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# Review on progress of the homemade 15T LTS solenoidal background magnets using for material test facility and ultra-high magnet fabrication:

## Magnet Design, Manufacture and Test

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*25-July-2024*

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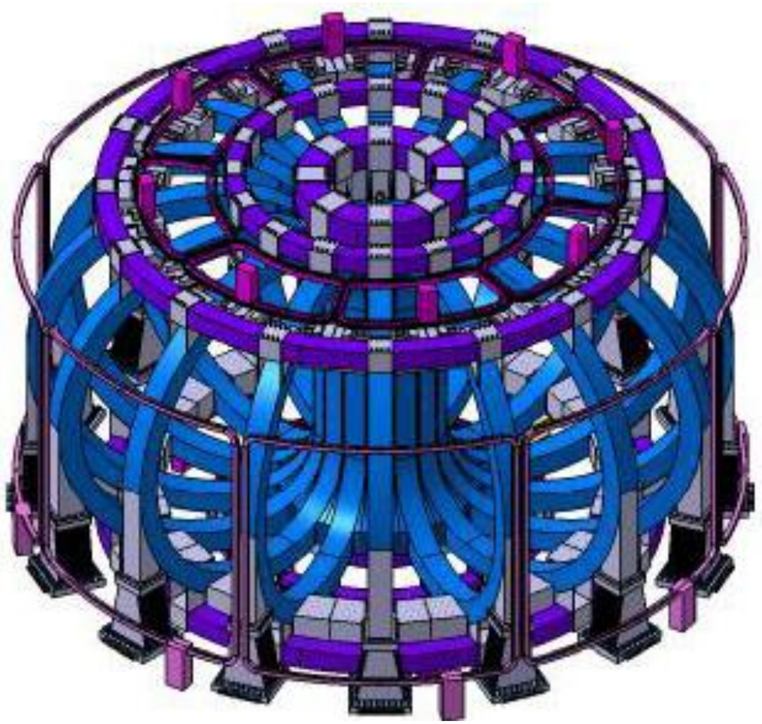
# Introduction

## Special character of Fusion magnet

- Difficult to maintain (complex structure)
- Large dimension, heavy weight, precise shape
- Low margin operation
- Multi-physical environment
- High energy density and stored energy



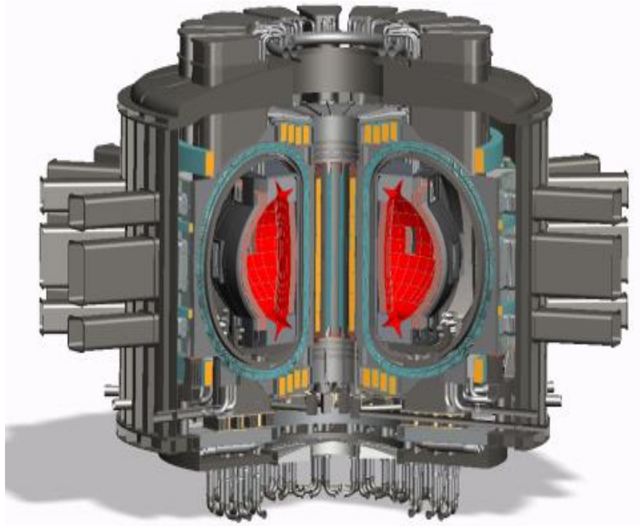
**Defect events**

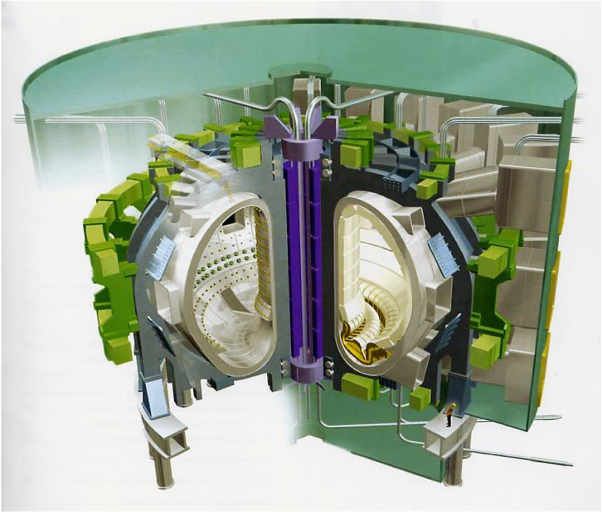
- Superconducting stability
- Coil temperature
- Mechanical damage
- Insulation damage
- Helium leak
- Joint defect
- Quench detection

# Introduction

## Future fusion device: Higher magnetic field, Larger current, Larger stress

| Reactor name | ITER | EU-DEMO | CFETR |
|---|---|---|---|
| Max. Field (T) | 10.8 | ~13.5 | 14.4 |
| Max. Current (A) | 68 | ~80 | ~96 |
| TF coil (m) | 12.6×9.0×0.97 | 14×10×1.2 | 21.3×12×1.2 |
| Energy (GJ) | 41 | 109 | 120 |





# Introduction



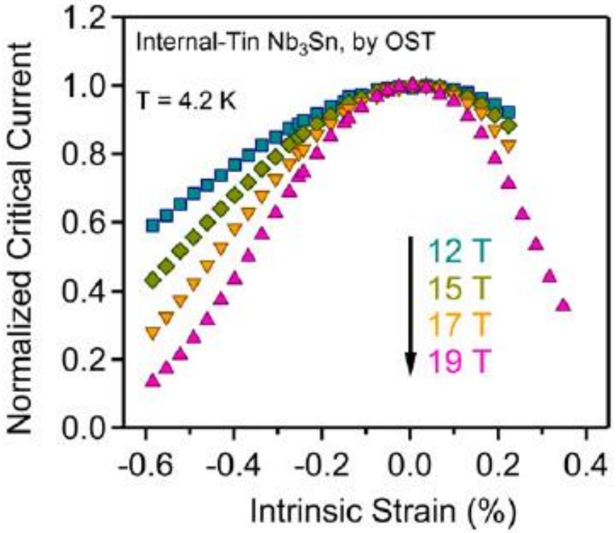
## S.C. material test facilities: Serve the future fusion device

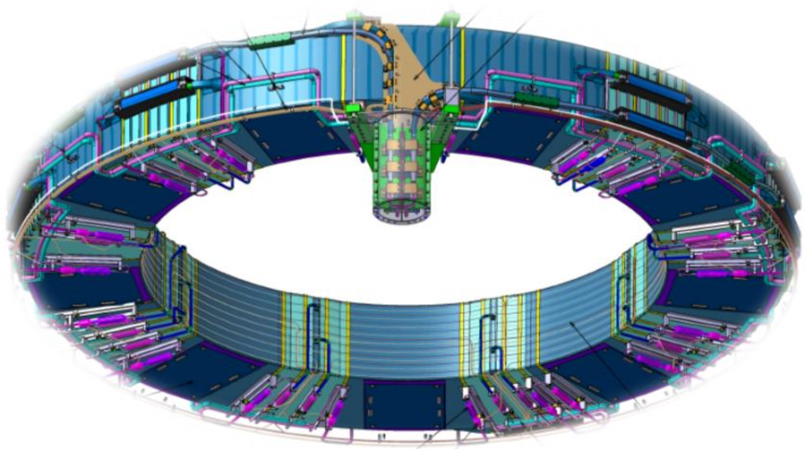
I. Study and assess material damage mechanical properties

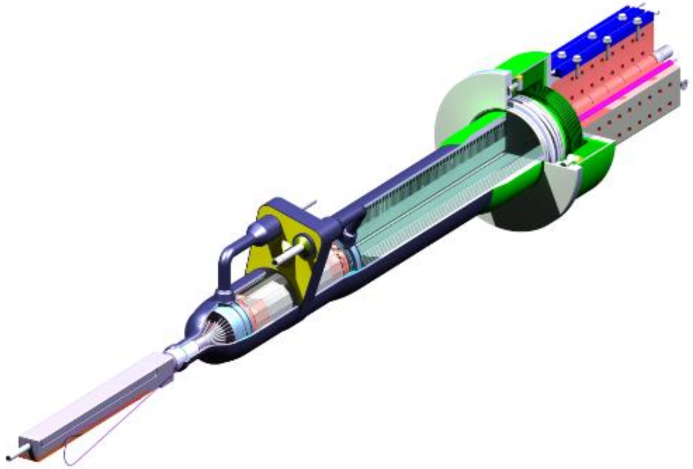
II. Develop and qualify key technologies of applied superconductivity

III. Carry out the safety operation studies on S.C. magnet at complex electromagnetic condition

IV. For planned coils acceptance tests





# Introduction



## Facilities list of the CRAFT project: ¥ 2.7 billion ≈ € 0.34 billion (09/2019-06/2025)

| | |
|---|---|
| • **1. S.C. Material testing facility** | • 11. CFETR divertor development |
| • **2. S.C. Conductor testing facility** | • 12. CFETR divertor testing faculty |
| • **3. S.C. magnets testing facility** | • 13. EAST divertor upgrade |
| • **4. CFETR CSMC and testing facility** | • 14. ECRH System |
| • 5. CFETR HTc coil and testing | • 15. NNBI system |
| • 6. CFETR TF and testing | • 16. LHCD system |
| • 7. Cryogenic testing facility | • 17. ICRF system |
| • 8. Power supply testing facility | • 18. Blanket testing facility |
| • 9. Large Linear plasma testing facility | • 19. RH testing facility |
| • 10. Mater Control facility | • 20. VV and installing testing facility |

| | | |
|---|---|---|
| Auxiliary system | 1、Power distribution system | 3、Cryogenic system |
| | 2、Cooling water system | 4、Power supply system |

# Introduction: Material test facilities



## Scientific objectives

- To master scientific and the intrinsic physical properties and service behavior of materials for superconducting magnets in complex and extreme environments, and to carry out engineering application research.

## Composition and main parameters

2.1 **SC material performance research platform: 19 T, 2 kA**

2.2 AC Loss research platform: 0.01-0.2 Hz,1500 kN/m

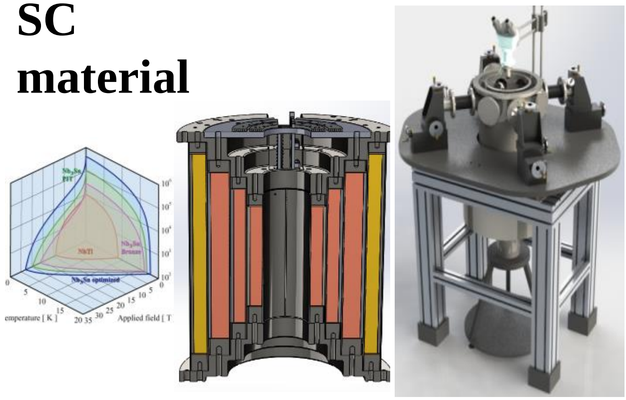
2.3 Structure material performance research platform: 2500 kN

2.4 Thermo-hydraulic research platform: 3.8-300 K

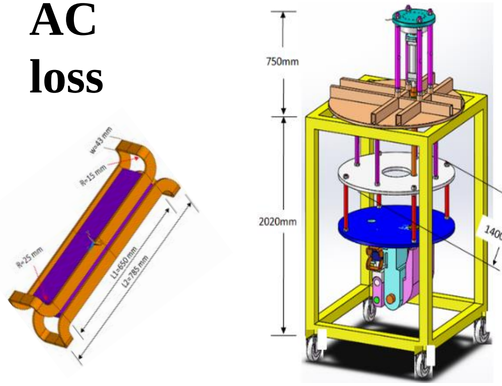
2.5 NDE technology research platform: 350 kV (X-Ray)

2.6 High voltage research platform: 0-100 kV

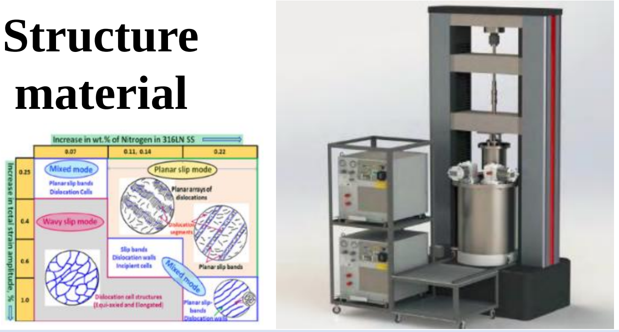
**SC material**



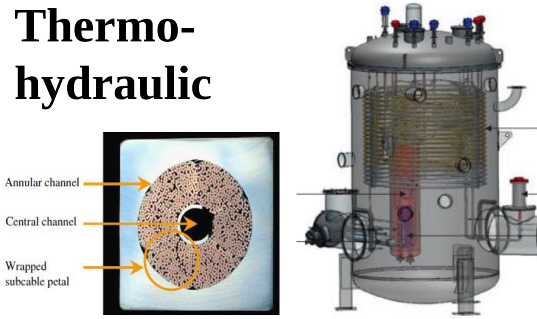

**AC loss**



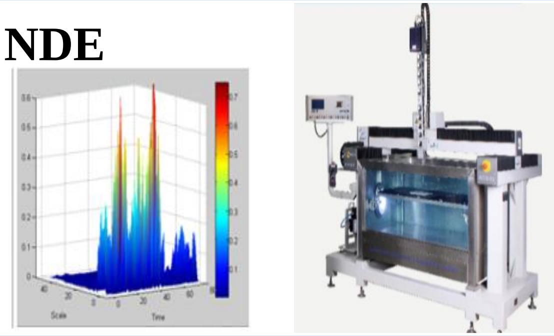

**Structure material**




**Thermo-hydraulic**




**NDE**



**High voltage**

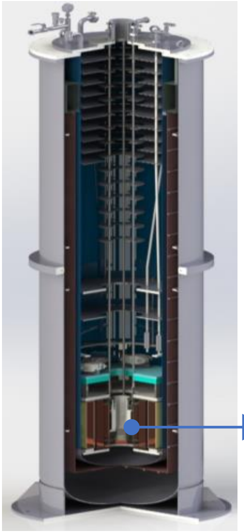
# Introduction: Research platform for S.C. materials

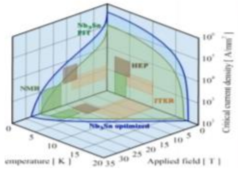


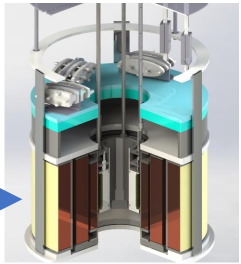
## Test platform for S.C. material properties

Research on the current transporting properties of superconducting materials under complex working conditions and acknowledge the evolution mechanism.

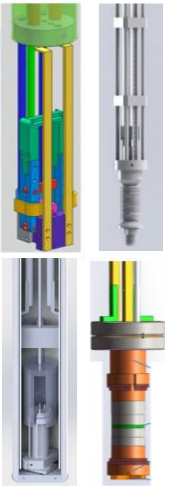
| Items | Specifications |
|---|---|
| Background magnetic field | 0-19T |
| Test temperature margin | 4-80K |
| Temperature stability | 0.03K（4-20K）<br>0.1K（20-80K） |
| Applied axial strain | -1%~1% |
| Current capability | 0-2000A |





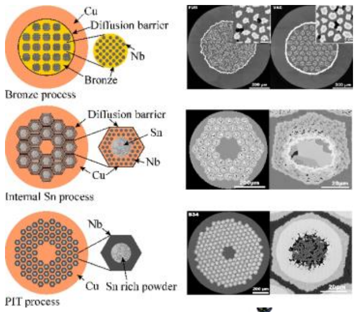


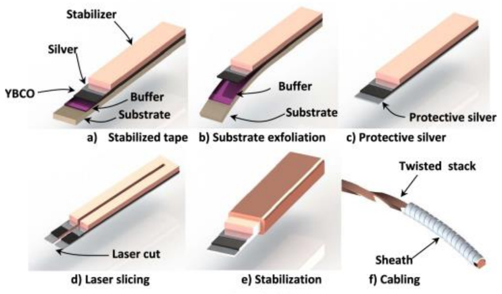
19 T magnet

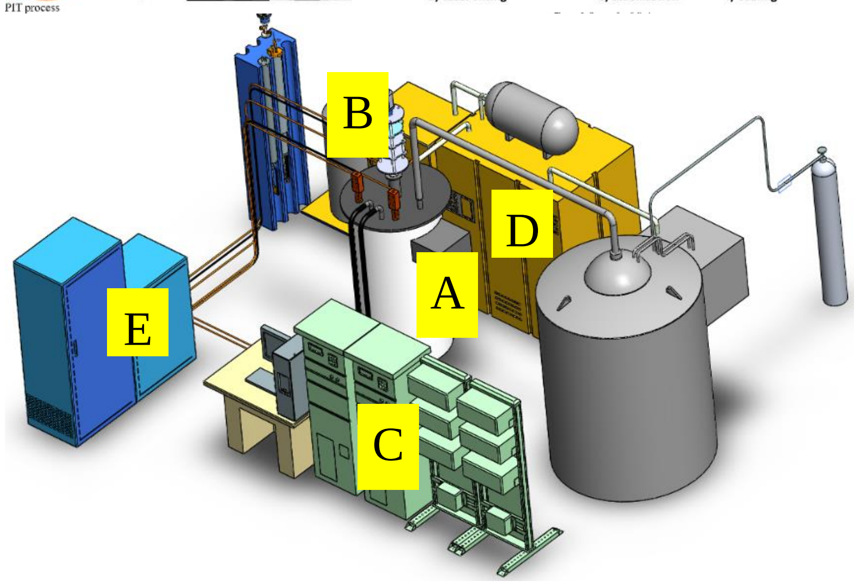


Sample holders

- **Background field magnet system:** Higher field, Larger bore
- **Multi-functional sample holders:** Variable axial strain, transverse mechanical-stress, temperature and magnetic field.



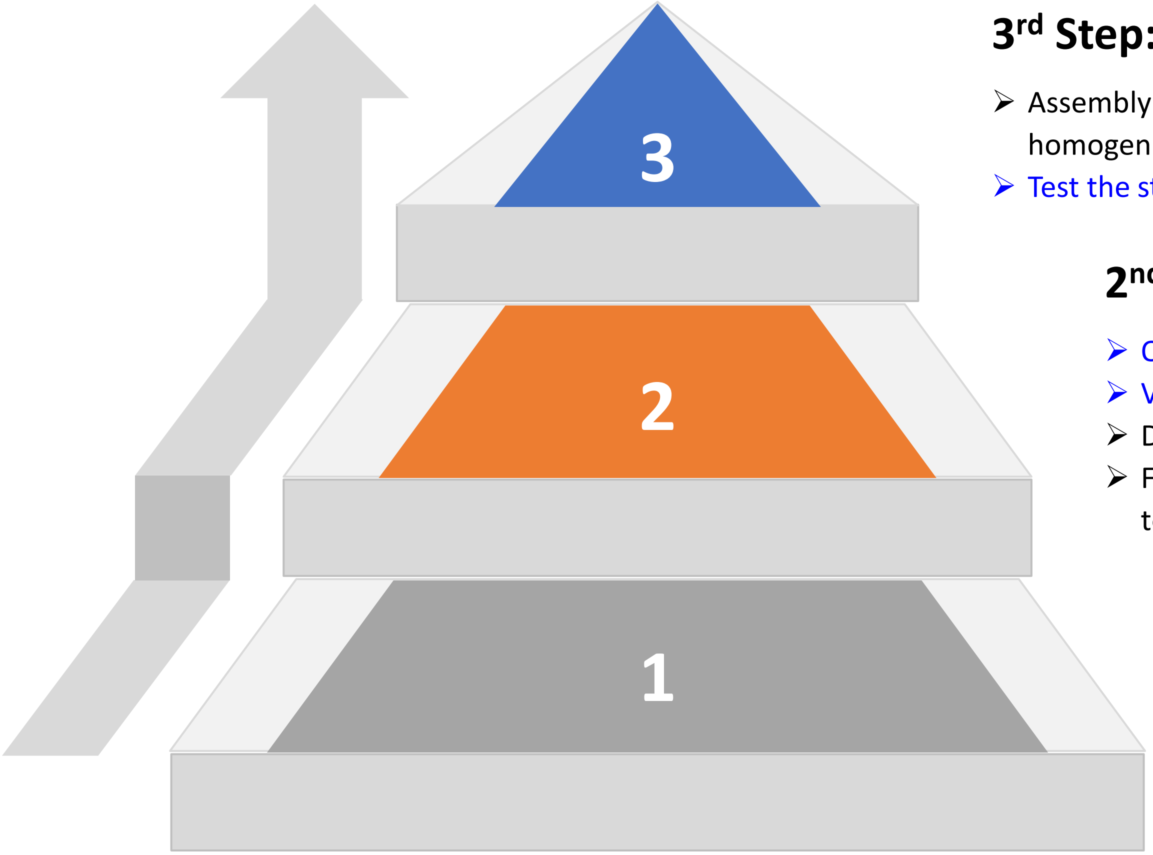




A. Background field magnet system
B. Critical performance test sample holders
C. Data acquisition and controlling system
D. Intelligent helium cycling system
E. Power supply with high accuracy

# Introduction



## 19 T all-superconducting magnet with a 70 mm aperture




### 3rd Step: 01/2024-12/2024

- Assembly the LTS background magnet and the HTS insert coil, examine the target magnetic field and homogeneity of the central magnetic field;
- Test the stabilities of the 19 T/70 mm all-superconducting magnet with various S.C. sample experiments.

### 2nd Step: 01/2021-12/2023

- Optimize and lock the key technologies of construction 15 T LTS solenoidal magnets;
- Verify the stability and reliability of the process for making 15 T/70 mm LTS solenoidal magnets;
- Do the S.C. sample experiments with different insert sample test-setups in the 15T/70mm magnets;
- Fabricate a 15 T/150 mm LTS solenoidal magnet and a 5 T/70 mm HTS double-pancake insert coil, test their properties independently.

### 1st Step: 09/2019-12/2020

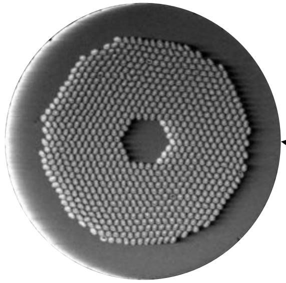
- Complete the construction of the fundamental devices for S.C. magnet fabrication;
- Design and make trail LTS coils to verify the key technologies for building high-field LTS superconducting magnets;
- Fabricate a 15 T/70 mm LTS solenoidal magnet, finish the properties examination.

## Challenges for building high-field magnets with a large bore

- When magnetic field is **larger than 9 T @4.2 K**, **$Nb_3Sn$** is the first choice
  - ❑ **Round wire** is easy to wind a coil;
  - ❑ **Price** is much lower than YBCO tapes;
  - ❑ **Quench** property is better.

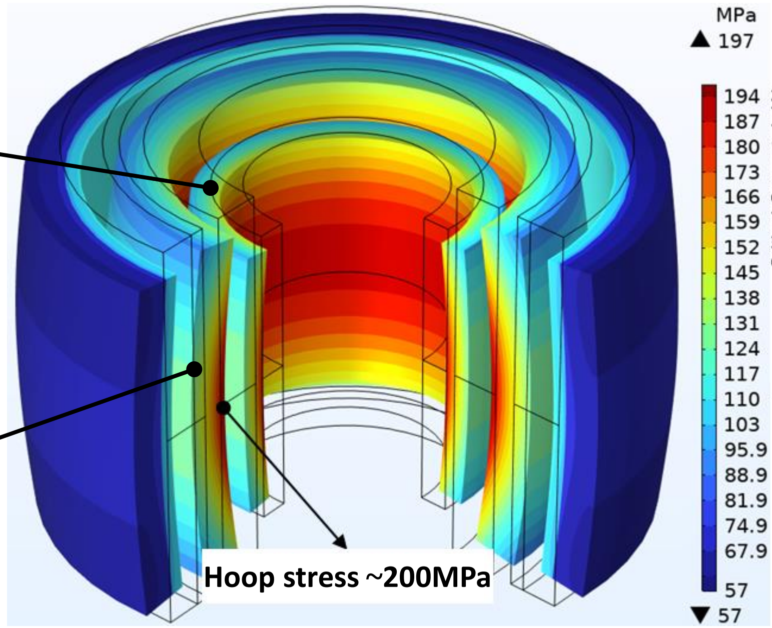
**BUT**

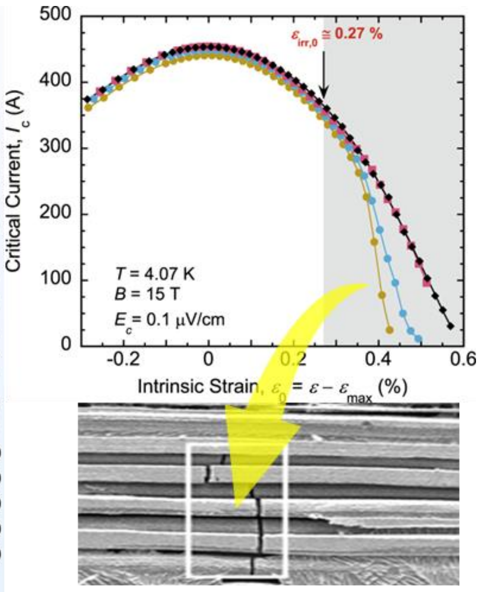
1. Process is complex, require **heat-treatment;**
2. Extra care is necessary due to the **high strain-sensitivity;**
3. **Precise stress control** has to be ensured.



H.P. $Nb_3Sn$

IT $Nb_3Sn$




Crack due to over-stress

- **Higher magnetic field** and **larger aperture size** produce **larger stress** on $Nb_3Sn$ coils and **higher energy storage**
  - ❑ **Over-banding layers** are necessary for adding pre-stress and used to limit the deformation of coils due to the Lorenz’ force;
  - ❑ **Insulation** and **Quench protection** are significant important due to the possible partial discharge and over-stress during quench.

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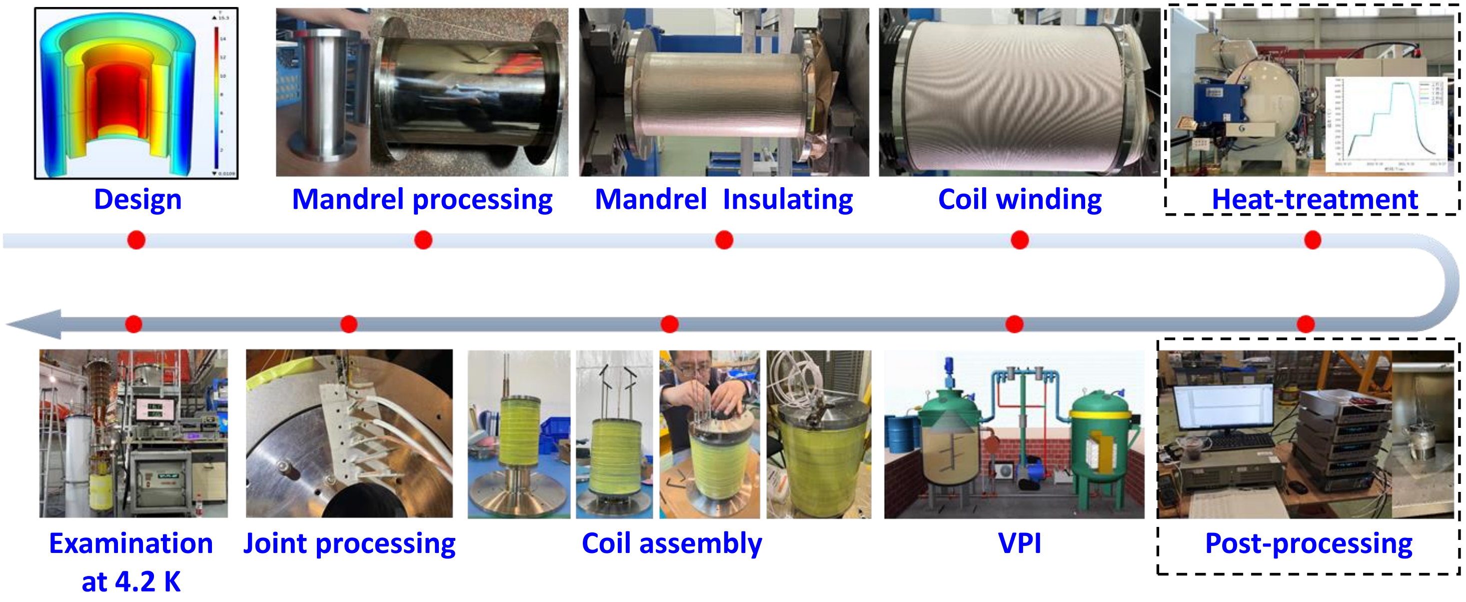
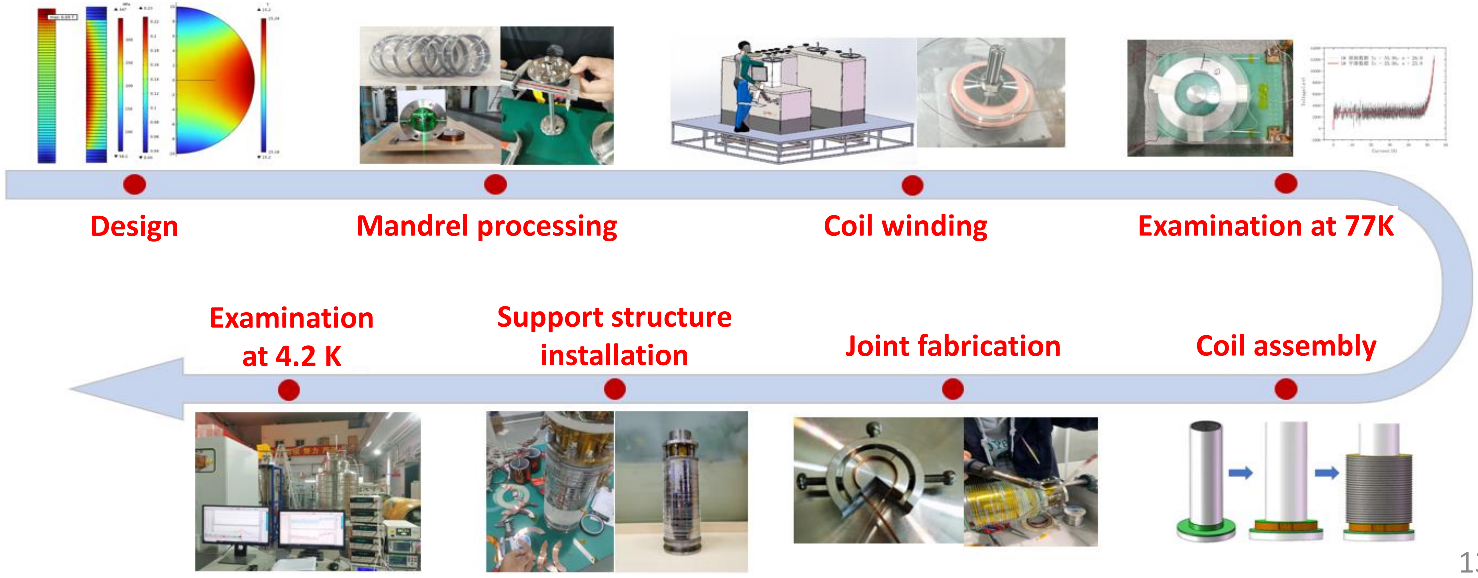
# Main progress: Flow chart of S.C. magnet fabrication

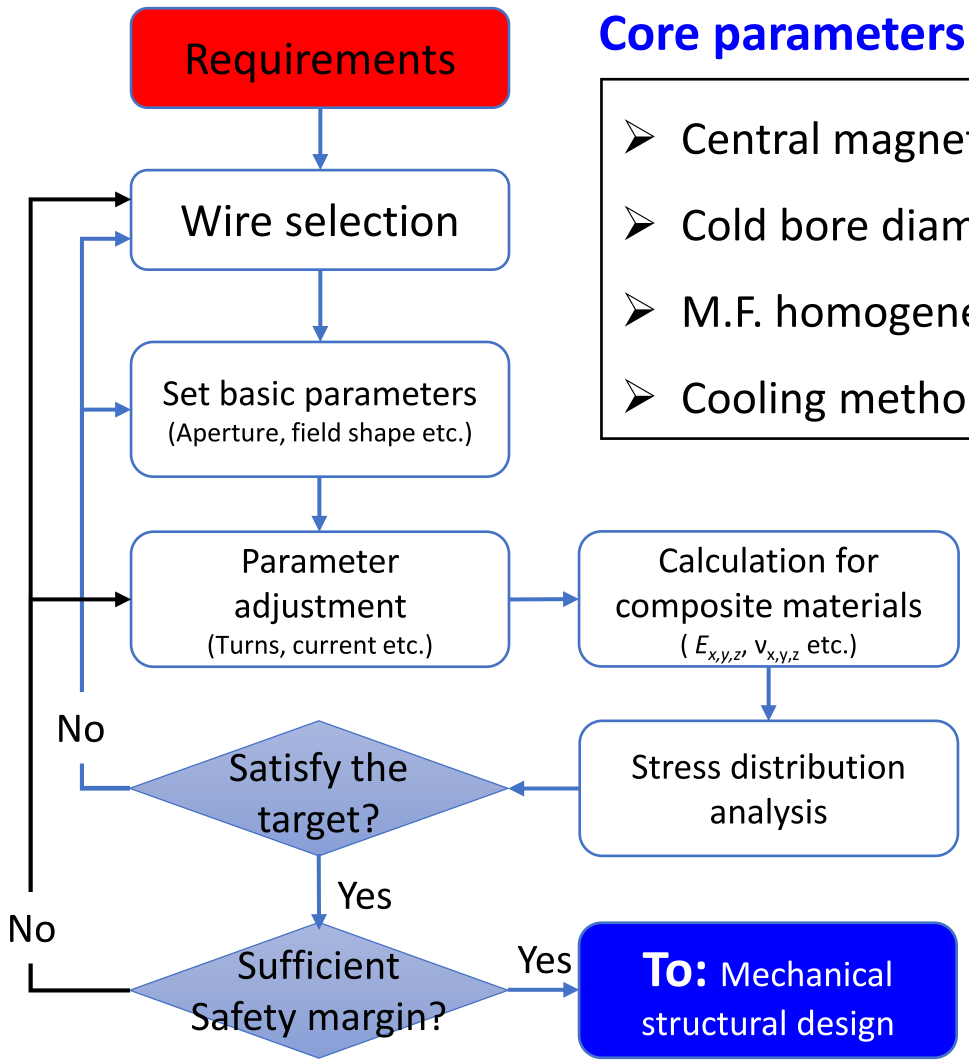
## Coil wound with $NbTi/Nb_3Sn/MgB_2$ wire




## Coil wound with *RE*BCO tape



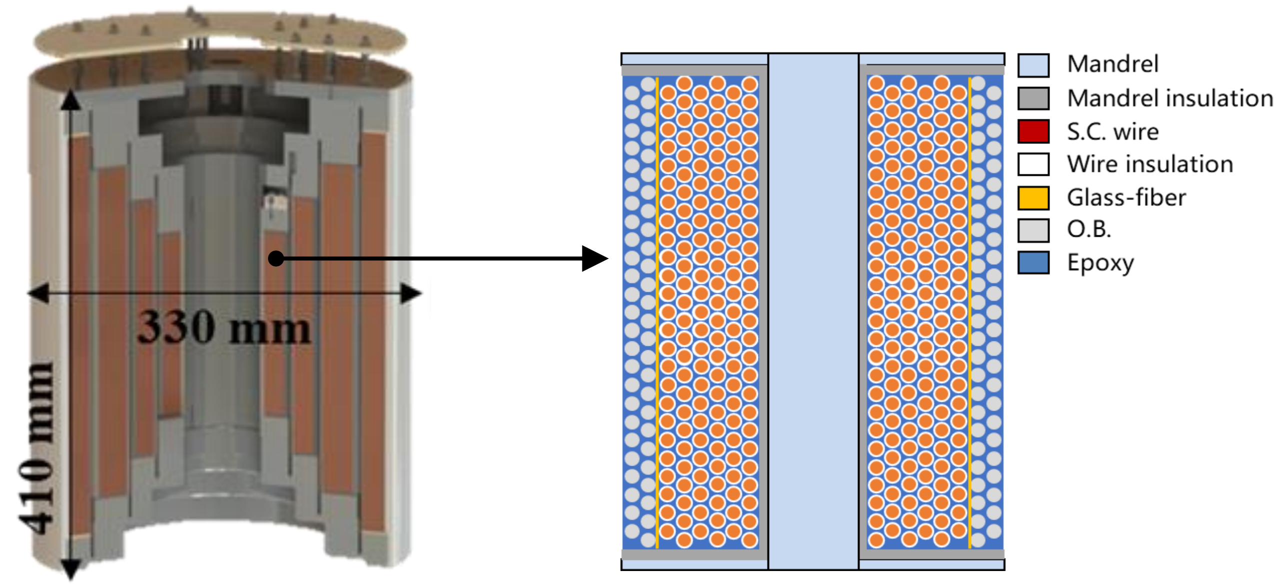
# Main progress: Magnet design




## Core parameters:

- Central magnetic field: ≥15 T@4.2 K
- Cold bore diameter: ≥ 70 mm
- M.F. homogeneity: ≤ 0.1% @ Ø10 mm×10 mm
- Cooling method: LHe

- Multiple coils → **reduce cost**
- Orthogonal odd-even winding
  → **Enhance structure stability**
- Single wire winding is used

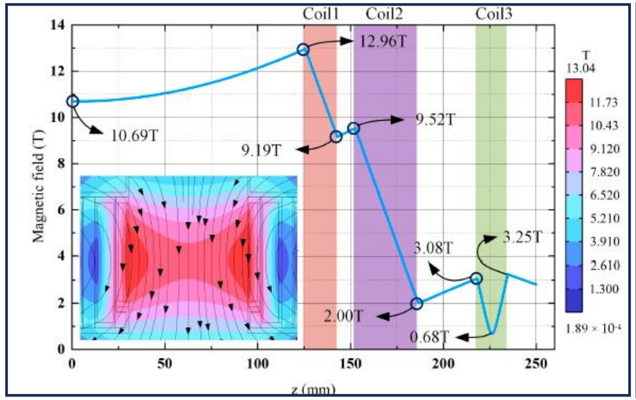


# Main progress: Magnet design

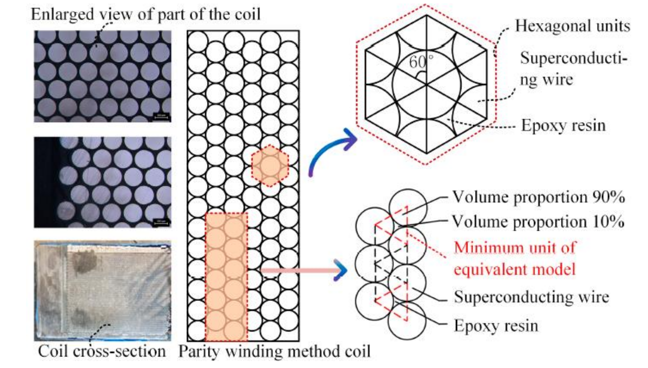


## Electromagnetic simulation & stress analysis & safety margin evaluation

### Electromagnetic simulation

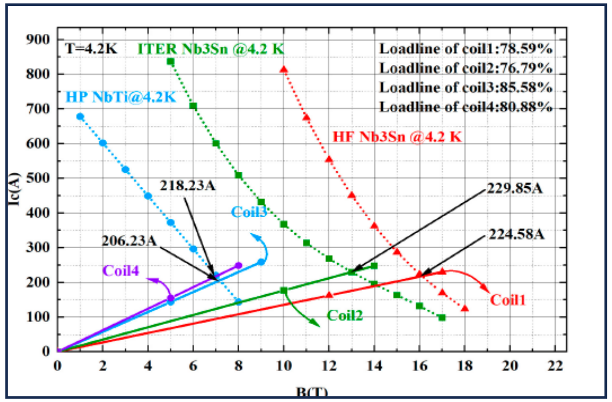



### Mechanical properties' calculation of the composite materials

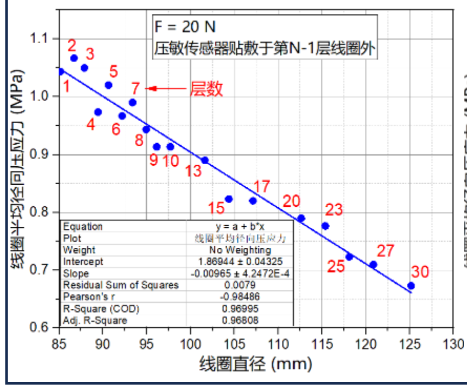


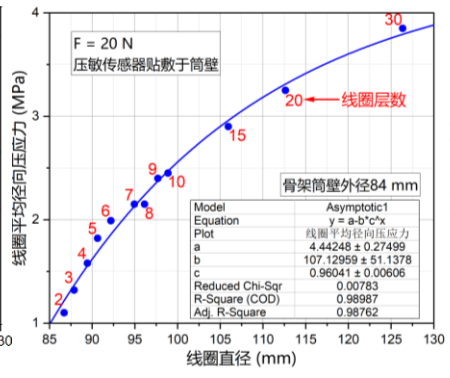

| Name | NbTi Coil | $Nb_3Sn$ Coil | 316L |
|---|---|---|---|
| E-R/GPa | 51.56 | 59.7 | 207 |
| E-PHI/GPa | 116 | 165 | 207 |
| E-Z/GPa | 51.56 | 59.7 | 207 |
| υ-RPHI | 0.2964 | 0.354 | 0.29 |
| υ-PHIZ | 0.296 | 0.36 | 0.29 |
| υ-RZ | 0.2964 | 0.354 | 0.29 |
| G-RPHI/GPa | 16 | 17.6 | - |
| G-PHIZ/GPa | 44.75 | 60.6 | - |
| G-RZ/GPa | 16 | 17.6 | - |
| $\rho/kg/m^3$ | 6535 | 7048 | 7960 |

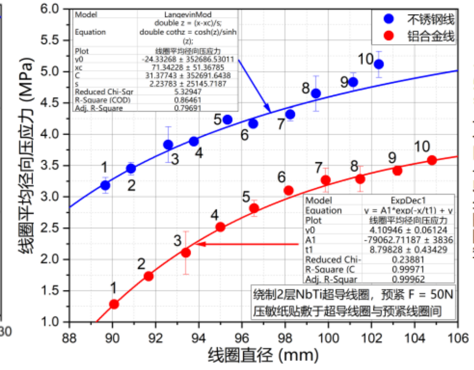
### Load-line evaluation

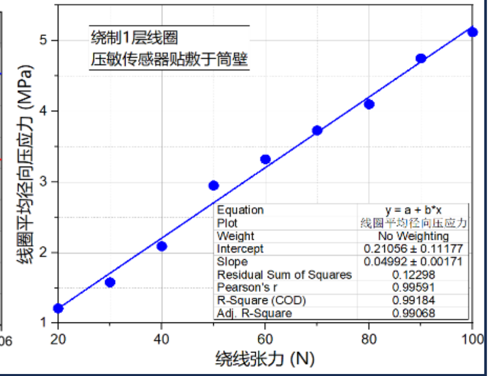



### Experiments of the relationship between radial stress distribution and outer diameter of coils, material types, tension force of prestress coils

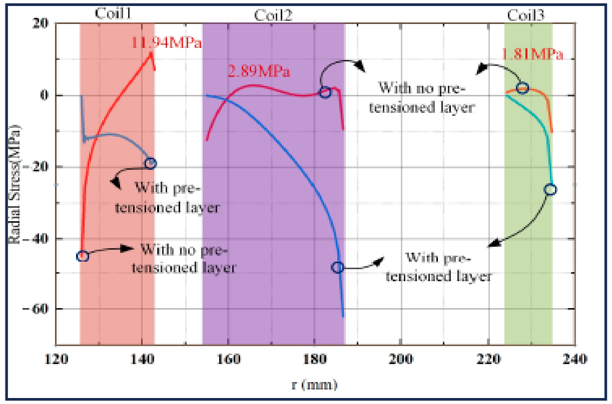



### Stress evaluation



# Main progress: Magnet design

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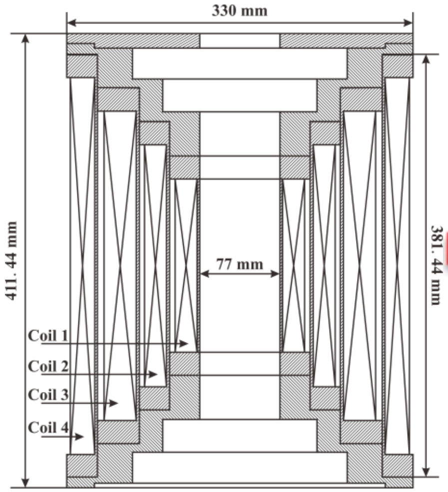
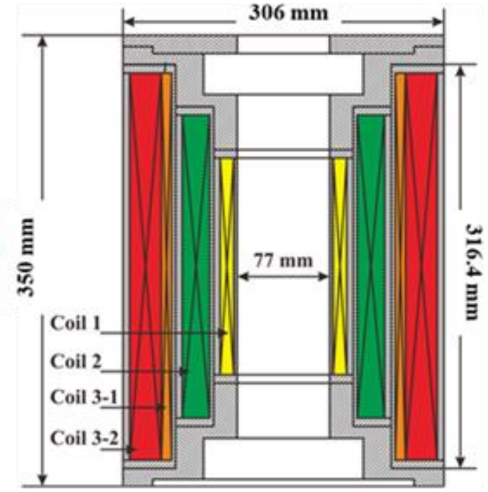
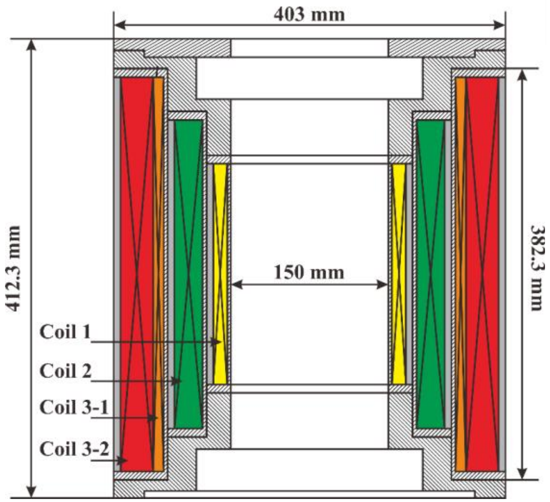


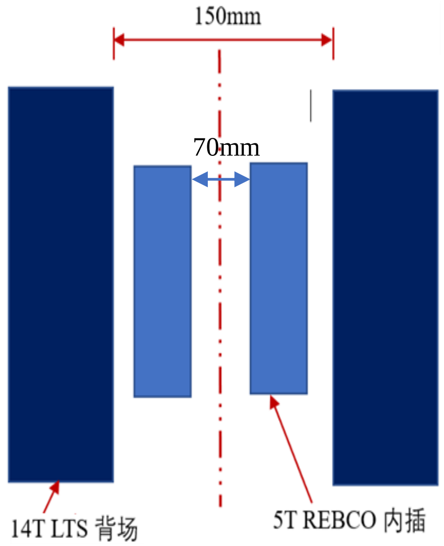

1st 15 T/77mm




2nd 15 T/77mm




15 T/150mm




19 T/70mm

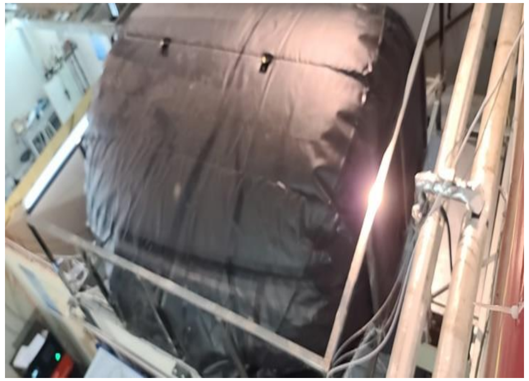
| | 1st 15 T/77 mm | 2nd 15 T/77 mm | 1st 15 T/150 mm | 5 T/70 mm HTS |
|---|---|---|---|---|
| Coil numbers | 4 | 3 | 3 | 14 DP |
| Bore diameter/mm | 77 | 77 | 150 | 70 |
| Current /A | 116.2 | 118.6 | 107.5 | 220 |
| Target M.F. /T | 15 | 15 | 15 | 5 |
| M.F. homogeneity | ≤ 0.1% @Ø17 mm×13 mm | ≤ 0.1% @Ø20 mm×14 mm | ≤ 0.1% @Ø22 mm×16 mm | -0.052%~0.026% @Ø10 mm×10 mm |
| Max. loadline /% | 82.5% on innermost coil | 86.2% on inner most coil | 85.0% on innermost coil | 45.5% on terminal coils |
| Inductance /H | 181.8 | 109.0 | 359.4 | 0.24 |
| Energy storage /MJ | 1.2 | 0.8 | 2.1 | 0.0059 |
| Magnet outer diameter /mm | 330 | 306 | 403 | 142 |
| Magnet hight /mm | 411.4 | 350 | 412.3 | 313 |

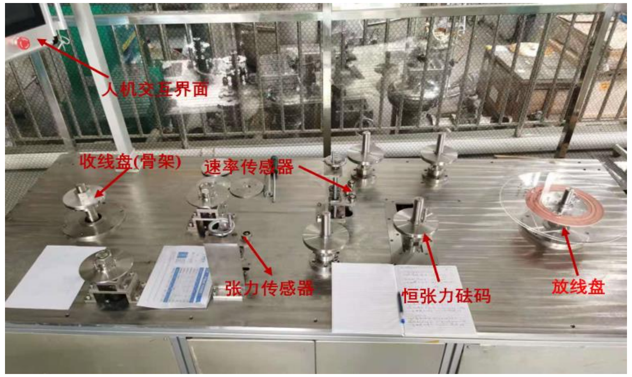
# Main progress : Manufacture



## Infrastructure construction

**Since 2019** → **To 2021**






Constant tension automatic **winding machine**

Max. winding speed: 40 r/min
Min. winding tension: 1 kg

Vacuum **heat-treatment** oven

Max. temperature: 1000℃
Temp. stabilization: ± 3℃

Manual and automatic **VPI systems** for densely wound coil

Max. temperature: 160℃
Temp. stabilization: ± 3℃

LHe **circulation** system

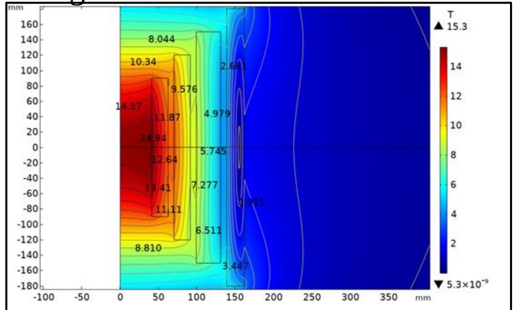
Balloon volume : 100 $m^3$
LHe output: 20 L/day

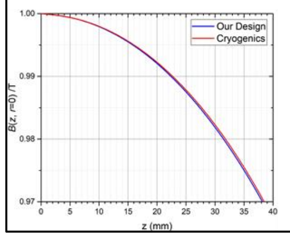
# Main progress: Manufacture & Test

## First homemade 15 T/ 77mm $Nb_3Sn$+NbTi hybrid magnet

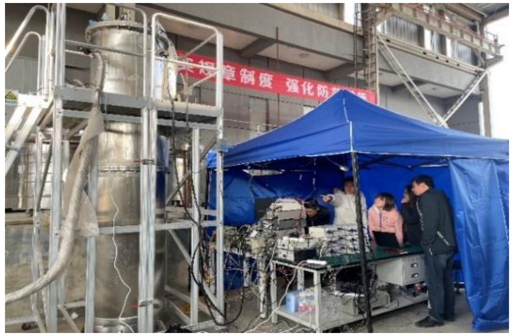
**Since 2019** → **To 12/2020**

Design

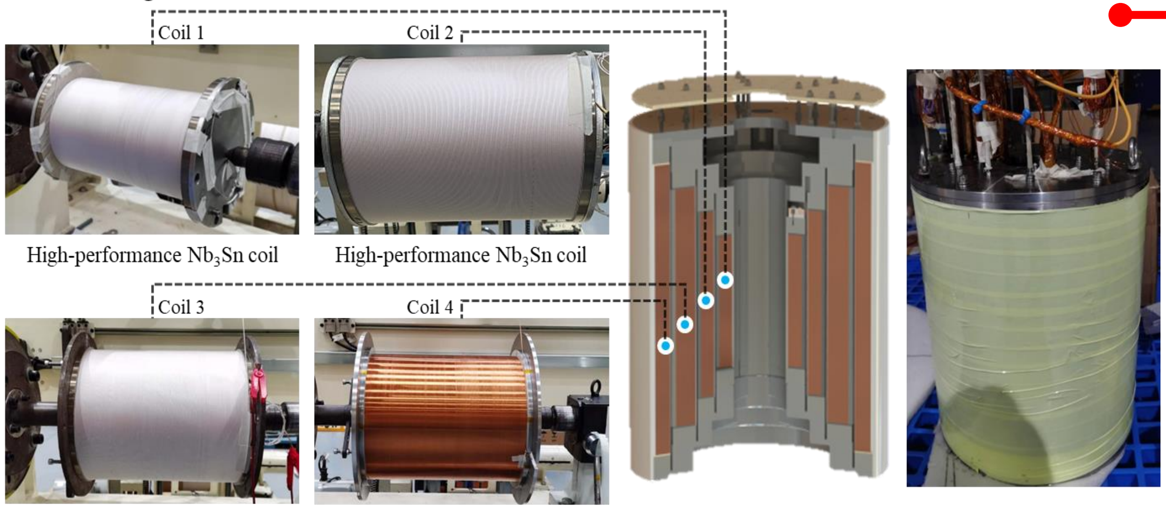



Homogeneity in longitudinal orientation ≤1% @ ~45 mm(≈ parameter of cryogenics magnet)



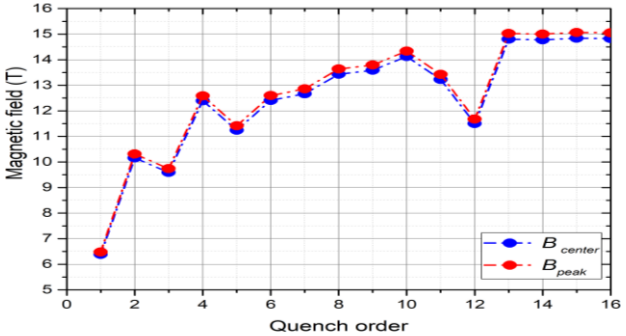
Coil winding



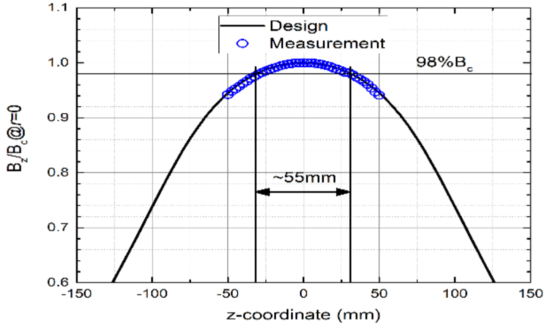

High-performance $Nb_3Sn$ coil — High-performance $Nb_3Sn$ coil

ITER-type $Nb_3Sn$ coil — NbTi coil — Magnet assembly diagram — Assembled magnet

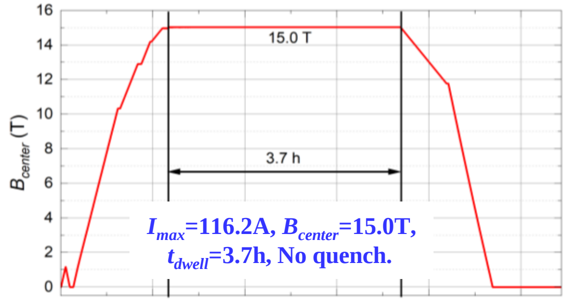
**Has been used for ASIPP superconducting material performance testing, with a running time of ≥ 3 years**

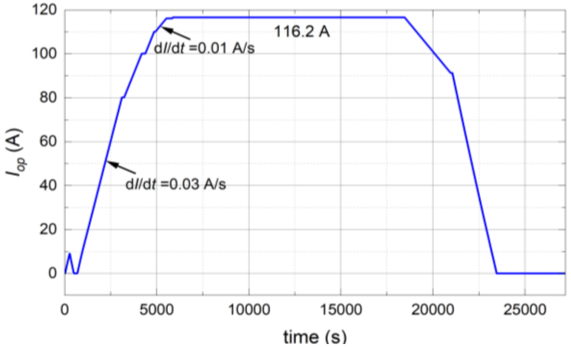



**Reach to 15T after 15 quenches**




**Satisfy the homogeneity requirement**




**Stable operation**

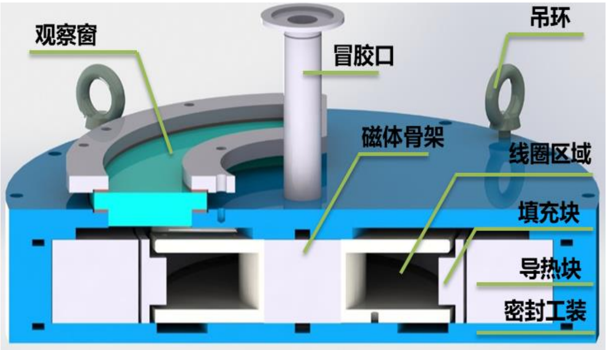
**LHe consumption ~3000L， ~190 L/training， ~€10,000/training**

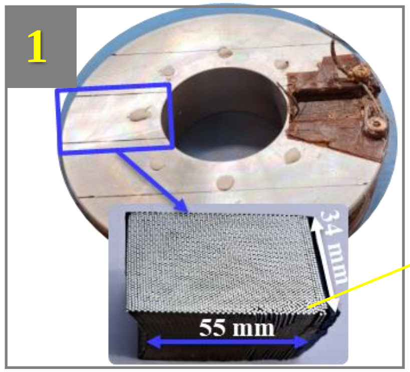
# Main progress: Manufacture & Test

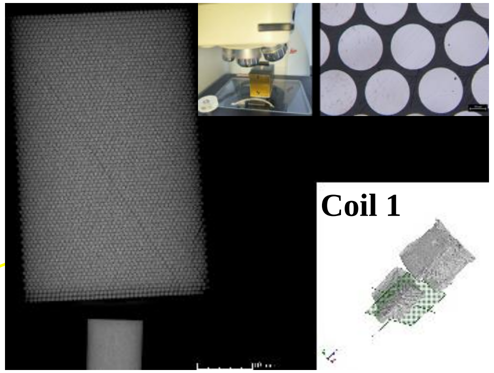


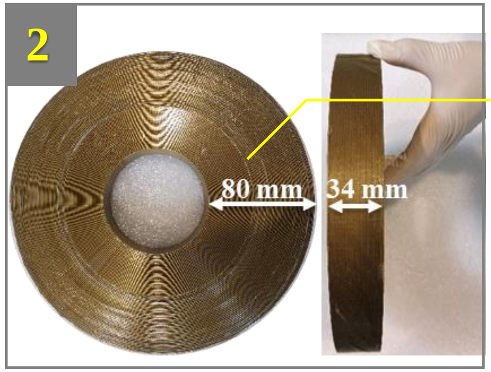
## Verification of the VPI progress on close-packed coils with thickness >30 mm

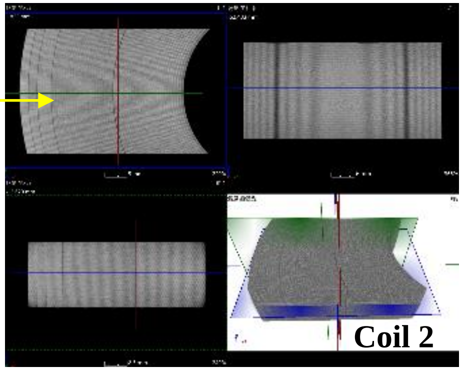
Since 2019 → To 2023



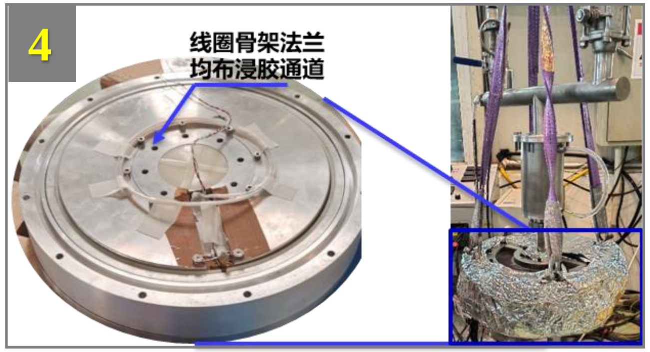





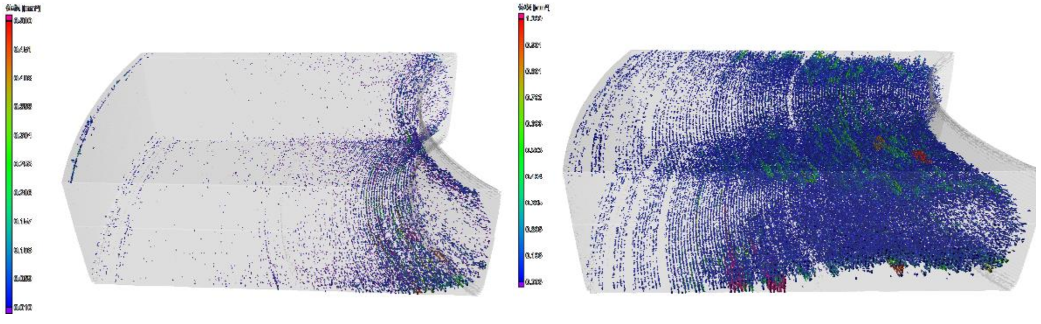



1. **Influence of viscosity** to completeness of VPI
2. **Filling ability** of current technology for coils with different thickness
3. Influence of **increasing impregnation channels** on completeness of VPI

Examination by using **accelerator scan diagnosis** with outcome：

1. So far, it's **difficult** to define clearly the **gray value region** of gaps；
2. Gap **distribution** and **identification** results depend on **parameter setting**；

Examination by using **accelerator scan diagnosis** of Coil 2

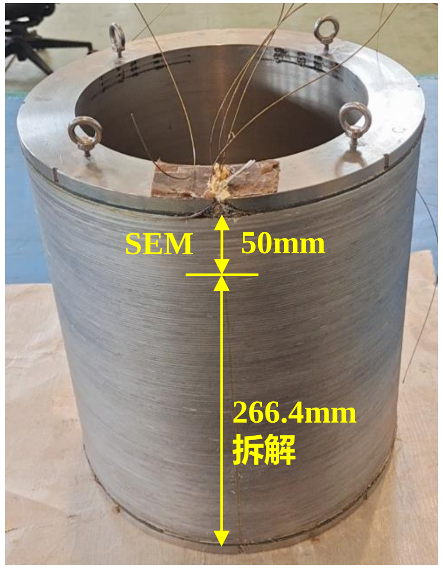


| | | |
|---|---|---|
| Material volume [mm³] | 78681.461 | 77450.578 |
| Defect volume [mm³] | 146.821 | 1300.542 |
| Defect ratio [%] | 0.19 | 1.65 |

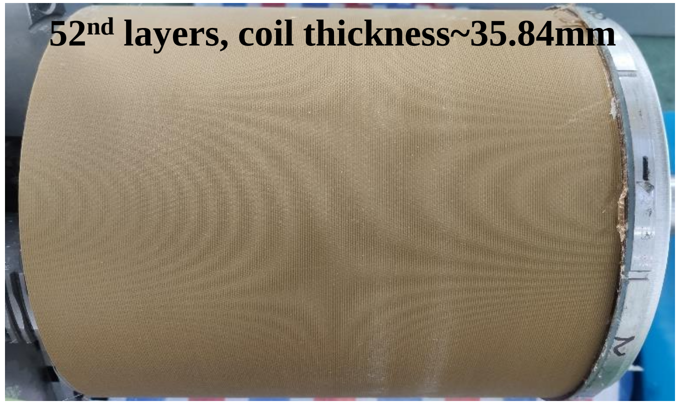
# Main progress: Manufacture & Test

## Verification of the VPI progress on close-packed coils with thickness >30 mm

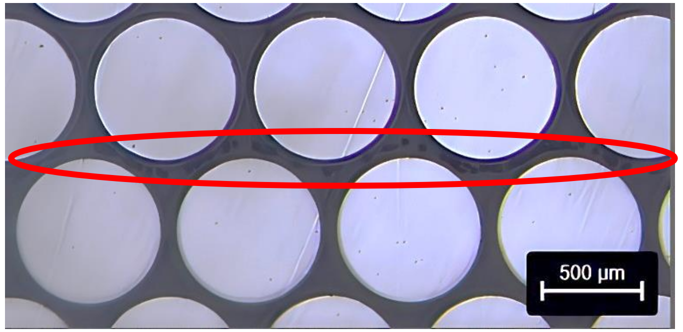
Since 2019 → To 2023








**Conclusion：**

1. Epoxy uniformly distribute in the coil；
2. Small bubbles exist in the coil, uncertainty impact on the stabilization of the coil；

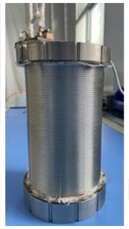
Current VPI process can be used to impregnate h~316mm，t~38.9mm close-packed coils with a 14±4μm inter-turn space

# Main progress: Manufacture & Test

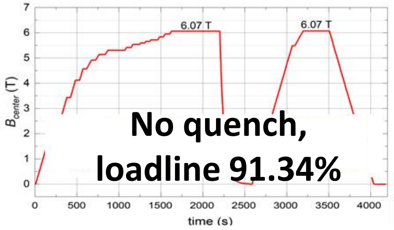
## Compact homemade 15 T/77 mm $Nb_3Sn$+NbTi hybrid magnet

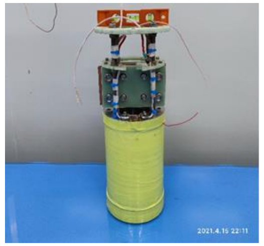
Since 2019 → To 2023

**Methods to reduce the training quench**
- Increase the uniform winding density
- Improve the magnet support structure
- Increase the gap filling factor

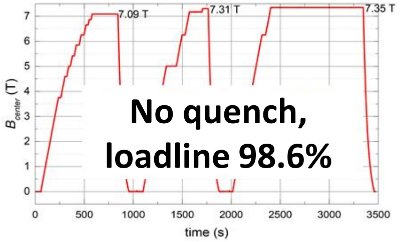


| Parameters | Values |
|---|---|
| $D_{in}$/mm | 80 |
| $D_{out}$/mm | 137 |
| Hight of magnet/mm | 231.5 |
| Number of layers | 10 |
| Number of turns | 1825 |
| Central M.F. /T | 5.64 |
| Current/A | 500 |
| Load line (Theori.) | 86.2% |

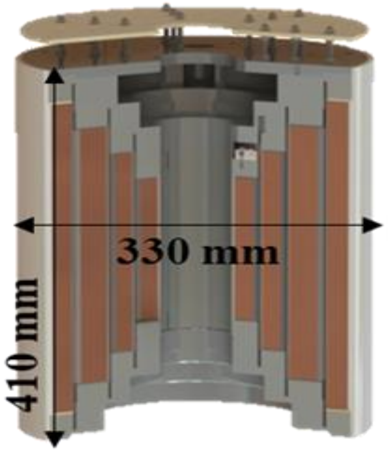


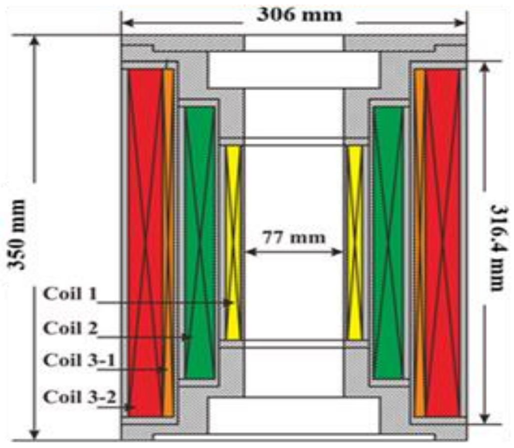

| Parameters | Values |
|---|---|
| $D_{in}$/mm | 72 |
| $D_{out}$/mm | 137 |
| Hight of magnet/mm | 231.5 |
| Number of layers | 30 |
| Number of turns | 6885 |
| Central M.F. /T | 7.0 |
| Current/A | 170 |
| Load line (Theori.) | 95.3% |




**Made in 2020**




**Made in 2023**



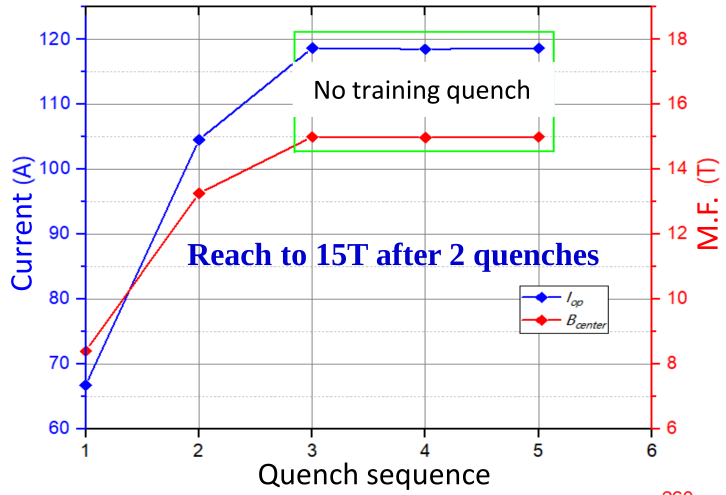

| Compact 15 T/77 mm magnet | | Coil 1 | Coil 2 | Coil 3 | |
|---|---|---|---|---|---|
| Parameters | Unit | H.P. $Nb_3Sn$ | ITER $Nb_3Sn$ | H.P. NbTi | ITER NbTi |
| $D_{in}$ of coil | mm | 82.8 | 137.8 | 225.0 | 238.7 |
| $D_{out}$ of coil | mm | 117.3 | 206.6 | 238.7 | 296.2 |
| Number of turns | | 3570 | 9860 | 3995 | 16779 |
| Hight of coil | mm | 177.3 | 245.1 | 316.4 | 316.4 |
| Current | A | 118.6 | | | |
| Central M.F. | T | 2.6 | 4.9 | 1.5 | 6.1 |
| Inductance | H | 109.0 | | | |
| Energy storage | MJ | 0.8 | | | |

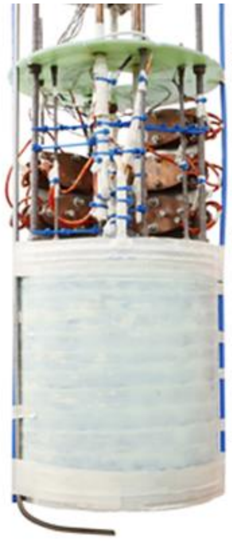
# Main progress: Manufacture & Test

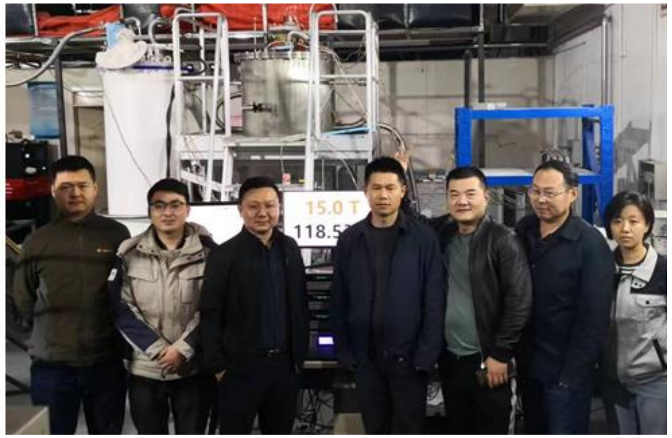
## Compact homemade 15 T/77 mm $Nb_3Sn$+NbTi hybrid magnet

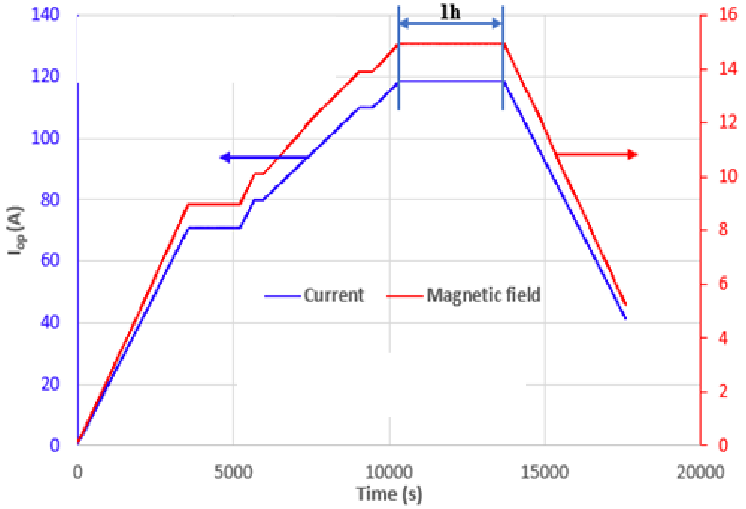
**Since 2019** → **To 2023**

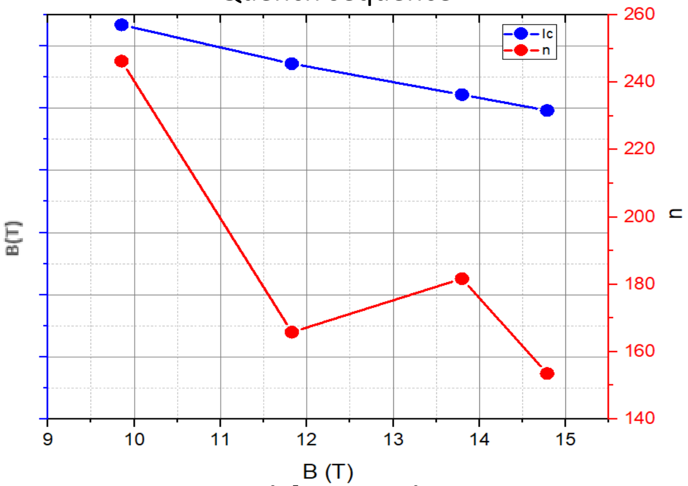
- **High operating parameters**： Loadline~**86.2%**， M.F. homogeneity **≤0.1%@ Ø20×14mm**
- **Impact resistance**： more than 10 active quenches and thermal cycling, **No properties degradation**
- **Reliability**： running for half year, **very stable**
- **Practicality**： Have already submit to **S.C. material research platform**
- **Economical**： Cost is **reduced by ~1/4** compare to the 1st product






$I_c(B)$ test with U-spring setup

# Main progress



## Comparison between similar products globally

| Parameters | ASIPP | Oxford instruments | Cryogenic | Jastec |
|---|---|---|---|---|
| Central M.F. | 15.0T | 14.0T | 14.0T | 16.0T |
| Cold bore dia. | 77mm | 77mm | 70mm | 52mm |
| M.F. homogeneity | ≤0.1% @ Ø20mm×14mm | ≤0.1% @ Ø10mm ×10mm | ≤0.1% @ Ø10mm×10mm | ≤0.1% @ Ø10mm×10mm |
| Coil dimension | 340mm × Ø306mm | 400mm × Ø280mm | 410mm × Ø240mm | 390mm × Ø360mm |
| Operating current | 118.6 A | 107.0 A | 104.0 A | 120.5 A |

# Main progress: Manufacture & Test

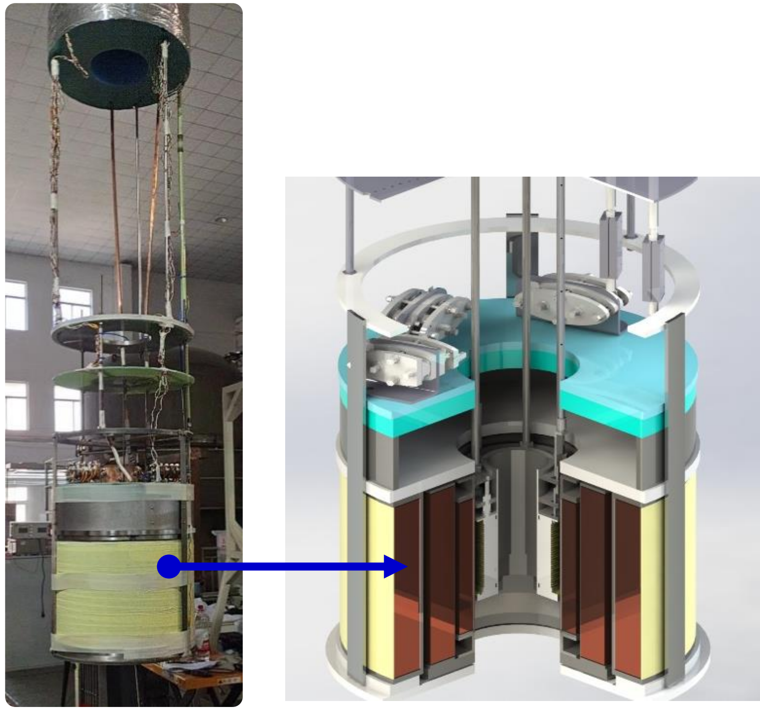
## 15 T & 150 mm $Nb_3Sn$+NbTi hybrid magnet

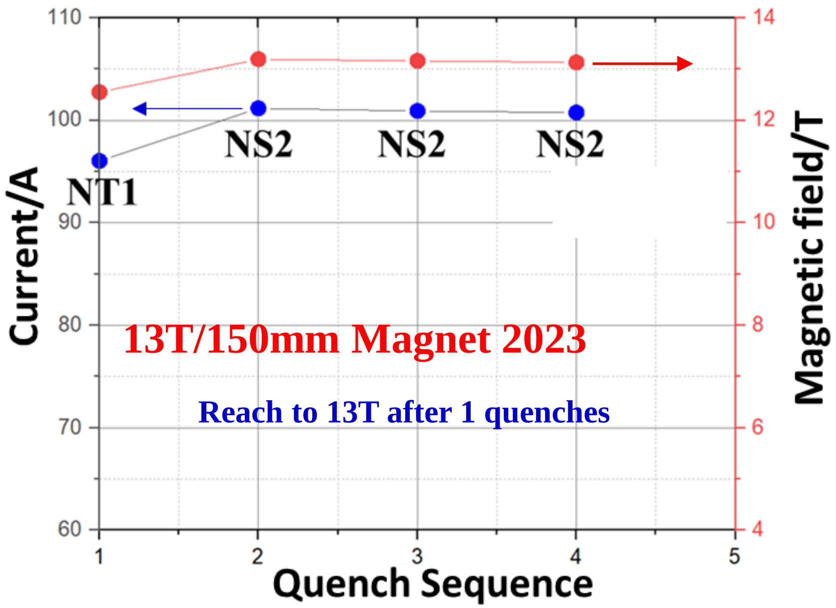
Since 2019 → To 2024

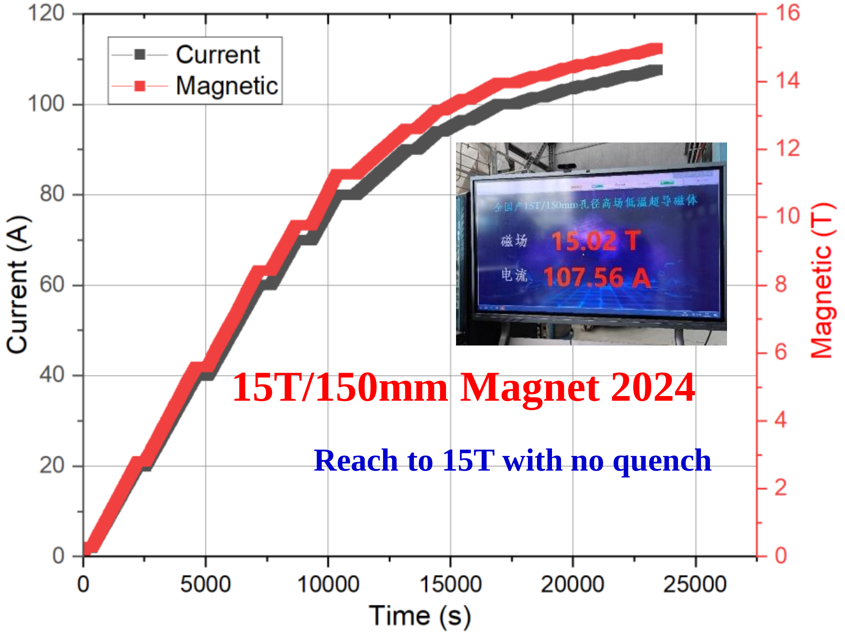
**Development of the high-field LTS superconducting magnet with a 150mm bore.**

**Results：**1 training quench， stable center magnetic field reaches to **13.17T**； ——2023.11

No quench, stable center magnetic field reaches to **15.02T**； ——2024.04





# Main progress: Manufacture & Test

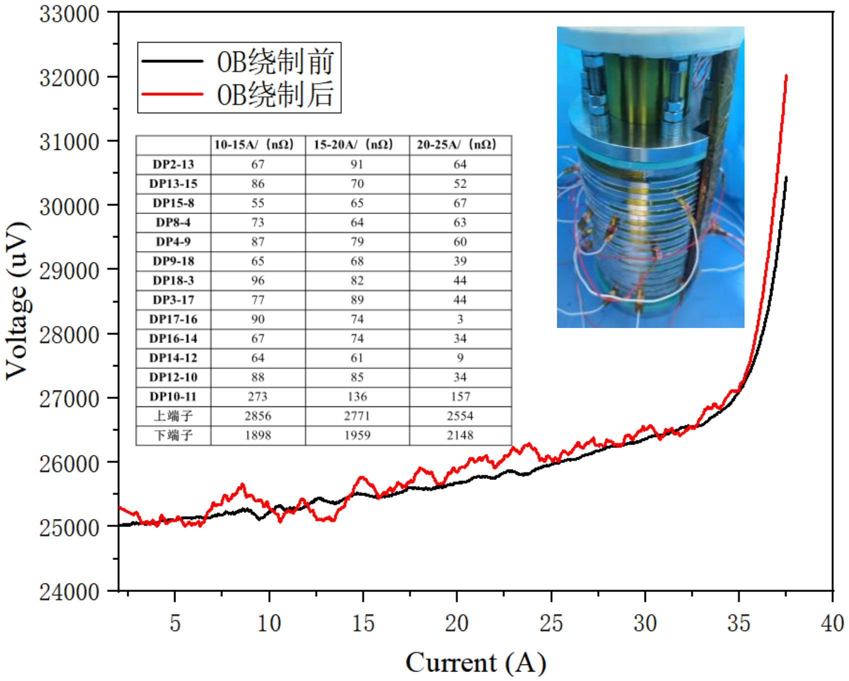


## 19 T & 70 mm $Nb_3Sn$+NbTi hybrid magnet

**Since 2019** → **To 2024**

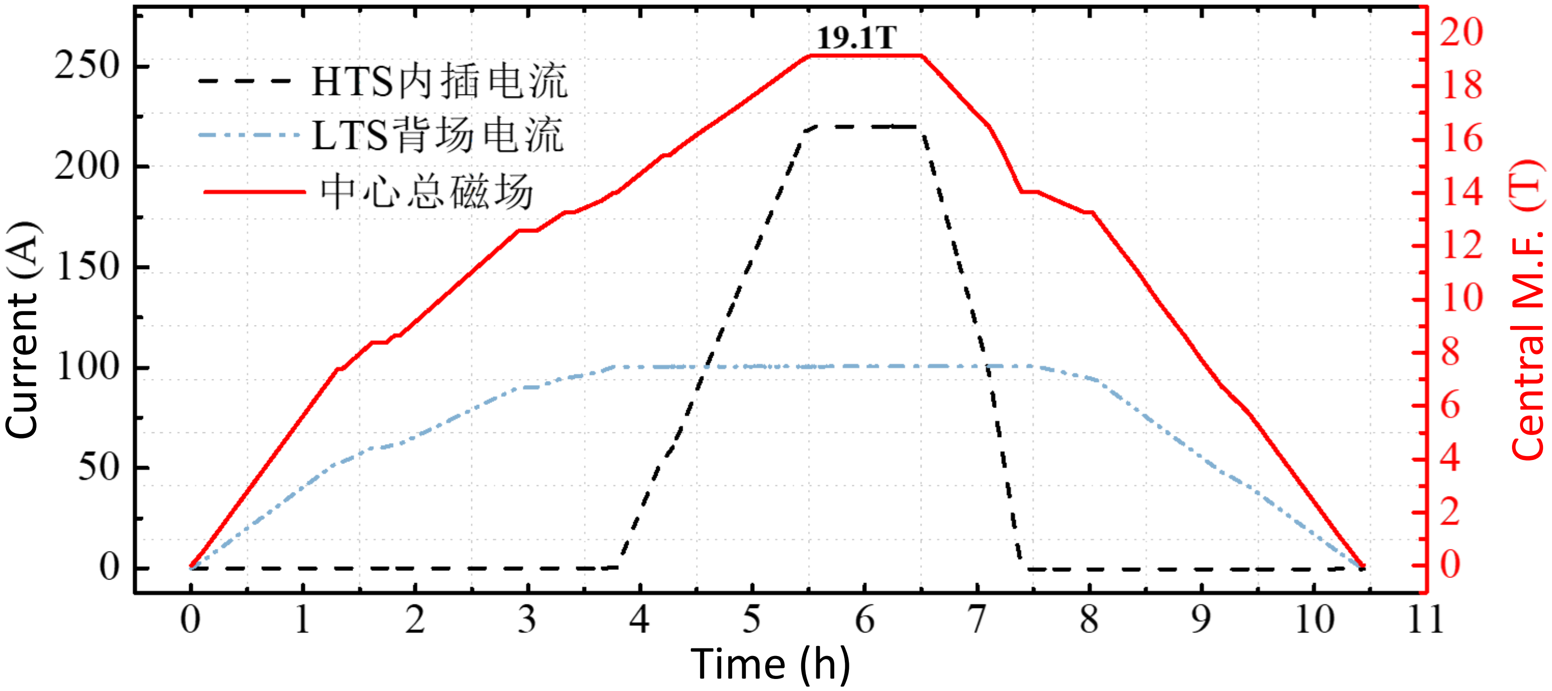
**Development of the high-field LTS + HTS all-superconducting magnet with a 70 mm bore.**

**Results：** No quench, stable center magnetic field reaches to **19.13T**； ——2024.05




| | 10-15A/（nΩ） | 15-20A/（nΩ） | 20-25A/（nΩ） |
|---|---|---|---|
| DP2-13 | 67 | 91 | 64 |
| DP13-15 | 86 | 70 | 52 |
| DP15-8 | 55 | 65 | 67 |
| DP8-4 | 73 | 64 | 63 |
| DP4-9 | 87 | 79 | 60 |
| DP9-18 | 65 | 68 | 39 |
| DP18-3 | 96 | 82 | 44 |
| DP3-17 | 77 | 89 | 44 |
| DP17-16 | 90 | 74 | 3 |
| DP16-14 | 67 | 74 | 34 |
| DP14-12 | 64 | 61 | 9 |
| DP12-10 | 88 | 85 | 34 |
| DP10-11 | 273 | 136 | 157 |
| 上端子 | 2856 | 2771 | 2554 |
| 下端子 | 1898 | 1959 | 2148 |

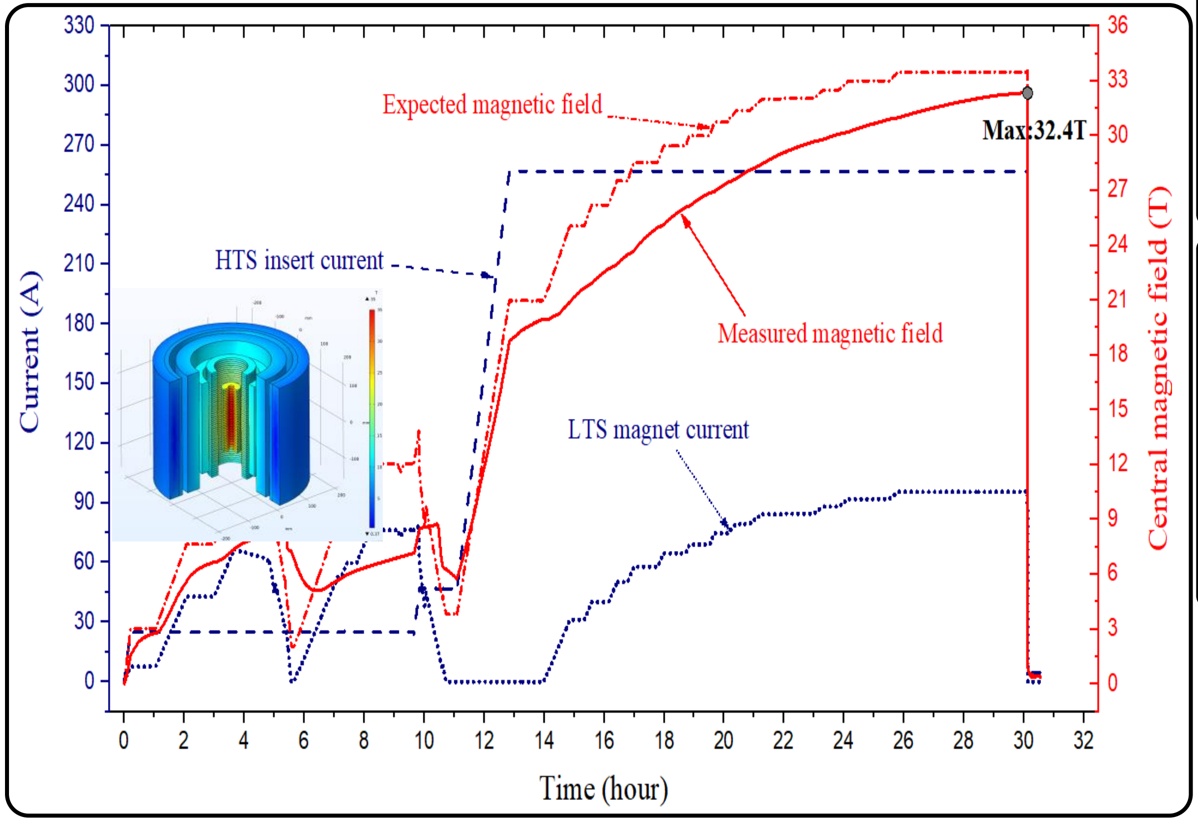
**5T@70mm HTS insert coil test at 77 K**



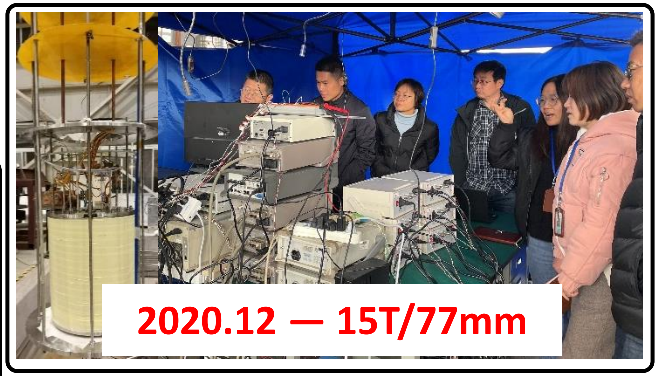

**19 T/70 mm magnet test at 4.2 K（~14+5)**

# Main progress

## Photo show

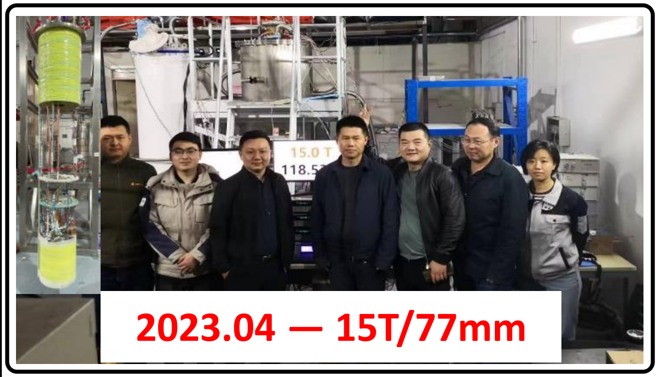



2023.12 — 32.4T

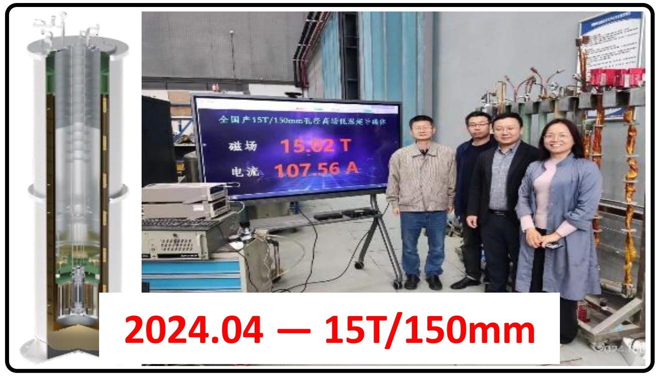


2020.12 — 15T/77mm

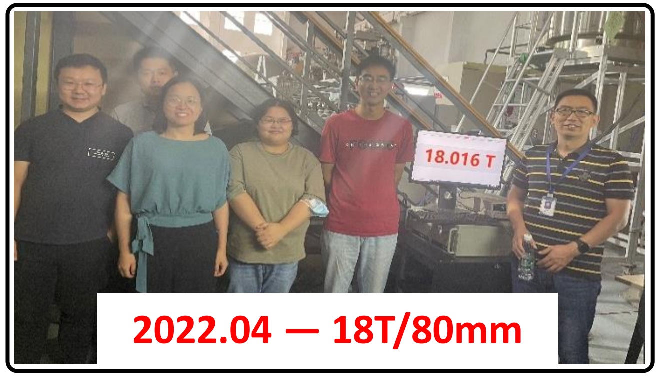
2023.12 — 32.4T



2023.04 — 15T/77mm



2024.04 — 15T/150mm



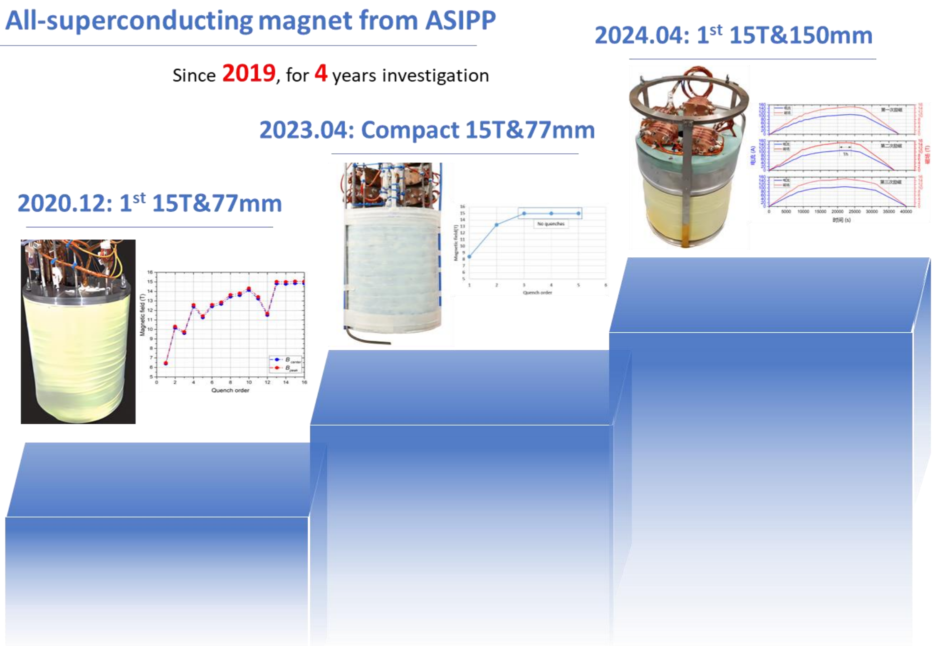

2022.04 — 18T/80mm


2024.05 – 19T/70mm

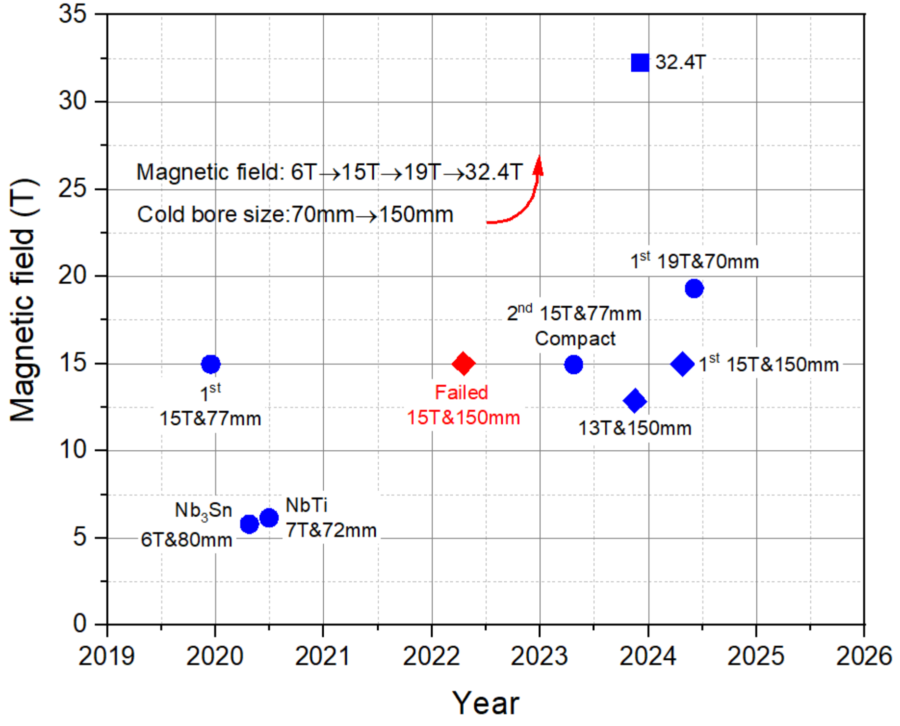
# Main progress



## Brief review of all-superconducting research since 09/2019




| Wire for coil | Number | Achievement |
|---|---|---|
| Copper | 1 | - |
| SS | 5 | - |
| $Nb_3Sn$ trail coil | 2 | 1 |
| NbTi trail coil | 1 | 1 |
| $Nb_3Sn$ real coil | 14 | 7(+1) |
| NbTi real coil | 6 | 4 |




| *Operating current* | *Storage energy* | *Outer diameter* | *Quench sequence* | *Load-line* |
|---|---|---|---|---|
| **116.7 → 118.6 → 107.5A** | **1.2 → 0.8 → 2.1MJ** | **330 → 306 → 475mm** | **16 → 2 → 0** | **82% → 86% → 85%** |

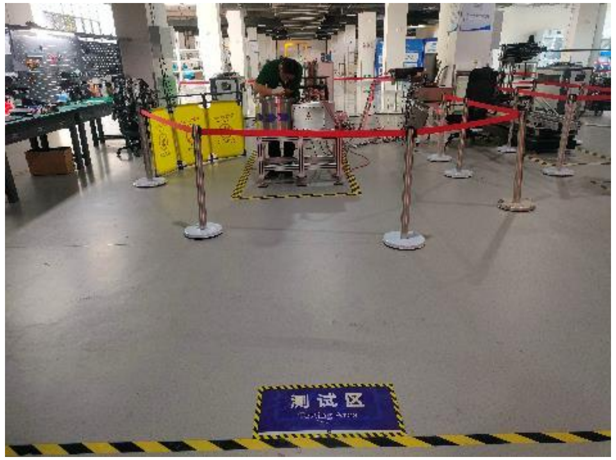
# Main progress: New production workshop




# Main progress: New production workshop



**Test, Assembly, Coil winding, Heat-treatment, VPI and Storage etc.**








# Contents

# Summary



I. To serve the material research of future fusion reactor construction, **15-19T** high-field all-superconducting magnets with bore diameter between **70-150mm** were built at the ASIPP supported by CRAFT project;

II. Fabrication of high-field S.C. magnets with a large bore is not easy, especially when using **$Nb_3Sn$ wire**, the quality requirements of **insulation**, **coil winding**, **stress-control**, **heat-treatment**, **VPI**, **joint process** and **quench protection** are significant strict;

III. After 4.5 years research, **two 15 T/77 mm** and **one 15 T/150 mm** LTS background magnets with relative high operating performance are fabricated at the ASIPP, which has already been used for S.C. material test facilities;

IV. Accompany with a **20 T/17 mm** and a **5 T/70 mm** HTS double-pancake insert coils, the target magnetic field of **32.4 T** and **19 T** were successfully reached;

V. More and more **high-field all-superconducting laboratory magnets** with robust performance are planned in future, magnet optimization is ongoing.

# Thanks for your attention


## Acknowledgements:

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—The Western Superconducting Technologies Co., Ltd;

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University of Twente
*The Netherlands*

西部超导材料科技股份有限公司
Western Superconducting Technologies Co.,Ltd.