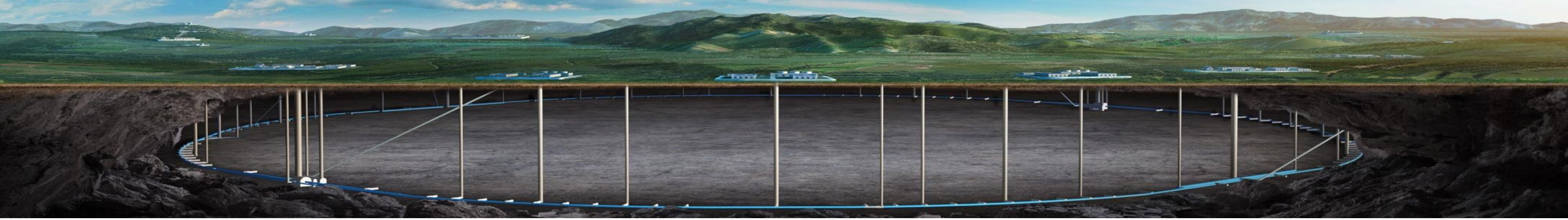


Progress of the High Field Magnet Program For the Next-generation Accelerators

Qingjin XU
for the Superconducting Magnet Group,
Accelerator Division, IHEP-CAS

Oct 27 2023

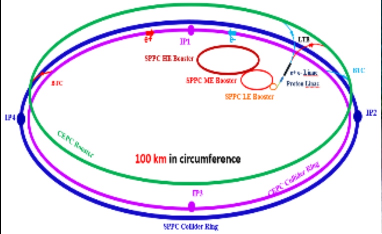
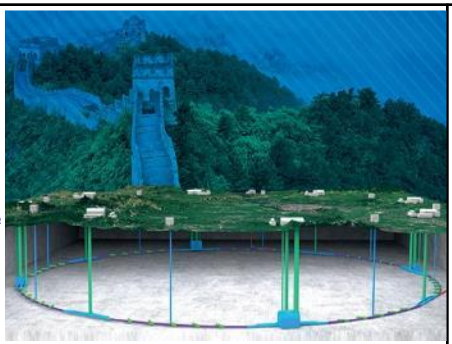
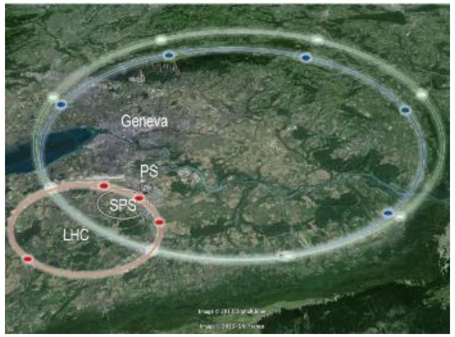
中国科学院
CHINESE ACADEMY OF SCIENCES

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

HFM annual meeting 2023, CERN, Oct 20- Nov 2 2023

Design Scope for the 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

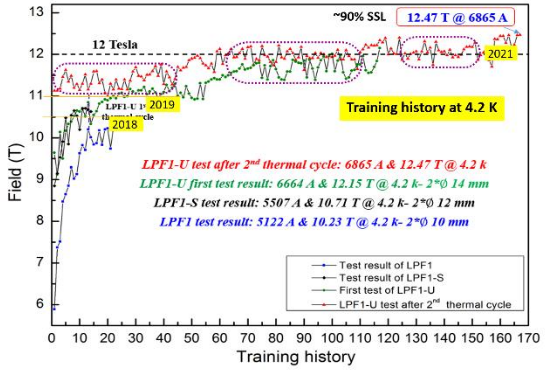
Field (T)

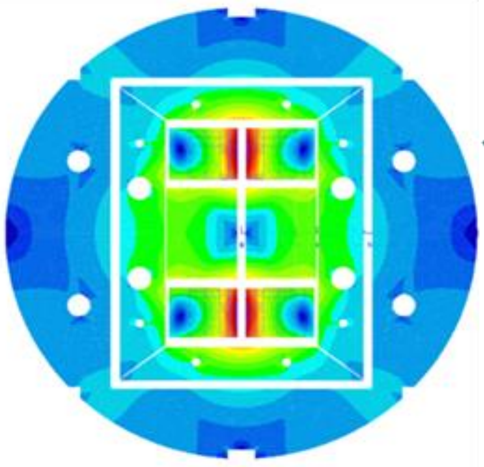
20

10

2018-2021, 12.47T @4.2K

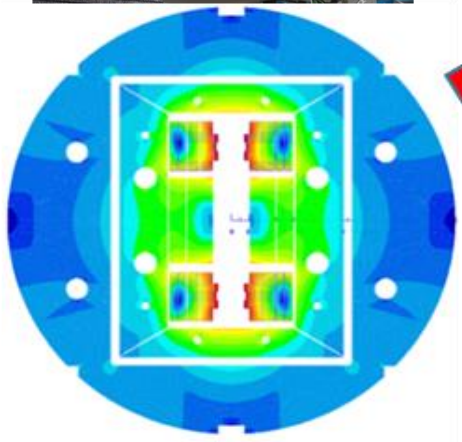
NbTi + Nb_3Sn

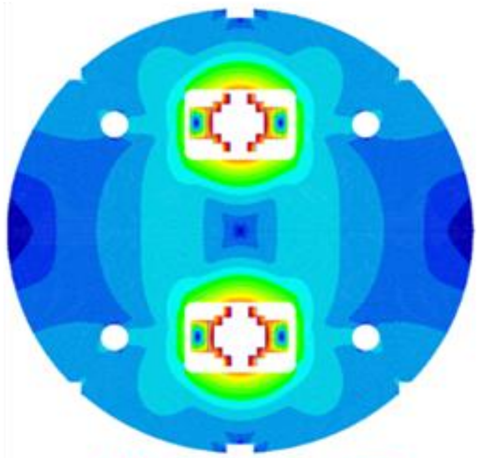




2021-2023 16T @ 4.2K

Nb_3Sn + HTS





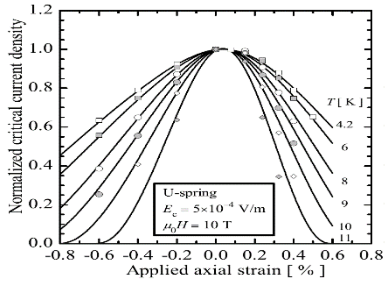
Nb_3Sn+HTS or HTS

2*ϕ45 aperture

20T @ 4.2K

With 10^{-4} field quality

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



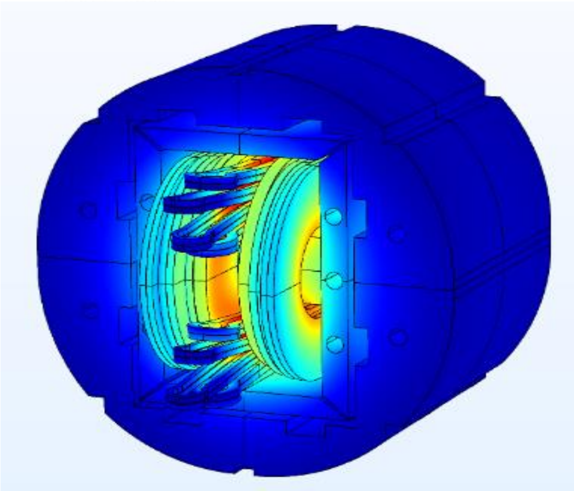
2018

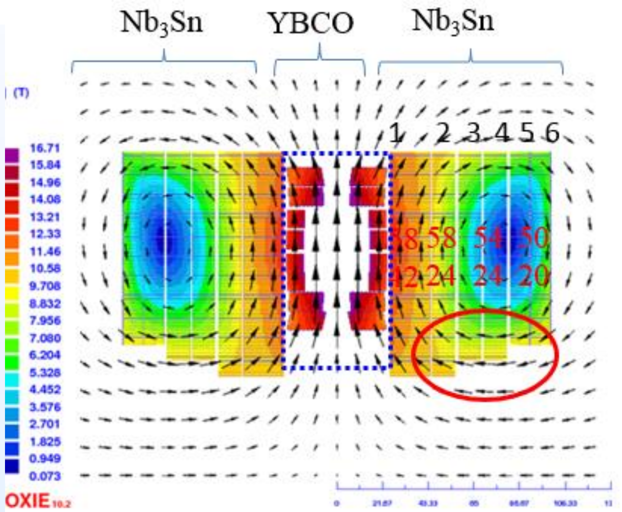
2028

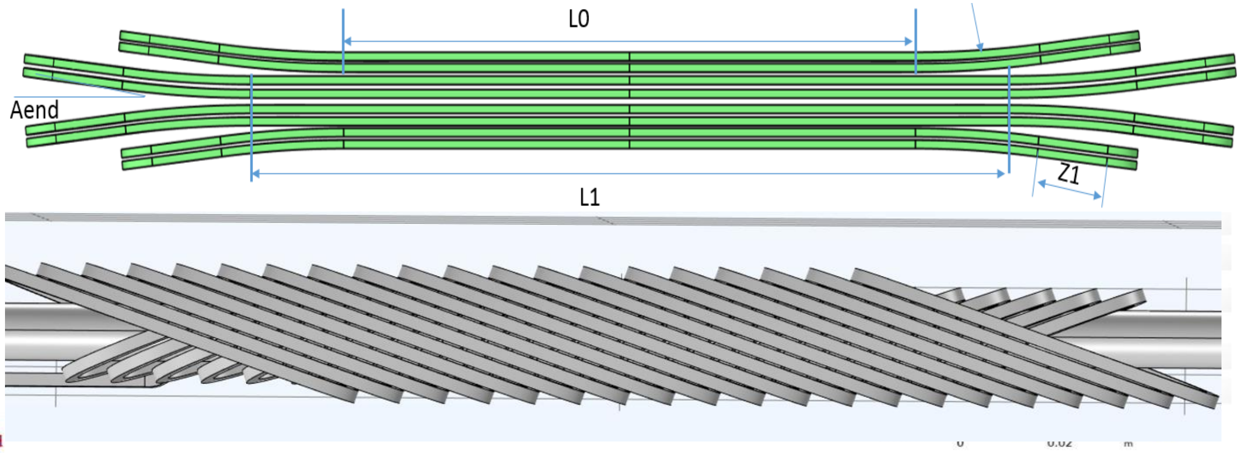
year

Development of the 16-T Model Dipole LPF3

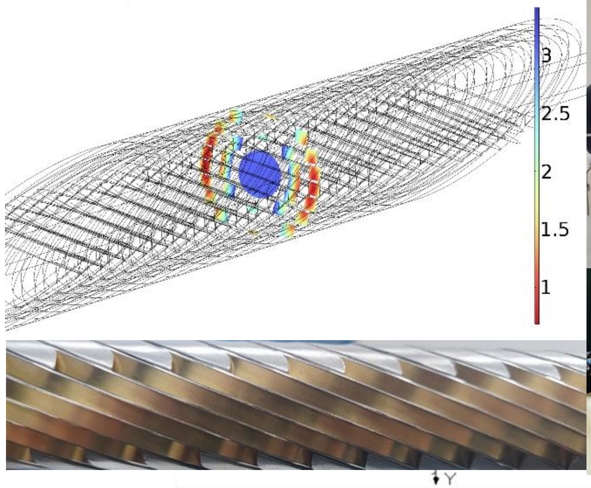
16 T Model Dipole LPF3: Nb_3Sn 13 T (*Common Coil with 55 mm gap*) + HTS 3 T inserts (*Block & CCT with ∅20 mm*)

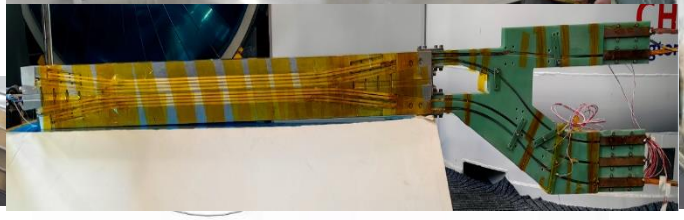


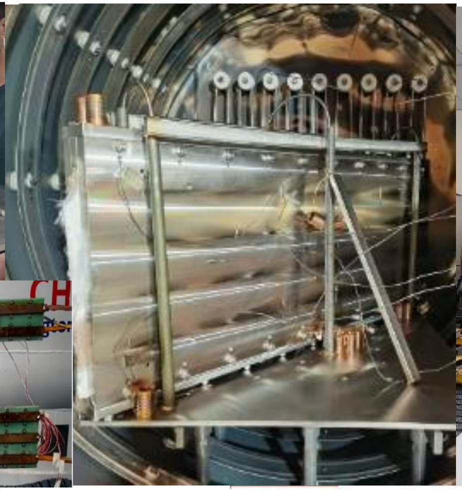




16-T 大孔径高场超导二极磁体 LPF3 (Nb_3Sn-13T+HTS-3T) 电磁设计



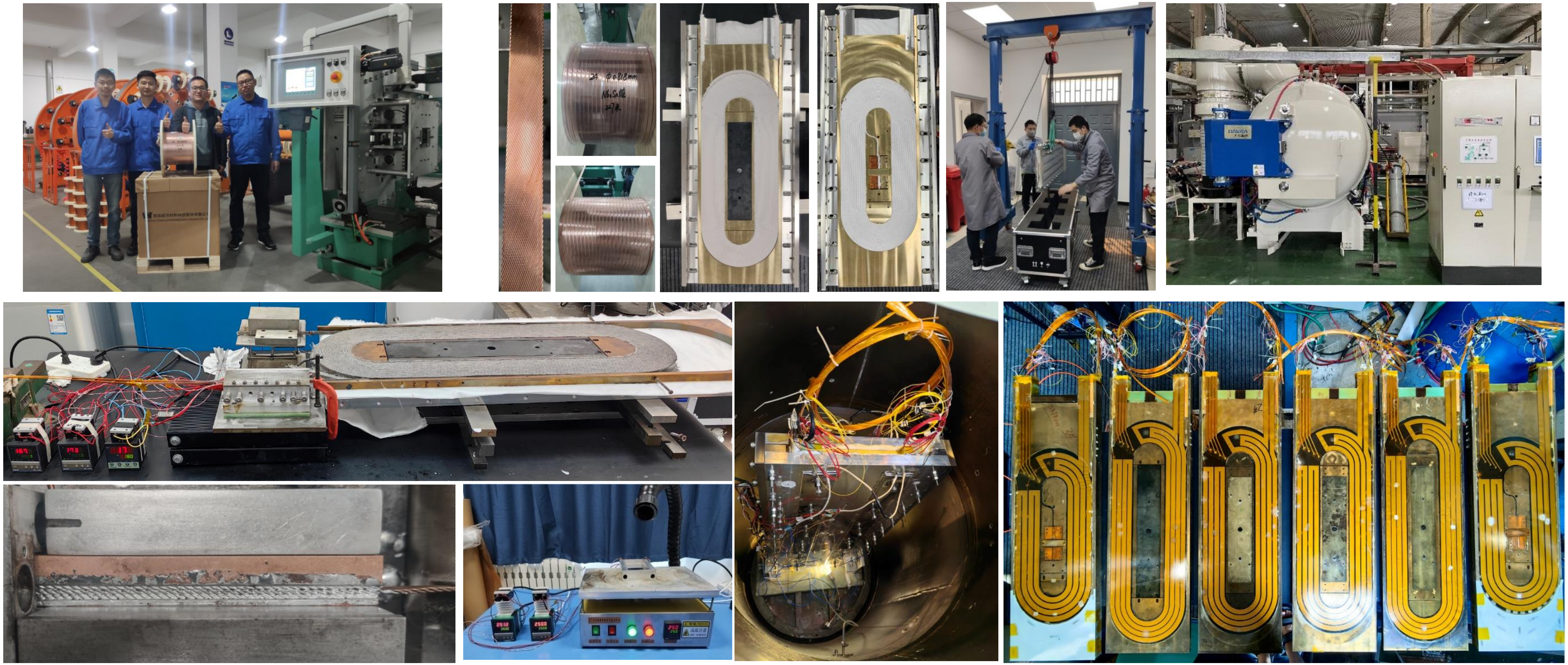




Development of the 16-T Model Dipole LPF3

The Nb_3Sn coils for LPF3

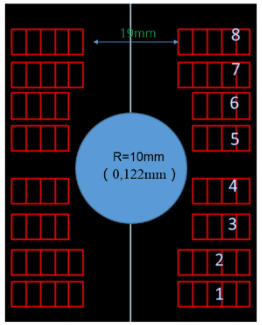
Chengtao Wang et al

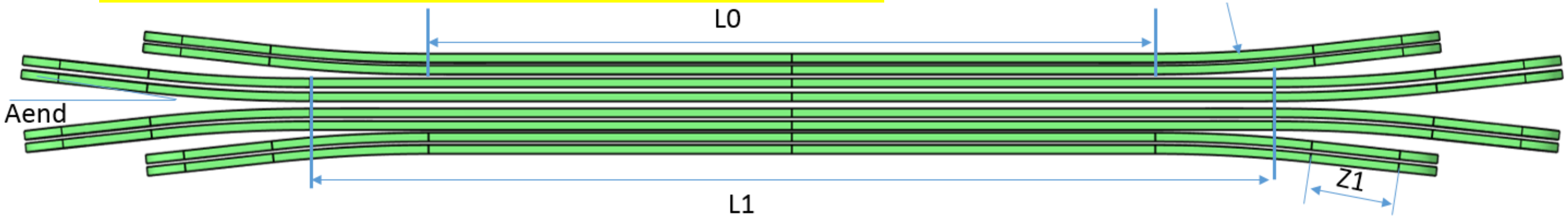


Development of the 16-T Model Dipole LPF3

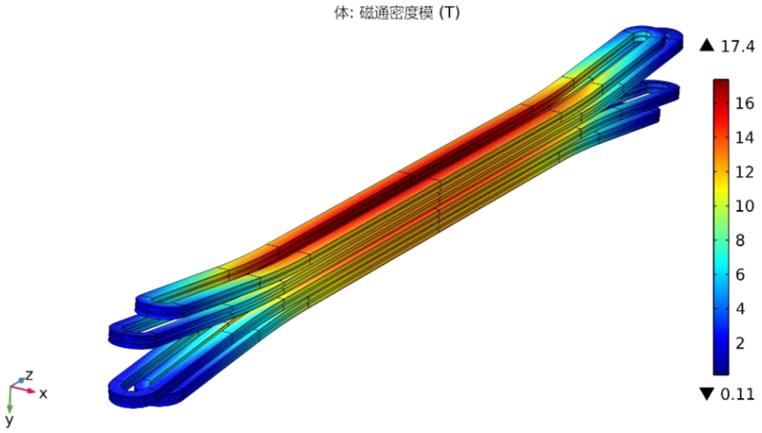
The ReBCO block insert coils for LPF3

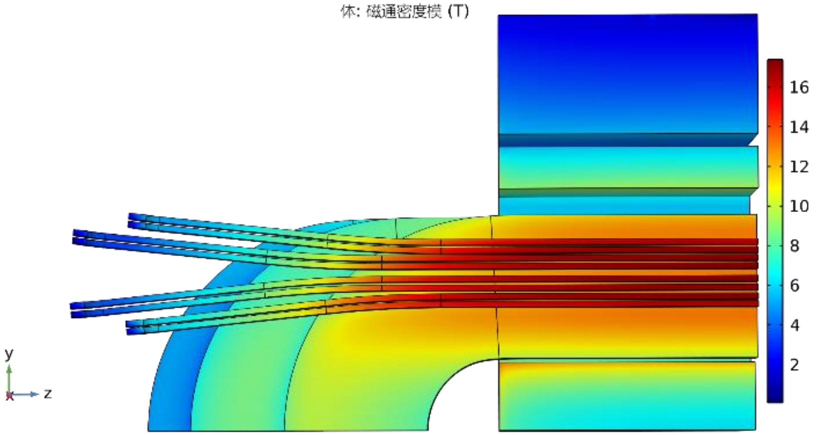
Ze Feng et al

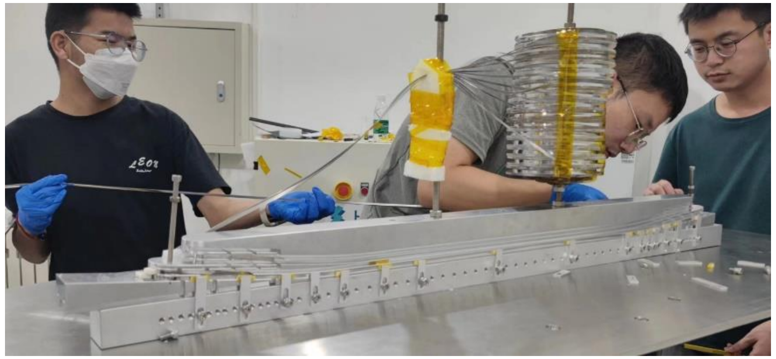


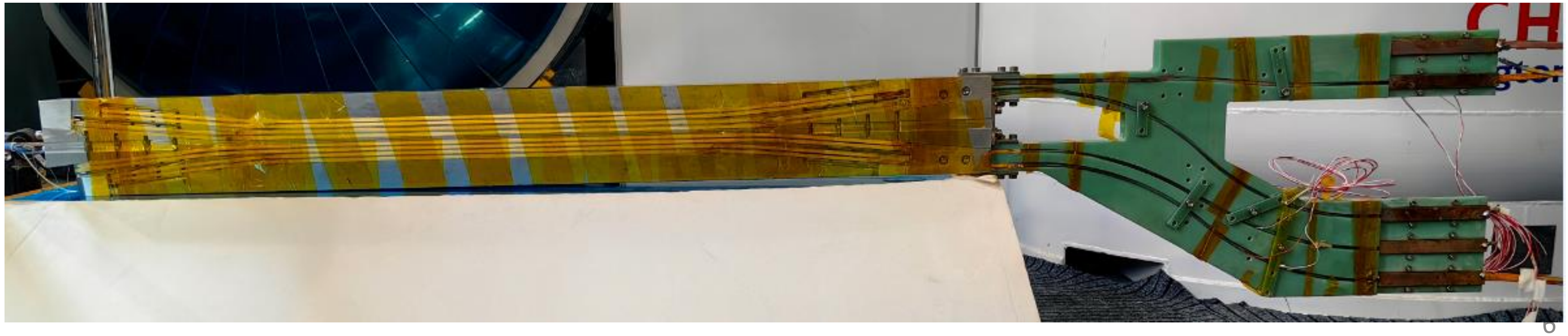


Parameters	Values
L0	409.6 mm
L1	540.2 mm
Rhard	800 mm
Aend	6 °
R1	9.5 mm
Z1	120 mm





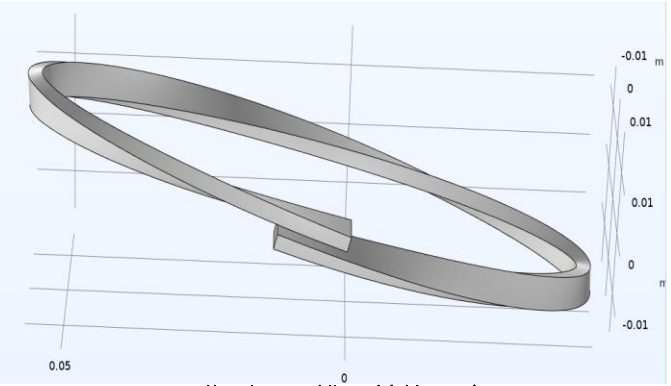




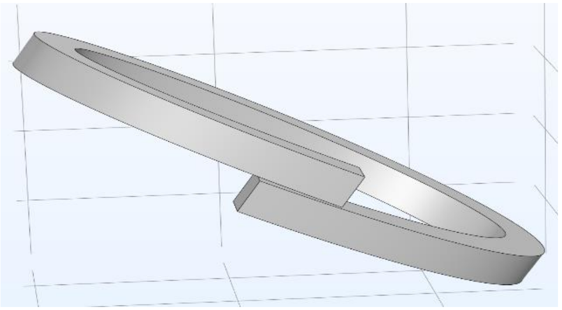
Development of the 16-T Model Dipole LPF3

The ReBCO CCT instert coils for LPF3

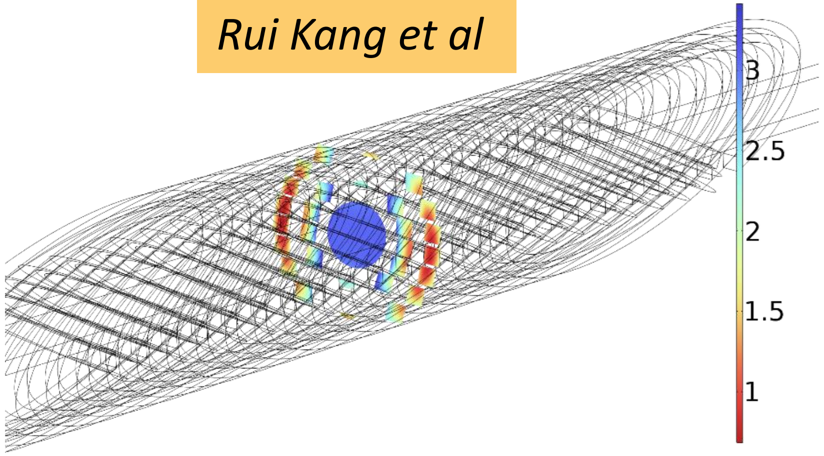
Rui Kang et al

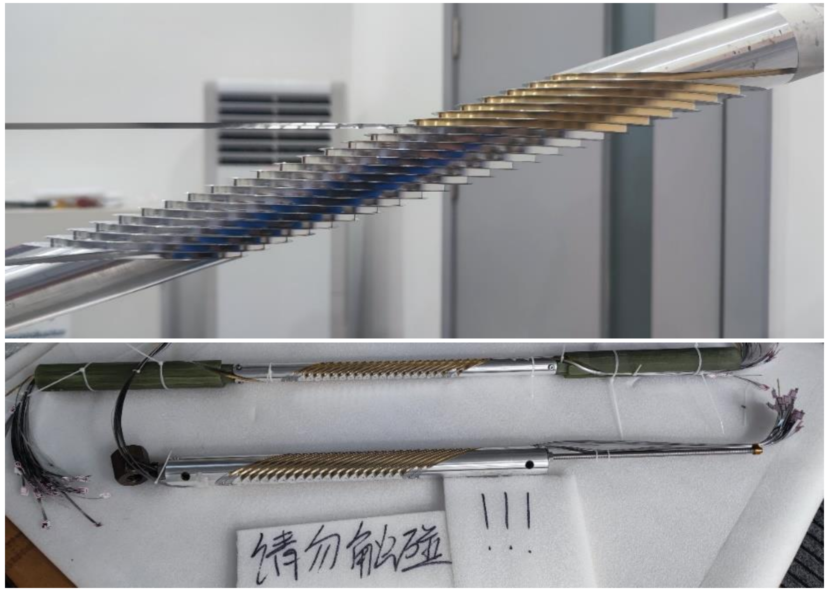


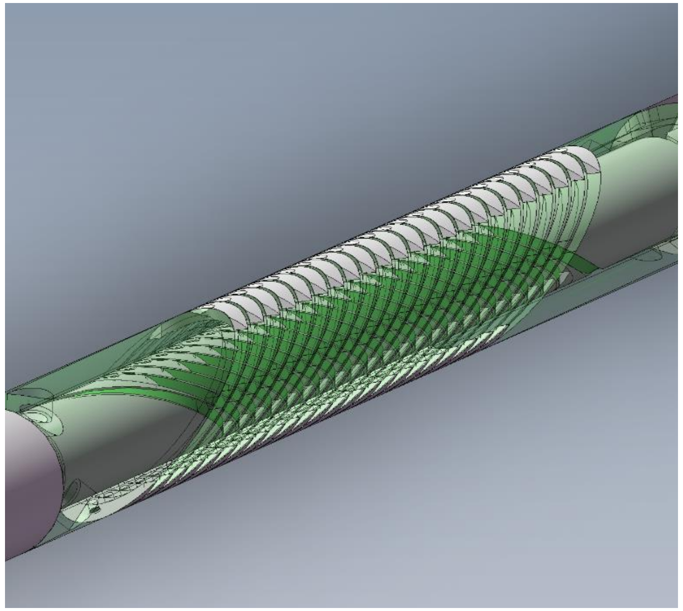
典型CCT线圈结构示意

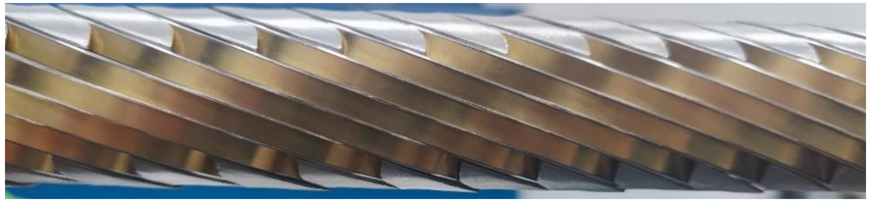


“斜螺线管”型CCT线圈结构示意





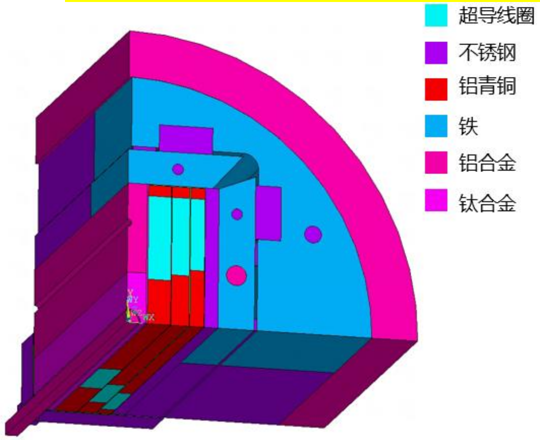


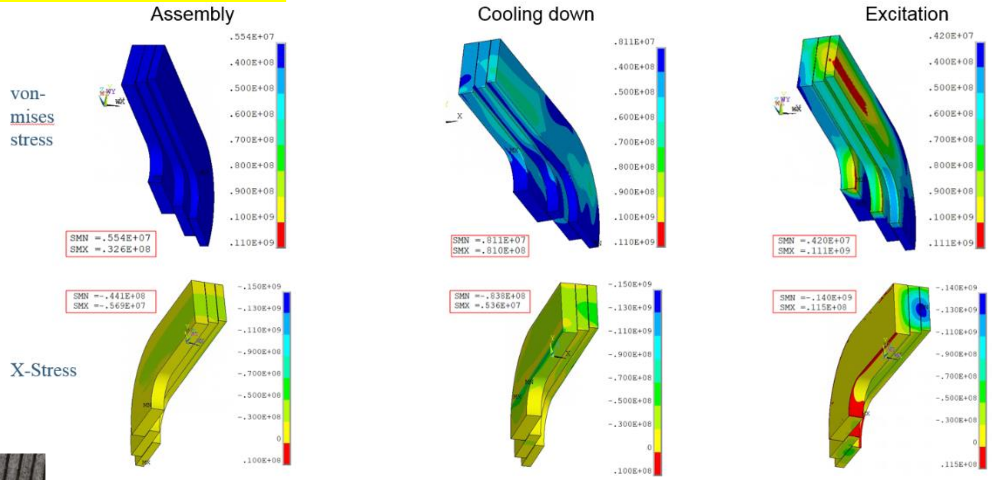


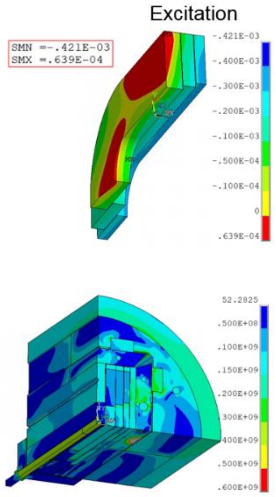
Development of the 16-T Model Dipole LPF3

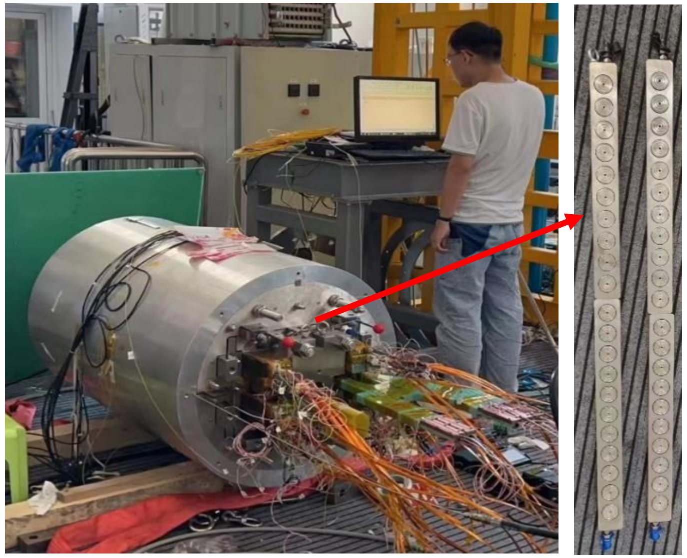
Pre-stress and assembly of LPF3

Yingzhe Wang et al



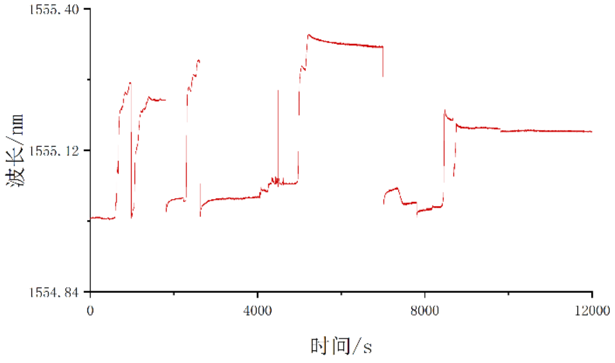






Pre-stress applied with commercial hydraulic jack

Stress monitoring during assembly with FBG



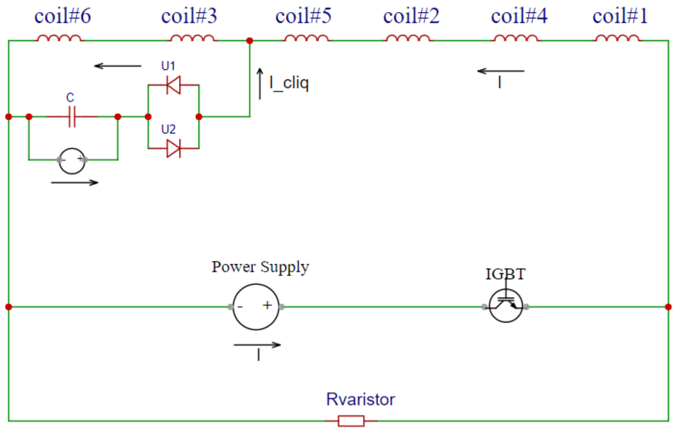
2023.8.29 Assembly completed

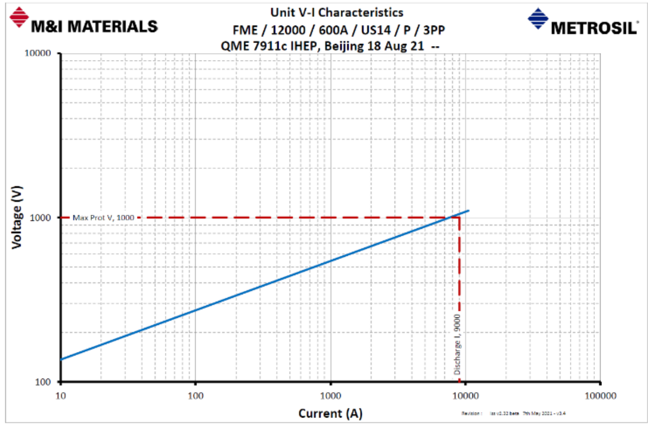
Development of the 16-T Model Dipole LPF3

Quench protection of LPF3

Jinrui Shi et al

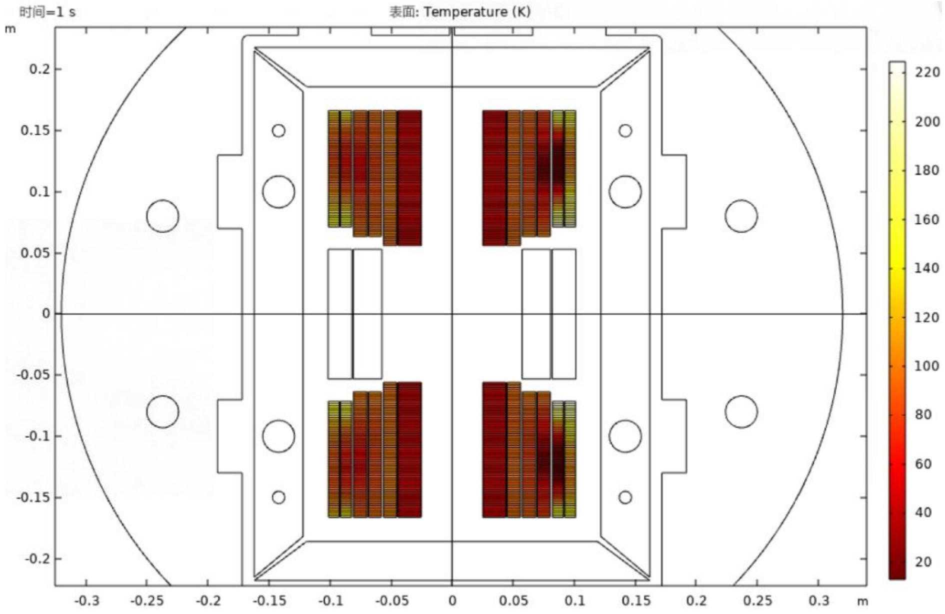
- **Varistor plus CLIQ** to protect the **Nb_3Sn** coils. The maximum hot spot is ~ 230 K
- **NI configuration plus dump resistor** to protect the 2 **HTS** insert coils

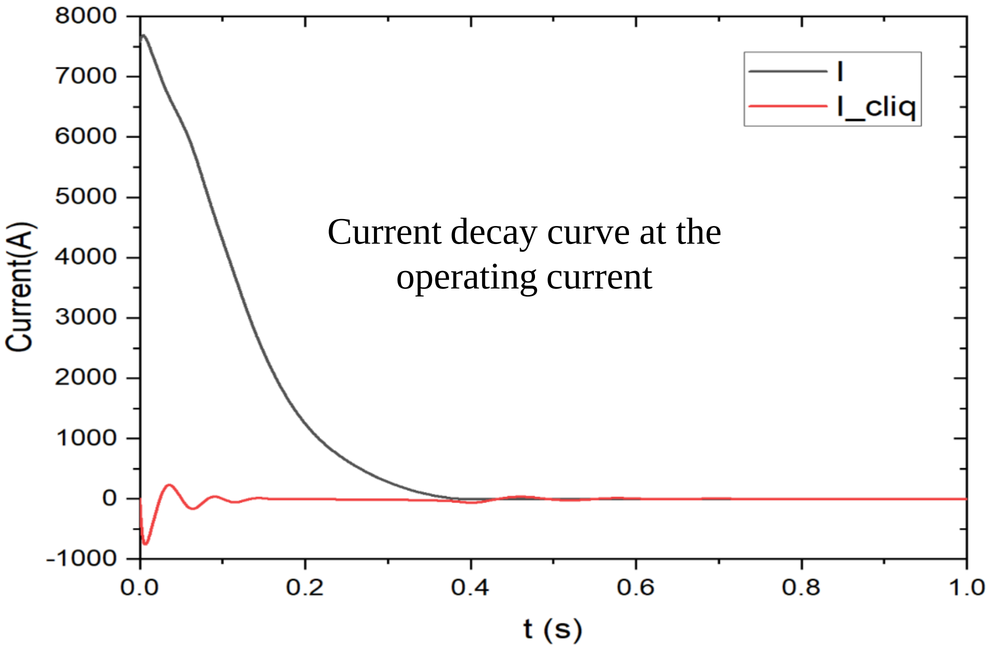




Feasibility study of applying the no-insulation coil on accelerator magnets

Rui Kang, Hongjun Zhang et al



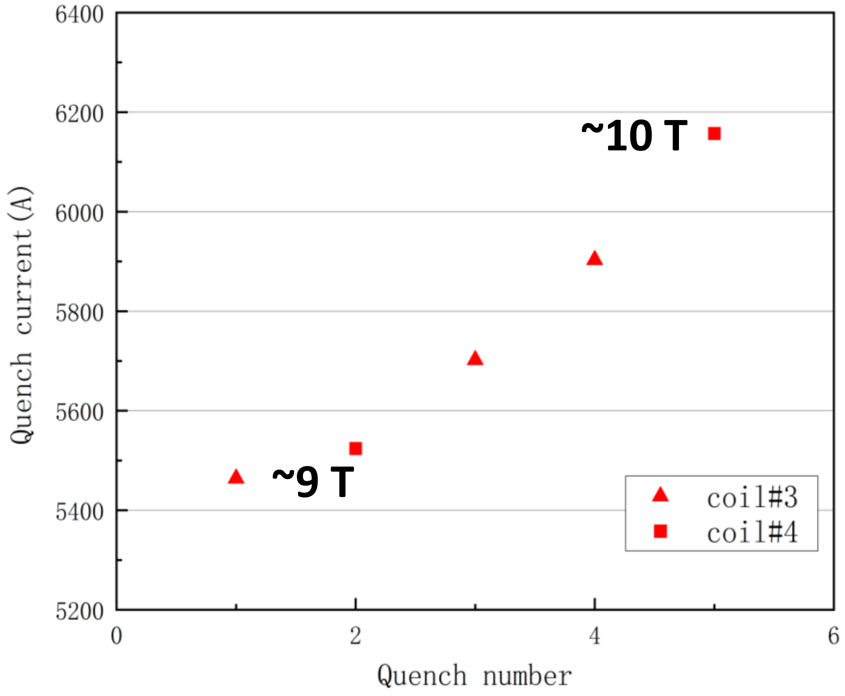


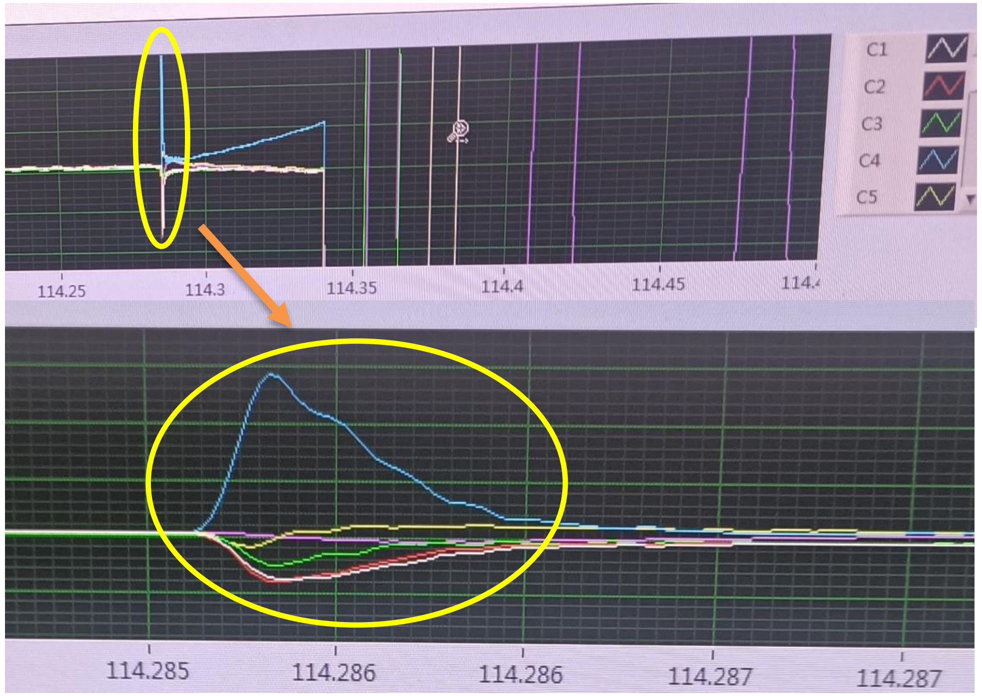
Development of the 16-T Model Dipole LPF3

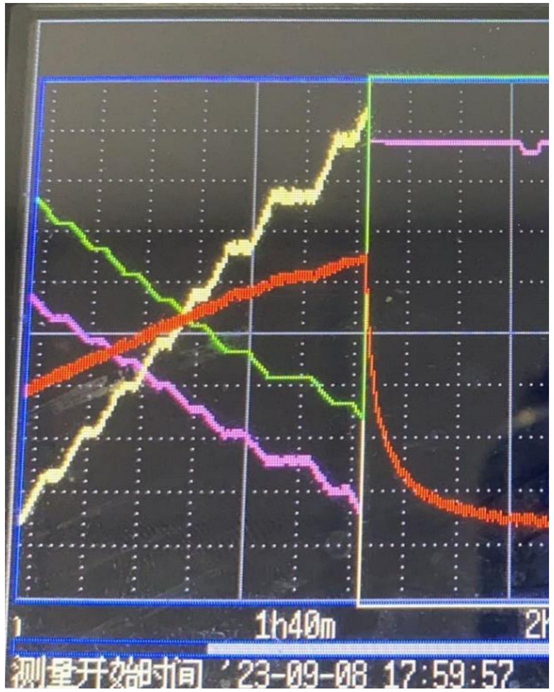
Preliminary fresh test results just last week!

Wei Li et al

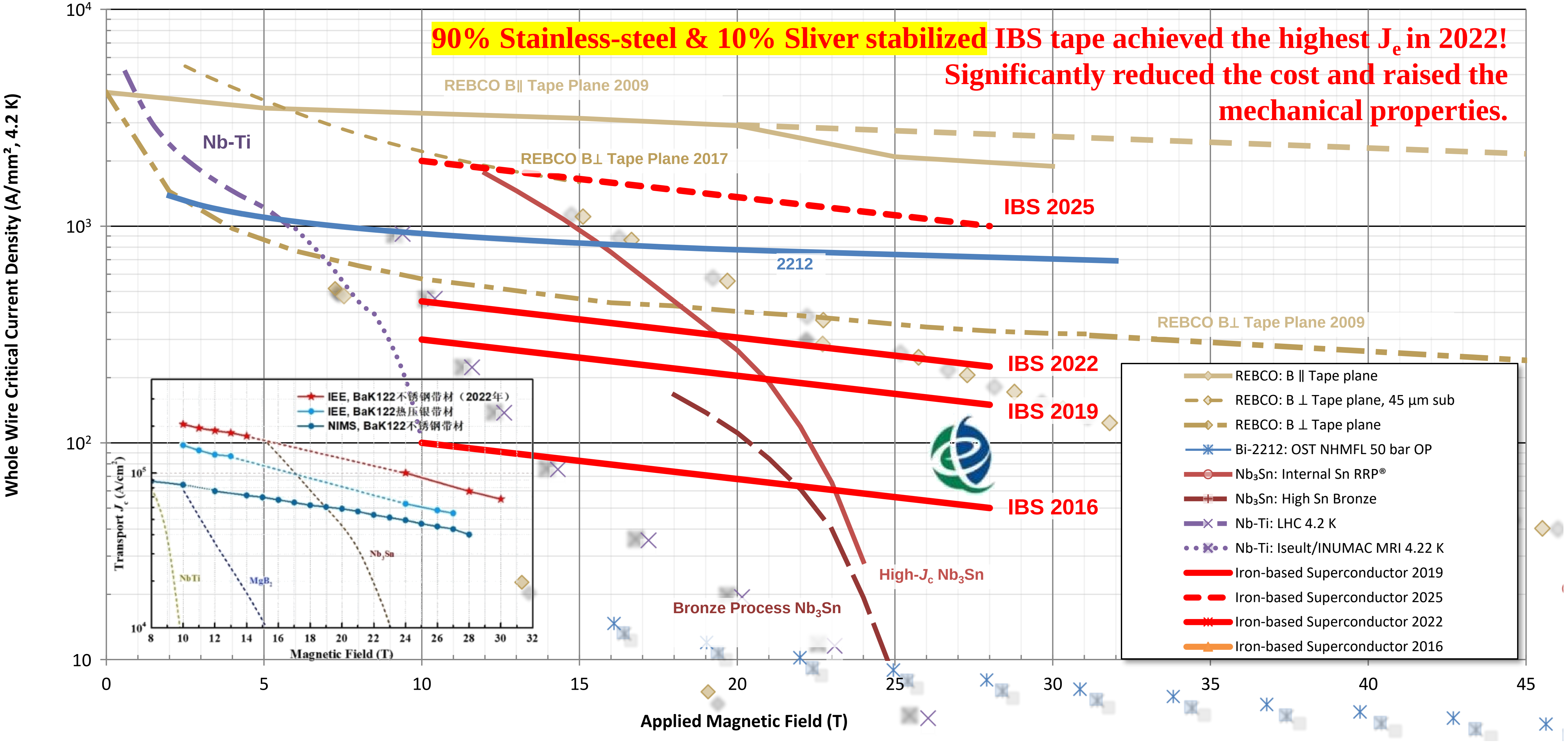
- The 1st preliminary test carried out in the week Sep 3-8 2003. The 6 Nb_3Sn coils were firstly ramped
- 5 quenches occurred from 9 to 10 T, all caused by FLUX JUMP, but with an encouraging upward trend
- Test stopped due to the limited size of He recovery gasbag, > 100 m^3 He gas was evaporated during the 5th quench
- HTS CCT insert was ramped independently, quenched at 90% of the I_{op} with a linearly increased voltage curve, probably indicating a damage of ReBCO conductor durting the coil fabrication process







IBS Technology: Status and Outlook



IBS Technology: Status and Outlook

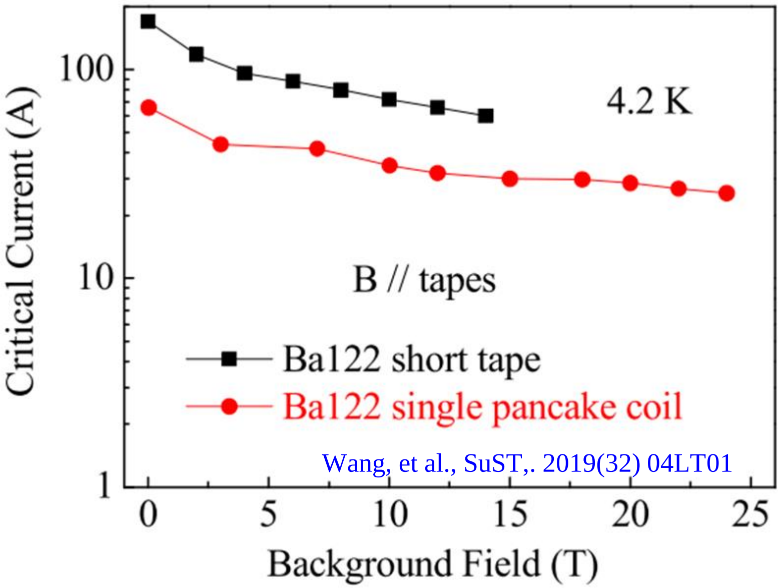
IOP Publishing Superconductor Science and Technology
Supercond. Sci. Technol. 32 (2019) 04LT01 (5pp) https://doi.org/10.1088/1361-6668/ab09a4

Letter

First performance test of a 30mm iron-based superconductor single pancake coil under a 24T background field

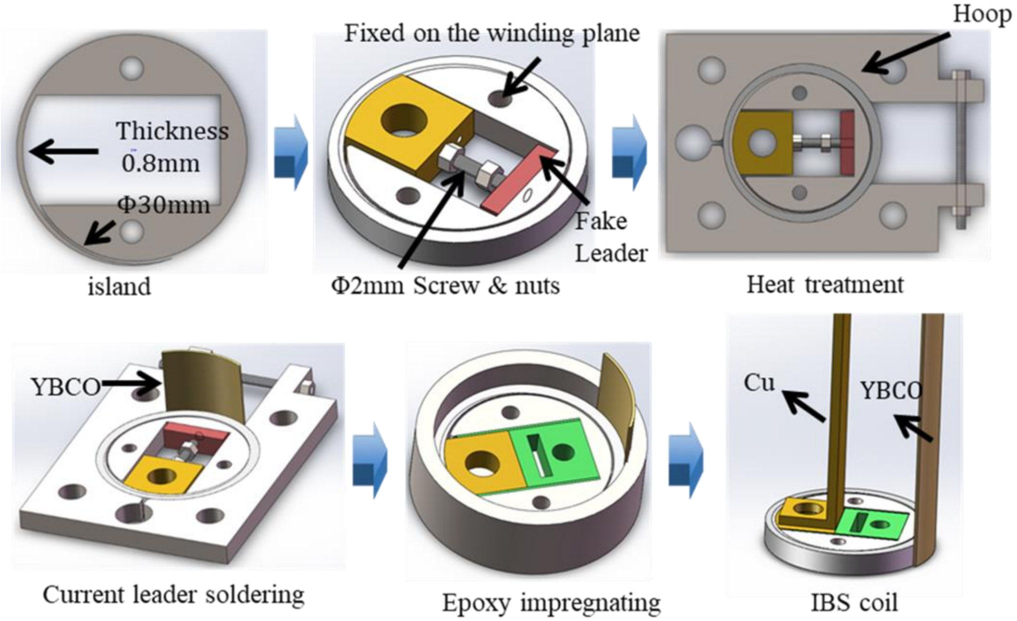
Dongliang Wang[1,2,5], Zhan Zhang[3,5], Xianping Zhang[1,2], Donghui Jiang[4], Chiheng Dong[1], He Huang[1,2], Wenge Chen[4], Qingjin Xu[3,6] and Yanwei Ma[1,2,6]

[1] Key Lab
Sciences,
[2] Universit
[3] Institute



Wang, et al., SuST,. 2019(32) 04LT01

The 1st IBS single pancake coil at 24 T



- The I_c of the IBS SPC at 24 T reach 40% of that at 0 T

12

IBS Technology: Status and Outlook

The 1st IBS racetrack coil with100-m Long IBS Tapes

- Inserted in the dipole magnet and tested at 4.2 K and 10 T

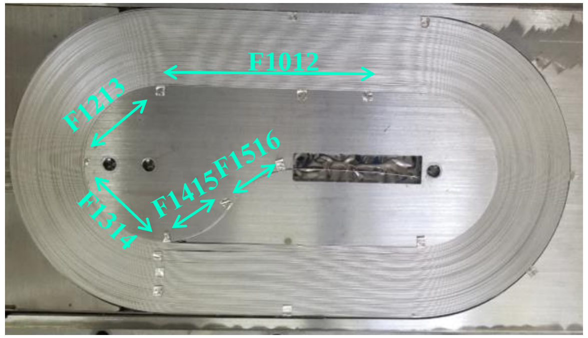
IOP Publishing Superconductor Science and Technology
Supercond. Sci. Technol. 34 (2021) 035021 (8pp) https://doi.org/10.1088/1361-6668/abb11b

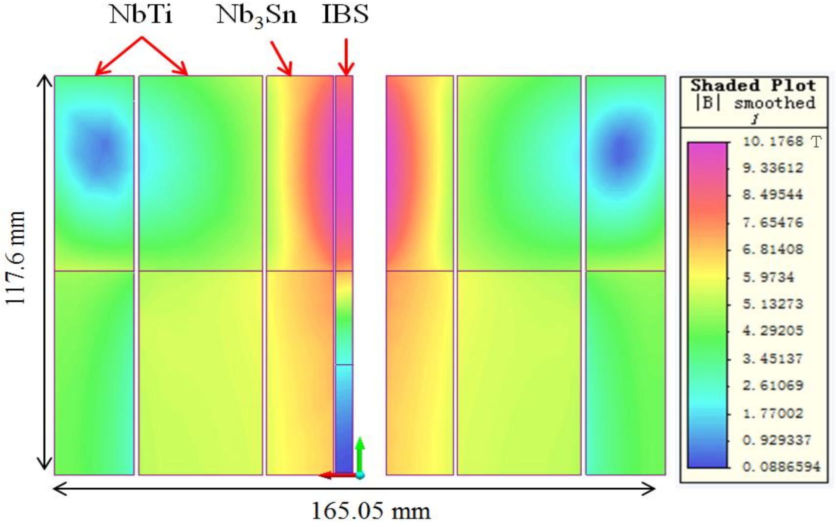
First performance test of the iron-based superconducting racetrack coils at 10 T

Zhan Zhang[1,2,6], Dongliang Wang[3,4,6], Shaoqing Wei[1,2], Yingzhe Wang[1,2,4], Chengtao Wang[1,2], Zhen Zhang[1,2,4], Huanli Yao[1,2], Xianping Zhang[3,4], Fang Liu[5], Huajun Liu[5], Yanwei Ma[3,4,7], Qingjin Xu[1,2,4,7] and Yifang Wang[1,4]

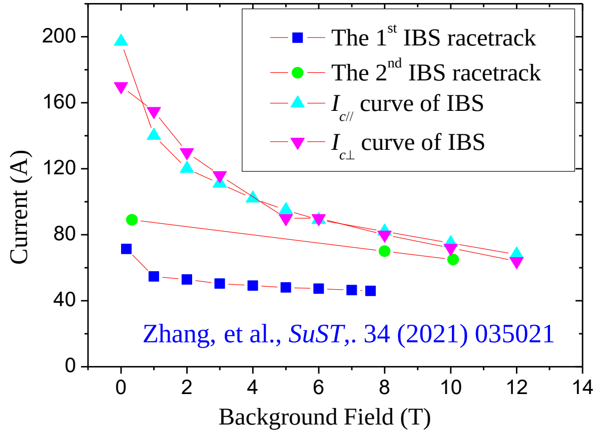
[1] Institute of High Energy Physics, Chinese Academy of Sciences, Beijing 100049, People's Republic of China
[2] Key Laboratory of Particle Acceleration Physics & Technology, Institute of High Energy Physics, Chinese Academy of Sciences, Beijing 100049, People's Republic of China
[3] Key Laboratory of Applied Superconductivity, Institute of Electrical Engineering, Chinese Academy of Sciences, Beijing 100190, People's Republic of China
[4] University of Chinese Academy of Sciences, Beijing 100049, People's Republic of China
[5] Institute of Plasma Physics, Chinese Academy of Sciences, Hefei 230031, People's Republic of China

E-mail: ywma@mail.iee.ac.cn and xuqj@ihep.ac.cn

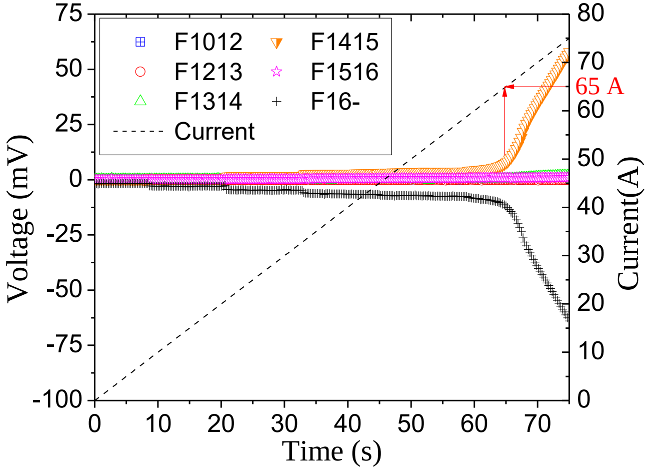




Quench Current w.r.t. Background Field of the IBS Racetracks Coils



Voltage Signals of the 2nd IBS Racetrack Coil Tested @ 10T



- Two racetrack coils have been made using the 100 m length IBS tapes.
- The I_c of the coil reached 86.7% of that of the short sample at 4.2 K and 10 T, and 81.25% of the quench current under 0 T.
- with highest compressive stress of 120 MPa.

IBS Technology: Status and Outlook

I_c of IBS tapes with different bending diameters

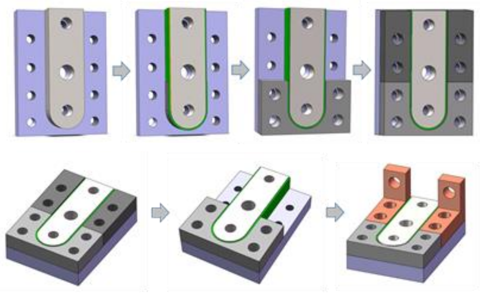
IEEE TRANSACTIONS ON APPLIED SUPERCONDUCTIVITY, VOL. 32, NO. 6, SEPTEMBER 2022 7300304

Effect of Bending Before Annealing on Current-Carrying Properties of Iron-Based Superconducting Tapes

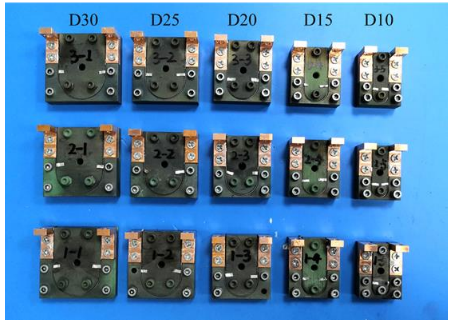
Chunyan Li, Rui Kang, Yanchang Zhu, Zhen Zhang, Yingzhe Wang, Chengtao Wang, Jin Zhou, Huanli Yao, Xianping Zhang, Dongliang Wang, Cong Liu, Fang Liu, Yanwei Ma, and Qingjin Xu

Abstract—The iron-based superconductor (IBS) is a good candidate for high field magnet applications. The bending effect and properties of IBS tapes were systematically investigated in this

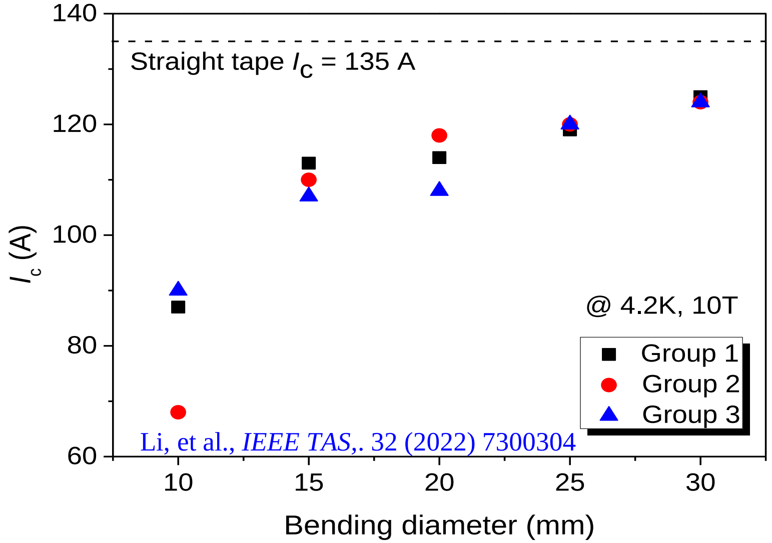
(IEECAS) [2]. This demonstrates the great potential of IBS tape for large-scale applications. A record critical current density

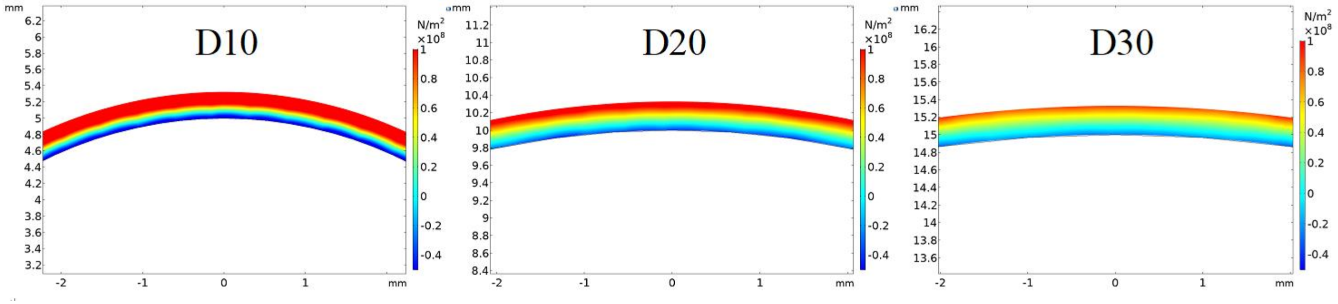


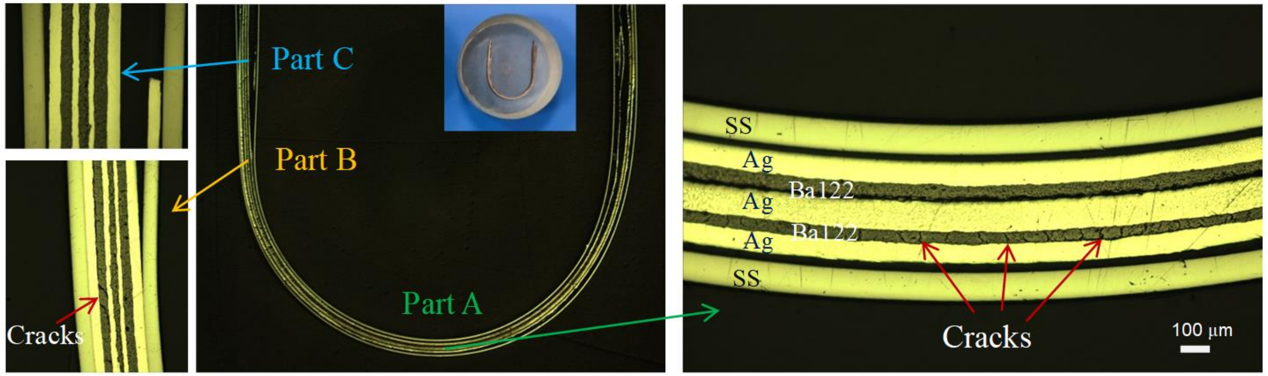
Preparition of bent IBS tape



Tested at 4.2 K and 10 T







- The attenuation curve of I_c performance with decreasing bending diameters for IBS tapes was obtained.
- Cracks appear regularly in part of the superconducting cores under tensile stress.

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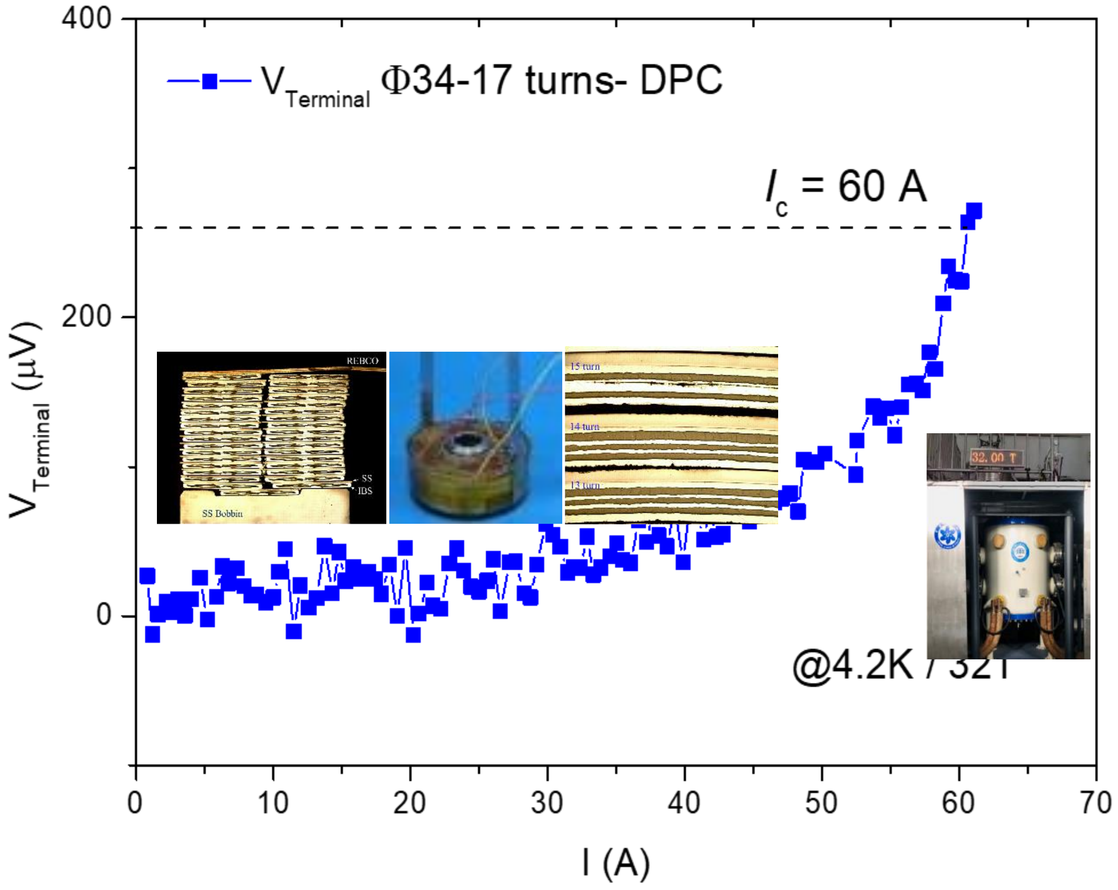
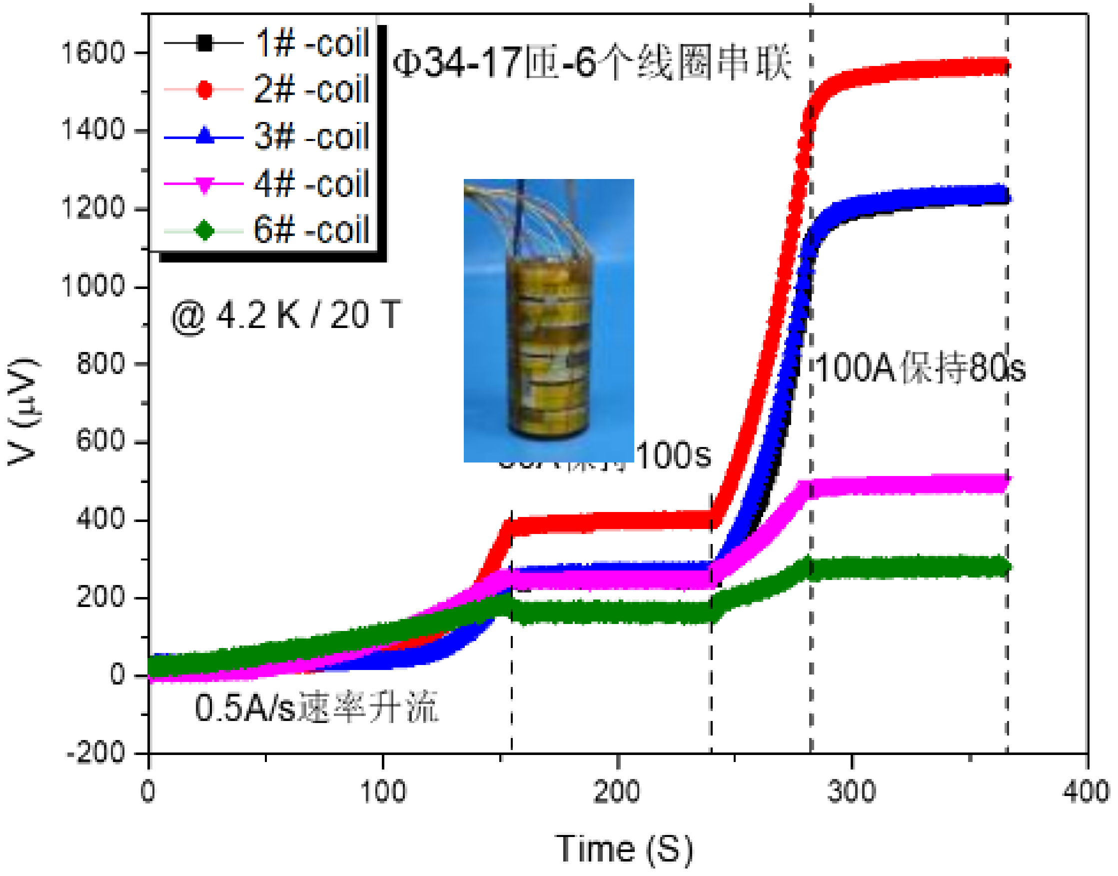
IBS Technology: Status and Outlook

The First IBS Solenoid Coil at 32 T background field

Chunyan Li et al

I_c of Φ34mm-17 turns-DPC reached **60 A at 4.2 K and 32 T, world's highest record up to now.**

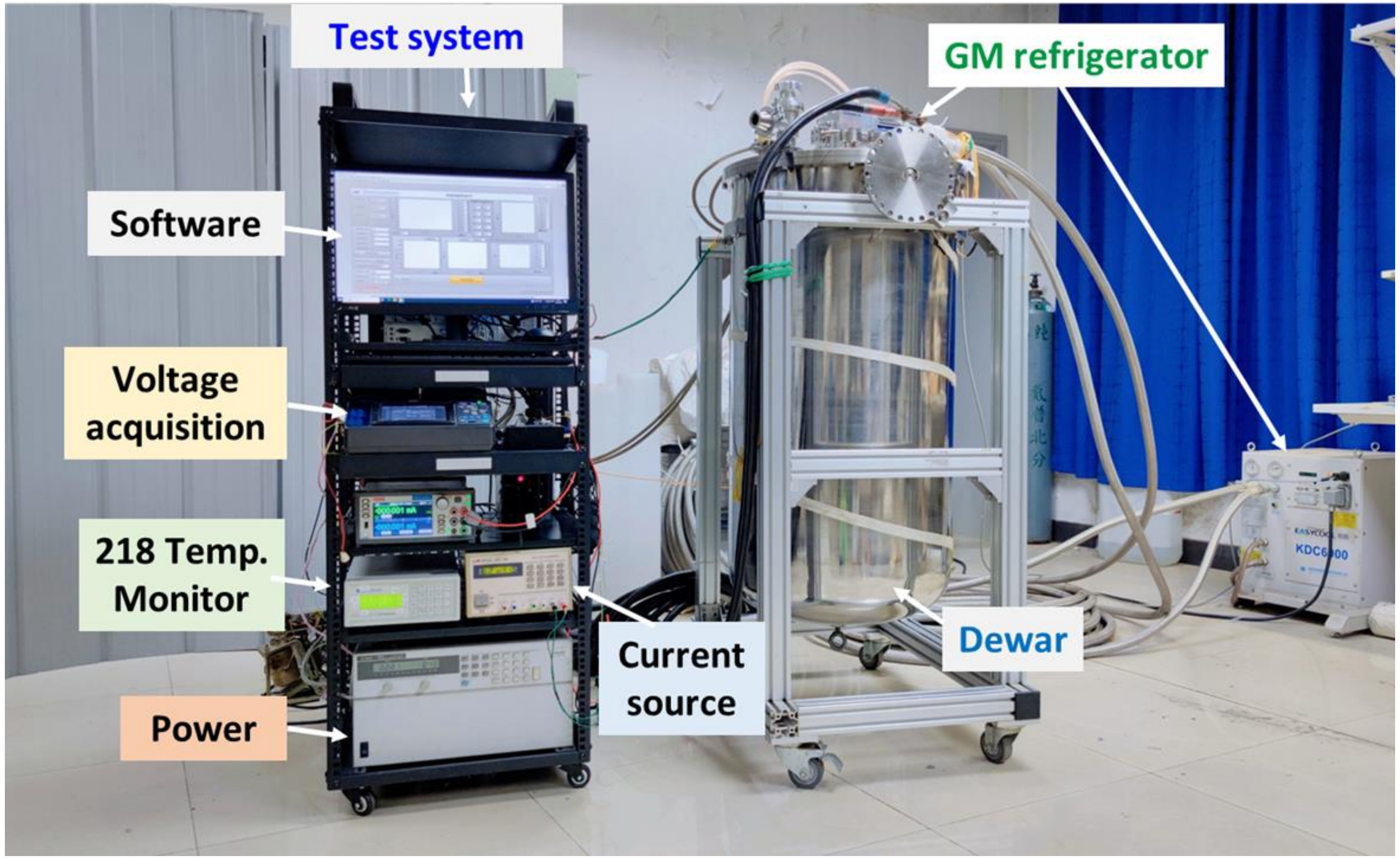


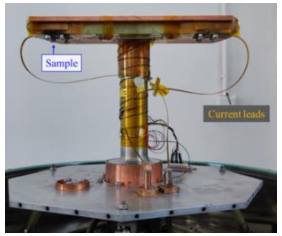


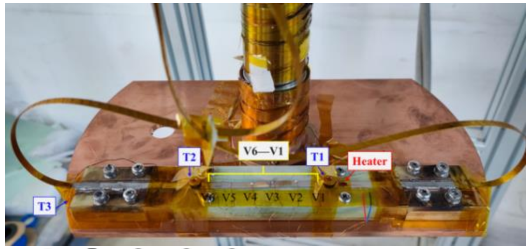
IBS Technology: Status and Outlook

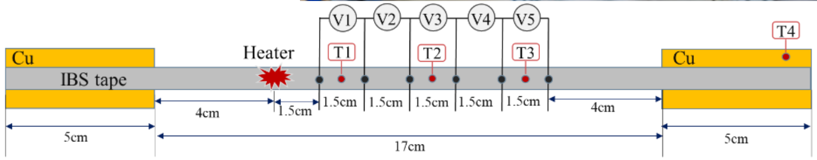
Quench propagation study of the IBS coils

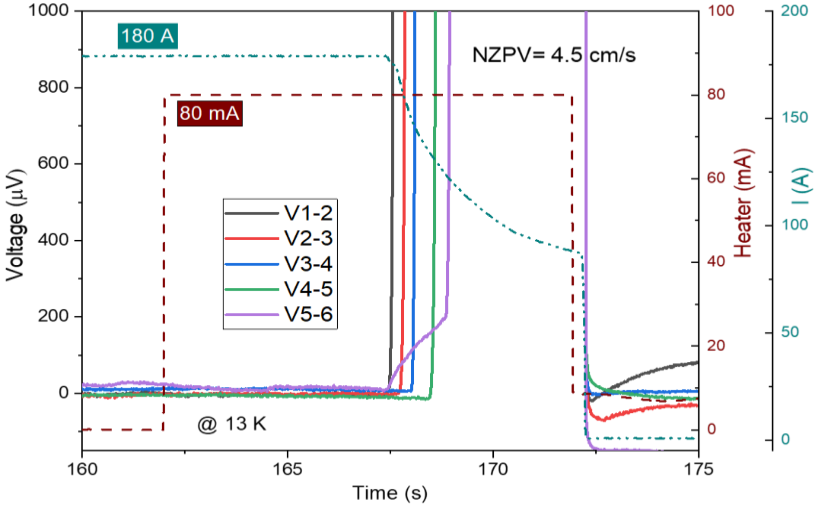
Chunyan Li et al





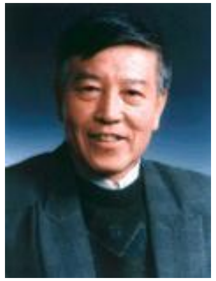




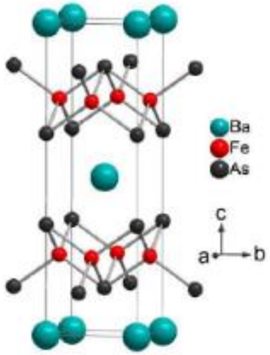


Experimental data shows significant quench propagation in the IBS coils! More testing will be carried out

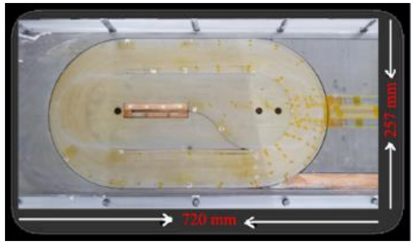
IBS Technology: Status and Outlook



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

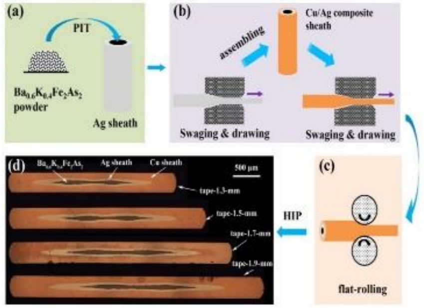
2016

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)



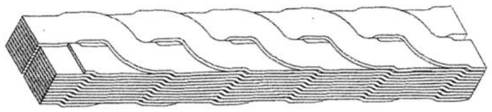
J_e of IBS expected to be similar as ReBCO in 5 years with better mechanical properties and lower cost

R&D of the HTS transposed cable: X-cable

Development of a Roebel-like Transposed Cable with the in-plane bending of HTS tapes

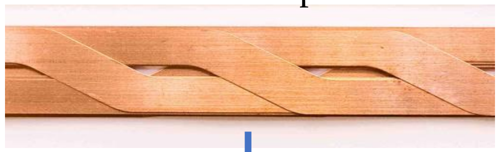
Martin N. Wilson proposed the idea in1997

In-plane transposed HTS cable



KIT proposed the Roebel cable concept by punching wide tapes to realize transposition in 2006

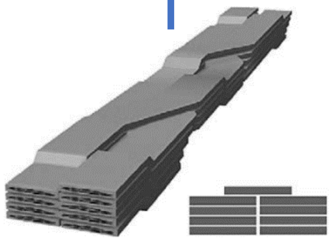
Punch-assemble transposed HTS cable



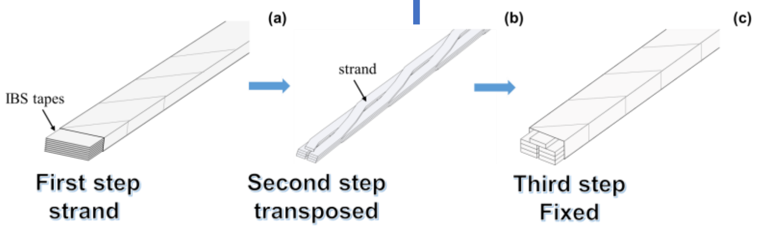
IHEP successfully fabricated the first in-plane transposed REBCO cable in 2020

In-plane transposed HTS cable

Juan Wang et al



Siemens developed a transposed cable with in-plane bending Bi-2223 tapes in 2004



IHEP proposed the transposed cable with **in-plane bending of HTS tapes** in 2017

IHEP successfully fabricated the first IBS transposed cable in 2021

R&D of the HTS transposed cable: X-cable

Development of a Roebel-like Transposed Cable with the in-plane bending of HTS tapes

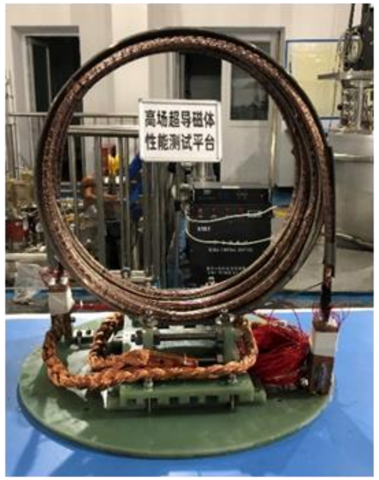
Juan Wang et al

2020.08

2020.10

2021. 01

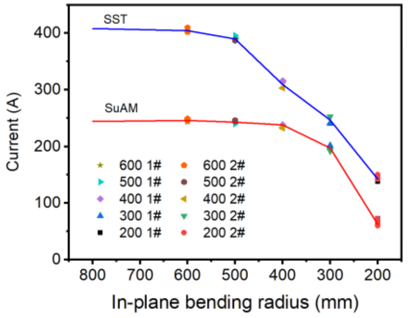
2021. 04

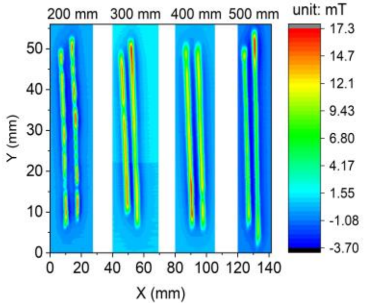


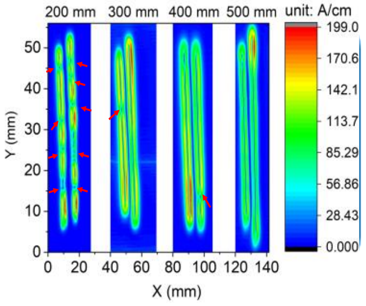
2021. 06

2021. 08

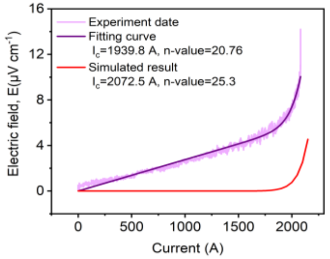
2023. 02



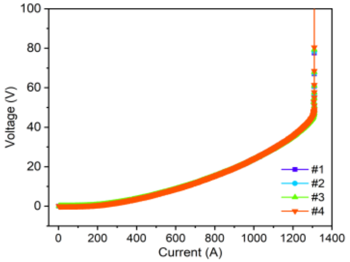




10 m REBCO 换位电缆

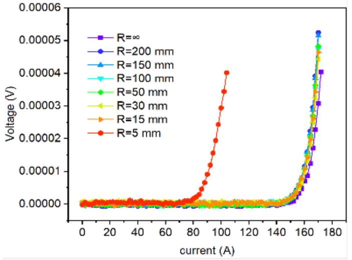


5 m IBS 换位电缆



6 m IBS 换位电缆

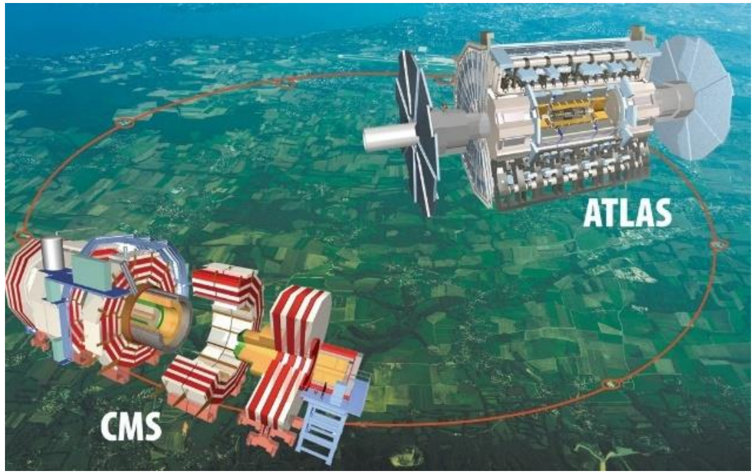
30 m REBCO 换位电缆



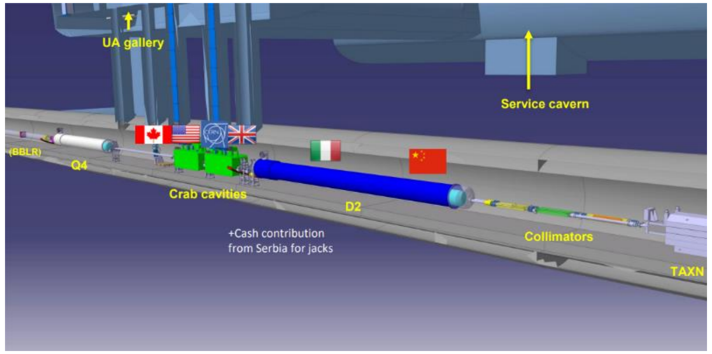
Development of CCT Magnets for HL-LHC

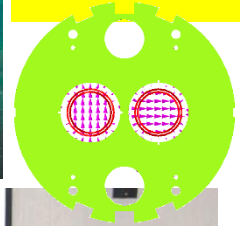
China provides 13 units CCT twin-aperture dipole magnets for HL-LHC

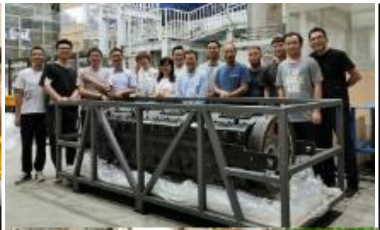
IHEP IMP 苏州八匹马超导科技有限公司 Superconductor Technology



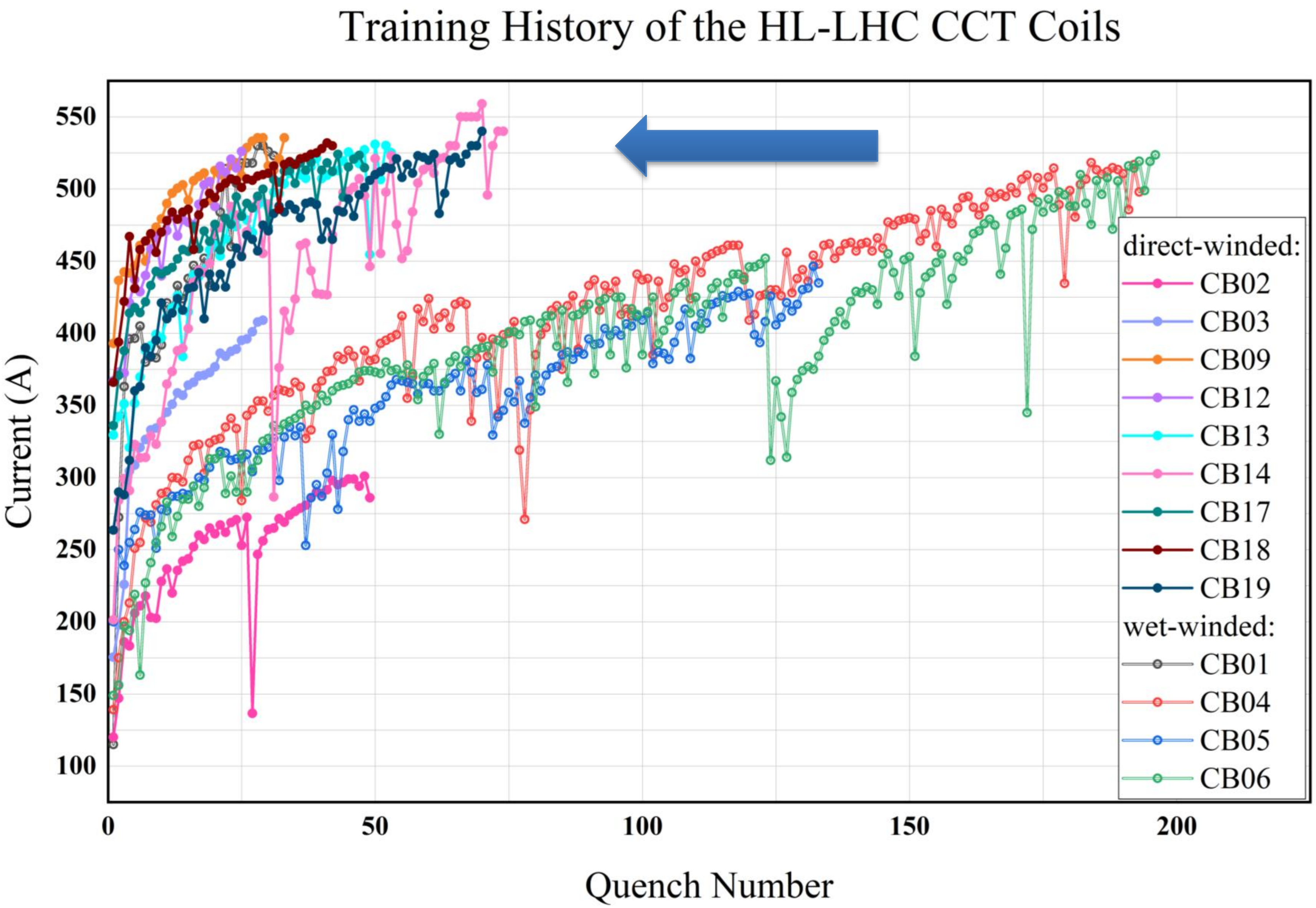
- To be installed in the ATLAS & CMS interaction regions, help to raise the luminosity by 5 times
- The 1st time CCT type magnets applied to an operating accelerator.







Development of CCT Magnets for HL-LHC



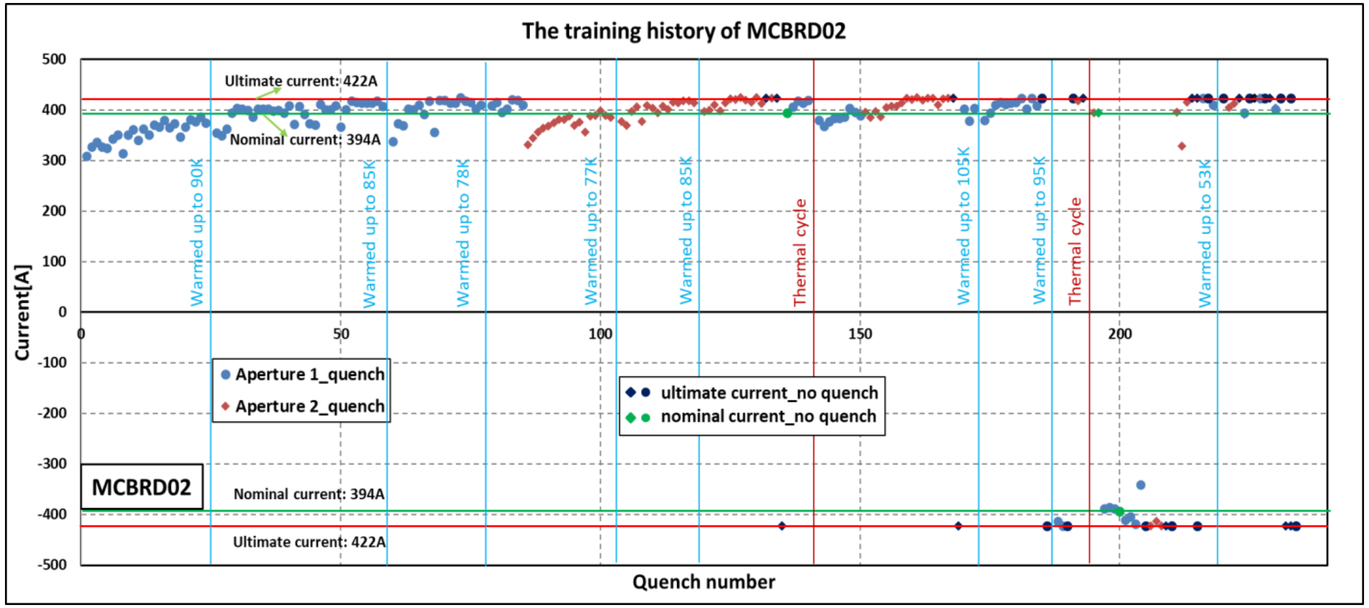
Successful design upgrade to solve the "long training problem", significantly reduced the times of quench during training, ensured the project progress "on track".

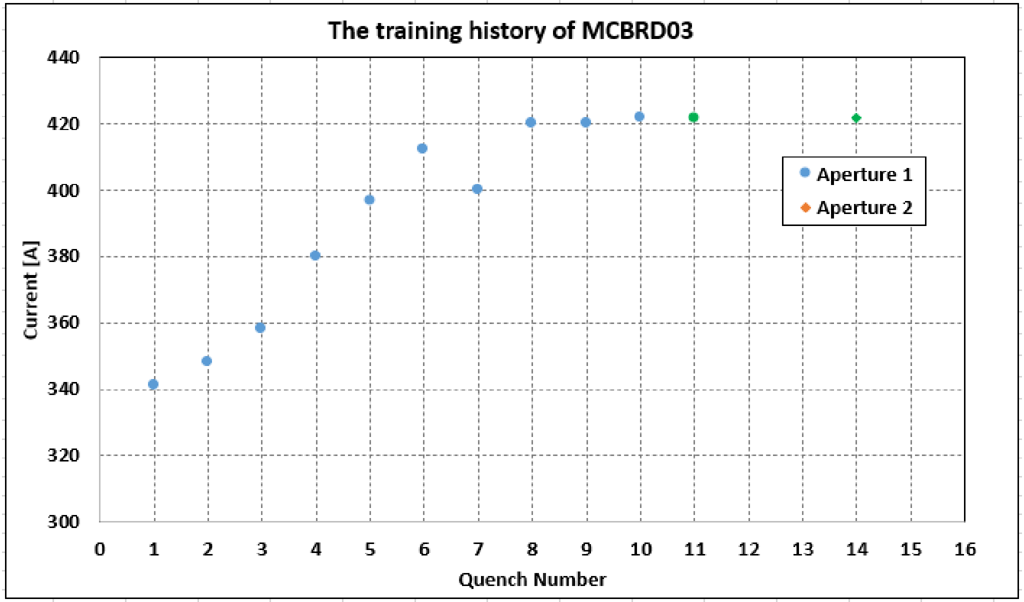
Development of CCT Magnets for HL-LHC

Training of MCBRD02 & MCBRD03

IHEP
IMP
Superconductor Technology
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.





Development of CCT Magnets for HL-LHC

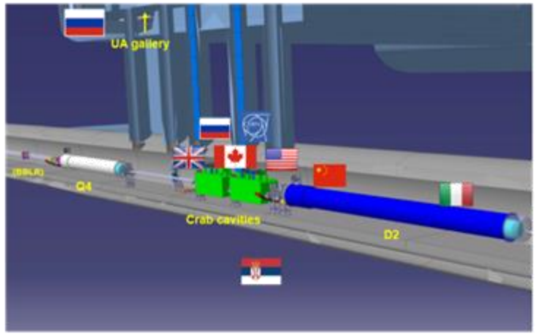
- 4 series CCT magnets have been fabricated; all of them reached the ultimate current and passed the field quality test. Components for 2 magnets being shipped to CERN; The 5th series magnet to be assembled in Nov 2023
- Production rate for the rest of series magnets: every 3 month per magnet

	Coil name	Winding method	Location	Coil stand-alone performance (4.2 K)	Magnet performance at 4.2 K
MCBRD01	MCBRD_CB01	Wet wind	CERN	530 A	Both apertures reached ultimate current 422 A, and passed 4-hour stability test
	MCBRD_CB03	Direct wind		410 A (training stopped due to the availability of the test station)	
	MCBRD_CB02	Direct wind	CERN	Failed to reach the design current	
MCBRD02	MCBRD_CB04	Wet wind	CERN	422 A (training stopped due to the availability of the test station)	Both apertures reached ultimate current 422 A, and passed 4*1 hour stability test
	MCBRD_CB06	Wet wind		530 A	
MCBRD03	MCBRD_CB09	Direct wind with new channel size	CERN	530 A	Both apertures reached ultimate current 422 A, and passed stability test
	MCBRD_CB12	Direct wind with new channel size		526 A (25 quenches)	
	MCBRD_CB14	Direct wind with new channel size	BAMA	530 A (30+34 quenches), put in quarantine	
MCBRD04	MCBRD_CB13	Direct wind with new channel size	IMP	530 A (20+33 quenches)	Both apertures reached ultimate current 422 A, and other tests will be implemented in the middle of Oct.
	MCBRD_CB17	Direct wind with new channel size		524 A (47 quenches)	
MCBRD05	MCBRD_CB18	Direct wind with new channel size	IHEP	530 A (43 quenches)	To be assembled in Nov 2023
	MCBRD_CB19	Direct wind with new channel size	IHEP	530 A (63 quenches)	
	MCBRD_CB20	Direct wind with new channel size	IHEP	*To be stand-alone tested*	
MCBRD_CB10, 11, 15, 16		Shipped to CERN for fabrication			

Development of CCT Magnets for HL-LHC

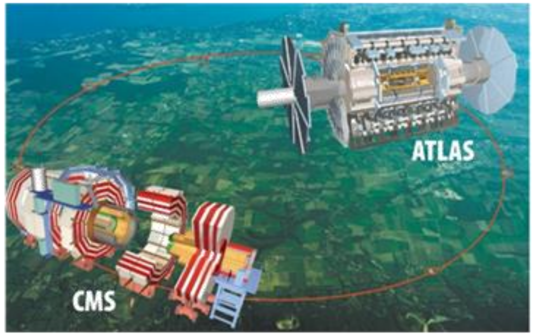
Milestone of the HL-LHC CCT Magnet Project

IHEP IMP Superconductor Technology 苏州八匹马超导科技有限公司



Agreement signed btw IHEP and CERN

The CCT magnet from China under test at CERN



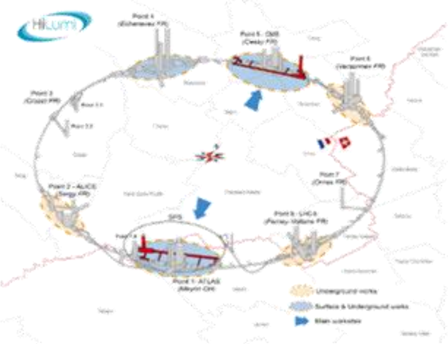
Installation to tunnel

2018	2020	2022	2024	2026	2027
Agreement signed btw IHEP and CERN	The qualified prototype delivered to CERN	The CCT magnet from China under test at CERN	All the 12 series CCT magnets delivered to CERN	Installation to tunnel	HL-LHC commissioning

The qualified prototype delivered to CERN

All the 12 series CCT magnets delivered to CERN

HL-LHC commissioning



Summary

- Long-term advanced superconducting magnet R&D for future high-energy accelerators is ongoing at IHEP-CAS
- 10+ T model dipoles being developed at IHEP, reached 12.47 T at 4.2 K in mid 2021. 16 T (Nb_3Sn+HTS) model dipole under test in 2023. 20 T accelerator magnets expected to be realized in 2020s
- 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! Significantly reduced the cost and raised the mechanical properties
- China & CERN Collaboration on accelerator technology: development of HL-LHC CCT magnets going well
- Looking forward to a world wide synergy on the advanced accelerator magnet R&D in future

Thanks for your attention