上海超导二代高温超导带材实用化研究进展

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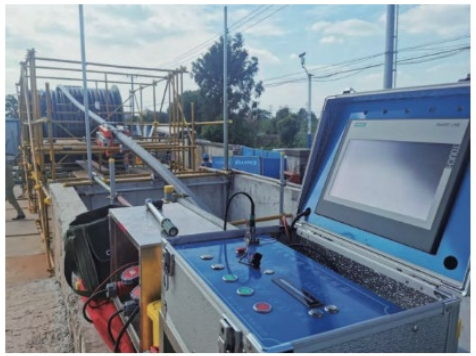
Presentation Outline

上海超导
SHANGHAI SUPERCONDUCTOR

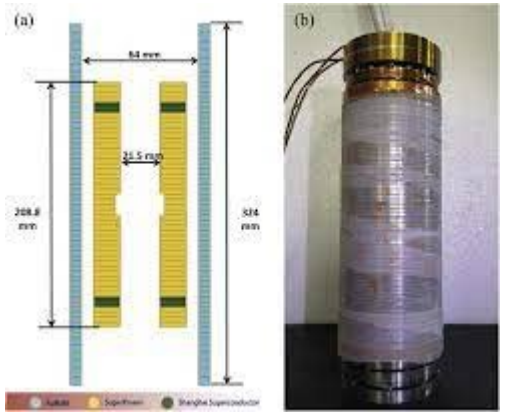
- **Current status of 2G-HTS in China**
- **Achievements at Shanghai Superconductor Technology (SST)**
  - Mass product
  - R&D
  - Applications
- **Conclusion and outlook**

二代高温超导现状



35 kV Shanghai HTS cable

World's first 160kV DC SFCL



World record 32.35 tesla DC all SC magnet

World's first MW-scale HTS induction heater

Yangtze River Delta superconducting value chain alliance

快速增长的核聚变产业

- ✓ **Commercial readiness of 2G HTS has initiated development appetite for fusion in China**
- ✓ **4 start-up companies set up since 2021**
- ✓ **successfully raised capital of >1 billion RMB altogether**

	Company	Founded in	Latest fundraising activity
1	Energy Singularity	2021 Jun	400 mRMB raised in first round in 2022 Mar
2	Sunist	2021 Oct	Multiple hundred mRMB angel investment raised in 2022 Jun
3	Shanghai Yixi	2022 May	50 mRMB seed investment raised in 2022 Sept
4	The 4th State	2022 Jul	To be announced
5	ENN	2000 Nov (2018 Apr)	Not applicable

上海超导科技股份有限公司

Establishment (2011)

- Private company funded by strategic investors
- Supported by Shanghai strategic emerging industries

Industry-Academia Cooperation

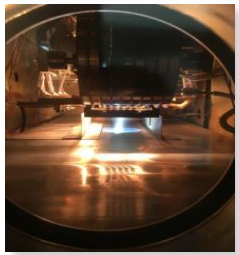
- Research Institute of Superconductivity
- Market/application-aligned R&D

Current Status

- Commercialized 2G-HTS conductors **since 2015**
- Ability to design and manufacture production equipment
- **100+ employees**, currently two main factory sites (Zhangjiang High-Tech Park & Songjiang Park for post processes)
- **Very recently, acquired by Jingda (the largest special magnet wire producer in China), significant production expansion underway**





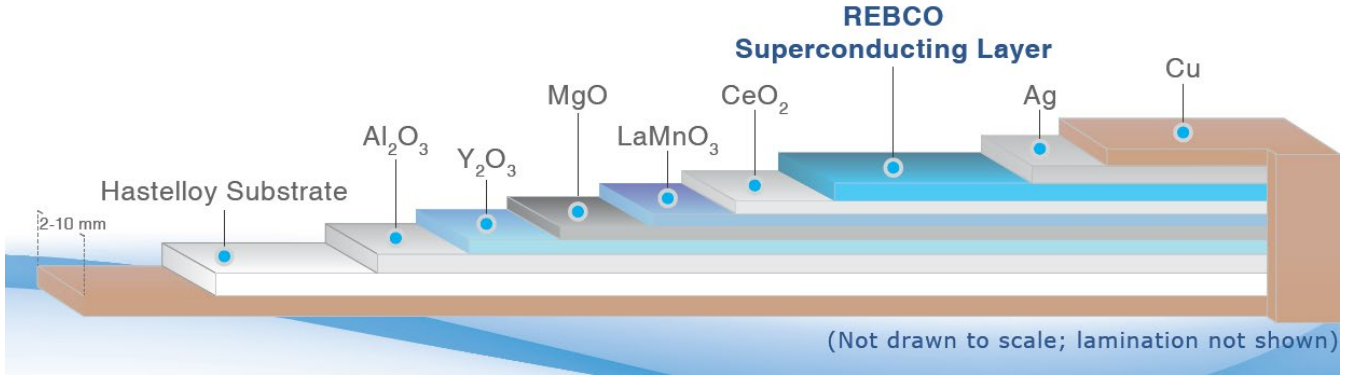


先进、稳定、高效的技术路线: PLD+IBAD

E-polishing	R2R PVD	R2R IBAD	R2R PVD	R2R PLD	R2R PVD	slitting	E-plating	lamination

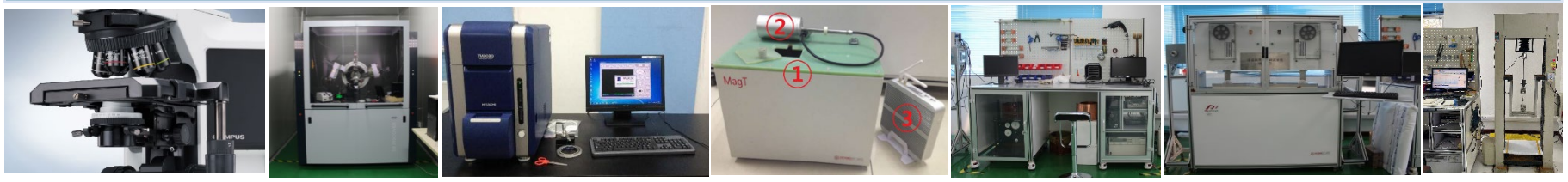
A reliable method

- High reproducibility
- Fast growth, high yield
- Tunable microstructure



Necessary QC process and equipment

Microstructure			Performance (superconductivity & mechanical)			
Optical microscopy	XRD	SEM	Tc	transport Ic	Inductive Ic	mechanical



多样化的产品

Grades	Standard	Standard Plus	Superior
Electrical	I_c(77K 0T)=300-420A/cm	I_c(77K 0T)=420-500A/cm	I_c(77K 0T)=500-550A/cm
Electromagnectic	I_c(4.2K 10T)=780-840A/cm	I_c(4.2K 10T)=840-980A/cm	I_c(4.2K 10T)=980-1120A/cm
Electromagnectic from 2022H2	I_c(4.2K 10T)=970-1050A/cm	I_c(4.2K 10T)=1050-1220A/cm	I_c(4.2K 10T)=1220-1400A/cm

Material and Auxiliaries

Core Equipment

HTS Tapes

Refrigerators

Both Tokamak Energy and MIT have concluded: 2G HTS material is essential to enable compact fusion.

Power Grid Application

FCLs

Guangdong Power Grid
- 500kV/3.15kA sat. iron-core FCL

Jiangsu ZTT
- 220kV/1.5kA AC type FCL

Guangdong Power Grid
- 500kV DC type FCL
- 10Mvar HTS synchronous condenser

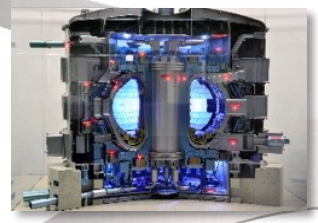
HTS Cable

Shanghai Demo by State Grid
- 1200 m，35 kV/2-3 kA
- In Xuhui CBD: Yishan to Wanping Transformer Stations

Shenzhen Demo by Southern Grid
- 500 m，10 kV/2 kA
- CBD: PingAn Financial Center

Electromagnet Application

HTS Magnet (Fusion, Accelerator)



Commonwealth Fusion System, US
- Commercial Compact Fusion
- Commercial power generation in 2030s

Tokamak Energy, UK
- Commercial Compact Fusion

Southwest Institute of Physics, China
- Fusion Research

CRRC
- HTS Maglev Train Prototype

CASIC
- "High Speed Flying Train" Demonstration Project

HTS Maglev Train

我们的实用化策略：高速脉冲激光沉积技术

上海超导
SHANGHAI SUPERCONDUCTOR

Production(A*m)=production time(s) × deposition efficiency(A*m/s)

=production time(s) × deposition length(m) × growth rate(m/s) × current density(A/m²)

Production time

- Utilization
- Effective working hours of product line

Deposition length

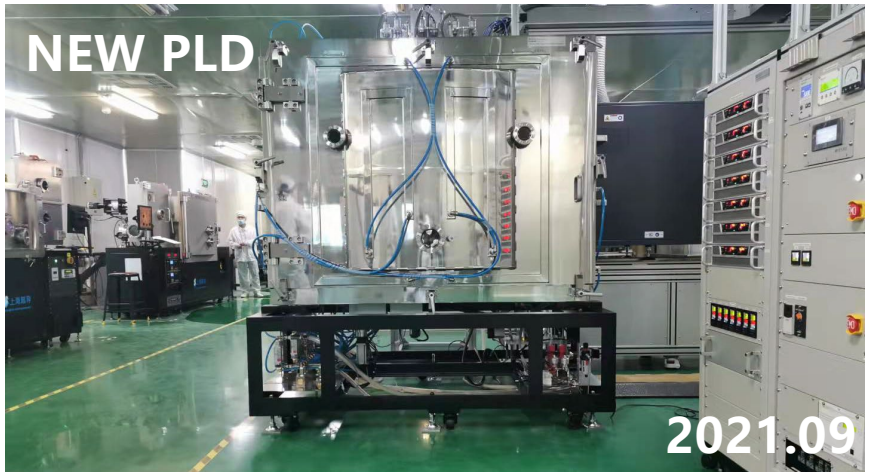
- Deposition area= length*1cm-w
- Enlarged by MPMT structure

Growth rate

- Dependent on laser power
- Limited by deposition kinetics process

Current density

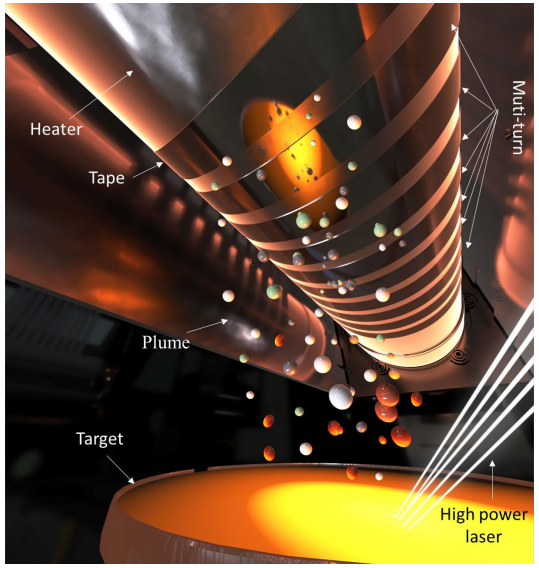
- Dependent on film quality
- Dependent on pinning centers

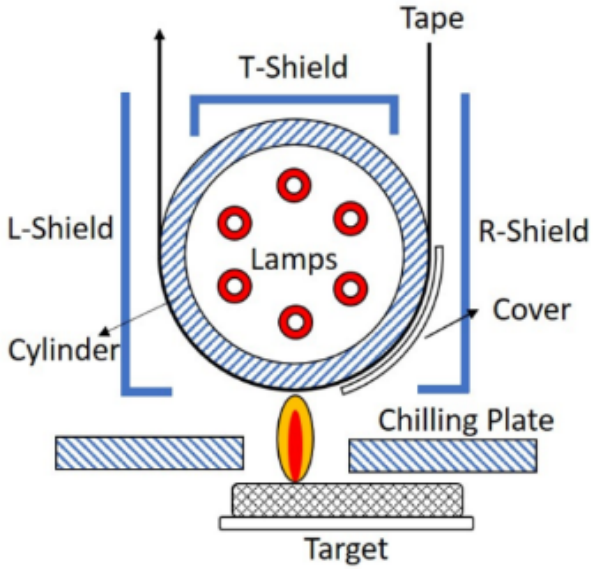


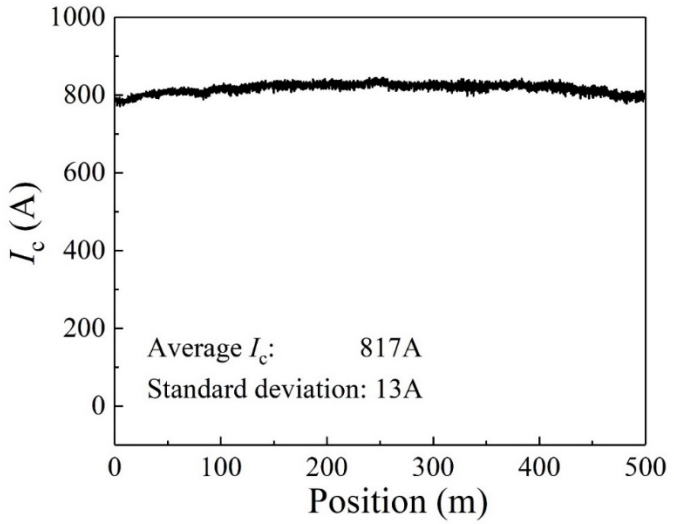
Other than more facilities (investments), what else can we do technically?

我们的实用化策略：高速脉冲激光沉积技术

- **Radiation Assisted Conductive Heating(RACH) system, leading to high temperature homogeneity under high travelling speed**
- Effective heating technique for high throughput
- Heating tapes from RT to ~900 °C in 3.5 seconds
- Temperature variation: ±4 °C
- Tape speed: >100 m/h
- **Unique growth conditions**: local overheating→ transit liquid phase → enhanced diffusion → quenching



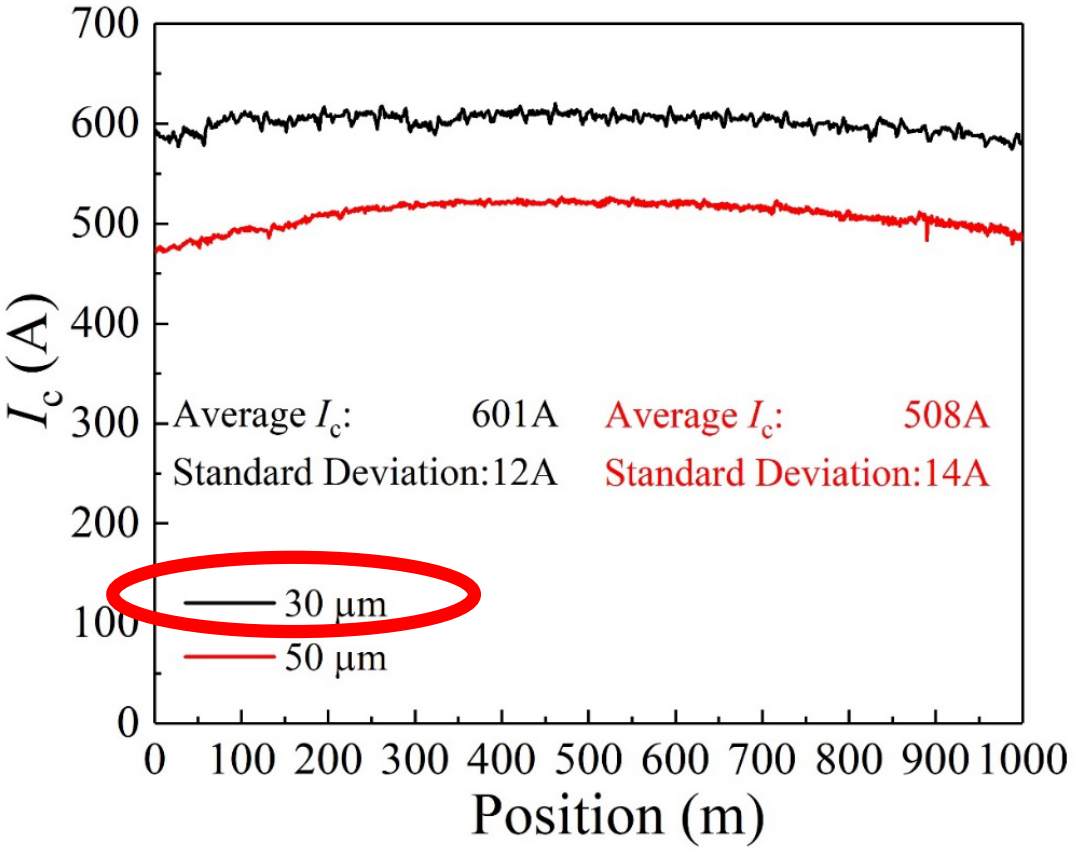


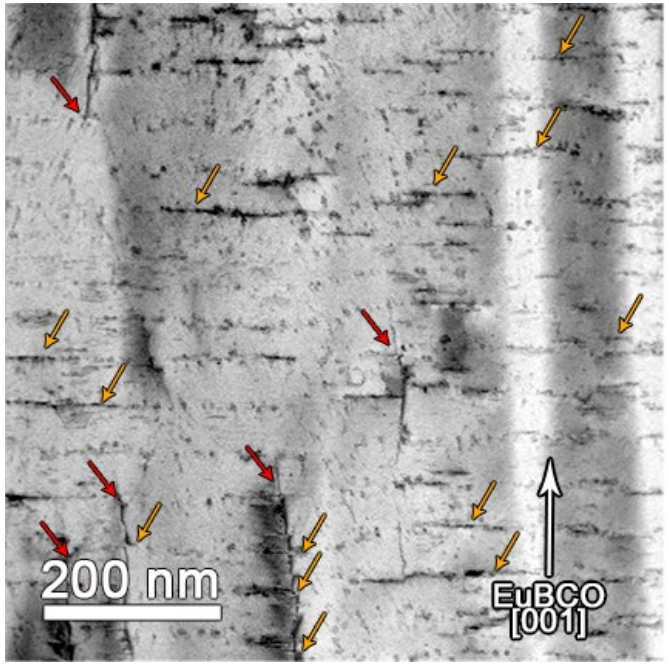


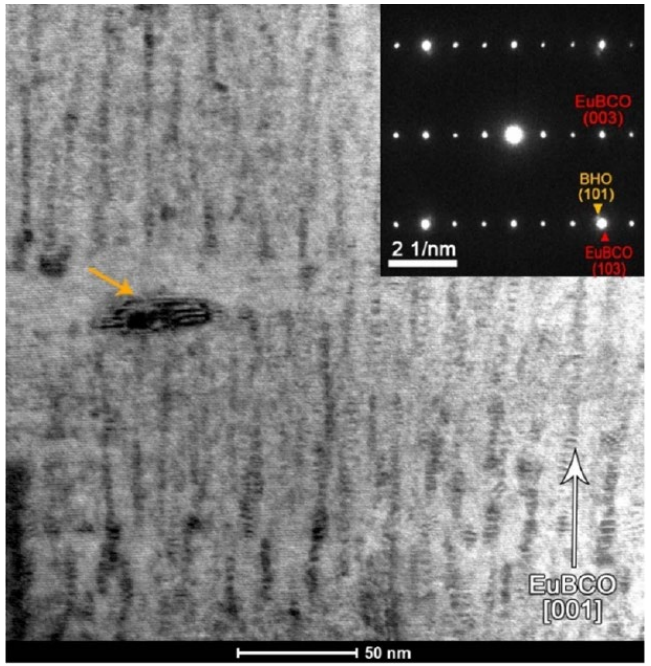
Annual production for a 300W PLD: >150 km*500 A i.e., in 2020, 300 + km (10 mm) was produced;

Zhao Y, et al. Supercond. Sci. Technol. 32 (2019) 044004;
Jiang G, et al. IEEE TAS, 2019, 29(5): 6600504.
Wu Y, , *et al.* Supercond. Sci. Technol. **34** (2021) 05LT01 (5pp)
Wu Y, et al. Materials Today Physics 18 (2021) 100400

面向强场应用的APC带材产品





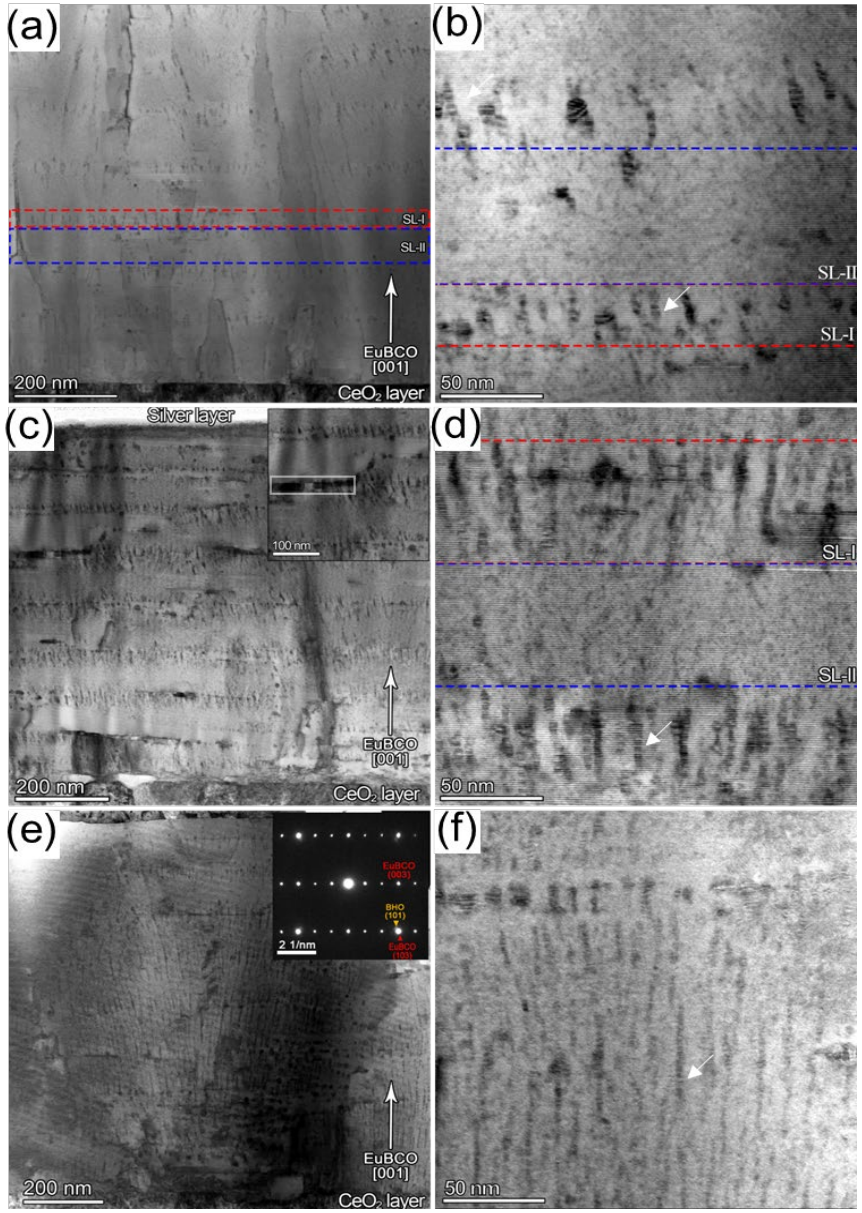


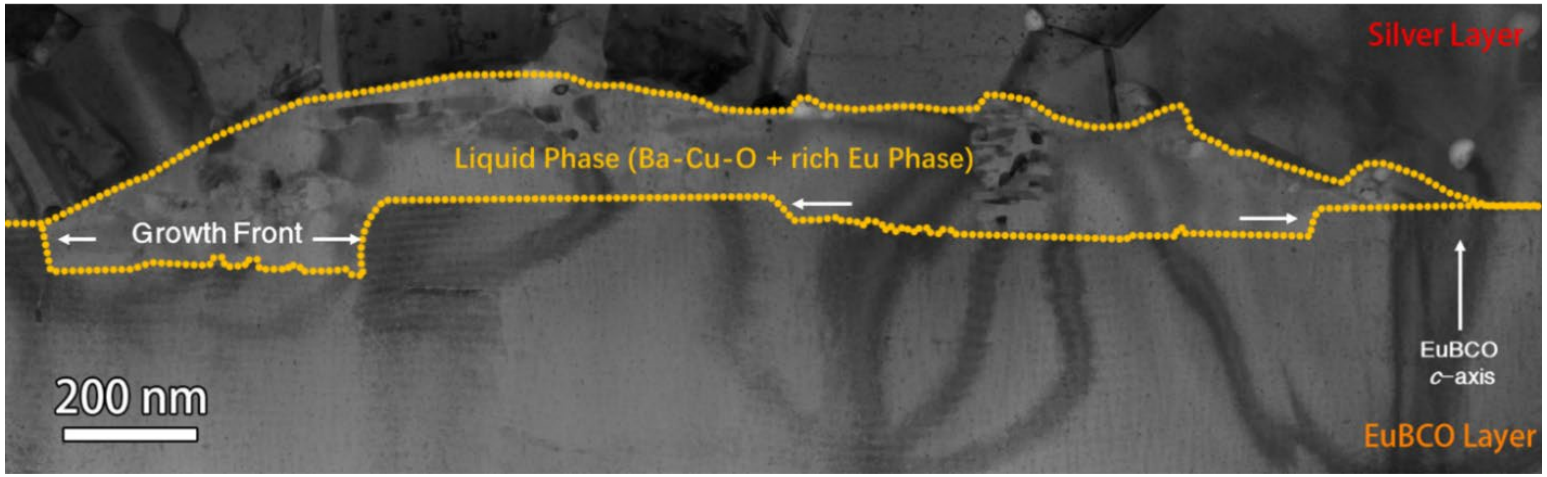
KM-class long REBCO tapes with high I_c achieved on 30 and 50 μm substrates

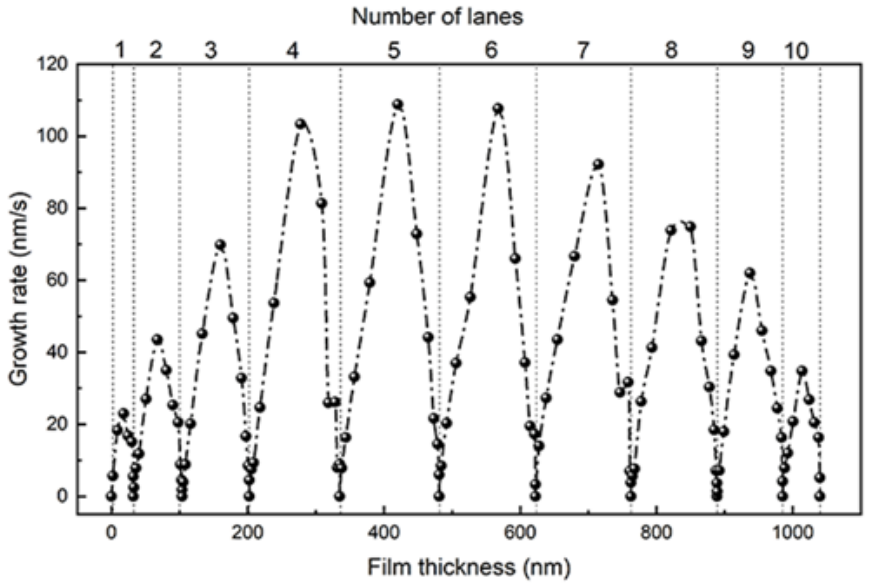
- ✓ **Inclined nano-rods and high density of stacking faults co-exist throughout the film thickness**
- ✓ **Tunable defect landscapes under high growth rates**

All the in-filed performance data available at http://htsdb.wimbush.eu/
Jiang G, Zhao Y, Zhu J, et al. SuST, 2020, 33(7): 074005.

面向强场应用的APC带材产品



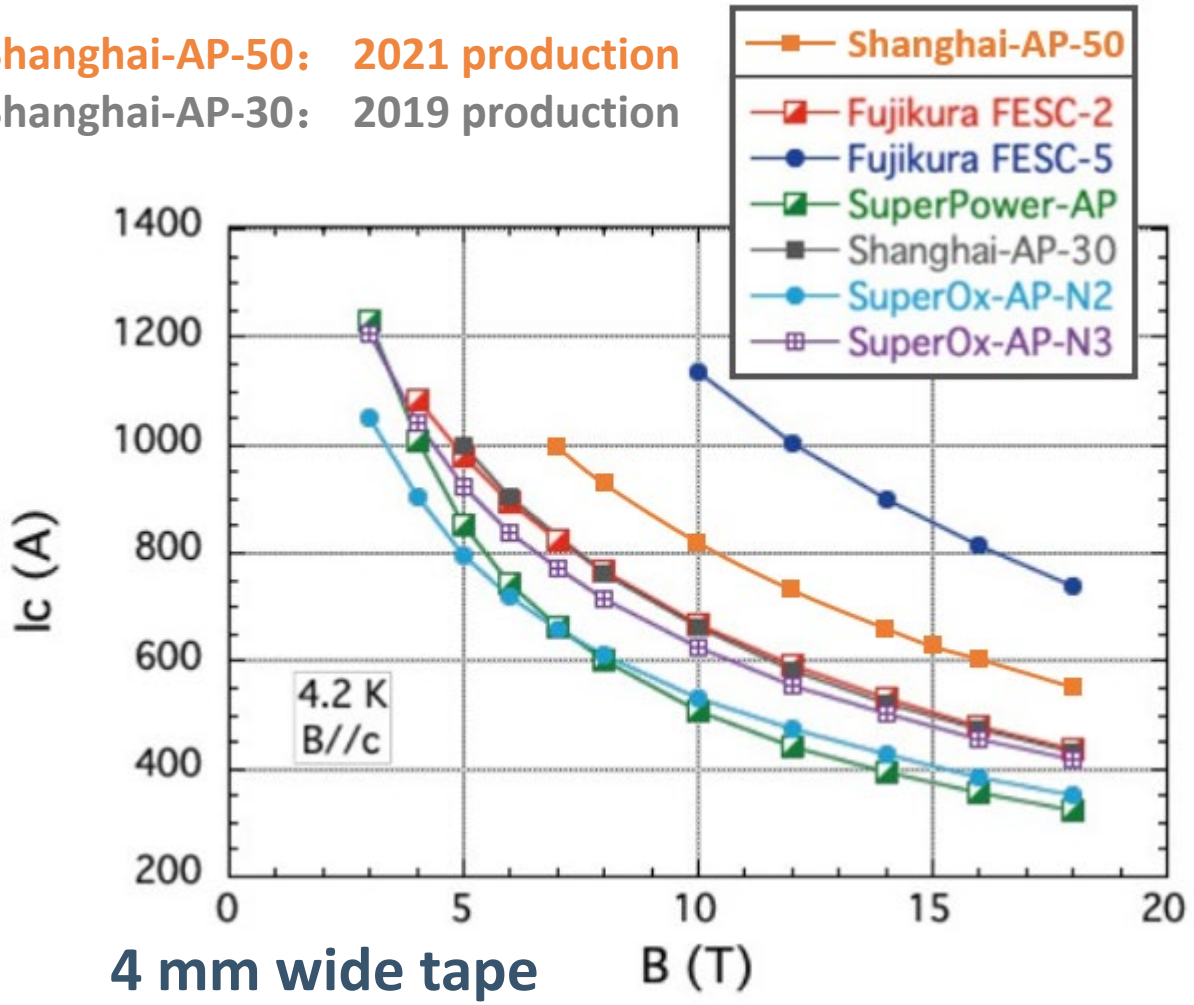




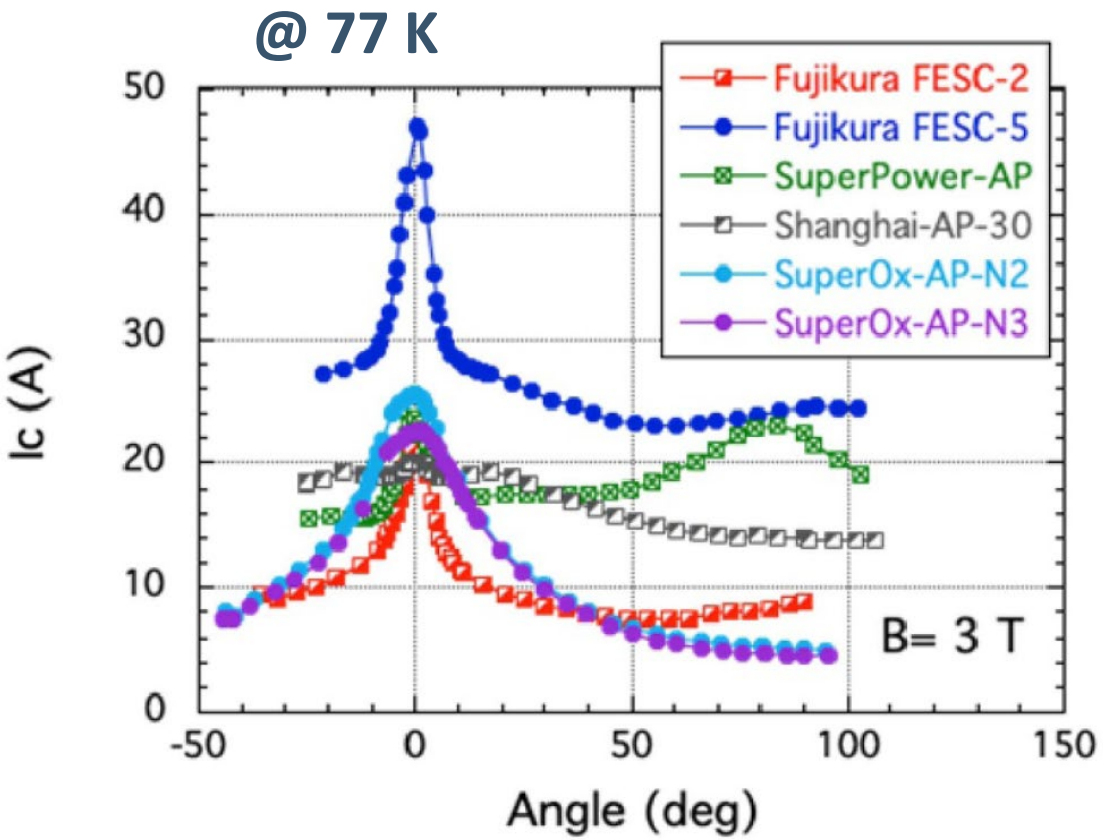
- Film body (with various level of dopant) and top-surface of the REBCO layer are detailed investigated by TEM;
- Formation of lamellar structure is associated with the periodic change of growth conditions during the multi-turn dynamic deposition.

面向强场应用的APC带材产品

Shanghai-AP-50： **2021 production**
Shanghai-AP-30： **2019 production**



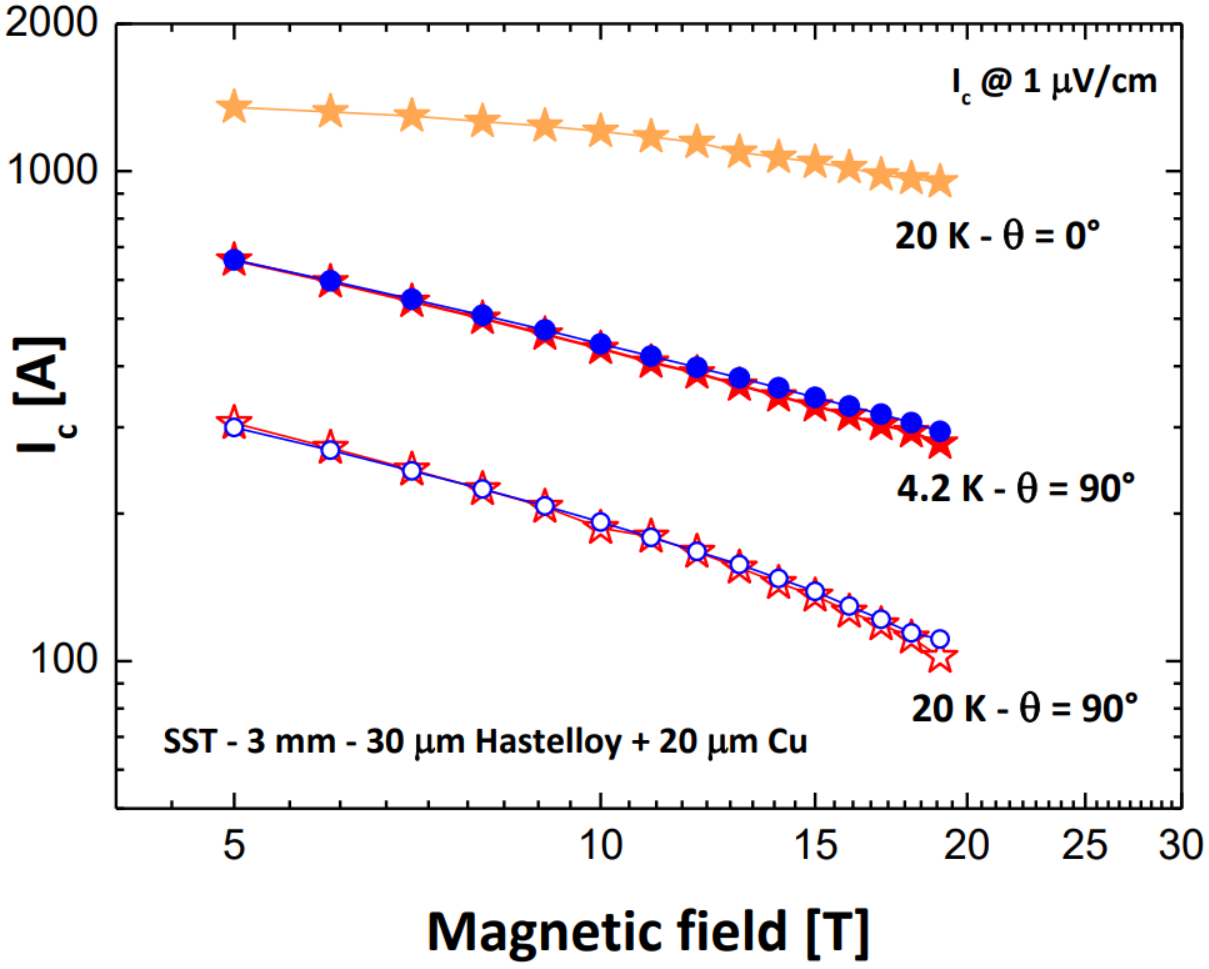
4 mm wide tape



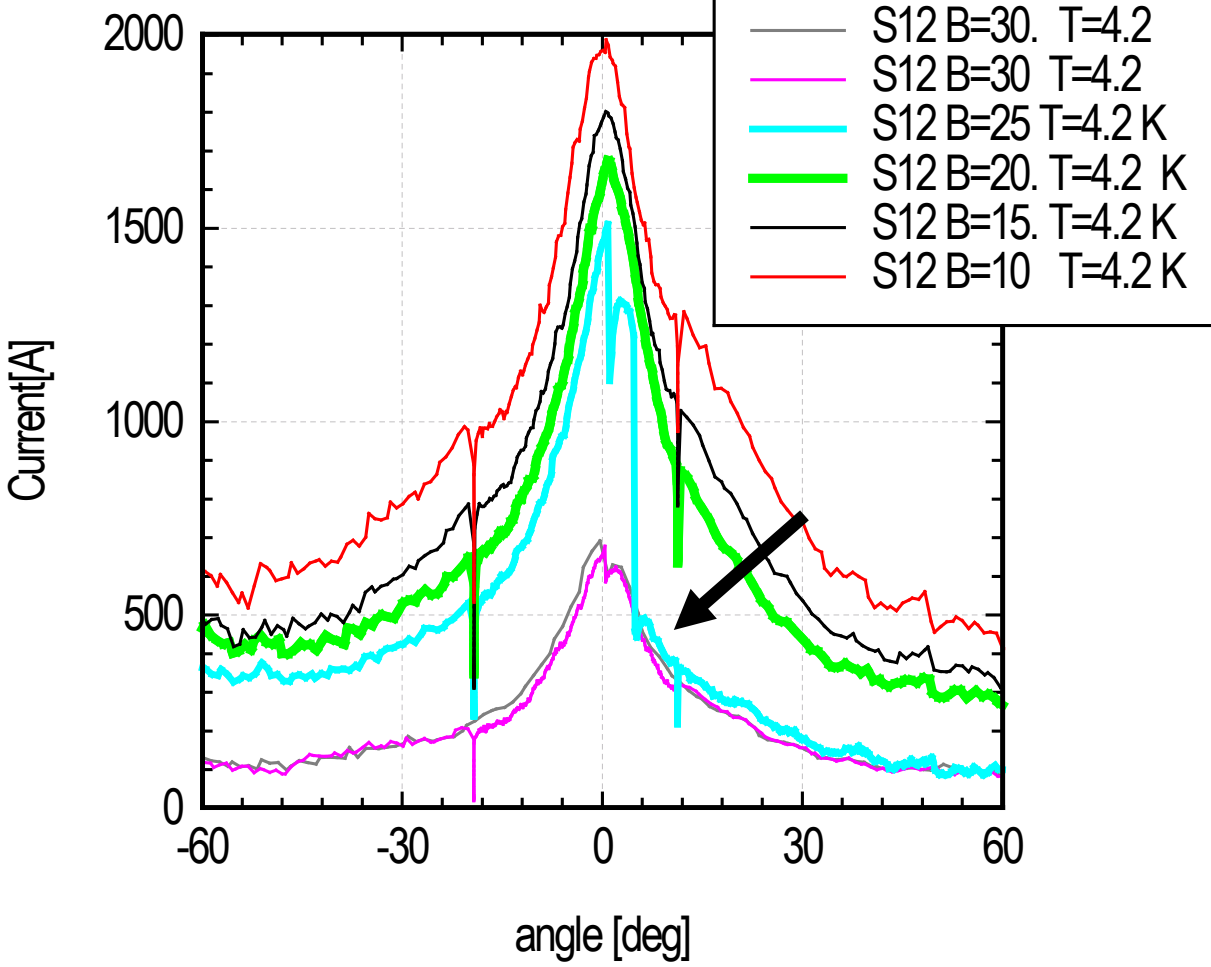
↖ Competitive Ic vs B (//c) at 4.2 K
↖ Continuous improvement of in-field Ic
↑ Weak anisotropy

Superconducting properties of commercial REBCO-coated conductors with artificial pinning centers. Supercond. Sci. Technol. 34 (2021) 105005 (13pp)

面向强场应用的APC带材产品

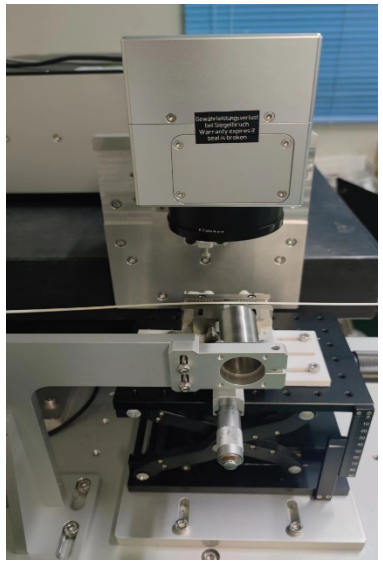


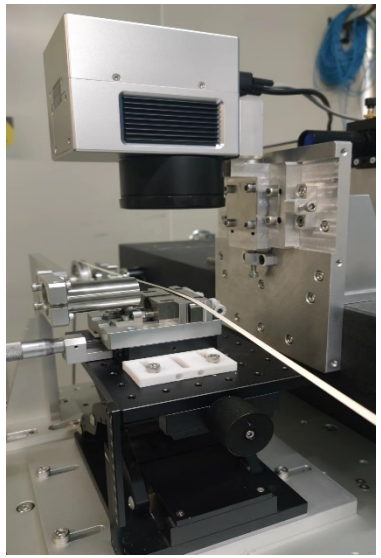
Measured by Prof. Carmine Senatore



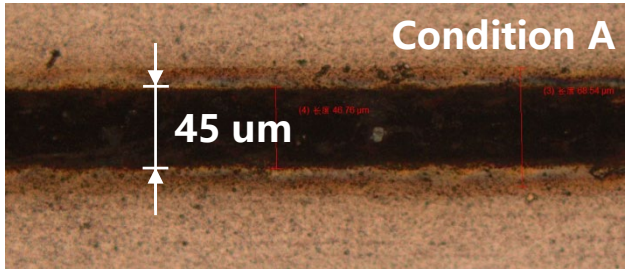
Measured by Dr. Jan Jaroszynski

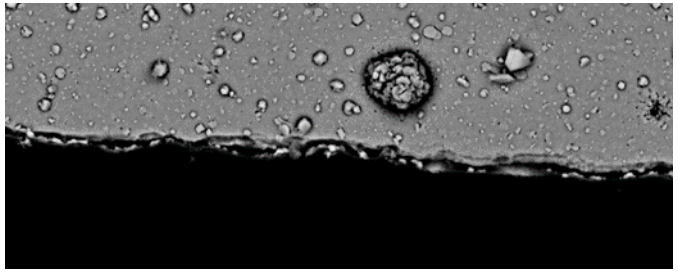
面向应用的技术研发：激光分切

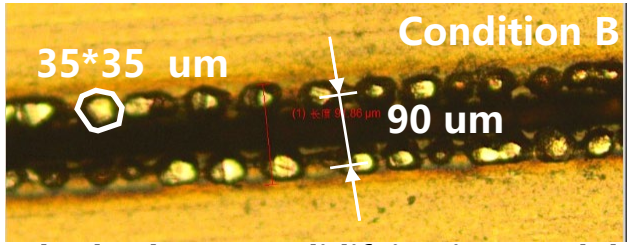


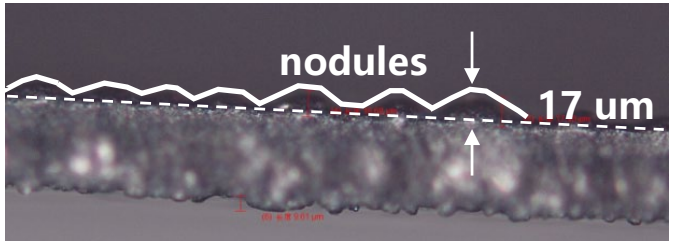


home-made R2R laser slitting setup

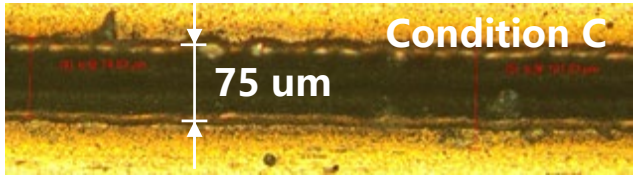


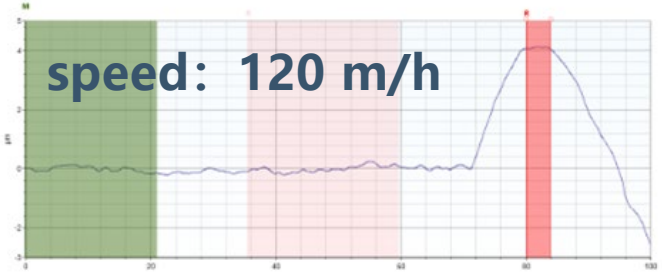






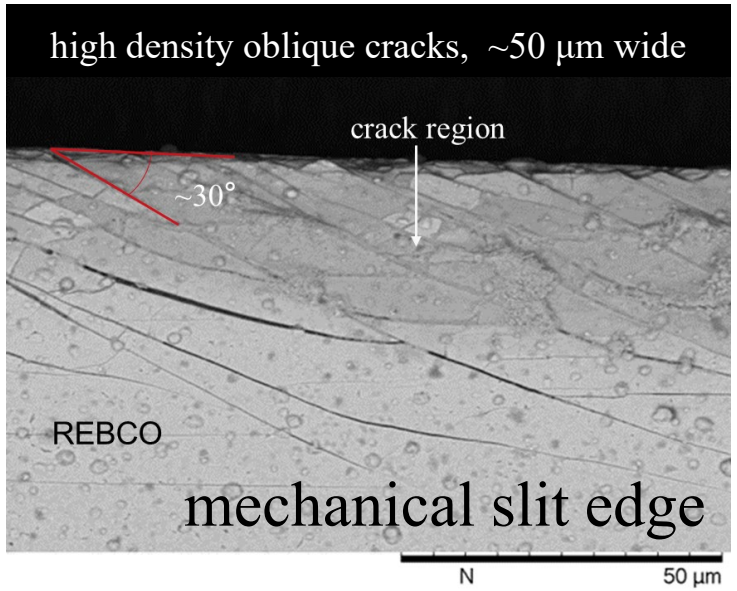
melted substrate solidifying into nodules

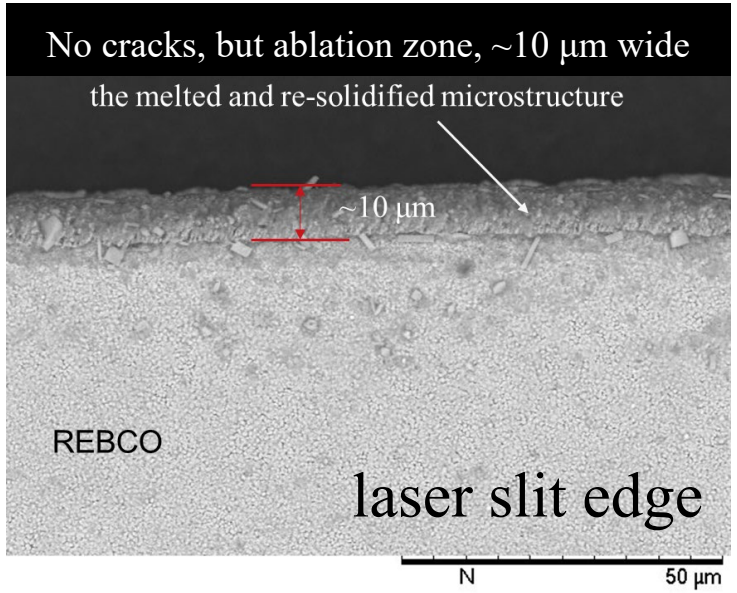


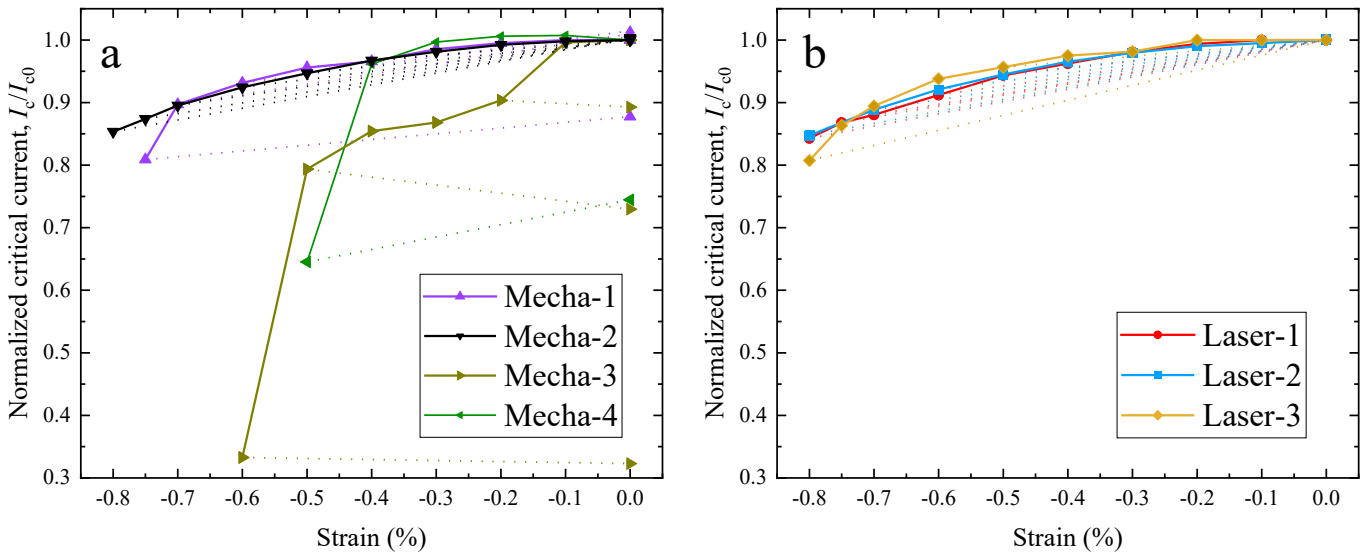


- Trade-off between speed and quality
- Appearance of nodules related to the thermal effect

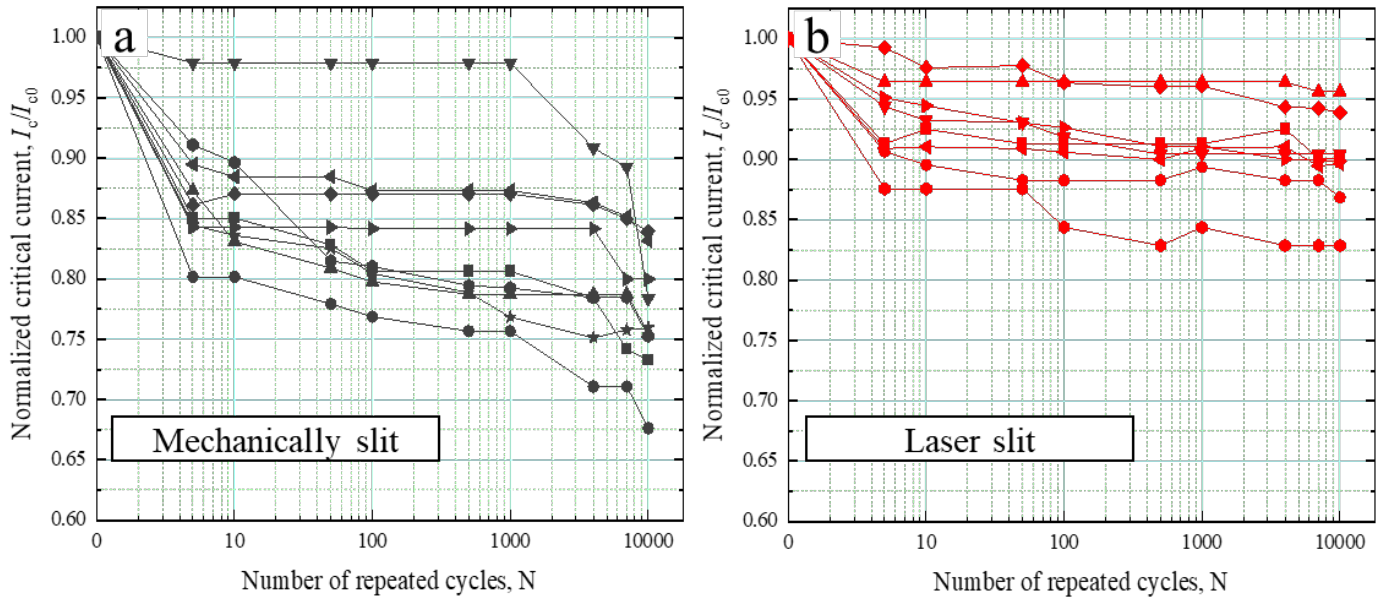
面向应用的技术研发：激光分切







normalized I_c versus compressive strain (LN2 condition)

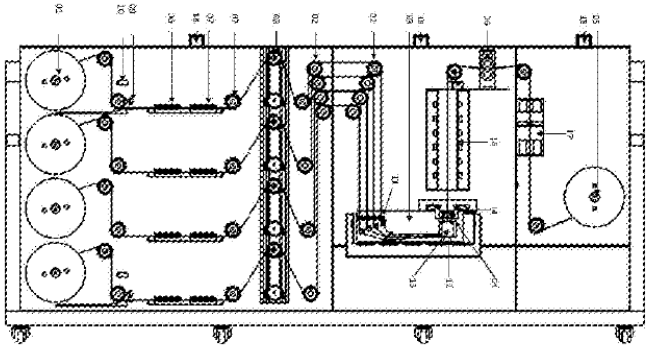


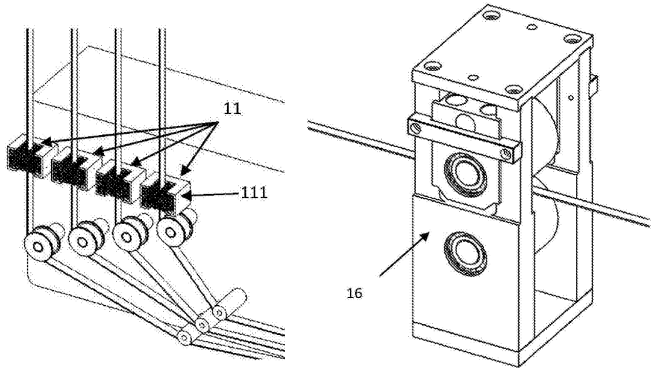
Relationship between normalized I_c and N, determined from tensile fatigue tests

Guo CJ, et al. Supercond. Sci. Technol. 35 (2022) 115009;

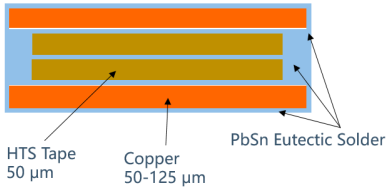
我们的实用化策略：面向应用的高度定制化

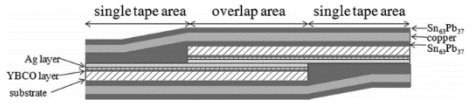
Lamination techniques for power applications

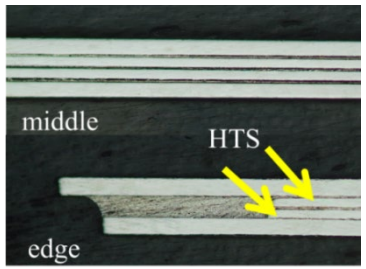


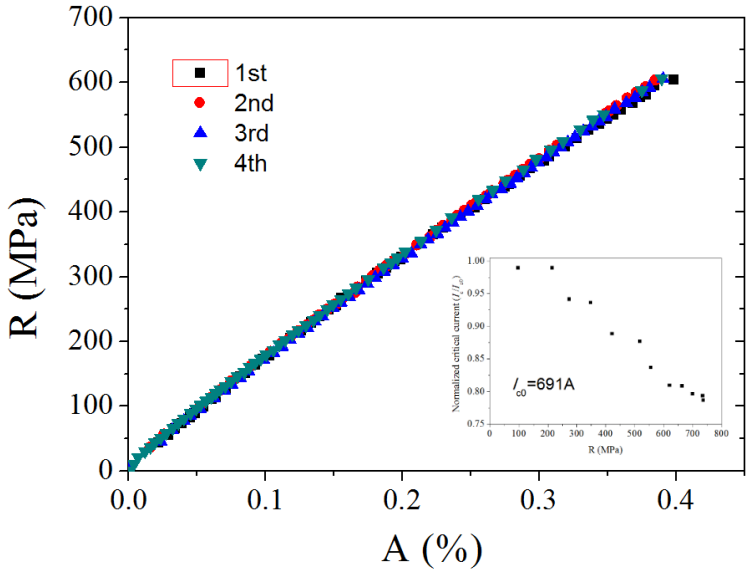


contactless low temperature and rapid cooling package techniques

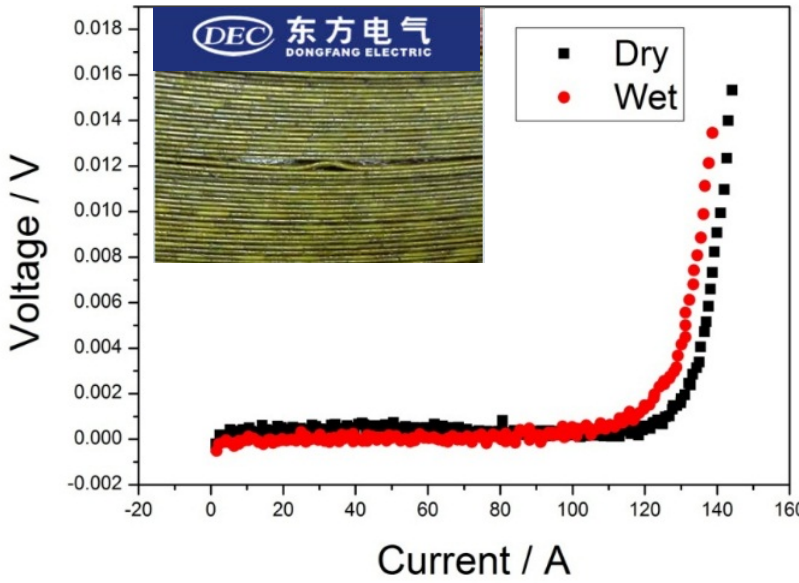








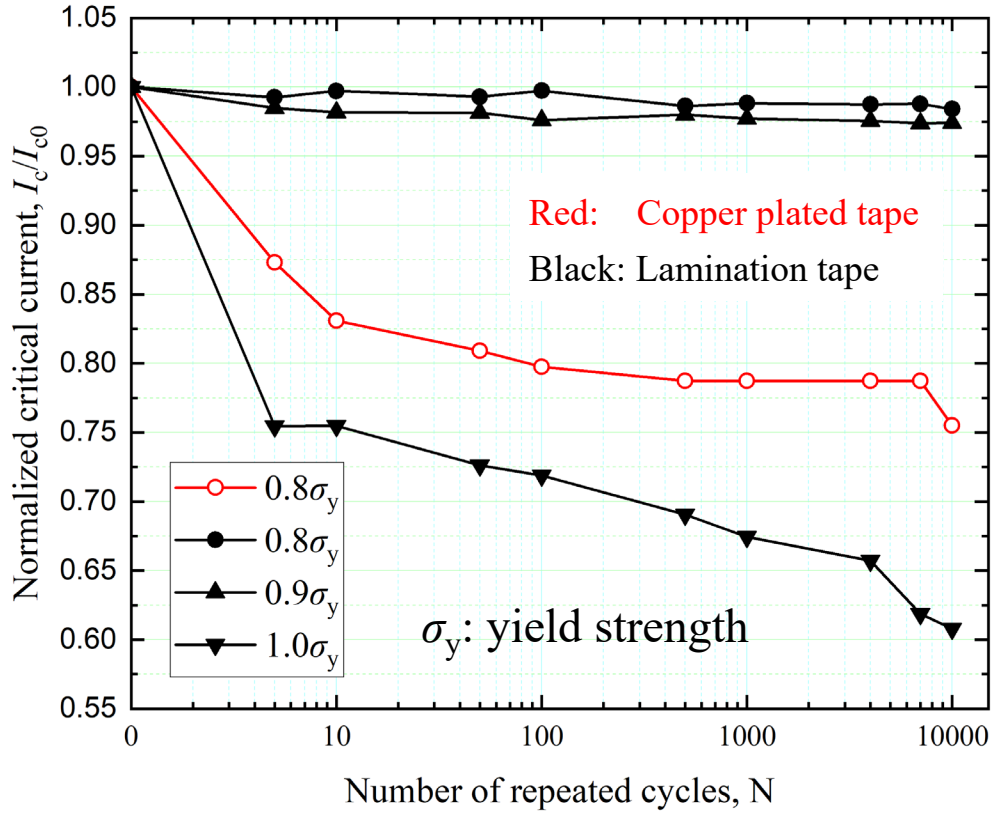
Double insert or optical fiber coupling
(For China Southern Power Grid SFCL project)

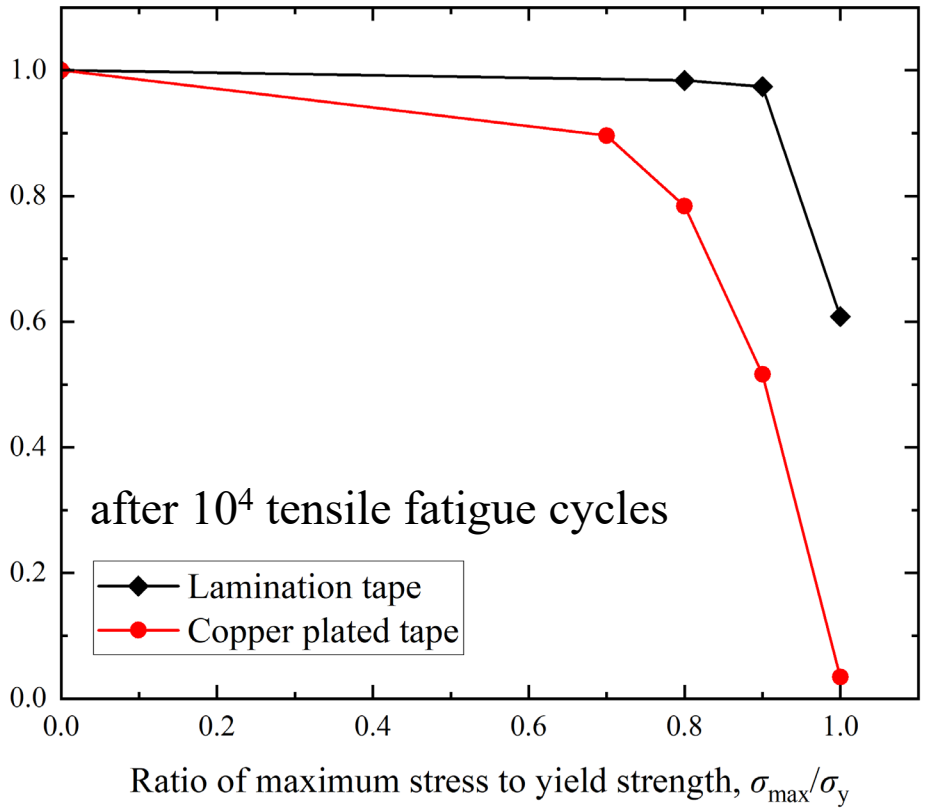


Minor I_c degradation after epoxy impregnation

- Automatic lamination equipment
- Wire edge fully covered
- Uniform and robust
- Copper / Brass / Stainless Steel

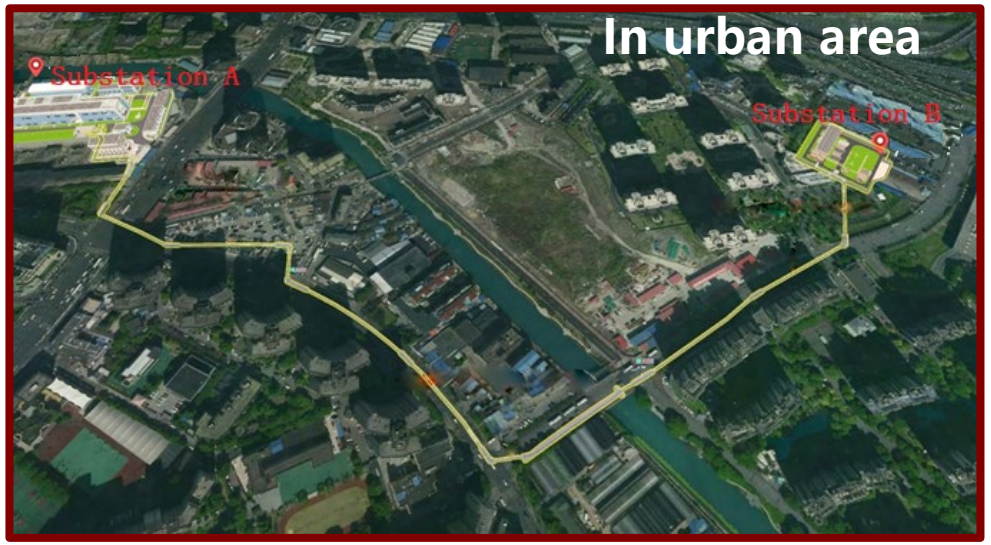
面向应用的技术研发：强鲁棒的封装带材

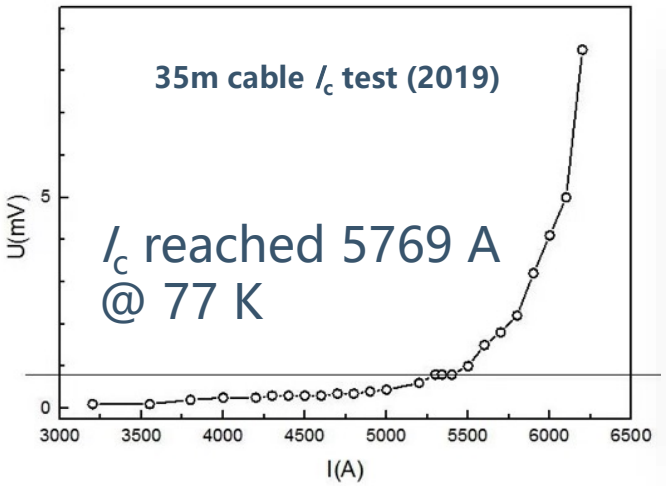




- Lamination is effective to improve the electro-mechanical behaviors of 2G-HTS tapes during uniaxial tensile fatigue tests.

应用案例1: 上海电缆项目





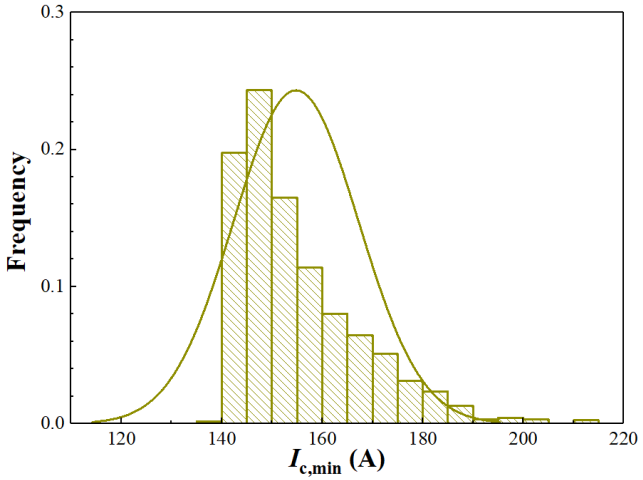
Key Parameters

Rated Voltage
35kV

Rated Current
2200A

Length
1200m

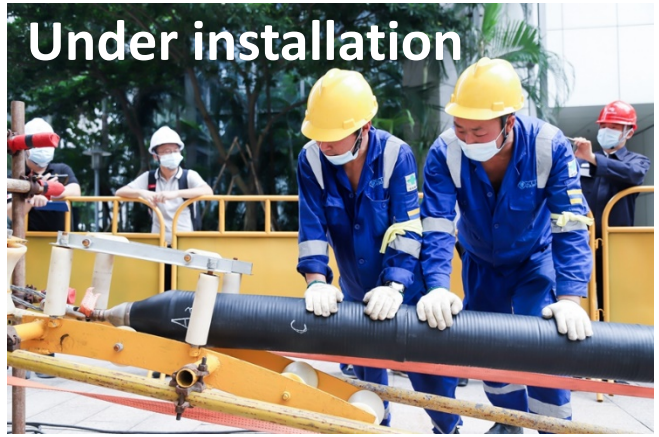
the 3 in 1 type



- 170+km, avg. piece length 150m, for conductor segment;
- HTS tape supply completed within 5 months in 2020;

Partly courtesy of Dr. Zong Shanghai Electric cable research Institute & (new company) Shanghai International Superconducting Technology Co., Ltd.

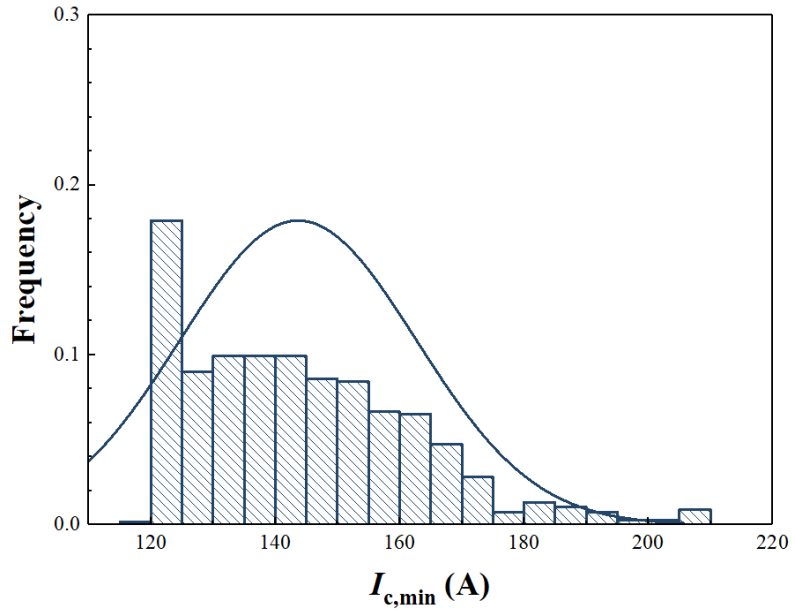
应用案例2: 深圳电缆项目



Project owner: Guangdong Electric Power Design
Designed by: Beijing Jiaotong University
Constructed by: Zhongtian Technology Group
Operated by: Shenzhen Power Supply Bureau
Cooling system by: CSIC Pride Cryogenic Technology Co., Ltd.

operation since late Sep 2021

- 500 m long HTS cable for Shenzhen Ping An Financial Center (height of 592.5 meters)
- Simplifying the power grid structure: reducing the construction of 110 kV substation, and save area of 500 m²



- 110 km, avg. piece length 150m
- HTS supply completed within 3 months

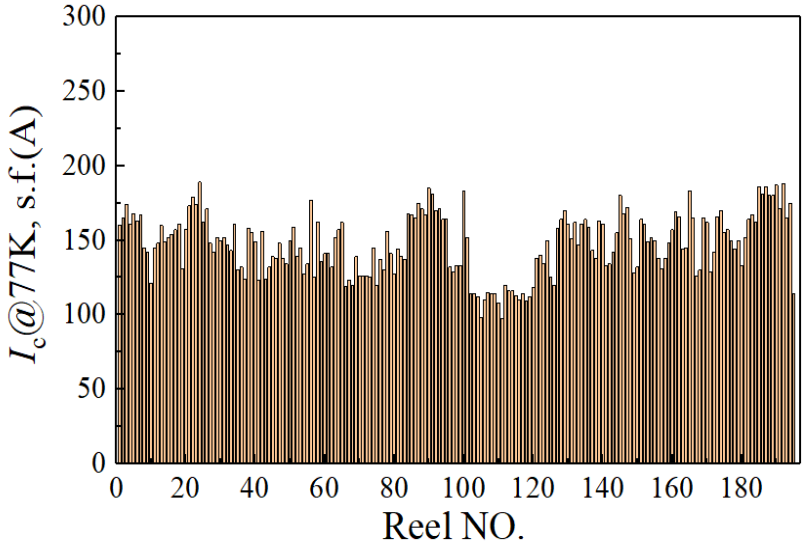
应用案例3: 核聚变磁体

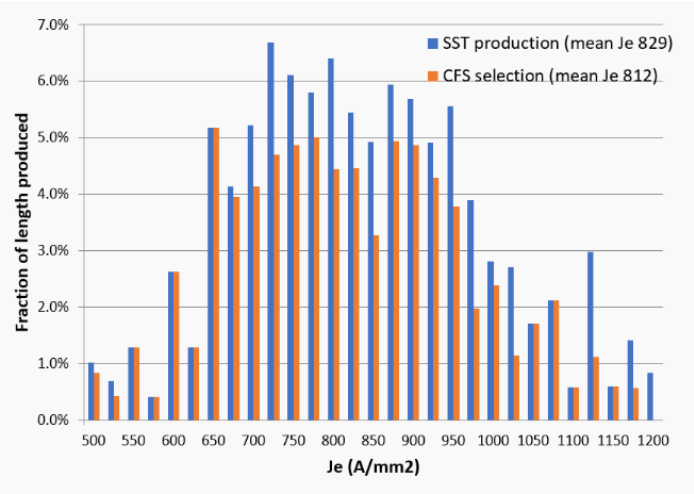
Compact Fusion/High-field Magnet

- MIT-CFS
- Tokamak Energy

customers' feedback:

- Stable product
- low rejection;
- Ave. J_e exceeding 750 A/mm²
- Comparable lift factor variation as peers

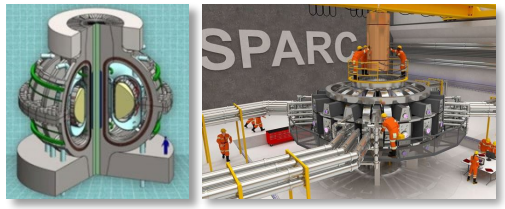


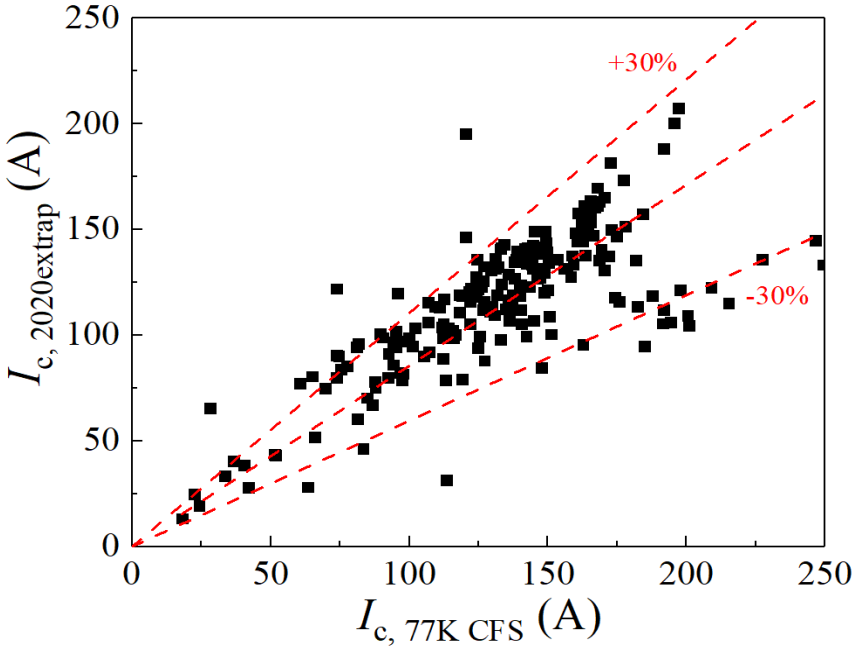


120+ km in total

Complete delivery in 2020

Commonwealth Fusion System (US)
Compact Fusion using 2G-HTS





总结

上海超导
SHANGHAI SUPERCONDUCTOR

■ 2G-HTS business outlook in China：

- Based on a large demand for electrical power, HTS business is close to commercialization in China
- Many demonstration projects, including power cable, FCL, high speed maglev train, magnets, are being conducted and planned.
- Commercial 2G-HTS tapes are highly anticipated, to be available at low price and well-customized properties.

■ Technological developments at SST:

- Large volume production by IBAD + high speed PLD,
  annual production > 1000 km/4mm (I_c=150-200A) ;
- Low temperature, high field properties improved by advanced APC, composition,…
- Thin tape(high Je): Now 30 μm in thickness available
- New slitting method: laser slitting without damage at the edges

Introduction of NEW journal

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SHANGHAI SUPERCONDUCTOR

ELSEVIER

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Four issues completed

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二代高温超导带材实用化面临的挑战

上海超导
SHANGHAI SUPERCONDUCTOR

Challenges	Causes	Suggestions
High cost/performance ratio	- Yield not high enough - Low volume raw material of inconsistent quality and no discount - Spare capacity of processing units upstream of REBCO deposition	- Cooperation of tape manufacturers to face raw material suppliers together - Production line segmentation to maximize capacity utilization
Reliability	- Industry-wise standardized QC procedure lacking, for both electrical and mechanical properties	-Tape manufacturers and customers cooperate to establish standardized QC procedures
Functionality for application	- Slitting→ defects & I_c loss - Limited width (not narrow enough) - Stablizer (e.g. Cu) plating issues - Mechanical strength - Quench detection and protection	- Manufacturer-customer collaboration at early stage of projects, to discuss what functionalities are required - Customer-orientated R&D