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# Manufacture of EAST VS In-Vessel Coil

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## HIGHLIGHTS

- ITER like Stainless Steel Mineral Insulation Conductor (SSMIC) used for EAST Tokamak VS In-Vessel Coil manufacture first time.
- Research on SSMIC fabrication was introduced in detail.
- Two sets totally four single-turn VS coils were manufactured and installed in place symmetrically above and below the mid-plane in the vacuum vessel of EAST.
- The manufacture and inspection of the EAST VS coil especially the joint for the SSMIC connection was described in detail.
- The insulation resistances of all the VS coils have no significant reduction after endurance test.

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## ABSTRACT

In the ongoing latest update round of EAST (Experimental Advanced Superconducting Tokamak), two sets of two single-turn Vertical Stabilization (VS) coils were manufactured and installed symmetrically above and below the mid-plane in the vacuum vessel of EAST. The Stainless Steel Mineral Insulated Conductor (SSMIC) developed for ITER In-Vessel Coils (IVCs) in Institute of Plasma Physics, Chinese Academy of Science (ASIPP) was used for the EAST VS coils manufacture. Each turn poloidal field VS coil includes three internal joints in the vacuum vessel. The middle joint connects two pieces of conductor which together form an R2.3 m arc segment inside the vacuum vessel. The other two joints connect the arc segment with the two feeders near the port along the toroidal direction to bear lower electromagnetic loads during operation. Main processes and tests include material performances checking, conductor fabrication, joint connection and testing, coil forming, insulation performances measurement were described herein.


## 1. Introduction

Studies have shown that the loss of vertical plasma position control will cause large thermal loads on Plasma Facing Components (PFCs) and can lead to plasma disruption events which produce large electromagnetic loads and other undesirable consequences [1], two sets of Active Feedback Control (AFC) coils were symmetrically arranged along the mid-plane in EAST for vertical plasma position control [2]. In the latest update round of EAST, the ceramic ring insulation AFC coils which serviced from 2006 were removed and replaced by new Vertical Stabilization coils [3]. ITER-like SSMIC was fabricated and used for the EAST VS In-Vessel Coil manufacture.

Till the end of March 2013, two sets totally four single-turn VS coils were manufactured and installed in place symmetrically above and below the mid-plane in the vacuum vessel of EAST.

The installation in EAST is the first time SSMIC is used for Tokamak In-Vessel Coils. The EAST VS coils manufacture processes mainly include SSMIC fabrication, coil forming and internal joint connection, coil test, etc. The flow chart of the EAST VS coils manufacture and installation are shown in Fig. 1.

## 2. Fabrication of SSMIC

Compared to ITER, the operating environment of the EAST VS coils is less severe, but still serious enough in terms of radiation and temperature which precludes the use of organic insulating materials and conventional methods for coil fabrication [4]. A Task Agreement (TA) "Final Design and Prototyping of the ITER In-Vessel Coils (IVC) and Feeders" [5] is now ongoing to advance the design of the ITER In-Vessel Coils (ELM and VS) toward final design review readiness including manufacture of one mid ELM and 120° segment

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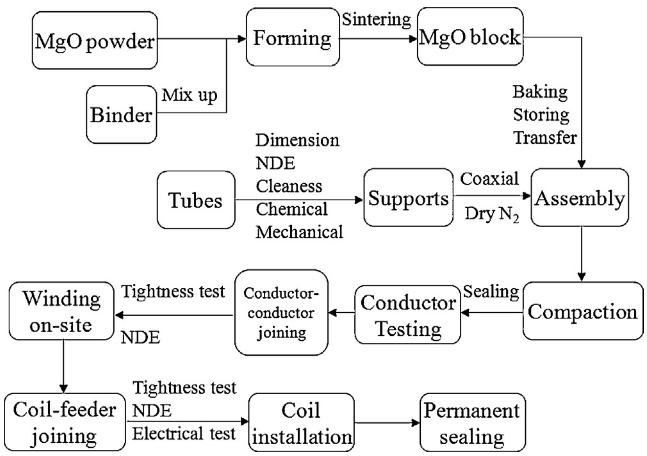


**Fig. 1.** Flow chart of the EAST VS coils manufacture and installation.

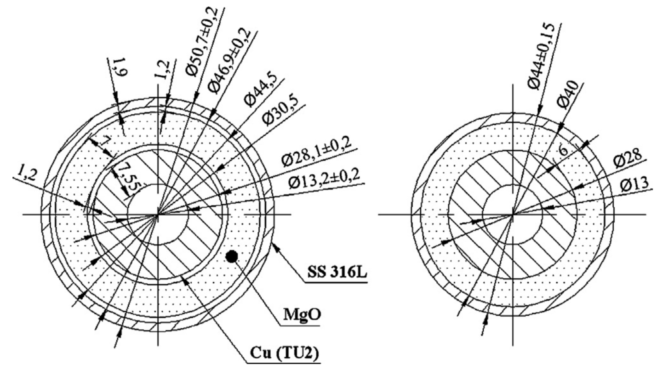


**Fig. 2.** Dimension of EAST VS SSMIC before compaction (left) and after compaction (right).

upper VS prototype coils. By the end of July 2012, the final dimension SSMIC for ITER ELM and VS coils were manufactured according to the Compaction Method (CM) developed at Institute of Plasma Physics of Chinese Academy of Sciences (ASIPP). Prototype SSMICs for ITER ELM and VS prototype coils were manufactured in January 2013. Ten EAST VS SSMICs were manufactured simultaneously. Each length of the manufactured EAST VS SSMIC is about 11 m.

### 2.1. Materials

Same as ITER, high purity Magnesium Oxide (MgO) is selected as the insulation material for the EAST VS SSMIC fabrication according to the study by CERN [6]. High purity MgO is viable at the lower radiation influence for EAST Tokamak (ITER – 3000 MGy, EAST – 1.3 MGy). The MgO can bear the highest baking temperature of 350 °C in EAST vacuum vessel which is much lower than the melting point 2852 °C. The purity and impurity of the MgO shall conform to ASTM E1652-03 Standard Specification when it was selected as Magnesium Oxide Crushable Insulators for both ITER and EAST SSMIC fabrication. Basing on the investigation and analysis of chemical composition for the MgO samples from several domestic suppliers by "National Inorganic Salt Product Quality Supervision and Inspection Center", the highest purity MgO (99.8%) was selected and used for EAST VS SSMIC. The detailed chemical composition of the selected MgO was shown in Table 1. Though the purity of the selected MgO extremely exceeds the requirement, the impurity of C content is a little bit higher than required, because the carbon electrode was used for the MgO powder production. One piece of 9.5 m ITER VS SSMIC using the same grade MgO had been sent to Princeton Plasma Physics Laboratory (PPPL) and then to Oak Ridge National Laboratory (ORNL) for an irradiation test. Thus some possible undesirable effects of using the MgO with a little higher C content in an irradiation environment can be determined from the followed electrical performance tests, including the insulation resistance, DC and AC endurance and electrical breakdown tests.

The detailed design dimensions of the EAST VS SSMIC are shown in Fig. 2. The thickness of the MgO insulation layer is 6 mm. The material of jacket is Stainless Steel 316L (SS 316L) which follows the same requirements of ITER superconducting conductor jacket. The water cooling passages of the hollow oxygen-free copper (TU2) has a diameter of 13 mm. Properties of the jacket and the copper conductor are listed in Table 2.

**Table 1**
Chemical composition of MgO.

| Item | Purity and impurity requirements | EAST VS |
|---|---|---|
| MgO, % | ≥99.4 | 99.8 |
| CaO, % | ≤0.35 | 0.01 |
| $Al_2O_3$, % | ≤0.15 | 0.05 |
| $Fe_2O_3$, % | ≤0.04 | <0.001 |
| $SiO_2$, % | ≤0.13 | 0.02 |
| C, % | ≤0.02 | 0.06 |
| S, % | ≤0.005 | 0.001 |
| B, % | ≤0.0035 | 0.004 |
| Cd, % | ≤0.001 | <0.0001 |

### 2.2. Fabrication

The EAST VS SSMIC was fabricated by a compaction machine which has the similar structure as the machine used for ITER TF/CC/MB/CB superconducting conductor compaction at ASIPP. Depending on the designed compression ratio for the conductor manufacture, the outside diameter of jacket was compacted from original dimension of 50.7 mm to the final dimension of 44 mm by the first several pairs of rollers gradually. And the last several pairs of rollers with good concentricity were used to control the straightening of the conductor better than 1 mm/m. The pre-formed hollow cylinder MgO blocks were manufactured and inserted into the gap between the SS 316L jacket and the copper conductor. Because that the MgO is very hygroscopic. Experiment indicated that the insulation resistance of the conductor without seal and exposed in air dropped from the level of G-ohm to M-ohm within half an hour. It leads the enormous difficulties of preventing moisture away from MgO during the SSMIC fabrication. The same problems occurred in the conductor-to-conductor and coil-to-feeder joining as well. Dry $N_2$ was used during SSMIC fabrication for moisture-prevention. Baking was implemented during the conductor-to-conductor and coil-to-feeder joining.

Investigations have carried out on the density compression ratio vs. compression pressure of a plenty of $\Phi$15 mm MgO pancakes. The MgO pancakes were formed with a forming pressure increased from 17 MPa to 169.9 MPa and sintered with temperatures of 1000 °C, 1050 °C, 1100 °C, 1150 °C, 1200 °C. The relationships of

**Table 2**
Properties of the jacket and the copper conductor (YS: Yield Strength, UTS: Ultimate Tensile Strength, HB: Brinell Hardness, TE: Total Elongation).

| Material | YS $\sigma$0.5 (MPa) | UTS (MPa) | HB | TE (%) | Conductivity (%IACS) |
|---|---|---|---|---|---|
| SS 316L | ≥173 | ≥483 | 140–150 | ≥35 | – |
| TU2 | ≥179 | ≥250 | 65–95 | ≥20 | ≥90 |

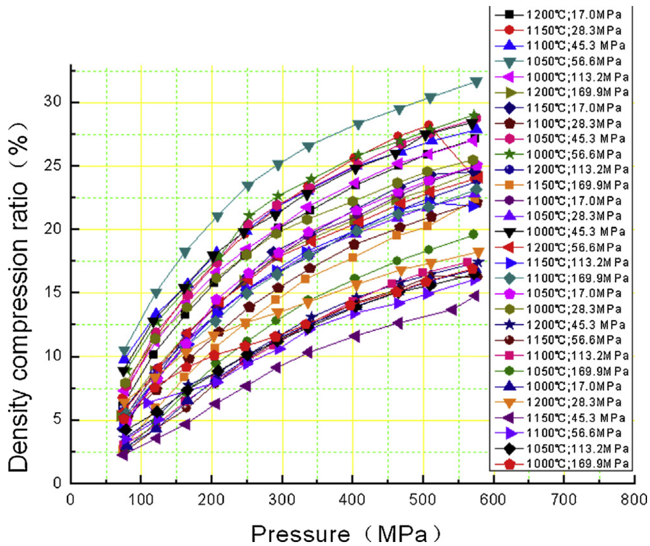


**Fig. 3.** Density compression ration vs. compression pressure.

density compression ratio vs. compression pressure of the pancakes with different forming conditions were shown in Fig. 3.

The results show that: (1) Lower forming pressure will get lower density and higher density compression ratio. But too low forming pressure will cause the MgO block be broken easily before sintering. It is better to control the density of the MgO block after sintering in the range of 2.2–2.3 g/cm$^3$. (2) The density of the MgO after compression is between 2.7 and 3 g/cm$^3$. The MgO density can reach to about 3 g/cm$^3$ with a compression pressure of 600 MPa. But too high compression pressure may lead the excessive compression of the jacket and copper conductor during SSMIC compaction. The density of the MgO block should be limited to a value less than 3 g/cm$^3$ after compaction. What should be noticed is that too lower density of the MgO insulation layer after compaction may lead poor mechanical support function during operation and cause a risk of too much reduction of the thickness at the inside bending region of the coil.

Dimension of the MgO block used for EAST VS coil was designed according to the required thickness and 29% density compression ratio of the MgO insulation layer after SSMIC compaction. The MgO block were manufactured and stored in the covered but not sealed clean turnover box before using. The MgO blocks should be baked at high temperature of more than 350 °C to decompose the possibly existed $Mg(OH)_2$ and to remove the absorbed moisture in the MgO block during storage.

The SS 316L and copper tubes were checked by ultrasonic test according to the standard GB/T 5777-2008 (Redrafting according to the standards ISO 9303:1989(E)) after other acceptance tests of the material. All the jacket and copper tubes are accepted by L2.5 level criterion for high pressure boiler tubes. All qualified tubes were

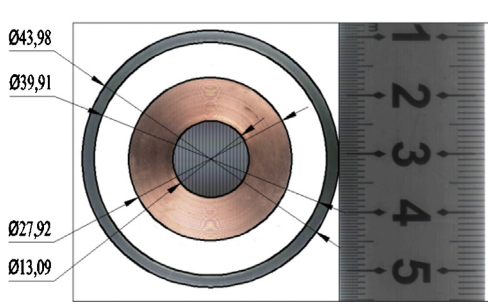


**Fig. 4.** Cross-section of the fabricated EAST VS SSMIC.

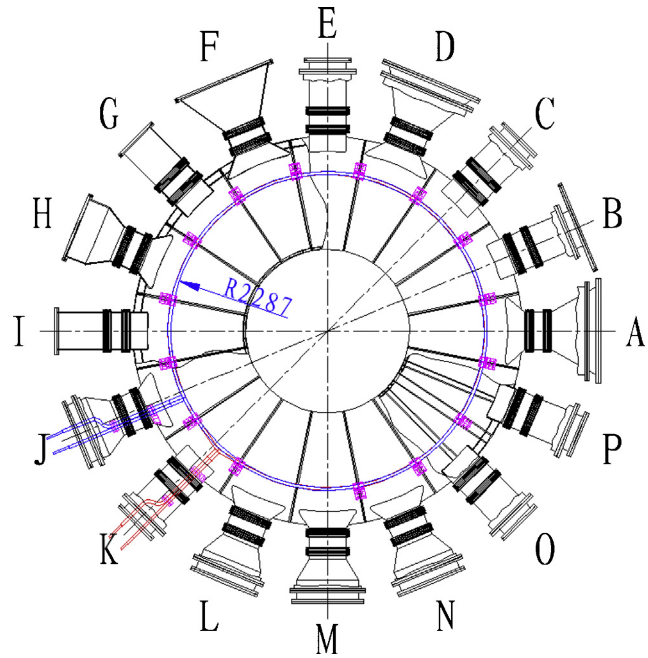


**Fig. 5.** Schematic installation location of EAST VS coils.

cleaned and baked by heat gun just before assembly. The backed MgO blocks were inserted into the gap between the jacket and the copper tube. The assembled conductor was moved to the height-adjustable supports and inserted into the compaction machine for compacting. Ten SSMICs were fabricated for manufacturing one prototype and four real EAST VS coils. The insulation resistances of all the SSMICs are better than 100 Gohm under DC 1000 V 1 min at room temperature. The outside diameter tolerance of all SSMIC is well controlled in the range of ±0.15 mm. Fig. 4 shows the scanned cross-section of the fabricated EAST VS SSMIC.

## 3. Installation of EAST VS Coil

Each VS coil includes one R2.3 m segment whose length is about 14.4 m and two feeders connected with the arc segment and led out from port J and K for current leads and cooling pipe connection (Fig. 5).

For each VS coil, two fabricated SSMICs were joined to a long piece at the workshop and then cut into three pieces: 15 m for arc segment and two 3.5 m for feeders. The 15 m SSMIC was supported to the height of the equatorial plane of EAST device and then inserted into the vacuum vessel from port A. A forming machine was located in the vacuum vessel near port C. A set of bending rollers driven by motor was installed at the platform of the forming machine. Totally three rollers were used to form the arc segment. Groove was manufactured on each roller with the same radius as the VS SSMIC, i.e. 22 mm to hold the conductor (Fig. 6). The straight VS SSMIC was clamped by the three rollers and driven by the motor to form the radius of 2.3 m arc segment. Finally, the 15 m straight SSMIC was formed to one turn R2.3 m arc segment with about 600 mm excess conductor. After forming, the arc segment was rotated inside the vacuum vessel to shift the two terminals to port J and K for feeder connection and leading out. Firstly, the formed R2.3 m segment and the feeders were put to the right position for 16 supports locating and welding. The position for joint connection was marked on the jacket of both the R2.3 m segment and the feeders to remove the reserved excess conductors. Then the arc segment and the two feeders of each VS coil were laid on a platform for joint manufacture.

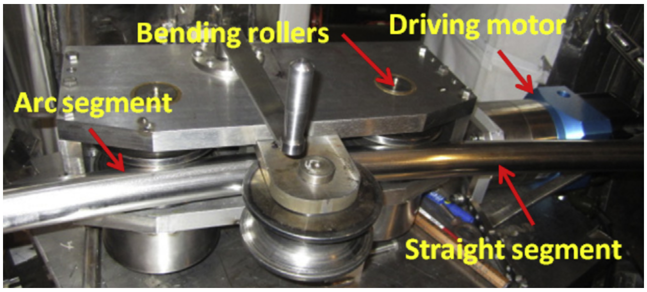


**Fig. 6.** Forming of the EAST VS coil in the vacuum vessel.

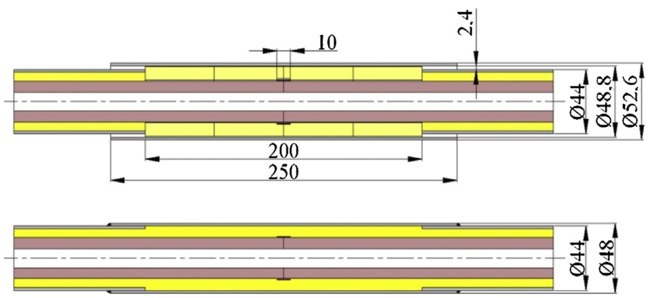


**Fig. 7.** Designed joint for EAST VS SSMIC (upper is before compaction and lower is after compaction).

A simple structure joint was designed as shown in Fig. 7 for the R2.3 m segment and feeders connection. For the joint, the compacted MgO and the same thickness stainless steel sleeve as the conductor jacket would get the similar insulation performance and strength as the SSMIC. Manufacture procedure of the joint include copper conductor brazing, MgO blocks insertion, compaction of the stainless steel sleeve, baking at least 0.5 m long SSMIC, welding of the sleeve to the SSMIC. Inspections for brazing and welding include visual inspection, helium leakage test, X-ray inspection, penetration test. After brazing of the copper tubes, pre-formed half MgO blocks were filled onto the exposed copper tube in the joint region. 250 mm SS 316L sleeve with a thickness of 2 mm was slid onto the MgO blocks and then compacted. The MgO blocks will be compacted into powder and the density of the MgO will increase 25% to the designed target value.

A split helical coil excited by an 80 kW induction power was designed for the copper brazing. Fig. 8 shows the details of the induction brazing of the copper conductor in the vacuum vessel.

**Fig. 8.** Induction brazing for copper conductor.

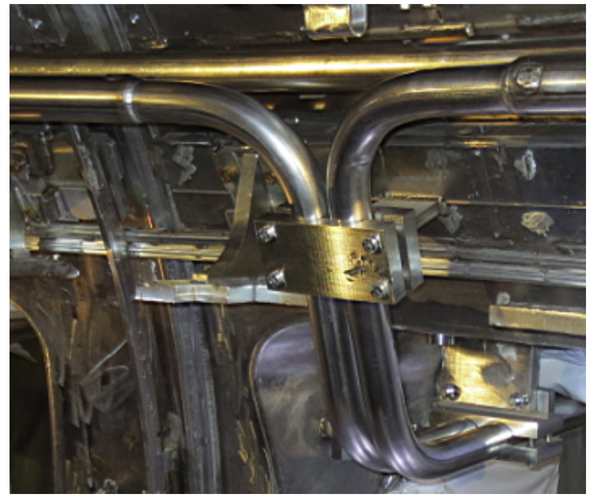

**Fig. 9.** VS coil and feeders installed in the vacuum vessel.

A set of spring clamping means was fixed on the support platform to make axially aligned and limit the gap between the two copper ends less than 0.1 mm. Three pieces 0.3 mm thick BCuP-5 filler were inserted in between the two ends of the copper before clamping. Throughout the heating and cooling, holding force on the two copper conductors was provided by the spring clamp to guarantee the brazing rate. One 10 mm wide and 1 mm thick copper ring was inserted and covered the gap to prevent misalignment during brazing and also to improve the strength. The qualified brazing sample showed 210 MPa ultimate tensile strength and failed at the base material. First surface and second surface samples passed the guide bend test according to ASME IX-QB-160. All the brazing joints were accepted by X-ray test according to standard AWS C3.5MC3.5-2007.

One 200 t hydraulic station was used for the SS 316L sleeve compaction. The compaction force reached about 170 t. One hole with a diameter of 3 mm was left on the sleeve for tightness test pipe welding. The two ends of the sleeve were manual welded to the SSMIC by the method of tungsten inert gas (TIG) welding. The qualified welding sample showed 480 MPa ultimate tensile strength and failed at the base material. All the TIG welds were accepted by X-ray test according to standard ASME IX-QB-191.

Both brazing welds and TIG welds were all accepted by penetration test according to standard ASME IX-QW-195.

All the brazing welds and TIG welds were checked by helium leakage test under 10 bar pressure and the leakage are all better than $1.0 \times 10^{-13}$ Pa m$^3$/s.

One of the upper VS coil and two feeders installed in the vacuum vessel is shown in Fig. 9.

## 4. Test results

After installation, four pairs of feeders outside of the vacuum vessel were sealed by ceramic insulation sealing. 250 mm long copper conductor of each feeder was left for current leads and cooling pipe connection. The insulation resistance of all the VS coils was tested before and after 4 kV AC endurance test. The insulation resistance are in the range of 58–83.5 Gohm which are all high than required 1 Gohm. The insulation resistances of all the VS coils has no significant reduction after endurance test.

The VS coils will be put into operation after the cooling of EAST in the end of 2013.

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