# Design and Test of a 10 MJ hybrid HTS Magnetic Energy Storage Module


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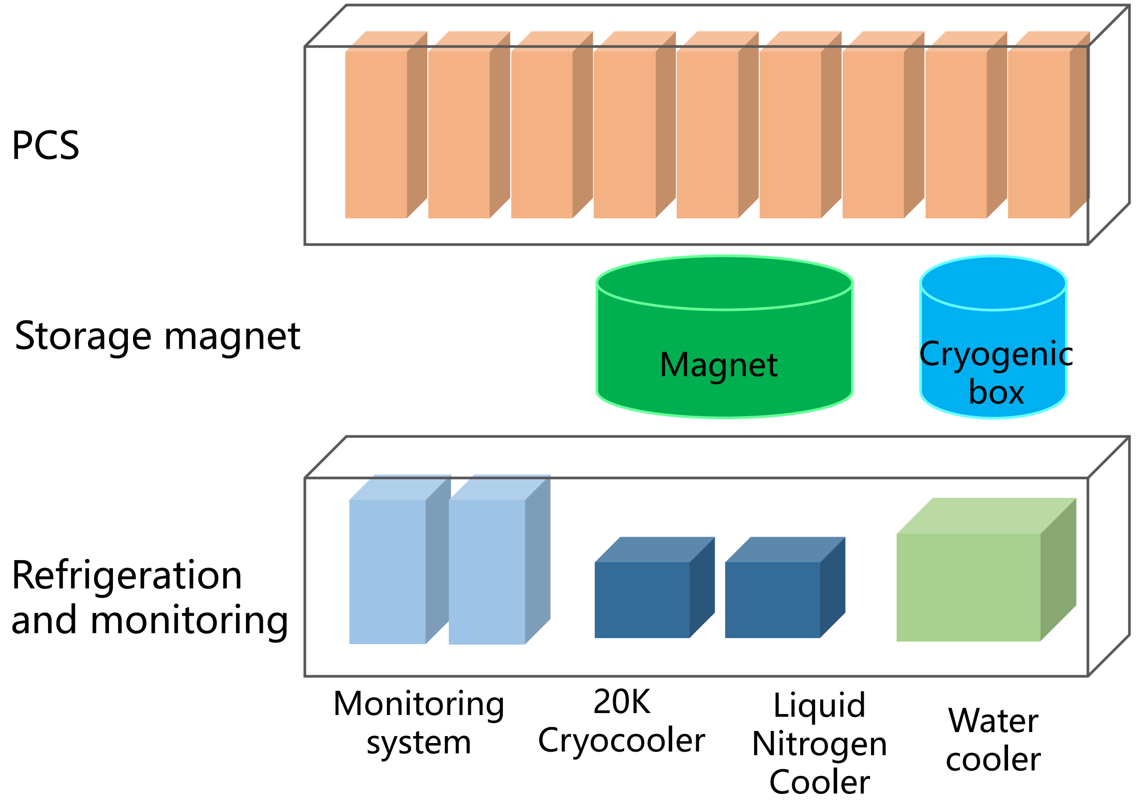
# 1、Project Background

## ■ Overall Structure

The superconducting magnetic energy storage (SMES) system mainly comprises the following components: superconducting storage magnet, refrigeration system, power conversion system(PCS), and monitoring and protection control system.

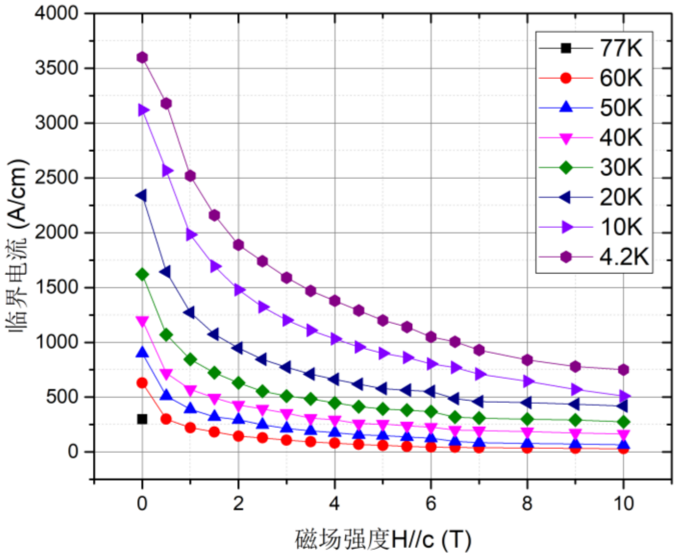



| Project | Parameters |
|---|---|
| **Maximum Operating Voltage** | **10 kV** |
| **Maximum Operating Current** | **1600 A** |
| **Maximum Energy Storage:** | 11.9 MJ |
| **Maximum Effective Output Energy** | **>10 MJ** |
| **Design Inductance** | **9.3 H** |
| **Maximum Outer Diameter of Magnet** | 2800 mm |
| **Maximum Height of Magnet** | 1280 mm |
| **Cooling Method** | Liquid hydrogen immersion cooling, low-temperature medium "zero evaporation" |
| **Magnet Cooling Medium** | **Liquid hydrogen/solid nitrogen** |
| **Cold Shield Cooling Medium** | Liquid nitrogen |
| **Operating Temperature Range** | 15~20.3 K (slightly negative pressure) |
| **Steady-State Operating Pressure** | ≤0.1 MPa |
| **Inverter Output Power** | **5 MW** |

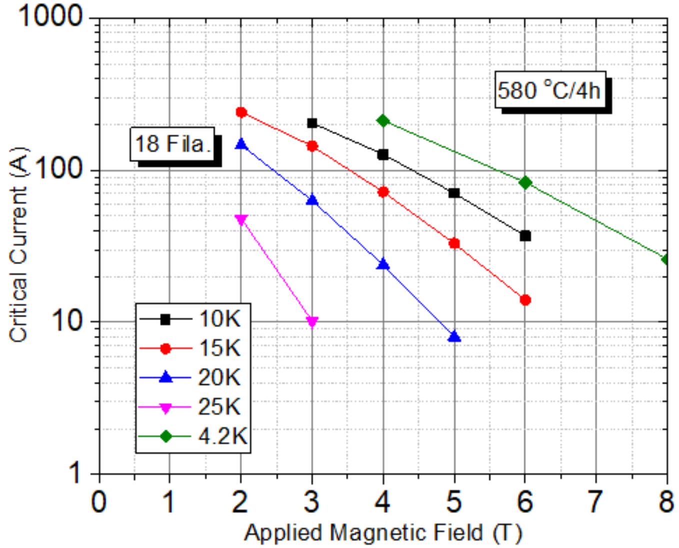
# 2、 Design of Superconducting Magnet

## ■ Parameters of High-Temperature Superconducting Material

Superconducting materials are boundary conditions for magnet design. Based on the material performance indicators for this project, $MgB_2$ and YBCO superconducting materials are selected. The hybrid magnet has better economic performance in the 20K temperature range.




$I_c(B,T)$ Curve of YBCO tape




$I_c(B,T)$ Curve of $MgB_2$ wire

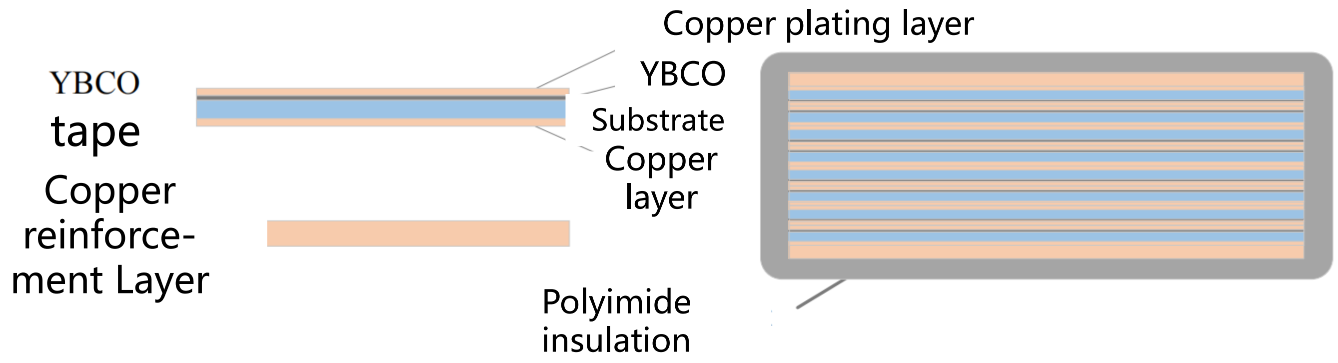
At 77K in self-field, Jc is greater than 25,602 A/mm². At 20K and a perpendicular field of 3.5T, Ic is greater than 320 A (for a 4.5 mm wide tape, design reference value).

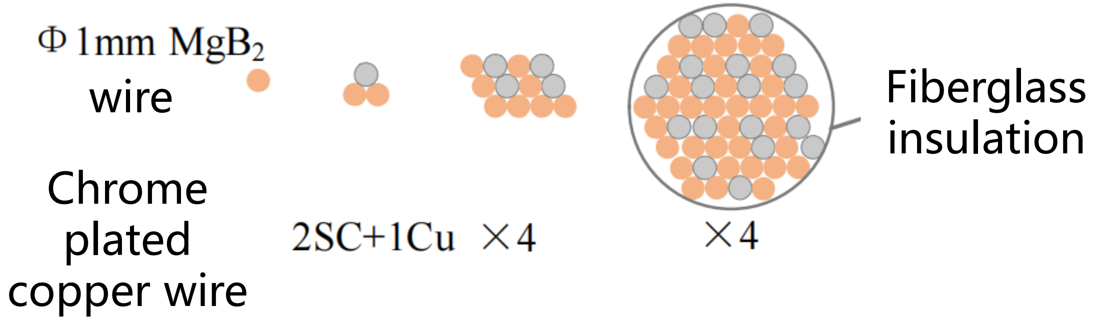
At 4.2K and 3T, Jc is greater than 2,378 A/mm². At 20K and a perpendicular field of 1.5T, Ic is greater than 200 A (for a 1 mm diameter wire, design reference value).

# 2、 Design of Superconducting Magnet

## ■ Superconducting Cable Structure and Parameters

The current-carrying capacity of a single wire is limited, so multiple wires need to be used in parallel to meet the design requirements. Therefore, both YBCO and $MgB_2$ in the design are implemented using cable structures.



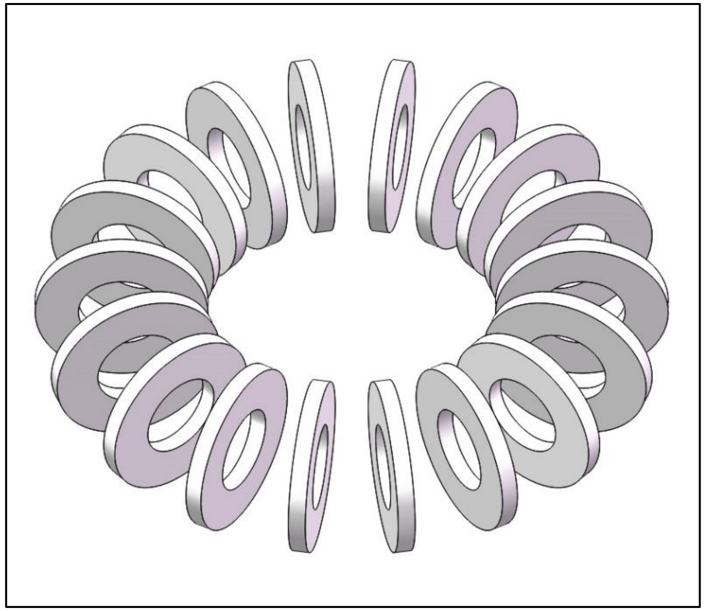

❑ **Basic structural dimensions of YBCO stacked cables**

❑ **Basic structural dimensions of $MgB_2$ cable**

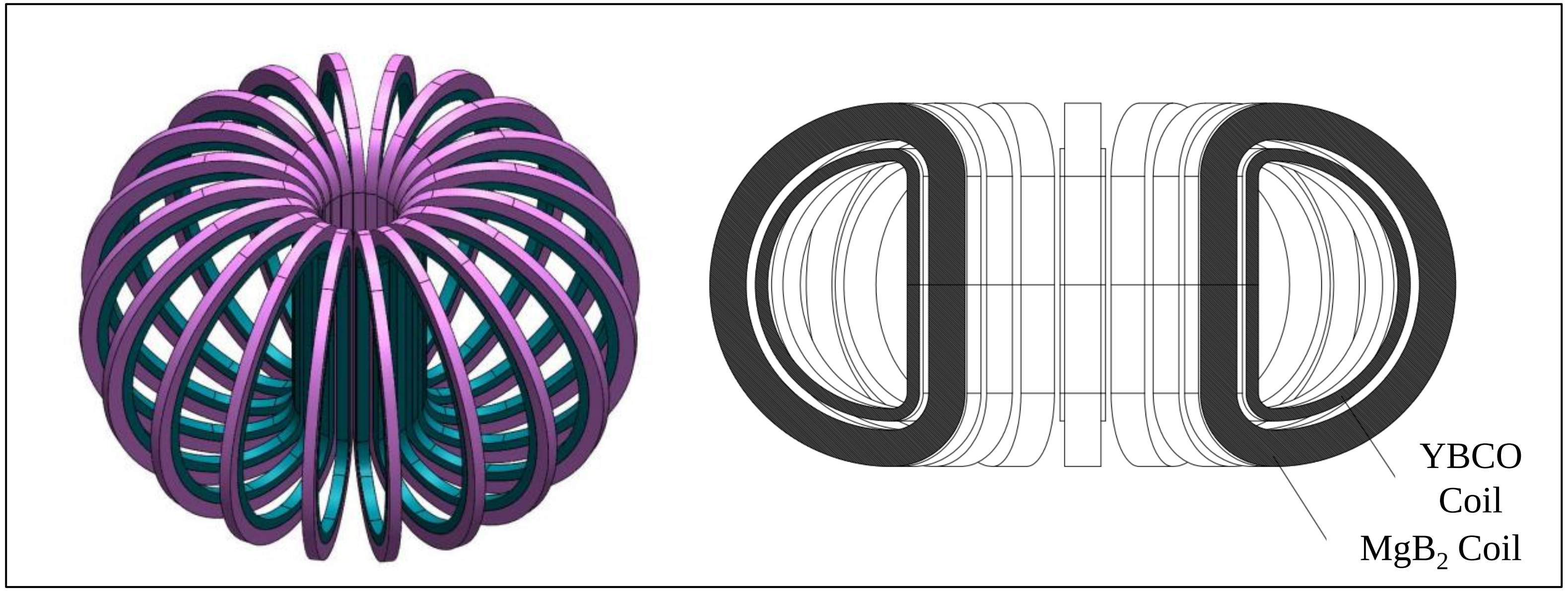
- The conductor of the YBCO cable uses an **8SC+2Cu** structure, with polyimide insulation. The overall dimensions are approximately **6.0 × 2 mm.**
- The $MgB_2$ cable uses a **(2SC+1Cu)×4×4** structure, with 32 superconducting cores. It is insulated with fiberglass and has an overall diameter of approximately **φ10.0 mm**.

# 2、Design of Superconducting Magnet

## ■ Basic coil unit selection



Schematic Diagram of a Circular Toroidal Magnet Structure



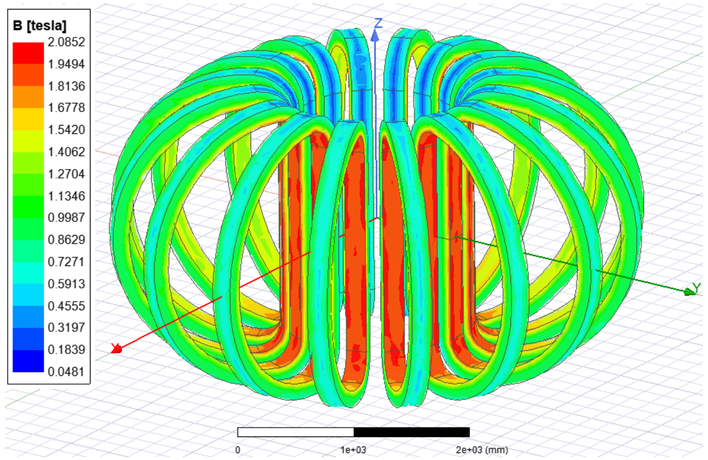

Schematic Diagram of a "D-Type" Toroidal Magnet Structure

Compared to the circular toroidal magnet, the "D-Type" toroidal magnet

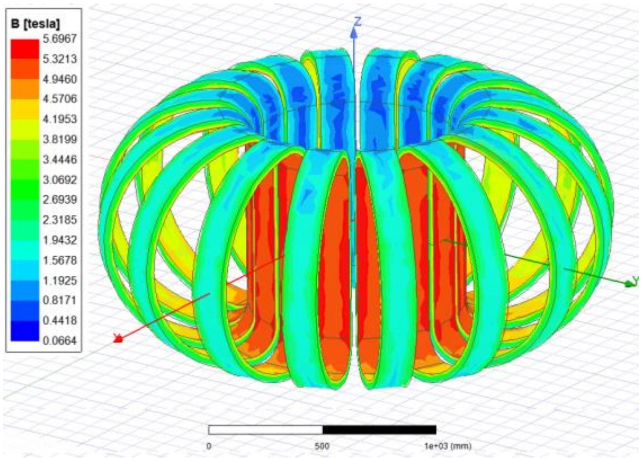
- Has Higher Mechanical Stability
- Features a More Compact Structure with Higher Energy Density

# 2、 Design of Superconducting Magnet

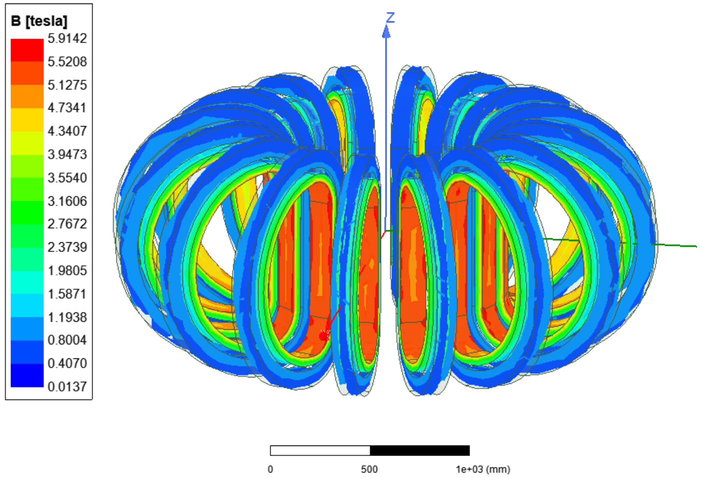
## ■ Comparison of Plans




❑ Pure $MgB_2$ magnet




❑ Pure YBCO magnet




❑ $MgB_2$+YBCO hybrid magnet

| Project | Pure $MgB_2$ magnet | Pure YBCO magnet | $MgB_2$+YBCO hybrid magnet |
|---|---|---|---|
| **Operating current *I*op** | 1400A | 1650A | 1600A |
| **Length of wire *L*wire** | >1150km（φ1.0mm multicore） | >235km(4.0mm narrow tape) | 166km($MgB_2$)， 155km(YBCO) |
| **Highest magnetic field** | 2T | 6T | 1.25T($MgB_2$), 5.91T(YBCO) |
| **Magnet volume** | large（φ5.0*2.5m) | small（φ2.2*1.2m） | smaller（φ3.0*1.3m） |

# 2、 Design of Superconducting Magnet

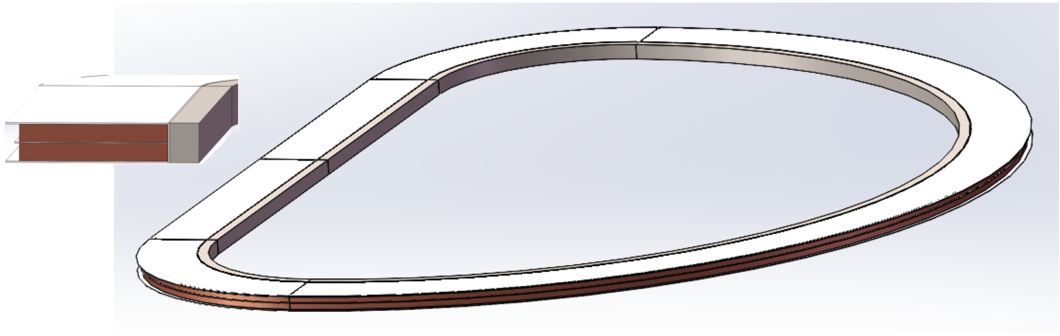
## ■ Main Design Parameters of Superconducting Magnets

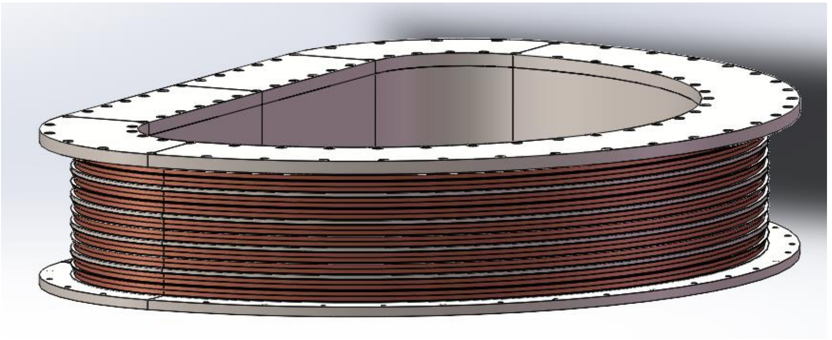
| Project | | | parameters |
|---|---|---|---|
| Overall Parameters | Maximum Operating Voltage | | **10 kV** |
| | Maximum Operating Current | | **1600 A** |
| | Maximum Operating Temperature | | **20 K** |
| | Maximum Stored Energy | | 11.9 MJ |
| | Maximum Effective Output Energy | | **10 MJ** |
| | Design Inductance | | **9.3 H** |
| | Maximum Outer Diameter | | 2800 mm |
| | Maximum Height | | 1280 mm |
| | Magnet Mass | | ~12 000 kg |
| | Cooling Method | | Liquid Hydrogen Immersion Cooling |
| Base Supercon-ducting Materials | $MgB_2$ Supercond-ucting Wire | Diameter | 1 mm |
| | | Critical Current (20K, 1.5T) | >200 A |
| | | Wire Length | 166 km |
| | YBCO Supercond-ucting Tape | Width | 4.5 mm |
| | | Thickness | 0.075 mm |
| | | Critical Current (20K, 3.5T) | 320 A |
| | | Tape Length | 155 km |

| Project | Parameters | |
|---|---|---|
| | $MgB_2$ | YBCO |
| Coil Height $H_{mag}$ | 1272.0 mm | / |
| Magnet Cable Length $L_{mag\_cable}$ | 4762 m | 18504 m |
| Tape/Wire Length $L_{wire}$ | 166 km | 155 km |
| Maximum Surface Magnetic Field $B_{max}$ | 1.25 T | 5.91 T |
| Surface Magnetic Field (Vertical Field) $B_{ymax}$ | / | 3.55 T |
| Coil Self-Inductance $L$ | 0.42 H | 6.4 H |
| Total Magnet Inductance | Two magnets in series: 9.3 H (Mutual Inductance 1.22 H) | |

# 2、 Design of Superconducting Magnet

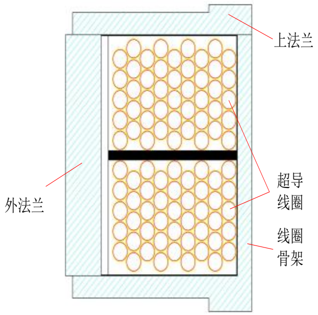
## ■ Structural Design

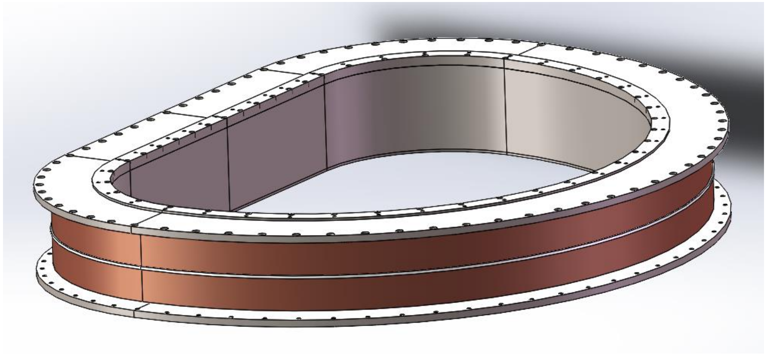




❑ **Schematic diagram of YBCO double-pancake superconducting coil structure** ❑ **Structure of YBCO Superconducting Coil Assembly**

Double pancake YBCO coil winding →Assemble coil onto non-metallic core tube (interlayer non-metallic insulation and liquid hydrogen flow channels)→Install top and bottom flanges →Weld internal current leads →Assemble external fixing ring→ Fabricate external current leads → Overall Vacuum Epoxy Casting and Curing → Complete the Single YBCO Superconducting Coil



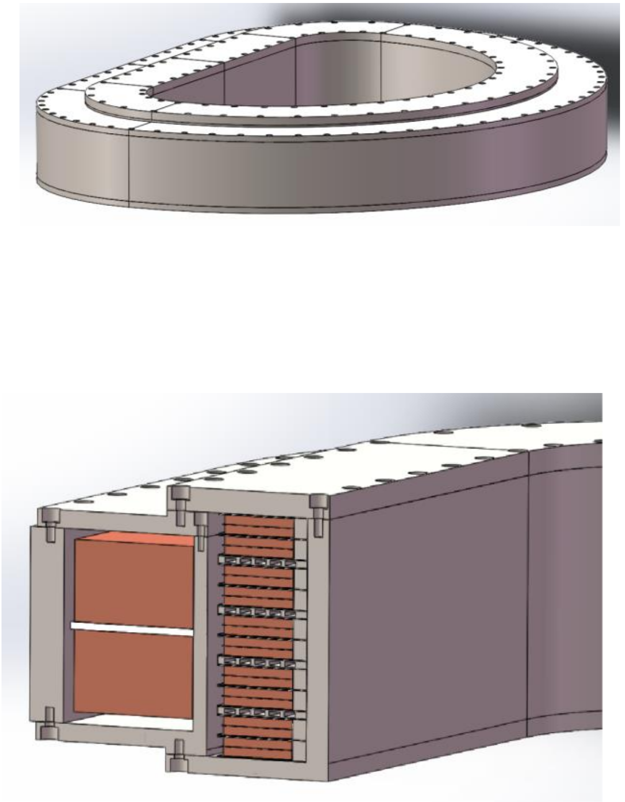
❑ **Design Scheme for $MgB_2$ Superconducting Coil Structure** ❑ **Structure of $MgB_2$ Superconducting Coil Assembly**

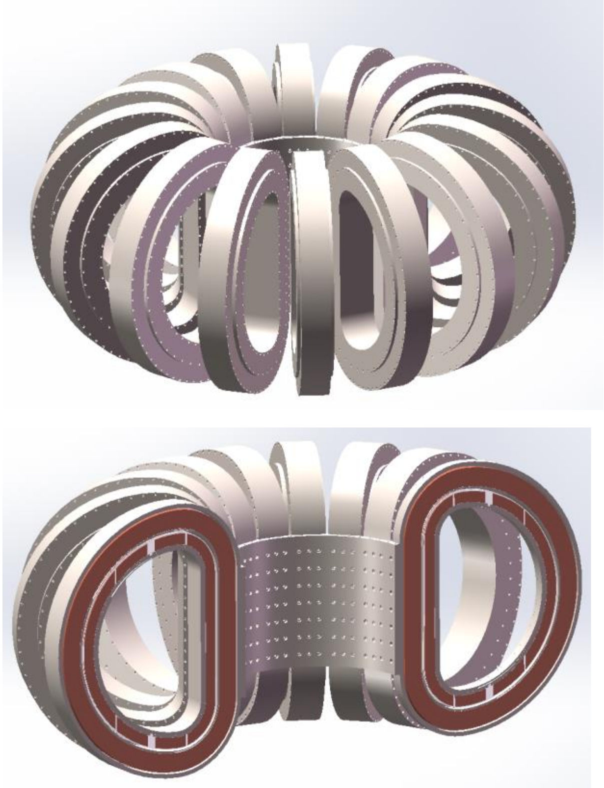
$MgB_2$ solenoid coil winding→ Install outer flange (316L) → Install top flange (316L) → Overall heat treatment →Overall vacuum epoxy casting and curing → Current lead processing → Complete the Single $MgB_2$ Superconducting Coil

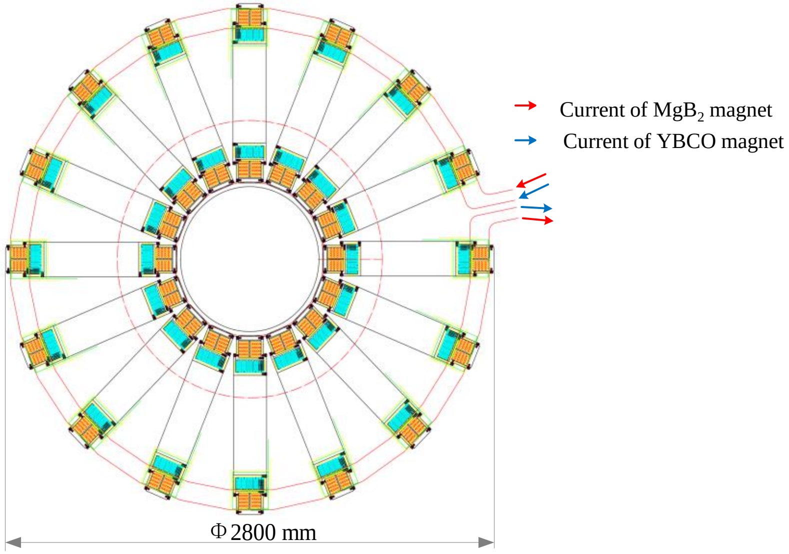
# 2、 Design of Superconducting Magnet

## ■ Structural Design

### Overall structural design scheme of $MgB_2$+YBCO hybrid superconducting coil







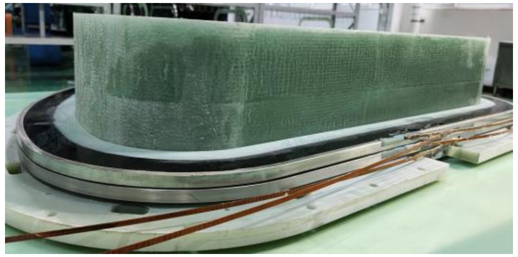

- ❑ **$MgB_2$+YBCO hybrid superconducting coil**
- ❑ **Schematic diagram of 10 MJ superconducting magnet structure**
- ❑ **Schematic diagram of current connection for 10 MJ superconducting magnet**

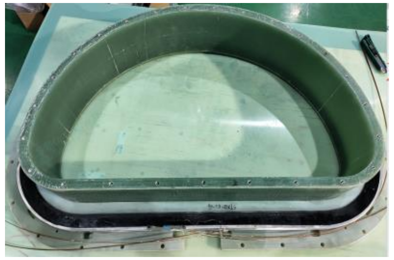
$MgB_2$ solenoid coil is assembled outside the YBCO coil (16 sets) → The coil sets are installed circumferentially on a 316L stainless steel core tube (each of the 16 sets is installed separately) → Forming a toroidal magnet

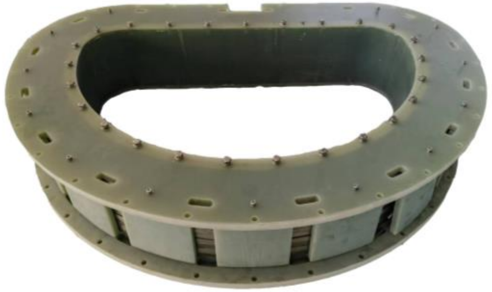
# 2、 Design of Superconducting Magnet

## ■ Structural Design

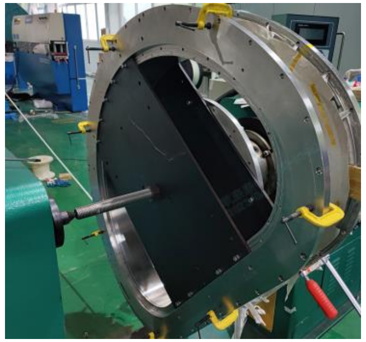
**YBCO superconducting magnet**

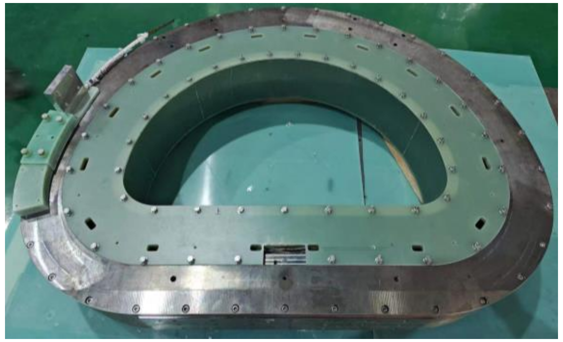






**$MgB_2$ superconducting magnet**

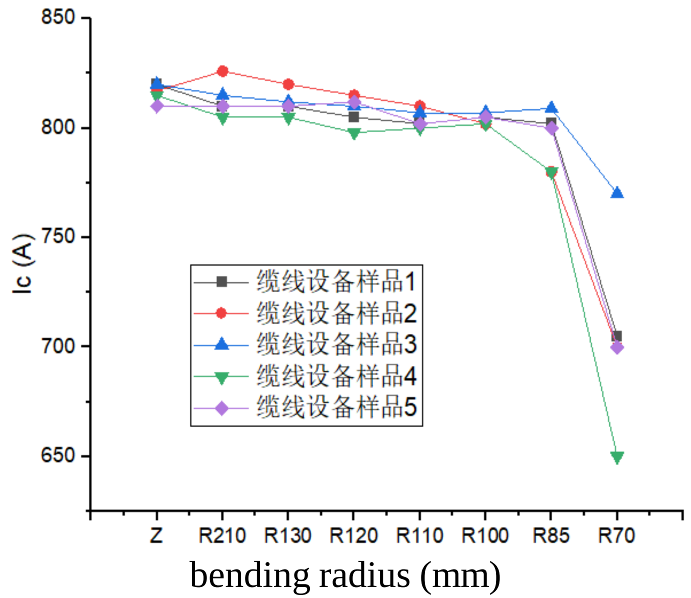


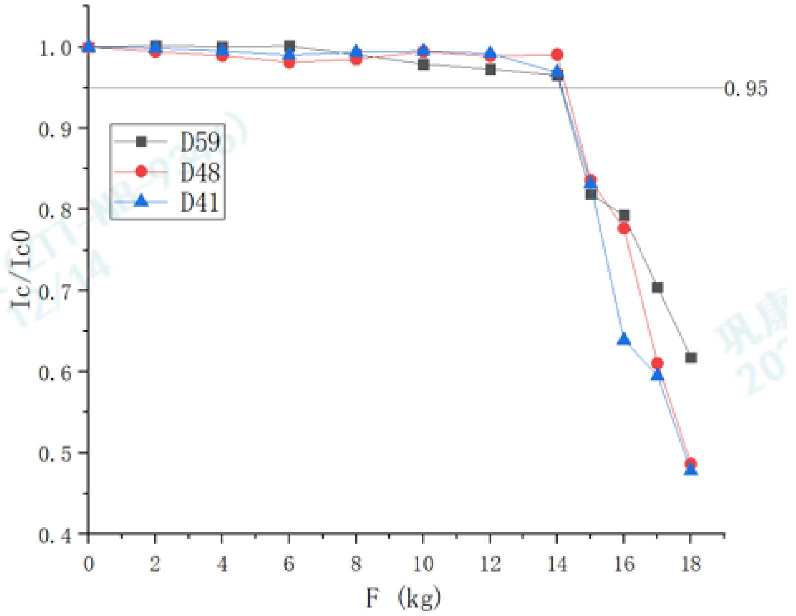


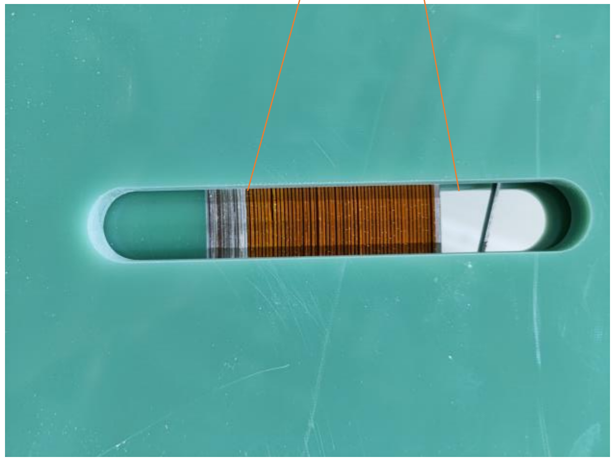
**Hybrid superconducting magnet**

# 3、Superconducting Cable Research

## ■ YBCO Stacked Cable Development



**8+2 HTS Stacked Cable**

- Short Sample **Ic=840 A**, with stable performance across multiple sample tests.
- Under **R85** bending, there is no retreat, and the bending strain is 0.35% without retreat, meeting the requirement of magnetic winding bending radius R120.

- Degradation begins under a tensile force greater than 140 N for a single HTS tape. After testing, the stacked cable equipment was found to withstand a tensile force of 11N on a single tape at the winding reel position, which is much lower than the maximum tensile force of 140N on a single tape.

# 3、 Research on Superconducting Cables

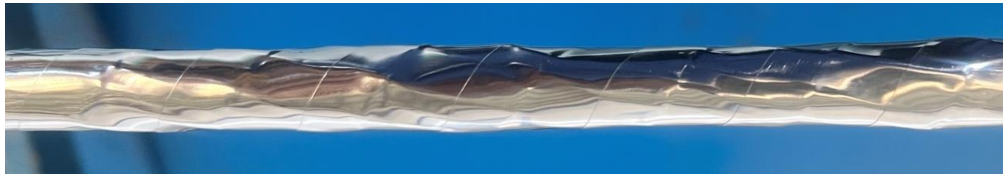
## ■ Development of MgB2 cable

Primary Cable


Secondary Cable


Tertiary Cable

| $MgB_2$ Cable | Design Pitch | Measured Pitch |
|---|---|---|
| Primary Cable | 35±2mm | 35mm |
| Secondary Cable | 85±5mm | 86mm |
| Tertiary Cable | 120±10mm | 127mm |
| Cable Structure | 3*3*4*Φ1.0mm | |



Tertiary Cable with Wound Steel Tape

## ■ Development of MgB2 cable

Completion of a single 300-meter $MgB_2$ superconducting cable

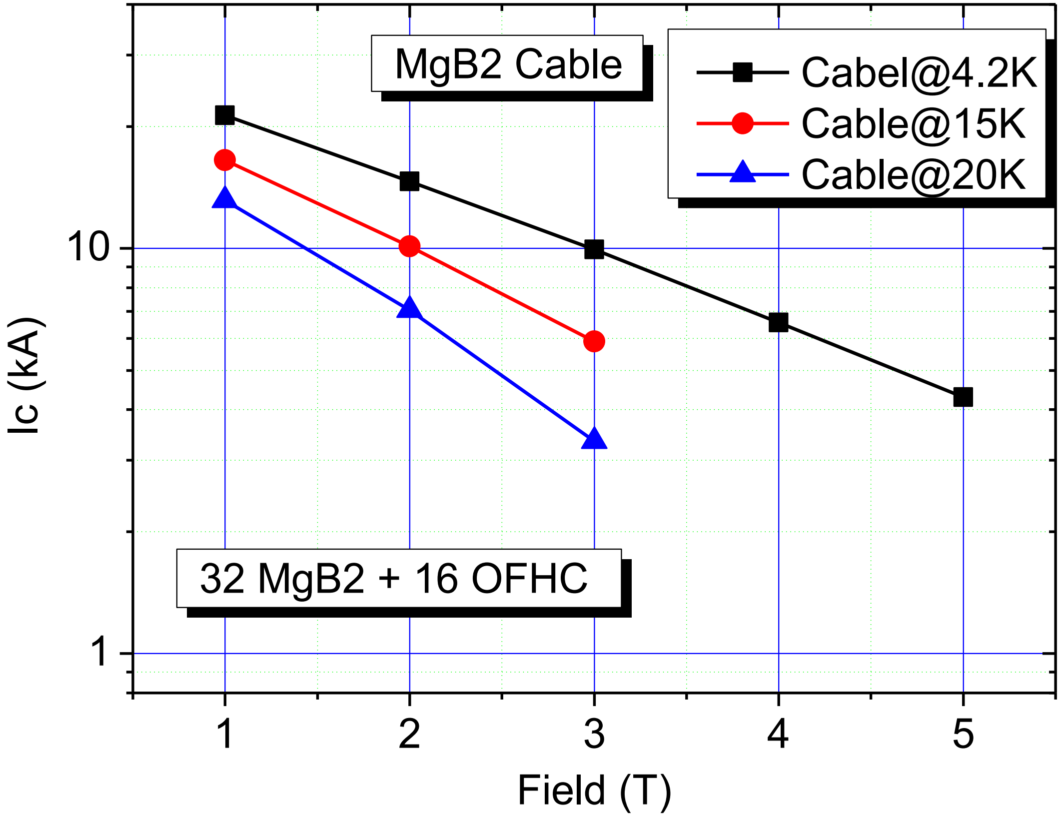
$MgB_2$ Primary Cable

$MgB_2$ Cable

300-meter $MgB_2$ Cable

# 3、 Research on Superconducting Cables

## ■ Development of MgB2 cable



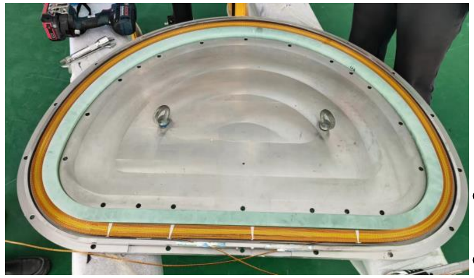

| Test Temperature | Background Field | Critical Current |
|---|---|---|
| 4.2 K | 4 T | 6.56 kA |
| 20 K | 2 T | 7.04 kA |

# 4、Development and Testing of Superconducting Coil Modules

## ■ Superconducting Magnet Technology Validation

Completed the development of one set of superconducting magnets with full parameters. Conducted current flow tests and insulation withstand voltage tests under liquid helium immersion cooling, systematically validated the material preparation, cable manufacturing, coil manufacturing, magnet insulation, and structural mechanical stability.

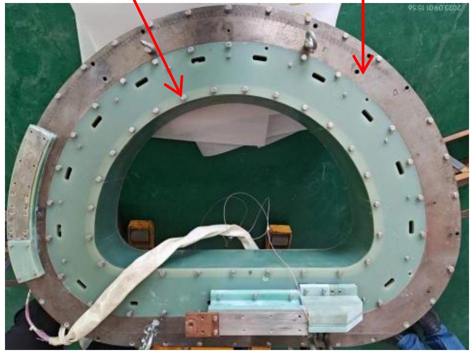
**Heat treatment of MgB2 coil**



**Single YBCO double-pancake coil**

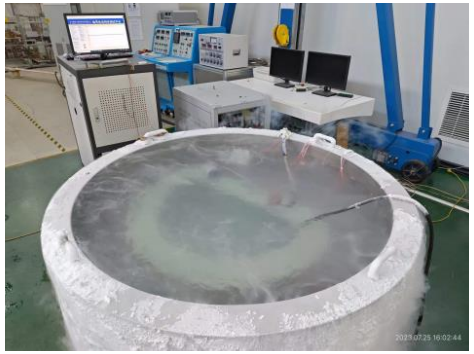
**YBCO coil**

**$MgB_2$ coil**

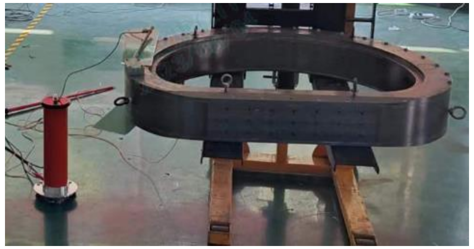


**Integrated superconducting magnet**

- **$MgB_2$ Coil**: 90 turns, 280m cable
- **YBCO Coil**: 10 double-pancake coils in series, each double-pancake coil with 44 turns and 113 meters of cable, totaling 1130 meters of cable.



**Cryogenic cycling and YBCO current flow testing of integrated system under liquid nitrogen**

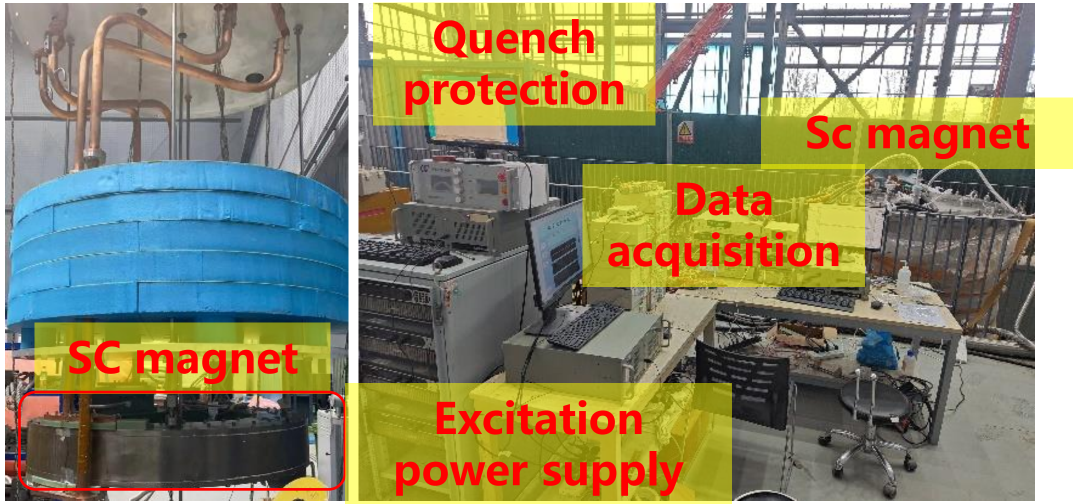


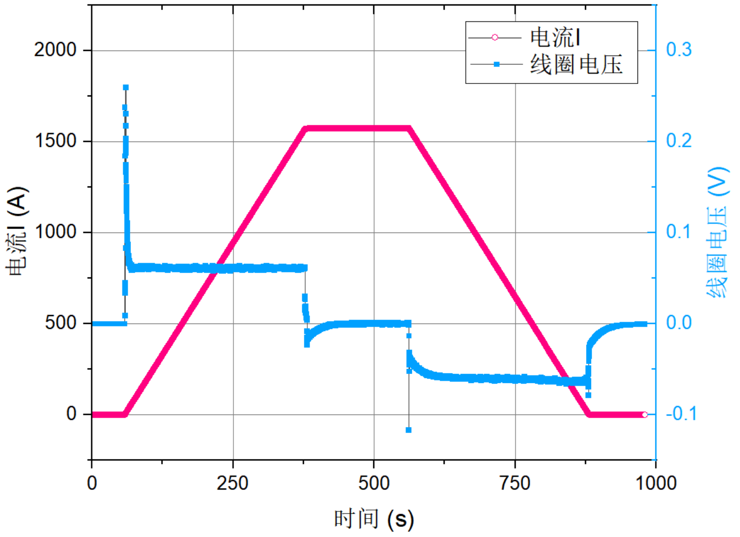
**15kV DC withstand voltage test**

## ■ Superconducting Magnet Technology Validation

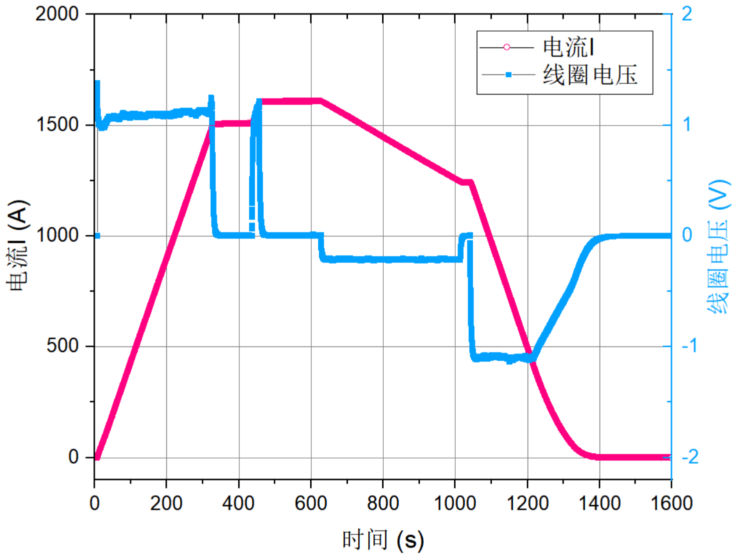
Current flow testing with solid nitrogen cooling, validating structural mechanical stability:

- MgB2 Coil: Individual current flow of 1600 A;
- YBCO Coil: Individual current flow of 1600 A;
- Hybrid Coil: Overall current flow of **1600 A (design value)**

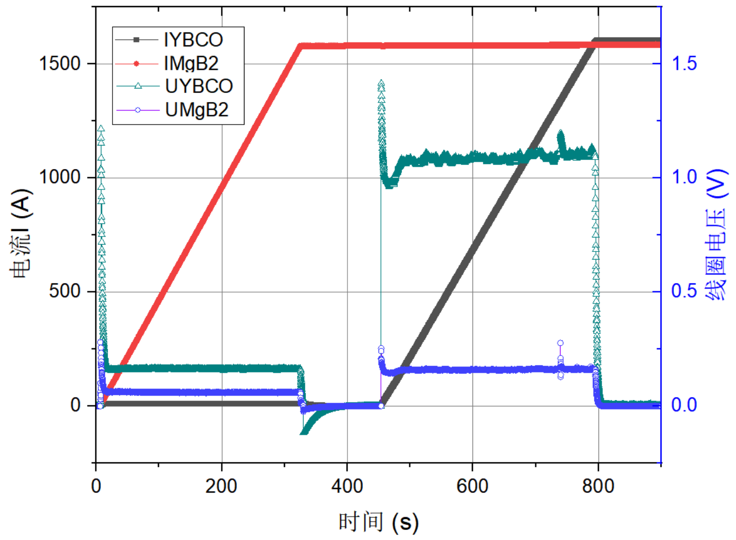



**$MgB_2$ Coil individual current flow of 1600 A**




**YBCO Coil individual current flow of 1600 A**




**MgB2+YBCO Coil Current Flow of 1600 A**

# Thanks!