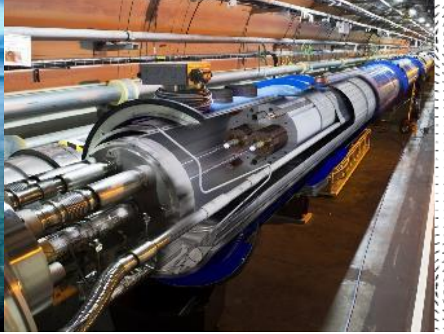
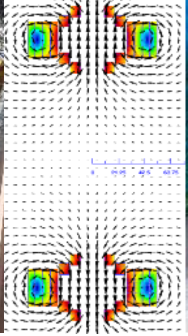



Progress of the High Field Magnet Technology for the High-energy Particle Accelerators

Qingjin Xu

for the Superconducting Magnet Group at
the Accelerator Division, IHEP

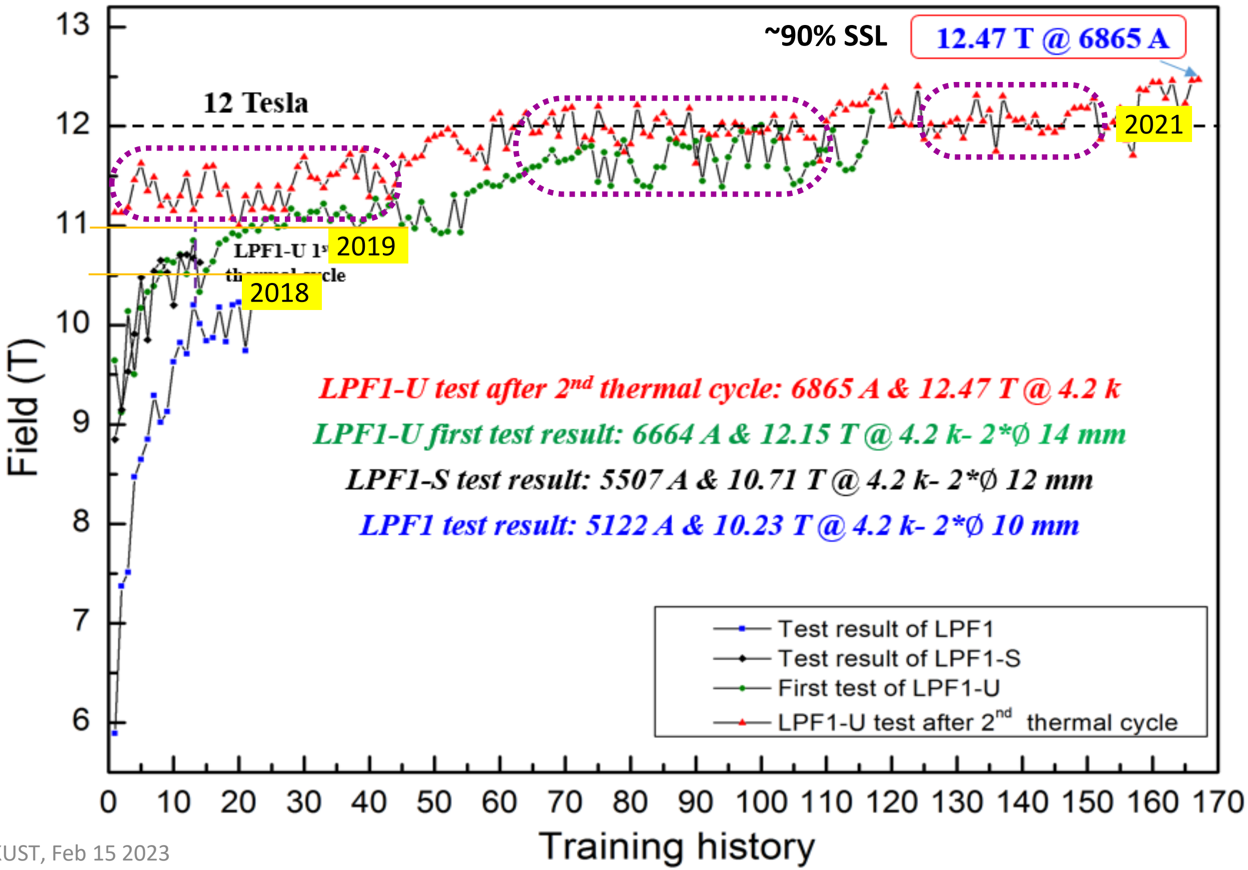
Feb 15 2023

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 CAS

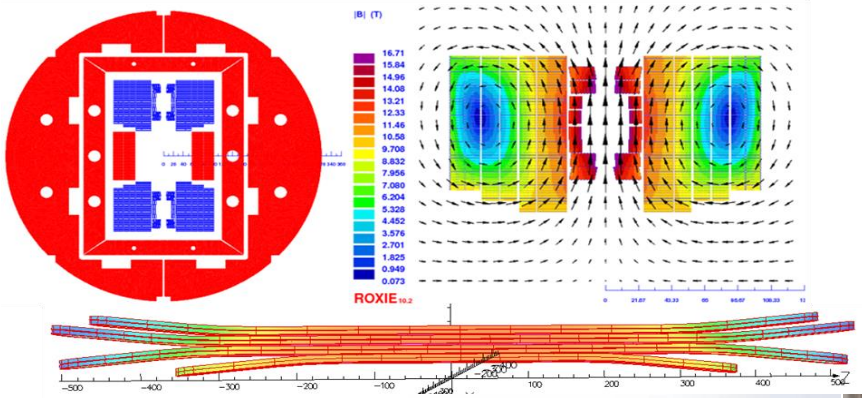
IAS Program on High Energy Physics (HEP 2023), HKUST, Feb. 12-16 2023

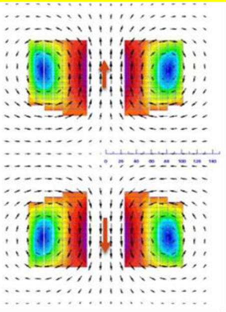
R&D of the High Field Model Dipoles

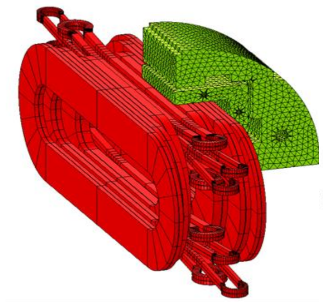


R&D of the High Field Model Dipoles

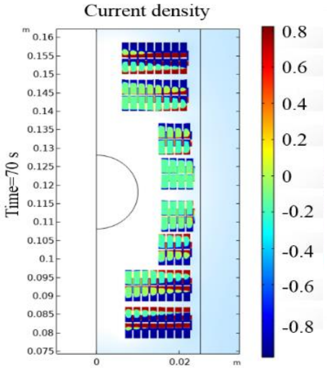
16 T Model Dipole: Nb_3Sn 12~13 T + HTS 3~4 T

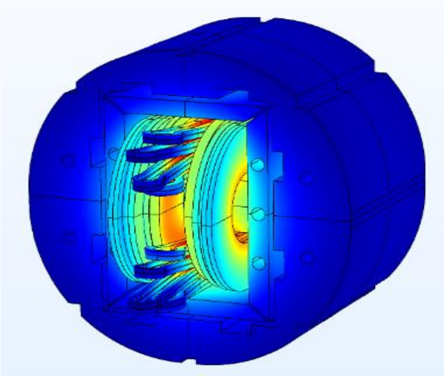


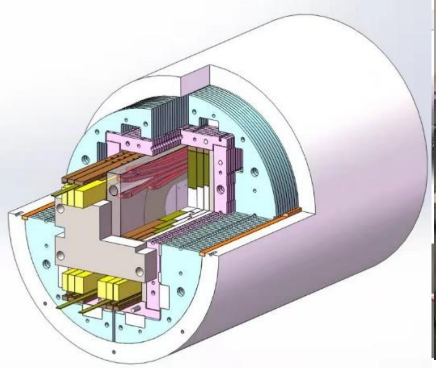




16-T 大孔径高场超导二极磁体 LPF3 (Nb_3Sn-13

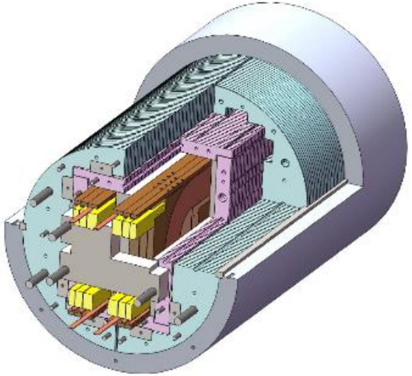




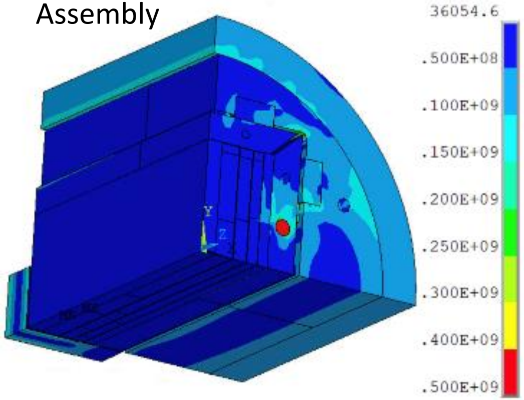


R&D of the High Field Model Dipoles

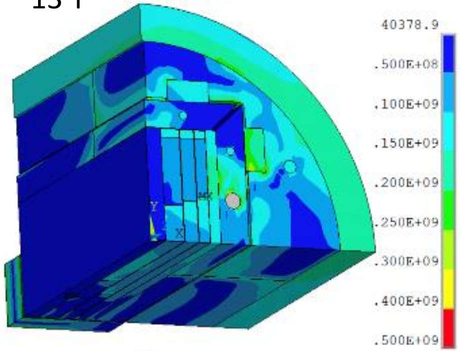
Stress distribution in different loading steps



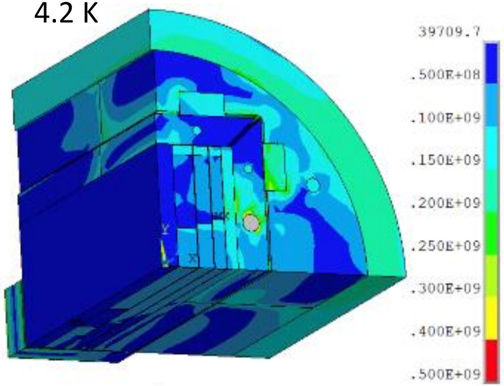
Assembly

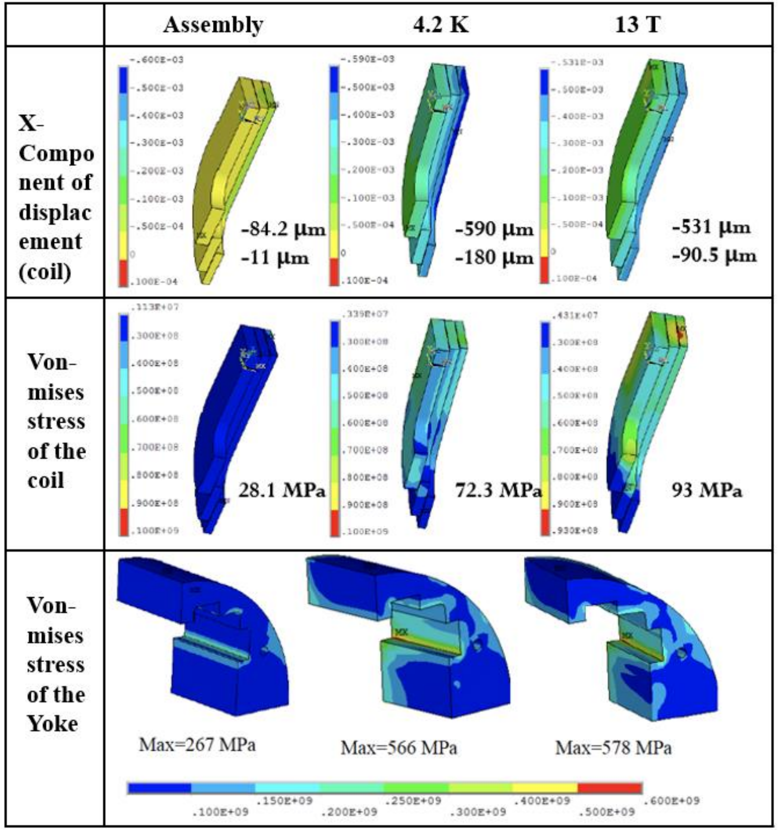


13 T



4.2 K





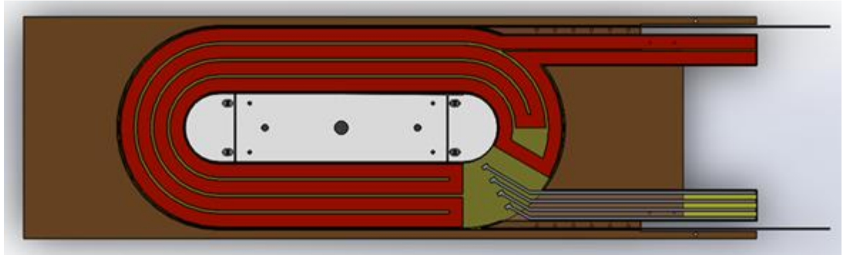
Quench protection of the magnet

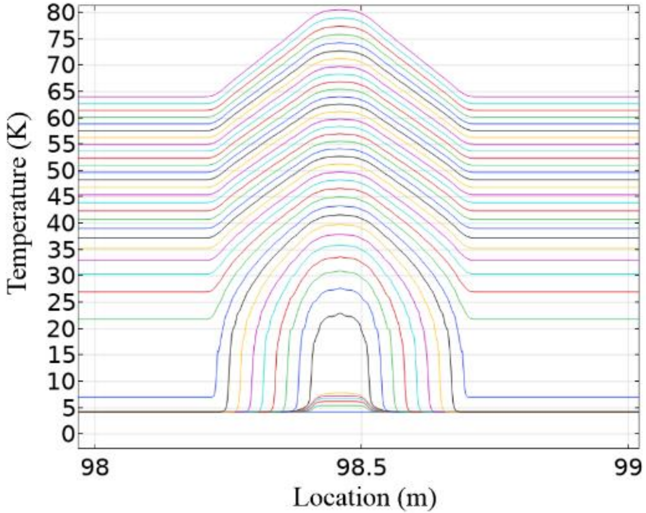
Indcoil	74[mH]	0.074 H	inductance of magnet
I0	7580[A]	7580 A	operation current
Ti	4.2[K]	4.2 K	operation temperature
Bm	13.01[T]	13.01 T	max magnet field
tdelay	10[ms]	0.01 s	delay time
Vdet	100[mV]	0.1 V	threshold voltage

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.



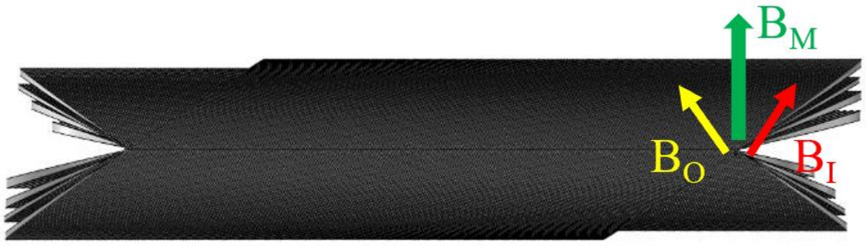


Temperature distribution near hot spots

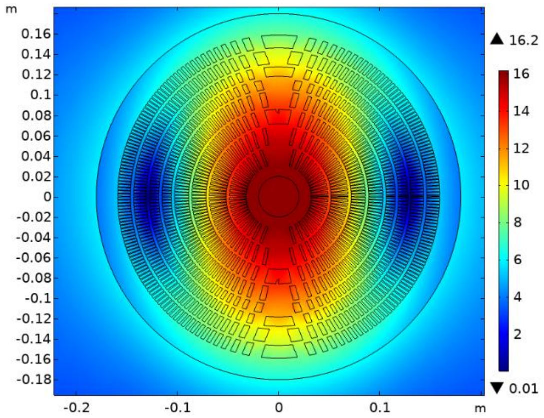
R&D of the High Field Model Dipoles

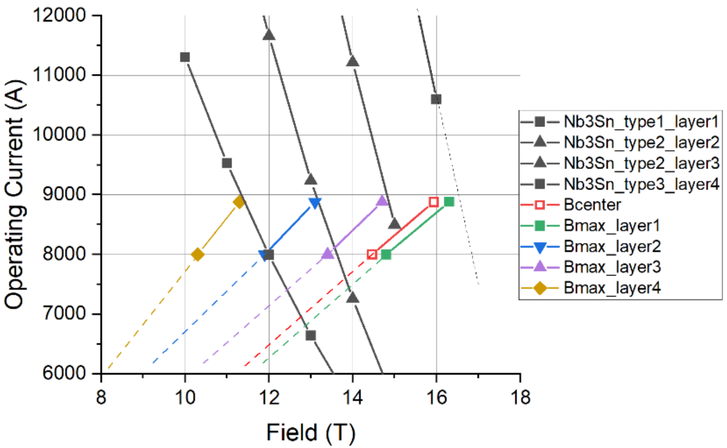
16-T Dipole with CCT configuration

- ➢ 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



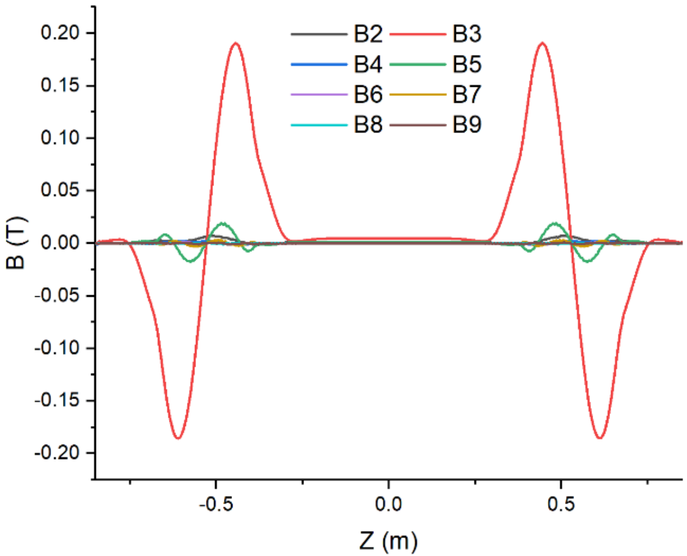


CCT subscale

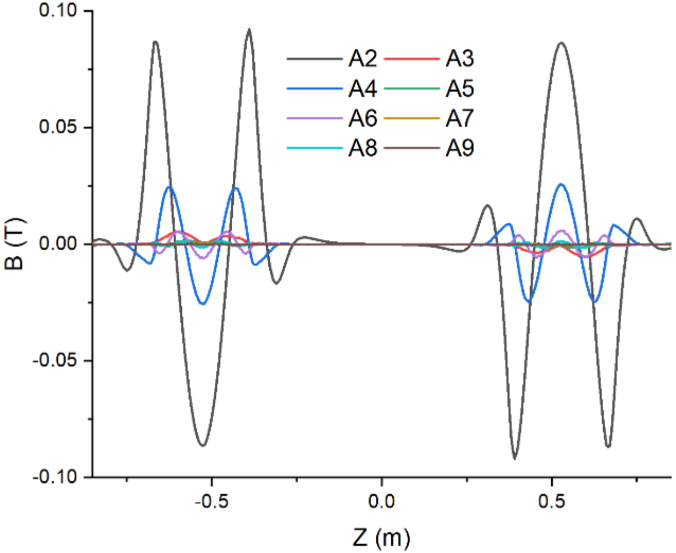
At 4.2 K, the magnet produces 16 T at 100% load-line with 8.8 kA operating current

R&D of the High Field Model Dipoles

High-order harmonics along axis - Bn



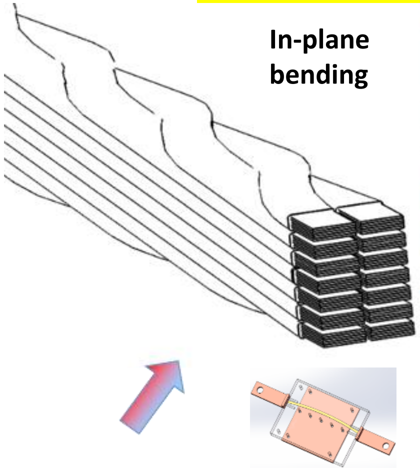
High-order harmonics along axis - An

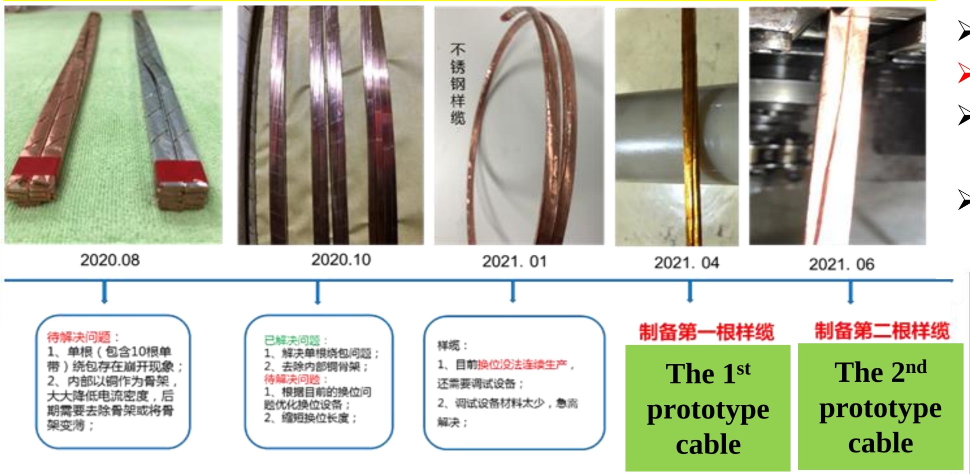


Harmonics: 10^{-4}	b2	a2	b3	a3	b4	a4	b5	a5	b6	a6	b7	a7	b8	a8
Cross section-2D	0.6259	0.0119	2.9824	-0.0006	0.0537	0.0002	0.5189	0.0002	0.0183	-0.0020	-0.0845	0.0016	-0.0036	0.0009
Integrated-3D	1.5989	0.0101	3.8649	-0.0320	0.3047	0.0802	1.4069	-0.0175	0.0750	-0.3695	0.1163	0.0734	-0.0223	-0.2090

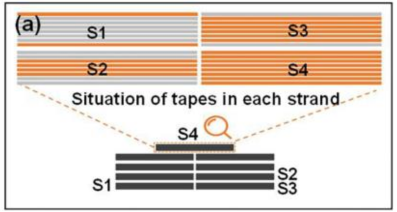
R&D of the High Field Model Dipoles

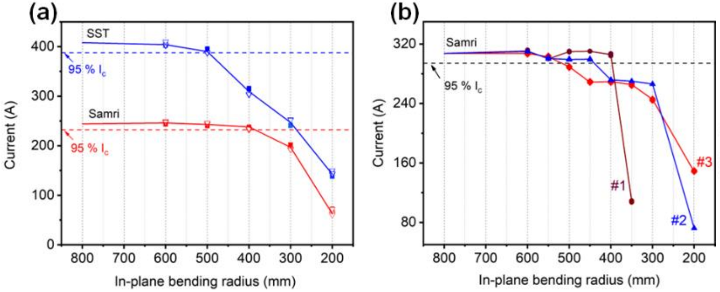
Development of a Roebel-like Transposed Cable with the in-plane bending of HTS tapes

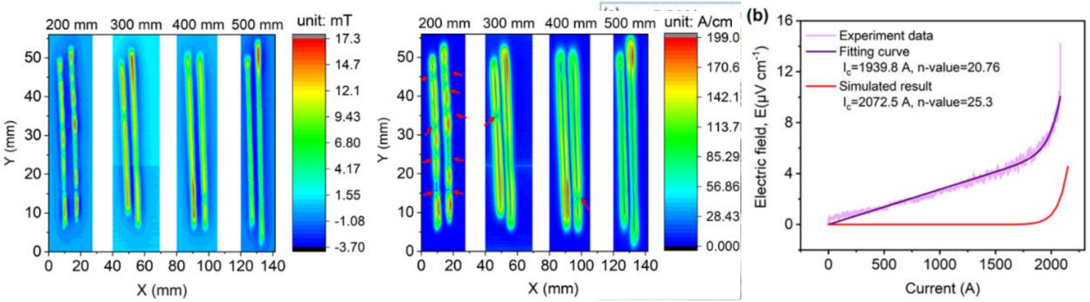




- 10-m prototype cable fabricated
- **Cable current reached 2000 A**
- Most of the tapes extracted from the cable showed no degradation.
- High field coils wound with the cable to be fabricated and tested







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

R&D of the High Field Model Dipoles

Field (T)

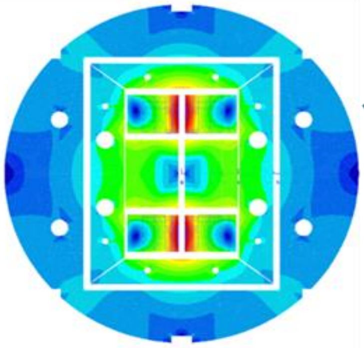
Roadmap for Future

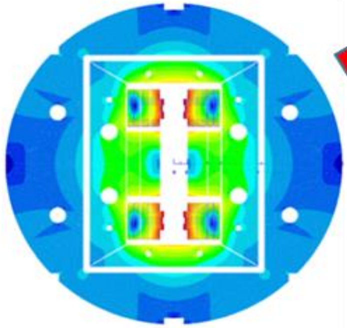
20

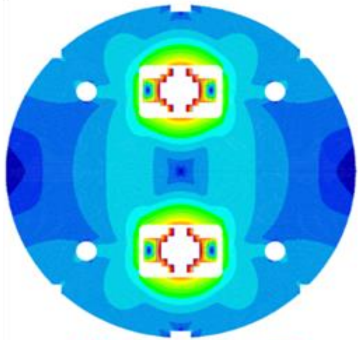
10

Nb_3Sn+HTS
2*ϕ30 aperture
15T @ 4.2K

NbTi+Nb_3Sn
2*ϕ10 aperture
10T @ 4.2K

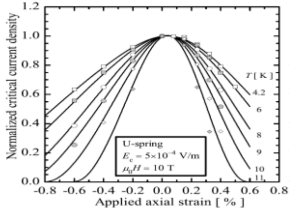






Nb_3Sn+HTS or HTS
2*ϕ45 aperture
20T @ 4.2K
With 10^{-4} field quality

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

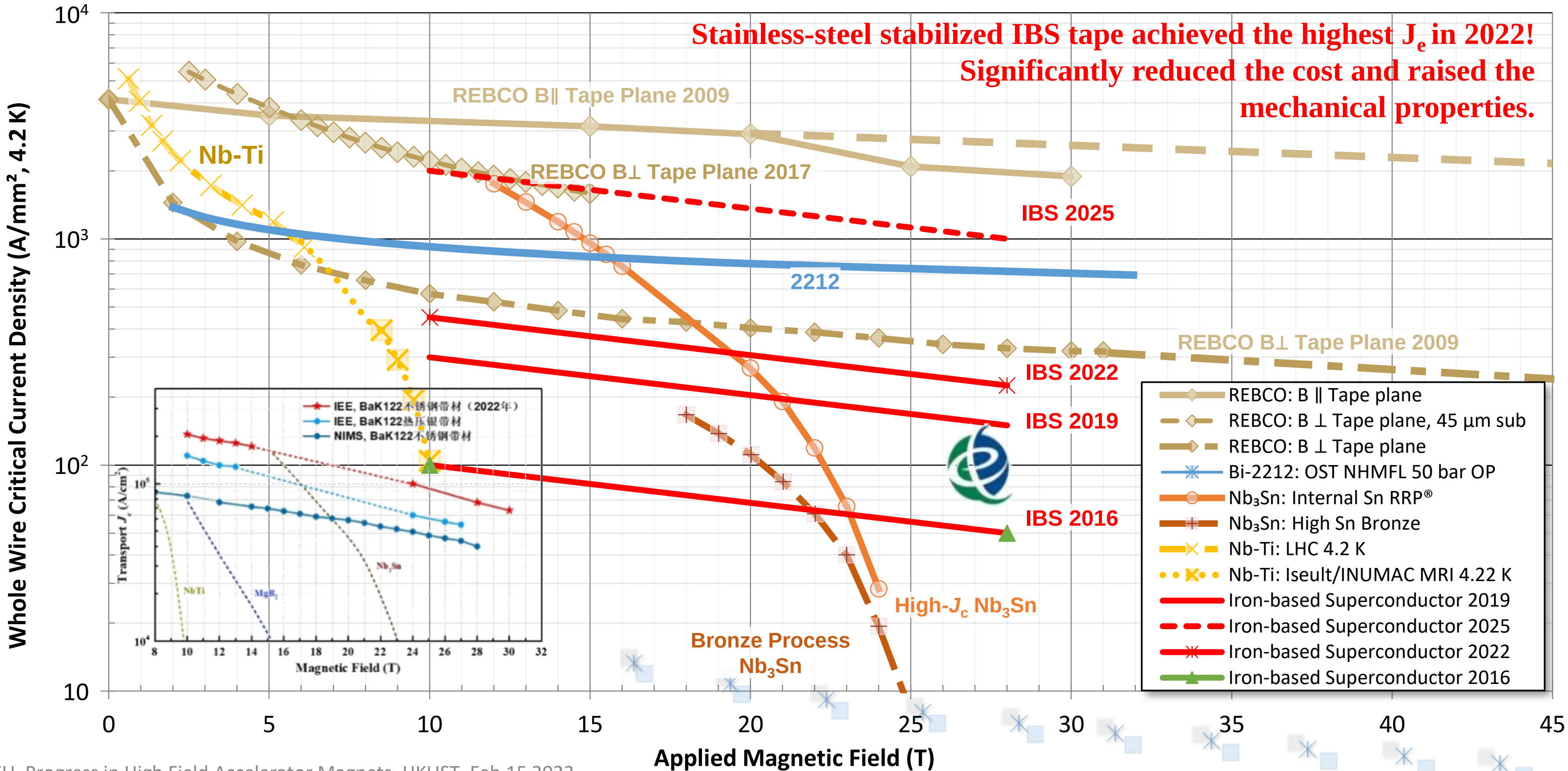


2018

2028

year

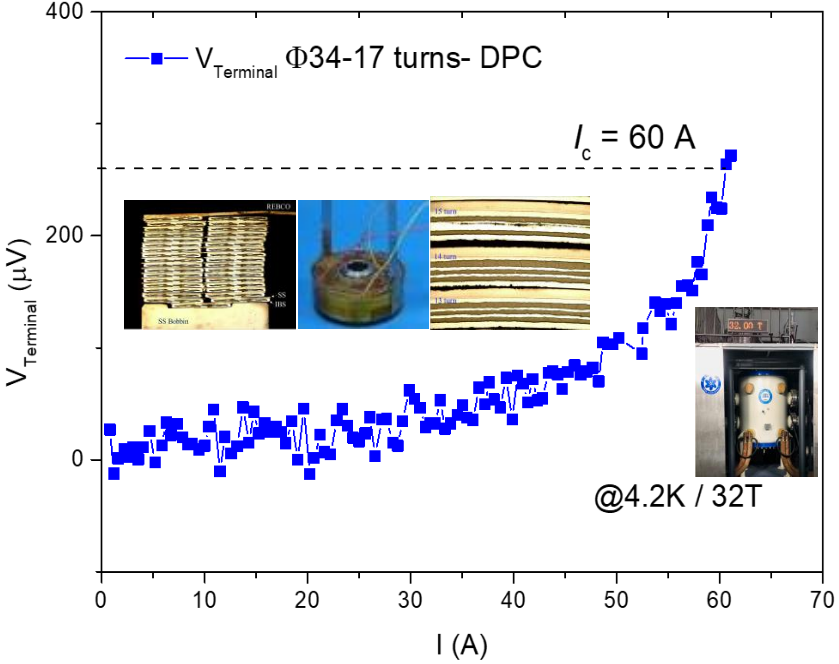
IBS Technology: Status and Outlook

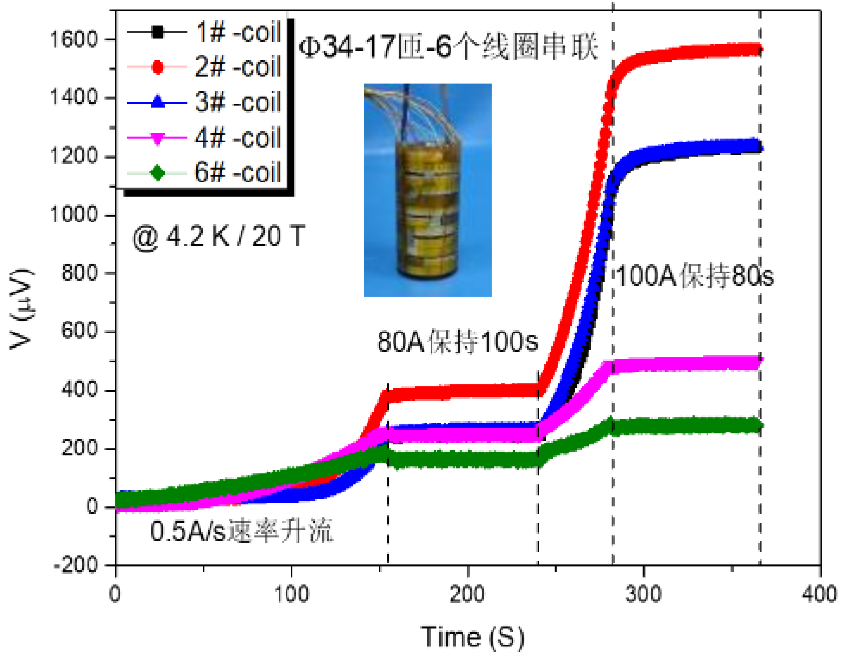


IBS Technology: Status and Outlook

The First IBS Solenoid Coil at 32 T background field

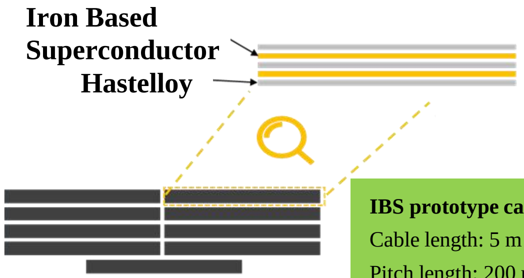
I_c of Φ34mm-17 turns-DPC reached **60 A at 4.2 K and 32 T, world's highest record up to now.**





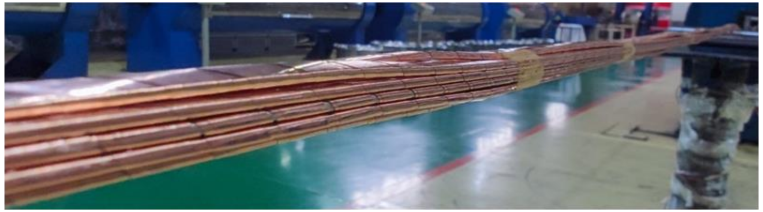
IBS Technology: Status and Outlook

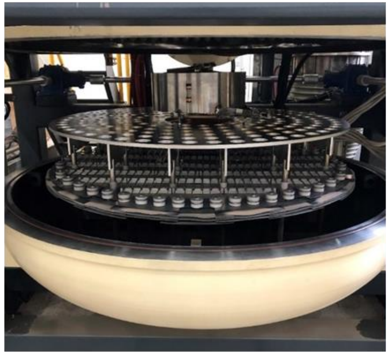
The First IBS Transposed Cable over 1000 A

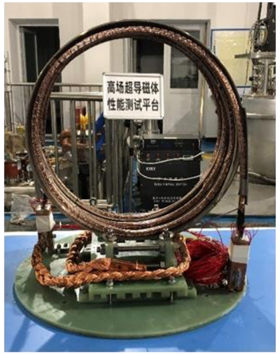


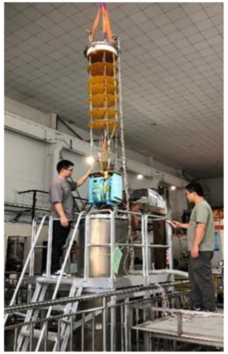
Cross section of the cable

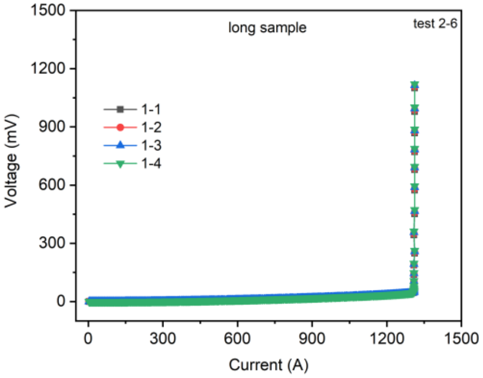
IBS prototype cable
Cable length: 5 m
Pitch length: 200 mm
Cable thickness: 10.5 mm
Current：>1300 A



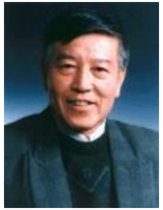




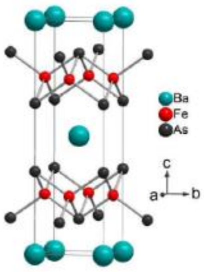




IBS Technology: Status and Outlook



Z. Zhao
IBS (T_c 55K)



2008.02
Discovery of IBS

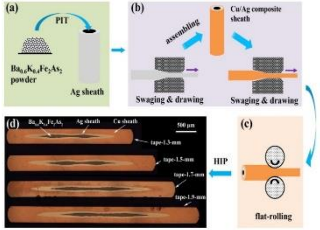
H. Hosono
IBS (T_c 26K)

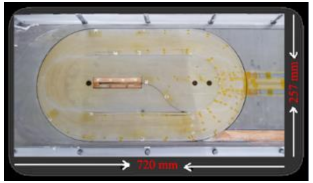
2008.04

2008.09
Discovery of 122 phase IBS

100-m 7-core IBS tape fabricated
J_e= 100 A/mm^2
@ 10 T, 4.2 K

2016





2018
IBS solenoid at 24 T
Racetrack at 8 T
J_e= 300 A/mm^2
@ 10 T, 4.2 K

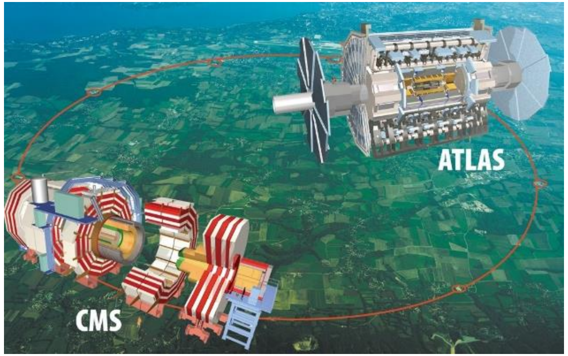
2020
IBS solenoid at 32 T
Racetrack at 10 T
1300A transposed cable
J_e> 450 A/mm^2
@ 10 T, 4.2 K

2022

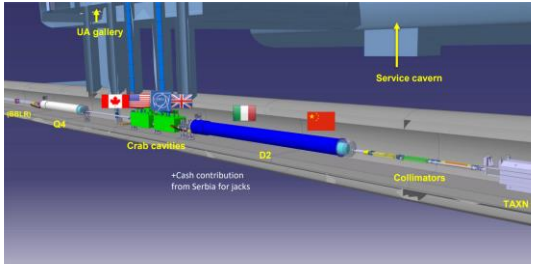
J_e of IBS expected to be similar as ReBCO in 5 years with better mechanical properties and lower cost

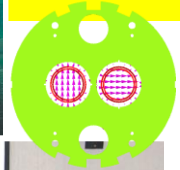
Development of CCT Magnets for HL-LHC

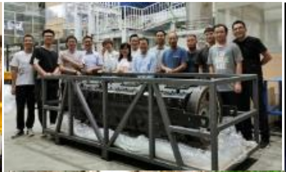
China provides 13 units CCT twin-aperture dipole magnets for HL-LHC



- 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.







All the magnets delivered to CERN passed the performance double-check at 1.9 K.

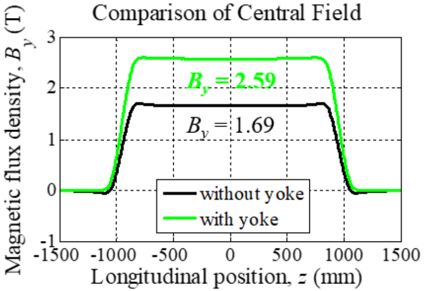
Test results of the 1st full-length prototype from China:

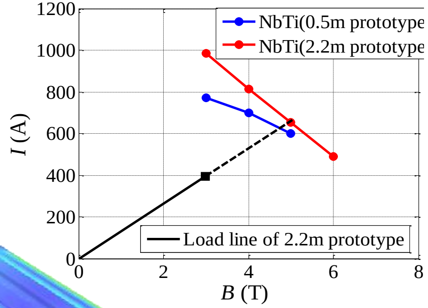
"Each aperture, individually and combined, arrived to ultimate current without quench"

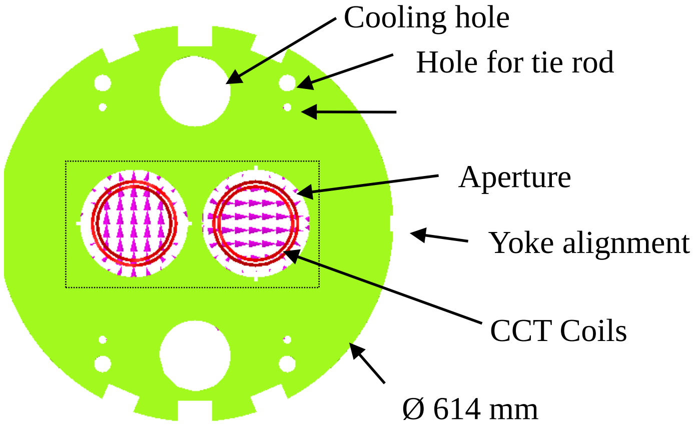
"Operation range test checked without quench"……

Development of CCT Magnets for HL-LHC

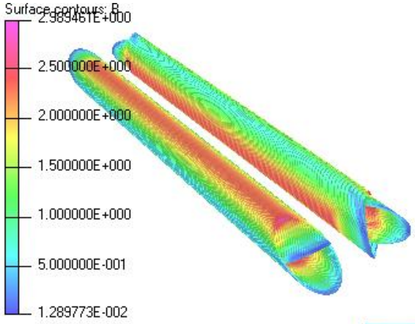
Items	Values
CCT skew angle	30°
No. of turns per layer	365
Slot size in former (mm)	2×5
Spacing per turn	5.222
Inside/Outside diameter of the former (mm)	Inner former:105.35/119.35 Inner former:120.80/134.85
Inside diameter of the groove/slot(mm)	1st layer: 109.15/119.15 2nd layer: 124.65/134.65
Reference radius (mm)	35
Diameter of aperture (mm)	105
Current (A)	395

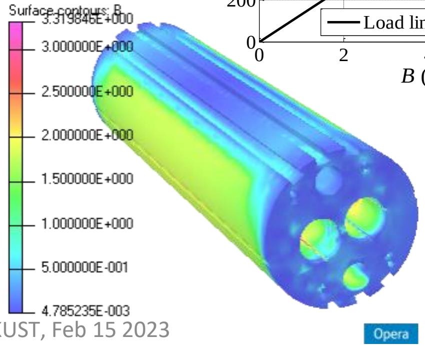






Items	Values
Diameter of yoke (mm)	614
Thickness of yoke lamination (mm)	5.8
Diameter of aperture (mm)	167
Position of aperture (mm)	94.19
Yoke key slot(mm)	8(3.01) ×6
Diameter of cooling hole (mm)	110
Position of cooling hole (mm)	205

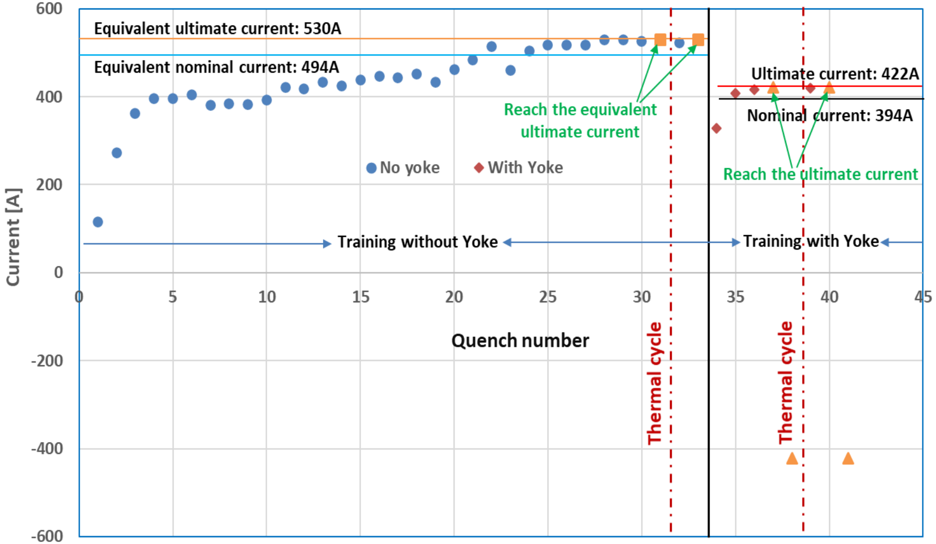




Training of MCBRD01

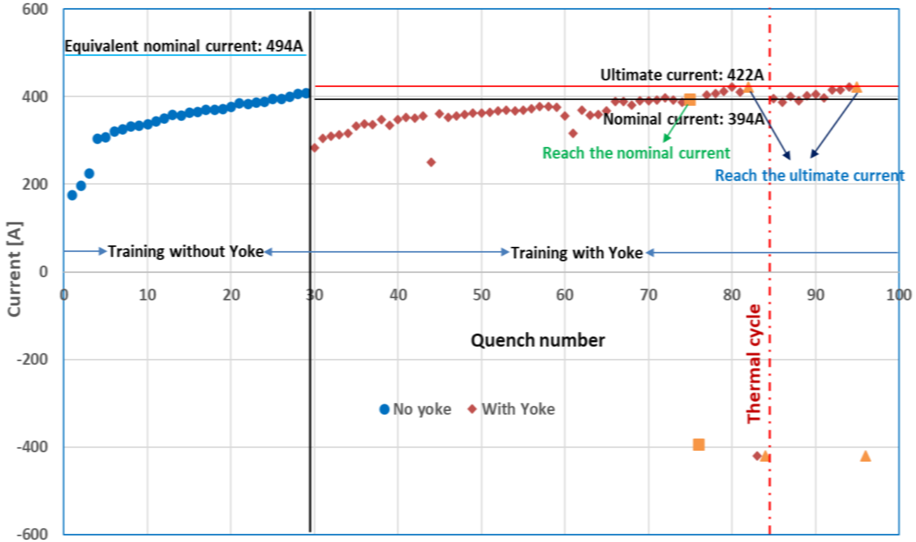
Aperture1 of the 1st series magnet

The 1st practice coil from Bama with new fabrication process wet wind plus 5-bar VPI.

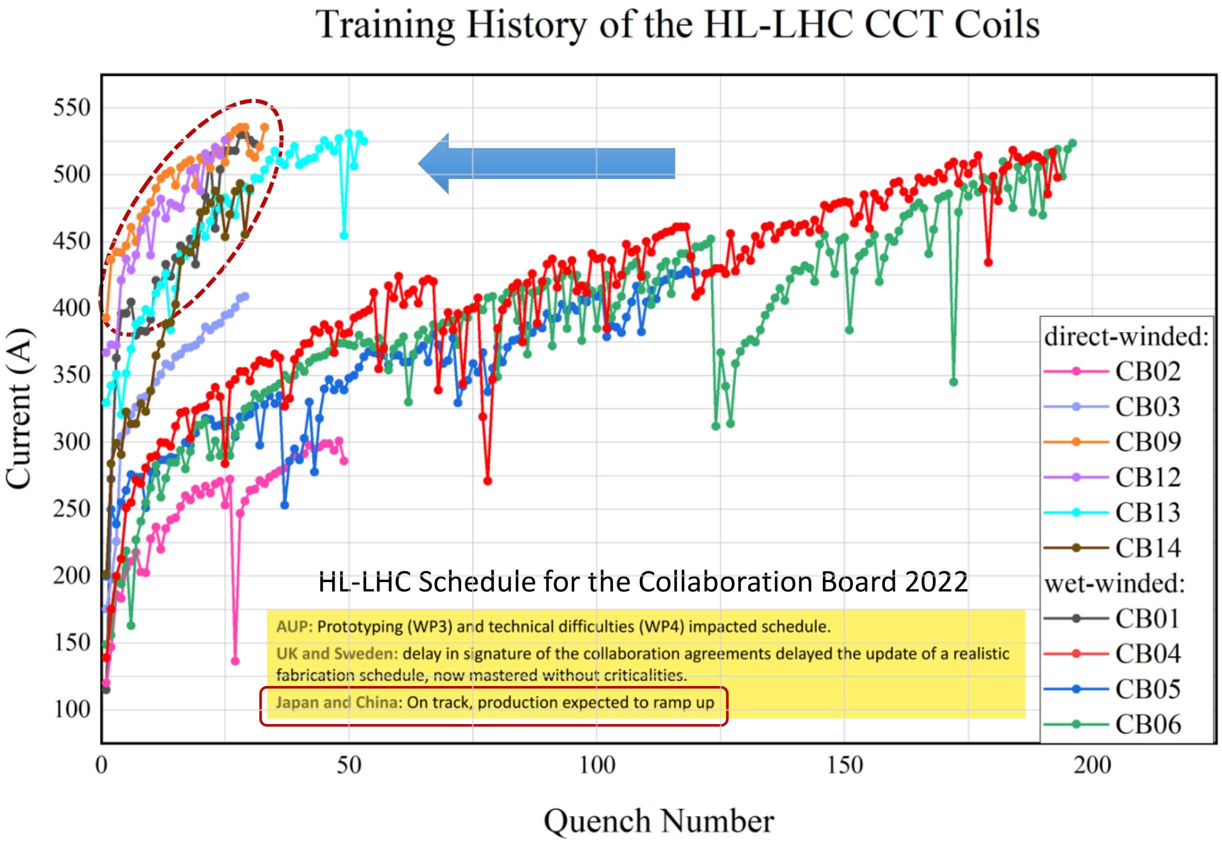


Aperture2 of the 1st series magnet

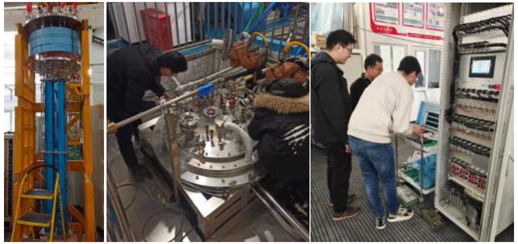
The 2nd coil from Bama with direct wind process plus 5-bar VPI, similar to the process of the 1st prototype.



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".



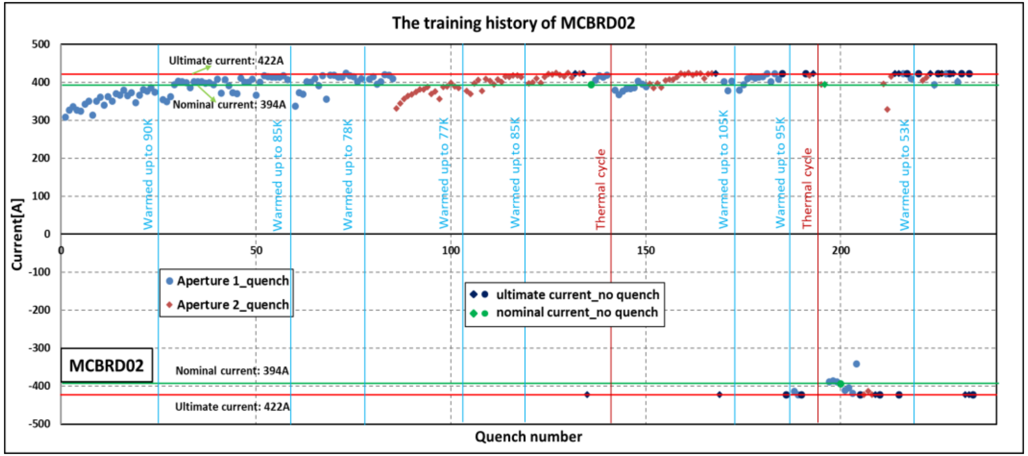
Development of CCT Magnets for HL-LHC

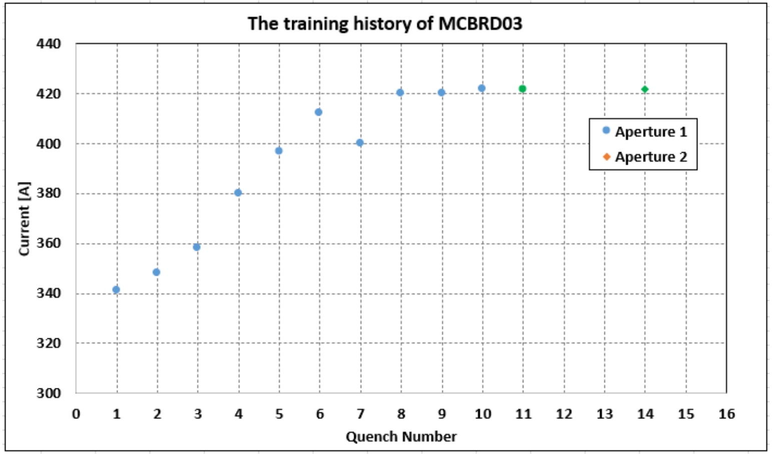
Training of MCBRD02 & MCBRD03





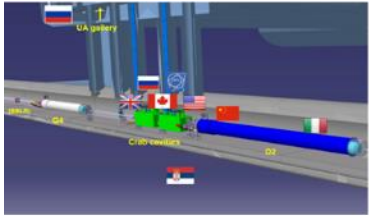
- AP1(CB12，25 quenches 526A) reached ±422A after 11 quenches.
- AP2(CB09, 33 quenches 530A; after thermal cycle >500A) reached ±422A without any quenches.



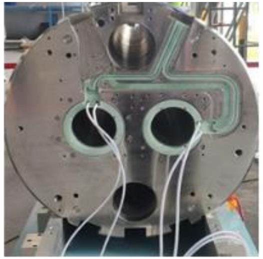


Development of CCT Magnets for HL-LHC

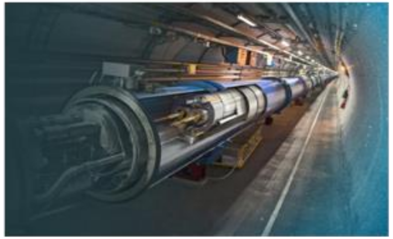
HL-LHC加速器升级中国贡献



合作协议签订



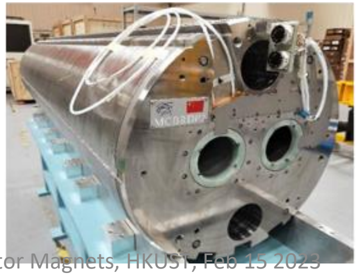
第一个正式磁体发往CERN
参加LHC束流调控



磁体隧道安装及调试

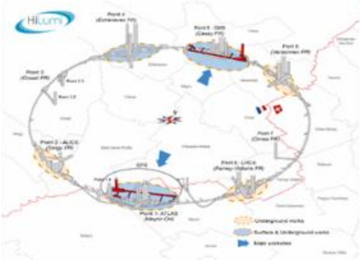
2018 — 2020 — 2022 — 2024 — 2026 — 2027

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



Summary

- Long-term advanced superconducting magnet R&D for future high-energy accelerators is ongoing at IHEP-CAS.
- Strong domestic collaboration for the advanced superconductor R&D (HTS & Nb_3Sn): Stainless-steel stabilized IBS tape achieved the highest J_e in 2022! Significantly reduced the cost and raised the mechanical properties.
- 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 development, and to be tested in 2023. 20+ T accelerator magnets expected to be realized in 2020s.
- China & CERN Collaboration on accelerator technology: development of HL-LHC CCT magnets going well.

Thanks for your attention!