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ACASC-Asian ICMC

上创超导 Shanghai Creative SuperConductor

Advance in Artificial Pinning of MOD-REBCO Superconducting Coated Conductors

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Shanghai Creative Superconductor Technologies Co., Ltd

Collaboration & Acknowledgement

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- 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

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Outline

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

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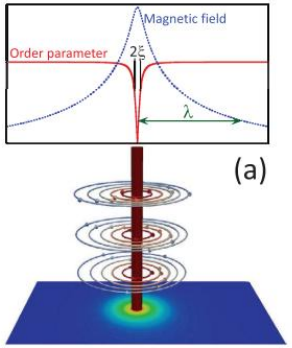
Defect types VS. film preparation methods

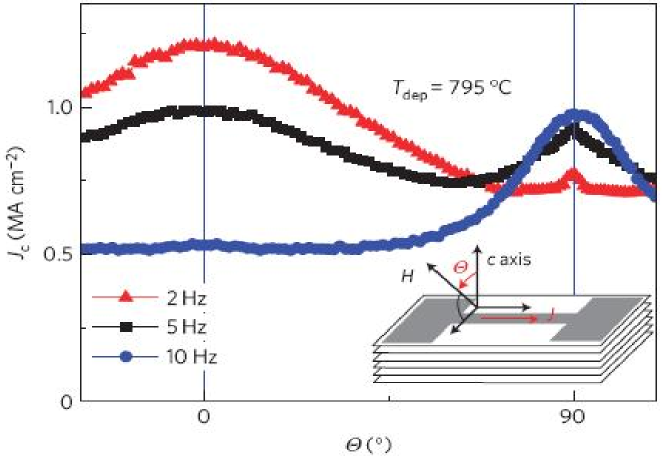
Magnetic Flux Core Size： 2ξ ~ 1-2 nm



Effective Flux Pinning Center Dimension： around 2ξ

WK Kwok et al., Rep. Prog. Phys. 79, 116501(2016)

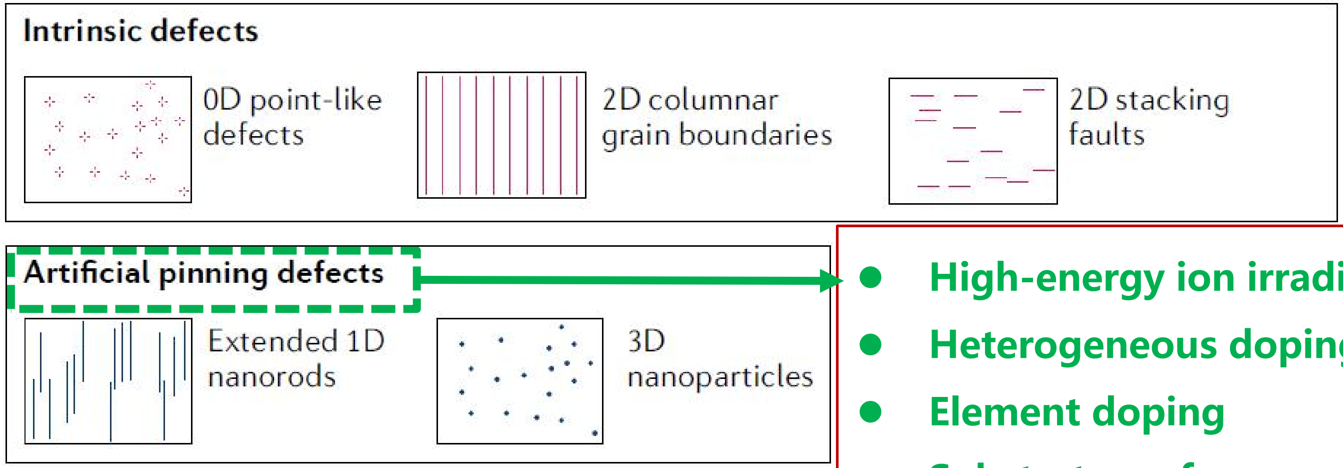
Magnetic transport anisotropy：



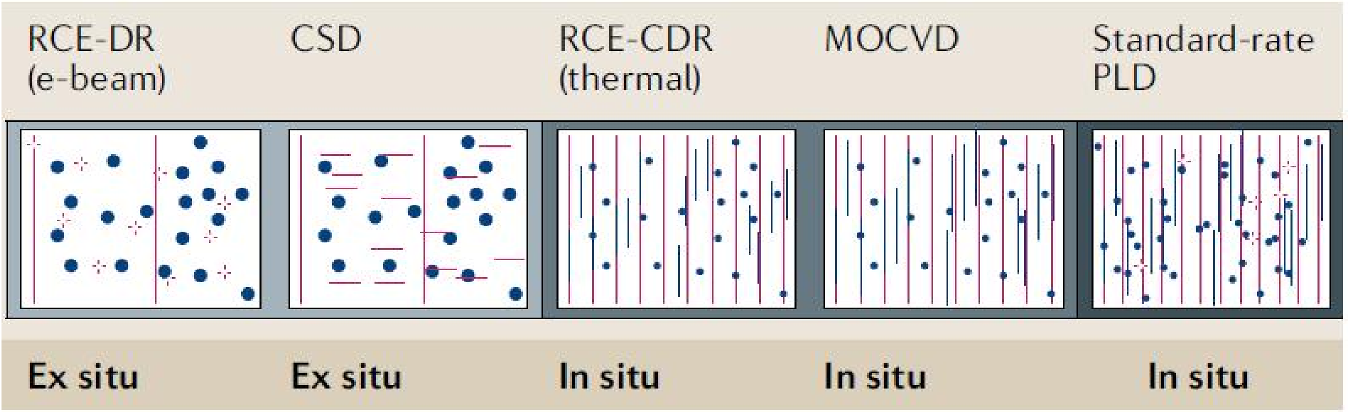
APC reduces the anisotropy

B. Maiorov et al., Nat. Mater. 8, 398 (2009)

Defect types as flux pinning centers in REBCO film:



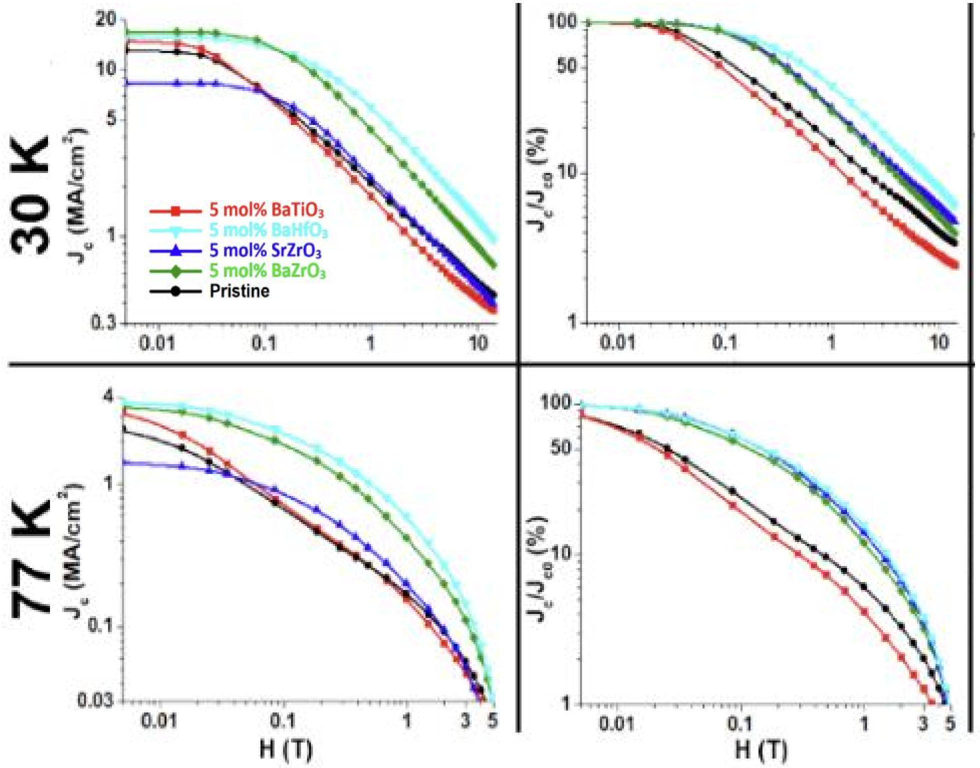
- High-energy ion irradiation
- Heterogeneous doping
- Element doping
- Substrate surface modification
- ……



MacManus- Driscoll et al., Nat. Rev. Mater., 6, 587-604(2021)

In-field performance VS. Application

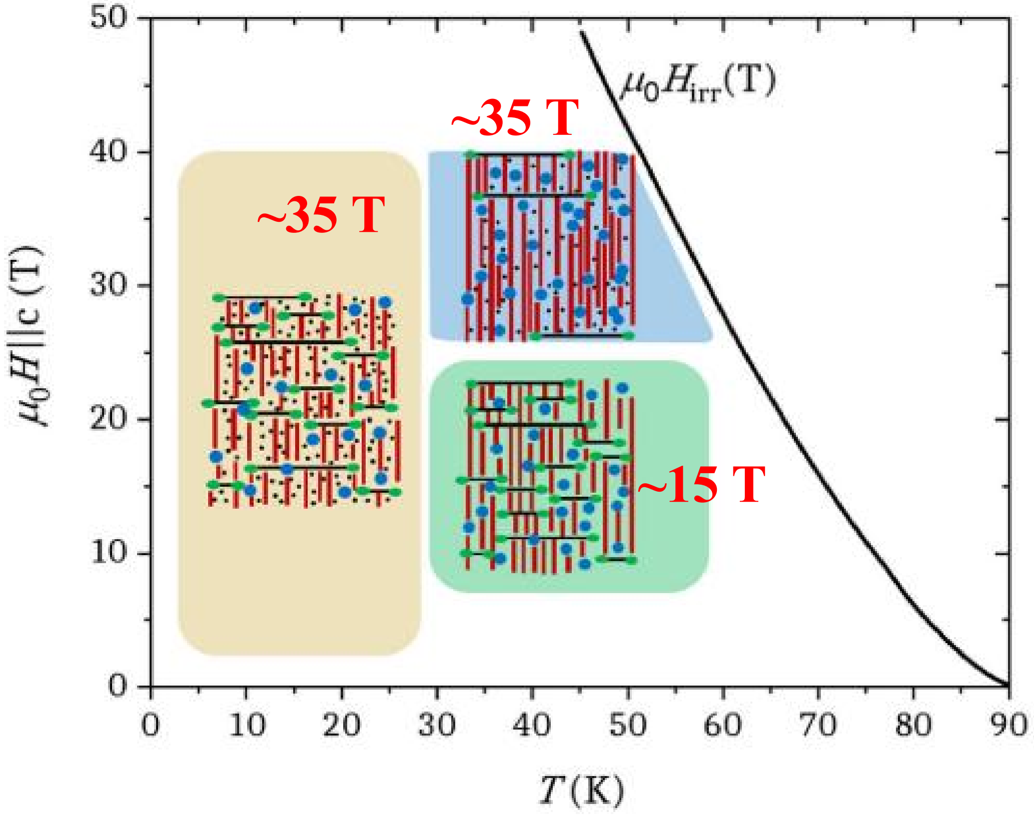
- BMO_3 nanocrystal technology: size control, highly dispersive
- Significant improvement of In-field J_c



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)

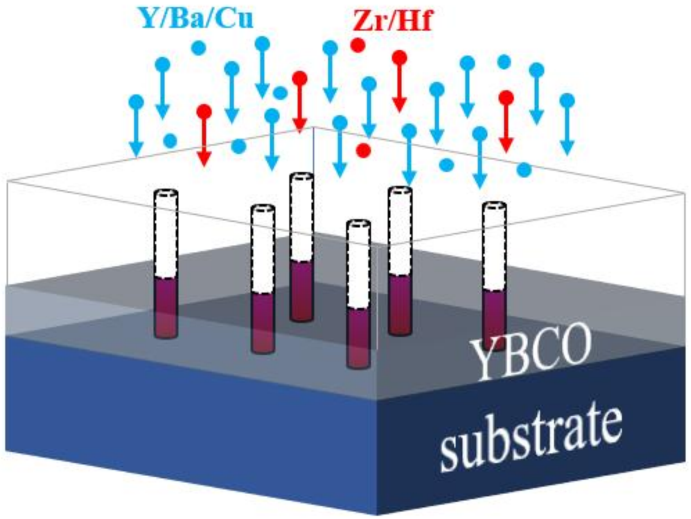
- **Mixed landscape in REBCO:**

small size defects result in strong pinning at high field, meaning the great advantage of nanocrystal addition in MOD route;

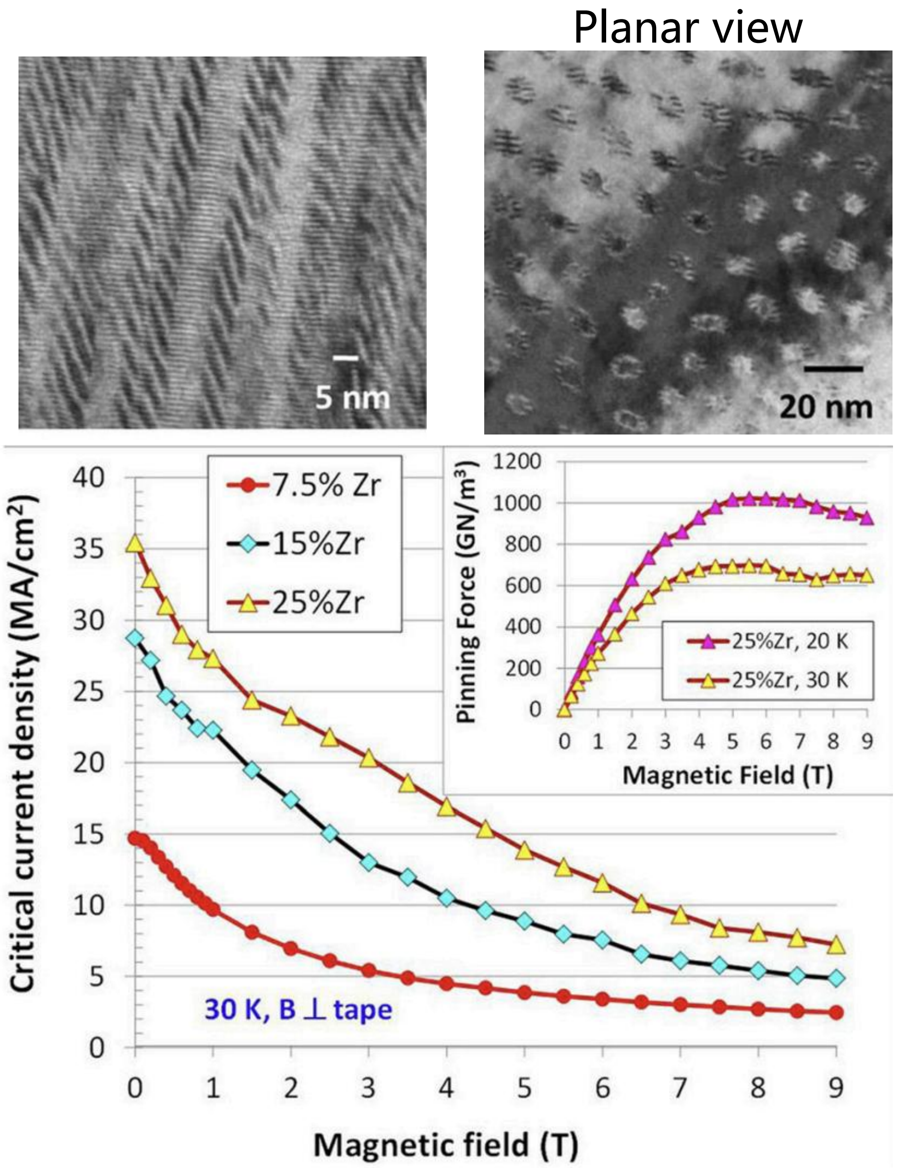


2022, VallèsF et al., Commun. Mater. 3, 45(2022)

Introduction of APCs: doping—*in-situ*



Controllable defects with size and morphology



V Selvamanickam et al., Appl. Phys. Lett. 106, 032601(2015)

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

Common columnar secondary phases: perovskite structural type oxides

- $BaZrO_3$、$BaHfO_3$、$BaSnO_3$、$BaY(Nb,Ta)O_5$

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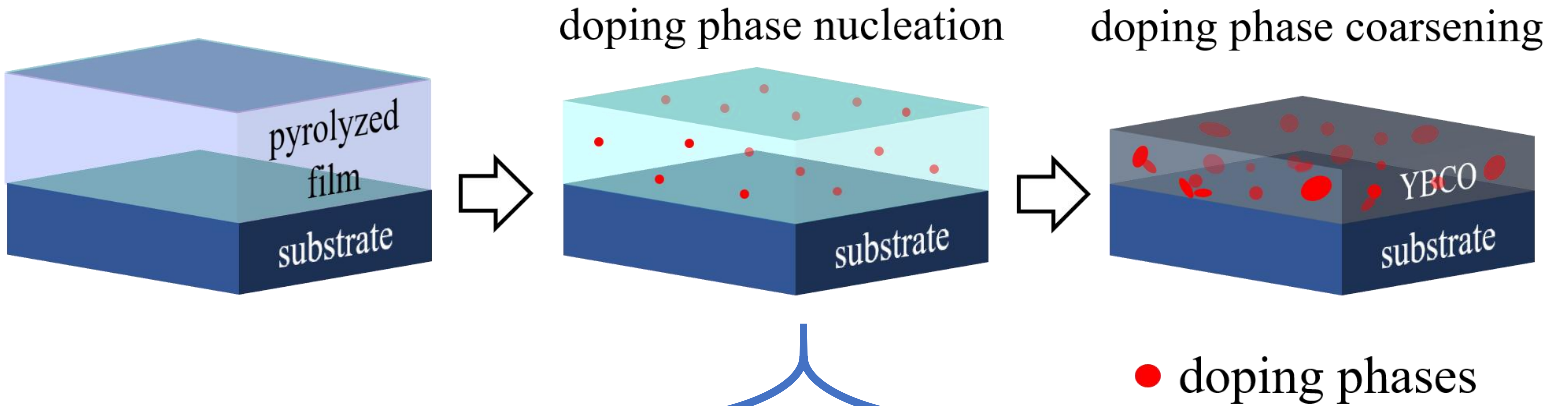
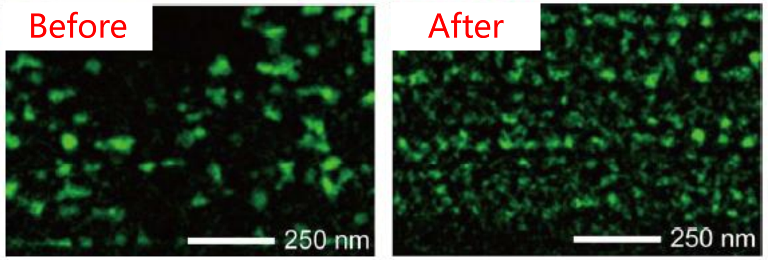
Introduction of APCs: doping—*ex-situ*

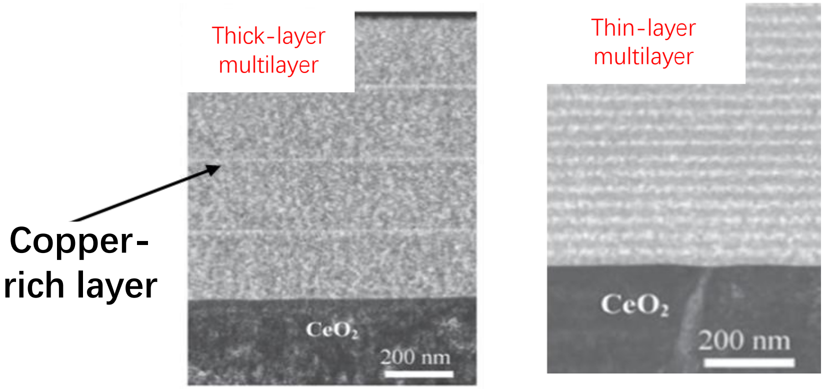
- Doping Zr/Hf/Mn/Sn element etc. ： large size and uneven distribution



Medium temperature treatment before high Temperature crystallization

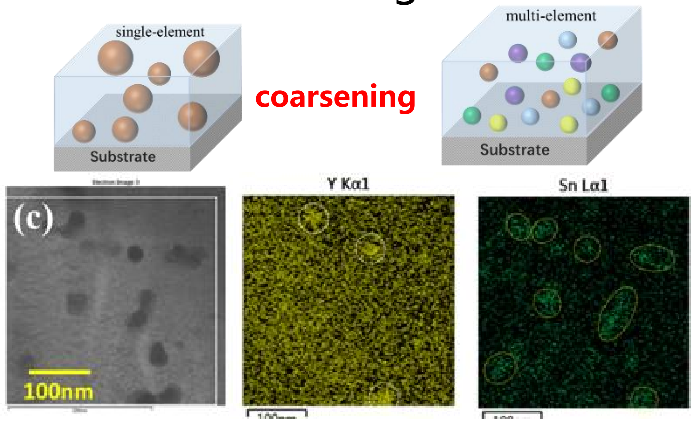


Ultrathin-layer methods:
Refine secondary phase particles



K Nakaoka et al., Supercond. Sci. Technol. 30, 055008(2017)

Multi-element doping to avoid coarsening



J Chen et al., J. Eur. Ceram. Soc. 42, 6542–6550(2022)

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Introduction of APCs: ion irradiation

Ion irradiation

- **Columnar defects**
- **Controllable density and orientation**

Ei: energy
Mi: mass
Φ: dose
Θ: injection angle

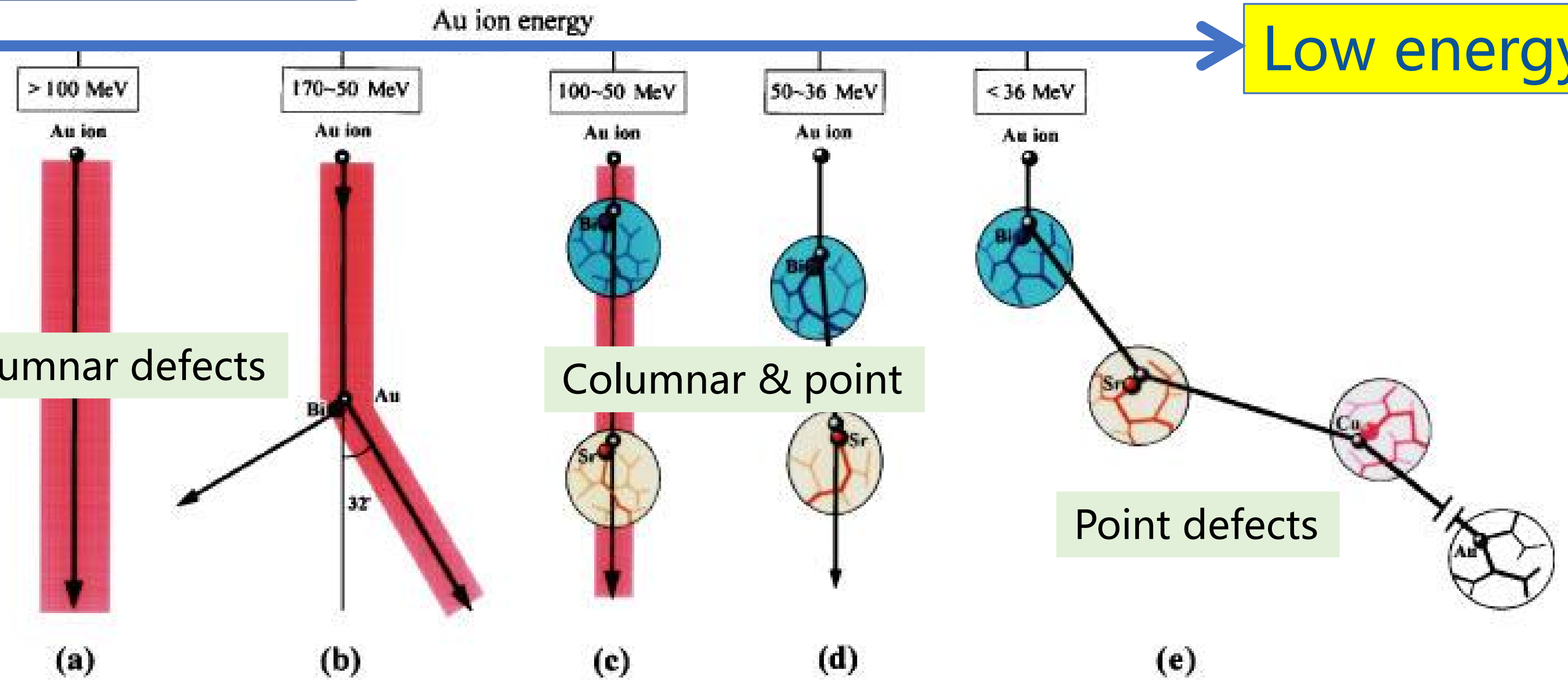
- **Defect size**
- **Defect shape**
- **Defect density**
- **Defect orientation**

Mechanism of ion irradiation

230 MeV Au-irradiated $Bi_2Sr_2CaCu_2O_x$ as an example:

High energy

Low energy



Columnar defects

Columnar & point

Point defects

H Matsui et al., App. Phys. Lett., 101, 232601 (2012)

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Outline

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2	**Technical route and performance of MOD tapes in SCSC**
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SCSC: an unique technical route!

上创超导
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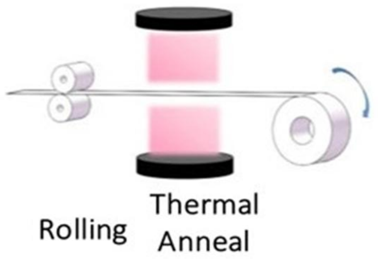
<table>
<tr><th>Metal Substrate</th><th>Buffer Layer
(texture building)</th><th colspan="2">HTS Layer
(epitaxial growth)</th><th>Typical Company</th></tr>
<tr><td>RABiTS工艺
</td><td>Epi-CeO/ YSZ
or LZO</td><td rowspan="3">Ex-Situ</td><td rowspan="2">MOD</td><td>AMSC、
d-NANO</td></tr>
<tr><td rowspan="4">IBAD工艺
</td><td rowspan="4">LMO/
epi-MgO/
IBAD-MgO</td><td>SCSC( )</td></tr>
<tr><td>RCE</td><td>SuNAM、THEVA</td></tr>
<tr><td rowspan="2">In-Situ</td><td>PLD</td><td>Fujikura、SST、SuperOX、
Bruker</td></tr>
<tr><td>MOCVD</td><td>SuperPower、SAMRI</td></tr>
</table>

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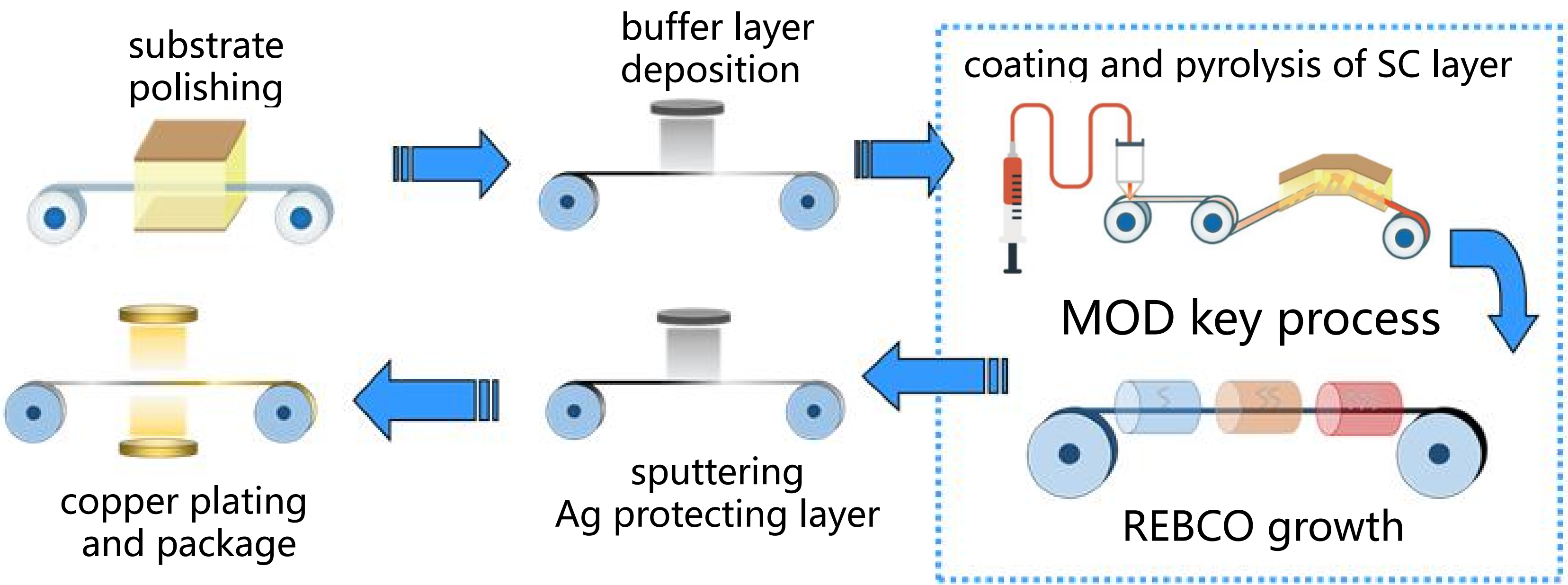
SCSC: industrial production lines



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

- Sliting &Package

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Latest developed MOD production lines with higher yield

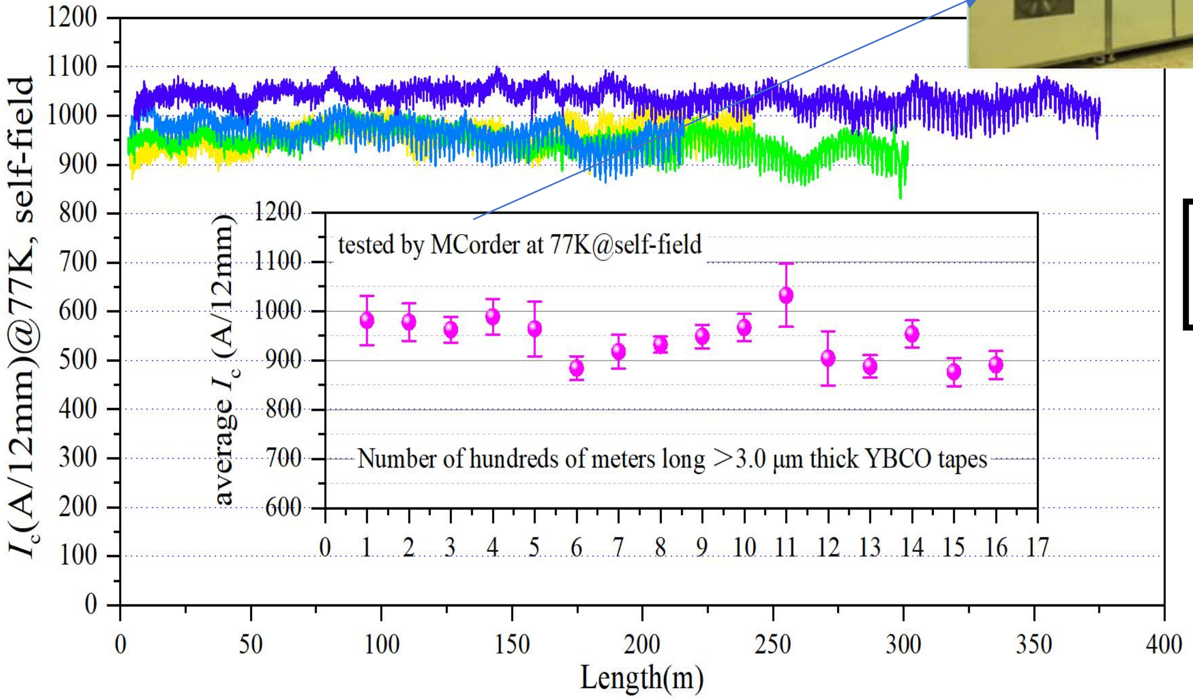
MOD-HTS process(1):
Coating and Low-temperature pyrolysis

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

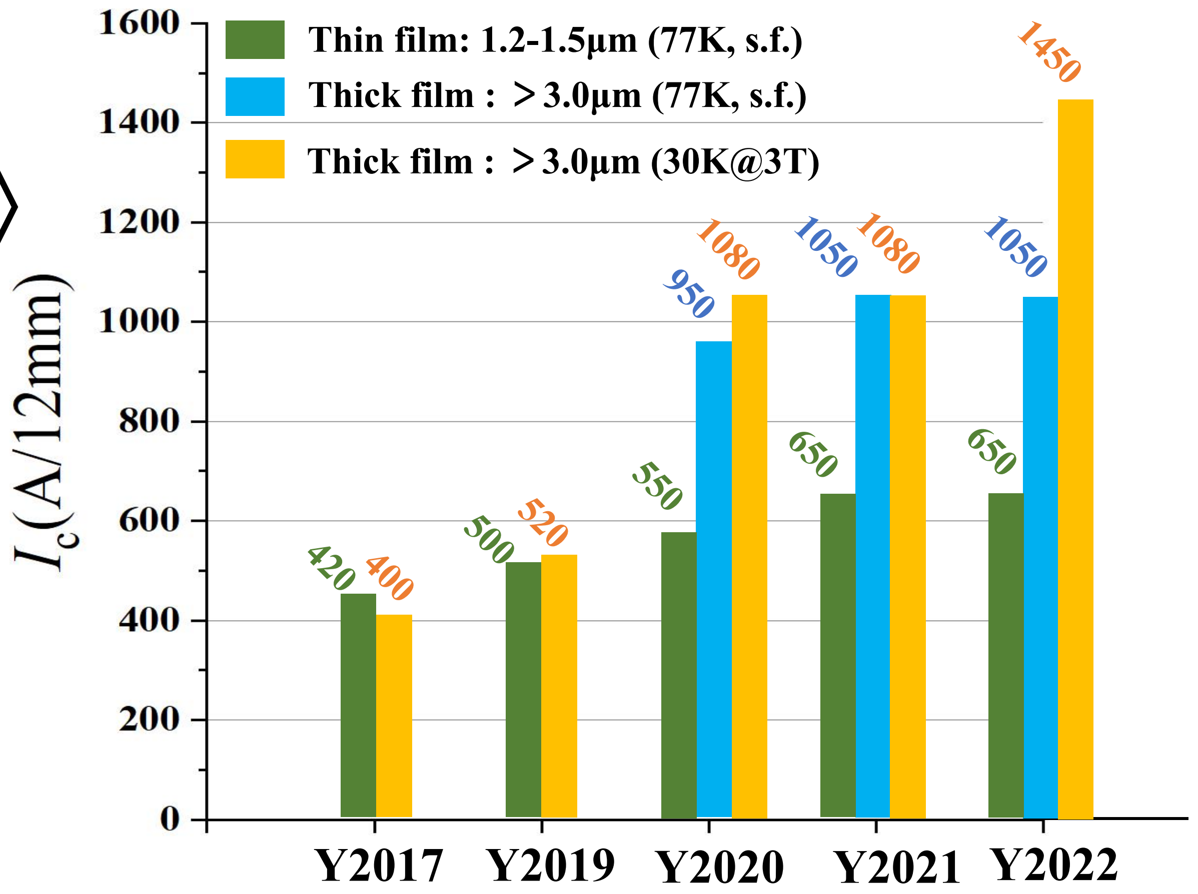
- Wider tapes of **20-40 mm**; **Double lanes** designed;
- Multiple production yields up to **400 km/year** reached.

A hundred-meter thick film long tape

- ✓ Stable preparation of >3μm BHO-YBCO thick film long tape



- ✓ BMO-added REBCO tape，4mm-width:
- 30K@3T： 450-500A
- 4.2K@20T： 280-300A



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

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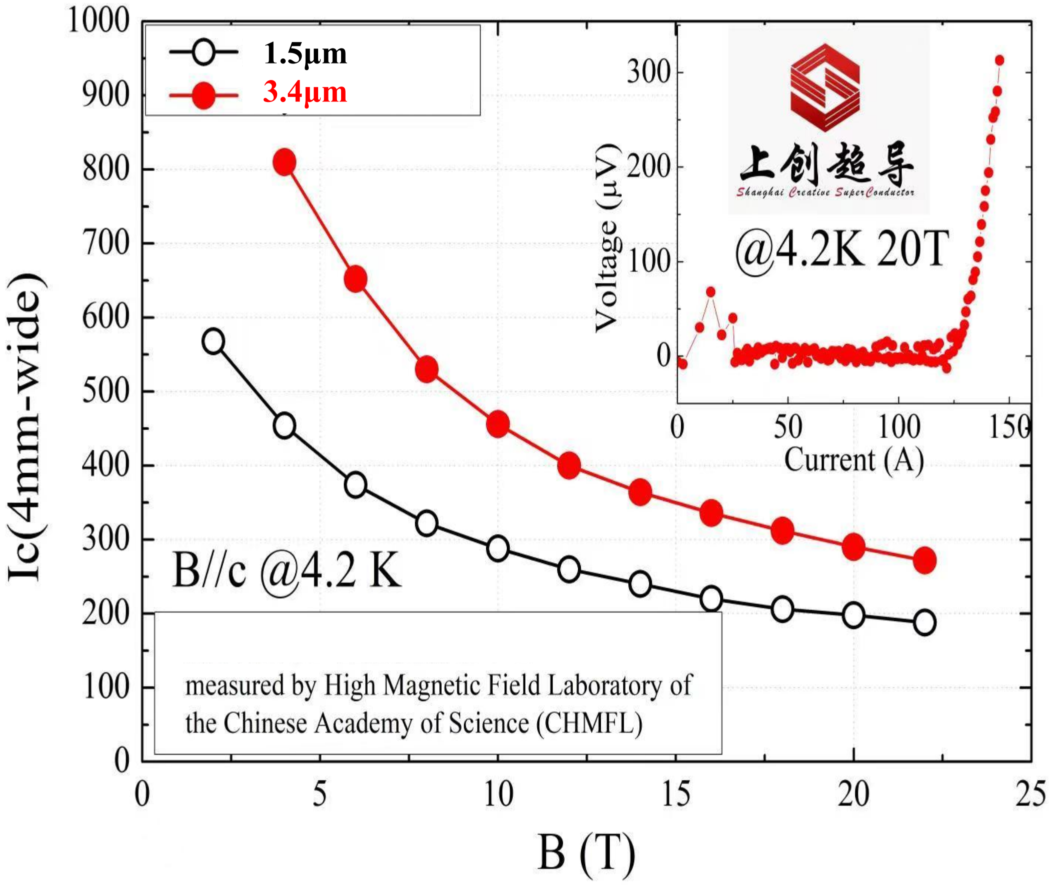
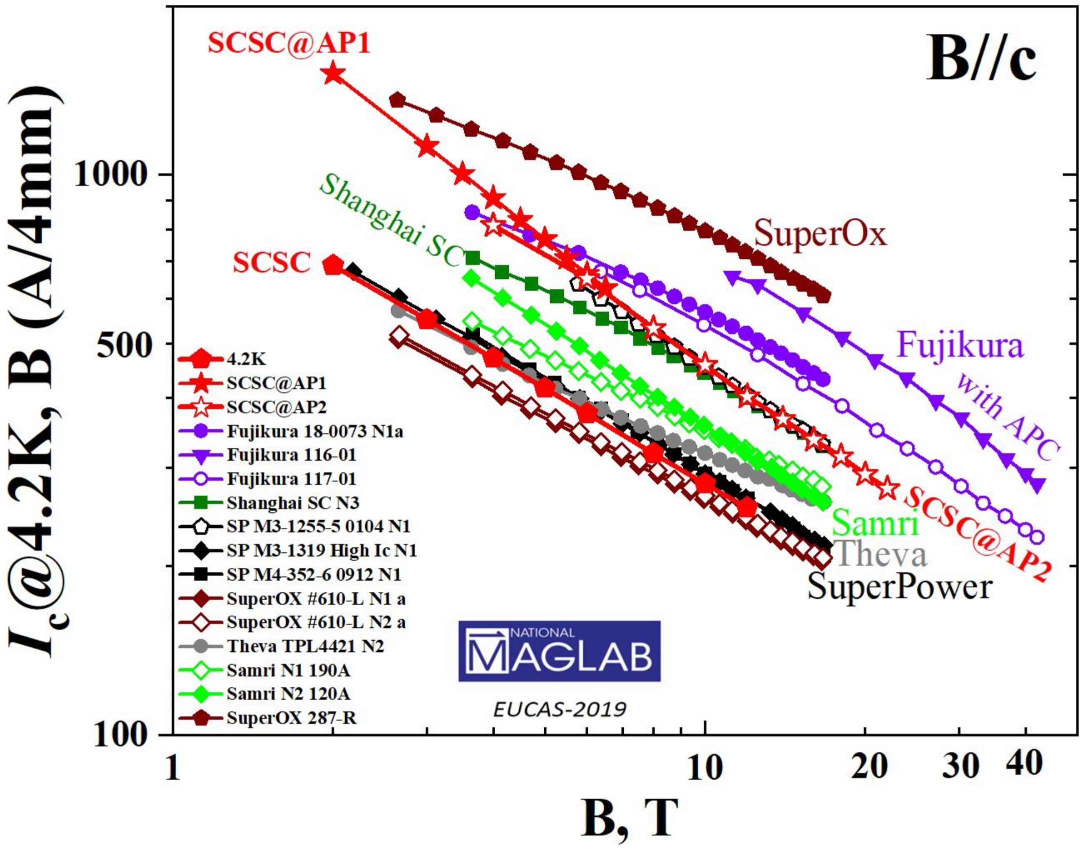
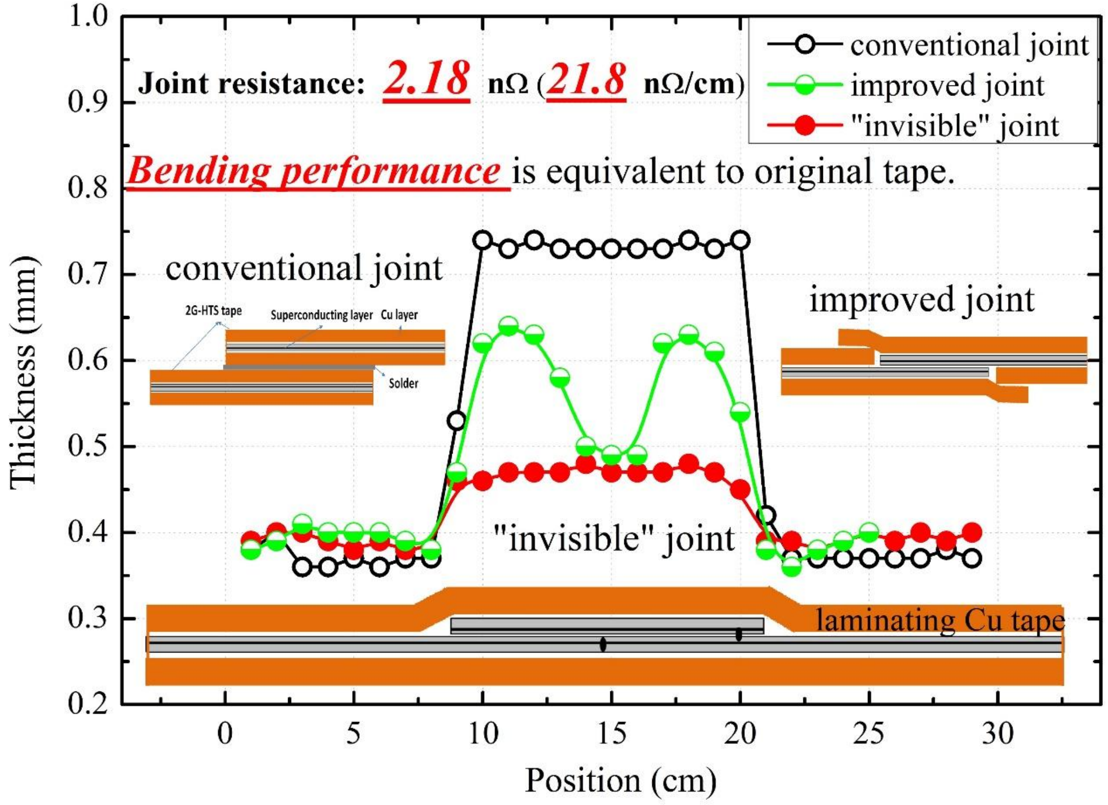
Performance of commercial MOD-YBCO tapes @SCSC

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

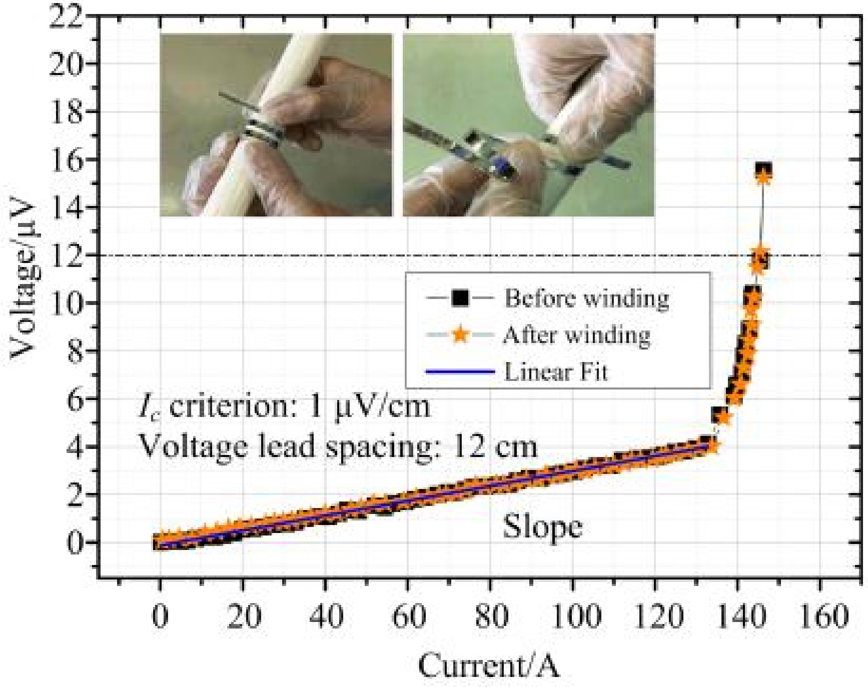




Excellent mechanical performance of tape joint



Diameter: 30 mm



① Thickness of Improved joint and "invisible" joint decrease 15-20% and 35-40%, respectively.

② Improved joint and "invisible" joint : Excellent winging performance.

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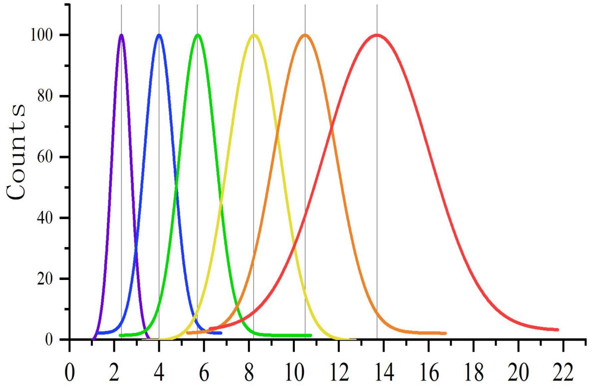
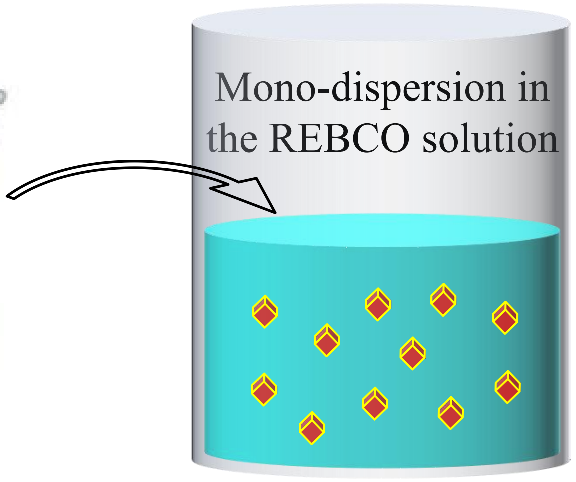
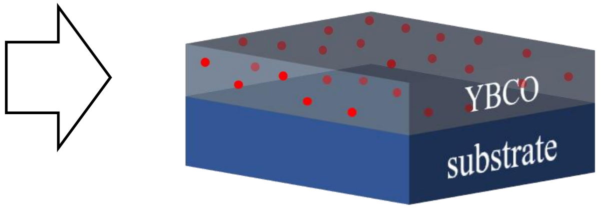
Controllable size of BMO nanocrystals



Control of BMO size (nm)

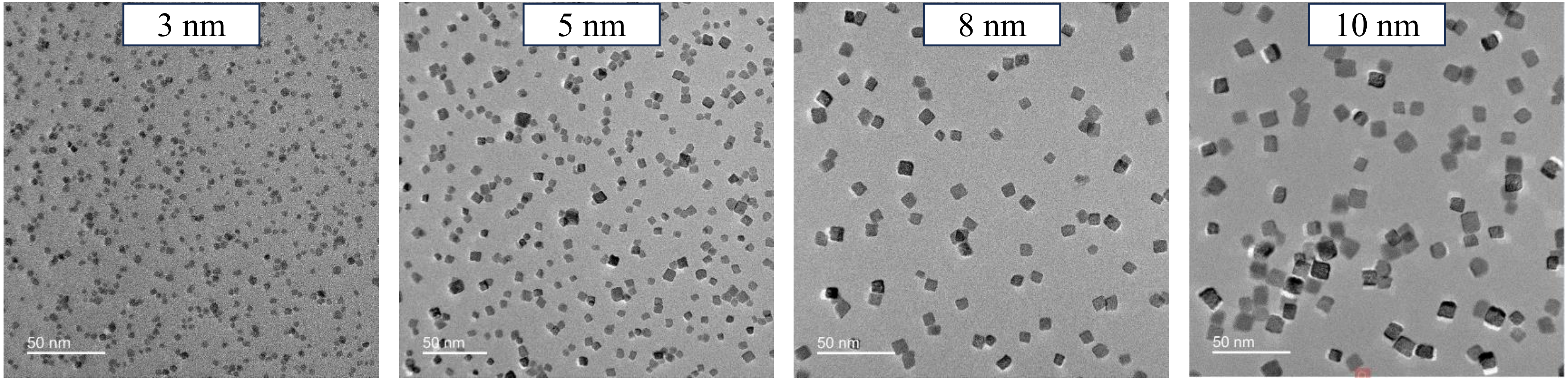
$BaZrO_3$ /$BaHfO_3$ nanocrystal synthesis





Random distribution in the REBCO film

Nanocrystal addition route: highly control of BMO size and distribution



BMO nanocrystals in REBCO film

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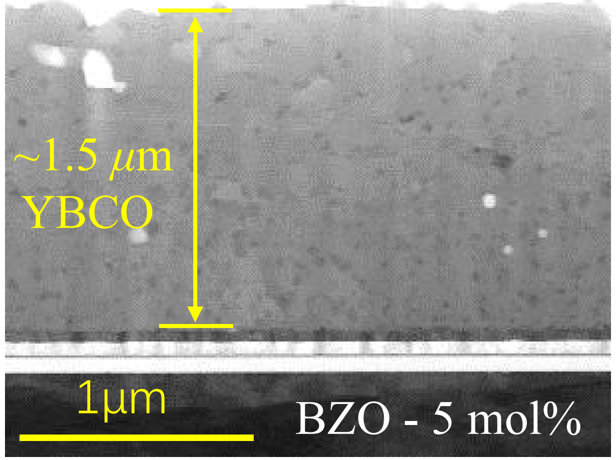
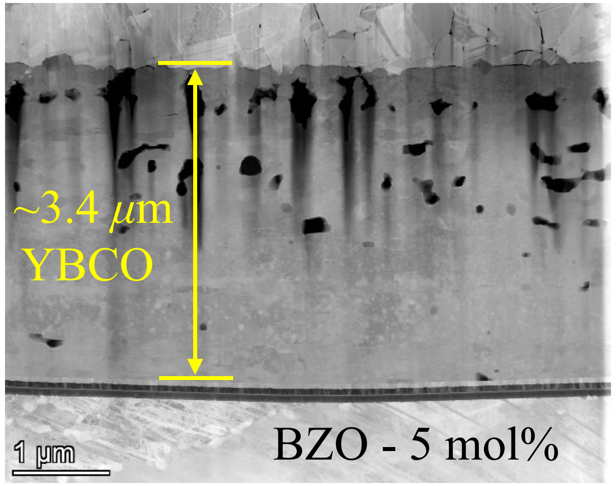
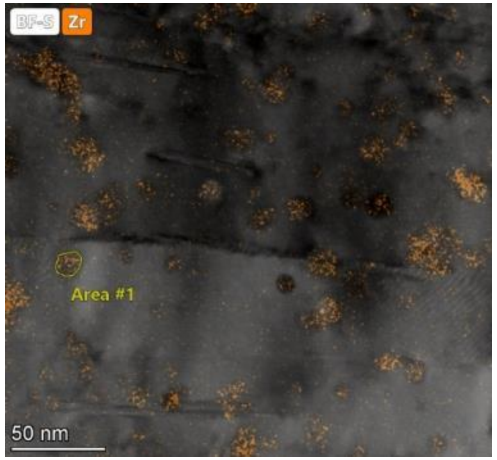
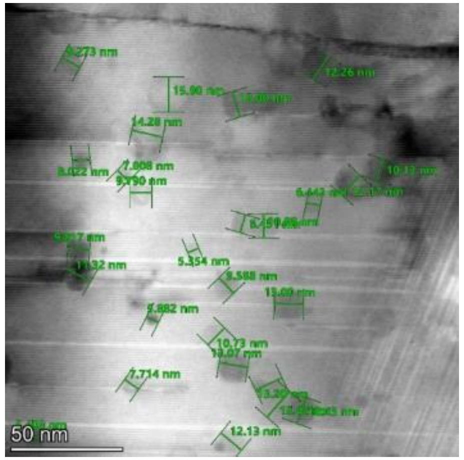
- ✓ Identical benefits of highly control of BMO size and distribution to both the REBCO films with thicknesses of 1.5 μm and 3.4 μm

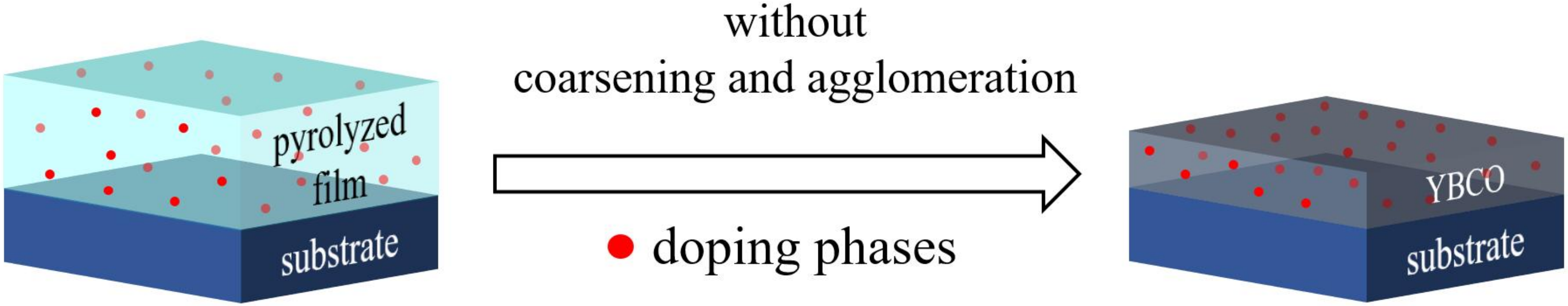






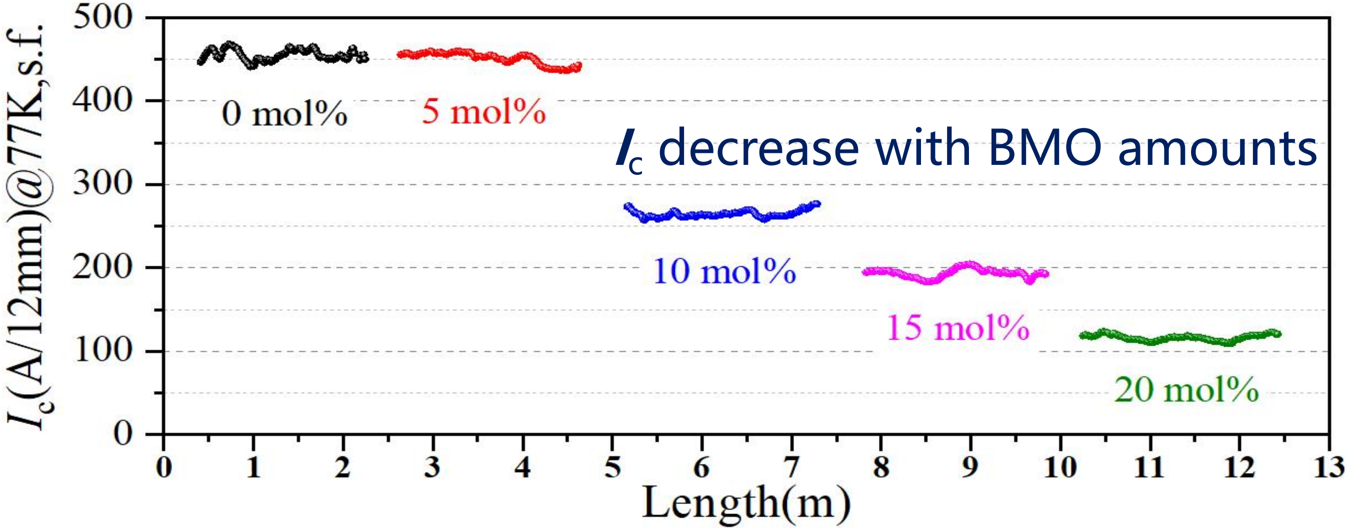


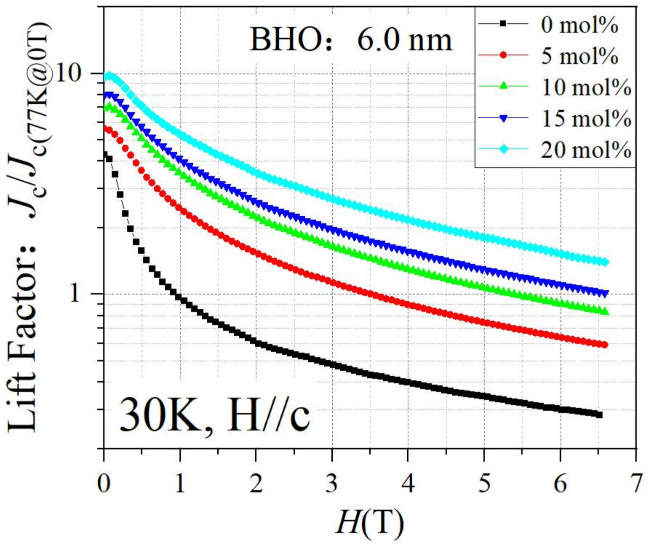
BZO: 8-12 nm

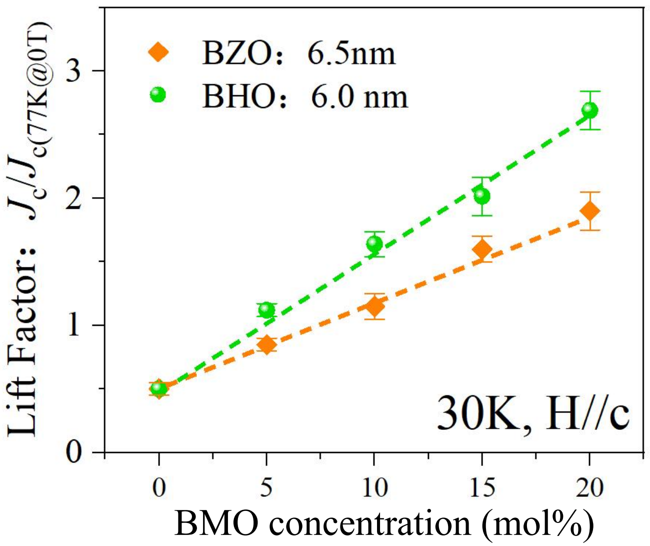


Performance of BMO-REBCO

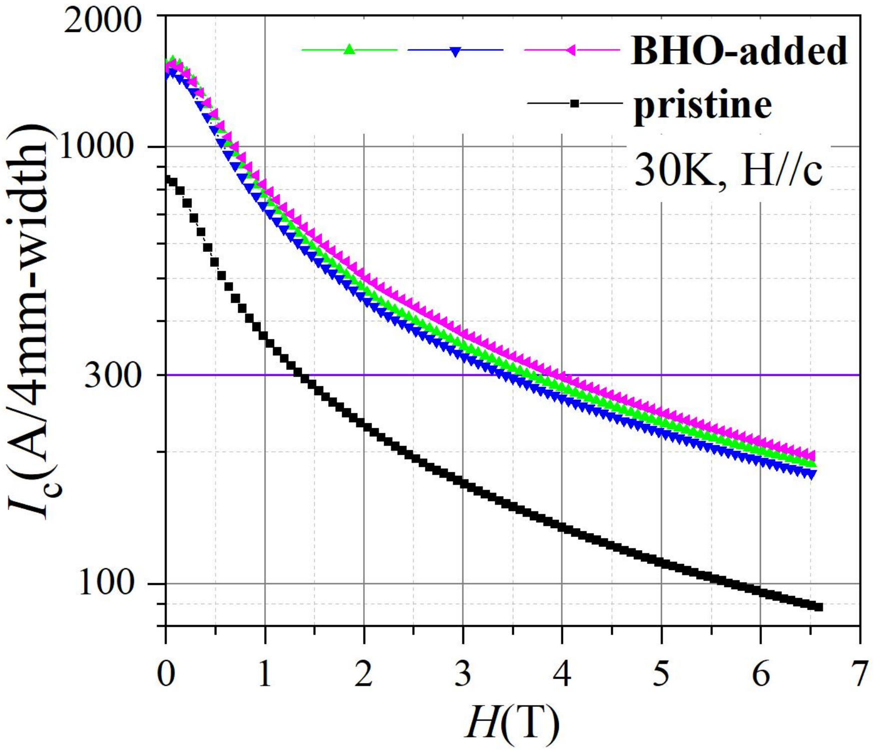
- I_c characteristic after BMO nanocrystal addition







- significant improvement of In-field I_c (higher lift factor of BHO than BZO)



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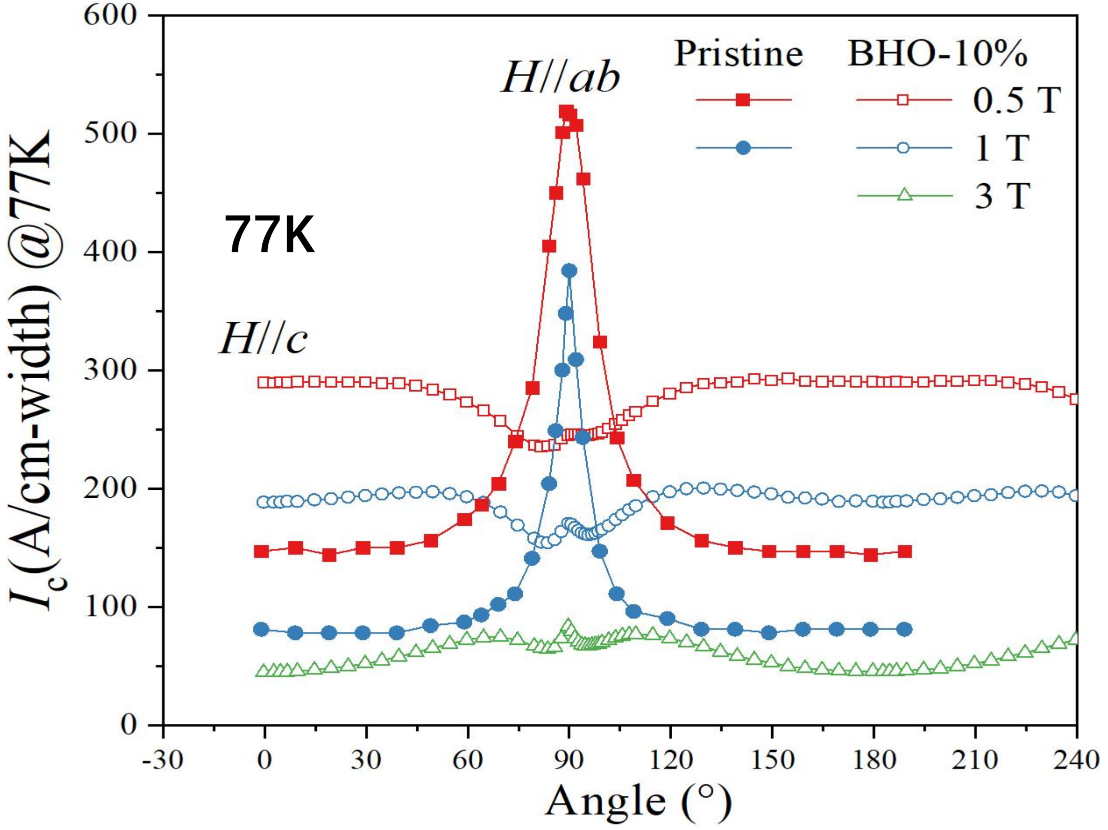
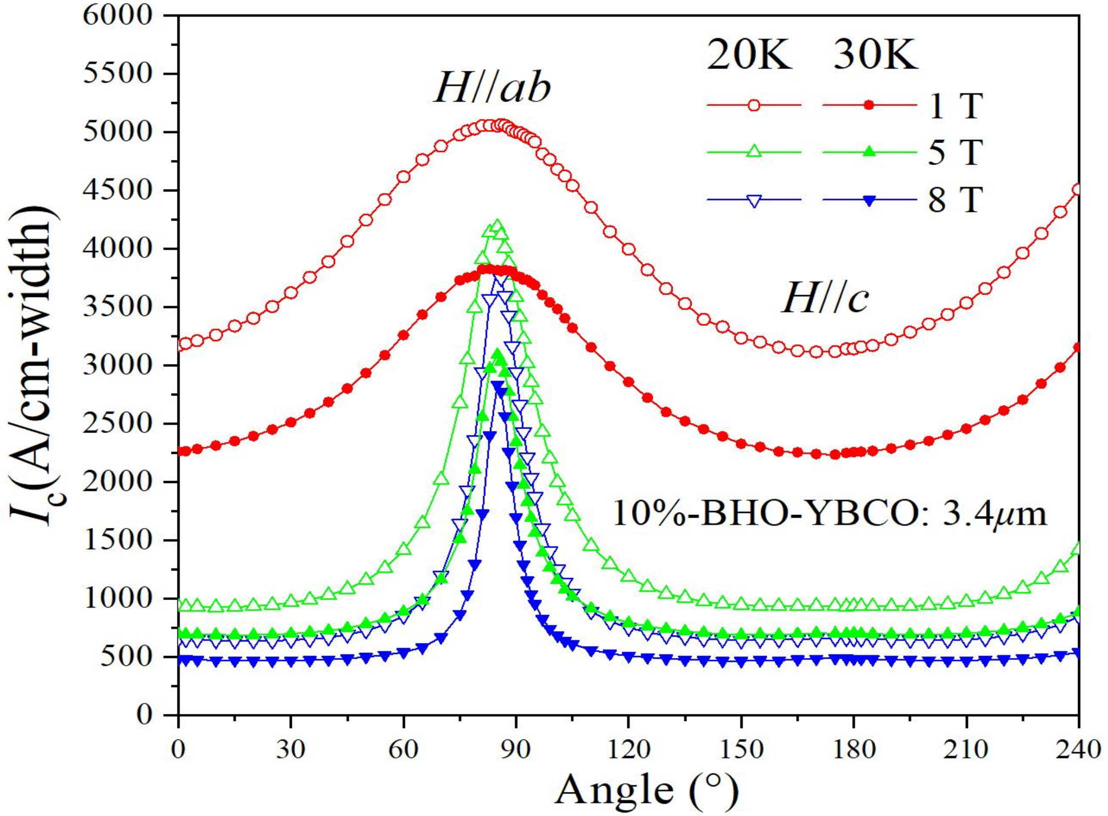
Anisotropic behavior with BMO additions





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

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Anisotropic behavior with BMO additions

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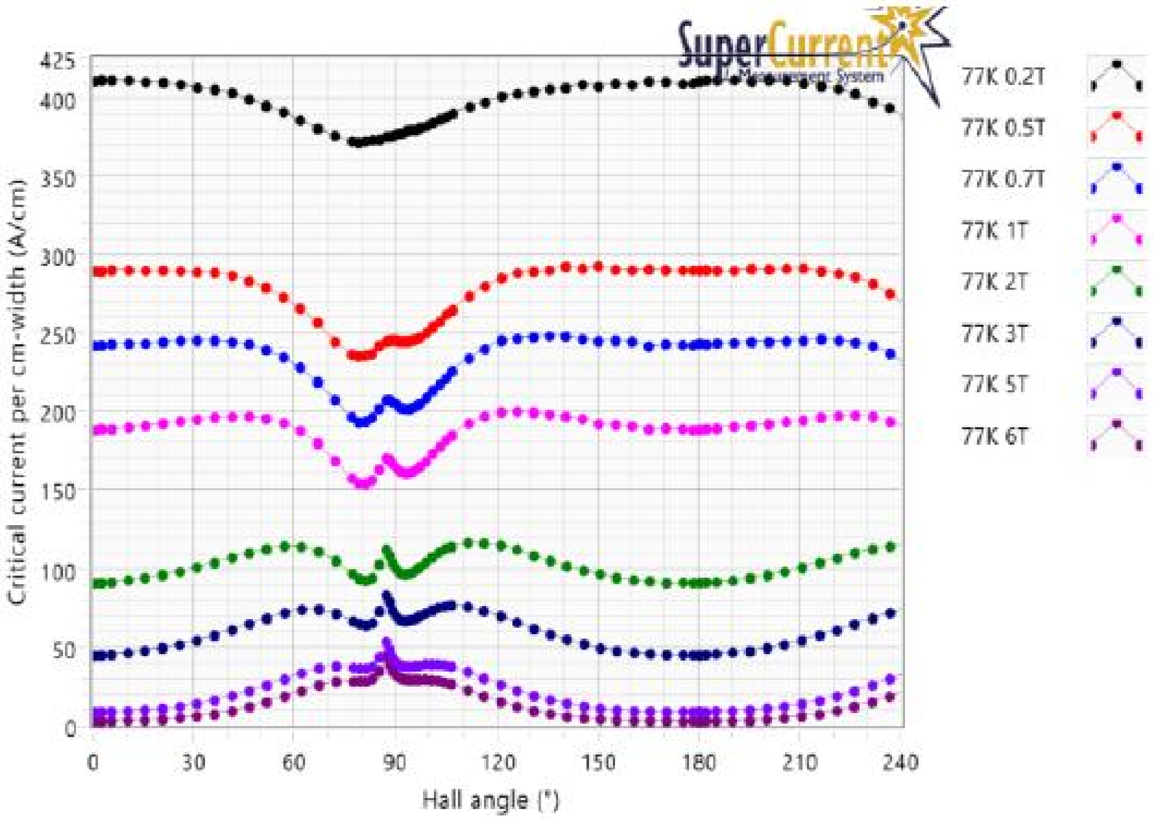
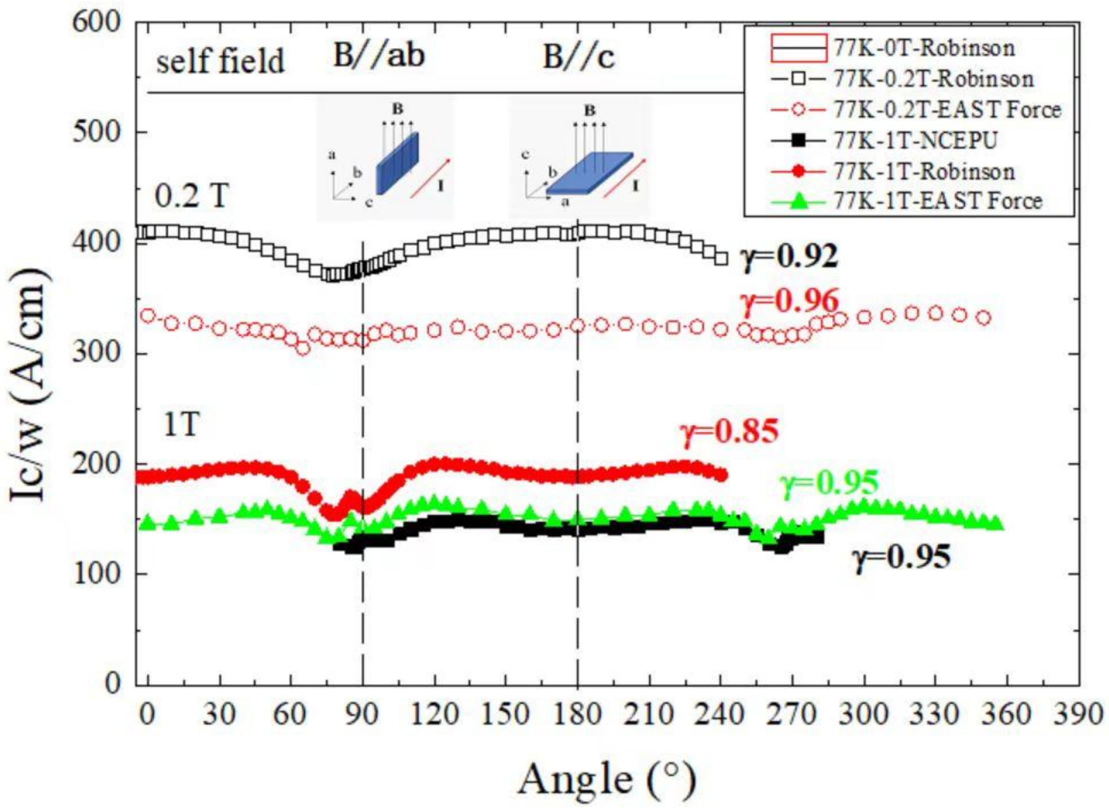
High T &Low T（77K,<2T）： J_c^{ab}/ J_c^{c}<1





* Measured by Robinson Research Institute (open), North China Electric Power University (NCEPU) (half open) and EAST FORCE superconducting (closed).

Thermal fluctuation VS. flux vortex

Thermal fluctuation intensity— temperature range in which fluctuations become stronger under 0T

Ginzburg number Gi:

$$Gi = \frac{1}{2}\left(\frac{\gamma k_B T_c}{H_{c0}^2 \xi_0^3}\right)^2 = \frac{1}{2}\left(\frac{8\pi^2 \gamma \lambda_0^2 k_B T_c}{\Phi_0^2 \xi_0}\right)^2$$

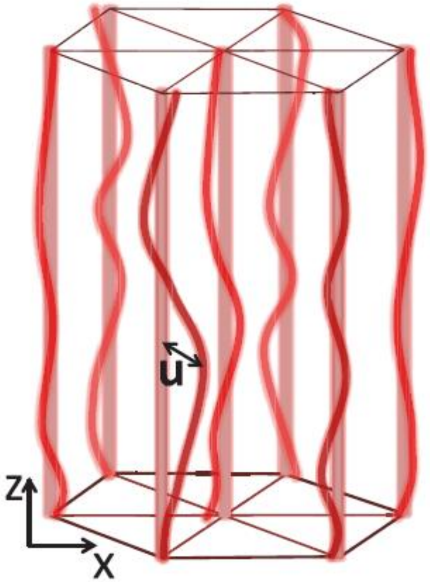
$$Gi = 0.0325(\gamma\kappa\ \lambda_0(\mathrm{cm})\ T_c(\mathrm{K}))^2$$

$Gi \sim 10^{-2}$ cuprates
$Gi < 10^{-7}$ low-T_c
Gi $10^{-4} \sim 10^{-3}$ iron-based

The flux vortex displacement (deformation)— the effect of fluctuations on the vortex line

Thermal fluctuation in HTS:

- **High T_c**
- **Small ξ**
- **High anisotropy**
- **Low supercurrent density**



$$u(z) = u_0 \cos(k_z z) \text{ with } \lambda^{-1} \ll k_z \ll \xi^{-1},$$

Wai-Kwong Kwok et al., Rep. Prog. Phys. 79,116501(2016)

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Isotropic behavior J_c with BHO additions

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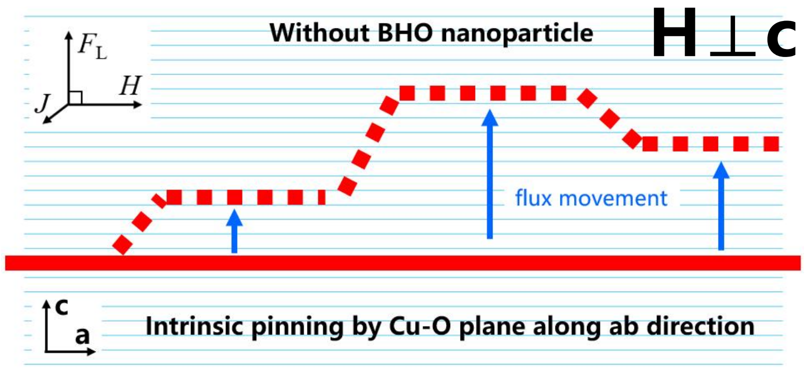
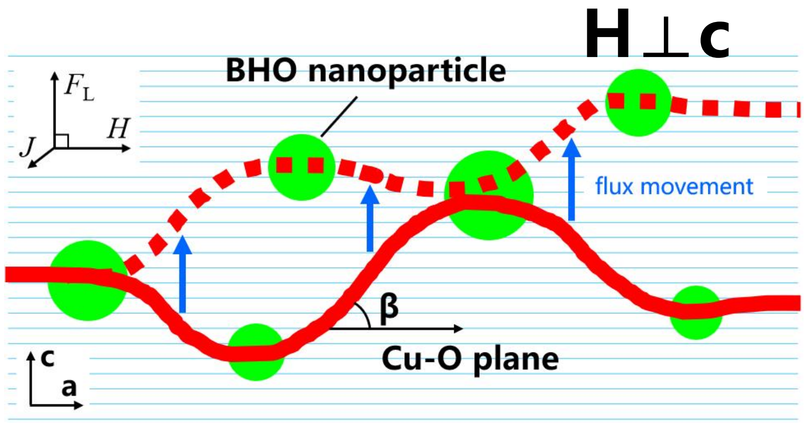
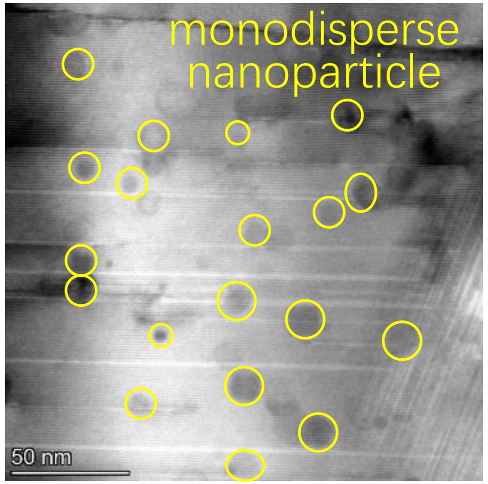
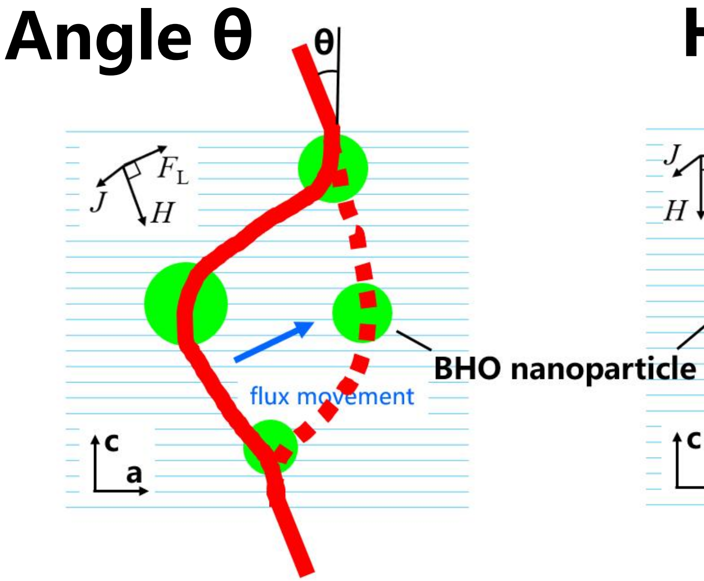
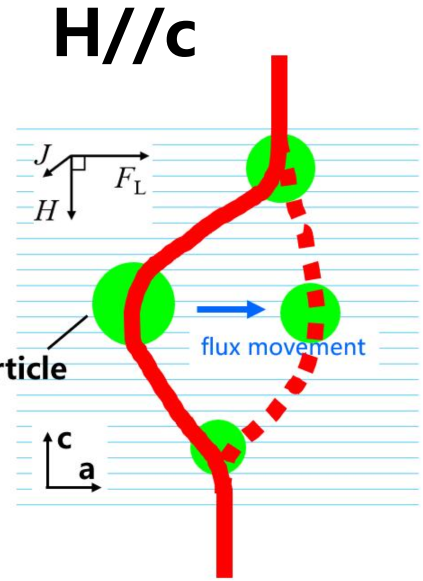










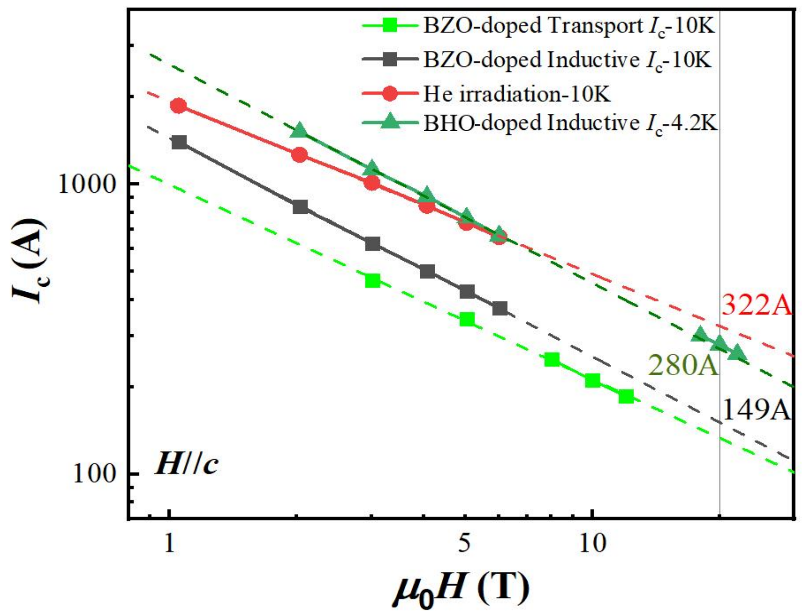
Tachiki-Takahashi model：

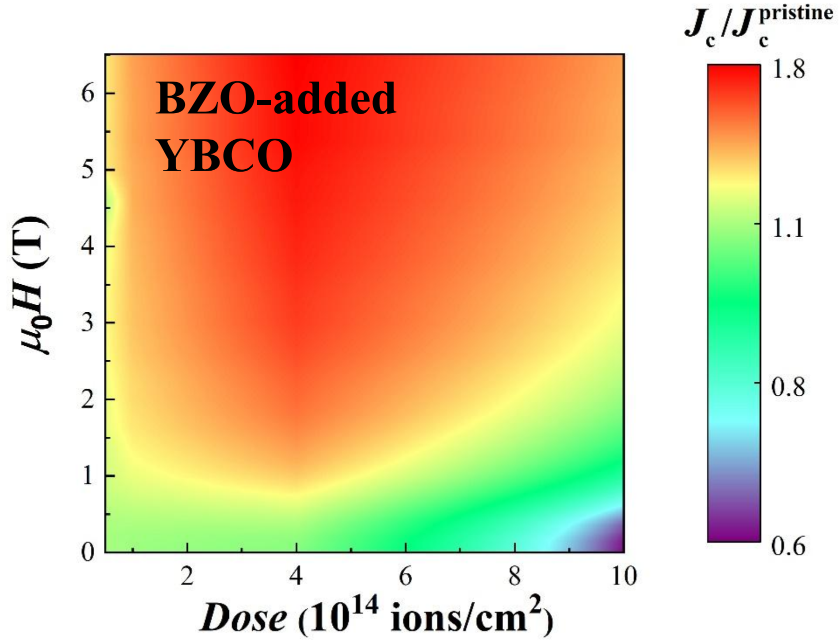
$$\boxed{J_c(\theta) = J_c(0)|\cos\theta|^{-0.5+\alpha}}$$

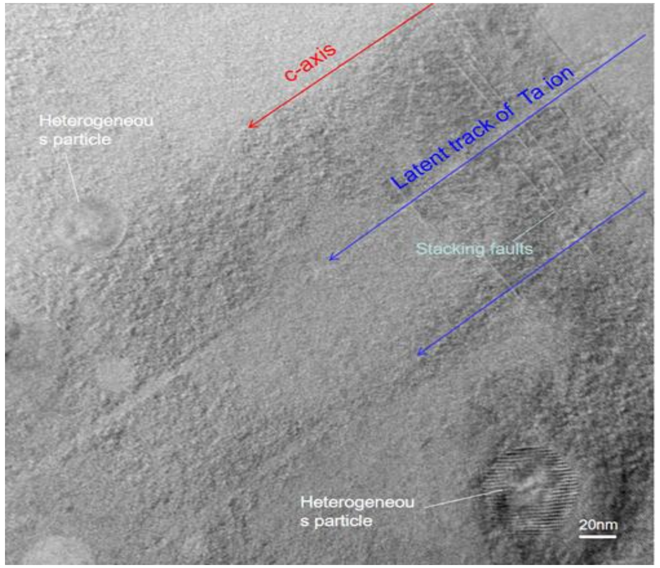
G. Blatter et al., Rev. Mod. Phys. 66, 1125(1994)

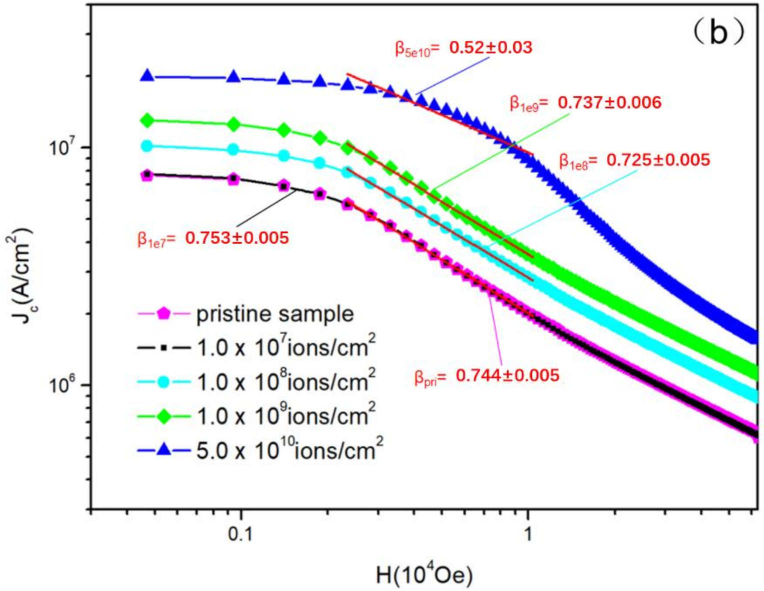
- ☐ **Intrinsic pinning only by Cu-O plane (along ab direction) without BHO particle**
- ☐ **Due to the strong pinning effect by randomly distributed BHO nanoparticle, most unfixed flux exhibit an angle to ab plane, resulting in lower J_c when θ near 0°**

APCs introduced by ion radiation









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- Yu Gu, Chuanbing Cai et al, J. Appl. Phys. 130, 085304 (2021).

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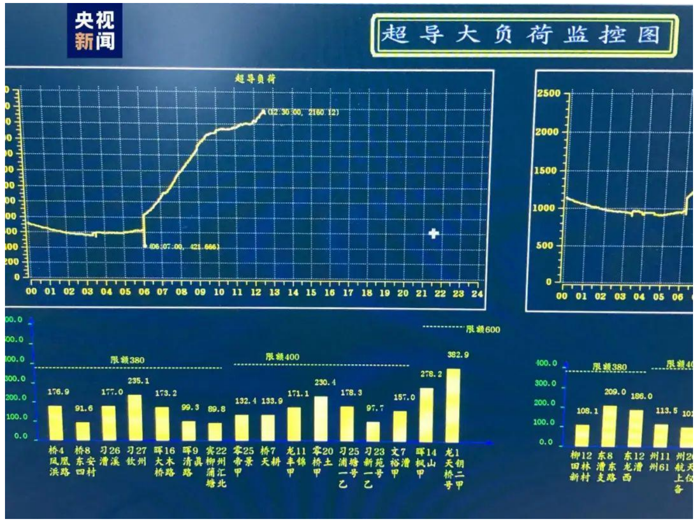
IEEE-CSC, ESAS and CSSJ SUPERCONDUCTIVITY NEWS FORUM (global edition), Issue No. 55, January, 2024. Invited presentation given at ACASC 2023, 30 Oct. 2023, Shanghai, China

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 M**aterials**: **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.



2G-HTS cable

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Conclusions

EUCAS2023 Bologna, Italy 3rd-7th September

上创超导 Shanghai Creative SuperConductor

- **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 pining 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.

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Thanks a lot for your attentions!

Welcome to visit and cooperate with SHU and SCSC

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