The development of HTS coil technology for next generation of fusion reactor

Jinggang Qin and HTS group

Institute of Plasma Physics, Chinese Academy of Sciences

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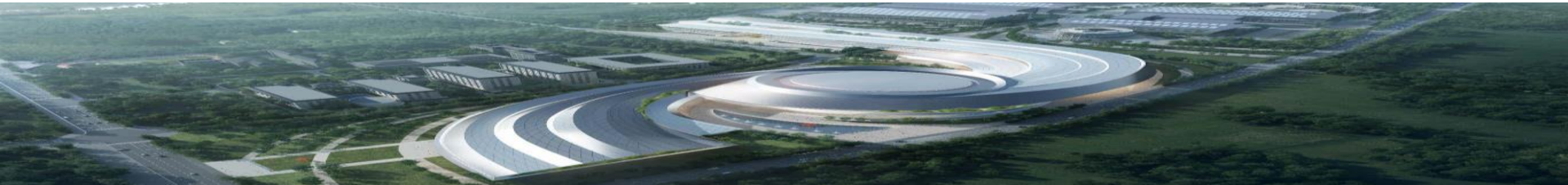


Collaborations and Acknowledgments

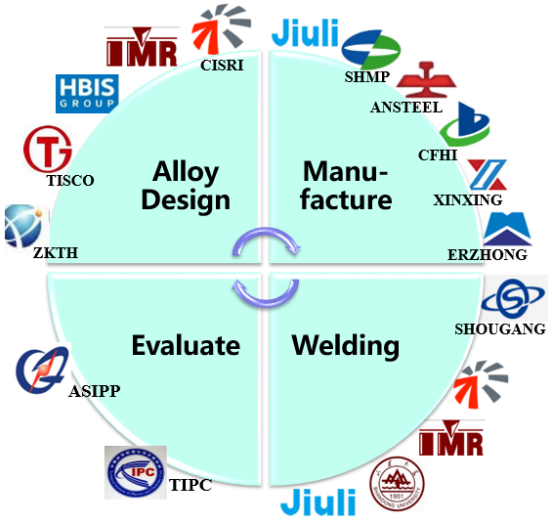
EUROfusion Europe-China collaboration - CFETR-DEMO: magnet group

Superconducting material suppliers: SSTC, NIN, Fujikura

Conductor/coil analysis, manufacturing and testing:

External experts:
Arnaud Devred

Research group on high strength material:



CONTENTS

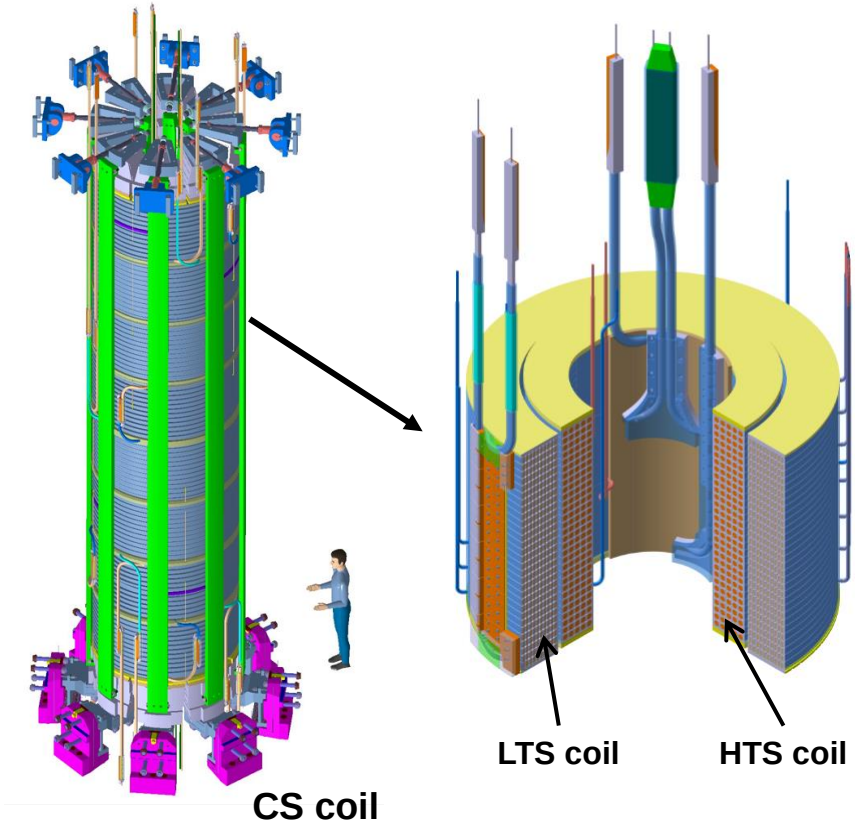
Part 01

Introduction

BEST CS coil – design concept

- The BEST CS coils are hybrid (HTS & LTS)
- CS conductor: Nb_3Sn & YBCO CICC

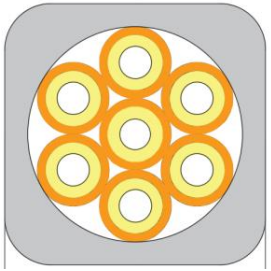
Overall weight (ton)	180
I_{op} (kA)	46.5
B_{max} (T)	18.8 (HTS) 12.4 (LTS)
Number of turns / per coil_HTS	150
Number of turns / per coil_LTS	300
Total Conductor length (m)	3100 (HTS) 9358 (LTS)
Voltage seconds	53Vs



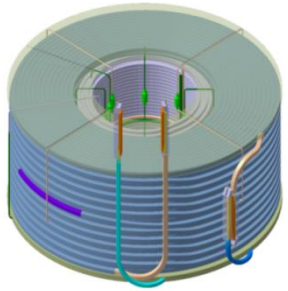
YBCO coil

REBCO HTS Tape

REBCO Sub cable



REBCO CICC



HTS Coil (>15T)

	Item	Parameters
YBCO tape	Width & thickness	4*0.1 mm
	Ic @77 K,self-field	>150 A
Sub-size cable	No. of cable	6
	OD of cable	~8.9 mm
	ID of spiral tube	2.4 mm
	No. of SC tapes	48
	No. of SC layer	16

Item	Parameter
Maximum field	~ 18.8 T
Iop of conductor	46.5 kA
No. of sub-cable	6
Jacket material	CHN01 (N50H)
Jacket thickness	4.3 mm
Outer dimension of jacket	42.5 x 42.5 mm
OD of CICC cable	~33.8 mm
Cooling method	Cable void & hollow pipe of sub-size cable

YBCO coil

☐ Planned/expected time schedule

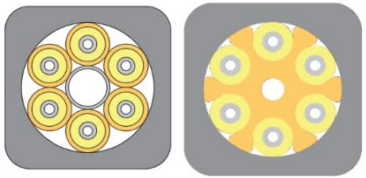
2020-2021
- CICC structure design
- sub-cable technology development

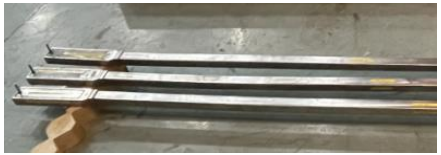
2022
CICC technology development

2023
CICC technology optimization

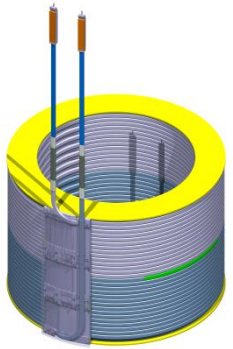
2024-2025
Long length CICC technology

2025-2026
Coil technology





First pair of HTS CICC Second pair of HTS CICC



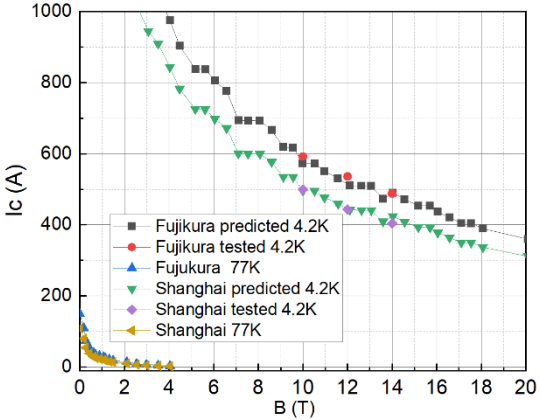
Part 02

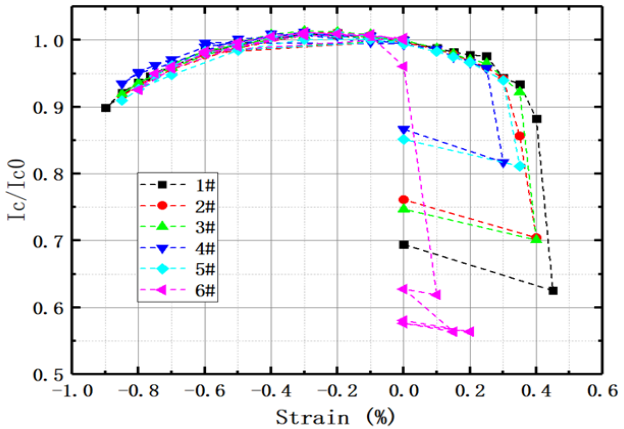
Research and development progress

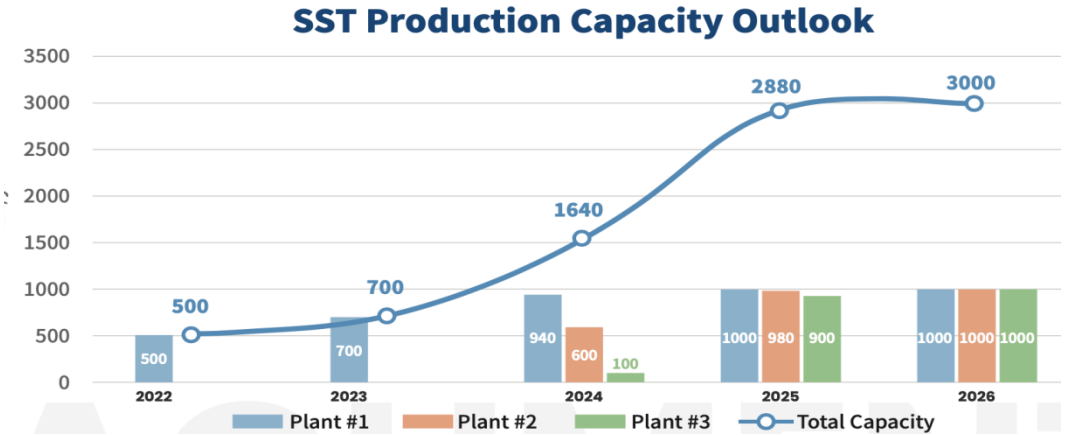
YBCO materials

YBCO tapes

- Tapes from SSTC Ic>250A@20T, 4mm;
- Ic with strain (-0.8 %-+0.4%) >90%;
- SSTC is focused on technology upgradation and new manufacture line construction;
- Totally, 3 manufacture lines can provide 3000km (10 or 12mm tapes) tapes in 2026;

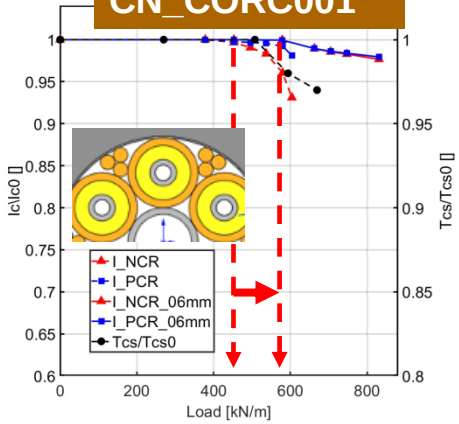






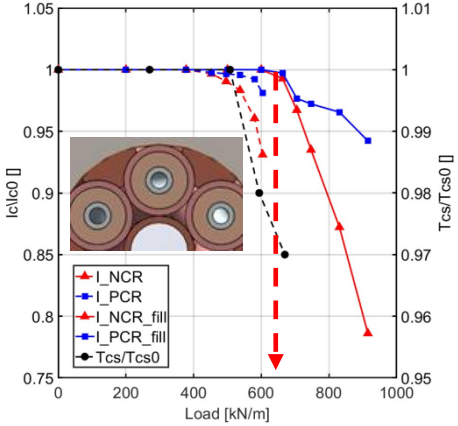
YBCO CICC

CN_CORC001



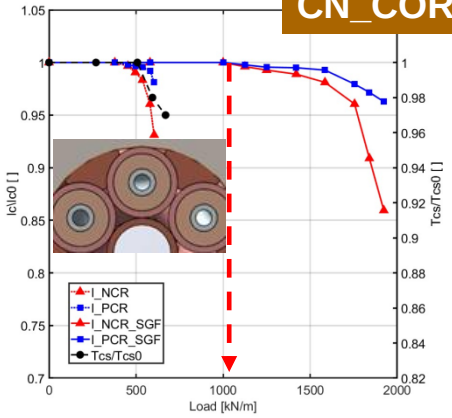
1.3 mm gap CORC SS spiral Irreversibility: ~ 400 kN/m

0.6 mm gap CORC SS spiral Irreversibility: ~ 580 kN/m

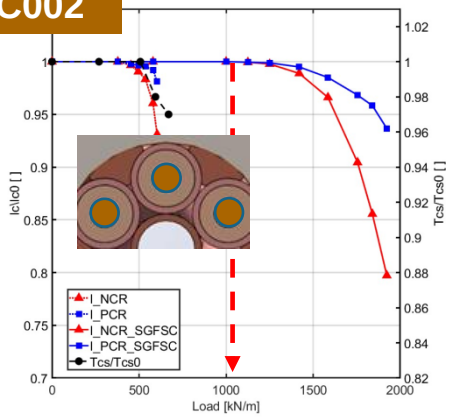


Original gap 1.3 mm **Cu-keystones** CORC SS spiral Irreversibility: ~ **600 kN/m**

CN_CORC002



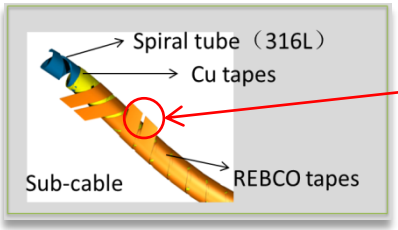
0.6 mm gap Cu-keystones CORC SS spiral Irreversibility: ~ **1000 kN/m**



0.6 mm gap Cu-keystones CORC solid Cu core Irreversibility: ~ **1000 kN/m**

CS	*I* [kA]	*B* [T]	*F*(*IxB*) [kN/m]
BEST	46.5	18.8	**874**
EU-DEMO	60	18	**1080**

*Mechanical analysis provided by A.Nijhuis

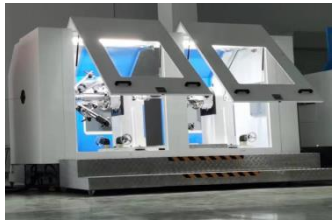


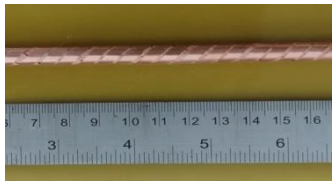
Key factors:

- **gap** between tapes in one layer

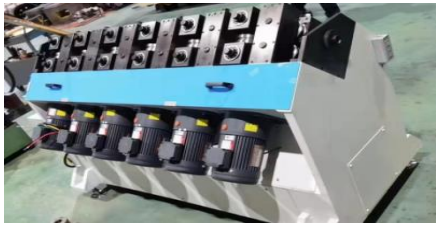
YBCO CICC

☐ Specimens manufacture technology (new sample, CN_CORC002)

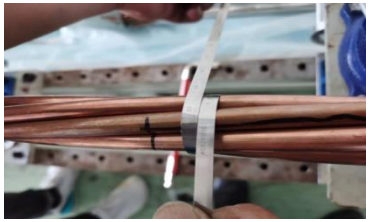


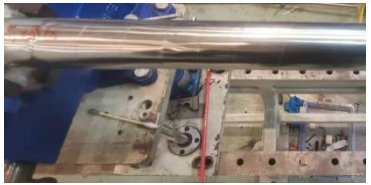


Winding

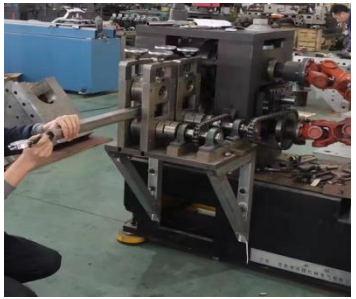


Cu tube Compaction

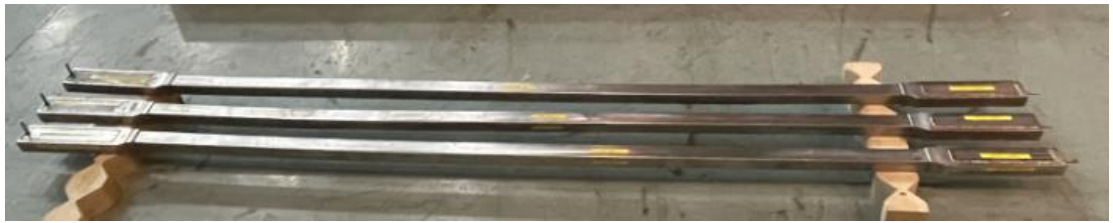




Twisting



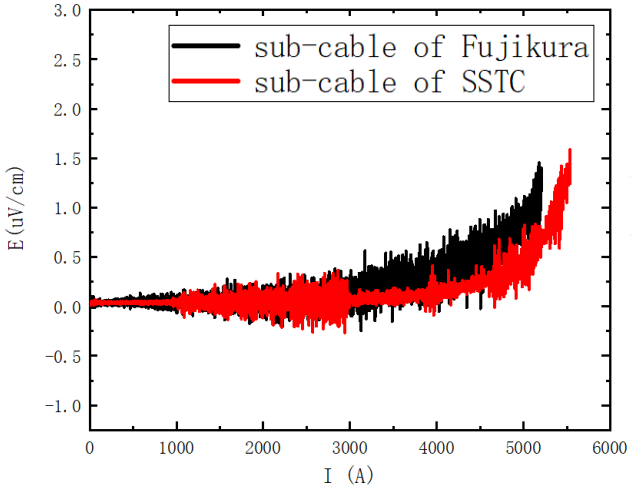
Jacket Compaction

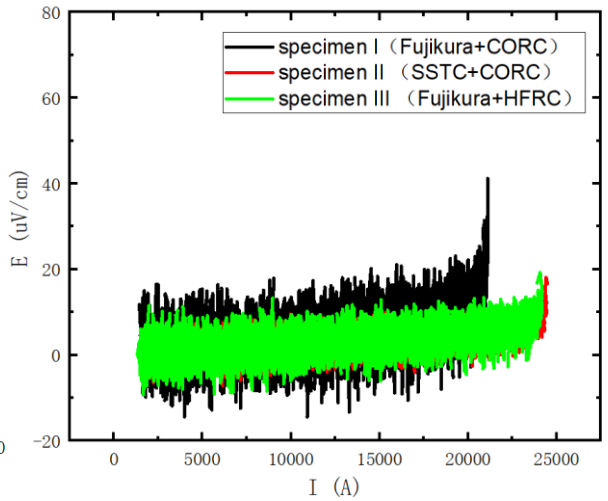


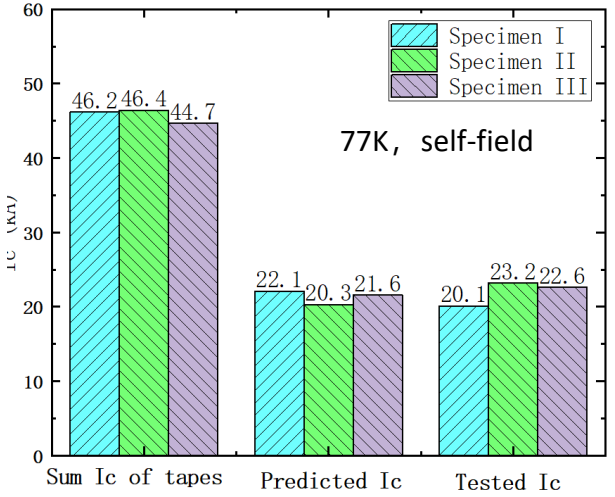
Send to Sultan lab in 02. 2024

YBCO CICC

☐ Sub-cable & CICC performance at 77K, Bsf in ASIPP







◆ Test results of Sub-cable：

Fujikura： Ic=5266 kA n~11；
SSTC ： Ic=5500 kA n=14；

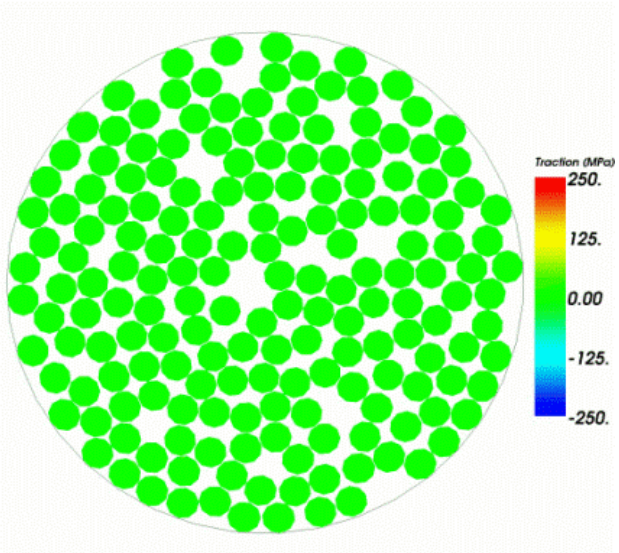
◆ Test results of CICC cable @77K、Bsf：

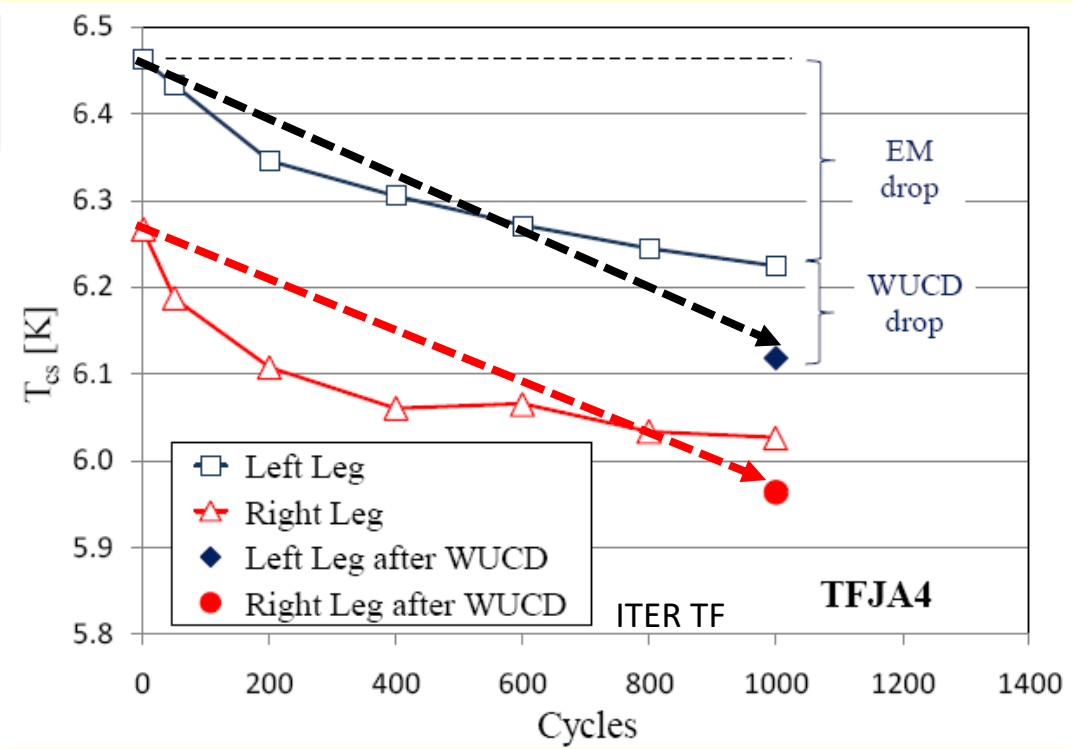
Specimen I: Ic=20.1 kA n=22, ~ 2 kA deviation of predicted Ic
Specimen II: Ic=23.2 kA n=33, ~3 kA deviation of predicted Ic
Specimen III: Ic=22.6 kA n=21, ~1 kA deviation of predicted Ic

No obvious performance degradation observed after the HTS CICC specimens manufacture.

YBCO CICC

Issue:
performance degradation X





[1] P. Bruzzone, LTS and HTS High Current Conductor Development for DEMO, SOFT14
[2] H. Bajas, Multifill simulation for CICC

YBCO CICC

◆DC test plan

- **Tcs：** 40kA, 47kA, 55kA, 60kA, 65kA @ 10.85T, 9T, 7T
- **EM cycles + Tcs：** 47kA, 55kA, 62kA, 69kA,75kA, 80kA，total: 1267 times
- **WUCD +Tcs：** RT & 4.5K，2 times
- **Quench (~15 criterion)：**

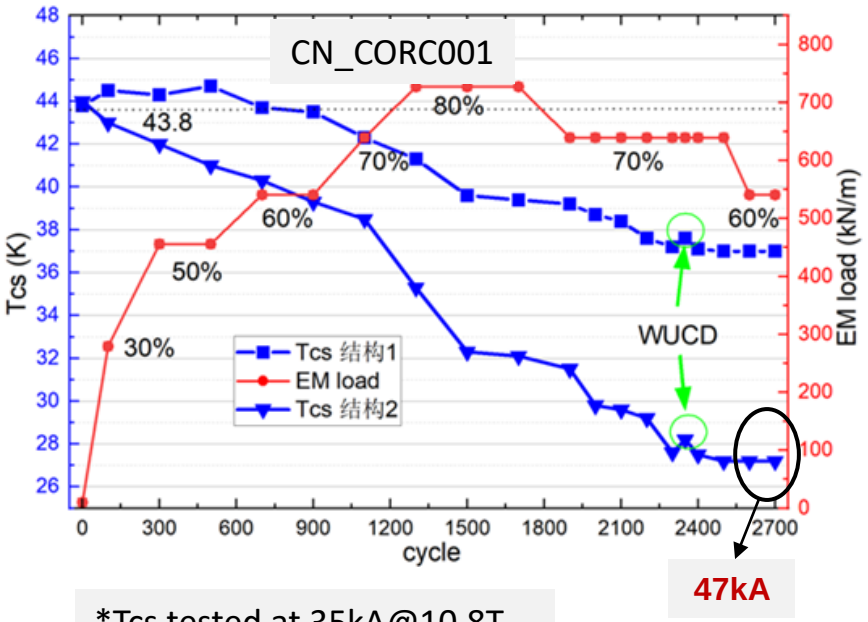
  4 times quench at 10.85T and 47kA/ 55kA/ 60kA/ 65kA

  3 times quench at 10.85T and 80kA

YBCO CICC

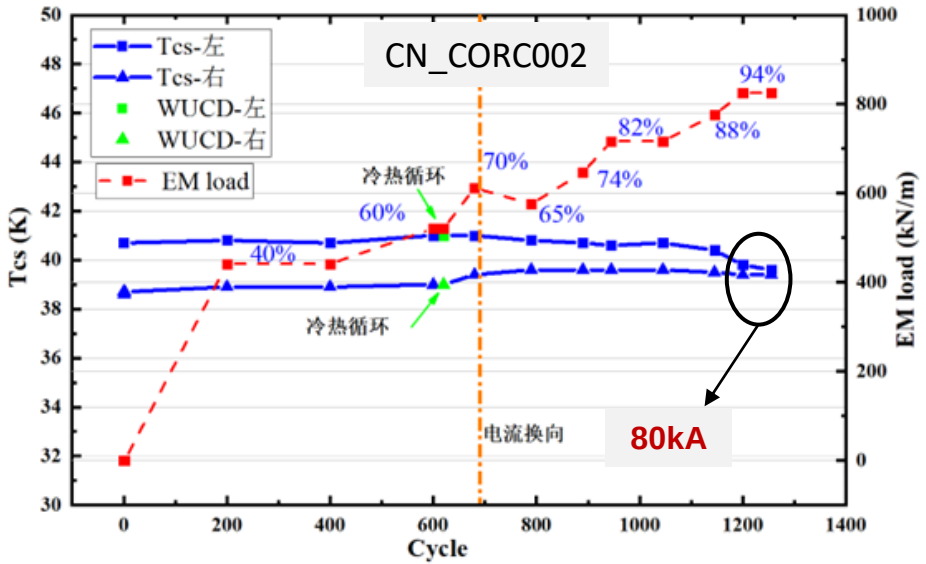
Tested at SULTAN facility: 10.8T, performance is stable for right leg with cyclings.

1st sample （2023.05）



*Tcs tested at 35kA@10.8T

2nd sample --2024.04



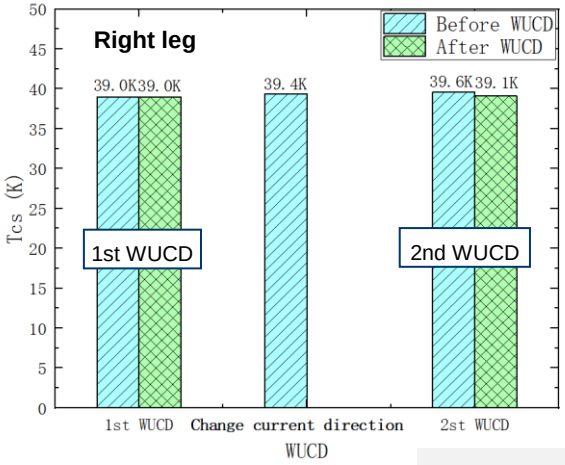
*Tcs tested at 40kA@10.8T

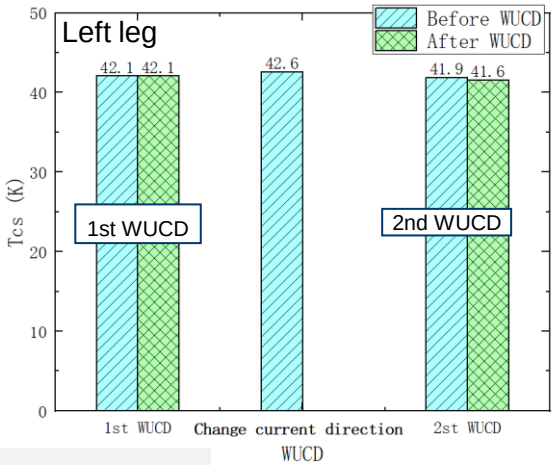
YBCO CICC

☐ WUCD during EM cycling (Tcs @40 kA, 10.85T)

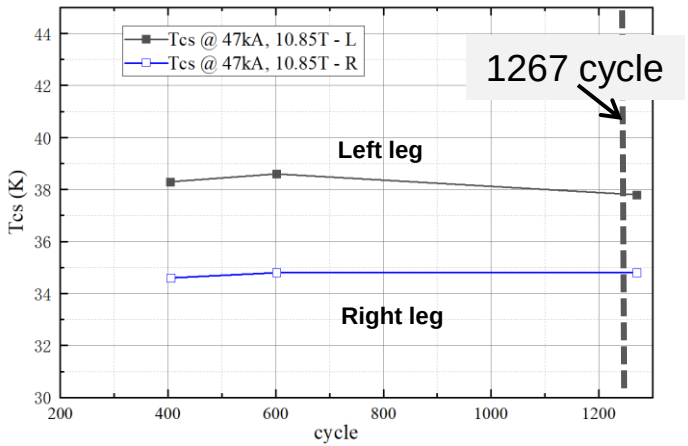
◆ Tcs performance before and after WUCD

- 1st WUCD: After 47 kA cycle
- 2nd WUCD: After 80 kA cycle





*Tcs tested at 40kA@10.8T



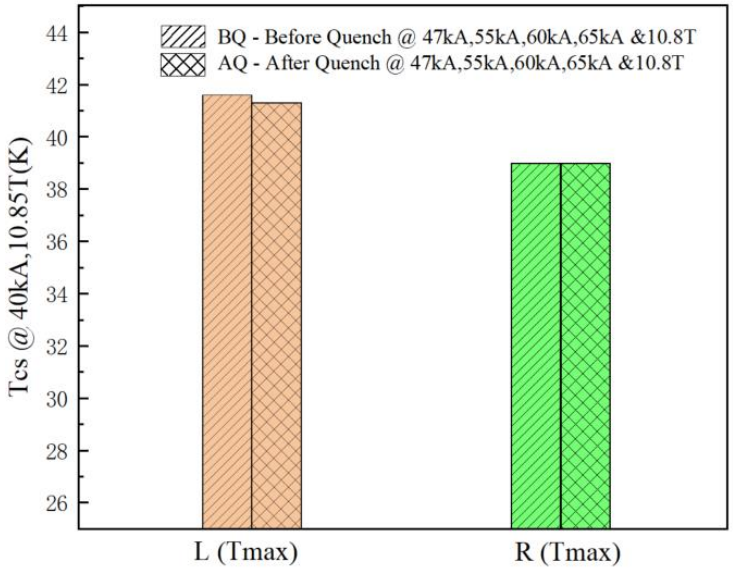
*Tcs tested at 47kA@10.8T

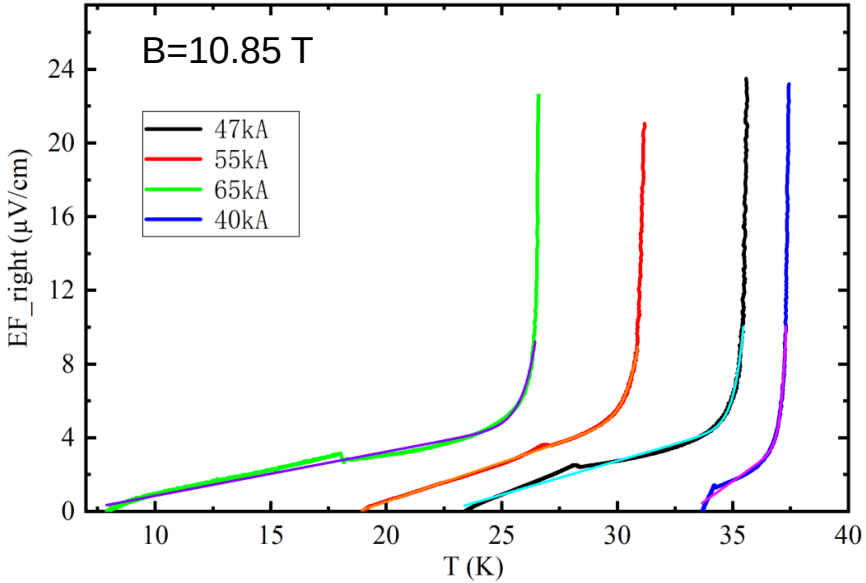
- No obvious degradation for two legs without the effects of WUCD cycling;

YBCO CICC

☐ Quench and Tcs comparison (Tcs @40 kA,10.85T)

◆ Quench criterion：~15 μV/cm



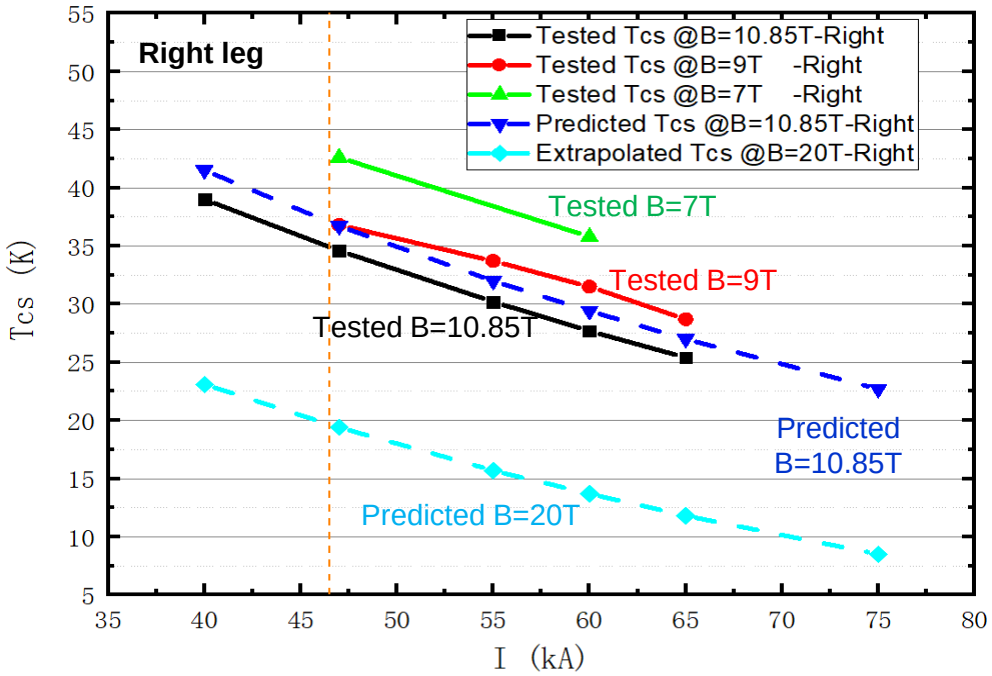


- No obvious degradation for the right leg after quench;
- ~1K degraded for the left leg after quench;

YBCO CICC

☐ Tested and predicted Tcs analysis

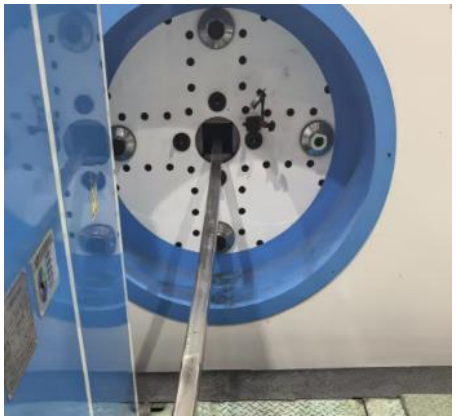
◆ Extrapolated Tcs for BEST CS magnet



- Trends in predicted T_{cs} and tested T_{cs} at 10.85 T are consistent.
- Tcs deviation ~1.5K.
- **Predicted Tcs @ 46.5 kA, 20 T: T_{cs}=18.8 K**

YBCO CICC--Long length conductor

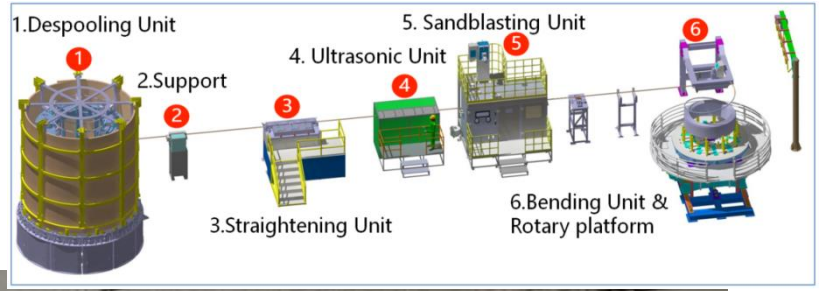
- **The first long conductor with 100m length has been finished. Dummy CICC, but some YBCO tapes inside.**



Samples sectioned for 77K self-field performance checking is on going.

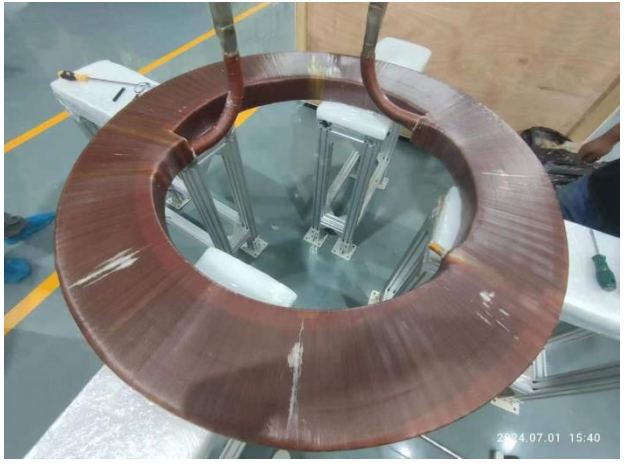
The technology of HTS coil

- **Coil manufacture line has been built.**
- **Full copper dummy coil has been finished.**



Main Plan in 2025

Task	Time schedule
Long length full-size HTS CICC	2025-04
First HTS coil winding	2025-09
First coil testing	2025-12



Bi2212 coil

REBCO & Bi2212

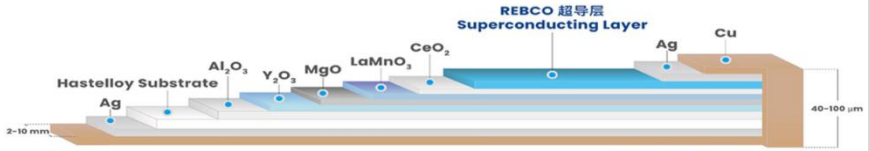
REBCO

Advantage:

- high DC
- no heat treatment

Disadvantage:

- tape, difficult to develop the CICC;
- high loss.



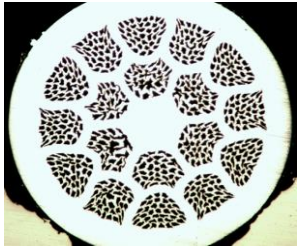
Bi2212

Advantage:

- high field high DC
- similar loss to ITER Nb_3Sn
- Round, suitable for CICC development
- Conductor technology is mature at present scale.

Disadvantage:

- Brittle, easily to be damaged during CICC manufacturing;
- special heat treatment-with O_2, high temperature, and high pressure.



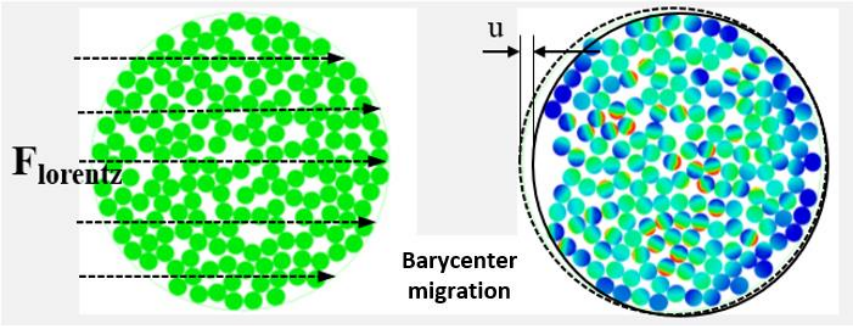
Which one will be successful ?

Bi2212 CICC design

Stability design structurally of Bi-2212 CICC:

Main problem:

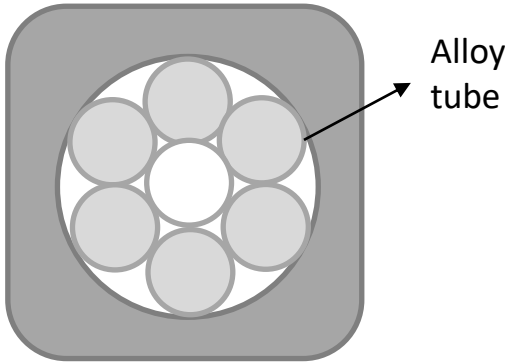
Large EM force cause performance degradation



*From Hugo's publication

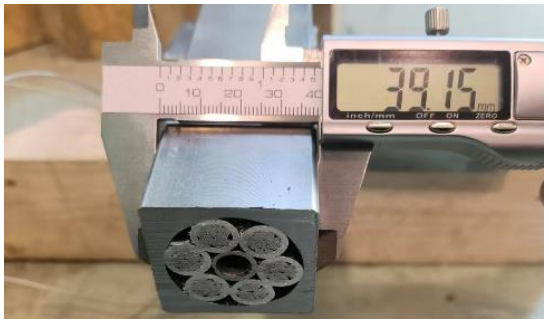
◆ **Structural design of full-size Bi-2212 CICC**

Typical structure of LTS conductor



(Stress Equalization Structure)

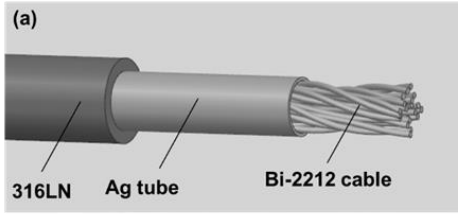
SES-CICC

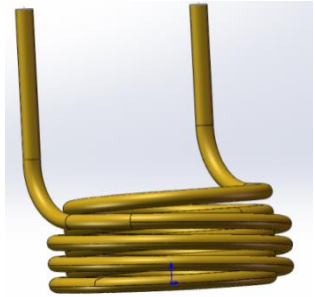


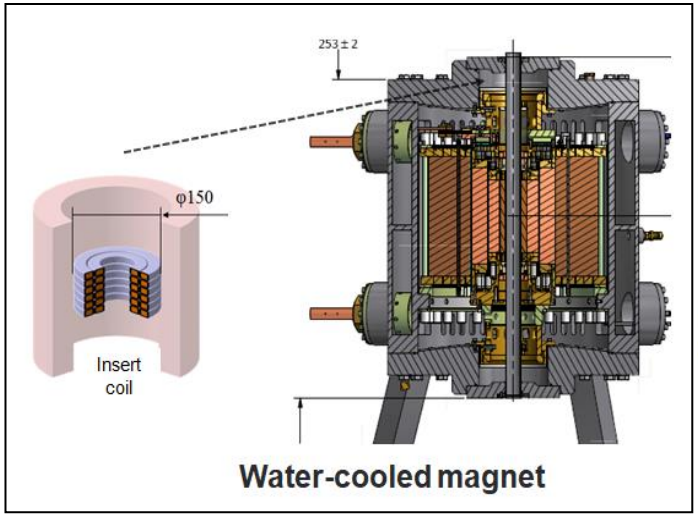
Bi2212 CICC design

◆ Sub-cable

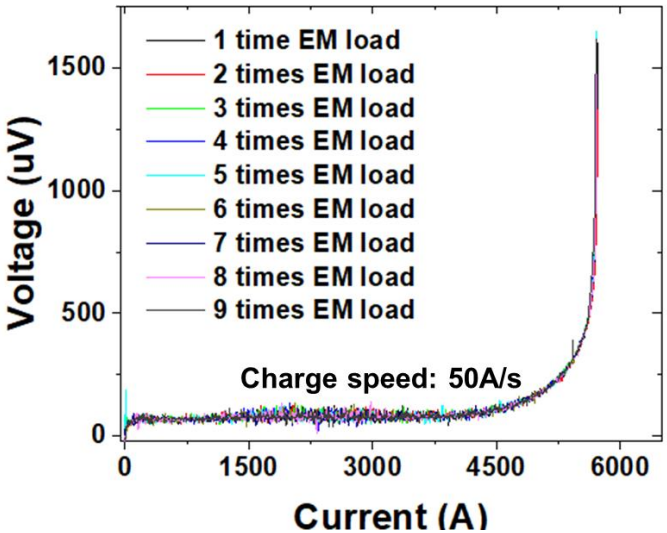
- **Back field: 18T，stable performance under EM cycling**





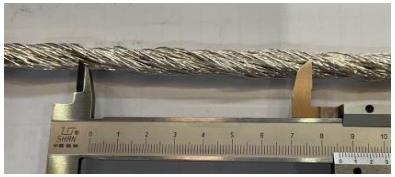


18 T, EM load ~101 kN/m



Current status of preparation for Bi-2212 full-size CICC

Currently, sections of structural design and physical fabrication have been completed !



Cabling of sub-cable

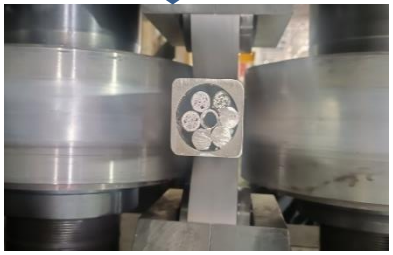
Silver tube compaction

Twisting

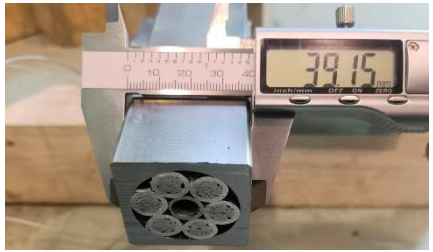
Silver fillers assembly

Silver tape assembly

Jacket assembly



Jacket Compaction



Preparation for heat treatment

Next step: Bi-2212 full-size CICC will be treated thermally and sent to SULTAN lab at the end of March.

Part 03

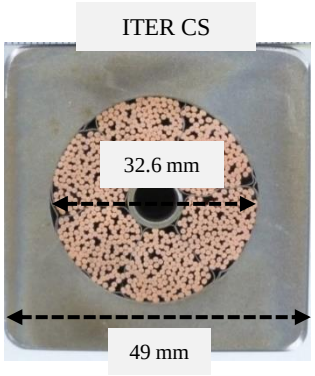
Summary

HTS: good choice and high advantage

- HTS + High strength jacket → more temperature margin, high current density

T_{cs} ~ 6.9K@45kA, 10.8T
(ITER-grade Nb_3Sn)

T_{cs} ~ 7.4K@45kA, 10.8T
(High Jc Nb_3Sn)



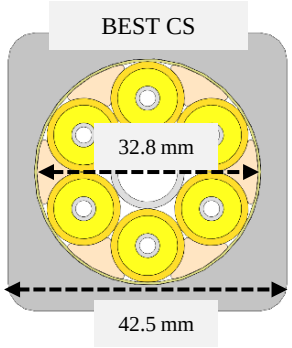
Operating condition：45kA, 13T
Current density：18.7A/mm^2
Strength margin：8.5%

LTS → HTS
316LN → N50
(YS: 1100MPa → 1500MPa)

37%↑

T_{cs} ~ 33.8K@47kA, 10.8T

T_{cs} ~ 17.5K@46.5kA, 20T



Operating condition： 46.5kA, 18.8T
Current density： 25.7A/mm^2
Strength margin： 16.1%

Summary

1. The HTS coil technology was developed for BEST CS;
2. The 2nd HTS CICC sample has been tested successfully in Sultan facility.
3. The HTS is good choice for high field development for future fusion reactor, but it is also big challenge, and the schedule is tight. More collaboration is needed and much better to push it.

Any collaboration is open and welcome!

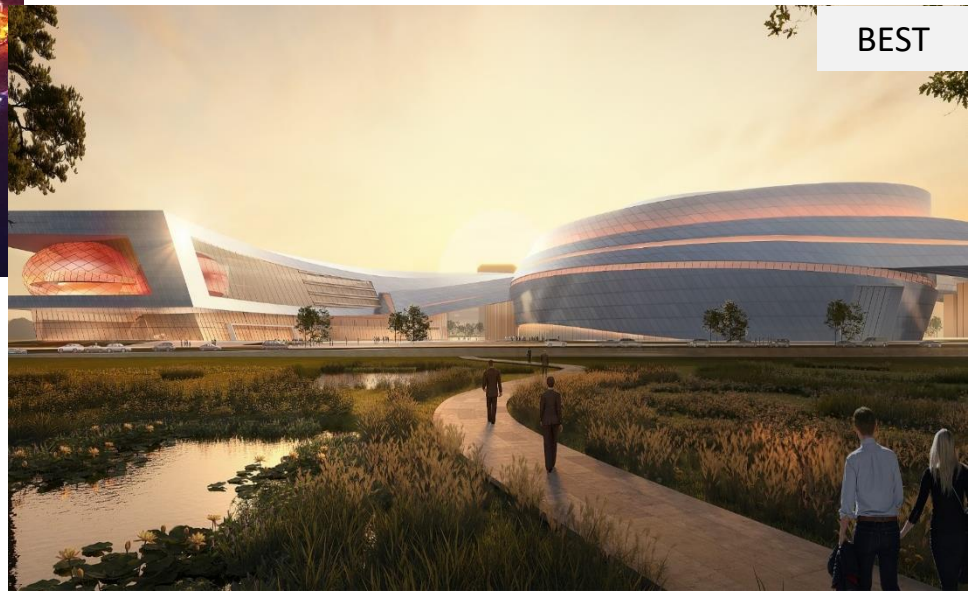
Collaboration is important and necessary

ASIPP, China, November 2023

KIT, Germany, March 2024

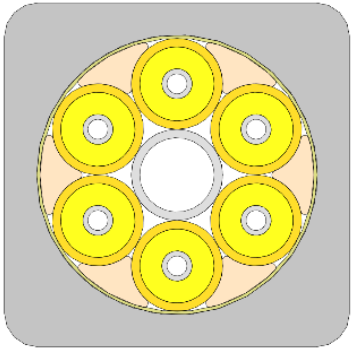
CRAFT

Welcome to ASIPP!



BEST

Thanks a lot for you attention!



Right leg:
copper inside sub-cable

Left leg:
spiral inside sub-cable