LECTURE for ASSCA2026

Feb 3 2026

Superconducting Magnets for Particle Accelerators

From LTS to HTS: Recent Advances, Challenges, and Expectations for Future

Technology
LTS → HTS

Field Strength
14 T → 20 T

Qingjin XU IHEP-CAS

LECTURE STRUCTURE

Lecture Overview

01 Fundamentals

Fundamental role of superconducting magnets in modern particle accelerators and key performance metrics

02 LTS Technology

Nb-Ti and Nb_3Sn — the proven workhorses powering current-generation accelerators like LHC

03 HTS Technology

REBCO and Bi-2212 high-temperature superconductors enabling fields beyond LTS

04 Critical Challenges

Quench protection, mechanical stress, manufacturing complexity, and cost barriers

05 ReBCO Quench Protection

Comprehensive analysis of detection, propagation, and protection strategies for ReBCO magnets

06 Roadmap for Future

Pushing the Boundaries of Magnetic Field Technology

07 Case Study: High Field Magnet Progress at IHEP-CAS

CHAPTER 01

Fundamentals

Why Superconducting Magnets Are Essential for Modern Accelerators

The Physics Behind High-Energy Particle Colliders

Particle Accelerator Physics: The Magnetic Field Challenge

The Physics Challenge

Particle accelerators require intense **magnetic fields to steer and focus high-energy particle beams** along curved trajectories. The **required bending radius is inversely proportional to magnetic field strength** — doubling the field allows half the circumference for the same particle energy.

> **Key Principle:** Higher magnetic fields enable more compact and cost-effective accelerators

LHC Example

8.33 Tesla dipoles bend 7 TeV protons around 27 km circumference. Without superconductivity, power consumption would exceed **1 GW**.

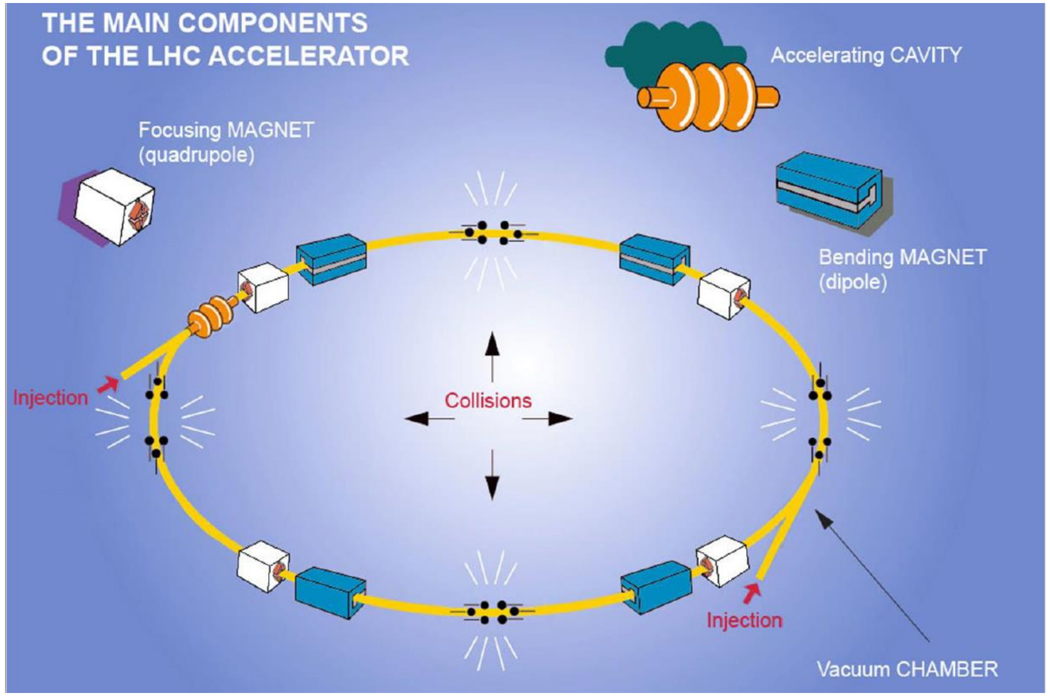
Superconductivity Advantage

Superconducting materials exhibit **zero electrical resistance** below critical temperature, enabling persistent current operation with negligible energy loss.

- **High current densities** (500-1500 A/mm^2 engineering)
- **Compact magnet designs with minimal heat generation**
- **Continuous operation** at cryogenic temperatures (1.9-4.2 K)

LHC Main Dipoles

1232 Dipole Magnets	**8.33 T** Dipole Field
1.9 K Operating Temp	**27 km** Bending Radius



Superconductivity Fundamentals: Zero Resistance and Critical Parameters

The Critical Surface

Superconductors have three critical parameters that define their operating envelope. Exceeding any limit causes a transition to the normal (resistive) state.

1. **Critical Temperature (Tc)**
   Maximum temperature for superconducting state
2. **Critical Field (Hc)**
   Maximum magnetic field
3. **Critical Current (Jc)**
   Maximum current density at given B, T

LTS vs HTS Critical Parameters Comparison

Material	Tc	Hc2 (4.2K)	Operating T	Status
Nb-Ti	9.2 K	~10 T	1.9-4.2 K	**Mature**
Nb_3Sn	18 K	~28 T	1.9-4.2 K	**Advancing**
REBCO	90-95 K	>100 T	4-50 K	**Emerging**

Type I vs Type II Superconductors

Accelerator magnets require Type II superconductors that can maintain superconductivity in high magnetic fields through partial flux penetration.

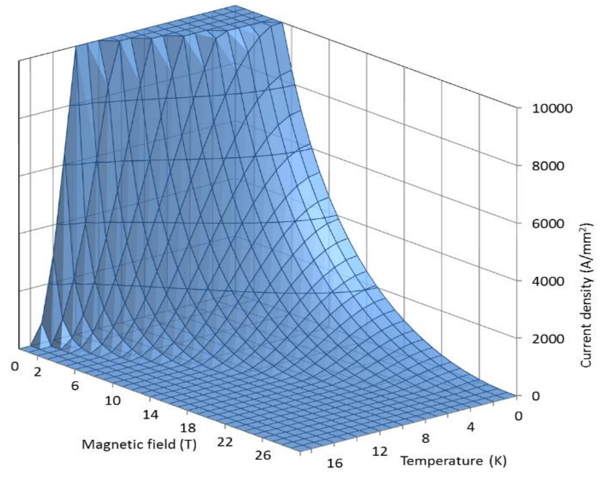
Type I (Soft)

Complete Meissner effect, low Hc. Not suitable for high-field magnets.

Type II (Hard)

Partial flux penetration, high Hc2. Required for accelerator applications.

Key Point: All practical accelerator superconductors (Nb-Ti, Nb_3 Sn, REBCO, etc) are Type II materials.



Dipole vs. Solenoid

Dipole

$$B = \mu_o J_e \frac{t}{2}$$

J_e – *Current density*

t – *Coil thickness*

- *Different coil configurations*

$$B_{dipole} = \frac{1}{2} B_{solenoid}$$

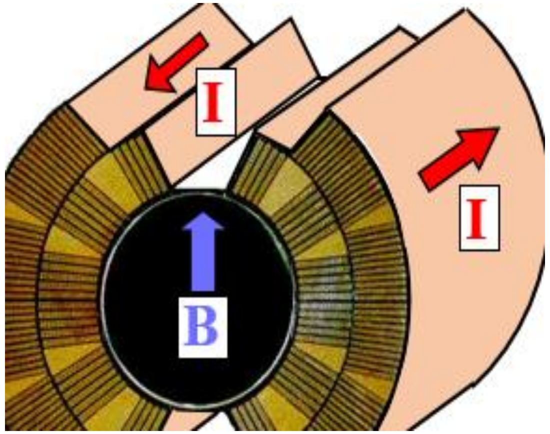
- *Limited coil width for dipole*
- *Magnetic shielding*
- *Cost*

Solenoid

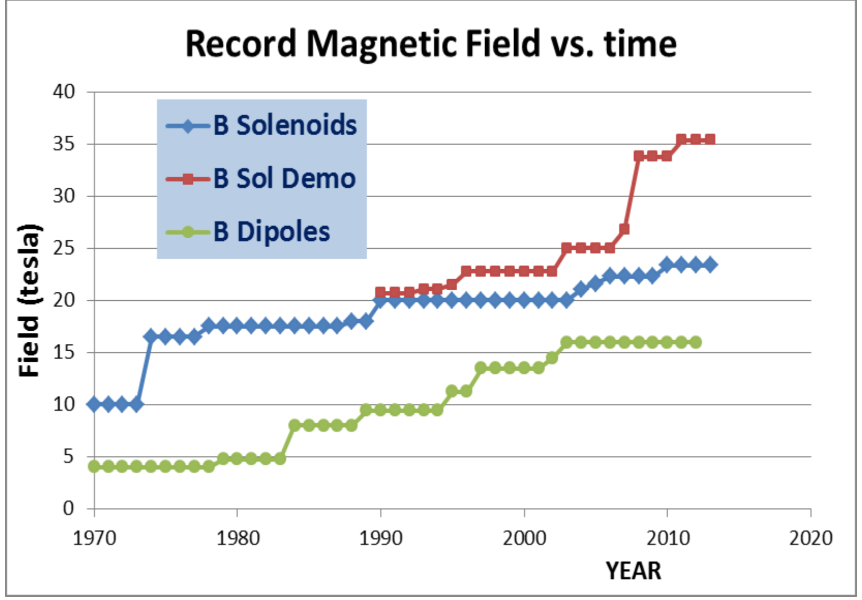
$$B = \mu_o J_e t$$

J_e – *Current density*

t – *Coil thickness*



LHC dipole



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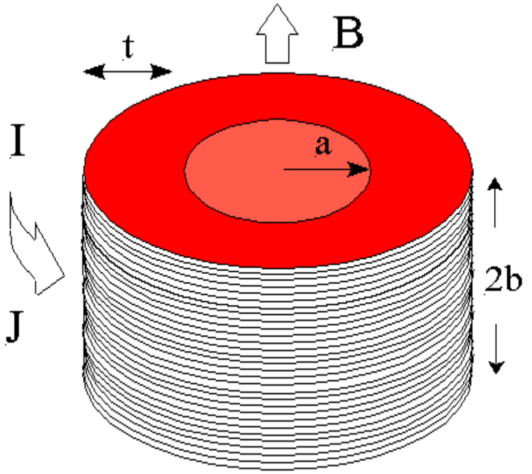

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CHAPTER 02

LTS Technology

Nb-Ti and Nb_3Sn — The Workhorses of Current-Generation Accelerators

Proven Technology Powering LHC, Tevatron, and RHIC

PROVEN TECHNOLOGY

Niobium-Titanium (Nb-Ti): The Industry Standard

Material Properties

Nb-Ti is a ductile alloy that enables conventional wire drawing and cable fabrication. This exceptional workability makes it the industry standard for accelerator magnets.

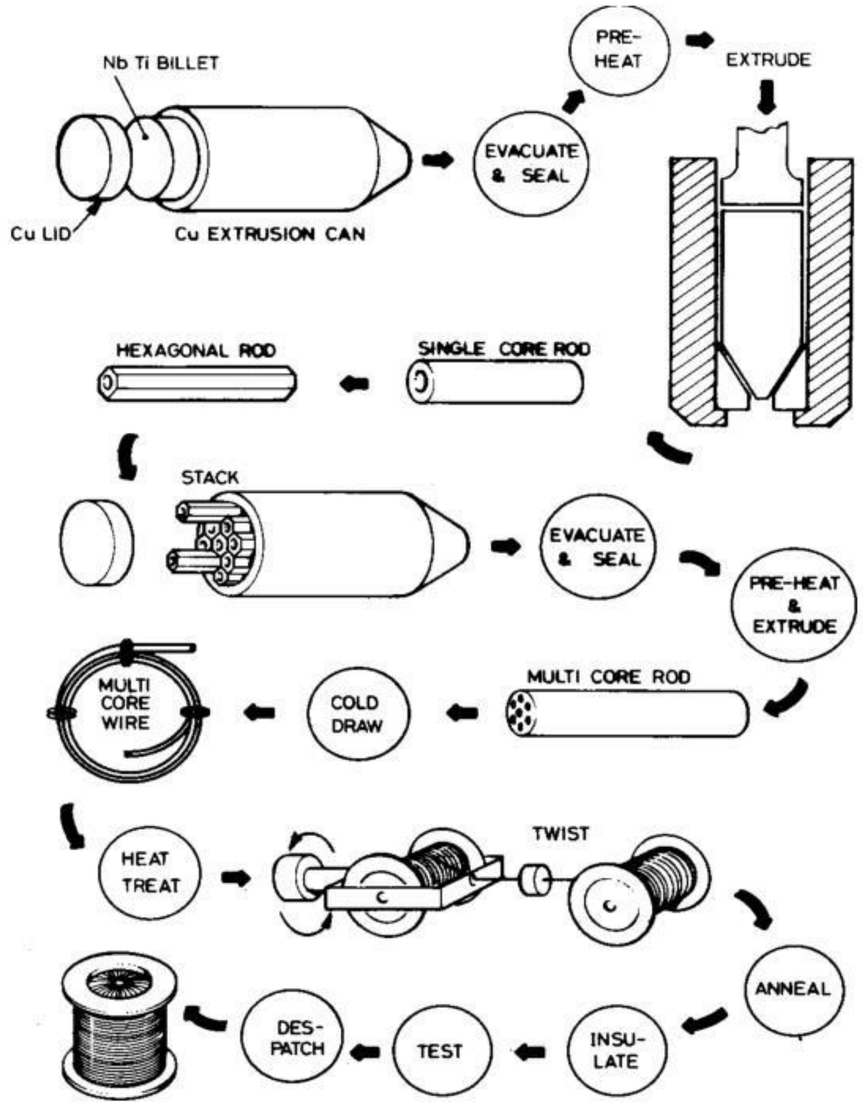
Critical Temperature	Field Limit @ 4.2K	Jc @ 5T, 4.2K
9.2 K	~10 T	~3000 A/mm^2 (non-Cu)

Manufacturing Process

1. **Billet Assembly**
   Stack Nb-Ti rods in Cu matrix (150-250 mm diameter)
2. **Hot Extrusion**
   Achieve metallurgical bond at elevated temperature
3. **Cold Drawing**
   Reduce to final wire diameter with area reductions
4. **Heat Treatment**
   380-400°C for ~100h total to optimize α-Ti precipitates

Applications

LHC, Tevatron, RHIC, and most operating accelerators



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PROVEN TECHNOLOGY

Niobium-Tin (Nb_3Sn): The High-Field Enabler

Material Properties

Nb_3Sn is an intermetallic compound with superior high-field performance compared to Nb-Ti, but requires complex heat treatment.

Critical Temperature	Practical Limit
18 K	~16 T
Upper Critical Field	**Jc @ 12T, 4.2K**
28-30 T	>2650 A/mm^2

"Wind-and-React" Challenge

The brittle intermetallic requires a complex manufacturing process:

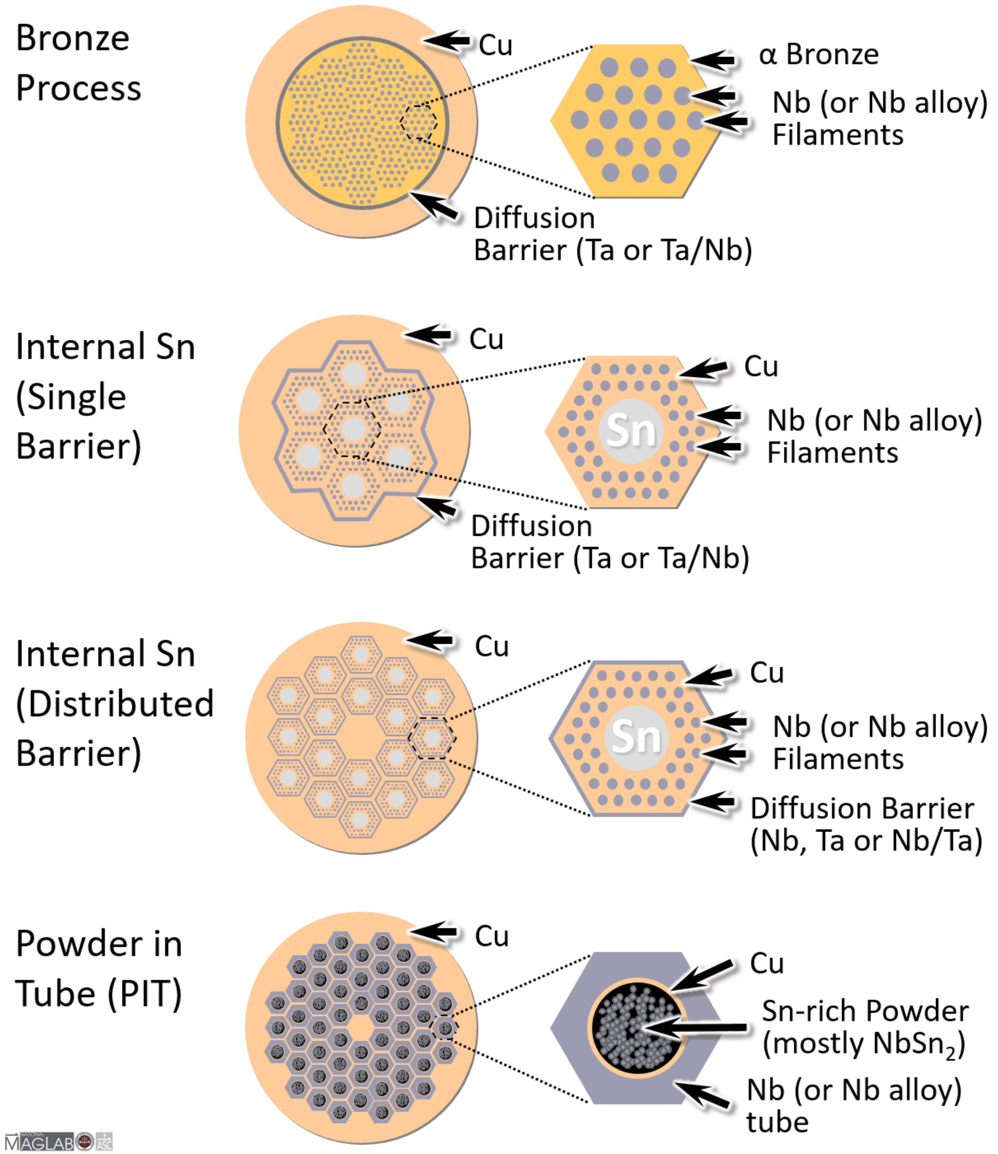
1 Coil wound with unreacted strands

2 Heat treatment at 650-750°C for 100-200 hours

3 Forms superconducting A15 phase in situ

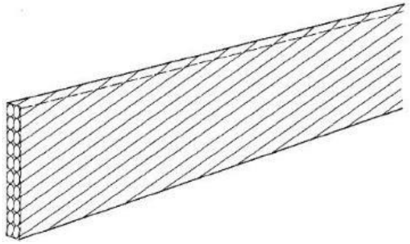
Key Applications

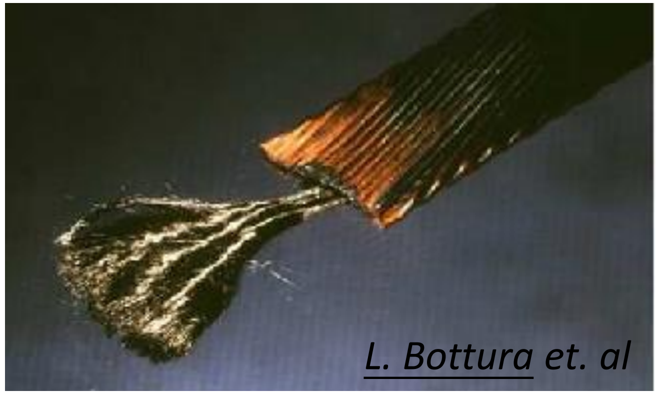
HL-LHC 11T Dipoles — First operational Nb_3Sn in a collider



PROVEN TECHNOLOGY

Rutherford Cable





1 Rectangular Cable

Form rectangular cable with narrower width and lower packing factor using 42-spool compact cabling machine

2 Keystone Cable

Keystoning using two-roll die with variable gap, fixed keystone angle and cable width

Key Challenge: Maintaining mechanical stability while minimizing damage to delicate internal architecture of RRP Nb_3Sn strands

HL-LHC 11T Dipole Cable Specifications

Strands	Width	Keystone Angle
40	14.7 mm	0.79°
Mid-Thickness	**Transposition**	**Cabling Degradation**
1.269 mm	15°	<3.5%

Strand Diameter Measurement

Verify 0.700±0.003 mm specification

Cross section Inspection

Check for imperfections (crossovers) during fabrication

Dimensional Control

Cable thickness and width measurements every 3 cm

Microstructural Analysis

Cross-section analysis for internal damage

Electrical Characterization

V-I and V-H tests at 4.2K and 1.9K

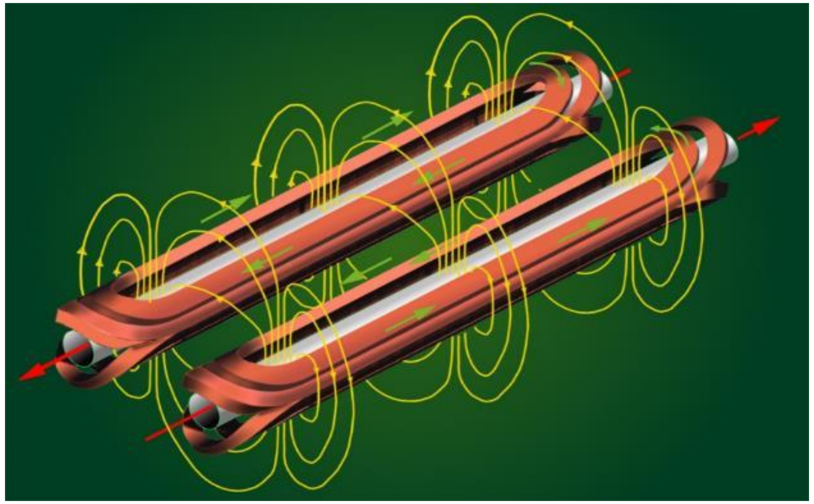
PROVEN TECHNOLOGY

Coil Configurations for Dipole Magnets

Efficiency, field quality, stress management, quench protection...

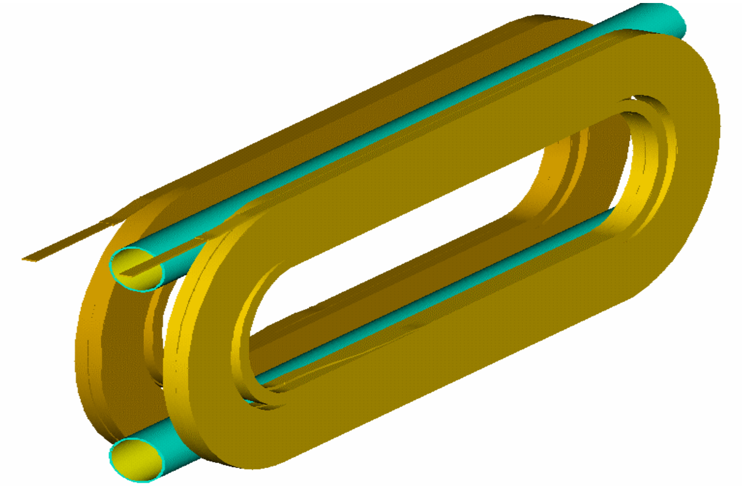
Cos-**th**eta dipole

Highest efficiency, complicated ends with hard-way bending



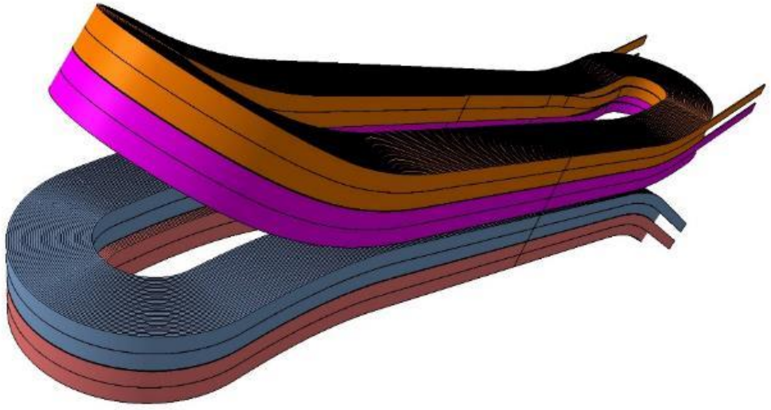
Common coil dipole

Simplest structure with large bending radius, lower efficiency



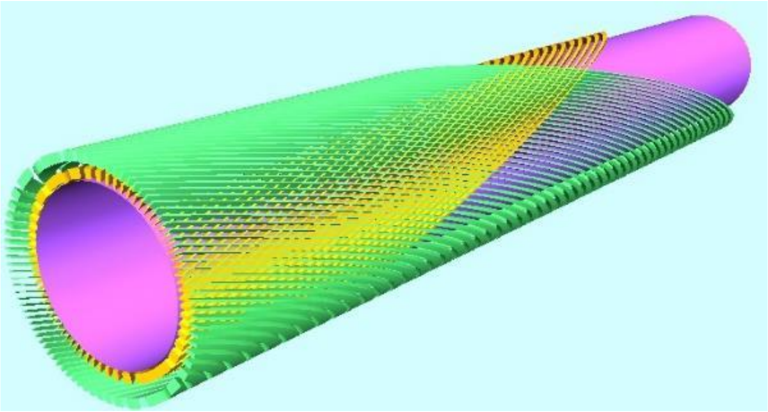
Block type dipole

Simpler structure with hard-way bending, lower efficiency



Canted cos-theta dipole

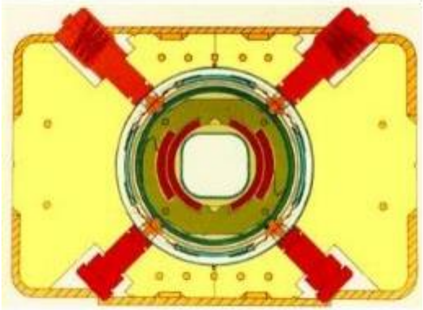
Lowest stress level in coil, lowest efficiency

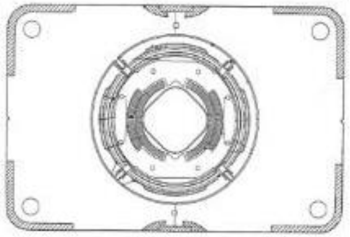


PROVEN TECHNOLOGY

The Dipole Magnets in Past Years

Tevatron





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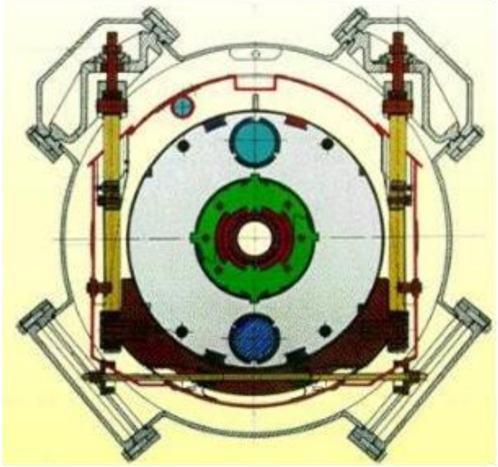

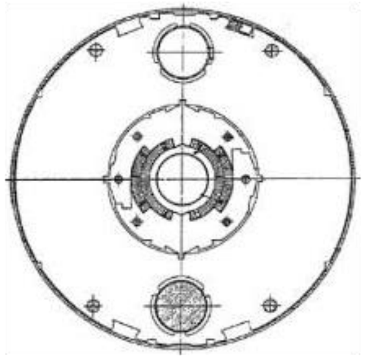

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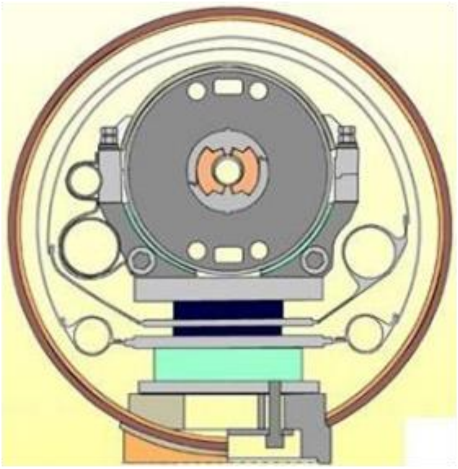
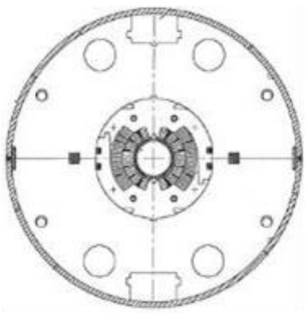
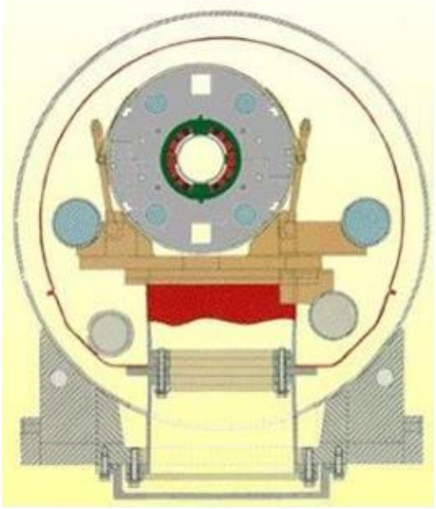
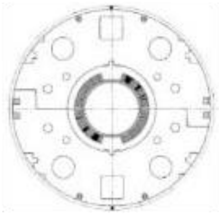


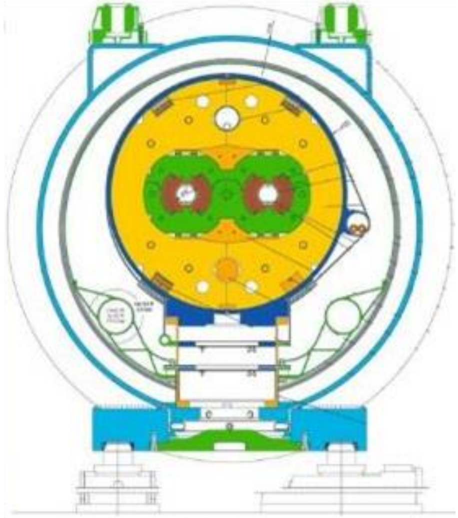


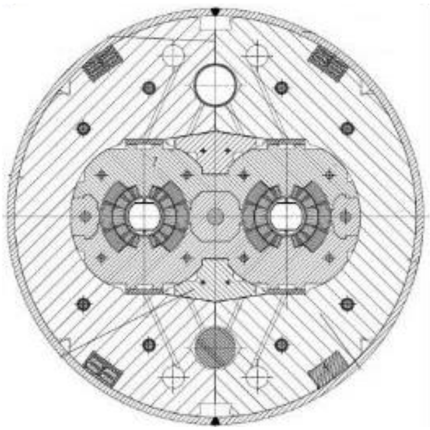
RHIC





LHC





HTS Technology

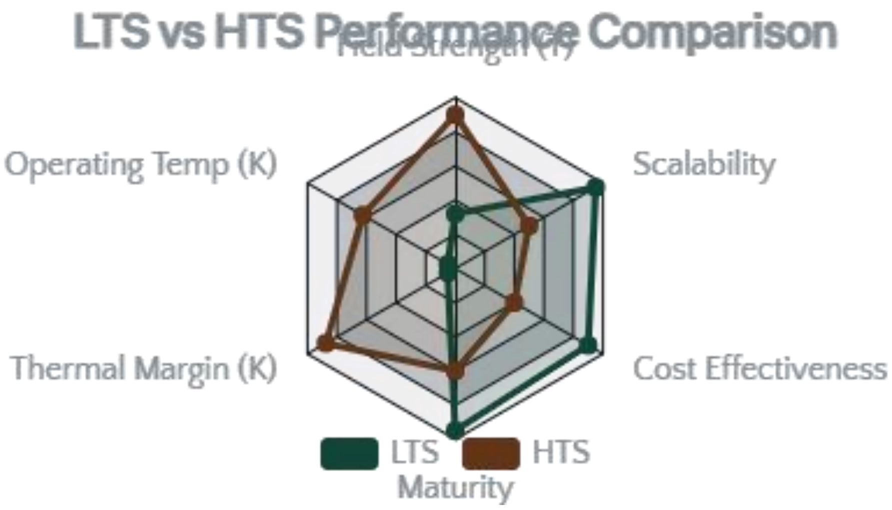
Enabling Fields Beyond LTS

The Next Generation of High-Field Superconductors

Technology Comparison: LTS vs HTS Performance Summary

LTS Technology: Proven and Mature

- **Nb-Ti:** 8-10 T capability, mature manufacturing
- **Nb_3Sn:** HL-LHC demonstrating 11-14 T
- 16 T target within reach with ongoing R&D
- Practical limit ~16 T



HTS Technology: Breaking Barriers

- **48.7 T** demonstrated, **35.1 T** full SC
- **20-50+ T** fields achievable
- Operates at **4-50 K** with large thermal margins
- Hybrid: practical path to 20 T

HTS vs LTS Operating Envelope

Temperature Range
LTS: 1.9-4.2 K
HTS: 4-50 K

Field Capability
LTS: 10-16 T
HTS: 20-50+ T

Thermal Margin
LTS: 2-4 K
HTS: 10-80 K

Cost
LTS: Low
HTS: High to Moderate

Entering the HTS Era: REBCO and Bi-2212 Superconductors

Rare-Earth Barium Copper Oxide REBCO

Tc (YBCO)	@ 20K
90-95 K	>35 T
Operating	Hc2 limit
4-50 K	100+ T

2G Tape Technology

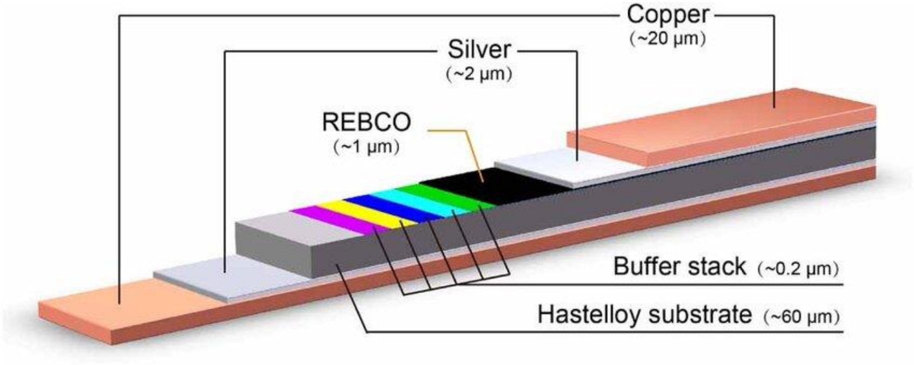
Tape Architecture: ~4-12 mm wide, ~0.1 mm thick multilayer structure: Hastelloy substrate + buffer layers + 1-2 μm REBCO film + Ag cap + Cu stabilizer.

Advantages

- No reaction heat treatment
- Industrial availability
- High strength substrate
- Operates at 20-50 K

Challenges

- Strong anisotropy
- Delamination, limited bending radius
- Screening currents
- High cost



Bismuth Strontium Calcium Copper Oxide Bi-2212

Tc	@ 4.2K
~85 K	~20 T
Operating	Wire
4-20 K	Round

Isotropic Round Wire

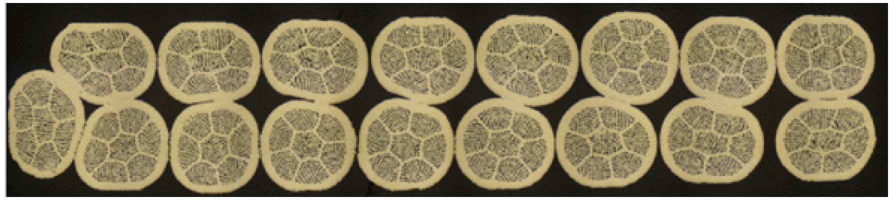
Wire Architecture: Multifilamentary round wire in Ag matrix, 0.8-1.4 mm diameter, 500-1000 filaments. Requires over-pressure reaction (OPR) at 50-100 bar, 880-900°C.

Advantages

- Isotropic properties
- No field orientation dependence
- Built-in current sharing
- Compatible with cosine-theta coils

Challenges

- Complex reaction process
- Ag matrix cost
- Filament uniformity
- Strain sensitivity



All-HTS 20+ Tesla Accelerator Magnet?

- **Precondition (Iron based conductor, ReBCO, Bi-2212,…)**
  - ➢ The Je of the HTS conductors is high enough for accelerator application
  - ➢ The cost is lower than or similar with the LTS conductors
  - ➢ Mechanical performance is qualified

- **Main challenges of the HTS technology**
  - ➢ Quench protection： quench propagation speed of HTS conductors is about two orders of magnitude lower than the LTS case
  - ➢ Cable fabrication： how to fabricate high-current cable with tapes?
  - ➢ Coil layout： compact, high efficiency, stress control, …
  - ➢ Field quality control： 10-4 field uniformity needed for accelerators

- **Advantages of the all-HTS magnet：**
  - ➢ Possibility of raising the operation temperature of the magnet （4.2K -> ?K）

Hybrid Magnets: Combining LTS and HTS for 20+ Tesla

The Hybrid Concept

Hybrid magnets strategically combine HTS for high-field regions (where LTS cannot operate) with LTS for lower fields (where it is cost-effective).

Field Distribution

Inner Coils (HTS)	REBCO (30-50mm bore)
Outer Coils (LTS)	Nb_3Sn and Nb-Ti

REBCO tape operates at >15 T where Nb_3Sn is limited

Nb_3Sn and Nb-Ti provide cost-effective background field

Key Design Innovations

1. Common Coil Design
   Simplest structure
2. Shell-based Structure
   Using shrink stress after cooling
3. Field Quality
   Reduces persistent current harmonics

20+T Hybrid Accelerator Magnet Design

Central Field	Aperture
20+ T	30~50 mm
Stored Energy	Yoke Diameter
2+ MJ/m	900 mm

Hybrid Benefits

Cost Reduction	Field Increase
30-40%	25-30%

CHAPTER 04

Critical Challenges

Quench Protection, Mechanical Stress, and Manufacturing Barriers

Overcoming Technical Hurdles on the Path to 20+ Tesla

CRITICAL CHALLENGE 1

Quench Detection and Protection in HTS Magnets: Overview

The Fundamental Problem

Quench protection in HTS magnets is fundamentally different and more challenging than LTS due to dramatically slower normal zone propagation.

LTS Magnets	HTS Magnets
m/s	**cm/s**
Normal Zone Propagation	Normal Zone Propagation

2-3 Orders of Magnitude Slower!

Voltage Detection Limitations

- Inductive voltage from ramping masks resistive signals
- Power supply noise interferes with μV-level detection
- Small normal zones generate insufficient voltage

Required Sensitivity

10^{-8}-10^{-9} Ω

Innovative Detection Methods

Fiber Optic Sensors (FBG)

Detect localized temperature changes through wavelength shifts

Acoustic Detection

Active ultrasonic methods using Doppler effect

Heating causes local sound velocity variation

Split Conductor

Two parallel conductors with SC joints

Protection Strategies

Passive

- Non-Insulated
- Metal-Insulated
- AC Loss

Active

- Heaters
- CLIQ

CRITICAL CHALLENGE 2

Mechanical Stress and Strain Management

Electromagnetic Forces

High-field magnets experience enormous electromagnetic forces that threaten structural integrity.

$$P = B^2 / (2\mu_0)$$

Electromagnetic Pressure

8 T	25 MPa
16 T	100 MPa
21 T	175 MPa
30 T	360 MPa

Strain Degradation Risk

REBCO tapes are extremely sensitive to strain. Excessive bending or tensile stress degrades critical current irreversibly.

Bending Strain	Tensile Strain
<0.3-0.5%	<0.4-0.6%

Compressive Strain

Can cause delamination

Challenge: Manage high magnetic stress while keeping REBCO strain <0.4%

Manufacturing Limits of the ReBCO coils

- Bending radius: 15-30 mm
- Complex coil ends challenging
- Anisotropic properties

CRITICAL CHALLENGE 2

Field Quality and Harmonics Control

Field Harmonics as Diagnostic Tool

Field harmonics offer a powerful tool to examine mechanical structure of accelerator magnets. Large deviation from nominal values suggests mechanical defects.

RHIC Experience

Field quality analysis identified two magnets with flaws before they left the factory

Harmonic symmetry reveals defect location

Trends indicate tooling wear or gradual changes

HL-LHC Challenges

Quench Training

Nb_3Sn magnets require 20-30 training quenches to reach design field

Due to epoxy cracking and mechanical settling

Degradation Control

Managing strain degradation during cooldown critical

Conductor performance sensitive to mechanical stress

Key Innovation

First operational use of Nb_3Sn in a collider, proving high-field LTS technology at industrial scale

LHC Field Quality Excellence

Integrated Field Uniformity

<1 unit (10^{-4})

Achieved through precision coil geometry and iron yoke optimization

CRITICAL CHALLENGE 3

Screening Current Effects and Field Quality Challenges

The Screening Current Problem

HTS materials exhibit persistent shielding currents that oppose changes in magnetic field, leading to field distortion and temporal drift.

Impact: Magnetic field distortion and temporal drift degrade field quality, critical for NMR and accelerator applications

Impact on Applications

Accelerator Magnets

Beam optics requires precise field quality

NMR Magnets

Field homogeneity critical for spectral resolution

Critical Finding

REBCO coil screening current-induced field is **5× larger** than Bi-2212, and significantly larger than LTS magnets

Central Field Formula

$$B_c = J \cdot a_1 \cdot F(\alpha,\beta)$$

$F(\alpha,\beta)$ = Shape factor of solenoid

Shape Factor Dependence

Screening current effects depend strongly on coil geometry:

Key Insight: Same central field can have different screening current effects depending on coil shape

Mitigation Strategies

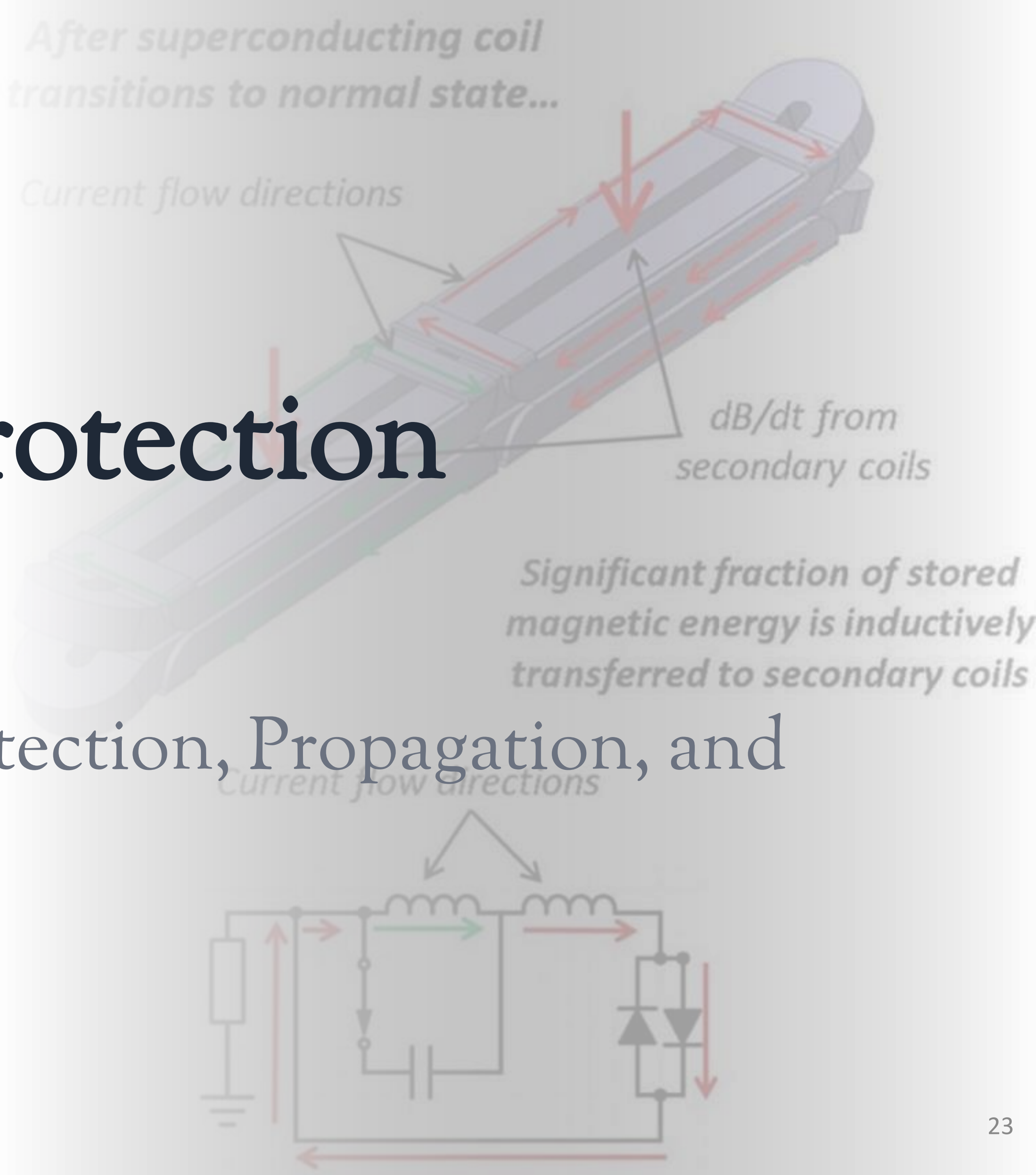
1. **Current Sweep Reversal**
   HTS requires several % reversal (vs 0.2-0.5% for LTS)
2. **Optimized Current Distribution**

CHAPTER 05

ReBCO Quench Protection

Comprehensive Analysis of Detection, Propagation, and Protection Strategies

The Critical Challenge for HTS Magnets



The ReBCO Quench Challenge: Why It's Fundamentally Different

Extremely Slow Normal Zone Propagation

LTS Magnets

1-10

m/s

ReBCO Magnets

1-10

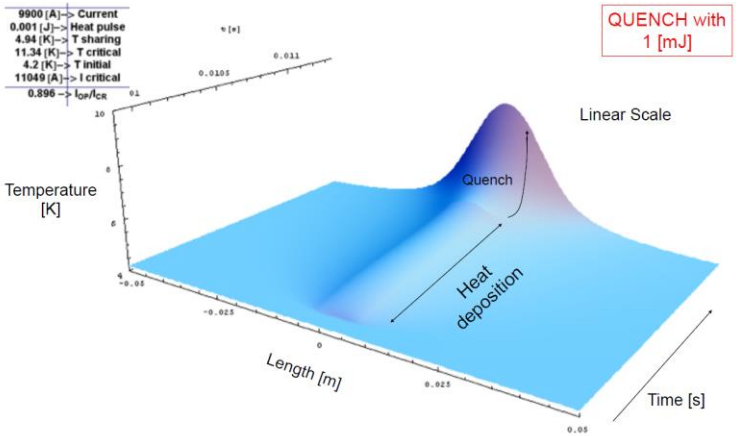
cm/s

2-3 Orders of Magnitude Slower!

High Thermal Stability

ReBCO has ~100× larger stability margin than LTS

- Large enthalpy requires more energy to initiate quench



High Stored Energy Density

Energy Concentration

High current density leads to large stored energy per unit volume

Hot Spot Risk

Localized heating can reach destructive temperatures quickly

The Consequence

Isolated hot spots develop with extremely slow growth, making conventional voltage-based detection methods nearly impossible before damage occurs

The Challenge Summary

Slow NZPV + High stability + Large stored energy = Unique protection requirements

Normal Zone Propagation Velocity (NZPV): Physics and Measurement

NZPV Physics

Velocity depends on **current density**, **temperature margin**, and **material properties**.

Adiabatic Approximation

$$v = \sqrt{(k \cdot J^2 / \rho \cdot C)}$$

k: thermal conductivity, J: current density, ρ: resistivity, C: heat capacity

NZPV strongly dependent on I/Ic ratio

Measurement Techniques

- Voltage tap arrays along conductor
- Fiber optic temperature sensing
- Thermal imaging (infrared)
- Acoustic emission detection

Experimental Results

YBCO Coated Conductor @ 4.2K

I/Ic = 0.5	I/Ic = 0.8
~2 cm/s	~8 cm/s

Longitudinal vs Transverse

Longitudinal NZPV	Transverse NZPV
1-10 cm/s	0.1-1 cm/s
Along the tape direction	Turn-to-turn (10-100× slower due to insulation)

Factors Affecting NZPV

Stabilizer Amount/Conductivity: More copper increases thermal diffusion

Heat Transfer: Cooling efficiency affects propagation

Interfacial Resistance: Between superconductor and stabilizer

Advanced Detection Technologies: Fiber Optic and Acoustic Methods

Fiber Optic Sensors (FBG)

Fiber Bragg Grating (FBG) sensors detect localized temperature changes through wavelength shifts with high sensitivity.

Operating Principle

Temperature change → Bragg wavelength shift → Real-time monitoring

Temperature Sensitivity

<1 K

Can detect small temperature rises before quench

Other Detection Techniques

Rayleigh Scattering: Distributed temperature sensing along fiber

Interferometric Methods: High-precision phase detection

Acoustic Detection

Active ultrasonic methods using Doppler effect detect quench-induced thermal and mechanical changes.

Operating Principle

Heating causes local sound velocity variation → Phase shift detection

Advantages

- Immune to electromagnetic interference
- Distributed sensing capability
- Fast response time (<1 ms)

Digital Image Correlation (DIC): Visual and Full-Field Quench Detection

DIC Technology

DIC is an innovative detection method providing visual and full-field perception of quench occurrence and propagation through strain measurement.

Operating Principle

Quench occurrence and propagation are accompanied by strong thermal and magneto-mechanical responses, captured as full-field strain evolution

Experimental Validation

YBCO coated conductor tape in cryogenic chamber, quench triggered by local spot heater

Results: Thermoelastic strain-rate criterion for quench occurrence, strain contours for normal zone propagation

Key Advantages

1. **Non-Contact**
   No physical connection to magnet required
2. **EMI Immune**
   Insensitive to electromagnetic interference
3. **Full-Field Coverage**
   Complete spatial information of quench evolution
4. **High Spatial Resolution**
   Micron-level displacement measurement

Future Potential: DIC is expected to provide a new technique for quench issues and basic measurements on strain/stress behaviors in extreme environments of high-field HTS magnets

Superconductor Science and Technology, 10.1088/1361-6668/ac3f9d, 2021

Passive Protection: Non-Insulated (NI) ReBCO Coils

NI Winding Technique

The no turn-to-turn insulation winding technique enables current to bypass local normal-state areas through radial turn-to-turn contacts.

Self-Protecting Mechanism

"Quench Current Bypass" — Current flows radially through turn-to-turn contact resistance

Characteristic Resistance (Rc)

Sum of turn-to-turn contact resistances

Surface Contact Resistance

10-70 $\mu\Omega\cdot cm^2$

Winding Tension Impact

Higher tension → Lower Rc → charging vs. protection

Experimental Validation

NI REBCO coils tested Record

1580 A/mm^2

Survived quench in liquid helium at 4.2 K

Successful Test Examples

8.7-T/91-mm REBCO	510 A/mm^2
9-T/78-mm MW REBCO	895 A/mm^2
26-T/35-mm MW REBCO	392 A/mm^2

All magnets survived multiple quench tests

Key Insight: NI coils demonstrate self-protecting behavior through electromagnetic quench propagation between pancakes

NI Coil Limitations and Variants: PI and MCI

Major Drawback: Slow Charging

Due to radial current paths through turn-to-turn contacts, NI coils have long charging time constants

Time constant at 4.2K

Mins ~ Hours ~ Days

Charging Speed

~12×

Faster than NI, stainless steel coating tapes

Partial Insulation (PI)

Charging Speed

~5×

Faster than NI, measured in LN_2 at 77K

Implementation

Strategic insulation layers allow controlled current paths

Metallic Cladding Insulation (MCI)

Implementation

Thin stainless steel layer on tape surface provides controlled resistance

PI and MCI Advantages

✓ Faster charging

✓ Better field stability

✓ Reduced delay

PI and MCI Disadvantages

⚠ May compromise self-protection at 4.2K

⚠ Requires careful optimization

⚠ More complex manufacturing

Layer-Wound NI (LNI)

Novel winding method solving field delay issues in layer-wound coils through intra-layer no-insulation technique

Active Protection: Quench Heaters — Design and Implementation

Quench Heater Principle

External heaters thermally induce normal zone in superconducting coil by resistive heating.

Design Requirements Timeline

Detection Time	~10 ms
Heater Delay	5-10 ms
Uniform Heating	10-30 ms

Heater Technologies

- Stainless steel heater strips
- Copper-nickel alloys
- Polyimide-insulated foils

Challenges for HTS

Slow Thermal Diffusion

Heat must cross insulation layers, which is inherently slow

Large Enthalpy

HTS requires more energy to initiate quench due to high thermal stability

CERN Experience: Heater failure is main cause of magnet rejection at CERN

Secondary Loop Method

Embedded copper wire as heater for enhanced NZP

Provides direct heating to conductor with lower thermal resistance

CLIQ Technology: Principles and Advantages

CLIQ Principle

Coupling Loss Induced Quench (CLIQ): Capacitor bank discharged into coil, generating oscillating currents that create inter-filament and inter-strand coupling losses.

Heating Mechanism

AC Magnetic Field ↓

Eddy Currents ↓

Resistive Heating ↓

Normal Zone Propagation

Key Advantage: CLIQ heating mechanism is in principle more effective than thermal diffusion, enabling faster and more uniform quench initiation

Advantages Over Heaters

1. **More Effective Heating**
   Direct in strand matrix vs thermal diffusion across insulation
2. **Robust Electrical Design**
   Lower failure rate than quench heaters
3. **No Interference**
   Doesn't interfere with coil winding technology
4. **Easy Installation**
   Easy to install and replace in case of malfunctions

CERN and IHEP Test Results

- Solenoid, dipole, quadrupole magnets
- Nb-Ti and Nb_3Sn conductors
- Various sizes and inductances
- Consistent performance across configurations

AC Loss Heating: Alternative Active Protection Method

AC Loss Heating Principle

Using hysteretic and eddy current losses to heat superconductor and initiate quench.

Loss Mechanisms

Hysteretic Losses

In superconducting filaments due to magnetic field changes

Eddy Current Losses

In stabilizer and substrate materials

Implementation

Controlled AC current injection or rapid field variation

Advantages

1. **Combined with CLIQ**
   Enhanced heating when combined with coupling loss systems
2. **No Physical Contact**
   Can be induced without direct electrical connection
3. **Distributed Heating**
   Can provide more uniform heating across coil

Challenges

Precise Control Required: Must avoid excessive heating that could damage conductor

Frequency Optimization: Optimal frequency depends on conductor geometry and materials

Hot Spot Temperature Calculation: Adiabatic Model

Adiabatic Hot Spot Model

The adiabatic approximation assumes all Joule heating goes into temperature rise of the conductor.

Energy Balance

$$\int I^2 R \, dt = \int C \, dT$$

Joule heating = Temperature rise

MIITs Concept

$$\text{MIITs} = \int I^2 \, dt$$

Mega Ampere²·seconds — measure of heating

Copper Resistivity

$$\rho(T) = \rho_0[1 + \alpha(T - T_0)]$$

Calculation Procedure

Step 1: Determine MIITs

Calculate from protection scenario (current decay profile)

Step 2: Material Properties

Copper resistivity: $\rho(T) = \rho_0[1 + \alpha(T - T_0)]$

Step 3: Temperature Rise

Use material properties to find temperature rise

$$T_{max} = f(\text{MIITs, material})$$

Example Calculation

For given magnet parameters, calculate maximum allowable MIITs for 250 K hot spot limit

Typical values

10-100 MIITs

for accelerator magnets

Hot Spot Temperature: Finite Element Modeling

Coupled Electro-Thermal Modeling

Finite element method provides more accurate hot spot prediction by including cooling effects and spatial variations.

Model Components

- Current distribution (3D)
- Joule heating calculation
- Thermal diffusion
- Cooling effects
- Material properties (T, B dependent)

Software Tools

- ANSYS Multiphysics
- COMSOL
- TALES (CERN)
- Custom FEM codes

Example: 21T Hybrid Quench Simulation

Simulation Setup

3D model with detailed geometry, material properties as functions of temperature and field

Results

- Hot spot temperature distribution
- Quench propagation visualization
- Mechanical stress prediction
- Validation against experimental data

Peak Stress @ 480ms

140 MPa

Longitudinal compression

Protection Limits: Insulated vs Non-Insulated vs Metal-Insulated

Analytical Estimation Method

Insulated

Characteristics
Conventional design with full turn-to-turn insulation

Protection Challenge
Slow NZPV, requires active protection

Hot Spot Risk
High — energy concentrated in small volume

Non-Insulated

Characteristics
No turn-to-turn insulation, radial current paths

Protection Advantage
Self-protecting through current bypass

Trade-off
Slow charging, field delay

Metal-Insulated

Characteristics
Thin metal layer provides controlled resistance

Protection Balance
Intermediate between insulated and NI

Optimization
Metal thickness controls Rc

Parameter Impacts on Protectability

Coil Size
Larger coils → More challenging protection

Metal Insulation Thickness

Stabilizer Copper
More Cu → Improved protection

Conductor Modification for Enhanced NZPV

Modification Strategies

Doped-Titania Insulation

Experiments show 2-3× improvement in transverse NZPV with doped-titania insulation compared to Kapton

Stabilizer Optimization

Increase amount/conductivity of copper stabilizer for better heat transfer and current redistribution

Effect: Higher thermal conductivity → Faster heat spreading

Interfacial Resistance Engineering

Increase resistance between superconductor and stabilizer to promote faster current redistribution

Effect: Current diffusion length decreases → Faster NZP

YBCO Pancake Coil Results @ 4.2K, 5T

Kapton	Doped-Titania
6.75 layers/s	14.16 layers/s

~2× improvement in transverse propagation

Implementation Considerations

Conductor Uniformity: Modifications require uniform superconductor layer

Manufacturing Complexity: Additional processing steps increase cost

Long-term Reliability: Need validation through accelerated aging tests

Trade-offs

Pro: Enhanced NZPV — Modifications can increase NZPV by 2-3×

Con: Reduced Stability — May reduce thermal stability margin

Hybrid Protection Systems: Combining Multiple Methods

Hybrid Protection Concept

Combining CLIQ + heaters + energy extraction for optimal performance and redundancy.

Synergy Principle

CLIQ: Fast initial response (<35 ms)

Heaters: Ensure complete coil coverage

Extraction: Remove stored energy

Design Optimization

- Trigger thresholds for each system
- Timing sequence optimization
- Redundancy for reliability

Temperature Distribution Comparison

Conventional Heaters

400 K Hot Spot Temperature

Non-uniform heating, thermal diffusion delays

CLIQ Only

250 K Hot Spot Temperature

Faster response, more uniform

Hybrid System

<200 K Hot Spot Temperature

Most homogeneous, lowest peak temperature

ReBCO Quench Protection: The Path Forward

ReBCO quench protection remains one of the most critical challenges for high-field HTS magnets. The combination of slow NZPV, high stability margins, and large stored energies requires innovative, multi-layered protection strategies.

Advanced Detection

- Fiber optics
- DIC imaging
- Multi-threshold voltage

Innovative Protection

- NI/PI/MCI coils
- CLIQ/E-CLIQ
- Hybrid systems

Sophisticated Modeling

- Adiabatic models
- FEM simulation
- Coupled electro-thermal

Global Collaboration

- CERN leadership
- National labs
- Industry partners

The Next Decade Will Determine the Feasibility of 20+ Tesla ReBCO Accelerator Magnets

Innovation + Collaboration = Success

CHAPTER 06

Roadmap for Future

CEPC-SPPC, FCC, and the Path to 20+ Tesla Magnets

The Next Generation of Discovery Machines

FUTURE VISION

Technology Roadmap to 16-20 Tesla

CEPC-SPPC & FCC

The CEPC-SPPC at IHEP or Future Circular Collider at CERN represents the next major frontiers, with 100 km tunnel hosting an integrated physics program spanning the late 2030s through the end of the 21st century.

Phase 1

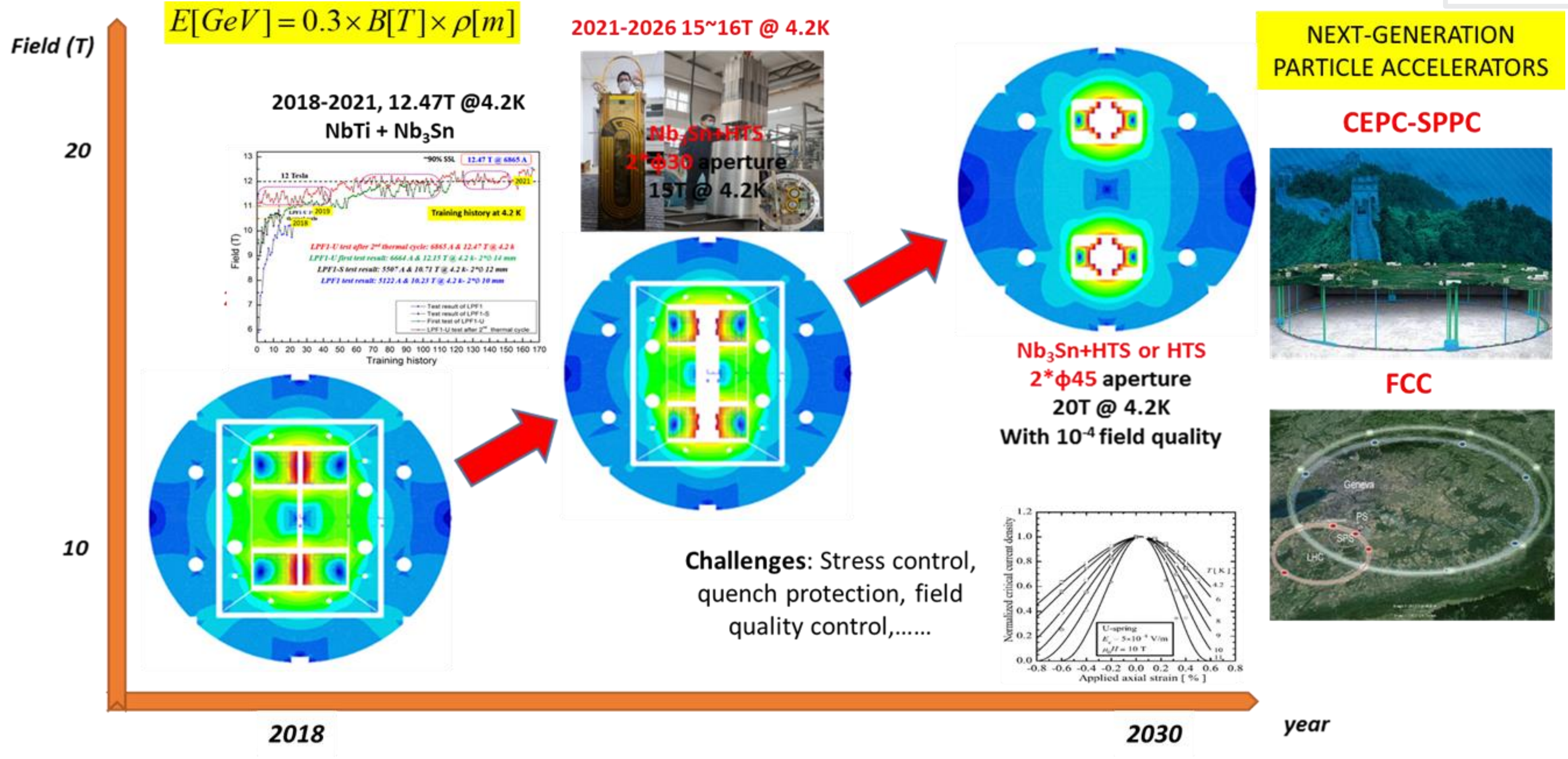
FCC-ee or CEPC (2030s-2040s)

300+ GeV e^+e^- Higgs Factory

Phase 2

FCC-hh or SPPC (2040s+)

100 TeV pp collider with 20+ T accelerator magnets



SPPC Magnet Specifications

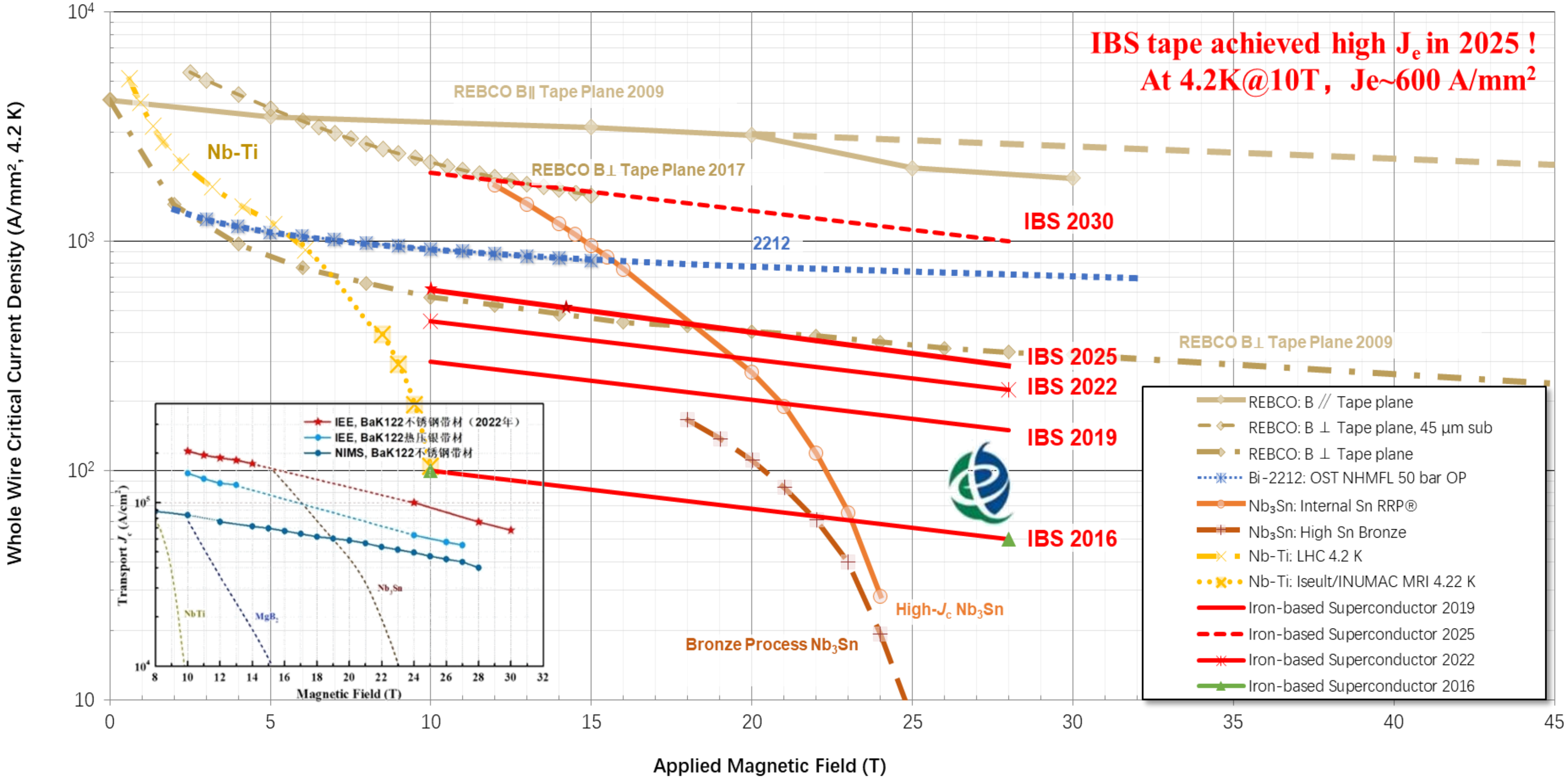
Dipole Field Target	Bending Radius
20 T	~10 km
Dipole Quantity	**Tunnel Length**
~6,000	100 km
Magnetic Length	**Aperture**
14~15 m	40~50 mm

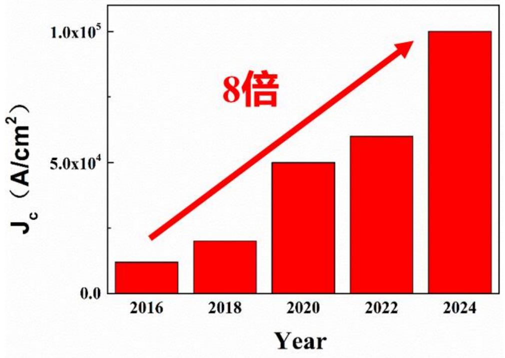
FUTURE VISION

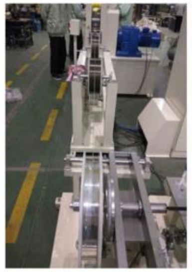
Iron-Based Superconductors

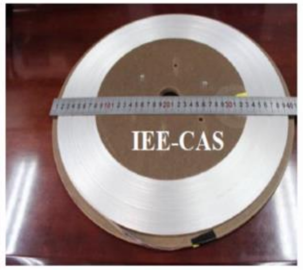
Wire Geometry & Bendability: Powder-in-tube processed round wires with 30–100 micron filaments tolerate 15 mm bend radius without Ic loss.

Cost & Field Positioning: 11- and 122-type IBS exhibit Tc 30–55 K and Hc2 > 70 T, yet use Fe, Se, As, Sn—elements 10–50× cheaper than Re or Ag. Jc > 500 A/mm² @ 10 T, 4.2 K is already demonstrated in 100 m lengths, positioning IBS between Nb_3Sn and REBCO in both cost and performance.









FUTURE VISION

Global Collaboration and Application Expansion

Global Collaboration Network

CERN
Coordination & leadership

Fermilab
Nb_3Sn & HTS development

BNL
Hybrid magnet R&D

LBNL
Quench protection

ORNL
Materials research

KEK/IHEP/IEE
Asian collaboration

Coordination: European Strategy for Particle Physics, US P5, China HFM

Synergies with Fusion Energy

Fusion energy demand driving REBCO production scale-up benefits accelerator technology through industrial scale economies.

Application Areas

Fusion Energy
ITER, private fusion companies

NMR/MRI
35T+ spectrometers

Space Propulsion
Electromagnetic thrusters

Power Applications
Cables, transformers, SMES

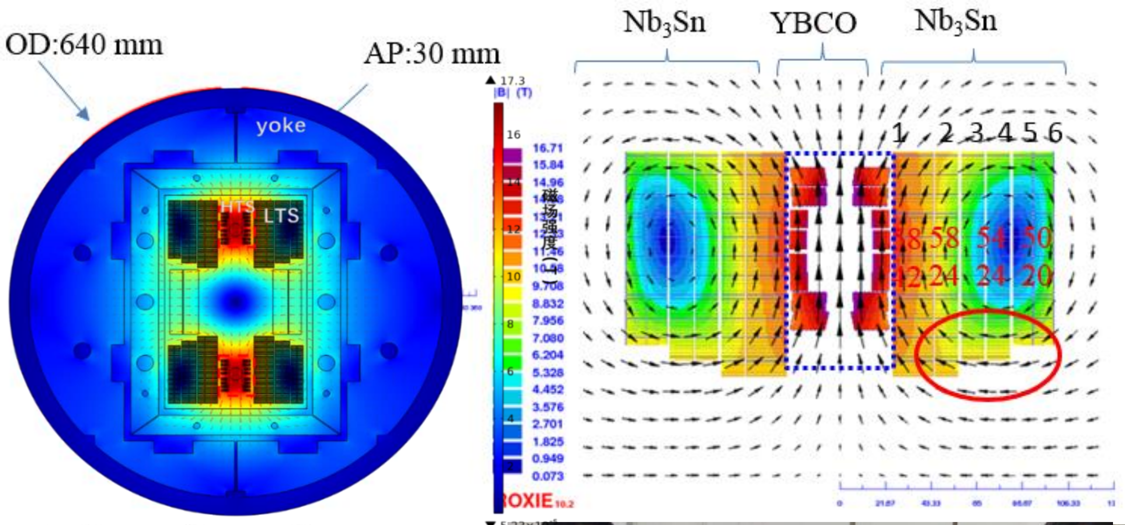
CHAPTER 07

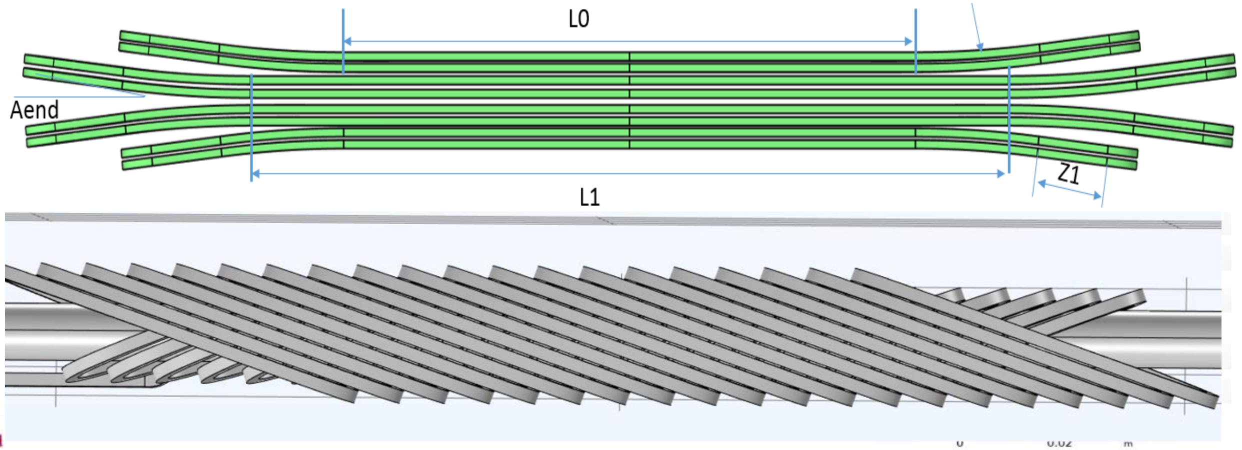
Case Study

High Field Magnet Progress at IHEP-CAS

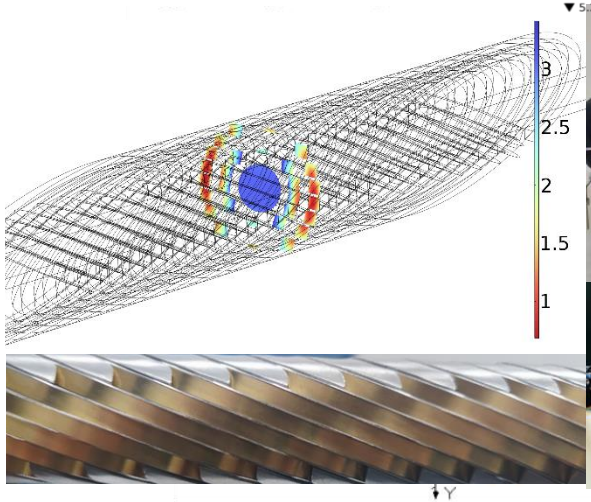
Development of the Model Dipole LPF3

16 T Model Dipole LPF3: Nb_3Sn 13 T (*Common Coil with 55 mm gap*) + HTS 3 T inserts (*Block & CCT*)





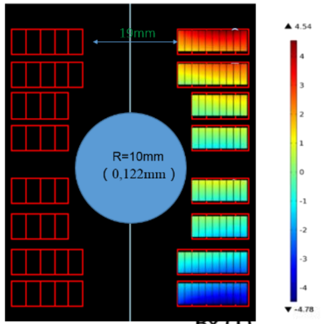
16-T 大孔径高场超导二极磁体 LPF3 (Nb_3Sn-13T+HTS-3T) 电磁设计

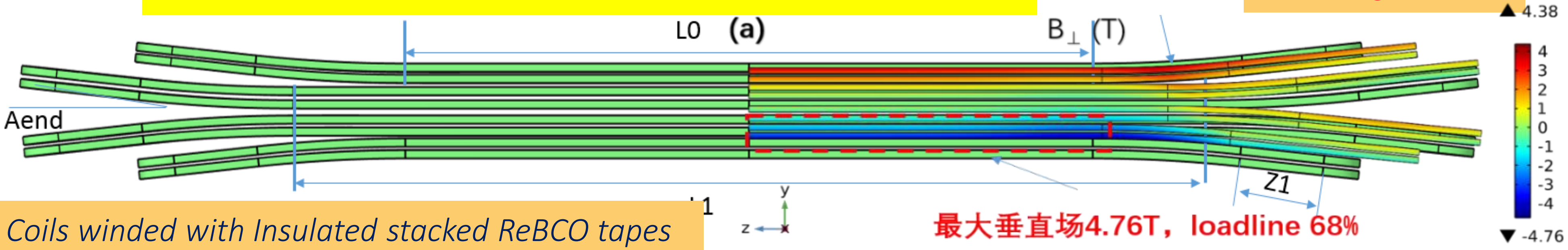


Development of the Model Dipole LPF3

The ReBCO block insert coils for LPF3

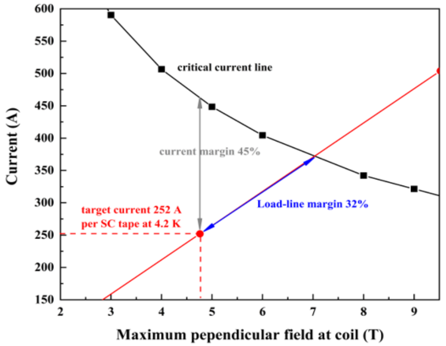
Ze Feng et al

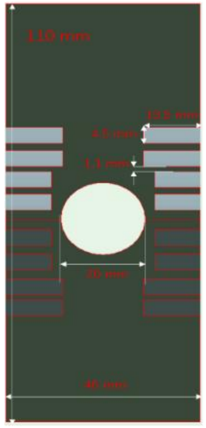




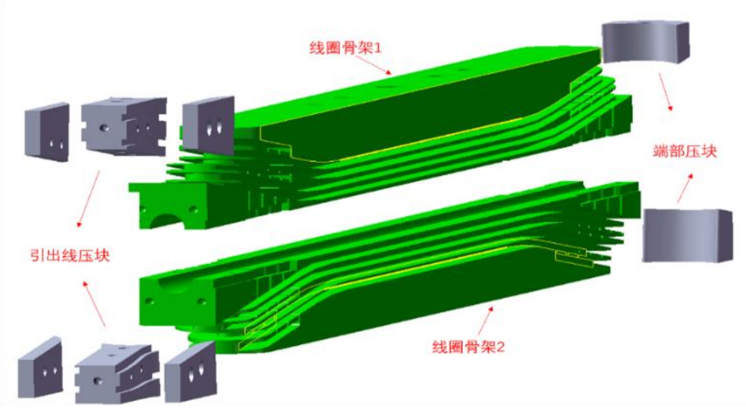
Parameters	Values
L0	409.6 mm
L1	540.2 mm
Rhard	800 mm
Aend	6 °
R1	9.5 mm
Z1	120 mm

Coils winded with Insulated stacked ReBCO tapes





磁体骨架的剖面图

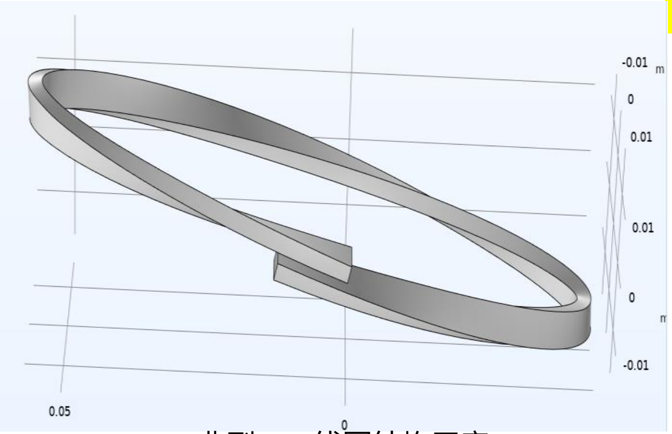


磁体骨架的三维爆炸视图

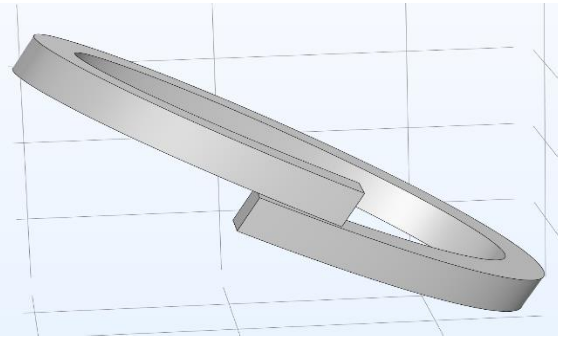
Development of the Model Dipole LPF3

The ReBCO CCT instert coils for LPF3

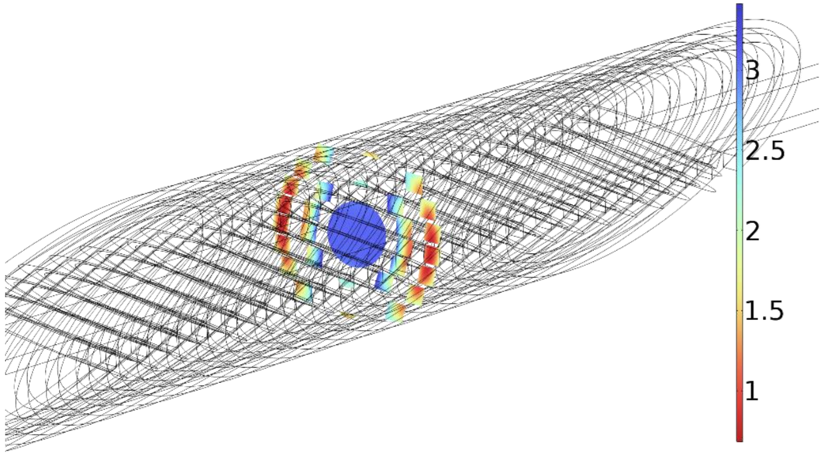
Rui Kang et al

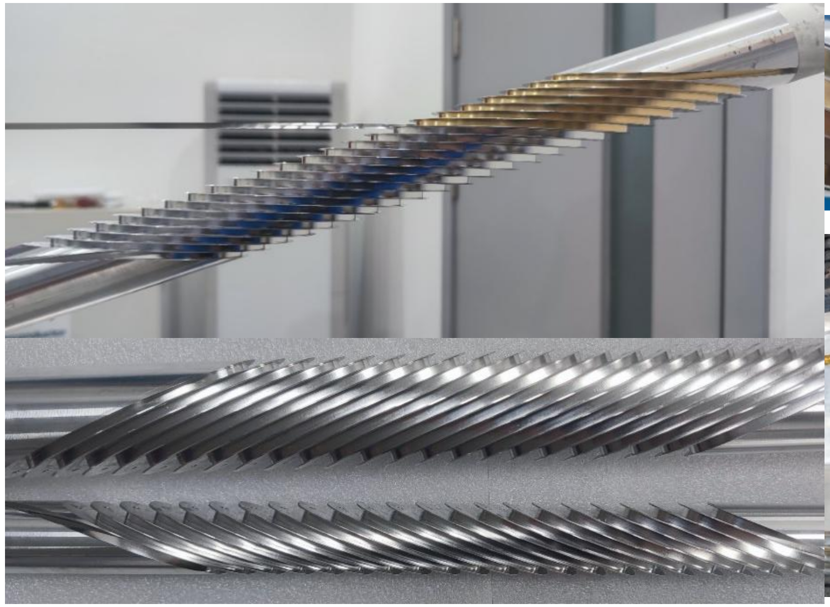


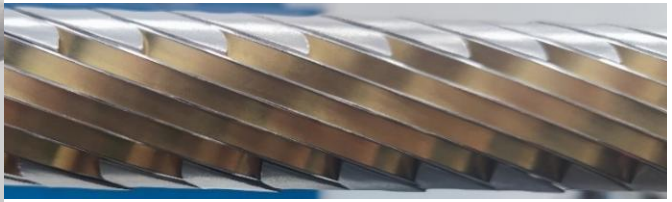
典型CCT线圈结构示意

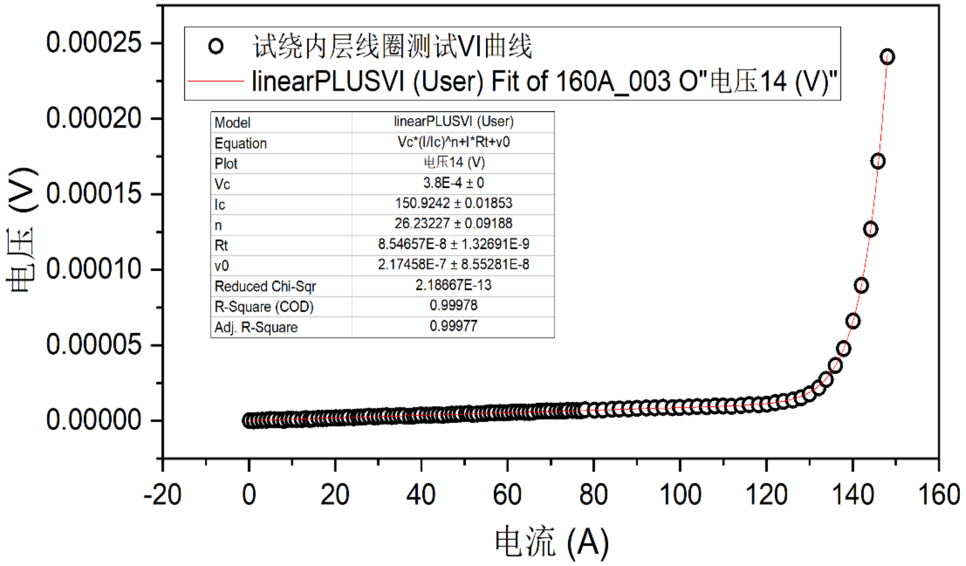


“斜螺线管”型CCT线圈结构示意





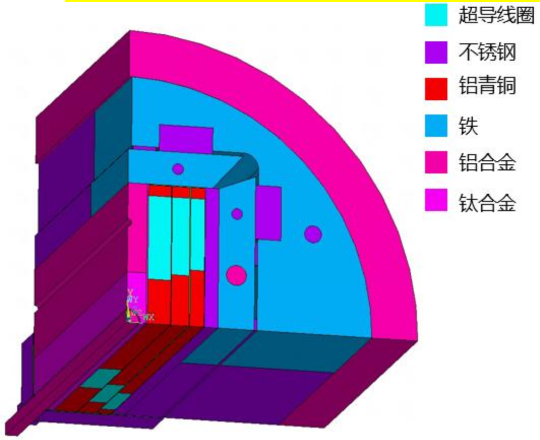


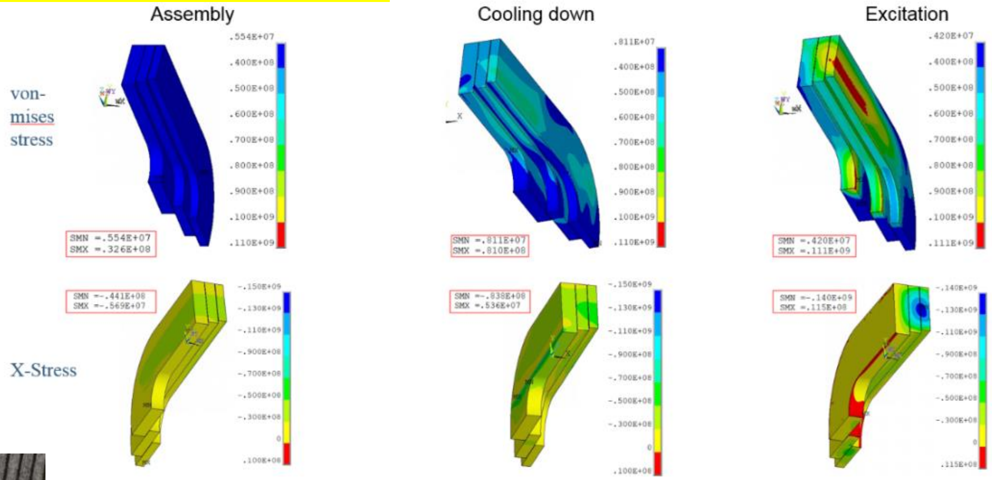


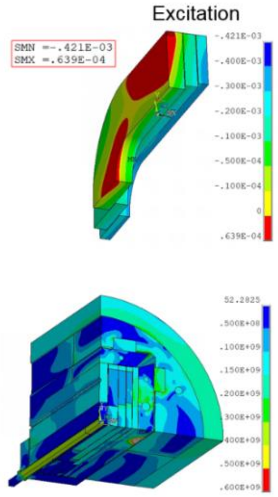
Development of the Model Dipole LPF3

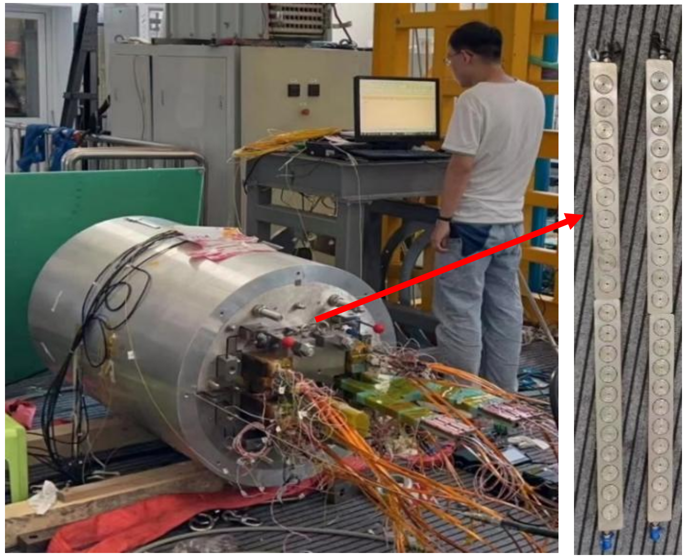
Pre-stress and assembly of LPF3

Yingzhe Wang et al



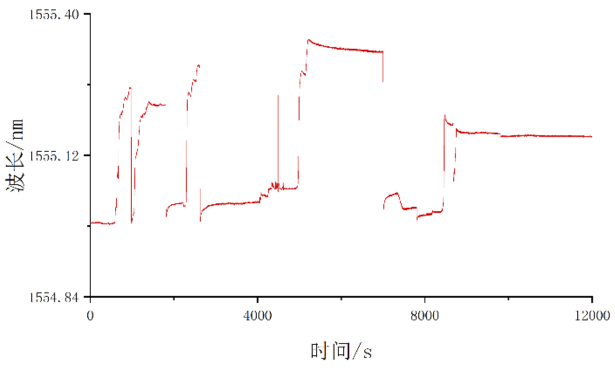






Pre-stress applied with commercial hydraulic jack

Stress monitoring during assembly with FBG



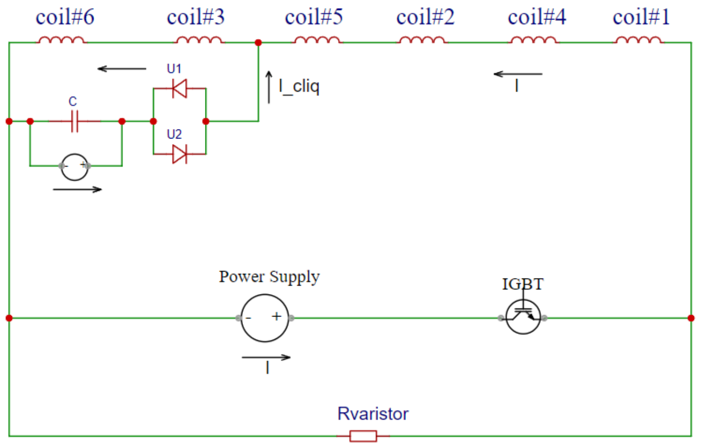
2023.8.29 Assembly completed

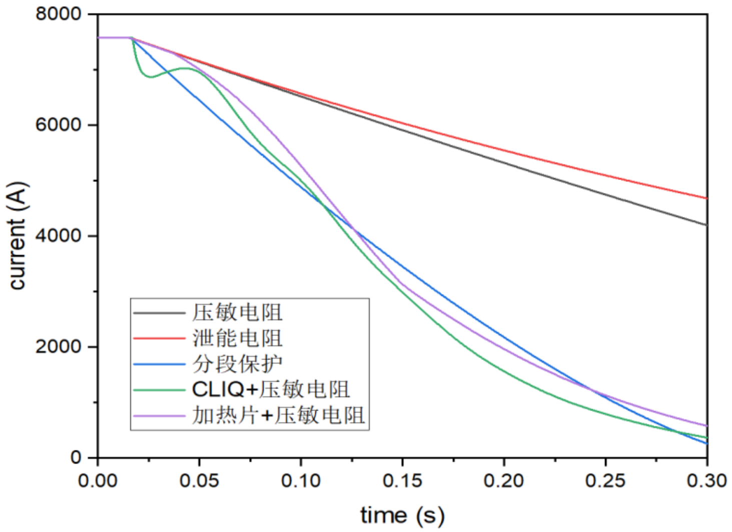
Development of the Model Dipole LPF3

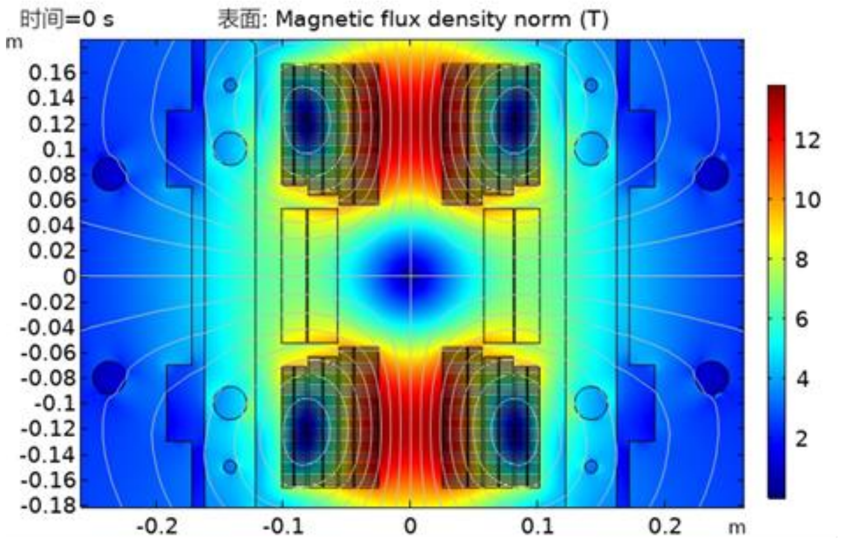
Quench protection of LPF3

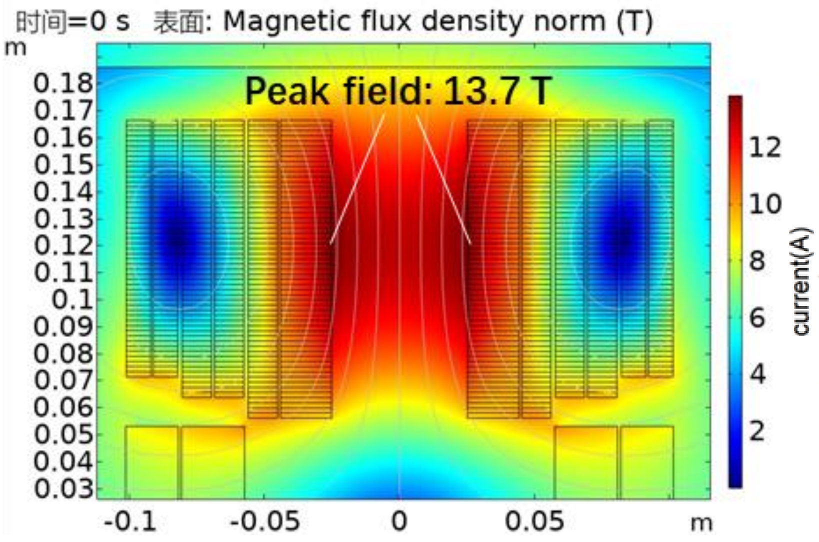
Jinrui Shi et al

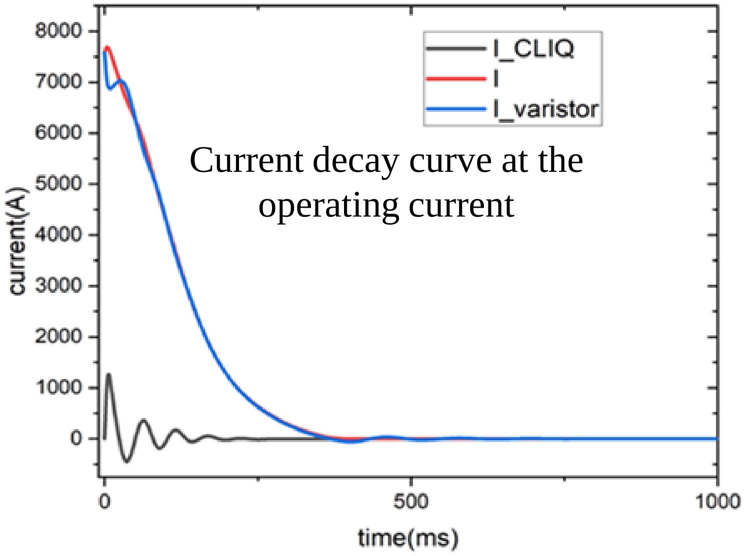
- **Varistor plus CLIQ to protect the Nb_3Sn coils. The maximum hot spot is ~ 230 K**
- **NI configuration plus dump resistor to protect the 2 HTS insert coils**









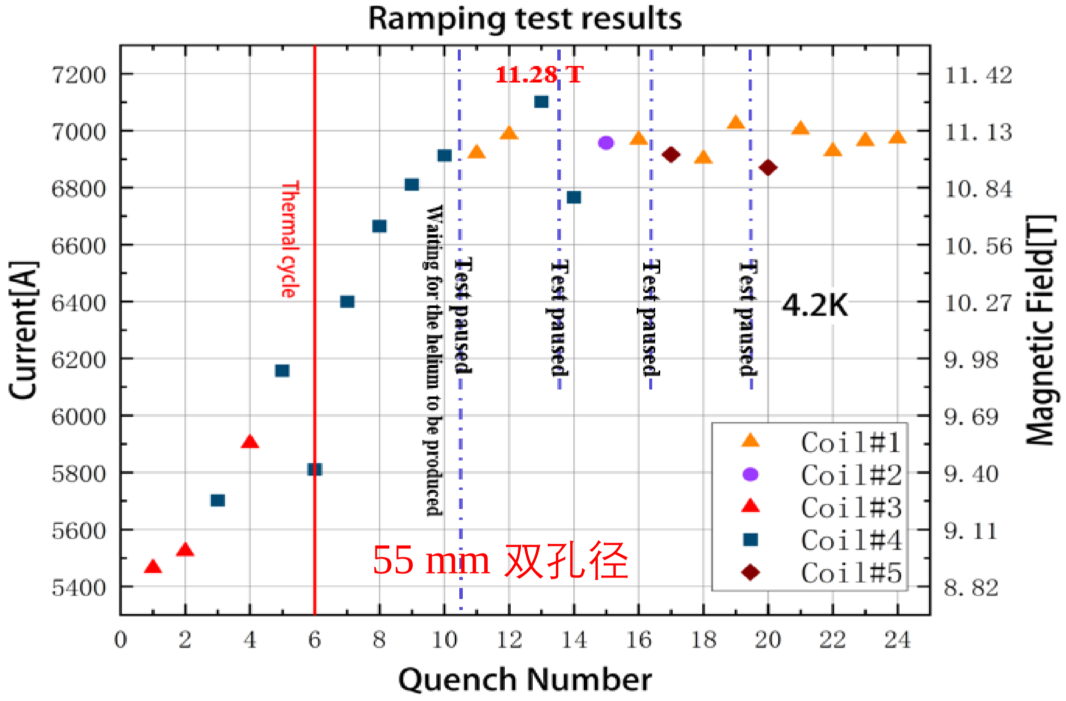


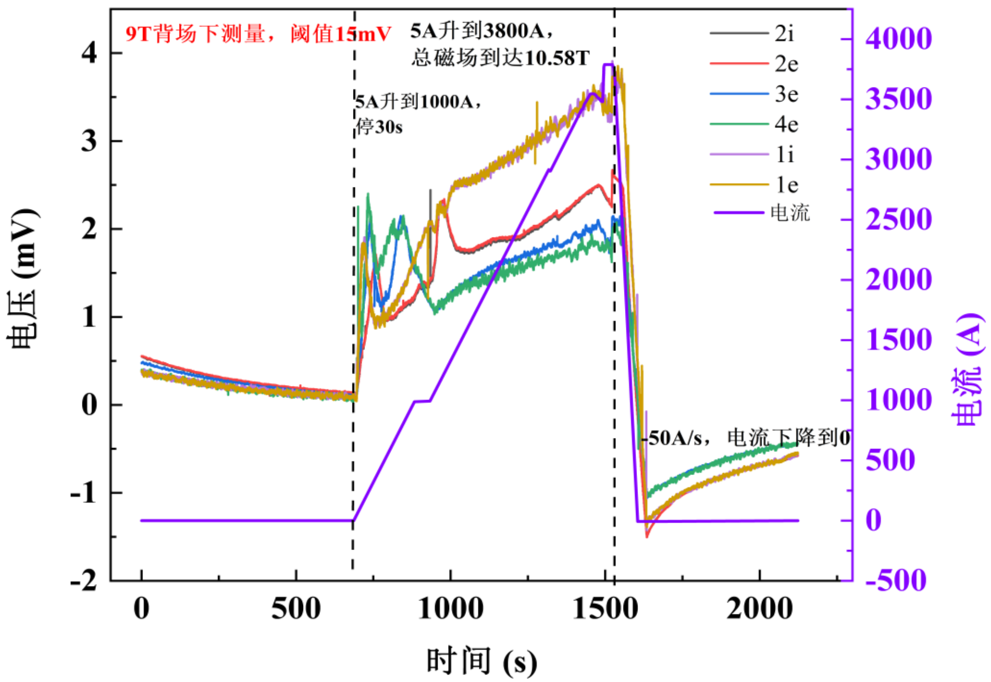
Development of the Model Dipole LPF3

Performance test in Sep to Dec 2023

Wei Li et al

- The **Nb$_3$Sn coils were trained firstly, maximum current reached ~85% of I$_{op}$ in Dec 2023, but showed an unstable plateau at 11 T due to one of the outmost Nb$_3$Sn coil, probably due to insufficient pre-stress during assembly, and enhanced field on most inner Nb3Sn coils due to the HTS screen current!**
- **HTS block coil was ramped independently to 100% of I$_{op}$ at 9 T background field, with long time delay of field. Current leads failure limited the hold time of the I$_{op}$ and the field**

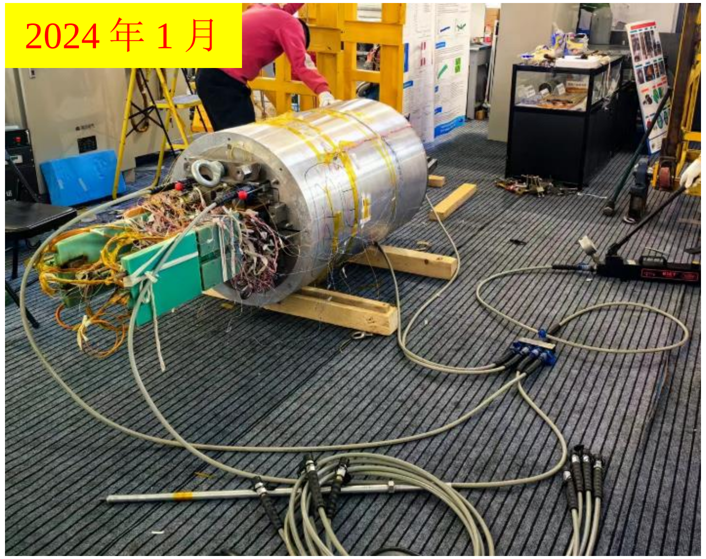


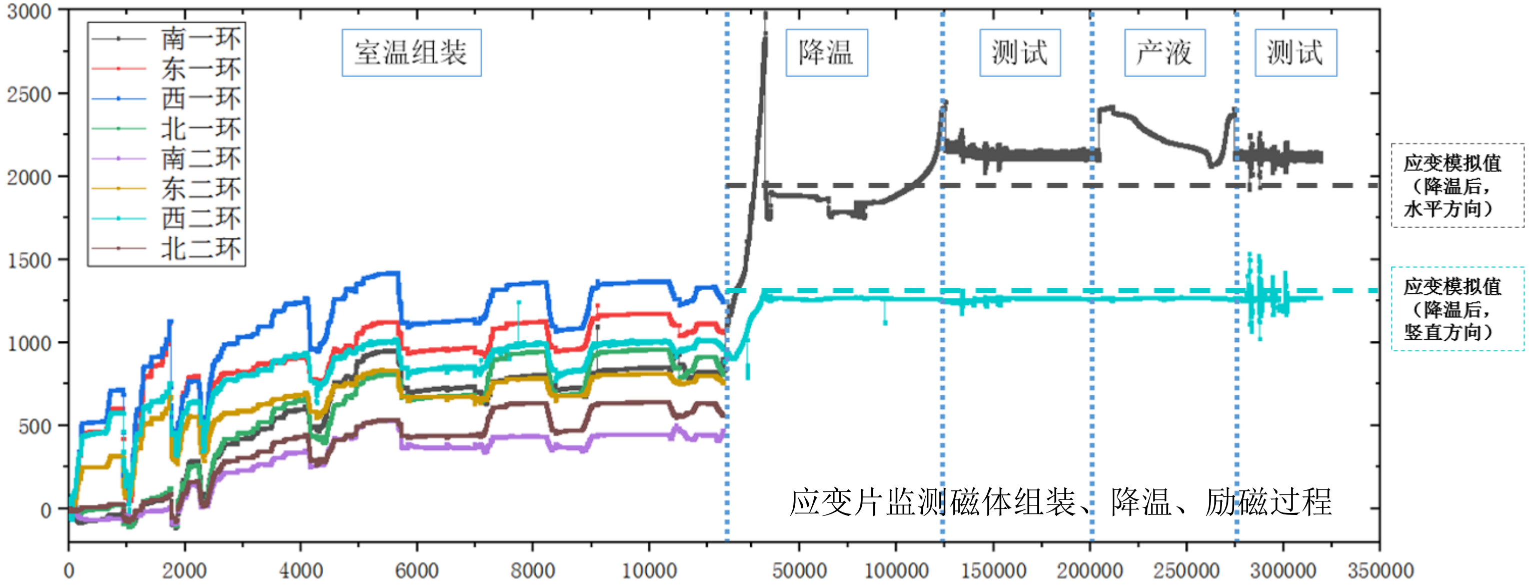


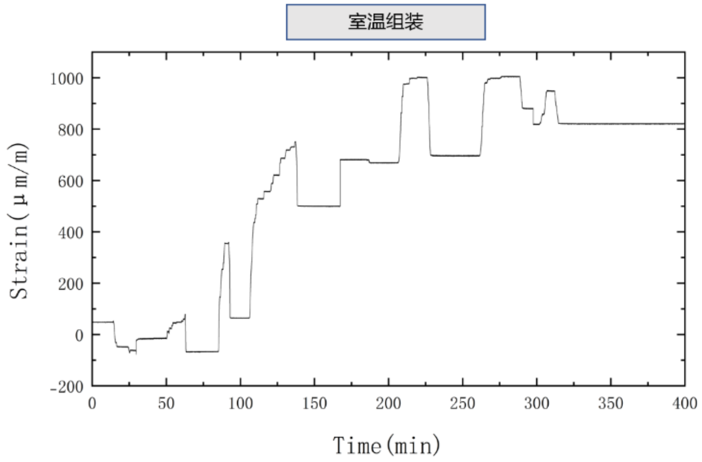
Development of the Model Dipole LPF3

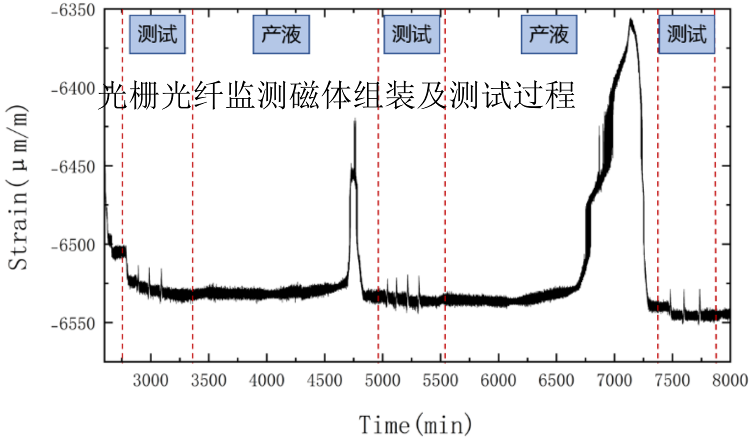
Reassembly of the magnet with enhanced pre-stress in Jan 2024

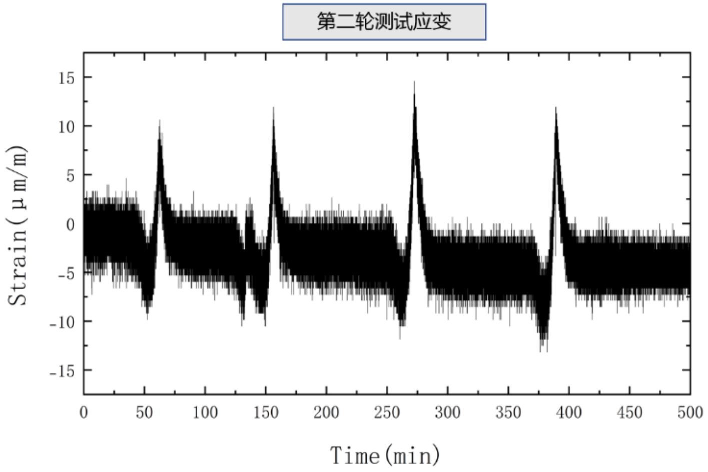
Xin Chen et al







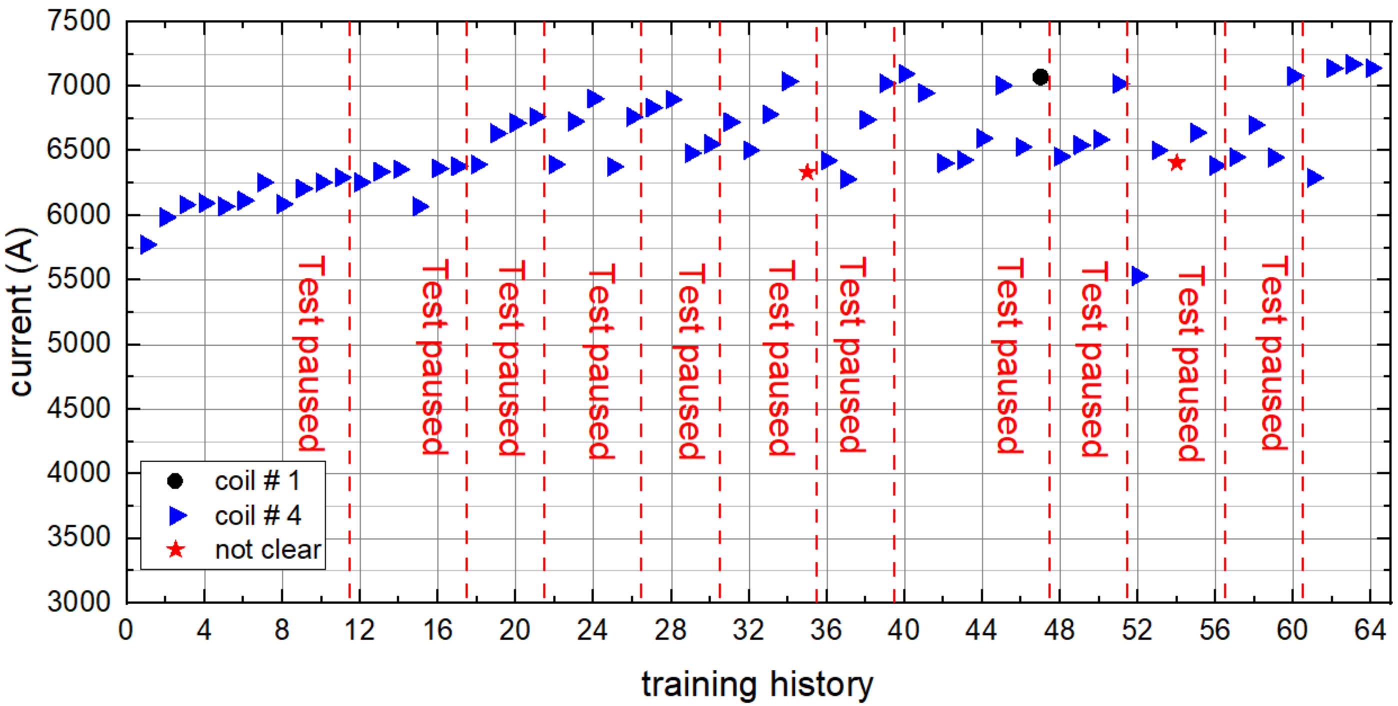


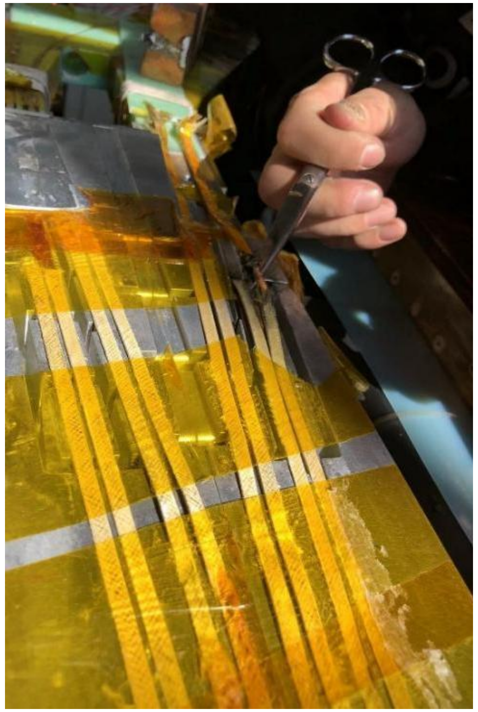


Development of the Model Dipole LPF3

Performance test in Feb 2024

- The Nb_3Sn coils showed very unstable performance in the 6300-7000 A region due to one of the inner most coils, but finally passed this region and reached **~87% of I_{op}** in the beginning of March 2024
- HTS block coil was ramped independently **to 120% of I_{op}** to test its ultimate performance, burned one of the leads. Disassembly after test showed serious deformation of conductor at the hard bending section.

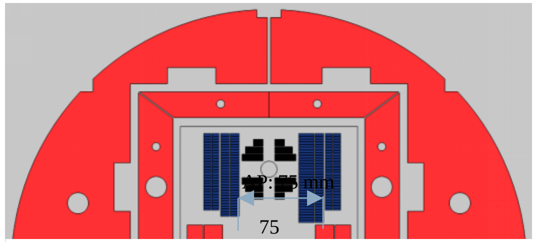


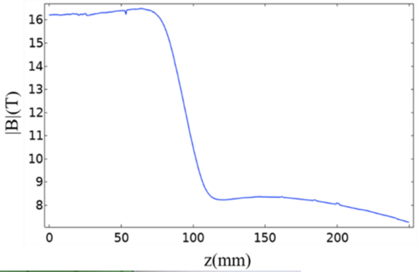


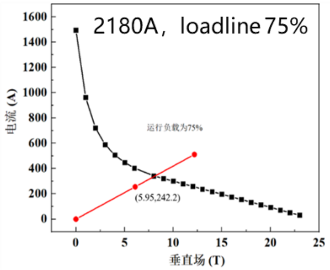
Development of the Model Dipole LPF3

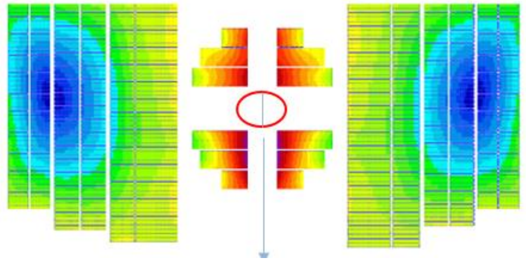
New design and fabrication of the new Coils   Jun to Oct 2024

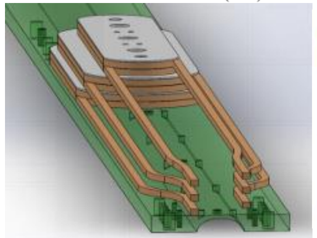
Target field：10 T (LTS) + 6 T (HTS) with MI



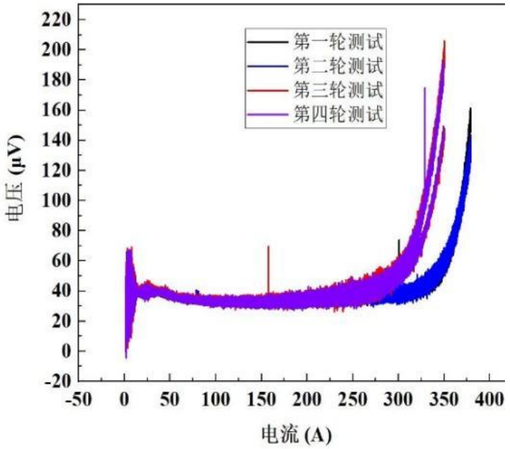


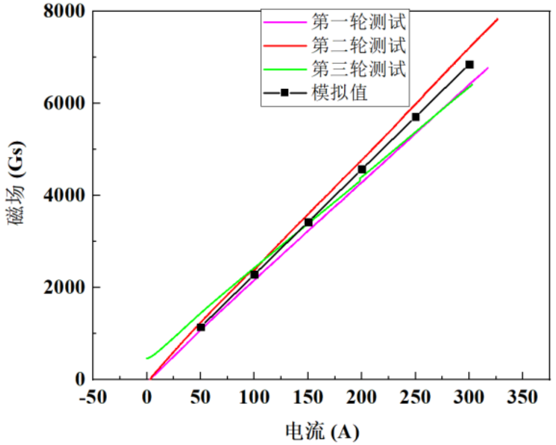


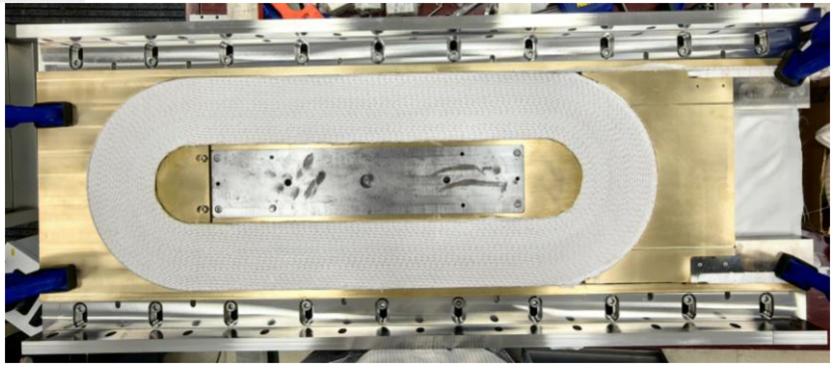


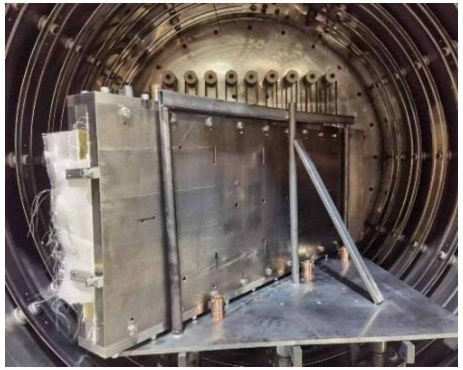


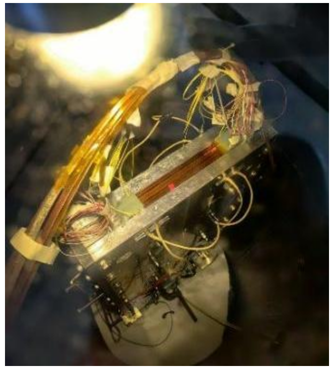
Preliminary test results of the new HTS coils at 77K







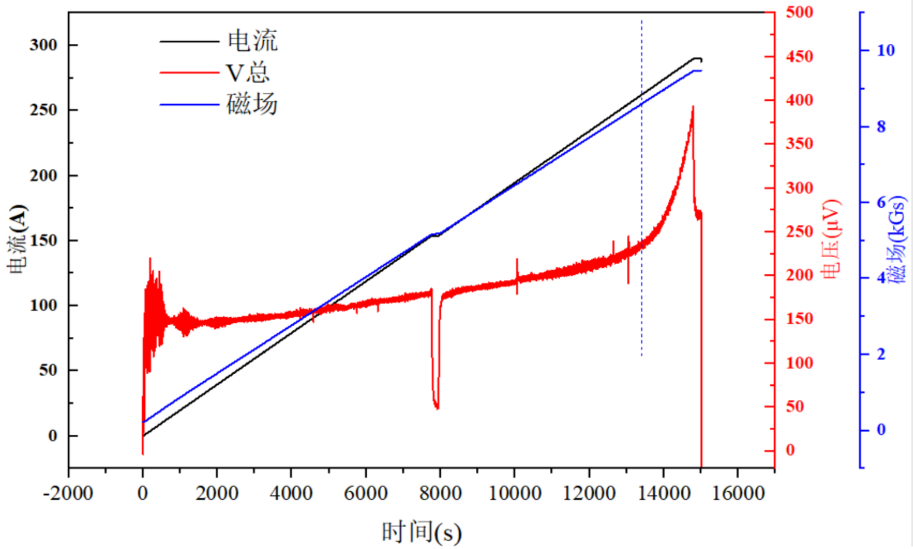




Fabrication of the 2 new Nb_3Sn coils with OST wires

Development of the Model Dipole LPF3

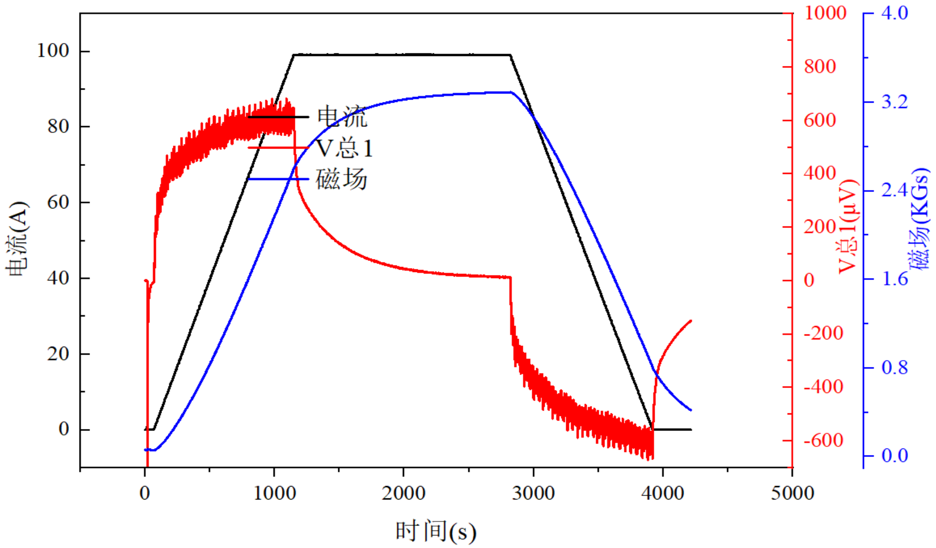
Field delay of HTS coil significantly changed after magnet assembly



Stand-alone test at 77K

0.93 T @ 77 K， 290A

Field delay ~12 s



Test after magnet assembly at 4.2K

0.32 T @ 4.2 K， 100 A

Field delay ~58 min

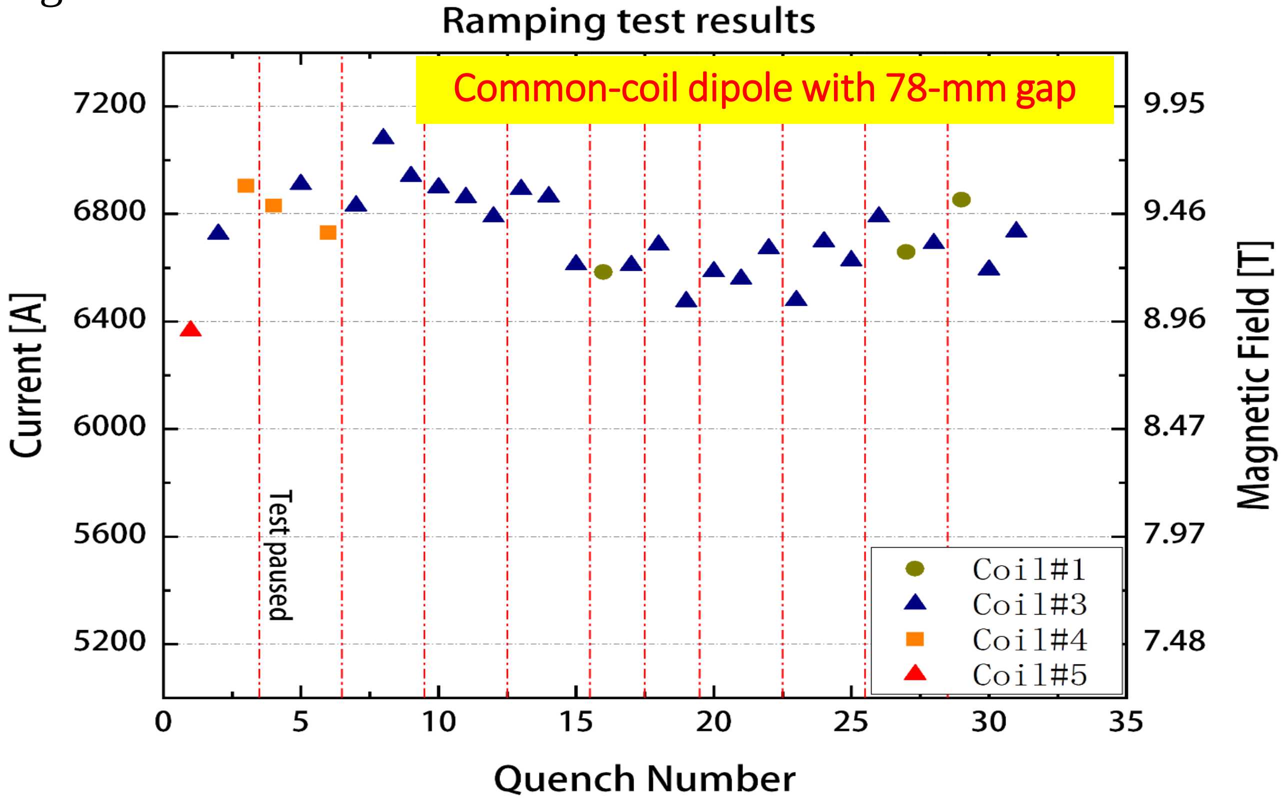
Possibly due to the large pre-stress applied to the HTS coils

Development of the High Field Model Dipoles

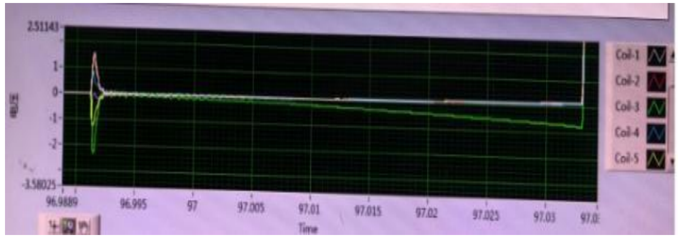
Test of the LPF3-U magnet at 4.2 K   Nov. 2024 to Jan. 2025

LPF3-U 磁体组装完成

Main challenges: The LTS coils are strongly coupled with the HTS coils in magnetic field and stress during LTS training. the HTS induced current enhance the field strength and stress of the adjacent LTS coils, and the frequent training quench of LTS cause irreversible degradation of the HTS coils.



- Nb_3Sn coils reached 9.8 T, 98 % of the design value.
- Coupling between HTS & LTS caused difficulties to the training of LTS
- Most of quenches occured in the inner Nb_3Sn coils.
- LTS still have potential for performance improvement. More R&D needed on training tests……



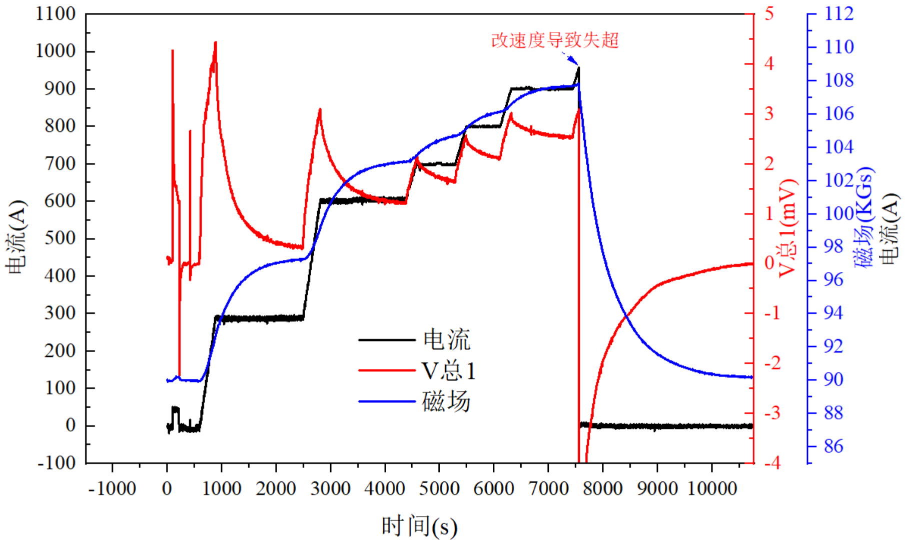
Development of the High Field Model Dipoles

Test of the LPF3-U magnet at 4.2 K   Nov. 2024 to Jan. 2025

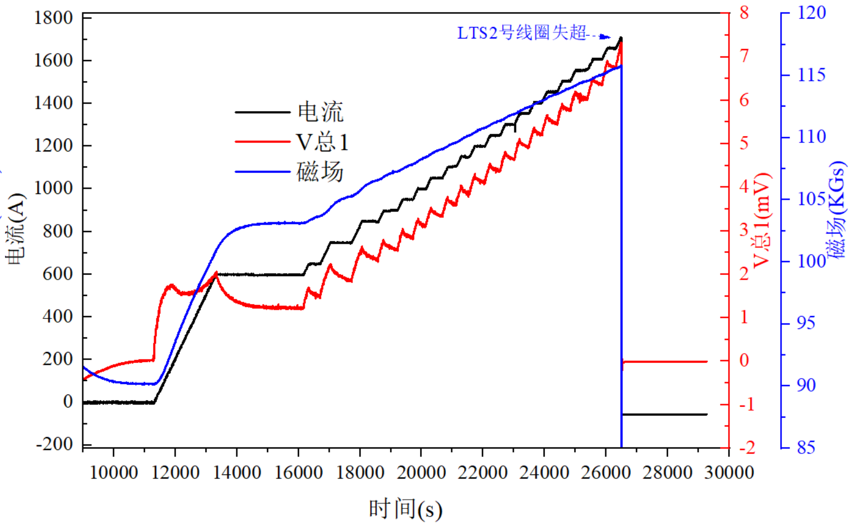
The HTS coils reached a maximum excitation current of 2.5 kA (115 % of the design current) in 9 T background field, but generally degraded along with the training of LTS coils, and provided a magnetic field significantly below the design value with long delay.

HTS Stand-alone test @77 K → HTS Test after assembly @77 K → Training of LTS coils →

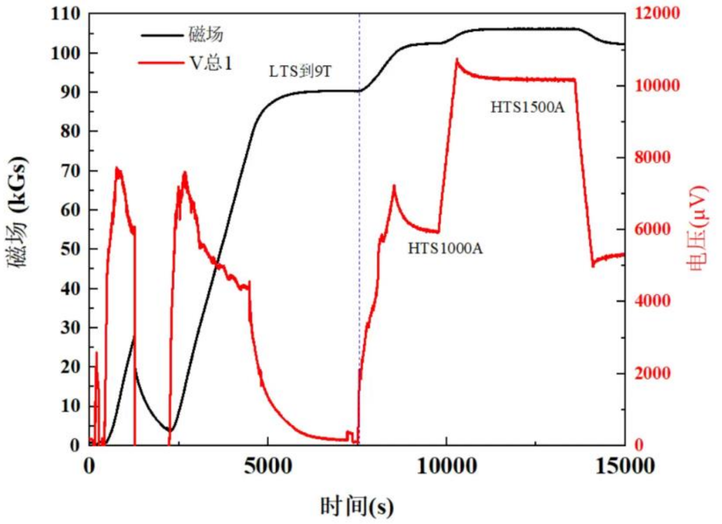
1st HTS test with 9 T BG field → 2nd HTS test with 9 T field → LTS training → 3rd HTS test with 9 T field



1st HTS test with 9 T BG field



2nd HTS test with 9 T BG field

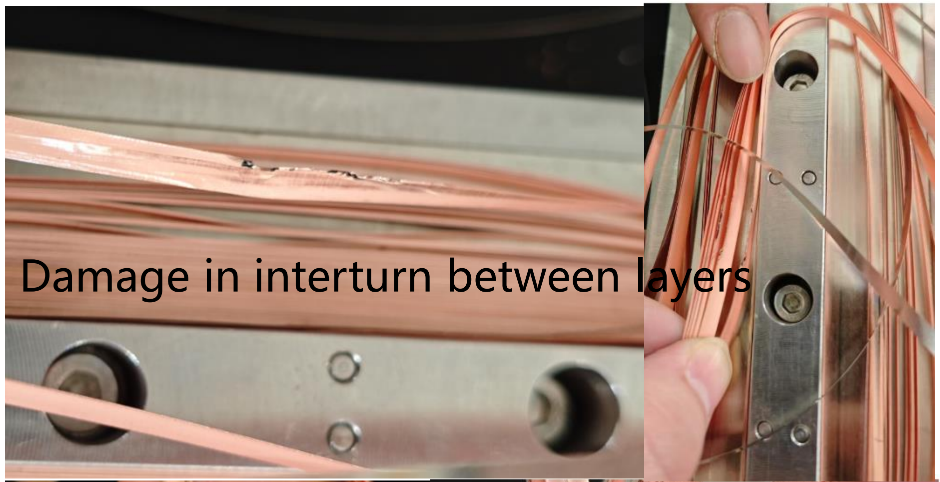


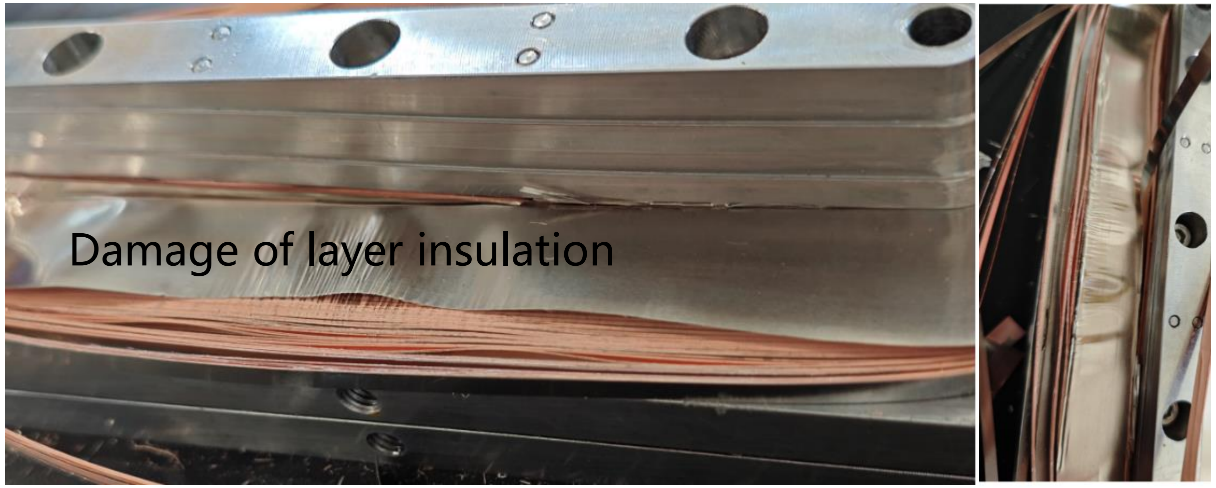
3rd HTS test with 9 T BG field

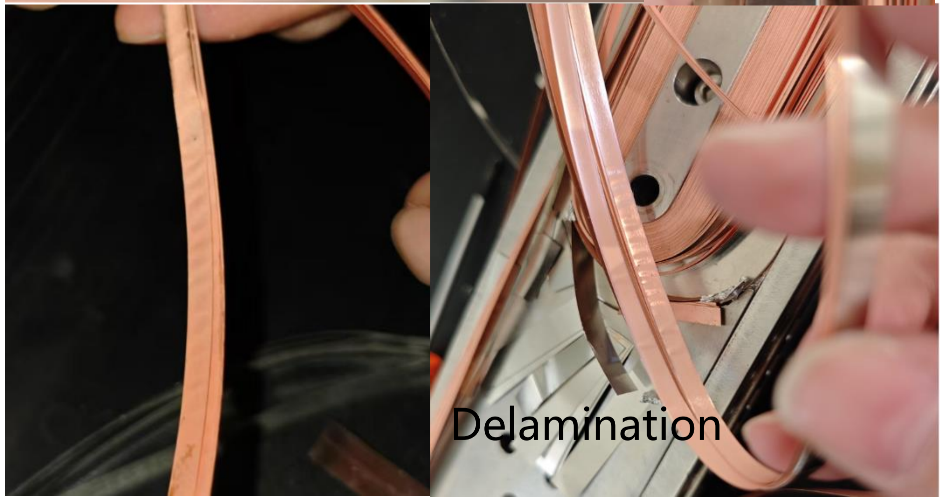
Development of the High Field Model Dipoles

Disassembly of the magnet and HTS coils in Jan 2025

After disassembly, Serious damage of the outer HTS coils observed: conductor delamination, damage of layer insulation..., caused by strong coupling (between LTS and HTS) induced electromagnetic forces during the training of LTS







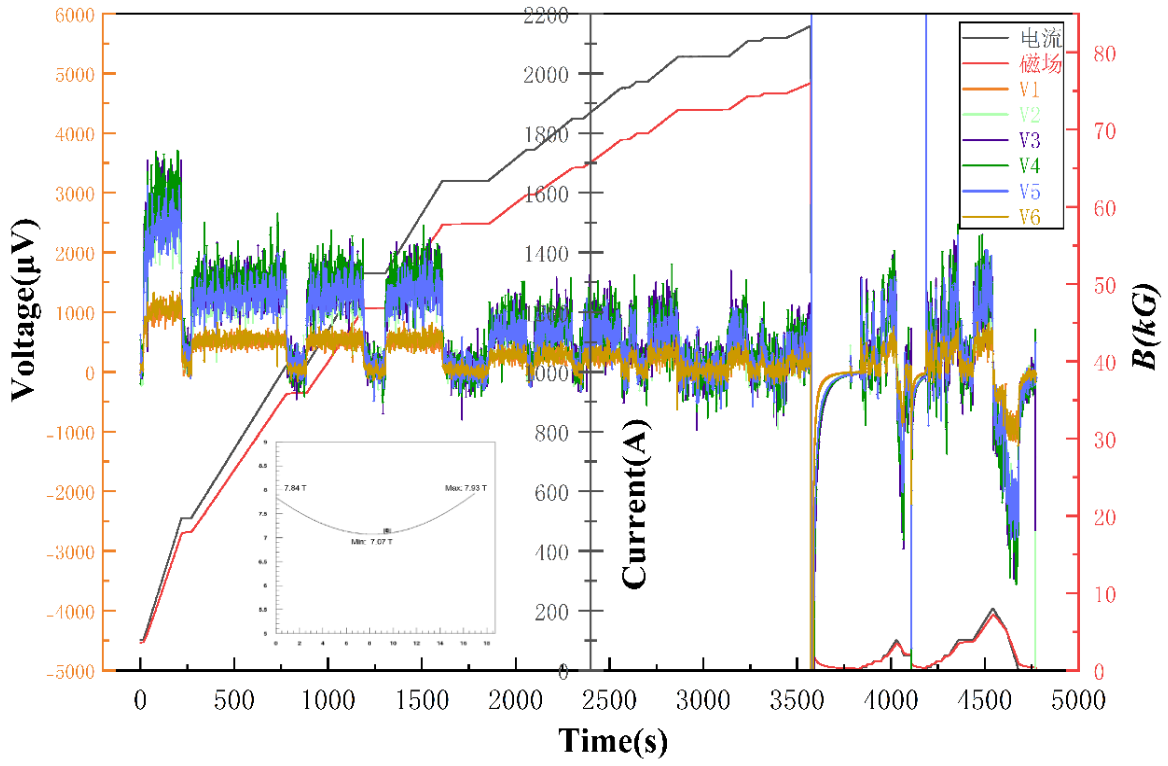
Development of the High Field Model Dipoles

Refabrication and test of the new HTS coils in Summer 2025

HTS stand alone: 2159 A, 7.6 T in the aperture@ 4.2 K

Maximum field on the coil (calculated): ~10 T

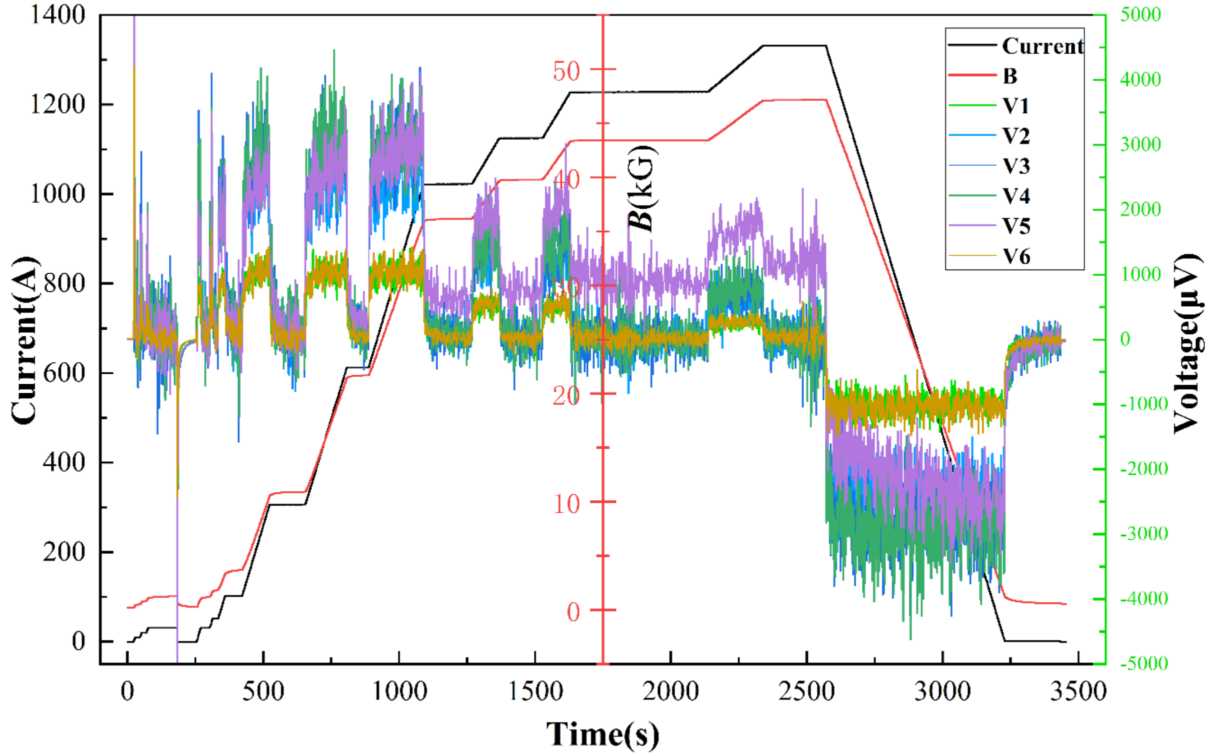
Performance limited by a power failure: current discharged in 1 s



Power failure at 2159 A damaged 1 of 6 HTS coils

Resistive voltage appeared in #5 coil from ~800 A;

bypassing #5 coil for the following tests



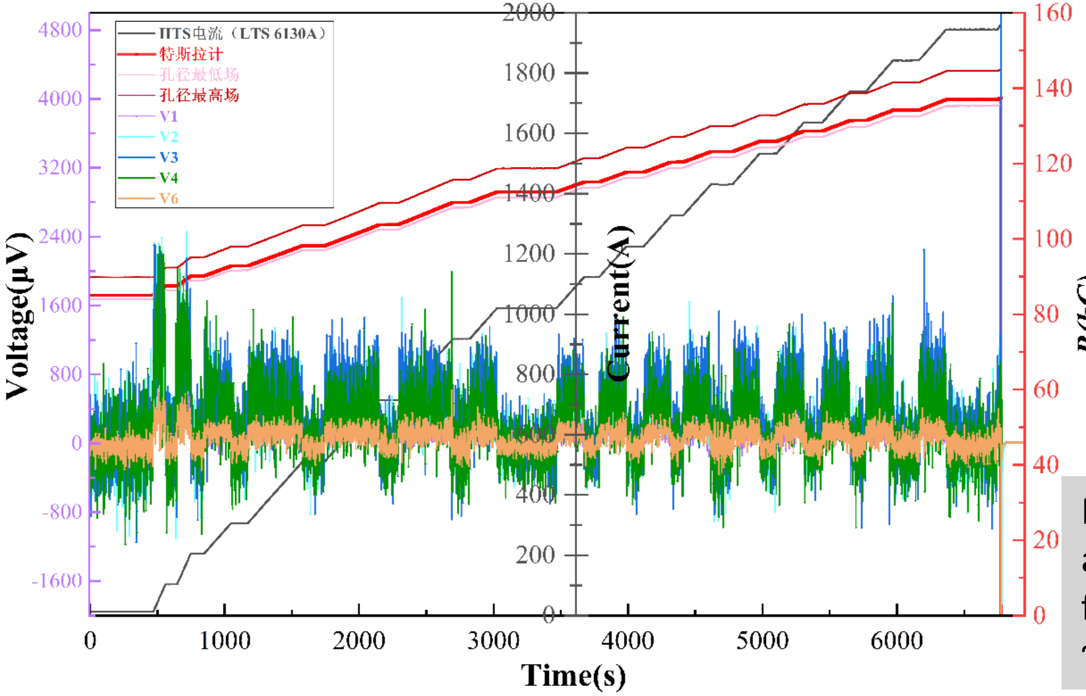
Development of the High Field Model Dipoles

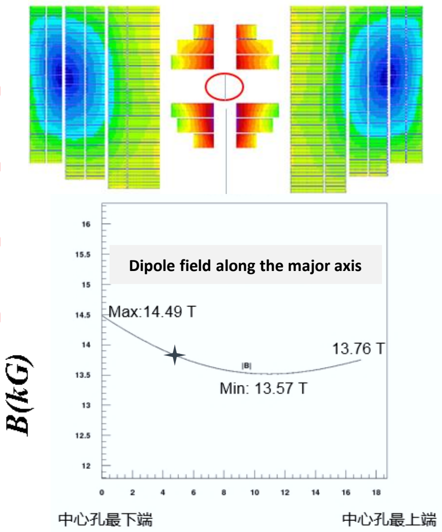
Refabrication and test of the new HTS coils in Summer 2025

2nd powering with LTS: #3 HTS coil quench at 1959A, and after 0.4156s, the LTS quench detection system triggered. The current decay time of HTS is 1.3 s, and LTS is 0.7718 s;

2nd HTS powering with Nb_3Sn at 4.2K

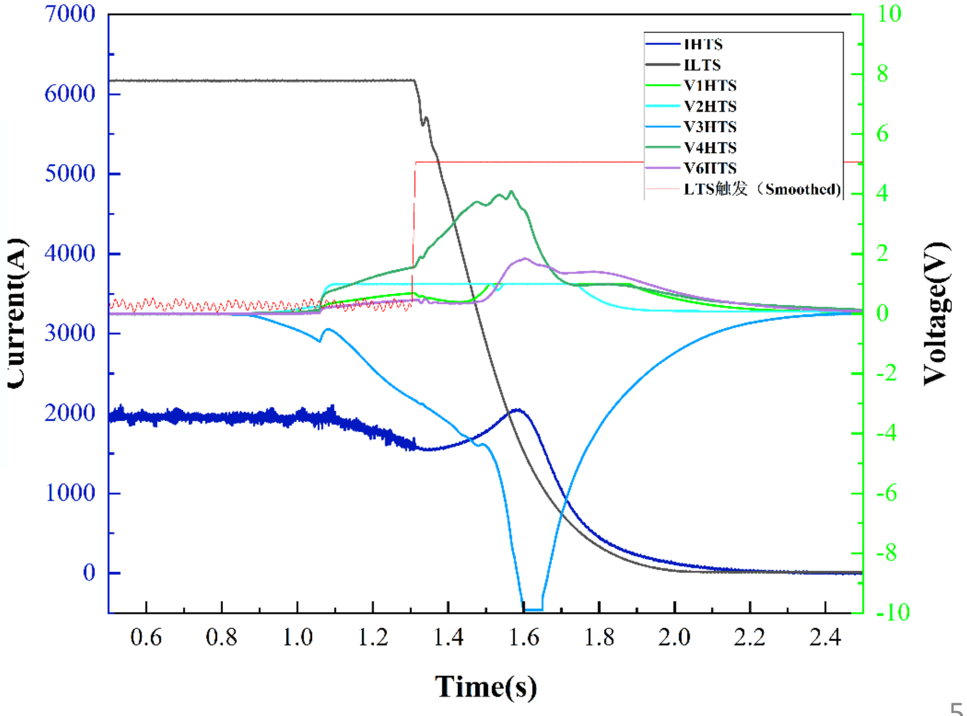
Quench at HTS 1959 A & LTS 6130 A (bypassing #5 HTS coil)





Field map within the aperture. The highest field in the HTS coil ~16.2T (calculated)

Voltage and current variations during the quench



Development of the High Field Model Dipoles

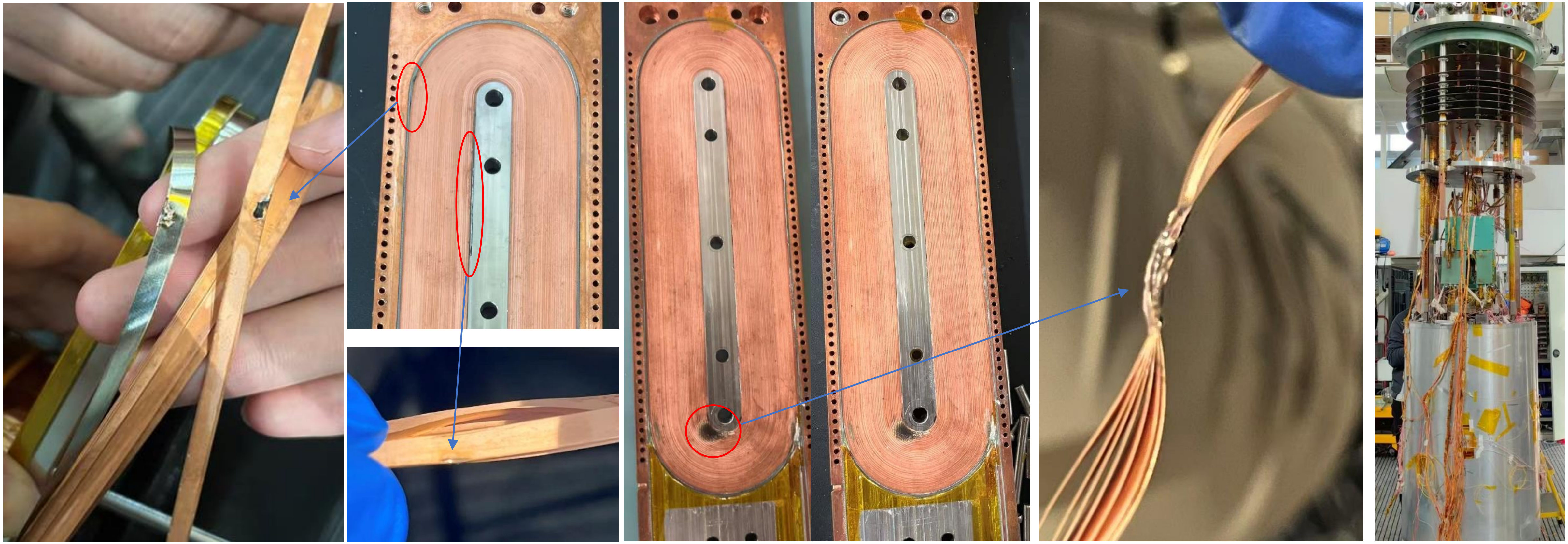
Refabrication and test of the new HTS coils in Summer 2025

- Power failure damaged coil (#5 coil) during the stand-alone test: conductor partially burned at the coil end
- Quench at 14 T damaged coil (#3 coil) during powering with Nb_3Sn coils: conductor burned at the bending section
- **New ReBCO coils have been fabricated and assembled in the magnet, test with be done in Jan 2026**

#5 coil

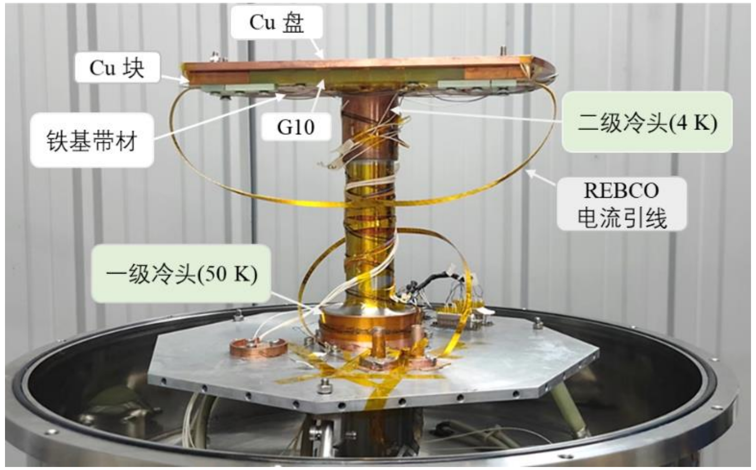
#3 coil inner

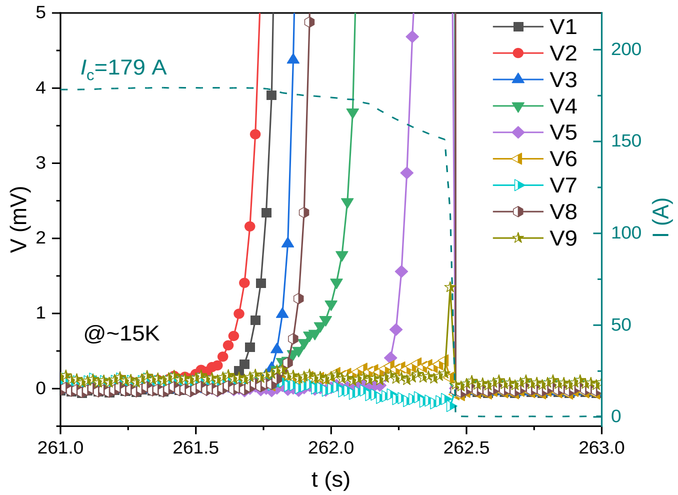
#3 coil outer

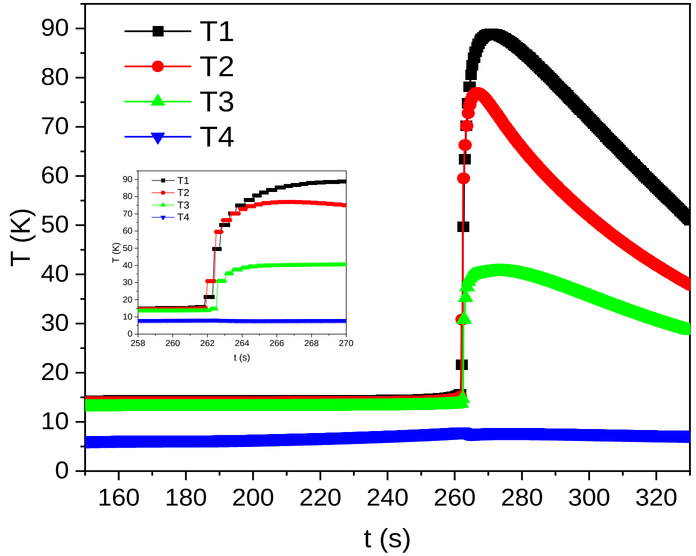


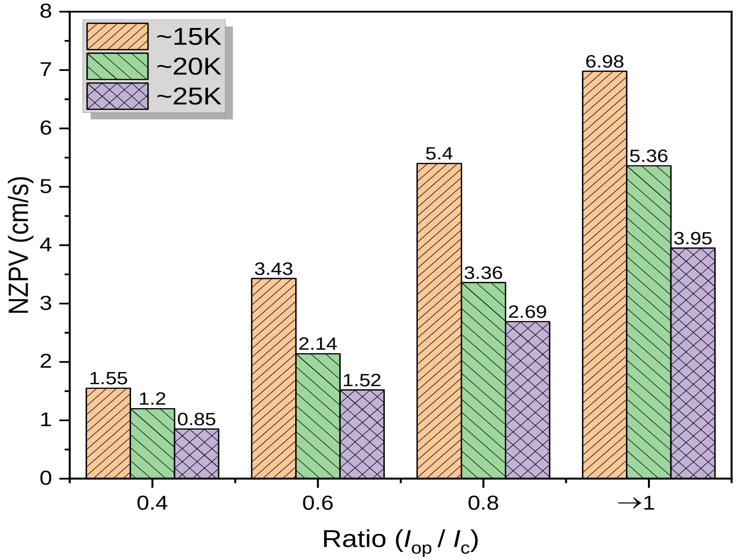
IBS Technology: Status and Outlook

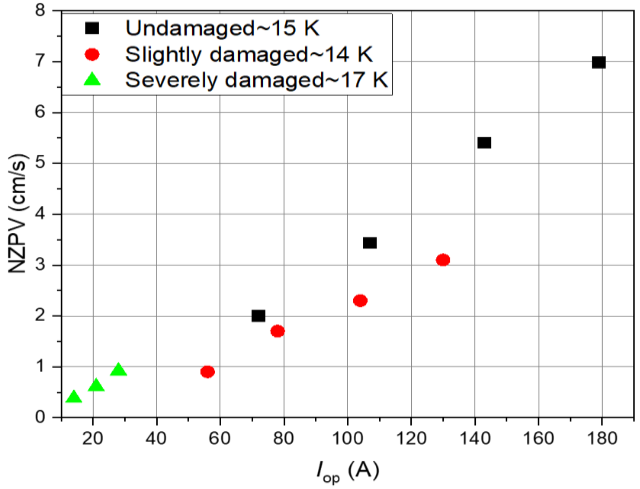
Quench propagation study of the IBS tapes and coils









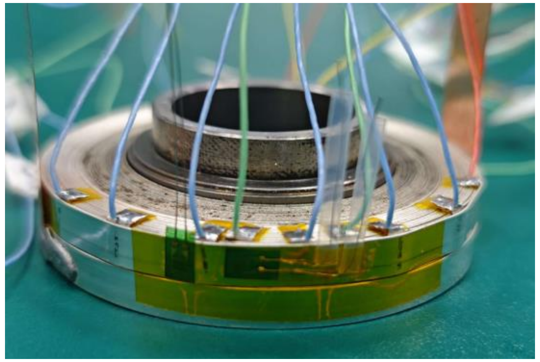


In 15~17K, when the transmission current of iron-based superconductor is 14-179A, the corresponding NZPV value is 0.4– 7cm/s

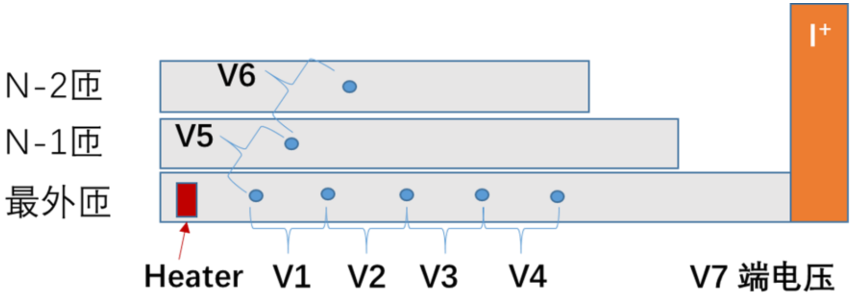
Chunyan Li et al. Supercond. Sci. Technol. 37 (2024) 085021

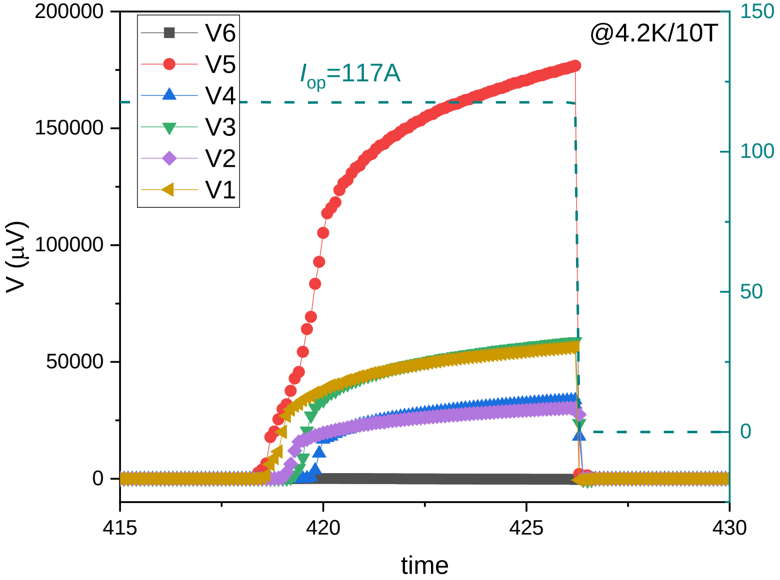
IBS Technology: Status and Outlook

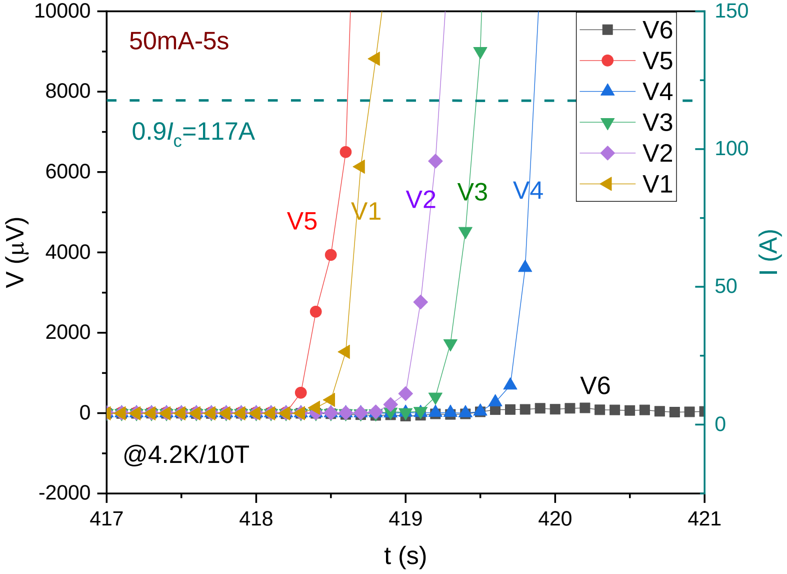
Quench propagation study of the IBS tapes and coils



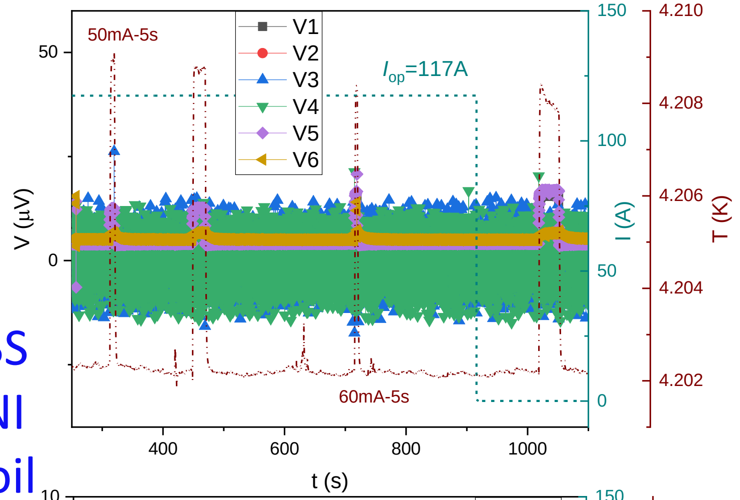
IBS-MI coil

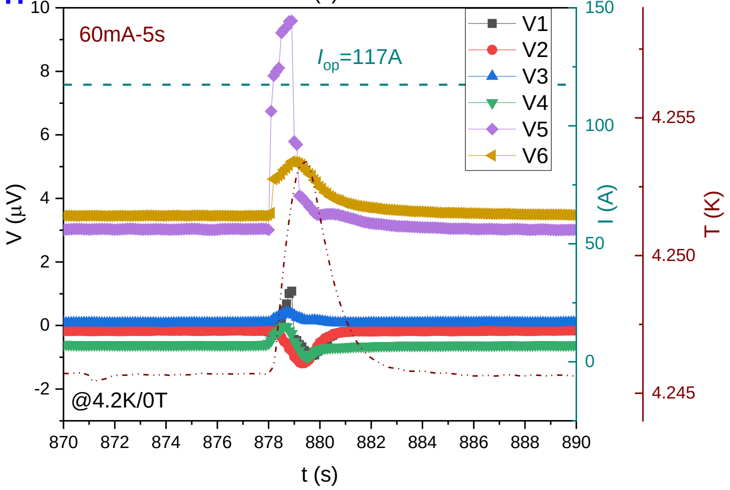






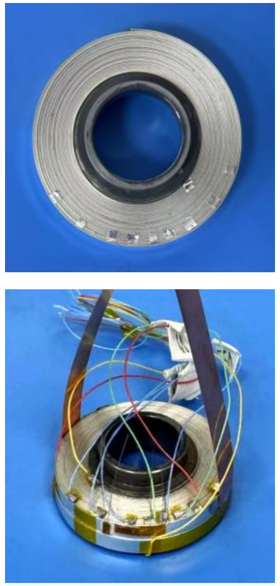
IBS -NI coil





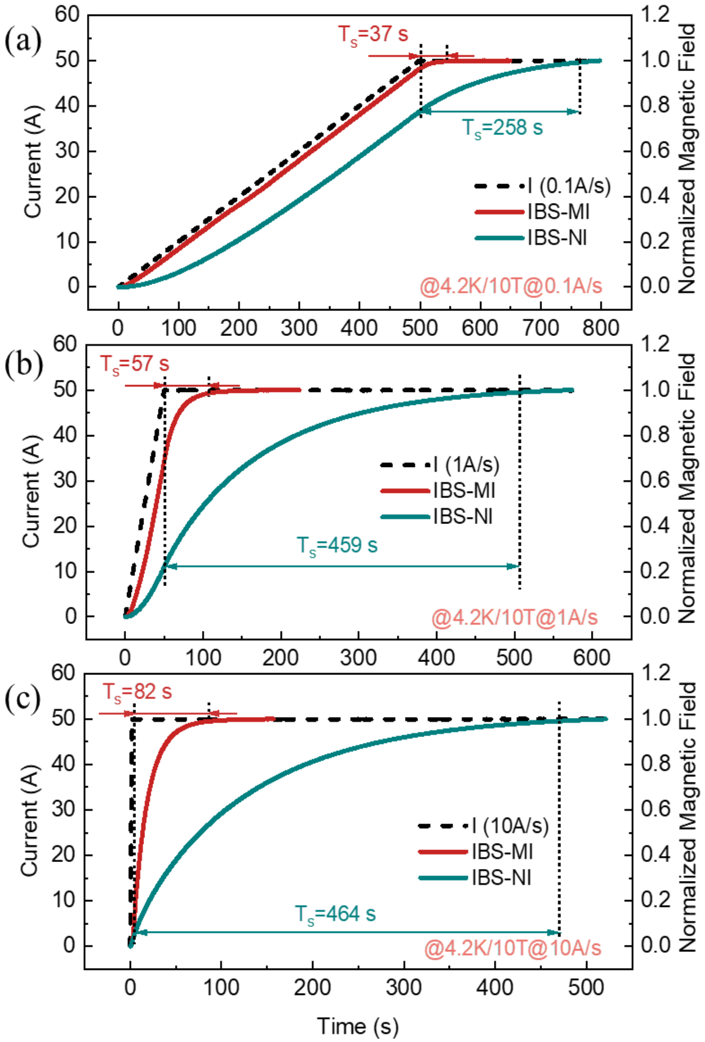
IBS Technology: Status and Outlook

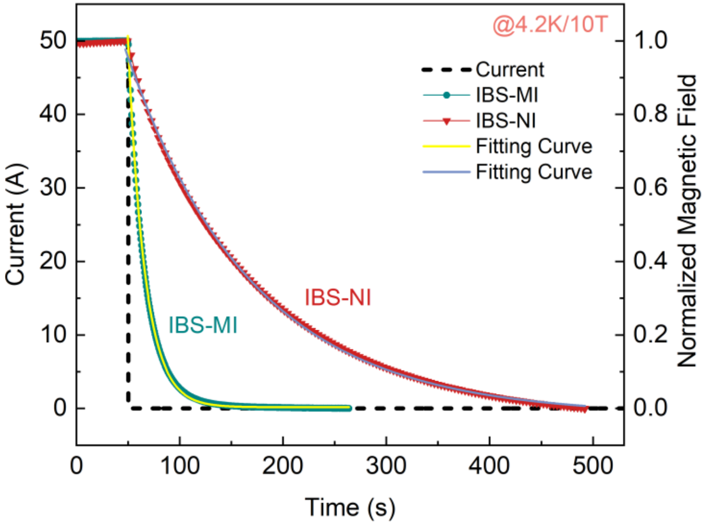
Performance comparison with different fabrication methods

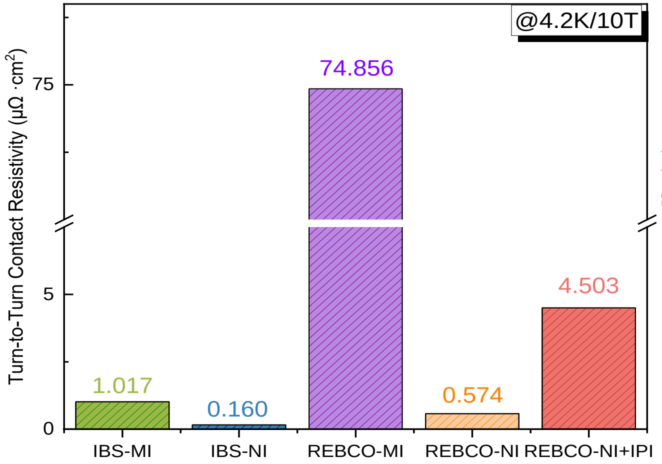


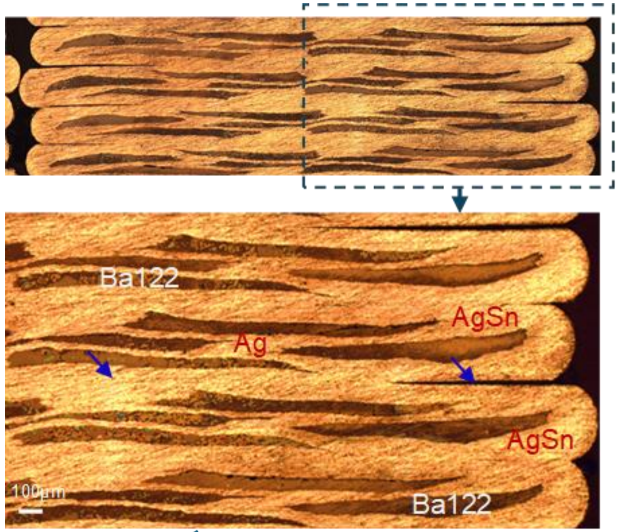
IBS coil

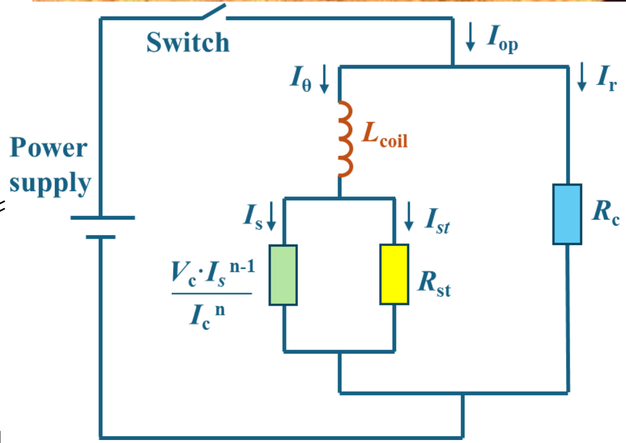
REBCO coil







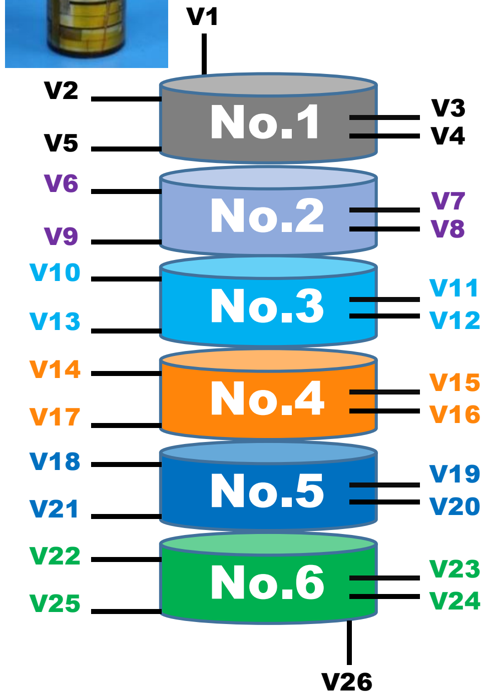




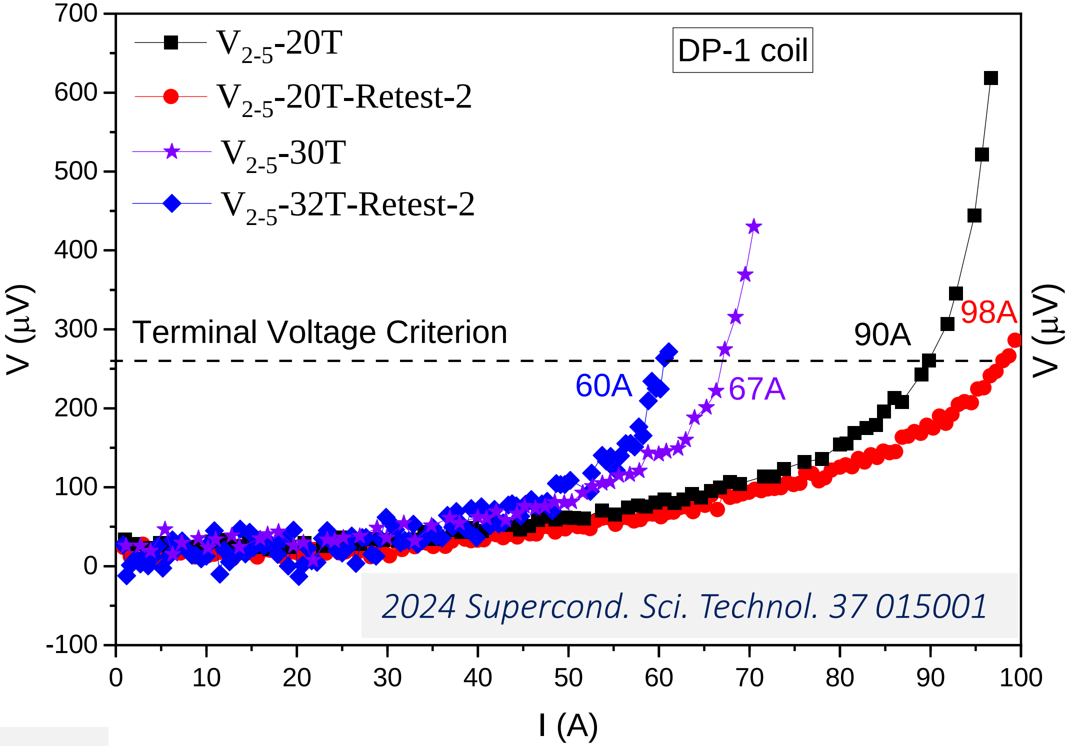
Fan Ren, Chunyan Li et al. Supercond. Sci. Technol. 38 (2025) 125007

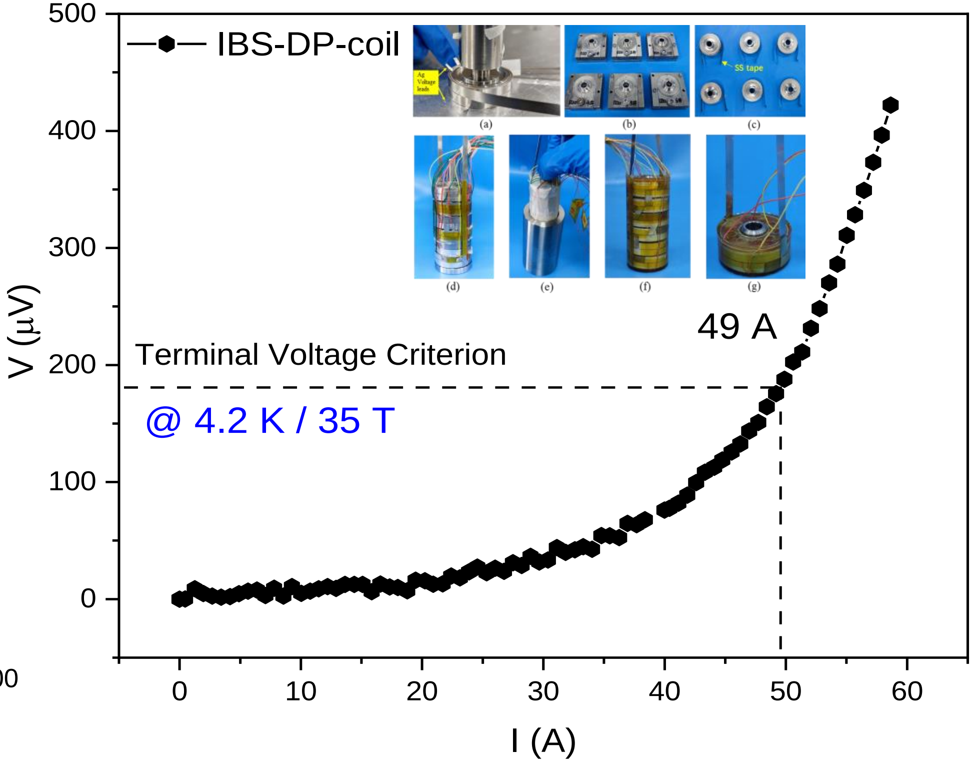
IBS Technology: Status and Outlook

IBS Solenoid Coil tested at 32-35 T background field



DP-6串联线圈电压引线图



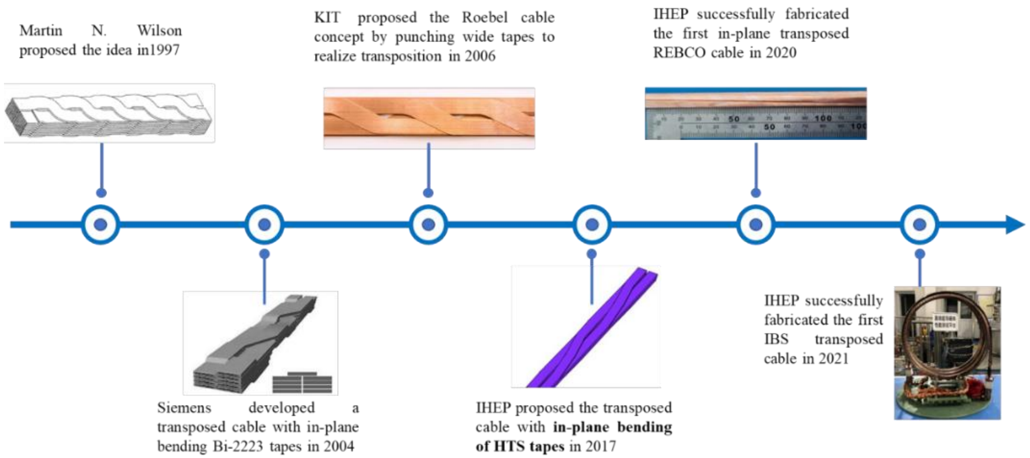


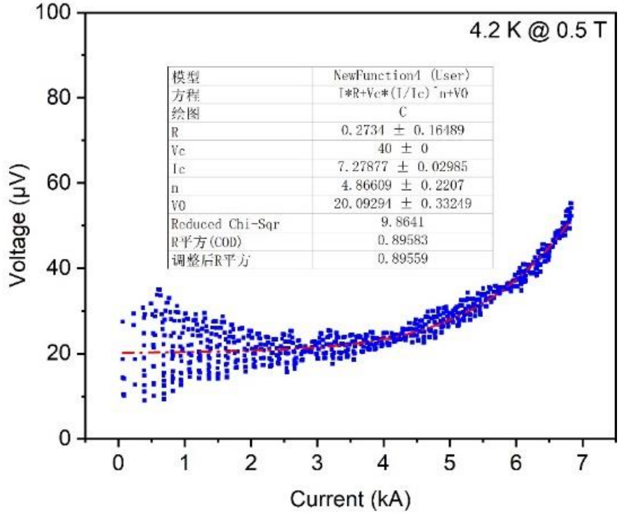
Fabricated a series-connected IBS coil consisting of six DP coils and tested at 32-35 T background field

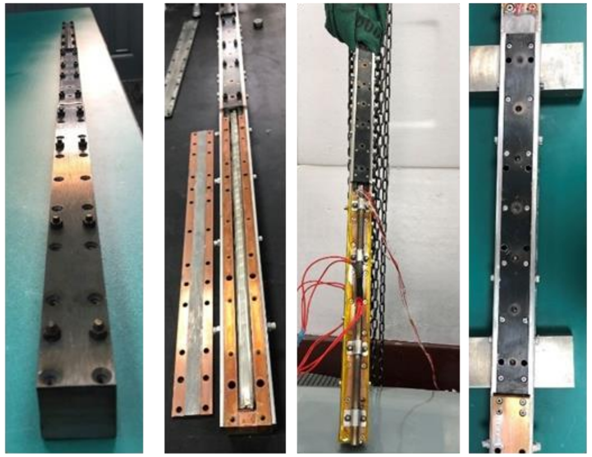
IBS Technology: Status and Outlook

Development of the first 7-kA class IBS transposed cable

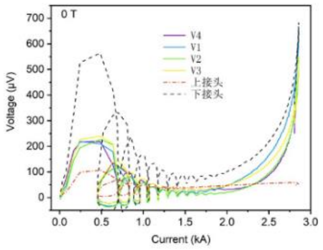
测试电缆热处理







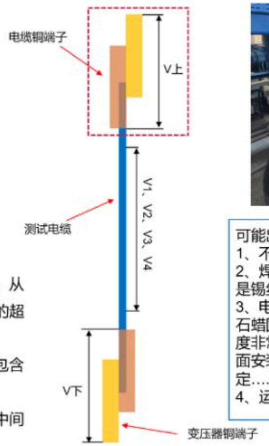
热处理后样品 接头焊接 石蜡固化

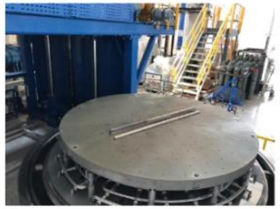


1、上接头、V1-V4、下接头将电缆分成3部分，从V-I曲线可以确定上接头焊接质量很好，且包含的超导带性能没有损伤；

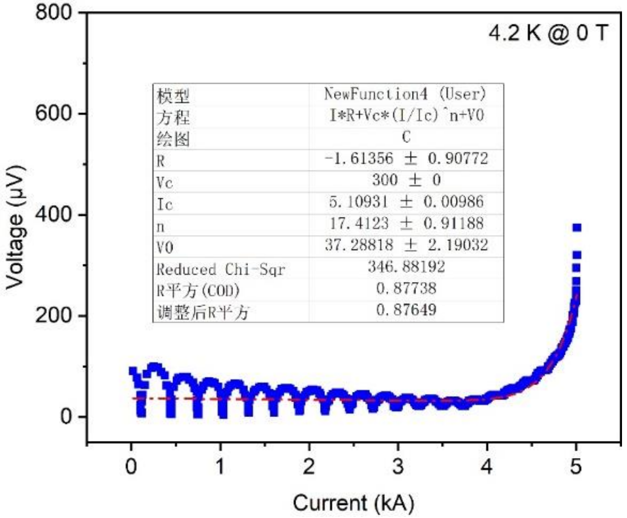
2、下接头的V-I曲线出现非线性的转变，说明包含在下接头中的超导带性能出现损伤；

3、V1-V4的转变和下接头几乎一致，是否证明中间部分的超导带也受到损伤？





可能出现问题的地方：
1、不锈钢接头替换成铜接头（操作非常小心）
2、焊接头时罐锡的小孔位置容易损伤（熔的都是锡丝）
3、电压引线用的比较粗，焊完后翘着，虽然用石蜡固化了，有一定的保护作用，但是石蜡的强度非常低，组装的时候，下部电压引线是折到背面安装的，有可能损伤，等样品邮寄回来确定.....
4、运输.....（包装的很好）



Conclusions

Summary and Outlook — The Future of High-Field Accelerator Magnets

The Path to 20+ Tesla

Technology Comparison: LTS vs HTS Performance Summary

LTS Technology: Proven and Mature

Nb-Ti

8-10 T capability, mature manufacturing

~10,000 km in LHC

Nb_3 Sn

HL-LHC demonstrating 11-14 T

~1500 km for upgrade

16 T Target: Within reach with ongoing R&D

Practical limit ~16 T for LTS technology

HTS Technology: Breaking Barriers

48.7 T Hybrid Solenoid Demonstrated

FAMU-FSU Demo4, Oct 2025

14+ T HTS+LTS Model Dipole Demonstrated

China IHEP, July 2025

20+ T Dipole Fields

Achievable with HTS technology

4-50 K Operation

Large thermal margins

Hybrid: practical path to 20 T

Critical Challenges and Innovative Solutions

Key Challenges

Quench Protection

NZPV 2-3 orders slower than LTS. Requires innovative detection and protection strategies.

HTS Materials and Manufacturing Scale-up

Fusion market driving 15-20% CAGR production growth

Mechanical Integration

Managing 7.5+ MN/m forces while keeping REBCO strain <0.4%.

Cost & Scalability

REBCO at $50-150/kA·m. Need 1 km+ lengths and industrial production.

Field Quality

Screening current effects, training quenches, harmonic control.

Solutions

Hybrid Magnet Architecture

Combining LTS and HTS for optimized cost-performance ratio

Global Collaboration

CERN, US, Asia, industry partners……

Pushing the Boundaries of Magnetic Field Technology

Superconducting magnets have enabled the greatest discoveries in particle physics

From the Higgs boson at the LHC to future discoveries at the next-generation high energy accelerators

the relentless pursuit of higher magnetic fields continues to push the boundaries of our knowledge and technological capability.

8.33 T	11 T	20+ T
LHC Today	HL-LHC	SPPC & FCC-hh
Discovery Era	Precision Era	New Physics Era

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