High Field Magnet R&D for the Next-generation High Energy Particle Accelerators

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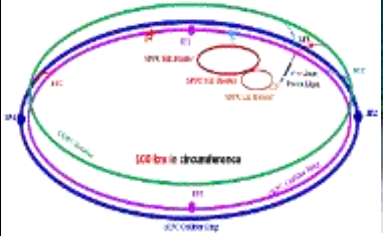
中国科学院高能物理研究所
Institute of High Energy Physics
Chinese Academy of Sciences

Design Scope for Next-generation Accelerators

$$E[GeV] = 0.3 \times B[T] \times \rho[m]$$

High Energy Circular Colliders for next decades	**SPPC**  	**FCC** 
Proposed institution	IHEP-CAS, China	CERN, Europe
Proposed dates	2012	2013
Site of the project	China	Europe
Baseline technology	IBS 20~24 T to reach 125-150 TeV, Nb_3Sn etc as options	Nb_3Sn 16 T to reach 100 TeV
Timeline	Construction at 2040s	Construction at 2050-60s
Cost	*	**

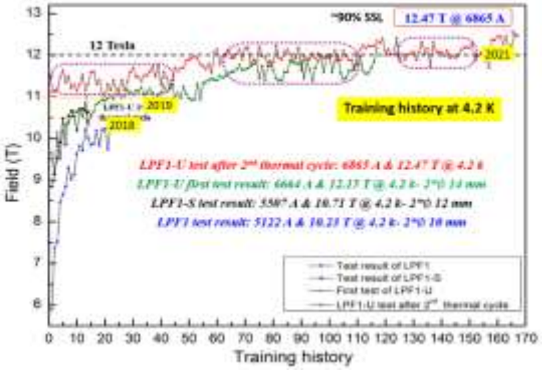
Roadmap of the High Field Magnet R&D at IHEP

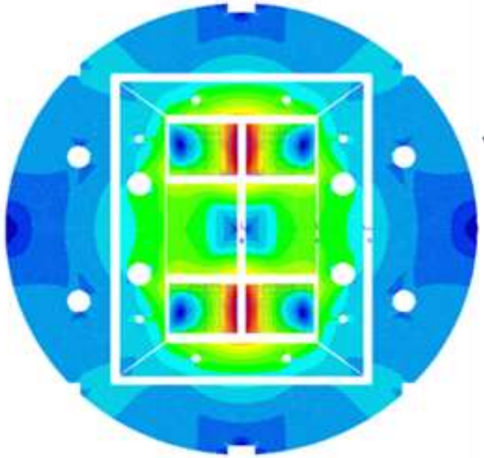
Field (T)

20

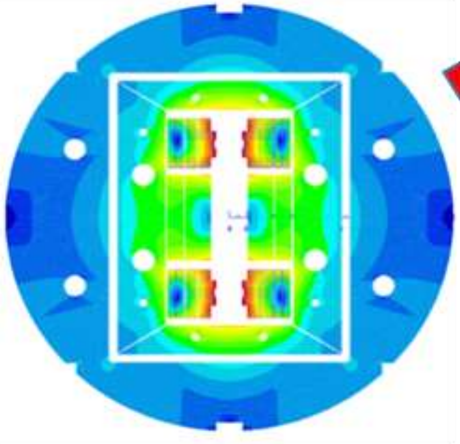
10

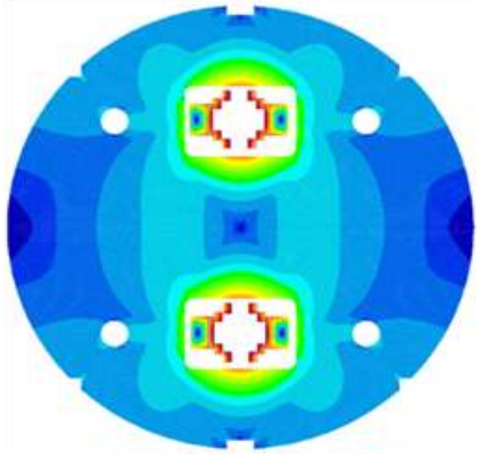
2018-2021, 12.47T @4.2K
NbTi + Nb_3Sn





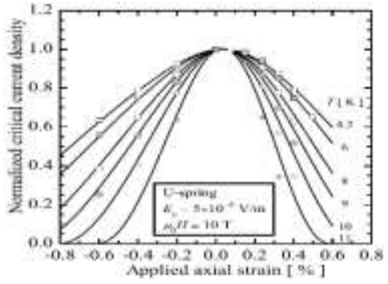
2021-2024 16T @ 4.2K
Nb_3Sn + HTS





Nb_3Sn+HTS or HTS
2*ϕ45 aperture
20T @ 4.2K
With 10^{-4} field quality

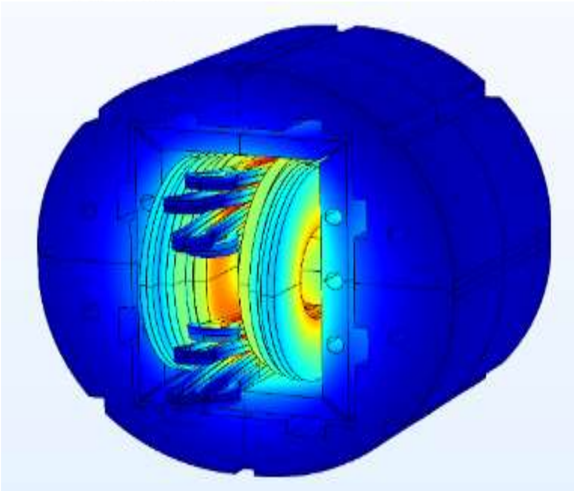
Challenges: Stress control, quench protection, field quality control,……

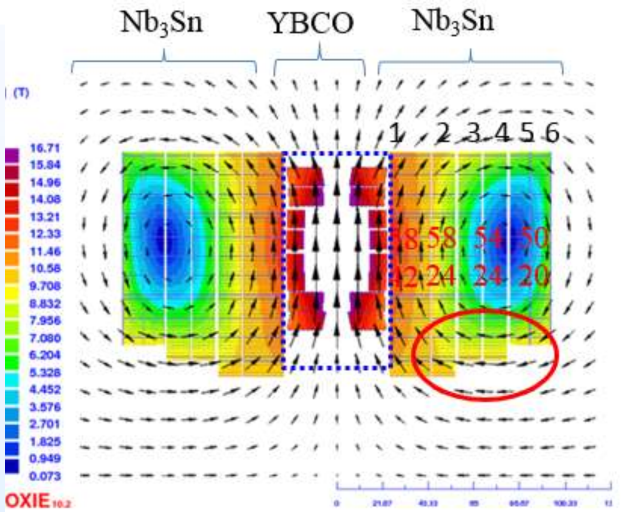


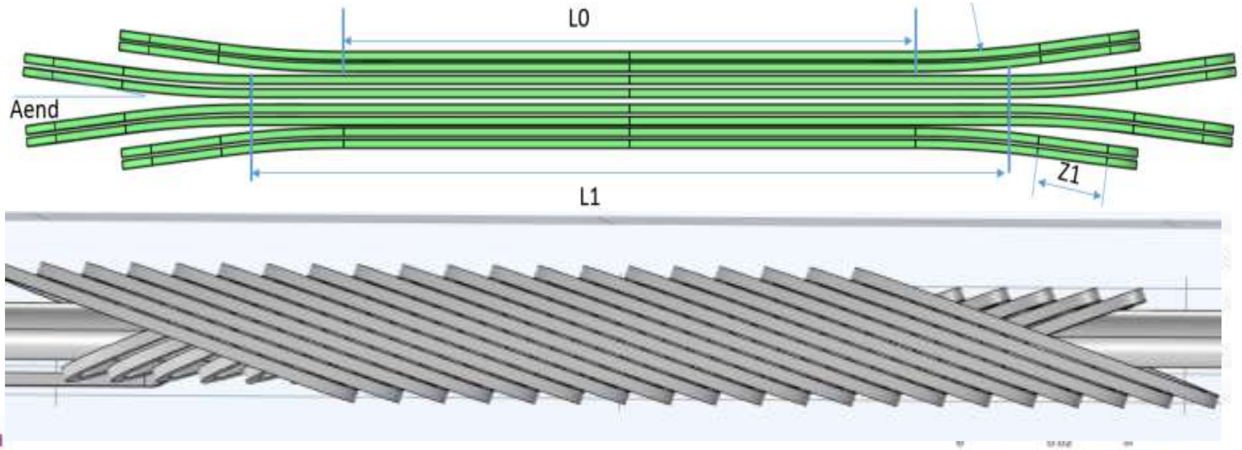
2018 2028 year

Development of the 16-T Model Dipole LPF3

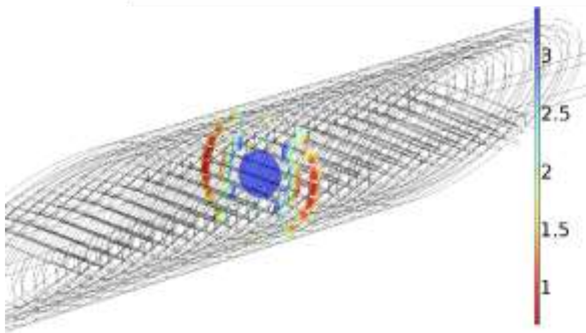
16 T Model Dipole LPF3: Nb_3Sn 13 T (*Common Coil with 55 mm gap*) + HTS 3 T inserts (*Block & CCT*)

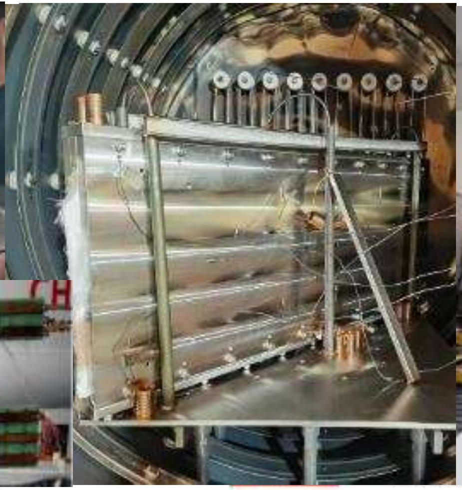






16-T 大孔径高场超导二极磁体 LPF3 (Nb_3Sn-13T+HTS-3T) 电磁设计





Development of the 16-T Model Dipole LPF3

The Nb_3Sn coils for LPF3

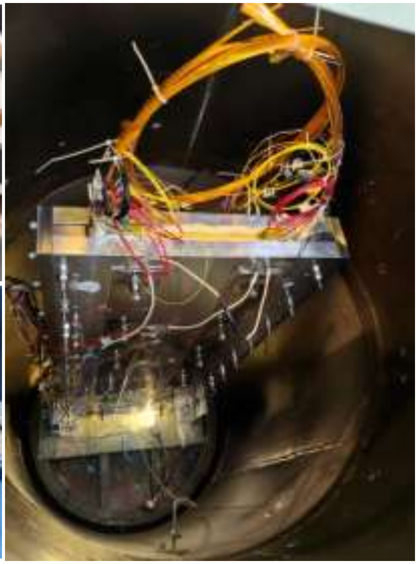
Chengtao Wang et al







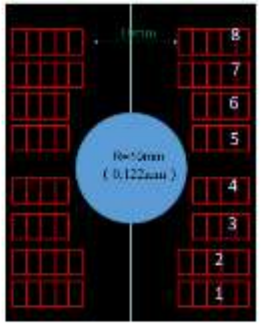


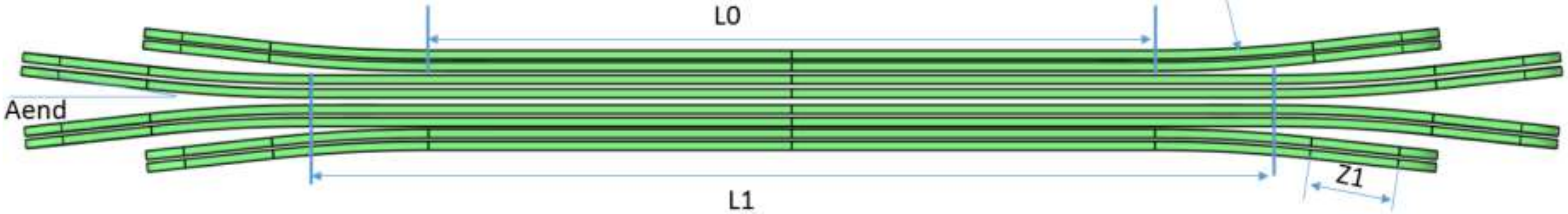




Development of the 16-T Model Dipole LPF3

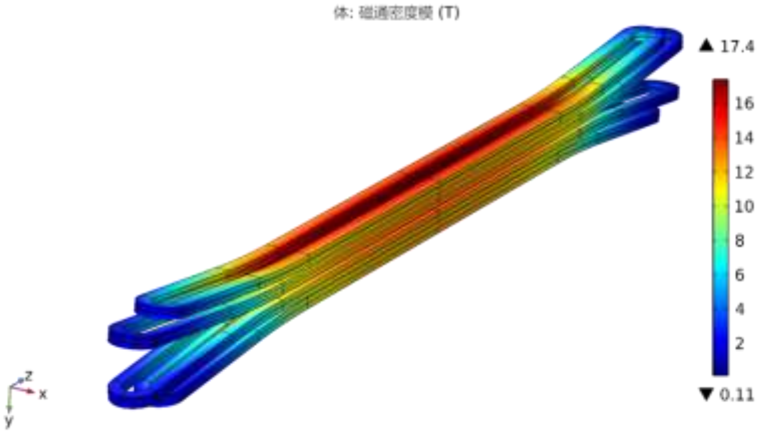
The ReBCO block insert coils for LPF3

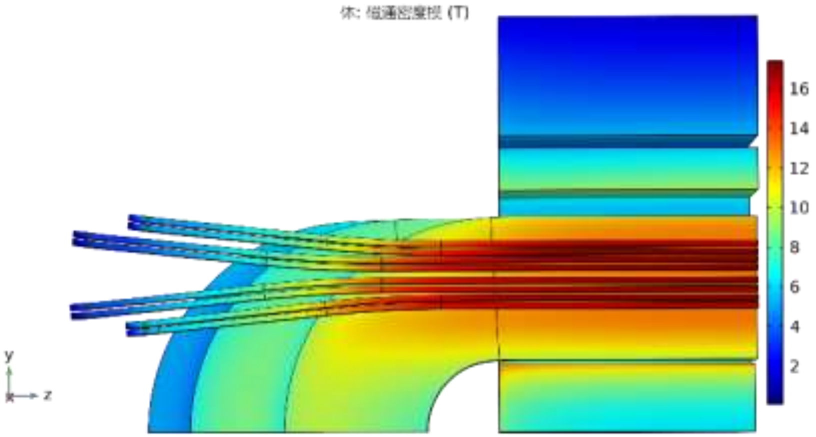
Ze Feng et al

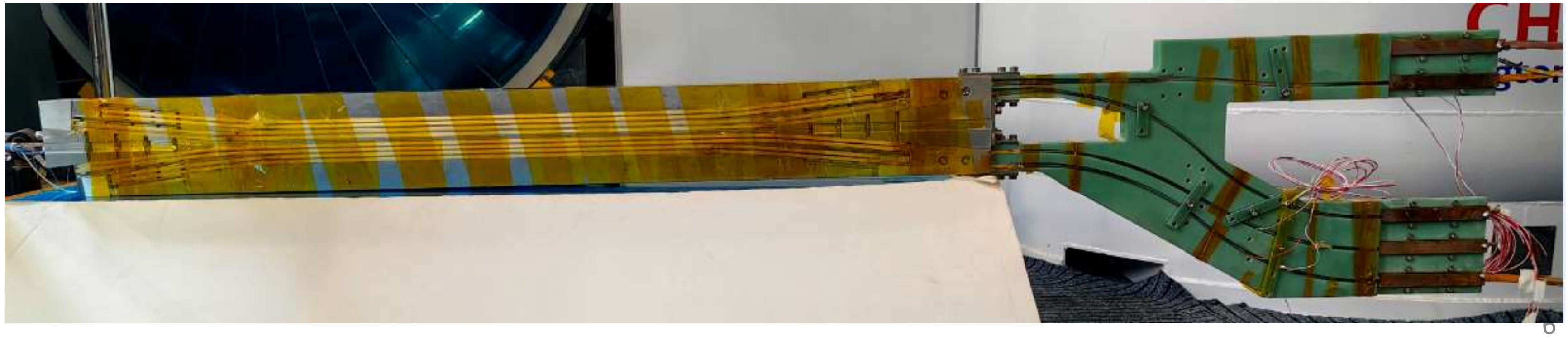




Parameters	Values
L0	409.6 mm
L1	540.2 mm
Rhard	800 mm
Aend	6 °
R1	9.5 mm
Z1	120 mm



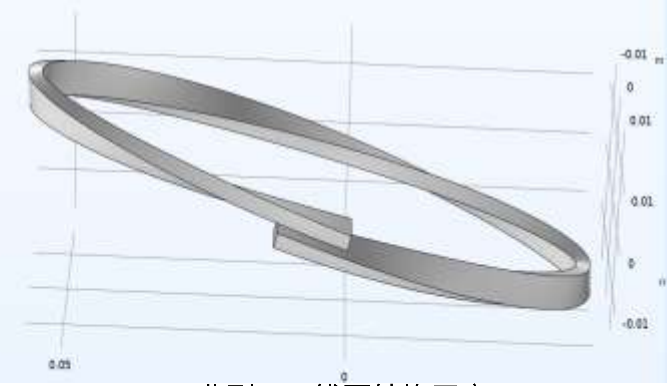




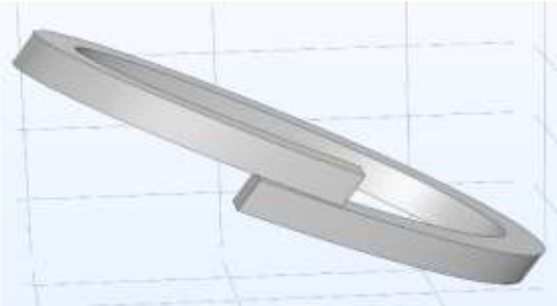
Development of the 16-T Model Dipole LPF3

The ReBCO CCT instert coils for LPF3

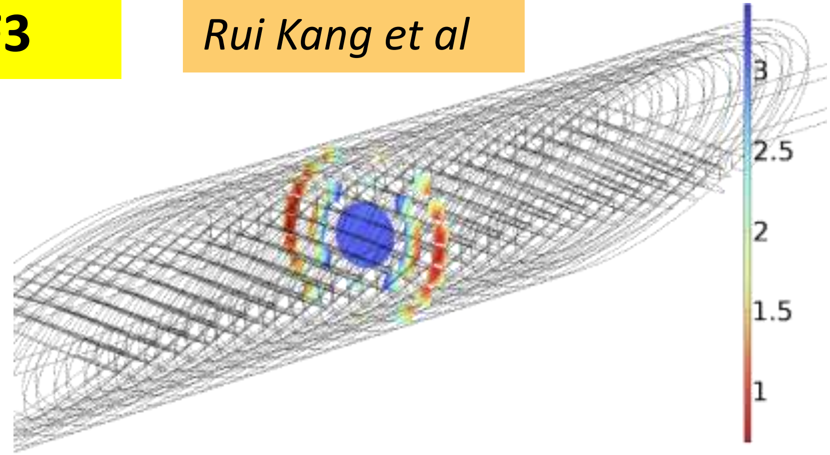
Rui Kang et al

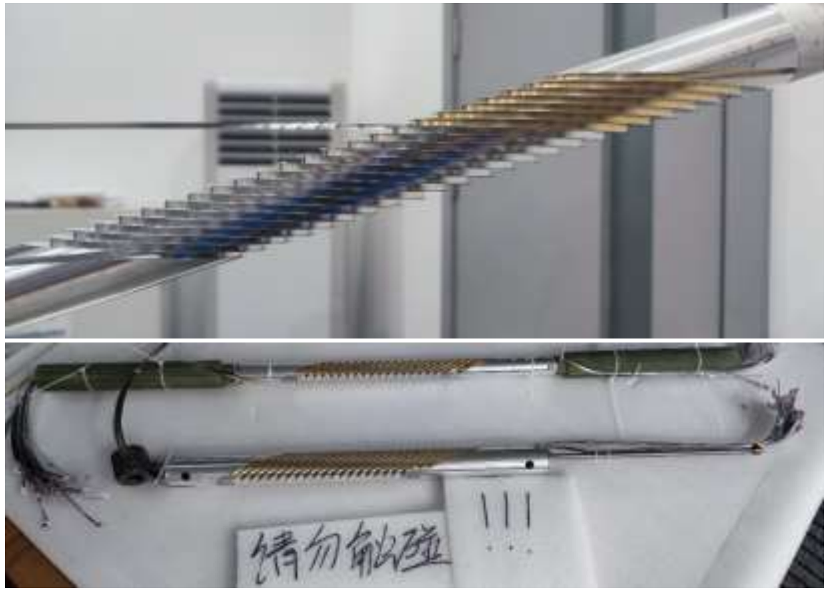


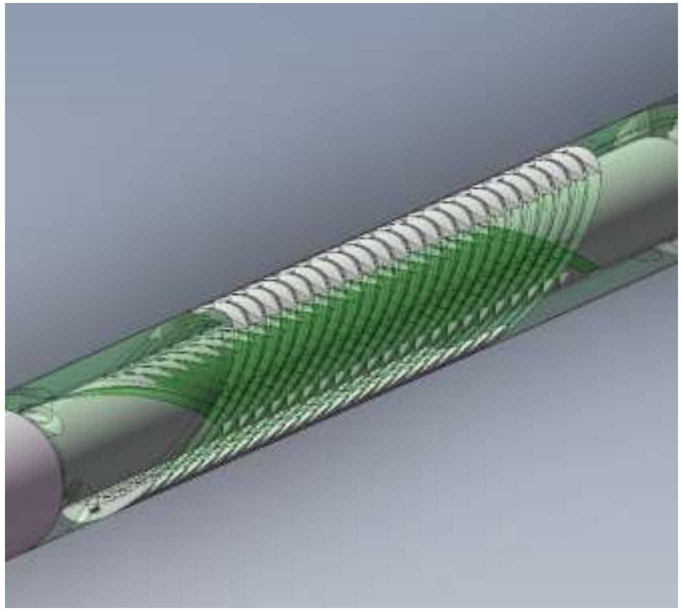
典型CCT线圈结构示意



“斜螺线管”型CCT线圈结构示意



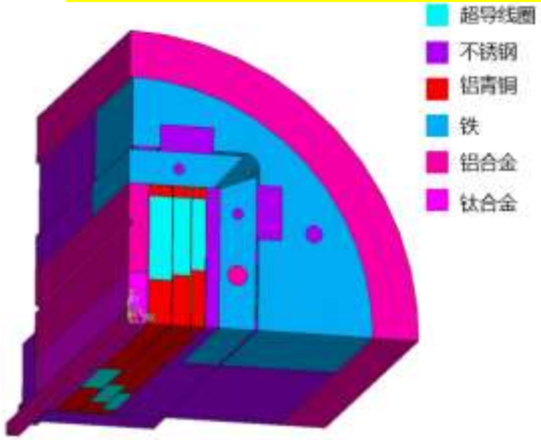


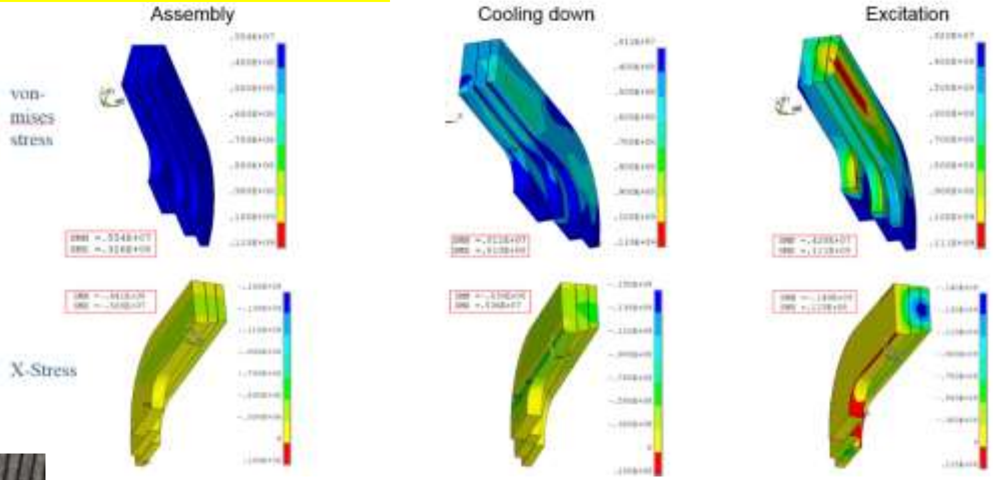


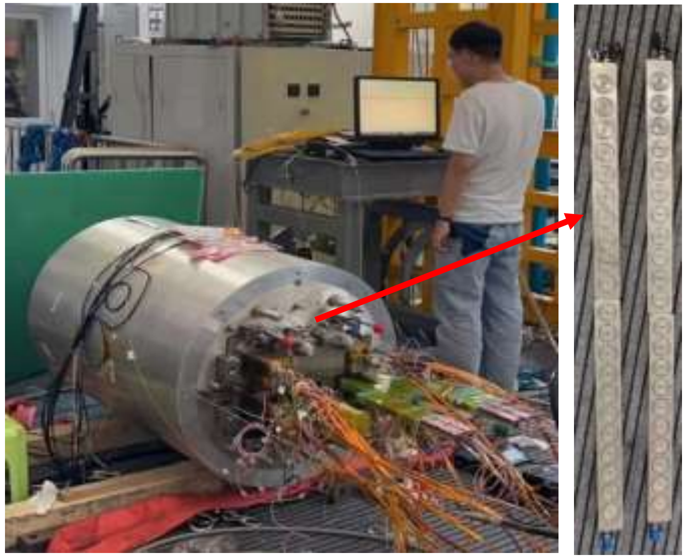
Development of the 16-T Model Dipole LPF3

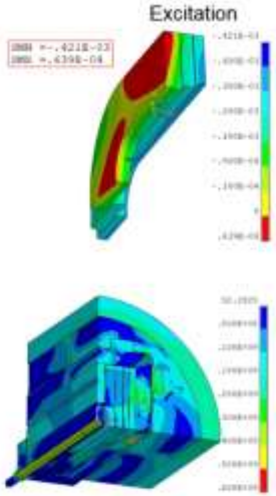
Pre-stress and assembly of LPF3

Yingzhe Wang et al

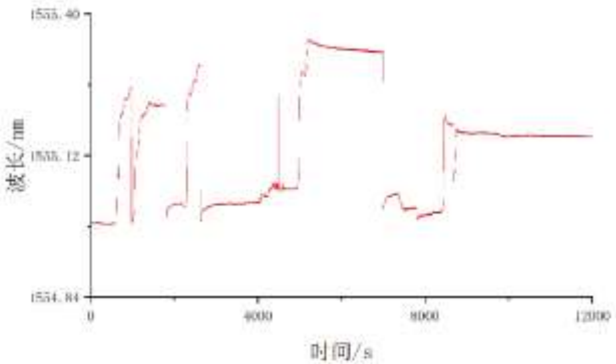








Stress monitoring during assembly with FBG



Pre-stress applied with commercial hydraulic jack

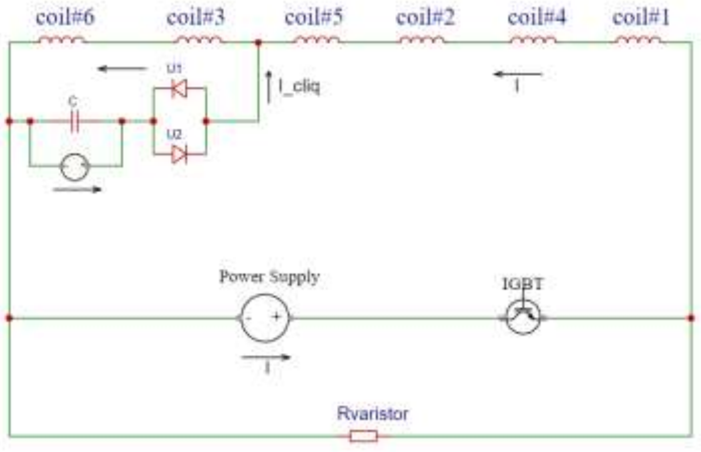
2023.8.29 Assembly completed

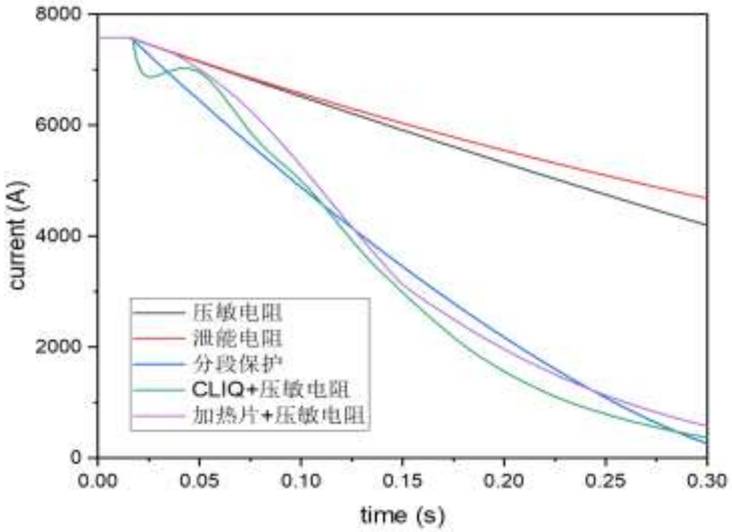
Development of the 16-T Model Dipole LPF3

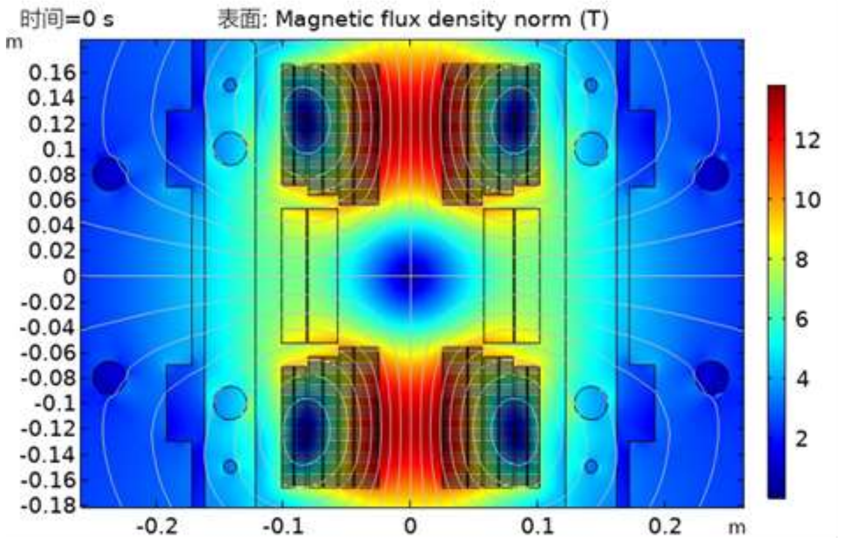
Quench protection of LPF3

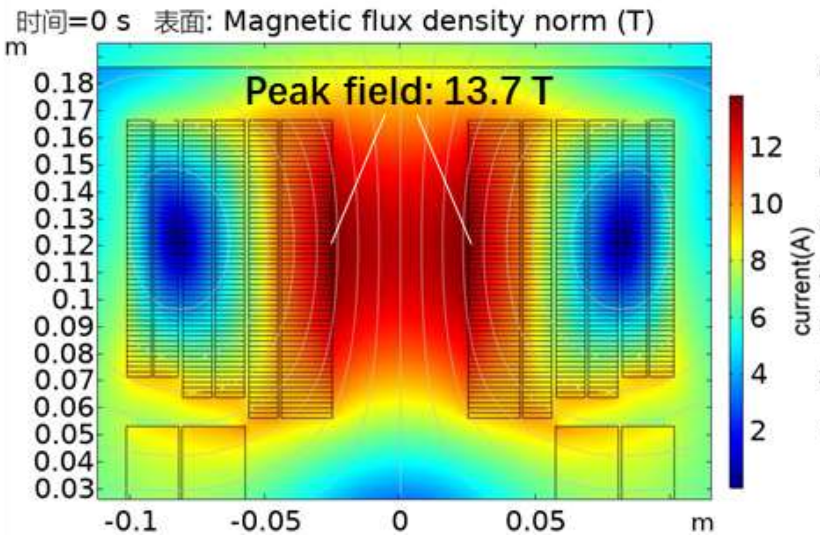
Jinrui Shi et al

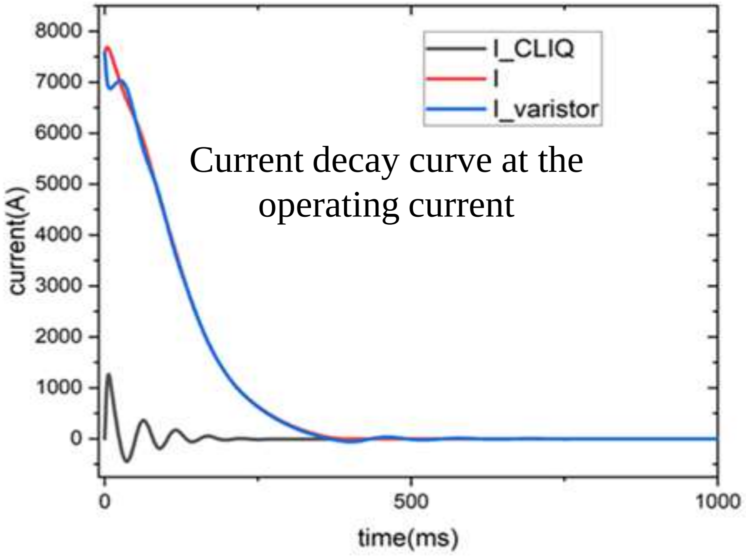
- **Varistor plus CLIQ** to protect the **Nb_3Sn** coils. The maximum hot spot is ~ 230 K
- **NI configuration plus dump resistor** to protect the 2 **HTS** insert coils









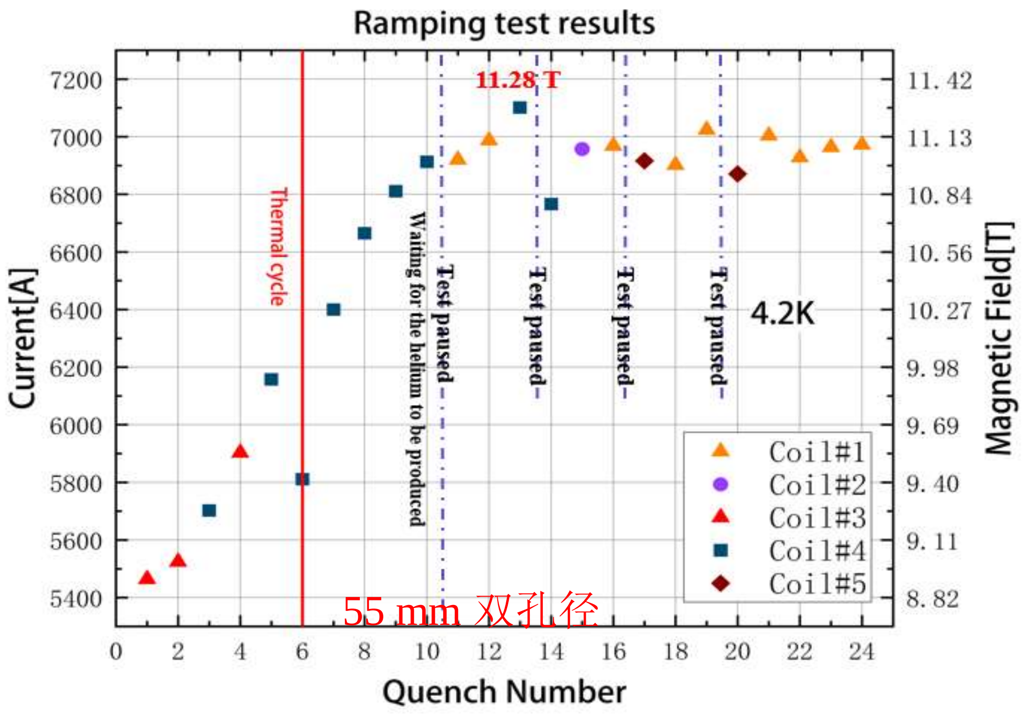


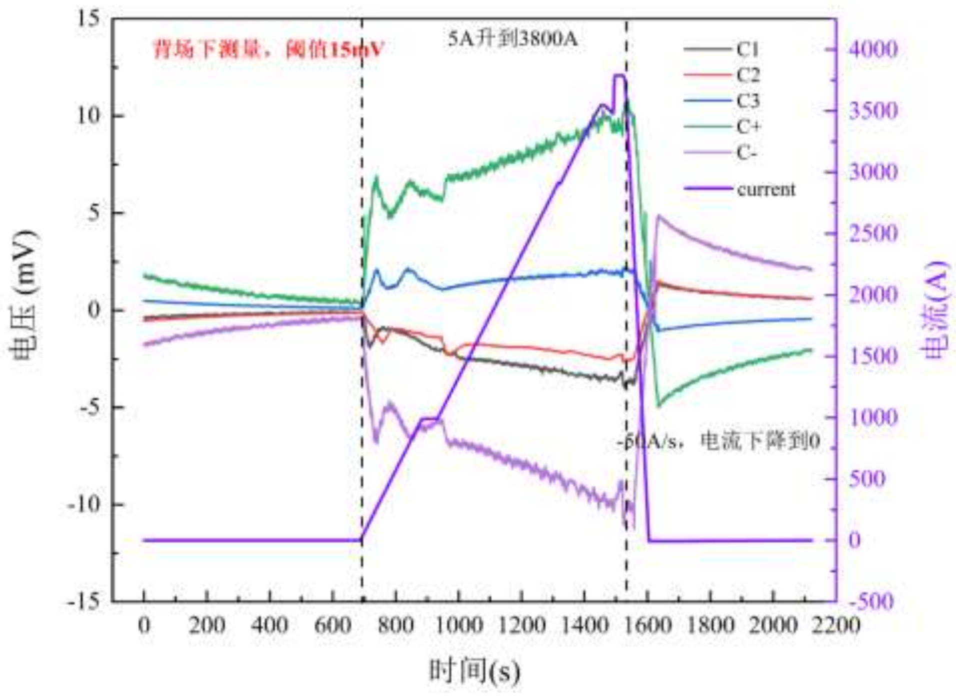
Development of the 16-T Model Dipole LPF3

Performance test ongoing from Sep 2023

Wei Li et al

- **The Nb_3Sn coils were trained firstly, maximum current reached ~85% of I_{op} in Dec 2023, but showed an unstable plateau at 11 T due to one of the outmost Nb_3Sn coil, probably due to insufficient pre-stress during assembly**
- **HTS block coil was ramped independently to 100% of I_{op} with negligible terminal voltage**

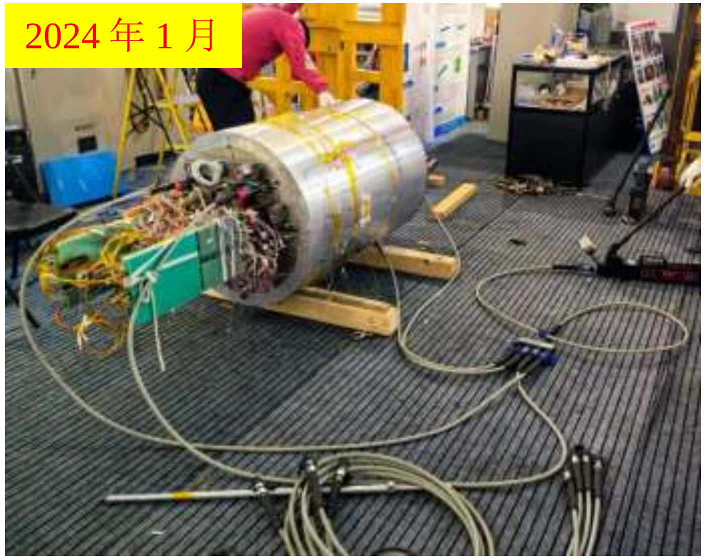


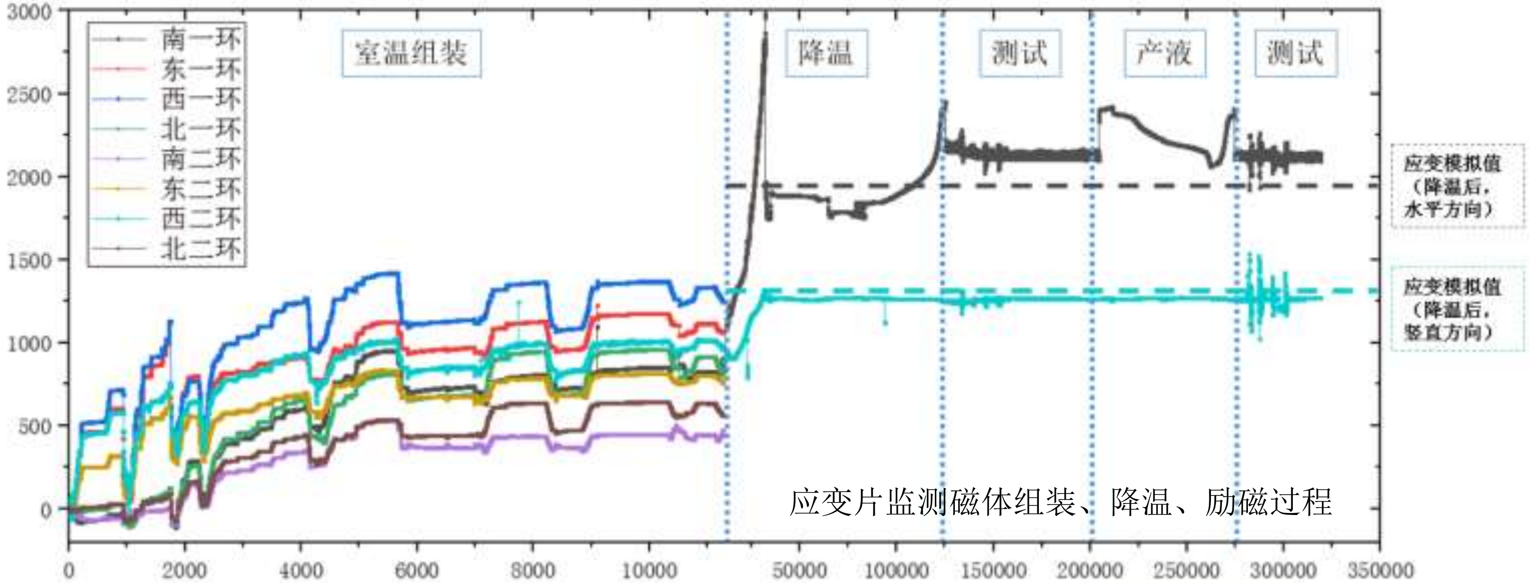


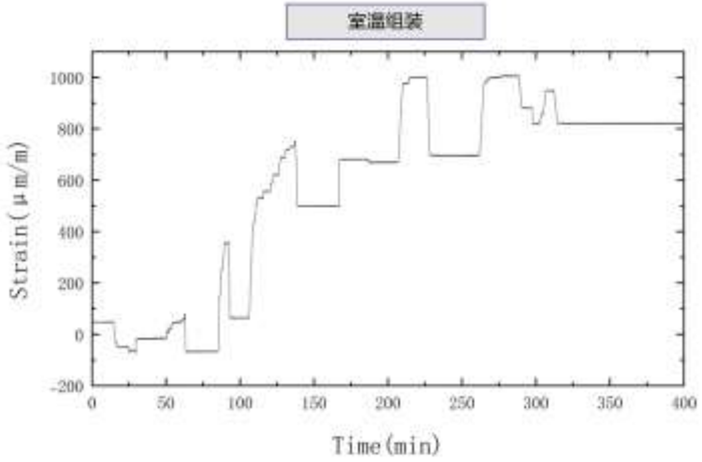
Development of the 16-T Model Dipole LPF3

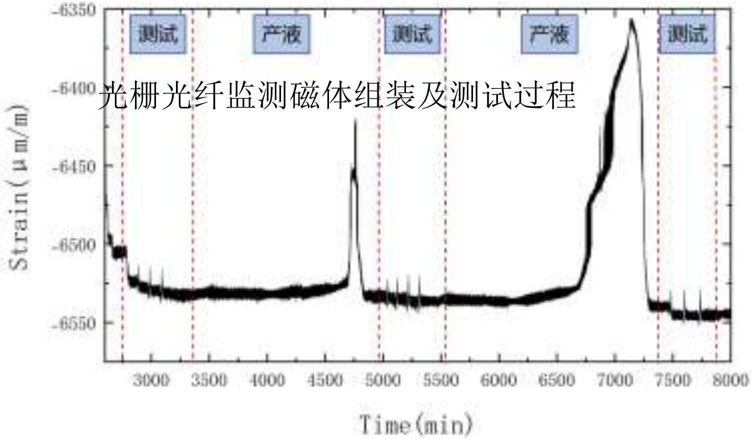
Reassembly of the magnet with enhanced pre-stress

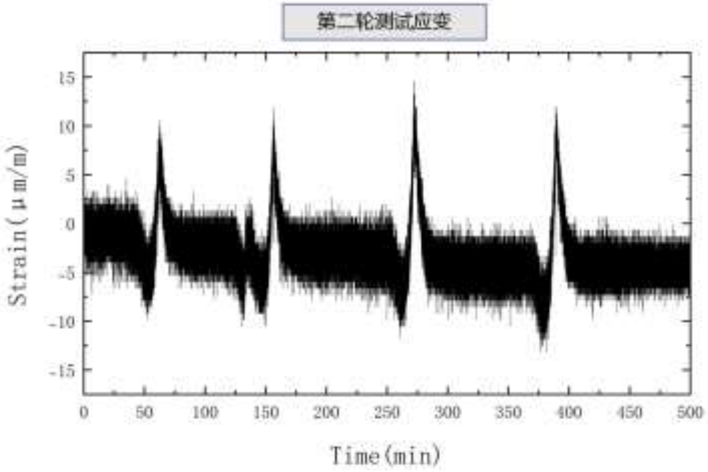
Xin Chen et al







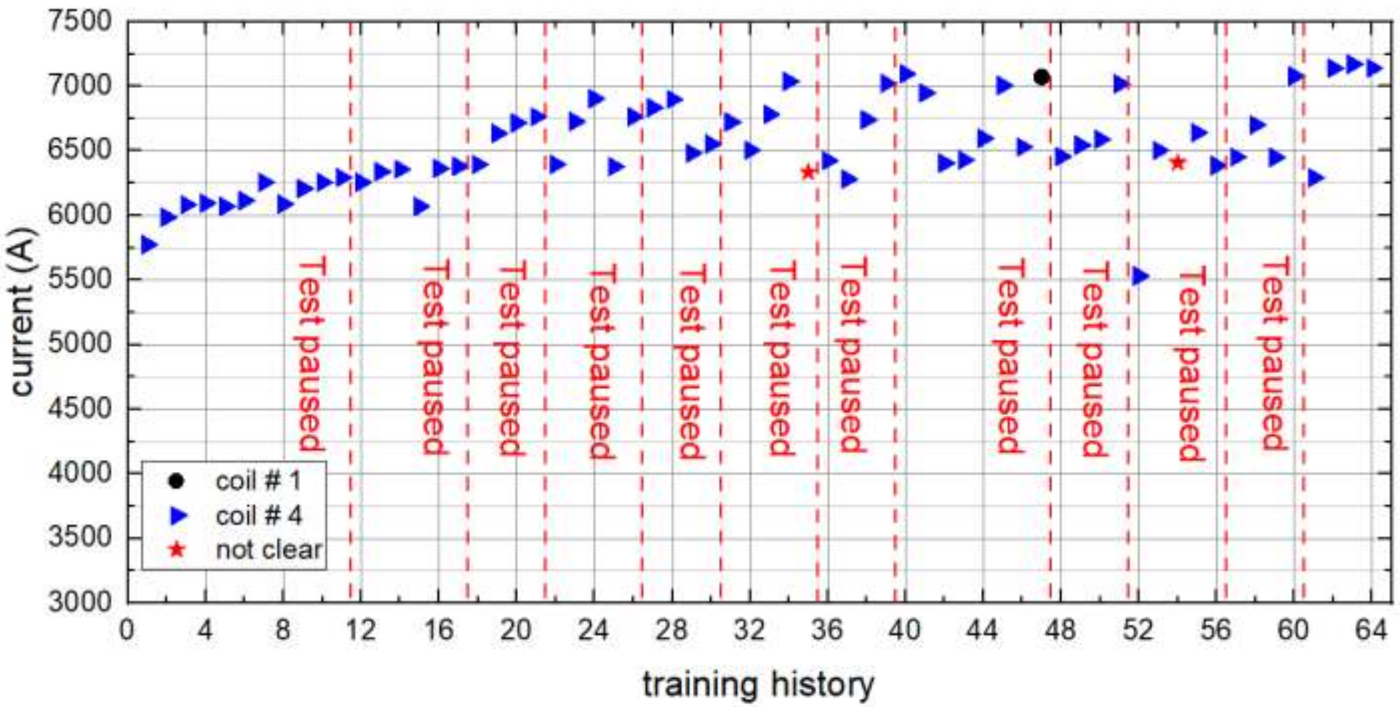


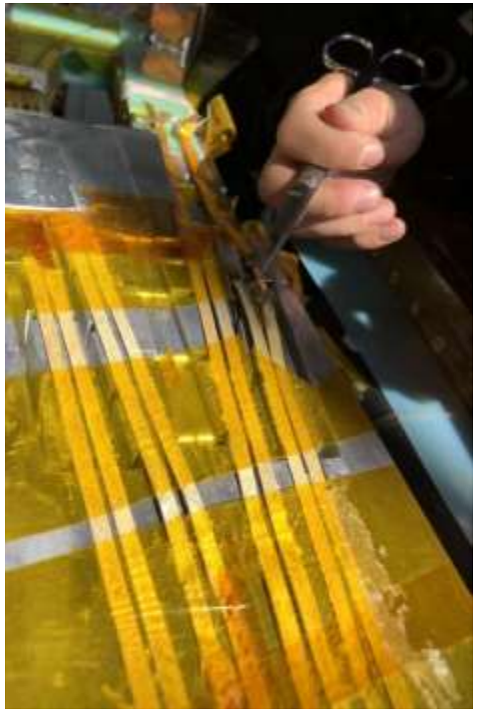


Development of the 16-T Model Dipole LPF3

The 2nd Performance test in Feb 2024

- The Nb_3Sn coils showed very unstable performance in the 6300-7000 A region due to one of the inner most coils, but finally passed this region and reached ~87% of I_{op} in the beginning of March 2024
- HTS block coil was ramped independently to 120% of I_{op} to test its ultimate performance, but one of the lead was damaged due to the quench.





Development of the 16-T Model Dipole LPF3

Accident in Mar 14 2024

- The operator **forgot to follow the most important step of the test manual**: turn on the quench detection system, and powered the Nb_3Sn coils to high current directly. **2 of 6 Nb_3Sn coils were serious damaged during a quench**
- Plan for next months: **establish a hardware interlock protection system**, and re-fabricate 2 new **Nb_3Sn coils and 2 HTS coils,** to reach 16 T by the end of 2024

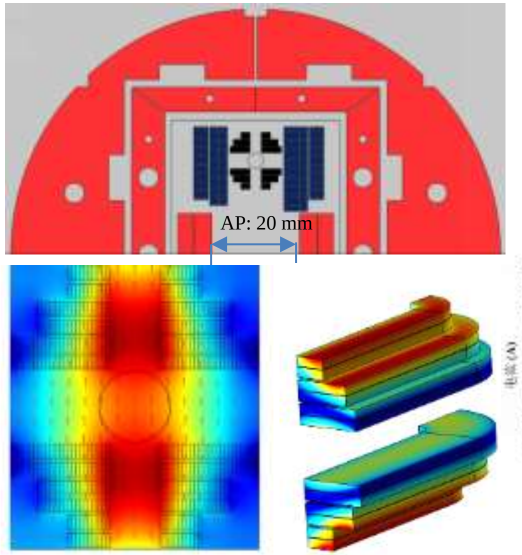


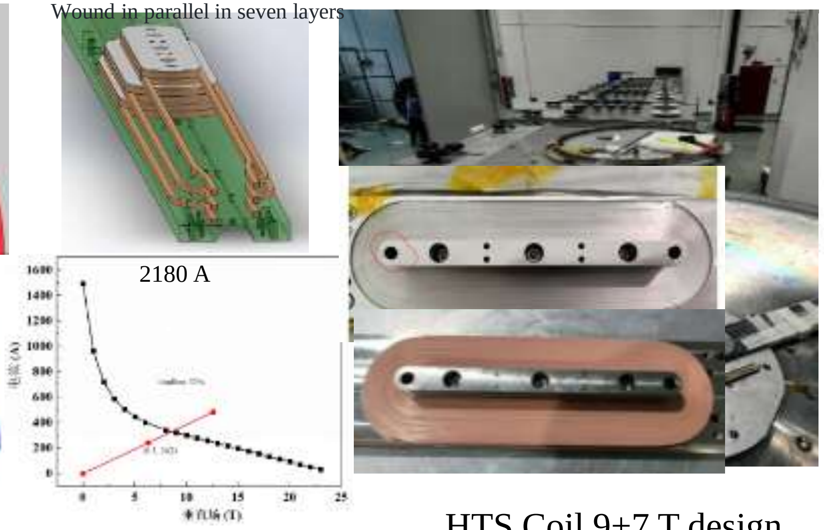

Development of the 16-T Model Dipole LPF3

Fabrication of the new Nb_3Sn & HTS Coils

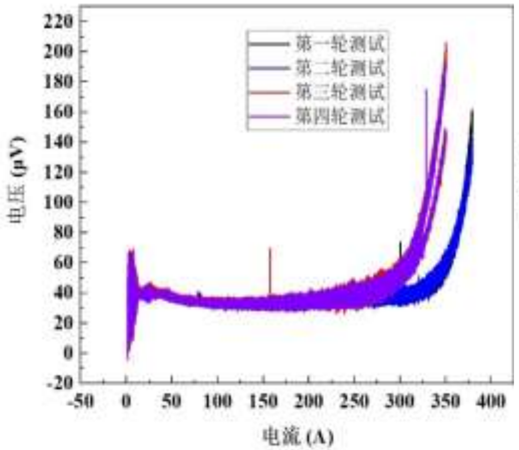
Reassembly of the LPF3 magnet start from Oct., to be tested in Nov and Dec 2024

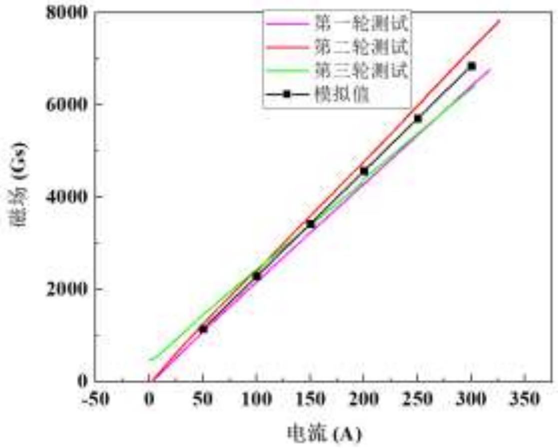
已完成新的铌三锡线圈所需的20芯、24芯、26芯及42芯卢瑟福缆的制作，线圈的绕制、热处理及固化





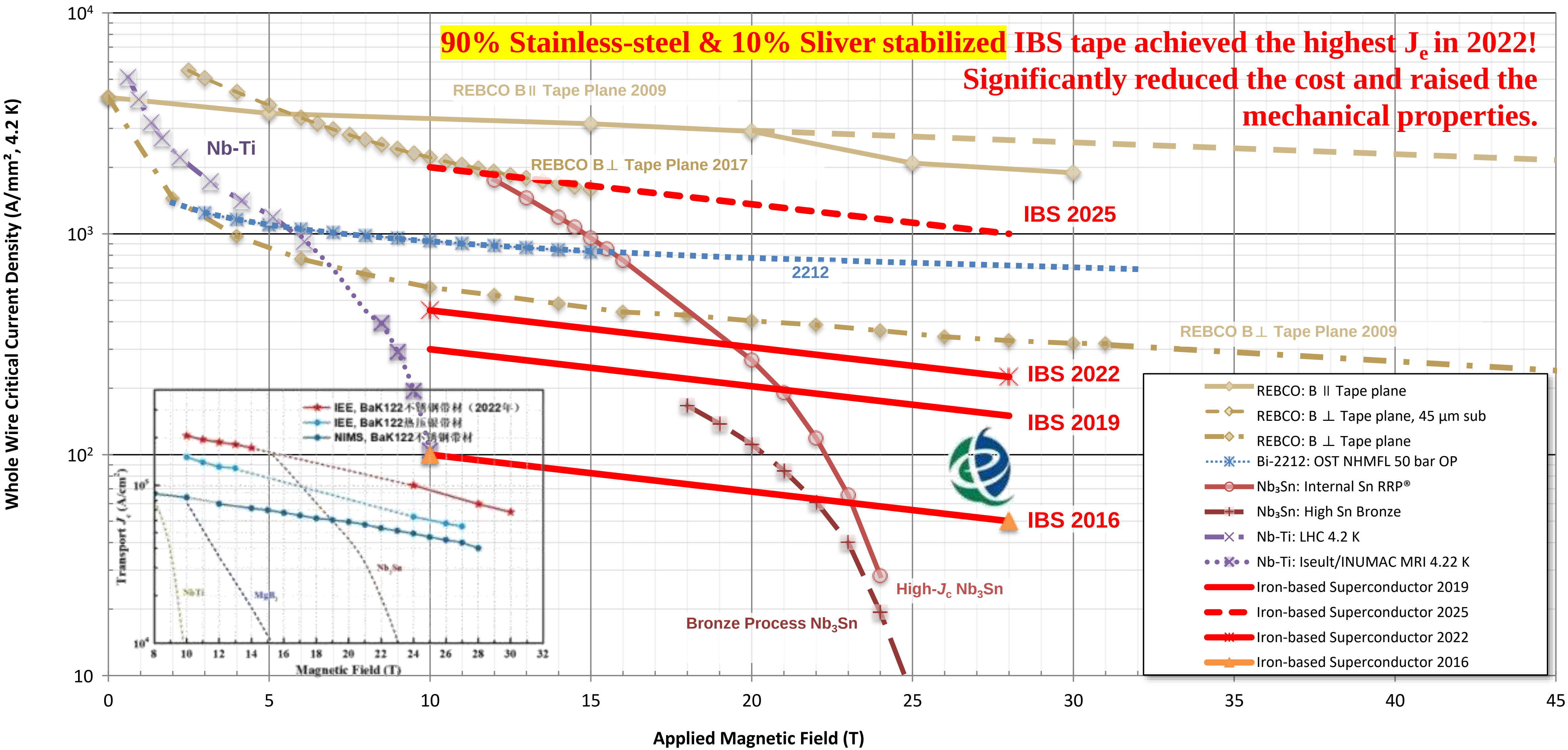
HTS Coil 9+7 T design





已完成新HTS 线圈的制作，液氮测试结果达到设计值

IBS Technology: Status and Outlook

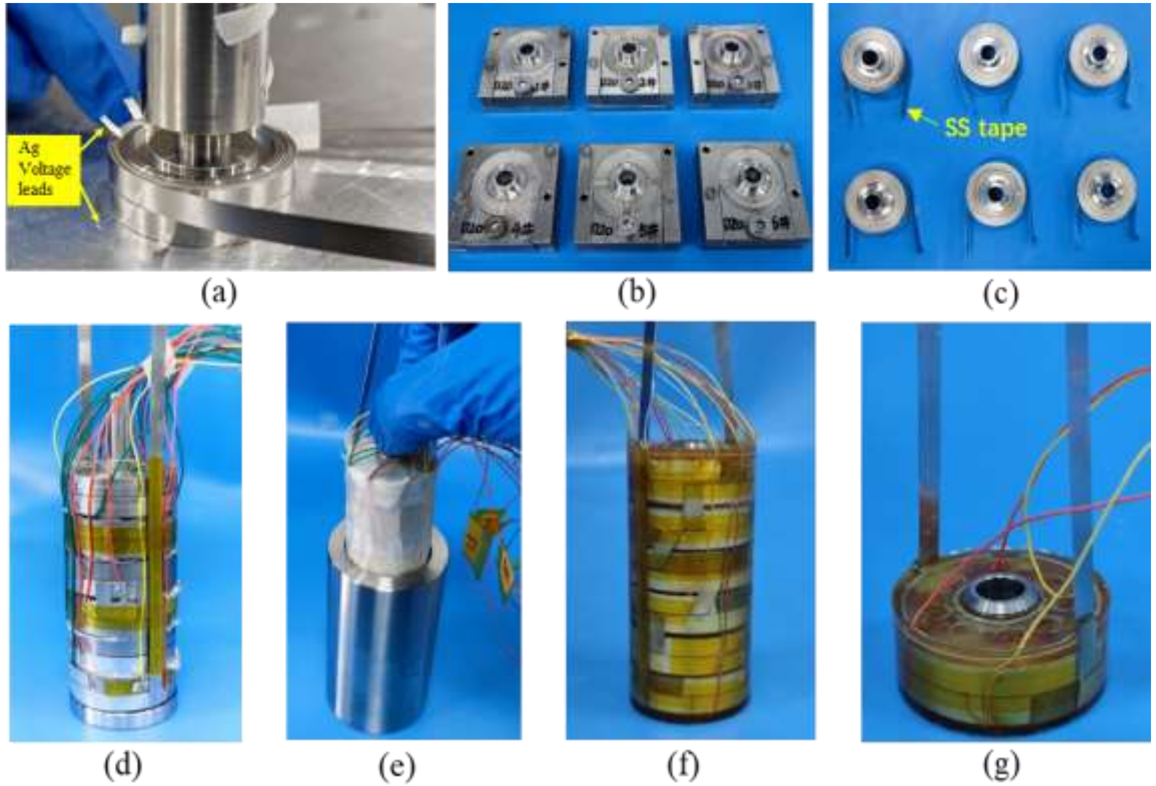


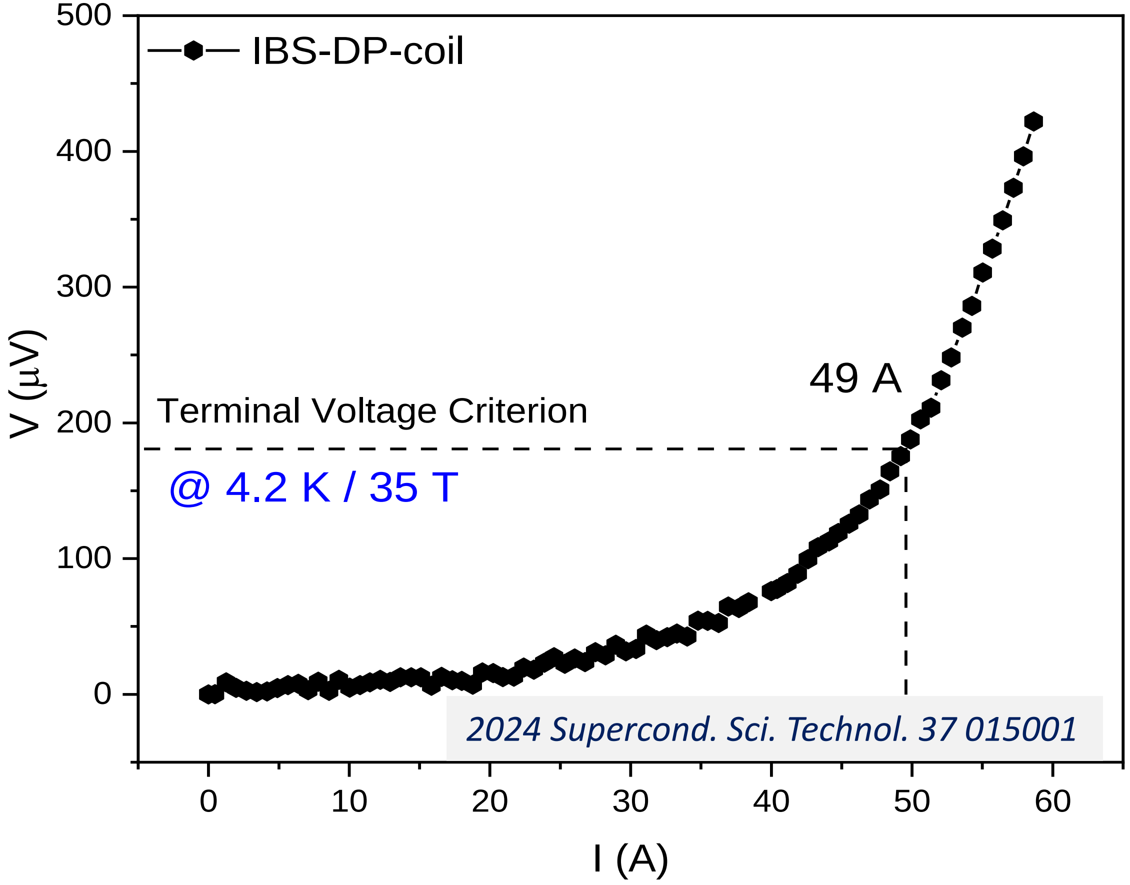
IBS Technology: Status and Outlook

The First IBS Solenoid Coil at 32 T background field

Chunyan Li et al

I_c of Φ34mm-17 turns-DPC reached **49 A at 4.2 K and 35 T, world's highest record up to now**



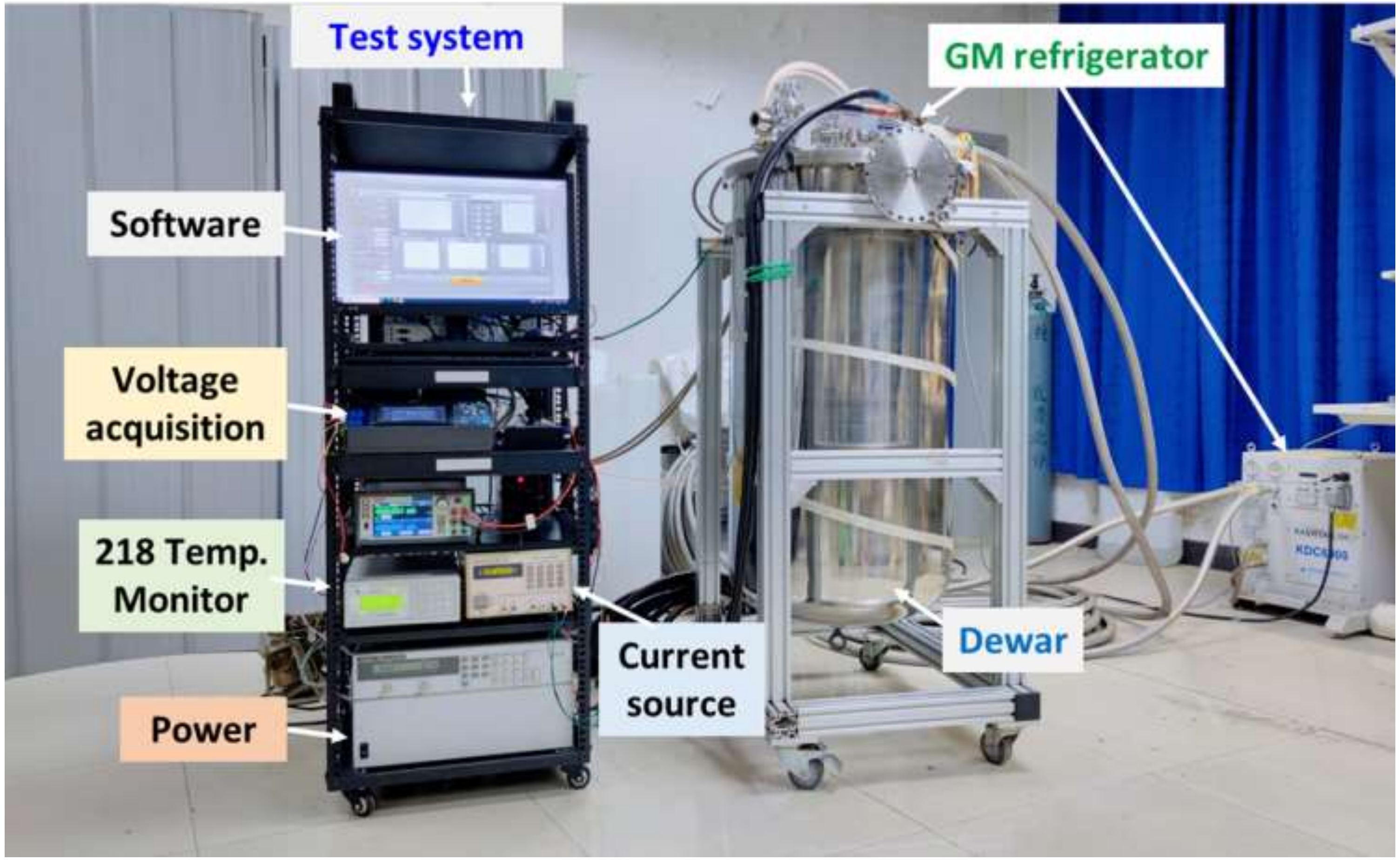


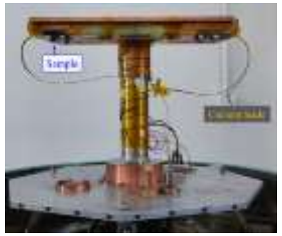
Successfully fabricated double pancake coils and a series-connected coil consisting of six DP coils

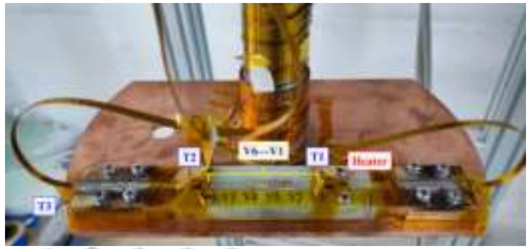
IBS Technology: Status and Outlook

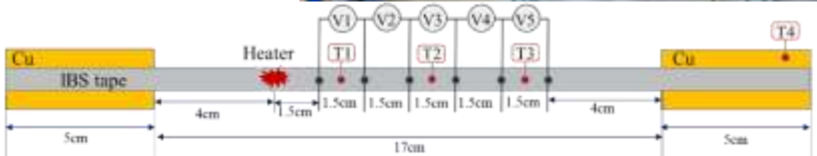
Quench propagation study of the IBS tapes and coils

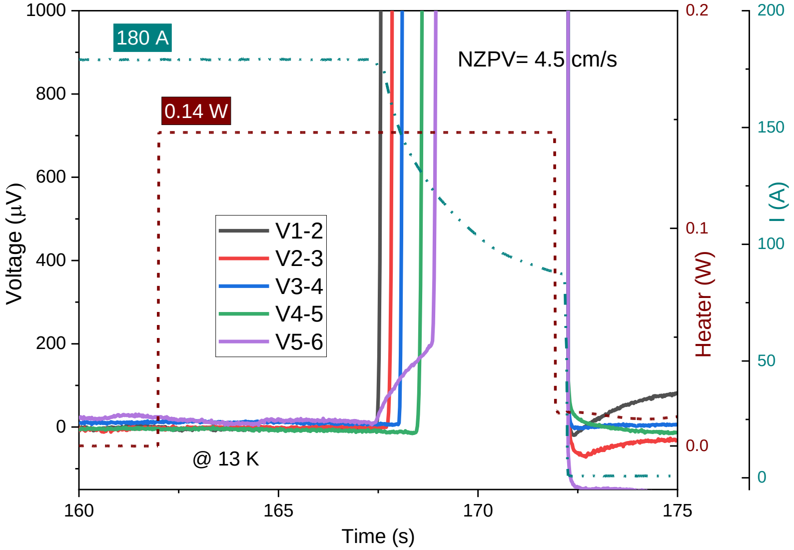
Chunyan Li et al











IBS Technology: Status and Outlook

Quench propagation study of the IBS tapes and coils

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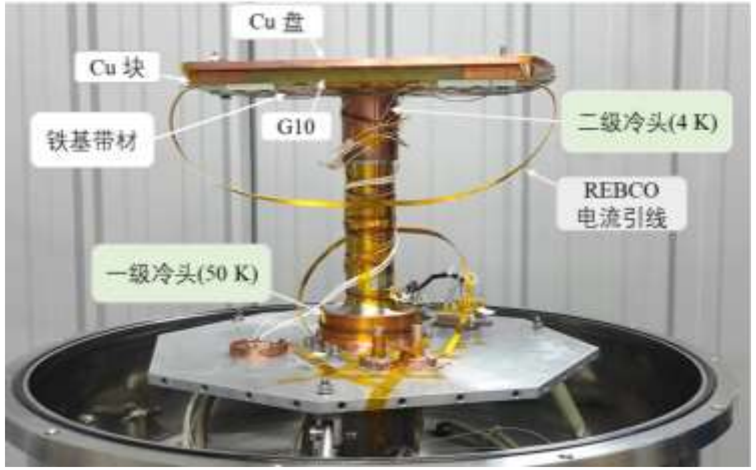
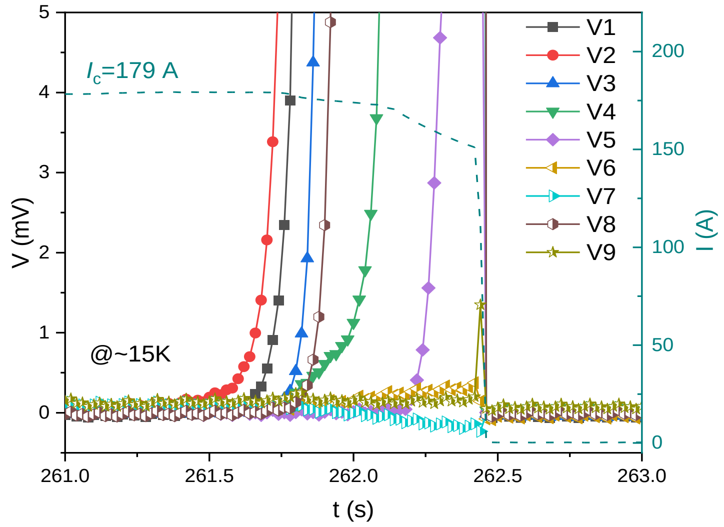
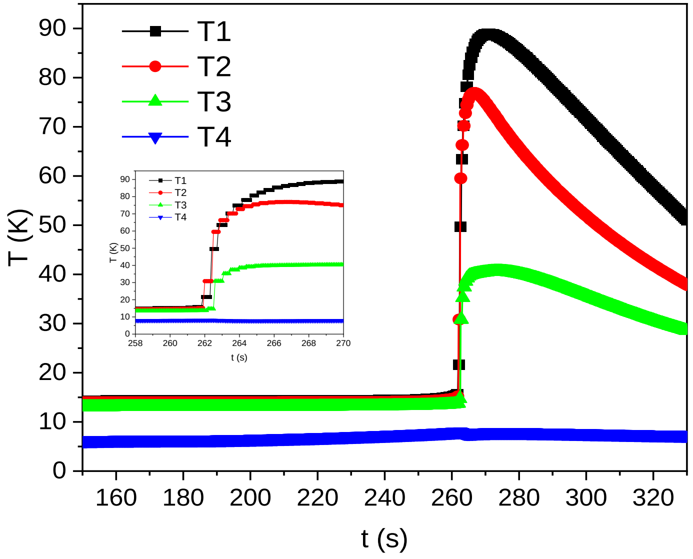
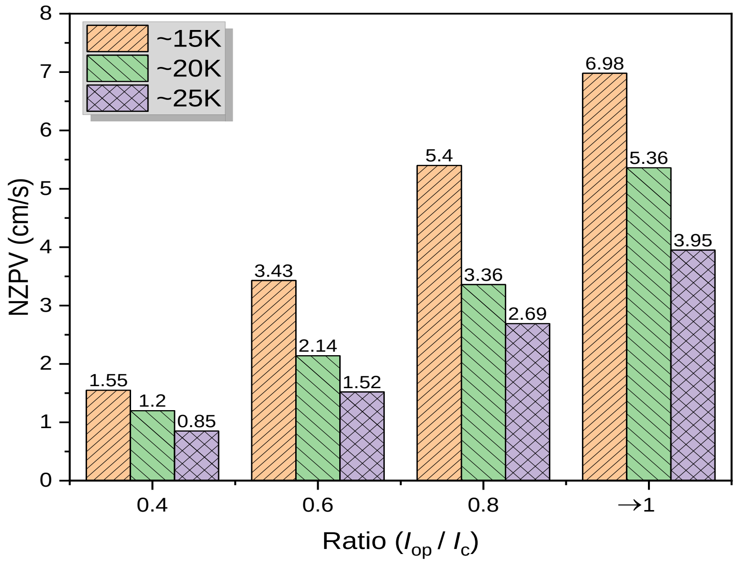
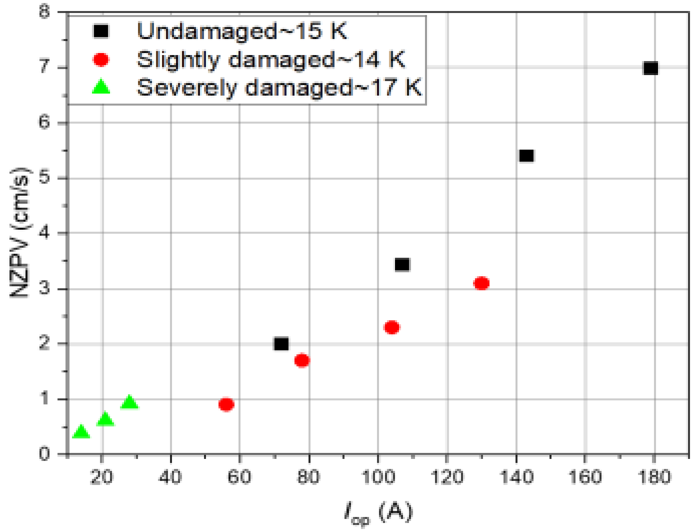








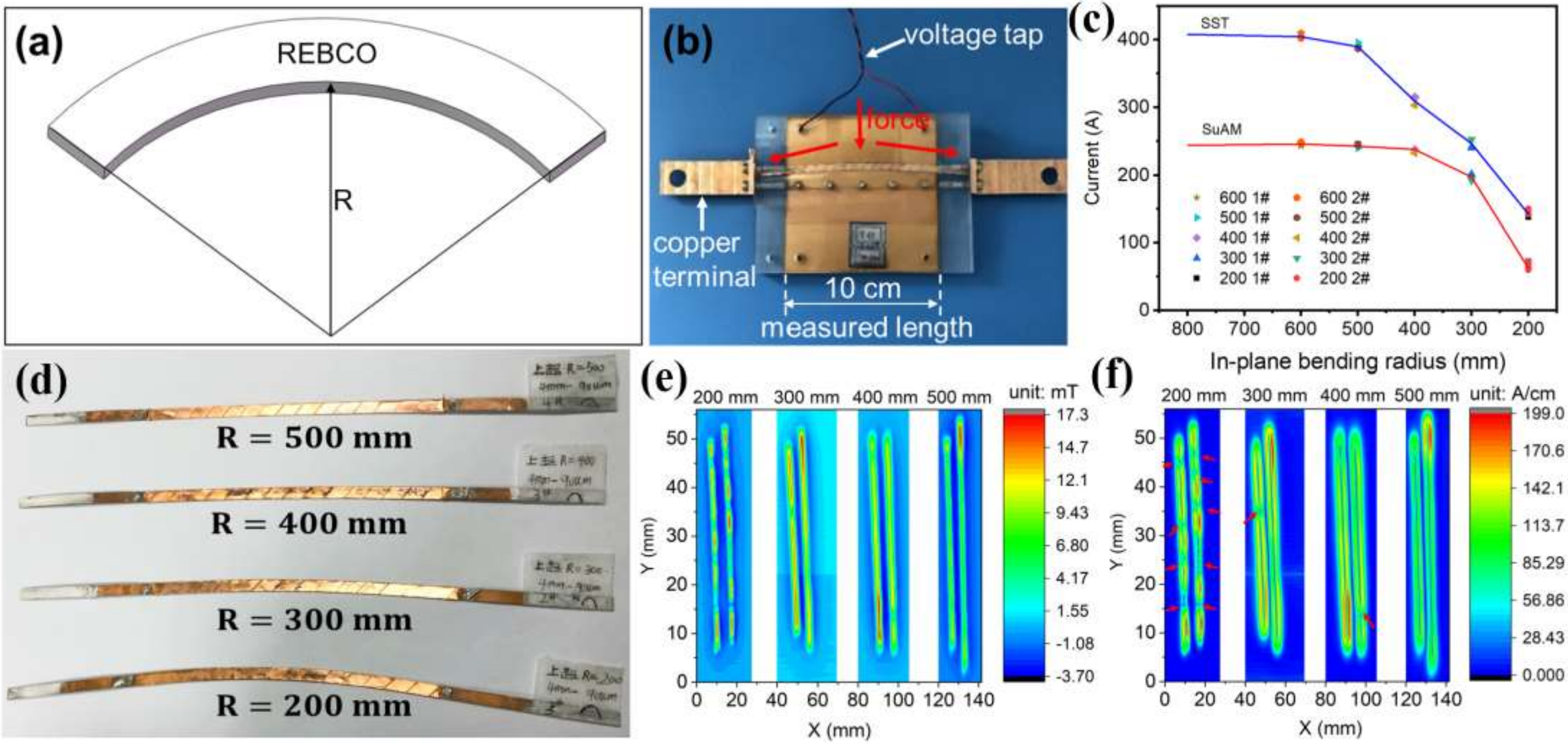


In 15~17K, when the transmission current of iron-based superconductor is 14-179A, the corresponding NZPV value is 0.4– 7cm/s

IBS Technology: Status and Outlook

Development of the kA class IBS transposed cable

Juan Wang et al



J. Wang et al, *Superconductivity* 3 (2022) 100019

IBS Technology: Status and Outlook

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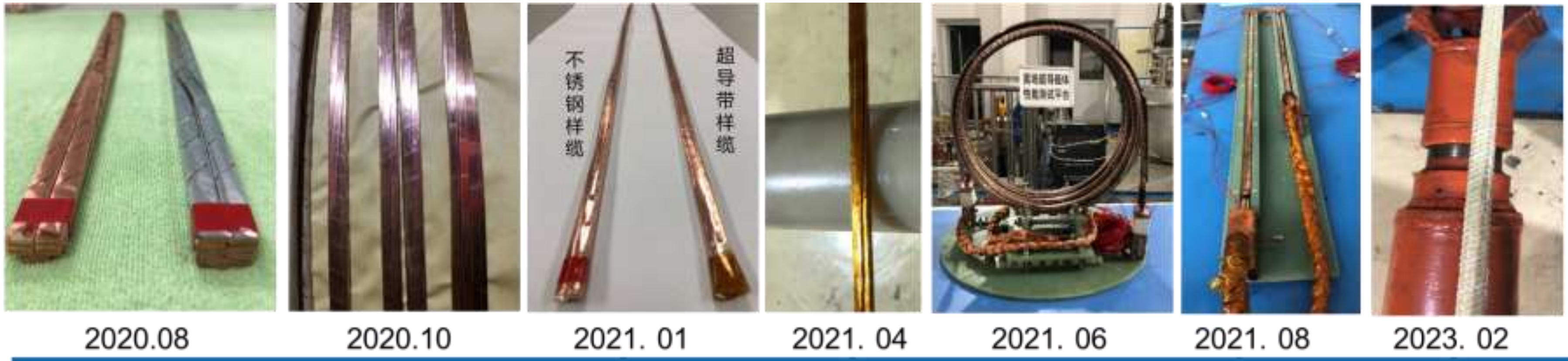


待解决问题：
1、单根（包含10根单带）绕包存在崩开现象；
2、内部以铜作为骨架，大大降低电流密度，后期需要去除骨架或将骨架变薄；

已解决问题：
1、解决单根绕包问题；
2、去除内部铜骨架；
待解决问题：
1、根据目前的换位问题优化换位设备；
2、缩短换位长度；

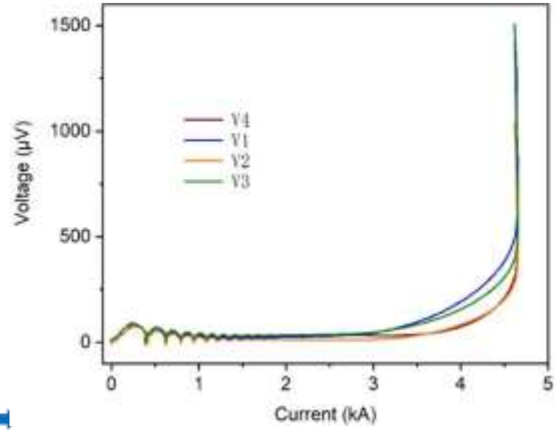
已解决问题：
通过不锈钢假缆，优化电缆参数，

10 m REBCO 换位电缆

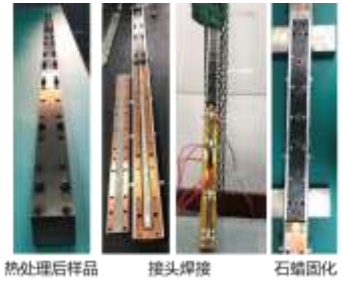
5 m IBS 换位电缆

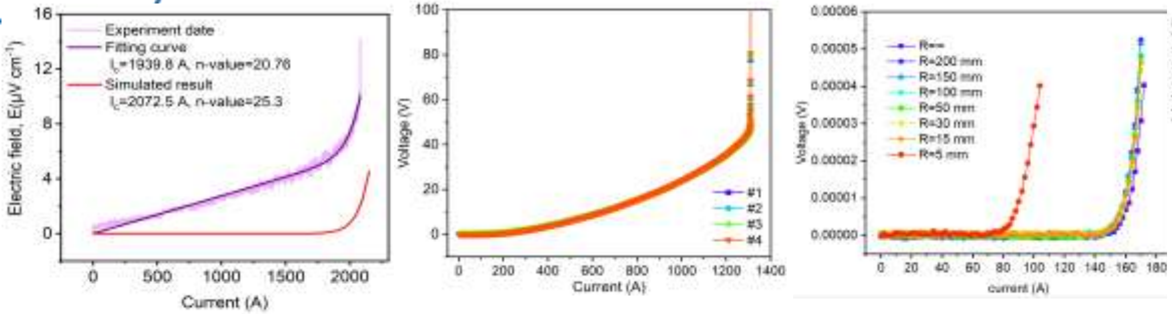
6 m IBS 换位电缆

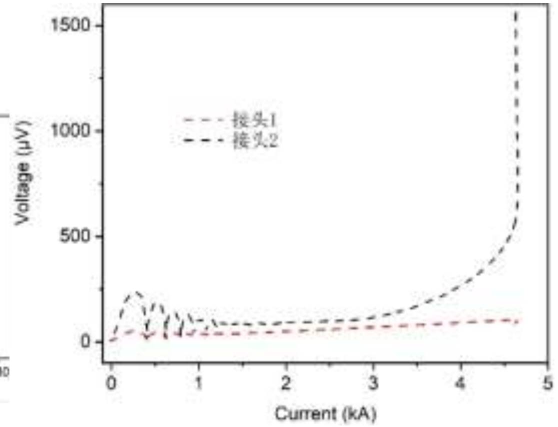
30 m REBCO 换位电缆



4.2K@0.5T IBS换位电缆载流性能达到4660A

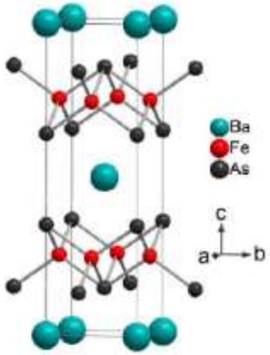




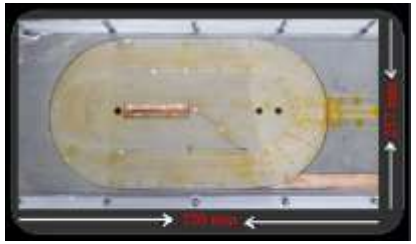


IBS Technology: Status and Outlook

Z. Zhao
IBS (T_c 55K)



100-m 7-core IBS tape fabricated
J_e= 100 A/mm²
@ 10 T, 4.2 K



IBS solenoid at 32 T
Racetrack at 10 T
1.3 kA transposed cable
J_e > 450 A/mm²
@ 10 T, 4.2 K

2008.02 — Discovery of IBS

2008.04

2008.09 — Discovery of 122 phase IBS

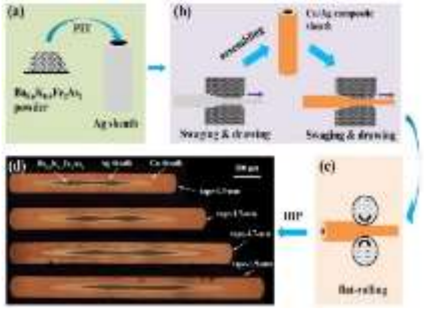
2016

2018 — IBS solenoid at 24 T, Racetrack at 8 T, J_e= 300 A/mm² @ 10 T, 4.2 K

2020

2022

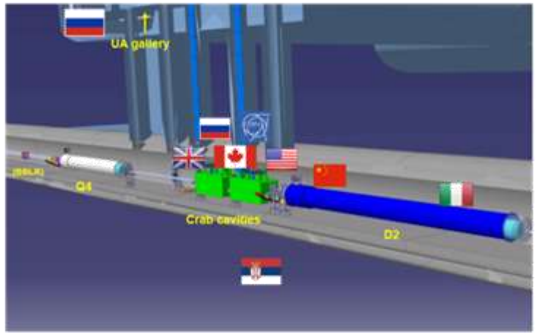
H. Hosono
IBS (T_c 26K)



J_e of IBS expected to be similar as ReBCO in 5 years with better mechanical properties and lower cost

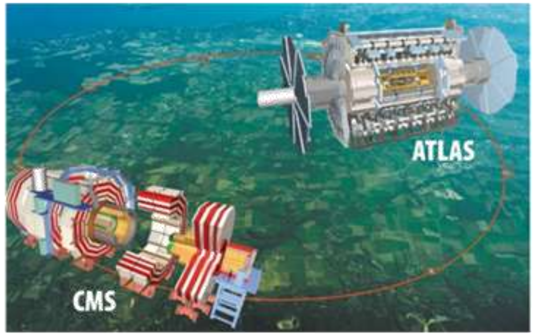
Development of CCT Magnets for HL-LHC

Milestone of the HL-LHC CCT Magnet Project



Agreement signed btw IHEP and CERN

The CCT magnet from China under test at CERN



Installation to tunnel

2018 — Agreement signed btw IHEP and CERN

2020 — The qualified prototype delivered to CERN

2022 — The CCT magnet from China under test at CERN

2024 — All the 12 series CCT magnets delivered to CERN

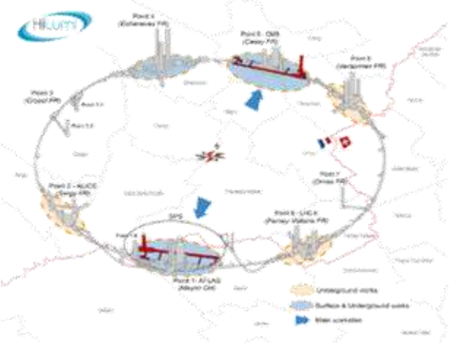
2026 — Installation to tunnel

2027 — HL-LHC commissioning

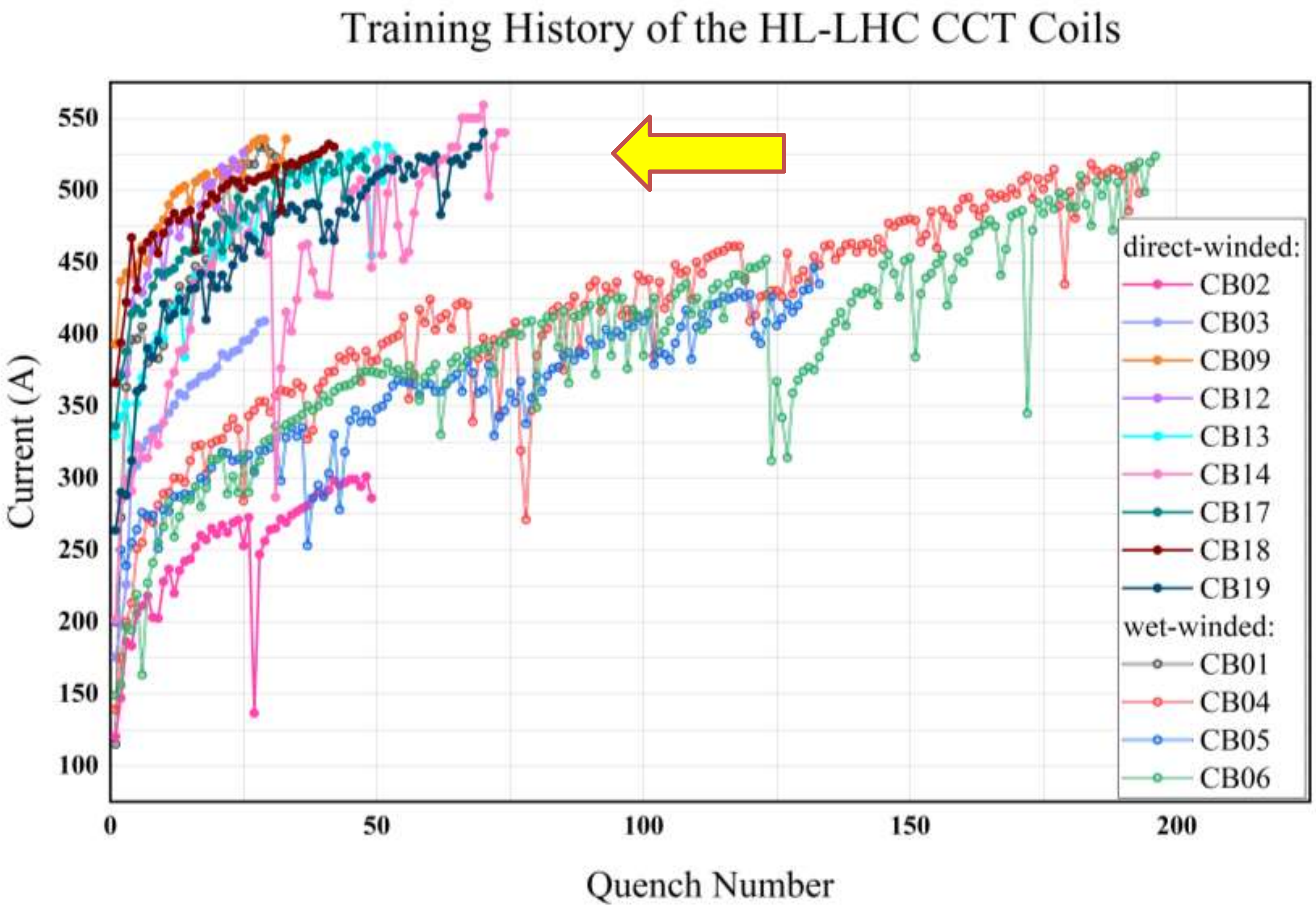
The qualified prototype delivered to CERN

All the 12 series CCT magnets delivered to CERN

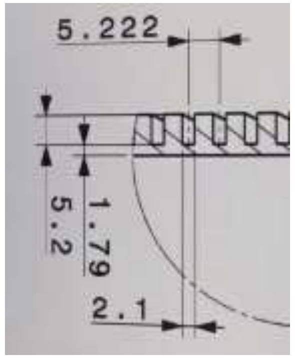
HL-LHC commissioning

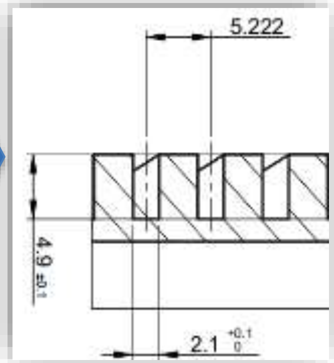


Development of CCT Magnets for HL-LHC



Successful design upgrade to solve the "long training problem", significantly reduced the times of quench during training, ensured the project progress "on track".





Development of CCT Magnets for HL-LHC

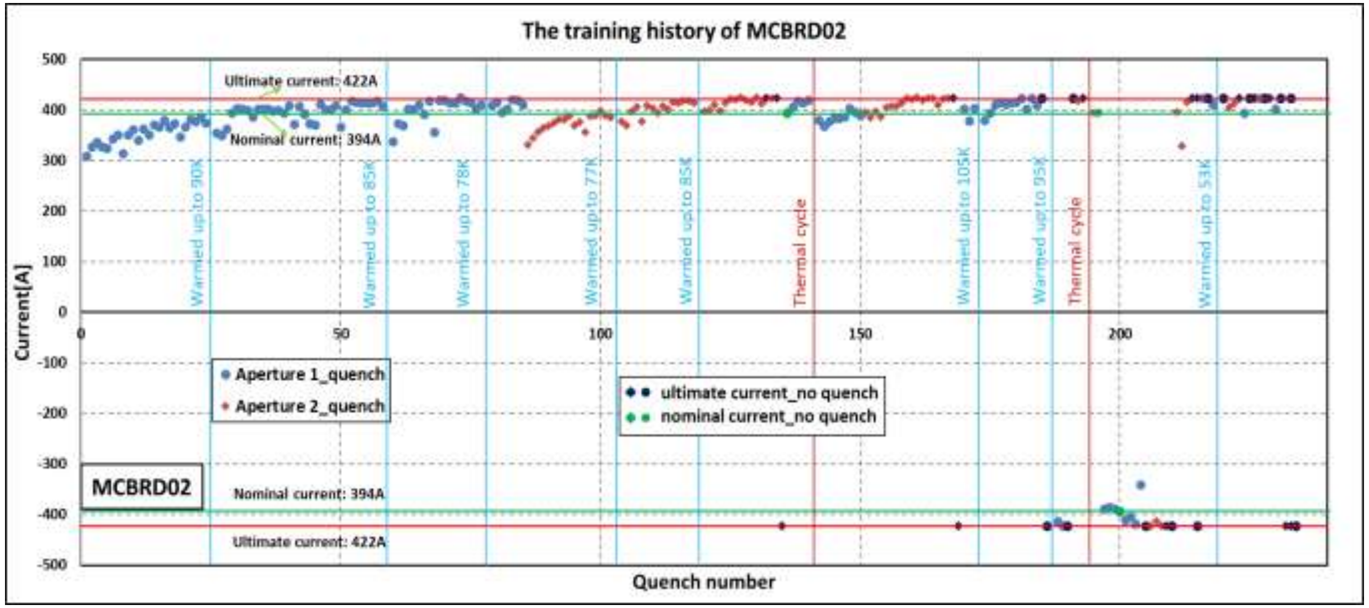
Training of MCBRD02 & MCBRD03

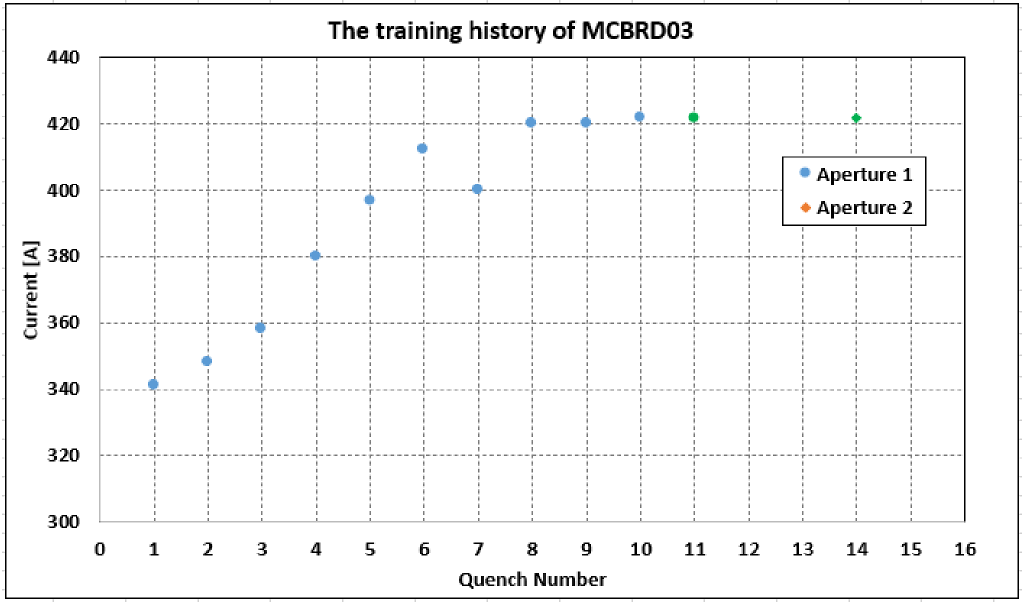
苏州八匹马超导科技有限公司





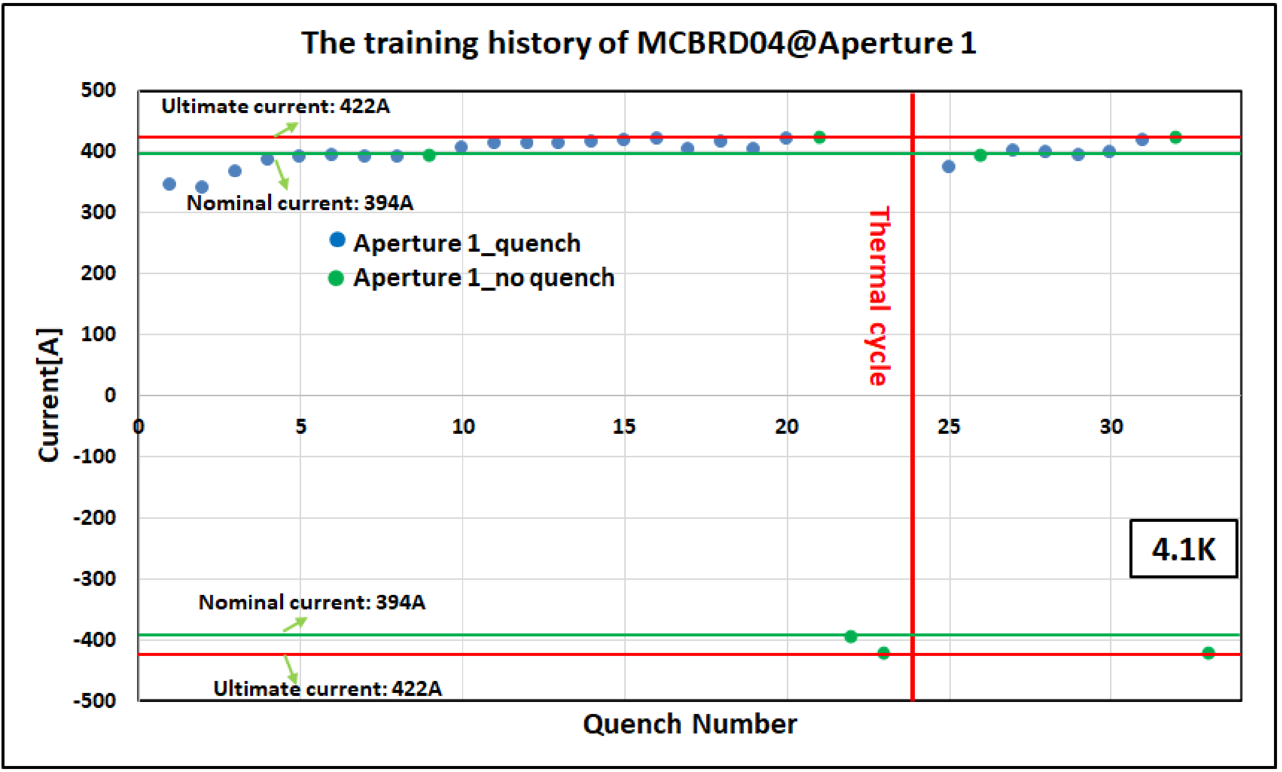
- AP1(CB12，25 quenches 526A) reached ±422A after 11 quenches.
- AP2(CB09, 33 quenches 530A; after thermal cycle ＞500A) reached ±422A without any quenches.

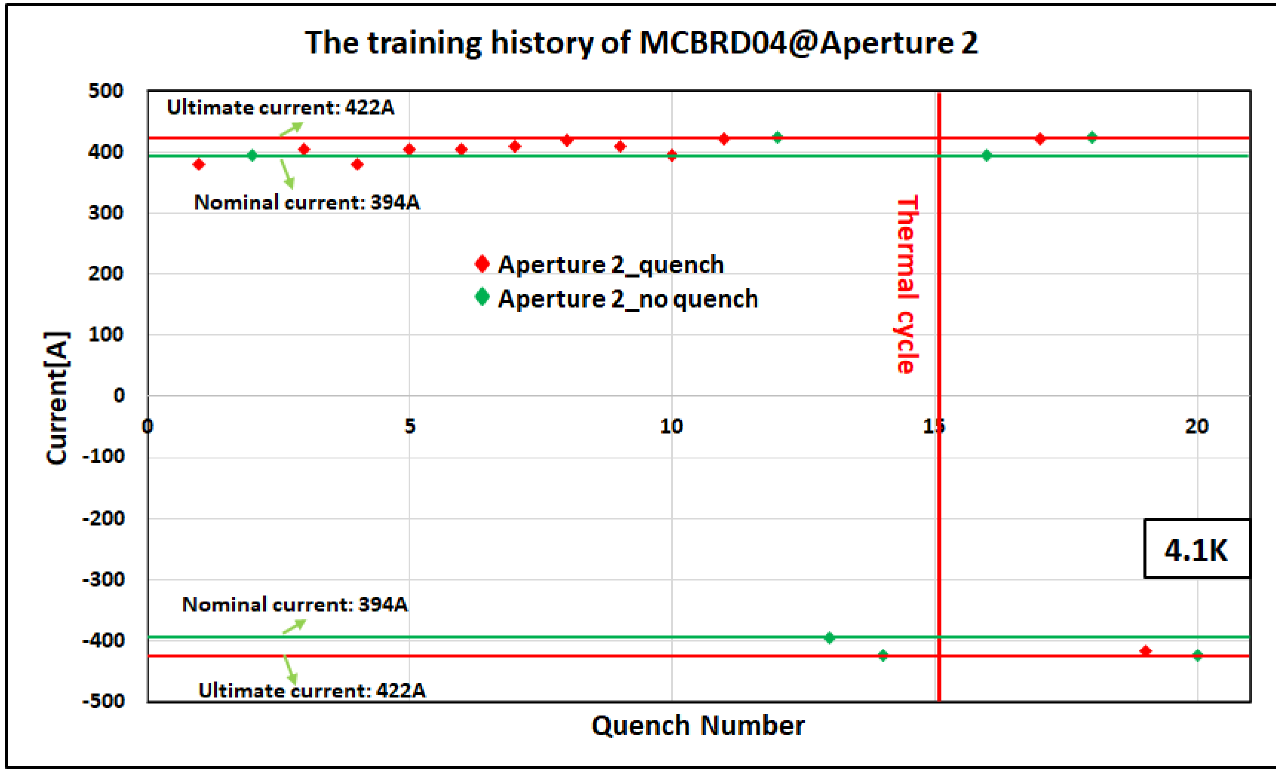




Training of MCBRD04

Satisfying performance at 4 K for both apertures, tested at IMP-CAS





Development of CCT Magnets for HL-LHC

- 6 series CCT magnets have been fabricated, successfully reached the design target and delivered to CERN
- Production rate for the rest of series magnets: every 3 month per magnet; to be completed by Oct 2025

	Coil name		Winding method	Location	Coil stand-alone performance (4.2 K)		Magnet performance at 4.2 K
MCBRD01	AP1	MCBRD_CB01	Wet wind	CERN	530 A		Both apertures reached ultimate current 422 A, and passed 4-hour stability test
	AP2	MCBRD_CB03	Direct wind		410 A		
MCBRD_CB02			Direct wind	CERN	Failed to reach the design current		
MCBRD02	AP2	MCBRD_CB04	Wet wind	CERN	422 A		Both apertures reached ultimate current 422 A, and passed 4*1 hour stability test
	AP1	MCBRD_CB06	Wet wind		530 A		
MCBRD_CB05，07，08			Wet wind	IHEP			
MCBRD03	AP2	MCBRD_CB09	Direct wind with new channel size	CERN	530 A		Both apertures reached ultimate current 422 A, and passed stability test
	AP1	MCBRD_CB12	Direct wind with new channel size		526 A (25 quenches)		
MCBRD04	AP2	MCBRD_CB13	Direct wind with new channel size	CERN	530 A (20+33 quenches)		Both apertures reached ultimate current 422 A, and passed stability test
	AP1	MCBRD_CB17	Direct wind with new channel size		524 A (47 quenches)		
MCBRD_CB10, 11, 15, 16			Shipped to CERN for fabrication				
MCBRD05	AP1	MCBRD_CB18	Direct wind with new channel size	IMP	532 A (42 quenches)		Assembled in April, *tested in October*
	AP2	MCBRD_CB19	Direct wind with new channel size		530A (68 quenches)		
MCBRD06		MCBRD_CB14	Direct wind with new channel size	BAMA	530 A (30+34 quenches)		*Assembled in September, (test @1.9K at CERN)*
		MCBRD_CB21	Direct wind with new channel size	BAMA	530 A (119quenches)		
MCBRD07		MCBRD_CB20	Direct wind with new channel size	BAMA	530A (68 quenches)		*Assemble in November (test @1.9K at CERN)*
		MCBRD_CB22	Direct wind with new channel size	IHEP	*Ready for stand-alone test*		
MCBRD08		MCBRD_CB23	Direct wind with new channel size	IHEP	*Ready for stand-alone test*		*Assemble in January 2025 (test @1.9K at CERN)*
		MCBRD_CB24	Direct wind with new channel size	BAMA	Waiting for VPI	VPI in new factory	
MCBRD09		MCBRD_CB25	Direct wind with new channel size	BAMA	*Dividing the SC wires*	All these apertures will be fabricated in the new factory of BAMA.	*Assemble in April 2025 (test @1.9K at CERN)*
		MCBRD_CB26	Direct wind with new channel size	-	*Fabrication in Aug.*		
MCBRD10		MCBRD_CB27	Direct wind with new channel size	-	*Fabrication in Oct.*		*Assemble in July 2025 (test @1.9K at CERN)*
		MCBRD_CB28	Direct wind with new channel size	-	*Fabrication in Dec.*		
-		MCBRD_CB29	Direct wind with new channel size	-	*Fabrication in next Feb.*		-

Summary

- Long-term advanced superconducting magnet R&D for future high-energy accelerators is ongoing at IHEP-CAS
- 16 T (Nb_3Sn+HTS) model dipole has been fabricated at IHEP-CAS and under performance test at 4.2 K. Re-fabrication of damaged coils completed in October 2024, reassembly and test from November 2024
- Strong domestic collaboration for the advanced superconductor R&D (HTS & Nb_3Sn): Stainless-steel-Silver stabilized IBS tape achieved the highest J_e in 2022! IBS coil I_c reached 49A at 35 T. 5kA class transposed cable developed.
- HL-LHC CCT magnets going well, to be installed in the tunnel from 2026

Thanks for your attention!