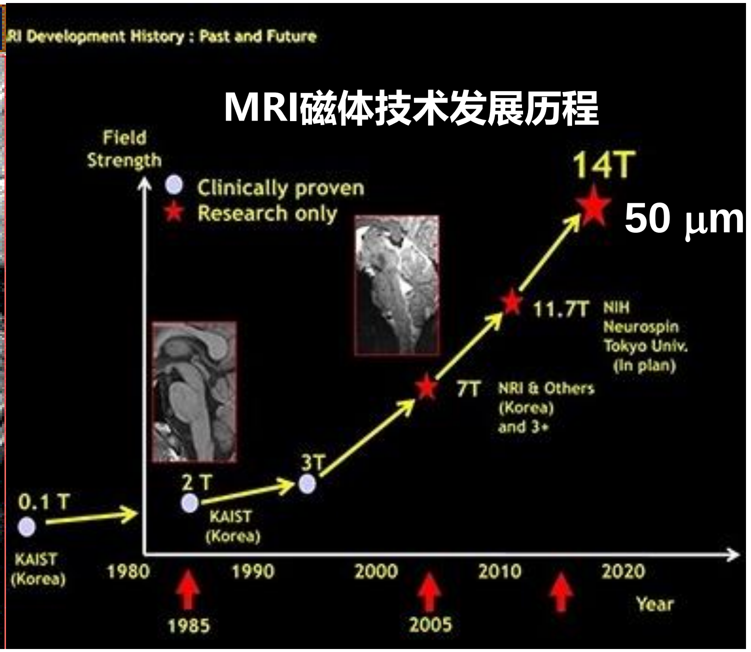
脑科学研究及疾病诊断

- **超高场MRI系统分辨率高**，在脑科学研究、早期脑部及心脏疾病、**早期癌症和肿瘤诊断**方面，有着十分重要的应用。
- 国内在高场MRI研究领域处于起步阶段。

高场强 → 高信噪比（SNR） → 高分辨率



高场下MRI系统成像分辨率对比



超导磁共振成像--快速增长的市场

高端的医疗

1.磁共振成像(MRI)己广泛应用于医学诊断中。
2.目前全世界医院中的MRI约有80%采用超导磁体。

人民健康需求
日益增长

国家	每百万人口约拥有MRI设备台数
日本	38
美国/欧洲	54
韩国	7
中国	3

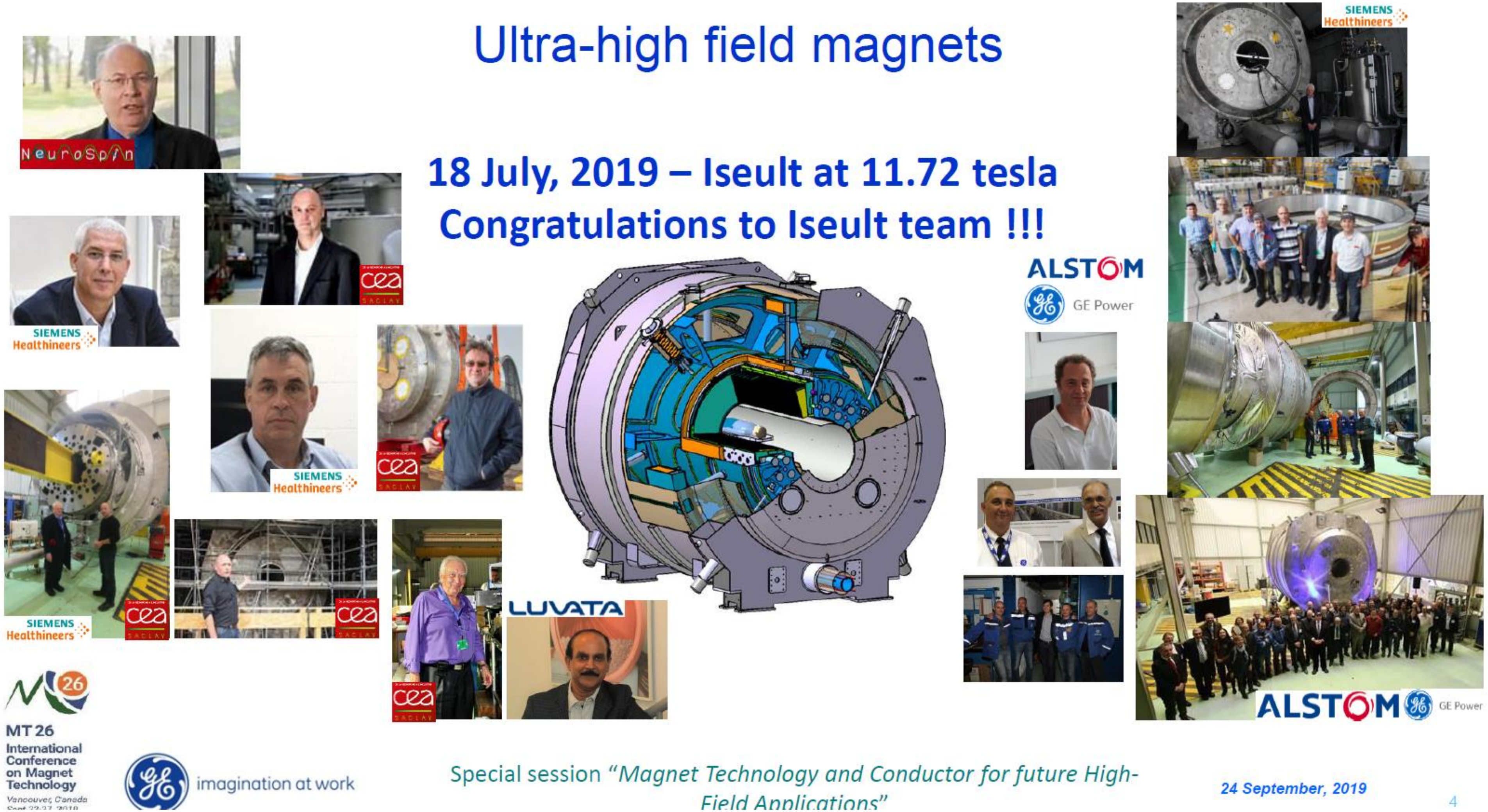
中国现有县级以上医院约16000家，未来10年每年将新增400一500台。据预测，未来10年在中国MRI就应该有上千亿元人民币的市场容量。

MRI中，NbTi线为主，2500吨/年

我国现状：相关超导材料和磁体目前仍然主要依赖进口，价格昂贵！限制自主创新！

法国CEA--世界首台11.7T核磁共振成像系统

MT-26, Vancouver, Sep. 2019



◆ 这台设备重132吨，长5米，外径5米，内径90厘米， 经过了六年的开发和近两年的安装调试。

◆ 相比目前的磁共振系统能够实现更高的时间和空间分辨率。

下一个目标—14.1T核磁共振全身成像系统

Unique ultra-high field MRI magnets after 11.7 T Iseult

Next step

Boost MRI magnet technology,
and magnet technology in general
to
14+ tesla, 600+ MHz

全超导高场磁体—发展现状

- **24.6 T** cryogen free SM

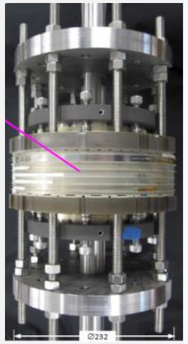
第一个真正用户型

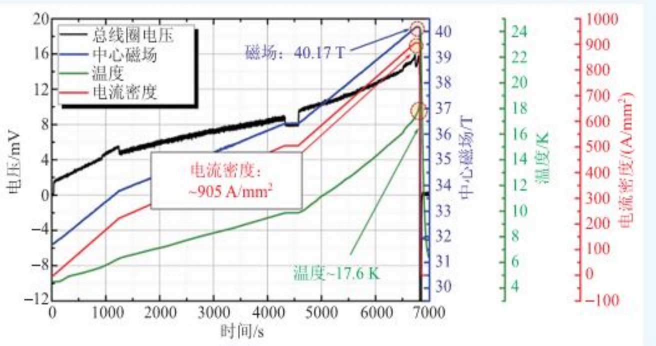
S. Awaji et al., SUST **30** (2017) 065001

- **32 T** at Tallahassee (NbTi, Nb_3Sn, RE-123) Huub Weijers – 2017.12

NATIONAL HIGH MAGNETIC FIELD LABORATORY

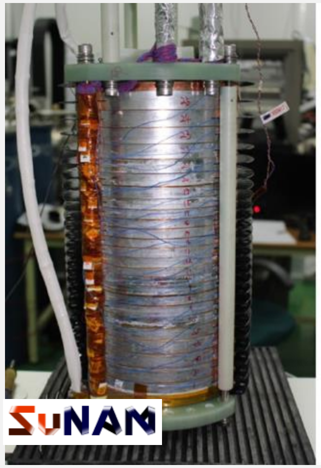
- 美国高场实验室 **45.5T** 混合磁体

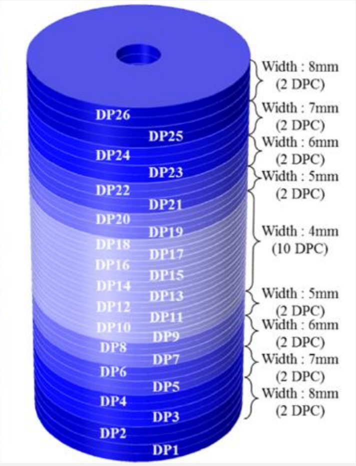




水冷磁体提供31.1 T，YBCO提供14.4 T，中心场达到45.5 T

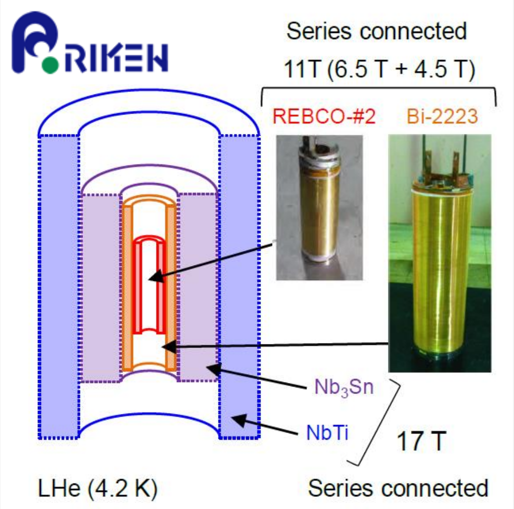
- **26.7 T, all RE-123**
  no insulation coils
  (radial current sharing)





S. Yoon et al., SUST **29** (2016) 04LT04

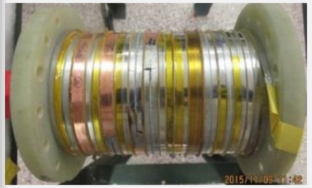
- **27.6 T** demonstrator for 1.3 GHz (30.5 T) NMR project



Y. Yanagisawa et al., SNF, STH42

- **32.35 T** @ 全超导磁体-2019.11
  中科院电工所

LTS: 15 T
YBCO内插:
17.35T



J. Liu et al., SUST **33** (2020) 03LT01

大孔径高场全超导磁体技术亟待加强

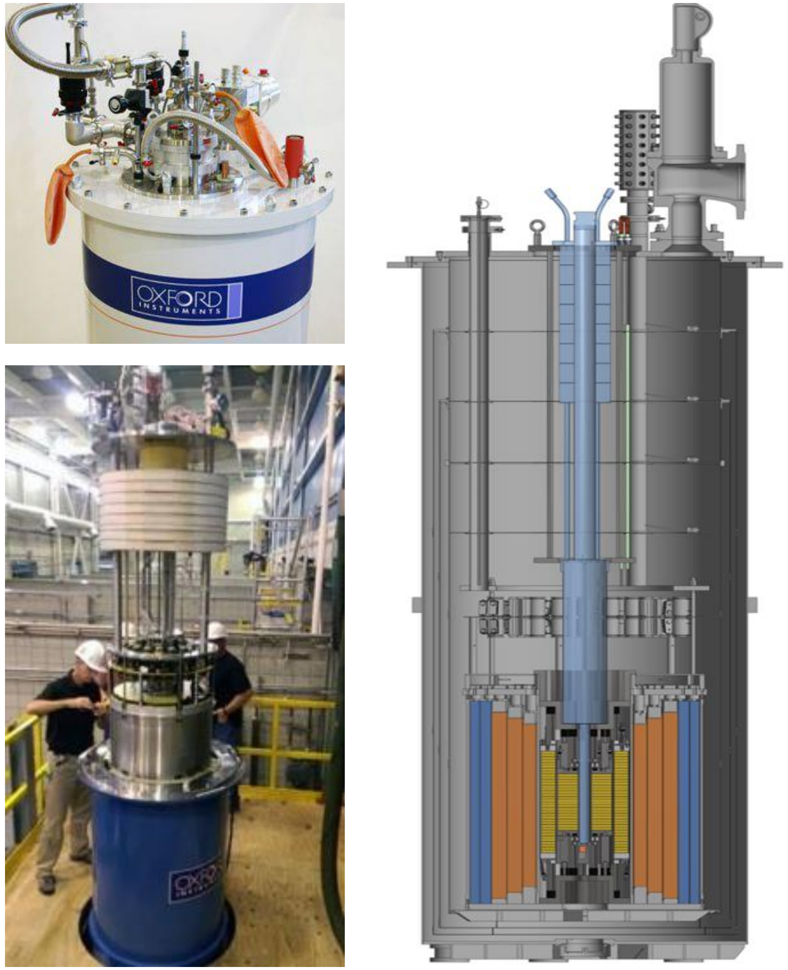
大孔径高场全超导磁体目前依赖进口，与国外有较大差距：

- 国外垄断，无谈判余地
- 价格高（价格约是成本的3倍以上）
- 国内需求强烈

部分产品价格：

场强（T）	口径（mm）	价格（万元）
15	150	~500
15	250	~2500
19	150	1600 (17年)
		2200 (19年)
20	52	~500

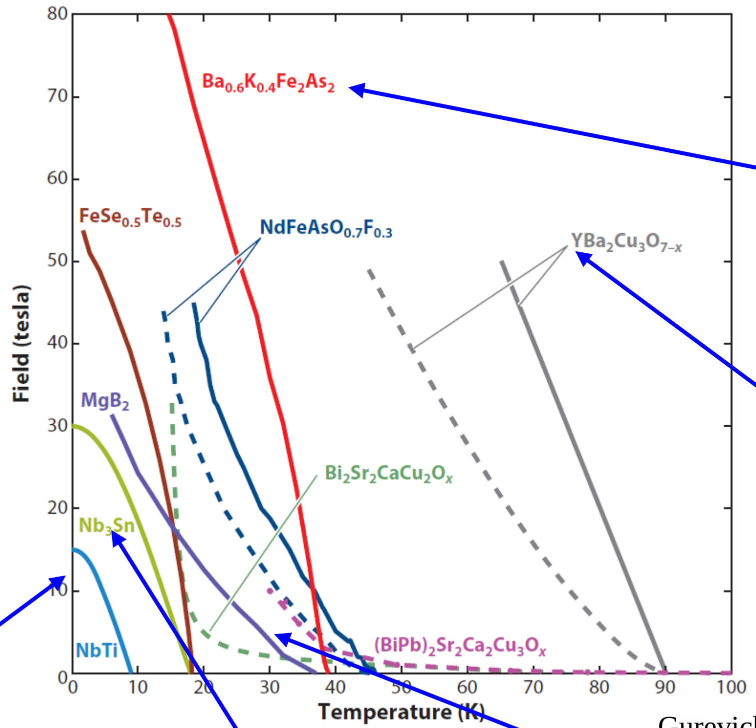
依托大科学装置积累的技术与人才基础，开展攻关，解决当前“卡脖子问题”！



牛津仪器公司大口径超导磁体

高温超导体的独特性和不可替代性

高场强的需求已逐渐突破了传统超导材料的极限，同时规模化应用对制冷成本的要求，需要使用临界温度更高的超导材料，因此高温超导材料是未来高场磁体应用的必需选择。



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

IBS
May do better
for magnets of >20T
if commercialization

Bi2212 or YBCO
for DC magnets
of >20T
if cost comes

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

Nb_3Sn
for magnets of 9-20T

MgB_2
not for high field magnets but niche market 1-3T, 4-20K

- ◆ 由于氧化物超导体和铁基超导体的上临界场极高，在低温下可以远高于100T。
- ◆ 因此，用来制造磁场大于20T以上的超导磁体。
- ◆ 而低温超导体难以实现 X

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三、铁基超导线材的制备与性能提高

四、铁基超导线材的实用化制备研究

五、结论与展望

新型超导材料–铁基超导体（IBS）的发现

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

T_c= 26 K

Februry, 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†‡§

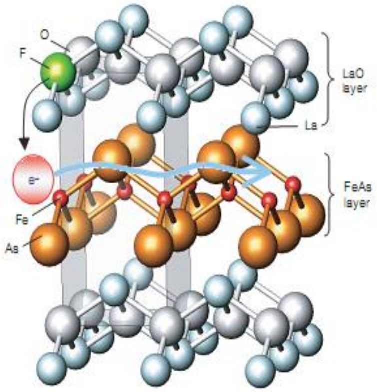
ERATO-SORST, JST, Frontier Research Center, Tokyo Institute of Technology, Mail Box S2-13, Materials and Structures Laboratory, Tokyo Institute of Technology, Mail Box R3-1, and Frontier Research Center, Tokyo Institute of Technology, Mail Box S2-13, 4259 Nagatsuta, Midori-ku, Yokohama 226-8503, Japan

hosono@msl.titech.ac.jp

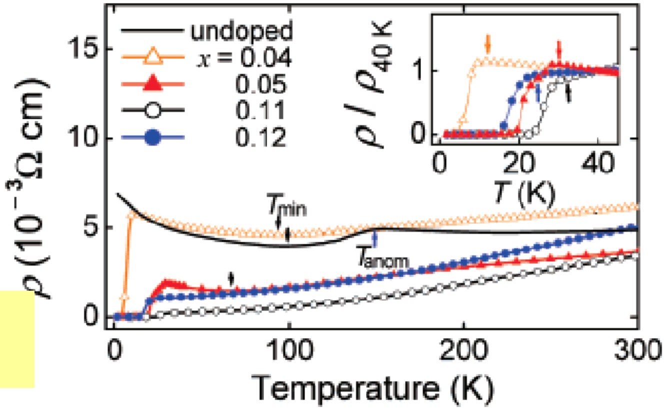
Received January 9, 2008

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 %.



细野秀雄
Hideo Hosono



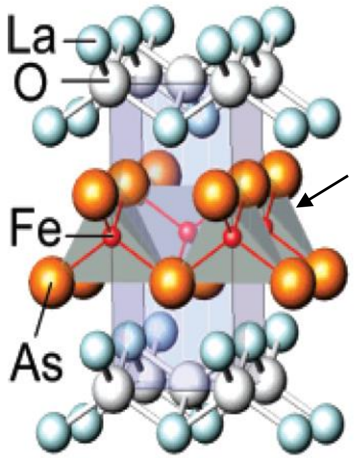
美国《科学》认为是最有发展前景的新型高温超导体

Major classes of IBS families

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

--典型的层状结构，含有FeAs(Se)层

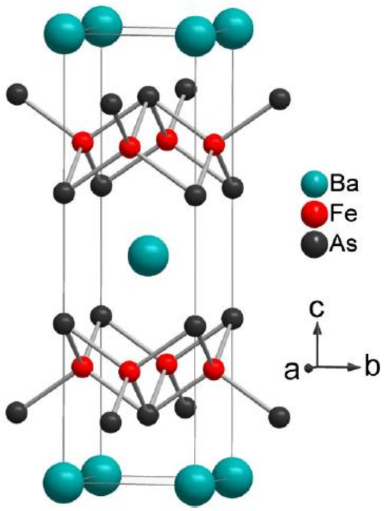
1111 Phase LnOFeAs



T_c ~55 K

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

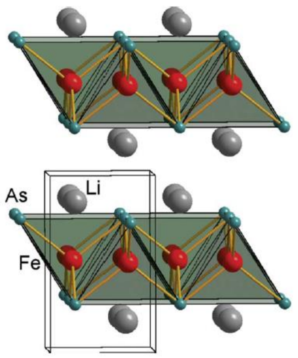
122 phase AFe_2As_2 (A=Ba, Sr, Ca)



T_c ~38 K

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

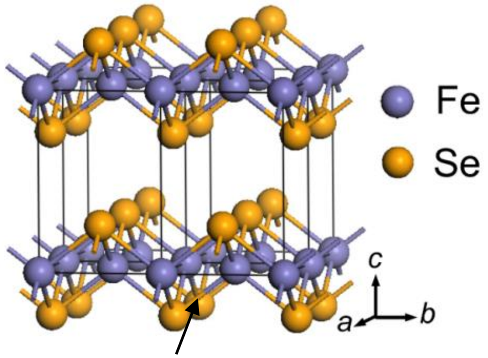
111 phase LiFeAs



T_c ~18 K

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

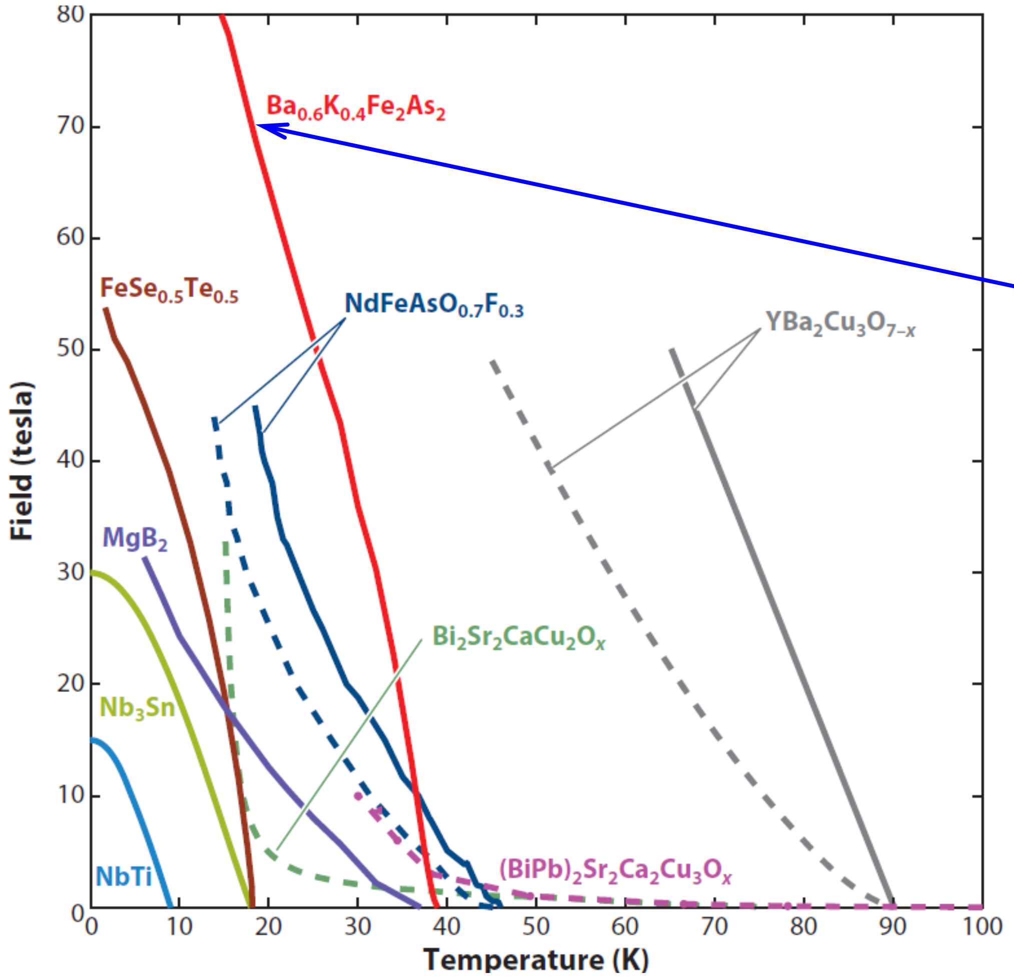
11 phase FeSe



T_c ~8 K

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

铁基超导体具有极高的上临界场 (H_{c2})



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

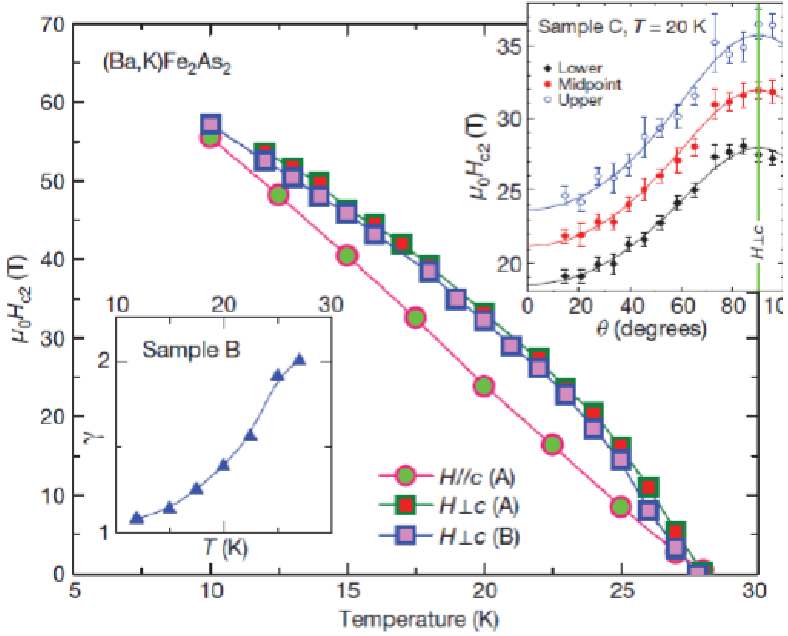
At 20 K, the H_{c2} can be >70 T where IBS outperform both MgB_2 and Bi-2223.

- **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**

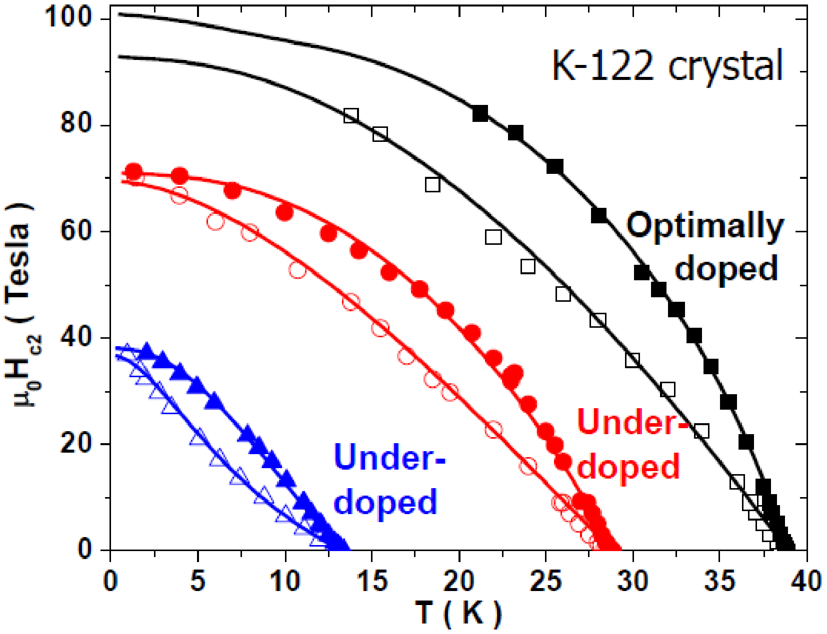
外推 H_{c2}(0 K) 可以超过 200 T，在20 K可产生 > 70 T，远远超过MgB_2 和LTS超导体 。

122铁基超导体 – 各向异性小

H_c anisotropy



Yuan et al. Nature 457, 565 (2009)



Tarantini et al. PRB 86, 214504 (2012)

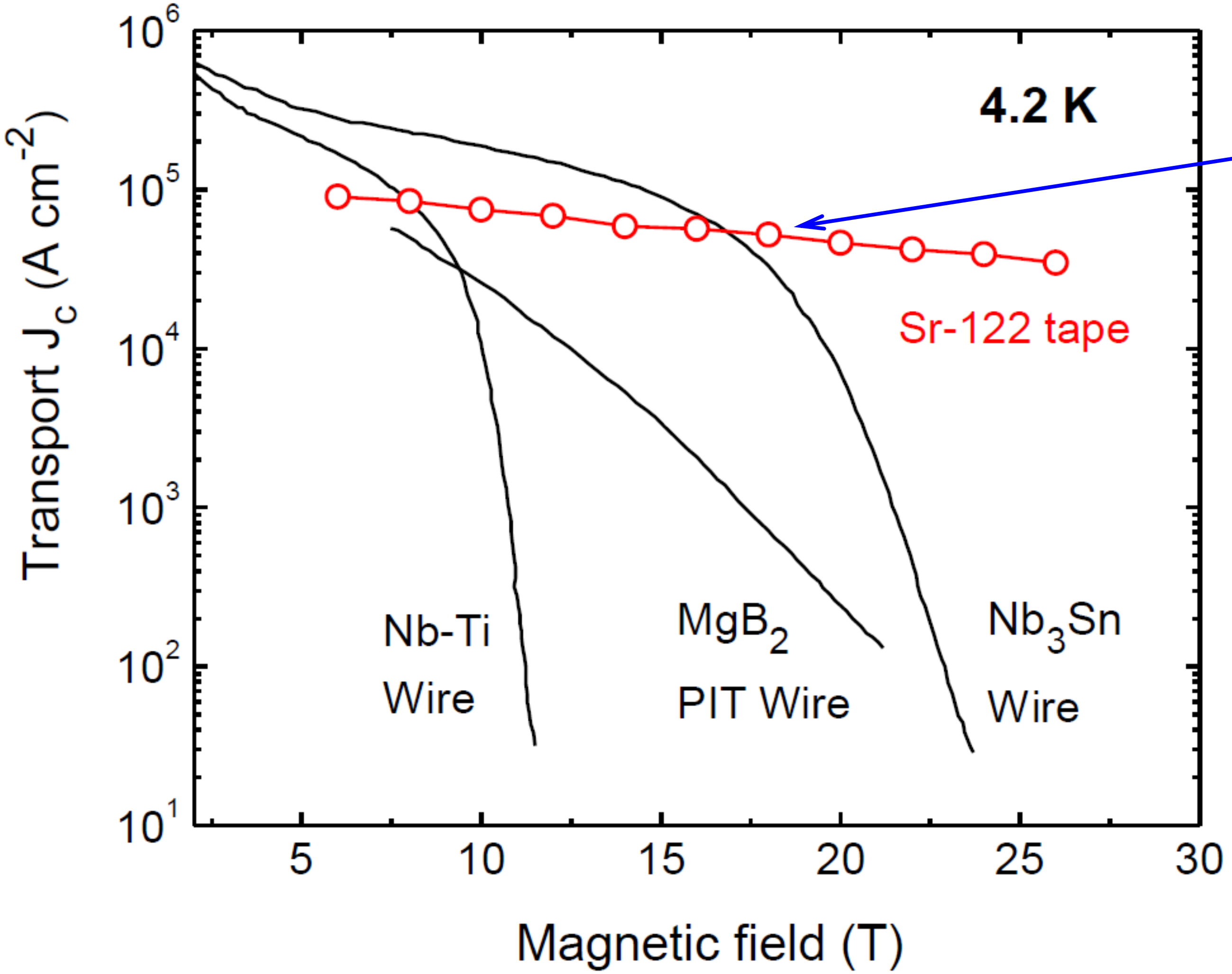
J_c anisotropy

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

铁基线材传输电流：对磁场不敏感，高场下的性能优异



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

明显优于Nb_3Sn材料

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

Parameters between different superconductors

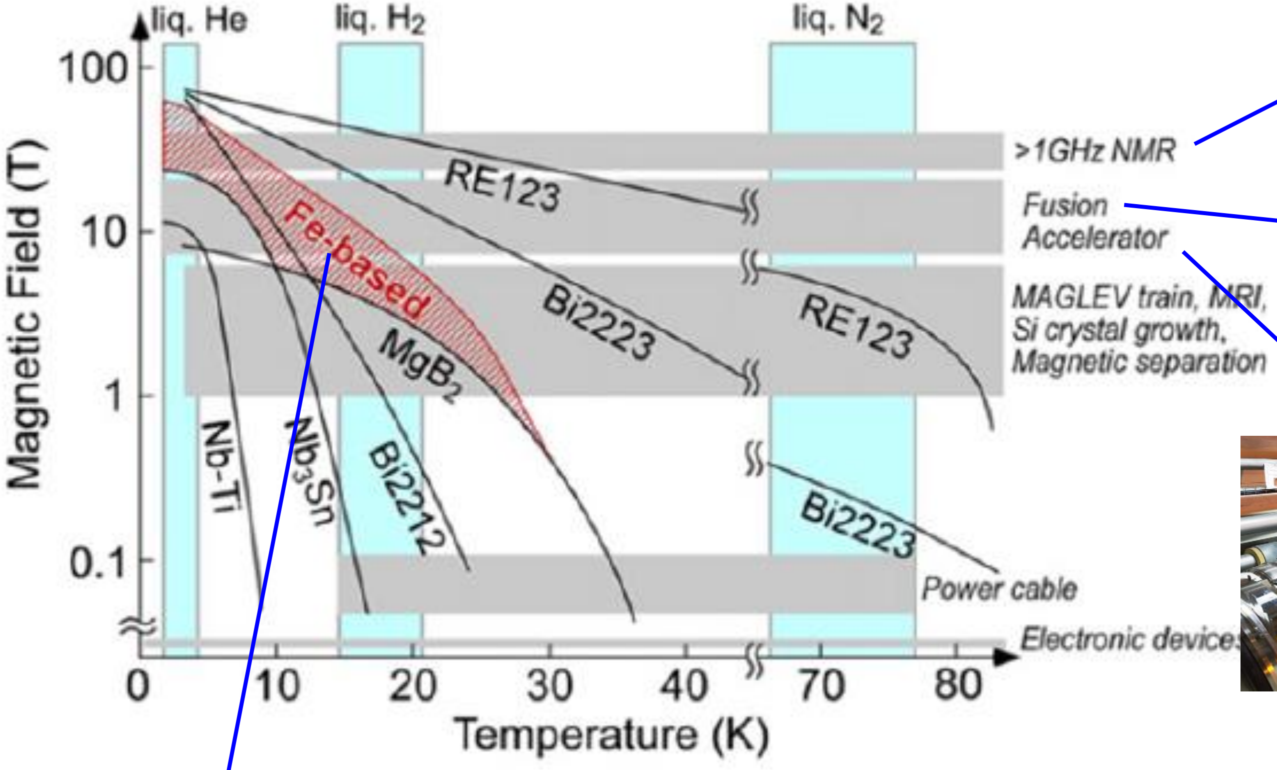
	LTS (NbTi, Nb_3Sn)	Cuprates	MgB_2	Iron-based
Pairing symmetry	s-wave	d-wave	s-wave	s-wave
Impurity	--	Sensitive	Sensitive	Robust
Maximum T_c	18 K	134 K	39 K	55 K
Operation temp.	≤4.2 K	≤77 K	≤25 K	≤30 K
H_{c2}	~30 T	>100 T	~40 T	>100 T
Coherence length	3-4 nm	1.5 nm	6.5 nm	1.5-2.4 nm (122) 1.8-2.3 nm (1111)
Anisotropy (γ)	1	5-7 (YBCO) 50-90 (BSCCO)	~3.5	1-2 (122) 2-5 (1111)

- **Several similarities with *HTS*: High H_{c2}, small coherence length.**
- **But IBS, *lower anisotropy*, the *symmetry* is not a d-wave but an s-wave.**

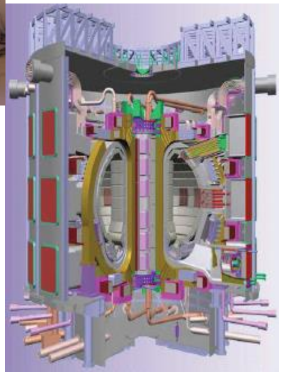
铁基超导材料是未来高场磁体的候选

现有材料难以实现！

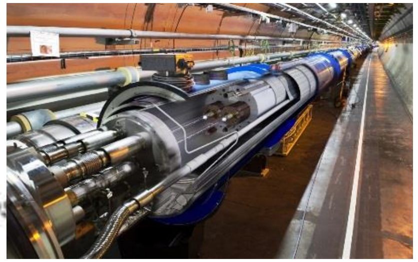
Shimoyama, ***SuST*** 27 (2014) 044002



>1GHz NMR
>23.5T



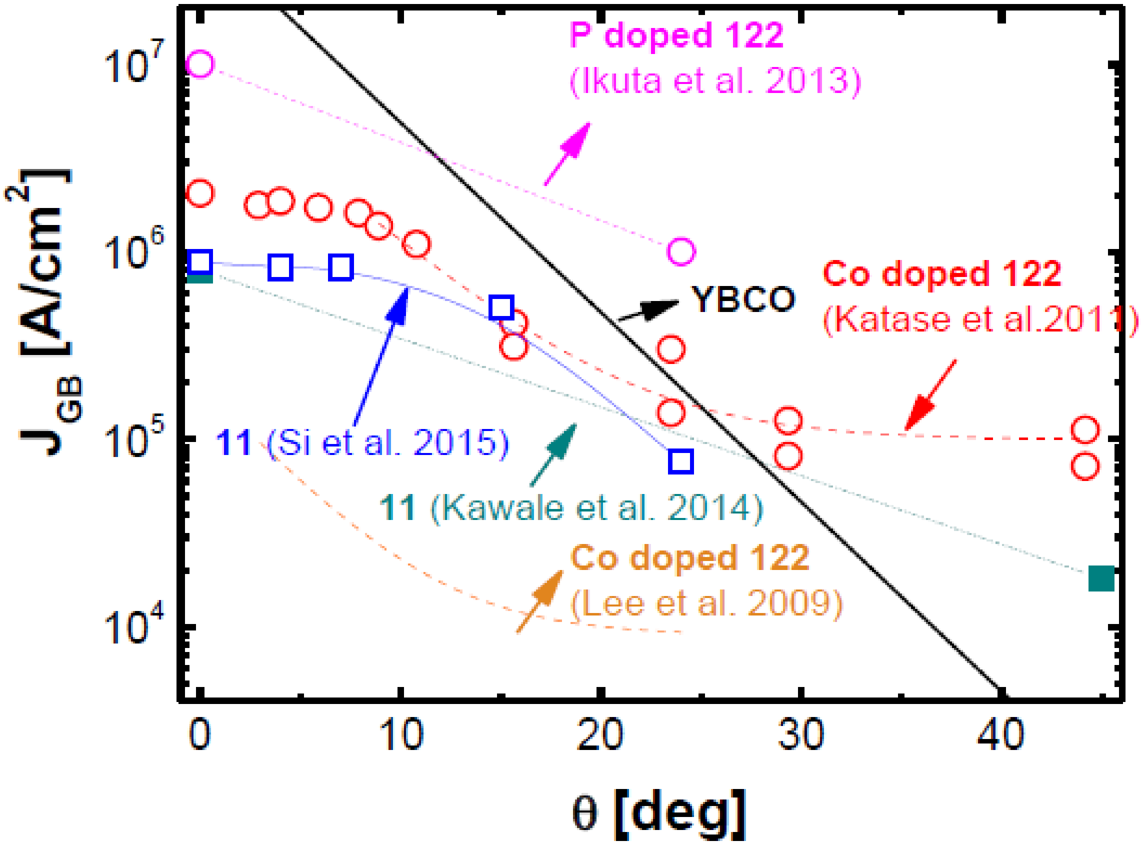
未来聚变堆
~15T（4.2 K）



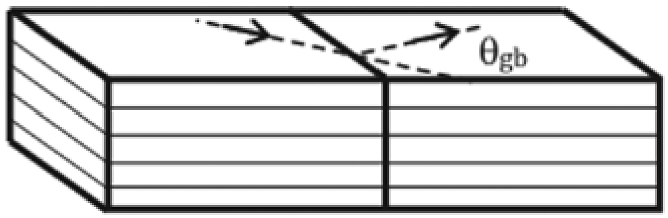
未来加速器
16-24T
（4.2 K）

被认为是高场磁体应用的新一代实用超导材料！

Grain boundary nature of 122 and 11 IBSs



M. Putti presented at EUCAS-2015



122 bicrystals
11 bicrystals

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

◆ Compared to cuprates, high and three dimensional grain orientation is not necessary for IBS.

◆ This feature is highly beneficial for the the realization of **cheaper conductors** and **PIT wires** for high-field magnets at low temperature.

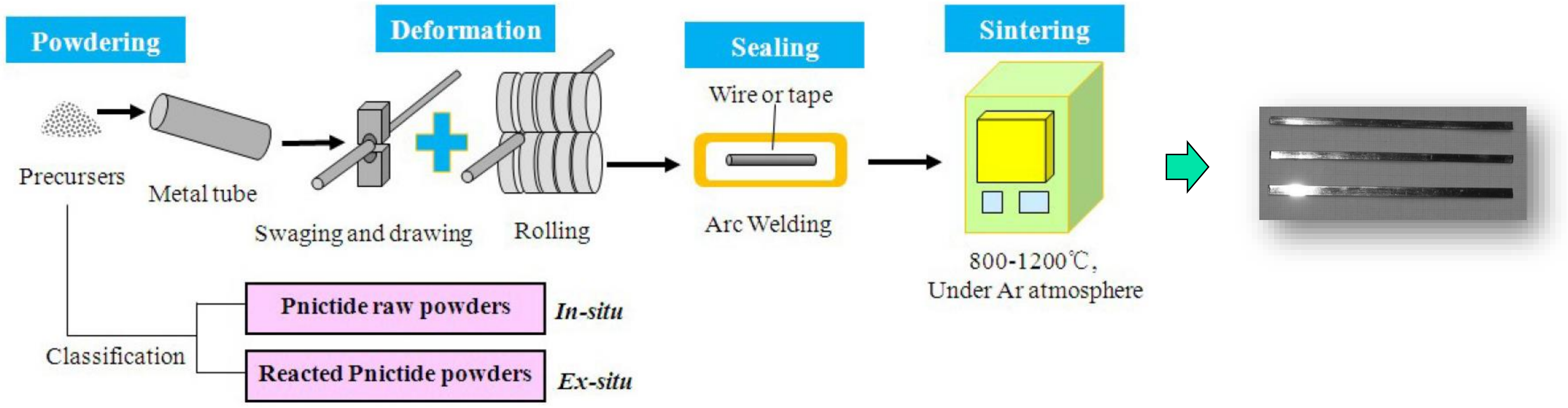
报告内容

铁基超导线带材 – PIT工艺 -- 制造成本低

与铜氧化物超导体相比，铁基超导体的晶界弱连接效应要小得多，可采用PIT工艺

铁基超导线材采用传统的粉末装管法(PIT)，即经拉拔、轧制及热处理等过程就可获得。已在制备Bi2223和MgB_2超导线带材中得到广泛应用。

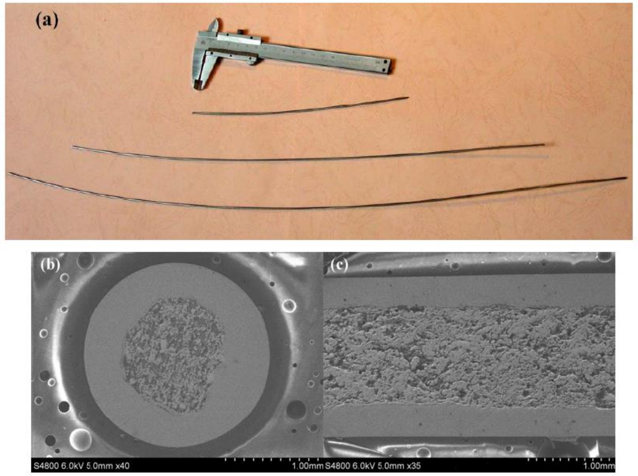
- 工艺简单，成本低廉，有利于规模化制备。
- 突出优点：可使用多种包套材料，如Ag、Fe、Cu、不锈钢或复合包套等；而铋系HTS线带材，只能使用Ag或Ag合金，因要透氧。



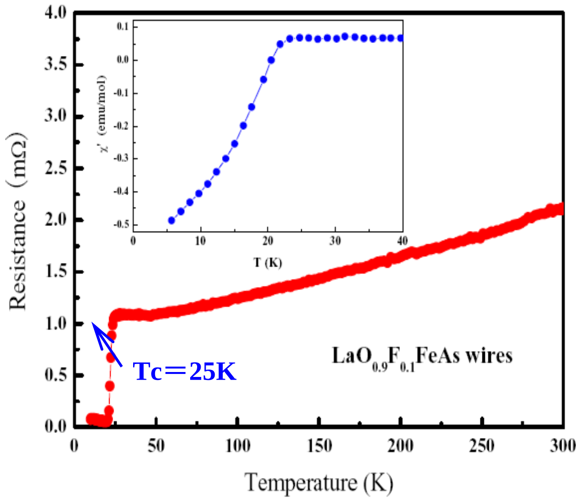
2008年4月，采用传统的粉末装管法，首次研制出新型铁基超导体线材

早期线带材

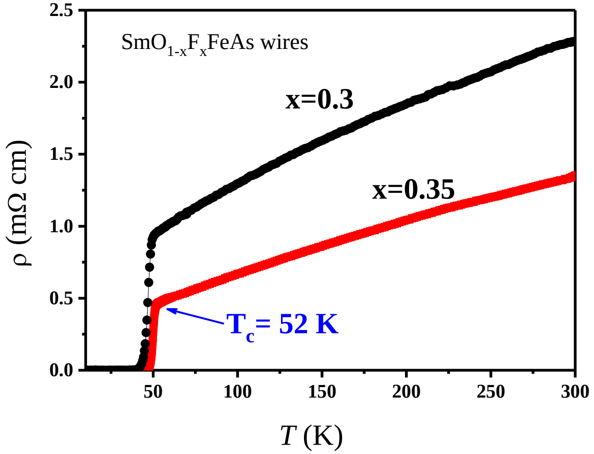
- 铁基线材临界电流密度非常低
- 主要是存在反应层、许多杂相、裂纹等



LaOFeAs



SmOFeAs



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

铁基超导线带材的发展

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

Phase I

线材初期

铁基线材研制

Jc-**100** A/cm^2

开始铁基线材的研究

Phase II

性能提高阶段

①

掺杂+织构+致密度
Jc-**10^4** A/cm^2@10T

打破当时停滞不前局面

②

致密度+织构协同调控
Jc-**10^5** A/cm^2@10T

达到实用化门槛

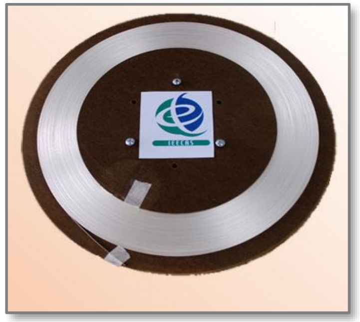
Phase III

实用化研究阶段

- 多芯线带材：7, 19, 114芯
- 应力应变测量
- 交流损耗、失超传播等
- 超导接头、超导线圈等

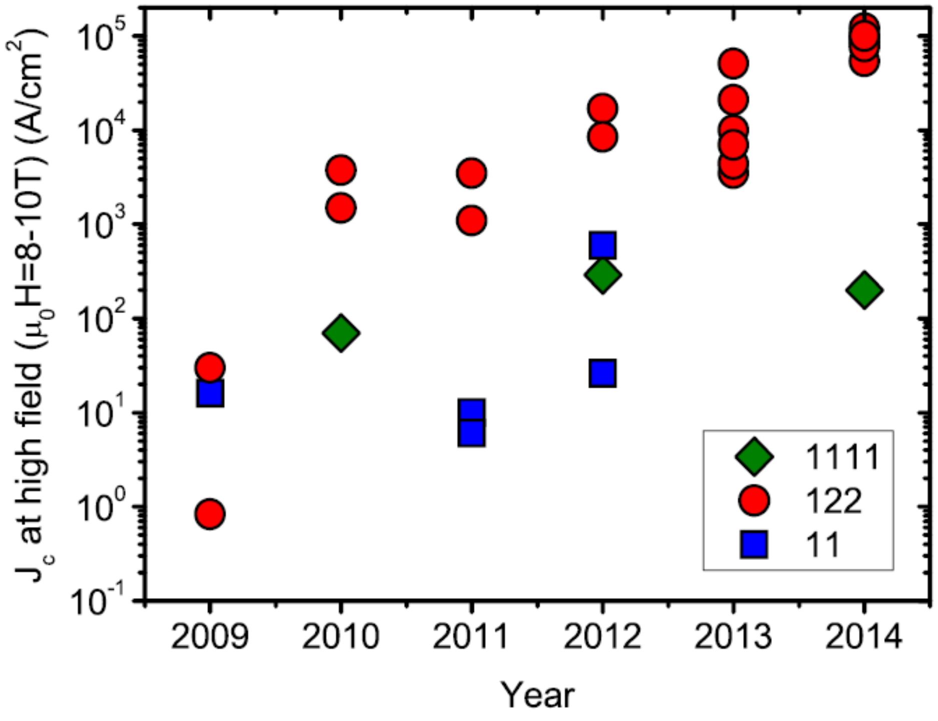
首根10米线材

首根100米铁基长线



铁基超导线带材国内外研究现状

Putti, ***Supercond. Sci. Technol.*** 28 (2015) 114005



主要研究单位：

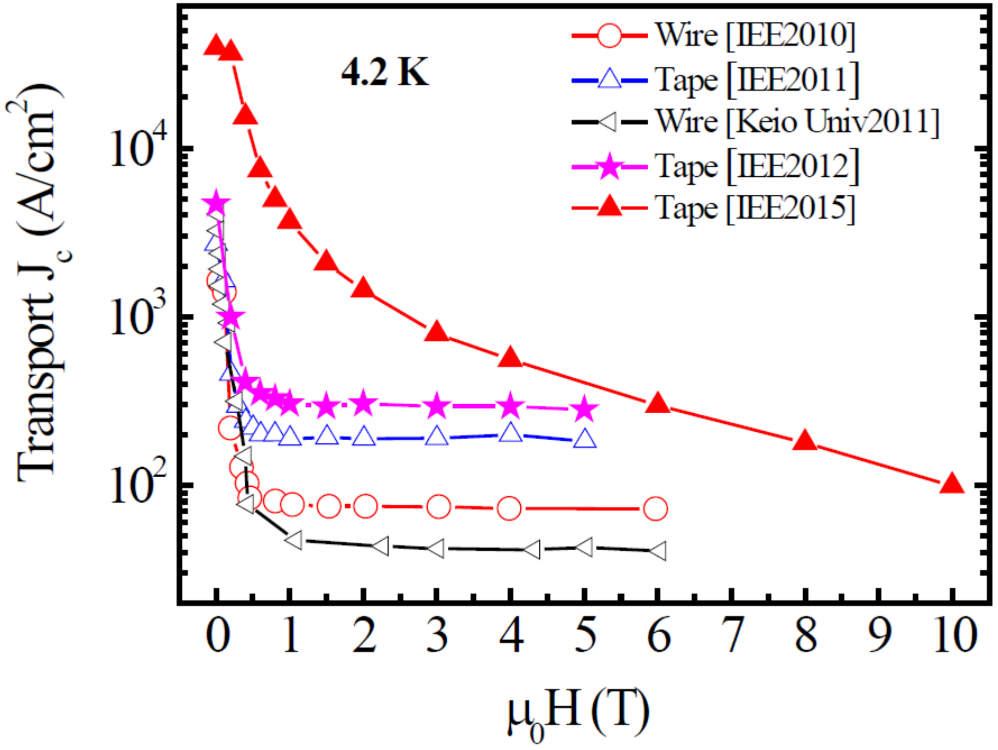
中科院电工所、
美国**Florida**高场实验室、
日本**NIMS**、
东京大学、
意大利热那亚大学、
美国橡树岭国家实验室、
日本**AIST**、
澳大利亚**Wollongong**大学、
美国**OSU**大学、
俄罗斯科学院、
英国牛津大学、
东南大学、
西北有色金属研究院等。

- 致力于提高磁场下的临界电流密度J_c；
- 铁基超导线带材主要集中在1111、122、11等体系；
- 其中122体系是目前最有实用化前景的铁基超导材料，发展最为迅速，性能提高也日新月异。

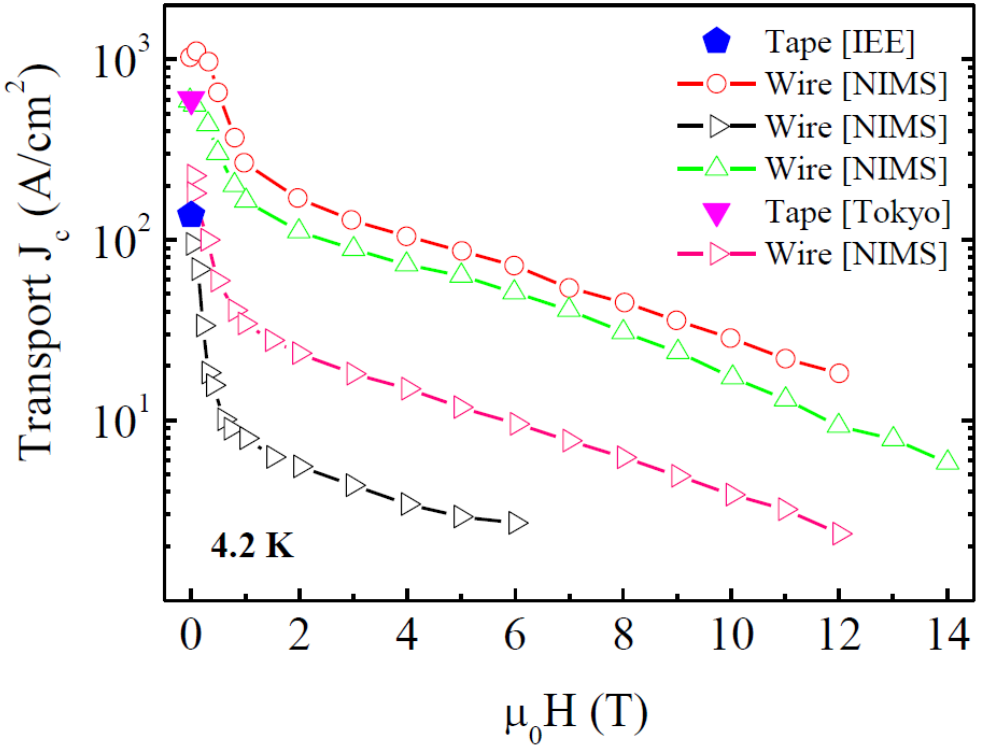
Compared to 122 tapes with J_c of 10^5 A/cm^2 @ 10 T

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.

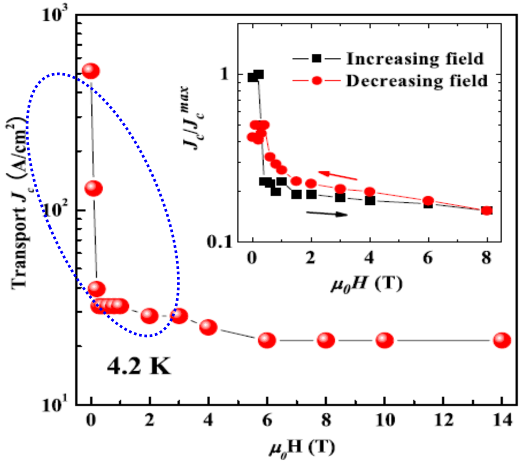
高性能铁基超导线材制备：面临的挑战

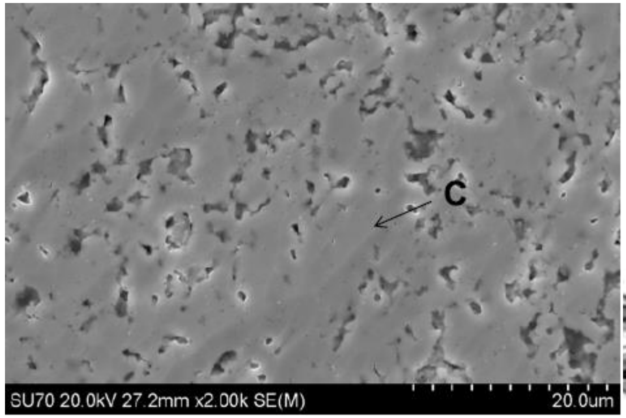
1、铁基材料属多相固态反应，杂相多，成相困难；

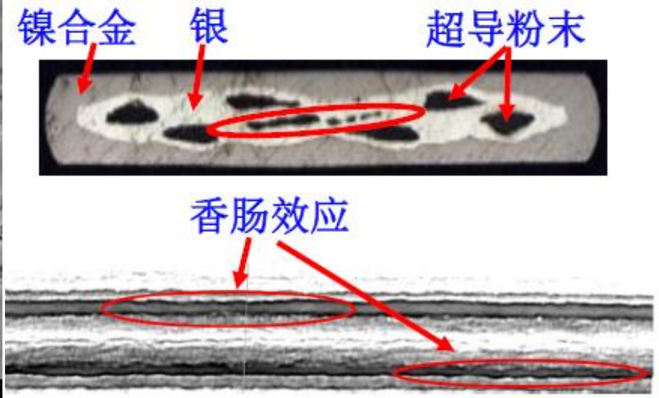
2、铁基超导体存在晶界弱连接问题；

3、热处理过程中易产生孔洞、裂纹等缺陷，晶粒连接性差；

4、长线加工过程中出现“香肠效应”。





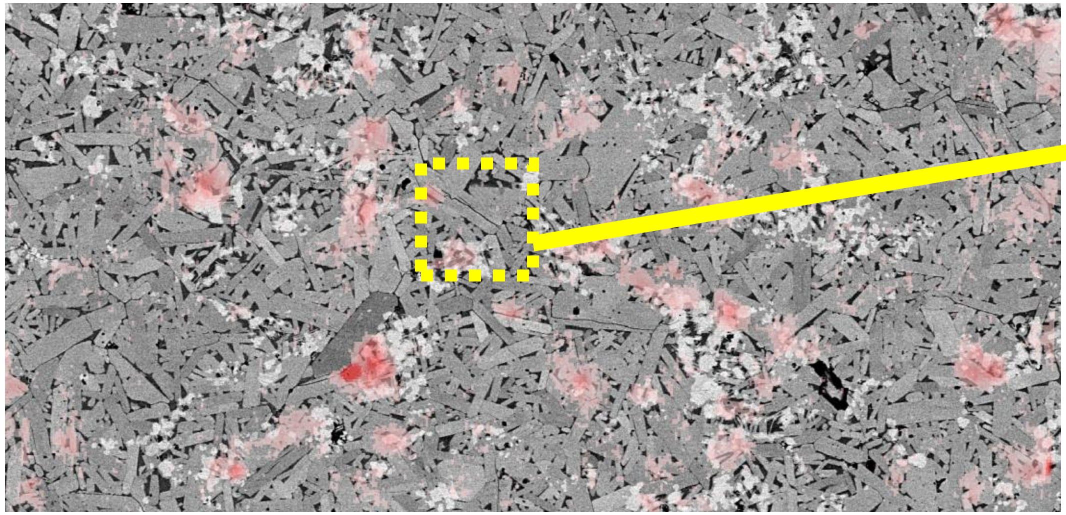


传输电流更大、性价比更高的铁基超导材料，推动其应用进程

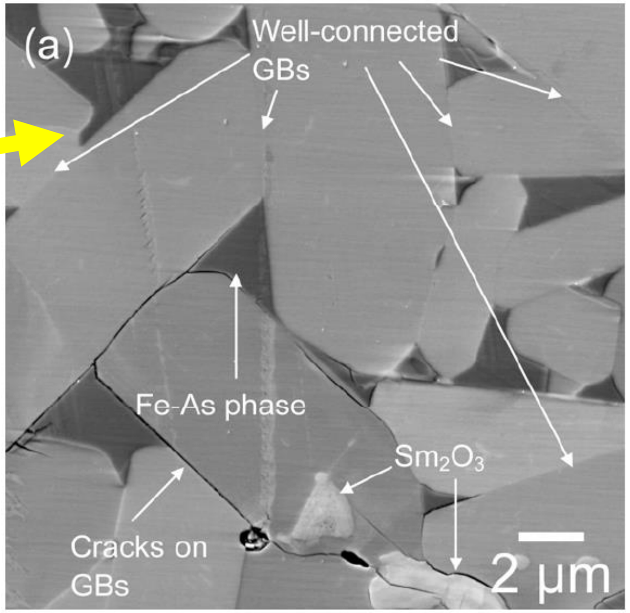
问题1：

铁基线材超导芯为多相固态反应，杂相多

Kametani et al., APL. 95, 142502 2009



Low Temperature Laser Scanning Microscopy (LTLSM) + SEM

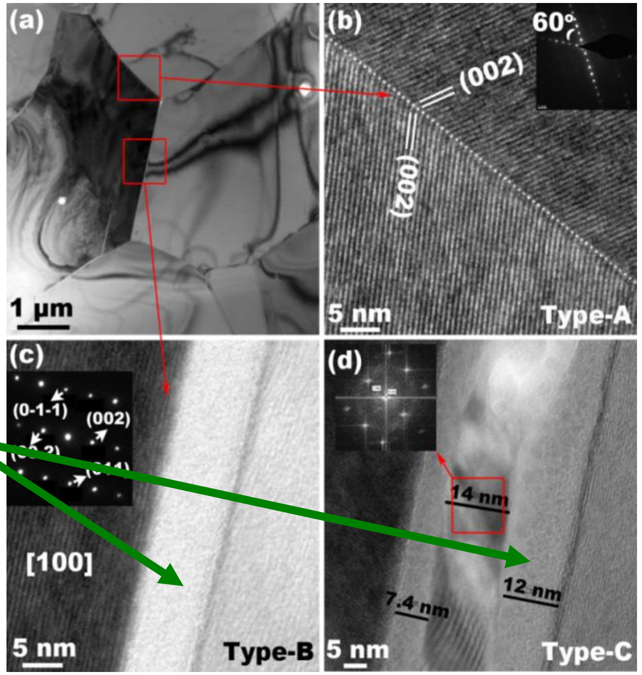


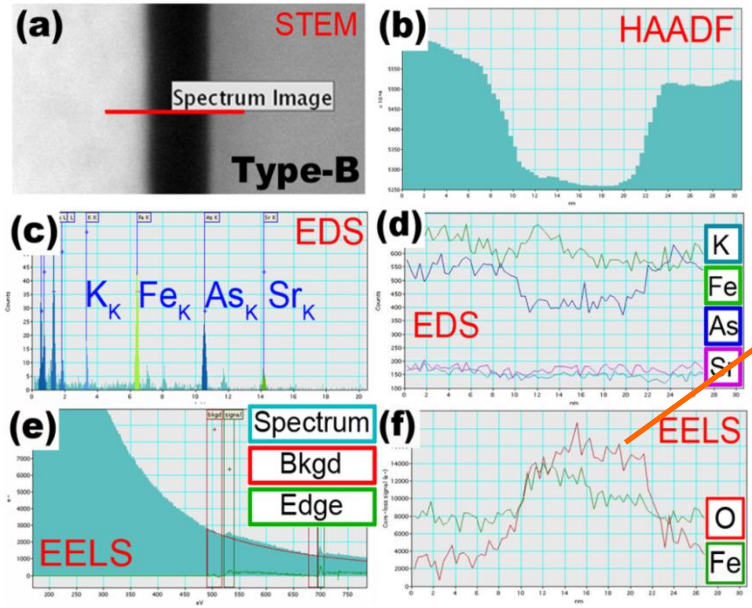
- Dissipation is clearly localized in cracked and impurity-rich regions
- **存在着大量杂相，如FeAs非晶相等，导致晶粒连接性差，是临界电流密度急剧下降的一个重要因素**

TEM-EELS研究发现: 122超导材料晶界存在许多10-30 nm厚的非晶层，严重影响超导电流的传输。

EELS: electron energy loss spectroscopy

An amorphous layer





A high level of oxygen at the boundaries.

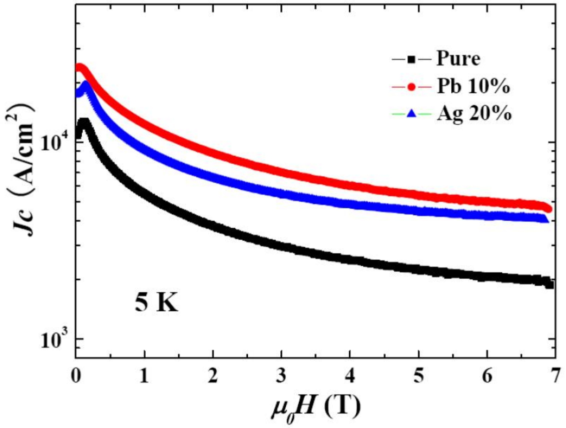
HAADF: high-angle annular dark field line scans

- 富氧非晶层的形成与制备过程中O元素的引入有关，降低样品中的O含量对改善晶粒连接性和大幅度提高J_c非常重要。
- 研究表明，高质量成相和良好的晶界结构是制备高J_c线带材的关键因素！

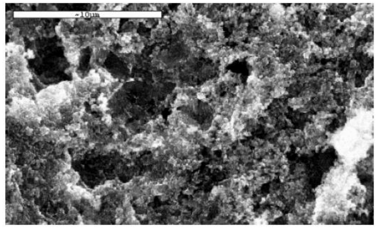
Wang et al, ***APL*** 98 (2011) 222504

采用化学掺杂—先位法，消除了杂相，大幅度提高了晶粒连接性

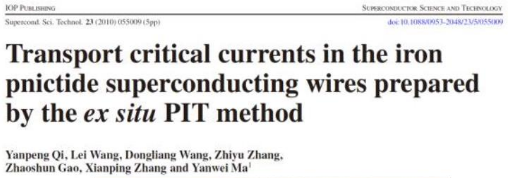
- 发现掺Ag或Pb粉可以有效改善晶粒连接性，Jc显著增加；
- 采用先位法：合成高质量前驱粉，消除了杂相。
- 目前先位法已成为国际上制备高性能铁基线材的通用手段。



SuST 23 (2010) 025027



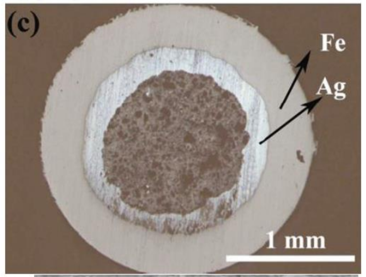
In Situ：loose, more second phases

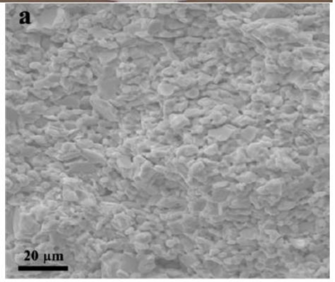


IOP Publishing
Supercond. Sci. Technol. 23 (2010) 055009 (5pp)

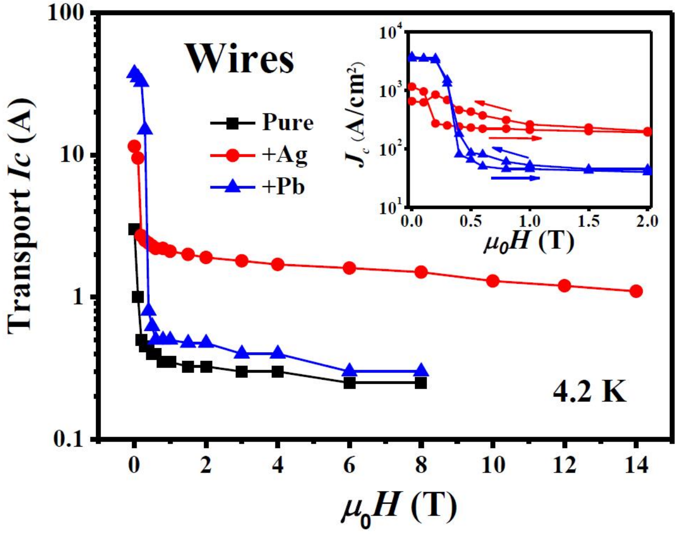
Transport critical currents in the iron pnictide superconducting wires prepared by the *ex situ* PIT method

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





Ex Situ：Dense & more 122



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

SuST 23 (2010) 055009

Lessons learned during the preparation of high quality 122 precursor

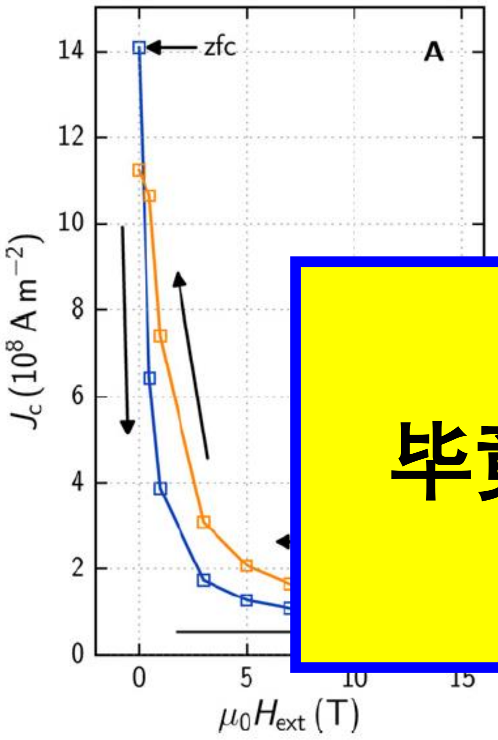
Less O_2 & rich K process

- ✓ **Phase purity of the wire samples is an important factor.**
- ✓ **For the 122 compounds, K loss and the formation of oxygen-rich amorphous layers are the main causes for the inhomogeneities and impurities.**
- ✓ **Since the element K is highly volatile and has a strong affinity to oxygen during the fabrication.**

$Ba_{0.6}K_{0.4}Fe_2As_2$ → $Ba_{0.6}K_{0.5}Fe_2As_2$

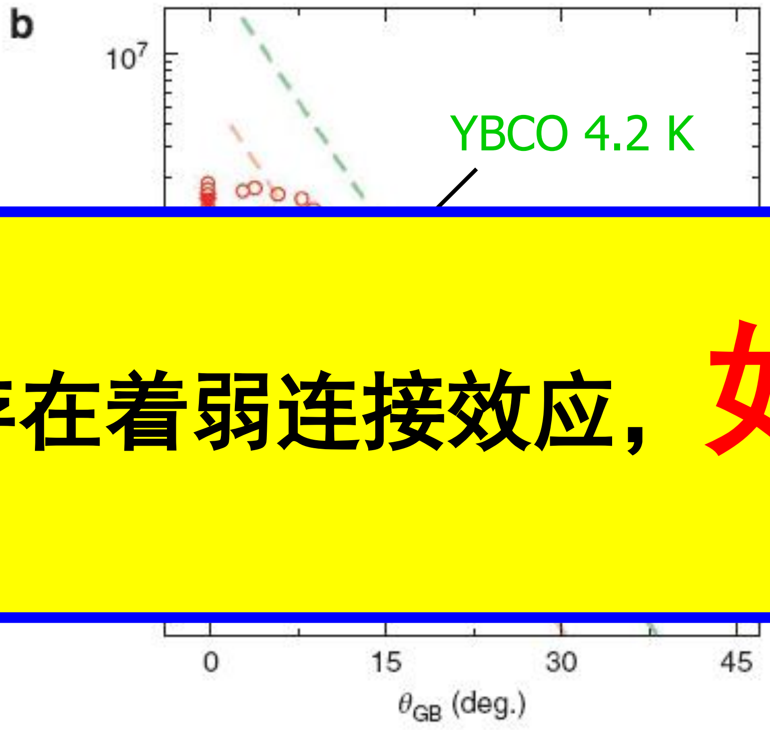
问题2：晶界弱连接问题– Intrinsic nature of dissipation

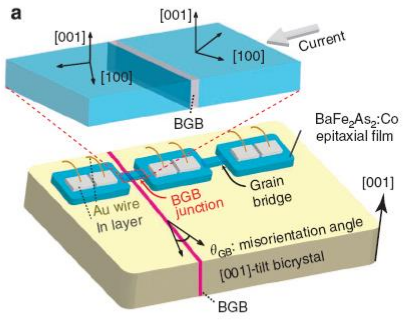
Hecher et al., *SuST* 29 (2016) 025004



Co doped Ba-122 thin films on bicrystals

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





毕竟存在着弱连接效应，**如何解决？**

不同弱连接效应，工艺也不同

- YBCO表现出显著弱连接效应，因此必须采用双轴织构薄膜工艺。
- 与铜氧化物超导体相比，铁基超导体的晶界弱连接效应要小得多，
- 能够采用成本较低的粉末装管法制备高性能线带材，应用前景更为乐观。

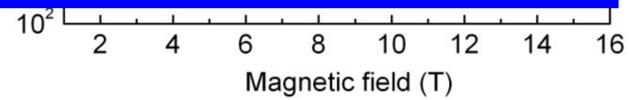
采用铁基超导轧制织构化方法，减少大角度晶界，有效解决了弱连接问题

铁基线材性能进一步提高的挑战 – Jc随晶界角度的增加迅速衰减

如何克服弱连接问题？

Sr122+Sn　　大变形率轧制　　织构化晶粒形成　　高温退火，促进晶粒连接

轧制织构化调控，实现了铁基线材传输电流的大幅度提升（提高一个数量级），打破了当时停滞不前的局面！

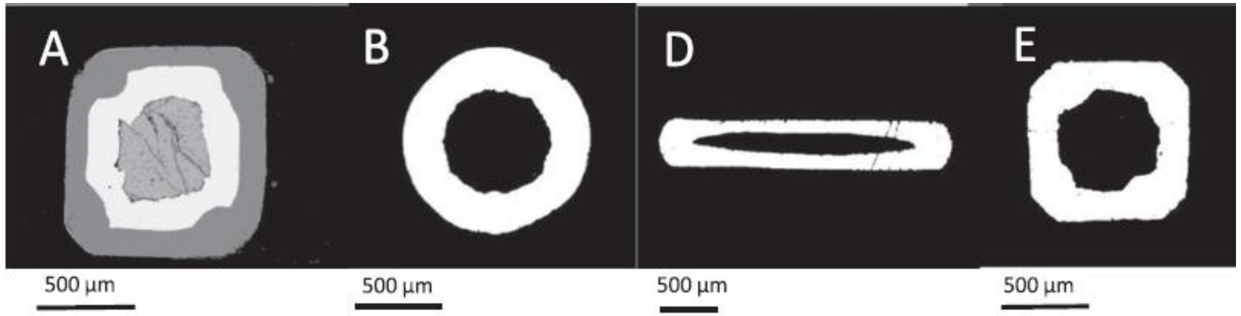


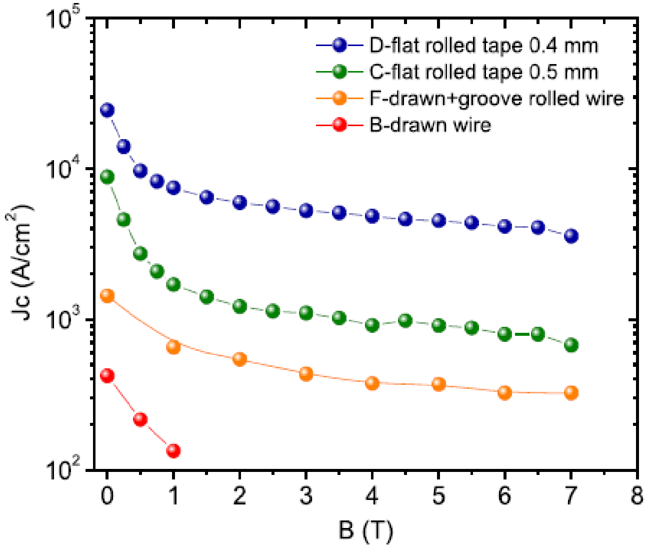
通过大变形率轧制织构方法，大幅度减少了大角度晶界；　**Jc由原来的10^3，提高到10^4 A/cm^2。**

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

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

4-5 grams



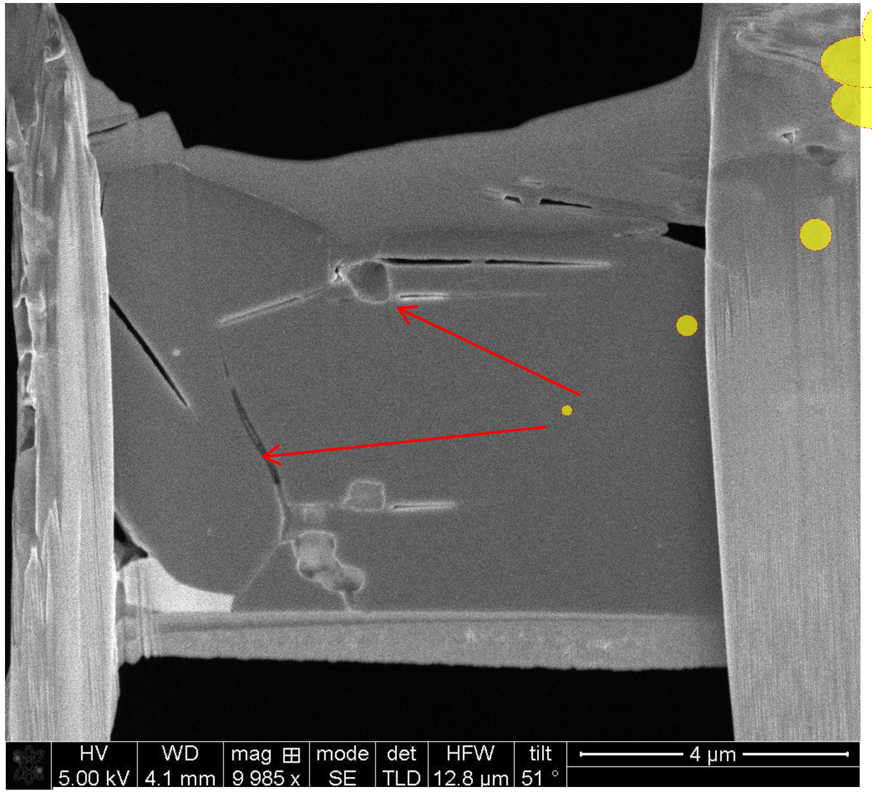


Sample (sheat)	Working	Size
A (Ni/Ag)	groove rolled wire	1×1 mm²
B (Ag)	drawn wire	Ø 0.9 mm
C (Ag)	drawn + flat rolled tape	0.5 mm
D (Ag)	drawn + flat rolled tape	0.4 mm
E (Ag)	groove rolled wire	0.9×0.9 mm²
F (Ag)	drawn + groove rolled wire	0.9×0.9 mm²
G (Ag)	groove rolled + flat rolled tape	0.4 mm

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

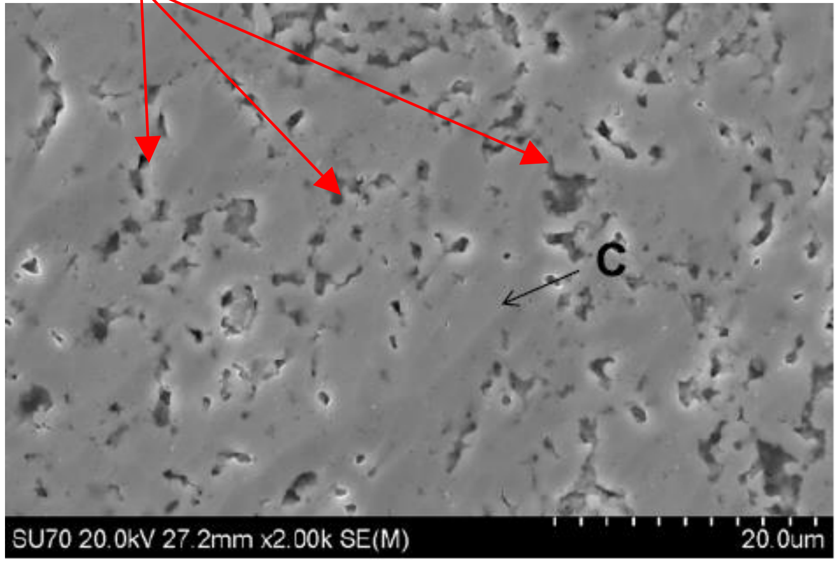
A. Malagoli et al., ***SuST*** 28 (2015) 095015

问题3：超导芯密度低也是导致铁基线材性能降低的一个重要因素—提高致密度



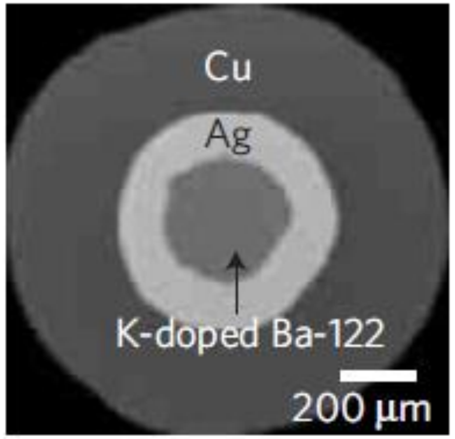
HRTEM - 晶界微观结构

存在孔洞



SEM - 微观结构

Hot isostatic pressing (HIP)--Ba-122 round wire



First Ba-122 round wire made in Florida State University

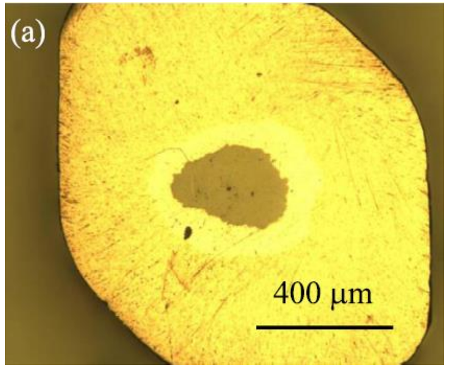
Weiss et al., ***Nature Mater.*** 11 (2012) 682

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

192 MPa, 600 ^{o}C

HIP
(during reaction)

- **The core density nearly 100%**
- **Almost no grain orientation (texture)**



Later Ba-122 wire made in the University of Tokyo

Pyon et al., ***SuST*** *31* (2018) 055016

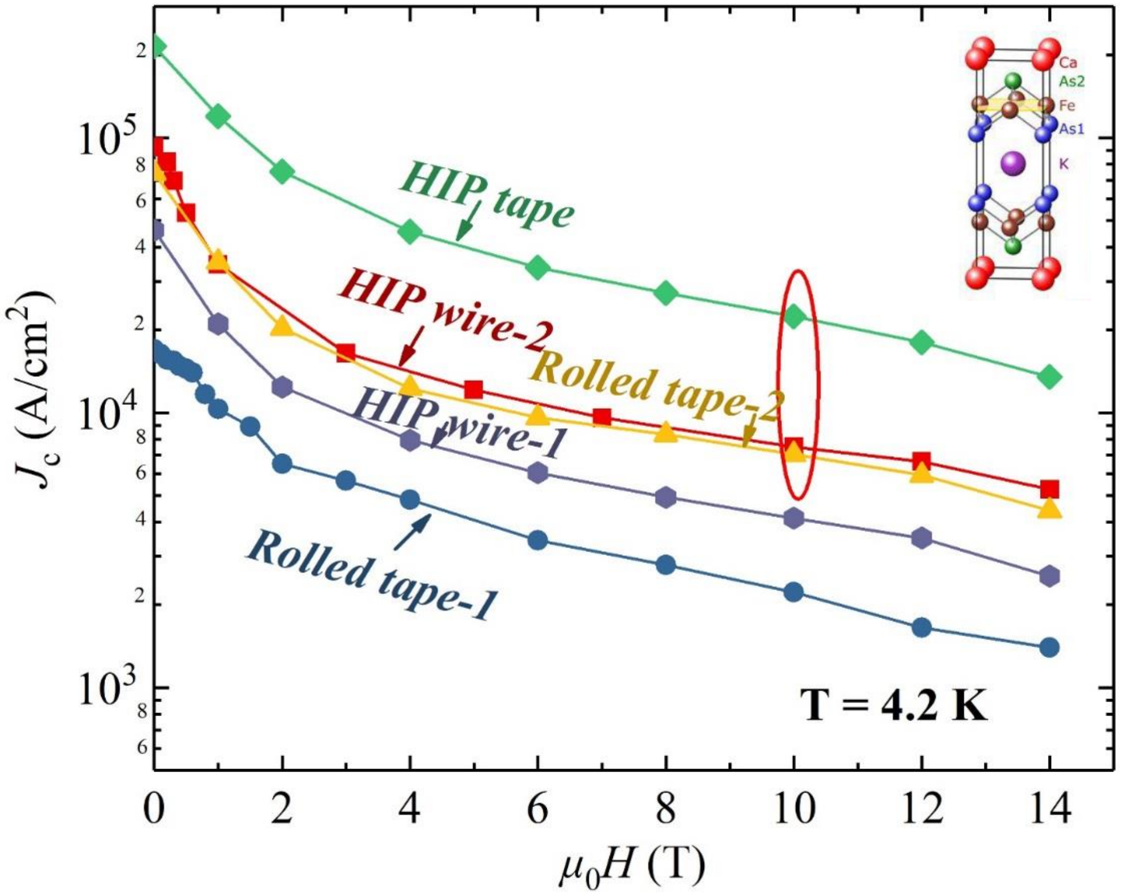
J_c (4.2 K, 10 T) = 3.8×10^4 A/cm^2 **@0T, J_c>1.7×10^5 A/cm^2**

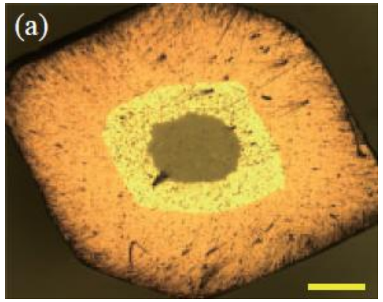
175 MPa, 700 ^{o}C

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

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

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





The highest J_c at 10 T

$CaKFe_4As_4$	J_c (4.2 K, 10 T)
HIP tape	22000 A/cm^2
HIP wire	7600 A/cm^2

- Cheng *et al.* ***SuST*** 32 (2019) 105014
- Pyon *et al.* ***APEX*** 11 123101 (2018)
- Cheng *et al.* ***SuST*** 32 015008 (2019)
- (unpublished)

- **For Ca1144, the transport J_c of wires and tapes is still low.**
- **When sintering temperature exceeds 500^{o}C, Ca1144 phase is not stable with Ag sheath.**

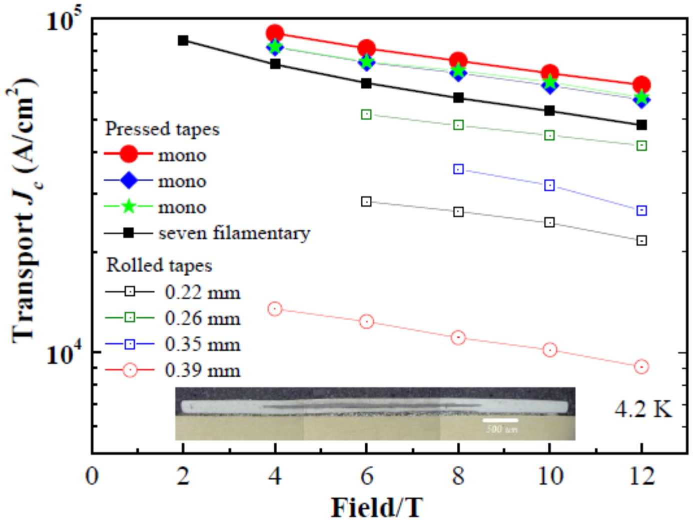
Cold pressing (before reaction)

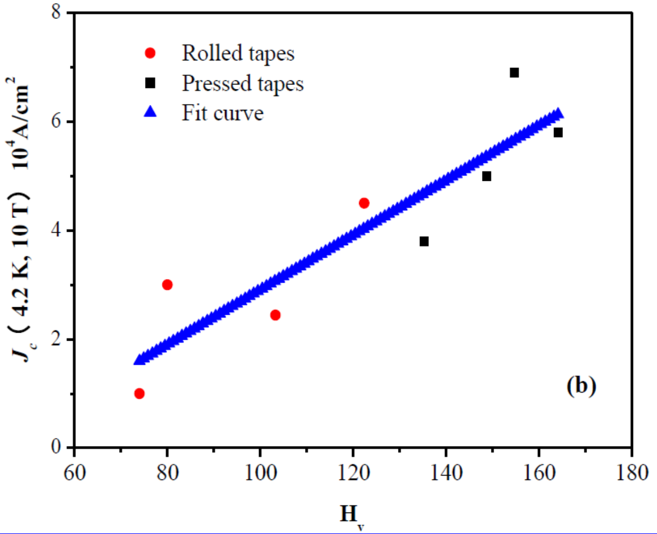
Ba-122 tapes by combined the rolling, cold pressing and sintering process-- Denser core yields higher J_c

--Ag-sheathed Ba122 tapes

Steps:

1		2		3		4		5
As-rolled tape (T 0.8mm)	→	**Sintering (800 ºC/2h)**	→	**Rolling T ~0.3 mm**	→	**Cold pressing 2 ~3 GPa**	→	**Sintering (800 ºC/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 (2014) 4465

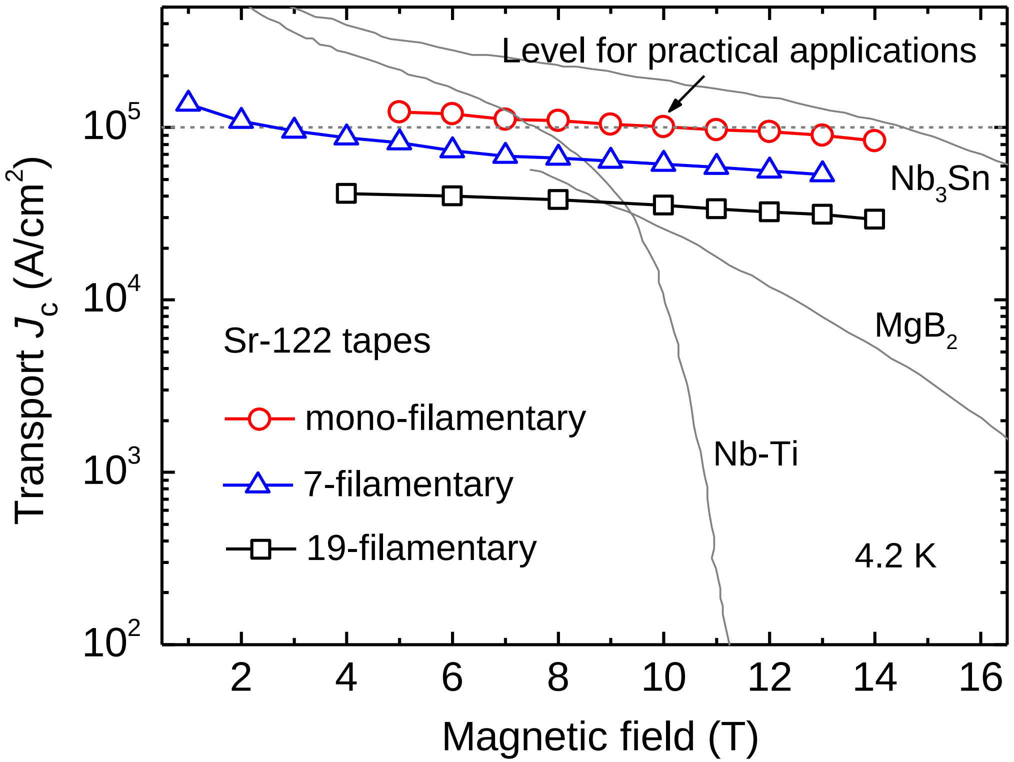
采用热压工艺，将载流性能首次提高到实用化水平

——（10^5A/cm^2@10 T）

--Sr122/Ag tapes

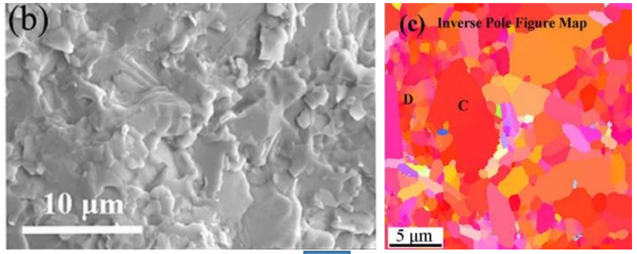
30 MPa, 850~900ºC

在国际上率先迈入实用化门槛!



实用化水平的门槛：
J_c =10^5 A/cm^2@10 T

性能，4.2 K下：
14 T, J_c = ~10^5 A/cm^2



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

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

Hot pressing (during reaction)

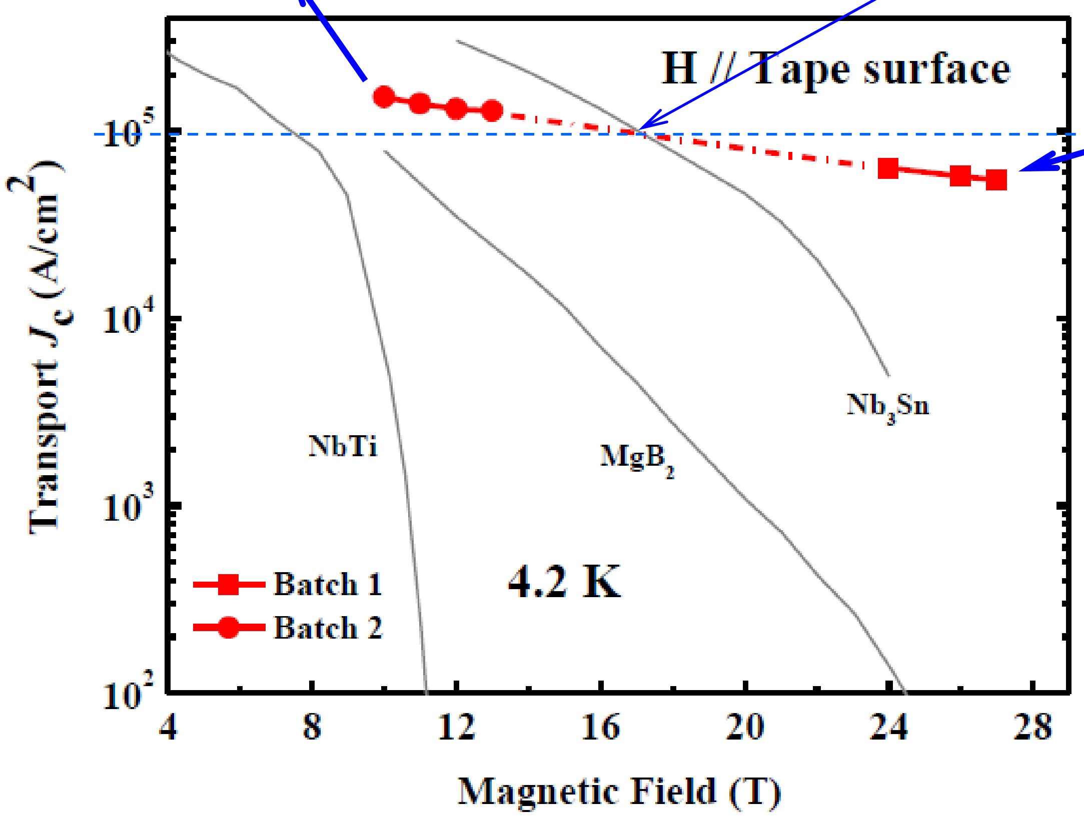
--$Ba_{0.6}K_{0.4}Fe_2As_2$/Ag tapes

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

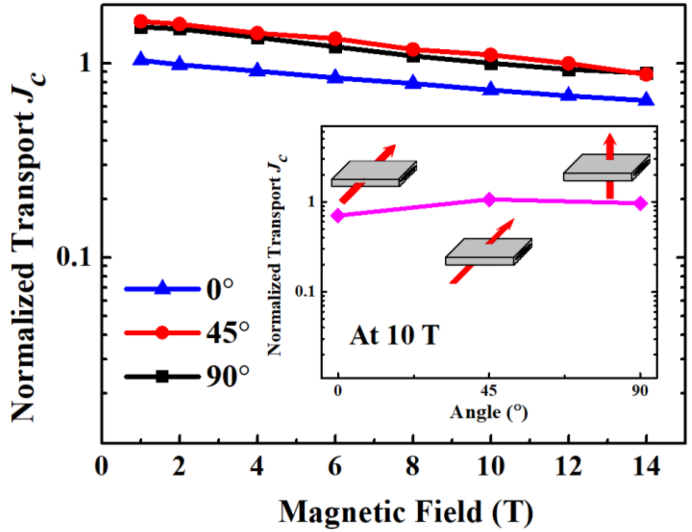
--Ic measured at HFLSM, *Sendai*

I_c = 437 A

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



At 27 T, $J_c = 5.5\times10^4$ A/cm^2



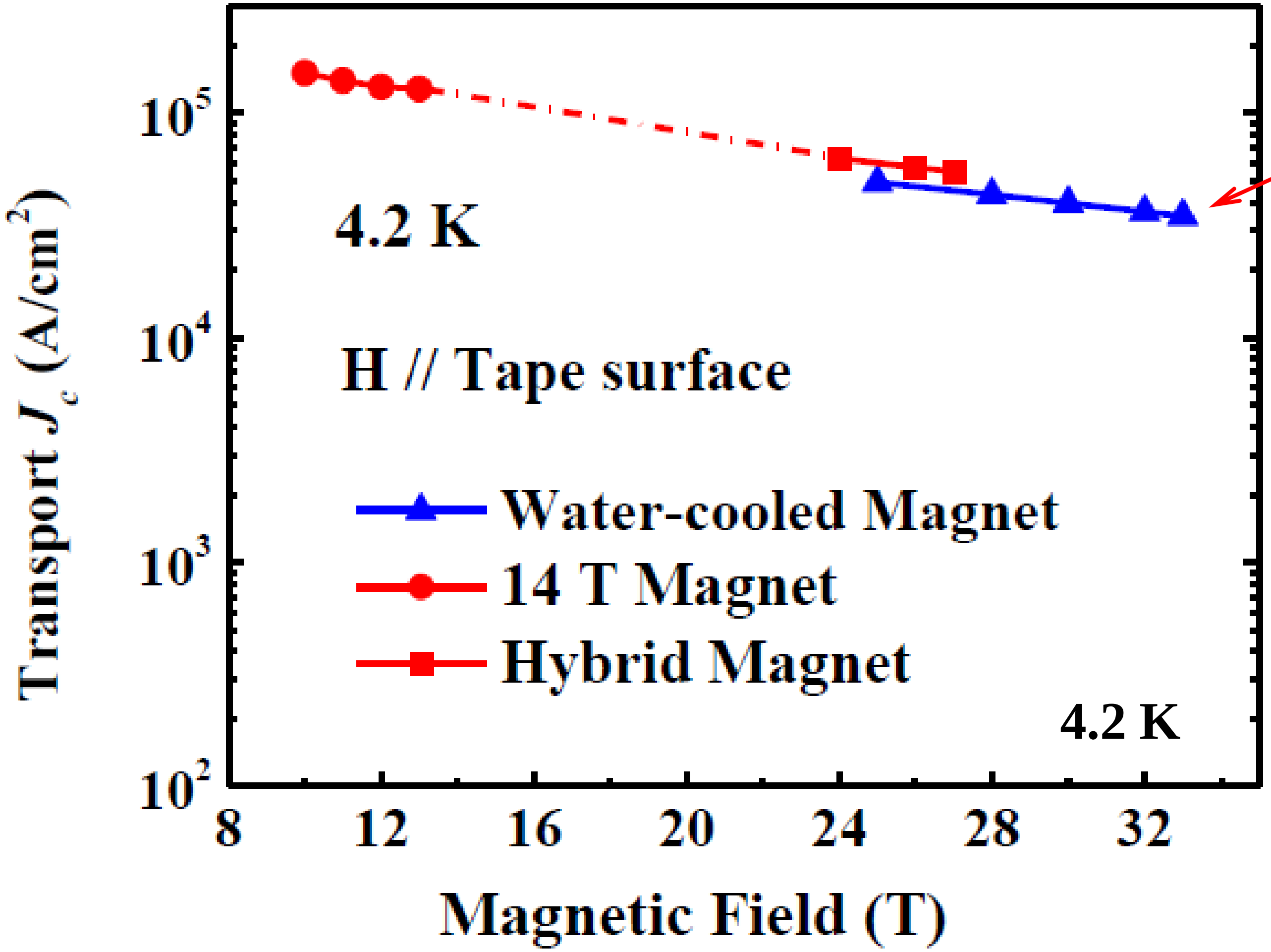
Huang et al., *SuST* 31 (2018) 015017

γ = 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*



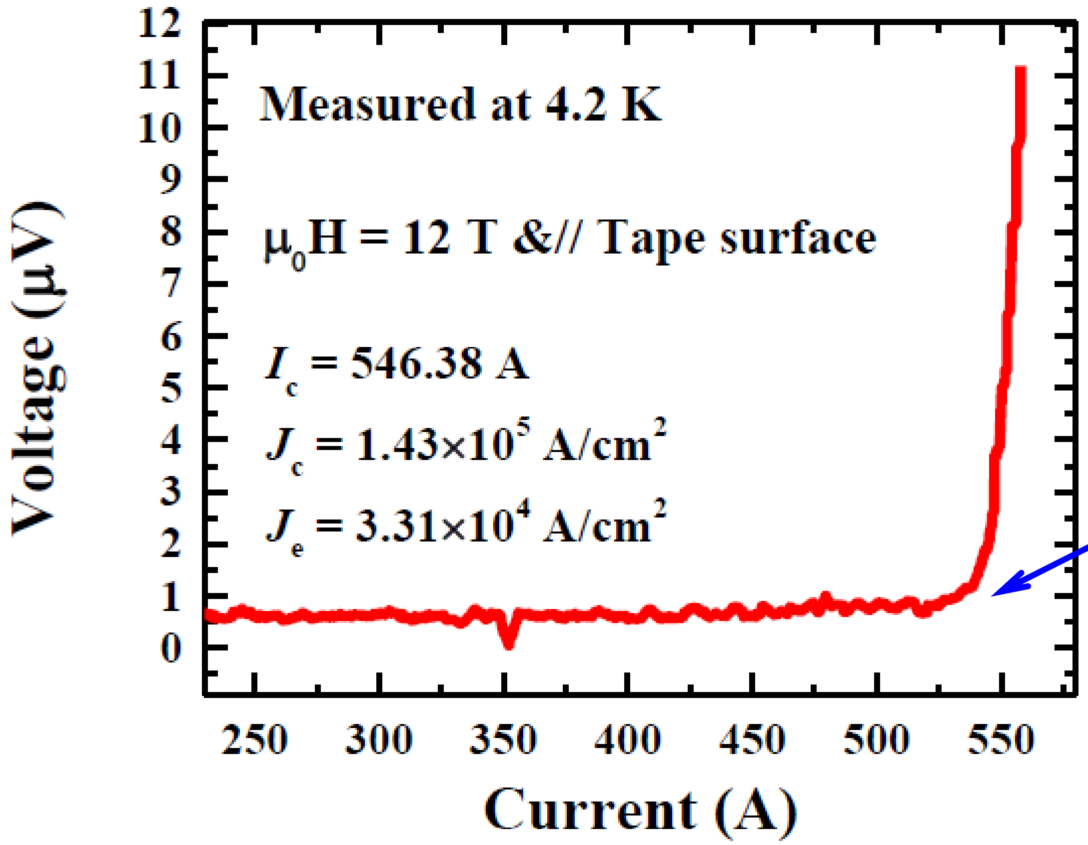
@ 33 T, J_c= 3.5×10^4 A/cm^2

35 T water-cooled magnet
(Heifei, China)

Latest result

Ba-122 tapes showed even higher J_c-B value

--measured at IPP-CAS



Hot-pressed samples

At 12 T,

I_c = 546 A

J_c = 1.43×10^5 A/cm^2

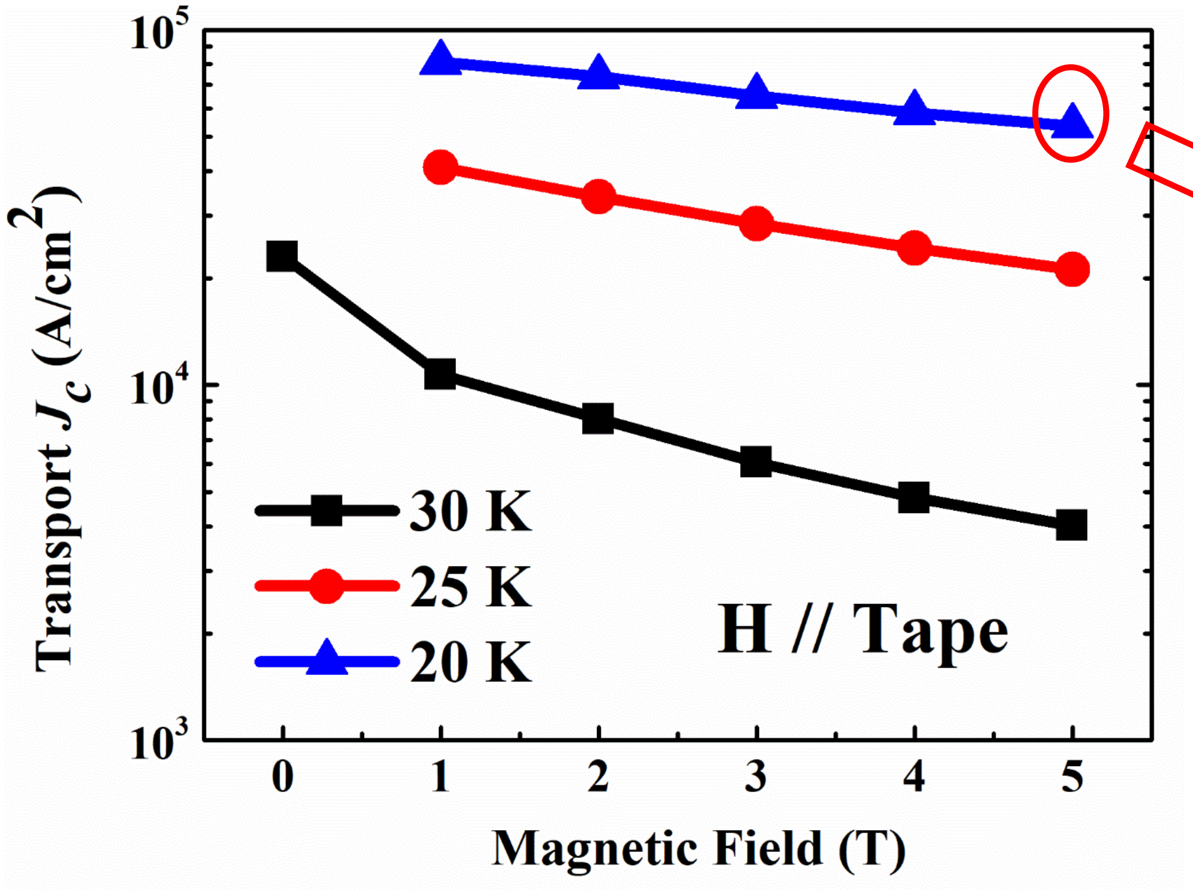
- **For hot-pressed tapes, at 12 T, 4.2 K, I_c= 546.38 A， J_c= 1.43×10^5 A/cm^2， correspondingly, J_c~ 1.6×10^5 A/cm^2 in the field of 10 T.**

在20-30 K中温区，性能优异

Measured at *Northeastern University* in China

在 20 K, 1 T条件下, 传输J_c~10^5 A/cm^2

热压BaKFeAs-122带材



5.4 × 10^4 A/cm^2
@ 5 T & 20 K

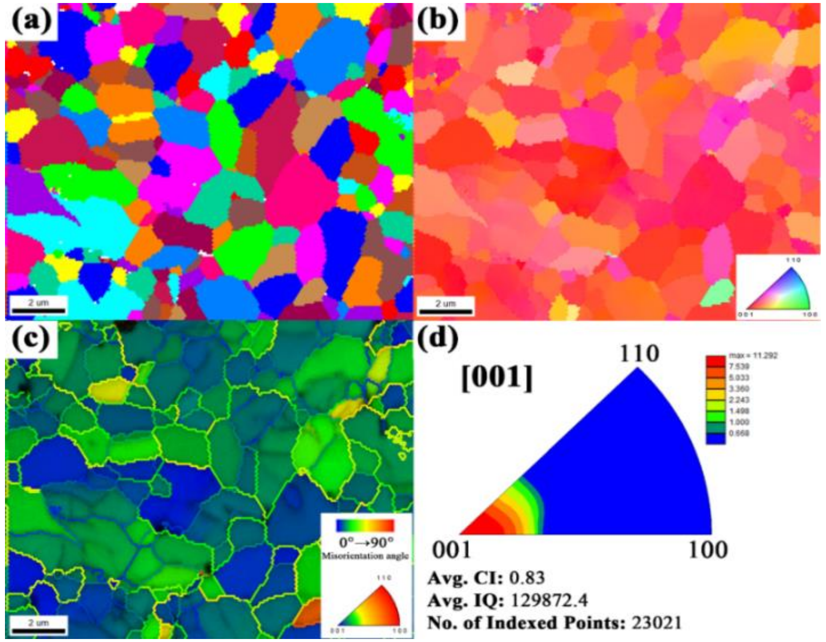
Huang et al., ***SuST*** 31 (2018) 015017

充分展示了中温区的应用潜力！（制冷机冷却）

致密度和织构度的协同调控是获得高J_c的关键

--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

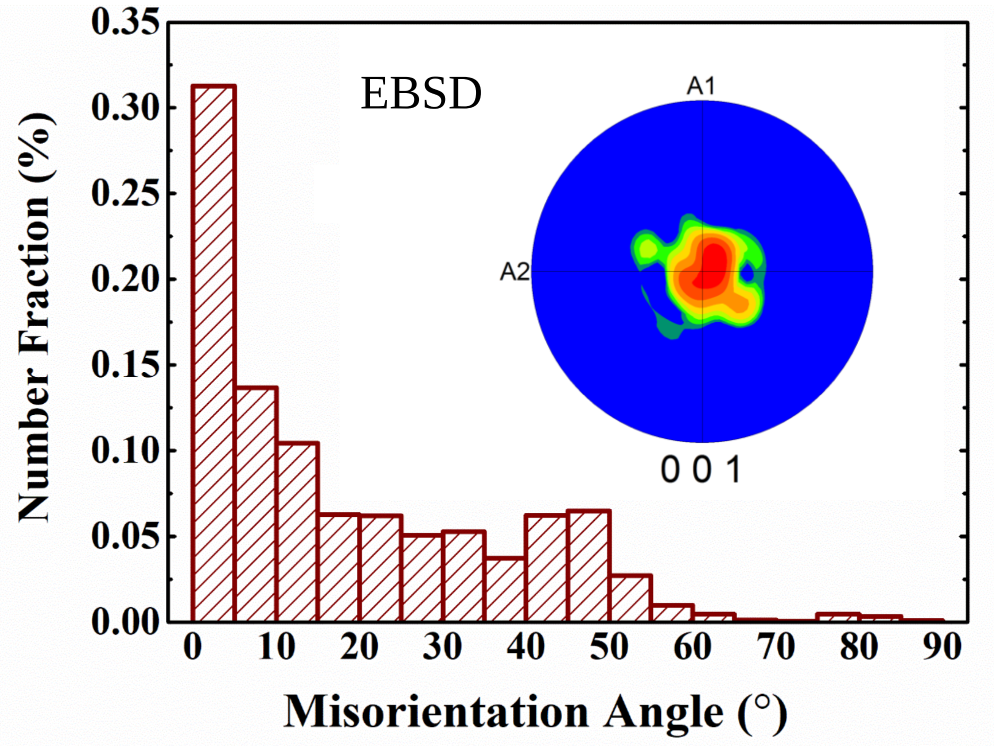
High core density

Good connectivity !

EBSD: Misorientation angle distribution

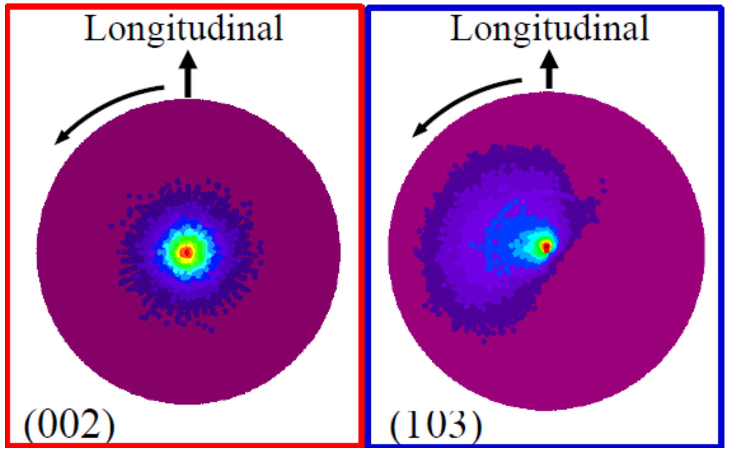
HP Ba-122 tapes

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

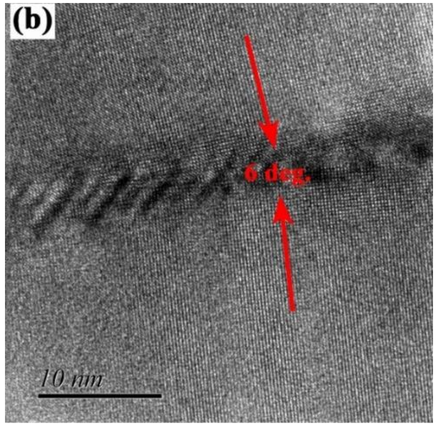


Courtesy of S. Awaji

Pole figure



TEM

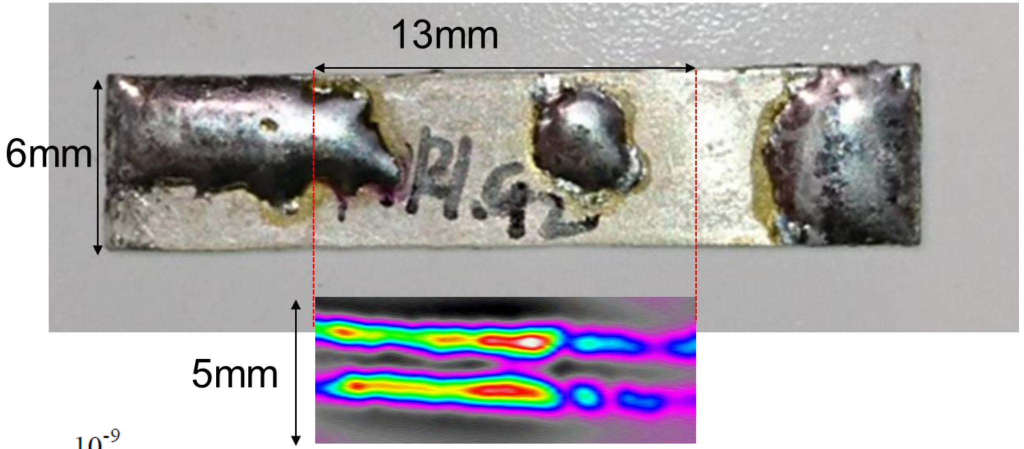


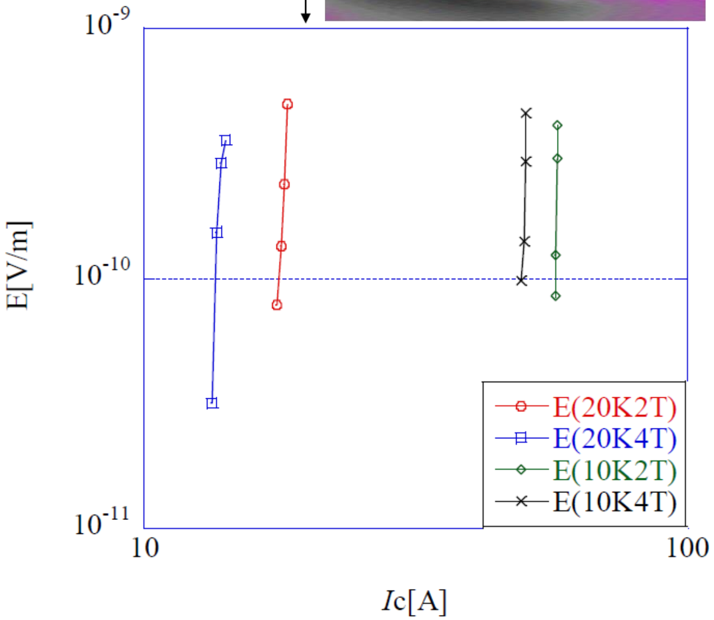
A large amount of grain boundaries below 10º are also detected, indicating that the weak-link problem is effectively suppressed in HP tapes.

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

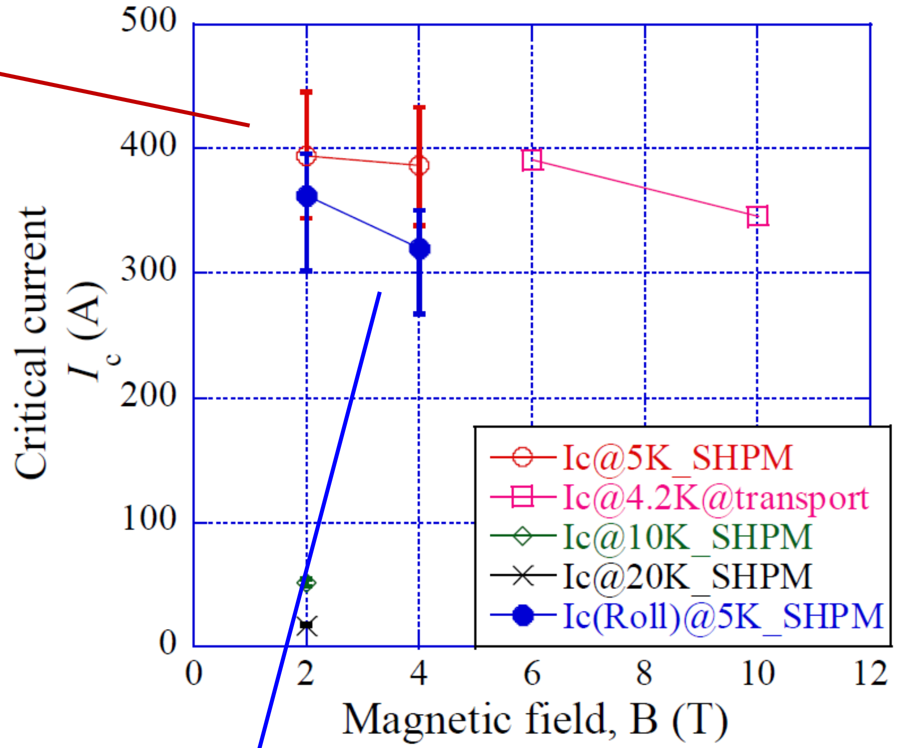
-- Measured by Kiss group Kyushu Univ.

Hot pressed Ba-122 tape





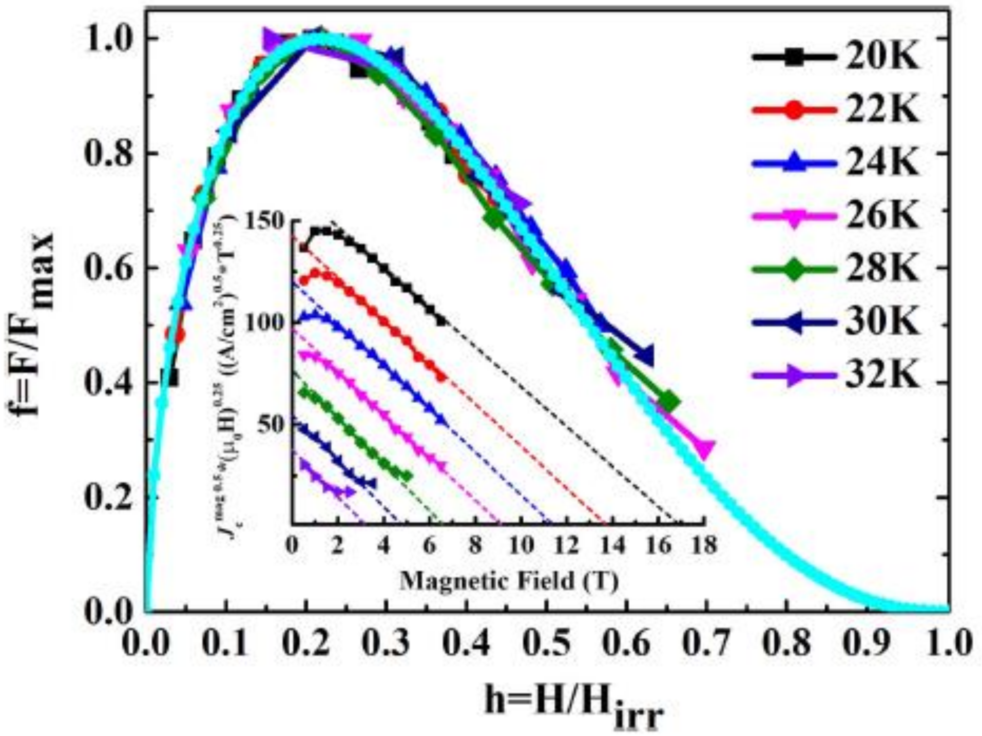
Temperature & Field	n value
10 K & 2 T	143.4
10 K & 4 T	77.9
20 K & 2 T	43.9
20 K & 4 T	39.4



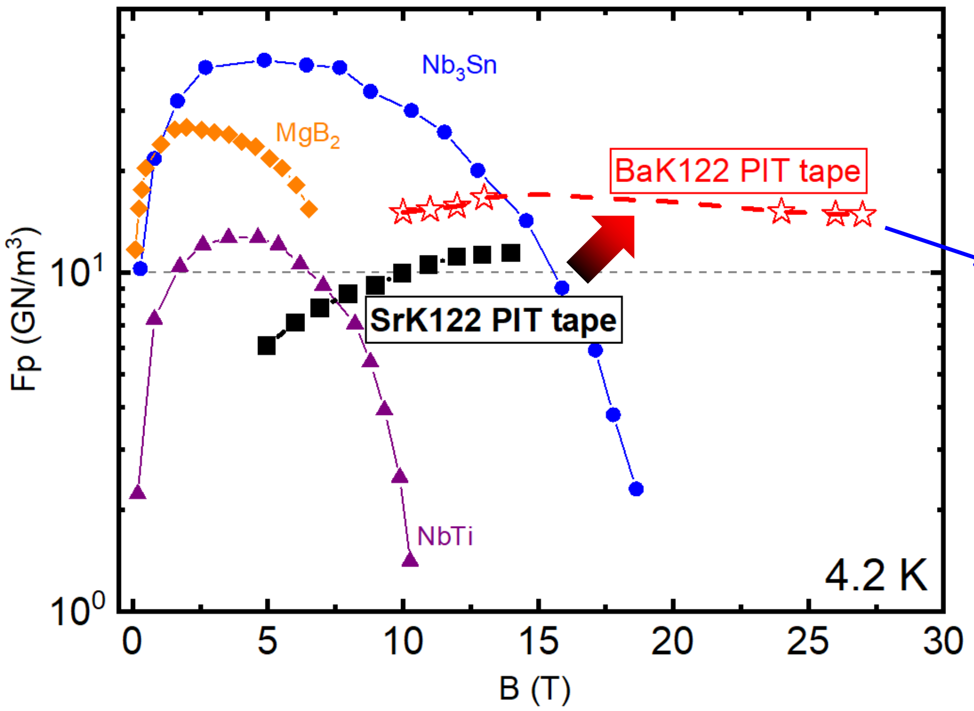
Rolled tape

Flux pinning mechanism in HP Ba-122 tapes

Normalized flux pinning force



Flux pinning force density



F_p^{max}

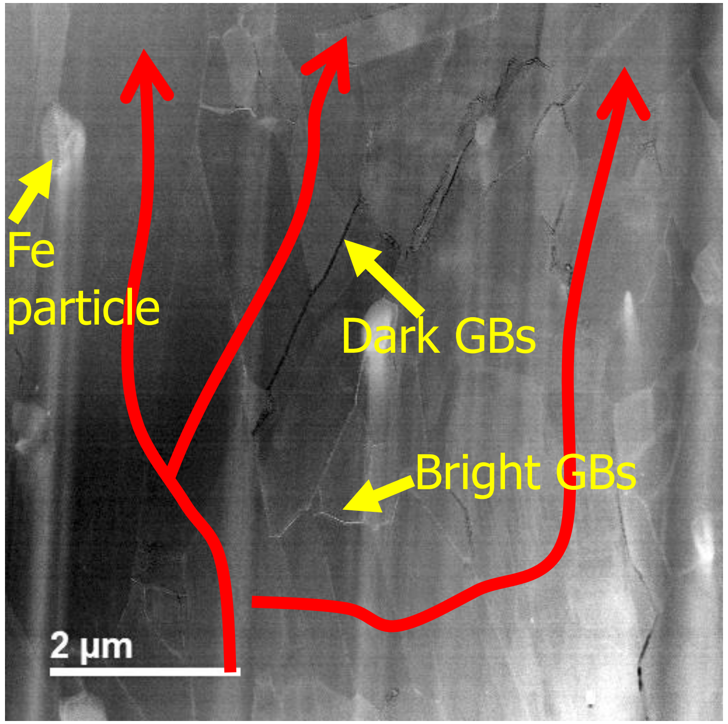
~17 GN/m³

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

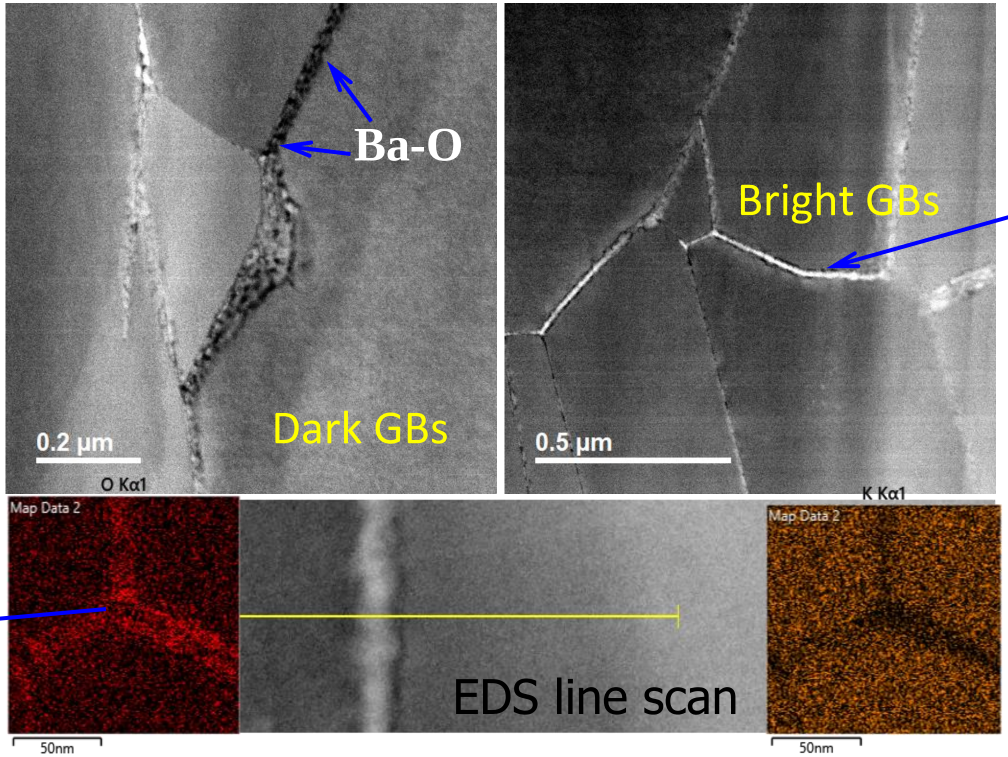
Bright field STEM for state-of- the art HP 122 tapes: Second phases at GB

HAADF

-- analysed by Larbalestier's group at FSU



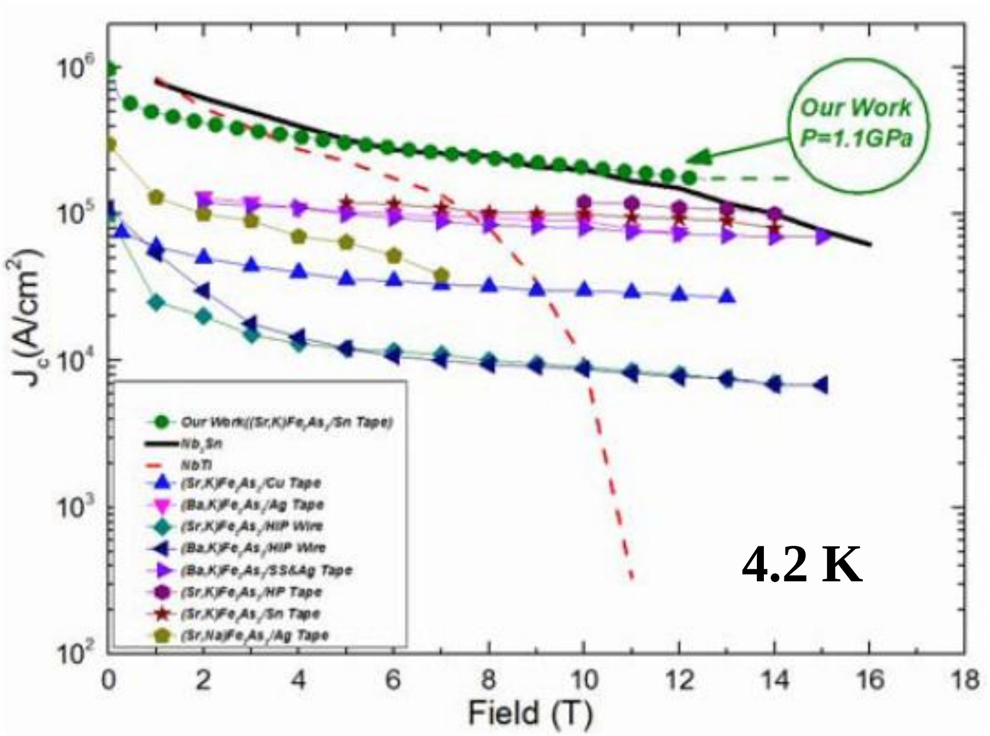
Many clear GBs in HP-122 tape



- The state-of-art high J_c tapes still contain many contaminated GBs which disconnect the Ba122 grains. The J_c can be largely improved if we can eliminate these secondary phases.
- Avoid oxidation of starting materials and LT sintering are important to further improve J_c.

Courtesy of F. Kametani

Magnetic J_c up to 3×10^5 A/cm^2 @ 4.2 K, 10 T can be achieved under Hydrostatic Pressure on 122 tapes



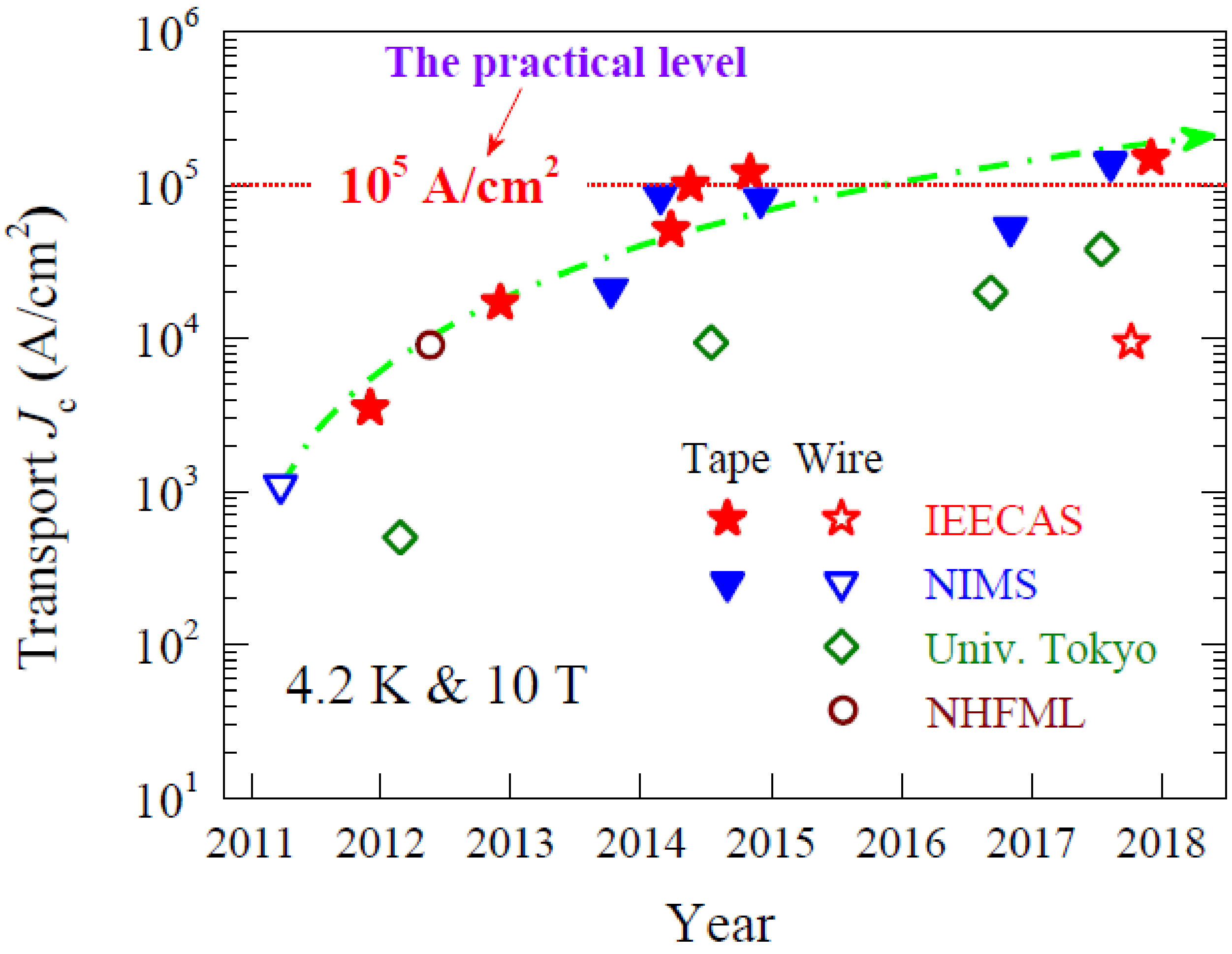
-- Collaborated with Prof. Xiaolin Wang, S. X. Dou, Wollongong Univ.

- ✓ Using PPMS, HMD high pressure cell and Daphne 7373 oil as the medium for applying hydrostatic pressure on Sr-122/Ag tape samples.
- ✓ Tape samples were measured under pressure.

- **The hydrostatic pressure of 1GPa can significantly enhance J_c in Ag-clad $Sr_{0.6}K_{0.4}Fe_2As_2$ tapes at different temperatures, e.g., ~2×10^5A/cm^2 at 13T, 4.2 K.**
- **Pressure can improve the grain connectivity and increase the pinning number density.**
- **The result demonstrated that the current IBS tapes/wires should have plenty of room for the J_c improvement.**

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

国内外铁基超导线材的传输性能最新比较



目前性能最高值

2018

1.5×10^5 A/cm^2

10^5A/cm^2 at 18 T

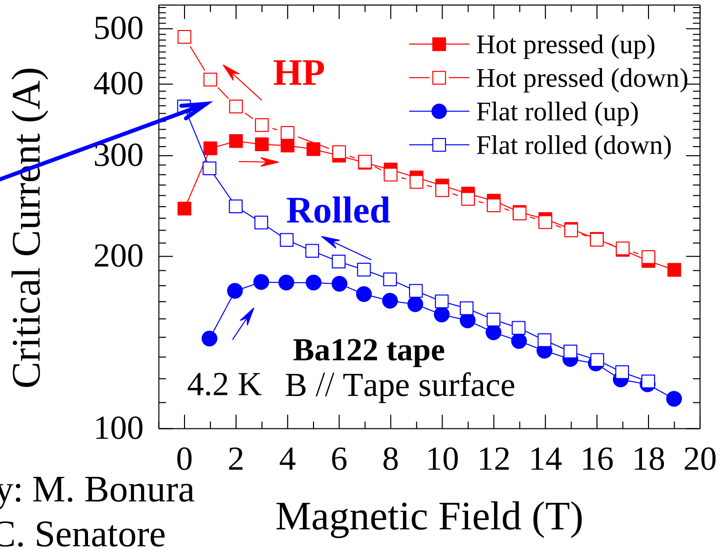
Next target: 10^5A/cm^2 at 30 T

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

Strategies to further improve J_c in 122 PIT wires

◆ **Reduction of secondary phases at GBs.**

◆ **To improve the texture degree,** especially increase the fraction of misorientation angle <9º.

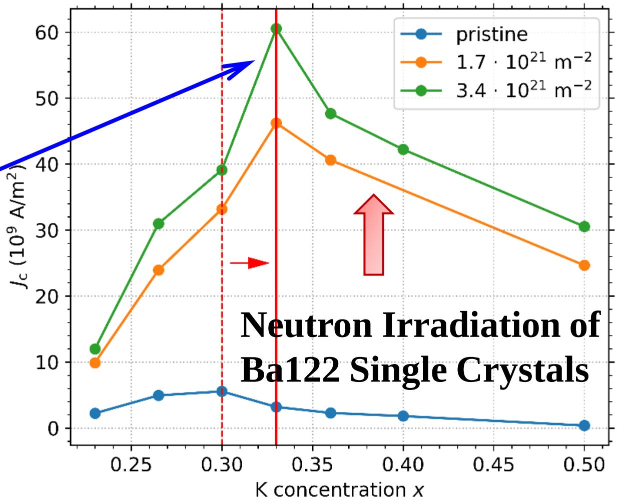


Courtesy: M. Bonura & C. Senatore

◆ **To further increase flux pinning force:**

(1) decrease grain size to make more GBs,

(2) increase point pinning sites, *e.g.* irradiation or the introduction of nano-particle inclusion.



Courtesy: M. Eisterer

报告内容

一、实用化超导材料简介

二、铁基超导体简介

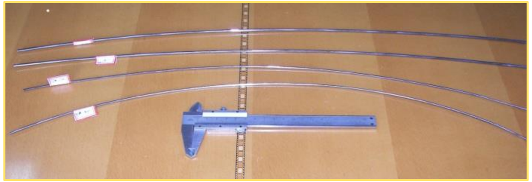
三、铁基超导线材的制备与性能提高

四、铁基超导线材的实用化制备研究

五、结论与展望

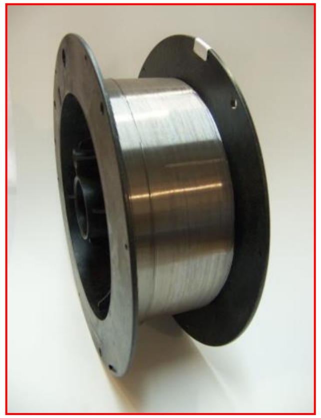
铁基材料实际应用还需解决的问题

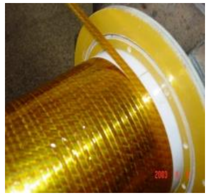
挑战	策略
1、降低AC loss/Quenching,	多芯线材
2、抵制大电磁力/热应力,	高强度线材
3、满足市场需求：Cost	低成本线材
4、规模化应用,	高均匀长线



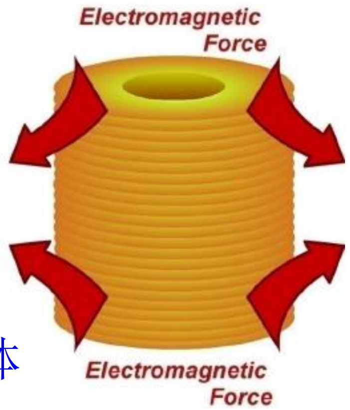
超导短样品:1m

长线





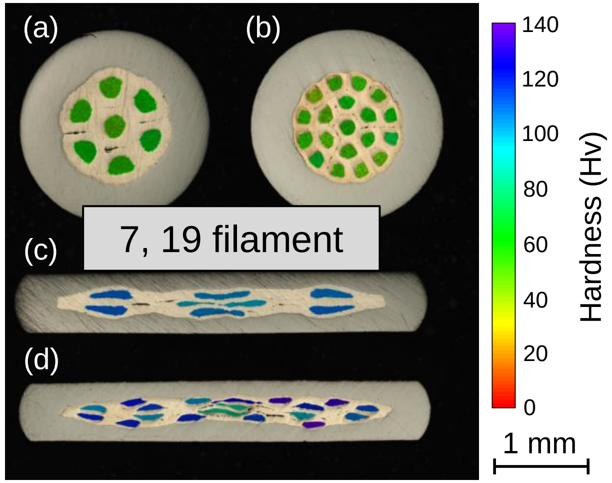
超导磁体



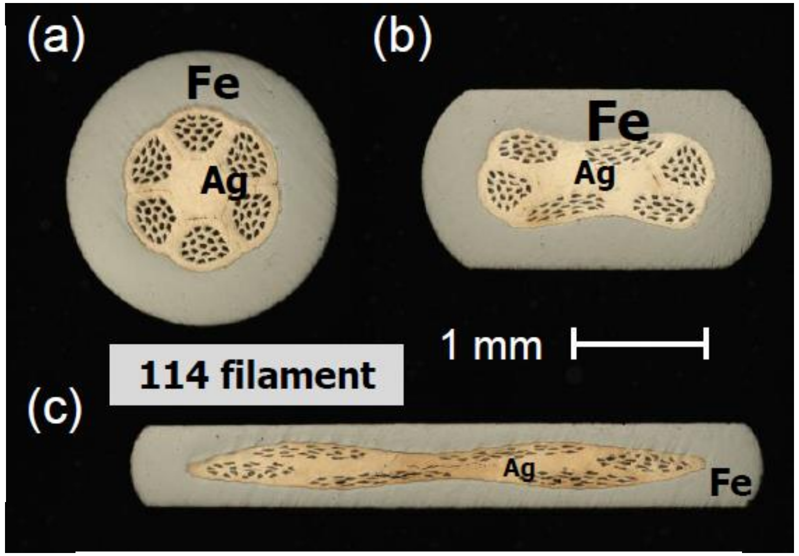
122铁基超导多芯线的研制

➢ 为了减少交流损耗，同时防止磁通跳跃，实际应用的导线必须为**多芯线材**。

IEECAS

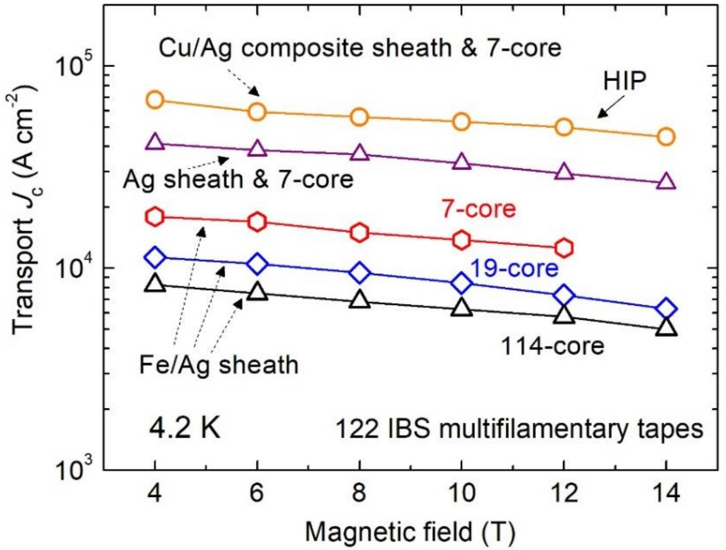


At 4.2 K, 10 T

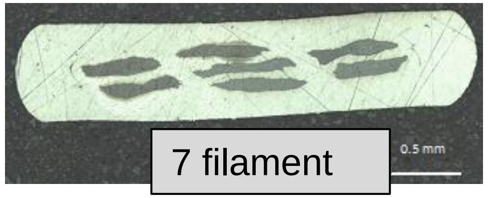


Yao et al., ***JAP*** 118 (2015) 203909

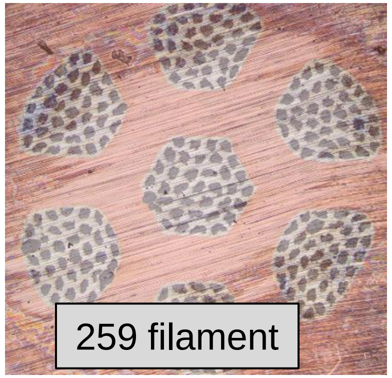
***J*$_c$, the very weak field dependence**



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

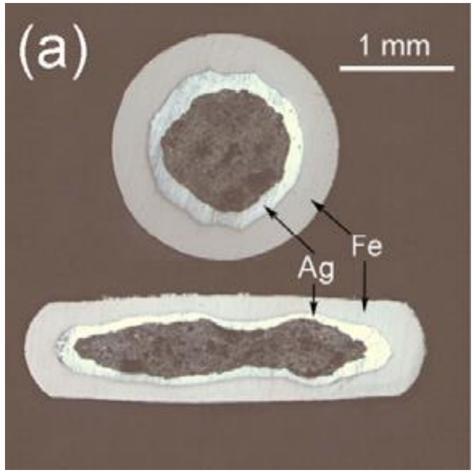


NIMS

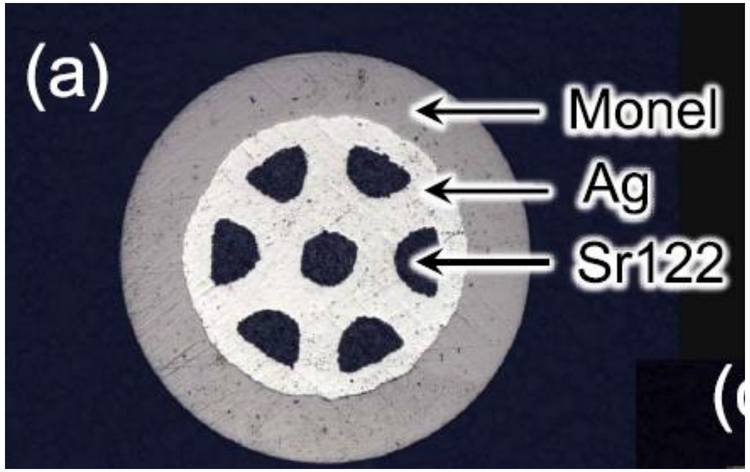


Florida

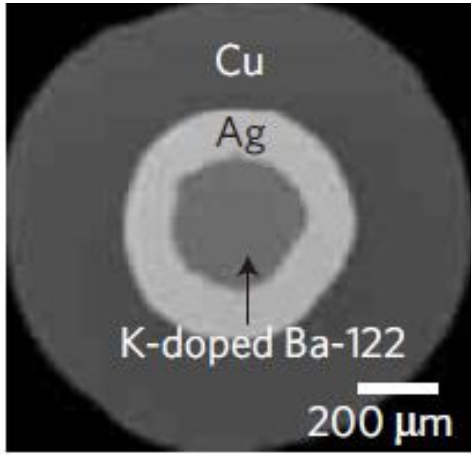
高强度铁基线带材的研制–
减少了银用量，具有优异的磁场性能



Fe/Ag, IEECAS

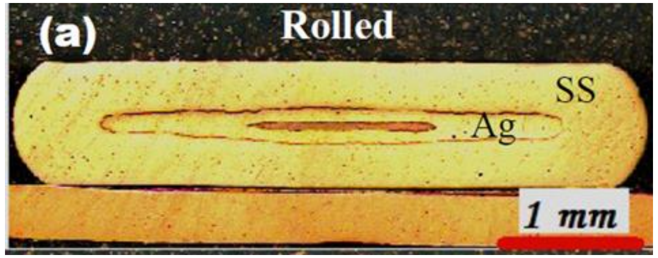


Monel/Ag, IEECAS

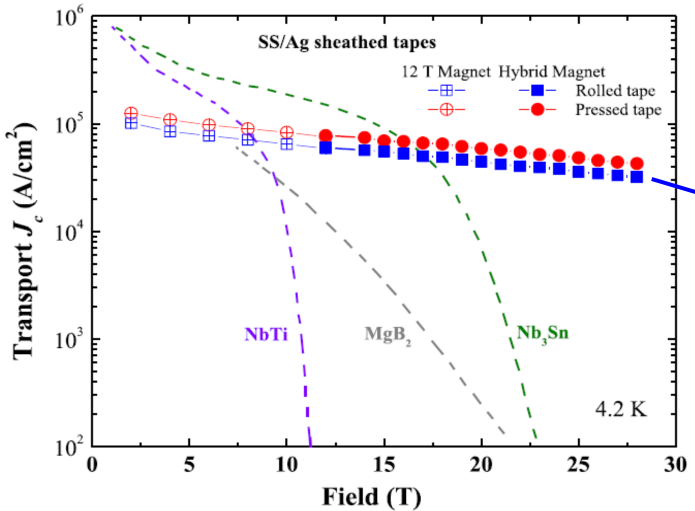


Cu/Ag, Florida

Cu/Ag, IEECAS



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

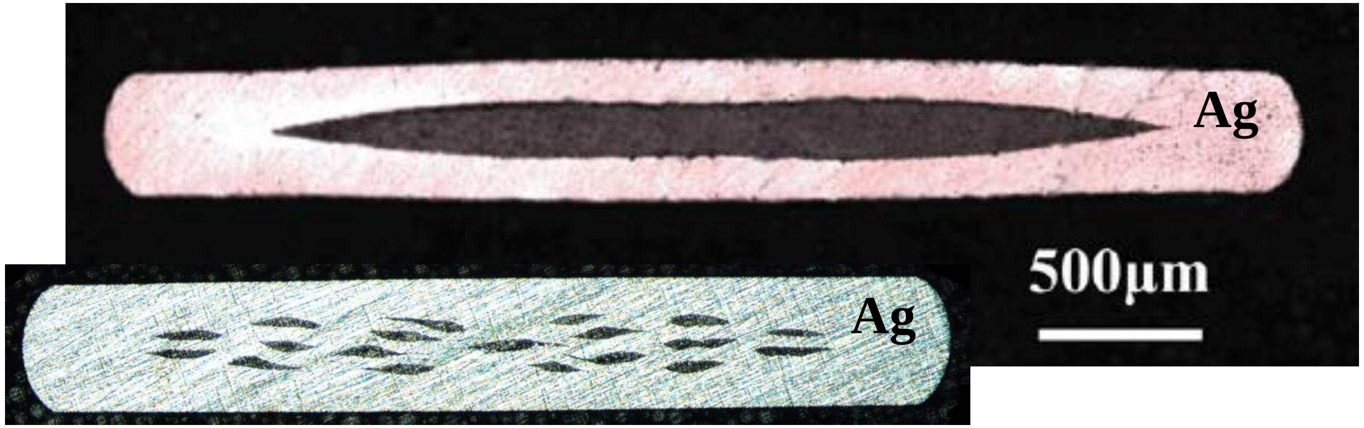


28T, J_c=3×10^4 A/cm^2

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

Ag is very expensive

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



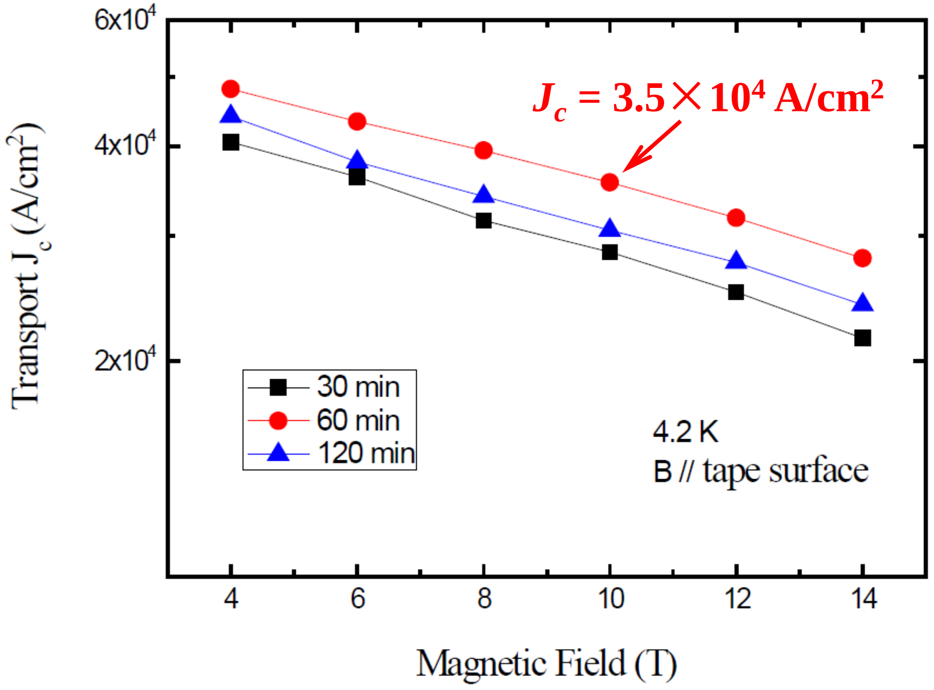
IEECAS, 2014

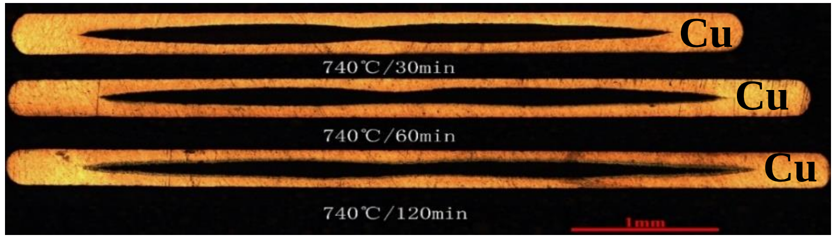
NIMS, 2014

制备出高性能Cu包套122铁基带材，降低成本

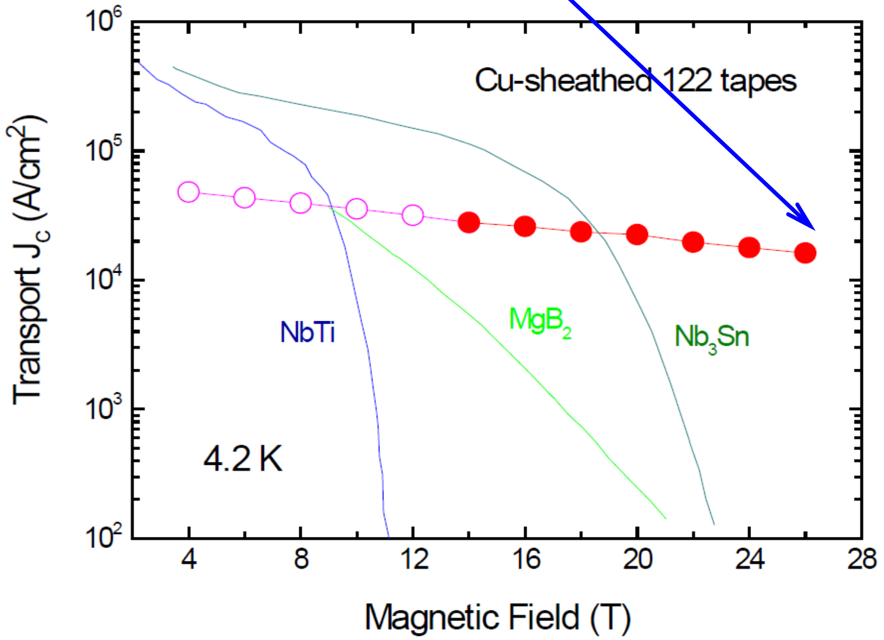
- Cu材料具有价格低、加工性能好、热传导率高等优点，是最理想包套材料。
- 采用低温快烧解决了铜包套与超导芯反应层的问题。

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





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



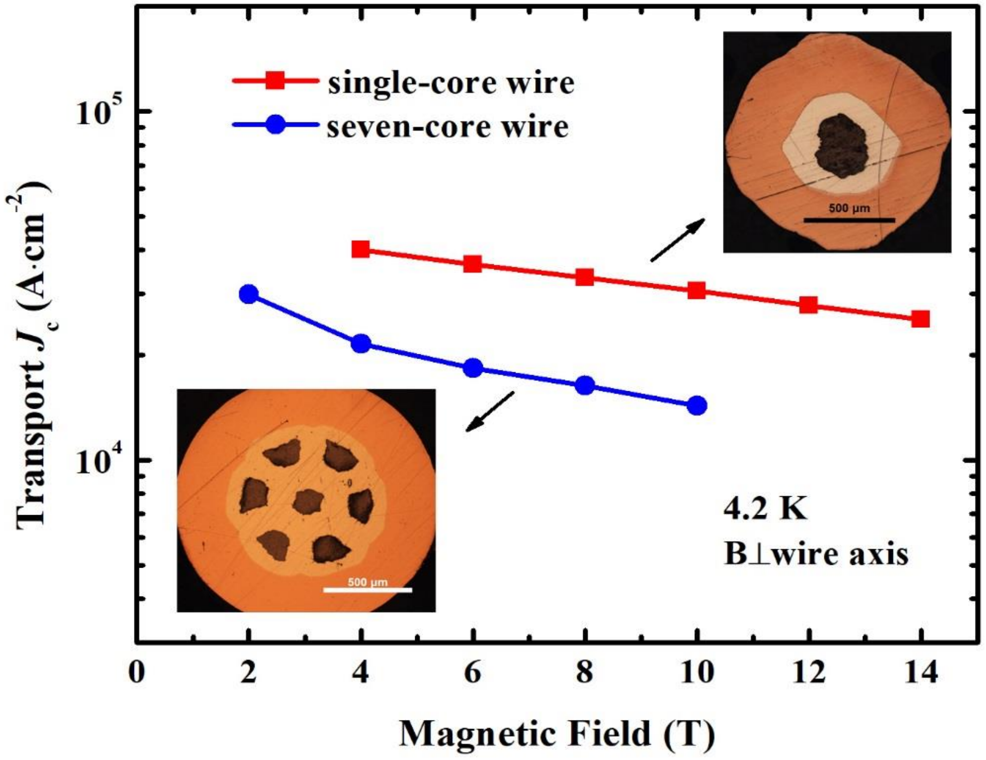
降低了铁基线材的制造成本，同时还可保证使用时的热稳定性

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

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

at 740ºC

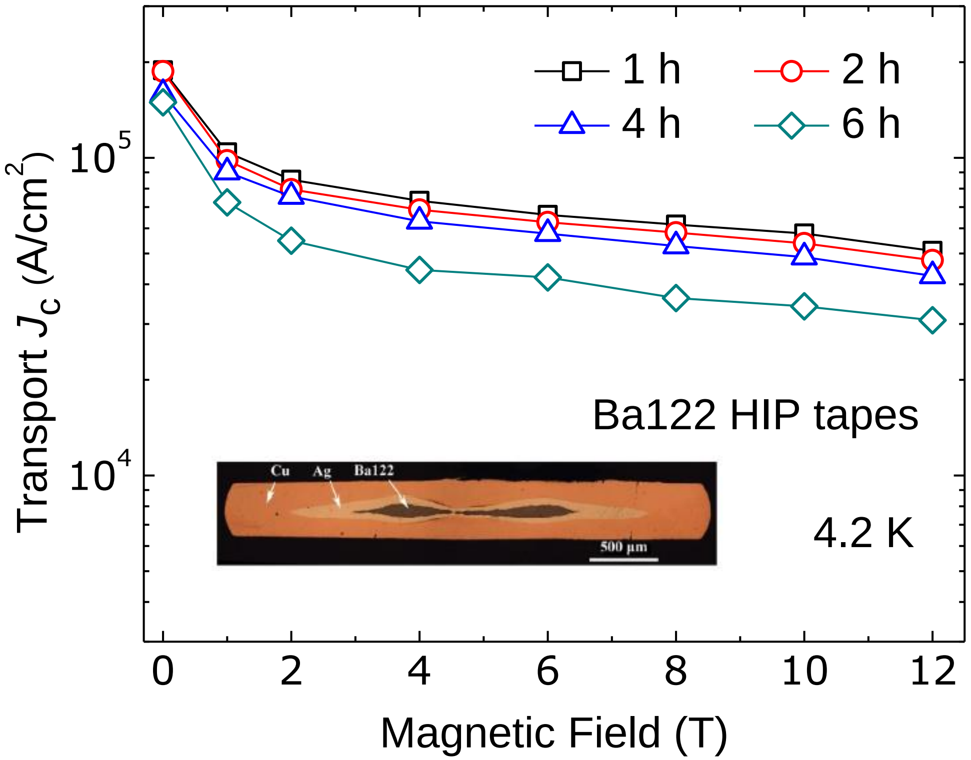
Ba-122/Ag/Cu round wires



J_c (4.2 K, 10 T) = 3.1×10^4 A/cm^2

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

Ba-122/Ag/Cu tapes



J_c (4.2 K, 10 T) = ~6×10^4 A/cm^2

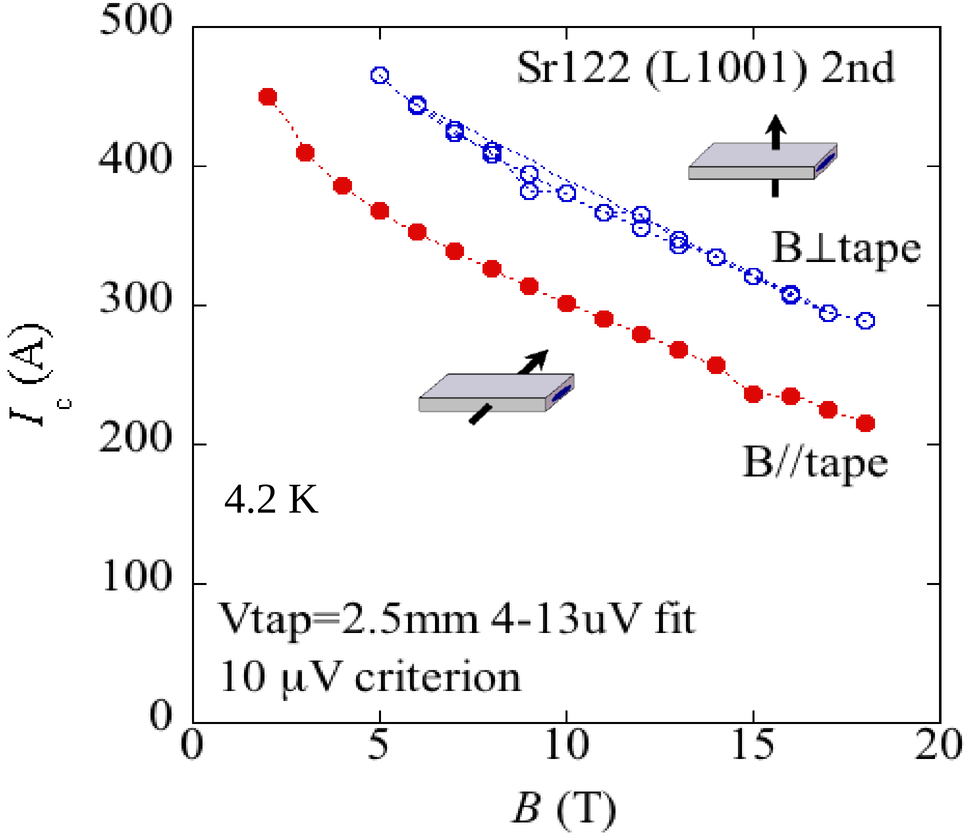
A scalable process (Rolling+HIP) ⇒

- **grain texture by flat rolling**
- **high density by HIP**

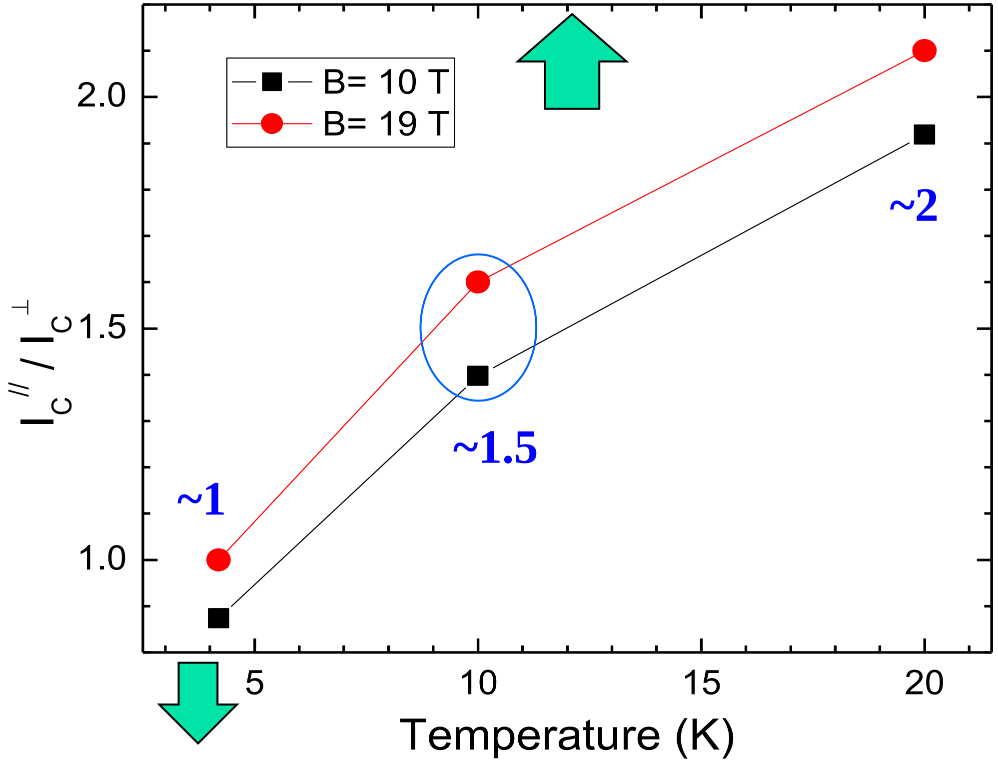
Liu et al., ***SuST*** 32 (2019) 044007

铁基超导带材具有很小的各向异性

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



Measured by ***C. Senatore*** group at Geneva Univ., ***SuST***2020

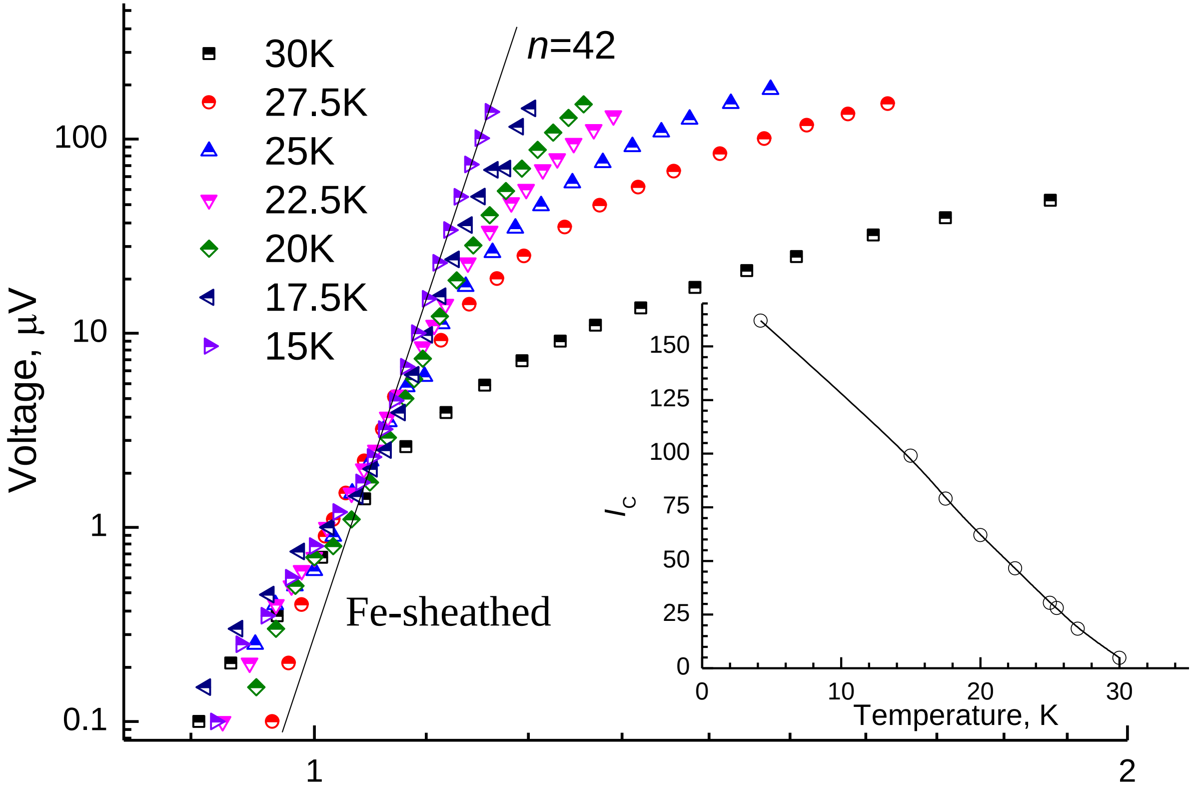


$I_C^{//} < I_C^{\perp}$ only at low temperature and fields

- **The I_c in applied magnetic fields is slightly higher in the perpendicular field ($I_c^{\perp}$) than in the parallel field ($I_c^{//}$).**
- **The anisotropy ratio ($\Gamma = I_c^{\perp}/I_c^{//}$) is quite low, less than 2, very good for applications.**

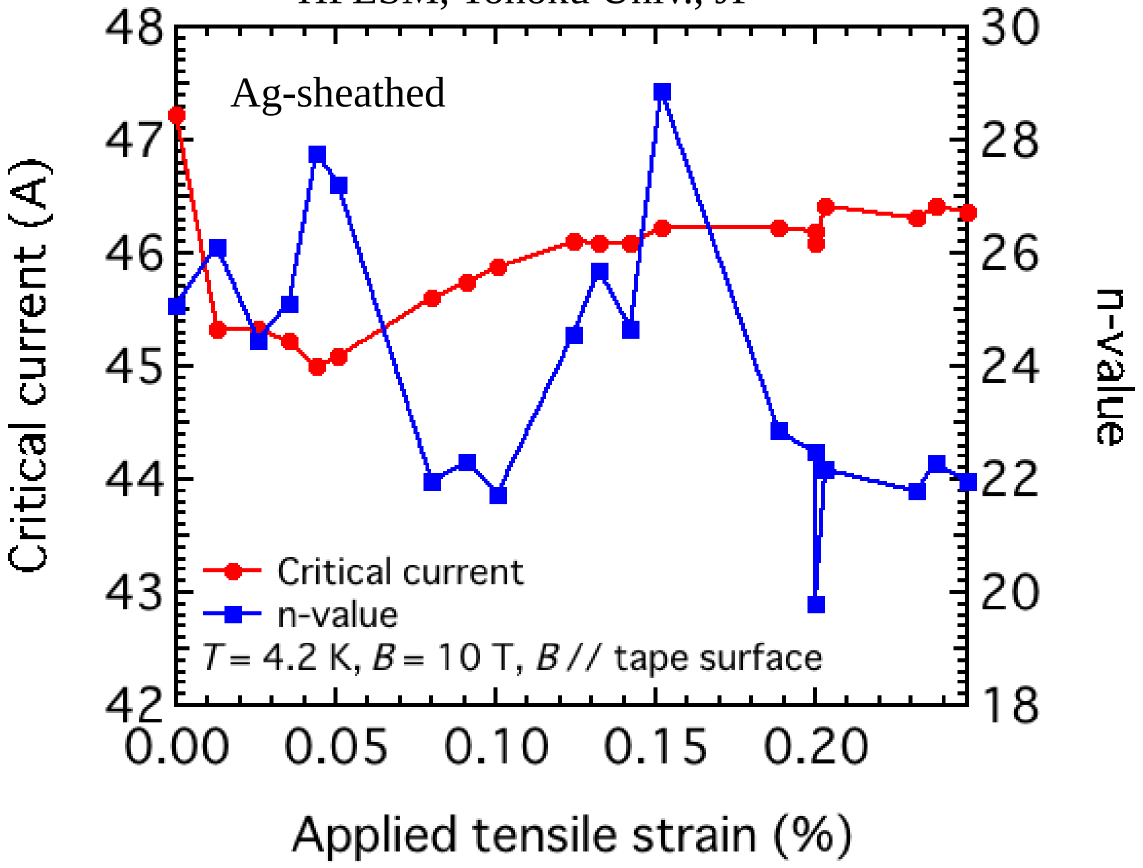
Temperature dependence of *n value* for Sr-122 tapes

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



Courtesy of Yifeng Yang

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



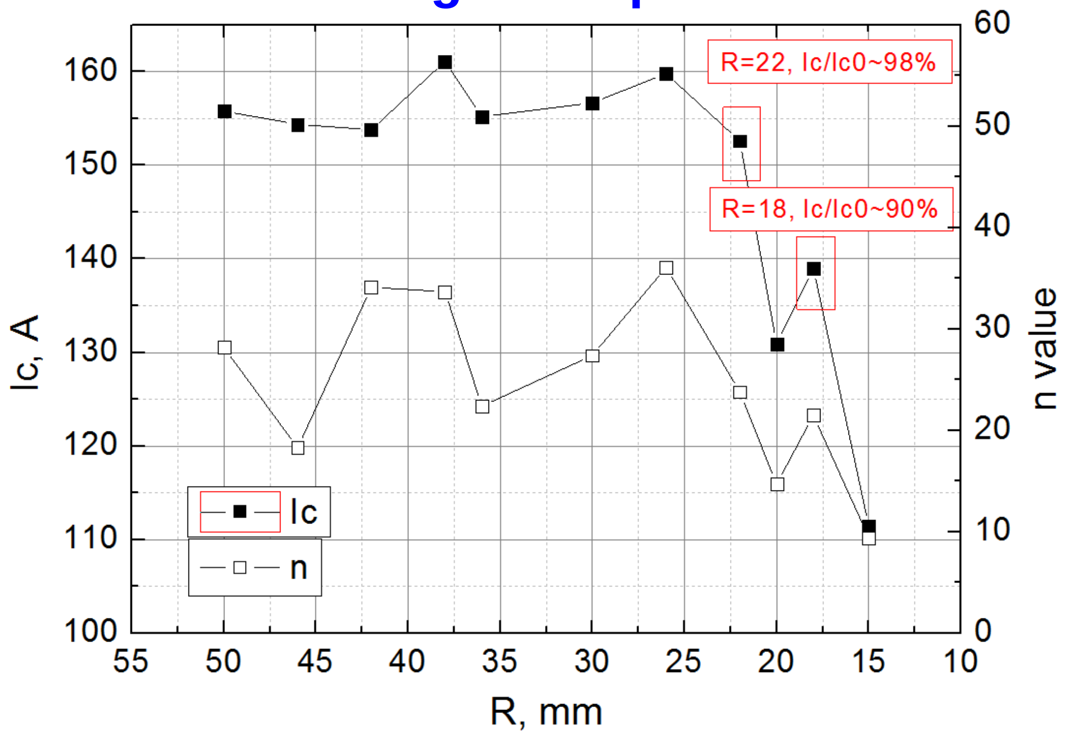
At 20 K, the *n value* was over 30

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

Straight → Bent → Straighten

Bending test of 122 IBS tapes

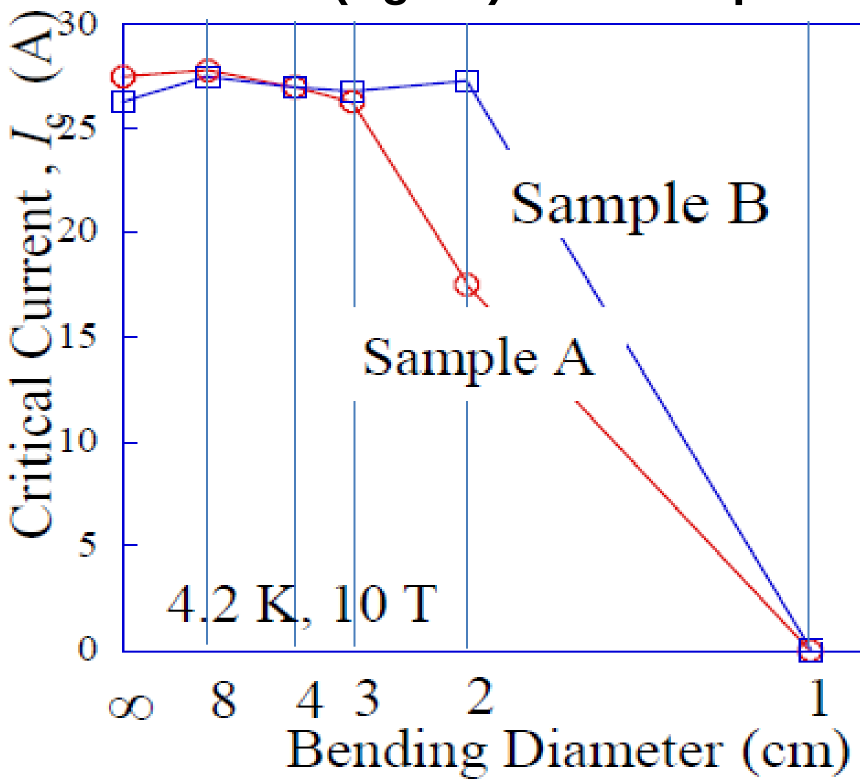
122/Ag IBS tapes



width ~ 4.5 mm, thickness = 0.3 mm

Cooperated with Prof. Huajun Liu in IPP-CAS

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

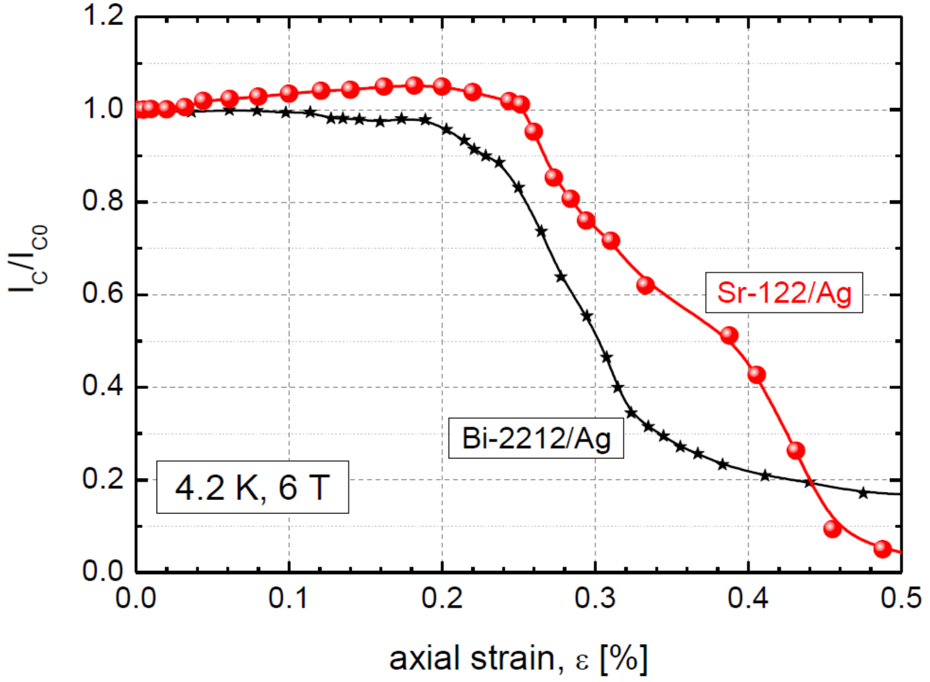


Courtesy of H. Kumakura

- **The critical bending diameter is 4.4 cm for Sr-122/Ag tapes in thickness of 0.3 mm.**
- **For high strength Ba-122 tapes, the bending diameter is even smaller, only of 2~3 cm.**

122铁基超导带材的应力应变特性

The first strain measurement under tensile stress

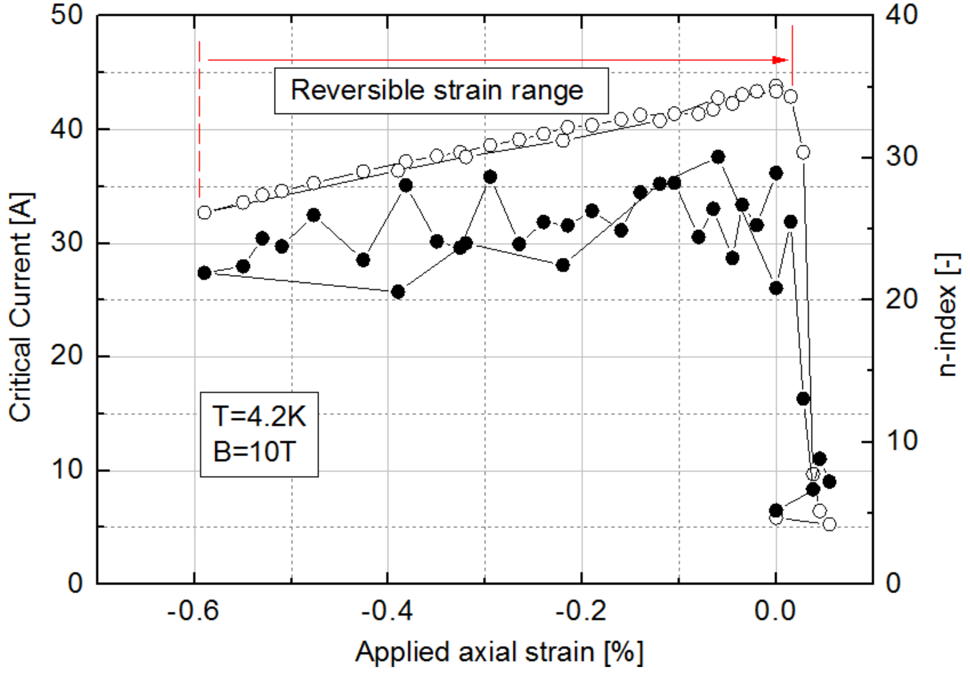


At 4.2 K, 10 T: I_c >125A
Irreversible strains: ε = 0.25%

Comparable to Bi2212

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

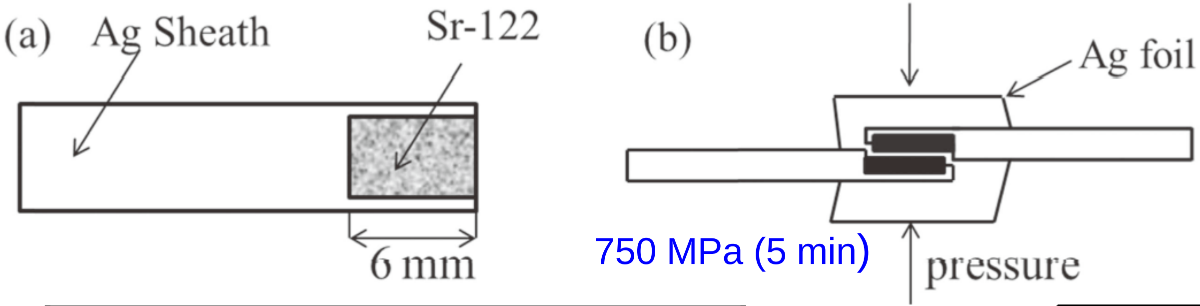
具有大的负不可逆应变，达-0.6%

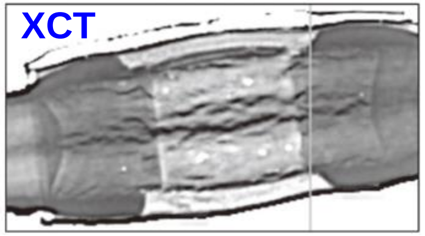


122线材在比较大的压缩范围内 (-0.6%)呈现可逆现象，好于YBCO!
这一发现对铁基超导材料未来的核聚变应用意义重大。

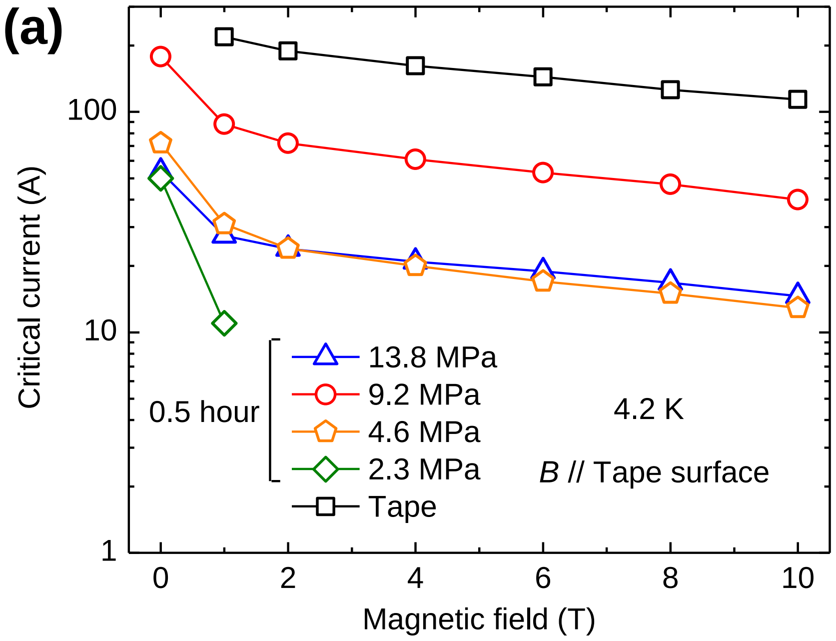
Liu et al., ***SuST*** 30 (2017) 07LT01

Development of superconducting joints between iron-based superconductor tapes

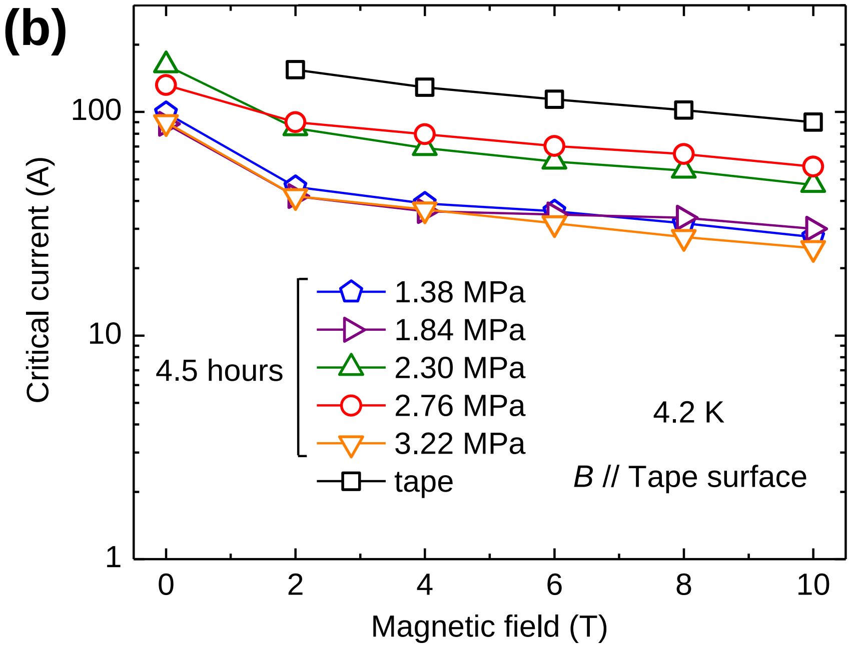




for persistent current operation



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



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

critical current ratio (CCR) = 35.3% → **Optimizing the HP pressure**

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

Outline

1 Background on iron-based superconductors (IBS)

2 High-J_c IBS films and Coated Conductors (CC)

3 Fabrication of PIT IBS wires

i) Strategies to improve J_c in 122 wires

ii) Practical properties of 122 IBS wires

iii) Long-length wire & inserted coils

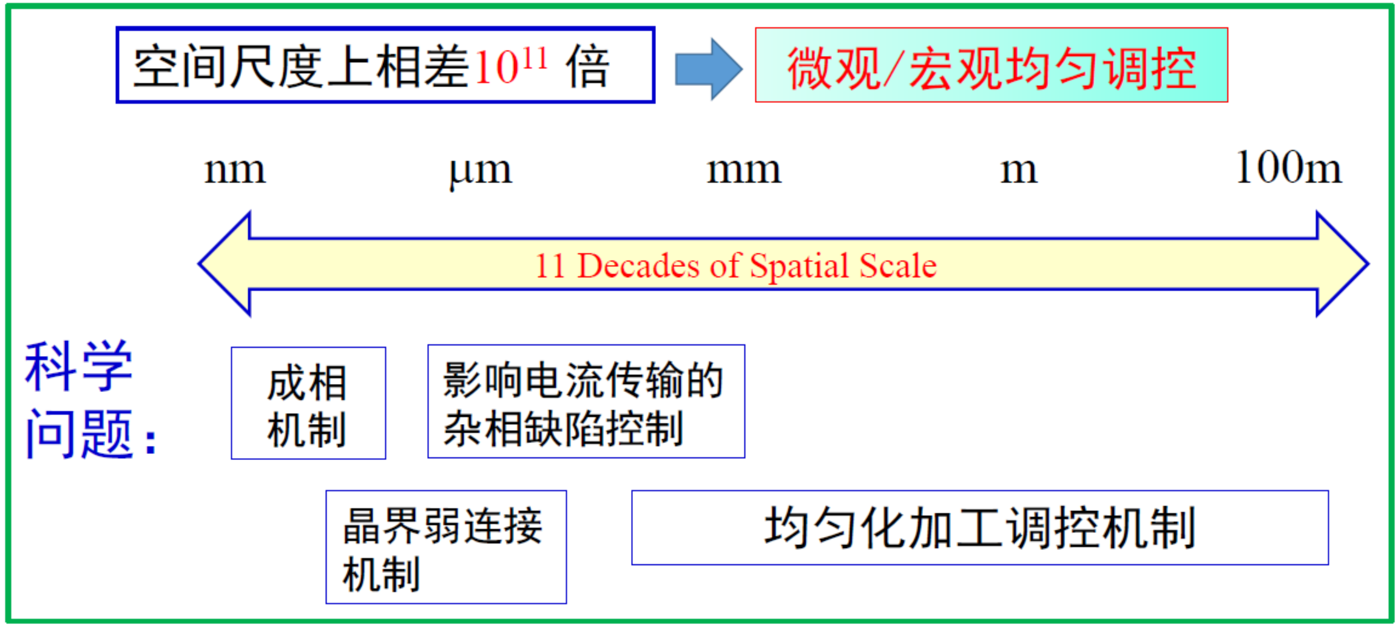
4 Conclusions

铁基超导材料大规模应用—亟待解决的问题

高性能铁基长线研制

百米级铁基长线，是铁基材料获得实际应用的基础

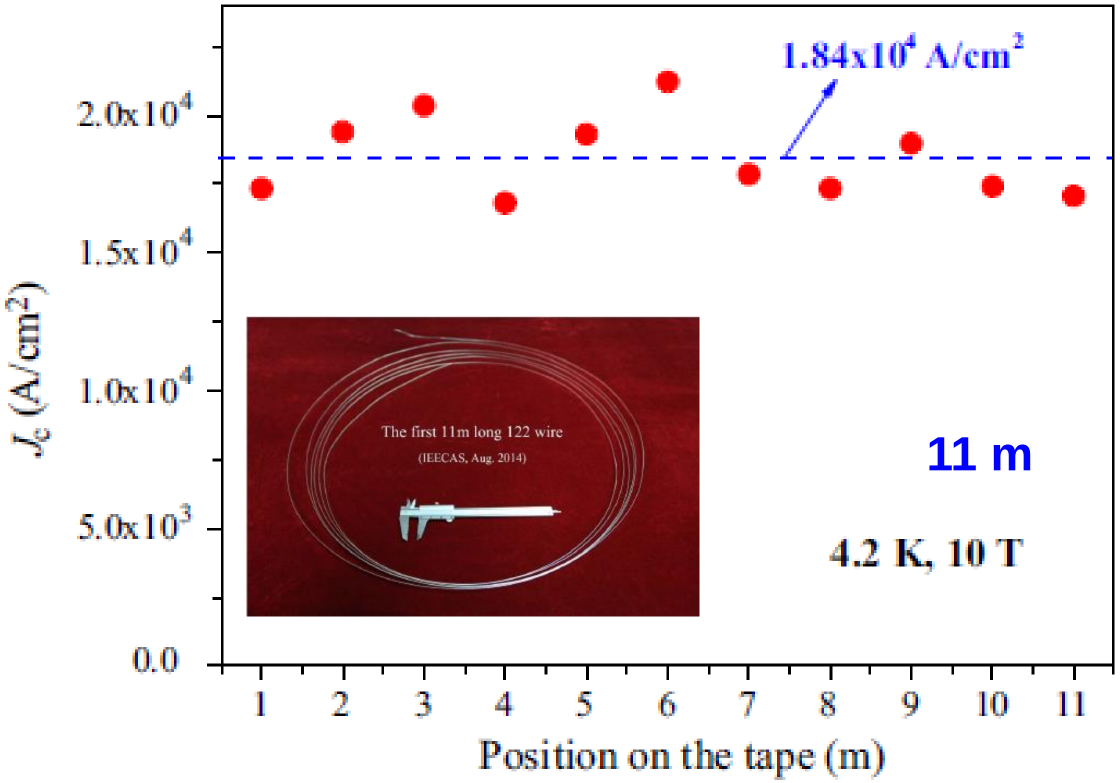
百米级超导长线是任何一种超导材料走向大规模应用的必经阶段！



Fabrication of the meter long 122 IBS wire

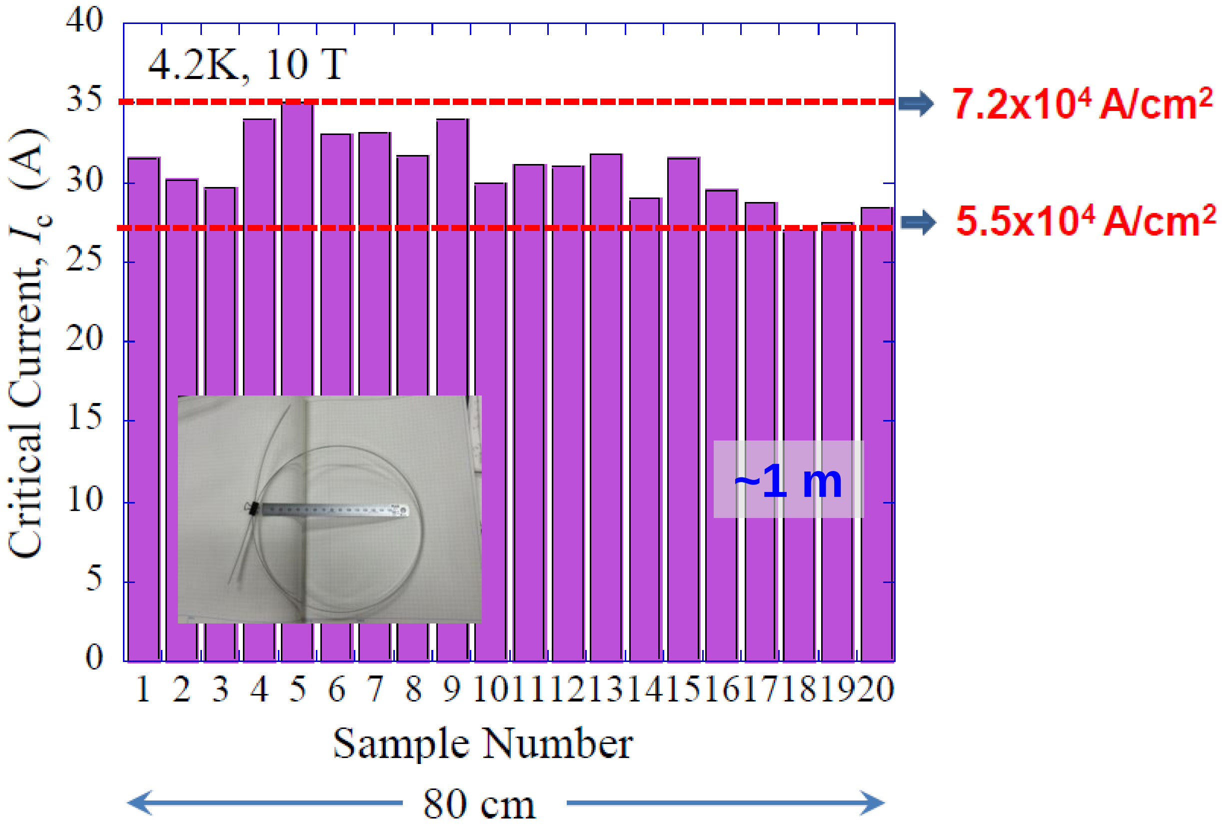
---by scalable rolling process

The fluctuations of the J_c is ~5% for 11 m long Sr-122/Ag tape



Ma, Physica C 516 (2015) 17-26

I_c distribution of a ~1 m long SUS316/(Ag-Sn)/Ba-122 tape



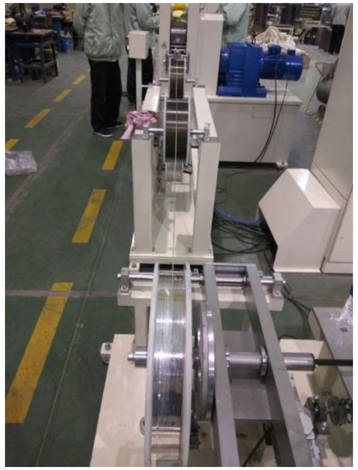
Challenging to longer length!

By courtesy of H. Kumakura

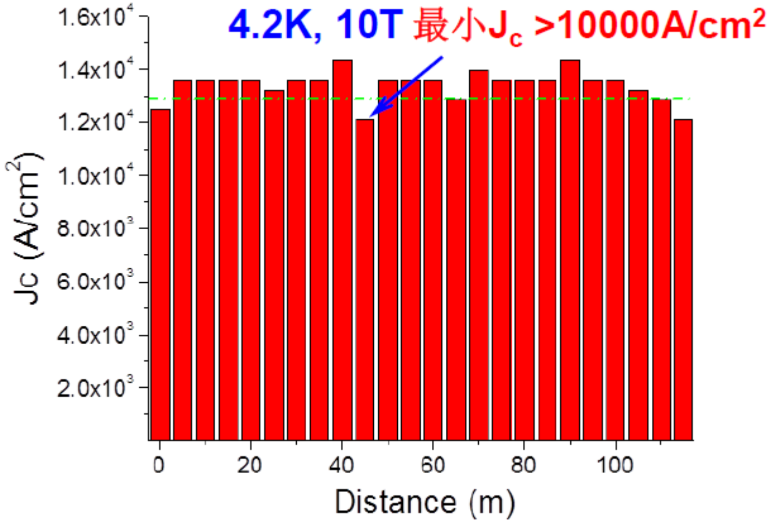
研制出国际首根100米量级铁基超导长线

➢通过对铁基长线的结构设计和加工技术优化，**有效解决了长线制备过程中的不均匀问题；**

➢**国际现状：**目前美、日、欧等国家的铁基超导线材制备还处于米级水平！



115 m long **7-filament** wire



在美国应用超导大会（ASC）上报道后，受到国际同行的广泛关注！
随后日本国际超导会议（ISS）特别安排作为‘**LateNews**’邀请报告。

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

向产业化应用迈出了关键的一步；占据了超导应用的制高点！

铁基超导发现者H. Hosono教授、国际知名超导专家 D. Larbalestier教授等纷纷表示祝贺

Congratulations ! This is a breakthrough in IBSC wires. Hope further success.

Hideo Hosono

Marina Putti

Congratulations ! Well done to you.

Many congratulations indeed! Will you make the world's first FBS magnet out of it too?

David Larbalestier

Naoyuki Amemiya

Congratulations! It's a milestone.

国内外媒体对百米铁基超导长线的关注

《新闻联播》进行了报道

获得2019年国际应用超导杰出贡献奖

该奖项每两年颁发一次，每次仅评选一位获奖者，旨在表彰近五年来在国际应用超导领域有卓越创新和重大科学贡献的个人。

这是我国科学家首次获得该奖项

--ESAS Award

2019年，英国格拉斯哥举办的第14届 欧洲应用超导大会（EUCAS）上

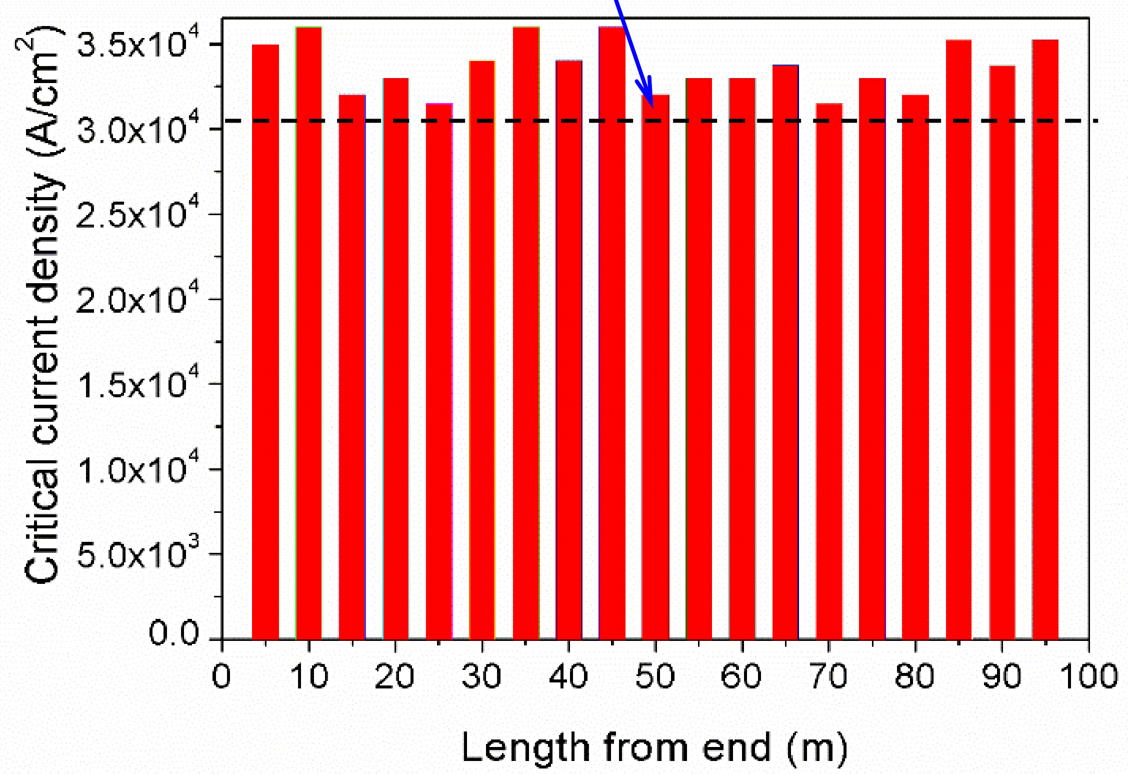
该奖项对马衍伟研究员的研究给予高度评价：“他基于对铁基超导体材料特性及其应用潜力的深刻理解和远见，创新设计并开发了铁基超导材料的系列关键技术，研制出高场临界电流达到实用化水平的铁基超导线材，成为铁基超导材料走向实际应用的新的里程碑”。

Recently, J_c of 100 m long tapes was further enhanced: >30000 A/cm^2 (4.2 K, 10 T)

3 times larger than the first!

Key steps to the application

@4.2K, 10T, transport J_c >30000 A/cm^2



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

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

Letter

研制出国际首个铁基超导高场内插线圈

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

-- Cooperated with Qingjin Xu group at IHEP-CAS

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

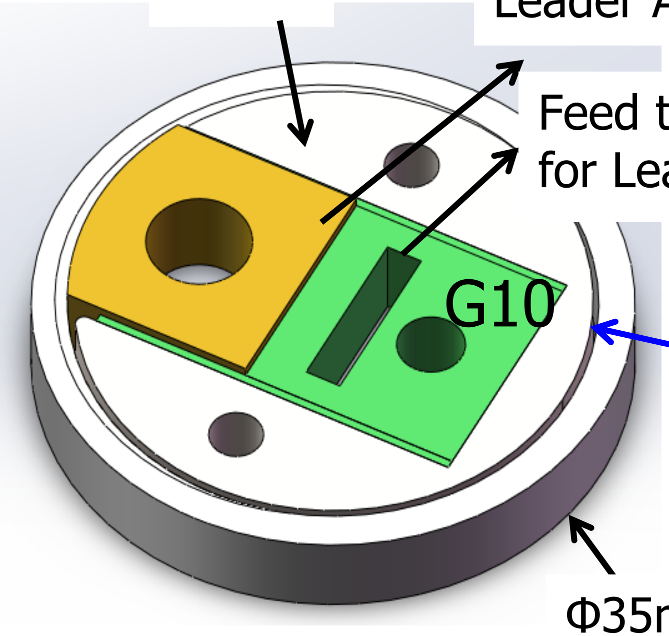


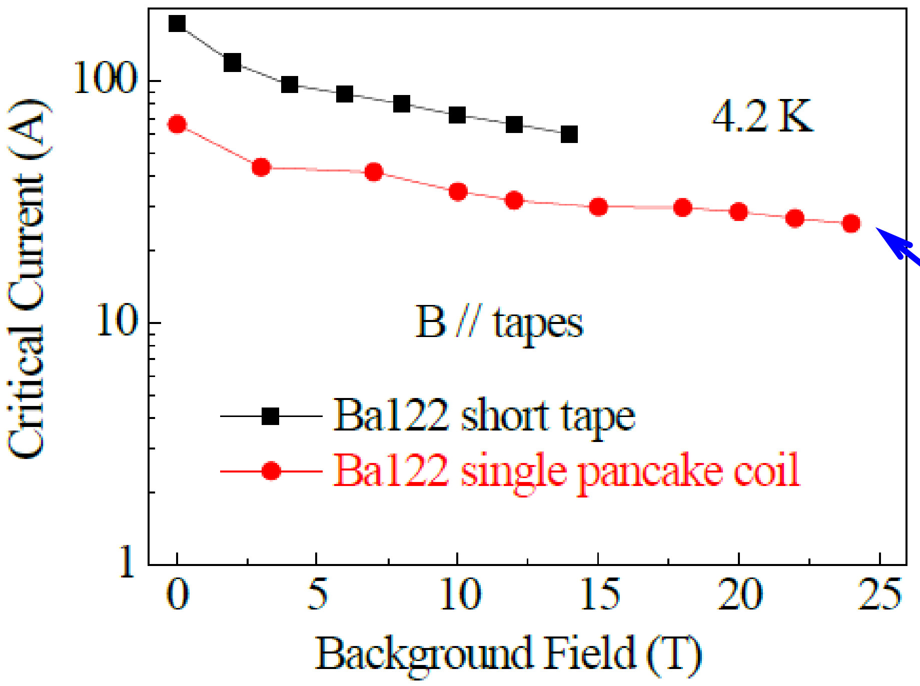
Table 2. Specification of single pancake coil

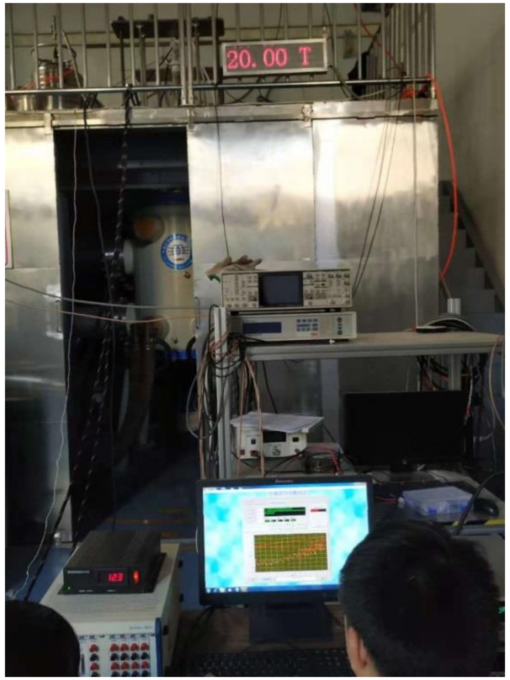
Parameter	Unit	Value
Inner diameter	mm	30
Outer diameter	mm	34.8
Height	mm	4.62
Thickness of stainless steel tape	mm	0.1
Turns		4.5
Total length of IBS wire	mm	450

在24T高场下具有优异的载流性能，验证了高场应用的可行性

--Measured at HMFL in Hefei

25T-HM, RT bore Φ38 mm





- **The I_c of the Ba122 coil showed weakly dependent on the magnetic field, like the short tape. (I_c=26 A in a field of 24 T)**
- **These results suggest that IBSs are very promising for high-field magnet applications.**

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

IOP Publishing Superconductor Science and Technology

Supercond. Sci. Technol. **32** (2019) 070501 (3pp) https://doi.org/10.1088/1361-6668/ab1fc9

CrossMark

Viewpoint

Constructing high field magnets is a real tour de force

Jan Jaroszynski
National High Magnetic Field, Laboratory, Tallahassee, FL, 32310, United States of America
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.

美国弗罗里达强磁场实验室在《超导科技》对该工作发表评述：

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.

"这是一个重要的结果"

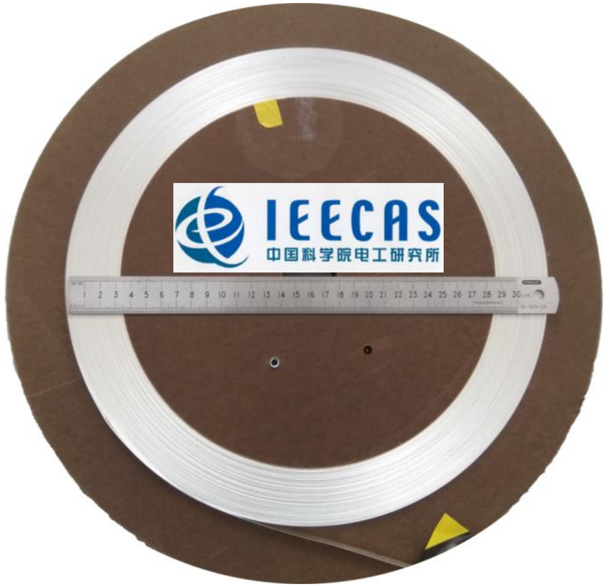
"铁基超导线的价格能够比Nb_3Sn低4-5倍"

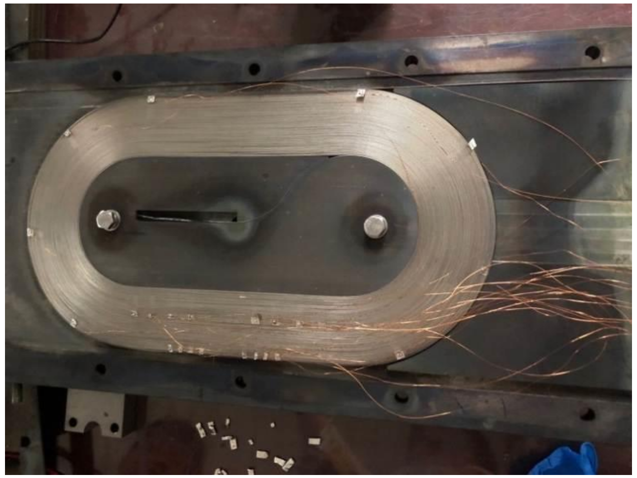
However, this is an important result, because at such high fields, coiled wires suffer from high tensile hoop stress that pushes them to the limits of their mechanical strength. In this high stress regime, critical current densities and critical fields are not what limit the generation of very high fields, these are forces exerted to the superconducting wires. Here, the Ba122/Ag/AgMn tape coil survived these forces.

使用100米铁基超导长线，研制出世界首个跑道型铁基超导线圈

Recently…

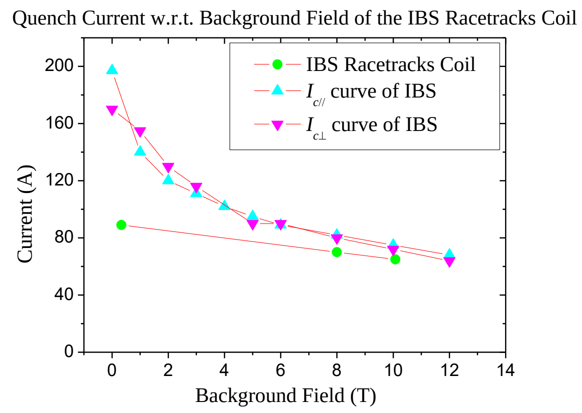
Made by Qingjin Xu group at IHEP





IBS Racetrack coil

磁体吊装进行低温测试



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

- 跑道型线圈在10 T背景场下临界电流达到短样性能的86.6%，验证了大尺寸铁基线圈在10T背景场下的优异的载流性能。
- 证明了铁基带材用于制备未来加速器磁体等高场大尺寸线圈的可行性。

-- to be published in ***SuST*** 2020

结论与展望

- ✓ 目前铁基超导材料正处于快速发展的研发阶段；
- ✓ 铁基超导线带材的传输电流密度在4.2 K和10 T下已超过10^5A/cm^{2}的实用化门槛，最高J_c=0.15 MA/cm^2；
- ✓ 研制出首根百米级铁基超导长线（最新长线性能又提高了3倍），为其规模化应用奠定了材料基础。
- ✓ 有望成为4.2-30 K 温区高场磁体应用的主要实用超导材料，如用于制造运行在4.2 K下、磁场强度超过20 T 的超导磁体，发展潜力大。

Challenges for the next stage R&D

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

→ e.g. critical current density $J_c > 10^5$ A/cm^2 **@** 4.2 K, 30 T

✓***Homogeneous long length tapes (if using rolling):***

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

✓***Low Cost High J_c Round Wires (if using HIP):***

→ i) instead of using Ag, ii) round wire is ideal for high homogeneity magnets

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

→ *Tensile, Bending*

Contributors:

Xianping Zhang, Chao Yao, Chiheng Dong, Dongliang Wang, Zhangtang Xu, He Huang, Shifa Liu, Zhe Cheng, Yanchang Zhu, Cong Liu

Institute of Electrical Engineering, CAS

Collaborators:

S. Awaji (I_c-B measurement)
HFLSM, Tohoku University, Japan

F. Kametani, C. Tarantini, E. Hellstrom, D. Larbalestier (STEM and GBs)
NHMFL, FSU, USA

Hai-hu Wen (Pinning properties)
Nanjing University, China

Huajun Liu (In-field I_c measurement)
IPP-CAS

W. K. Kwok, U. Welp (Irradiation)
Argonne National Laboratory, USA

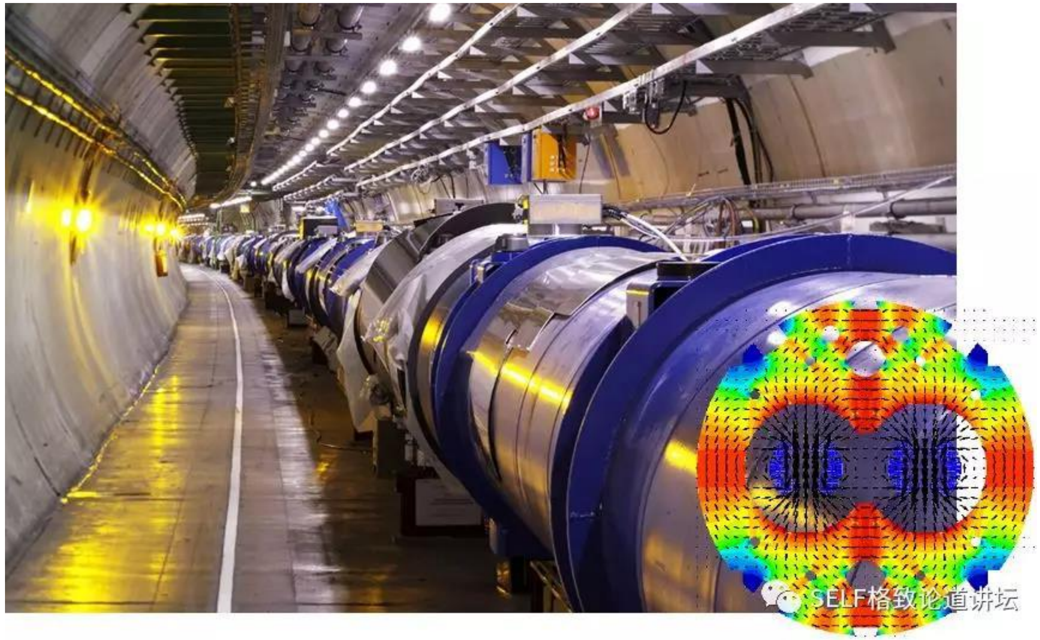
J. Hänisch, B. Holzapfel (J_c rising mechanism)
ITEP-KIT, Germany

Qingjin Xu (Coil design and fabrication)
IHEP-CAS

C. Senatore (I_c(T,B) measurement)
DQMP, Univ. Geneva

T. Kiss (Characterizing local microstructure and homogeneity of wires)
Kyushu University, Japan

Thank you for your attention!



From a movie： Avatar