



Advance in Artificial Pinning of MOD-REBCO Superconducting Coated Conductors

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Collaboration & Acknowledgement



- **Y.M. Lu, M.J. Li, Y.Q. Guo, X.M. Yin et al., @Shanghai Key Laboratory of High Temperature Superconductors, Shanghai University**
- **Y.J. Zhang, Y. Li, Q. Lu et al., @Shanghai Creative Superconductor Technologies Co., Ltd (SCSC)**
- **X. Z. Zhang, X. H. Zong et al., @ Shanghai Electric Cable Research Institute / Shanghai International Superconductor Technologies Co., Ltd**



上海大学
Shanghai University



1

Methods of introducing artificial pinning centers in HTS

2

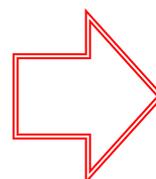
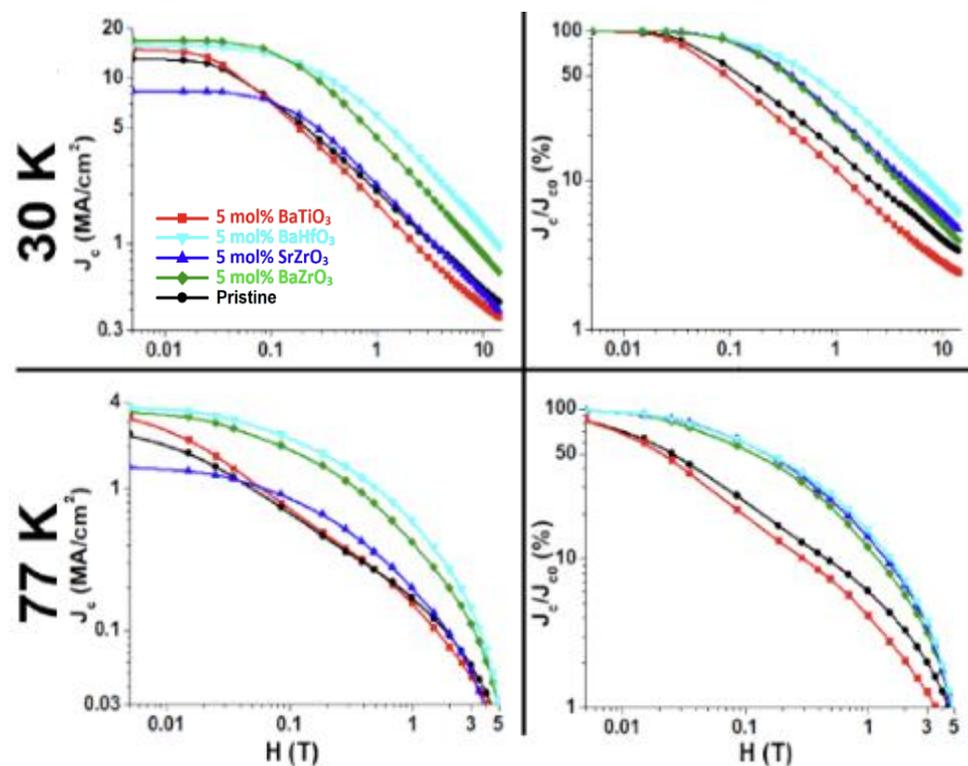
Technical route and performance of MOD tapes in SCSC

3

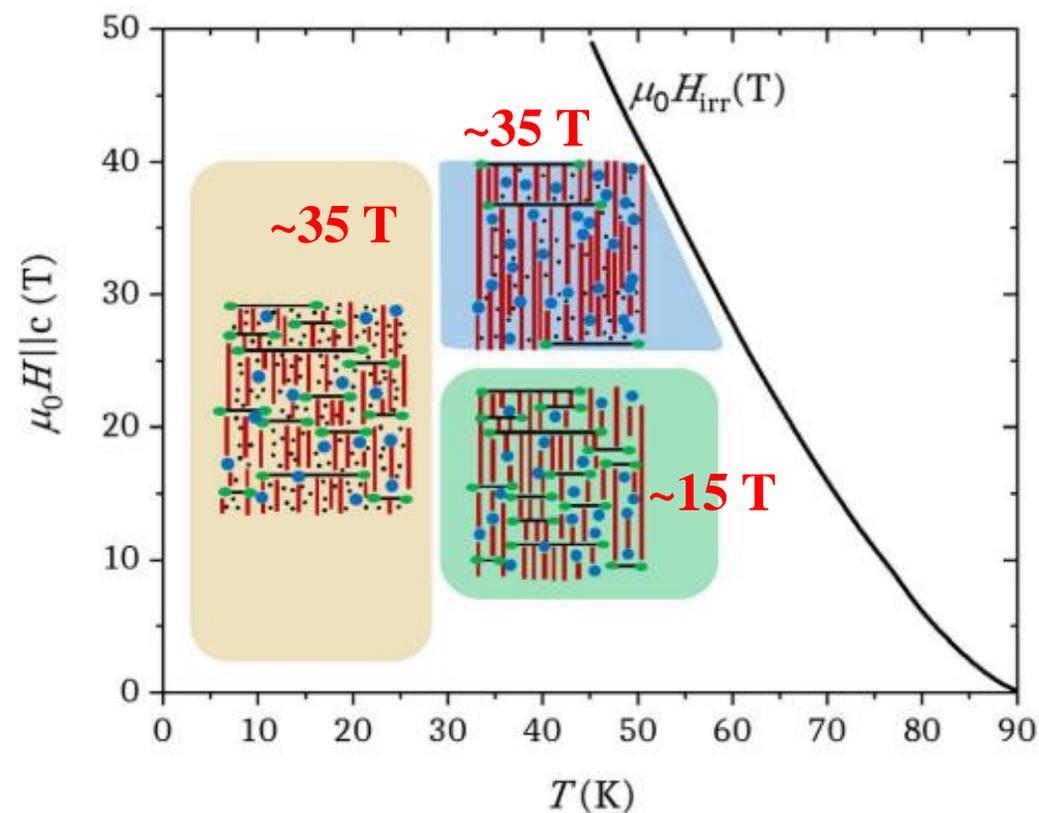
Recent progress of artificial flux pinning in MOD-REBCO

In-field performance VS. Application

- BMO₃ nanocrystal technology: size control, highly dispersive
- Significant improvement of In-field J_c



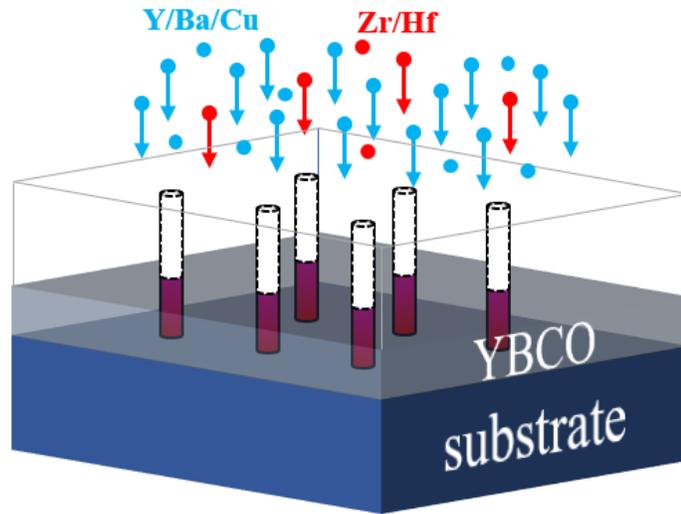
- **Mixed landscape in REBCO:** small size defects result in strong pinning at high field, meaning the great advantage of nanocrystal addition in MOD route;



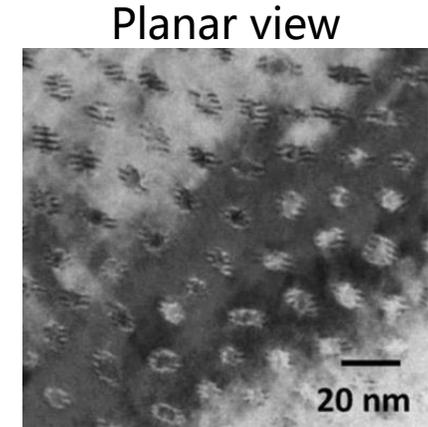
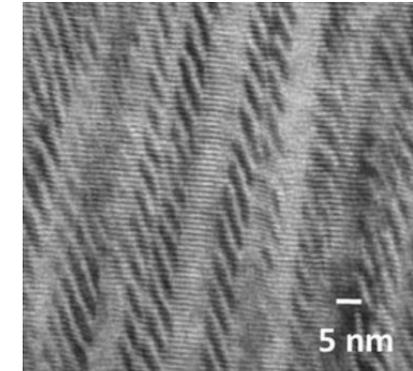
Ziliang Li, Sci Rep 9, 5828 (2019)
 J Díez-Sierra et al., ACS Appl. Nano Mater. 3, 5542–5553(2020)
 Soler, L., Nat Commun 11, 344 (2020)

2022, VallèsF et al., Commun. Mater. 3, 45(2022)

Introduction of APCs: **doping**—*in-situ*



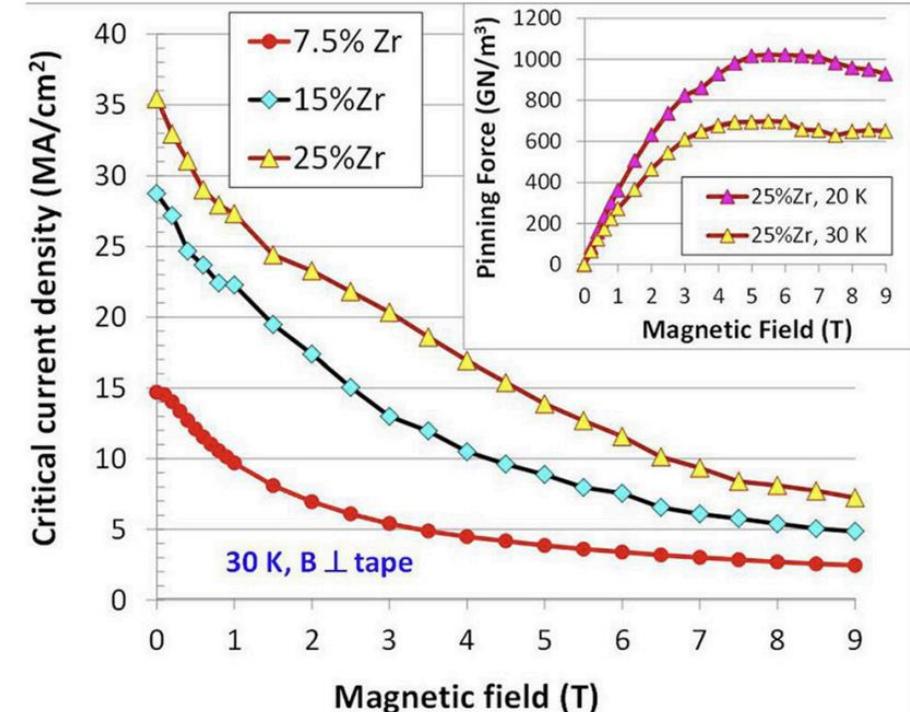
Controllable defects with size and morphology



◆ Secondary phase columnar growth of *in-situ* PLD & MOCVD film

Common columnar secondary phases: perovskite structural type oxides

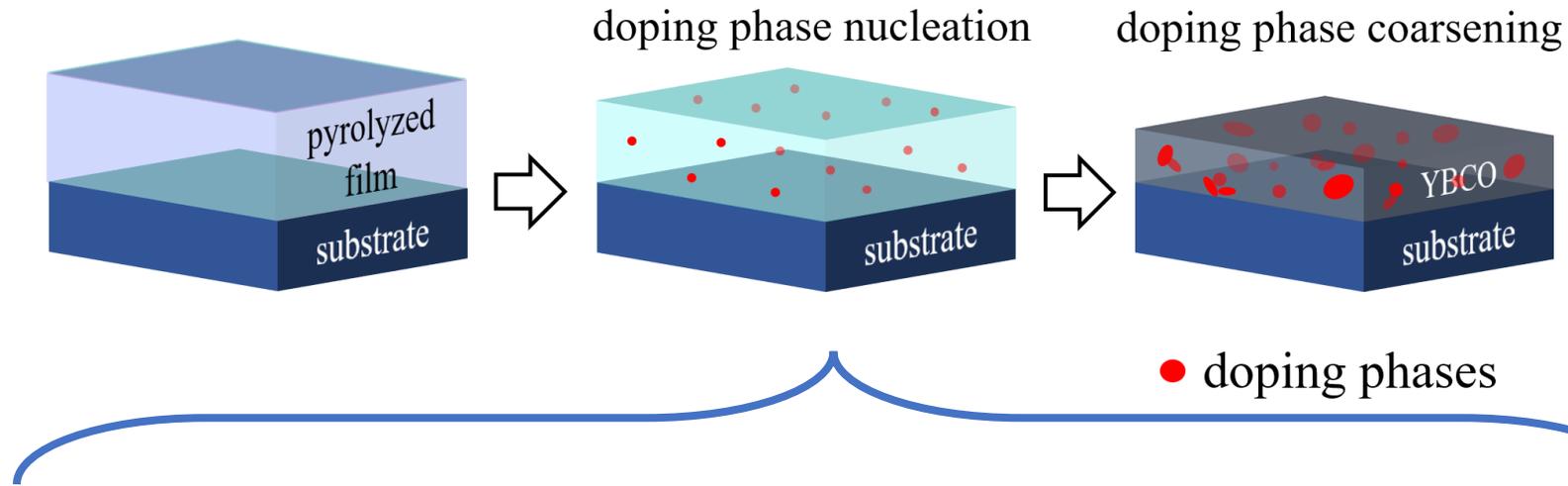
- BaZrO_3 、 BaHfO_3 、 BaSnO_3 、 $\text{BaY}(\text{Nb},\text{Ta})\text{O}_5$



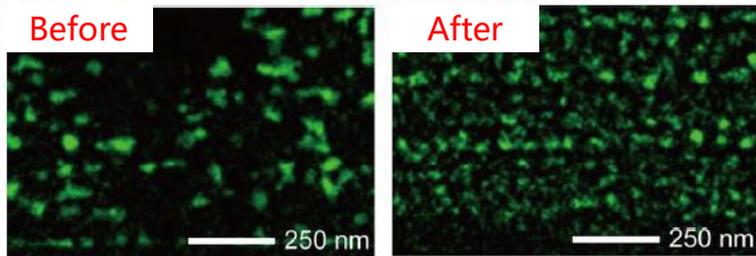
Introduction of APCs: **doping**—*ex-situ*



□ Doping Zr/Hf/Mn/Sn element etc. : large size and uneven distribution

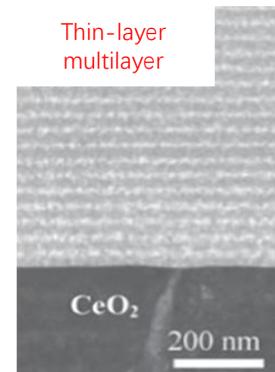
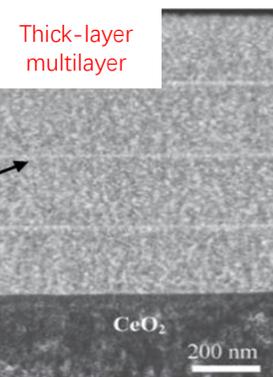


Medium temperature treatment before high Temperature crystallization

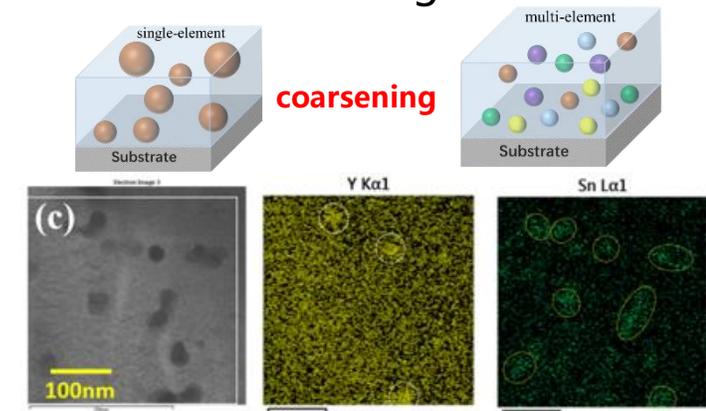


Copper-rich layer

Ultrathin-layer methods:
Refine secondary phase particles



Multi-element doping to avoid coarsening

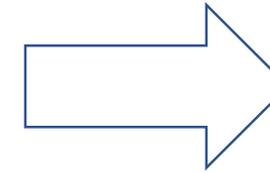


Introduction of APCs: ion irradiation

Ion irradiation

- Columnar defects
- Controllable density and orientation

E_i : energy
 M_i : mass
 Φ : dose
 Θ : injection angle



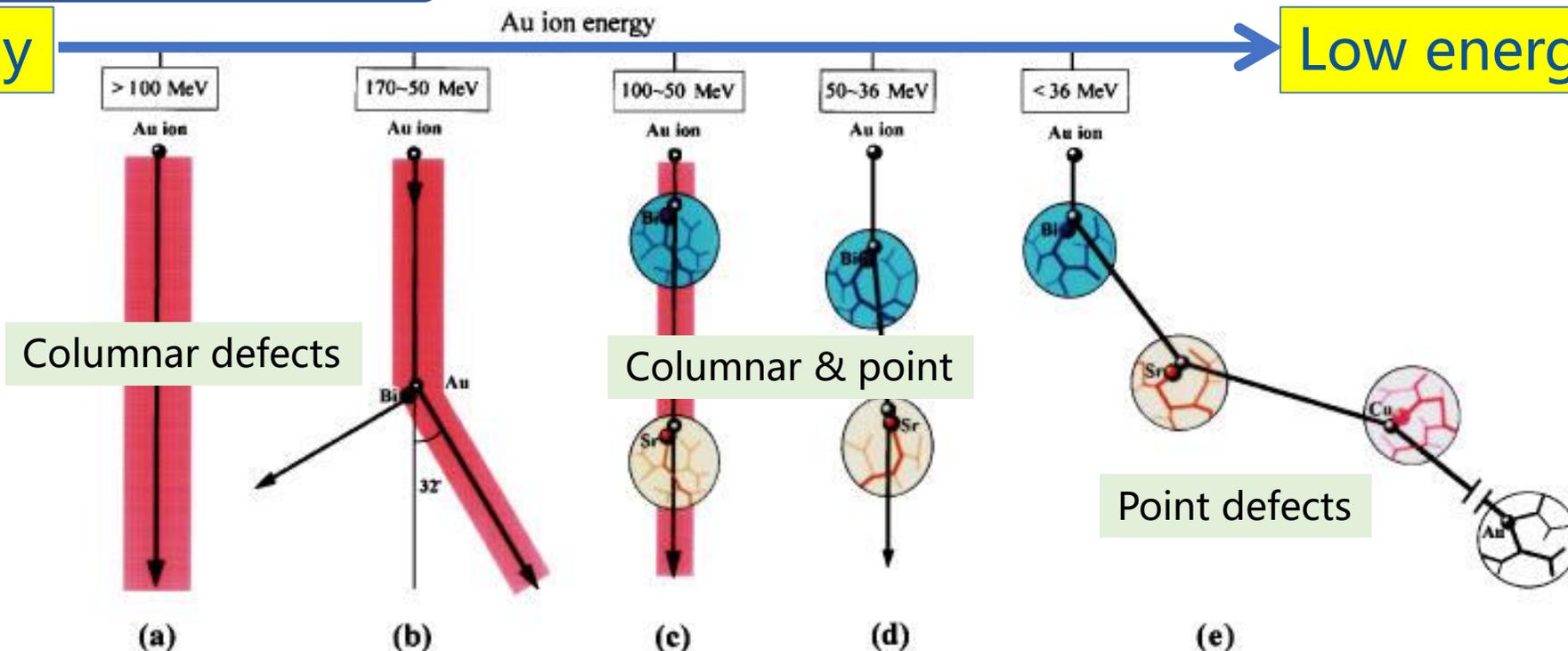
- Defect size
- Defect shape
- Defect density
- Defect orientation

Mechanism of ion irradiation

230 MeV Au-irradiated $\text{Bi}_2\text{Sr}_2\text{CaCu}_2\text{O}_x$ as an example:

High energy

Low energy



1

Methods of introducing artificial pinning centers in HTS

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Technical route and performance of MOD tapes in SCSC

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Recent progress of artificial flux pinning in MOD-REBCO

SCSC: an unique technical route!

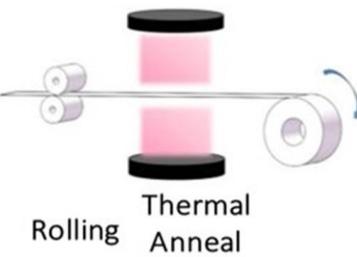


- **Shanghai Creative Superconductor Technologies Co., Ltd;**
- Established in August 2011;
- Leading for formulating national standards;
- 2G HTS wire production and development.



SCSC: an unique technical route!



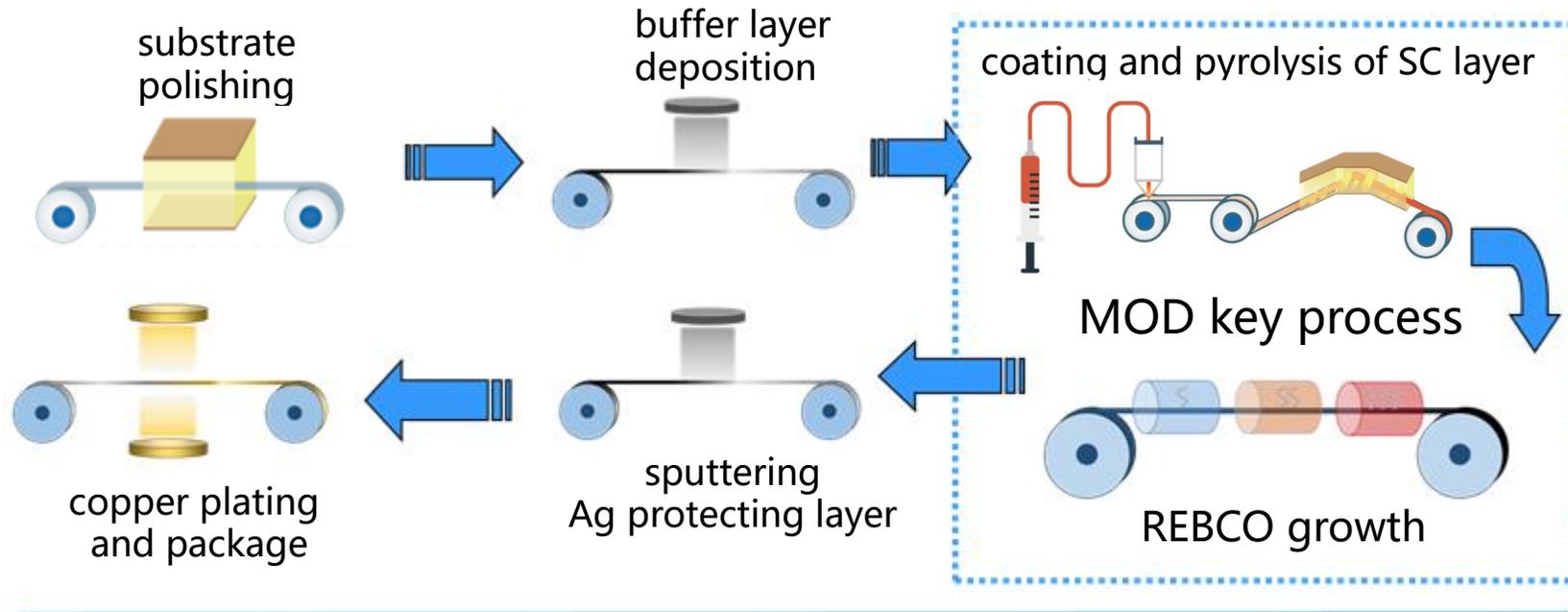
Metal Substrate	Buffer Layer (texture building)	HTS Layer (epitaxial growth)		Typical Company
<p>RABiTS工艺</p> 	<p>Epi-CeO/ YSZ or LZO</p>	<p>Ex-Situ</p>	<p>MOD</p>	<p>AMSC, d-NANO</p>
<p>IBAD工艺</p> 	<p>LMO/ epi-MgO/ IBAD-MgO</p>		<p>In-Situ</p>	<p>RCE</p>
		<p>PLD</p>		<p>SuNAM, THEVA</p>
		<p>MOCVD</p>		<p>Fujikura, SST, SuperOX, Bruker</p> <p>SuperPower, SAMRI</p>

SCSC: industrial production lines



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Shanghai Creative Superconductor

上海市高温超导重点实验室
HTS Shanghai Key Laboratory of High Temperature Superconductors



Low-cost MOD route

- No high vacuum
- Easy control of composition
- 100% utilization of solution
- Wider tapes & thicker HTS layer
- Large scale production

- Substrate polish

- Texture formation of buffer layers

- Coating and growth of HTS layer

- Slitting & Package



Latest developed MOD production lines with higher yield



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**MOD-HTS process(1):
Coating and Low-temperature pyrolysis**



**MOD-HTS process(2):
High-temperature crystallization**

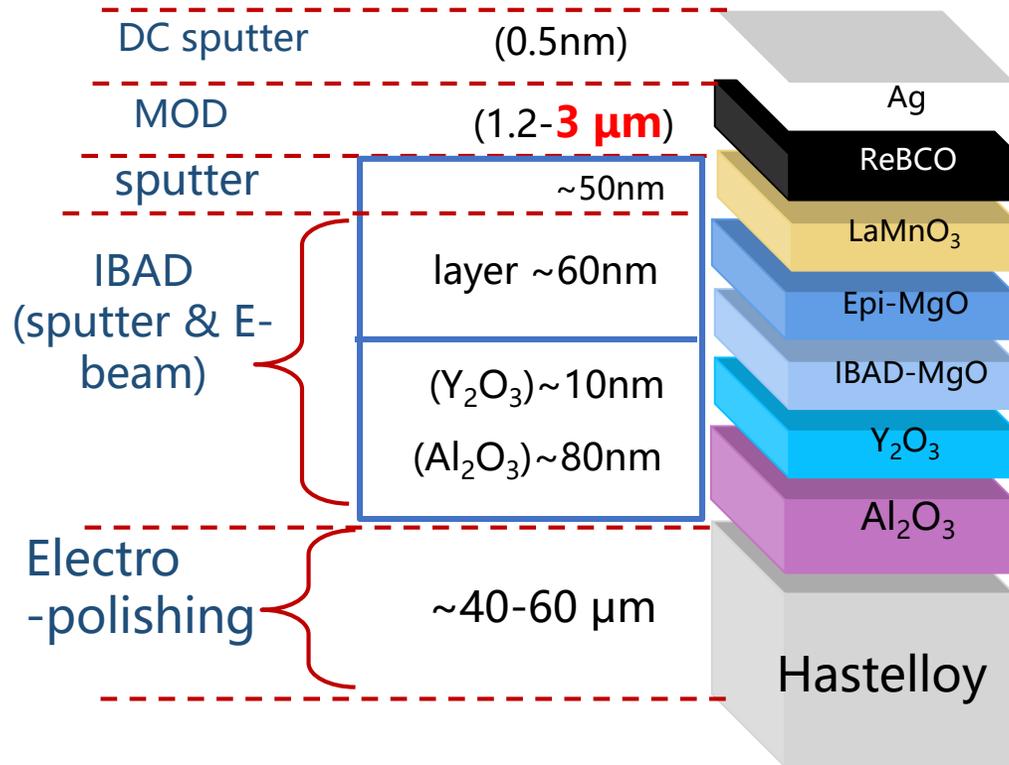
- Wider tapes of **20-40 mm**; **Double lanes** designed;
- Multiple production yields up to **400 km/year** reached.

Latest developed MOD production lines with higher yield



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■ Typical $I_c \sim 600 \text{ A}/12\text{mm}$ at 77K self-field

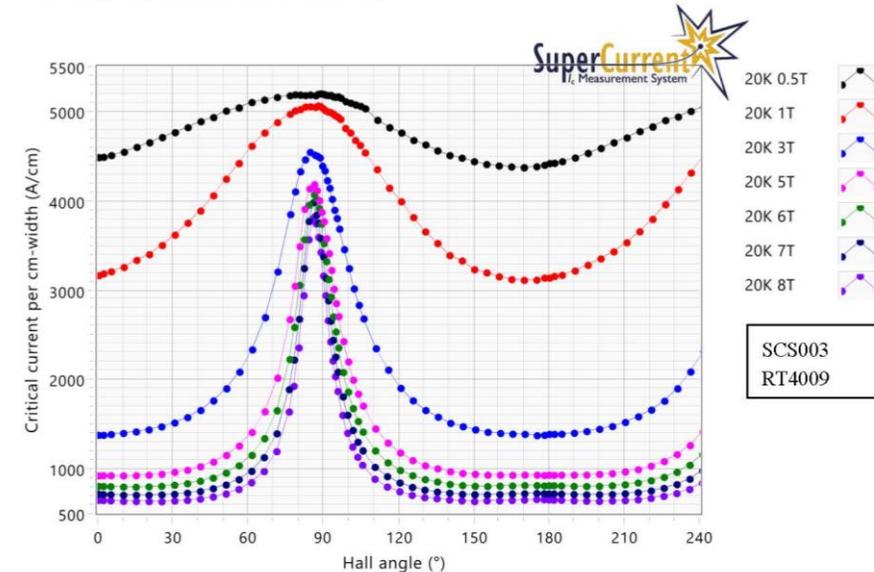


Robinson Research Institute



Sample RT4009 (SCS003)

1. Angle dependence scans of in-field I_c

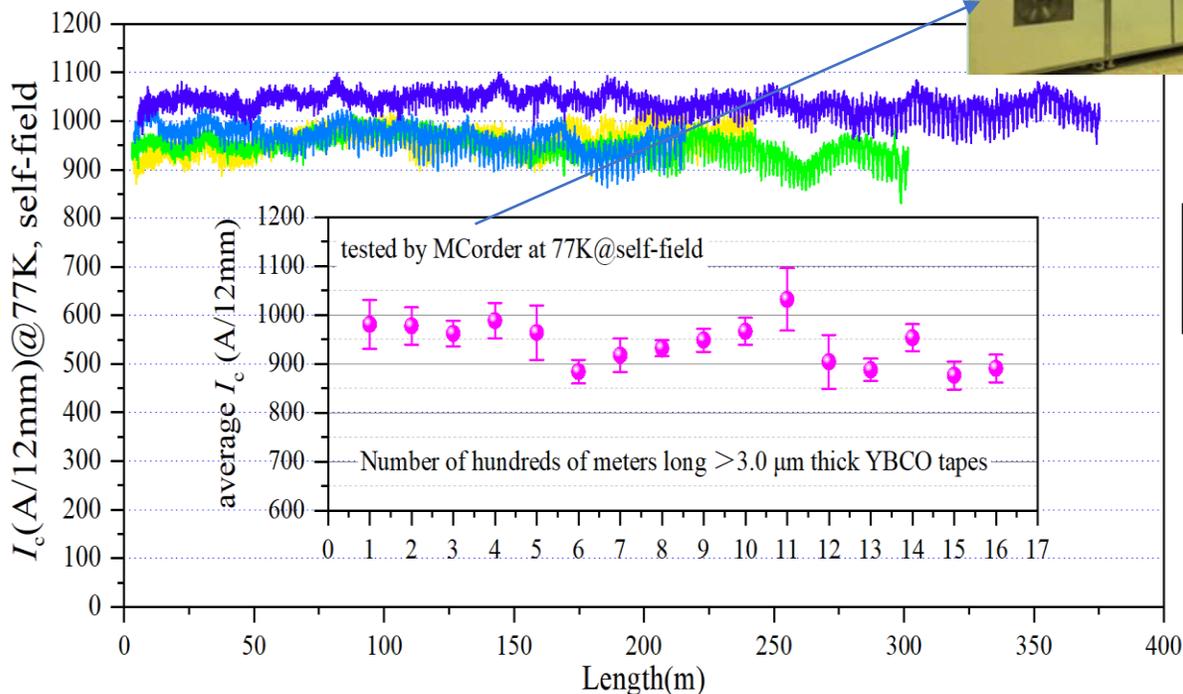


■ $I_c \sim 5250\text{A}/12\text{mm}$ at 20K, self-field

A hundred-meter thick film long tape



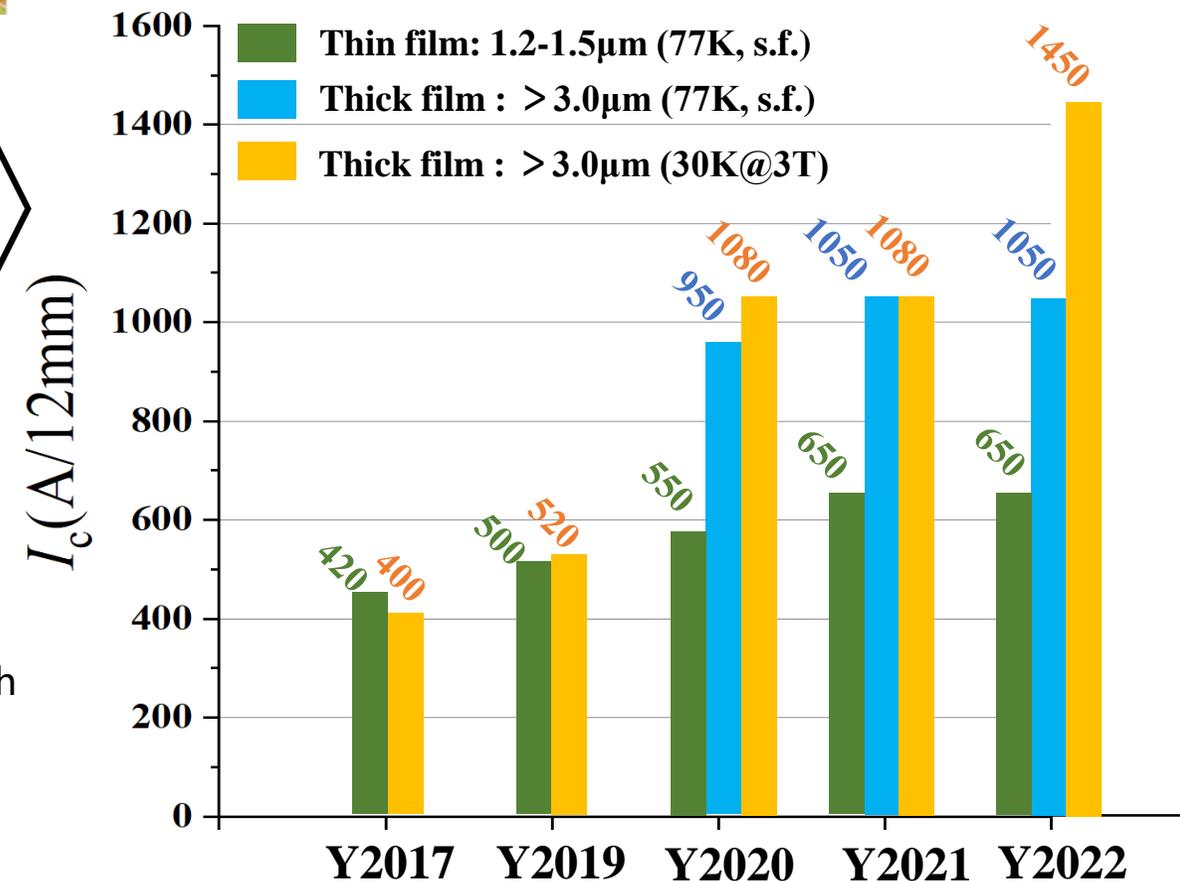
- ✓ Stable preparation of $> 3\mu\text{m}$ BHO-YBCO thick film long tape



- The $I_c(77\text{K}, \text{self-field})$ increased from 550A to $> 1000\text{A}(12\text{mm})$ with increased thickness;
- The in-field performance of MOD-YBCO improved with APCs.

- ✓ BMO-added REBCO tape, 4mm-width:

- 30K@3T : 450-500A
- 4.2K@20T : 280-300A

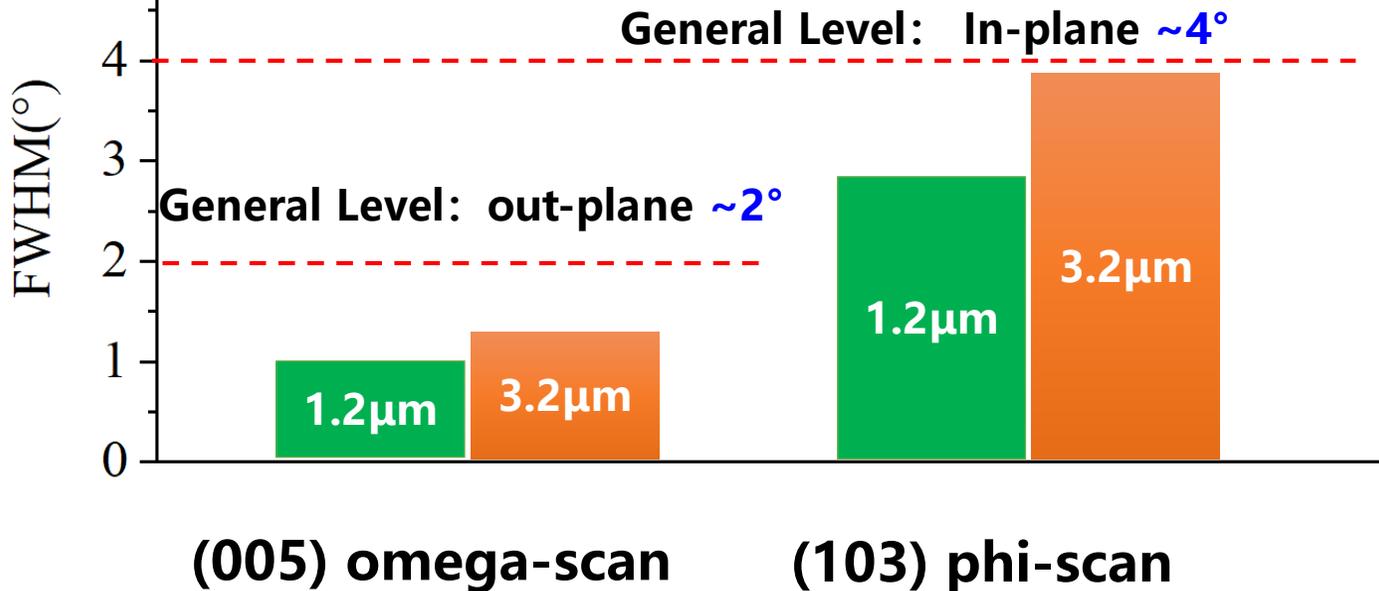
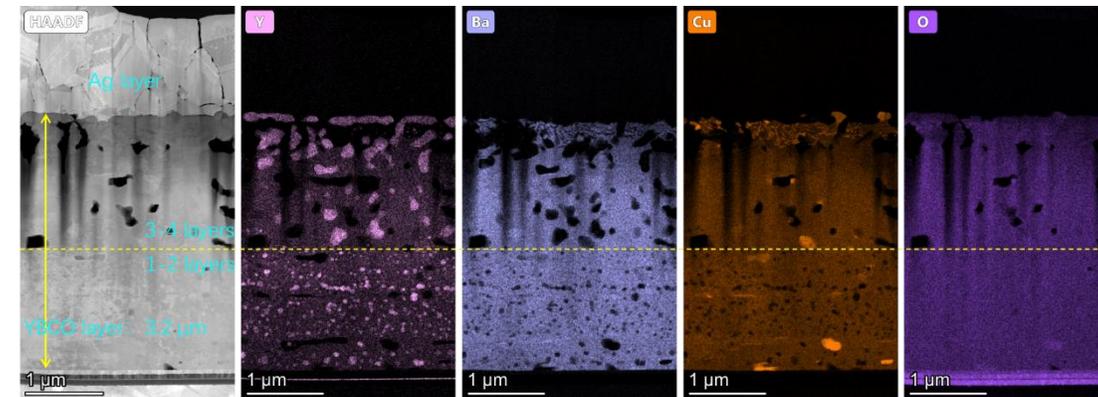
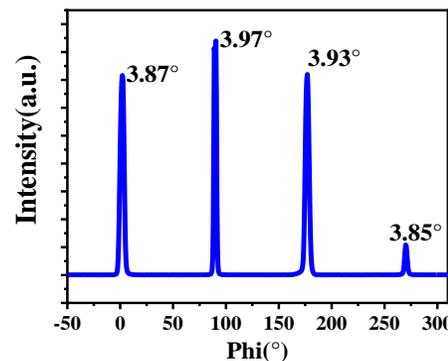
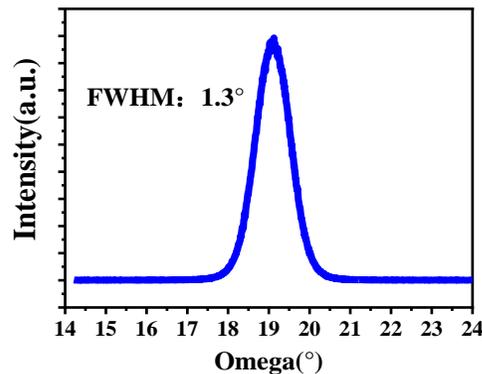


Texture of BMO-REBCO

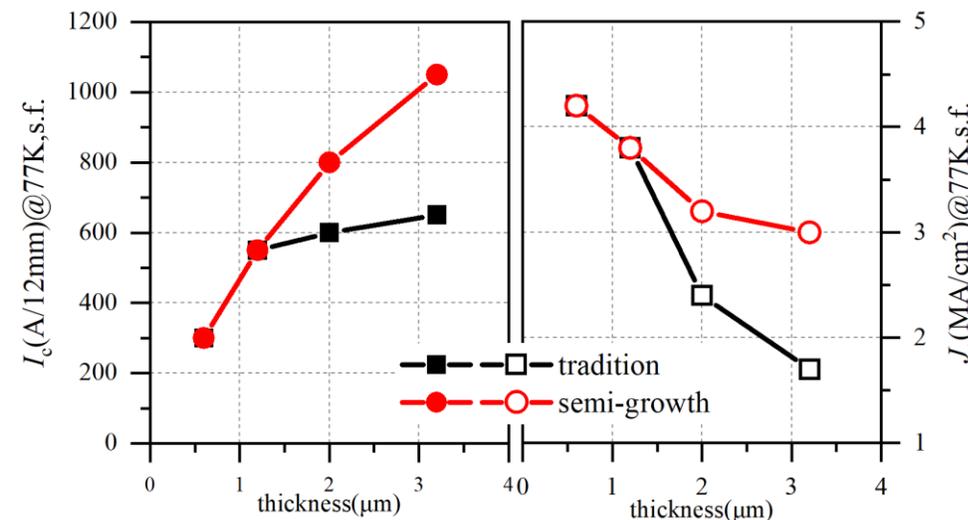
Two layers: $\sim 1.2 \mu\text{m}$

VS

Four layers: $3 \sim 3.2 \mu\text{m}$



✓ The $I_c(77\text{K, s.f.})$ increased linearly

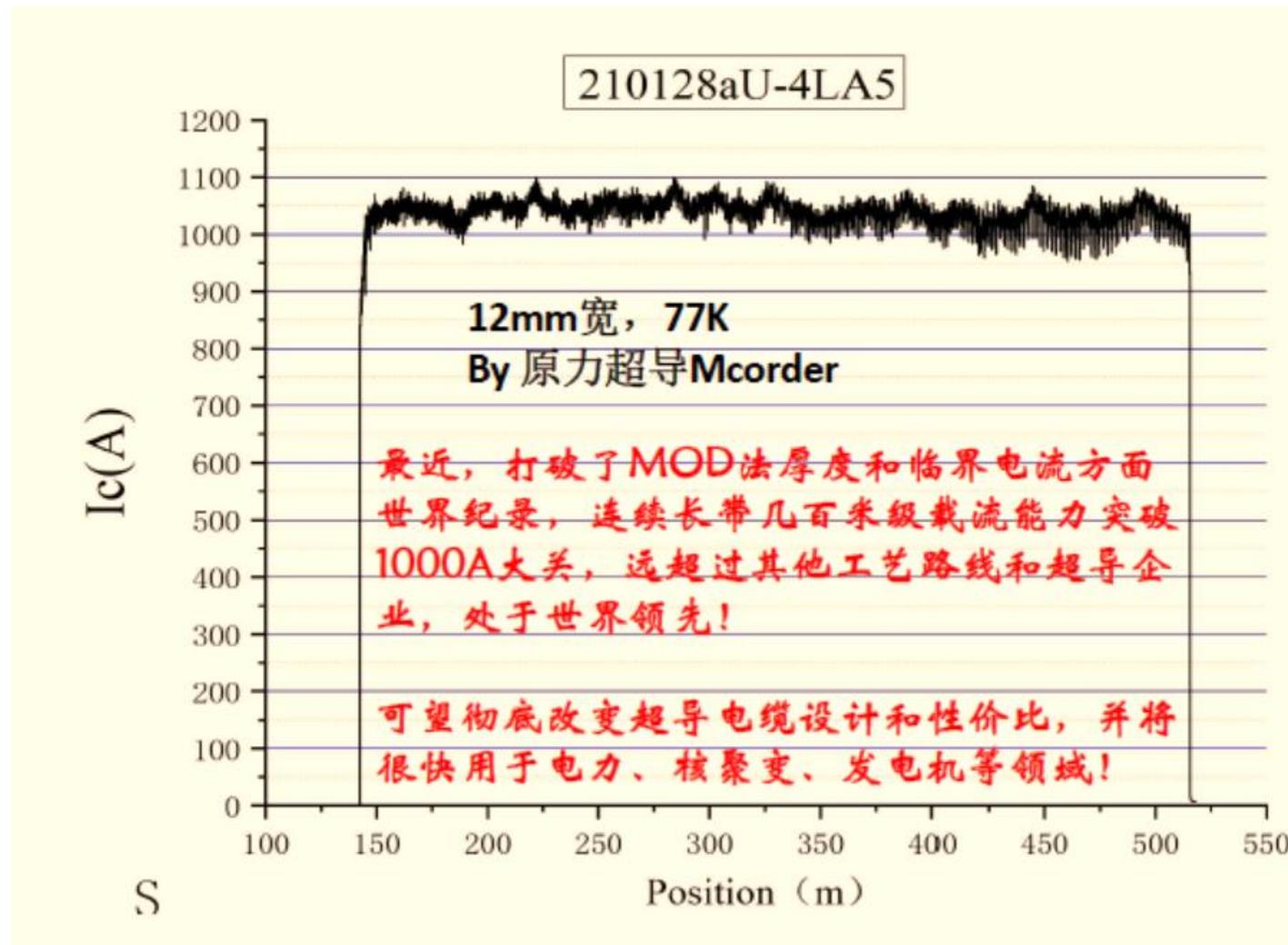


Performance of commercial MOD-YBCO tapes @SCSC



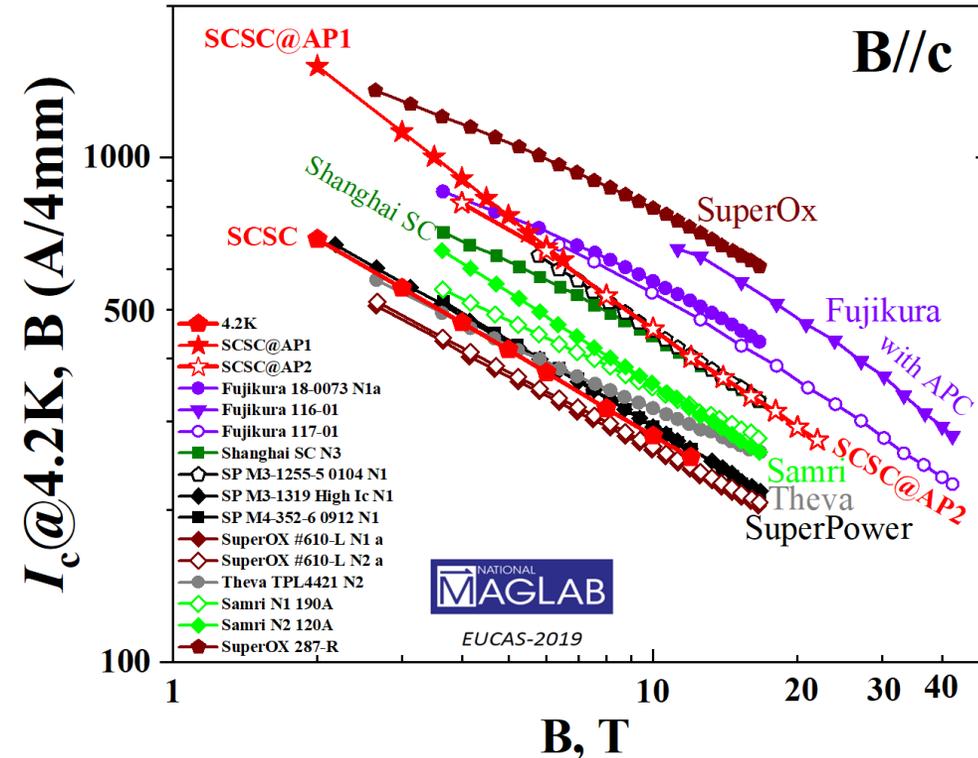
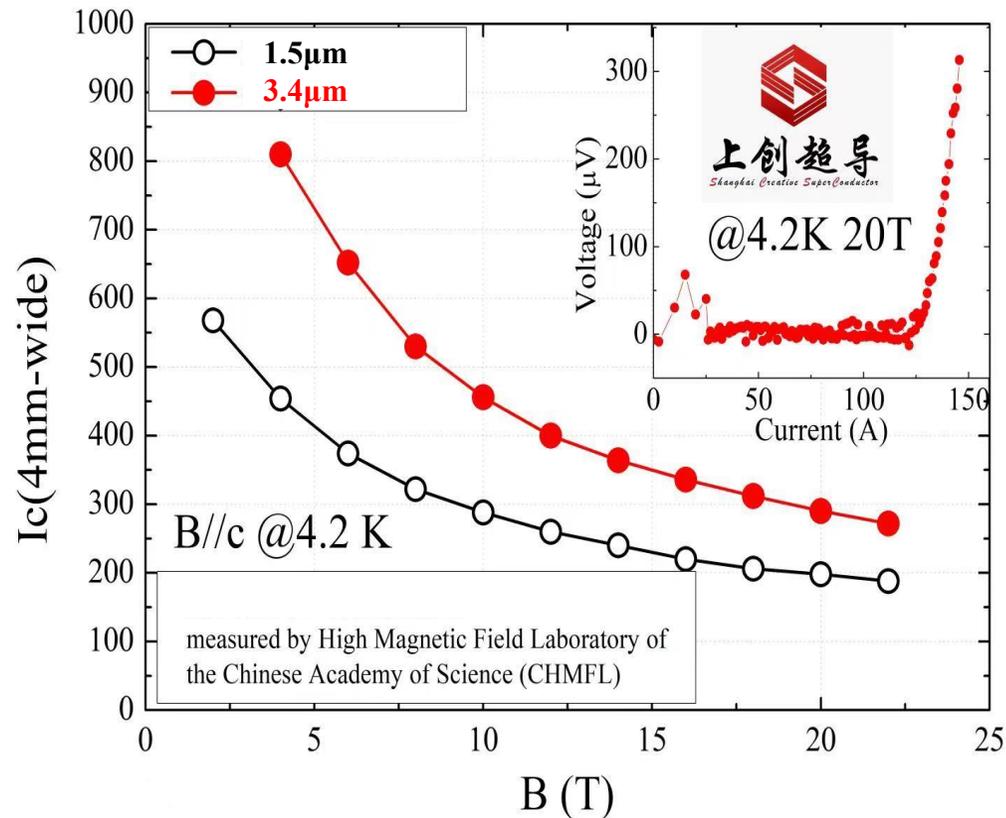
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1100A/12mm@400m

Higher in-field performance of 4mm-width long MOD-YBCO tape
(> 200m), **30K@3T : 450-500A; 4.2K@20T : 280-300A**



Specification & Technical Parameter

	SCST-W4	SCST-W6	SCST-W12	SCST-W4 (Advanced)	SCST-W6 (Advanced)	SCST-W12 (Advanced)
Width	4.0±0.1 mm	6.0±0.1 mm	12.0±0.1 mm	4.0±0.1 mm	6.0±0.1 mm	12.0±0.1 mm
Thickness	80-250 μm			80-250 μm		
Length	100-1000 m			100-1000 m		
Critical Bending Diameter	20 mm			20 mm		
Tensile Strength (Room Temperature)	> 400 Mpa			> 400 Mpa		
Min I_c (77K, self-fields)	90-180 A	160-300 A	300-600 A	300-350 A	450-550 A	900-1100 A
Stabilizer	Copper/Brass/Stainless steel			Copper/Brass/Stainless steel		

- Variable cooper thickness;
- Insulation:10-20 μm thin polyimide varnish; Lamination;
-Just ask.

1

Methods of introducing artificial pinning centers in HTS

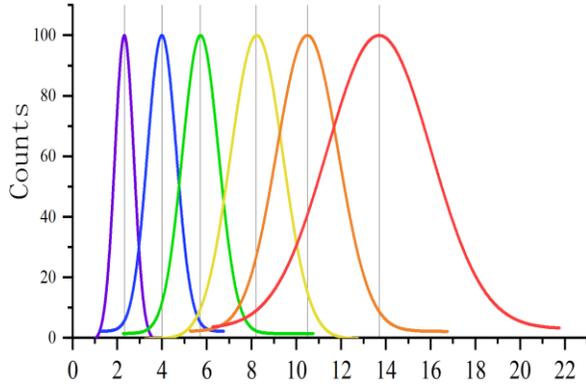
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Recent progress of artificial flux pinning in MOD-REBCO

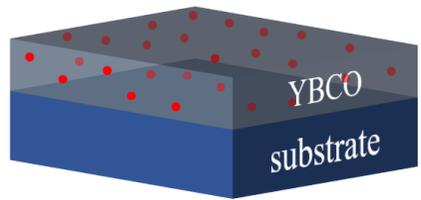
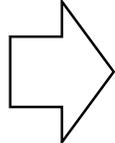
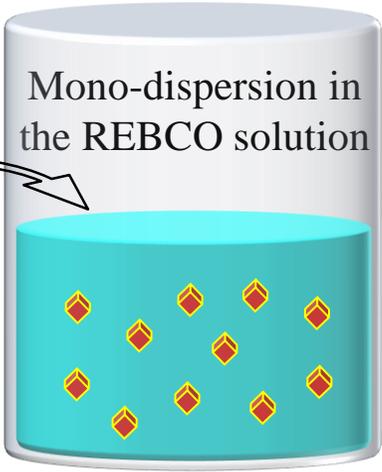
Controllable size of BMO nanocrystals



Control of BMO size (nm)

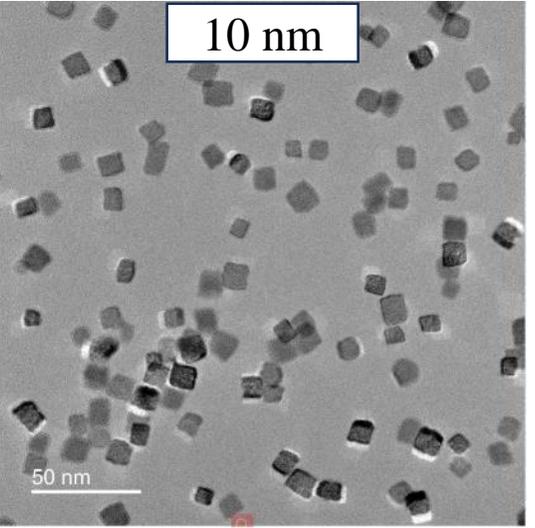
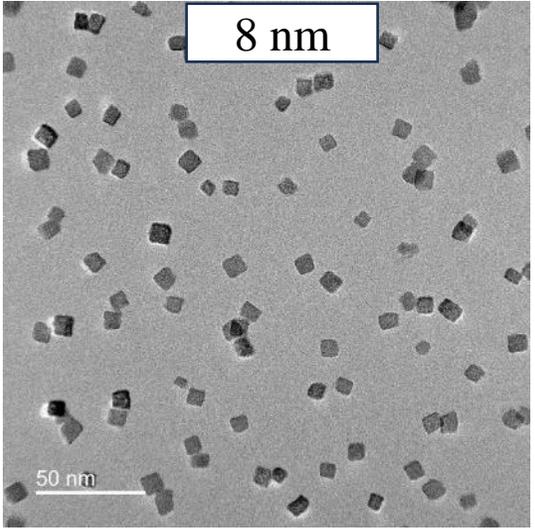
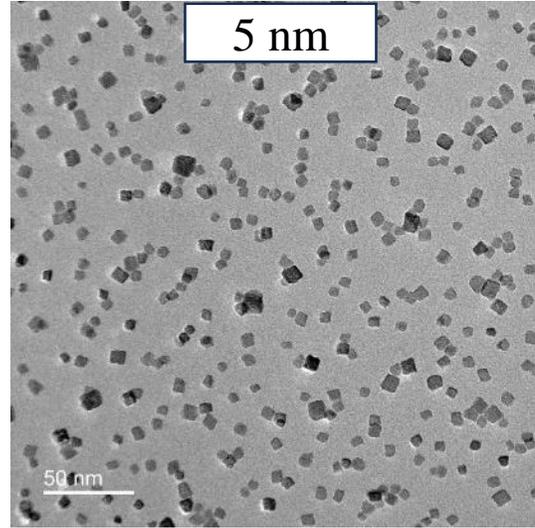
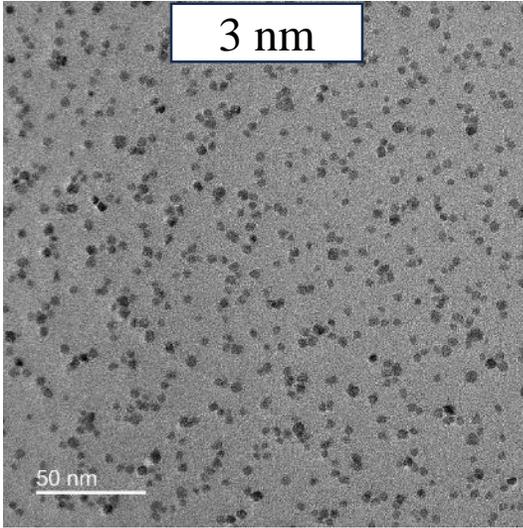


BaZrO₃/BaHfO₃ nanocrystal synthesis



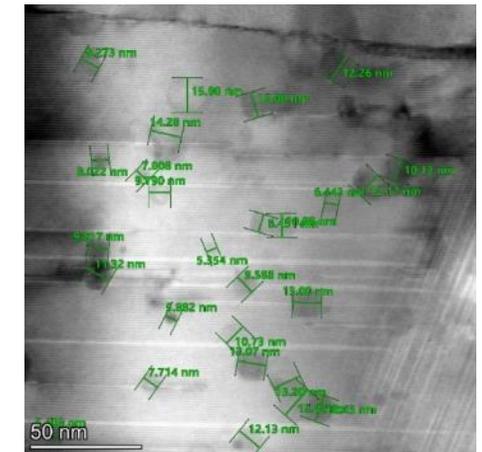
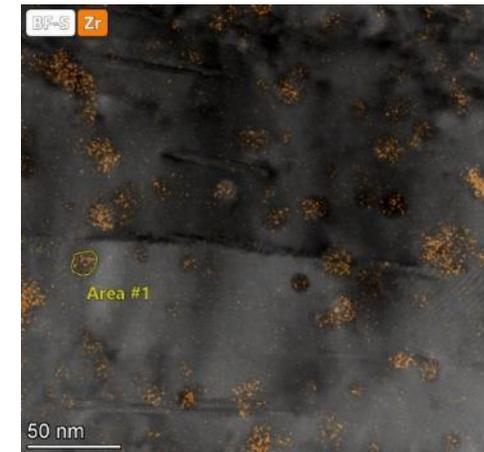
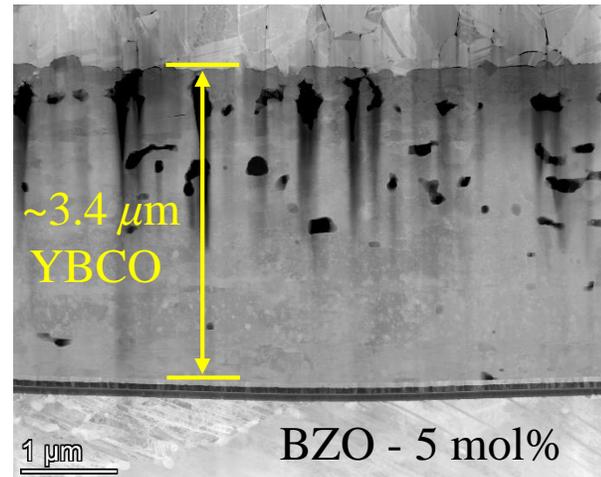
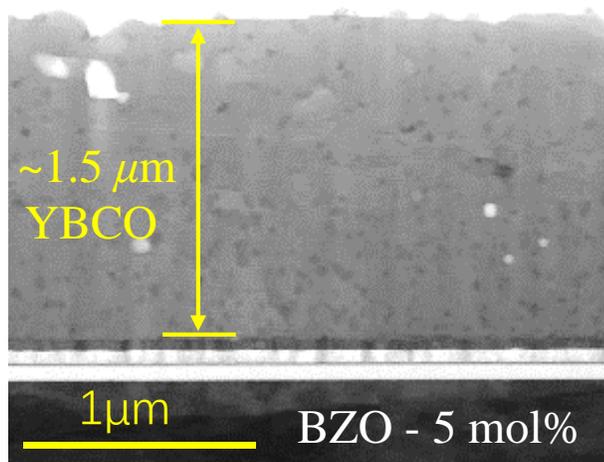
Random distribution in the REBCO film

Nanocrystal addition route: highly control of BMO size and distribution

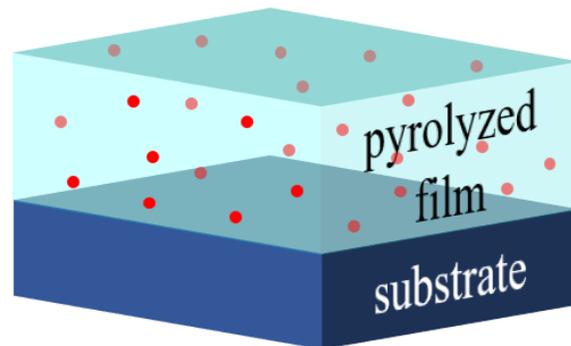


BMO nanocrystals in REBCO film

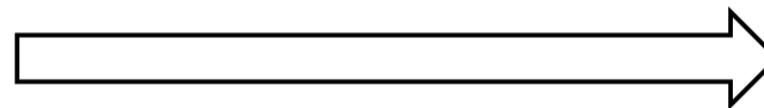
- ✓ Identical benefits of highly control of BMO size and distribution to both the REBCO films with thicknesses of 1.5 μm and 3.4 μm



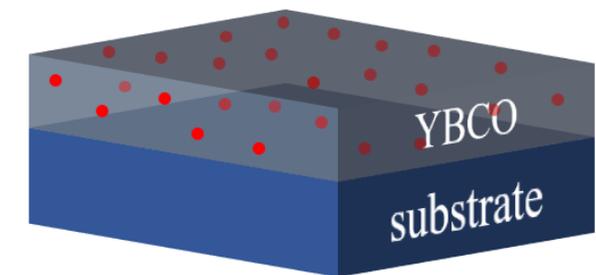
BZO: 8-12 nm



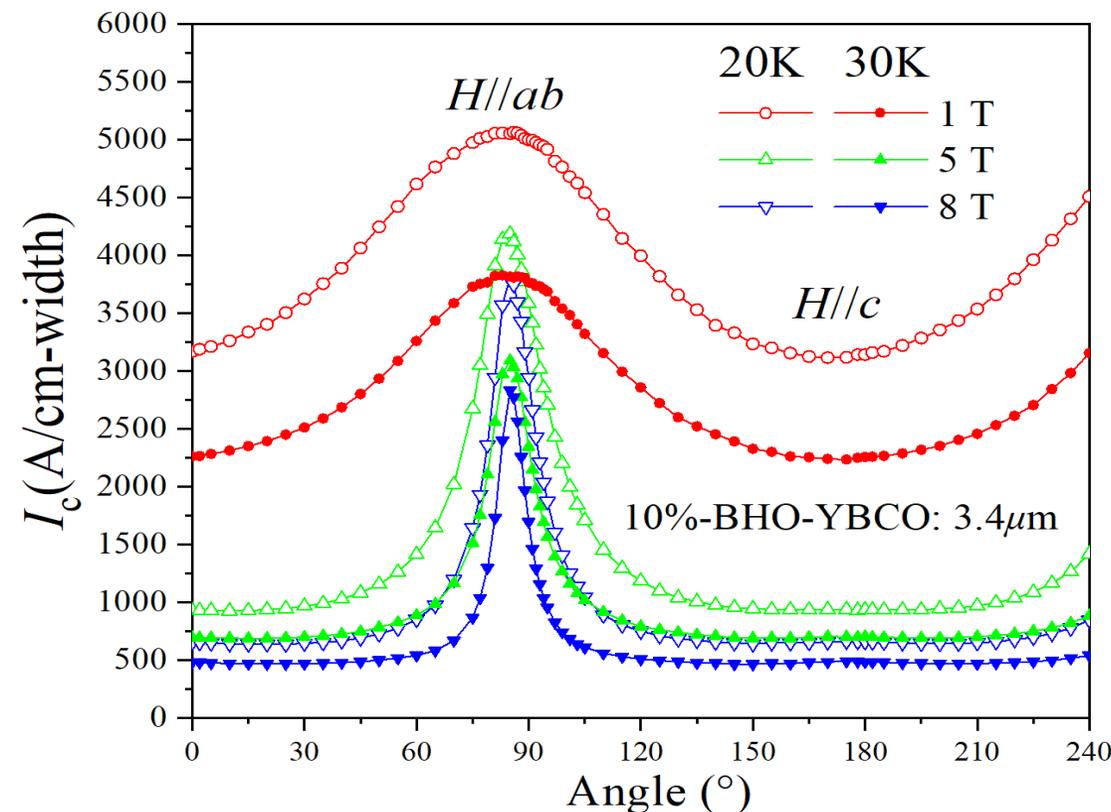
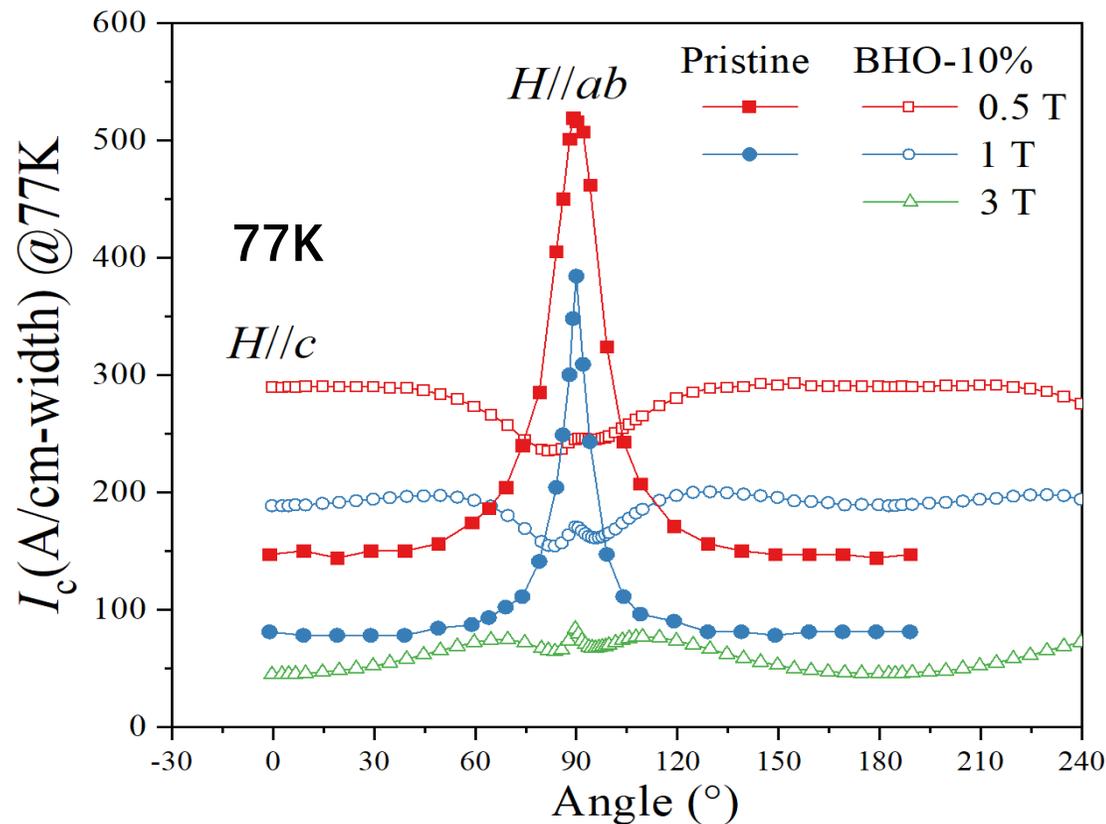
without
coarsening and agglomeration



● doping phases



Anisotropic behavior with BMO additions



The properties of BMO-added YBCO films at high temperatures and low fields : $I_c > I_{ab}$

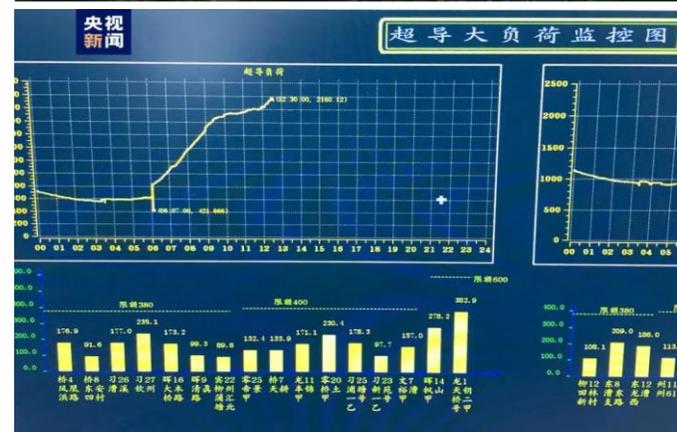
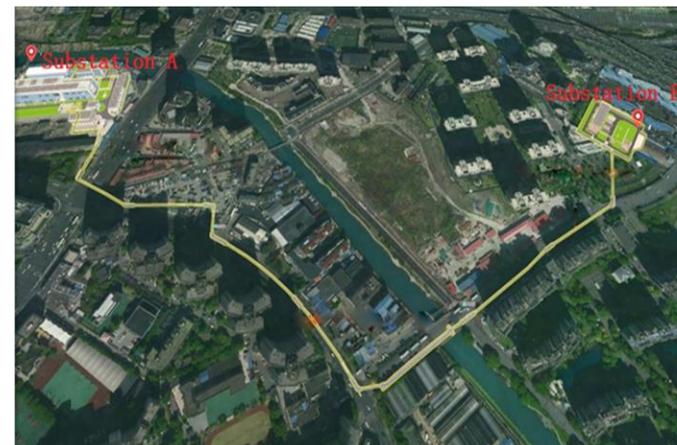
Shanghai km-class HTS cable demonstration project



1.2-km 35 kilovolt superconducting power cable transmission line

- Length: **1.2 km**
- Loading **Current: 2.2 kA**
- Loading **Voltage: 35 kV**
- HTS Materials: **2G tapes from SCSC & SST**
- Cable Structure: **Three-phase integrated**
- Total area: **Save 70% of underground pipe gallery space**

Km-class HTS cable demonstration project: the first three-core integrated HTS cable supplying the power to Xujiahui, Shanghai, **downtown of the metropolis** in the world.



Full load operation (2160.12A) on August 18th

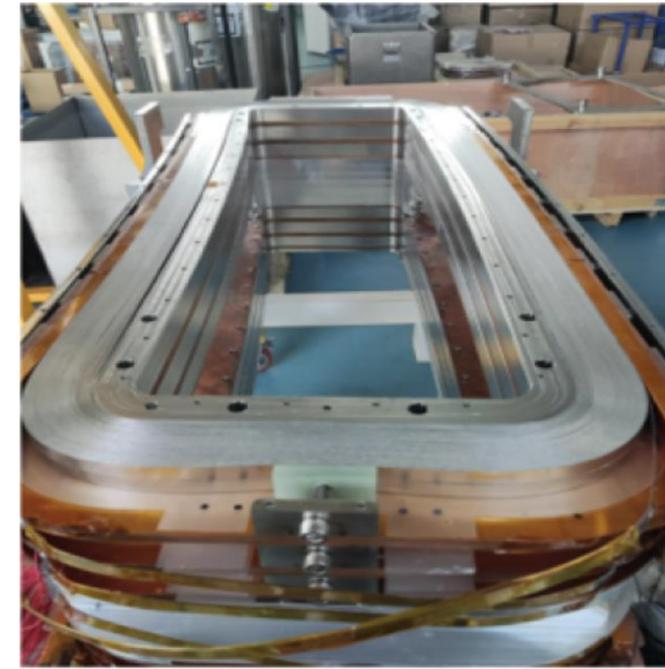
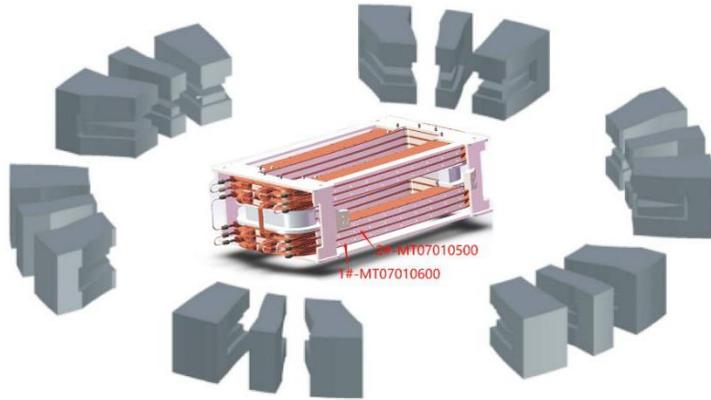


2G-HTS cable

2G-HTS Magnet Coil



Large-size magnet coil for special accelerator



- Beyond the energy limit of circular accelerator, up to 2GeV;
- Compact design, low power consumption, low operating cost;

Conclusions



- ◆ **Industrial MOD product line** built up in SCSC producing commercial tapes as long as 400m with I_c (77k, s.f) more than 300A/4mm, 1000A/12mm, thanks to HTS layer thickness up to **3 μm via innovative MOD processing**;
- ◆ Artificial flux pinning techniques including BZO/BHO nanocrystal addition as well as ion irradiation, resulting in higher in-field performance for present MOD tapes (4mm-width):
30K@3T : 450-500A; 4.2K@20T : 280-300A;
- ◆ **Km-class HTS cable demonstration project**: The world's first 35 kV kilometer-class superconducting transmission demonstration project has been operating at full capacity.



Thanks a lot for your attentions!



Welcome to visit and cooperate with SHU and SCSC

Email: 15821257268@163.com; Tel: +86 15821257268