中国科学院高能物理研究所
Institute of High Energy Physics, CAS
中科院高能所超导磁体组
Superconducting Magnet Group, IHEP

Recent Progress of the High Field Superconducting Magnet R&D for Next-generation Particle Colliders

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for the Superconducting Magnet Team of
IHEP-CAS

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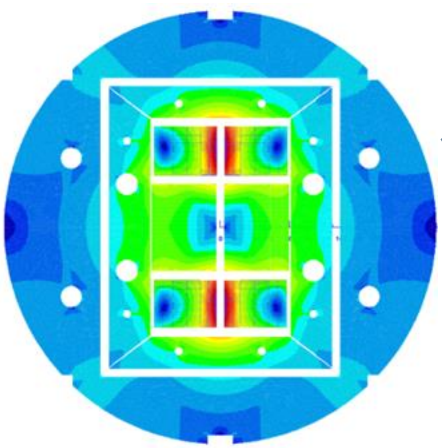
R&D Roadmap of the High Field Dipole Magnets

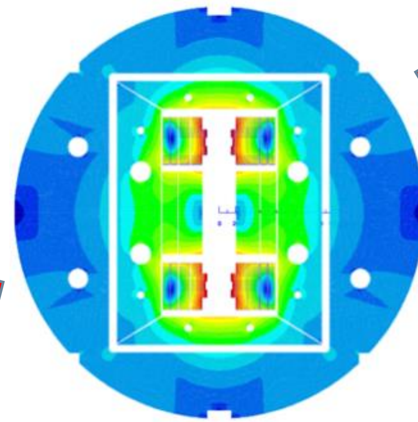
Field (T)

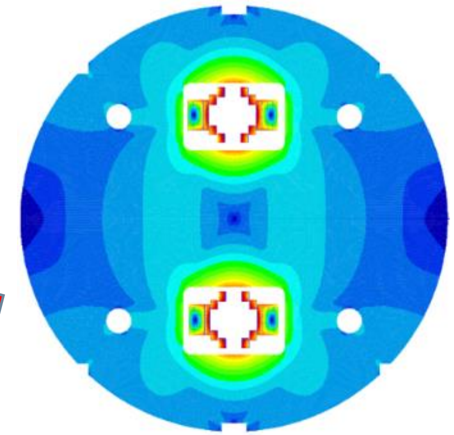
20

$NbTi+Nb_3Sn$
2*∅10 aperture
10T @ 4.2K
Challenges: Fabrication process, stress control



Nb_3Sn+HTS
2* ∅ 30 aperture
15T @ 4.2K
Challenges: Fabrication process, stress control, quench protection





Nb_3Sn+HTS or HTS
2* ∅ 45 aperture
20T @ 4.2K
With 10^{-4} field quality
Challenges: Stress control, quench protection, field quality control

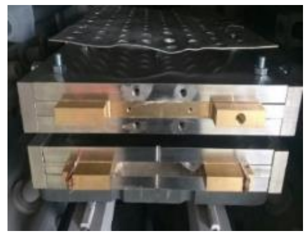
10

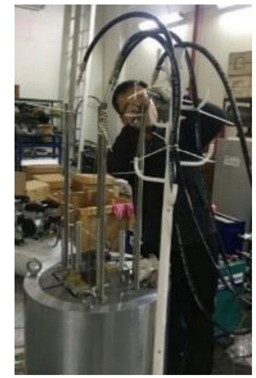
2018 ***2028*** ***year***

R&D Steps of the High Field Accelerator Magnets

Tension control, deformation
J_c and RRR degradation,
Flux jump…

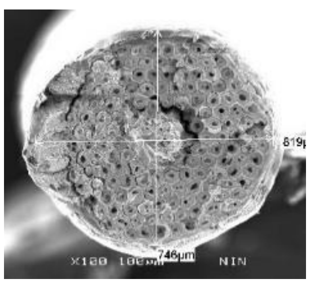
Temperature control, Thermal stress control
J_c and RRR degradation.



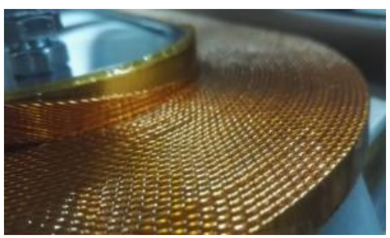


Pre-stress control
Stress of coils,
Mechanical Stability…

Cabling ➡ Coil winding ➡ HT ➡ VPI ➡ Magnet assembly ➡ Test

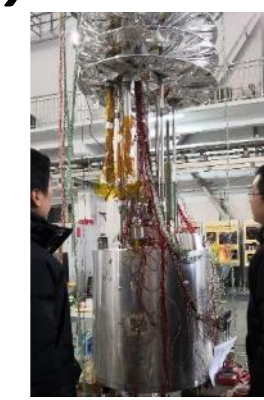


Material, Structure, Processing,…
$J_{c,}$ RRR, Cu ratio,
Filament size…



Stress control, Size control, Electrical insulation
J_c and Field quality degradation,
Electrical short…

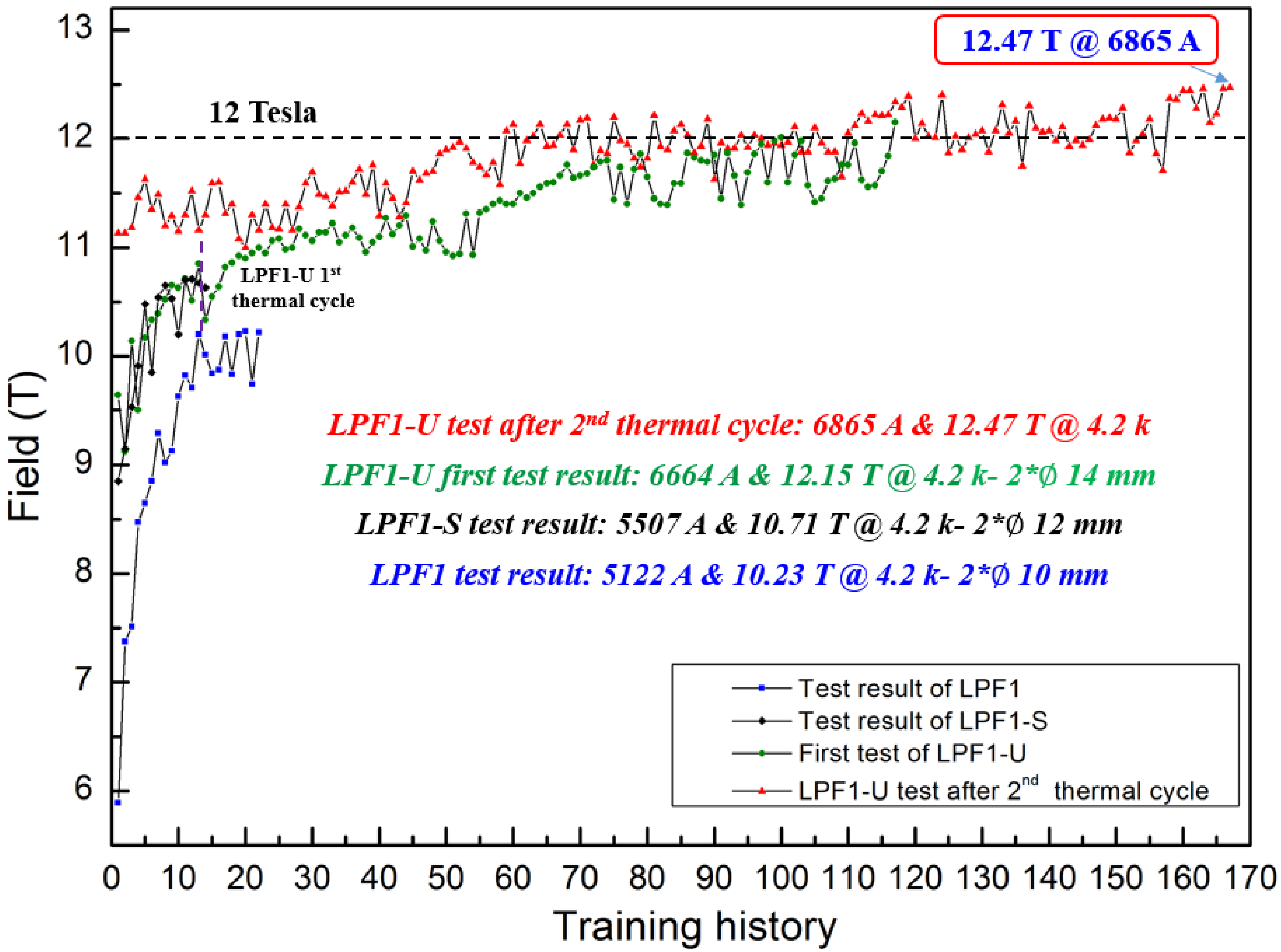
Impregnation quality control:
type of epoxy, procedures;
Mechanical strength and stability



EM force, Quench protection
Training,
Strain of coils…

High Field Model Dipole Magnet: 12.47T @ 4.2K

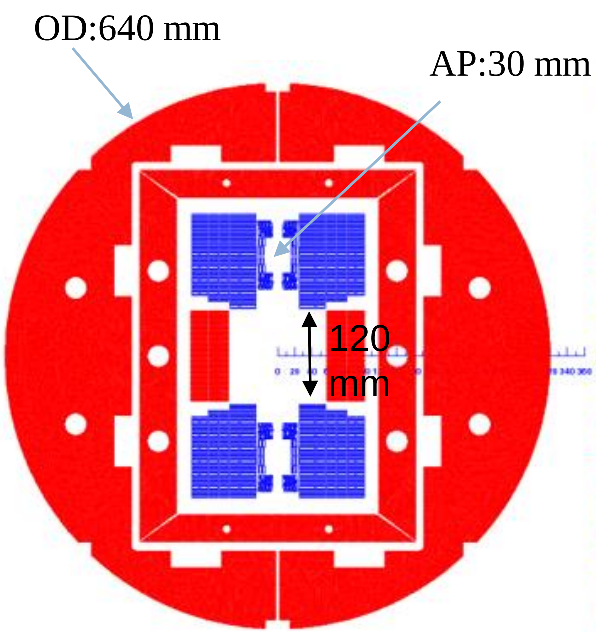
Picture of LPF1-U



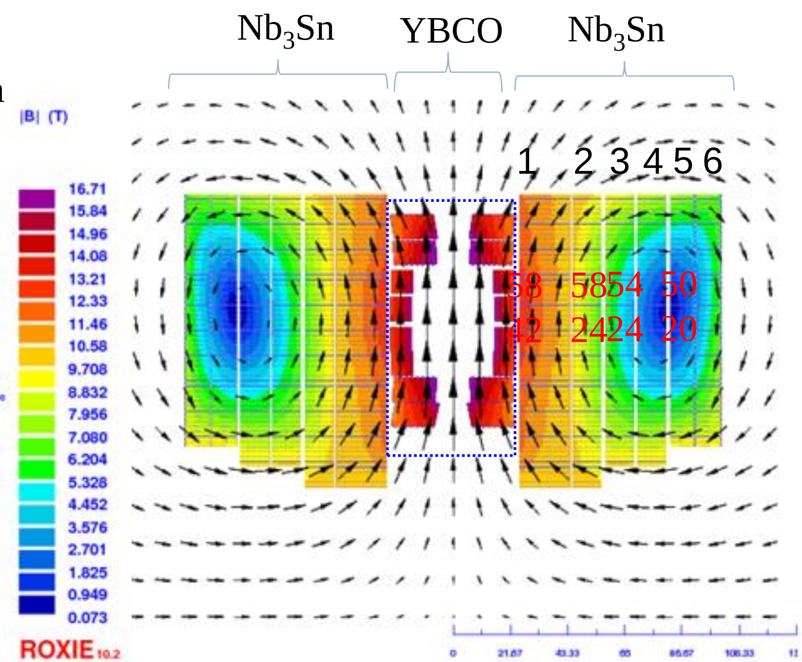
A maximum field of 12.47 T was achieved recently for the upgraded magnet of LPF1-U, beyond the dipolar field baseline required in SPPC.

High Field Model Dipole Magnet: 16-T Design

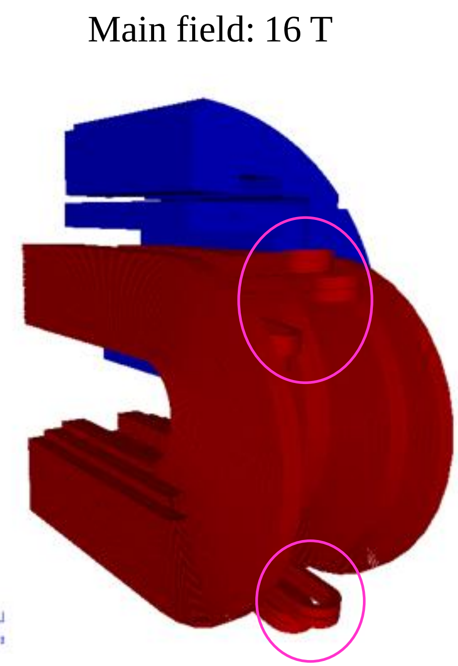
LTS (13 T) + HTS (3 T)



The cross-section of LPF3



Field and flux distribution in coils

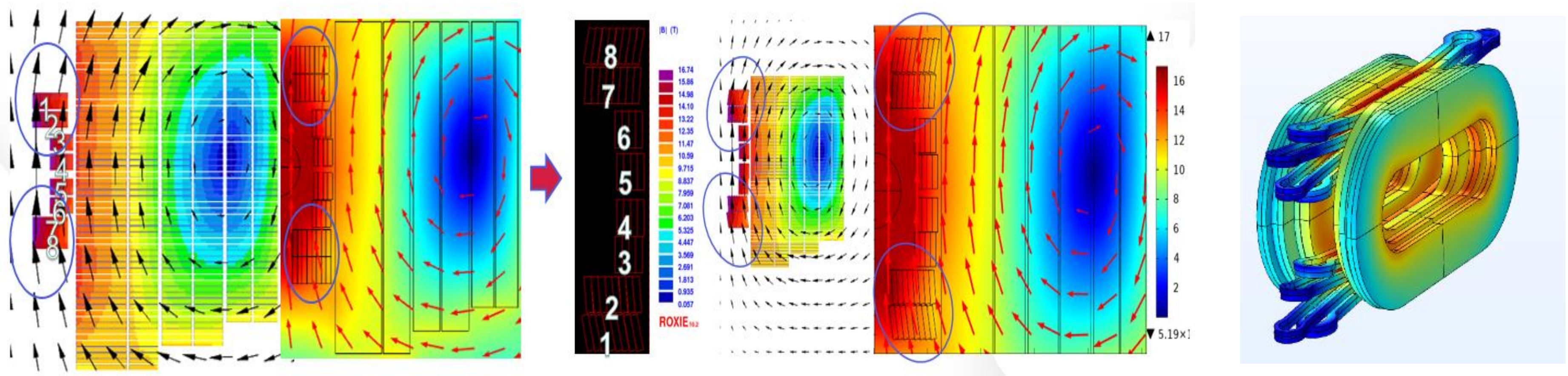


Coil layout (yoke 1/8)

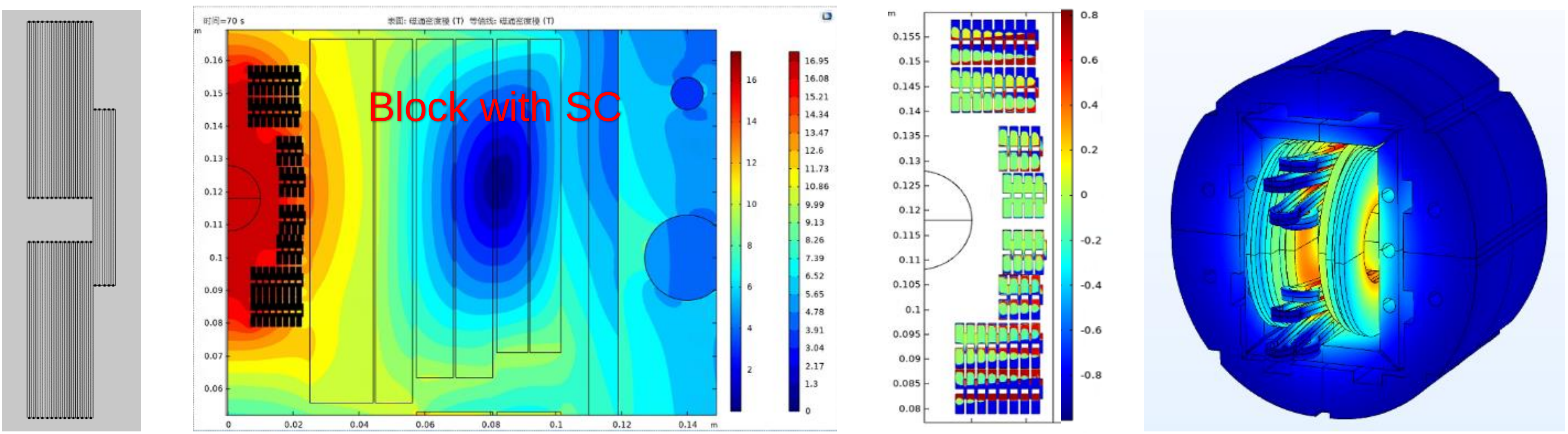
Main parameters of LPF3

Current	7580/143 A		Blocks	Block 1	Block 2	Block 3	Block 4	Block 5	Block 6	Block 7
Main field	16.03 T		Peak field (T)	12.81	10.68	10.82	10.58	10.48	10.38	16.18
			LL ratio (%)	77.66	75.61	77.56	76.15	78.45	77.87	-
Peak field	16.74 T		Blocks	Block 8	Block 9	Block10	Block11	Block12	Block13	Block14
			Peak field (T)	15.98	16.18	15.95	16.64	16.25	16.74	16.56
Harmonics	Max: 5.27 U		b3: -4.4	b5: -5.27	b7: -0.3	b9:-1.62	a2:-1.15	a4: 2.77	a6:-0.95	a8:-0.15

High Field Model Dipole Magnet: 16-T Design



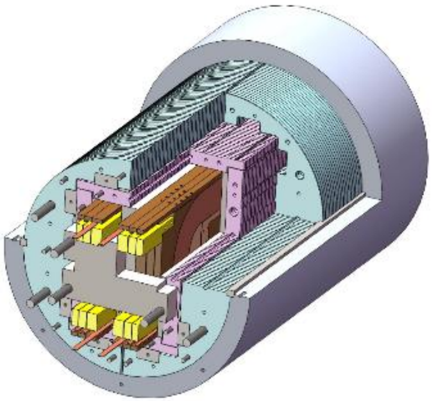
The angle between the flux direction and the tape wide surface has been optimized



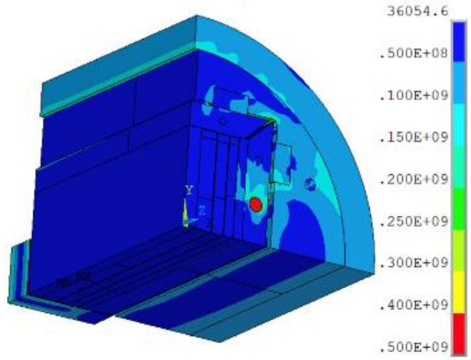
The effect of persistent current has also been analyzed and optimized

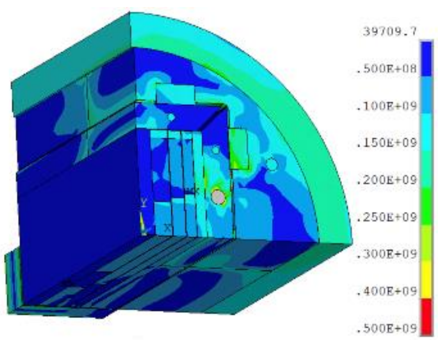
Harmonics	b3	b5	b7	b9	a2	a4	a6	a8
Unit	-3.2	-7.7	-3.8	-0.9	0.9	-5.5	-2.5	-0.6

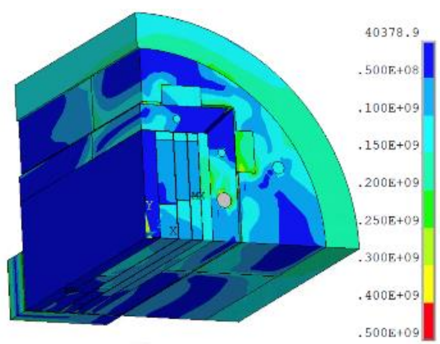
High Field Model Dipole Magnet: 16-T Design

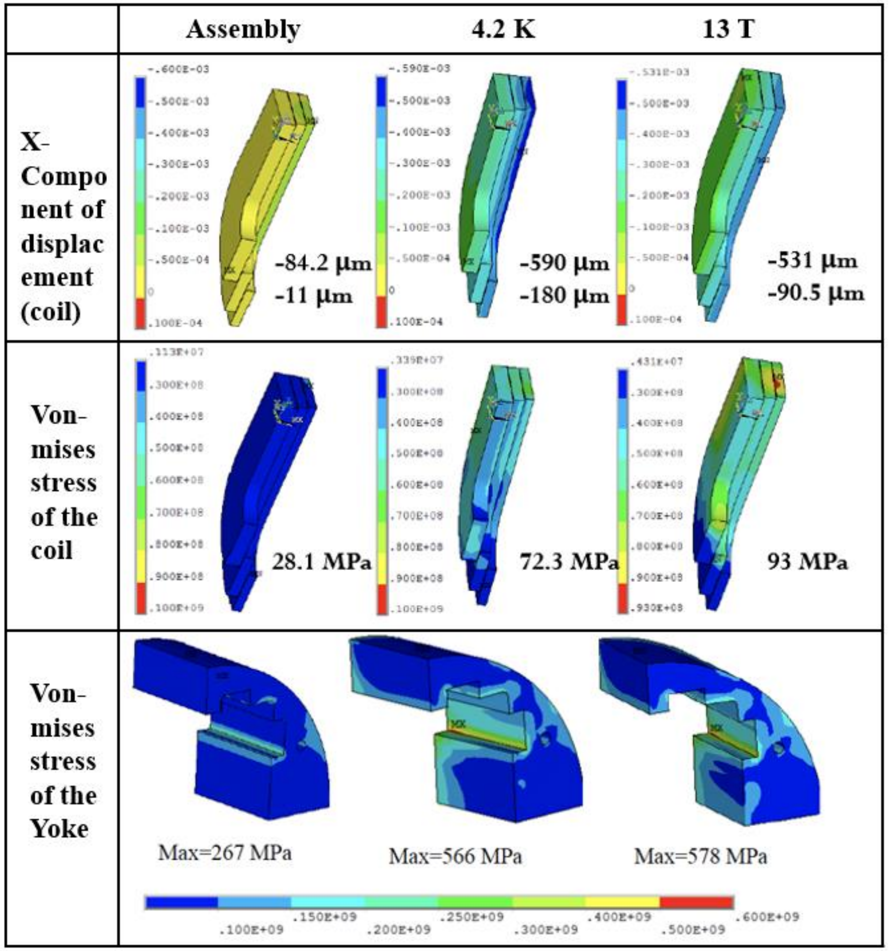


Magnet structure







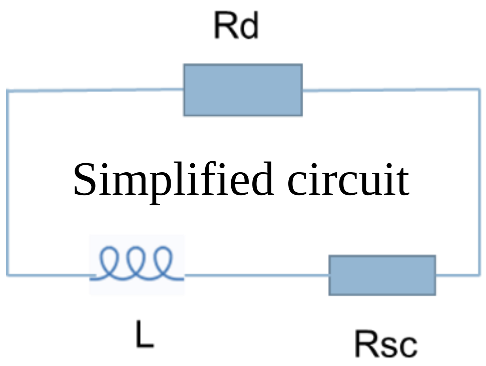


Stress distribution in different loading steps

- After assembly at RT: Peak stress on shell- 128 Mpa; On rod- 468 Mpa; On coils- 28.1 Mpa
- Cooling down at 4.2 K: Peak stress on shell- 215 Mpa; On rod- 618 Mpa; On coils- 72.3 Mpa
- Excited to 13 T: Peak stress on shell- 218 Mpa; On rod- 612 Mpa; On coils- 93 Mpa

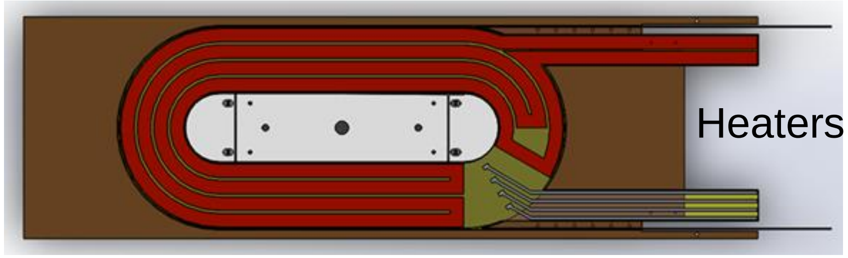
High Field Model Dipole Magnet: 16-T Design

- A simplified circuit was established in COMSOL
- A 1-dimensional adiabatic model was established
- Varistor and heaters are applied to the quench protection of LPF3



Main parameter of the magnet

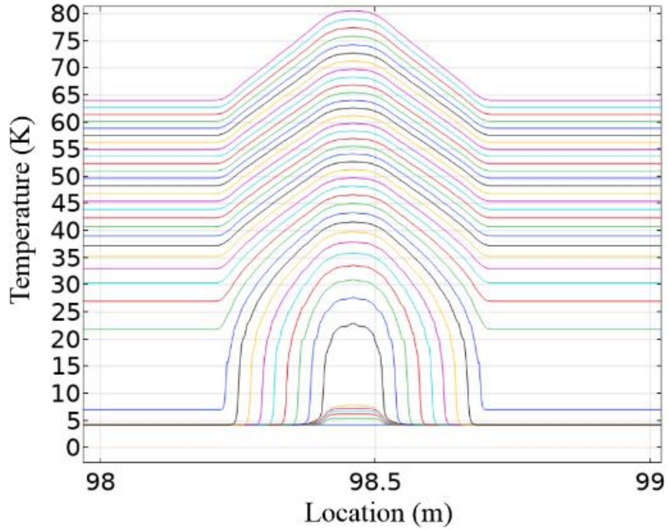
Indcoil	74[mH]	0.074 H	inductance of magnet
I0	7580[A]	7580 A	operation current
Ti	4.2[K]	4.2 K	operation temperature
Bm	13.01[T]	13.01 T	max magnet field
tdelay	10[ms]	0.01 s	delay time
Vdet	100[mV]	0.1 V	threshold voltage



Parameter of heaters

	Thickness of stainless steel /μm	Resistance/Ω	Power (W/cm^2)	Charging voltage/V	Resistivity
coil1	50	2.505	50	389.76	0.5μΩ·m
coil2	100	1.698	50	339.6	
coil3	100	1.878	50	375.6	

The calculation indicates that the temperature of hot spot is 237 K and the max voltage is 952 V. Safe.



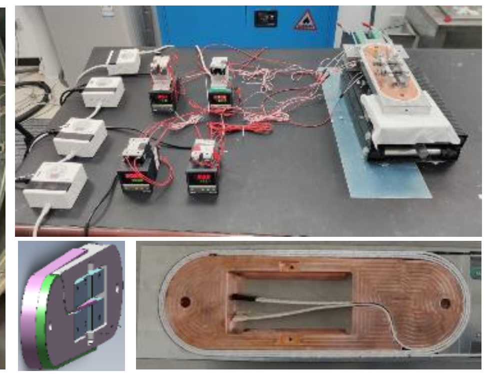
Temperature distribution near hot spots

High Field Model Dipole Magnet: 16-T Fabrication

Nb_3Sn Rutherford cable fabrication

Coil fabrication

Heat treatment test



Inner splice soldering

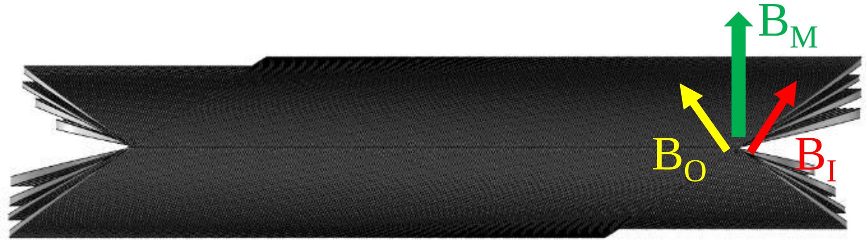
Pre-assembly

- **Nb_3Sn Rutherford cable has been fabricated for LPF3**
- **A dummy coil has been fabricated and heat treated to test the furnace property**
- **The inner joints fabrication test and the pre-assembly of LPF3 has been carried out.**
- **The coils of LPF3 is under construction and the fabrication of the LPF3 is expected to be competed in July.**

High Field Model Dipole Magnet: 16-T CCT option

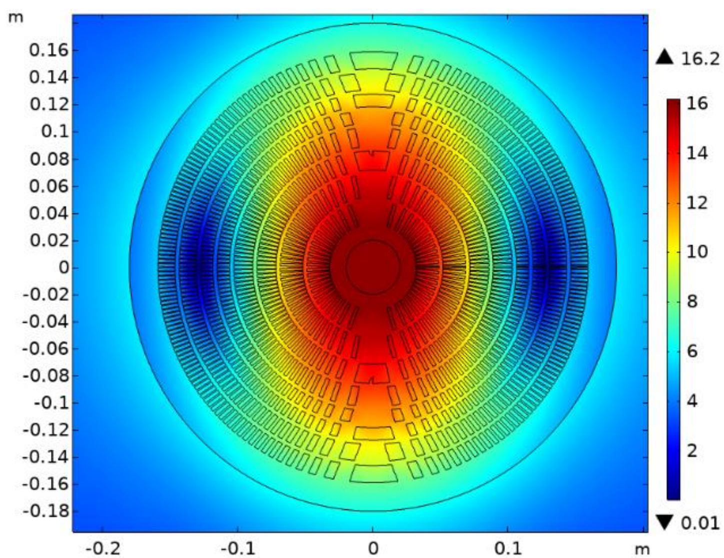
High lights:

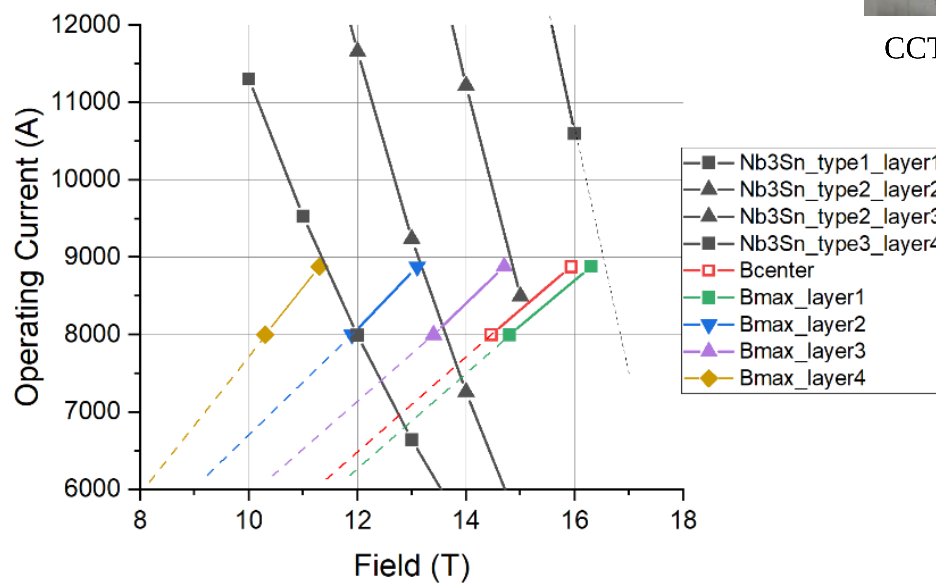
- Canted-Cosine-Theta (CCT) technology;
  - Superior field quality;
  - Stress management
  - Developed industrial assembly line;
- Graded Nb_3Sn Rutherford cables;
- Multiple replaceable coil modules;



The geometry of the 4 module CCT magnet

CCT subscale

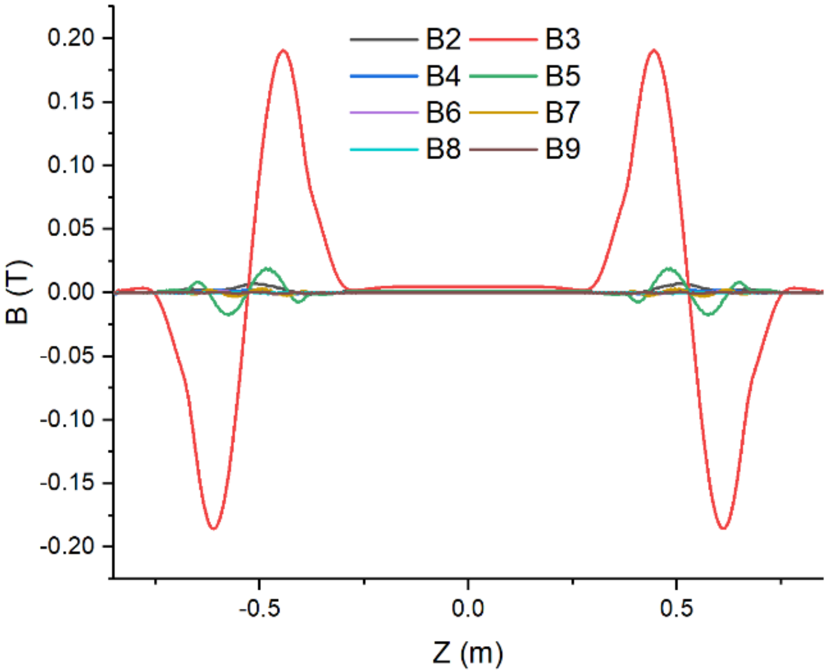




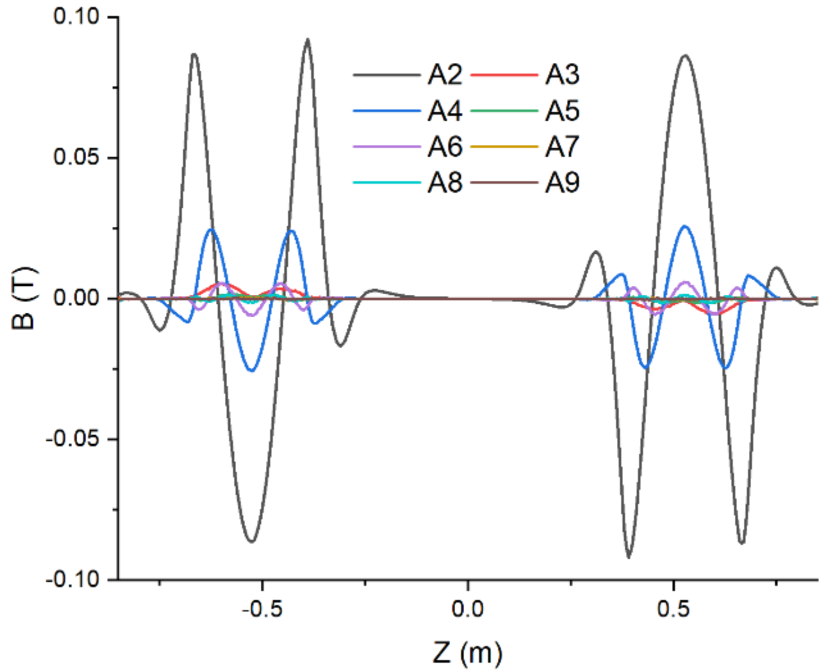
At 4.2 K, the magnet produces 16 T at 100% load-line with 8.8 kA operating current

High Field Model Dipole Magnet: 16-T CCT option

The CCT magnet has an intrinsic good field quality



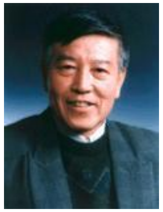
High-order harmonics along axis - Bn



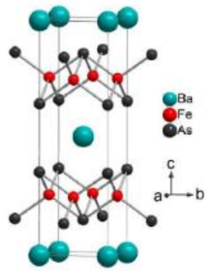
High-order harmonics along axis - An

Harmonics: 10^{-4}	b2	a2	b3	a3	b4	a4	b5	a5	b6	a6	b7	a7	b8	a8
Cross section-2D	0.6259	0.0119	2.9824	-0.0006	0.0537	0.0002	0.5189	0.0002	0.0183	-0.0020	-0.0845	0.0016	-0.0036	0.0009
Integrated-3D	1.5989	0.0101	3.8649	-0.0320	0.3047	0.0802	1.4069	-0.0175	0.0750	-0.3695	0.1163	0.0734	-0.0223	-0.2090

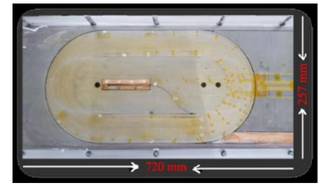
R&D Progress of the IBS Technology



Z. Zhao
IBS (T_c 55K)



100-m 7-core IBS tape fabricated



IBS solenoid at 32 T
Racetrack at 10 T

2008.02 — Discovery of IBS

2008.04

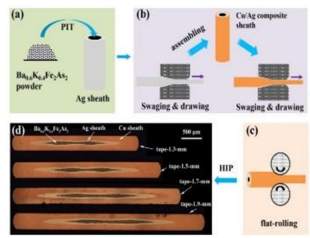
2008.09 — Discovery of 122 phase IBS

2016

2018 — IBS solenoid at 24 T, Racetrack at 8 T

2020

2022



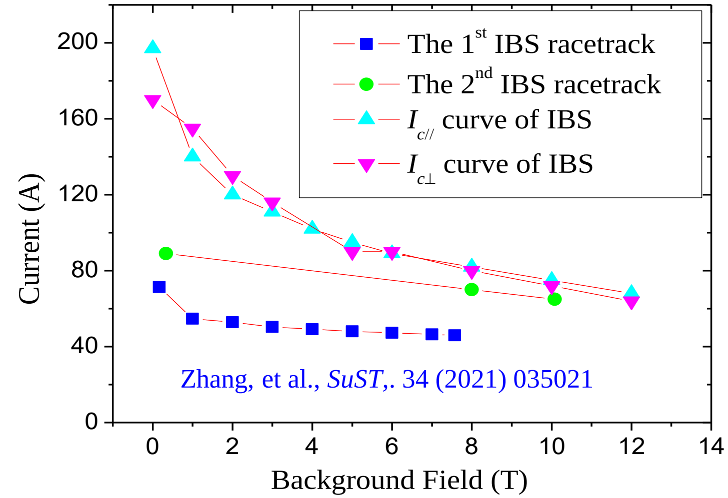
H. Hosono
IBS (T_c 26K)

- The **engineering current density** of the long-length IBS still needs a significant improvement, to reach the similar level as ReBCO or Bi-2212 conductors.
- The **materials of stabilizer** should be shifted to copper or any other low-cost metals to realize the low cost of IBS.
- **Structure and fabrication methods** of IBS and corresponding coils should be further optimized to minimize the J_c degradation at high field and high stress.
- And many other issues like detailed magnetic and mechanical properties study of IBS, quench detection and protection of the IBS coils / magnets and etc.

IBS Magnet R&D: Model Solenoid Pancake Coils

First IBS Racetrack Coil at 10 T

- Two racetrack coils have been made using 100- m length Iron-Based Superconducting tapes.
- The coils reached 86.7% of critical current of the short sample at 4.2 K and 10 T, and 81.25% of the quench current under self-field,
- with highest compressive stress of 120 MPa.



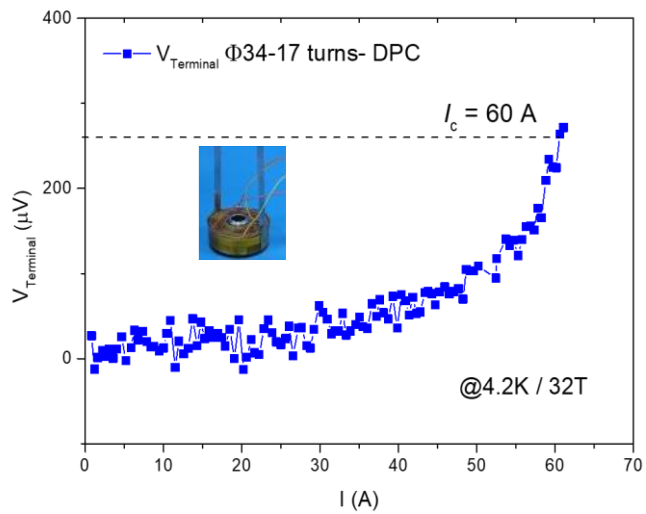
Comments from SUST reviewers:

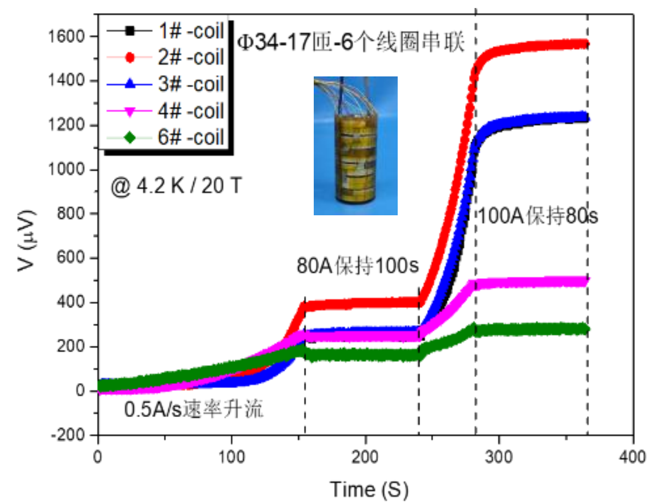
a) ...the new results that can have a strong impact on the conductor and magnet community.

b) ...demonstrated the great potential of Iron-Based Superconductor in the development of next-generation accelerators.

First IBS Solenoid Coil at 32 T

I_c of Φ34mm-17 turns-DPC reached **60 A at 4.2 K and 32 T,** a new breakthrough!





High Field Model Dipole Magnet: HTS Cable R&D

Cable design

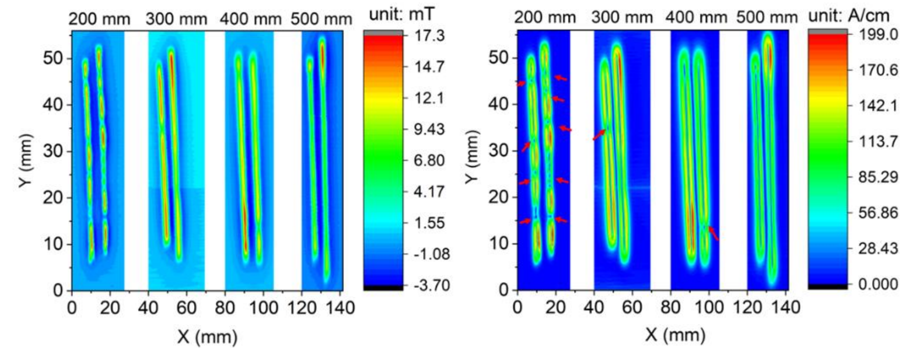
Schematic illustration of the transposed cable and the fabrication steps

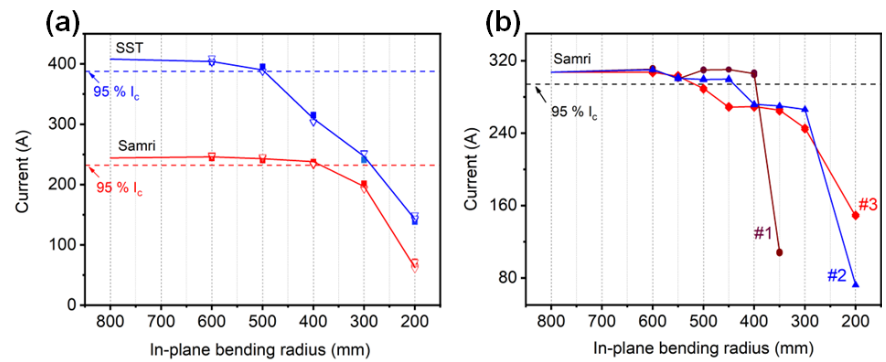
The advantages of the designed cable:

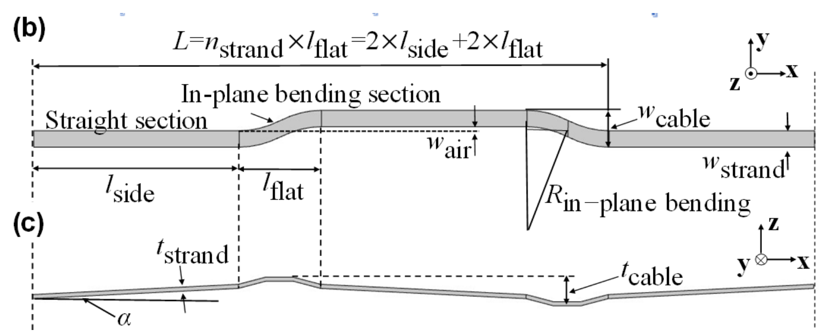
- High current-carrying compacity
- Low dynamic loss
- High mechanical stability

Time chart of research progress of transposed cables

In-plane bending performance of the REBCO tapes



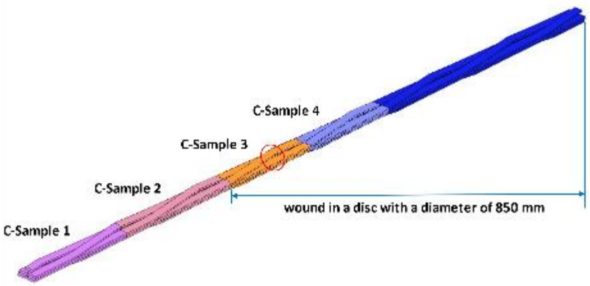


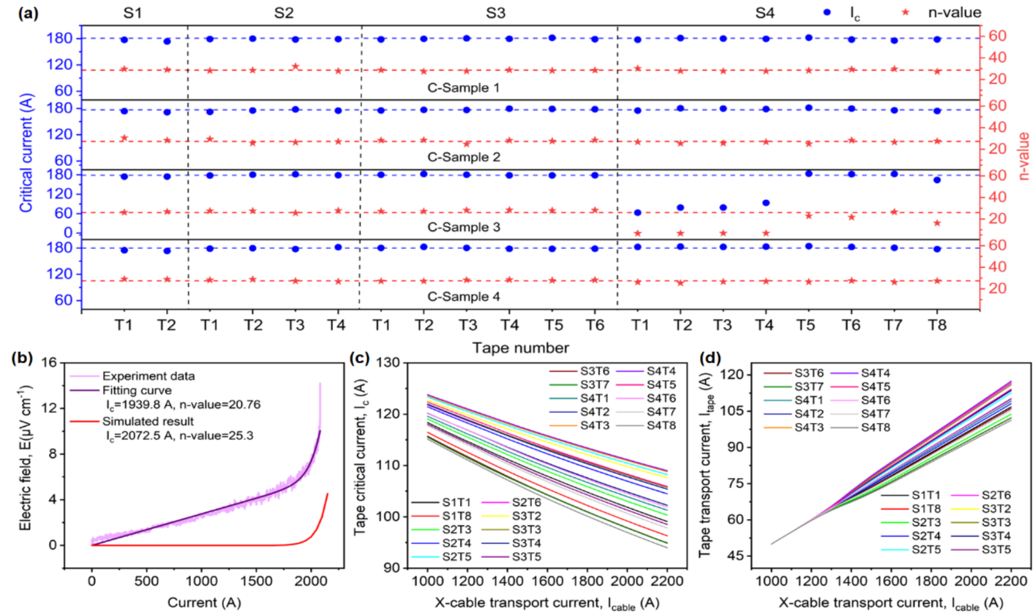


High Field Model Dipole Magnet: HTS Cable R&D

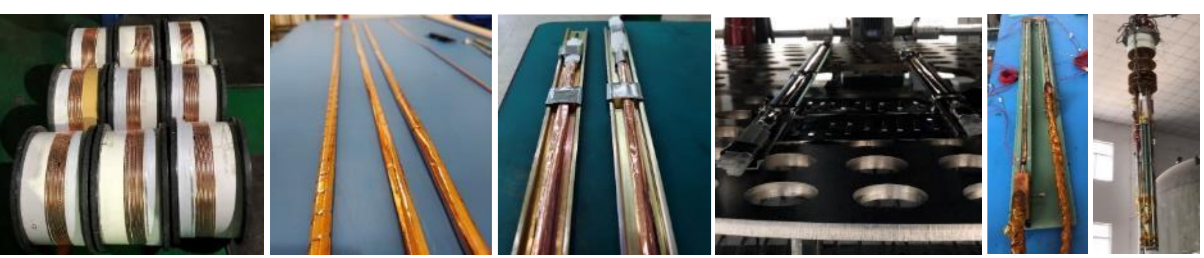
REBCO transposed cable

- 10-m cable samples bas been fabricated
- Most of the tapes extracted from the cable showed almost no degradation.
- **Cable current reached ~2000 A**

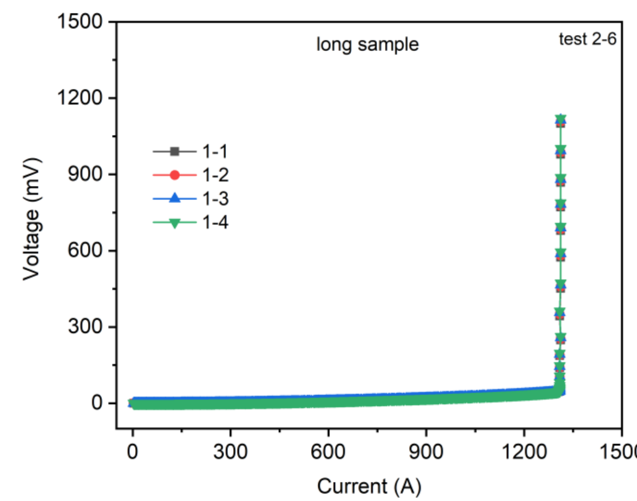




IBS transposed cable



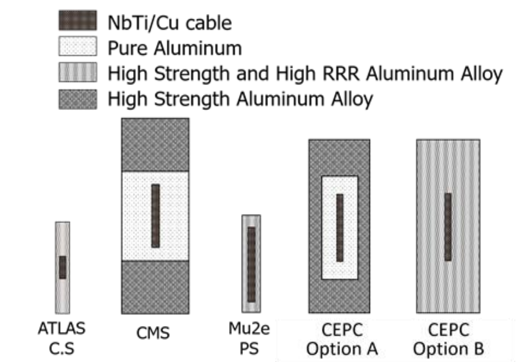
strand ⇨ cable ⇨ heat treatment ⇨ Terminal fabrication ⇨ test

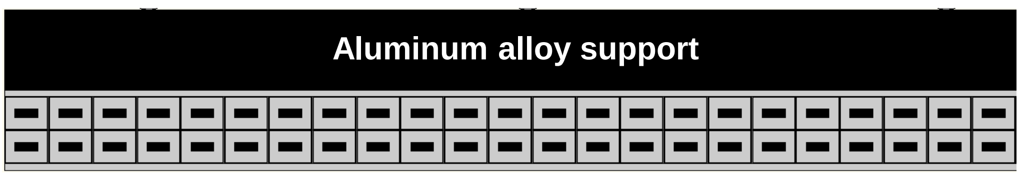


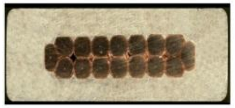
The measured V-I curves of the IBS transposed cable

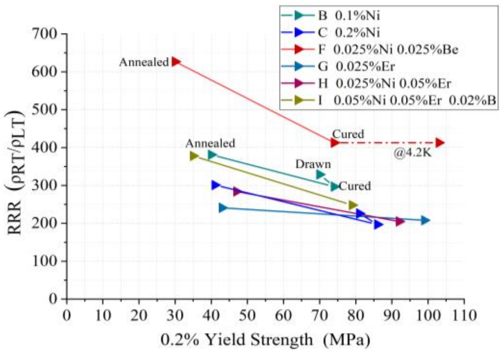
Superconducting Cable R&D for Detector Magnets

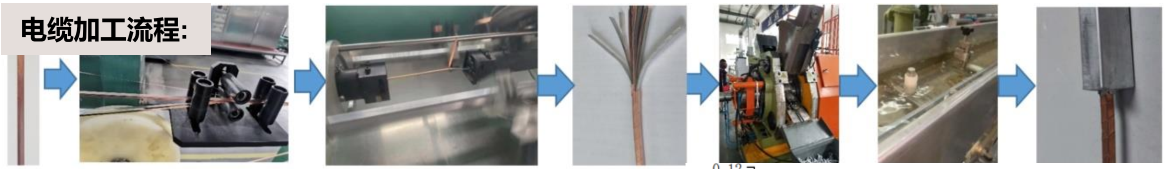
- Aluminum stabilized prototype LTS cables successfully developed.
- R&D of doped aluminum materials as high-strength cable stabilizers ongoing.
- The scheme of large-scale HTS detector magnets for CEPC proposed.
- Fabrication of the aluminum-stabilized HTS cable being further optimized and improved.

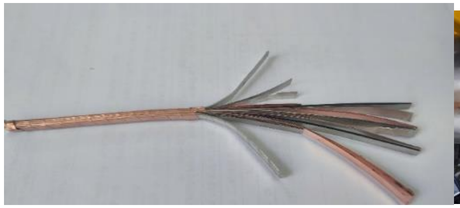


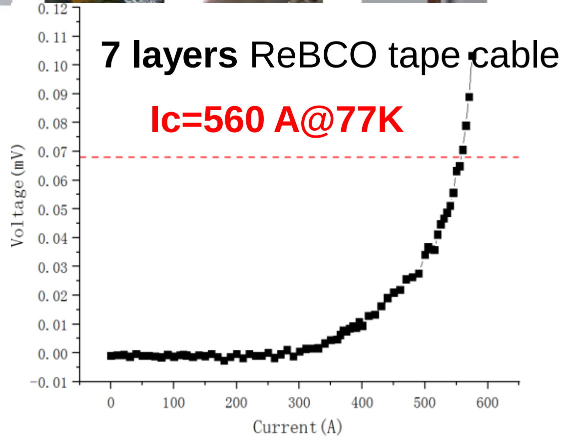








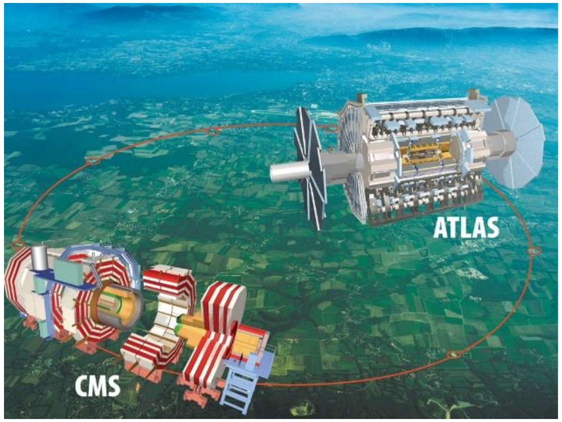




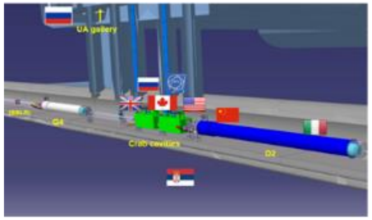
Development of CCT Dipole Magnets for HL-LHC

China provides 12+1 units CCT twin-aperture dipole magnets for HL-LHC project

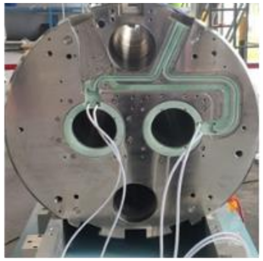
5Tm dipole field in the two apertures at 1.9K, To be installed in the ATLAS & CMS interaction regions.



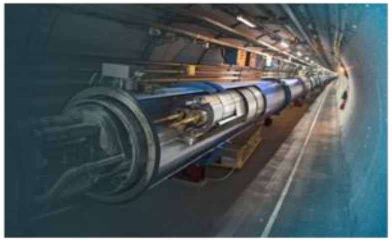
HL-LHC加速器升级中国贡献



合作协议签订



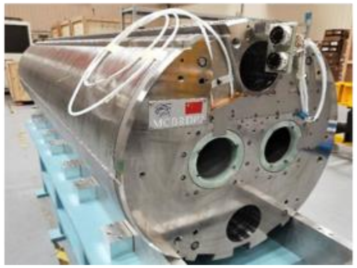
第一个正式磁体发往CERN
参加LHC束流调控



磁体隧道安装及调试

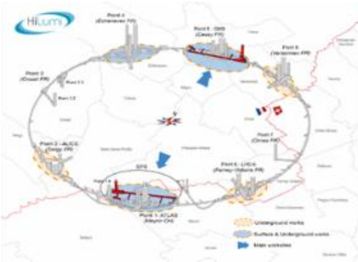
2018 — 2020 — 2022 — 2024 — 2026 — 2027

全尺寸样机通过测试后
发往CERN

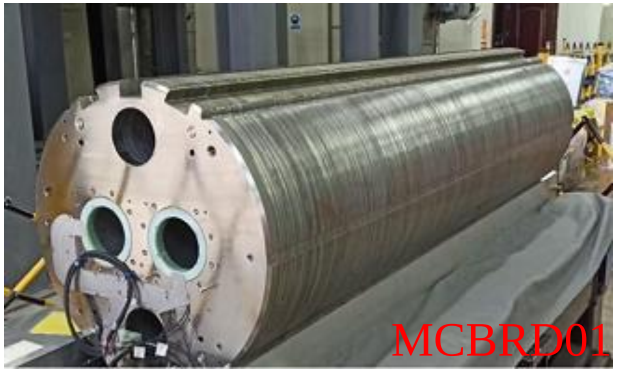


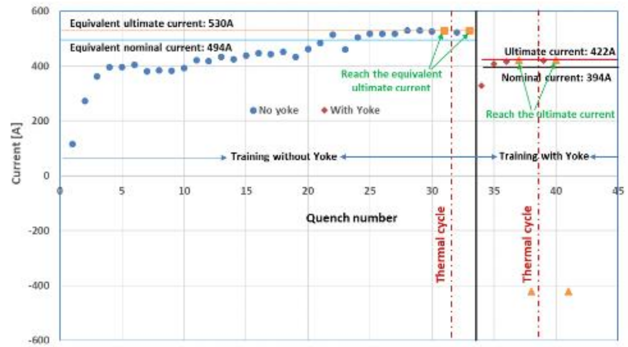
完成全部12套正式磁体
参加LHC束流调控

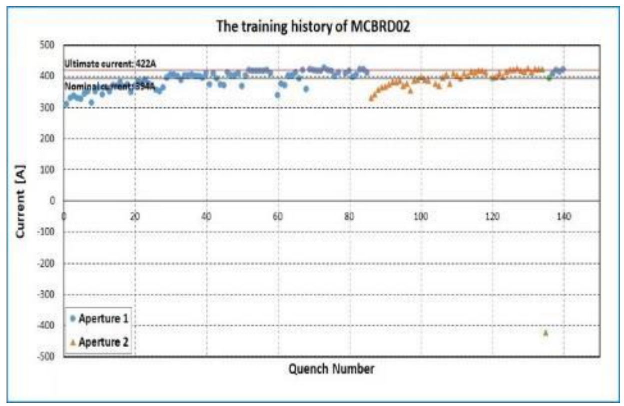
HL-LHC束流调试

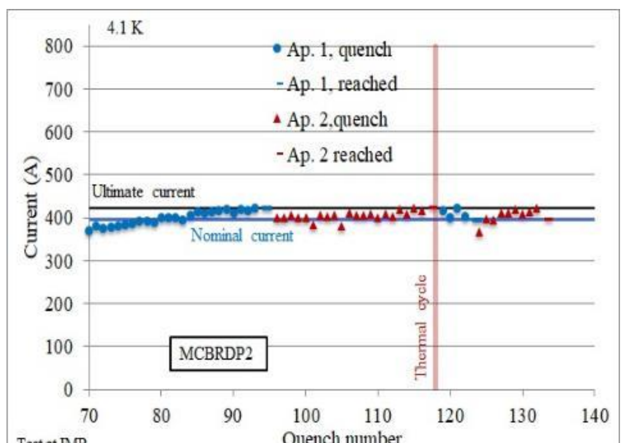


Development of CCT Dipole Magnets for HL-LHC









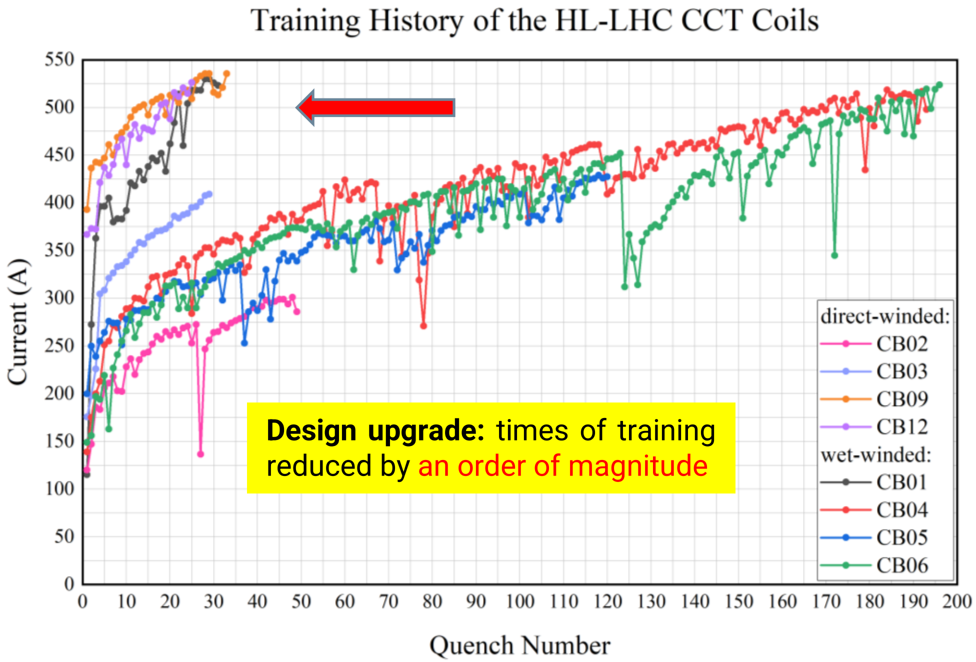
- The first set of CCT superconducting magnets MCBRD01 with satisfactory field strength and field quality, has been shipped to Europe in October, 2021.

- The assembly of the 2nd set of HL-LHC CCT superconducting magnets has been finished in Jan, 2022, passed the performance test at IMP in May, being shipped to CERN this month.

- Fabrication of a full size prototype magnet MCBRDP2 was completed in May, 2020. Both apertures reached the ultimate current.

Development of CCT Dipole Magnets for HL-LHC

- 2+10 apertures has been fabricated. Most of them can reach the design current, but with long training history.
- From CB09 an important modification to the design has been adopted, to improve the training performance of the CCT coils
- CB09 & CB12 tested at IHEP shows excellent training performance, demonstrated the expected effect of the design modification.



CB05 and 09 ready for stand-alone test at IHEP

Summary

- High field twin-aperture model dipoles being developed at IHEP, reached 12.47 T at 4.2 K in July 2021, aiming to reach 16 T in 3 years, and 20 T in 10 years.
- Advanced HTS & LTS superconducting cable under development for the application of high field accelerator magnets and detector magnets
- Strong domestic collaboration for the advanced superconductor R&D (IBS & ReBCO & Nb_3Sn): to significantly raise their performance and lower their cost.
- Quench current of the Iron-Based Superconducting double pancake solenoid coil reached 60 A at 32 T, new world record!
- CCT magnet project for HL-LHC going well, successful design upgrade to solve the long-training problem of previous CCT magnets.

Thanks for your attention!