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Experiment of low resistance joints for the ITER correction coil

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A test method was designed and performed to measure joint resistance of the ITER correction coil (CC) in liquid helium (LHe) temperature. A 10 kA superconducting transformer was manufactured to provide the joints current. The transformer consisted of two concentric layer-wound superconducting solenoids. NbTi superconducting wire was wound in the primary coil and the ITER CC conductor was wound in the secondary coil. The primary and the secondary coils were both immersed in liquid helium of a 300 mm useful bore diameter cryostat. Two ITER CC joints were assembled in the secondary loop and tested. The current of the secondary loop was ramped to 9 kA in several steps. The two joint resistances were measured to be 1.2 nΩ and 1.65 nΩ, respectively. © *2013 American Institute of Physics*. [http://dx.doi.org/10.1063/1.4773545]

I. INTRODUCTION

The ITER project is one of the largest international cooperation scientific experiments in the world.[1,2] The ITER magnet system includes 18 correction coils (CCs). The ITER CCs system is used to compensate field errors arising from misalignment of the coils and winding deviations from the nominal shape.[3,4] The CC conductor is a square-in-square cable-in-conduit conductor. Totally, there are 300 NbTi superconducting strands, which are cabled clockwise in five petals with a multistage cable pattern. China is in charge of manufacturing all the CC conductor and CCs. And the research and development of the CC joints have been conducted in China. In order to be easily assembled, the ITER CC joint was designed to be composed of two CC conductor terminals. The joint resistance should be less than 5 nΩ in ITER CCs design. Two CC joints were manufactured according to ITER CC requirement. The test method and results for the two CC joints are reported in the paper.

II. BASIC DESIGN

Instead of using an expensive power supply and large power consuming current leads, the superconducting transformer[5] principle is used to provide testing current of the CC joints. The test system consisted of a 300 mm useful bore diameter cryostat, a 10 kA superconducting transformer which could generate 10 kA secondary loop current, data acquisition, and quench protection system. The transformer would be inserted into the cryostat which is 1600 mm high as shown in Figure 1.

The transformer consists of two inductively coupled superconducting coils, the high-turn primary and the low-turn secondary. By energizing the primary coil, an amplified current will be induced in the secondary loop. The NbTi strand was chosen for the primary coil. The CC conductor was chosen for the high current secondary conductor. The secondary loop contained the two CC joints which needed to be tested. The main parameters of the 10 kA superconducting transformer are listed in Table I. The maximum magnetic field was calculated to be 0.74 T using ANASYS software. The coefficient of coupling was about 0.72. The inductance of the primary coil was 0.14 H. And self-inductance of the secondary coil was about 1×10^{-6} H. The total inductance of the secondary loop was calculated to be about 2×10^{-6} H. The superconducting coils would be immersed in LHe. A LHe level meter was used to detect the liquid level. A Hall sensor was used to measure the current in the secondary loop. The copper pigtail was used as current lead for the primary coil of the superconducting transformer.

The primary coil used 0.87 mm diameter multifilamentary NbTi-Cu composite with Cu:non-Cu ratio of 1.38. The residual resistance ratio (RRR) of the copper used was about 100. The filament diameter of the NbTi was 6 μm. The critical current at 4.2 K/5 T was 550 A. The secondary winding conductor was the CC conductor. The diameter of the strands was 0.73 mm. The critical current (I_C) was about 350-360 A at 4.2 K and 5 T background magnetic field. The n value was about 36. The RRR was 160. The ratio of Cu/non-Cu was about 2.3. The CC cable pattern was $3 \times 4 \times 5 \times 5$. The final dimension size was 19.2×19.2 mm^2. The operation current of ITER CC was 10 kA and the maximum magnetic field 4.07 T.[6]

III. MANUFACTURING OF THE TEST SYSTEM

The primary coil had a former made of 316 L stainless steel. The coil had an inner diameter of 156 mm and an outer diameter of 170 mm as listed in Table I. The two layers of polyimide film were wound on the surface of stainless steel former as insulation. Two epoxy hoops were fixed at the two ends of the stainless steel former as shown in Figure 2(a). Figure 2(b) shows the picture of the winding of the primary coil. There were 8 layers and 1032 turns of NbTi superconducting strands in the winding. The tension force of 4 kg was exerted on the wire when winding. Figure 2(c) shows the picture of the primary coil after epoxy impregnation.

The secondary coil was a one-layer winding consisting of two turns wound on a stainless steel former. A 20 m long CC conductor was manufactured for research and development of CC joints. About 7 km in length NbTi strands for

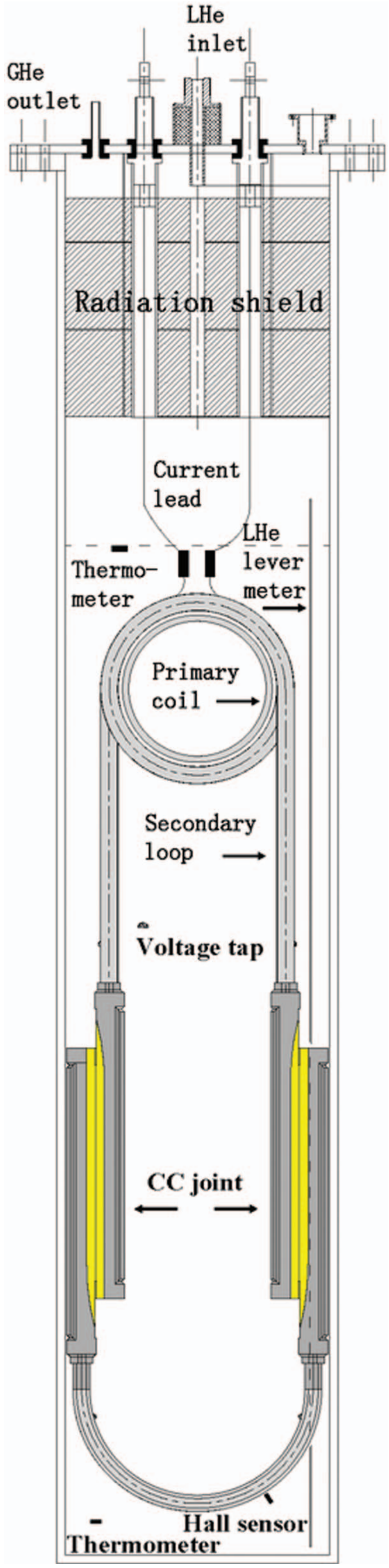

FIG. 1. The scheme of test system for ITER CC joint.

ITER CCs were used for this CC cable manufacturing. All cabling was made by twisting in the same direction. And final cable was compacted by rolling. Then the cable was inserted into 316 L round-in-round stainless steel jacket. The jacket was compacted onto the cable in a single step using sets of rollers. The final dimension of the CC conductor was

TABLE I. The main parameters of the superconducting transformer.

Item	Primary coil	Secondary coil
Winding type	Layer-wound	Layer-wound
Conductor	NbTi strand	CC conductor
Cooling	LHe	LHe
Turn	1032	2
Inner diameter (mm)	156	180
Out diameter (mm)	170	220
Height	120	46.4
Inductance (H)	0.14	1×10^{-6}
Operation current (kA)	0.2	10
Max. magnetic field (T)	0.74	
Coefficient of coupling	0.72	

19.2×19.2 mm^2. The void fraction was about 35.8%. Two lengths of conductors were cut from the 20 m long CC conductor to make secondary winding and joints. Two-layer polyimide film and glass fibre tape were wound on the surface of the conductors as insulation. The secondary coil had an inner diameter of 180 mm and outer diameter of 220 mm. Several layers of polyimide film were also wound on the surface of the stainless steel former as insulation. One length of the CC conductor was wound two turns and fixed on the former. And another one conductor was bent into a half circle as shown in Figure 3(a). The four ends of the two conductors were shaped and dismantled to manufacture the CC conductor terminals. Each two terminals were soldered together for a joint and two CC joints were formed. The primary coil was inserted into the secondary coil. The two coil former were welded together as shown in Figure 3(a). Two terminals of the primary coil were soldered with the copper pigtail current leads.

A LHe level meter was used to detect the liquid helium lever. A Hall sensor (Lake Shore HGCT-3020 series) was installed on the CC conductor to measure the current in the

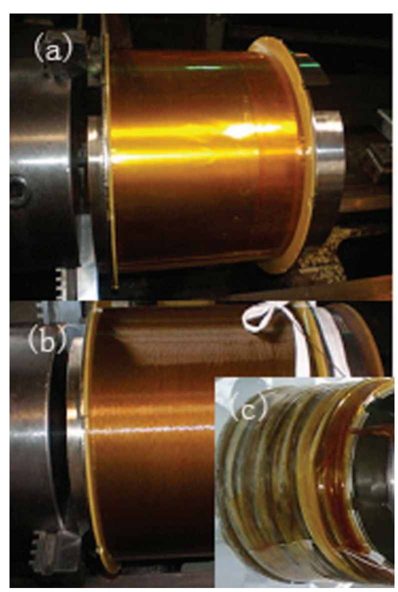

FIG. 2. The winding of primary coil of the superconducting transformer. (a) The stainless steel former. (b) The picture of winding of the primary coil. (c) The picture of the primary coil after epoxy impregnation.

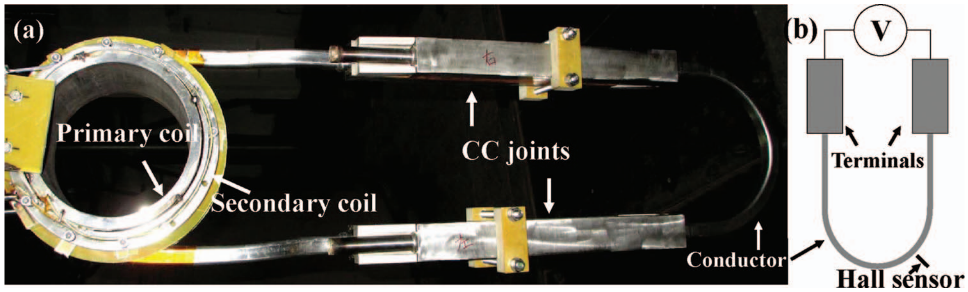

FIG. 3. (a) The picture of the 10 kA superconducting transformer. (b) The sketch map of Hall sensor calibration at room temperature.

secondary loop. Hall sensor can operate at the temperature range of 1.5 K-375 K. The Hall sensor was preliminary calibrated at room temperature by supplying a current up to 400 A through the open ends of the secondary loop as shown in Figure 3(b). The difference of the sensor magnetic sensitivity between room temperature and 4.2 K was about −0.7%. The error of the current measurements was estimated to be less than 1%. The voltage tap array location is shown in Figure 1. Each voltage tap was made by a stainless steel block spot welded to the conductor jacket. Four direct current nanovoltmeters were used to measure the voltage signals. There are the two joint voltages, the voltage of the Hall sensor and the terminal voltage of the primary coil. The current of the Hall sensor was provided by a constant current source.

IV. TEST RESULTS

The liquid nitrogen (LN_2) was used to pre-cool the superconducting transformer and the joints. The transformer and the joints were immersed in the LN_2. Then the pressure in the cryostat was increased and the LN_2 was pumped out of the cryostat. The LHe was used to cool the transformer from 80 K to 4.2 K. And the transformer and the joints were immersed in the LHe. The LHe level was maintained at approximately 1150 mm. The current varying rate of the primary coil was 40 A/min in the test. The current varying rate of the secondary loop was about 2500 A/min. The current in the secondary loop was ramped up to 9 kA in several steps. In order to decrease ripple voltage produced by the power supply of the primary coil, the primary current was kept constant in each step as shown in Figure 4. In order to calculate the current constant, the secondary current was ramped to 10 kA. Then, the primary current was kept constant and the secondary current decreased with time as shown in Figure 5. From the exponential decay curve of the secondary current, the current time constant was calculated to be about 820 s. Figure 6 shows the joint resistance test results. The joint resistances of 1.2 nΩ and 1.65 nΩ were measured. The total resistance of the secondary loop was 2.85 nΩ. The inductance of the secondary loop was calculated to be 2.0×10^{-6} H using the ANSYS software. The equation $\tau = L/R$, where τ is the current time constant, L the inductance of the secondary loop, and R the resistance of the two joints, was quoted to calculate the total resistance of the secondary loop. The total resistance of the secondary loop was deduced to be 2.45 nΩ. Because the secondary loop current was decreasing with time in the test, the measured voltage V consisted of V_1, which was caused by joint resistance and induced voltage V_2 which was caused by the current varying rate of the secondary loop. The induced voltage could be the main cause for the difference.

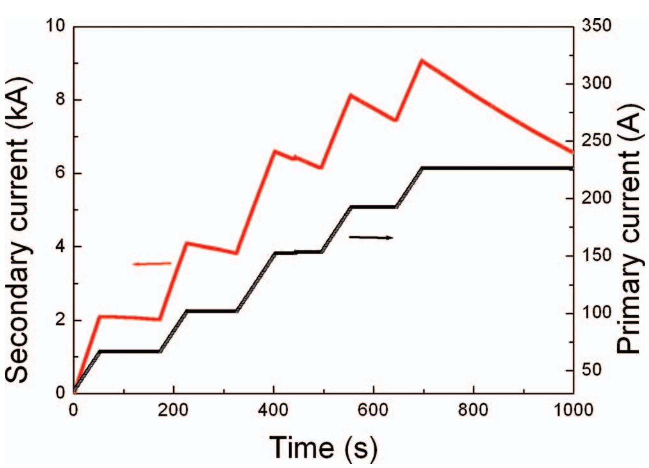

FIG. 4. The current of the primary and the secondary coils in the test. The black line was the primary current and the red one was the secondary current.

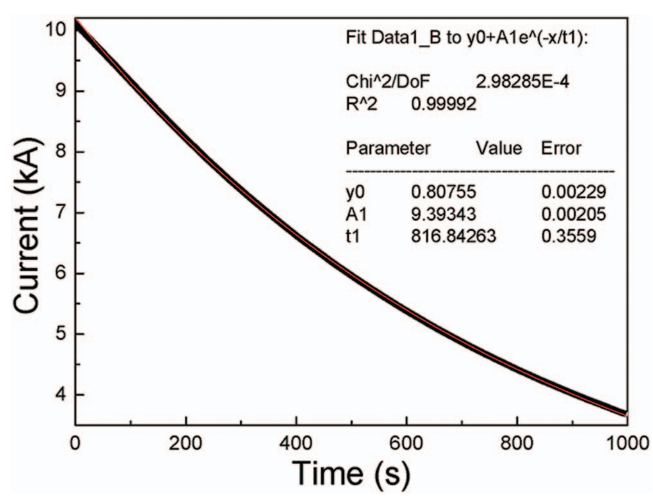

FIG. 5. The secondary loop current decreased with time when the primary current kept constant.

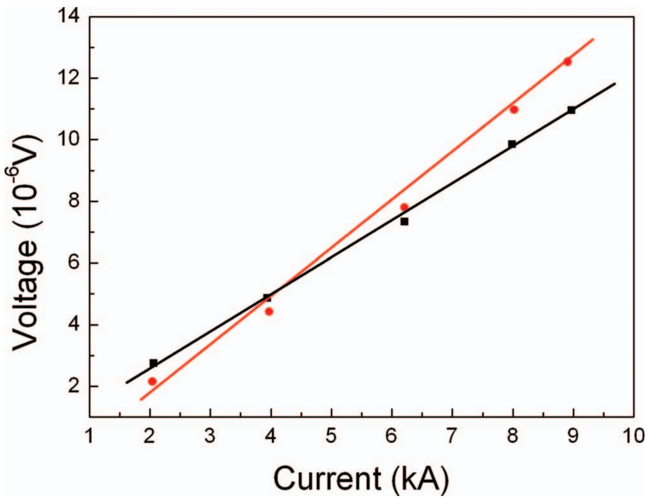

FIG. 6. Test results of the two joints.

V. CONCLUSIONS

A test system was set up to measure the ITER CC joints. A 10 kA superconducting transformer was designed and manufactured to provide the joints current. The NbTi strand was wound in the primary coil. One layer and two turns of CC conductor were wound in secondary coil. And the secondary loop contained the two CC joints. The primary and secondary coils were immersed in LHe. The secondary loop current was ramped to 9 kA in several steps. The joint resistances of 1.2 nΩ and 1.65 nΩ were measured.

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