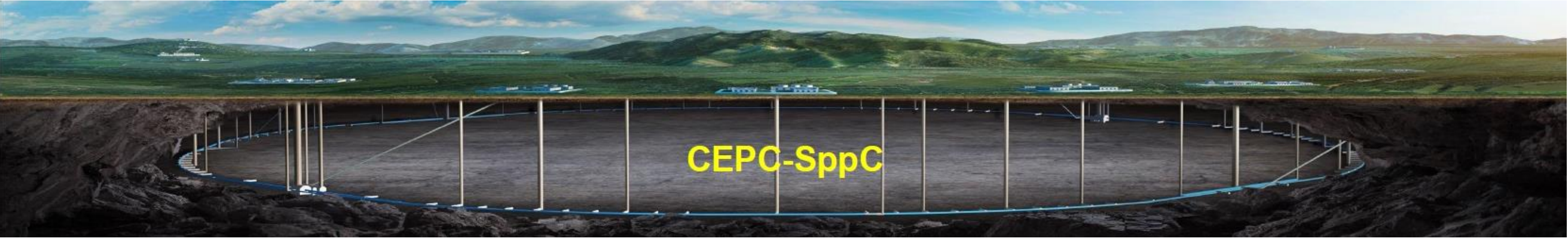
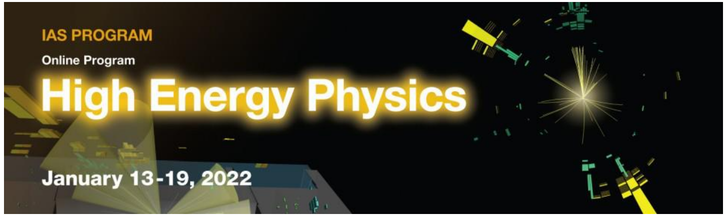


Progress of the High Field Magnet R&D at IHEP



Qingjin Xu

Jan 14 2022

中国科学院高能物理研究所
Institute of High Energy Physics, CAS

Colleagues & Collaborators

IHEP-CAS: *Chengtao Wang, Yingzhe Wang, Juan Wang, Chunyan Li, Rui Kang, Huanli Yao, Zhen Zhang, Jinrui Shi, Ze Feng, Wei Li, Ao Feng, Menglin Wang, Huan Yang, Ling Zhao, Zhilong Hou, Zhongxiu Liu,,…*

HIPS-CAS: *Huajun Liu, Tao Zhao, Yanlan Hu,…*

IEE-CAS: *Dongliang Wang, Xianping Zhang, Yanwei Ma,…*

Toly Electric: *Yu Zhao, Hean Liao, Bingxing Lu,…*

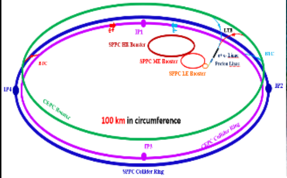
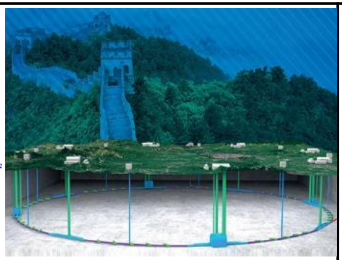
IMP-CAS: *Wei Wu, Xianjin Ou, Dongsheng Ni, Wenjie Liang,…*

Baoding Tianwei Electric*: Tao Xing, Xiongzhuang Li, Jun Jiao,…*

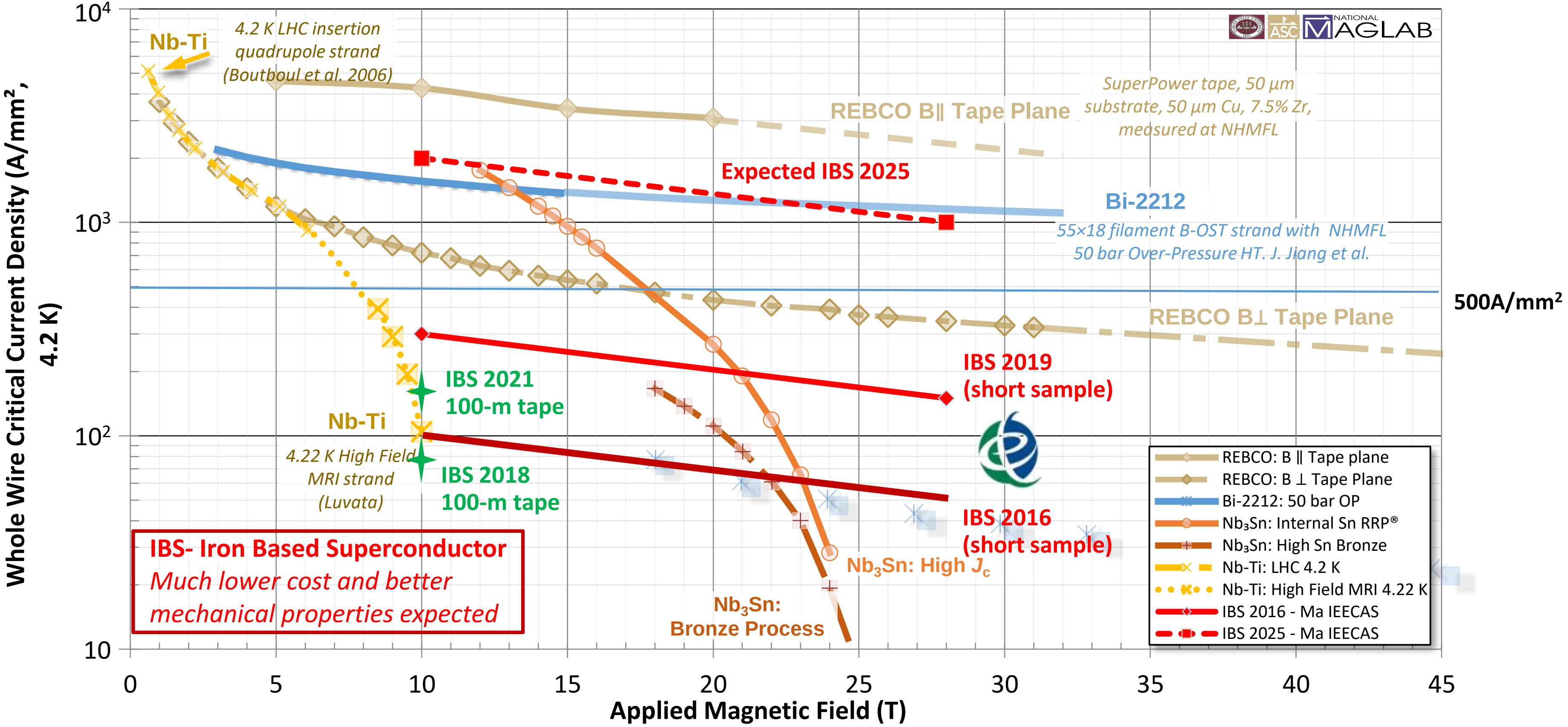
THU: *Timing Qu, Yufan Yan,……*

Magnet Design Scope for SPPC

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

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 12~24 T to reach 75-150 TeV, Nb_3Sn etc as options	Nb_3Sn 16 T to reach 100 TeV
Timeline	Construction at 2040s	Construction at 2050-60s
Cost	*	**

IBS Technology: Status and Outlook

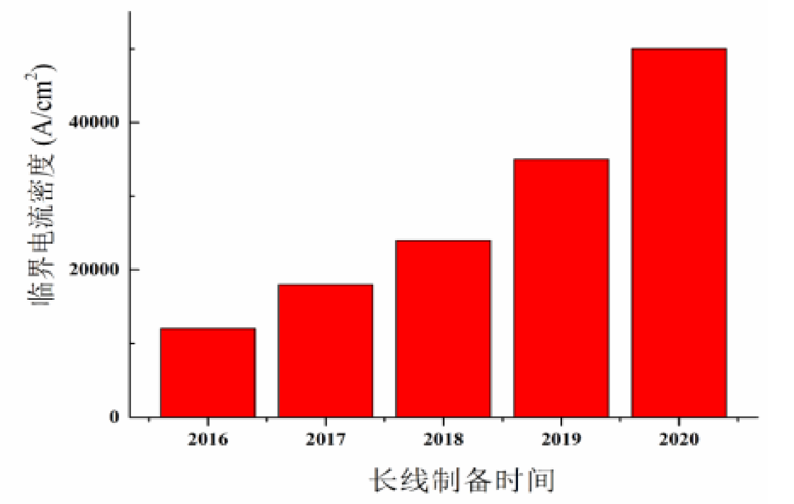


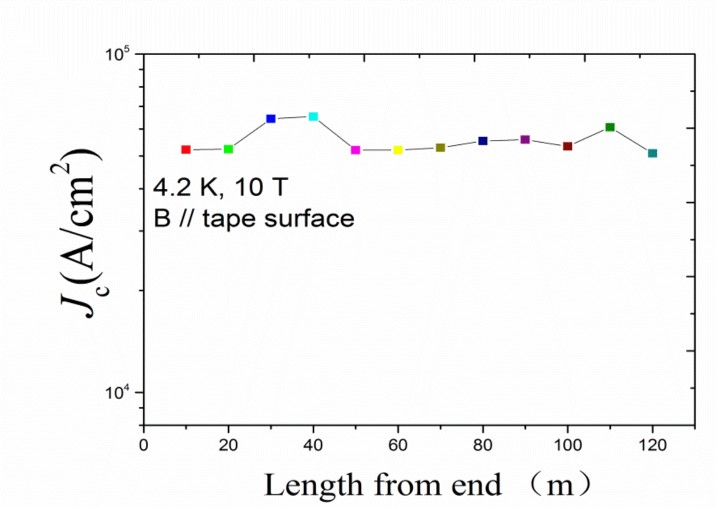
IBS Technology: Status and Outlook

100-m Long Ba122 Tapes by Rolling Process

- In 2020, J_c of a 100-m 7-core tape using the new fabrication technique reached 500 A/mm^2 @ 4.2 K, 10 T.
  Tape width 4.8 mm, tape thickness 0.3 mm. I_c > 260 A, J_e>180 A/mm^2.
- In 2018, J_c of such tape is 300 A/mm^2 @ 4.2 K, 10 T.

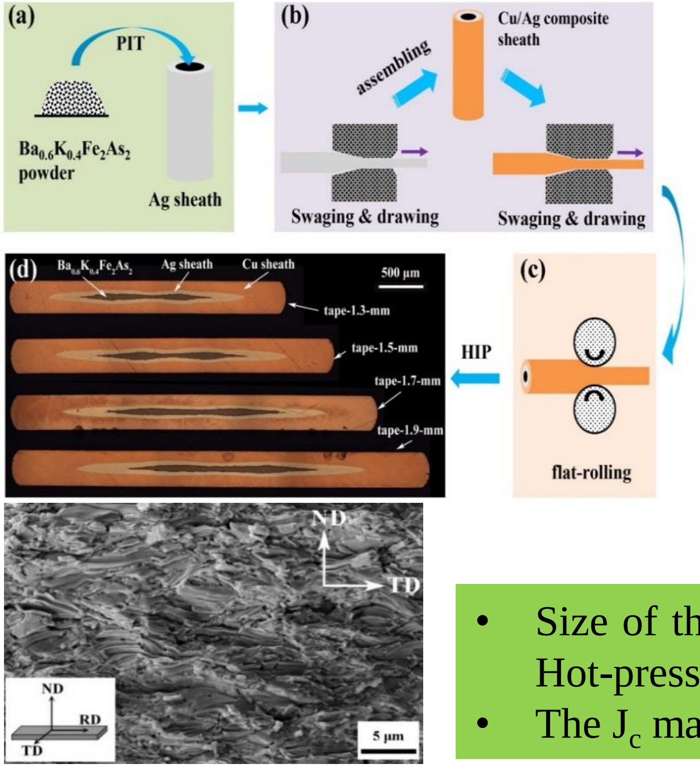
Prof. Y. Ma's Group, IEE-CAS

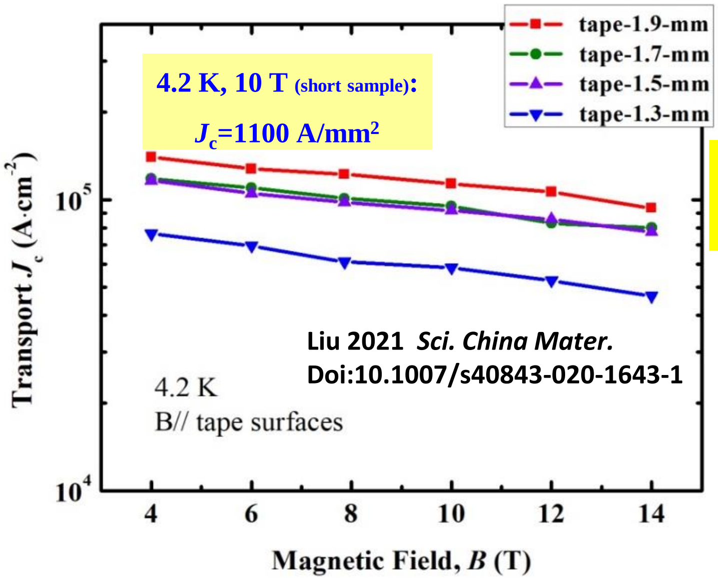




IBS Technology: Status and Outlook

Performance of HIP Ba122 Tapes with Cu/Ag Stabilizer





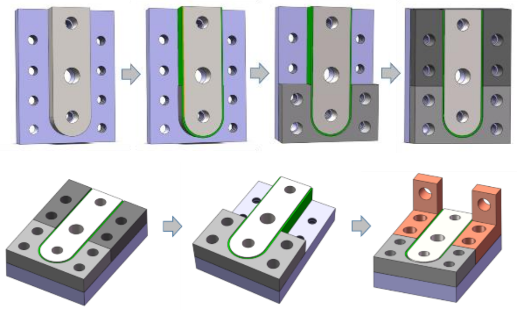
Liu 2021 *Sci. China Mater.*
Doi:10.1007/s40843-020-1643-1

Prof. Y. Ma's Group, IEE-CAS

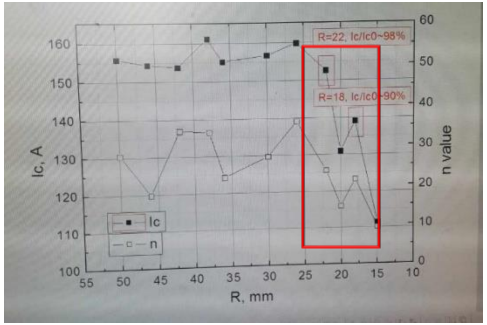
- Size of the grains was around 0.5 um, smaller than that in the Hot-pressed samples.
- The J_c may be improved with the increase the grain size.

IBS Technology: Status and Outlook

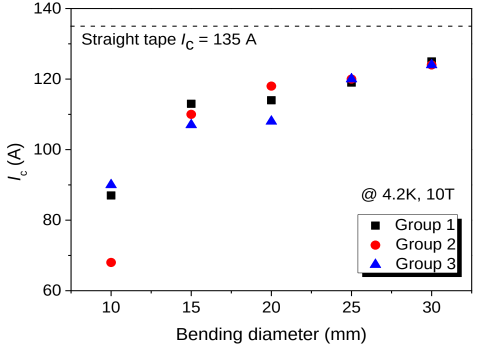
Minimum bending diameter measurement of the IBS tapes



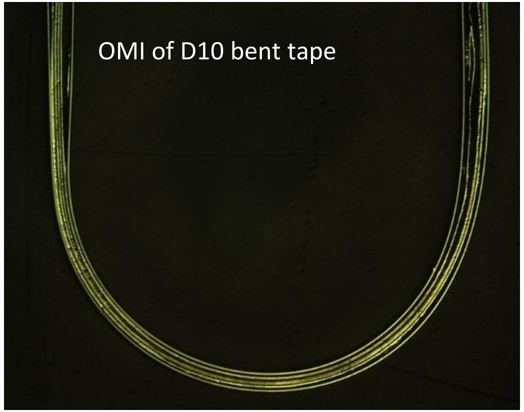
Preparition of bent IBS tape

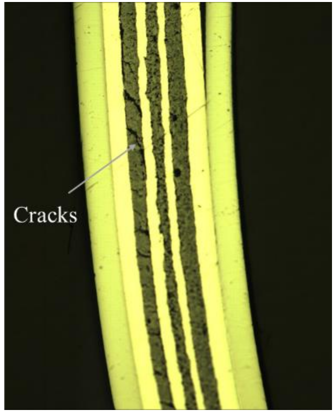


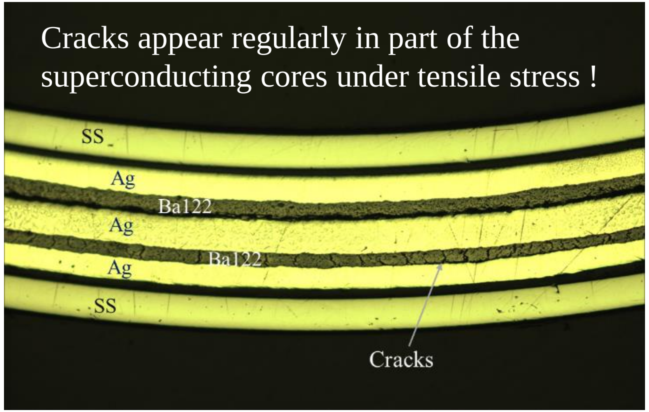
Sample results by ASIPP in 2018



Sample results by IHEP in 2021



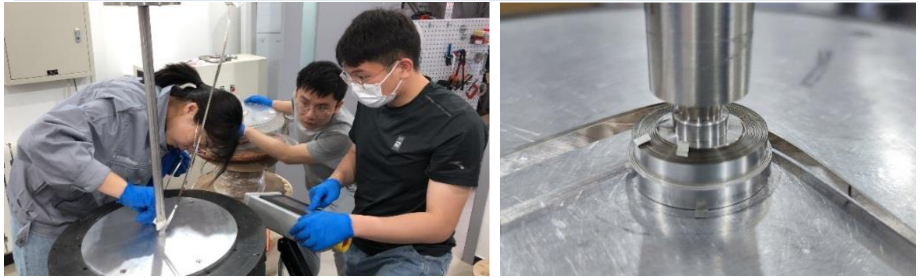




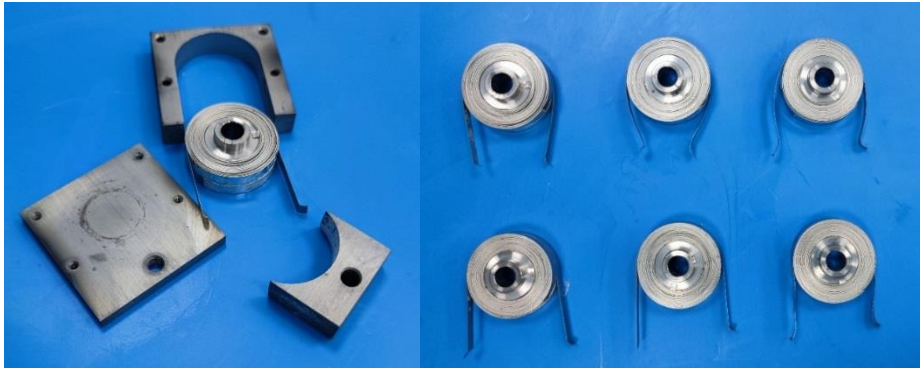
IBS Technology: Status and Outlook

Fabrication of High Field IBS solenoids

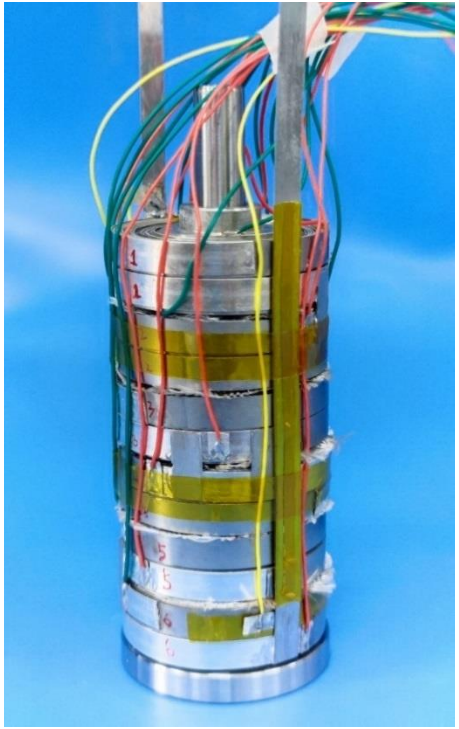
Fabrication of D20-17 turn-double pancake coils with IBS tapes



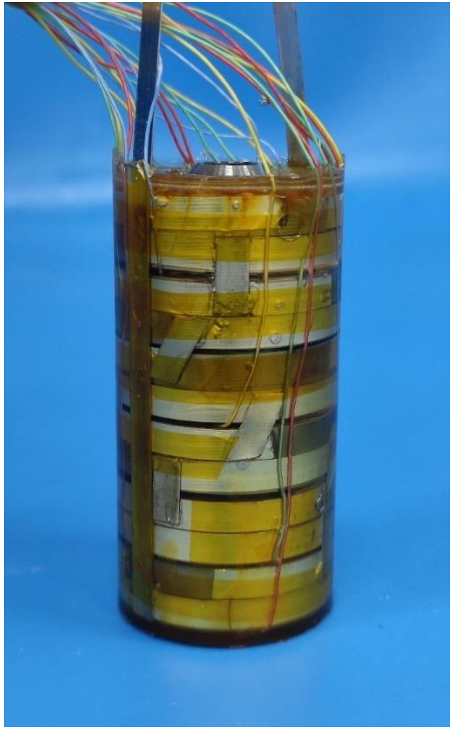
Coil winding of the IBS double pancake solenoids with 20-mm inner diameter



IBS double pancake solenoids after heat reaction



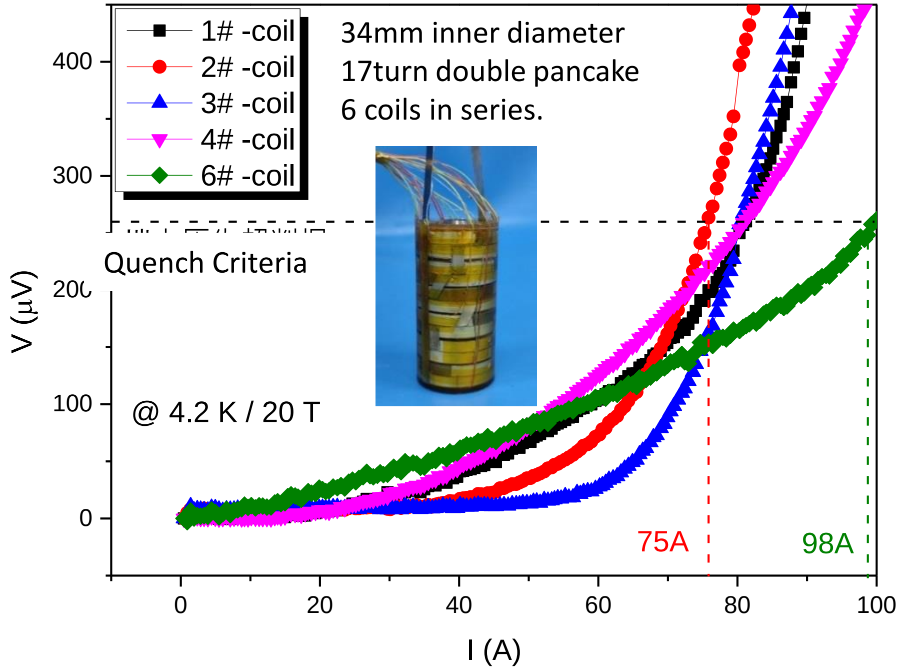
Series IBS double pancake solenoids

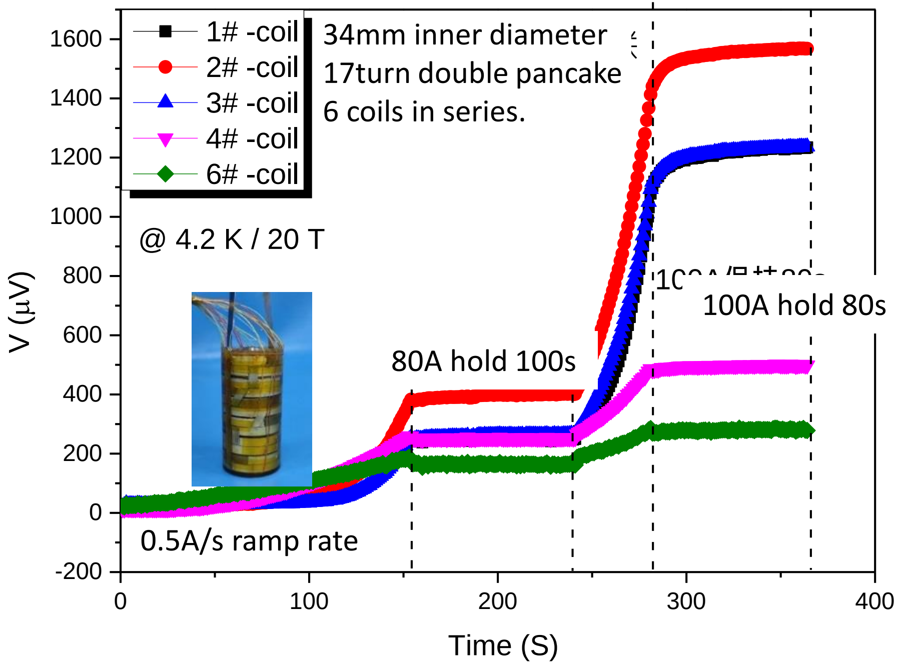


Impregnated Series IBS solenoids

IBS Technology: Status and Outlook

Performance test of the series IBS solenoids at 20 T background field



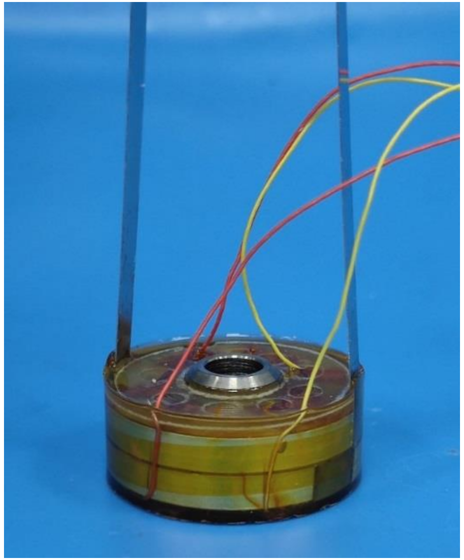


I_c of the series IBS solenoids reached 75 A at 20 T, and stable operation with 100 A

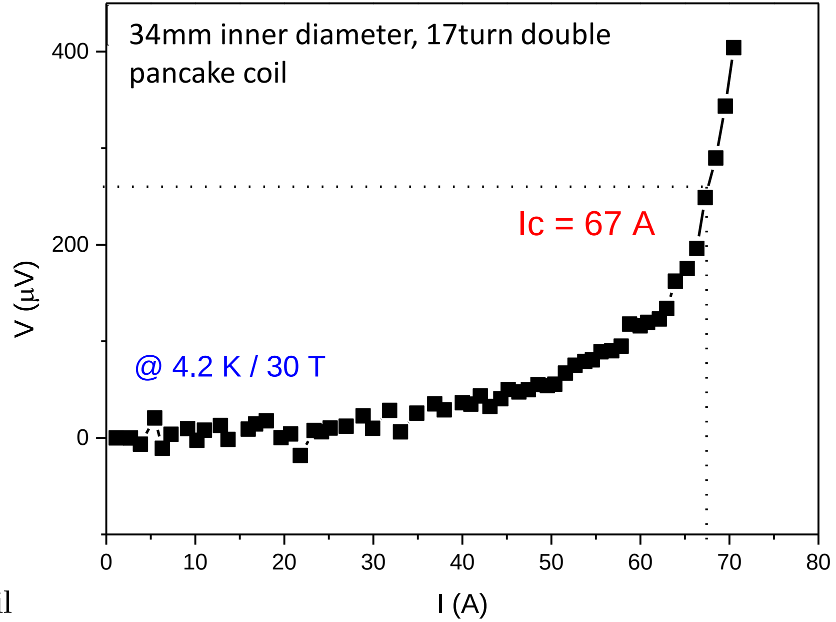
IBS Technology: Status and Outlook

Performance test of the double pancake IBS solenoid at 30 T background field

30T background magnet @ Hefei



D20-17turn-IBS double pancake coil

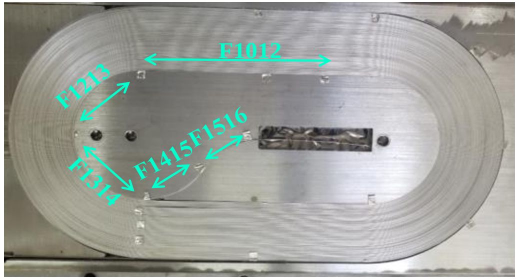


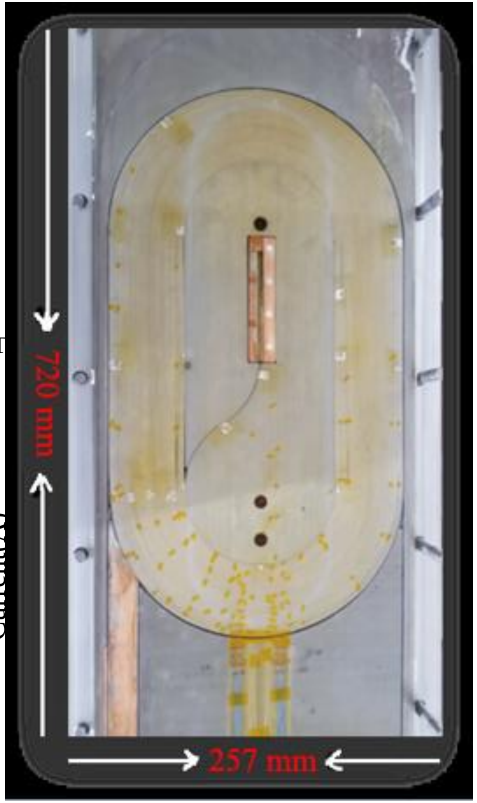
I_c of the IBS double pancake solenoid reached 67 A at 30 T. ***New record!***

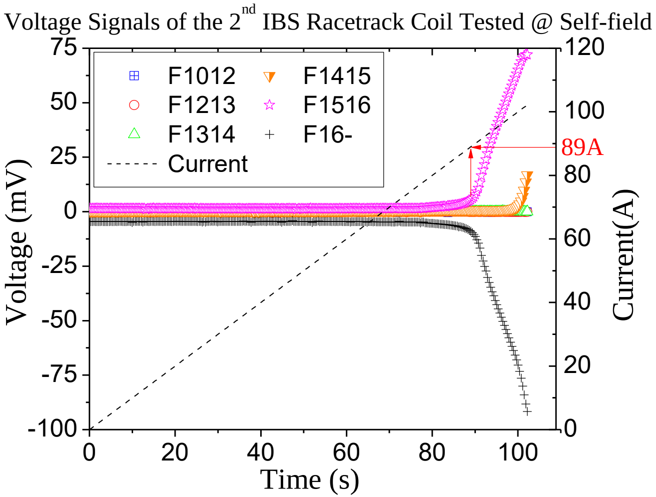
IBS Technology: Status and Outlook

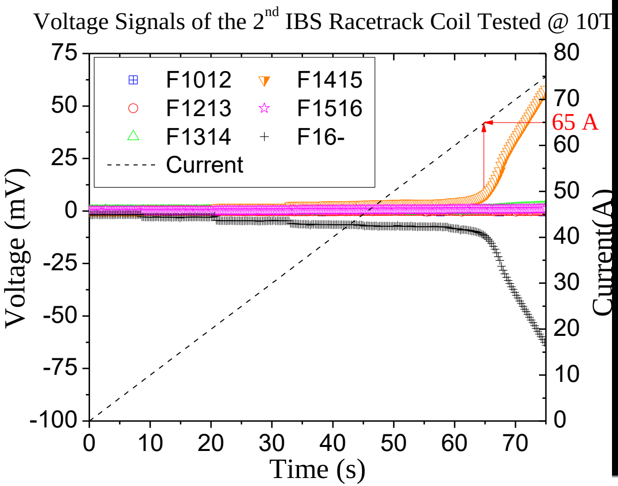
Racetrack Coils with 100-m Long IBS Tapes

Parameter	Value
Background field	0-10 T
Rate	1 A/s
Maximum pressure on IBS	120 MPa





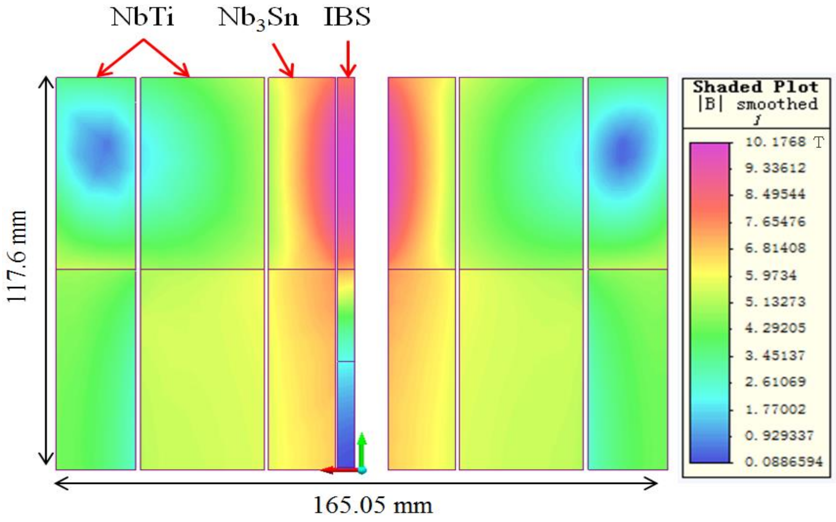




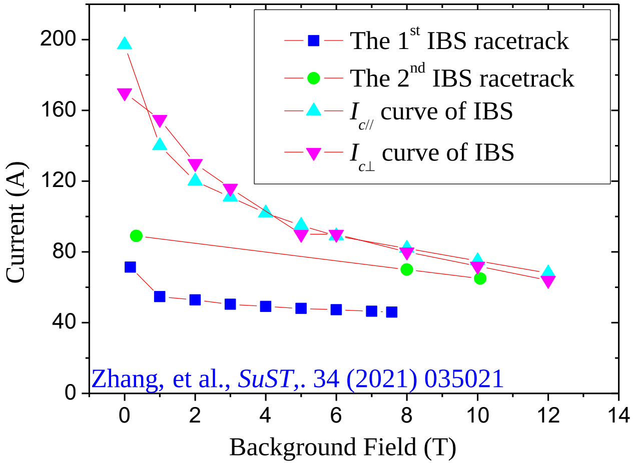
IBS Technology: Status and Outlook

Racetrack Coils with 100-m Long IBS Tapes

- Two racetrack coils have been made using the 100 m length IBS tapes.
- The coils reached 86.7% of critical current of the short sample at 4.2 K and 10 T.
- with highest compressive stress of 120 MPa.



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

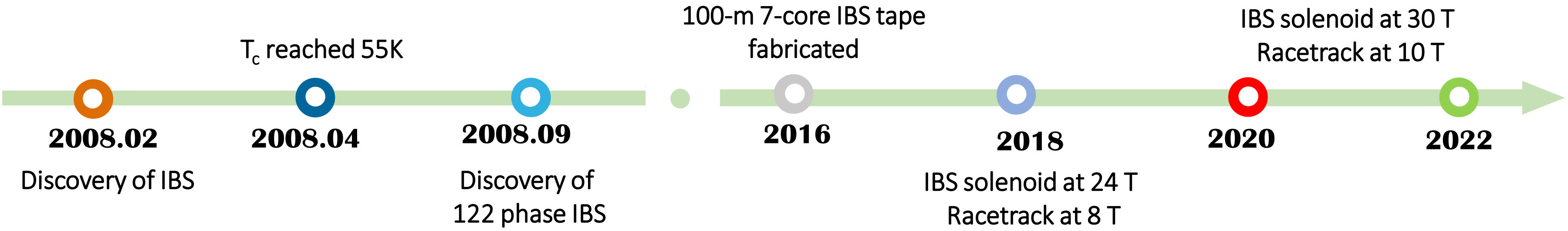


Comments from SUST reviewers:

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.

IBS Technology: Status and Outlook



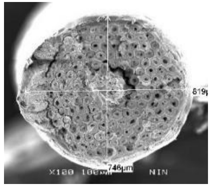
- The **engineering current density** of the long-length IBS still needs a significant improvement, to reach the similar level as ReBCO or Bi-2212 conductors.
- The **materials of stabilizer** should be shifted to copper or any other low-cost metals to realize the low cost of IBS.
- **Structure and fabrication 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.

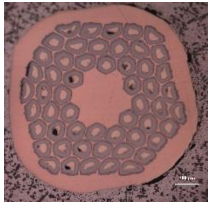
R&D Route for LTS High-field Accelerator Magnets

Superconductor → **Magnet Design** → **Coil Fabrication** → **Magnet Assembly** → **Performance Qualification**

Superconductor

J_c, RRR, Cu ratio,
Filament size,

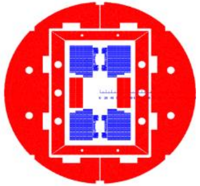


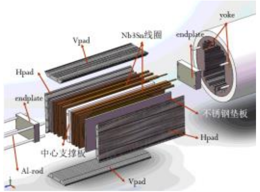


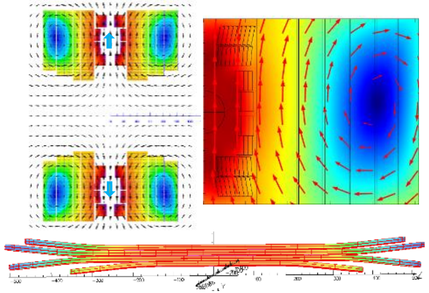
Material,
Cross section,
Processing,…

Magnet Design

Magnetic field strength,
EM force, quench protection,…



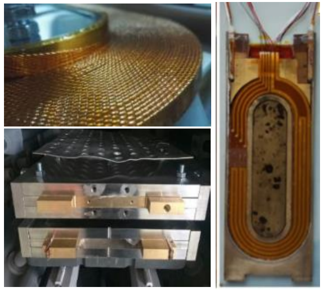




Magnetic field quality,
Persistent current effect,
Coil stress,…

Coil Fabrication

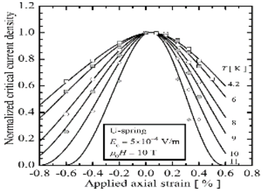
J_c and RRR degradation
Stress and dimension control

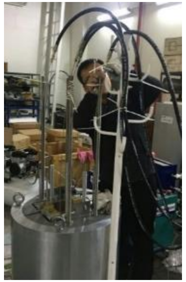


Impregnation quality control
Thermal stress control
Mechanical strength and stability

Magnet Assembly

J_c & strain curve of
the superconductor

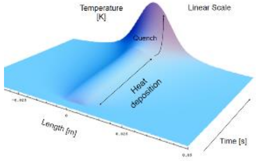




Pre-stress control
Dimension control,
Mechanical Stability

Performance Qualification

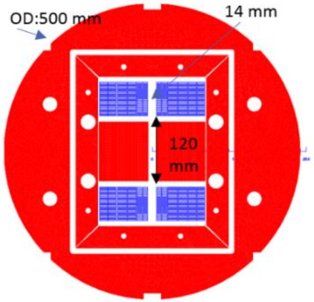
Quench protection
Hot spot, voltage,…

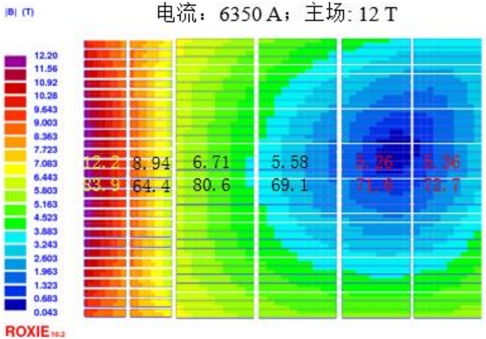


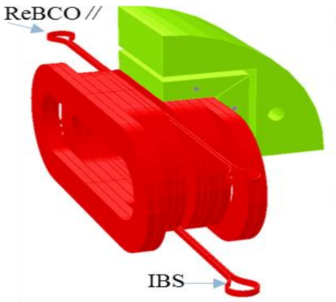
Training, Thermal-
magnetic instability,
Thermal cycle,…

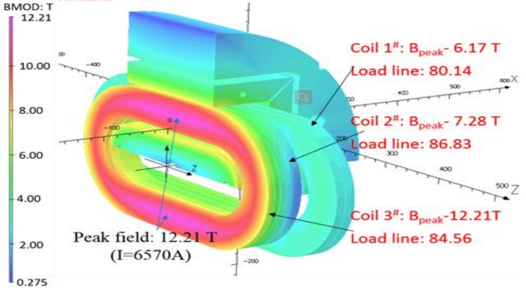
R&D of the 1st $NbTi+Nb_3Sn$ Model Dipole Magnet

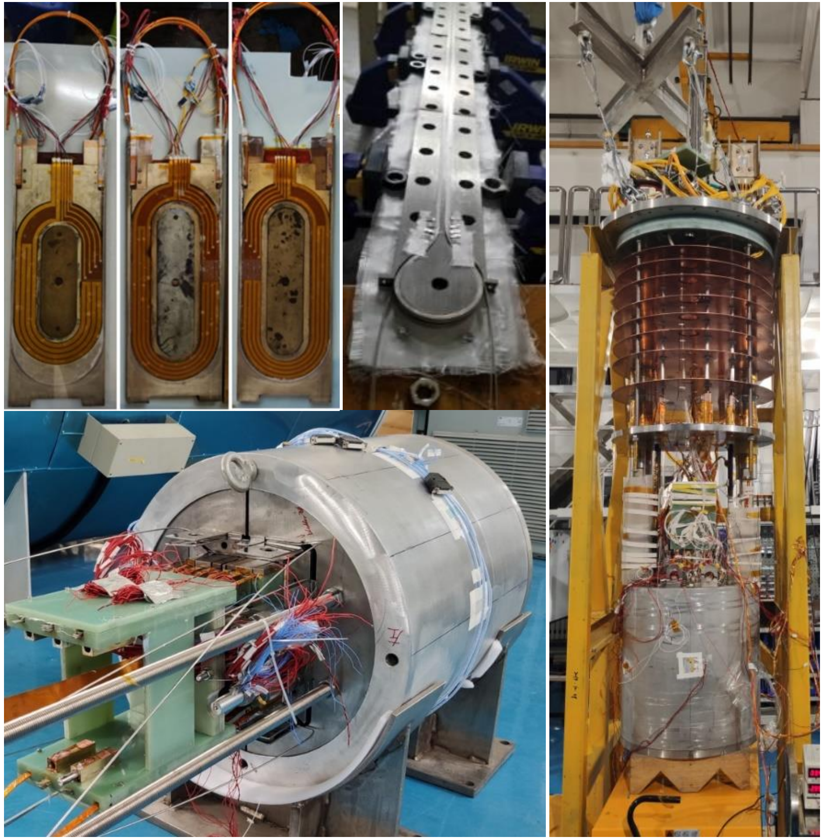
Development of a **$NbTi+Nb_3Sn$ twin-aperture** model dipole magnet from 2017.
Dipole field reached **12 T @ 4.2 K** in May 2021 and **12.47 T** after a thermal cycle.



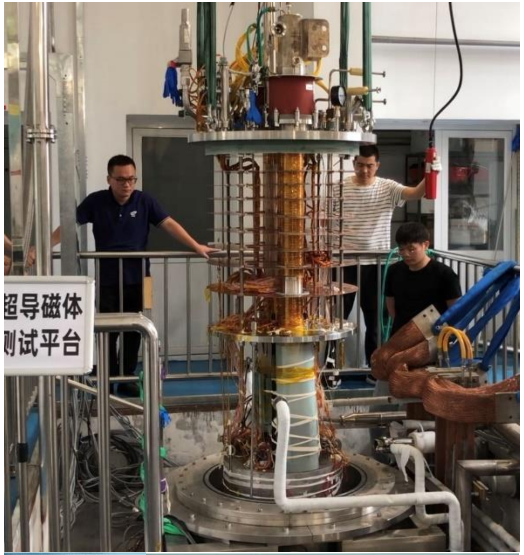


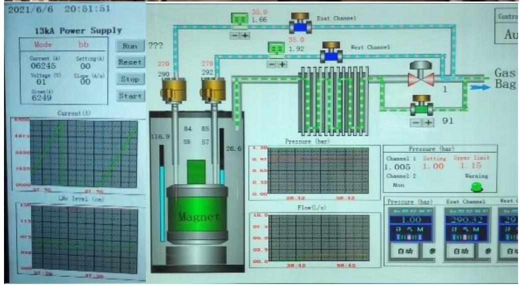


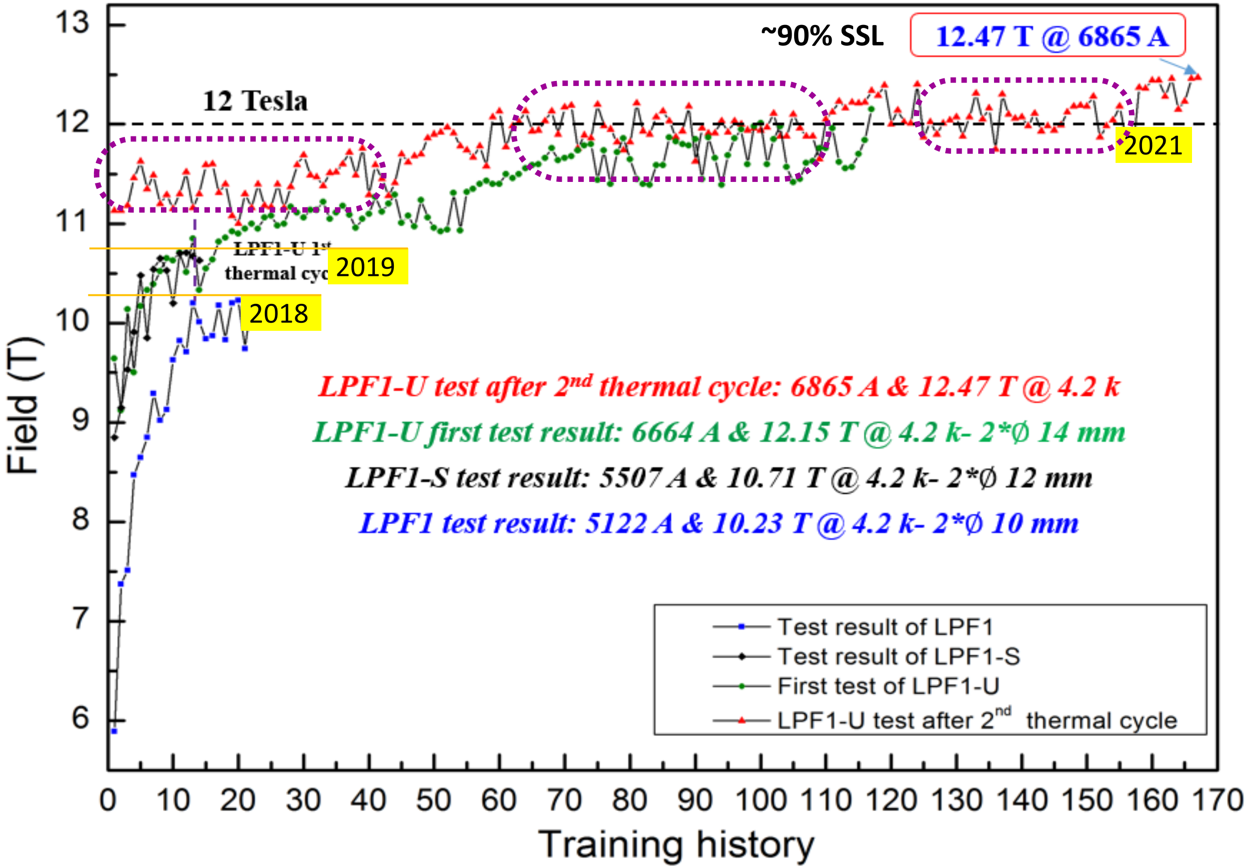




R&D of the 1st $NbTi+Nb_3Sn$ Model Dipole Magnet

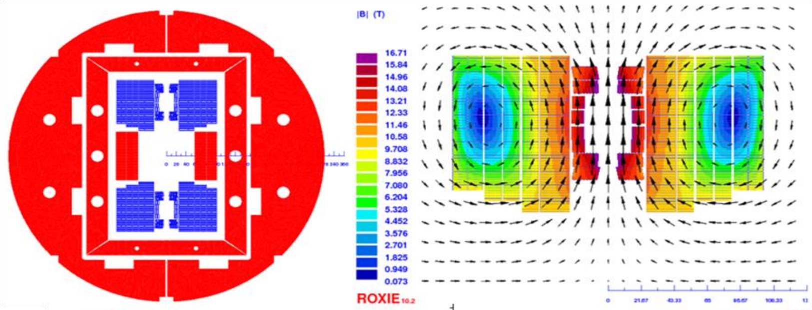


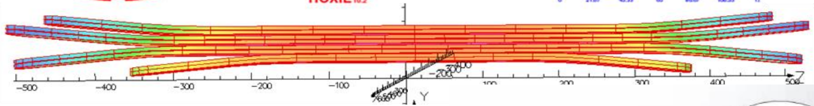


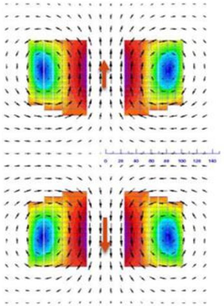


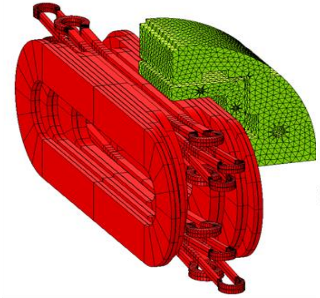
Development of the 16-T Hybrid Dipole Magnet

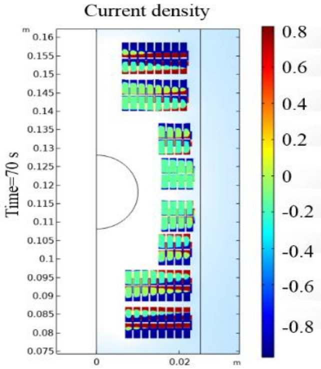
16 T Dipole: Nb_3Sn 12~13 T + HTS 3~4 T



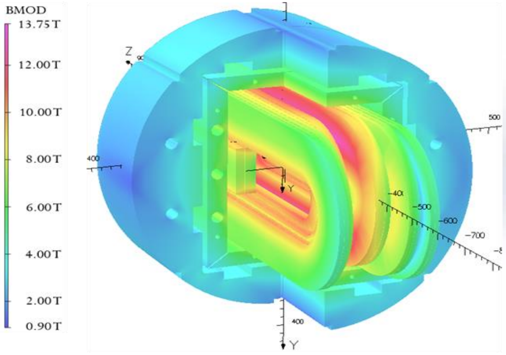


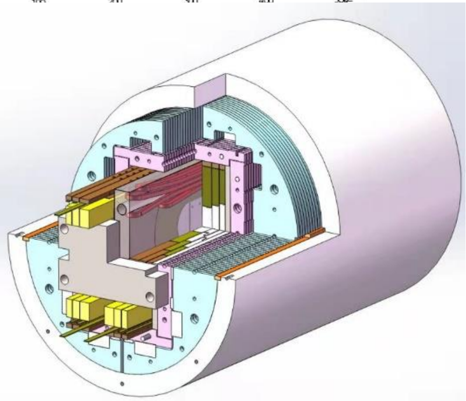




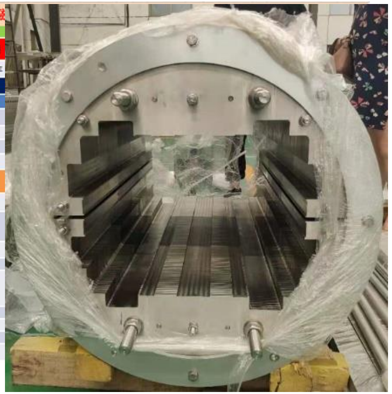


16-T 大孔径高场超导二极磁体 LPF3 (Nb_3Sn-13



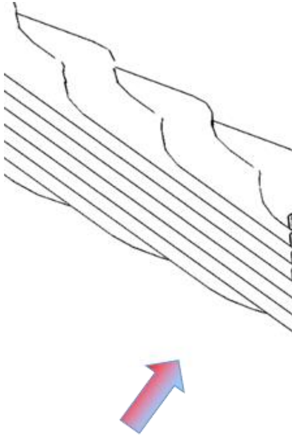


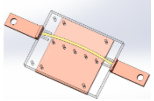
LPF3		6月				7月		
		一	二	三	四	一	二	三
线圈及磁体关键部件研制	铌三锡线到位							
	卢瑟福电缆绞制							
	铌三锡线圈制作							
	铌三锡线圈热处理							
	线圈内接头焊接							
	铌三锡线圈浸胶							
	Yoke，shell，pad，拉杆及线圈骨架加工等							
	应变测量系统搭建							
磁体组装	线圈组装，轴向调控：H，V 及 Z 向预紧力施加							
	线圈间接头焊接							
测试前准备	磁体杜瓦装配，电流引线焊接							
	信号线连接、霍尔探头连接，小电流测试、应变系统及数采系统调试							
	光栅光纤信号连接							
	磁体降温							
	电源/磁体调试							
磁体测试	磁体正式测试							

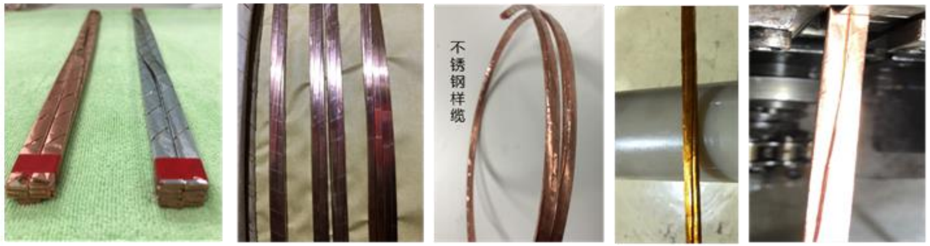


Development of the 16-T Hybrid Dipole Magnet

Development of a Roebel-like HTS Transposed Cable







2020.08 — 2020.10 — 2021. 01 — 2021. 04 — 2021. 06

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

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

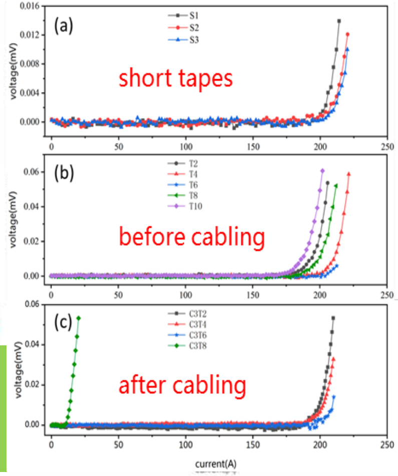
样缆：
1、目前换位没法连续生产，还需要调试设备；
2、调试设备材料太少，急需解决；

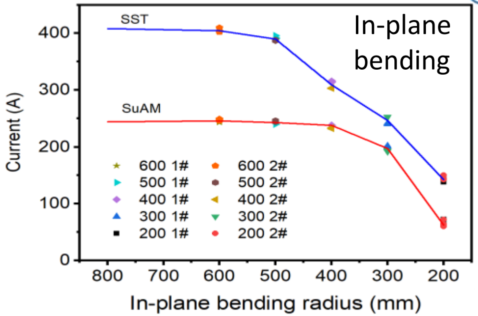
制备第一根样缆

The 1st prototype cable

制备第二根样缆

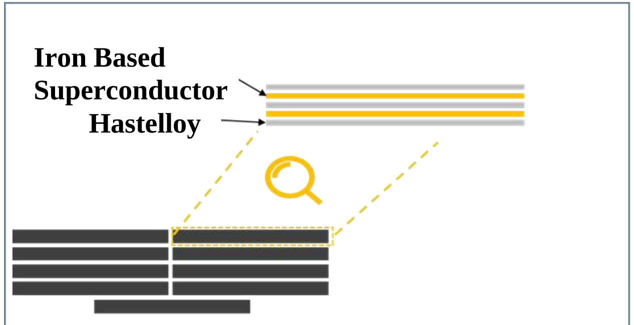
The 2nd prototype cable



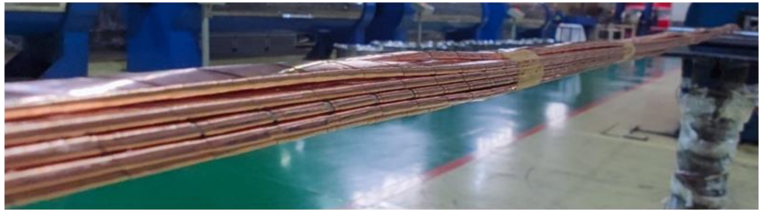


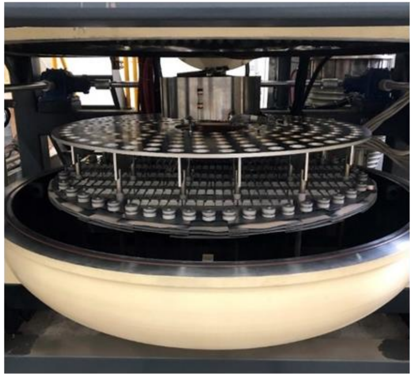
Development of the 16-T Hybrid Dipole Magnet

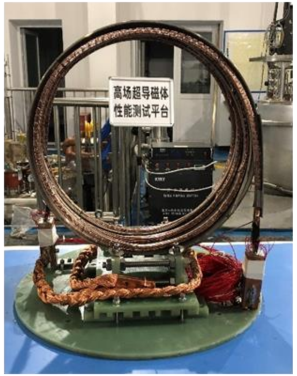
Development of a Roebel-like HTS Transposed Cable

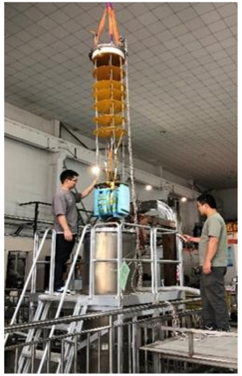


Cross section of the cable









IBS prototype cable

Cable length: 5 m

Pitch length: 200 mm

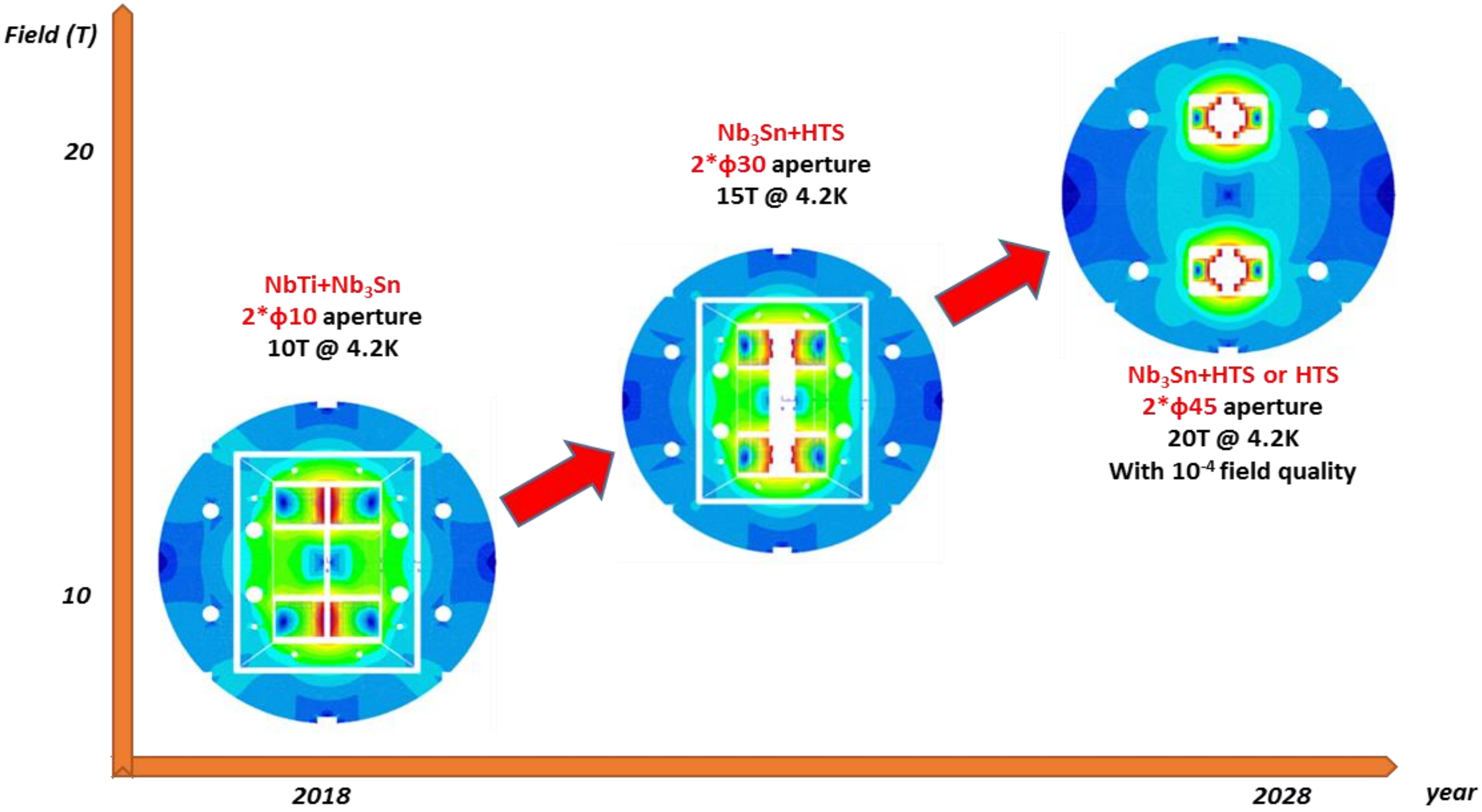
Cable thickness: 10.5 mm

Reaction temp.: 860°C

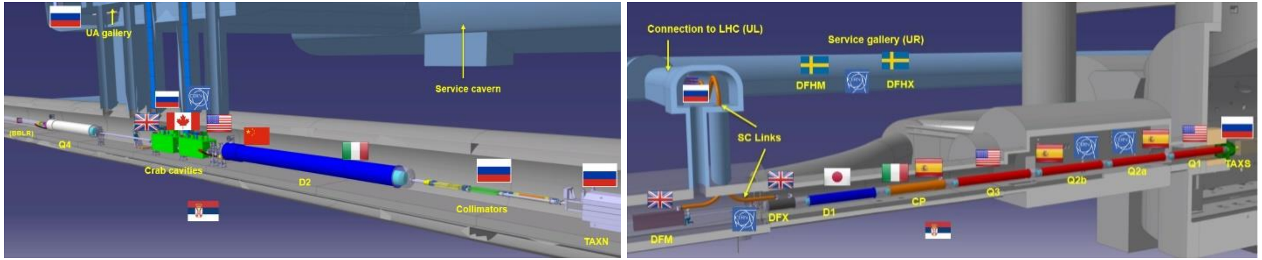
Test radius: 200 mm

Current： >1300 A

R&D Roadmap for Next Years

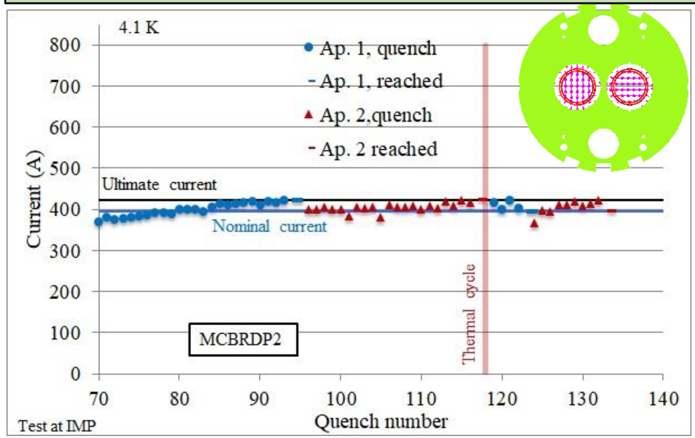


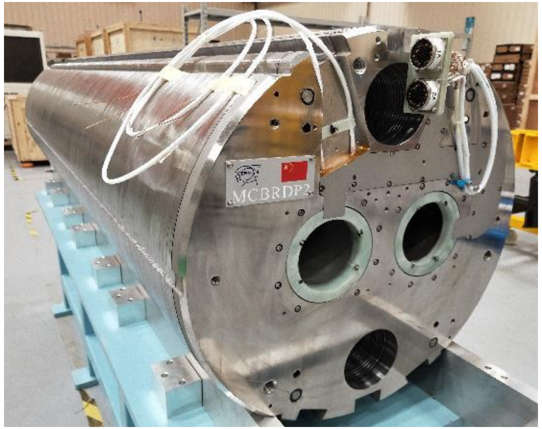
Status of the HL-LHC MCBRD CCT Magnets

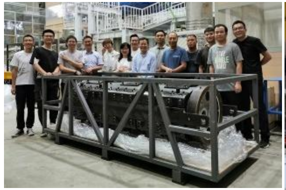


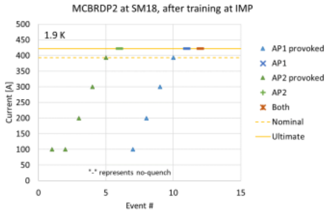
Layout of the HL-LHC Magnets and Contributors

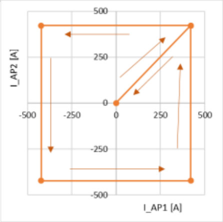
The 1st prototype magnet passed performance test at 4.2K in China, delivered to CERN in Aug 2020, and passed performance test at CERN in Dec 2020.





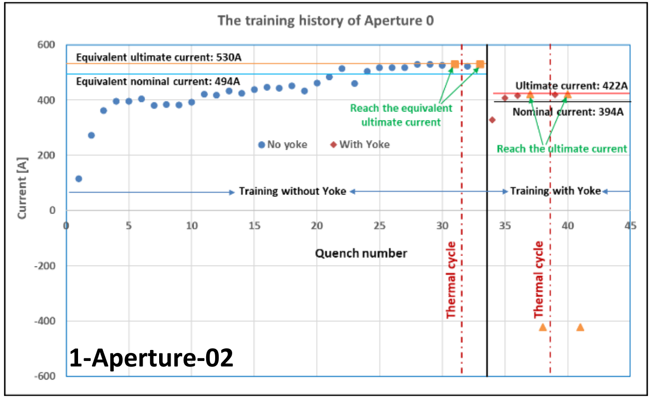


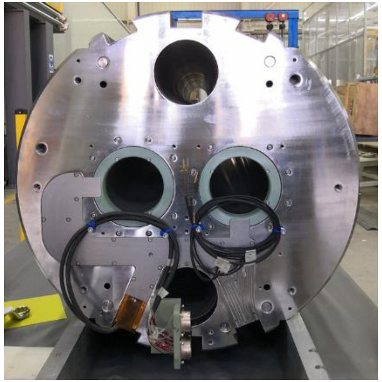


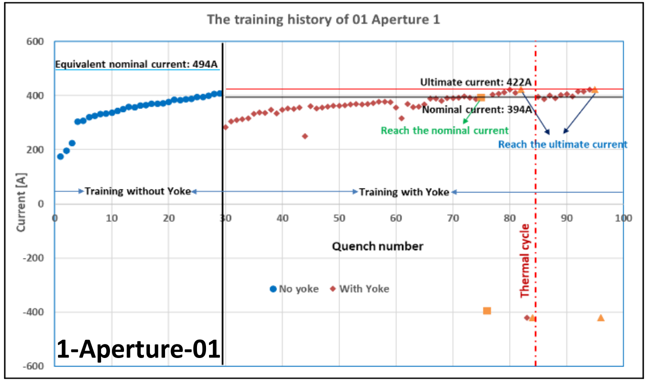


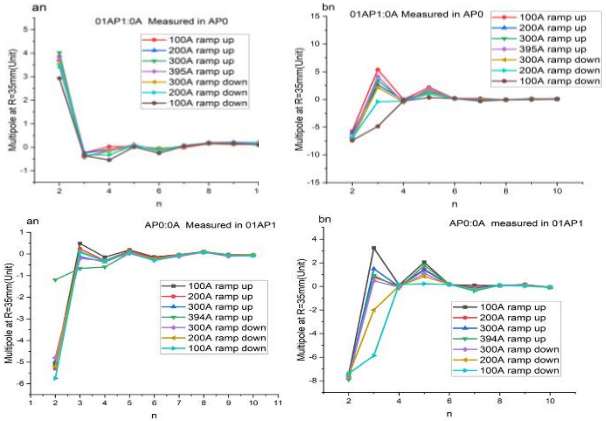
Status of the HL-LHC MCBRD CCT Magnets

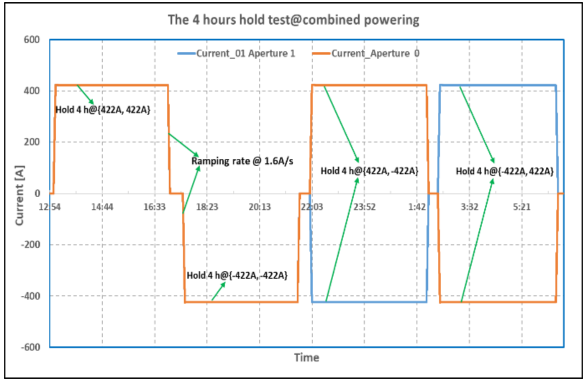
The 1st series magnet passed performance test at 4.2K in China and delivered to Europe in Oct 2021.
The remaining 11 sets of magnets will be delivered to Europe at a rate of 2~3 months per magnet







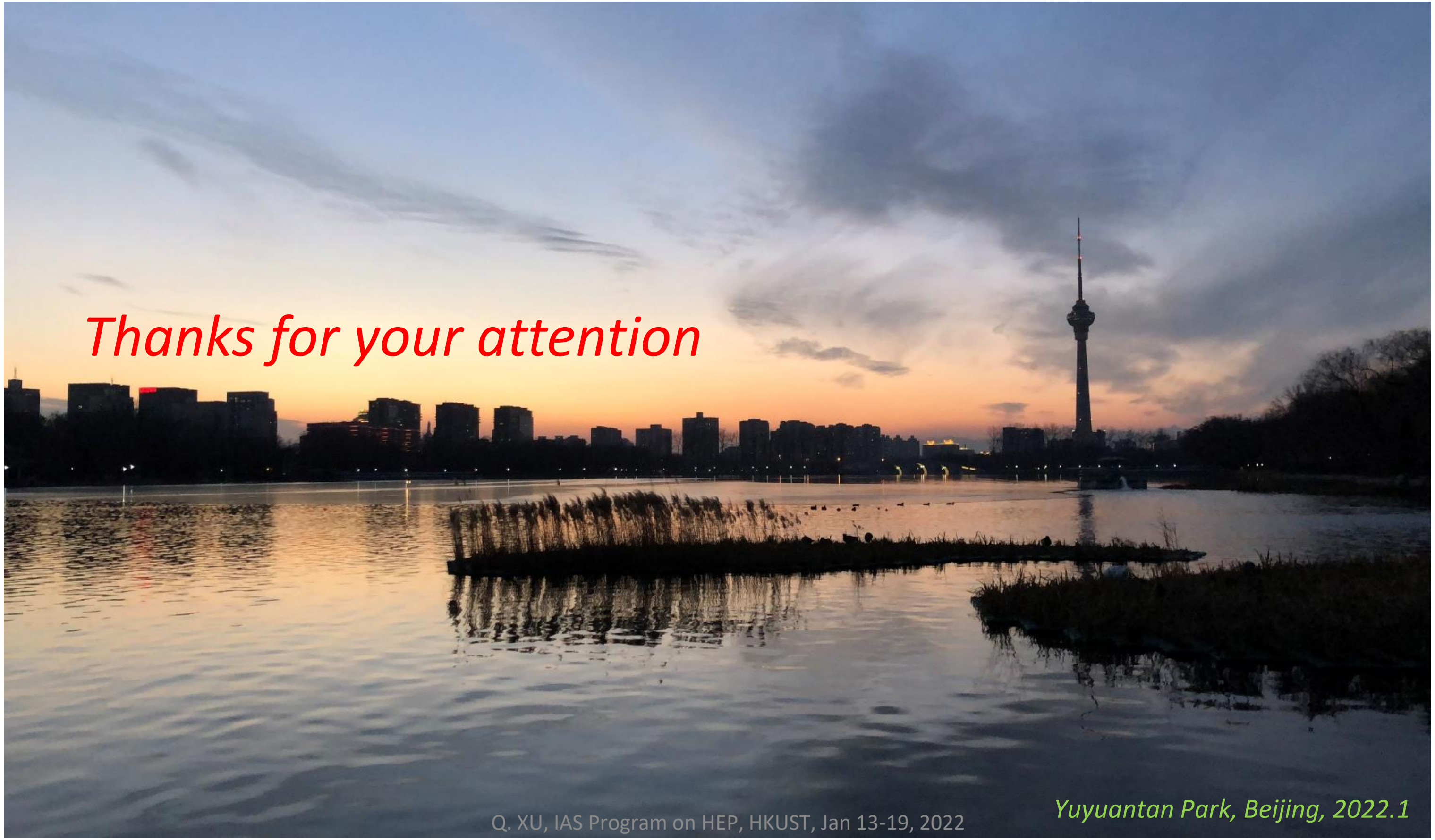




Summary

- *Strong domestic collaboration in China for the advanced superconductor R&D (HTS & Nb_3Sn): to significantly raise their performance and lower their cost.*
- *J_c of 100-m long 7-core Iron-Based Superconducting tape has reached 500 A/mm^2 @ 4.2 K, 10 T, corresponding to I_c >200 A, J_e>140 A/mm^2.*
- *Quench current of the Iron-Based Superconducting double pancake solenoid coil reached 67 A at 30 T, new world record!*
- *10+ T twin-aperture model dipoles being developed at IHEP, reached 12.47 T at 4.2 K in July 2021, aiming to reach 16 T (Nb_3Sn+HTS) in 3 years, and 20 T in 10 years.*

International collaboration *on high field magnet technology for next-generation particle accelerators are highly welcome!*


Thanks for your attention
Yuyuantan Park, Beijing, 2022.1