The Superconducting Magnets for EAST Tokamak

J. Wei, W. G. Chen, W. Y. Wu, Y. N. Pan, D. M. Gao, S. T. Wu, and Y. Wu

***Abstract*—The EAST is an Experimental Advanced Superconducting Tokamak. The mission of the EAST Project is to bring out scientific issues on the continuous nonburning plasma scenario of steady-state operation and engineering issues on establishing the basis of technology for superconducting tokamak. Superconducting magnets were chosen for all poloidal field (PF) and toroidal field (TF) systems since the engineering mission is to establish the technology basis of full superconducting Tokamak for future fusion reactors. The superconducting magnets of EAST consist of sixteen TF coils and fourteen PF coils (seven coil-pairs). To obtain the good performance of the superconducting magnets, all TF magnets and most PF magnets have been tested before assembly. The assembly of the main device was completed in the end of 2005 and at the beginning of 2006, we made successfully the first engineering commissioning of the EAST system. Up to now the EAST device has been used in 4 operation campaigns and has achieved good experimental results.**

***Index Terms*—EAST, superconducting magnet, Tokamak.**

I. Introduction

THE experimental advanced superconducting tokamak (EAST) was built at the Institute of Plasma Physics of Chinese Academy of Sciences (CASIPP) in January of 2006. The mission of EAST device is to develop the scientific basis for a continuously operating tokamak fusion reactor aiming at steady state advanced tokamak operation. The core of EAST project is a full superconducting tokamak with a non-circular cross-section of the vacuum vessel and actively cooled plasma facing components. There are two superconducting magnet systems in the tokamak machine. Firstly the superconducting toroidal field (TF) magnet system which consists of sixteen D-shaped coils. Secondly the superconducting poloidal field (PF) magnet system which consists of six central solenoid (CS) coils and three pairs of big circle coils. The largest PF coil has an outer diameter of 7.6 m [1]. The total cold mass at 4.5 K of superconducting magnet system is 194 ton.

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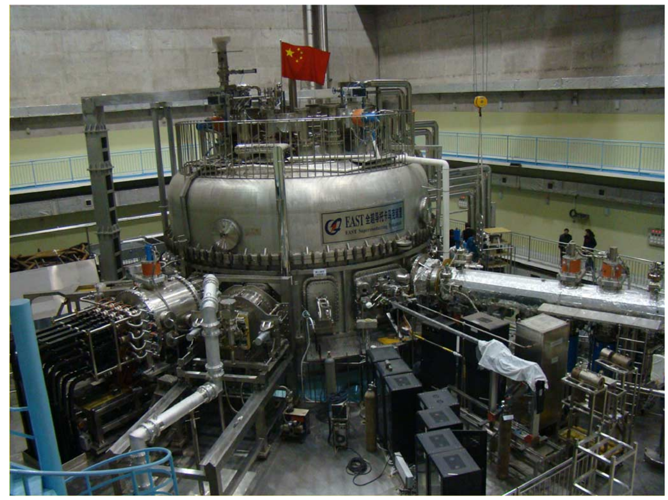

Fig. 1. The general view of the EAST device.

A cryostat with two thermal shields at 80 K encloses all the superconducting coils, the vacuum vessel and the support structures. The thermal shields are supported on the cryostat independently. The EAST machine overall dimensions are 10 m in height and 7.6 m in diameter. The total weight is 414 tons. Fig. 1 shows the general view of the EAST device.

II. The Superconducting Magnets of EAST

A. *Superconducting Toroidal Field Magnet System*

The superconducting toroidal field (TF) magnet system is one of the most important parts of the EAST device, which consists of sixteen coils disposed toroidally and spaced 22.5° apart, as shown on Fig. 2. The conductor used in the TF coils is a NbTi cable-in conduit conductor (CICC). The dimensions of CICC are (20.4 × 20.4) mm. The conventional lowest in-plane stress TF coil shape is the well-known "bending moment free D". The shape used for the EAST coils is close to a pure tension coil with reduced bending moments. The contour of the D-shaped coil consists of five arcs and a straight leg. The straight legs of the coils wedged to form an inner vault. The adjacent intercoil structure has a wedge-shaped-cross-section. External wedged blocks are also placed between coils to form an outer vault. These two vaults resist strong centering force and overturning torques. A total of sixteen insulating breaks provide galvanic insulation between coils. A returning turn in the TF system is used to compensate the toroidal component of the current of crossover lines between neighboring coils. There are sixteen horizontal openings at the mid-plane and thirty-two vertical openings at the top and bottom wedge blocks between neighboring coils for the vacuum vessel ports. The cryogenic-cooling system on each TF

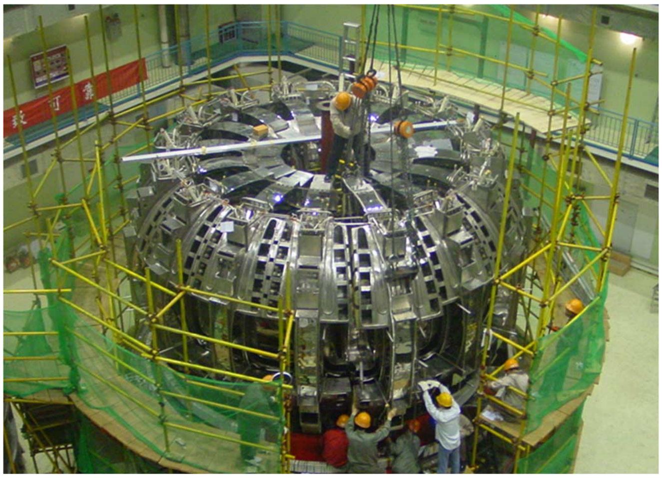

Fig. 2. The TF magnet system of EAST.

TABLE I
TF MAGNET SYSTEM CHARACTERISTICS

Major radius (R_0) (m)	1.7
Minor radius (a) (m)	0.4
Magnetic field at the plasma center (B_t) (T)	3.5 (4.0)
Maximum field at the coil (B_{max}) (T)	5.8 (6.5)
Number of TF coils	16
Total number of Ampere-turns (MAT)	30 (34)
Operating current (I_{op}) (KA)	14.3 (16.4)
Total stored energy (MJ)	300 (390)
Total length of CICC of the TF system (Km)	19.2
Total weight of the TF system (ton)	160

coil is composed of fourteen cooling lines connected in parallel. The local instrumentation and control system for the TF magnet consist of diagnostics, protection system, sensor interfaces and acquisition systems. The TF magnet system parameters are listed in Table I. And the values in the bracket are designed for upgraded operations.

The TF coil is wound in pancakes and the electrical insulation is composed of multiple layers of polyimide film-glass impregnated with epoxy resin. Each turn of the conductor is wrapped with half lapped glass cloth tape built up to a thickness of 0.5 mm. Glass epoxy felt (1 mm thick) is inserted between pancakes. A glass cloth roving is inserted into the corners formed by the juncture of the glass epoxy sheets and the rounded corners of the conduit. A wrap of half-lapped glass cloth tape built up to a thickness of 6 mm on the coil surface forms the ground insulation [2]. The allowable ground voltage in normal operation is about 5 KV.

The TF coil case in EAST machine is a 316LN stainless steel plate welded structures with full penetration welds. These case structures that encase each TF coil are used as the primary structure for the whole superconducting magnet system. All poloidal field (PF) coils and cold-mass support system attachments are fixed on the TF coil case structure. The shape of cross-sections of the TF coil case is a "keystone" for the straight leg and a rectangle for the curved parts. The thicknesses of the four walls of the coil cases are not equal. The steel plate of the inboard leg (nose) is 60 mm thick. The 16 TF coil case inboard legs are wedged together and centering forces are reacted by hoop compression. The steel plate of the outboard leg is 40 mm thick. The thicknesses of steel plate of two sideboards are not equal either, 25 mm for the wedged parts and 30 mm for the rest. The TF coil case is made of two halves welded together. The inter-coil structure is also a welded-up structure from 316LN stainless steel plate, with a thickness of 20 mm. The concept of mutual support between magnet components is adopted to ensure that in normal operation, all electromagnetic forces are reacted within the TF magnets, and there are no resultant forces transmitted through the gravity support system.

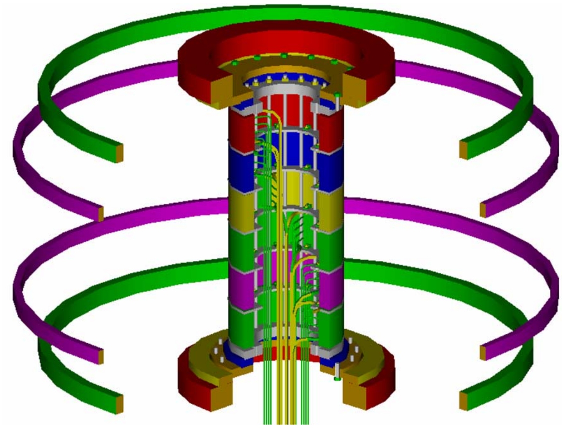

Fig. 3. The PF magnet system of EAST.

The outer surface of the TF case is equipped with a set of cooling channels which is composed of fourteen flat cooling tubes. The material of the flat tube is 316LN and the cross-sectional dimension is (22 × 8) mm. The flat cooling tubes are brazed to grooves on the case.

B. Superconducting Poloidal Field Magnet System

The poloidal field (PF) system consists of fourteen superconducting coils, including a stack of 6 central solenoid coils with a total height 3 m and a diameter of 0.72 m, 4 divertor coils and 4 large outer ring coils. A cable-in-conduit conductor (CICC) cooled by supercritical helium at 4.5 K is chosen as superconductor for all the PF magnets. PF coils have two types of superconducting conductor with different sizes and cabling configurations. One is (20.4 × 20.4) mm in size, 4 stages cabling and first stage with 2 superconducting NbTi strands plus 1 copper strand. It has been used for solenoid coils and divertor coils. The other is (18.6 × 18.6) mm in size, 4 stages cabling and first stage with 1 superconducting NbTi strand plus 2 copper strands, and this type of CICC is used for the 4 outer ring coils only. The PF system is supported on the TF magnets assembly. Fig. 3 shows the PF magnet system of EAST. The main parameters of the PF system are listed in Table II.

The maximum volt seconds capacity of the PF system is about 10 Wb if this is with reverse magnetization and the stray field

TABLE II
PF MAGNET SYSTEM CHARACTERISTICS

Number of PF coils	14
Maximum field (B_{max}) (T)	4.5
dB/dt (T/s)	< 7
Maximum operating current ($I_{op(max)}$) (KA)	14.5
Length of cooling channel (m)	124 to 171
Mass flow rate (g/s)	≥ 2

in plasma initiation region is less than 35 gauss. The peak magnetic field in the coil winding is about 4.5 Tesla [3]. Four types of modes for the shape of the plasma (namely Big-K double null, circle, Big-V double null and Single null) with different major radius, elongations and triangularity can be chosen during operation.

The PF coils are pancake wound only. The CICC starts from the inner diameter to outer diameter and continue from outer to inner diameters. The turn electrical insulation consists of 2 layers of polyimide tape and multiple layers of fiberglass. During winding, the conductor was first wrapped with 0.1 mm thick of fiberglass. Then one layer of half-overlapped fiberglass and polyimide were wrapped. Two fiberglass layers with quench detection wires are wrapped for the turn insulation at last. Between the pancakes, a 1.0 mm fiberglass layer is inserted to improve the pancake insulation. At the end of winding, a 5 mm thick fiberglass layer was wrapped as ground insulation. The current connections and liquid helium tubes are placed inside the bore of the solenoid except the two pairs of outer ring coils of which are placed inside the opposite two TF coil cases. Vacuum pressure impregnation (VPI) must be used for all PF coils and obtain monolithic windings so as to improve the capability of the insulation and structural strength.

III. Core Technologies for Superconducting Magnets

Most of superconductivity technologies have been developed in the qualification of manufacturing procedures of the superconducting magnets, such as CICC (Cable-in-Conduit Conductor), large scale superconducting coil winding, VPI (Vacuum Pressure Impregnation), case welding, final precision machining of the TF cases, cryogenic test of superconducting coils and so on.

A. CIC Conductor Manufacture

The conductor used for EAST is the CIC conductor type with a NbTi cable inside a 316LN stainless steel conduit. The main manufacturing processes include butt joints welding of conduit segments, cable insertion, conduit compaction and forming the final conductor section.

There are 60 welded butt joints in a 600 m CIC conductor conduit and a total of 3400 welded joints for the whole superconducting coils. To get high quality joints, the welding parameters were optimized according to the changes of the environment humidity and temperature. Joint area preheating and use of a welding mode with two cycles instead of primary one cycle has also been implemented.

If the strain or stress in the superconducting cable is too high during the insertion process, this may affect the stability and critical current (Ic) of CIC conductor. To sustain the insertion process smoothly, the inner protrusions of welding joints have been limited less than 0.10 mm and two groups of horizontal and vertical rollers near the entrance were set up to correct the cable section [4].

B. Large Scale Superconducting Coil Winding

Due to the high stiffness of the CIC conductor, pancake coils cannot be reliably wound by a simple tension device. A total of three winding lines were set up. Each line consists of pay-off spool, straightener, correcting roller set, sandblaster, preforming structure, rotating table, take-up spool and a NC winding control system. The outstanding features of the winding line are no strain pre-forming, 2D configuration and continuous winding. Utilizing the drive link of an AC servo motor and a harmonic decelerator the machine was able to achieve precision control within ± 0.10 mm for the turn and inflexion positions. The configuration errors of the winding were less than 1.0–1.5 mm.

Helium stubs must be used and welded on the conduit to shorten the cooling loop. The electrical joint, used for the internal connection of the coils was formed by compaction of the cable inside a case. After removing of the jacket and cable wrapping at the conductor ends, the two prepared conductor ends were separately inserted in two thin copper sleeves, which had been coated with Sn-Pb-Sb solder on both inner and outer surfaces. Then the ends were compacted to the required size with a hydraulic driving tool and enclosed by two half stainless steel cases. The two half cases then were sealed with tungsten-inert gas arc welding (TIG).

C. VPI Treatments

Two types of VPI technologies with "rigid mold" and "soft mold" have been used for EAST superconducting coils.

The conventional "rigid mold" VPI inside the oven was used for 10 small diameter PF coils and all 16 TF coils. Each PF coil was made with one VPI only but TF coil was made with two VPI treatments.

The new "soft mold" VPI technique has been developed and used for the four big outer PF coils. Instead of the conventional sealing structure of a stainless steel box, the coil outside was only wrapped with teflon tape, fiberglass tape, self-fusing tape and terylene tape step by step using the half-lap over wrap technique. Tape heaters were used for coil heating and the temperature was precisely computer-controlled. All the superconducting coils passed the turn insulation tests of 3000 V before VPI and the ground insulation tests of 5000 V after VPI.

D. Case Welding

The TF coil case is composed of a "D" shaped case and a cover of 316LN material. Cooling is provided by tubes soldered into grooves on the surface of the steel plates.

The SANDVIK 25.22.2LMn welding rods were used for shield metal arc welding (SMAW). All welds were X-ray tested. Vibration stress relief (VSR) treatments were also made in this process. For the closure welds of TF coil cases, great care was required to mitigate twist welding deformations and avoid overheating the epoxy insulation. A series of procedures were developed to relieve residual stresses in real-time. The deformation for the full case was less than 1.50 mm and the temperature at the surface of insulation was kept below 100 □.

E. Accuracy Machining of the TF Coil Case

The NC machining for TF coil case was divided into two steps: the first step was for the case welding parts, and the second step was for the integrated case after closure welding and second VPI. The programming errors were eliminated by setting up the 3D model of TF coil and using the CAM (computer aided manufacture) properties of the I-DEAS software. The NC fabrication program can be directly produced and imported into the control system. After NC machining the error of the wedge angle was less than 0.004° and the flatness error was less than 0.10 mm.

F. Cryogenic Test of Superconducting Coils

A test facility system that mainly consists of a large cryostat of 3.4 m in diameter and 6 m in height, a power supply system of 80 MW and a cryogenic and refrigerator system of 500 W/4.5 K was set up to test the superconducting coils at operation temperature. The four large PF coils with outer diameters from 5 m to 8 m had been qualified by testing a model coil made of same conductor in similar operation conditions. In total twenty-nine cryogenic tests were performed, in which sixteen TF coils, one CS coil, two divertor coils, one PF model coil and one CS subassembly were tested. The performances of electromagnetics, mechanics, and hydrodynamics of each coil were checked. The test results of all sixteen TF magnets are very similar and satisfy with the engineering requirements.

IV. Procedure of Assembly

The EAST Tokamak cross section is elongated vertically and composed of five nested shells, namely the superconducting toroidal field (TF) coils and poloidal field (PF) coils, the vacuum vessel (VV) and plasma facing components (PFCs), interior and exterior thermal shields (ITS and ETS) and the cryostat vessel (CV).

Considering the technical risks and the possible need to disassemble, the EAST general assembly was divided into two phases. In the first phase, finished in January of 2006, the assembly of all components was performed except for the VV neck tubes which could connect the body with the port of the VV, 1/16 inserting section and the PFCs. In the second phase, the remainder assembly was completed in July of 2006 after successfully passing the cool-down test and solving all the problems, which occurred in the engineering commissioning.

The main components were assembled in the following sequence: frame supports—CV and ETS bases—bottom PF coils—three tori (VV body, ITS and TF coils)—TF cryogenic tubes—central solenoid (CS) and upper PF coils—ETS middle ring and cover—ITS and ETS cryogenic tubes—CV middle ring and cover—engineering commissioning—VV 1/16 inserting section and neck tubes—PFCs [5]. The procedure for the three tori is the most important and also the most difficult.

In the assembly of the three tori, the 15 1/16 sections of the VV were welded to form the torus body except a slot of 1/16 inserting section. The VV was located in its position first and the 1/16 sections of the ITS and TF coils were inserted to their final positions one by one through the VV slot (Fig. 4). After assembly of the last 1/16 section of the TF coil, the last VV and ITS sections were installed and the TF coil structures were bolted to form a complete torus. The final connecting operations of ITS and VV could be easily made inside the VV, and spot welding was used for the temporary connection between the VV body and its 1/16 inserting section. Also the VV slot will provide the disassembly possibility for both ITS and TF coils if some leaks or other faults happen to the interior cooling loop. The 1/16 inserting section and the VV body were connected and welded together after the EAST device passed its engineering commissioning successfully.

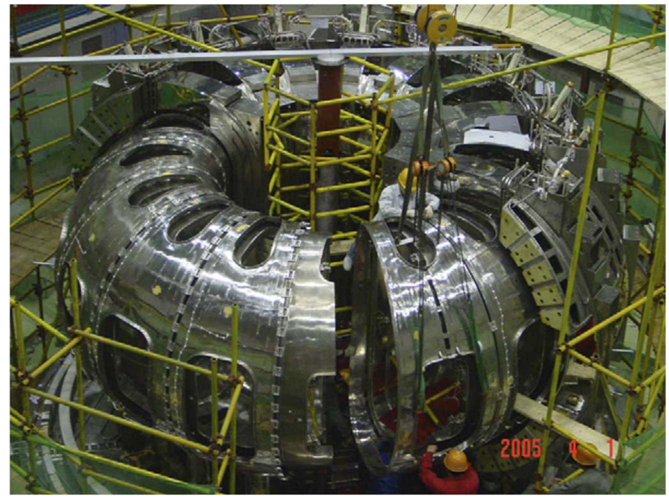

Fig. 4. Assembly of the three tori of EAST.

V. Conclusions

Some special technology applicable for fusion magnet is well developed during the construction of EAST, including the cable in conduit conductor with segregated copper wires; multi-pancake continuous winding; superconducting joint; epoxy vacuum pressure impregnation for insulation; axial and radial electrical breakers for cooling channel and vacuum break; quench detection compensation and HTS current leads for SC magnet.

The results of first commissioning show that EAST tokomak has been constructed successfully.

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