



Manufacturing Status of CFETR Central Solenoid Model Coil



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1. Summary

The central solenoid model coil (CSMC) is being developed to verify the large-scalar superconducting coil manufacture technology for CFETR in ASIPP. The CS model coil composed of Nb₃Sn and NbTi hybrid superconducting magnet can reach to 12 T maximum magnetic field. The main manufacturing processes of the coil are verified by its R&D. For now, all the five coils winding and those 2/3 terminals fabricating for all the five coils are finished, and the heat treatment for the Nb₃Sn inner coil is completed. The turn releasing and insulation wrapping process and station for the heat treated Nb₃Sn coil has been developed. The major remaining processes for the five coils are of the ground insulation wrapping and VPI, which the mockup coil VPI will be performed firstly to validate the VPI process.

2. Parameters for CSMC Coils

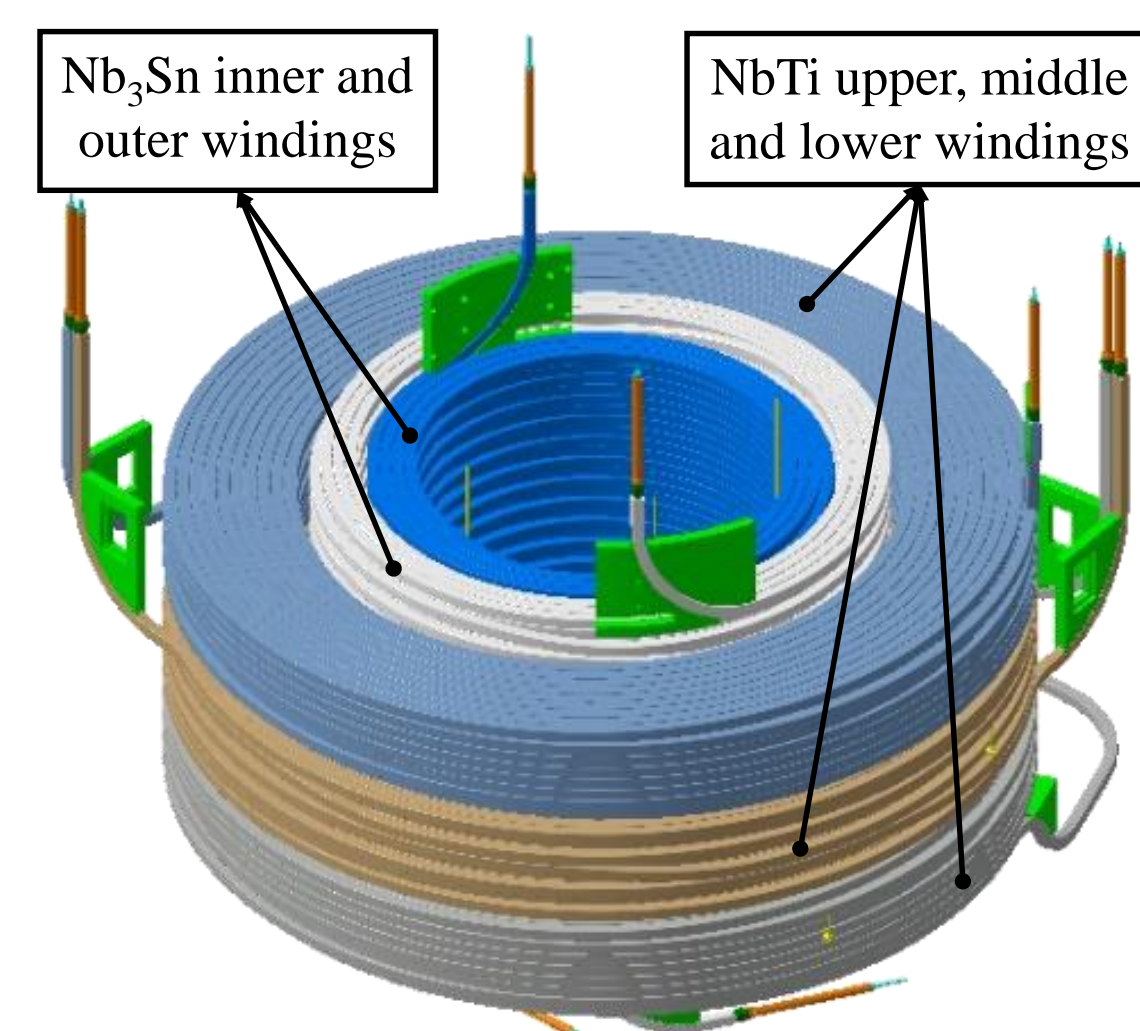


Fig. 1 CFETR CSMC windings

Table 1 The specification of Nb₃Sn and NbTi CICC

| Items | Nb ₃ Sn CICC | NbTi CICC |
|------------------------------|---------------------------|-------------------------------------|
| Jacket material | 316LN stainless steel | 316L stainless steel |
| External Dimension /(mm) | 49 × 49 | 51.9 × 51.9 |
| Diameter of inner bore /(mm) | 32.6 | 35.3 |
| Cabling pattern | (2sc + 1) × 3 × 4 × 4 × 6 | (3sc × 4 × 4 × 4) + 1Cucore |
| Cable twist pitches | First Stage: 20 ± 5mm | First Stage: 45 ± 5mm |
| | Second Stage: 45 ± 8mm | Second Stage: 85 ± 8mm |
| | Third Stage: 80 ± 10mm | Third Stage: 145 ± 10mm |
| | Fourth Stage: 150 ± 15mm | Fourth Stage: 250 ± 15mm |
| | Fifth Stage: 450 ± 20mm | Fifth Stage: 450 ± 20mm |
| Petal wrap | 0.1 mm thick, 70% cover | 0.05 mm thick, 50% cover |
| Cable wrap | 0.1 mm thick, 40% overlap | 0.10 mm thick, 40% overlap |
| Core pattern | n/a | Cu strand: 0.73mm Cu core 3: 2.85mm |
| Number of sc strand | 576 | 1152 |
| Void fraction | 32.5% | 34.1% |
| Central spiral | 8 × 10 mm | 10 × 12 mm |

Table 2 Parameters for CSMC winding

| Items | Nb ₃ Sn Coil | | NbTi Coil | | |
|---|-------------------------|---------------|---------------------|----------------|---------------|
| | Inner winding | Outer winding | Upper winding | Middle Winding | Lower winding |
| Winding type | Pancake | Pancake | Pancake | | |
| CICC dimensions /(mm) | 49 × 49 - Φ32.6 | | 51.9 × 51.9 - Φ35.3 | | |
| Turn / pancake insulation thickness /(mm) | 2.6/2.6 | 2.6/2.6 | 2.6/2.6 | | |
| Ground insulation thickness /(mm) | 3.1 | 3.1 | 3.1 | | |
| Clearance between windings /(mm) | 13.6 | | 41.2 | | |
| Num. of radial turns | 4 | 4 | 10 | | |
| Num. of axial turns | 32 | 32 | 8 | | |
| Total Num. of turns | 120 | 120 | 80 | | |
| Inner radius /(mm) | 740.6 | 971.8 | 1225.6 | | |
| Outer radius /(mm) | 953.2 | 1184.4 | 1776.8 | | |
| Height of main winding /(mm) | 1657.4 | 1657.4 | 442.2 | | |
| Operating current /(kA) | | | 47.65 | | |
| Maximum magnetic field /(T) | 12 | 8.42 | 6.1 | | |

The Nb₃Sn CICC (~1300 m) will be used for the internal high magnetic field (12T) winding, and the NbTi CICC (~2200 m) for the external low magnetic field (the maximum value < 6T) winding. Five windings all are pancake coils wound by one conductor in hand, the vacuum pressure impregnation (VPI) for each winding will be made separately and then assembly them finally.

3. Coil Manufacturing Processes

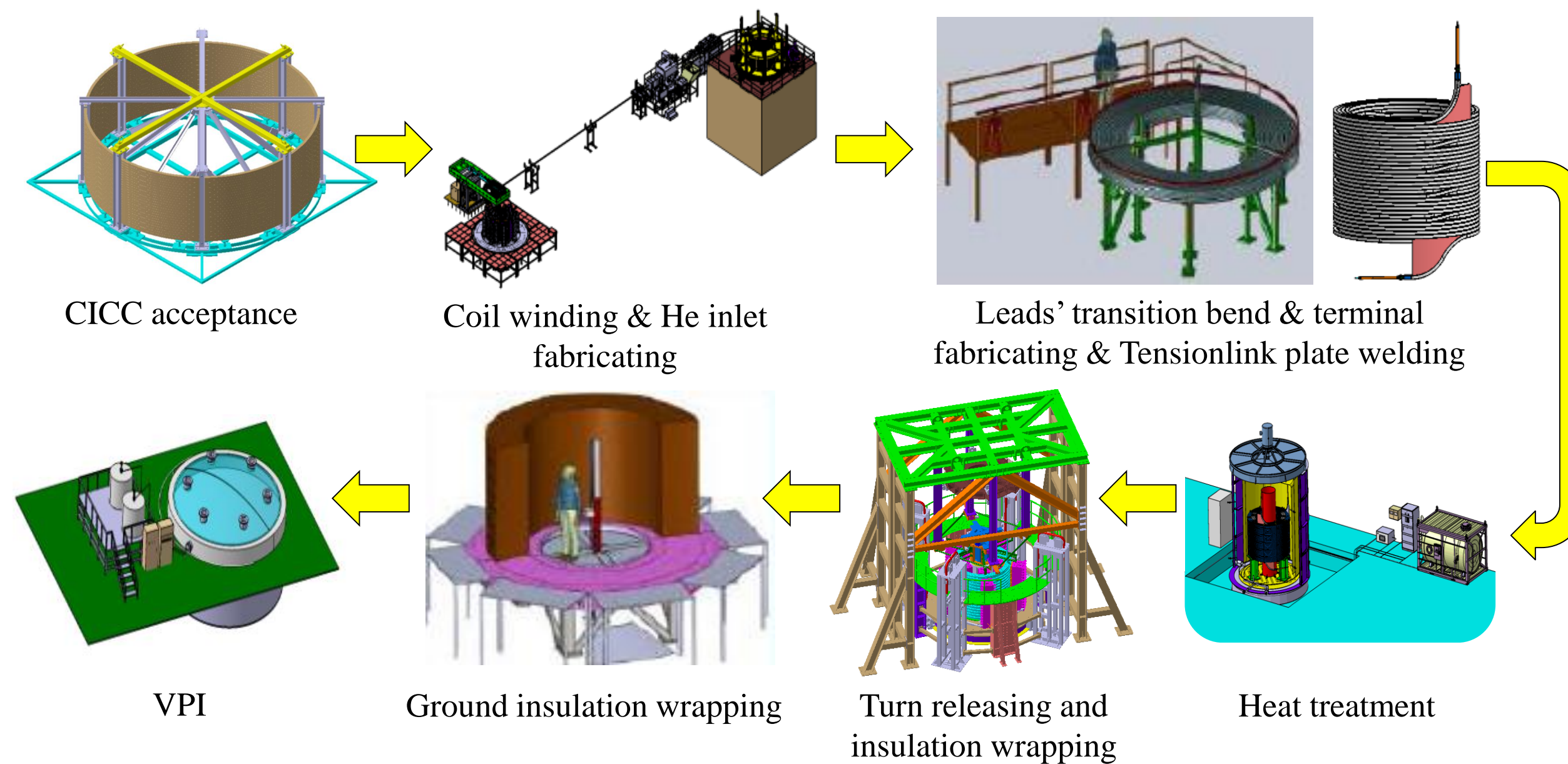


Fig. 2 Manufacturing processes of the Nb₃Sn coil

For the NbTi coil, the turn insulation wrapping is being done as the coil being wound. The other processes are similar to Nb₃Sn coil no heat treatment.

5. He Inlet Fabrication

There are nine He inlets for CSMC. According to the structural analysis of the circular and oblong boss, the max. stress intensity of the later one is lower than the former one, 661.6 MPa < 749.8 MPa. The oblong boss He inlet is chosen for the CSMC coils. The fabricating process included the groove preparing, welding, and NDE (LT and PT) is developed by R&D. The boss optimized is employed for the Nb₃Sn outer coil to increase the gap with the NbTi coil.

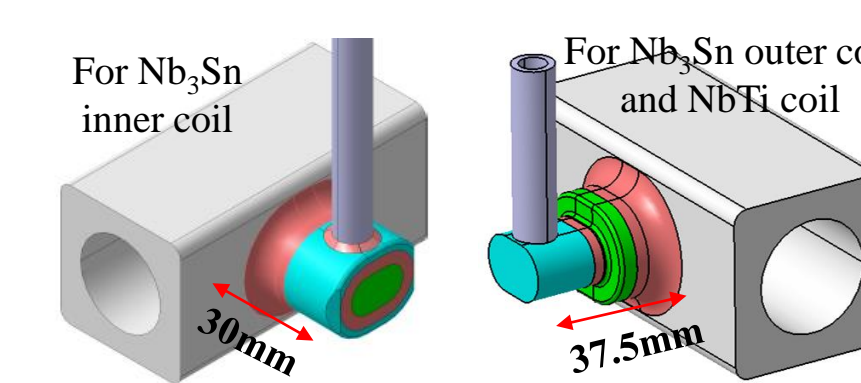


Fig. 6 Design of He inlet

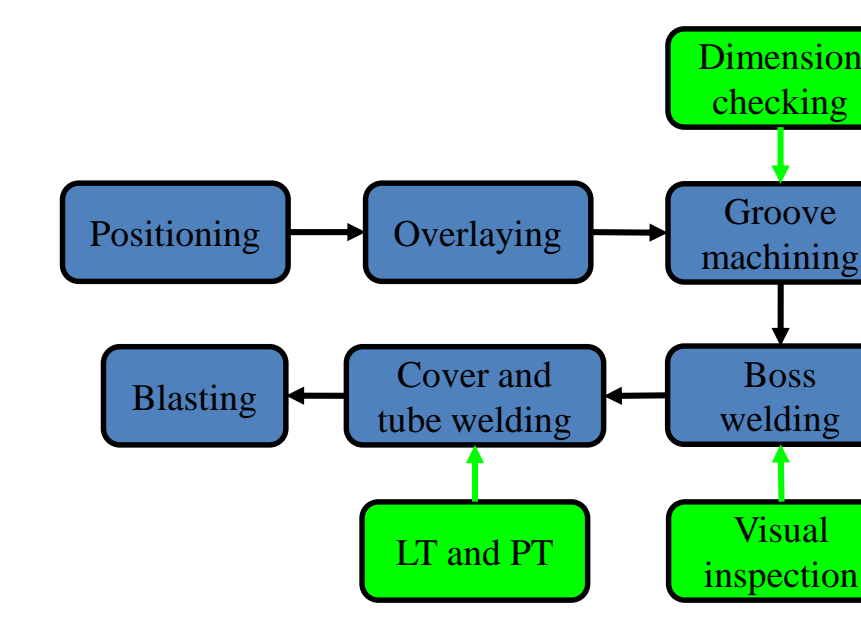


Fig. 7 MIP of the He inlet



Fig. 8 He inlet fabricated

4. Coil Winding & Terminal Fabricating

The coil winding of two Nb₃Sn coils had been completed in Oct. 2018. And the three NbTi coils had been wound from Nov. 2018 to Aug. 2019, which is being wound as the turn insulation wrapping. The turn insulation includes five layers and the thickness is 1.3 mm. The co-wound tap (CWT) of the pitch 450 mm is arranged on the second layer, and the two co-wound wires (CWW) are arranged on the two top R-corners. The inter-turn insulation test has been done when each pancake wound.

The R&D work of the superconductive joint had been done, and the NbTi-NbTi joint sample tested shows that the resistance is 0.488 nΩ @20 kA, 4.2 K. In addition, the NbTi-Nb₃Sn joint sample, tested in Sultan facility on Jun., and the results can be seen in my colleague poster (No. Thu-Mo-Po4.04-01[24], 26 Sep 2019, 08:45). The terminals of Nb₃Sn coils have been finished, the others are being performed.

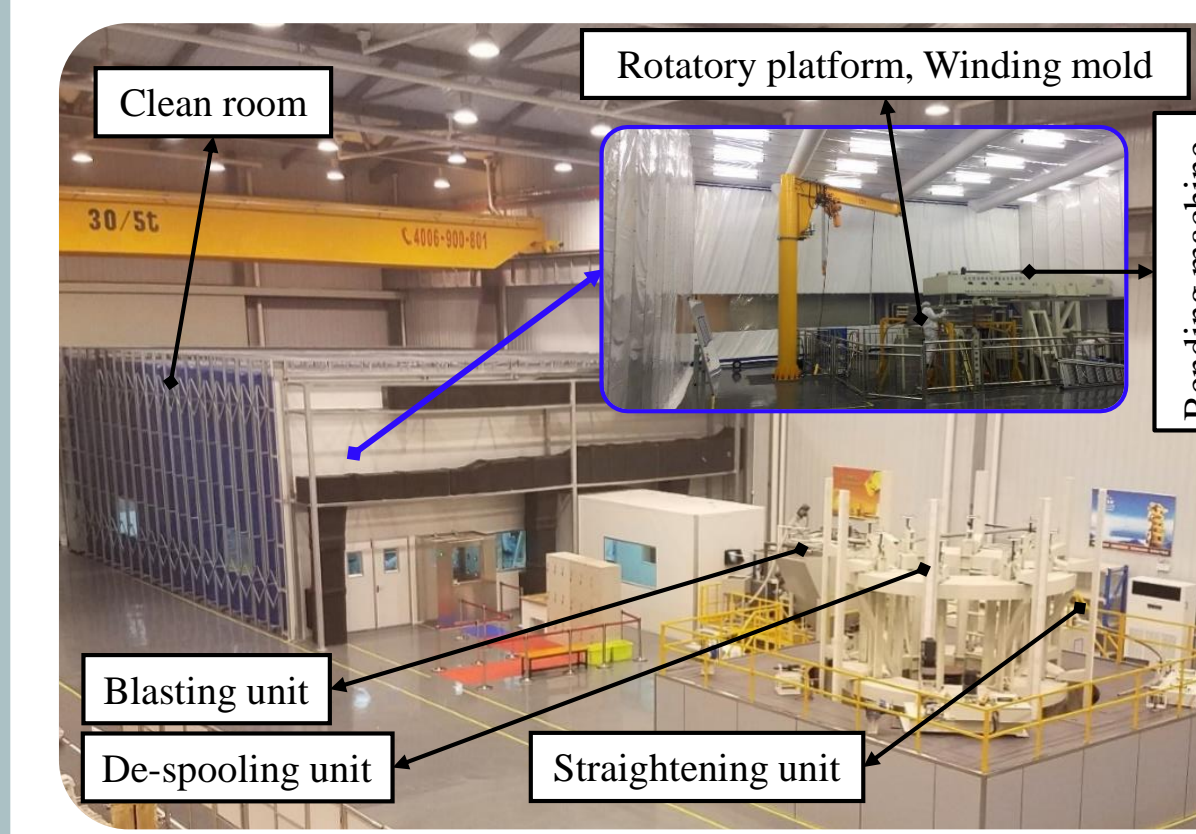


Fig. 3 Special winding line

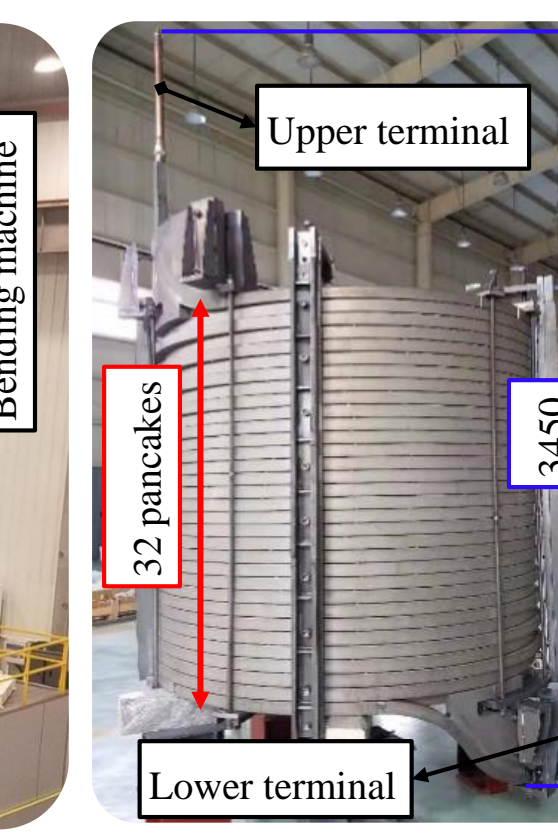


Fig. 4 Nb₃Sn inner coil wound

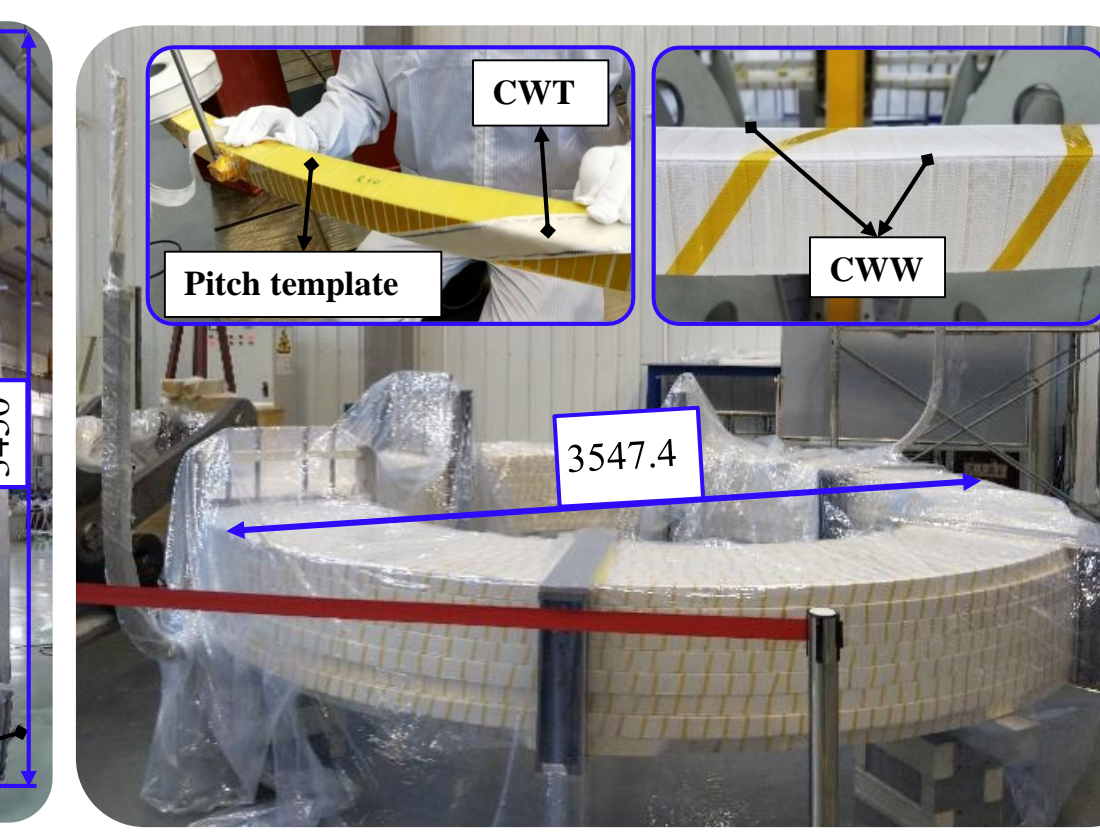


Fig. 5 NbTi middle coil wound with turn insulation

7. Turn Releasing and Insulation Wrapping

The heat treated Nb₃Sn coil is set on the turn transferring, releasing and insulation wrapping station. The max. pulling distance between two adjacent turns is designed 200 mm to guarantee the conductor strain to be lower than 0.1% during the turns' transferring, which is verified by the R774.5 mm turn's pulling experiment. The installation, debugging and commission of the turn releasing and transferring station is completed in Aug. this year. And the turn transferring and insulation wrapping for the heat treated 4 × 4 mockup coil has been done. The radial dimensions are ID 1497.4(0.09, 1.87) mm, and OD 1910.2(-1.42, 1.65) mm, meet the requirement 2 mm.

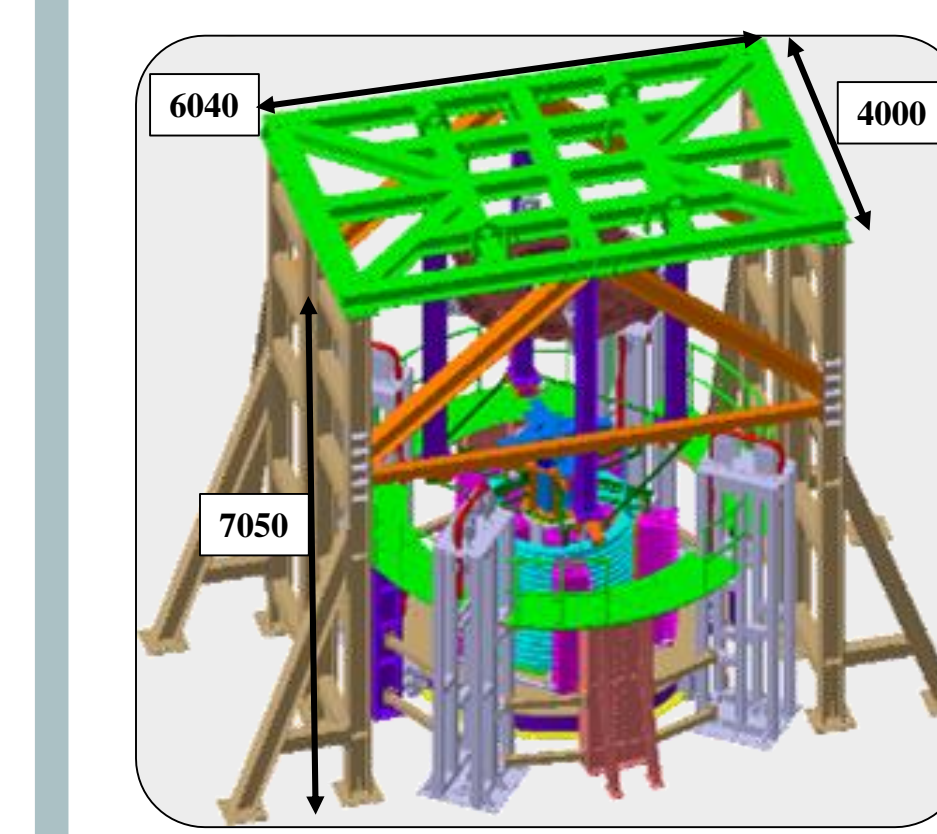


Fig. 11 Turn releasing station structural design

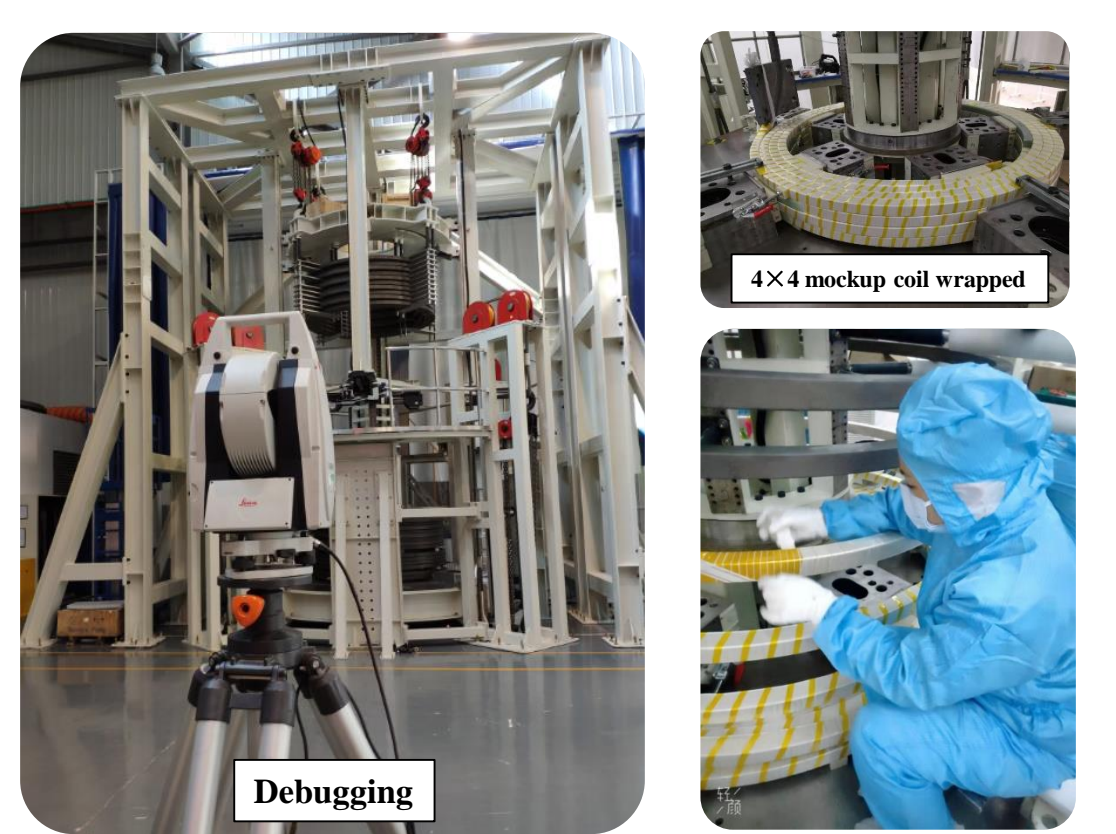


Fig. 12 Turn releasing station and insulation wrapping manual

6. Heat treatment

The superconductive status for the Nb₃Sn conductor is obtained by its heat treatment. The furnace with a muffle is designed to the heat treatment for Nb₃Sn coils.

The dummy coil's heat treatment experiment is conducted and the results show that that all the process indexes meet the technical requirements. The heat treatment of the Nb₃Sn inner coil is completed in Jun. this year, and the coil enlarges ~0.3 mm in the radial.

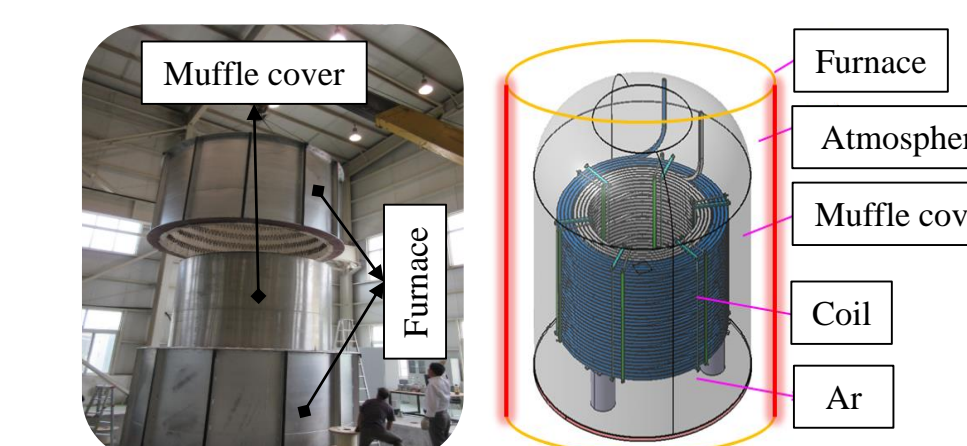


Fig. 9 Heat treatment furnace

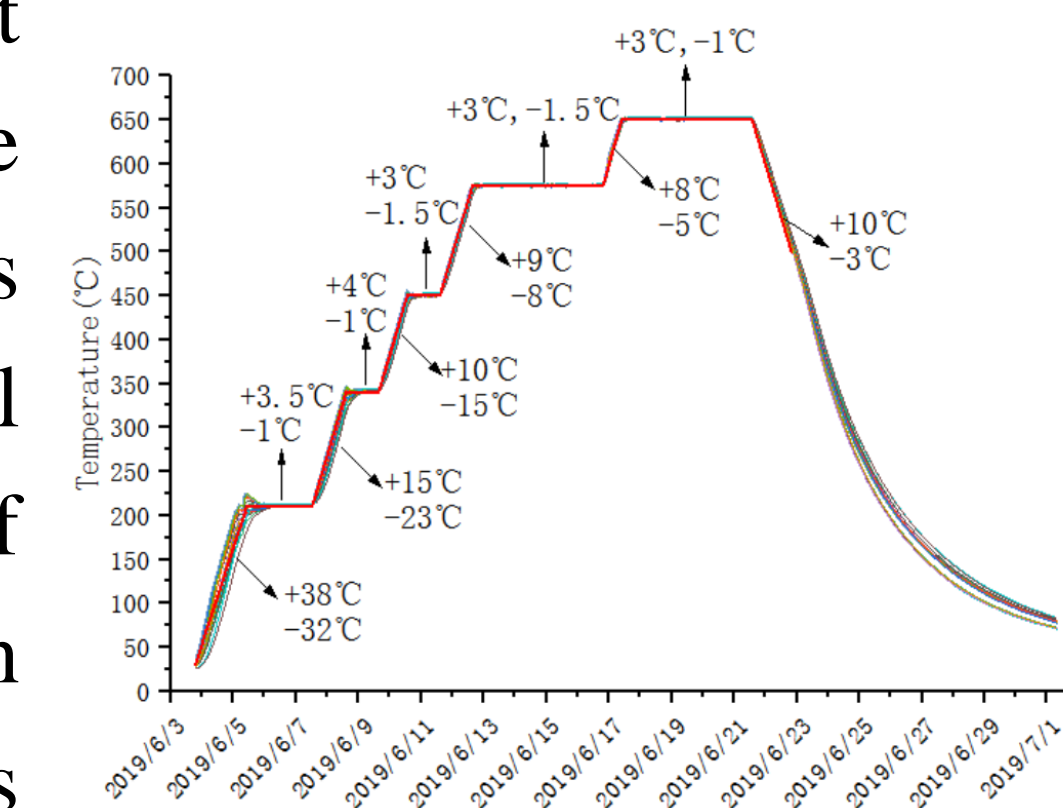


Figure 10 Temperature profile during heat treatment

8. VPI

The preliminary insulation structural design for the tapped pancake, joint, and He inlet are finished at the conceptual design phase. A serial of testing is conducted and the results show that that all the mechanical and electrical indexes meet the technical requirements.

The insulation wrapping process at the special area has been being in trial. The VPI mold design for all the coils have been finished. The VPI of the 4 × 4 mockup coil is planned to be performed firstly and then check its quality. Then the VPI of the NbTi middle coil will be started.

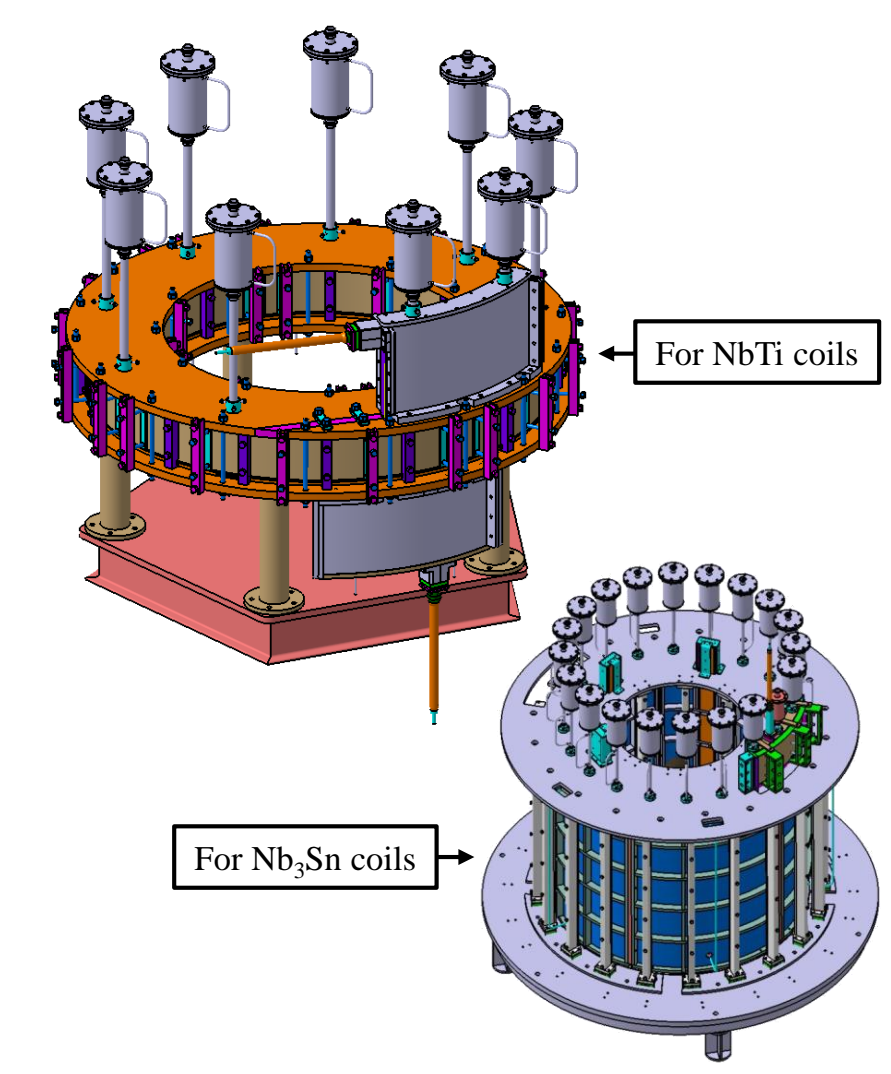


Fig. 13 VPI mold design