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Design, Fabrication and Testing of a Superconducting Electrodynamic Suspension Magnet with Coated Conductor Tapes

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Outline

1. Background
2. Systematic Design
3. Magnet Fabrication
4. Testing Results
5. Conclusion

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I. Background

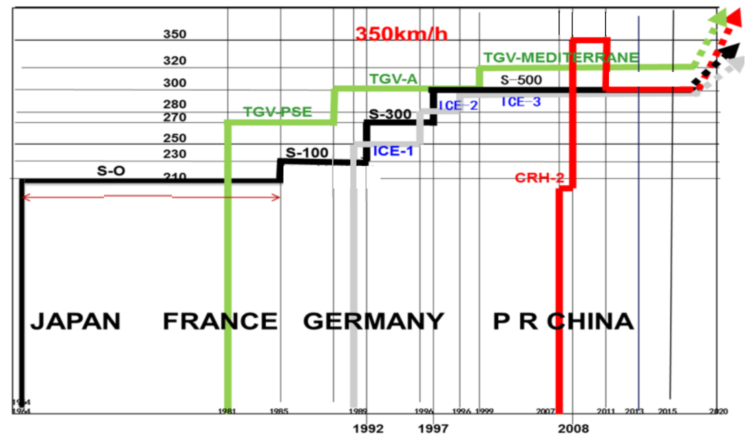
❑ Background


CRH


TGV


Shinkansen


ICE



Running speed of wheel-rail traffic

For the higher speed of ground transportation,

the maglev technology is a promising candidate

I. Background

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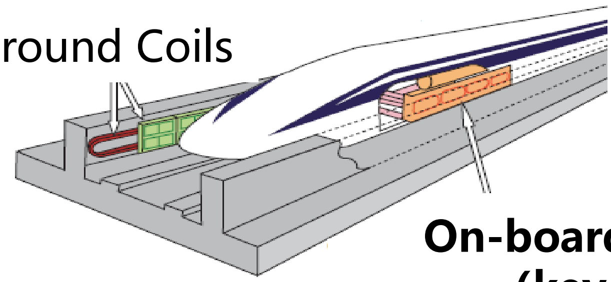
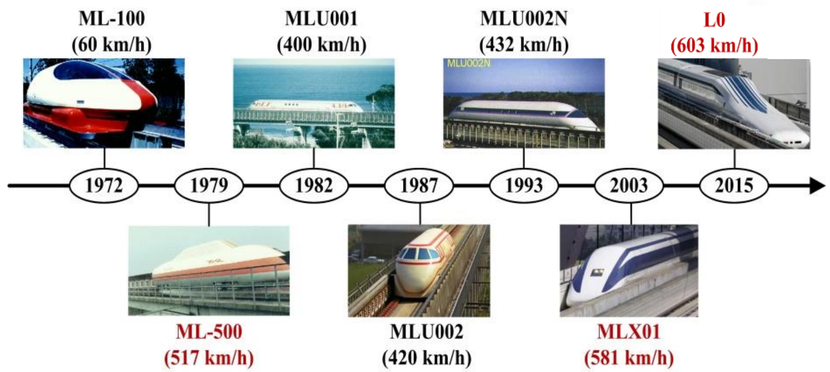
❑ Electrodynamic Suspension (EDS)

- Self-stable levitation
- Free-of control for levitation
- Large suspension gap (100mm+)

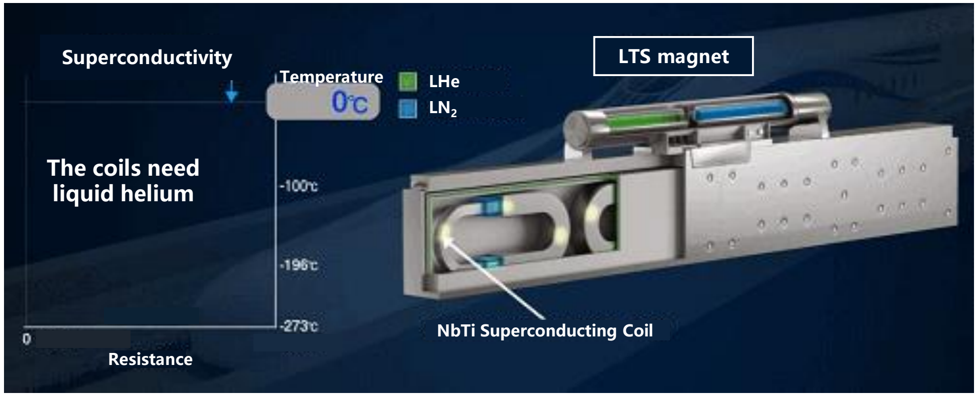
Development of EDS train

the world record of 603km/h





L0-type EDS Train
603km/h (April 2015)



I. Background

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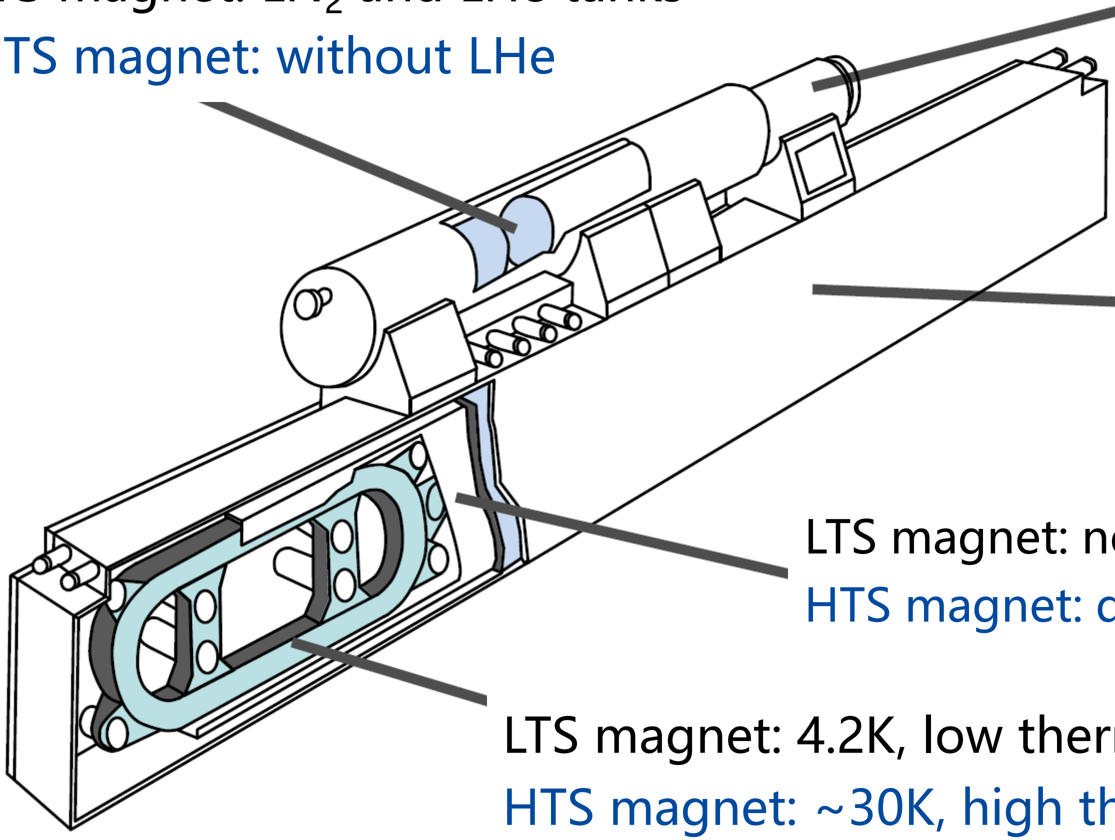
❑ Motivation

Using HTS magnet in EDS system:

LTS magnet: LN_2 and LHe tanks
HTS magnet: without LHe

HTS magnet:
Simple cryogenic system
Low power consumption
Light weight



HTS magnet:
Compact structure
Larger air gap

LTS magnet: need radiation shield
HTS magnet: dispensable radiation shield

LTS magnet: 4.2K, low thermal margin
HTS magnet: ~30K, high thermal stability

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I. Background

❑ Motivation

The comparison between commercial superconductors

Material	NbTi	BSCCO	REBCO
Operating Temperature	4.2K	<20K	30K
Critical Current	350A@4.2K, 5T	~140A@30K, 5T null@50K, 5T	~1100A@30K, 5T ~330A@40K, 5T
Critical Stress	884MPa@77K 1073MPa@4.2K	270-400MPa@77K	800-820MPa@77K 800-830MPa@4.2K

HTS materials already have the comparative performance as LTS

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2 **Systematic Design**

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II. Systematic Design

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❑ Structure design of the coils

Demands:

- Coil structure： racetrack
- Cooling method: conduction-cooling
- Closed-loop operation
- Detachable components

Design scheme and objective

Description	Objective
Number of coils	2
Operating temperature	<30K
Pole pitch	568mm
Total length	≤3km
Maximum field	>3T
Suspension capacity	>5kN
Guidance capacity	>3kN

Basic parameters of tapes

Parameter	Description
Material	REBCO
Insulation material	Polyimide
Width of tapes	6mm
Critical current	>300A@30K, 3T
Average *n* value	36@30K
Current homogeneity	±10%
Tensile stress	>300MPa
Peel stress	15MPa
Minimum bending radius	15~20mm
Tape length per pancake	≥160m

II. Systematic Design

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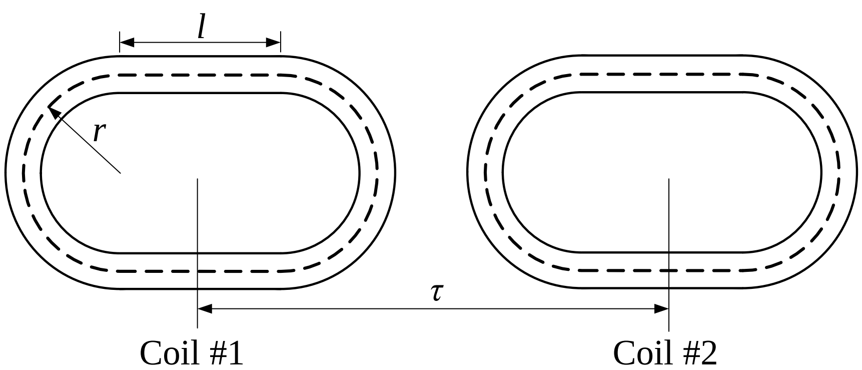
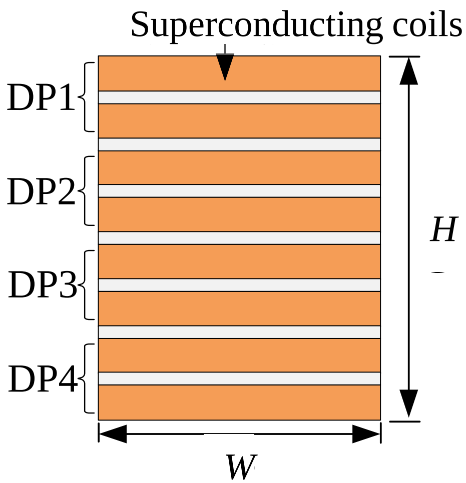
❑ Parameter optimization of the coils

Optimization objective:

Maximize the magnetomotive force





Racetrack structure (left) and cross section (right) of coil

Optimization objective

Max: $F = \dfrac{LN_{DP}}{l+\pi r} I_c(l, r, T, \mathbf{B})$

Constraint conditions

$$\begin{cases} 0.4 \le l + 2r + W \le 0.57, \\ 0.3 \le 2r + W \le 0.4, \\ r - \dfrac{W}{2} \ge 0.05,\ l - r \ge 0, \\ l \ge 0.1,\ r \ge 0.125, \\ I_0 \le 0.6 I_c \end{cases}$$

Monte Carlo →

Optimization results

$r = 125$ mm

$l = 200$ mm

$W = 52$ mm

$H = 62$ mm

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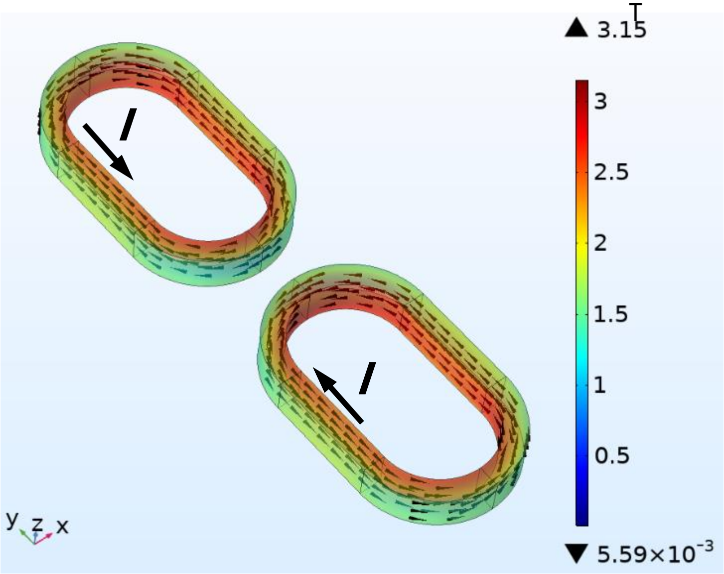
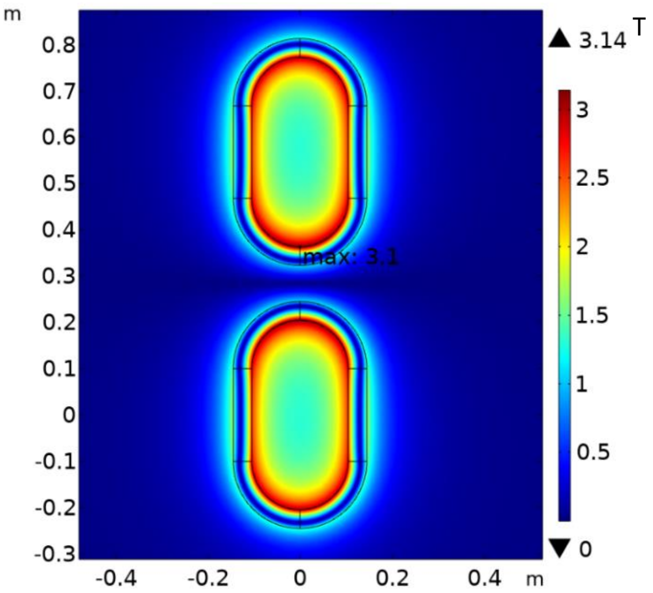
❑ Distribution of the coil magnetic field

When the coil is charged to **250A**, the maximum magnetic field produced by the two series-wound coils is about **3.15T**, located on the innermost turn of the round edge



Current density and magnetic field distribution of the coil



Magnetic field distribution at z=0mm of xy plane

II. Systematic Design

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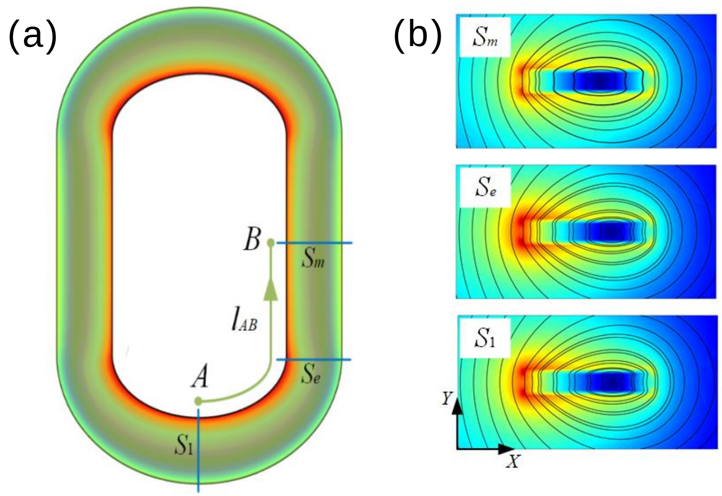
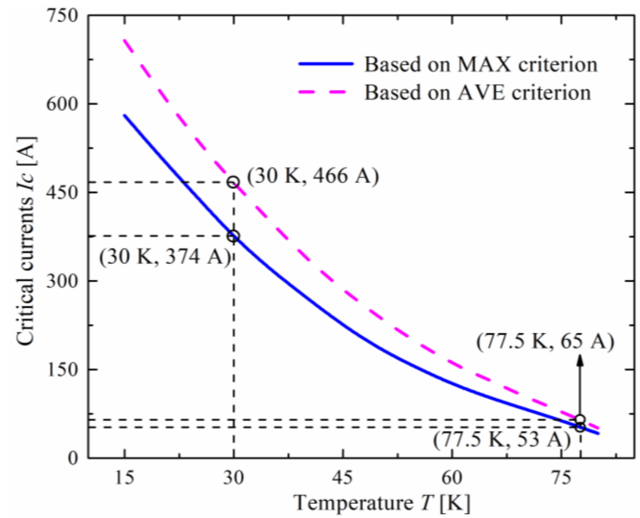
❑ Critical current of the coils

The dependence of critical current on operating temperature was calculated using the **self-consistent model** as follows



Calculation model of critical current of HTS coil



Temperature dependence of critical current

The critical current is required to be 420A considering a 40% safety margin. Therefore, the operating temperature should be **lower than 30K**

II. Systematic Design

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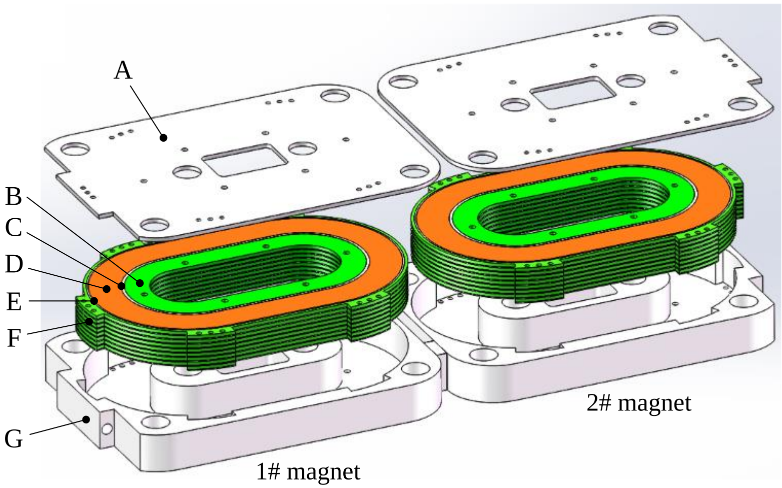
❑ Design of the coil skeleton

To ensure the **mechanical strength** of magnet, the coil skeleton we designed is shown as follow, considering the effect of thermal contraction and electromagnetic force



3D structure of coil skeleton

	Component	Material
A	Cover plate of coil case	6061
B	Coil inside skeleton	G10
C	Stress buffer components	High purity aluminum
D	HTS coils	REBCO
E	Stress buffer components	High purity aluminum
F	Coil outside fastener	G10
G	Coil case	6061

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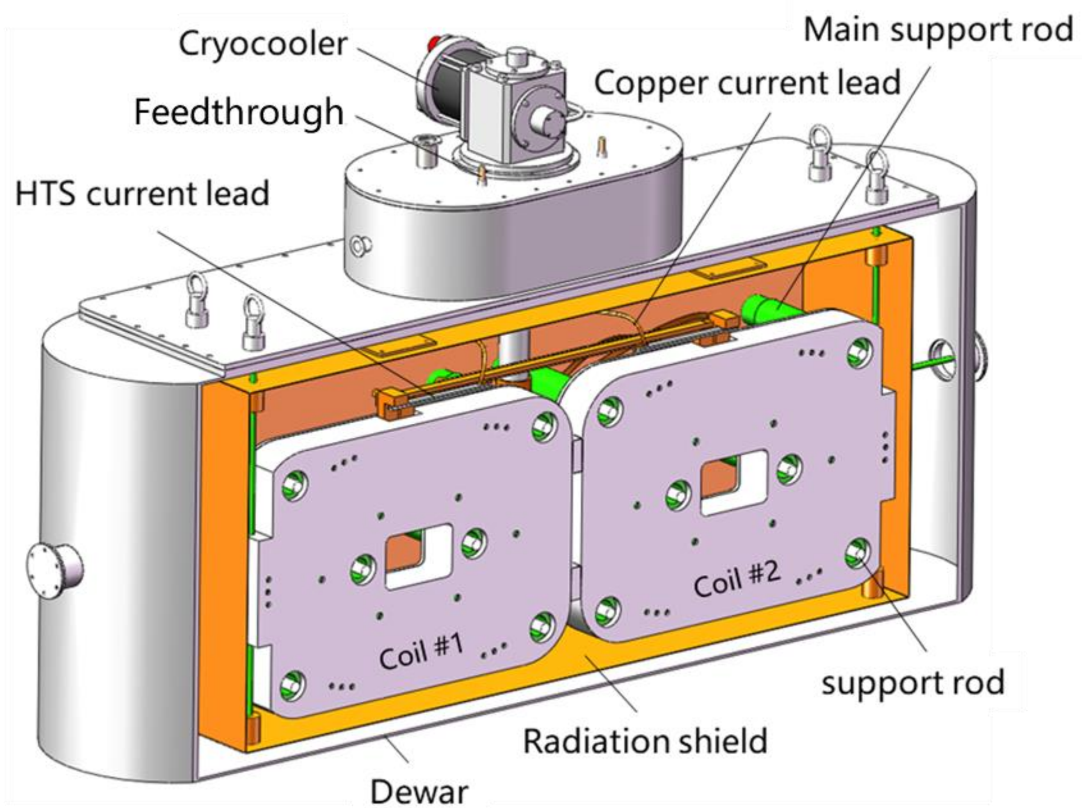
❑ Design of the cryostat

Target

- Operating temperature: 20 K
- Maximum deformation of dewar: <1.5 mm
- Vacuum level: <10^{-4} Pa
- The gap between coil and dewar: <30 mm



3D structure of conduction cooled on-board HTS magnet

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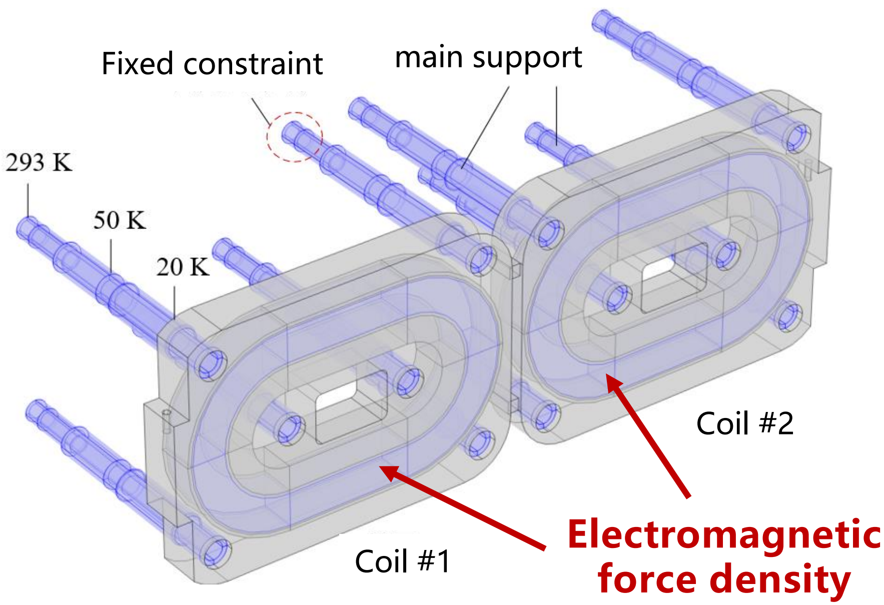
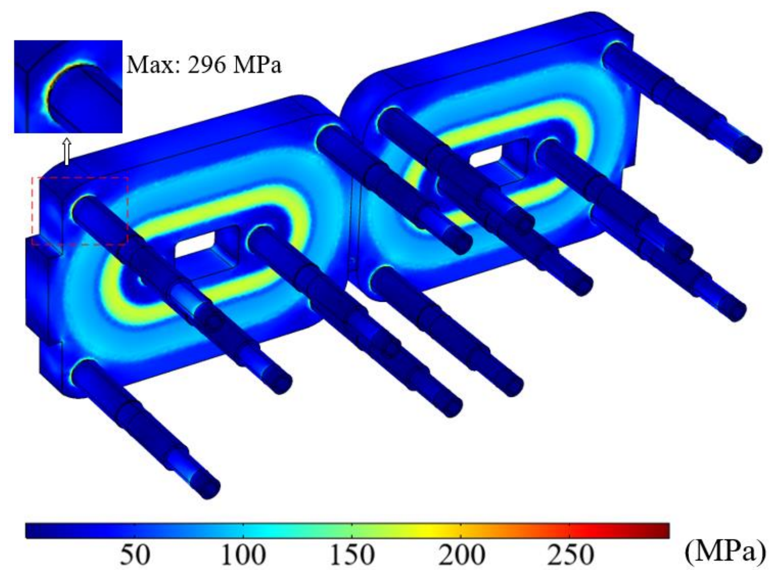
❑ Mechanical strength verification

- Thermal-mechanical coupling model was built to verify the mechanical strength of main support rod



Thermal-mechanical coupling model of main support rod



Stress distribution of main support rod and HTS magnet

✓ **Maximum stress lower than 75% allowable stress of material**

II. Systematic Design

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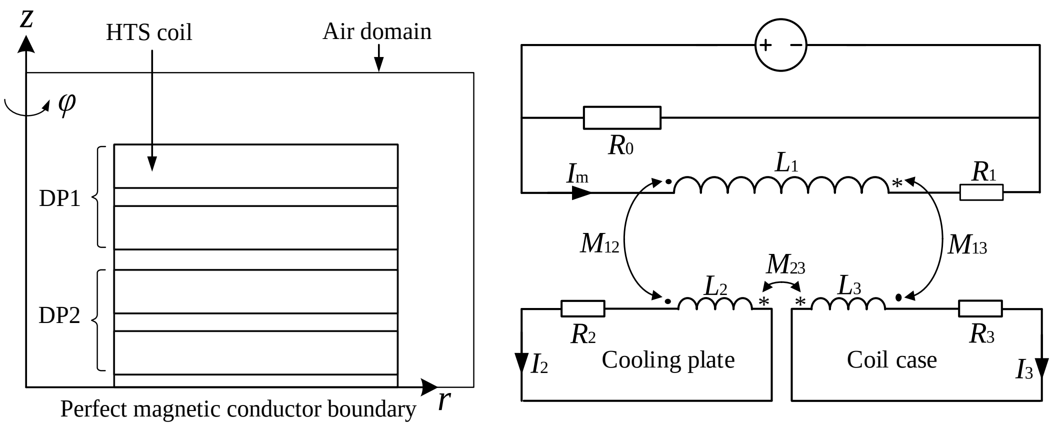
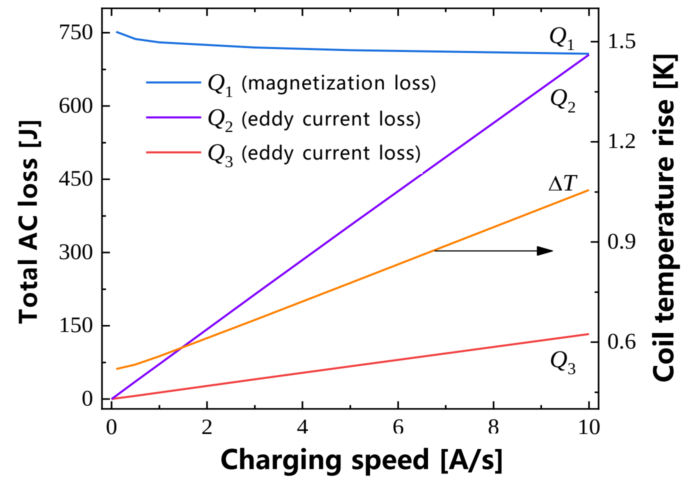
❑ Heat leakage evaluation

- Heat load： charging loss, conduction, radiation



Simulation model of magnetization loss (left) and eddy current loss (right) for HTS coil



Total AC losses and temperature rise per cycle

Heat load and temperature of cold head

Condition	1st-stage cold head		2nd-stage cold head	
	Heat load [W]	Temperature [K]	Heat load [W]	Temperature [K]
Cooling	23.44	41.60	1.22	3.90
Charging	31.39	47.40	1.22	3.84

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4 Testing Results

5 Conclusion

III. Magnet Fabrication

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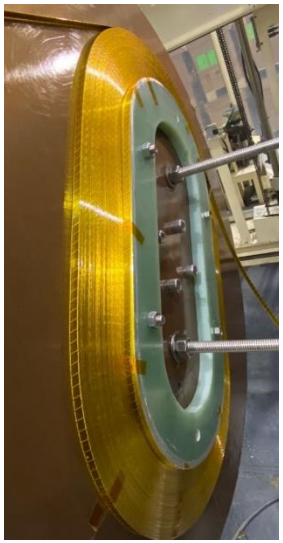
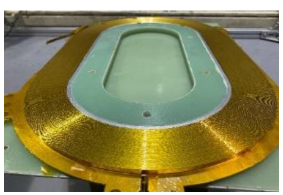
❑ Fabrication of coils

(a)

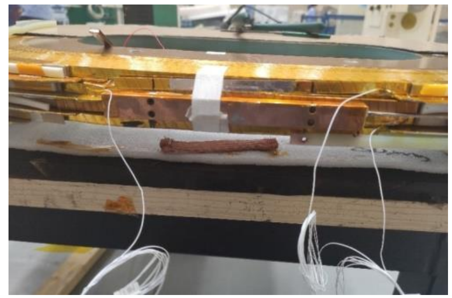


(b)

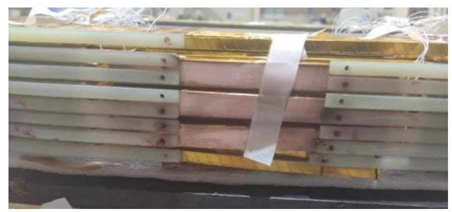


Series connect

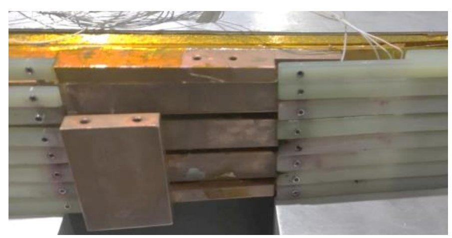
(c)



(d)



(e)

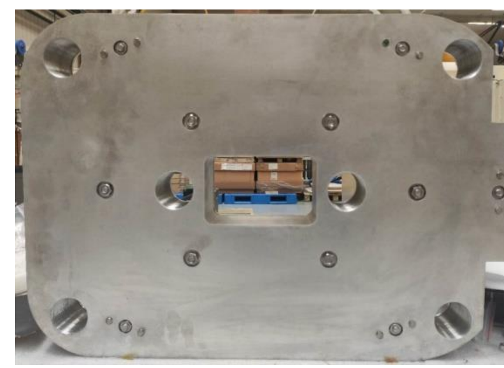


Assemble

(f)

Impregnate

(g)



Wind double pancake coils

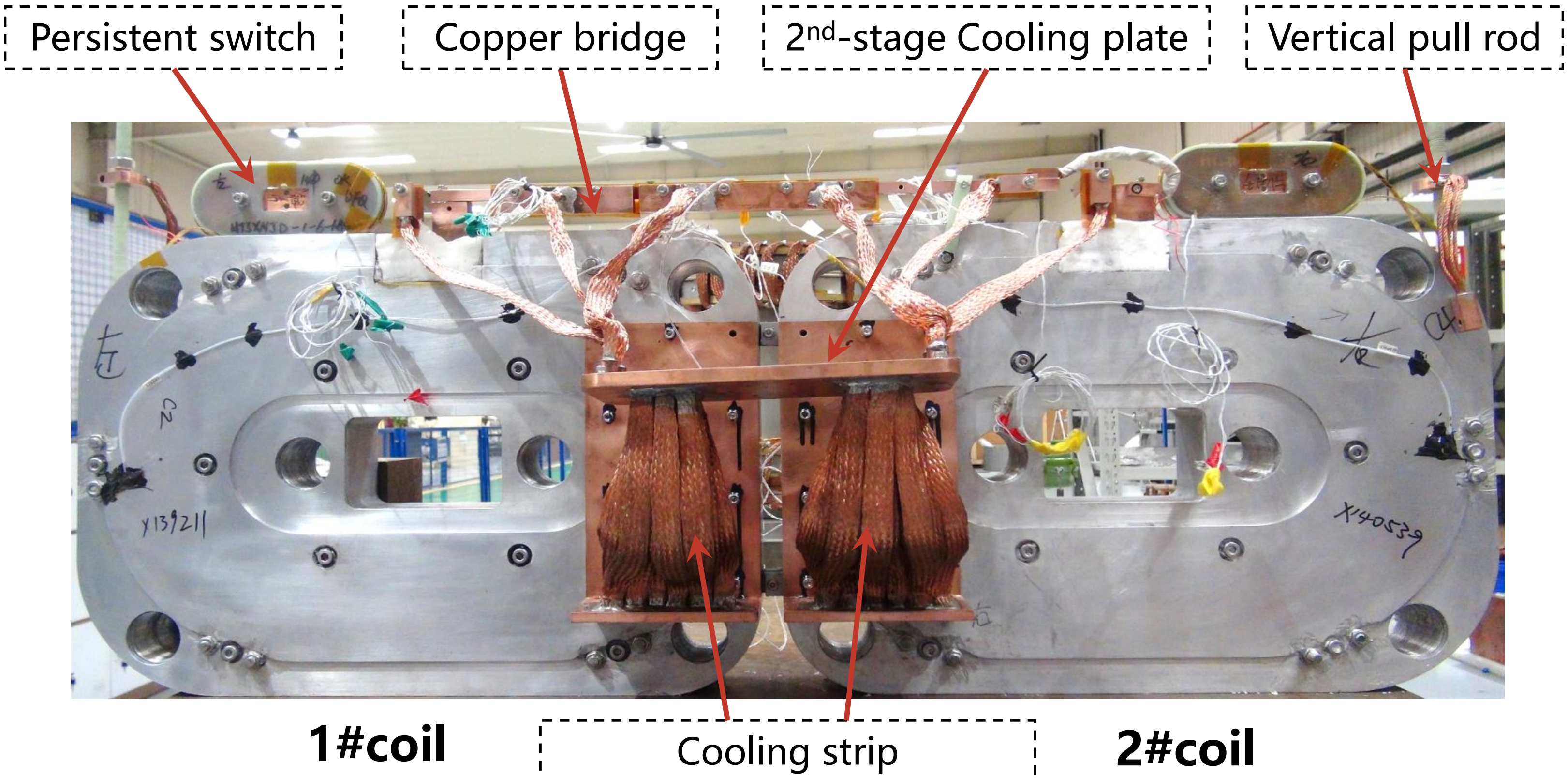
Weld copper electrodes and joints

Assembly and impregnation

III. Magnet Fabrication

❑ Assembly of coils

These two coils were seriesly connected by **copper bridge** with a HTS tape, in which they were wound along different directions to provide **reverse magnetic poles**



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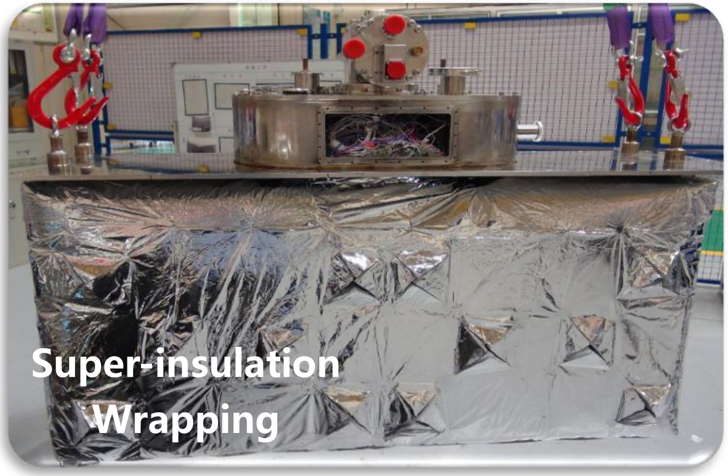
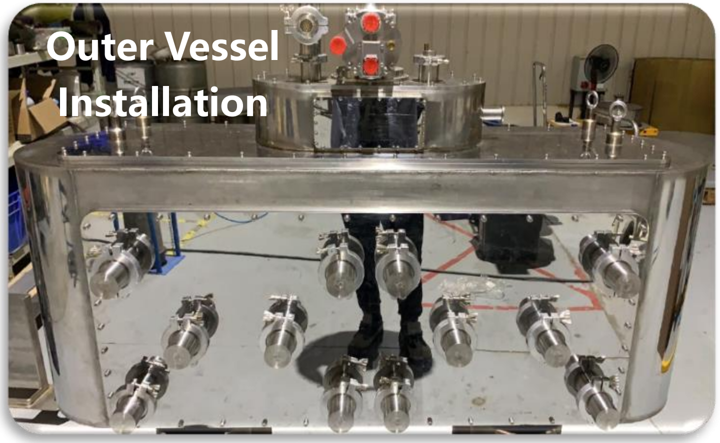
❑ Assembly of the magnet





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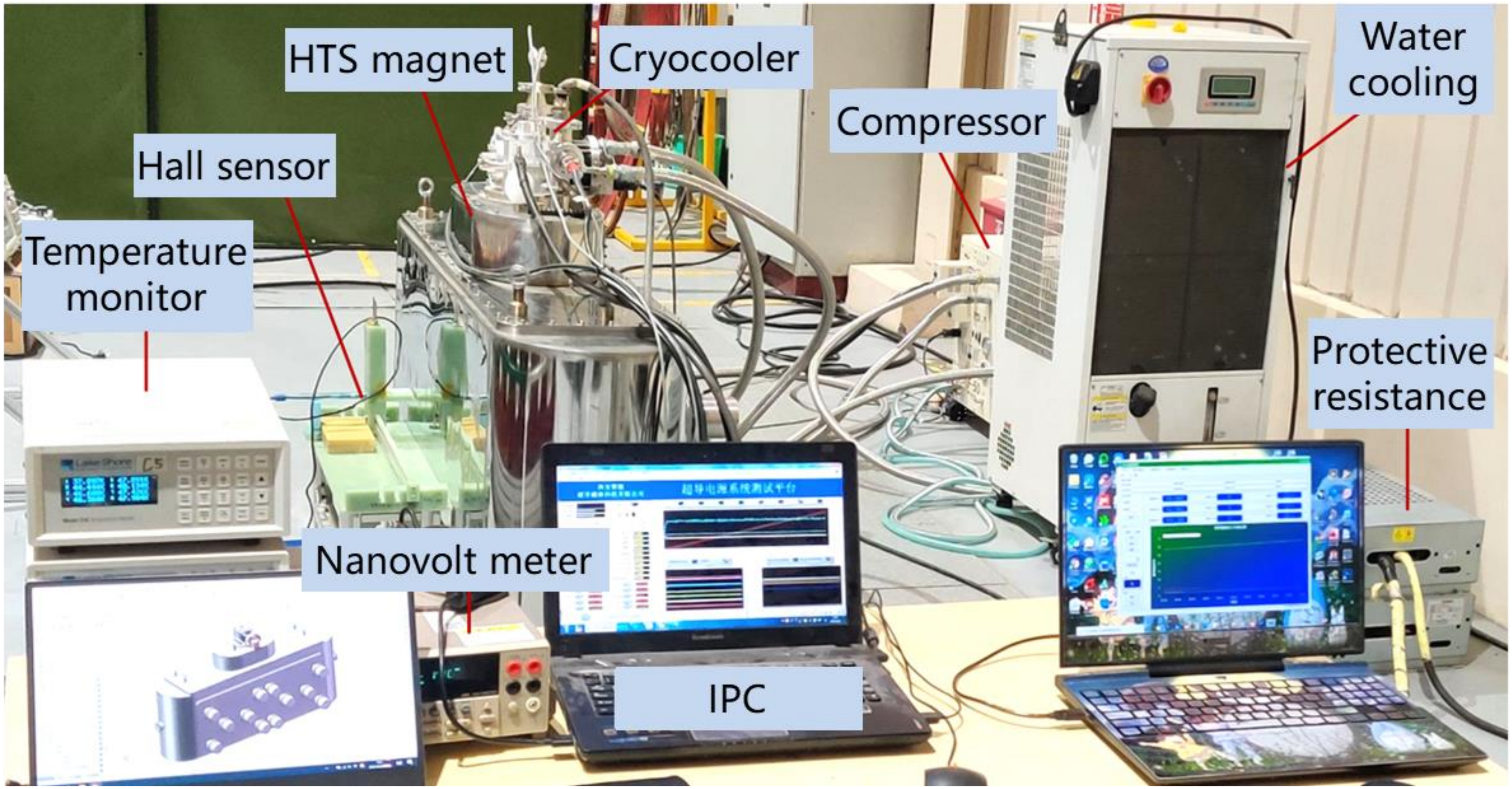
IV. Testing Results

❑ Measurement system

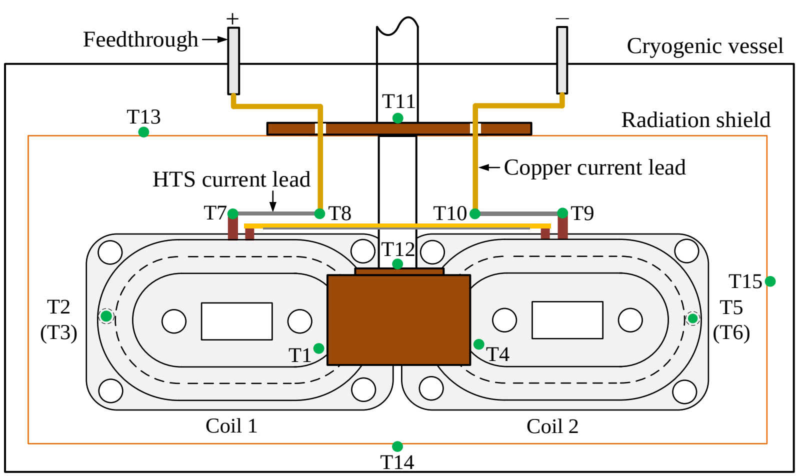


Electromagnetic-thermal measurement system

IV. Testing Results

❑ Sensor layout - Temperature

Temperature sensor	Sensor type and range	Position
C1	Cernox (>4K)	2nd-stage cooling plate
C2-C5		HTS coil skeleton
C6-C7		Upper HTS current leads
PT1	PT100 (>30K)	1st-stage cold head
PT2-PT6		Radiation shield
PT7-PT8		Lower HTS current leads



Temperature sensor layout

- Cernox temperature sensor is arranged at the coil skeleton, the 2nd-stage cold head and the HTS current leads
- PT100 temperature sensor is arranged at the 1st-stage cold head, radiation shield and the HTS current leads

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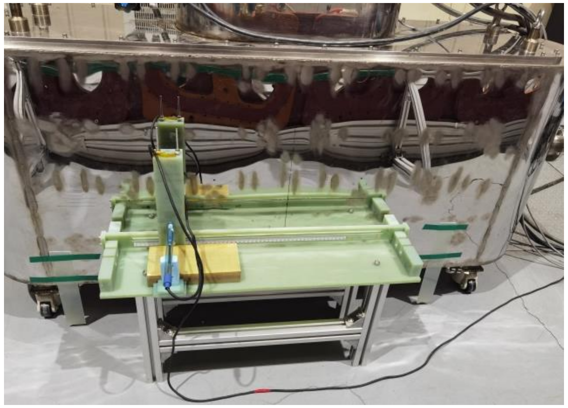
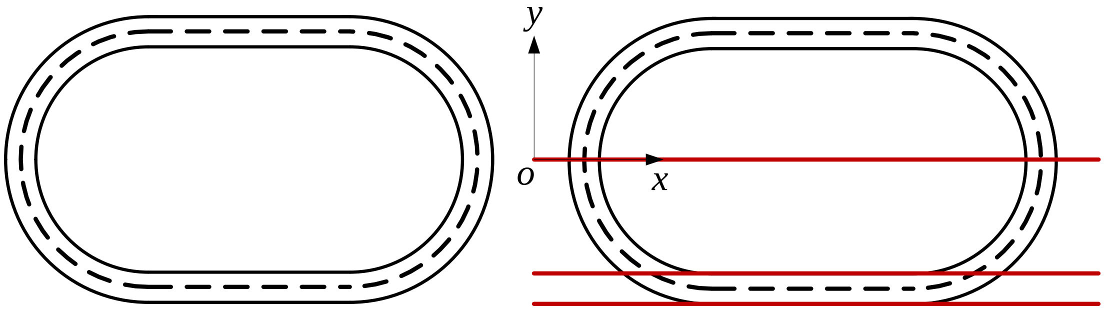
❑ Sensor layout - Magnetic field

- Considering the geometric symmetry, only a quarter region was measured
- The measurements were focused on the straight section
- The magnetic field distribution was measured at different air gaps



Experimental device

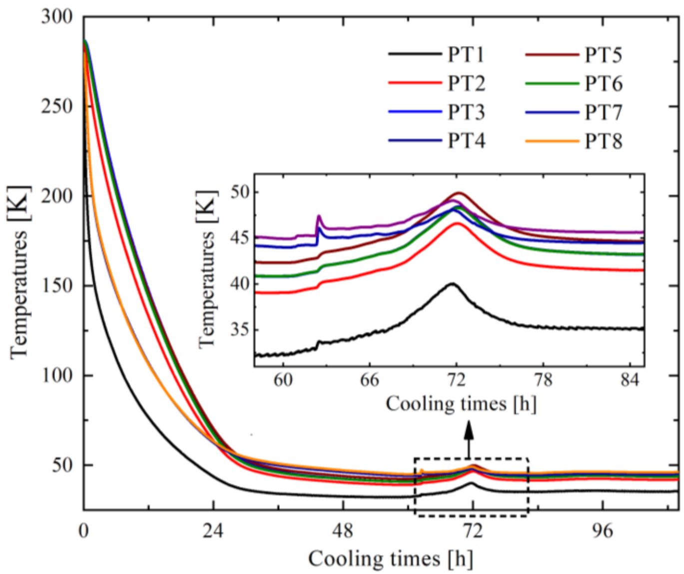


Magnetic field measurement position (Red line)

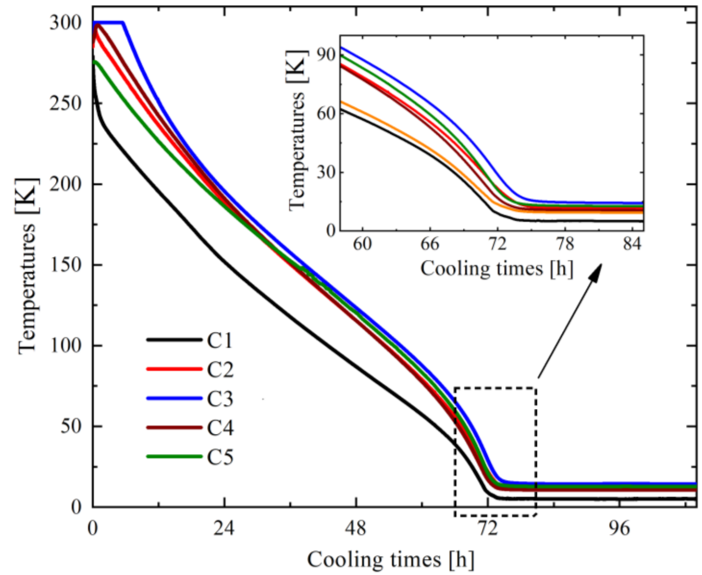
IV. Testing Results

❑ Cooling Test

- The vacuum (10^{-5}Pa) could remain >1 month without the pump



1st stage and radiation shield



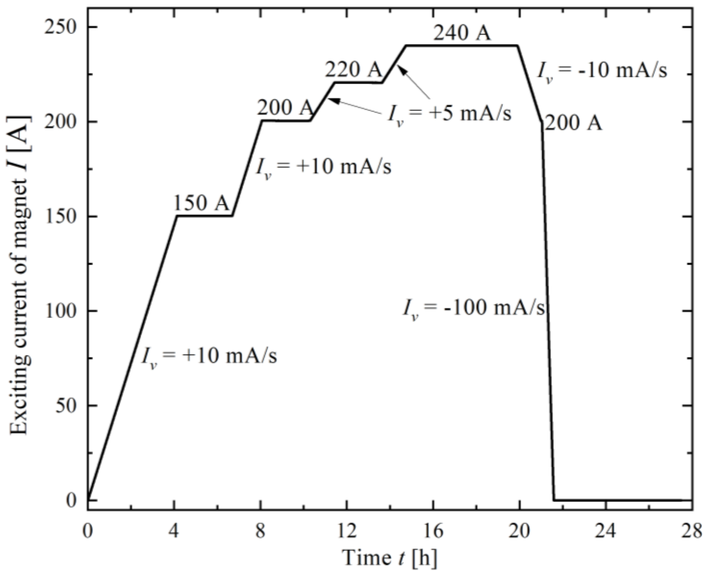
2nd stage and HTS coil

- ✓ Coil max/min: 14K/11K
- ✓ Left/right upper HTS current leads: 45/46K
- ✓ 1st/2nd cold head: 36K/5K
- ✓ Cooling time-consuming: ~75h

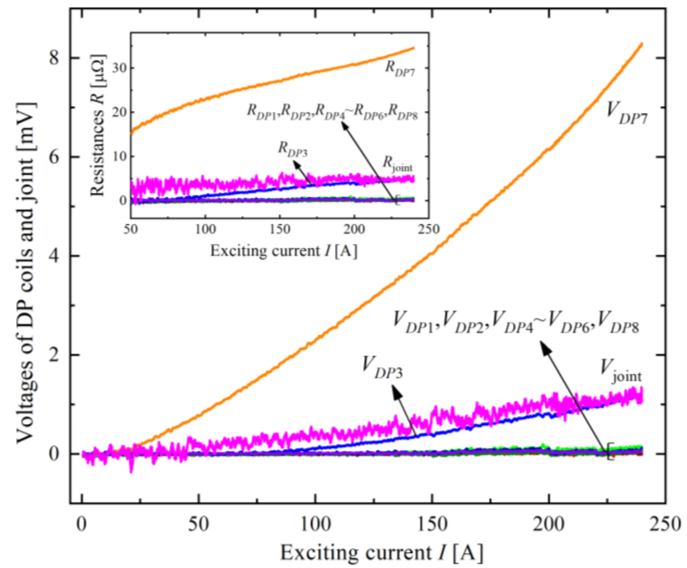
IV. Testing Results

❑ Charging test - Electrical characteristics

- Charging: 10mA/s to 150 A, and 5mA/s to 240A
- Discharging: -10mA/s to 200 A, and -100mA/s to 0A



Exciting current



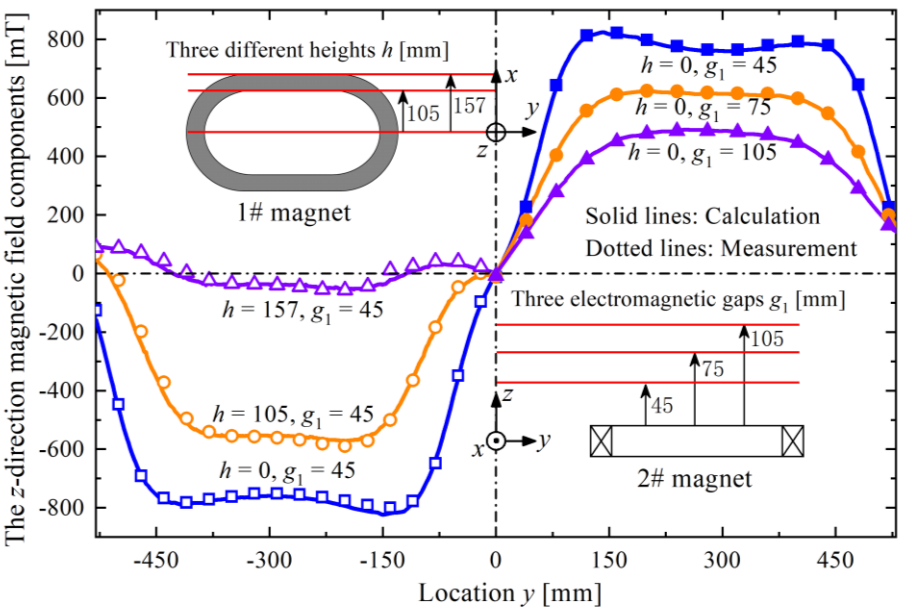
DC voltage and resistance

✓ Performance deterioration occurs in DP7 and DP3 , but their voltage is still lower than the quench criterion

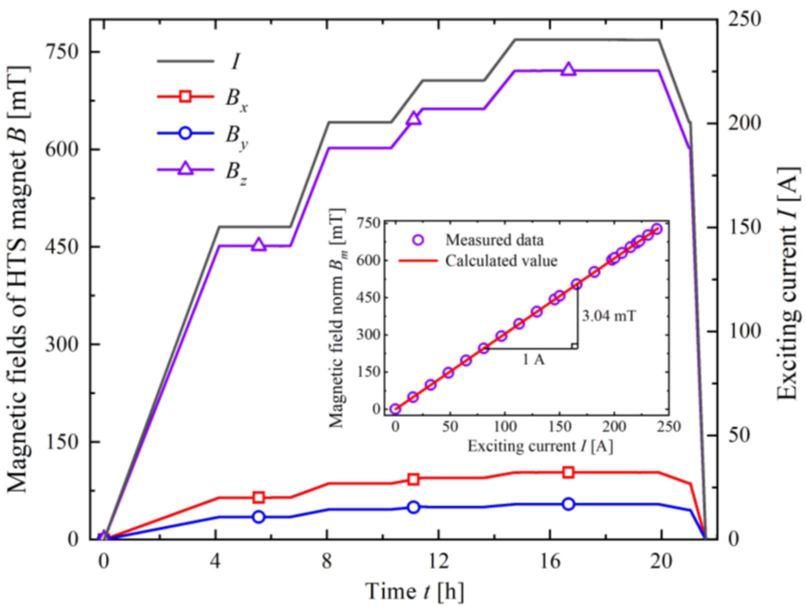
IV. Testing Results

❑ Charging test - Magnetic characteristics

- The magnetic field distribution of the magnet was tested at 25A, which is compared with the simulation results



Field spatial distribution at 25A



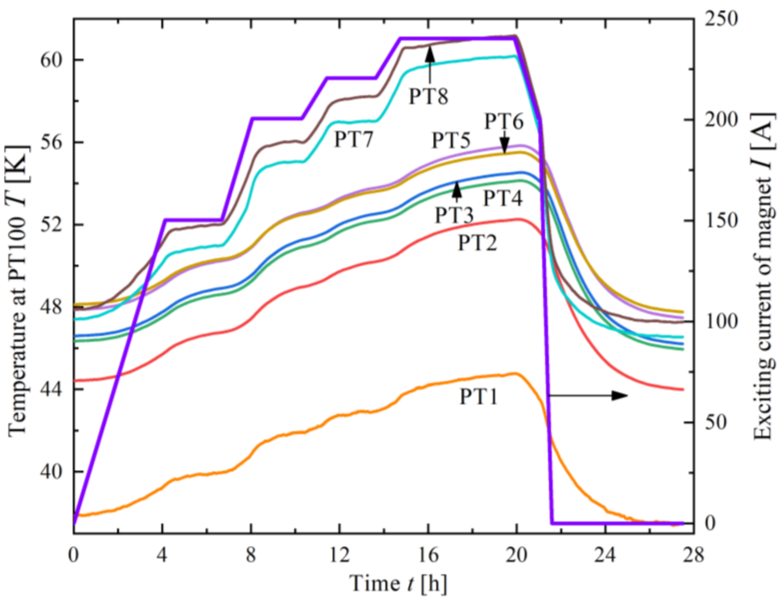
Magnetic field during charging

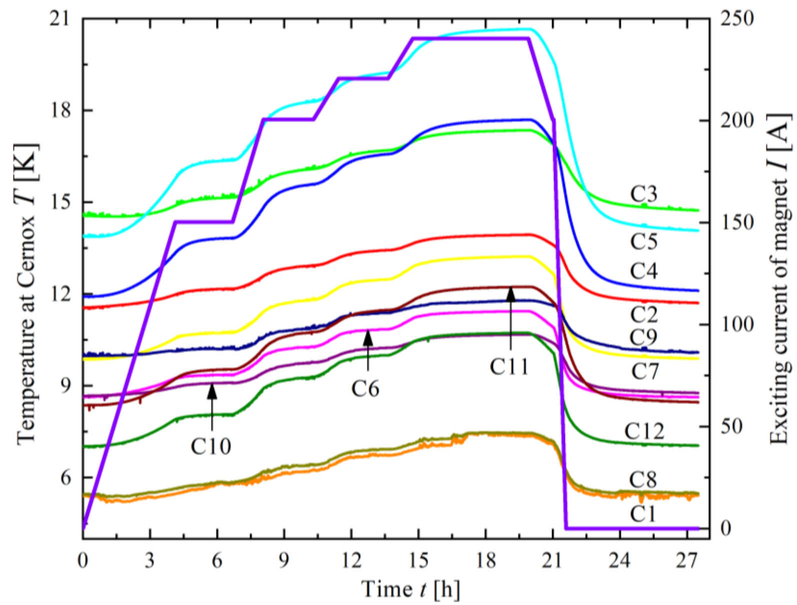
✓ The results verify: small installation error and stable mechanical structure

IV. Testing Results

❑ Charging test - Thermal characteristics

- The temperature of all components increase during charging
- After charging, the temperature gradually reached steady state





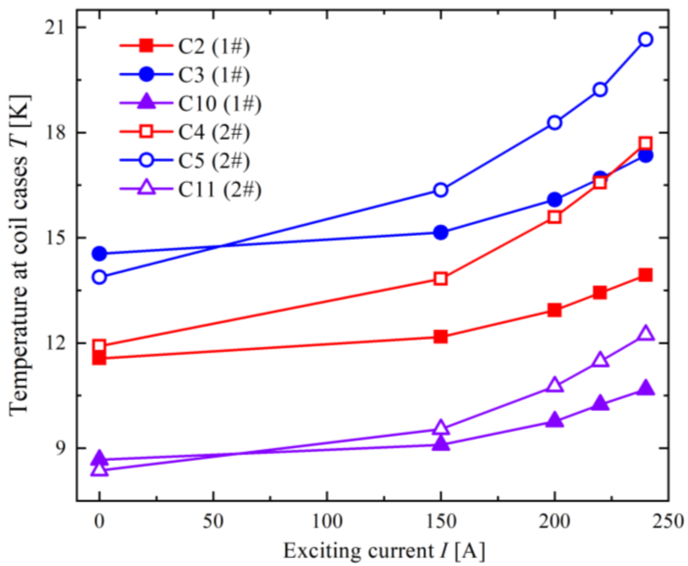
Radiation shield and HTS current lead

2nd-stage and coil skeleton

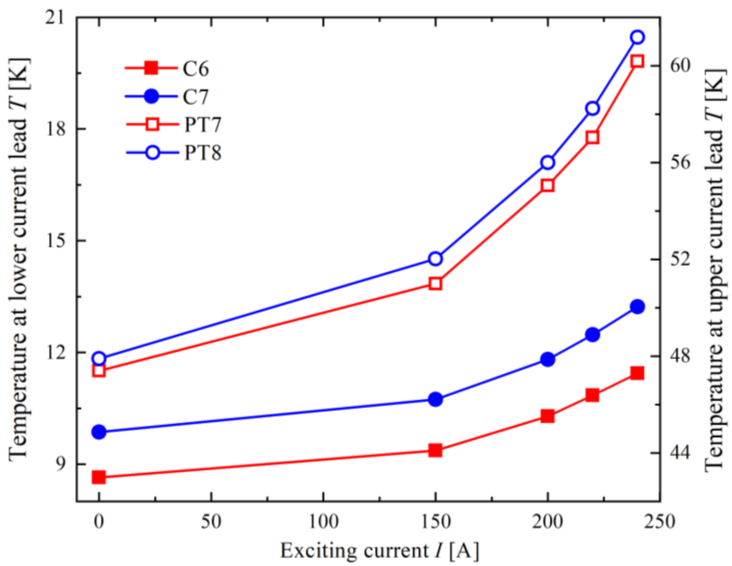
✓ The temperature of the HTS current lead and the right coil skeleton rises most significantly

❑ Charging test - Thermal characteristics

- The temperature at steady state was recorded to analyze the variation of the maximum temperature with current.



Max temperature of skeleton



Max temperature of upper lead

- ✓ Coil 2# temperature exceeds that of coil 1# due to the degenerative DP7
- ✓ The temperature rise of the upper current lead exceeds that of the lower one, due to the heat leakage from copper current lead

IV. Testing Results

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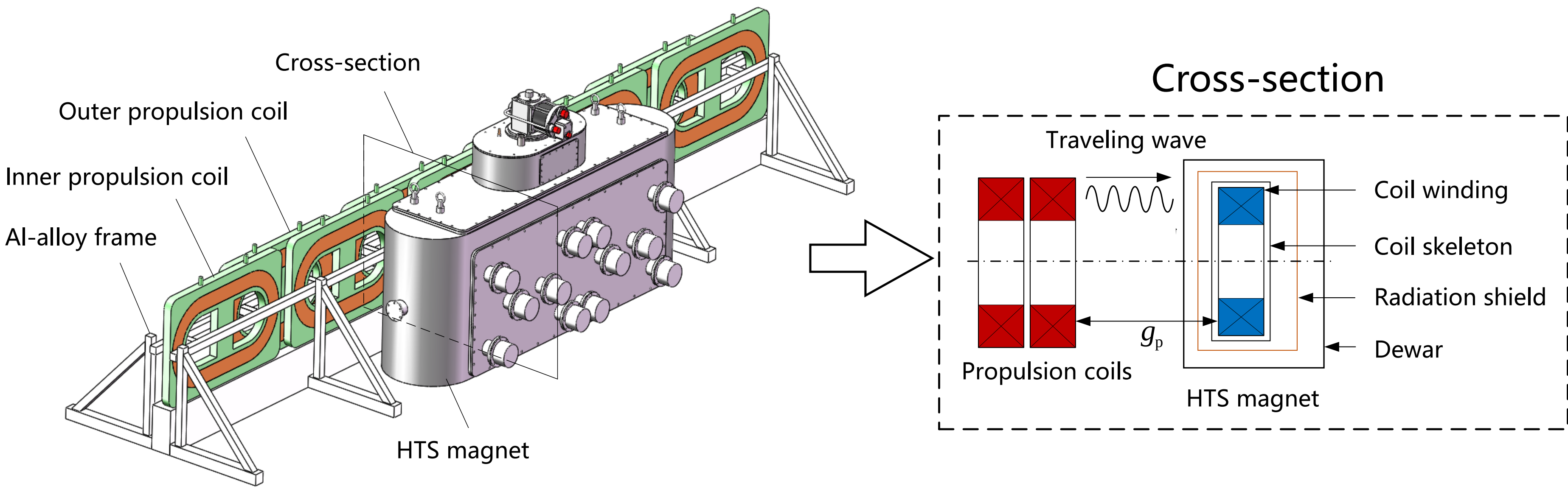
❑ Traveling magnetic field excitation

- The on-board magnet surfers traveling magnetic field excitation in abnormal condition (activating, braking and control failure)



Schematic diagram of HTS magnet and propulsion coils

✓ The equivalent experimental system was designed and fabricated to simulate the traveling magnetic field excitation of propulsion coil

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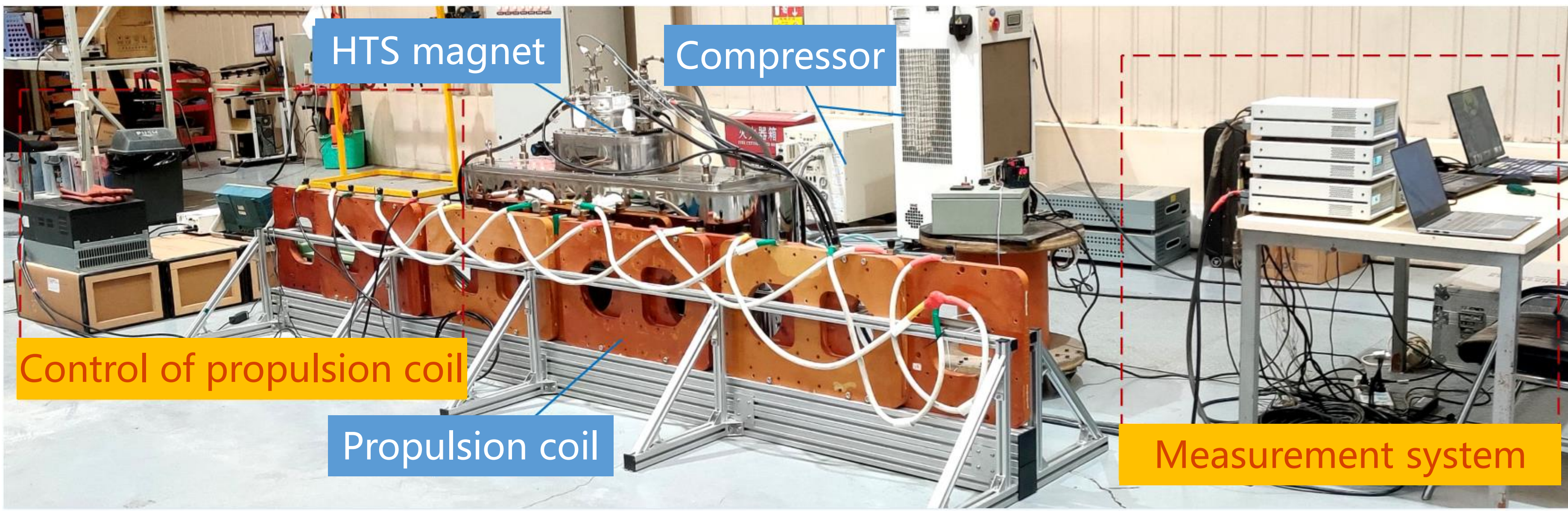
❑ Experimental platform – Thermal

- This experimental platform, simulating the traveling magnetic field excitation of propulsion coil, was built to evaluate the thermal performance of on-board magnet

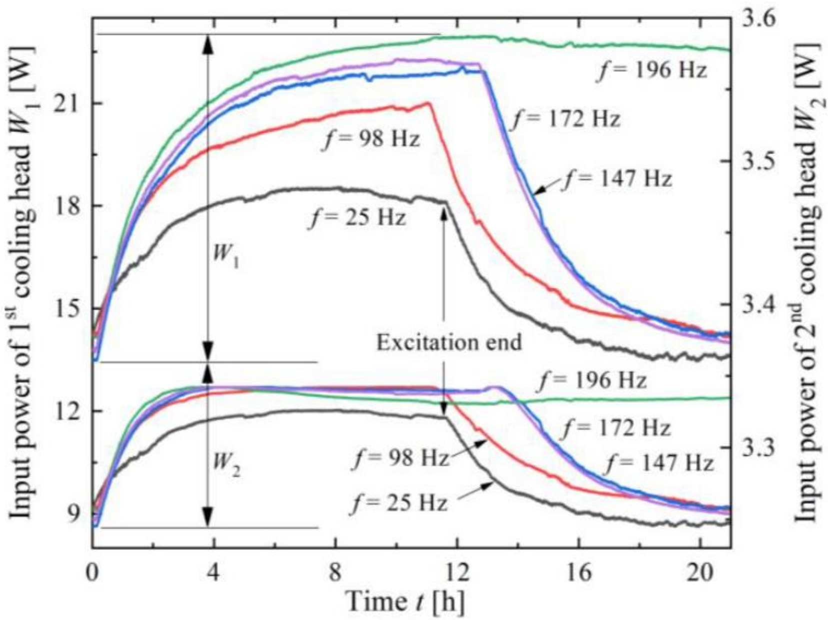


Traveling magnetic field excitation experimental scene

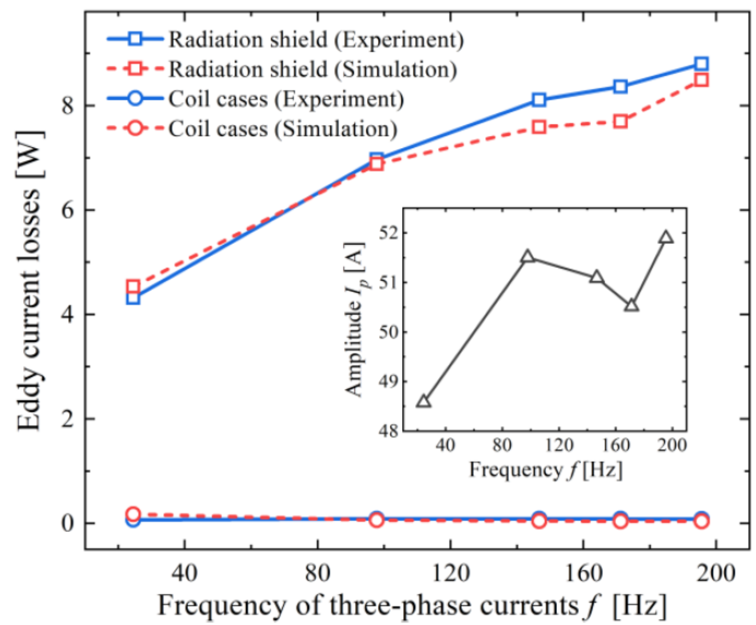
IV. Testing Results

❑ Thermal performance

- Eddy current losses were estimated by the temperature rise of the cold head based on cryocooler load map



Input power of cold heads



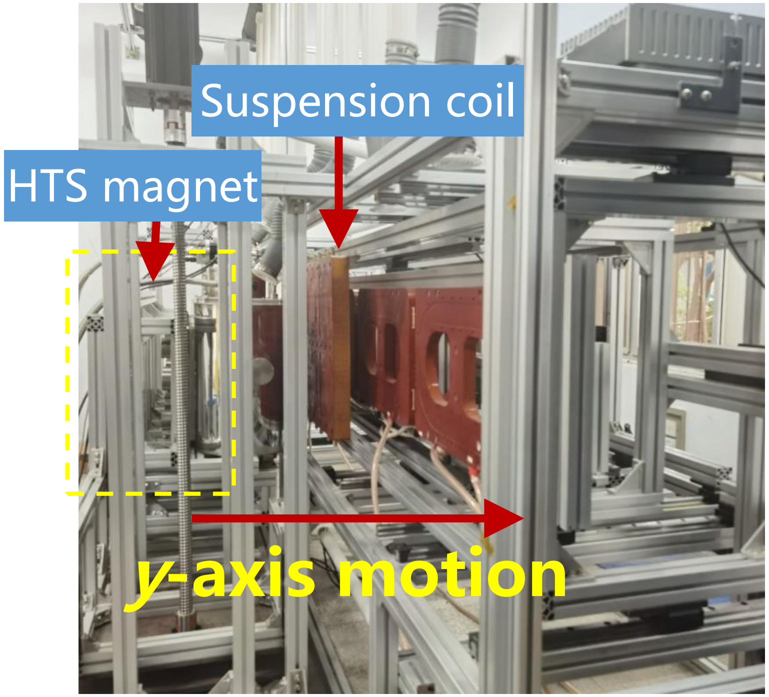
Eddy current loss

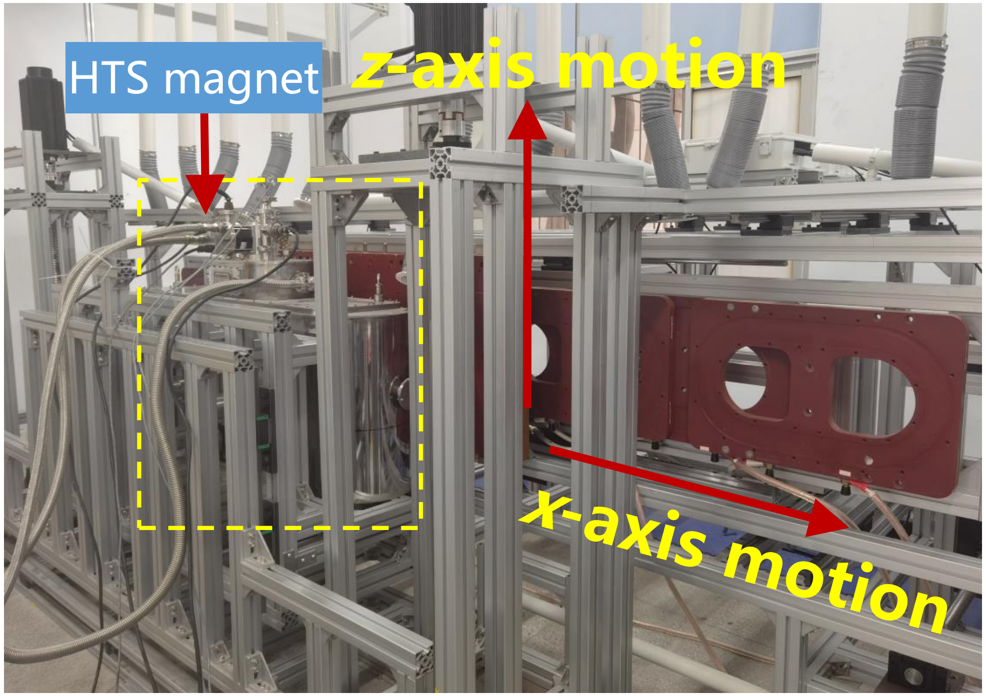
✓ The loss in coil cases is negligible due to the shield effect

✓ The eddy current loss is a major threat to the upper HTS current leads

❑ Experimental platform - Force

- This experimental platform was built to measure the electromagnetic force between the HTS magnet and the suspension coil





Electromagnetic force test platform

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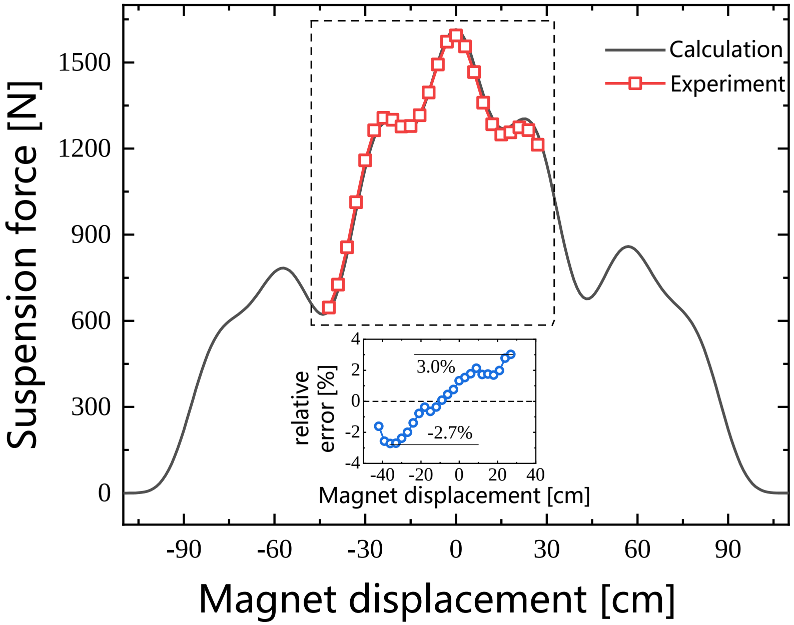
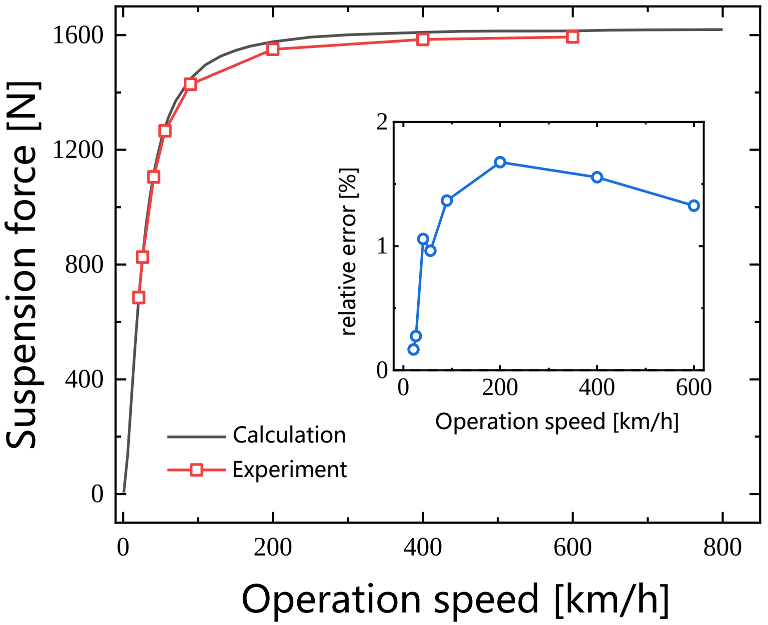
❑ Electromagnetic force

- The suspension forces of HTS magnet in different scenarios were tested and compared with the calculated results





Error < 3% **Error < 2%**

✓ The accuracy of the simulation model was verified by experiments

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Outline

1. Background
2. Systematic Design
3. Magnet Fabrication
4. Testing Results
5. **Conclusion**

V. Conclusion

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Until now

- Systematic design and fabrication of on-board HTS magnet and cryogenic system
- Cooling testing —— lowest temperature: 14K (cooling time 75h)
- Charging testing —— operating current: 240A (magnetomotive force 518kA)
- The thermal performance measurement and evaluation of the HTS magnet undergo the travelling magnetic field of ground propulsion coils
- Preliminary test of suspension force between HTS magnet and suspension coil

Soon in the future

- Charging testing of HTS magnet at current 300A with bigger power supply
- Electromagnetic force measurement between the magnet and ground coils
- Dynamic performance evaluation of the on-board HTS magnet
- …

Reference

For more information, please refer to:

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