IEEE-CSC, ESAS and CSSJ SUPERCONDUCTIVITY NEWS FORUM (global edition), Issue No. 59, May 2025. Presentation given at CCA 2025, March 11-13, 2025, Geneva, Switzerland.

HTS fusion technology status in China

Jinxing Zheng on behalf of China HTS fusion team

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Geneva, Switzerland
12 March 2025

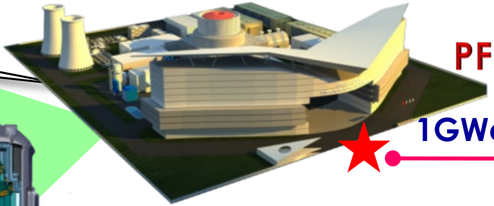
Institute of Plasma Physics, Chinese Academy of Sciences

Outline

IEEE-CSC, ESAS and CSSJ SUPERCONDUCTIVITY NEWS FORUM (global edition), Issue No. 59, May 2025. Presentation given at CCA 2025, March 11-13, 2025, Geneva, Switzerland.

Background of HTS technology for Fusion

1-2GW, 10-20 years engineering life, Secure, stable and tritium self-sustaining



PFPP

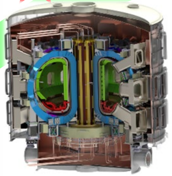
1GWe, electricity generating station

Steady-state long-pulse discharge, tritium breeding, dpa ~20, annual consumption of tritium ~6-10kg

CFETR

I: Q=1-5, steady-state, TBR>1, >200MW, 10dpa

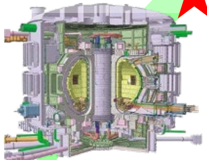
II: DEMO validation, Q>10, CW, 1GW, 50dpa



BEST

50~100MW, Q>1

Demonstration of power generation

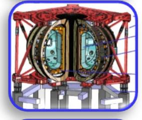


ITER

Phase I : Q=10, 400s, 500MW, Hybrid burning plasma

Phase I I: Q=5, 3000s, 350MW, Steady-state burning plasma

EAST Advanced PFC, advanced steady-state operation mode



HL-2M Advanced divertor, Hign power H&CD

J-TEXT Basic plasma

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Outline

IEEE-CSC, ESAS and CSSJ SUPERCONDUCTIVITY NEWS FORUM (global edition), Issue No. 59, May 2025. Presentation given at CCA 2025, March 11-13, 2025, Geneva, Switzerland.

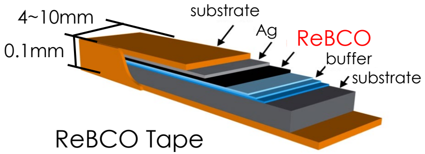
HTS technology development

● Key challenges for safe operation of fusion HTS magnets

—Critical performace, AC loss, Stability and Engineering preparation

ReBCO properties

- ✓ Flat strip structures
- ✓ Ceramic substrate



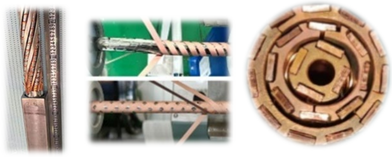
ReBCO Tape

Critical properties under fusion conditions

AC loss assessment and suppression

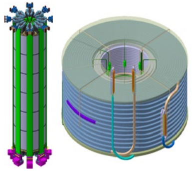
Stability margin evolution mechanism

Fusion high field superconducting magnets



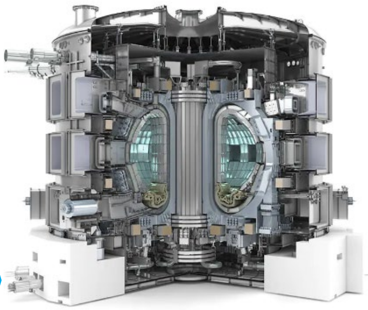
CICC CORC TMMC

HTS Cable



CS magnet

HTS Fusion magnets



China Fusion Engineering Test Reactor (CFETR)

B_{max} ~20T
Fusion Power >GW

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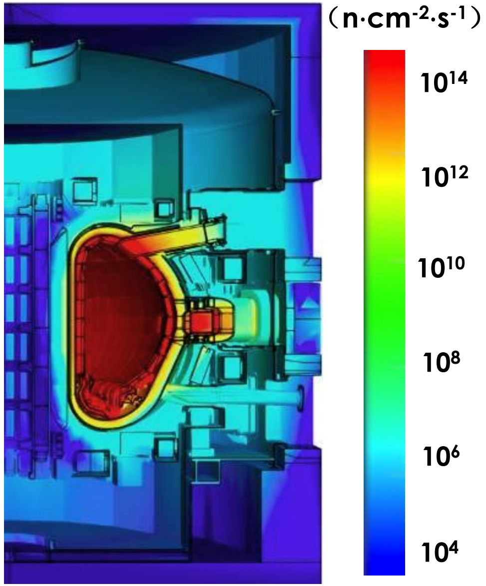
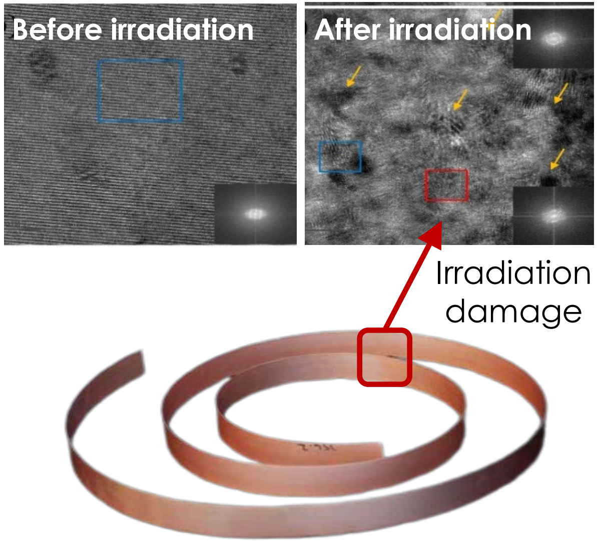
HTS Technology: (1) Critical Performance under Fusion Irradiation

- Neutron radiation produced by the **Fusion D-T reaction** will accumulate in the superconducting magnet, **causing critical performance degradation and affecting the safe operation**



Fusion flux density distribution



Irridation Causes microscopic damage to REBCO materials

TF Magnet peak cumulative dose

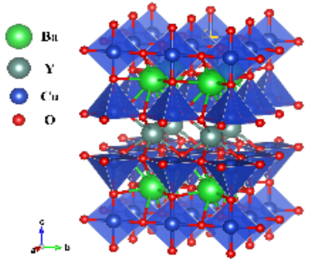
1.41×10^{6}Gy@2.5×10^{25}

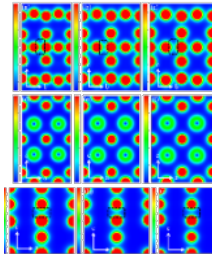
IEEE-CSC, ESAS and CSSJ SUPERCONDUCTIVITY NEWS FORUM (global edition), Issue No. 59, May 2025. Presentation given at CCA 2025, March 11-13, 2025, Geneva, Switzerland.

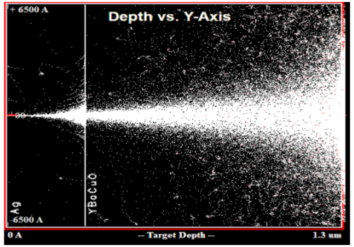
HTS Technology: (1) Critical Performance under Fusion Irradiation

- **Irridiation simulation of REBCO: based on first principles and molecular dynamics simulations.**
  - with appropriate irradiation, oxygen vacancies and lattice distortion are induced, forming effective pinning centers and improving J_c.
- **Irradiation experiments of REBCO: Proton/Gamma-ray/ Neutron irradiation**

Theoretical analysis of irradiation damage in HTS tapes





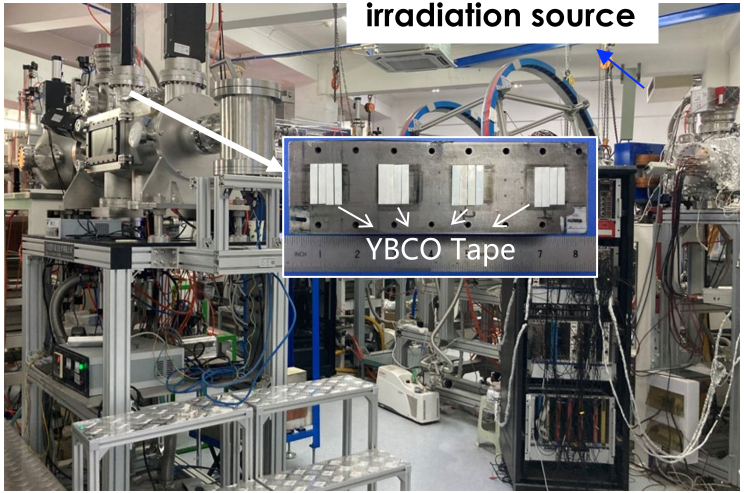


Structural model of YBCO

Particle incidence depth simulation

Irradiation fluence	Thickness of YBCO layer	Radiation damage (*DPA*)
5.0×10^{14} p/cm^2	1.5 μm	2.85×10^{-4}
1.0×10^{15} p/cm^2	1.5 μm	5.70×10^{-3}
2.0×10^{15} p/cm^2	1.5 μm	1.14×10^{-2}

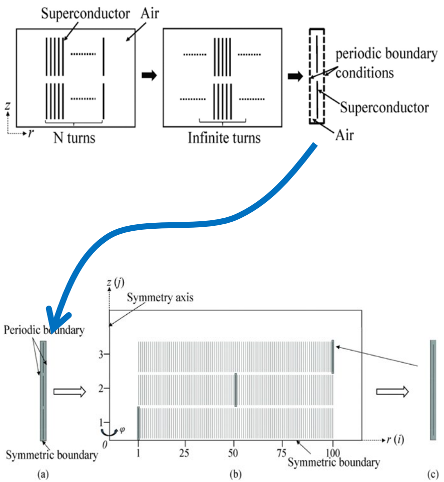
Irradiation Experiment on HTS tapes



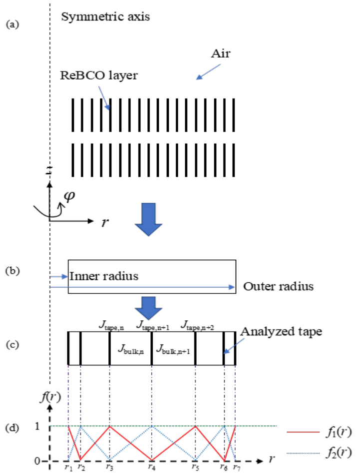
Ying Zheng, **Jinxing Zheng***, et al., Gamma radiation effects on high-temperature superconducting ReBCO tape, Superconductor Science Technology 37 045013, 2024
Ying Zheng, **Jinxing Zheng***, et al., Study on the Applicability of Neutron Radiation Damage Method Used for High-Temperature Superconducting Tape Based on Geant4 and SRIM, Science and Technology of Nuclear Installations, 2021, 2839746.

HTS Technology: (2) AC loss calculation Model

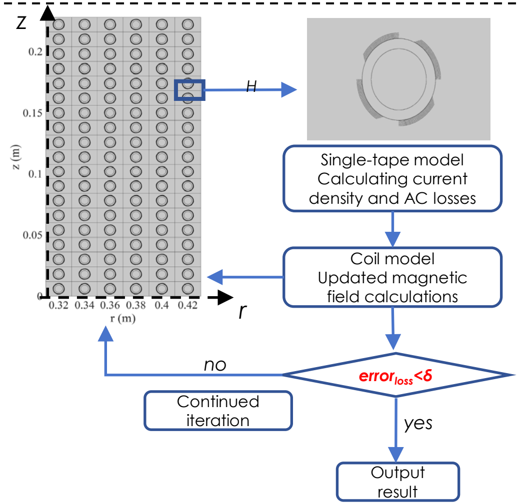
- **3 versions of multi-scale AC loss calculation method: to solve the problems of time-consuming and non-convergence of the AC loss calculation of large-scale HTS magnets**



Multiscale Methods 1.0:
Based on **H models**, Calculate the magnetic field before calculating the single-turn loss



Multiscale Methods 2.0:
Based on **T-A models**, simultaneous calculations, T-equation for losses, A-equation for magnetic field



Multiscale Methods 3.0:
Based on **an iterative computational framework**, multiple iterations to improve accuracy

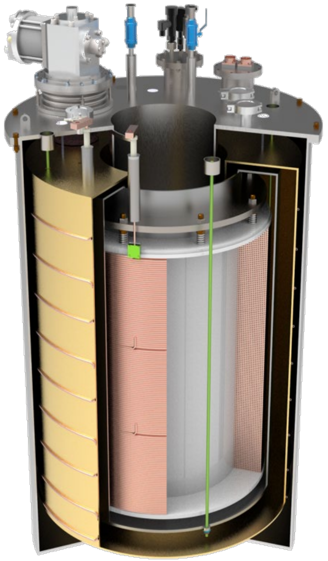
Lei Wang, **Jinxing Zheng*** et al., *Development of Multi-scale Model in Large-scale HTS Coils with Improved Coupling, IEEE TAS*, 29(6), 4702207, 2019.
Lei Wang, **Jinxing Zheng*** et al.,Real-Time Electromagnetic Simulations of Large-Scale REBCO Solenoid Coils by Combination Model, *IEEE TAS*,34(2), 4300207, 2024

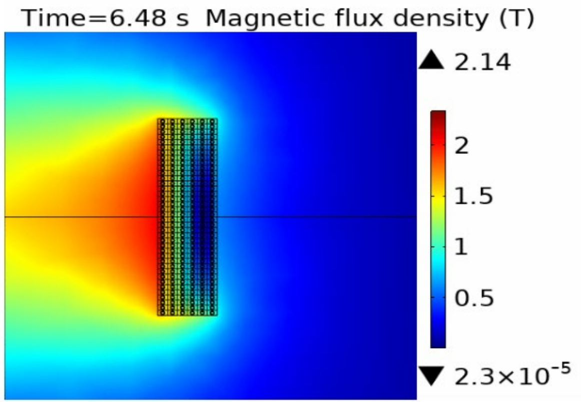
HTS Technology: (2) AC loss calculation Model

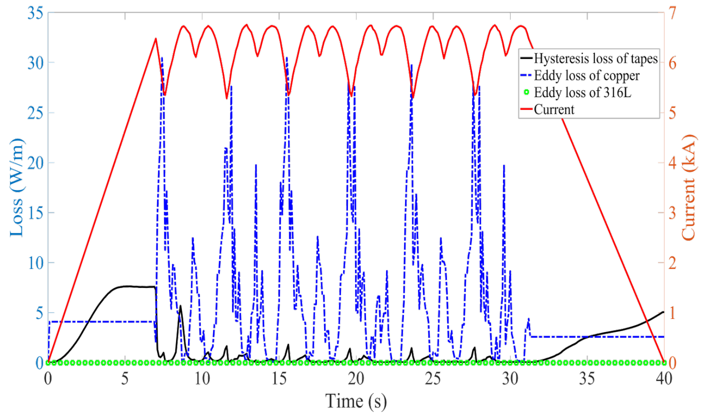
- **Applications and advantages of multiscale methods: can be applied to both 2D and 3D calculations, dramatically improving computational efficiency with high accuracy**

✓ **AC loss calculation of solenoid coil prepared with HTS spiral-wound conductor (like CORC)**

✓ **Compared with other computational methods:** Higher solution accuracy and faster computation time



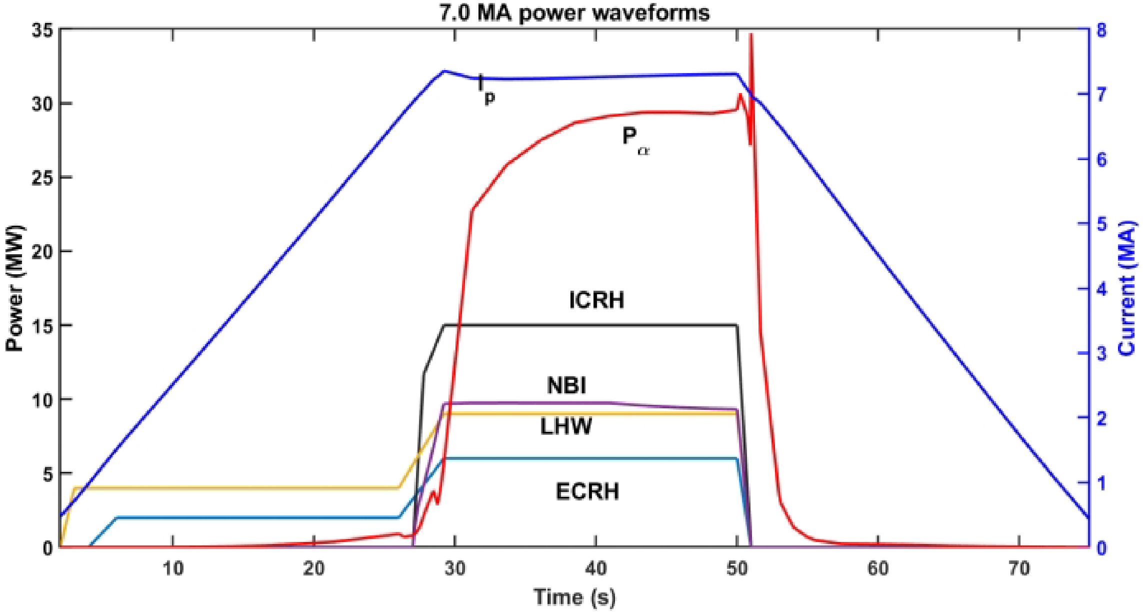




Lei Wang, ***Jinxing Zheng**** , *Comparative Study of Four Finite-Element Models for Electromagnetic Simulations of Large-Scale REBCO Coils Using Homogenization Technique, IEEE Transactions on Applied Superconductivity*, 34(3), 4902605, 2024.

HTS Technology: (3) Stability Analysis Model

- Systematic stability model is established, it can realize accurate **AC loss and Nuclear heat loading, achieving 0.01 K high-precision temperature margin calculation**



Nuclear Heat of BEST Fusion device with 130 MA Fusion Power

Technical Difficulties:

- ☐ Dynamic AC loss and Nuclear Heat Deposition
- ☐ Location to calculate minimum Temperature Margin
- ☐ 0.01 K ΔT accuracy and 1 mm position accuracy

Yudong Lu, **Jinxing Zheng***, et al, An improved analysis method for assessing the nuclear-heating impact on the stability of toroidal field magnets in fusion reactors Nuclear Science and Techniques, 35(6): 96 2024

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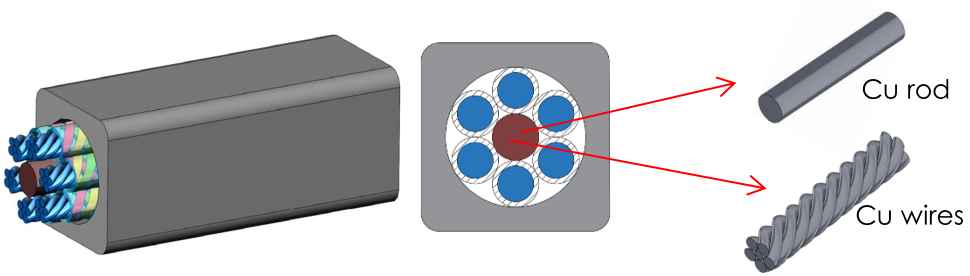
HTS Technology: (3) Stability Analysis Model

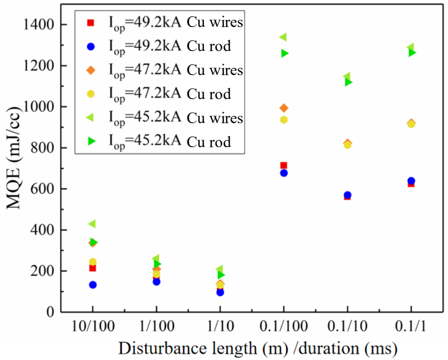
- **Established stability analysis model is used to calculate temperature margin of ReBCO conductors for fusion reactor high-field environments**

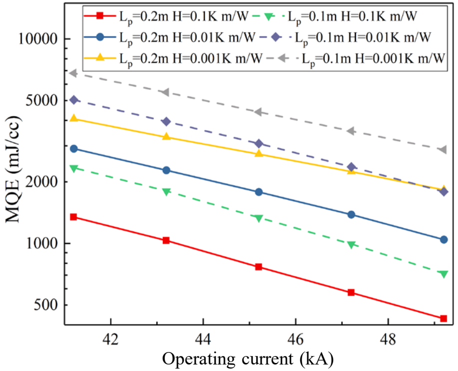


Schematic of REBCO conductor and Different Centre Skeleton (Cu wires and Cu rod)

The main parameter of REBCO conductor

Maximum operating current (kA)	49.2
Peak magnetic field (T)	14.32
Operation temperature (K)	4.2
CORC diameter (mm)	10.4
Cable diameter (mm)	32
Centre Skeleton Diameter (mm)	8





The MQE calculations for the conductors were completed quickly and accurately.

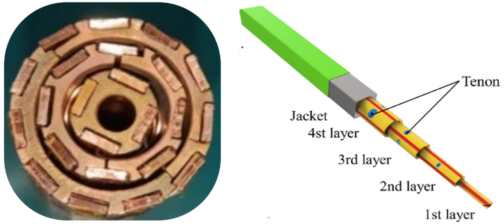
IEEE-CSC, ESAS and CSSJ SUPERCONDUCTIVITY NEWS FORUM (global edition), Issue No. 59, May 2025. Presentation given at CCA 2025, March 11-13, 2025, Geneva, Switzerland.

HTS Technology: (4) HTS Conductor

- **HTS conductors are the only option for realizing 15 T to 20 T class magnetic fields**
  - ✓ Many kinds of HTS conductor structures have been proposed in China

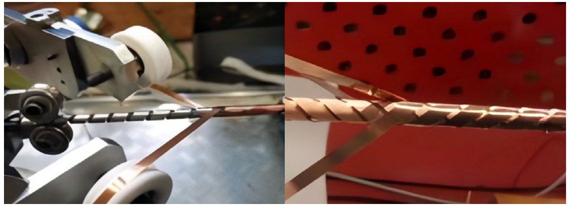
Institute of Plasma Physics, Chinese Academy of Sciences

CORC with variable winding angles, 10kA@10K，self-field



The Tenon-mortise-based modularized conductor (TMMC) , 10.8kA@77K, SF

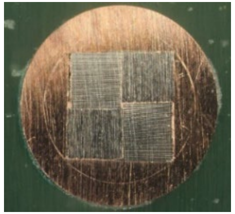
Hefei International Applied Superconductivity Center and Institute of Plasma Physics



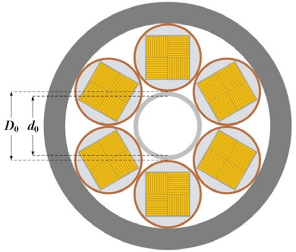
Highly Flexible ReBCO Cable
Ic~10.6kA @4.2K，20T

CORC-CICC, 6kA@4.2K，21T

North China Electric Power University



Quasi-isotropic conductors,
2.3 kA@77K, self-field

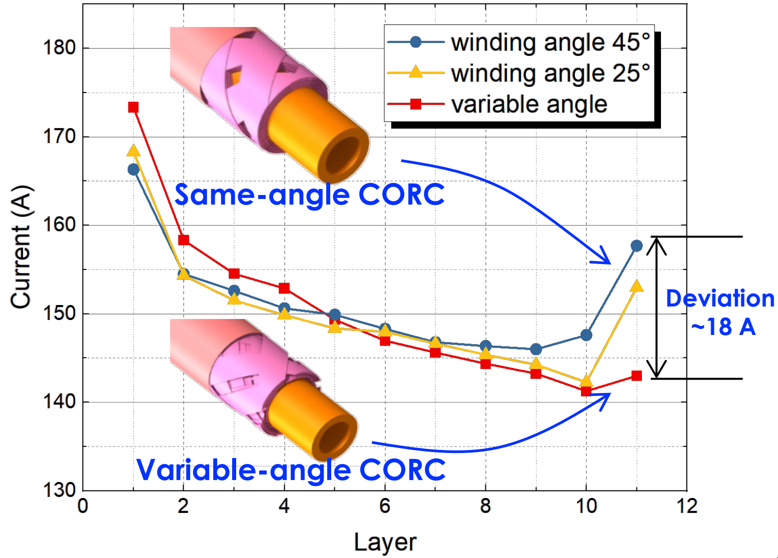


Q-IS-CICC
20 kA@77K, 0.5T

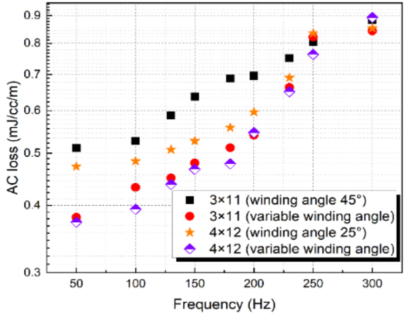
HTS Technology: (4) HTS Conductor (variable-angle CORC)

- **The variable-angle CORC optimise current distribution and reduce the current sharing of the outer tapes by adjusting the winding angle of each tape layer, thus significantly reducing overall losses**

✓ **The reduction of current flowing through the outermost tapes.**



✓ The CORC cable with variable winding angles **achieves 31% loss reduction**



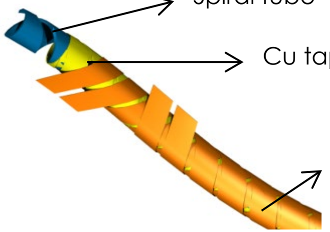
AC losses of four structural conductors at different frequencies (50 mT)

Winding angle	layers	Ac loss	Reduction
45°	3×11	0.41mJ/cycle/m	31%
variable	3×11	0.28 mJ/cycle/m	

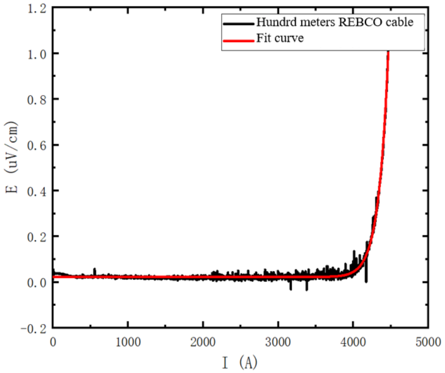
Jinxing Zheng* et al, High temperature superconducting CORC cable with variable winding angles for low AC loss and high current carrying SMES system, 36, 115032, 2023

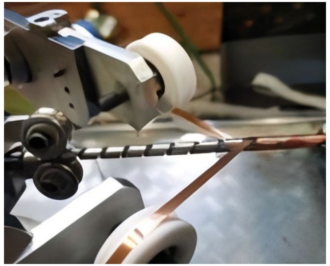
HTS Technology: (4) HTS Conductor (HFRC and CORC-COCC)

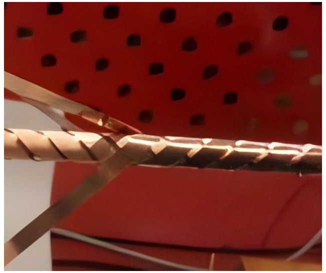
- **Highly Flexible REBCO Cable （HFRC） : use spiral tube as the mandrel to wind the REBCO tapes**
- **Full size CORC-CICC conductor sample have been manufactured and tested at Sultan lab**



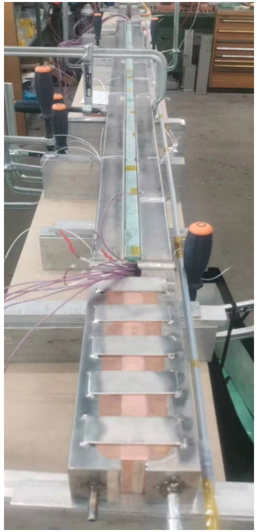
Highly Flexible REBCO Cable（HFRC）

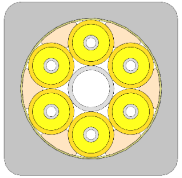


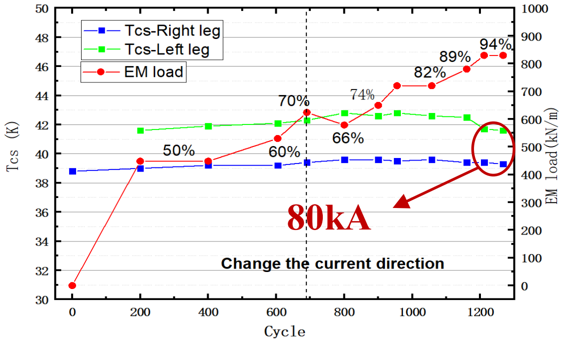




Hundred meters cable
Ic~4468 A，n=34.1@77K，SF







Tests carried out for performance verification
- ✓ 1266 EM cycles
- ✓ 2 WUCD (RT-4.5K) cycles
- ✓ Quench campaigns @ **47kA, 55 kA, 60kA&65kA**

Huan Jin, et al.,Bending performance analysis on YBCO cable with high flexibility, Superconductivity, 7, 100054, 2023

IEEE-CSC, ESAS and CSSJ SUPERCONDUCTIVITY NEWS FORUM (global edition), Issue No. 59, May 2025. Presentation given at CCA 2025, March 11-13, 2025, Geneva, Switzerland.

HTS Technology: (4) HTS Conductor (New TMMC)

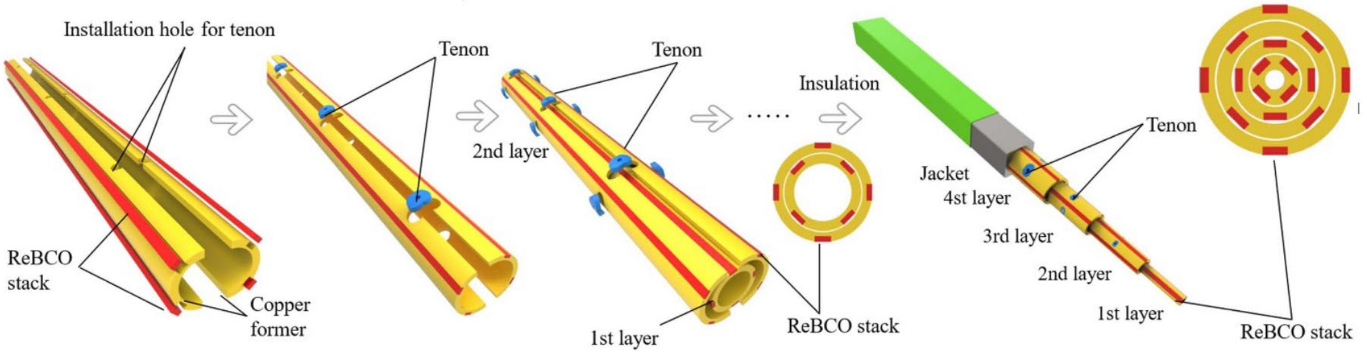
- **The New Tenon-mortise-based modularized conductor (TMMC) is designed for reducing AC loss and increase current capacity**

✓ Outer layer provide **shielding effects** to inner layers.

✓ The two adjacent sub-conductors are assembled with the full-disaligned configuration to **reduce AC losses**.

Chinese ancient architecture

Mortise and tenon



Step 1：cooper former and REBCO stack

Step 2：Install tenon to complete the first layer

Step 3：Complete the assembly of the second layer

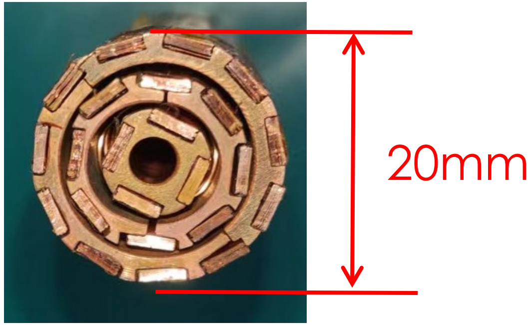
TMMC cable (45° arrangement for sub-conductor)

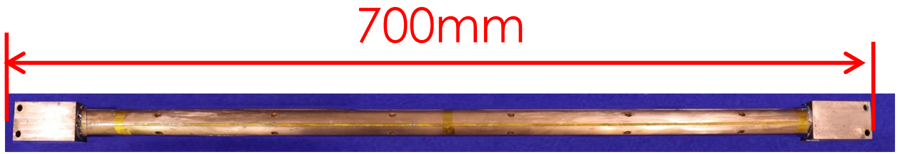
Jinxing Zheng* et al., A newly developed 10 kA-level HTS conductor: innovative tenon-mortise-based modularized conductor (TMMC) based on China ancient architecture, Superconductor Science and Technology, 37, 056006, 2024

IEEE-CSC, ESAS and CSSJ SUPERCONDUCTIVITY NEWS FORUM (global edition), Issue No. 59, May 2025. Presentation given at CCA 2025, March 11-13, 2025, Geneva, Switzerland.

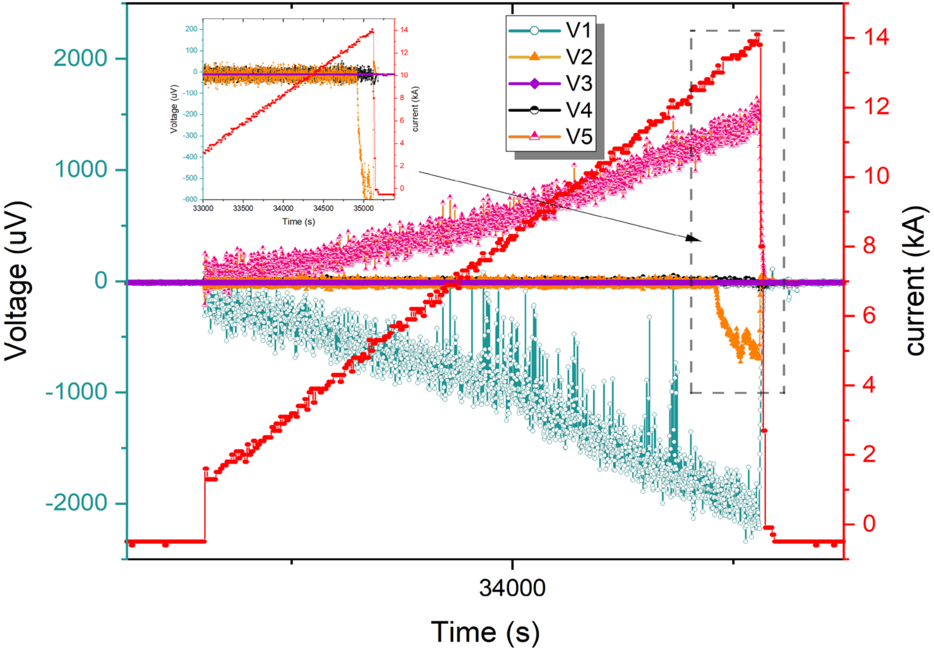
HTS Technology: (4) HTS Conductor (New TMMC)

- The **TMMC conductor** is manufactured and tested at 77K, **Ic=13.69 kA@77K,SF.** Engineering critical current density is **18.1 A/mm²**





3-layer TMMC conductor

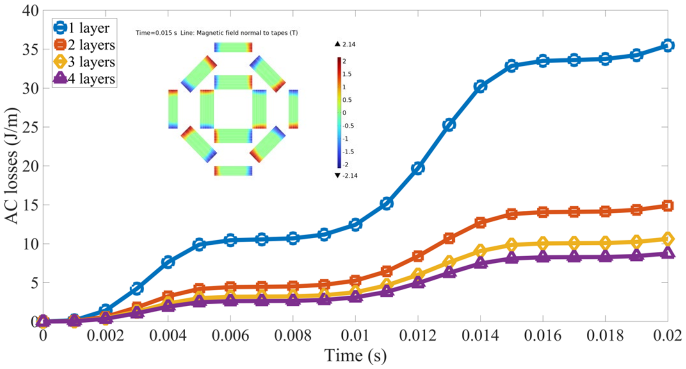


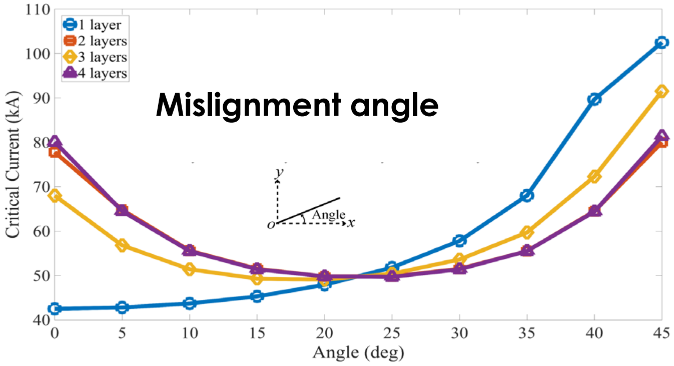
Ic Test of TMMC conductor with liquid nitrogen
13.69 kA@77K, Self-field

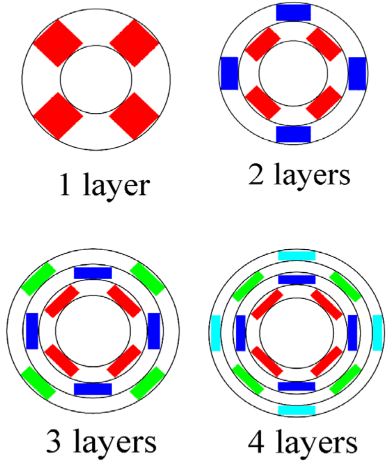
Jinxing Zheng* et al., A newly developed 10 kA-level HTS conductor: innovative tenon-mortise-based modularized conductor (TMMC) based on China ancient architecture, Superconductor Science and Technology, 37, 056006, 2024

HTS Technology: (4) HTS Conductor (New TMMC)

- **Design and Preparation process optimization to improve Engineering J_c of TMMC**
  - ✓ Change the number of layers and mislignment angle to reduce AC loss
  - ✓ Reduce the thickness of former and increase the density of HTS stacks







Jinxing Zheng* et al., A newly developed 10 kA-level HTS conductor: innovative tenon-mortise-based modularized conductor (TMMC) based on China ancient architecture, Superconductor Science and Technology, 37, 056006, 2024

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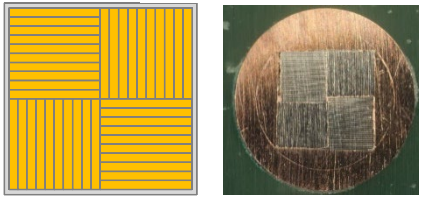
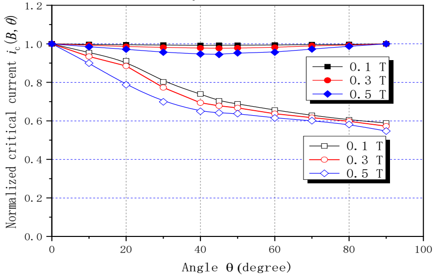
HTS Technology: (4) HTS Conductor (Quasi-isotropic HTS Strands)

- **Development of CICC made from Quasi-isotropic HTS Strands**

Q-IS

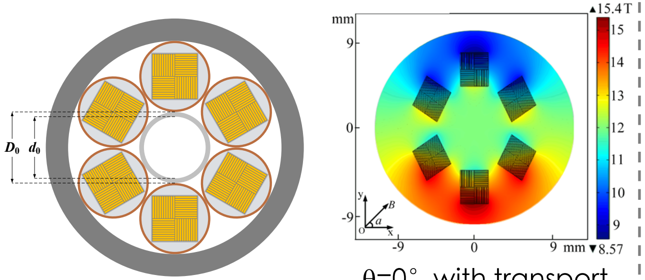


Quasi-isotropic HTS Strands



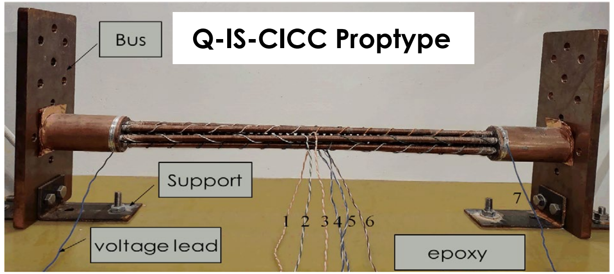
Better critical characteristics at different angles of the external magnetic field

Q-IS-CICC



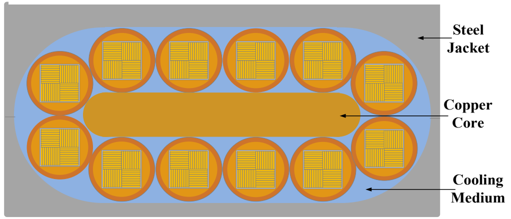
Q-IS-CICC

θ=0° with transport 236.76kA@12 T

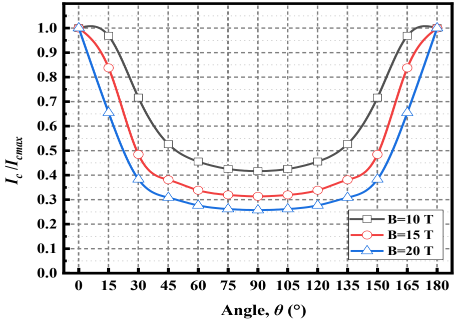


Tested Ic=12.5kA@1.5T,77K

Q-IS-Rutherford Cable



Q-IS-Rutherford Cable



Designed Critical current at 4.2K

#This work is form North China Electric Power University

Cheng Junhua, et al, IEEE Trans. Appl. Supercond.,35(5): 4800608(8pp), 2025.
He Ye, et al, IEEE Trans. Appl. Supercond. 35(5): 4800207(7pp), 2025.

Outline

IEEE-CSC, ESAS and CSSJ SUPERCONDUCTIVITY NEWS FORUM (global edition), Issue No. 59, May 2025. Presentation given at CCA 2025, March 11-13, 2025, Geneva, Switzerland.

China Fusion Engineering Test Reactor (CFETR)

Participation in ITER

1.PF6 Magnet manuface
2.TF conductor development
3.100% CC coil development
4.100% Feeder development
5.CC & Feeder Conductors
6.TF magnet support
7.Power supply system

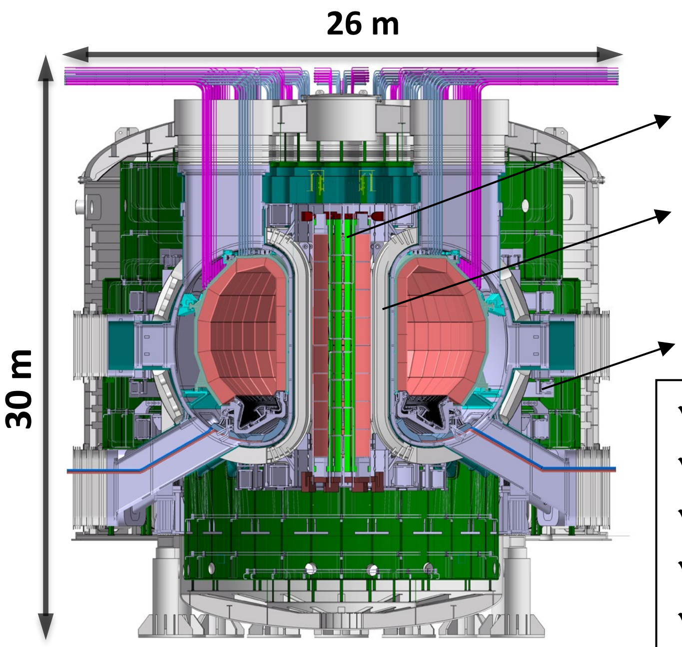
CFETR Engineering design

1.3 years conceptual design (2012~2014)
2.7 years engineering design (2015~2021)

CRAFT construction

1.HTS conductor
2.TF protype manufacture
3.CSMC and testing facility
4.SC conductor testing facility
5.SC material testing facility
6.SC magnet testing facility

- Explore and master fusion DEMO level key technologies
- Establish the method and standard for CFETR development



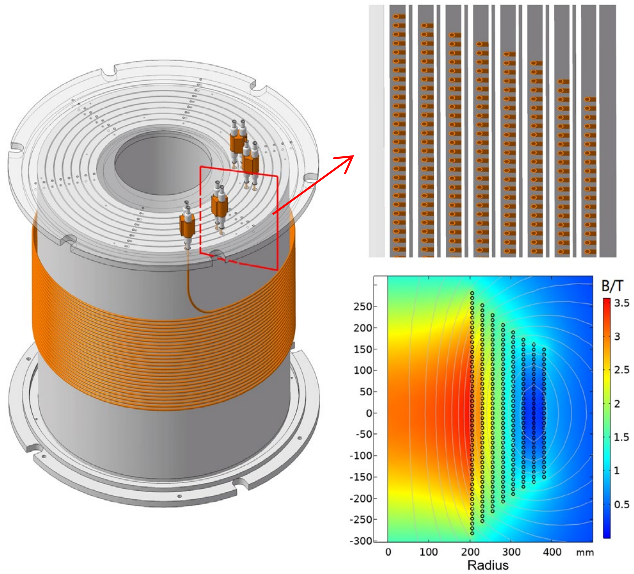
China Fusion Engineering Test Reactor

- ✓ Fusion power ~ 1000 MW
- ✓ Plasma Ip=11~15MA,
- ✓ R=7.2 m,
- ✓ B_t=6.5T;
- ✓ Safe and stable, realize long-pulse steady-state operation;

Development of HTS Solenoid Coil in ASIPP

● High current capacity HTS solenoid coil with forced-flow cooling

- ✓ 8 sub-solenoid coils assembled coaxially and connected in series.
- ✓ It is cooled by forced-flowing cooling with high cooling efficiency.



The conductor arrangement inside solenoid coil and magnetic field distribution

Main parameters of solenoid coils

Parameter	Value
Operating current	6 kA
Layers in radial direction	8
Height of coil	985 mm
Inner/Outer diameter of coil	194.5mm/415.5mm
Total length of tapes	20.58 km
Inductance	28.21mH
Cooling	Forced-flow with supercritical helium

Solenoid coil

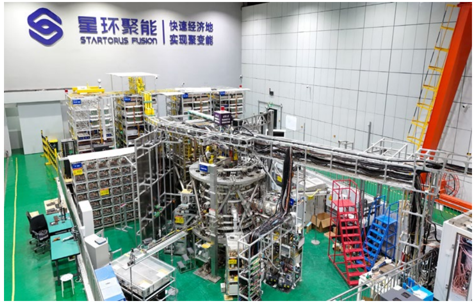
Jinxing Zheng, et al., *Engineering Design of 1 MJ HTS SMES System With kA-Level Current Capacity for NICA Accelerator, IEEE TAS*, 34(8), 4606405, 2024
Ming Li, **Jinxing Zheng**, et al., Engineering Design of Forced-Flow Cooling HTS Cable for SMES System With High Current Capacity, *IEEE TAS*, 34(5), 5700105, 2024

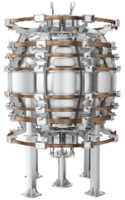
IEEE-CSC, ESAS and CSSJ SUPERCONDUCTIVITY NEWS FORUM (global edition), Issue No. 59, May 2025. Presentation given at CCA 2025, March 11-13, 2025, Geneva, Switzerland.

Startorus Fusion HTS Fusion Device

- **Startorus Fusion is located in Xi'an, China, and is dedicated to the commercial application of fusion energy and the development of related technologies.**

2022-2024



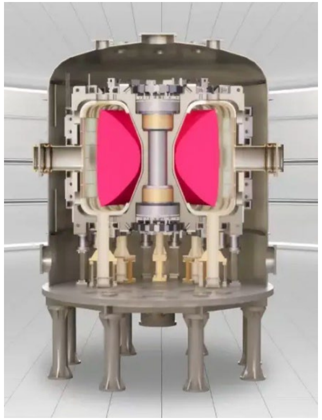


SUNIST-2: copper
Startorus Fusion &
Tsinghua University

Initial engineering validation

2024-2025

NTST: LN cooled copper Startorus Fusion



Current Position

$0.8<\delta<0.8$

R_0: 0.72 m

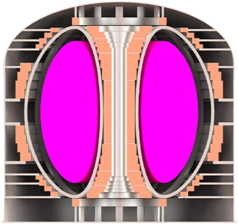
a: 0.4 m

κ: 2.2

B_T: 1 T

Negative triangularity exploration and cryogenic operation

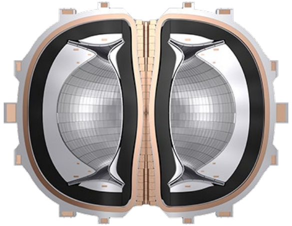
2024-2027



CTRFR-1: HTS
Startorus Fusion

Full engineering verification

2027-2030



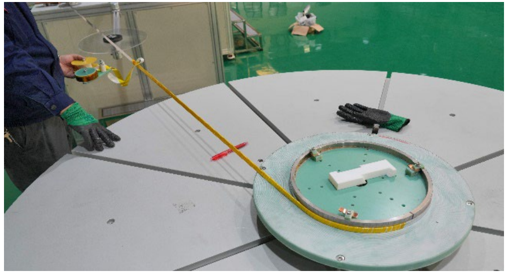
CTRFR-2: HTS
Startorus Fusion

Demonstration fusion power plant

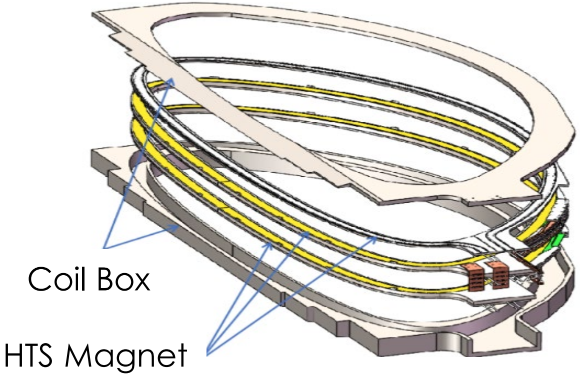
IEEE-CSC, ESAS and CSSJ SUPERCONDUCTIVITY NEWS FORUM (global edition), Issue No. 59, May 2025. Presentation given at CCA 2025, March 11-13, 2025, Geneva, Switzerland.

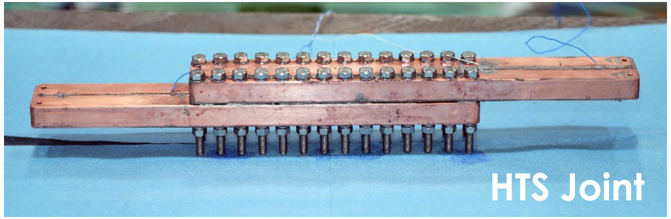
Startorus Fusion HTS Fusion Device

- **R&D of HTS magnets**
  - ✓ 3 T D-shaped TF magnets for next step spherical tokamak
  - ✓ Ultra compact CS magnets for next step spherical tokamak



Compact CS magnets





D-shaped TF magnets

Energy singularity HTS Fusion Device

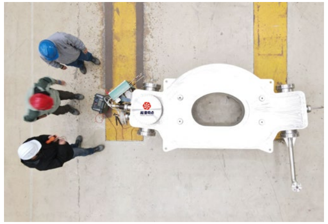
- **Energy Singularity built and operated first all HTS tokamak—HH70**
  - ✓ HH70 was built and operated in 2024, all-HTS tokamak, validated and demonstrated HTS application in fusion device.

HH70

R_0 0.75m

B_0 1T, B_{max} 3.1T

the world's first HTS tokamak



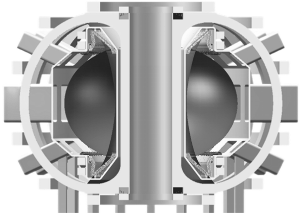
Jingtian magnet

$B_{coil} \geq 25T$

$J_e \geq 180MA/m^2$

to retire risk for HH170 TF magnet

2025 estimate



HH170

R_0 1.65m

B_0 10T, B_{max} 25T

the most economic tokamak to achieve $Q_{DT}^{eq} \geq 10$

2027 estimate

HH380 D-D Reactor

R_0 3.8m, B_0 12T, B_{max} 29T

$P_{electric}$ 500MWe, P_{fusion} 1.3GW

to demonstrate electricity production

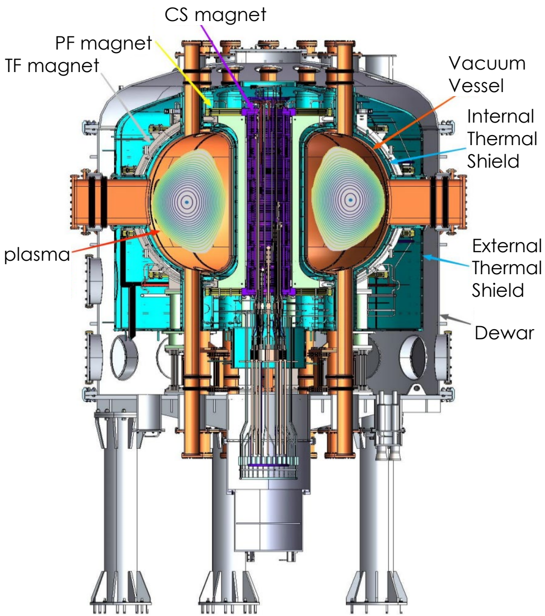
early 2030s

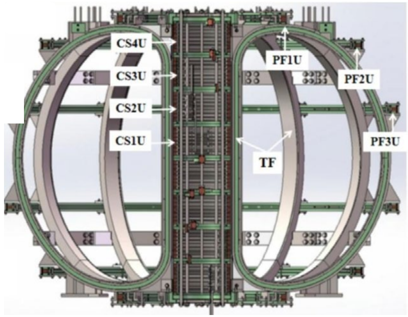
Li Z Y, Pan Z C, Zhang Q J, et al., Development and construction of magnet system for world's first full high temperature superconducting tokamak, Superconductivity. 12, 100137, 2024.

IEEE-CSC, ESAS and CSSJ SUPERCONDUCTIVITY NEWS FORUM (global edition), Issue No. 59, May 2025. Presentation given at CCA 2025, March 11-13, 2025, Geneva, Switzerland.

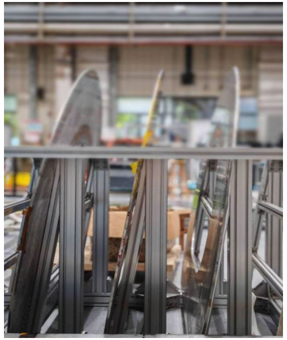
Energy singularity HTS Fusion Device

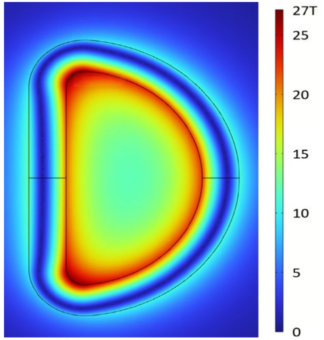
- **HH70 supports the next generation HH170 R&D of the Energy Singularity**
- **“ Jingtian ” magnets are currently being developed with a target: Bmax≥ 25T**

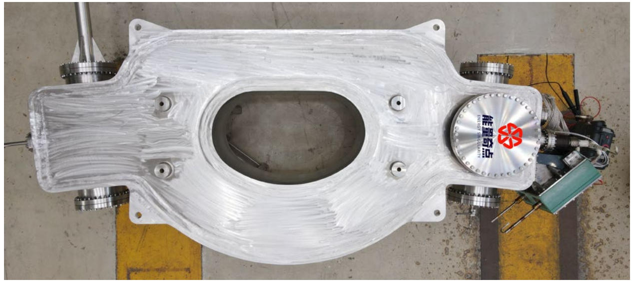




HH70 HTS Tokamak





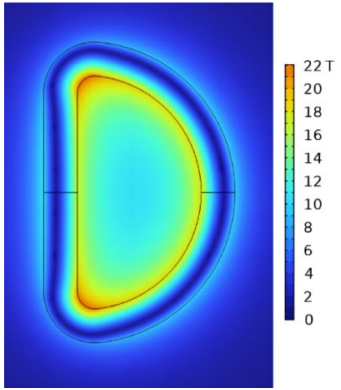


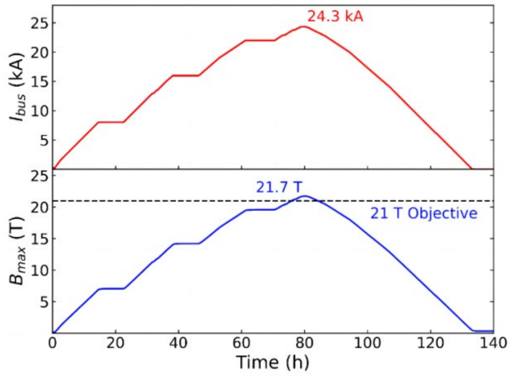
Jingtian HTS magnet

IEEE-CSC, ESAS and CSSJ SUPERCONDUCTIVITY NEWS FORUM (global edition), Issue No. 59, May 2025. Presentation given at CCA 2025, March 11-13, 2025, Geneva, Switzerland.

Energy singularity HTS Fusion Device

- “ Jingtian ” magnets has generated a magnetic field of up to **21.7 T** in the first round of through-flow experiments, **setting a record for the highest magnetic field in a large-aperture, HTS D-shaped magnet.**





“Jingtian” magnet was energized with a current of **24,300 A**. The total number of ampere-turns in the magnet reached **9,260,000 a-t**, and the J_{ce} of the winding reached **157 million A/m²**.

IEEE-CSC, ESAS and CSSJ SUPERCONDUCTIVITY NEWS FORUM (global edition), Issue No. 59, May 2025. Presentation given at CCA 2025, March 11-13, 2025, Geneva, Switzerland.

Other HTS Application: (1) Superconducting motor

- Based on fusion superconducting magnet technology, successfully developed **HTS motor in aircraft propulsion** (98% efficiency, heat leakage <5W)
- Assembled with the **UAV "LQ-H"** and accomplished **flight verification**

✓ 98% efficiency,
✓ Heat leakage <5W

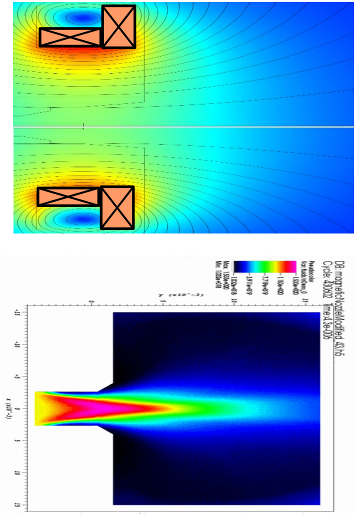
Flight verification (Flight altitude ~500m，Total weight: ~150kg)

Zheng J X*, et al., Flight verification of cooling self-sustaining high-temperature superconducting motor, *Superconductor Science Technology* 37 07LT02, 2024
Sun JX, **Zheng JX***, et al., *Design of Axial Flux HTS Machine Prototype and AC Losses Calculation, IEEE Transactions on Applied Superconductivity*, 33(8), 5203906, 2023

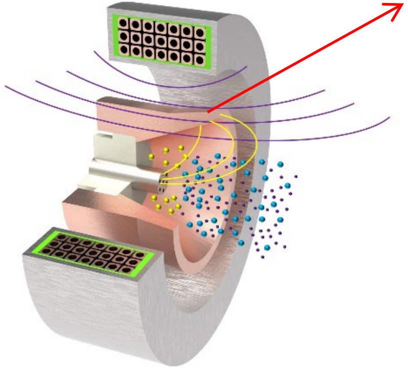
IEEE-CSC, ESAS and CSSJ SUPERCONDUCTIVITY NEWS FORUM (global edition), Issue No. 59, May 2025. Presentation given at CCA 2025, March 11-13, 2025, Geneva, Switzerland.

Other HTS Application: (2) Superconducting MPDT

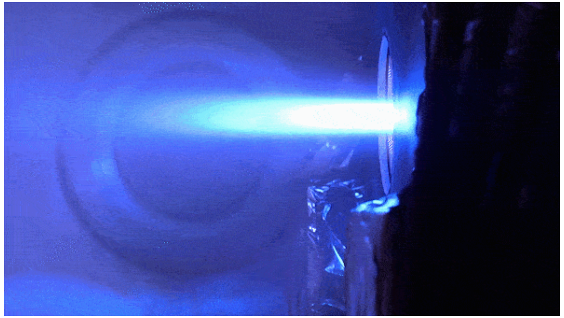
- **Based on the high precision gradient field superconducting magnetic potential control technology, the 100 kW SC magnetoplasmadynamic thruster (MPDT) has been successfully developed**



Gradient field magnetic potential optimization



Superconducting magnet



- **Specific impulse>6000s**
- **Thurst>5.0N**
- **Efficiency>70%)**

Aftab H, **Zheng JX***, et al., Exploring efficiency in next generation high temperature superconducting-enhanced applied field magnetoplasmadynamic thrusters: A combined numerical and experimental study, *Acta Astronautica* 223 448-61, 2024

Liu HY, **Zheng JX***, et al., Research on the Gradient-Field Superconducting Magnet for Magnetoplasmadynamic Thruster Performance Improvement, *IEEE TPS*.,50(12), 2022

Zheng JX*, et al, Integrated Study on the Comprehensive Magnetic-Field Configuration Performance in the 150 kW Superconducting Magnetoplasmadynamic Thruster, Scientific Report 11,20706, 2021

Outline

Summary

- HTS technology is the key to construction of the next generation of compact fusion reactors
- The research on the technology of HTS fusion device has been fully carried out in China. The research on the technology of high-field HTS magnet has just been initially established.
- ASIPP has carried out a series of research works on critical performance, AC loss, Stability analysis and engineering preparation of HTS conductors. High-field HTS insert magnet and fusion magnet above 20 T are being developed in ASIPP.
- Several companies in China (Startorus Fusion & Energy singularity and so on) have established small-scale HTS fusion experimental devices. The fusion device with a higher magnetic field will be built in the next step.

Acknowledgements

We are very grateful to the following for their information and assistance!

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EPFL

合肥国际应用超导中心
HEFEI INTERNATIONAL APPLIED SUPERCONDUCTIVITY CENTER

华北电力大学
NORTH CHINA ELECTRIC POWER UNIVERSITY

能量奇点
ENERGY SINGULARITY

上创超导
Shanghai Creative SuperConductor

清華大學
Tsinghua University

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Thank you for your attention!

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