高温与高场超导材料及其应用技术研讨会，
2016.4.27-29，上海

Bi-2212高温超导线材的制备及性能进展

报告人：李成山

西北有色金属研究院
西部超导科技股份有限公司
中科院等离子所

2016年4月28日

报告内容

国外Bi-2212线材及应用进展

西北院Bi-2212线材制备

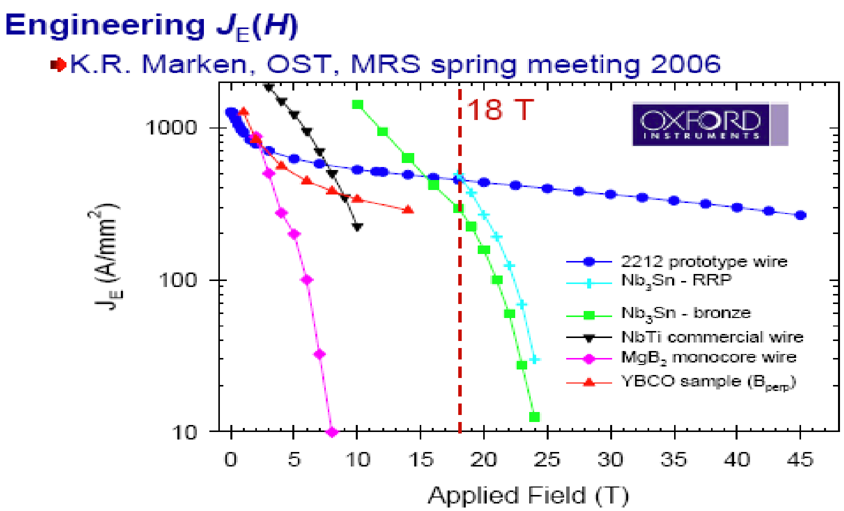
Bi-2212导体初步结果（等离子所、西北院）

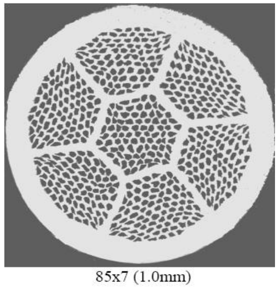
简单总结

$Bi_2Sr_2CaCu_2O_x$ (Bi-2212)超导材料

Bi-2212 超导材料的特点

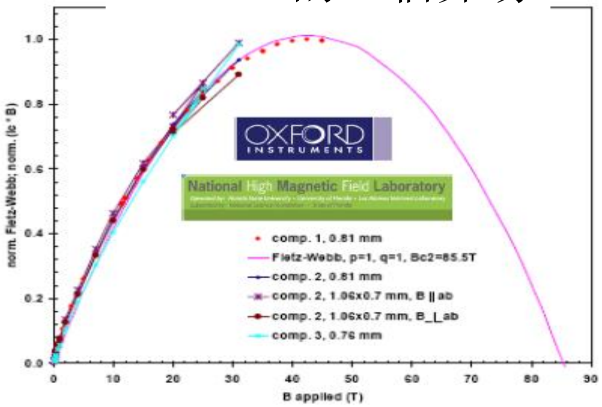
- 临界温度为85K，上临界磁场为100T (4. 2K)
- 在4. 2K温区具有优异的磁场载流性能
- 可制备成各向同性的圆线并可以绞缆





Bi-2212线材截面

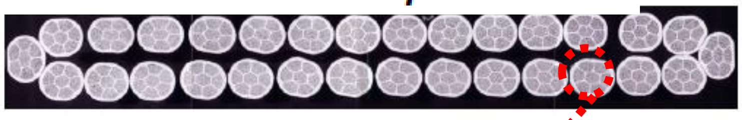
Bi-2212的上临界场



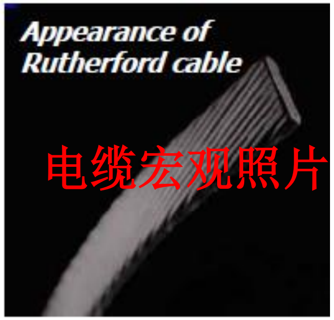
高温超导材料中，Bi-2212是唯一可制备成各向同性圆线的材料，适宜于制备高场内插线圈，同时也 是目前制备高温超导大电流导体的可选材料

日本Bi-2212卢瑟福电缆

MT-19 at Genova Sep. 19 2005



Cross section of 0.8mmd-30st Rutherford cable

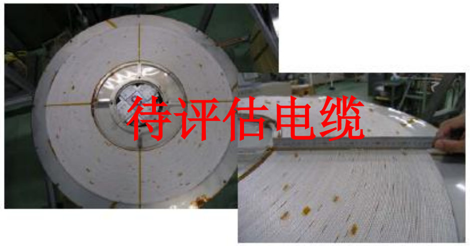


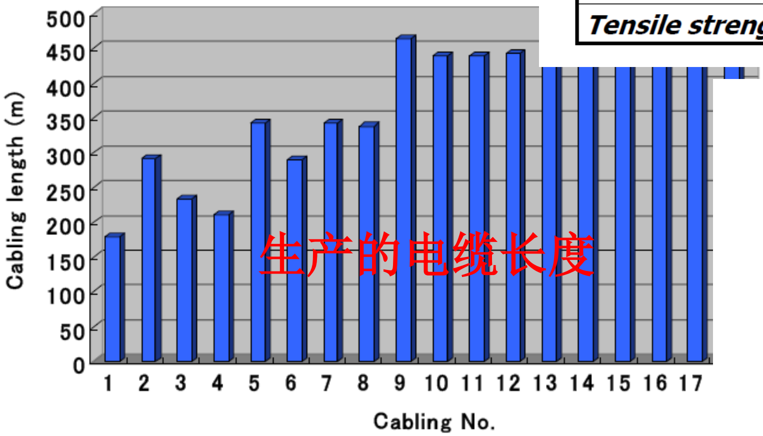
0.81mm^d
427 filament
Ag/SC=2.8
Ic =640A
Jc=490kA/cm^2

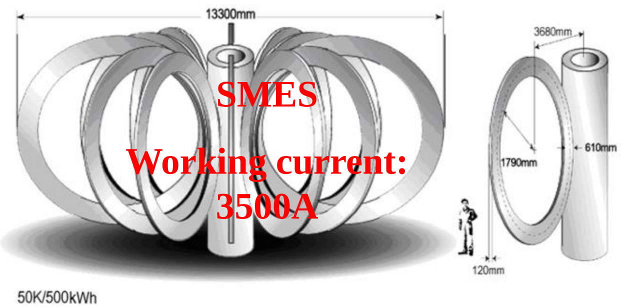
SHOWA ELECTRIC WIRE & CABLE CO.

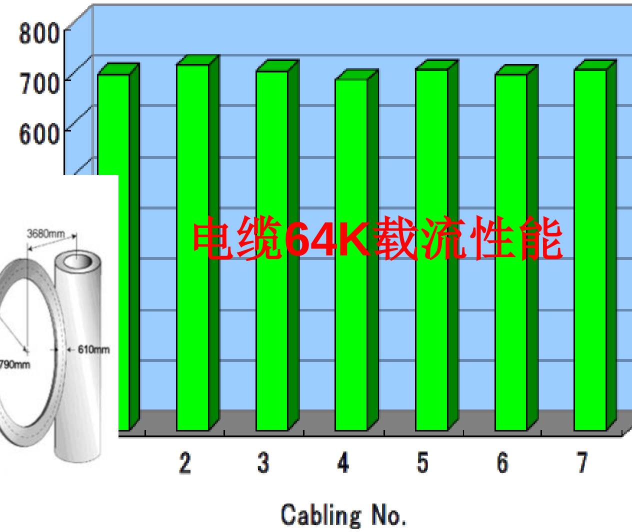
Specification of Bi2212 Rutherford Cable for NEDO-SMES Project

Diameter of strand	0.81～0.82mmϕ
Number of strand	30
Piece length of cable	>200m
Cable thickness	1.55 ～1.65mm
Cable width	13.3 ～13.7mm
Cabling pitch	85 ～95mm
Ic value	>625A (@64K) Estimate → 10kA (@4..
n value	>7.0 (10^{-6}～10^{-9}V/cm)
Tensile strength	>80MPa









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韩国Bi-2212卢瑟福电缆

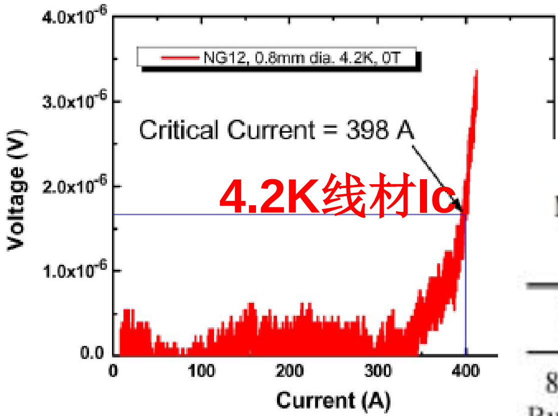


TABLE I
MICROGRAPH OF CROSS SECTION AND APPEARANCE OF FABRICATED RUTHERFORD CABLES

Type	Cross section	Appearance
8 strand Rutherford cable		
20 strand Rutherford cable		
30 strand Rutherford cable		

...rd cabling machine for Bi-2212/Ag strand was designed and KERI and Nexans Korea.

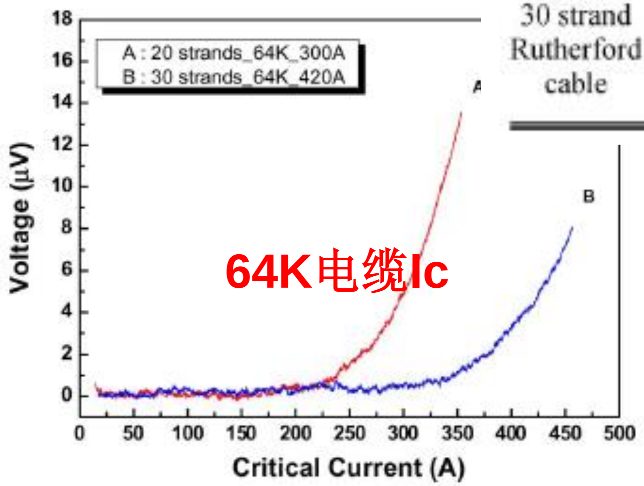


Fig. 7. Critical current properties of 20 strands and 30 strands Bi-2212 Rutherford cables at 64 K.

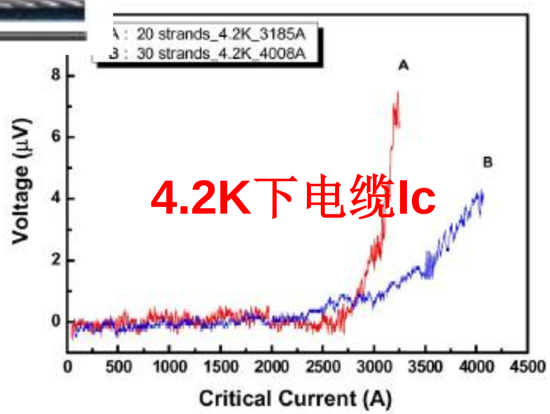
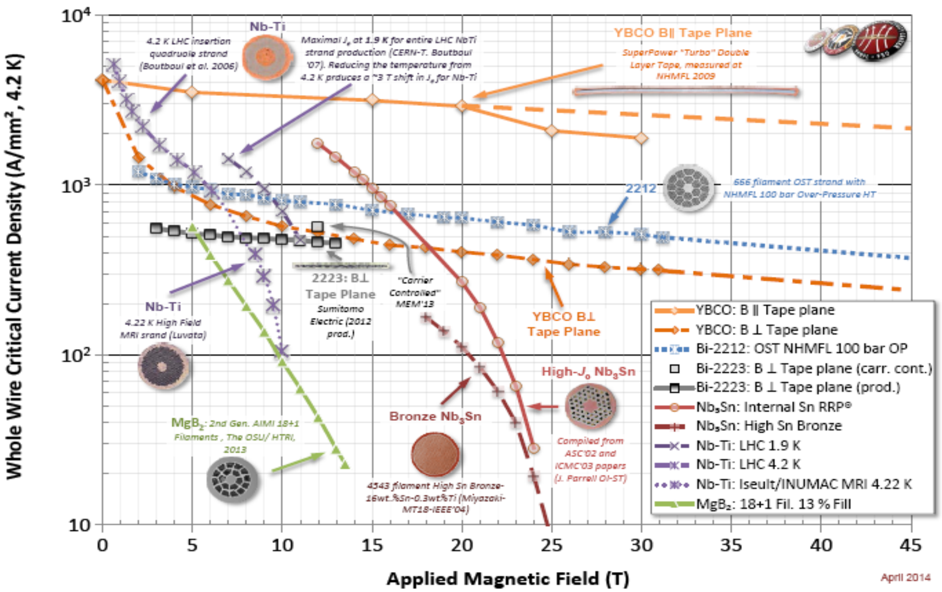
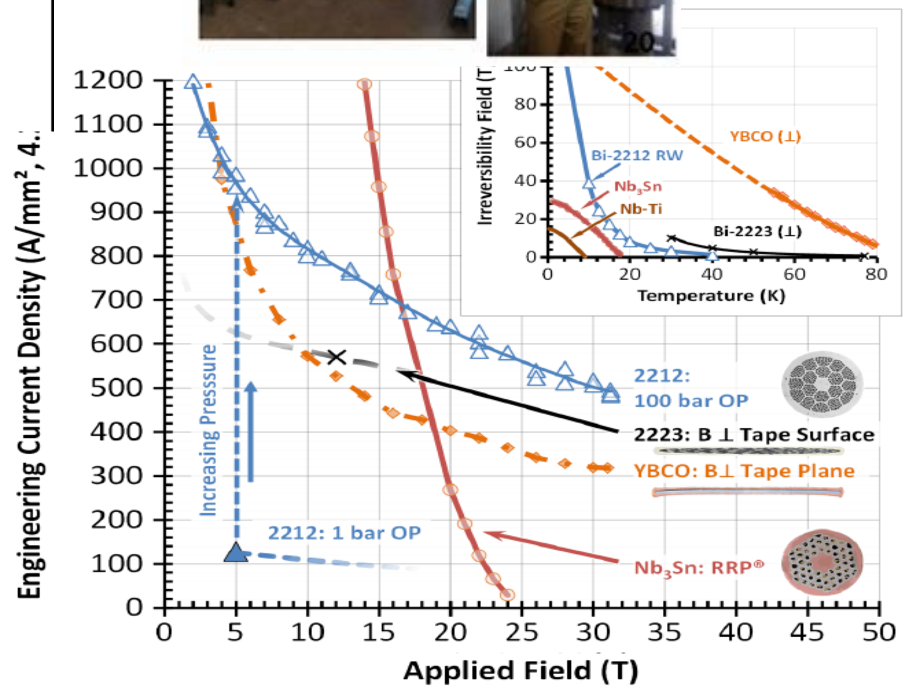


Fig. 8. Critical current properties of 20 strands and 30 strands Bi-2212 Rutherford cables at 4.2 K.

采用高压热处理提高Bi-2212线材性能



100bar，900℃
14cm*50cm



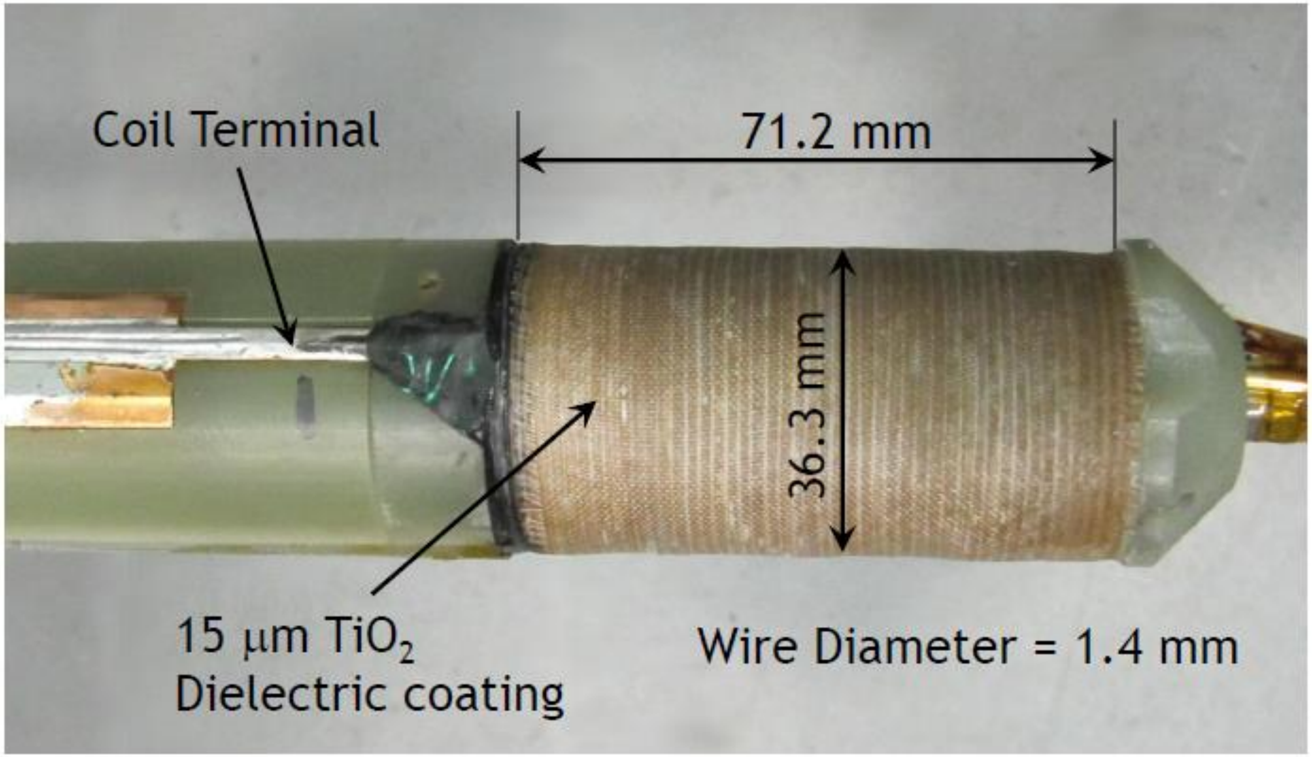
采用高压热处理（100atm），

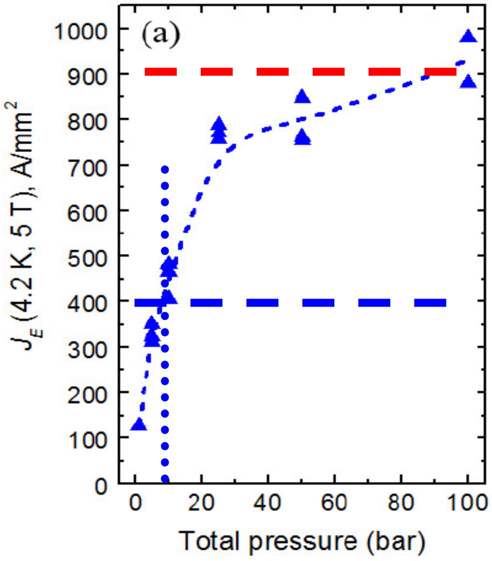
2212线材性能大幅提高：

Jce在20T为640A/mm²，30T仍然可达520A/mm²

D. C. Larbalestier 2014 nature

高压处理制备Bi-2212内插线圈





采用高压热处理（10atm)制备的小型内插磁体在**31T**的背景场下产生**2.6T**的磁场

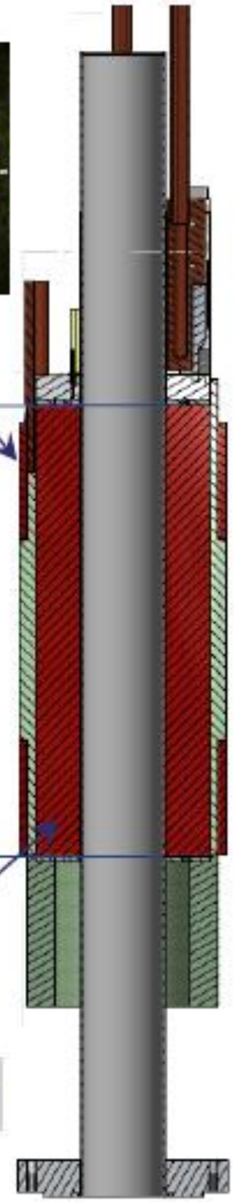
"Platypus": A Bi-2212 NMR Demo-Magnet

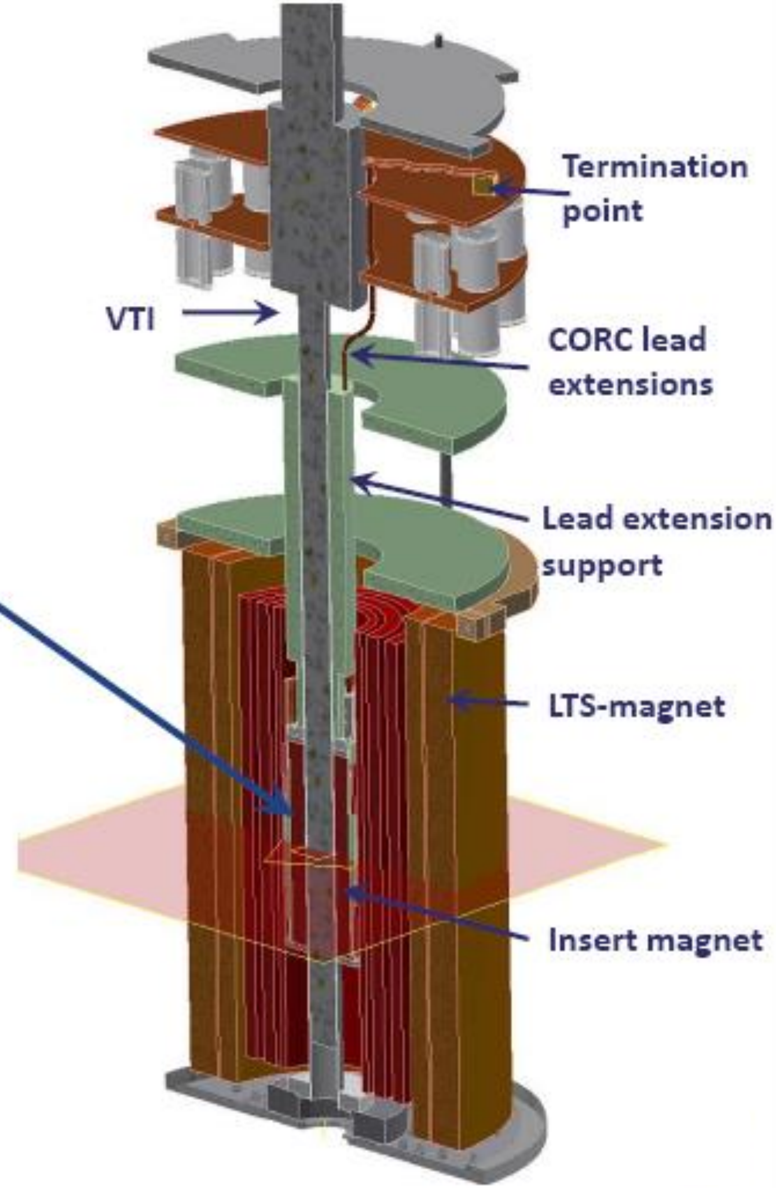
Goals:

- MagSci Goal: 30 T NMR magnet using HTS
- NMR demo magnet of ~ 1 GHz (24 T) with ppm field homogeneity and stability
- Hybrid LTS/HTS coil with all conductors twisted, round and multifilament (16 T Nb-Ti/Nb_3Sn + 8 T Bi-2212)

Status:

- Novel 2212 HTS technology has been led by NHMFL
- All sub-systems demonstrated
- Platypus test planned for summer 2015
- Strong DOE-HEP and CERN support for conductor development with industrial partner OST





Bismuth Strand and Cable Collaboration BSCCo

Fermilab BROOKHAVEN NATIONAL LABORATORY

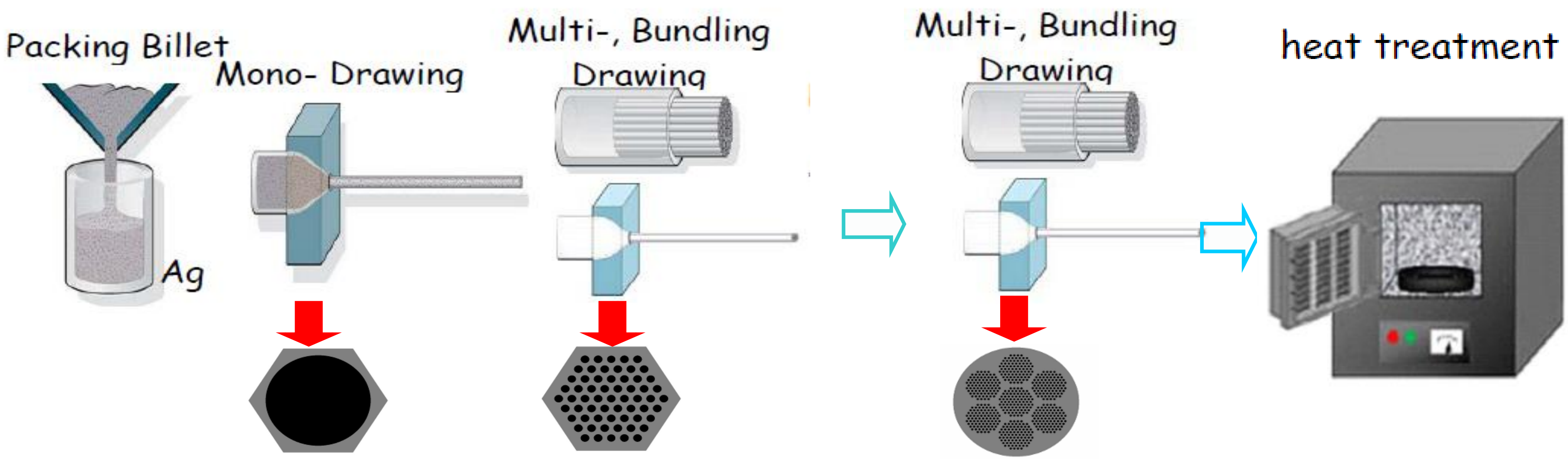
美国高温超导加速器磁体项目

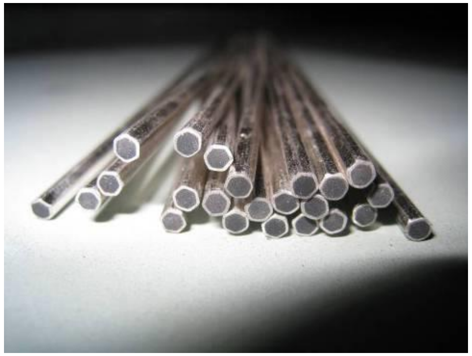
美国极高场磁体联合计划（VHFSMC) 将用2212卢瑟福电缆绕制22T加速器跑道磁体

A LABORATORY-UNIVERSITY-INDUSTRY COLLABORATION FOR THE DEVELOPMENT OF MAGNETS WITH FIELDS > 22 TESLA USING HTS CONDUCTOR

A proposal to the Office of High Energy Physics, Department of Energy
(Attention Dr B P Strauss)
At a cost of $6 million for 3 years
On behalf of the
Very High Field Superconducting Magnet Collaboration (VHFSMC)
Principal Investigators
Alvin Tollestrup (Fermilab) and David Larbalestier (National High Magnetic Field Laboratory, Florida State University)
Representing a collaboration of groups at BNL, FNAL, FSU-NHMFL, LANL, LBNL, NIST, and Texas A&M University

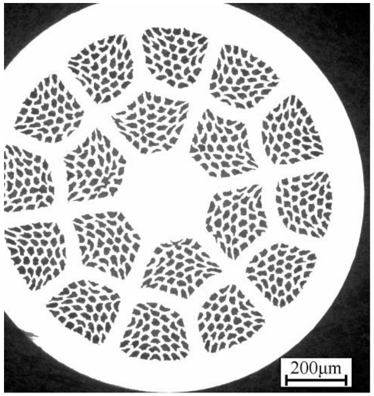
西北院采用PIT法制备Bi-2212线材





单芯线材宏观照片

多芯线加工过程的宏观照片



最终线材微观结构照片

目前可小批量制备100-200米Bi-2212线材

线材金相照片

加工过程中的2212单芯线材

准备退火的2212多芯线材

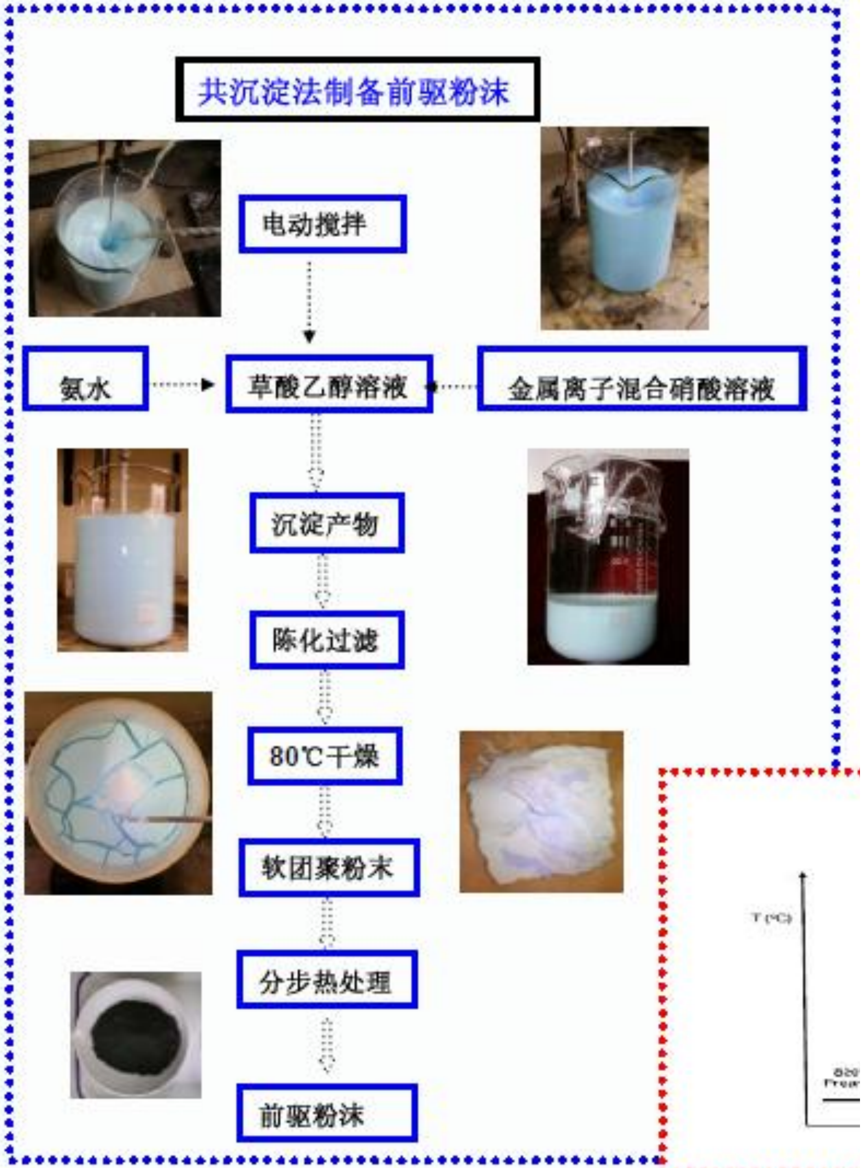
热处理后的2212线材

100-150米Φ1.0mm的Bi-2212线材

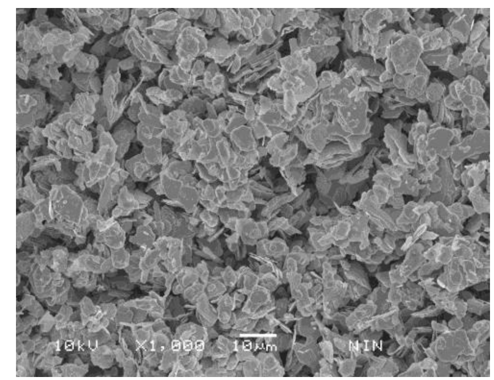
100米SiO2绝缘和加工后的线轮装2212线材

◆西北院已初步完成Bi-2212线材制备技术研究，可制备单根长度100-200米Bi-2212线材

Bi-2212前驱粉末制备



优化了粉末共沉淀制备技术，实现小批量稳定制备，粉末指标优于法国Nexans公司，
满足线材制备需求

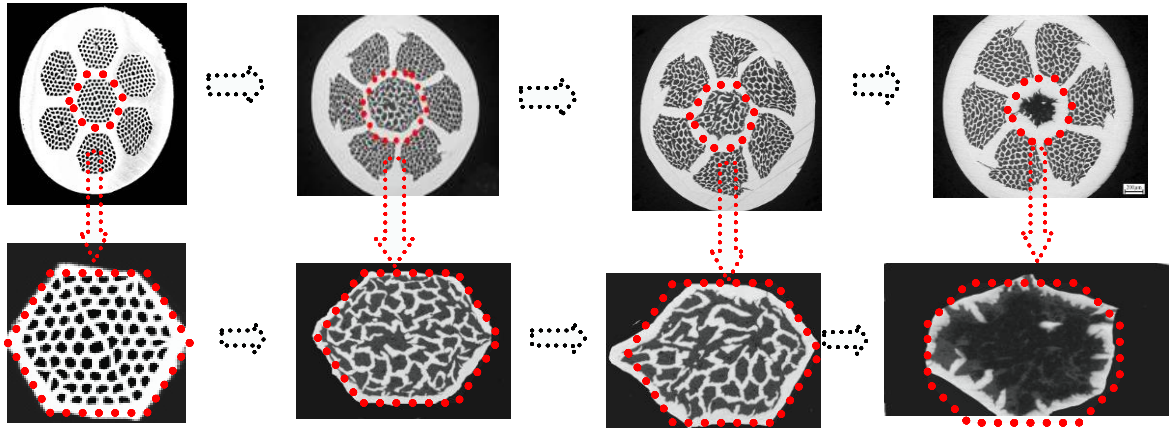


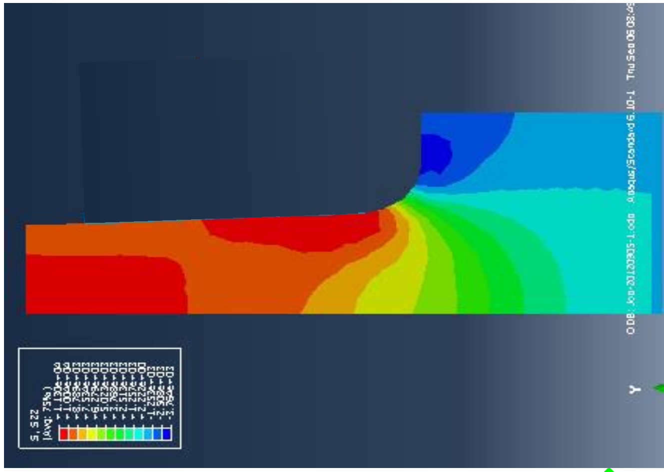
	Nexans公司	西北院
2212含量	96-97%	97-98%
残余C含量	300ppm	200ppm
粒度	**5~7μm**	**3~6μm**

Bi-2212线材的设计及加工

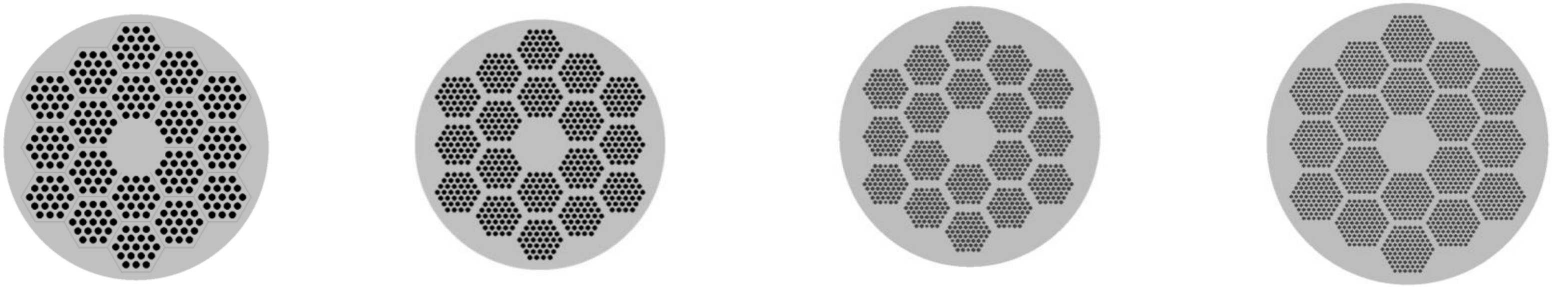
完成了多芯Bi-2212线材的加工技术研究，采用中心金属丝增强的设计解决了多芯线材中心的断芯难题，显著改善了线材加工均匀性

85×7芯线材加工过程中微观结构演变





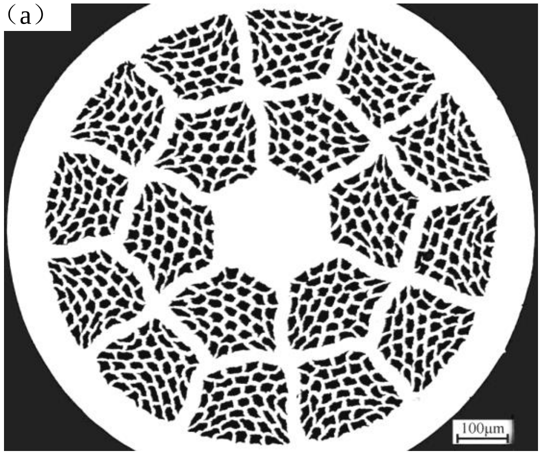
芯部增强型线材结构设计



19×18　37×18　61×18　91×18

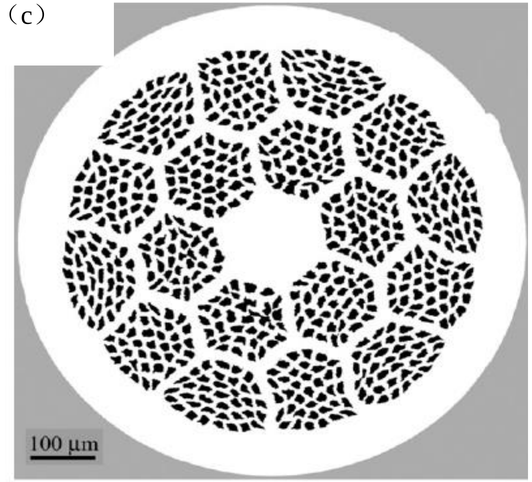
多批次线材的芯丝均匀

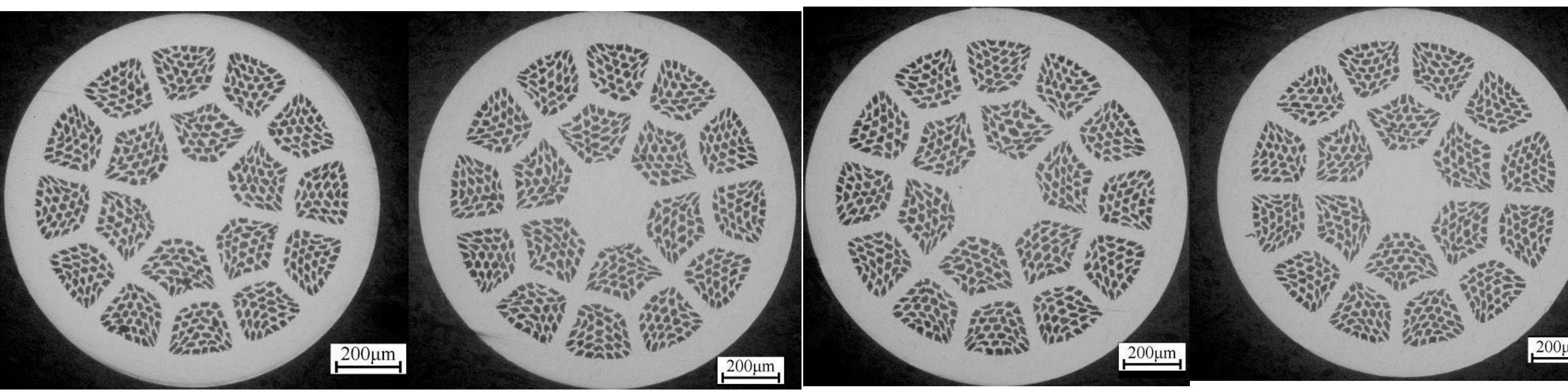
（a）



芯丝放大

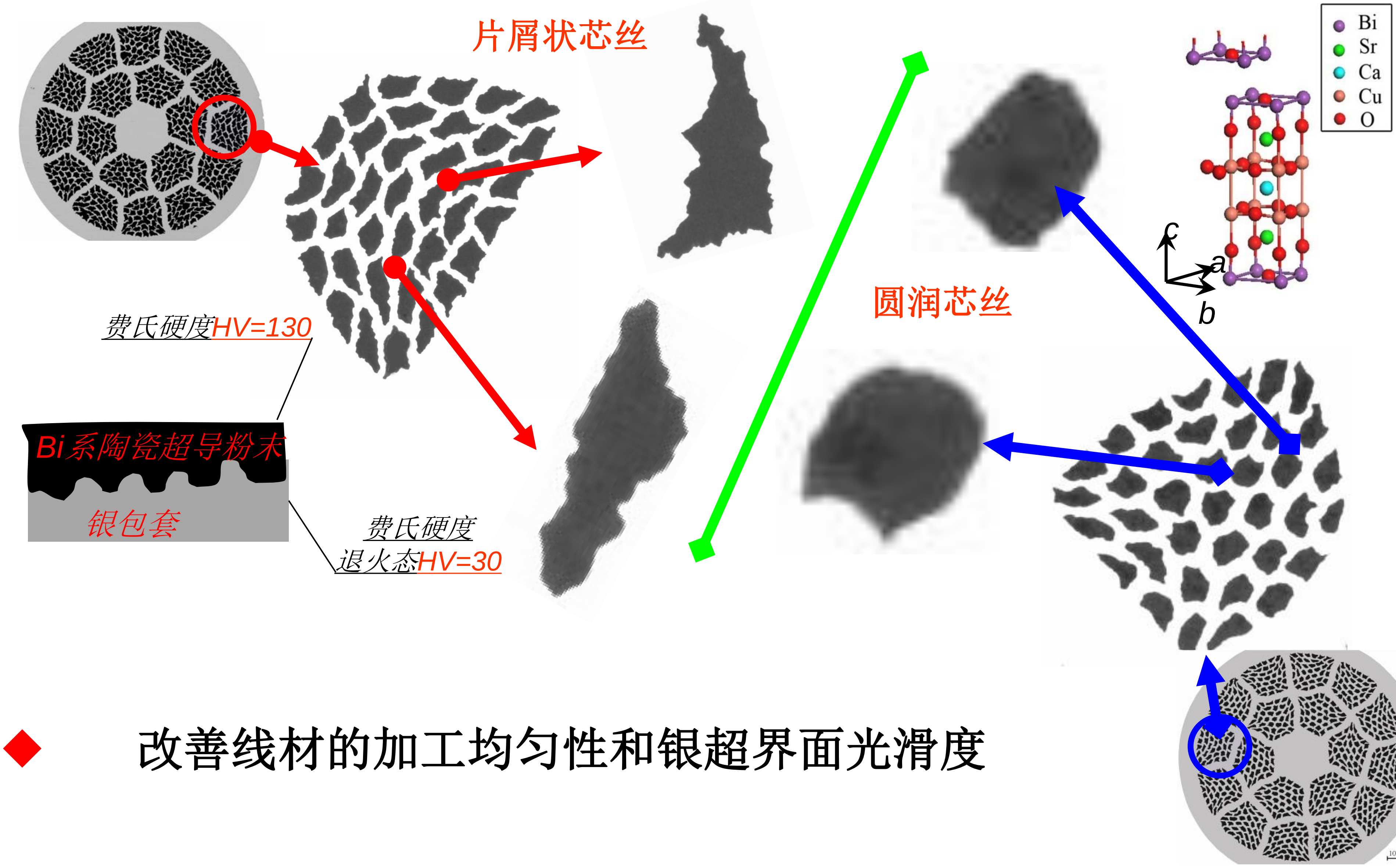
（c）





通过对加工过程和加工模具进行优化，制备的多批次线材结构均匀，芯丝形状规整，无断芯现象

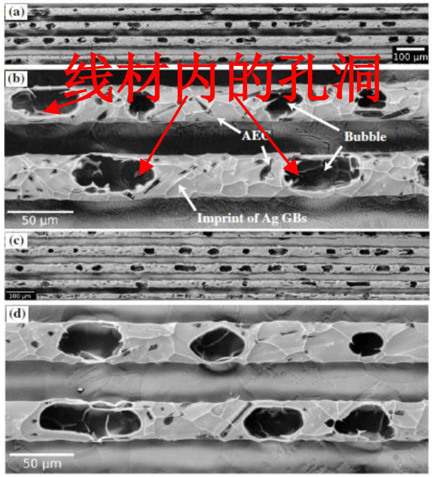
包套和粉末改性提高线材加工均匀性



◆ 改善线材的加工均匀性和银超界面光滑度

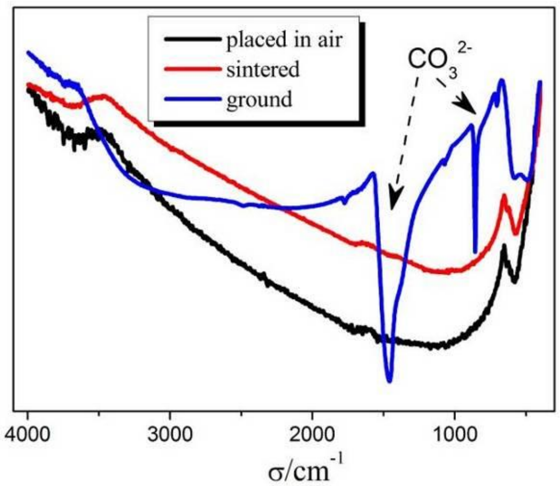
Bi-2212线材的孔洞

线材纵剖面

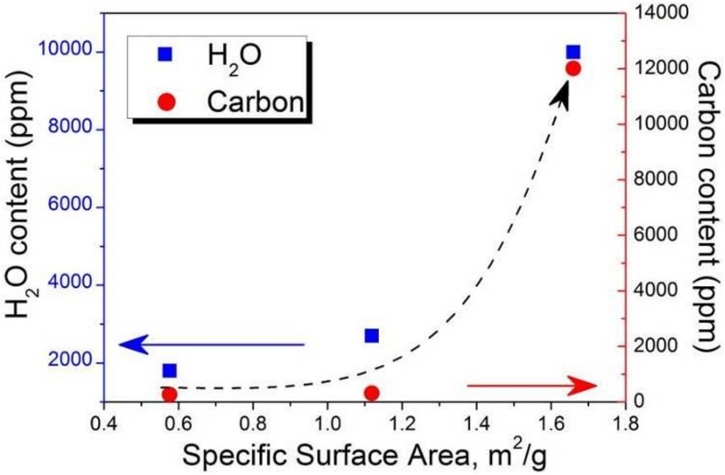


C Scheuerlein Supercond. Sci. Technol. 24 (2011) 115004 (10pp)

粉末的傅里叶红外光谱分析



水、碳含量及表面积



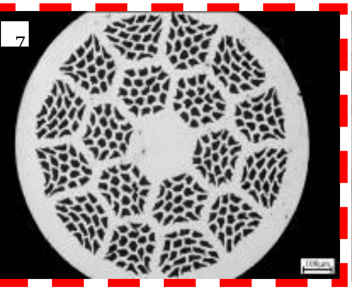
粉末表面吸附气体和间歇气体是造成线材热处理孔洞的重要原因

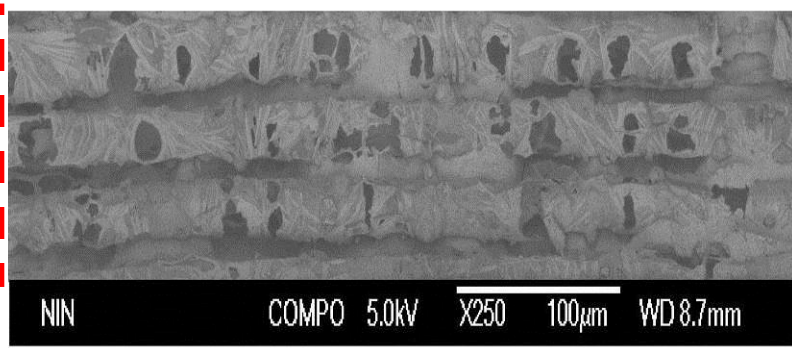
除气装置安装照片

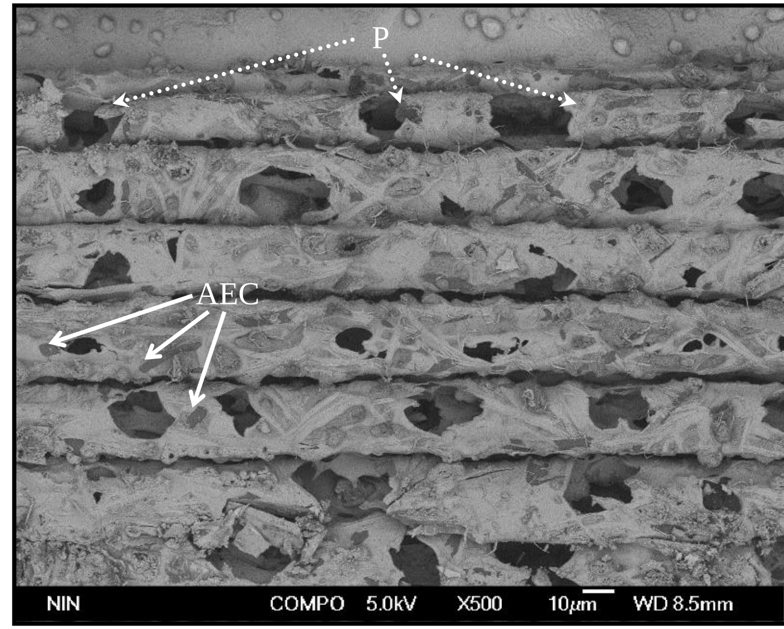
粉末采用真空装管

真空机械装管：真空研磨后，真空振台震动装管，并密封

Bi-2212线材气孔的消除

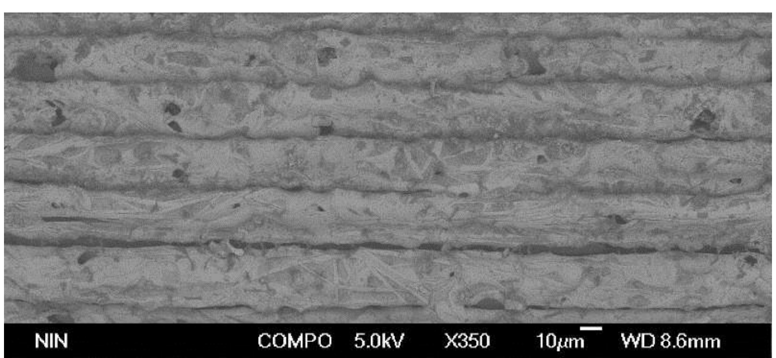


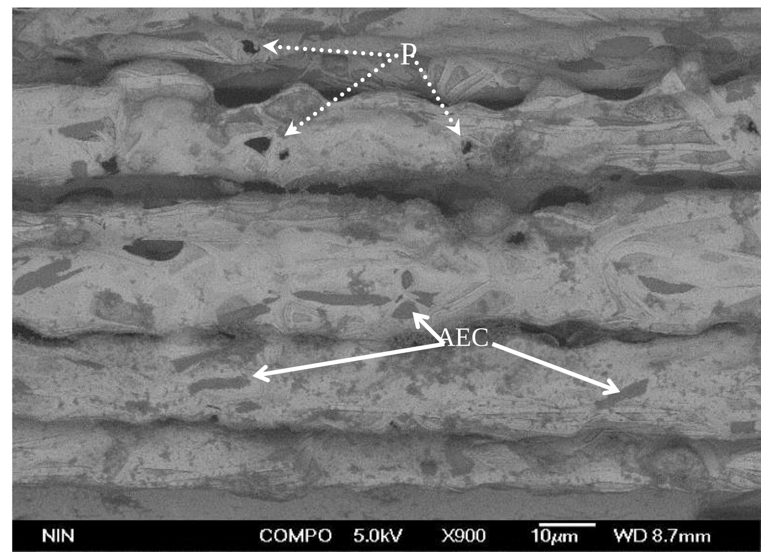




工艺改进前线材的气孔情况

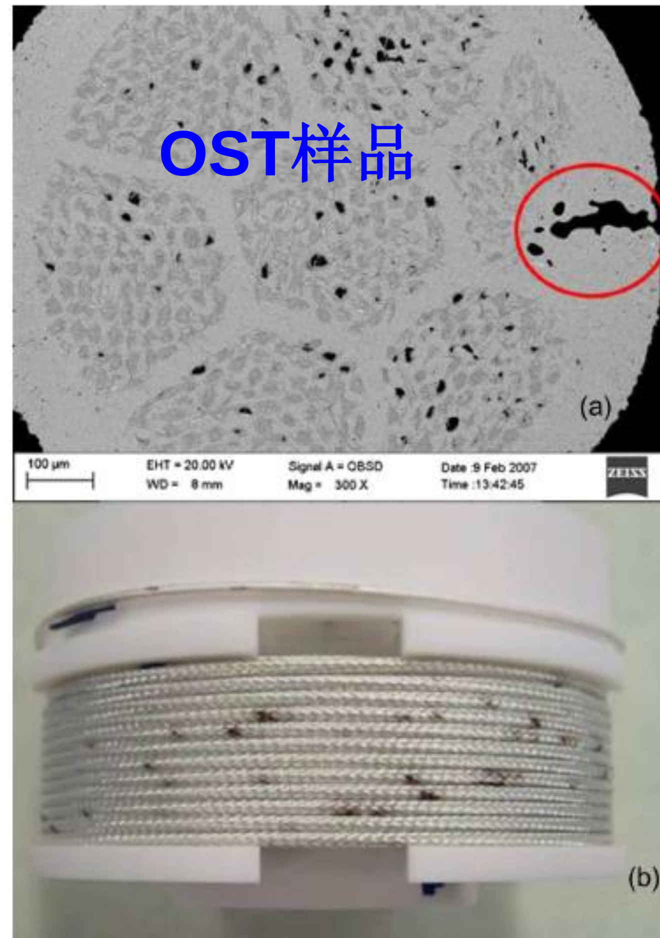
工艺改进后样品的气孔情况





线材的渗漏问题基本解决

美国OST样品



◆采用除气工艺，有效防止了内部气体在线材银层形成气孔，防止了线材的热处理渗漏问题

Bi-2212超导线材性能

短样：

I_c=890 A

J_{ce}=1100 A/mm²

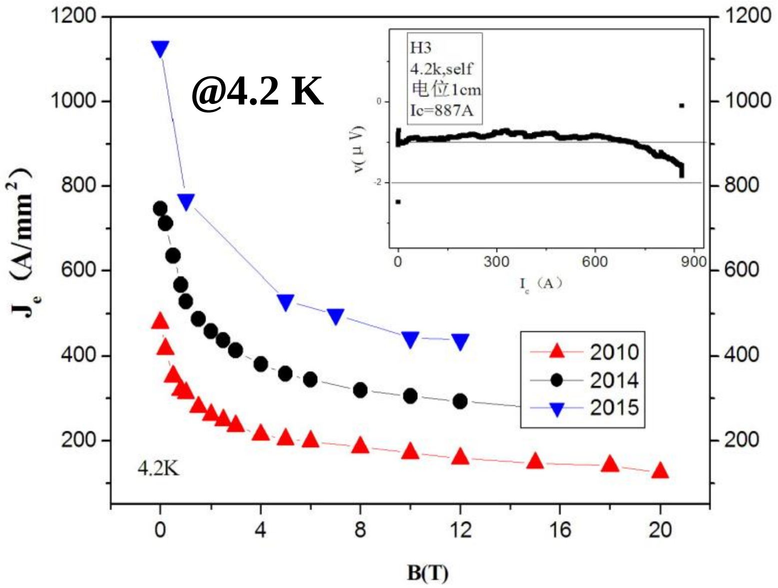
J_c=5200 A/mm²

(4.2 K，自场)

百米级长线最高性能：

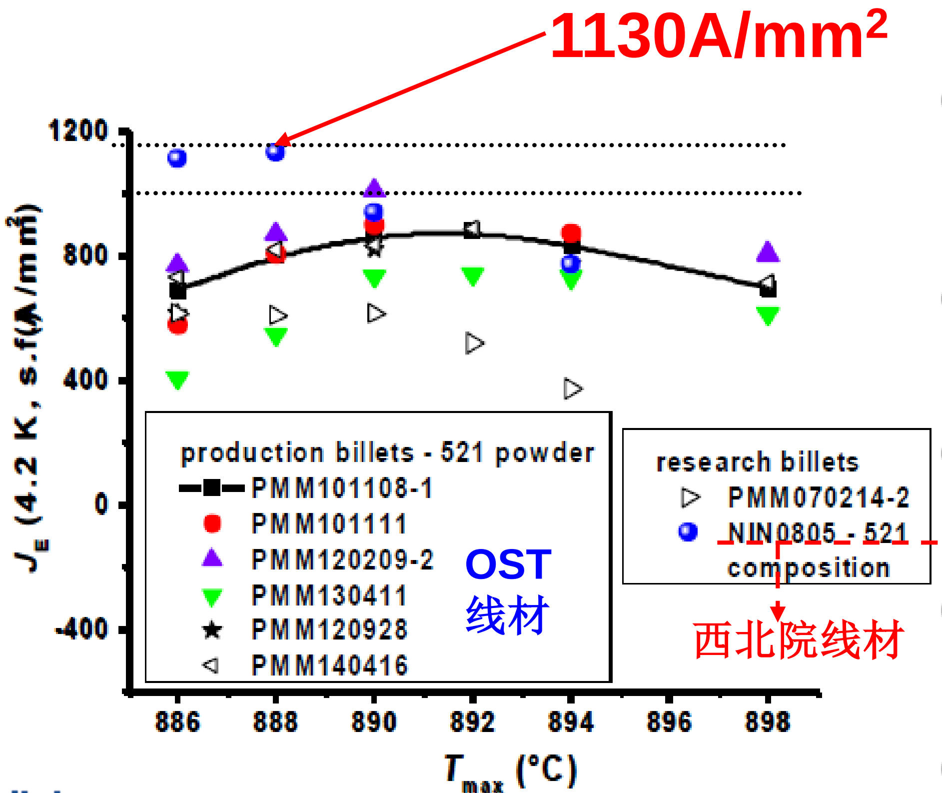
4.2 K, 0 T: J_{ce} ~ 920A/mm²，J_c ~ 4400 A/mm²。

4.2 K, 20 T: J_{ce} ~ 270A/mm²，J_c ~ 1200 A/mm²。



Bi-2212 线材在4.2 K，20 T，J_c >1000 A/mm² ,基本满足高场磁体和大电流缆线应用

J_E of commercial/research billets produced in the last decade – 1 bar standard processing



- PMM101108-1, PMM101111, PMM120928
  - 37x18, 0.8 mm, 521 comp.
- PMM120209-2, PMM140416
  - 85x18, 1.2 mm, 521 comp.
- PMM130411
  - 19x36, 0.8 mm, 521 comp.
- PMM070214
  - 37x18, 0.8 mm, not 521
- NIN0805
  - 37x18, 1.0 mm, 521

Fermilab

Developing accelerator magnet technology based on Bi-2212 round wire: Breakthroughs, progresses, and crucial next steps

Tengming Shen

Fermi National Accelerator Laboratory

ICFA

ICFA Mini-workshop on High Field Magnets for pp Colliders, Shanghai, June 14-17, 2015

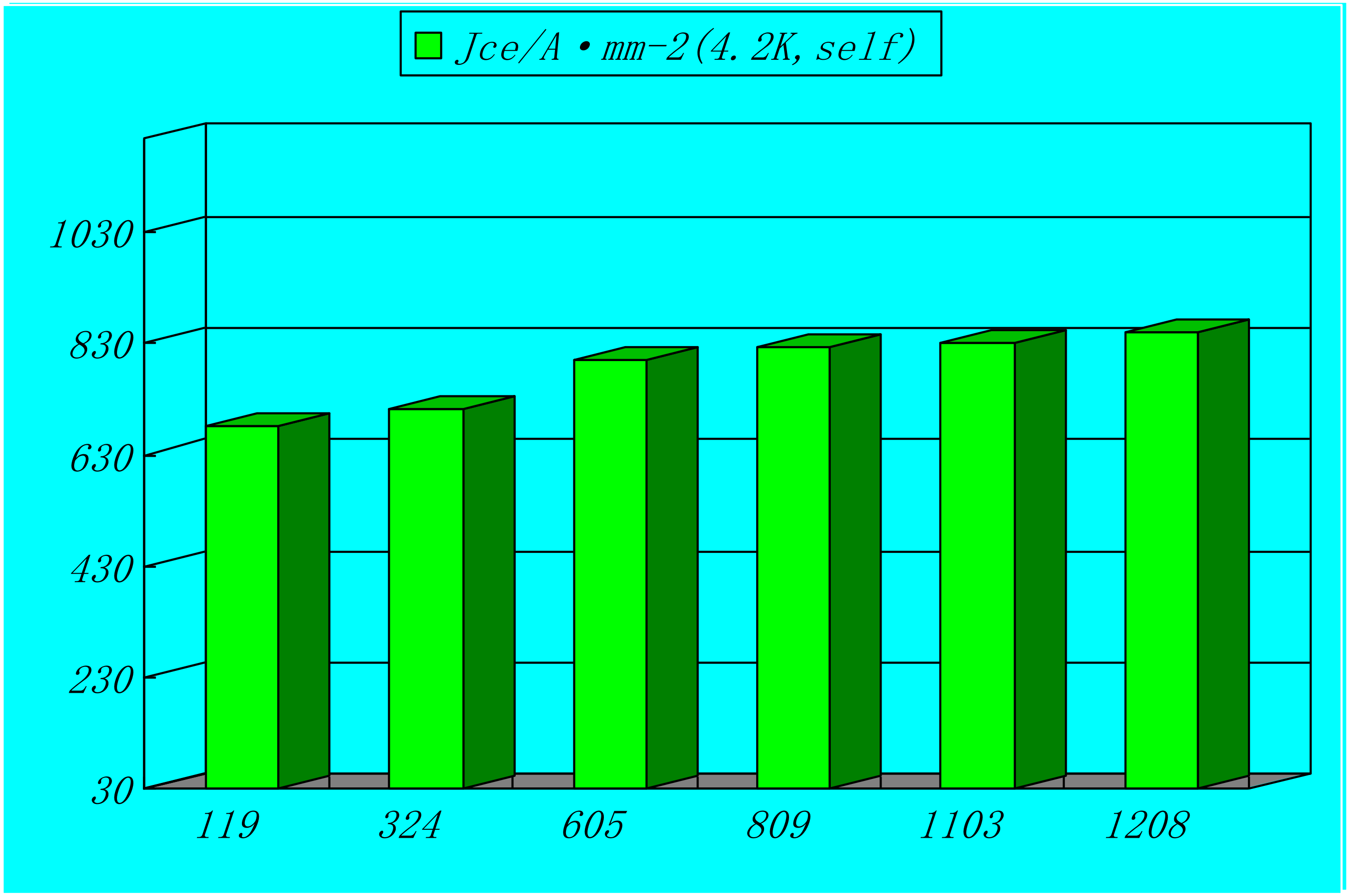
With inputs from Pei Li and Liyang Ye

Work was supported by the Office of High Energy Physics, U.S. Department of Energy through a FY12 early career award.

美国费米实验室测试并报道我们的结果

（ICFA pp Collider Miniworkshop,Shanghai,2015)

制备的2212线材批次性能趋于稳定

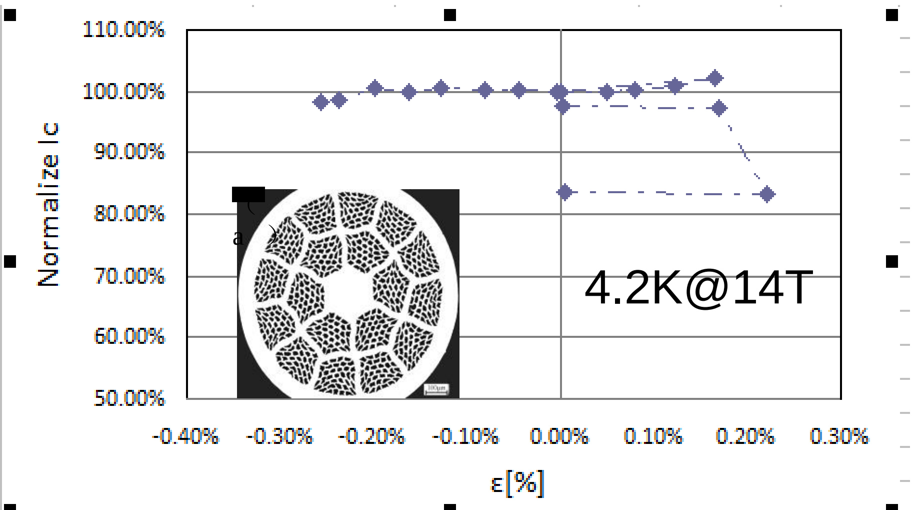


最好短线 1100A/mm²，长线 700—900A/mm²

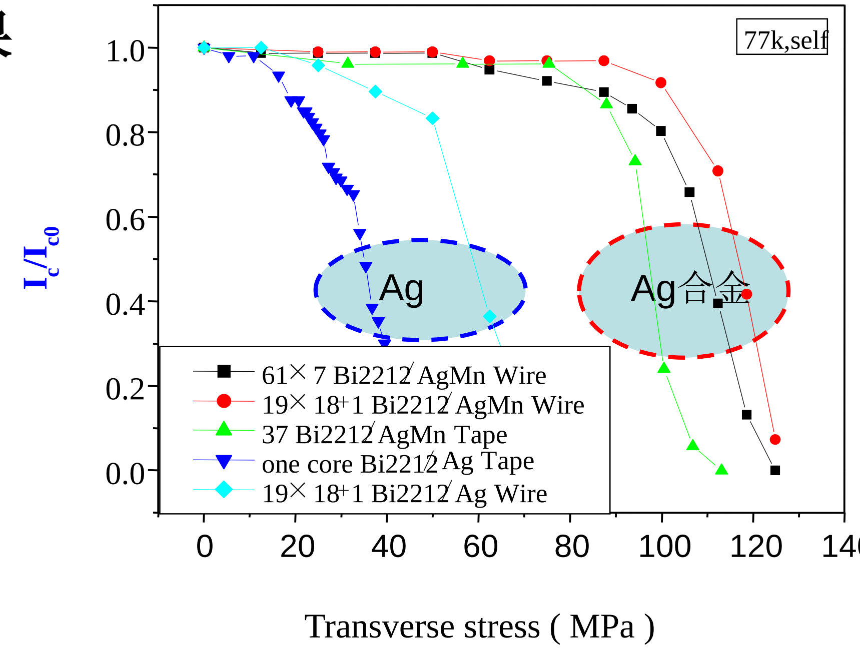
制备的多批次2212线材性能逐步提高并趋于稳定

Bi-2212线材的力学性能

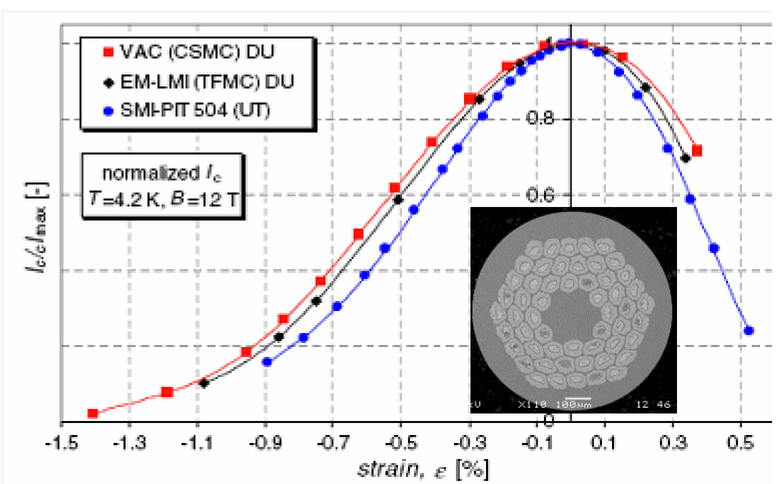
西北院线材在荷兰TWENTE大学测试结果



临界电流与拉伸、压缩应变的关系



Bi-2212线带材临界电流与拉伸应力的关系



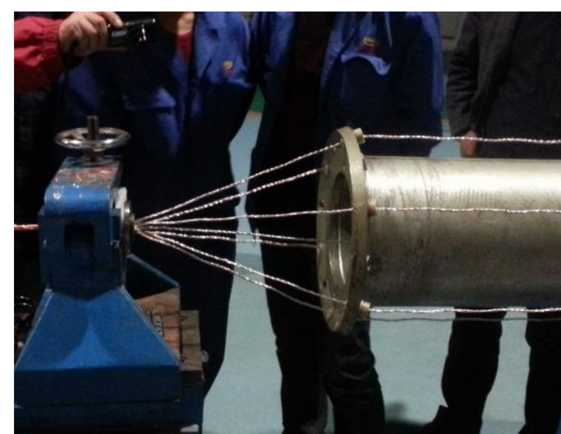
Nb3Sn临界电流与拉伸、压缩应变的关系

◆银合金Bi-2212线材的拉伸强度可到100MPa

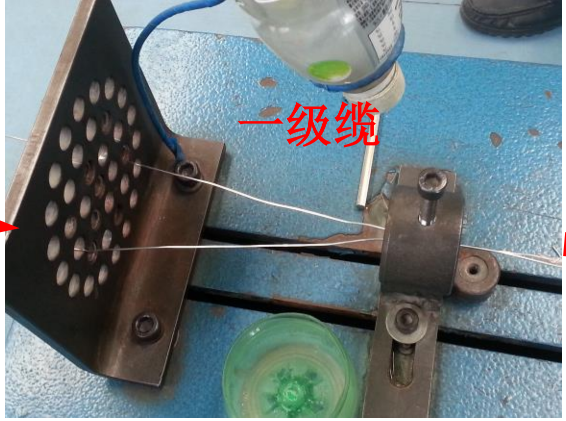
◆在小应变区间（拉应变约为0.2%, 压应变约为0.3%），Bi-2212线材的拉伸和压缩性能稍优于Nb3Sn

Bi-2212 导体研制
（等离子所、西北院）

在甘肃长通采用42根线材绞制出第一根Bi-2212 电缆



2线



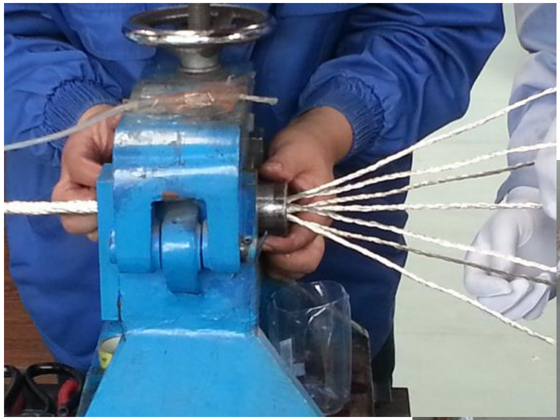
3根
一级缆

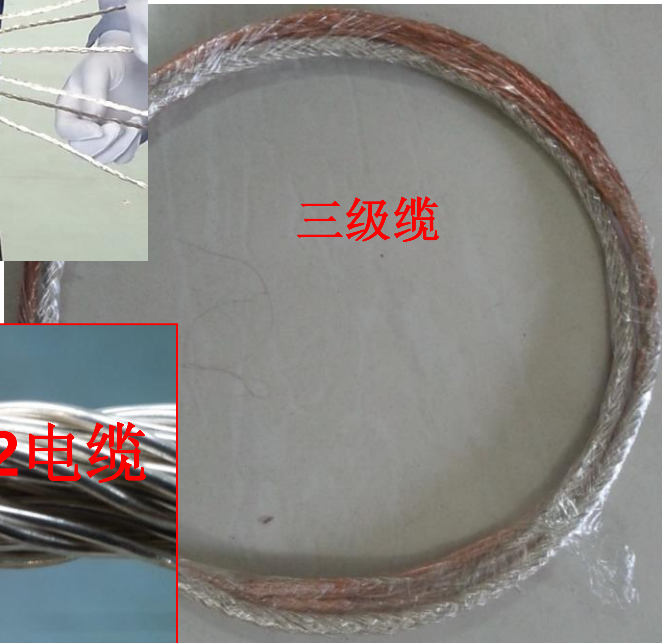
二级缆

7根
二级缆

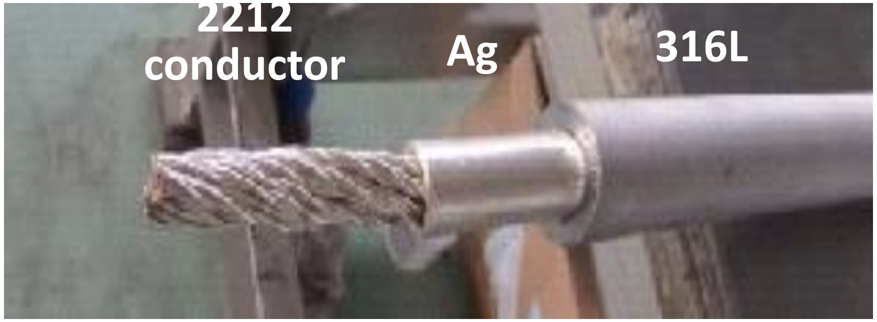
线材参数	线材编号	0805,
	线材尺寸	1.0mm
	最大拉应变	15%
	拉伸强度	140N
	线材Ic	**640A**
一级缆参数	线材根数	2
	张力	20N
	节距	18-20mm
二级缆参数	一级缆根数	3
	张力	20N
	节距	49
	转速	100r/min
三级缆参数	二级缆根数	7
	张力	30N
	节距	90mm
	转速	50r/min

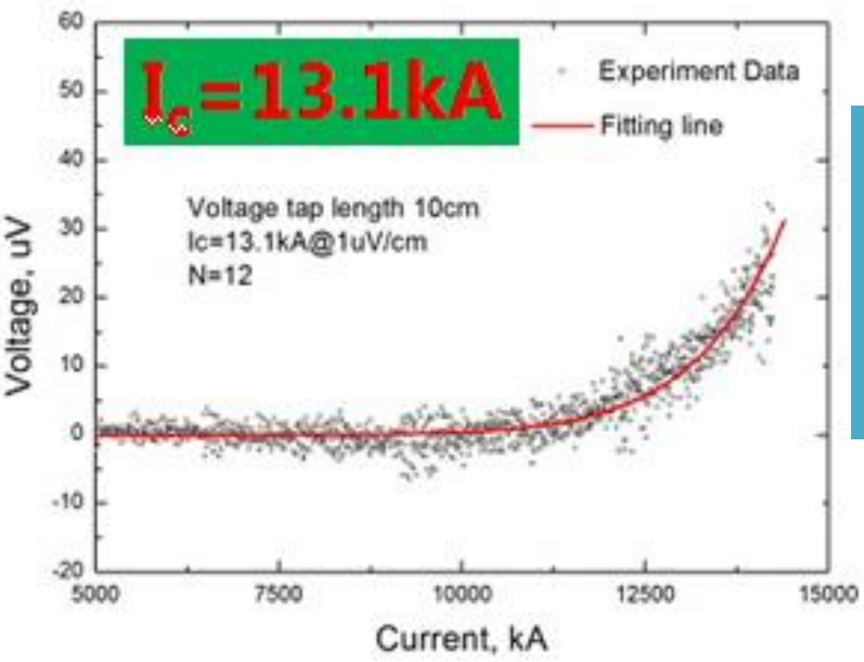
设计了一种短节距的电缆：
结构：**2x3x7—20x49x90mm**





Bi-2212三级缆测试





Current	Self -fields
10 kA	0.44 T
11 kA	0.484 T
12 kA	0.528 T
13 kA	0.572 T

Bi-2212导体在4.2K，自场下临界电流达到1.3×10^{4}A

总 结

Bi-2212线材性能基本满足高场磁体和大电流缆材制备需求

高压热处理可大幅度提高Bi-2212线材性能

西北院已可小批量制备百米级高性能Bi-2212线材

Bi-2212有可能在聚变堆CICC导体和加速器磁体中获得应用

谢　谢