High Field Superconducting Magnet R&D for the High Energy Particle Accelerators at IHEP-CAS

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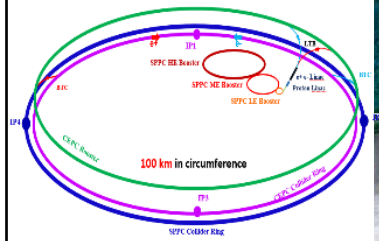
Accelerator Division, IHEP-CAS
May 2025

中国科学院
CHINESE ACADEMY OF SCIENCES

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 time	2012	2013
Site of the project	China	Europe
Baseline technology	IBS baseline 20~24 T to reach 125-150 TeV, Nb_3Sn+HTS as options	Nb_3Sn 14 T to reach 90 TeV Or Nb_3Sn+HTS to reach 20 T
Timeline	Construction at 2040s	Construction at 2050-60s
Cost	/	/

Roadmap of the High Field Magnet R&D at IHEP

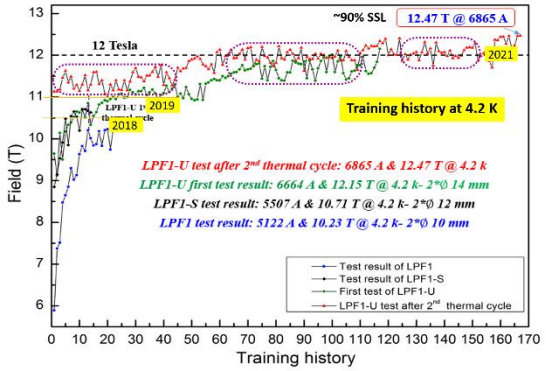
Field (T)

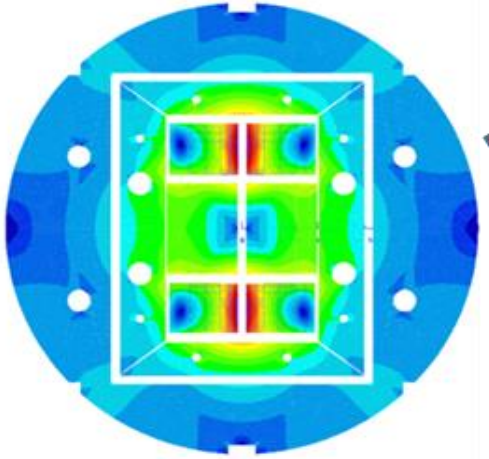
20

10

2018-2021, 12.47T @4.2K

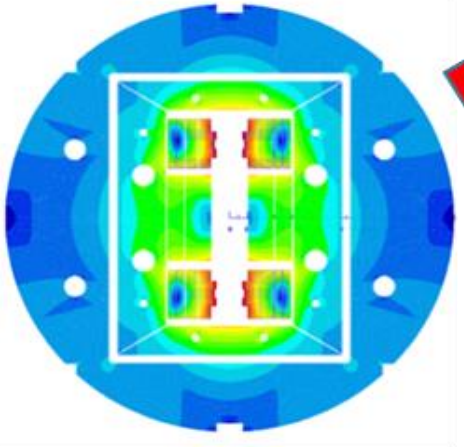
NbTi + Nb_3Sn

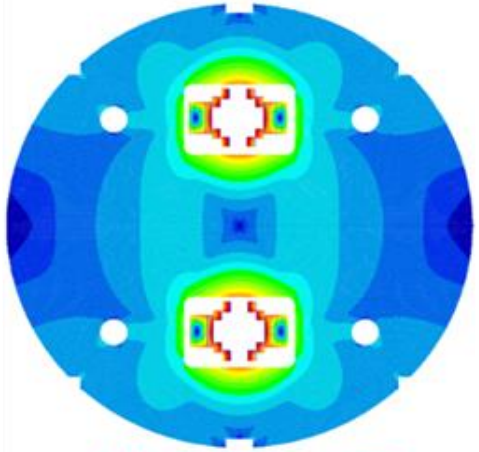




2021-2025 16T @ 4.2K

Nb_3Sn + HTS





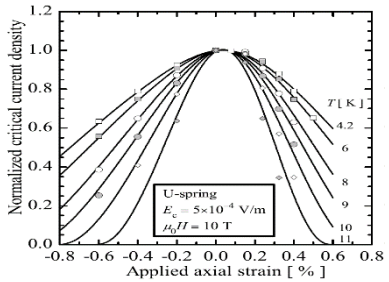
Nb_3Sn+HTS or HTS

2*ϕ45 aperture

20T @ 4.2K

With 10^{-4} field quality

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



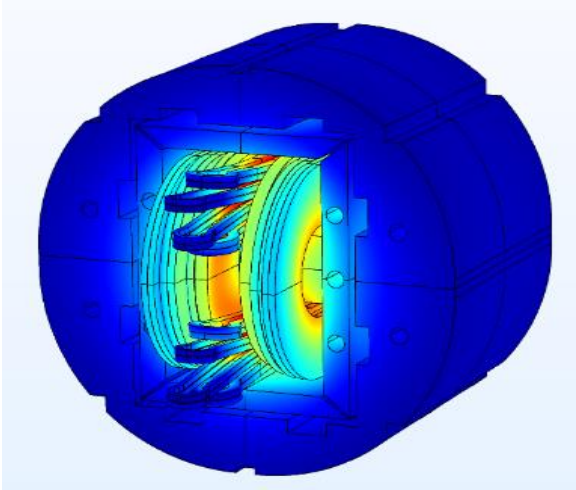
2018

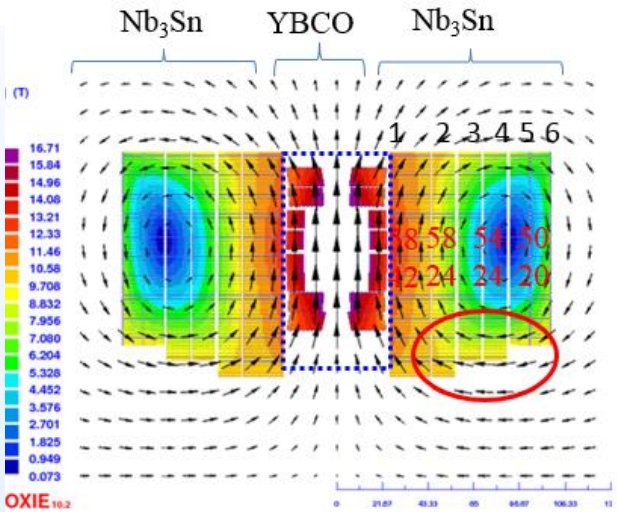
2028

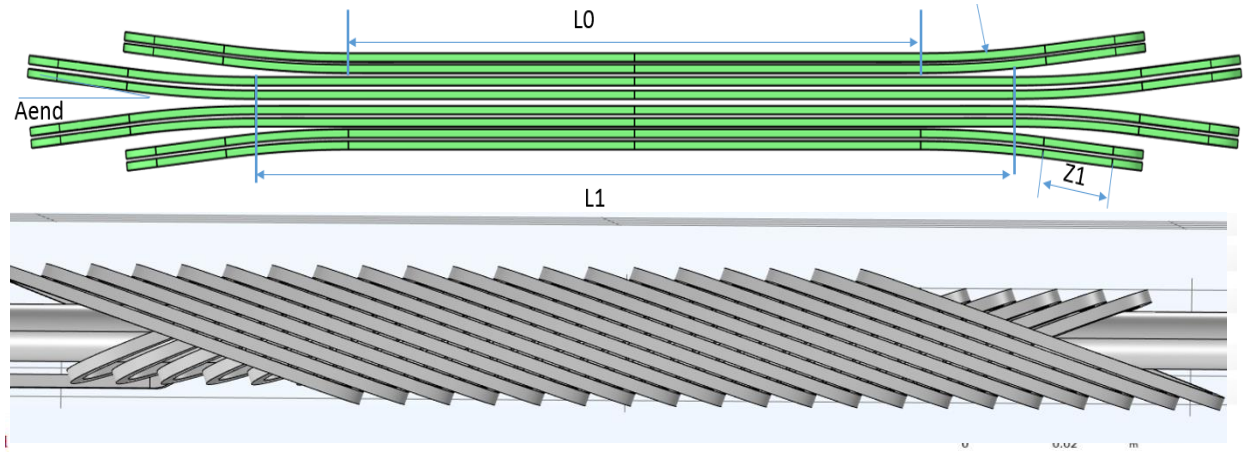
year

Development of the 16-T Model Dipole LPF3

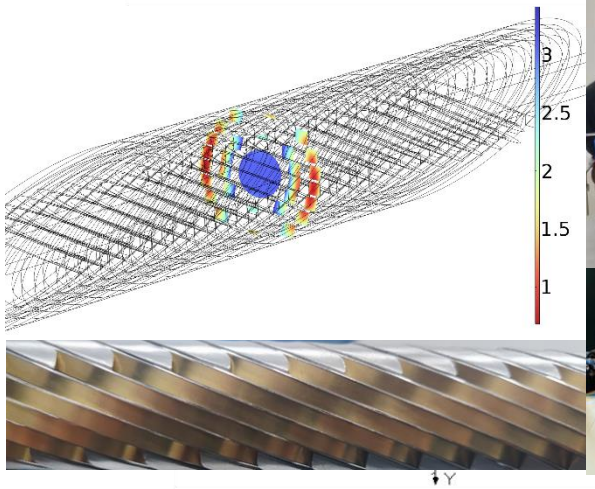
16 T Model Dipole LPF3: Nb_3Sn 13 T (*Common Coil with 55 mm gap*) + HTS 3 T inserts (*Block & CCT*)







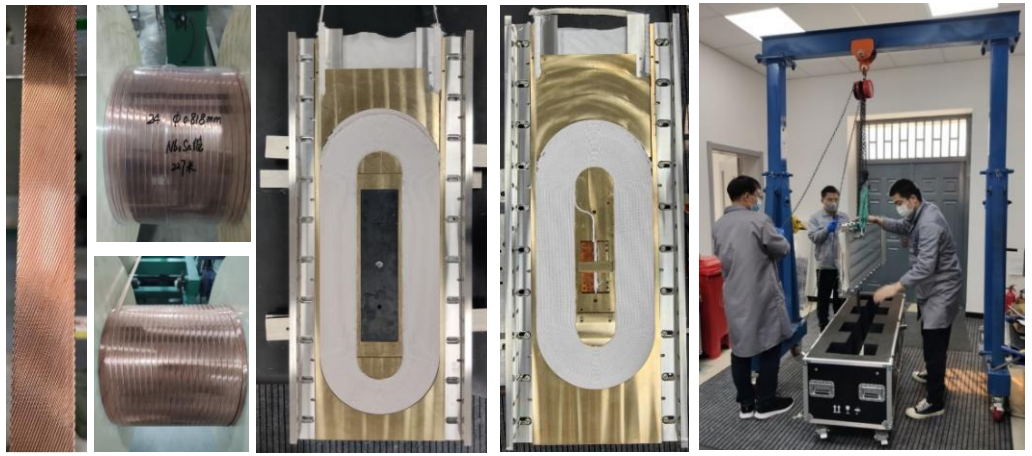
16-T 大孔径高场超导二极磁体 LPF3 (Nb_3Sn-13T+HTS-3T) 电磁设计

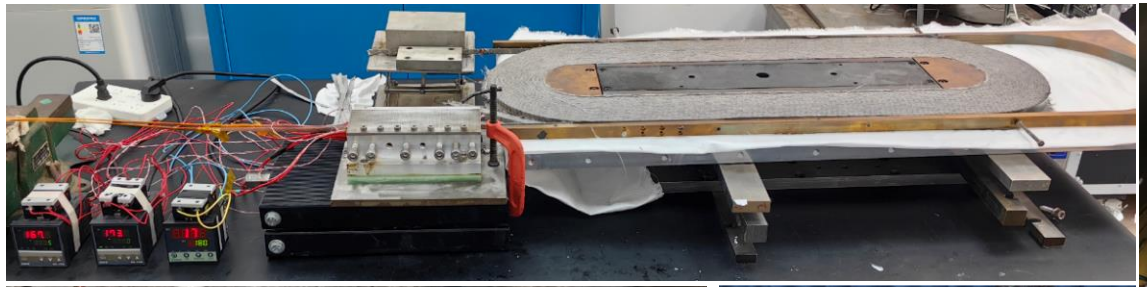


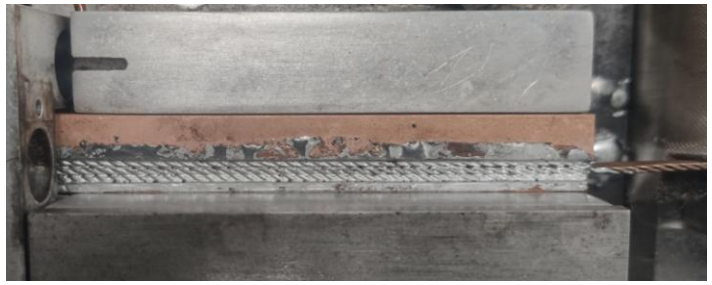
Development of the 16-T Model Dipole LPF3

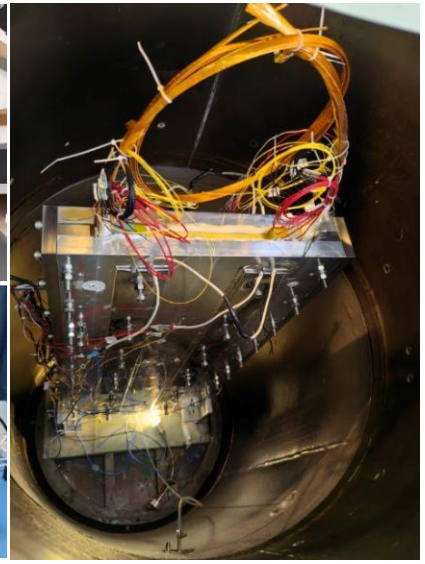
The Nb_3Sn coils for LPF3

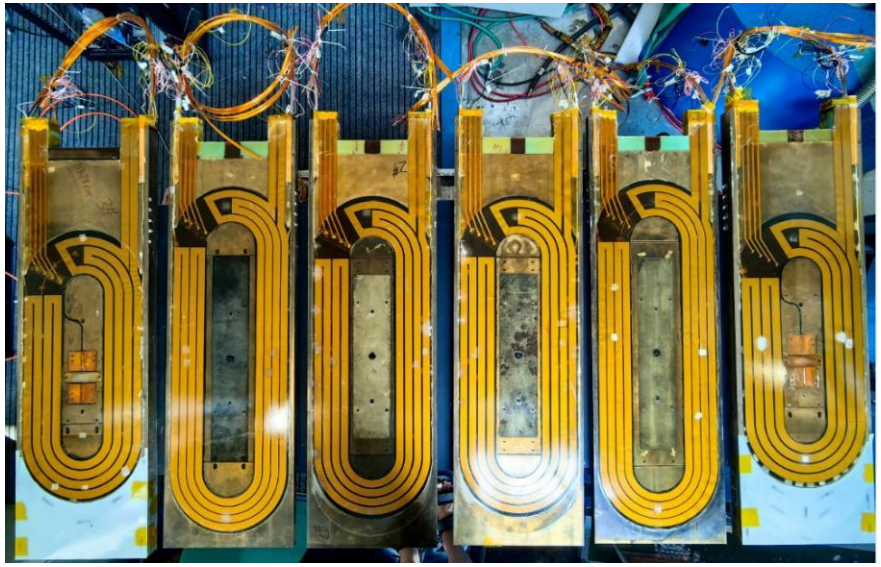
Chengtao Wang et al







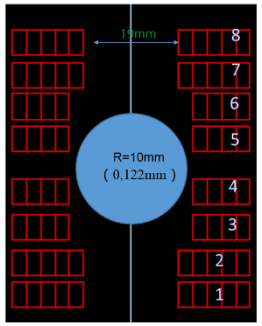


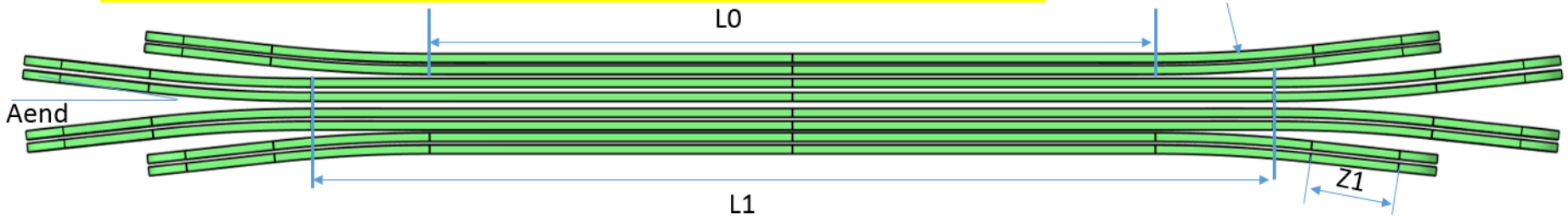


Development of the 16-T Model Dipole LPF3

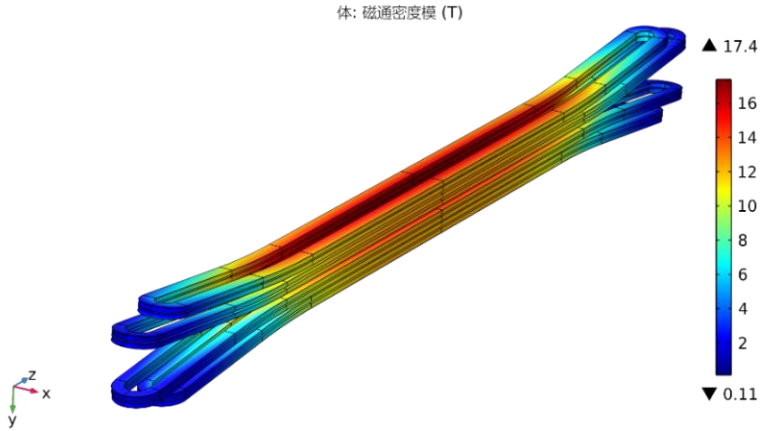
The ReBCO block insert coils for LPF3

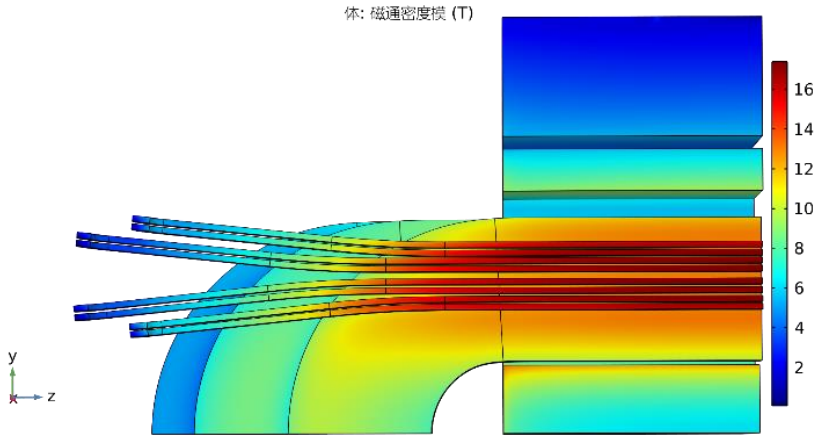
Ze Feng et al

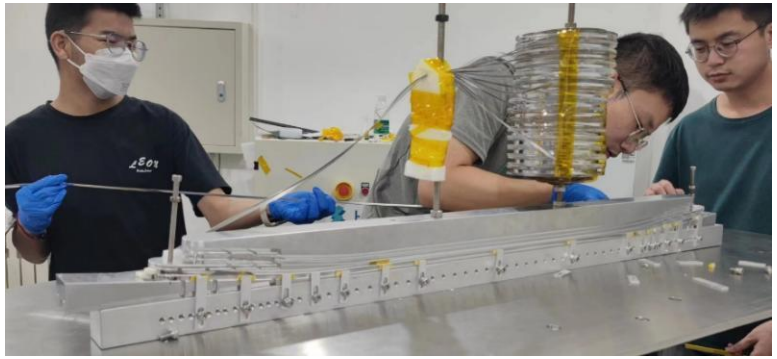


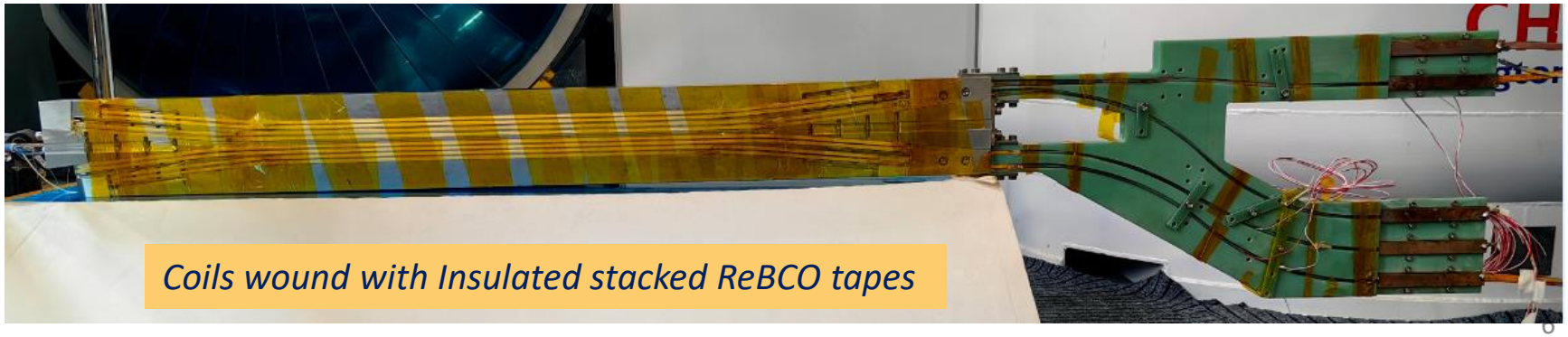


Parameters	Values
L0	409.6 mm
L1	540.2 mm
Rhard	800 mm
Aend	6 °
R1	9.5 mm
Z1	120 mm







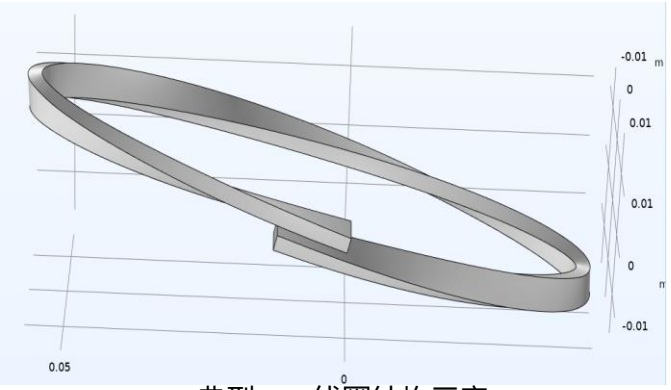


Coils wound with Insulated stacked ReBCO tapes

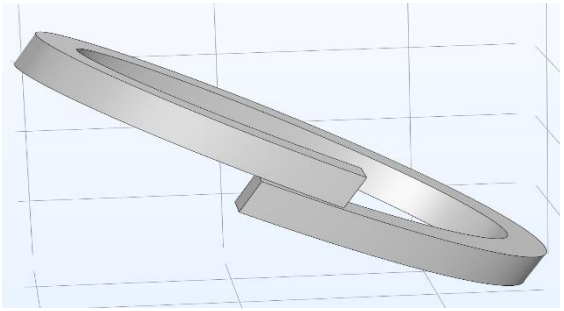
Development of the 16-T Model Dipole LPF3

The ReBCO CCT instert coils for LPF3

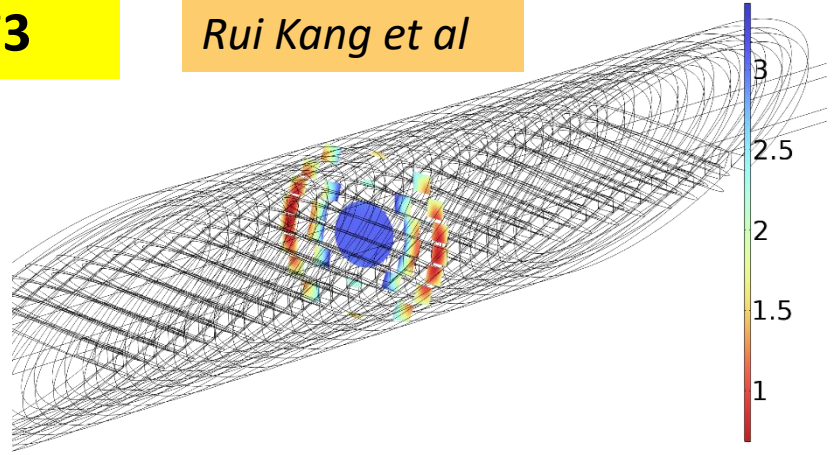
Rui Kang et al

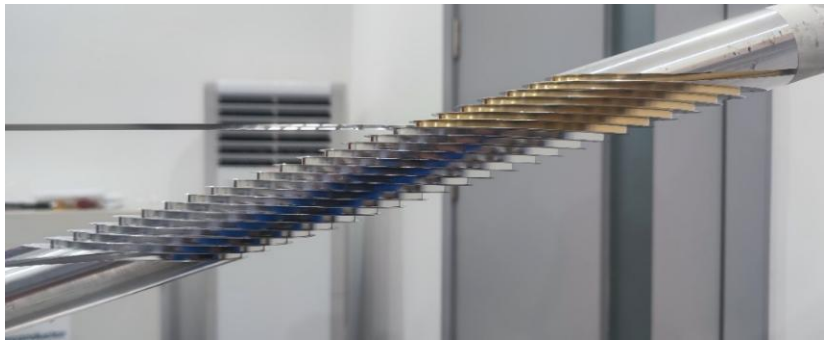


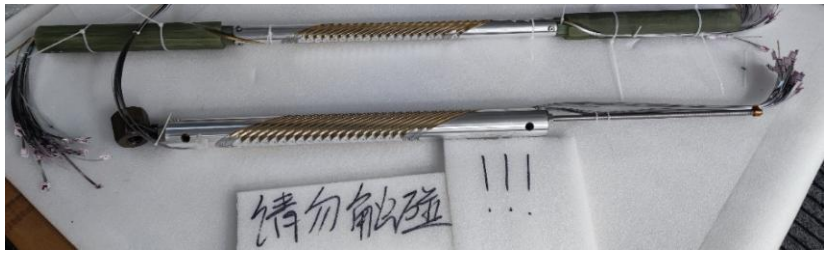
典型CCT线圈结构示意

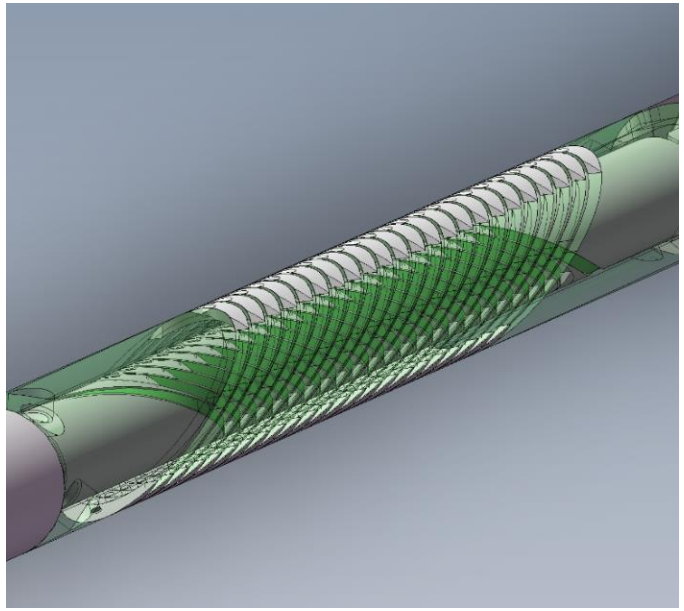


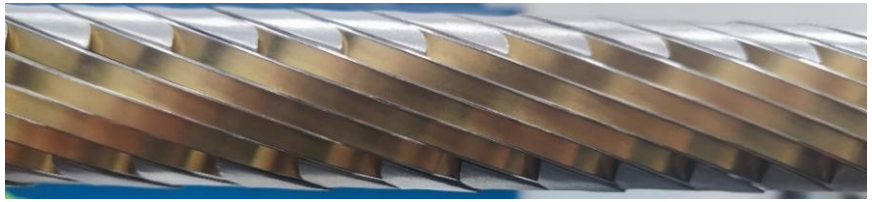
“斜螺线管”型CCT线圈结构示意







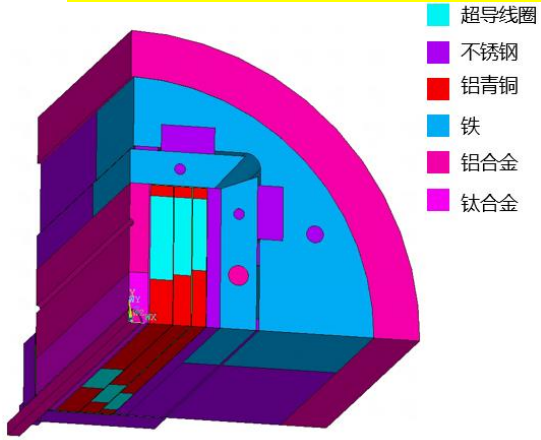


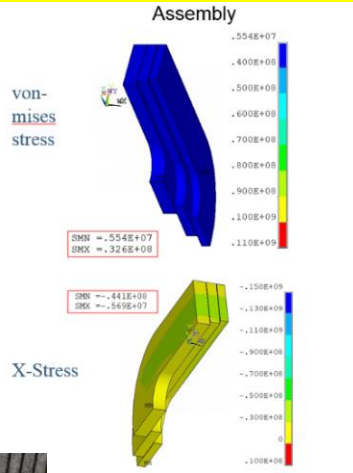


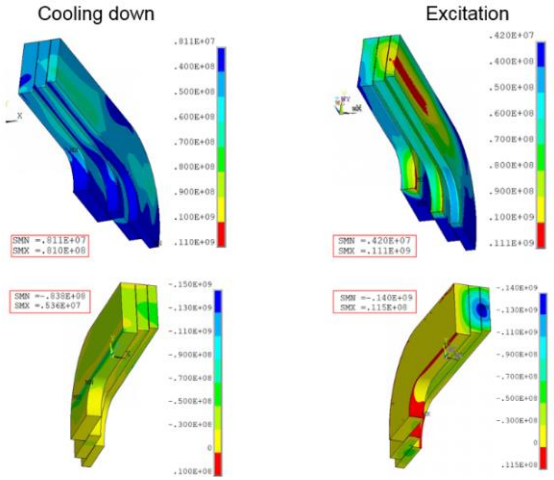
Development of the 16-T Model Dipole LPF3

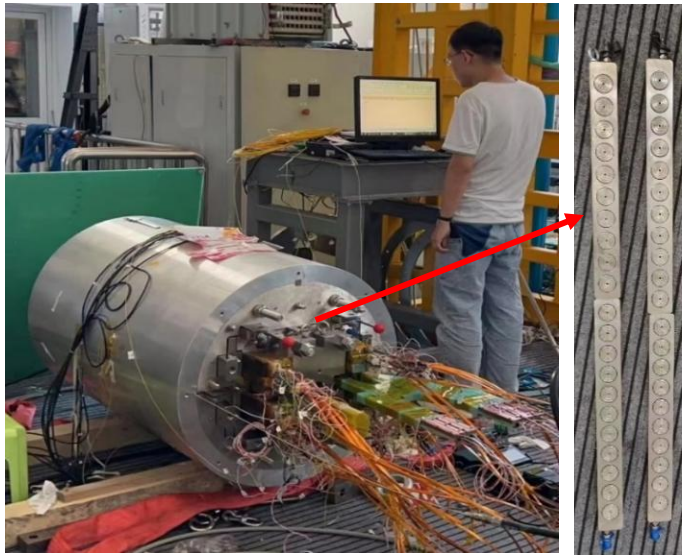
Pre-stress and assembly of LPF3

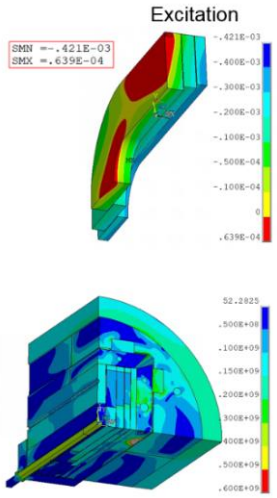
Yingzhe Wang et al





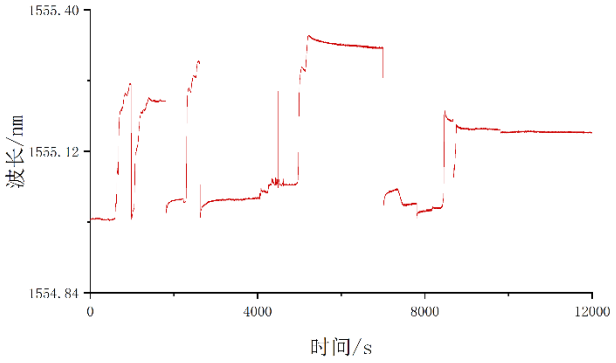






Pre-stress applied with commercial hydraulic jack

Stress monitoring during assembly with FBG



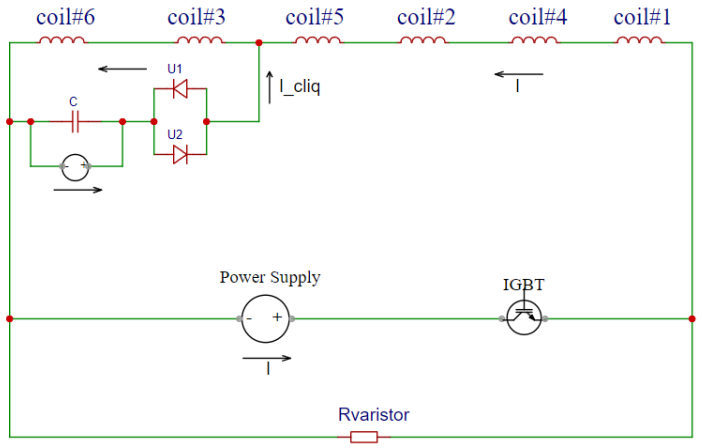
2023.8.29 Assembly completed

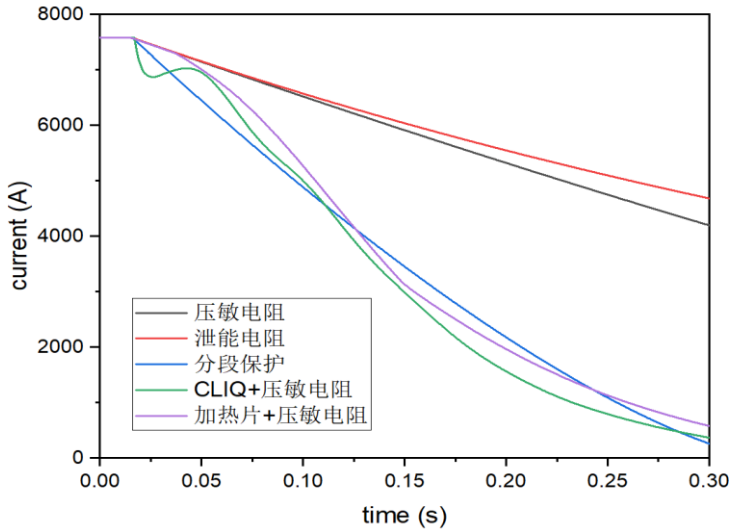
Development of the 16-T Model Dipole LPF3

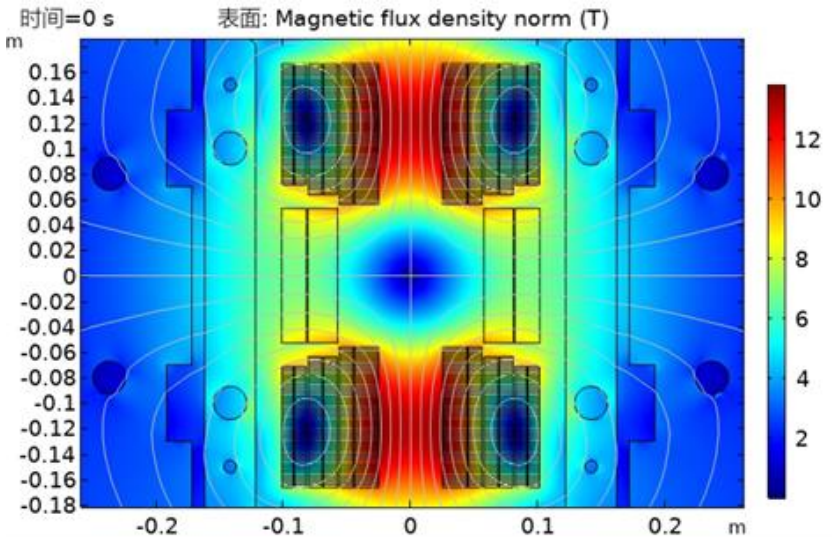
Quench protection of LPF3

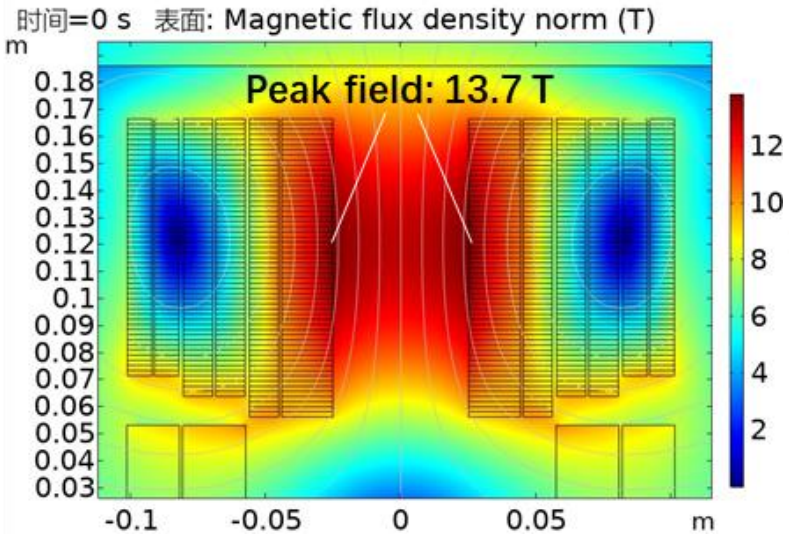
Jinrui Shi et al

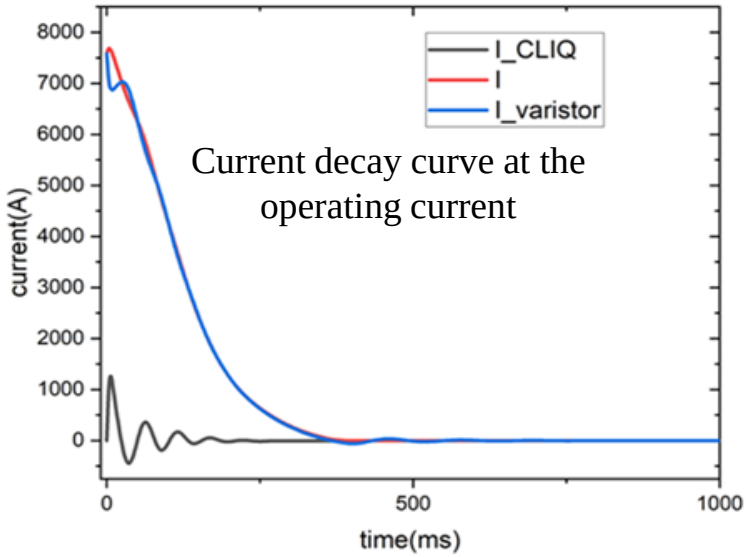
- **Varistor plus CLIQ to protect the Nb_3Sn coils. The maximum hot spot is ~ 230 K**
- **NI configuration plus dump resistor to protect the 2 HTS insert coils**









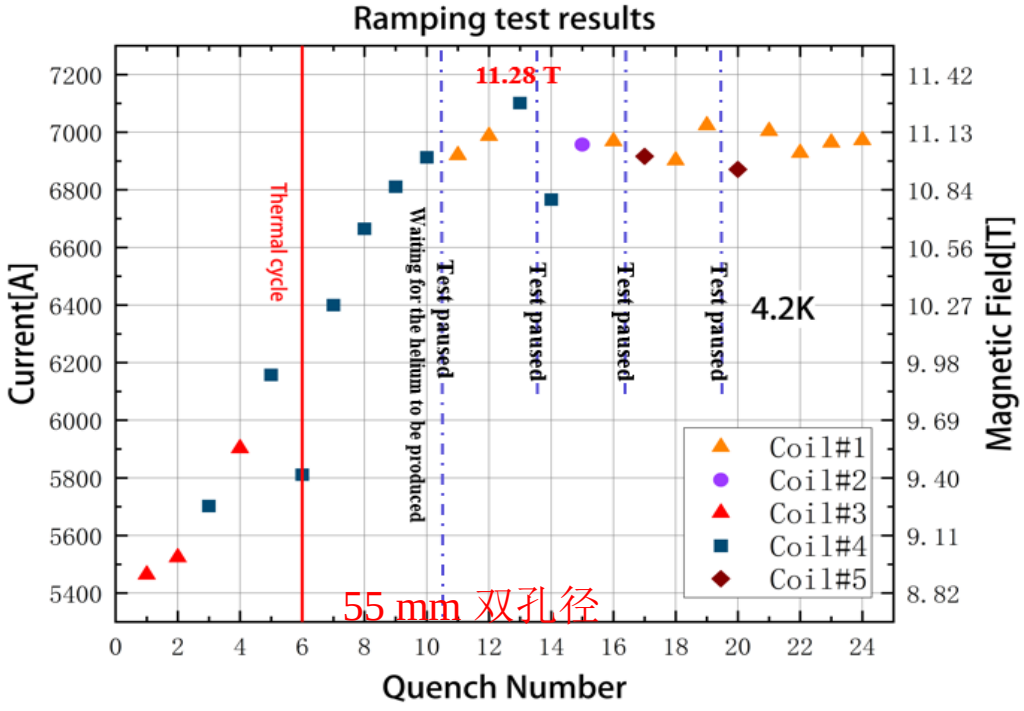


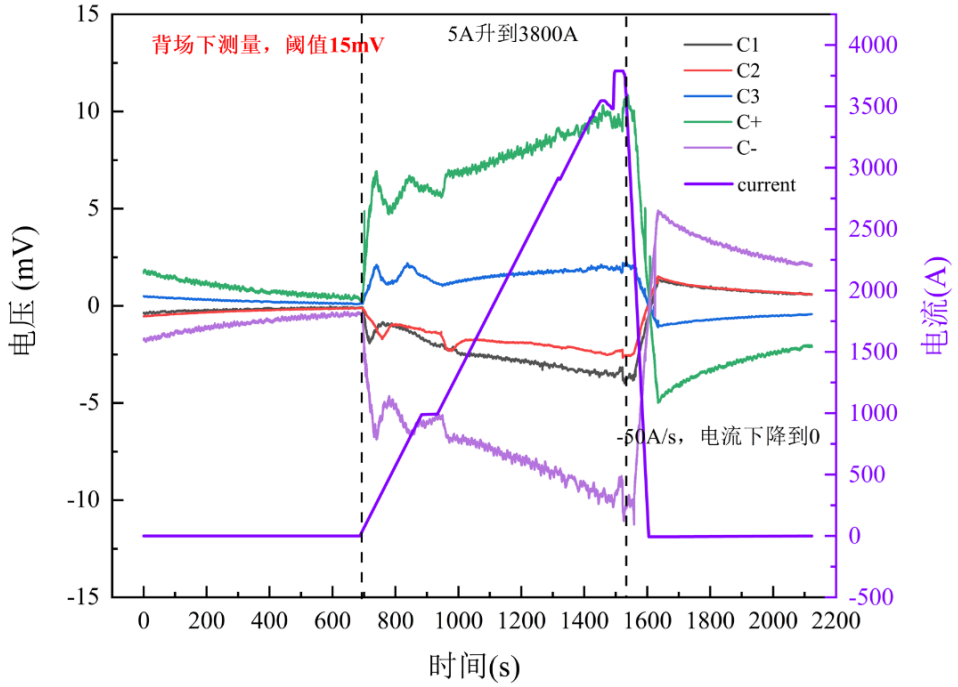
Development of the 16-T Model Dipole LPF3

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, **and enhanced field on most inner Nb3Sn coils due to the HTS screen current!**
- HTS block coil was ramped independently **to 100% of I_{op}** with negligible terminal voltage at 9 T background field

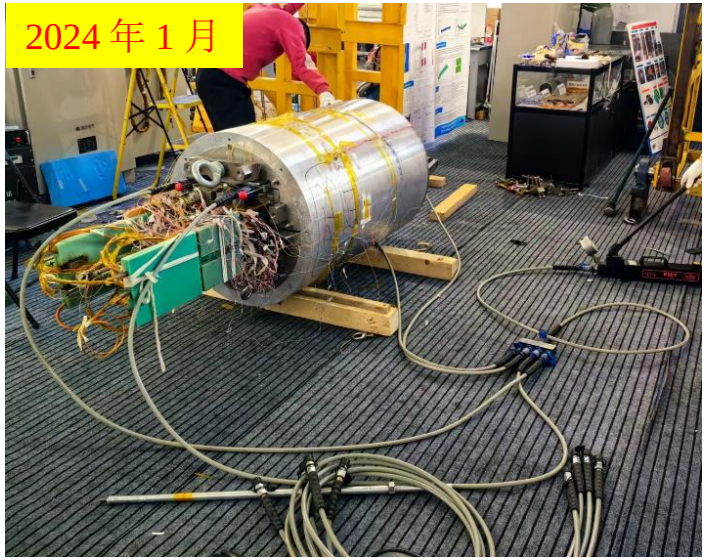


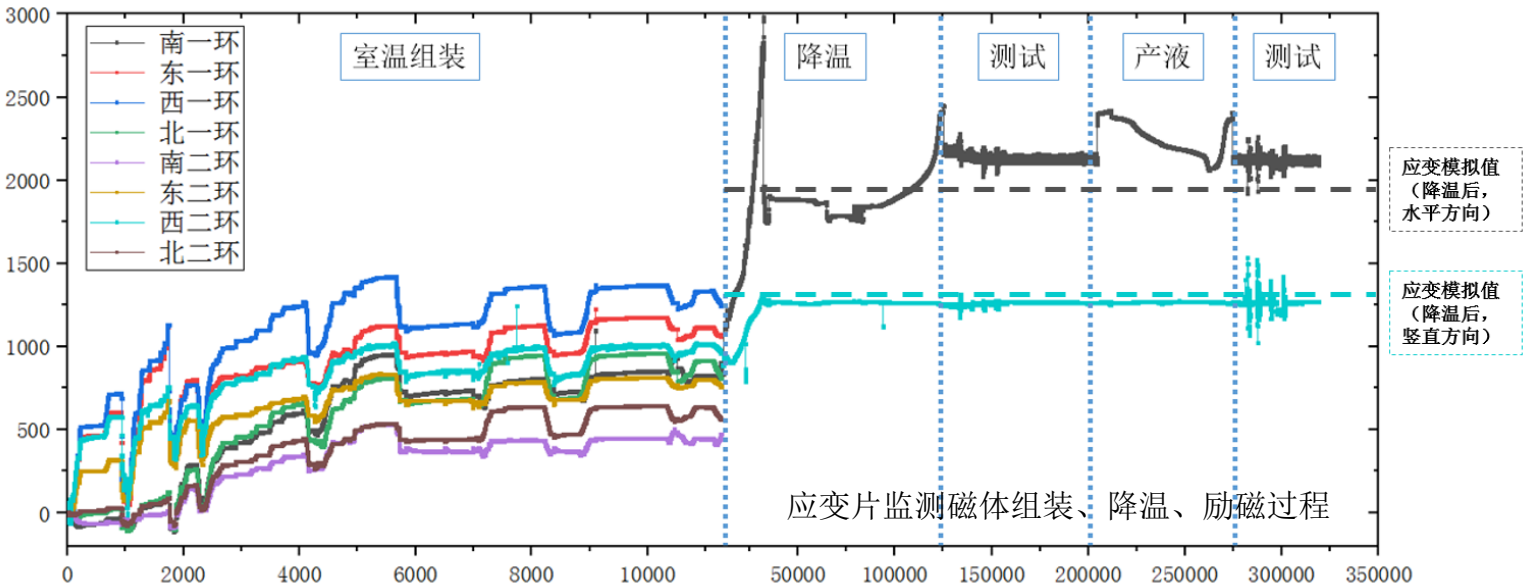


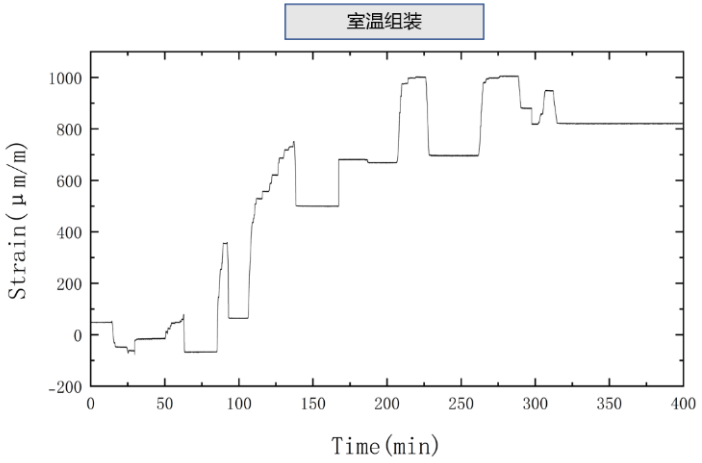
Development of the 16-T Model Dipole LPF3

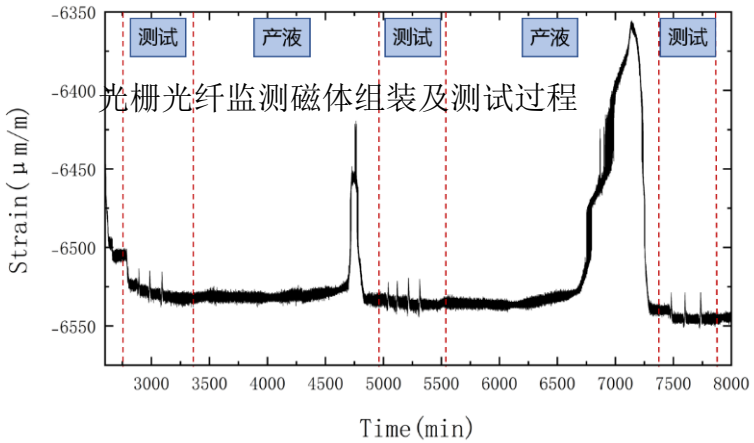
Reassembly of the magnet with enhanced pre-stress

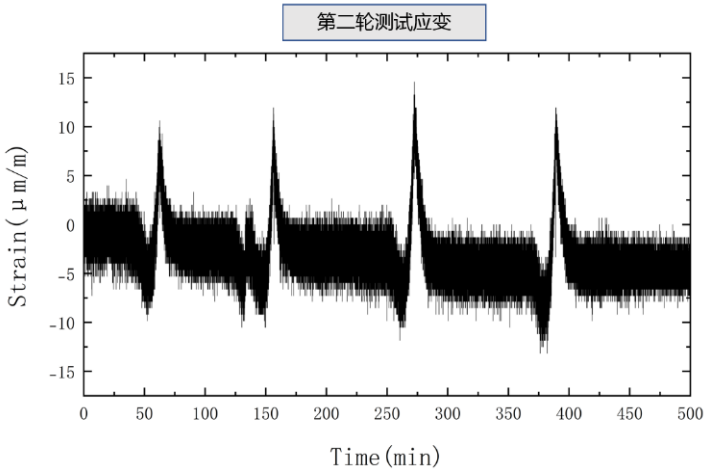
Xin Chen et al







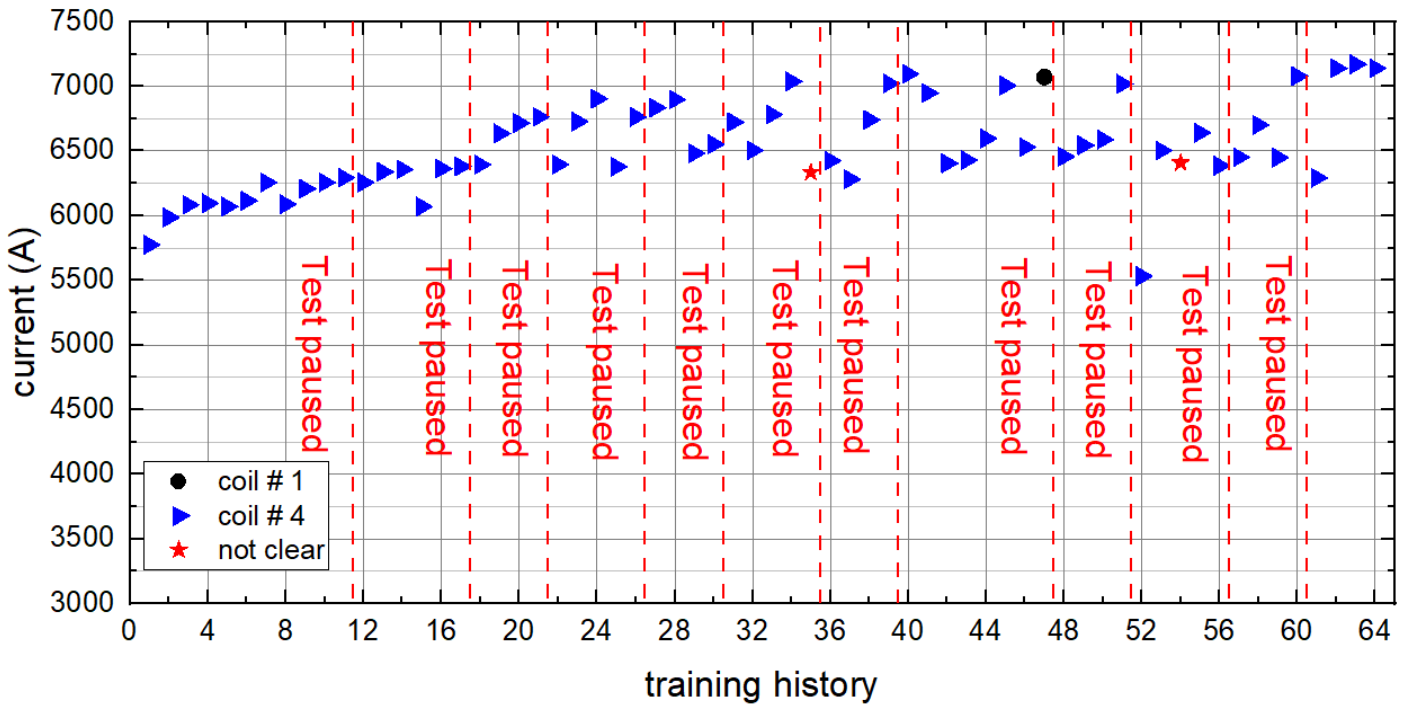


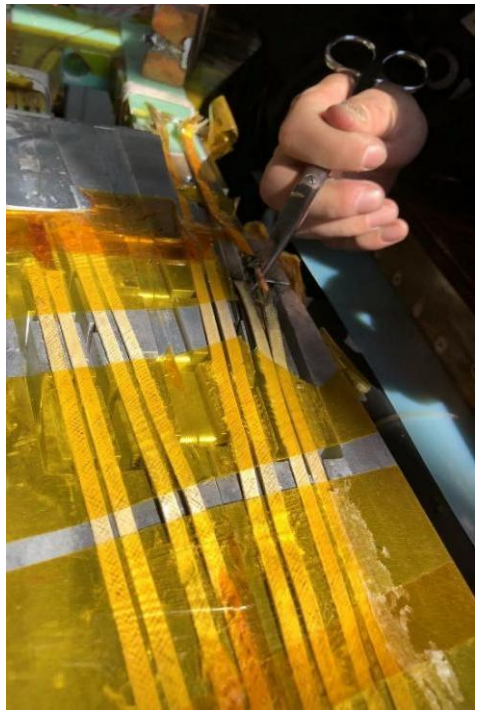


Development of the 16-T Model Dipole LPF3

The 2nd Performance test in Feb 2024

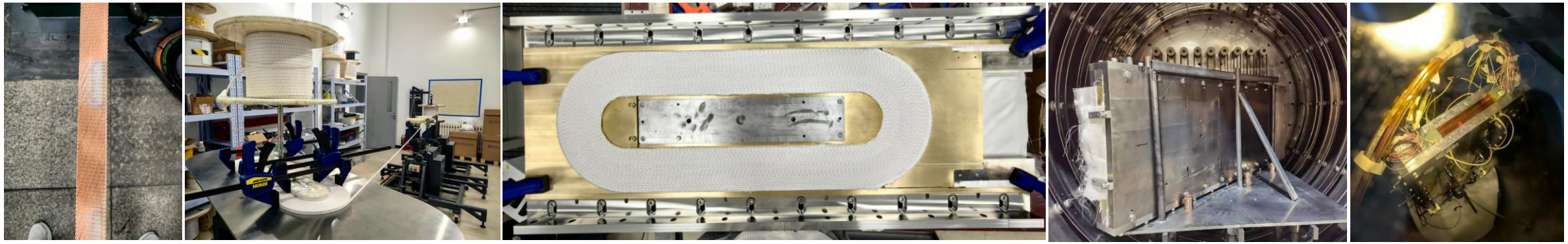
- The Nb_3Sn coils showed very unstable performance in the 6300-7000 A region due to one of the inner most coils, but finally passed this region and reached ~87% of I_{op} in the beginning of March 2024
- HTS block coil was ramped independently to 120% of I_{op} to test its ultimate performance, but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



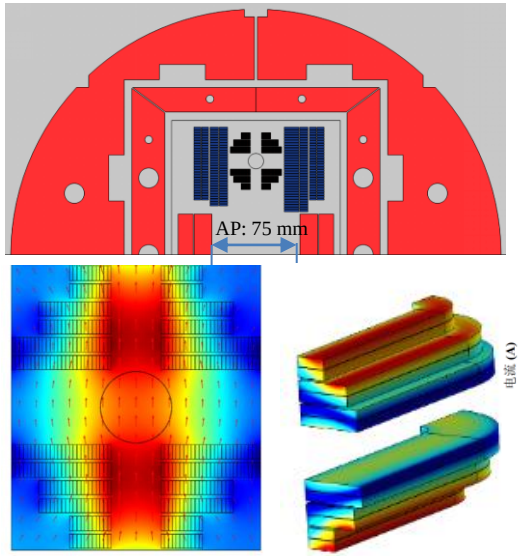


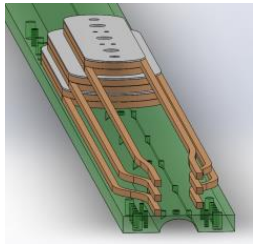
Development of the 16-T Model Dipole LPF3

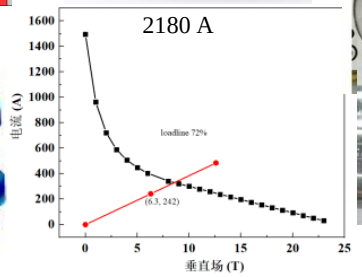
Fabrication of the new Nb_3Sn & HTS Coils Jun. to Oct. 2024



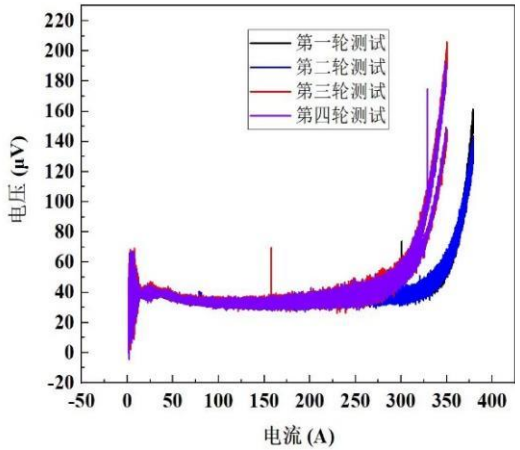
Fabrication of the 2 new Nb_3Sn coils with OST wires

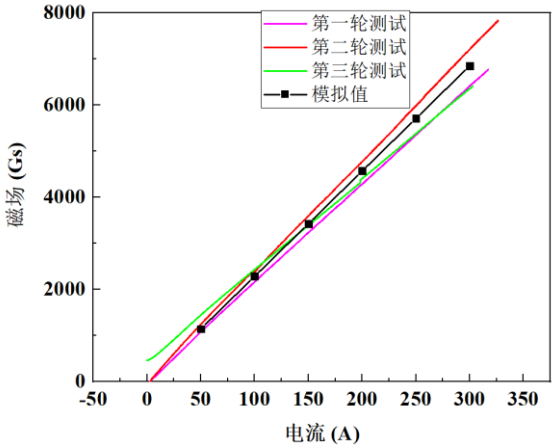






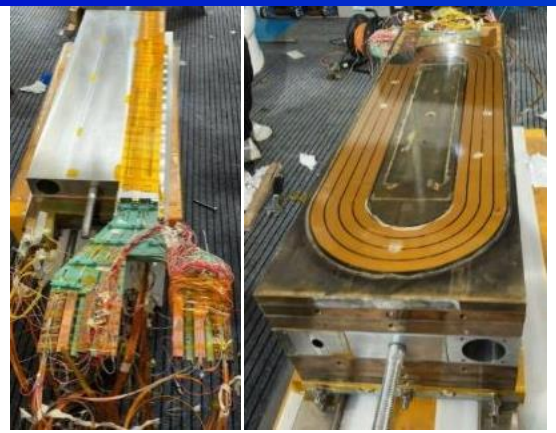
Preliminary test results of the new HTS coils at 77K

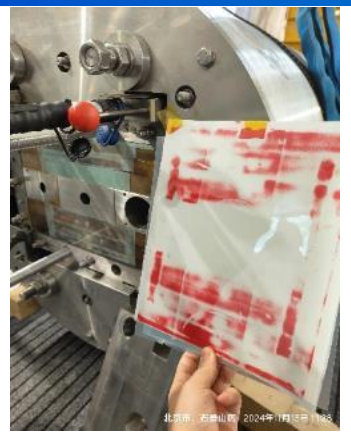




Target field：10 T (LTS) + 6 T (HTS)

Development of the 16-T Model Dipole LPF3





Reassembly of the LPF3 magnet

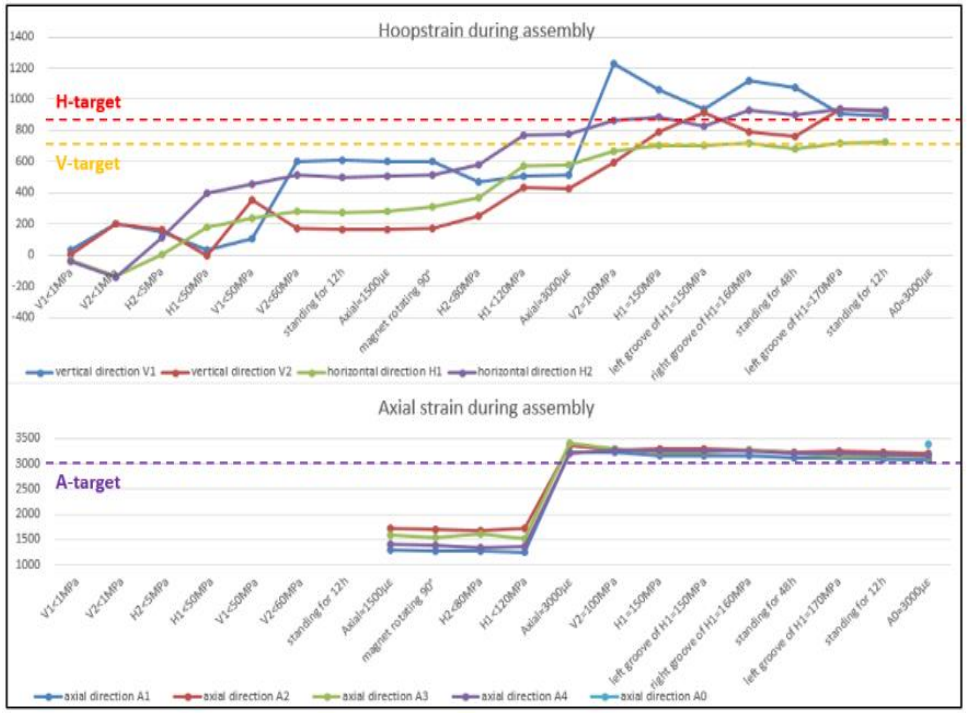
LTS 线圈 + HTS 线圈桶外组装

线圈组件竖直吊装

线圈轴向找齐

LPF3-U 磁体组装

预紧力施加步骤及key片厚度	竖直方向		水平方向		轴向				
	西	东	北	南	西北	东南	东北	西南	中
1. 西打压，无示数：（7.6+2）+0.5	36	8	-29	-37					
2. 东打压，14Mpa：（4.6+2）+1+0.2	205	201	-134	-142					
3. 南打压，<5MPa：4+2（中间3*2）	155	168	8	114					
4. 北打压，<50MPa：4+2（中间2*2+1+0.5）	37	1	184	398					
5. 西打压，<50MPa：7.6+2+1	105	353	241	457					
6. 西塞不锈钢块+2+1+0.5									
7. 东打压，60MPa：4.6+2+1+0.5	606	171	281	512					
11. 15 9：42	607	164	277	504					
8. 轴向打压：	603	164	279	512	1288	1718	1584	1401	
9. 旋转90°（东朝上→南朝上）	606	174	308	514	1281	1709	1541	1380	
10. 南打压：80MPa/66MPa 4+2+0.5-3*2-4+2+0.2*2	473	253	373	584	1281	1679	1609	1337	
11. 北打压:120MPa 4+2+0.5-3*2-4+2+0.5	511	432	576	773	1257	1712	1517	1372	
12. 轴向打压：	515	430	580	776	3228	3353	3409	3210	
13. 南塞不锈钢片（yoke与pad间隙太小，塞不进不锈钢块）									
14. 东打压：100MPa：4.6+2+2	1229	597	672	863	3238	3277	3302	3276	
15. 东塞不锈钢片									
16. 北打压：150MPa 4+2+0.5+0.2-3*2-4+2+0.5	1061	789	705	886	3166	3287	3234	3243	
17. 西北单侧打压：150MPa 4+2+0.5+0.2-3*2-4+2+0.5+0.2	935	913	707	829	3166	3287	3234	3243	
18. 东北单侧打压：160MPa 4+2+0.5+0.2+0.2-3*2-4+2+0.5+0.2	1122	794	722	928	3163	3275	3284	3252	
11. 18 15：34	1079	762	681	901	3114	3234	3199	3216	
19. 西北单侧打压：170MPa 4+2+0.5+0.2+0.2-3*2-4+2+0.5+0.2+0.2	906	939	719	938	3113	3258	3162	3209	
北塞不锈钢片									
11. 19 14:40	891	924	727	927	3090	3238	3166	3193	
20. 加轴向中间杆					3061	3214	3138	3163	3388

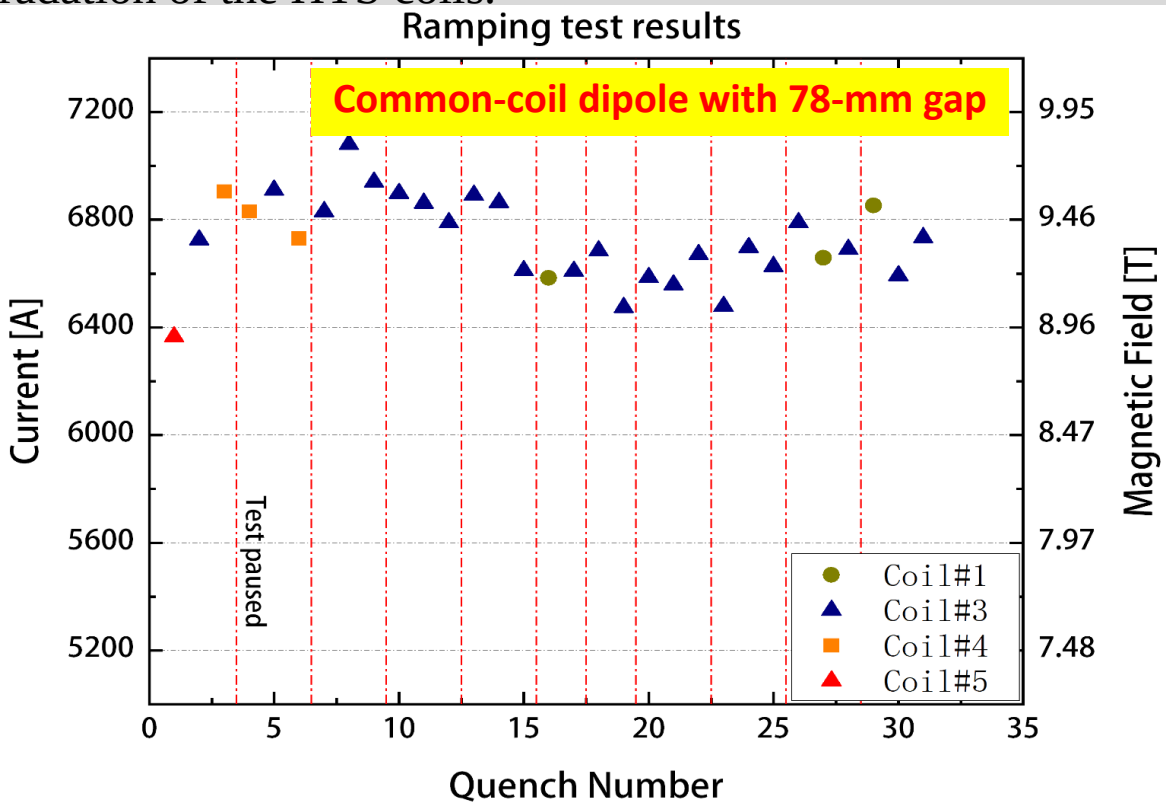


Development of the 16-T Model Dipole LPF3

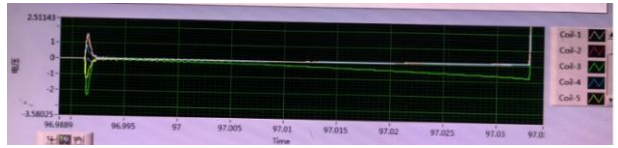
LPF3-U 磁体组装完成

Test of the LPF3-U magnet Nov. 2024 to Jan. 2025

Main challenges: The LTS coils are strongly coupled with the HTS coils in magnetic field and stress during LTS training. the HTS induced current enhance the field strength and stress of the adjacent LTS coils, and the frequent training quench of LTS cause irreversible degradation of the HTS coils.

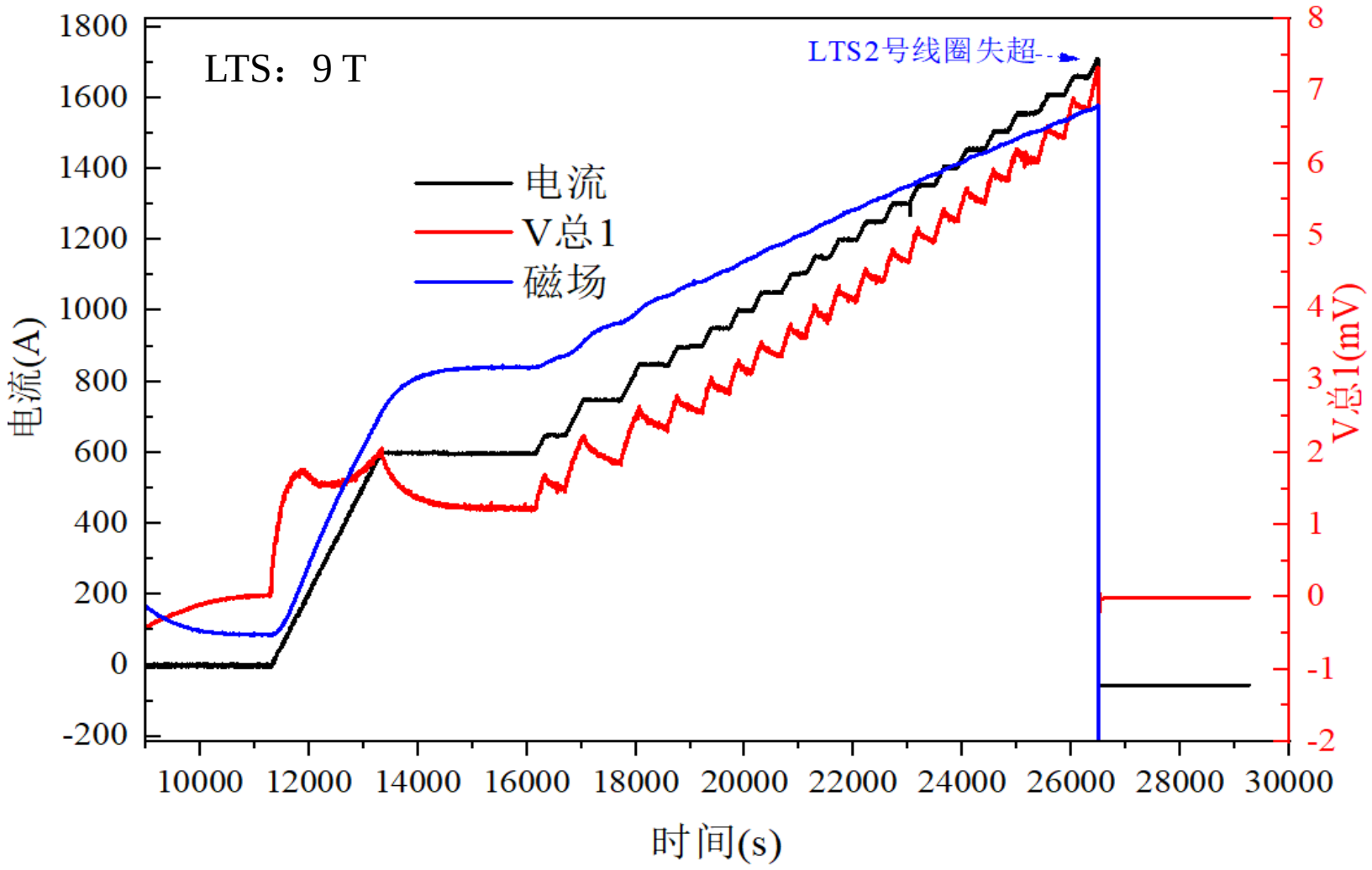


- Nb_3Sn coils reached 6905 A、9.6 T after 3 quenches, 97 % of the design value.
- Strong coupling between HTS and LTS caused difficulties to the training process of LTS
- Most of quenches occured in the most inner Nb_3Sn coils.
- LTS still have great potential for performance improvement. More R&D needed on training tests……



Development of the 16-T Model Dipole LPF3

Test of the LPF3-U magnet **Nov. 2024 to Jan. 2025**



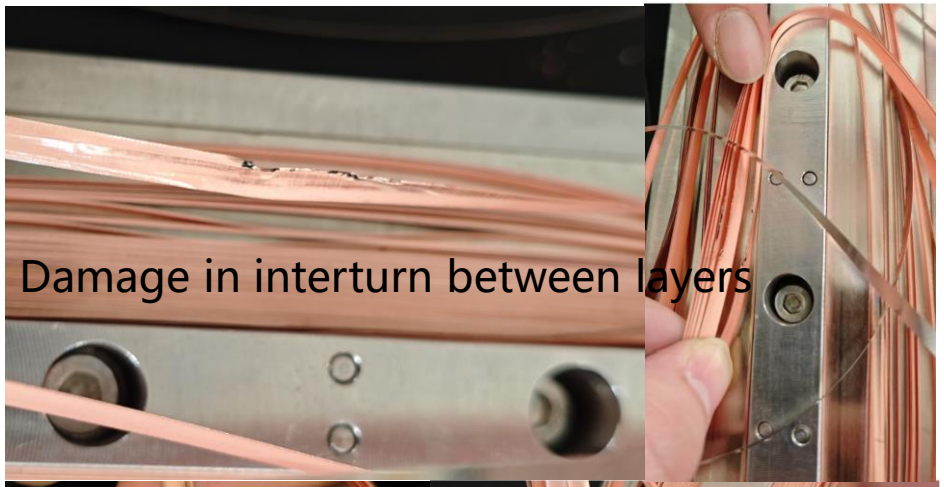
- The HTS coils subjected to several excitation tests in both self-field and 9 T background field, with a maximulatem excitation current of 2.5 kA (115 % of the design current) in 9 T background field.

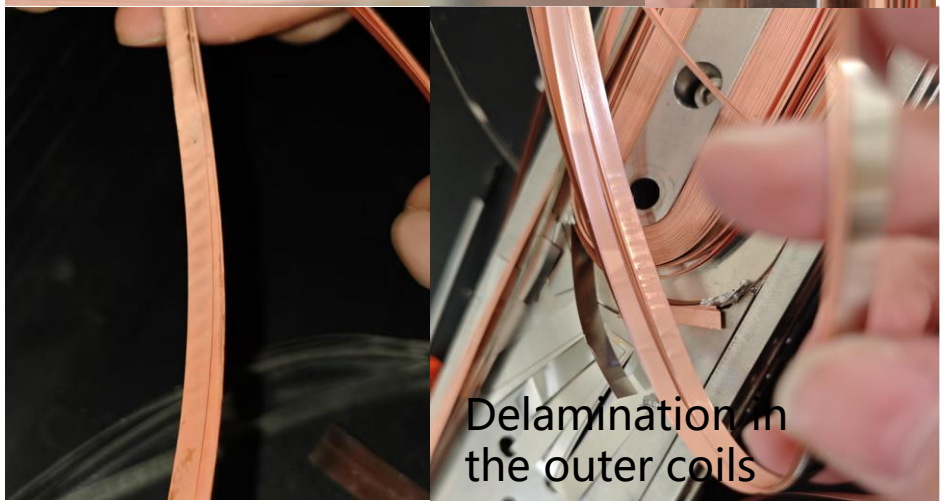
- HTS coils provide a magnetic field significantly below the design value: long delay, current short circuit inside the coil, and irreversible degradation.

Development of the 16-T Model Dipole LPF3

Damage of the HTS coils during the test with LTS

After disassembly, Serious damage of the outer coils was observed. could be caused by strong coupling (between LTS and HTS) induced electromagnetic forces during the training of the LTS coils.

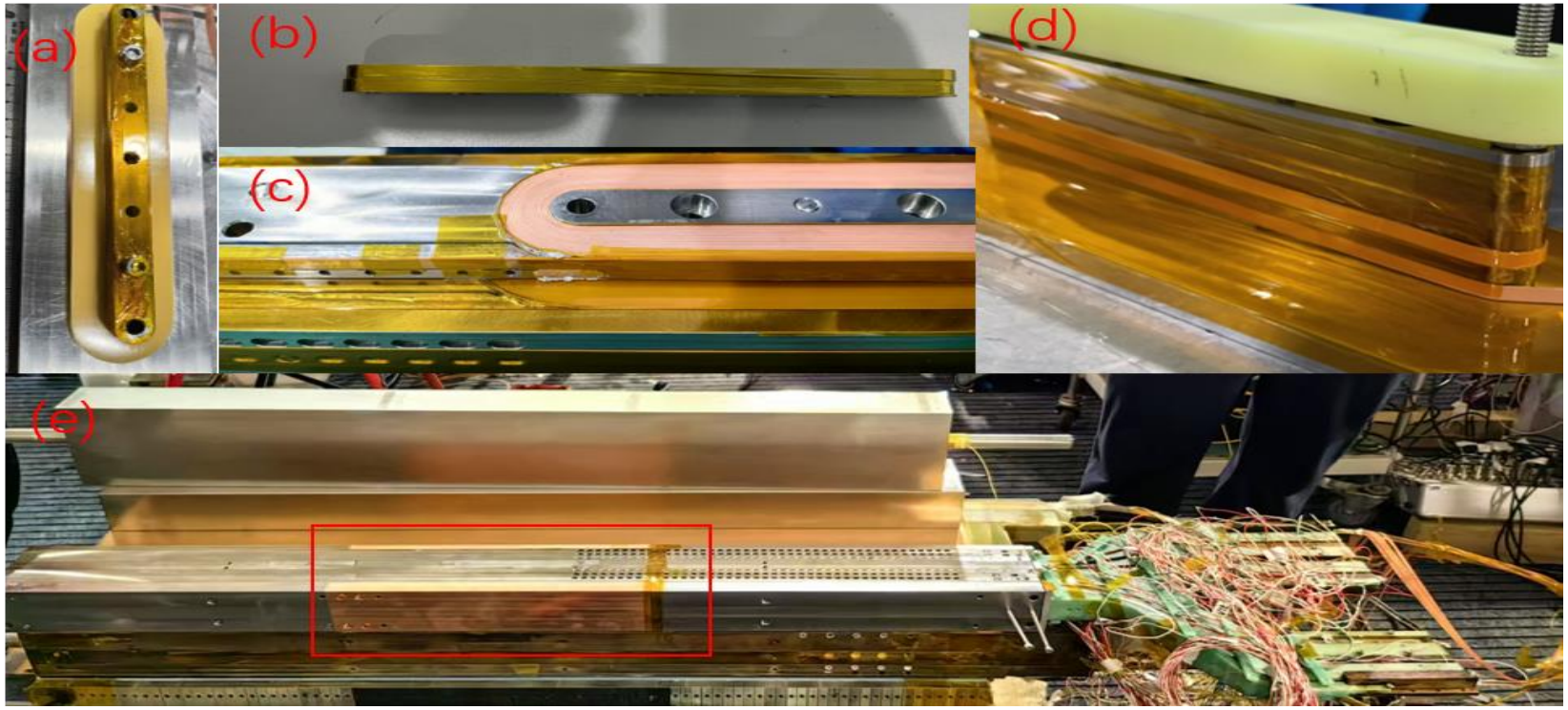




Development of the 16-T Model Dipole LPF3

Refabrication of the new HTS coils

- To reduce time constant , the interlayer insulation in the double-pancake coil was replaced from stainless steel to G10, polyimide and G10 were also added between the coil and the former
- To mitigate the impact of LTS quench, testing of the HTS coil was conducted before LTS training. Additionally, high-purity copper and HTS tapes were deployed around the HTS coil to prevent rapid magnetic field variations during the quench

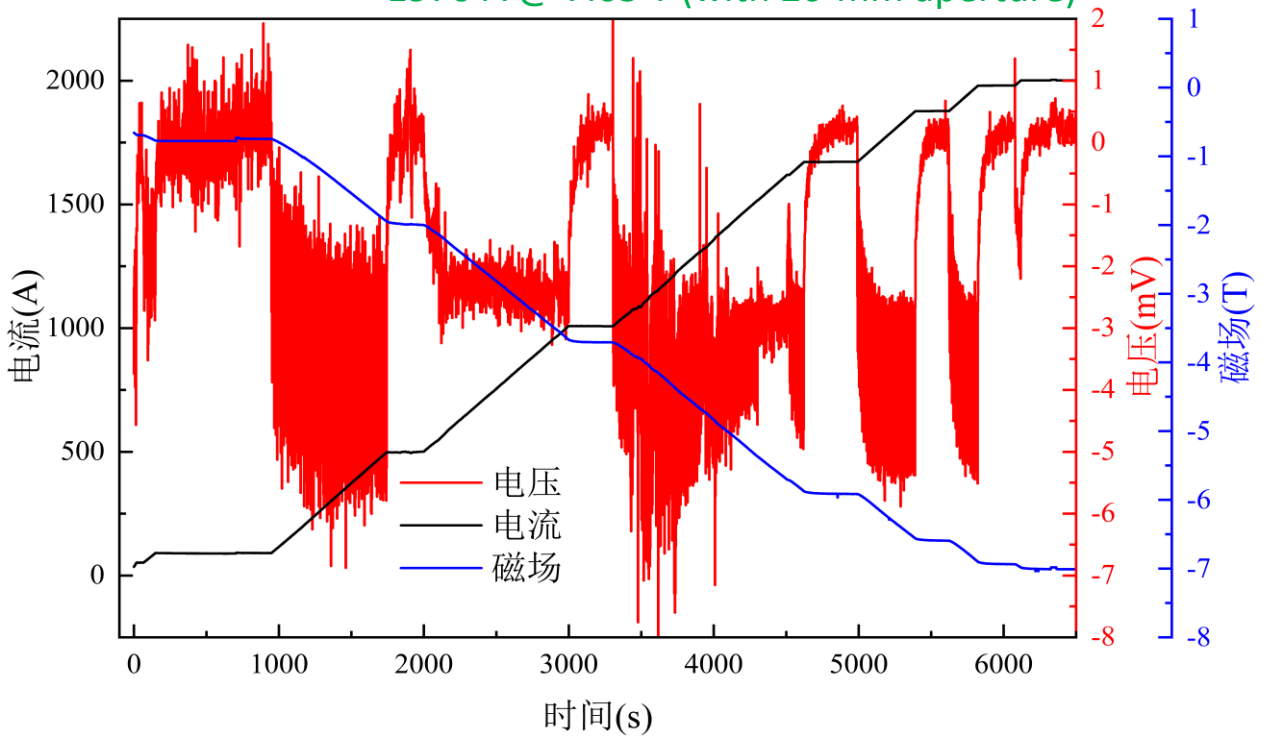


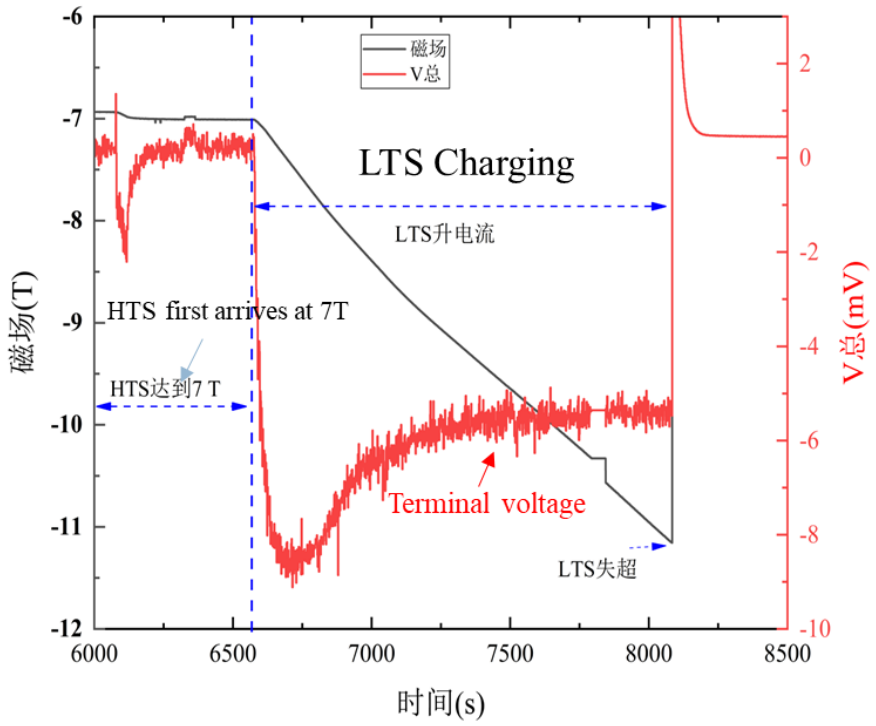
Development of the 16-T Model Dipole LPF3

Performance of the new HTS coils

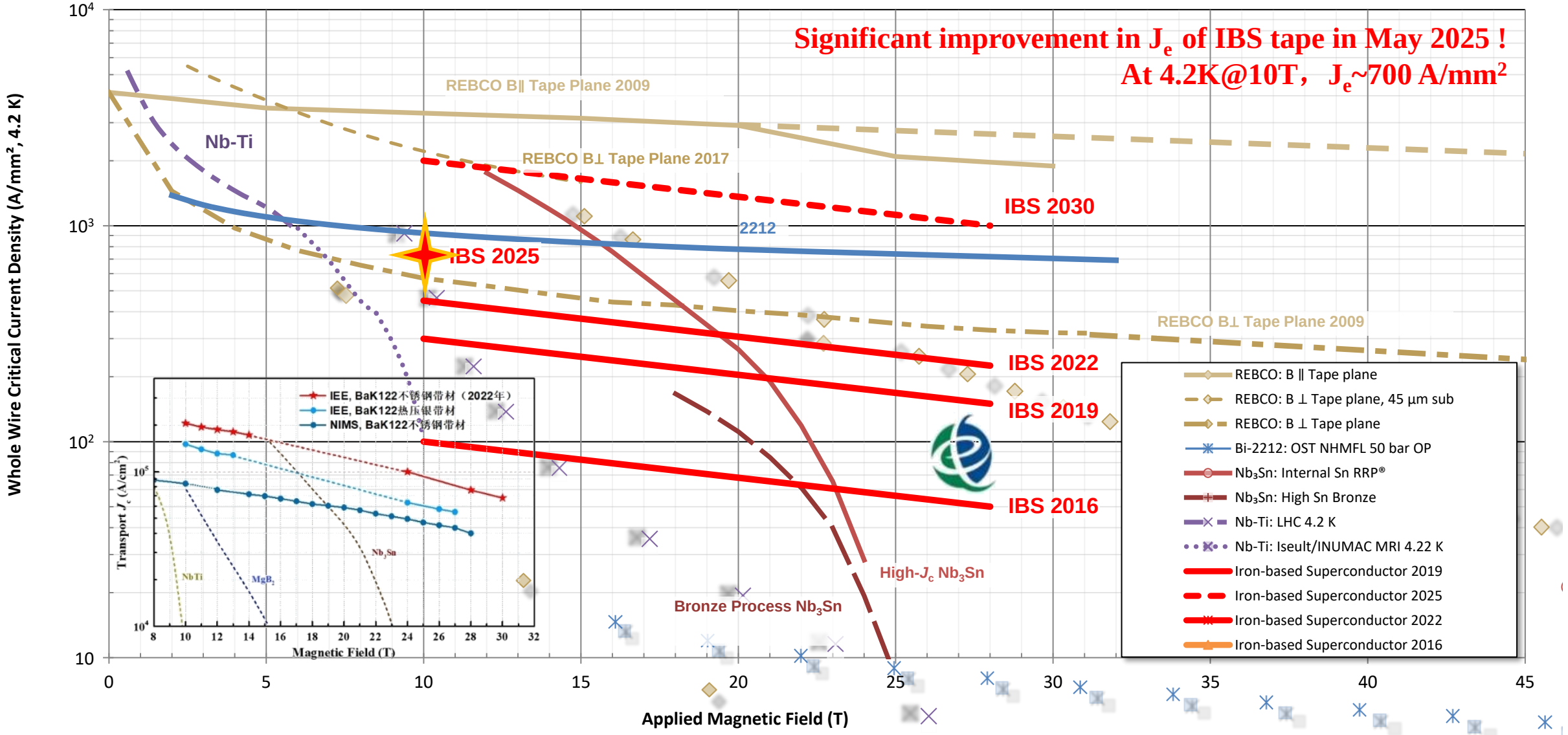
- The new coil achieved 7.05 T at 4.2 K under self-field, with relatively small field delay (time constant τ = 4 min)
- The excellent performance before LTS powering confirms that the pre-stress does not damage the coil
- However, when powering with LTS, 2 of 6 HTS coils damaged during an unexpected quench of LTS
- HTS coils are being fabricated again with more improvements, to prevent damage during LTS quench, to be tested again in early June 2025

1970 A @ 7.05 T (with 20-mm aperture)





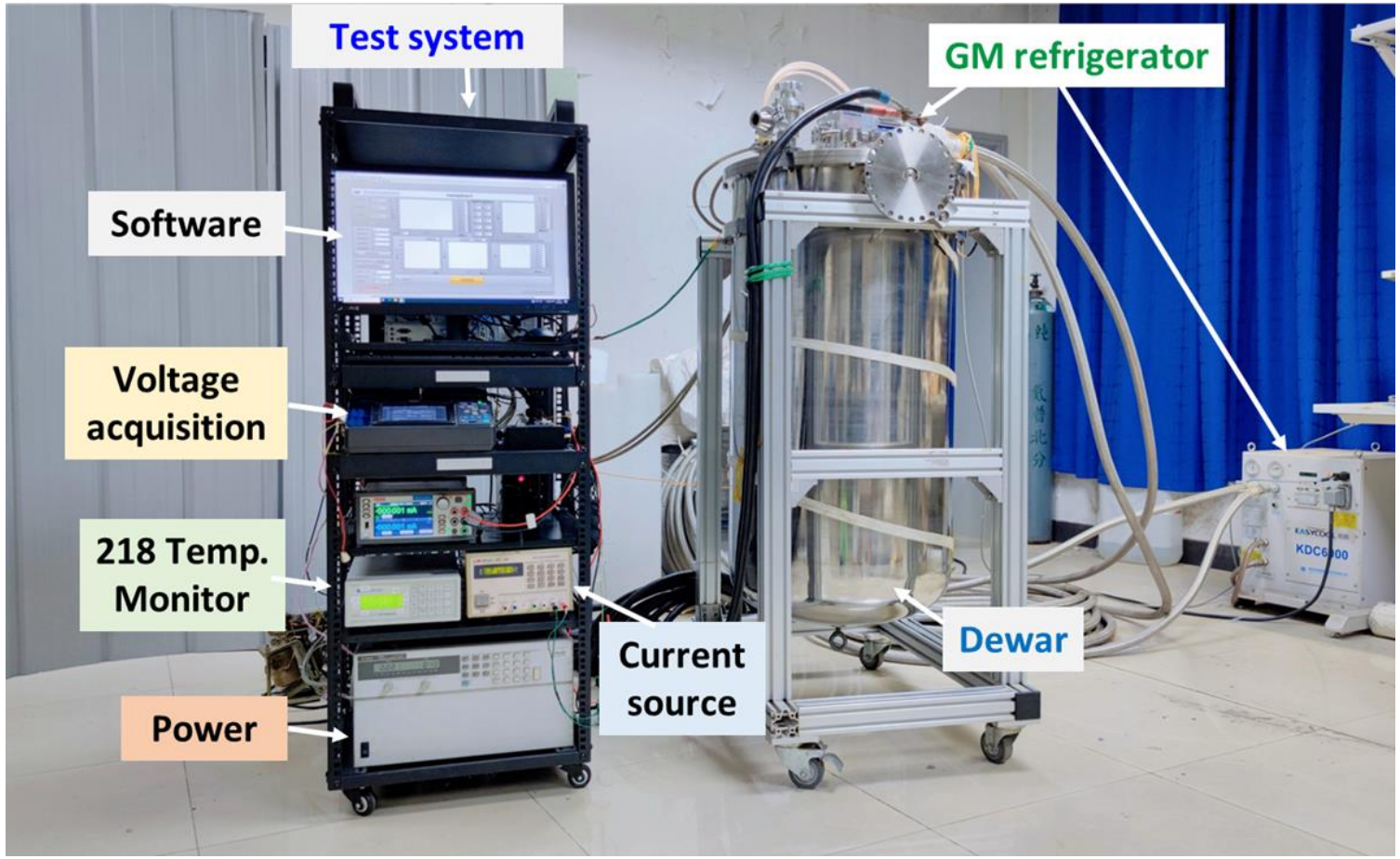
IBS Technology: Status and Outlook

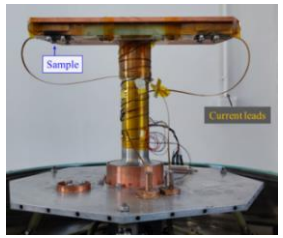


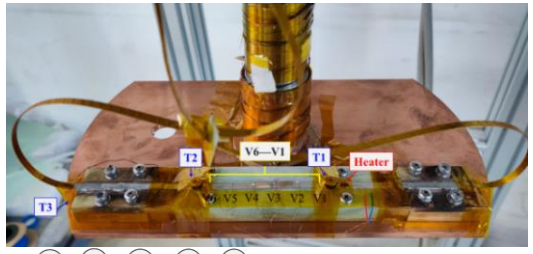
IBS Technology: Status and Outlook

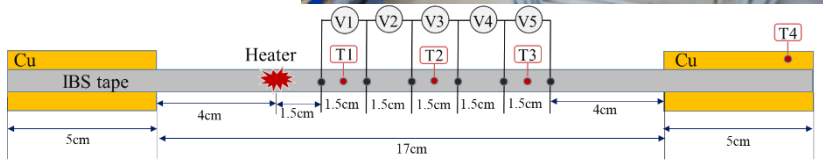
Quench propagation study of the IBS tapes and coils

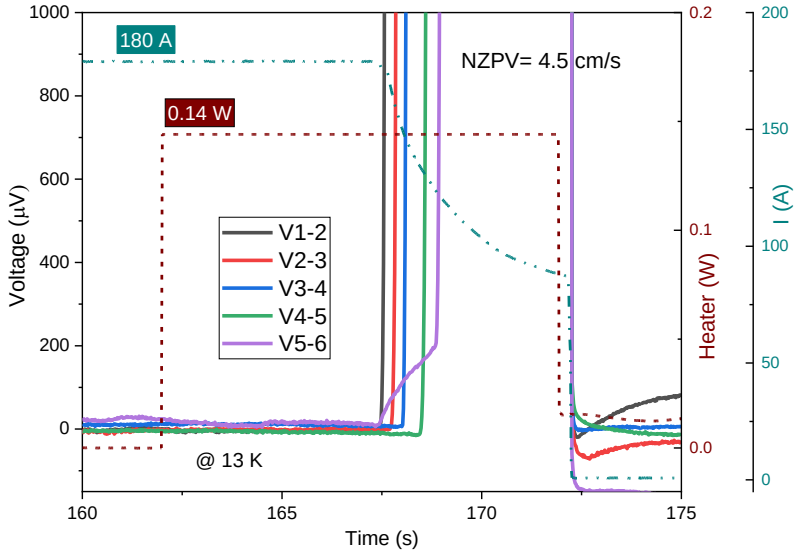
Chunyan Li et al







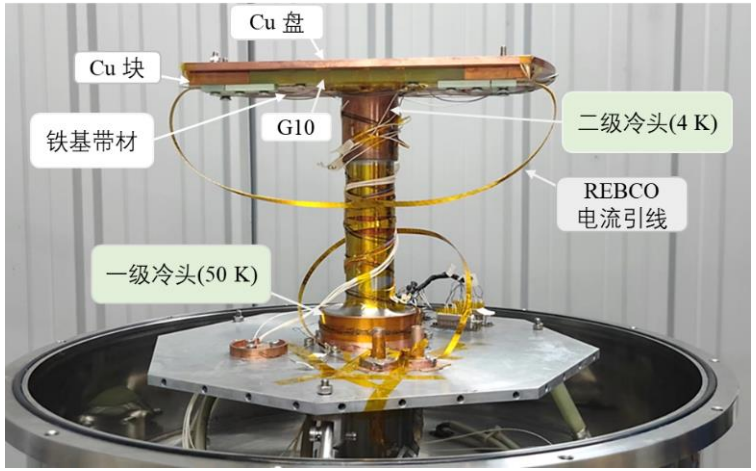


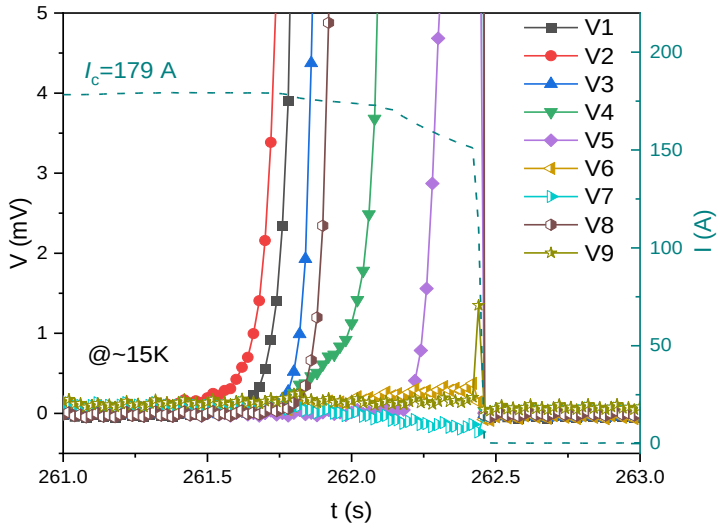


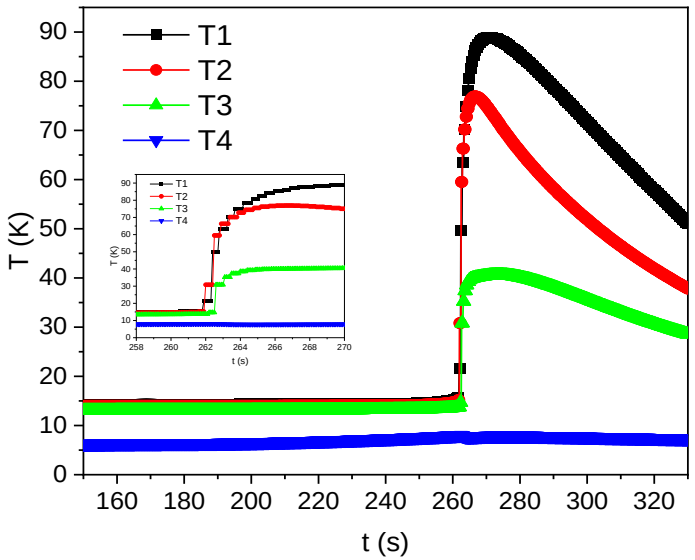
IBS Technology: Status and Outlook

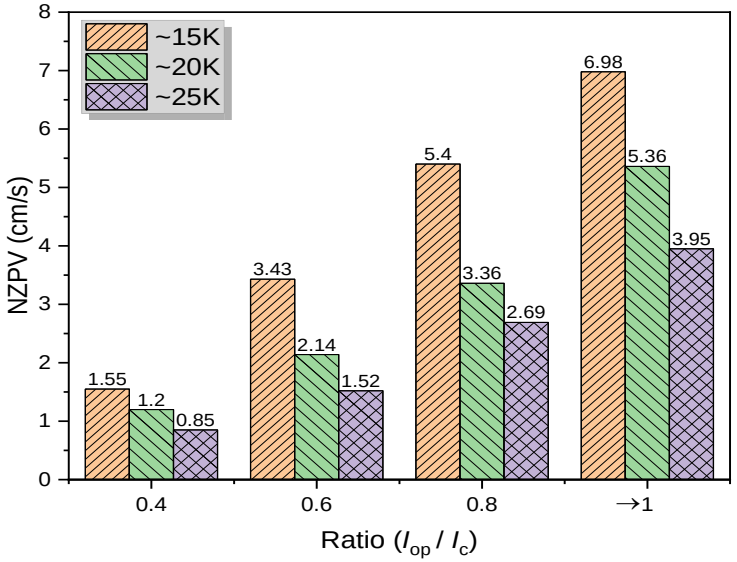
Quench propagation study of the IBS tapes and coils

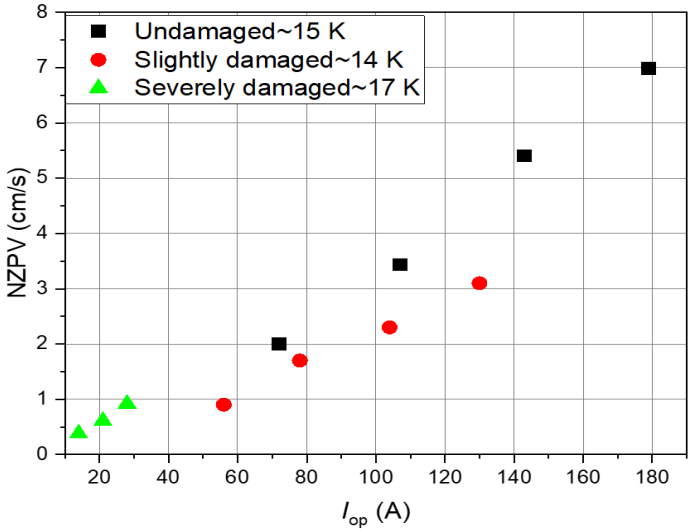
Chunyan Li et al











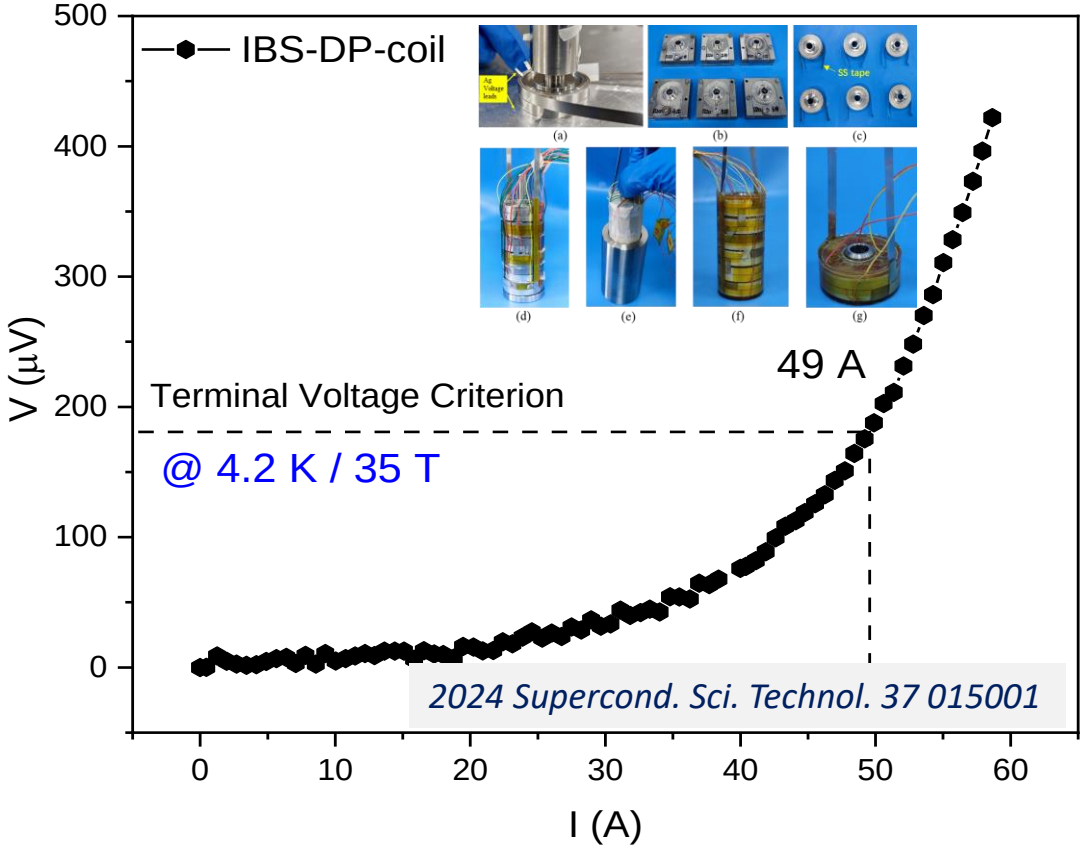
In 15~17K, when the transmission current of iron-based superconductor is 14-179A, the corresponding NZPV value is 0.4– 7cm/s

IBS Technology: Status and Outlook

The First IBS Solenoid Coil at 35 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**

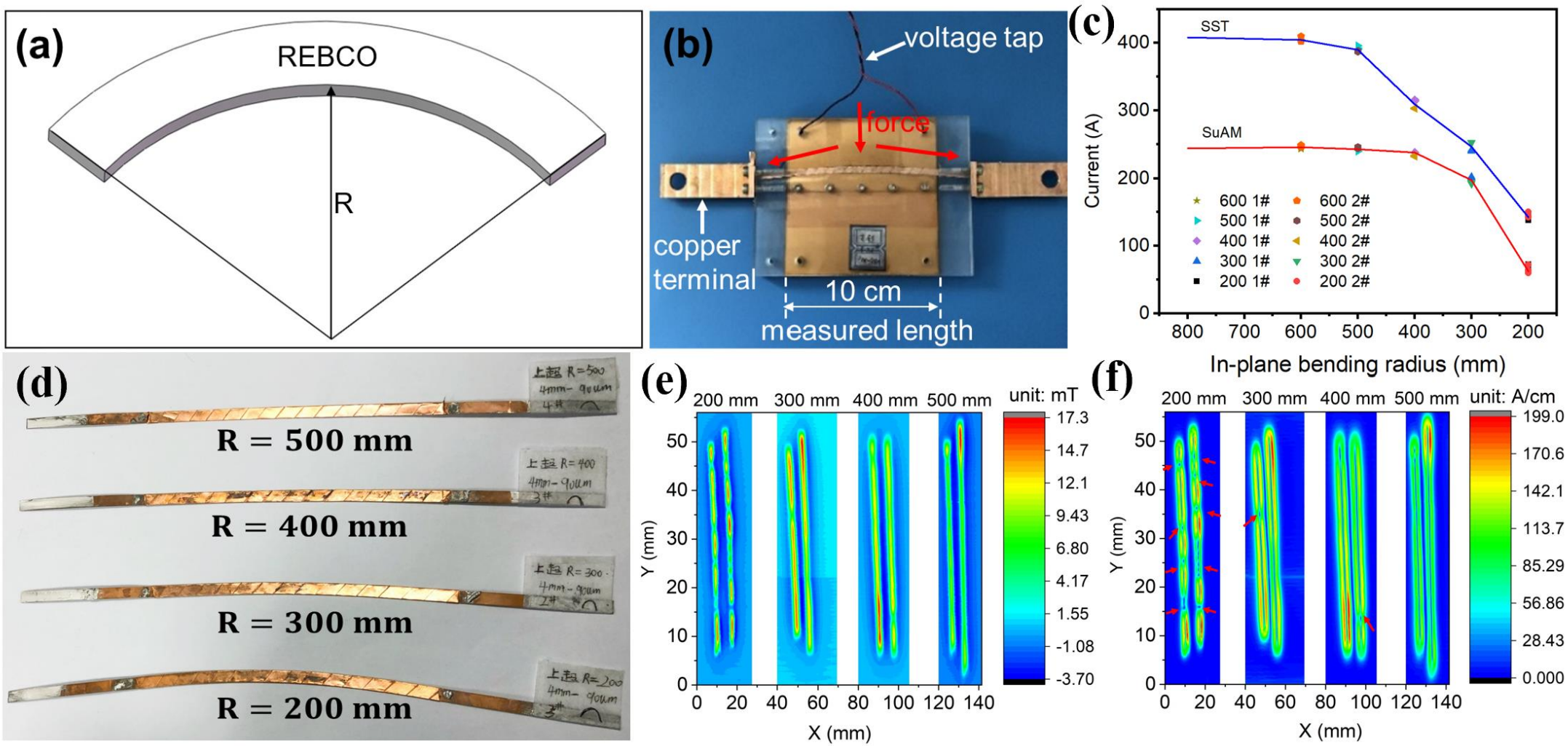


Fabricated a series-connected IBS coil consisting of six DP coils and tested at 35T background field

IBS Technology: Status and Outlook

Development of the ReBCO and IBS transposed cable

Juan Wang et al



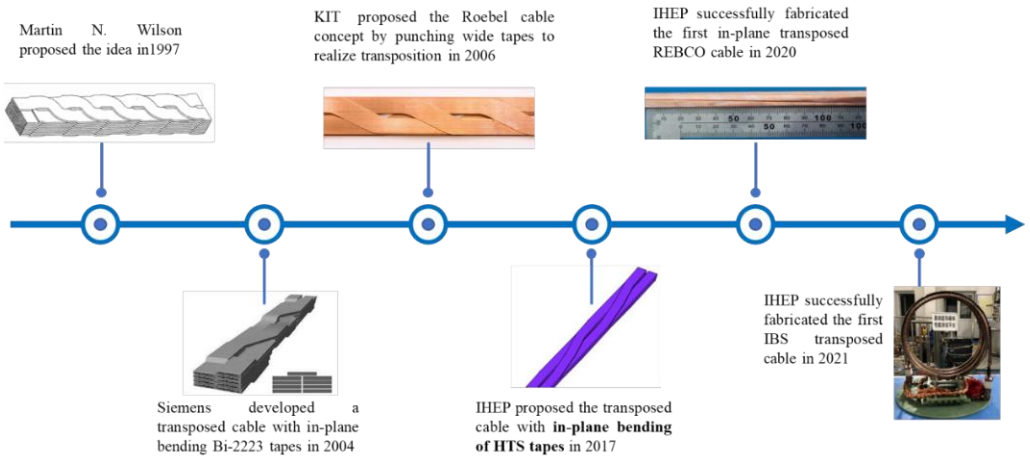
J. Wang et al, *Superconductivity* 3 (2022) 100019

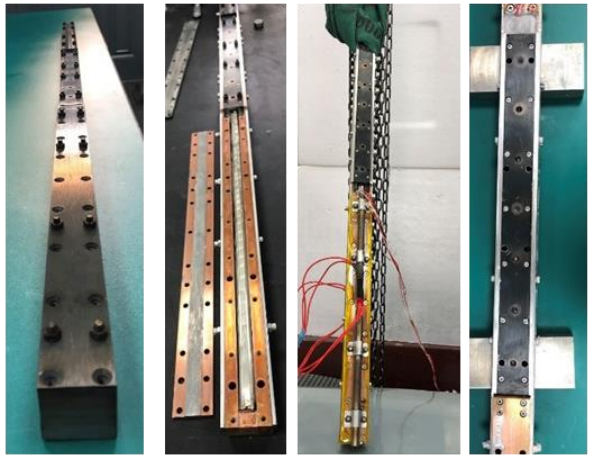
IBS Technology: Status and Outlook

Development of the world's first 7-kA class IBS transposed cable

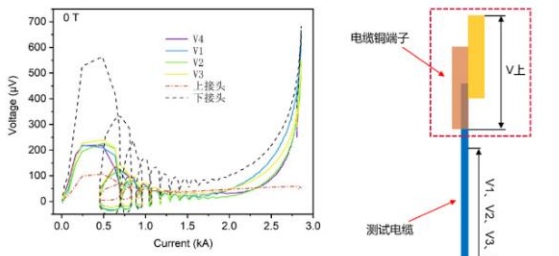
Juan Wang et al

测试电缆热处理





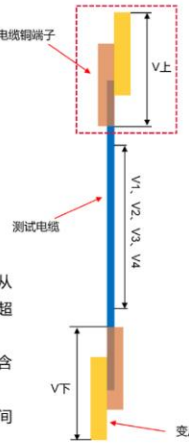
热处理后样品　　接头焊接　　石蜡固化



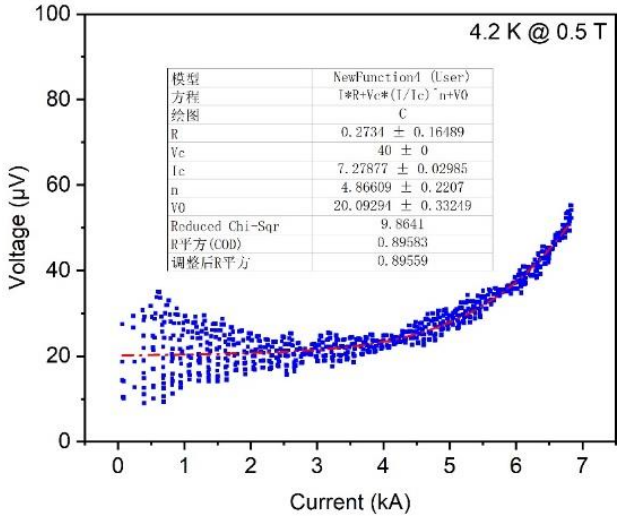
1、上接头、V1-V4、下接头将电缆分成3部分，从V-I曲线可以确定上接头焊接质量很好，且包含的超导带性能没有损伤；

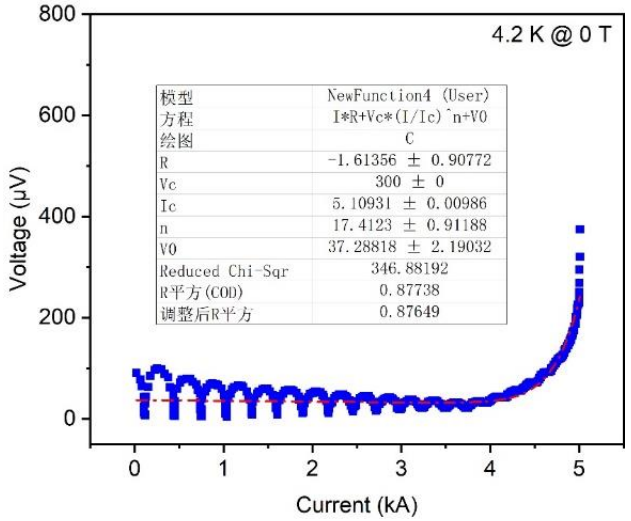
2、下接头的V-I曲线出现非线性的转变，说明包含在下接头中的超导带性能出现损伤；

3、V1-V4的转变和下接头几乎一致，是否证明中间部分的超导带也受到损伤?



可能出现问题的地方：
1、不锈钢接头替换成铜接头（操作非常小心）
2、焊接头时罐锡的小孔位置容易损伤（熔的都是锡丝）
3、电压引线用的比较粗，焊完后翘着，虽然用石蜡固化了，有一定的保护作用，但是石蜡的强度非常低，组装的时候，下部电压引线是折到背面安装的，有可能损伤，等样品邮寄回来确定.....
4、运输.....（包装的很好）





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 are being developed at IHEP-CAS. Many lessons learned regarding the strong coupling and protection of HTS and LTS coils during quench; very challenging and some key issues still to be solved
- Strong domestic collaboration for the advanced superconductor R&D (HTS & Nb_3Sn): Significant improvement in J_e of IBS tape achieved in May 2025, IBS coil I_c reached 49A at 35 T. 7kA class IBS transposed cable successfully developed
- Worldwide collaboration is expected to challenge the 20-T class accelerator magnets in the next 10~20 years

Thanks for your attention!