



# The progresses of the REBCO magnets with pancake coils for high field applications exceeding 20T

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# Content

- **Introduction of high-field ReBCO magnet**
  
- **Development Progress Overview**
  - **High-field ReBCO insert coil**
  - **All ReBCO HTS magnet**
  
- **Summary**



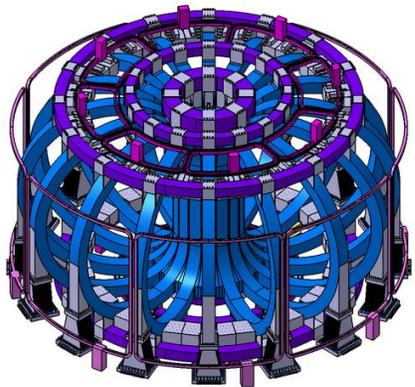
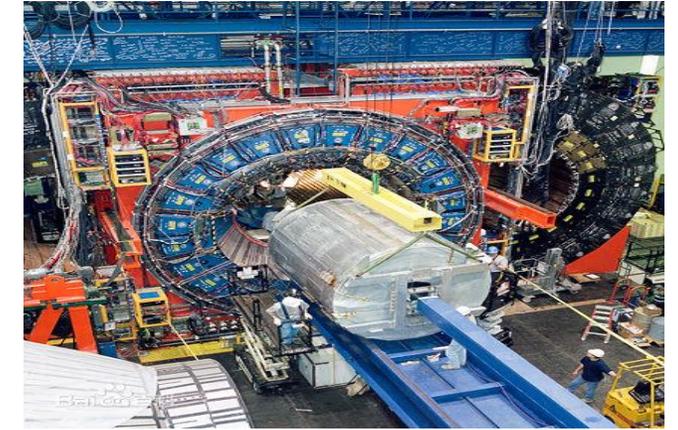
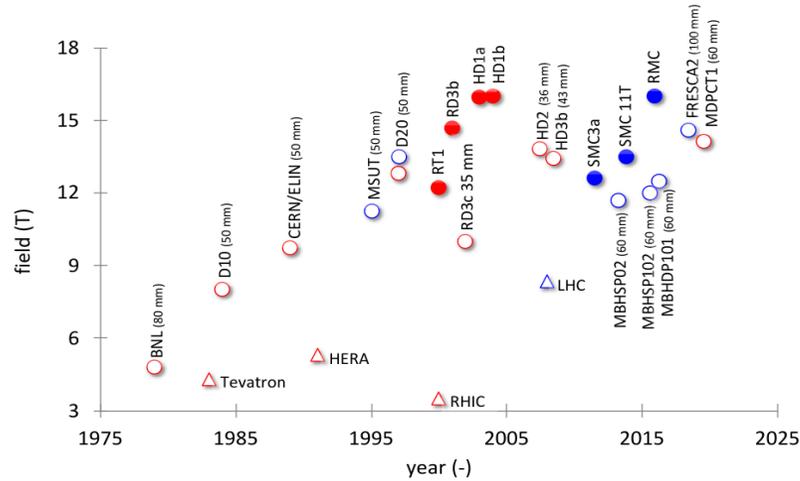
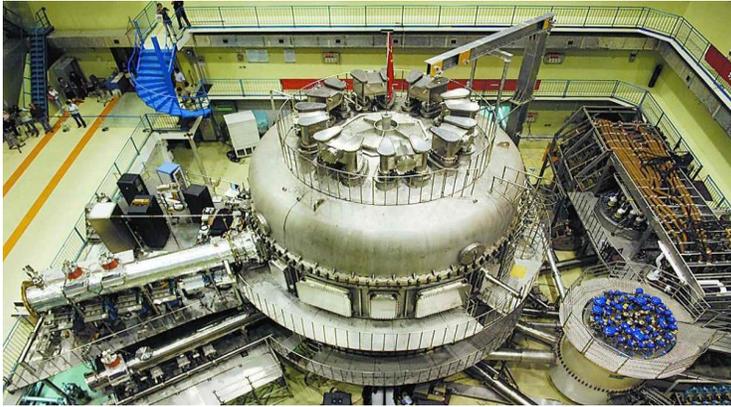
# Content

- **Introduction of high-field ReBCO magnet**
  
- Development Progress Overview
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- Summary



## The Need For High Fields

- High field application, fusion reactor, high energy particle accelerator, nuclear magnetic resonance(NMR)...

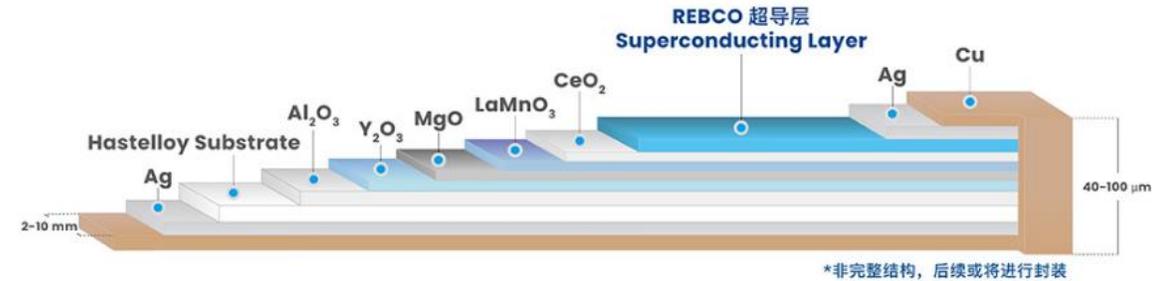


High magnetic field  
 ↓  
 Higher performance  
 Higher temperature operation  
 ↓  
 New cooling option  
 Higher current density  
 ↓  
 Compact design!!!!

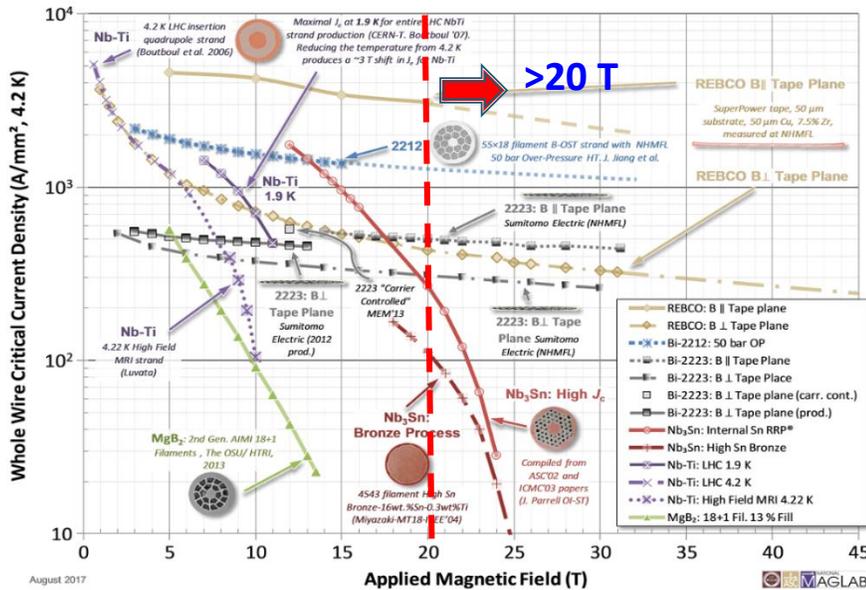


## Advantages of REBCO tapes

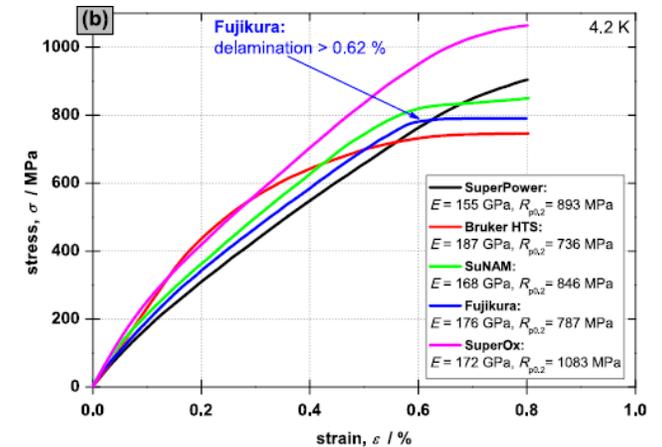
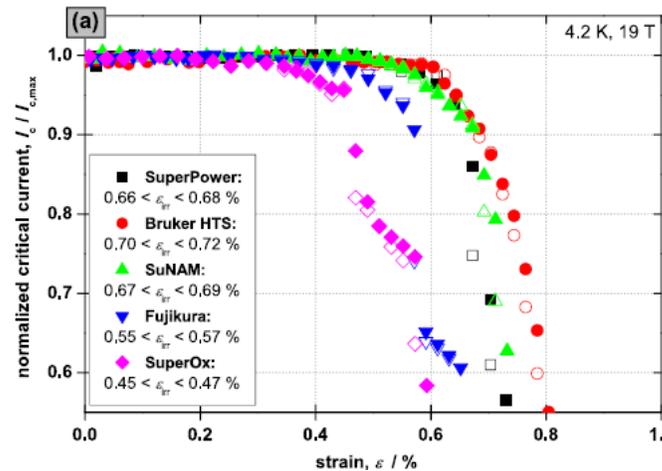
- ✓ High transport current under high magnetic field
- ✓ High mechanical strength due to Hastelloy
- ✓ Commercial production capacity



SSTC 2G HTS tape



Adapted from P. Lee



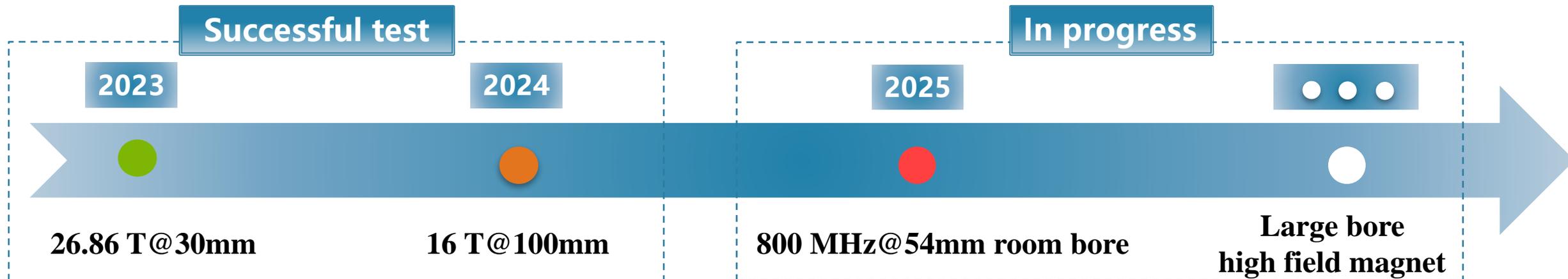


## □ Research plan and objectives

### ● Ultra high field high temperature superconducting insert coil: HTS insert (NI/MI)+LTS backfield

- |         |  |         |
|---------|--|---------|
| Step 1: | 20T all SC magnet (6T REBCO insert+14T@70mm LTS)   | ✓       |
|         | ↓  |         |
| Step 2: | 25T all SC magnet (11T REBCO insert+14T@70mm LTS)  | ✓       |
|         | ↓  |         |
| Step 3: | 35T all SC magnet (20T REBCO insert+15T@150mm LTS) | Ongoing |

### ● Large diameter all-REBCO HTS magnet





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  - All ReBCO HTS magnet
  
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## 20 T all superconducting magnet

### Overall goal:

- Achieve a central magnetic field of at least 6 T within a 14 T LTS background magnet (6 T REBCO insert coil)
- Master the R & D process of high field REBCO insert coil

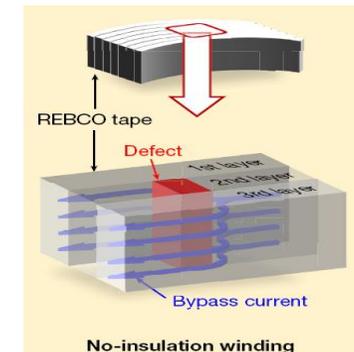
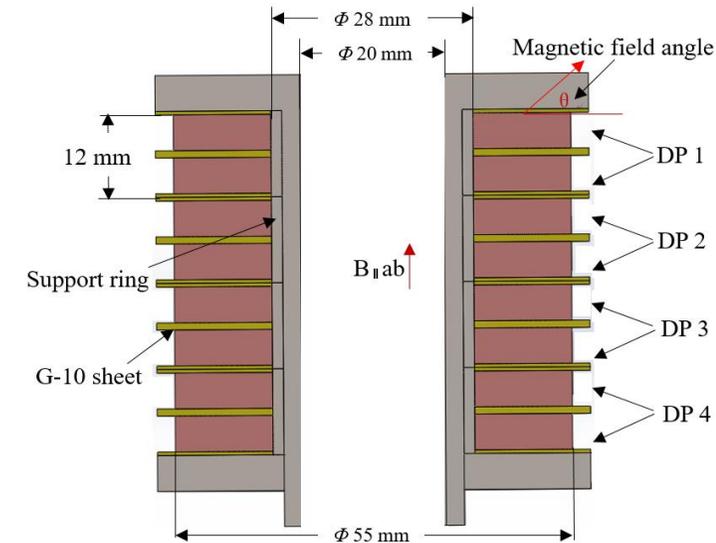
### Key parameters of 6 T REBCO insert coil

Parameters	Value
Free bore	20 mm
Winding inner diameter	28 mm
Winding outer diameter	55 mm
Coil height	48 mm
Number of double pancakes	4
Total number of turns	600
Total tape length	80 m
Operating temperature	4.2 K
Operating current	410 A
Inductance	7.75 mH

### Parameters of the domestic REBCO tapes

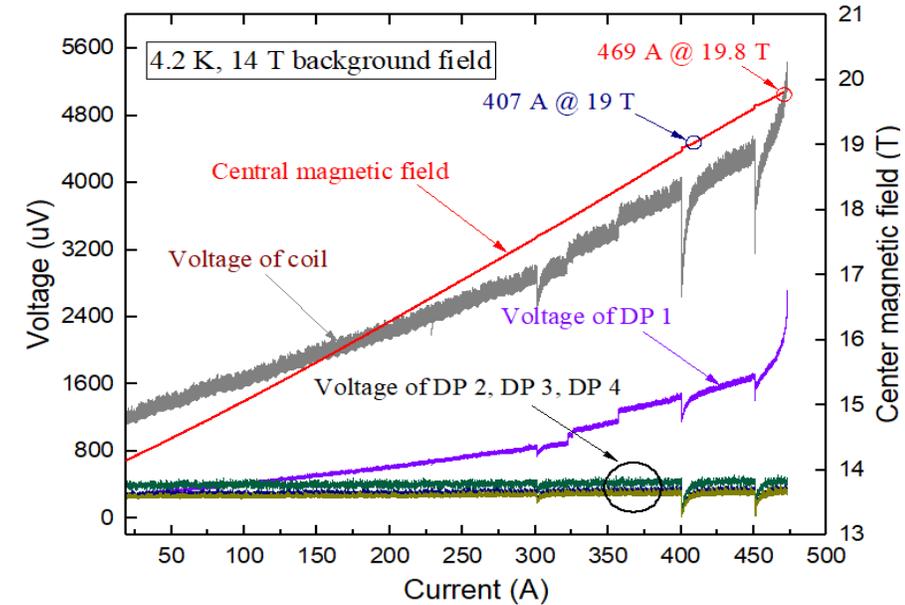
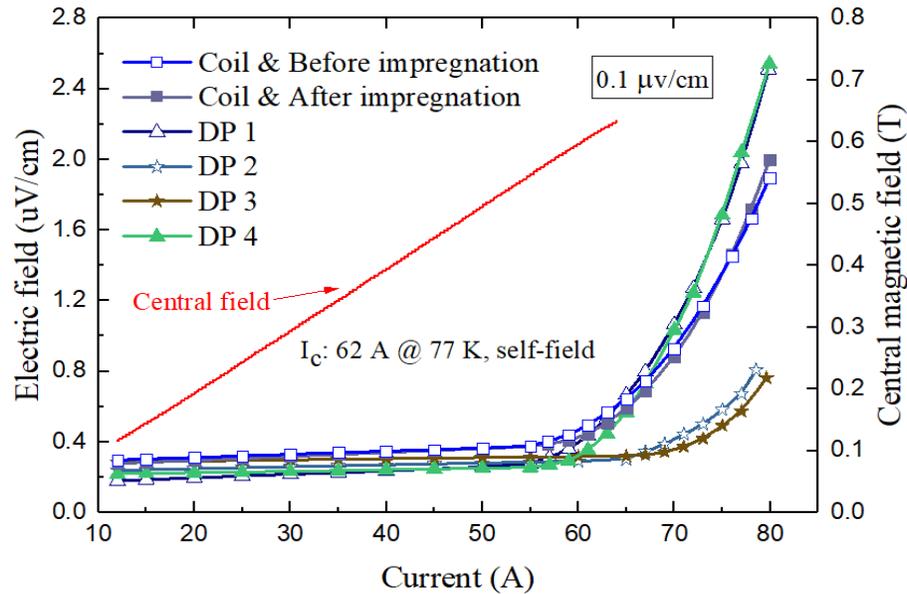
Parameters	Unit	Value
Manufacturer		Samri
Width	mm	5
Thickness	$\mu\text{m}$	180
Substrate / thickness	$\mu\text{m}$	Hastelloy/50
Stabilizer / thickness	$\mu\text{m}$	Copper/50
$I_c$ (77K, self-field)	A	190

- No-insulation winding
- Epoxy resin impregnation
- Max hoop stress/strain: 218 MPa/0.22%



## 20 T all superconducting magnet

Test results:

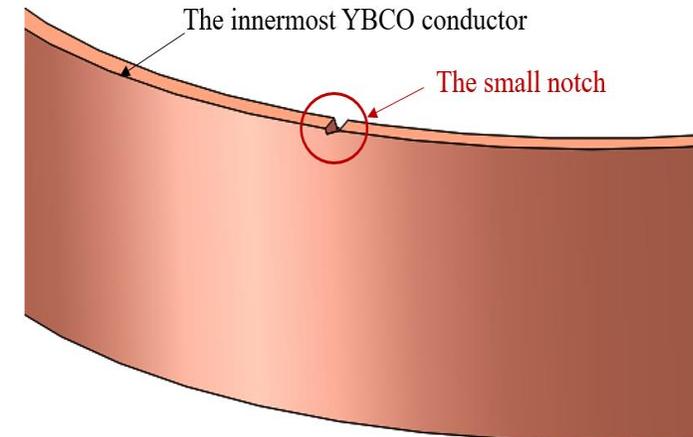
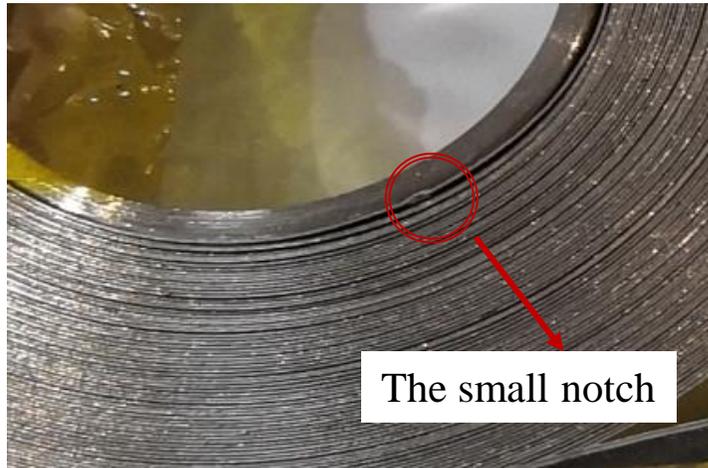


- $I_c = 62 \text{ A @ } 0.1 \mu\text{V}/\text{cm}$
- The double-pancake at the end first experience superconducting transition
- No degradation of critical current after impregnation

- $B_{\text{max}} = 19.8 \text{ T @ } 469 \text{ A}$
- Poor performance of DP 1 leads to premature quenching of the insert coil

## 20 T all superconducting magnet

Analysis of quenching reason:



- **A small notch** appeared in the innermost REBCO tape of DP1 due to improper winding procedures, and the superconducting layer may have been damaged
- The transport current behavior of DP 1 was normal in the test at 77 K
- **The large electromagnetic force** caused the notch or cracks to **grow or even break**

## 25 T all superconducting magnet

### Overall goal:

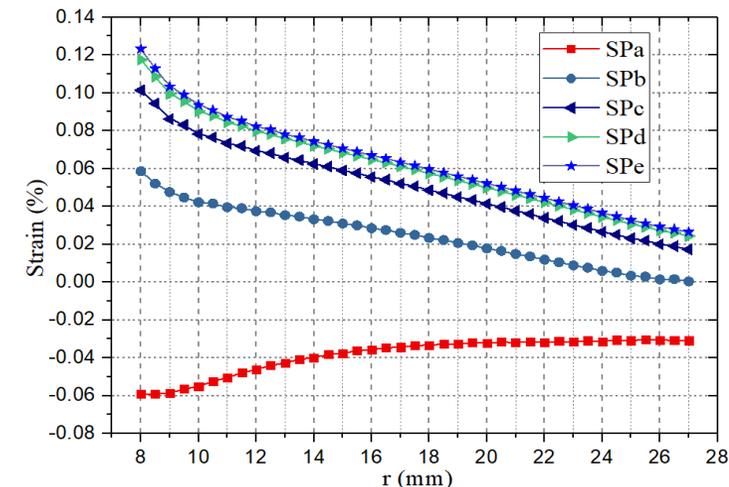
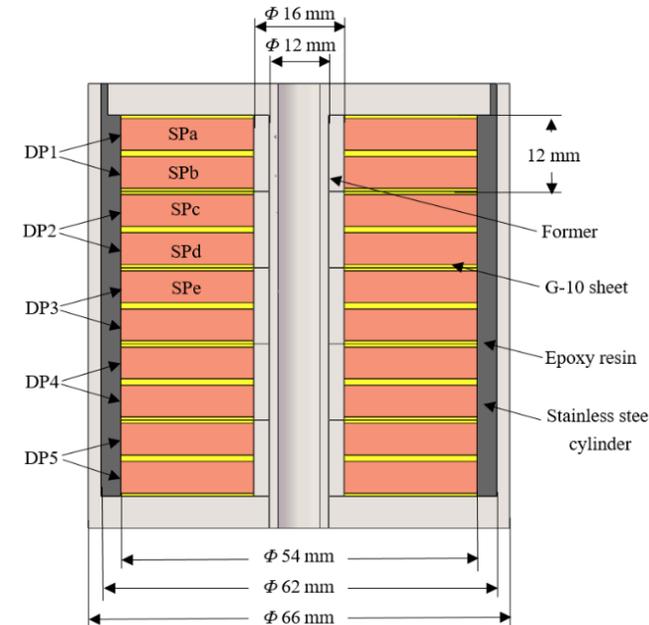
- $B_{max}=25\text{ T}$  @  $14\text{ T}$  &  $70\text{ mm}$  LTS background magnet  
(**11 T REBCO insert coil**)
- First demonstration of domestic REBCO tapes on high field coil above  $20\text{ T}$

### Key parameters of 11 T REBCO insert coil

Parameters <sup>↙</sup>	Value <sup>↙</sup>
Coil height <sup>↙</sup>	60 mm <sup>↙</sup>
Winding inner diameter <sup>↙</sup>	16 mm <sup>↙</sup>
Winding outer diameter <sup>↙</sup>	54 mm <sup>↙</sup>
Number of single pancakes <sup>↙</sup>	10 <sup>↙</sup>
Total number of turns <sup>↙</sup>	1900 <sup>↙</sup>
Total tape length <sup>↙</sup>	220 m <sup>↙</sup>
Operating current <sup>↙</sup>	323A <sup>↙</sup>
Max hoop stress <sup>↙</sup>	398 MPa <sup>↙</sup>
Max Br <sup>↙</sup>	3.52T <sup>↙</sup>
Inductance <sup>↙</sup>	38.8 mH <sup>↙</sup>

### Parameters of the domestic REBCO tapes

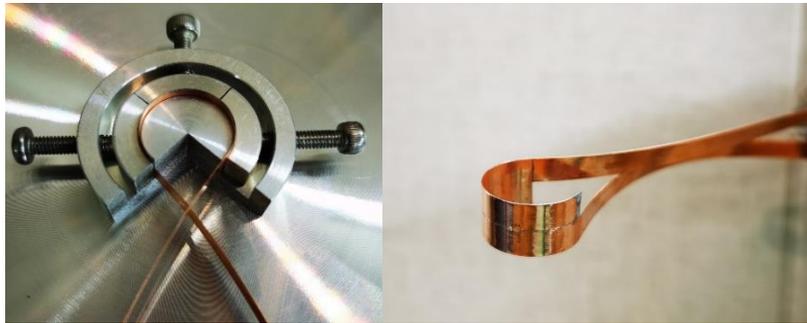
Parameters	Unit	Value
Width	mm	5
Thickness	$\mu\text{m}$	100
Substrate / thickness	$\mu\text{m}$	Hastelloy/50
Stabilizer / thickness	$\mu\text{m}$	Copper/45
Matrix/ thickness	$\mu\text{m}$	Silver/1.5
Min. winding diameter	mm	15
Critical stress@77K	MPa	>530
Critical strain@77K	%	0.32%
$I_c$ @77K, self-field	A	250



- 0.1mm thick REBCO tapes provided by SSTC
- No-insulation winding
- Epoxy resin impregnation

## 25 T all superconducting magnet

Manufacture of 11 T REBCO insert coil:

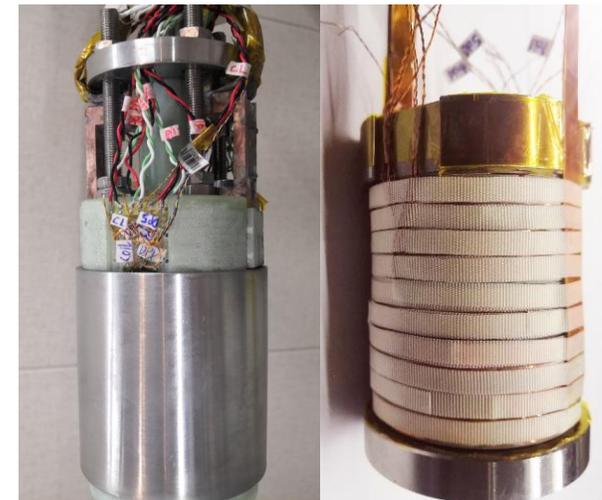


Inner joint in the insert coil

- Single pancake coil was applied due to excessive in-plane bending strain
- Adjacent single pancakes are electrically connected by inner joint
- The area of the soldering area: 320 mm<sup>2</sup>  
Average joint resistance value: 50 nΩ @77 K



Winding of single pancake coil

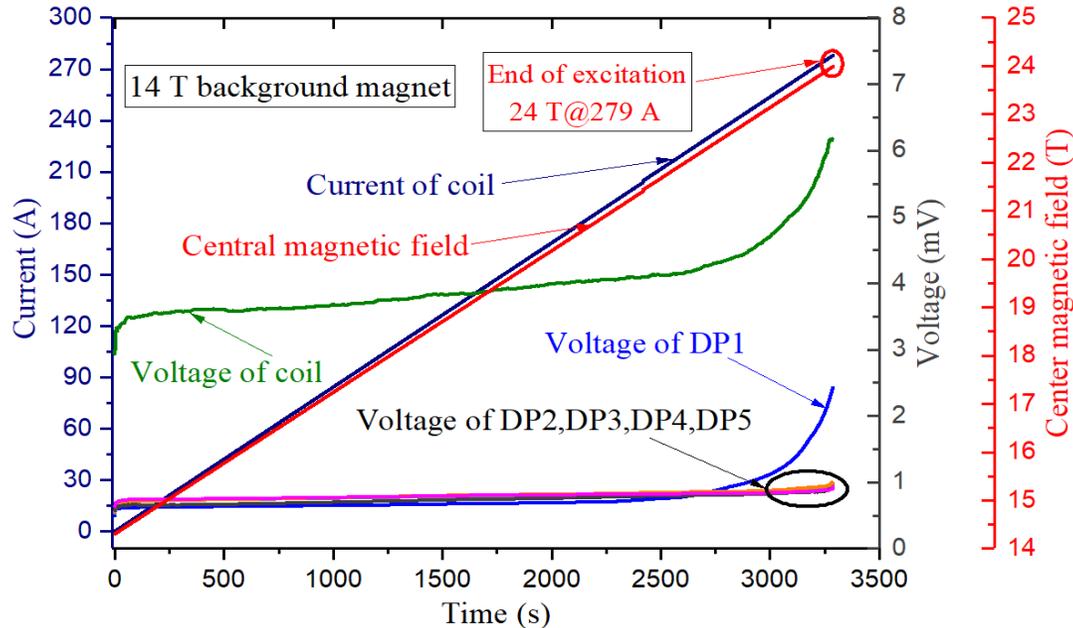


Assembly of insert coil

## 25 T all superconducting magnet

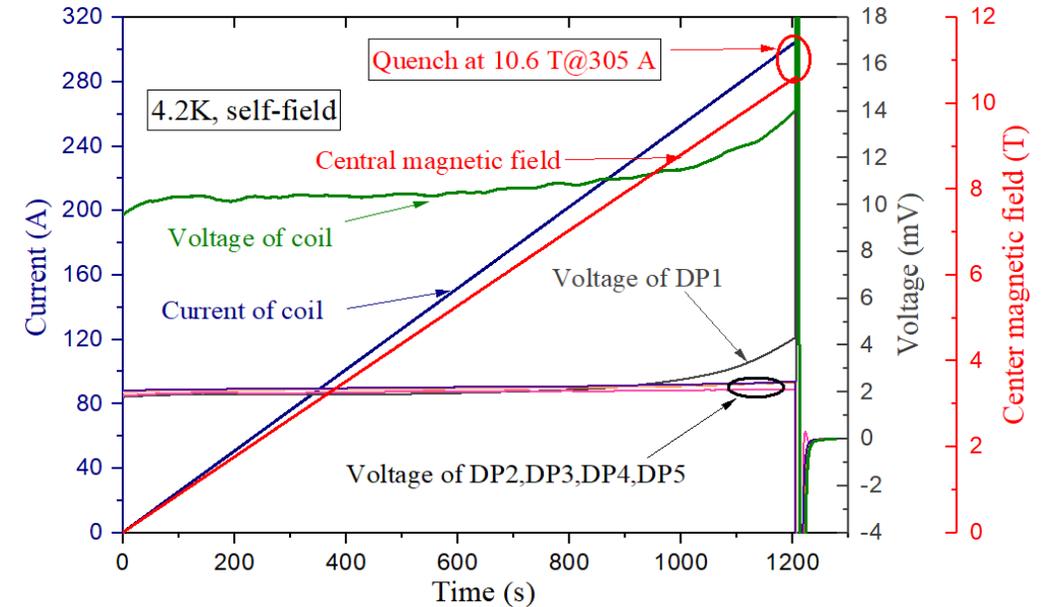
### Test results:

#### ➤ 4.2 K, 14 T background field



- Current ramping rate: 5 A/min
- 232 A DP 1 at the end first experience superconducting transition

#### ➤ 4.2 K, self-field



- Current ramping rate: 15 A/min
- Voltage behaviors of the five DPs are similar to that in 14 T background field

The combined effect of the vertical field at the end and the temperature rise caused by the accumulation of helium bubbles leads to the premature transition of DP 1

# 35 T all superconducting magnet

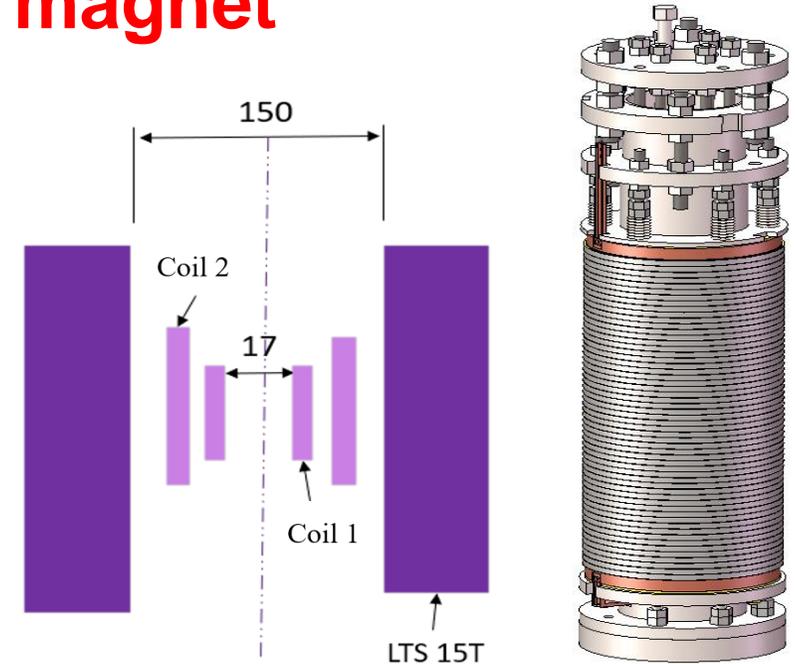
## Overall goal:

- Achieve a central magnetic field of at least **20 T** in self-field and **35 T** within a 15 T & 150 mm LTS background magnet

## Key parameters of 20 T REBCO insert coil

Parameters	Unit	Coil 1	Coil 2
Winding inner diameter	mm	17	92.4
Winding outer diameter	mm	52.7	134.7
Over-banding thickness	mm	6.8	1.65
Co-winding thickness	μm	-	50
Overall height	mm	168	280
Number of DP	-	20	28
Turns per pancake	-	210	90
Total conductor length	m	840	1820
Inductance	H	0.266	0.833
Operating temperature	K		4.2
Operating current	A		245
Current density	A/mm <sup>2</sup>	950	219
Field contribution	T	14.9	5.1

- Two sets of coils are coaxial nested in series
- Coil1: no-insulation winding  
Coil2: metal-insulation winding
- Strengthened by outer metal over-banding

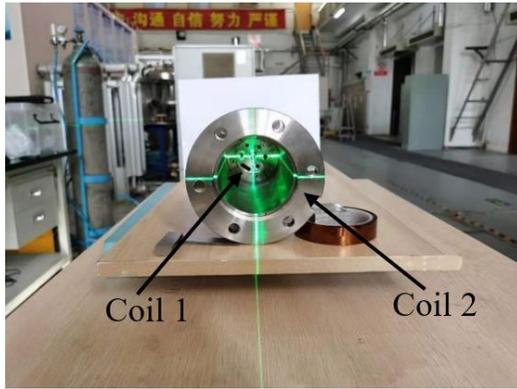


## Parameters of the SSTC REBCO tapes

Parameters	Unit	Coil 1	Coil 2
Width	mm	4	4.8
Total thickness	μm	85	185
Silver matrix thickness	μm	3	3
Copper stabilizer thickness	μm	15	110
Hastelloy substrate thickness	μm	50	50
Critical tensile stress (4.2 K)	MPa	>700	>450
I <sub>c</sub> (77K, self-field)	A	>130	>120

# 35 T all superconducting magnet

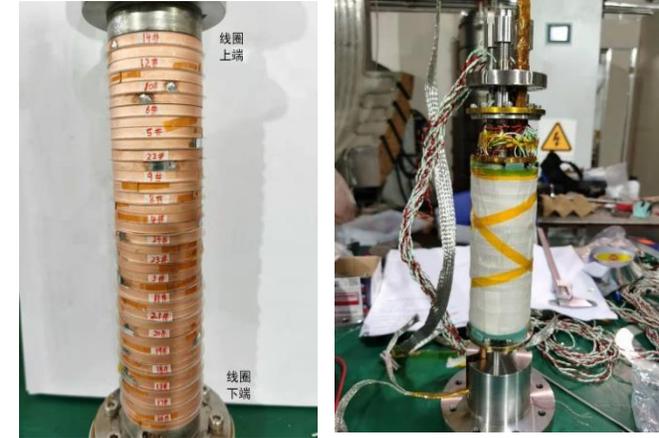
## Assembly of 20 T REBCO insert coil:



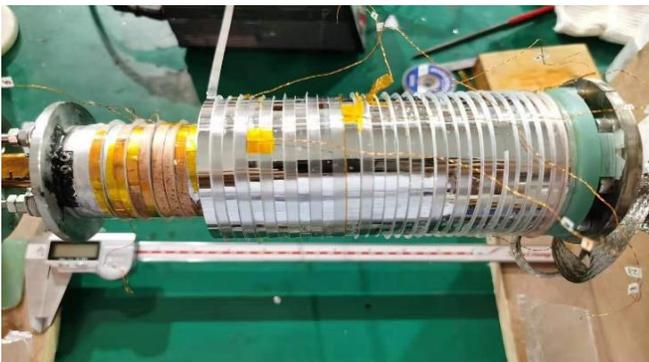
Installation of radial support



Soldering of outer joint



Assembly of coil 1



Winding of over-banding



Assembly of coil 2



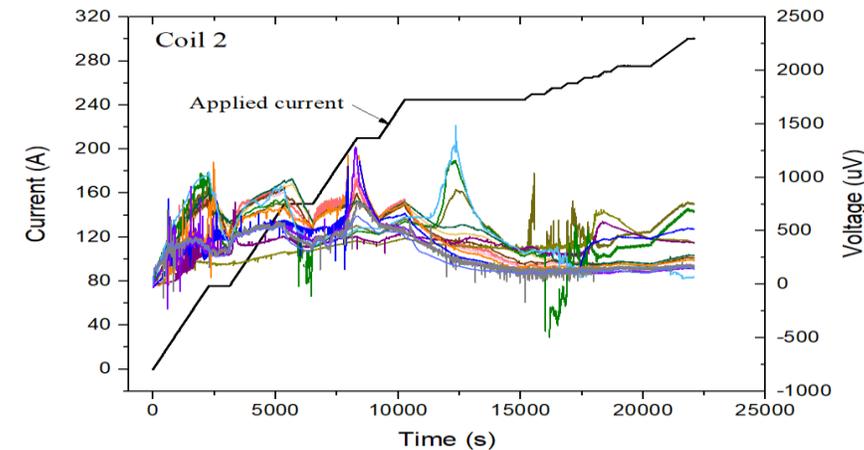
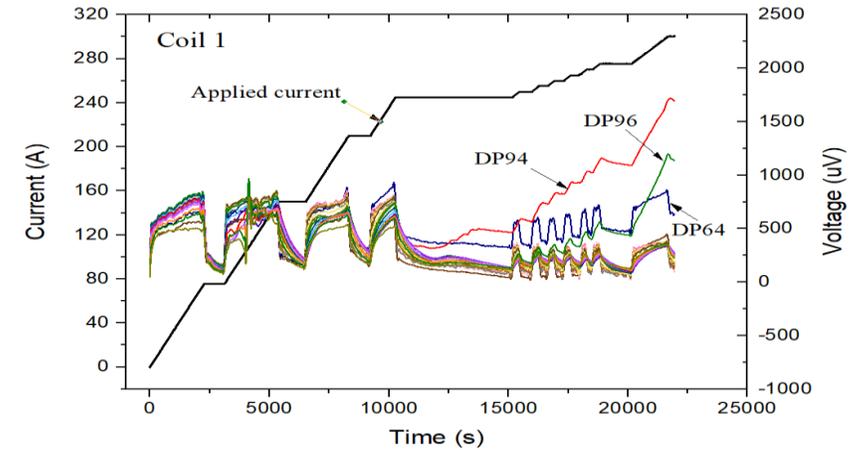
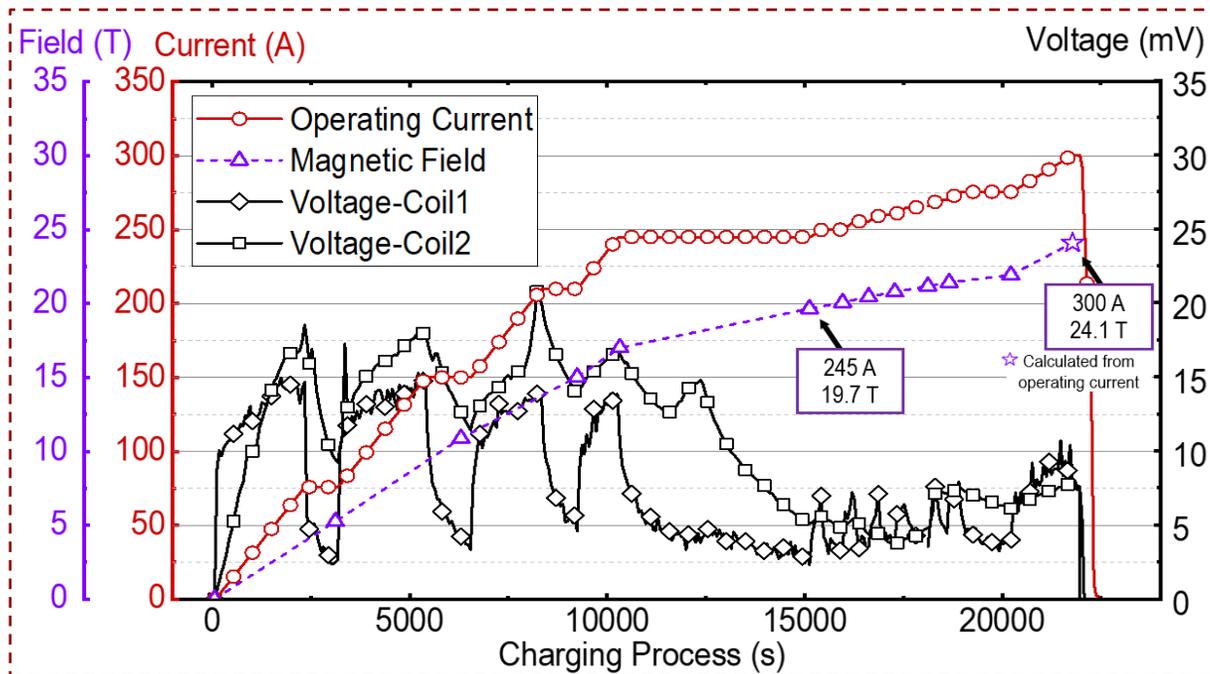
Nested assembly  
of coil 1 and coil 2



## 35 T all superconducting magnet

### Test results at 4.2 K in self-field:

- The current was successfully increased to the design value(245A), and the measured magnetic field was **19.8 T**
- The maximum current reached 300 A, and the maximum magnetic field reached **24.1 T**

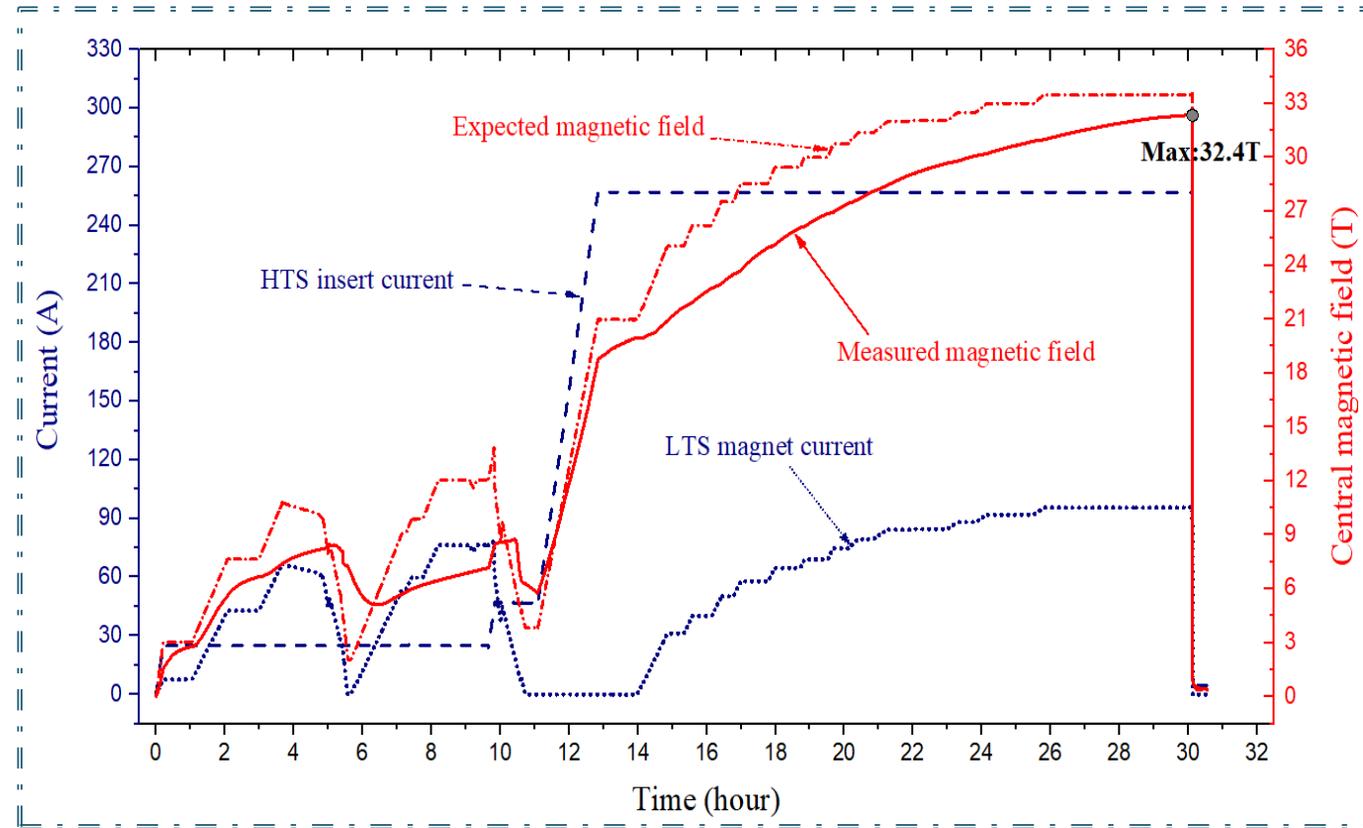
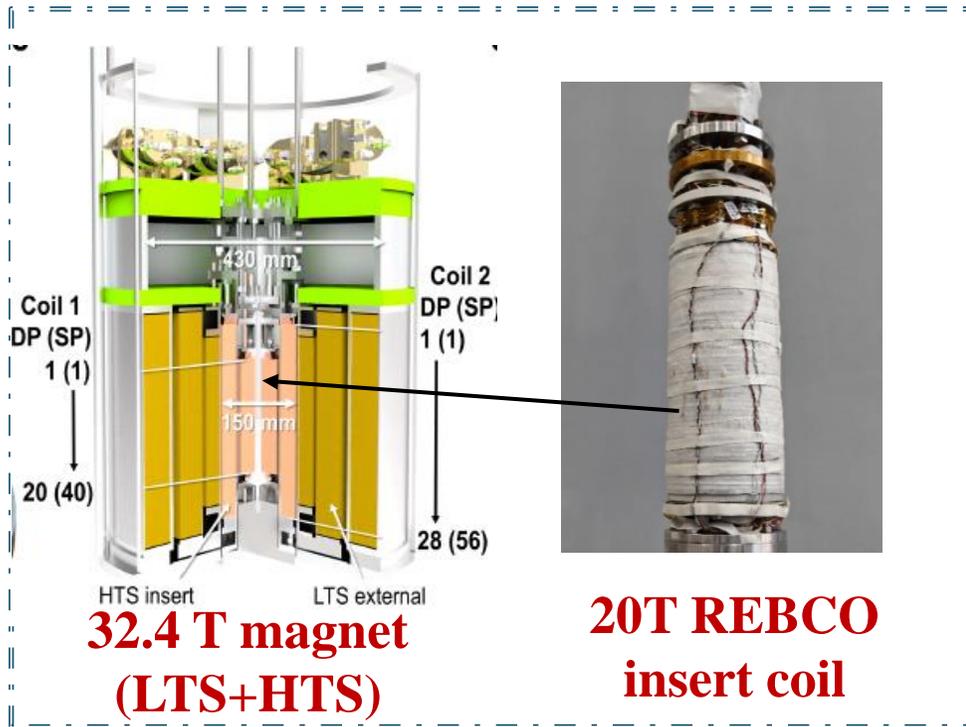


The voltage of DP64 DP94 and DP96 in Coil1 rised in the later stage of excitation (due to poor performance inner joint)

## 35 T all superconducting magnet

Latest test results at 4.2 K in LTS background magnet:

- The REBCO insert coil reaches the target current (257 A) at a rate of 2 A/min, after which the background magnet begins to excite.
- The maximum measured magnetic field reached **32.4 T** (LTS 12.4T+HTS 20T).



Charging process of 32.4T all superconducting magnet

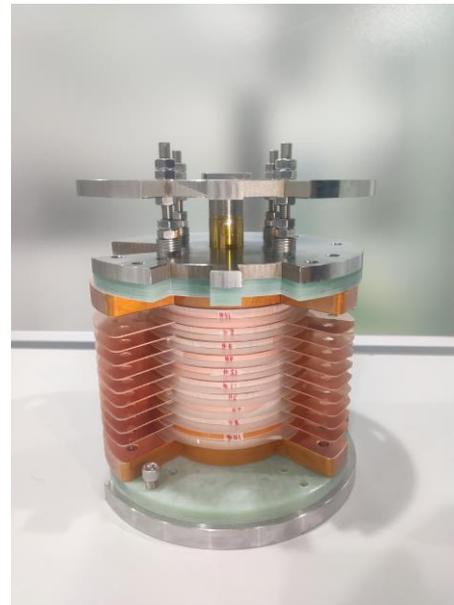
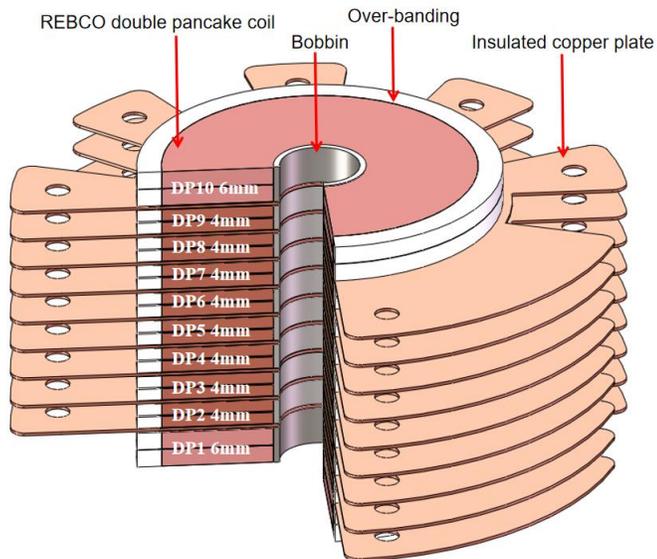


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  - **All ReBCO HTS magnet-26.8T@30mm superconducting magnet**
  
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## □ 20T@30mm all REBCO magnet

- Design goal: **20 T @10 K, self-field**
- Multi-width no insulation(MW-NI) winding & cross-turn filling technology to improve winding current density、electromagnetic safety margin and mechanical strength
- REBCO tape are all supplied by SSTC

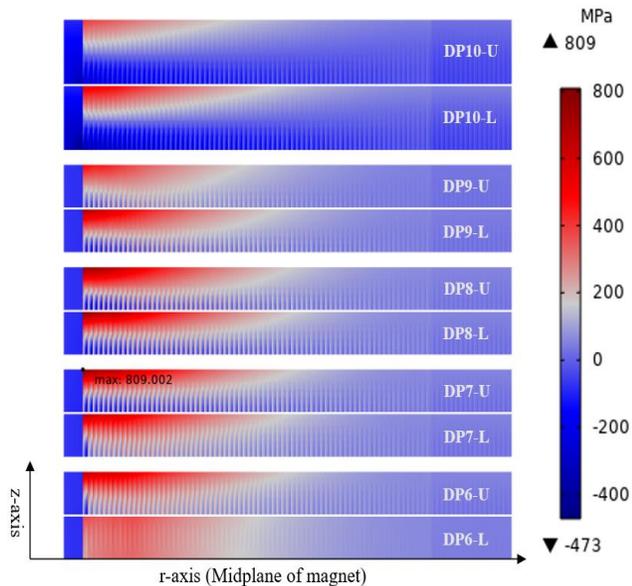
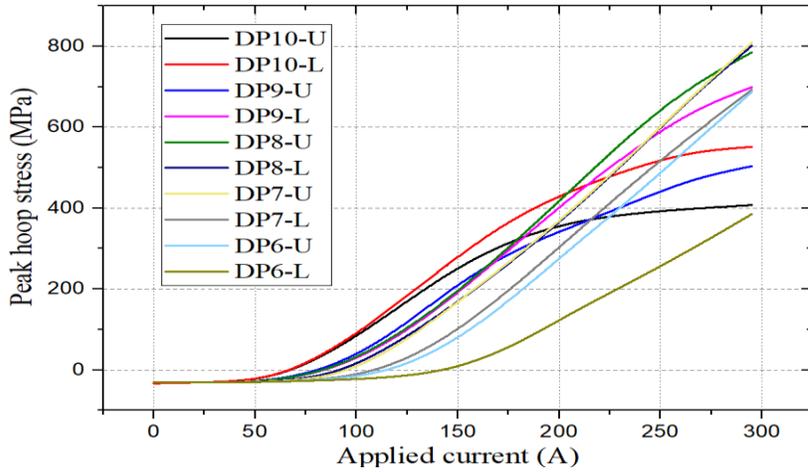


## Key parameters of 20T magnet

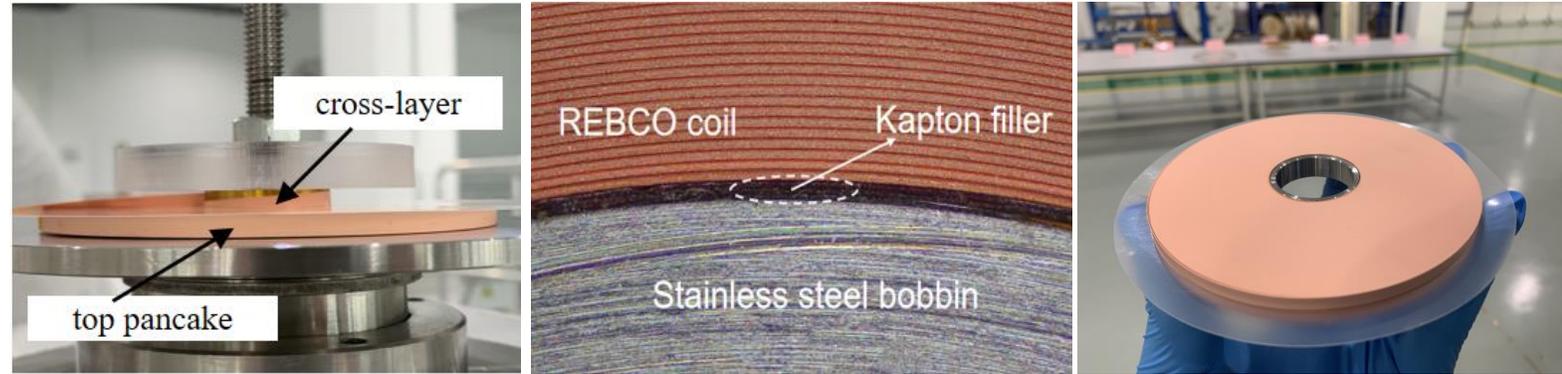
Parameters	DP2-DP9	DP1&DP10
Pancake-Pancake spacer [mm]	0.1 (G10)	
Insulated copper plate [mm]	1	
Coil I.D <sup>a</sup> [mm]	30	
Coil O.D <sup>a</sup> [mm]	103.98	
Overall height <sup>a</sup> [mm]	102.6	
Turns per pancake	426	
Over-banding thickness [mm]	8.5	
<b>Number of DPs</b>	<b>8</b>	<b>2</b>
Average Conductor per DP [m]	~180	~180
Conductor total length [km]	~1.8	
Magnet constant <sup>b</sup> [T/A]	0.091	
Inductance [H]	1.57	
$I_{op}$ at 20.2 T <sup>c</sup> [A]	232	
$I_{op}/I_q$ at 20.2 T@10 K/4.2 K <sup>c</sup>	0.66/0.61	
$I_{op}$ at 26.86 T <sup>c</sup> [A]	295.5	
$I_{op}/I_q$ at 26.86 T <sup>c</sup>	0.86	
Engineering current density at 26.86 T [A/mm <sup>2</sup> ]	869.1	579.4
Peak radical field at 26.86 T [T]	6.31	7.98
Stored energy at 26.86 T [kJ]	68.5	
Peak hoop stress at 26.86 T [MPa]	809	
Peak hoop strain at 26.86 T [%]	0.52	

## 20T@30mm all REBCO magnet

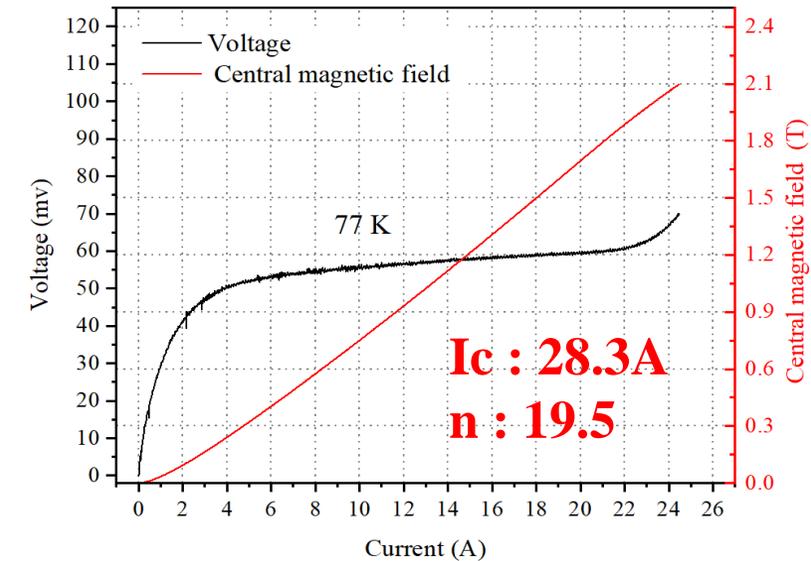
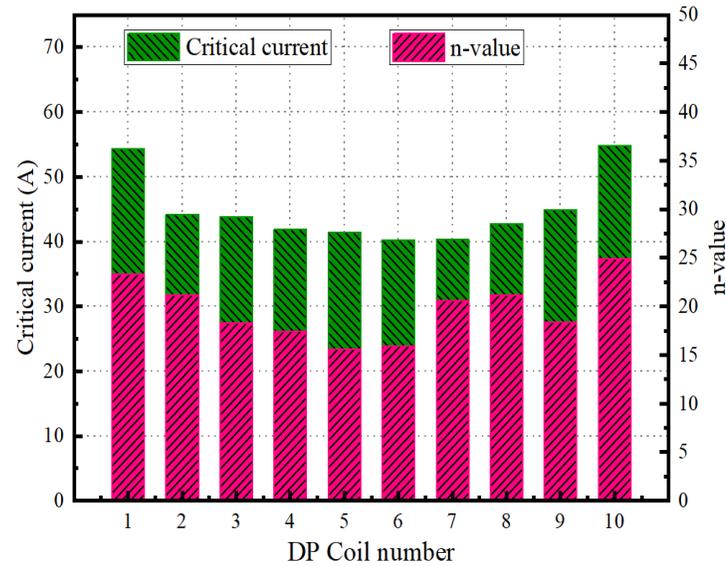
### Mechanical analysis



### Magnet fabrication



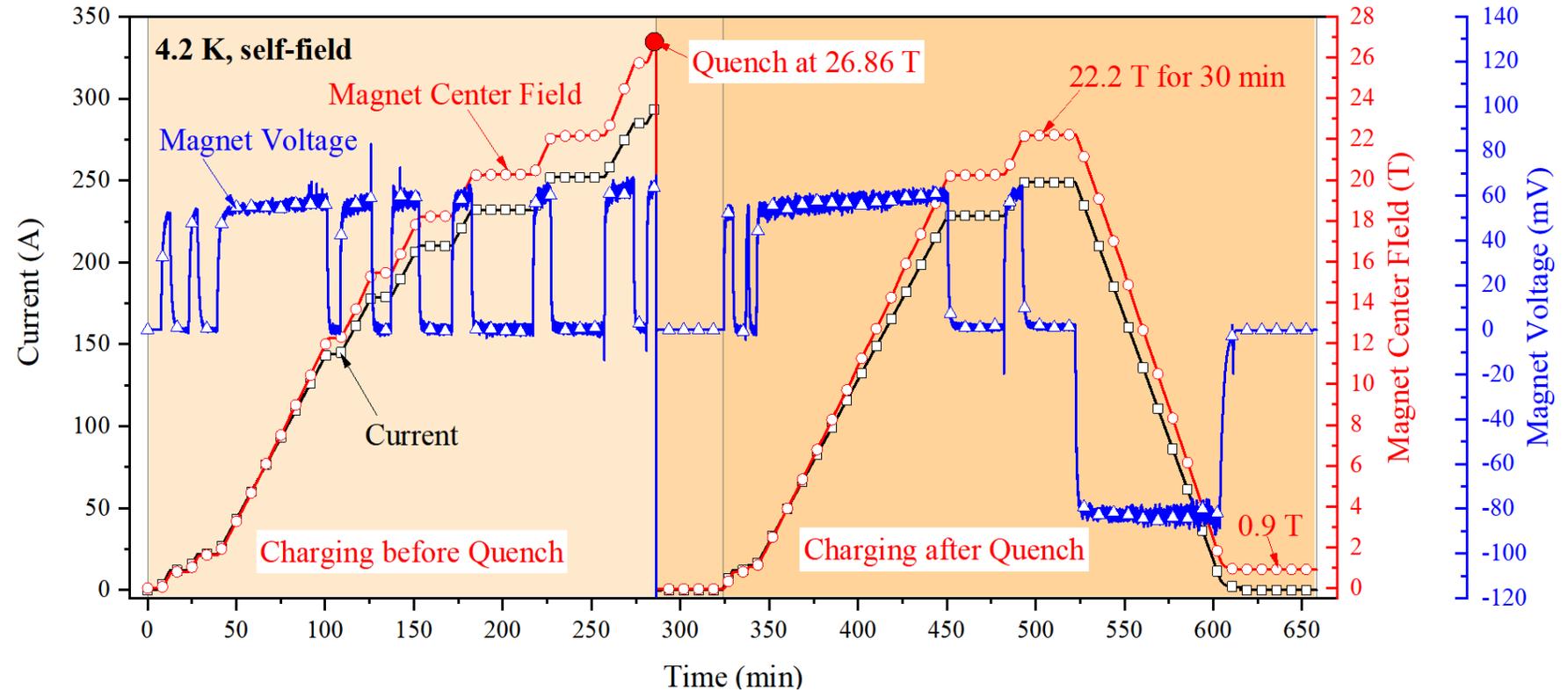
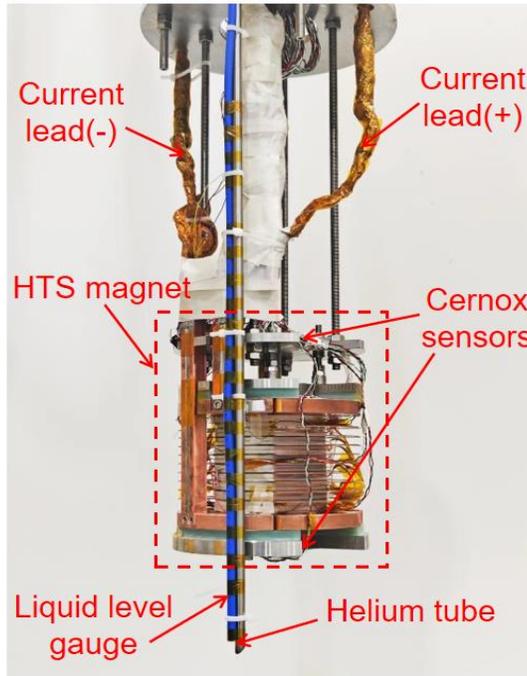
### DPs coil and magnet test at 77K



- The average  $I_c$  and n values of DP1&DP10 are 54.5A and 24.1
- The average  $I_c$  and n values of DP2-DP9 are 42.4A and 18.6

## □ 20T@30mm all REBCO magnet

- The highest measured central magnetic field reached **26.86 T (Record-high DC field from all-HTS magnet)**
- The current operating point ( $I_{op}/I_c$ ) at 26.86T@295.5A was **0.86**
- After the quench of the magnet, the magnet successfully reached 22.2 T again and remained stable for **30 min**, and the superconductivity of the magnet did not decline significantly





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## □ 16T@100mm all REBCO magnet

Magnet Parameters (without SC)	
Coil I.D	112[mm]
Coil O.D	161.8[mm]
Overall height	245.7[mm]
Turns per pancake	262
Number of DPs	28
Average conductor per DP	226
Conductor total length	6328[m]
Inductance	11.5 [H]
Operating current	243A
Engineering current density	639.5[A/mm <sup>2</sup> ]
Peak radical field	6.69[T]
Stored energy	339.5[KJ]
Peak hoop stress	394[MPa]
Over-banding thickness	8.5[mm]
Central magnetic field	16[T]

### ➤ Project objective

- Central magnetic field: **16 T @4.2 K, self-field**
- Cold-bore diameter: **100 mm**

### ➤ Technical route

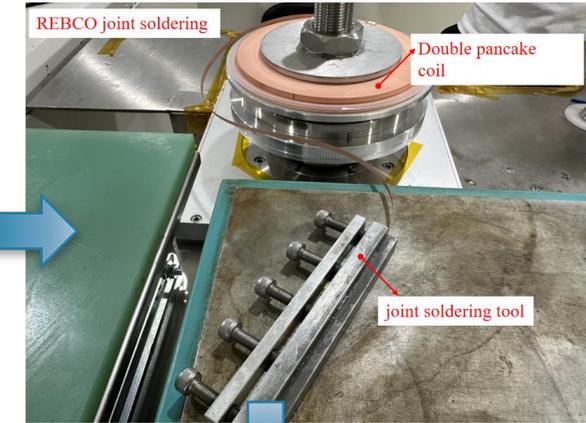
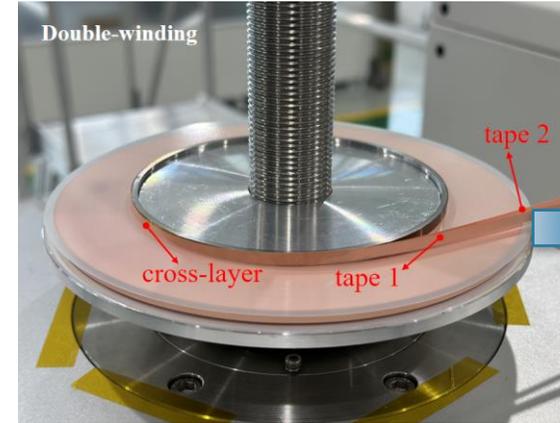
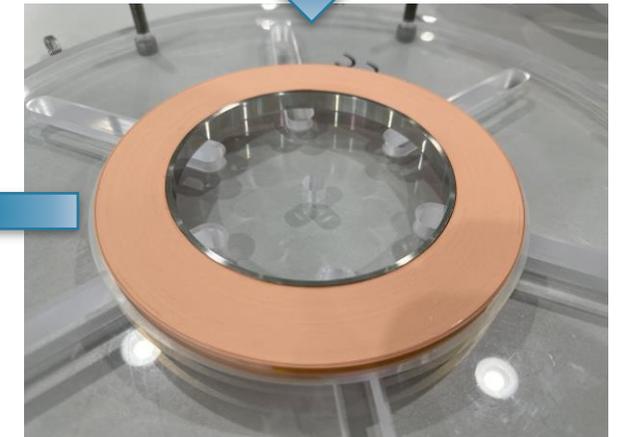
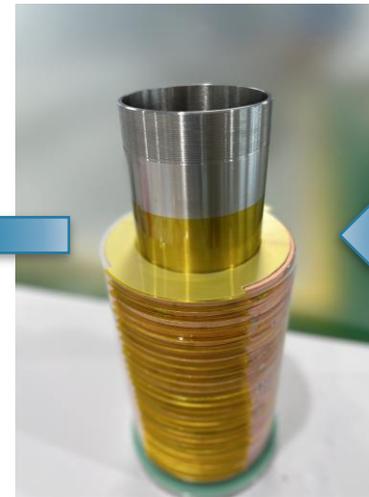
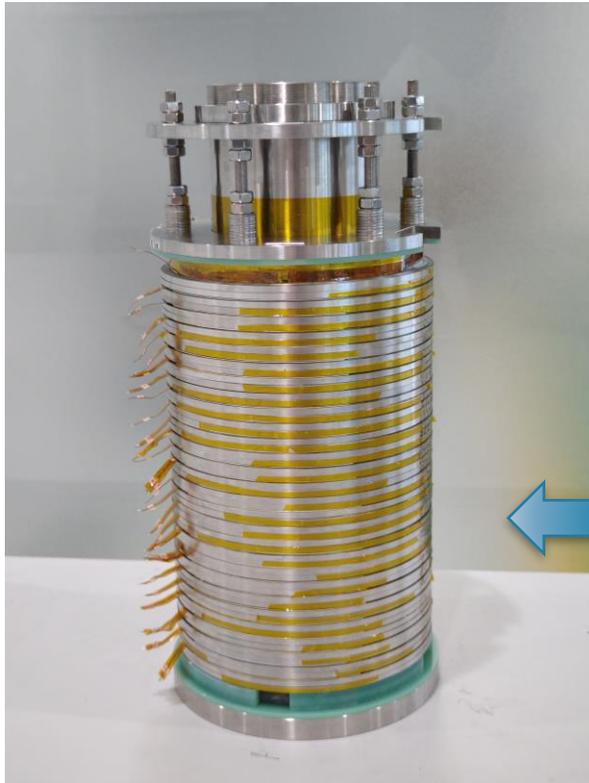
- Tape specification: 4mm×0.095mm, provided bySSTC
- NI winding and end DPs double-winding technology
- Preparation technology of low resistance and high mechanical properties joint
- Axial preloading of magnet and metal support between two double pancakes(DPs)



## □ 16T@100mm all REBCO magnet

### ➤ Magnet winding and assembly process

- Each DP coil contains two inner joints(Except for the end coil), superconducting layer soldering to reduce resistance .

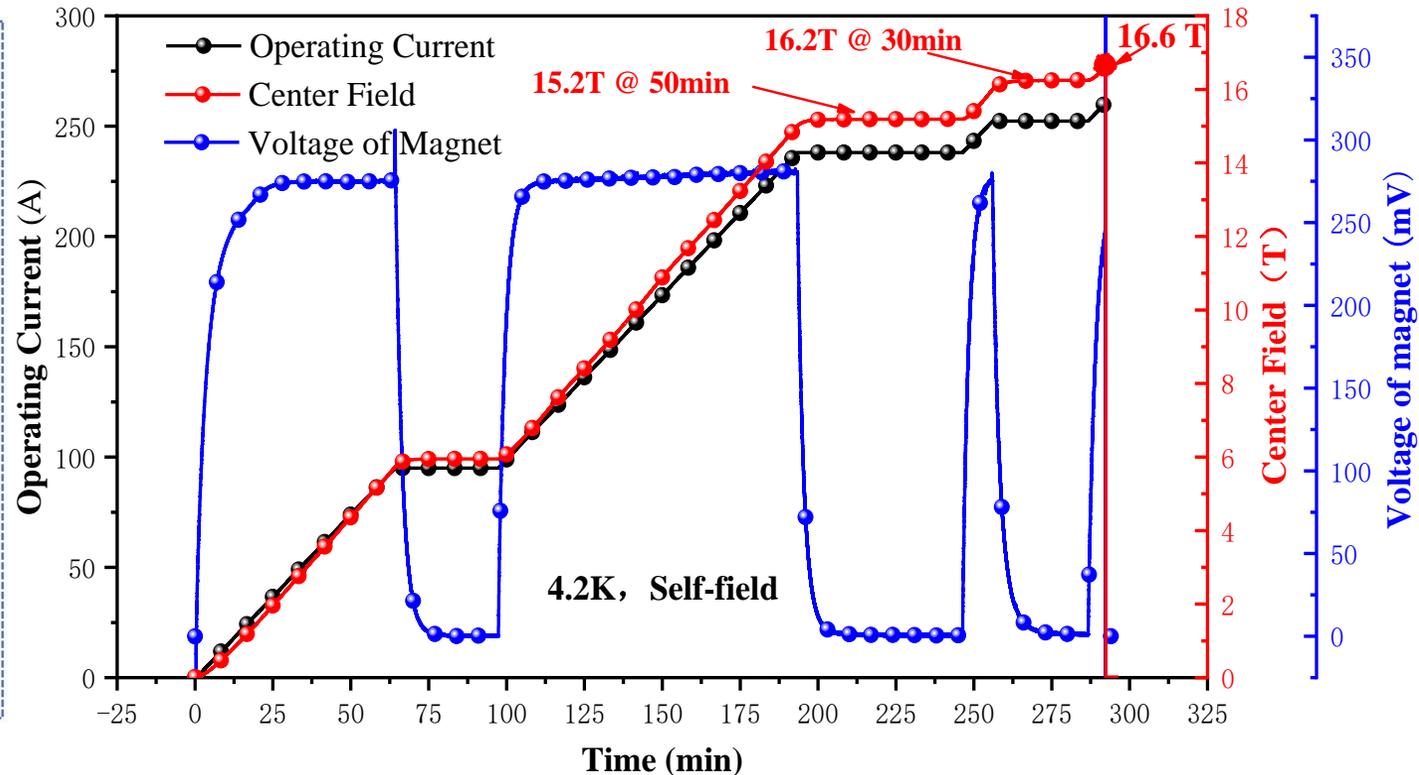
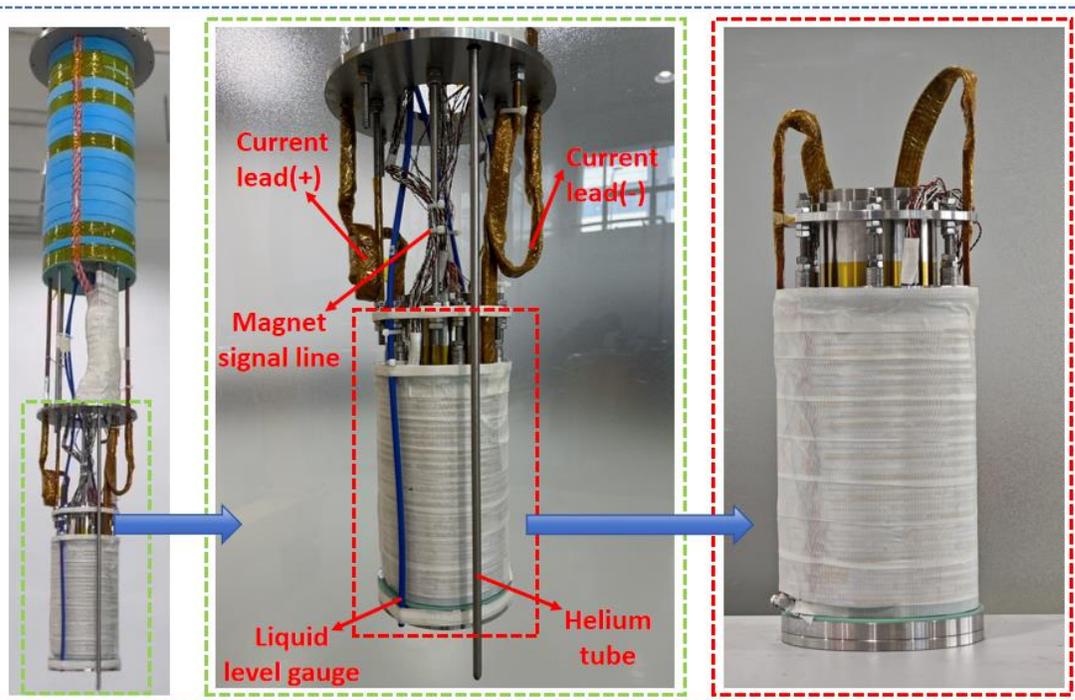




## □ 16T@100mm all REBCO magnet

### ➤ Magnet test at 4.2K, self-field

- The central field of the magnet reaches **15.2T** and runs stably for **50min**; When it further increases to **16.2T**, stable operation for **30 min**
- Maximum center field up to 16.6 T ( $I_{op}/I_c$  up to 0.84)





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- **Summary**



## Summary

- **32.4 T full superconducting magnet** (LTS+HTS) has been successfully developed
- **26.86 T all-REBCO magnet** has been successfully developed
- **16 T@100mm cold-bore REBCO magnet** has been successfully developed

## Prospect

- Optimize the magnet design and manufacturing process to achieve the design goal of 35T full superconducting magnet
- Continue to carry out the design and development of large bore all HTS magnets
- Expand cooperation in multiple fields of HTS magnets



# Thank You Very Much!

