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The cryogenic system for ITER CC superconducting conductor test facility

Jinqing Peng *, Yu Wu, Huajun Liu, Yi Shi, Jinglin Chen, Zhibin Ren

Institute of Plasma Physics, Chinese Academy of Sciences, No. 350, Shushanhu Road, Hefei 230031, PR China

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ABSTRACT

This paper describes the cryogenic system of the International Thermonuclear Experimental Reactor (ITER) Correction Coils (CC) test facility, which consists of a 500 W/4.5 K helium refrigerator, a 50 kA superconducting transformer cryostat (STC) and a background field magnet cryostat (BFMC). The 500 W/4.5 K helium refrigerator synchronously produces both the liquid helium (LHe) and supercritical helium (SHe). The background field magnet and the primary coil of the superconducting transformer (PCST) are cooled down by immersing into 4.2 K LHe. The secondary Cable-In-Conduit Conductor (CICC) coil of the superconducting transformer (SCST), superconducting joints and the testing sample of ITER CC are cooled down by forced-flow supercritical helium. During the commissioning experiment, all the superconducting coils were successfully translated into superconducting state. The background field magnet was fully cooled by immersing it into 4.2 K LHe and generated a maximal background magnetic field of 6.96 T; the temperature of transformer coils and current leads was reduced to 4.3 K; the inlet temperature of SHe loop was 5.6 K, which can meet the cooling requirements of CIC-Conductor and joint boxes. It is noted that a novel heat cut-off device for High Temperature Superconducting (HTS) binary current leads was introduced to reduce the heat losses of transformer cryostat.

1. Introduction

International Thermonuclear Experimental Reactor (ITER) is an experimental tokamak (magnetic confinement fusion) research project which aims to demonstrate that it is possible to produce commercial energy from fusion to meet the humankind's future energy requirement [1]. ITER project is one of the largest international-cooperation scientific experiments in the world, which is proceeding in the engineering construction phase.

ITER CC (Correction Coils), one types of superconducting coils of ITER device, are used to compensate field errors which arisen from misalignment of the coils and winding deviations from the nominal shape caused by fabrication tolerances, distortion tolerances and assembly tolerances. There are 18 multi-turn correction coils, consisting of six top CC, six bottom CC and six side CC. The ITER CC are made of Cable-In-Conduit Conductor (CICC), fabricated by multistage sub-cable of NbTi superconducting strand, and would be cooled by supercritical helium.

According to its procurement arrangement, ITER CC conductor will be produced and subjected to dedicated test in China. Therefore, a large superconducting conductor test facility with large current (50 kA) and high magnetic field (7 T), known as ITER CC test facility, has been built recently in the Institute of Plasma Physics, Chinese Academy of Sciences (ASIPP) [2]. The primary objective of the CC conductor sample test is to properly assess the critical performance of current and temperature (I_C, T_{CS}) of the tested conductors under the simulation operating conditions and to confirm whether the tested conductor meets the ITER CC's performance requirements.

ITER CC test facility mainly consists of cryogenic system, background magnet, current superconducting transformer, conductor short sample cryostat, power supply system, vacuum pumping system, control and data acquisition system and instrumentations [3] (see Fig. 1). The peak field provided by background magnet could reach to 6.96 T at 4.2 K. The current superconducting transformer could supply 50 kA current for the test facility [4].

This paper is concerned with design and construction of the cryogenic system of ITER CC test facility. As an important part of this test facility, the helium cryogenic system must be able to provide adequate flow rate, pressure, and refrigeration capacity to cool down and maintain all the magnets and conductors in superconducting state under normal operating conditions. This paper firstly presents the overall structure of the cryogenic system and the design of the cooling loop based on the required cooling temperature, helium pressure and mass flow rates of different superconducting magnets. As a main work, the detailed structural design of the superconducting transformer cryostat is described. It is noted that in order to reduce the heat losses of transformer cryostat, a novel heat cut-off device for HTS binary current leads was introduced in this paper. Finally, the commissioning experiment results are achieved and analyzed.

* Corresponding author. Tel.: +86 551 5593256; fax: +86 551 5591310.
E-mail address: jallen@mail.ustc.edu.cn (J. Peng).

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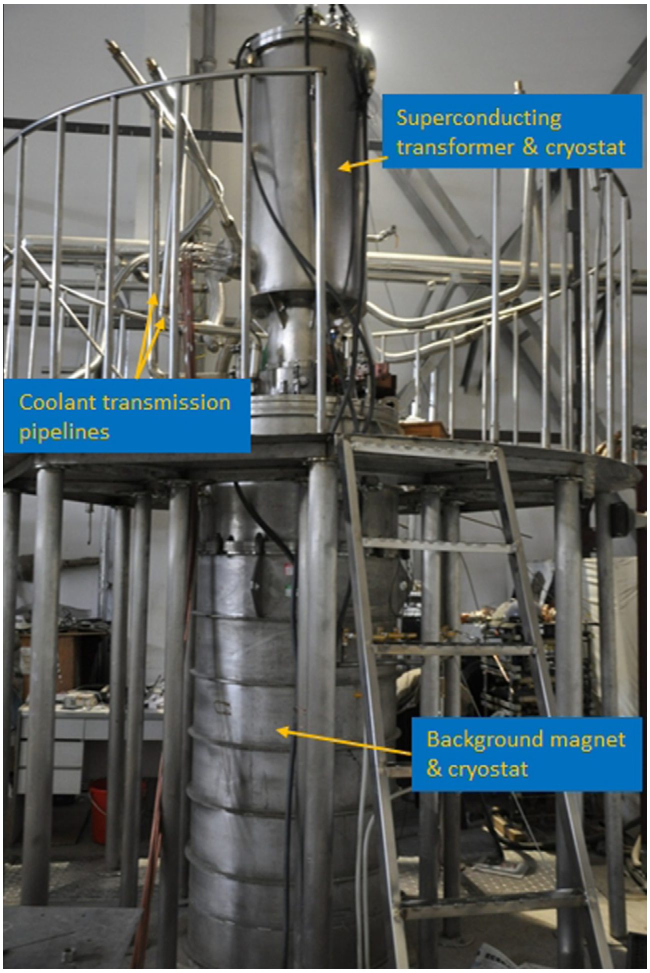

Fig. 1. Overview of ITER CC test facility.

2. The design of cryogenic system

The cryogenic system of ITER CC test facility mainly consists of a 500 W/4.5 K helium refrigerator, a 50 kA current superconducting transformer cryostat (STC) and a 7 T background field magnet cryostat (BFMC) (see Fig. 2). The 500 W/4.5 K helium refrigerator is connected with the STC and BFMC by transmission pipelines. It is mainly used for producing 4.2 K liquid helium (LHe) to immerse and cool down the background field magnet and the primary coil of the superconducting transformer (PCST). In addition, it can also supply the forced-flow supercritical helium (SHe) of 4.5 K/3.5 bar to cool down the secondary coil of superconducting transformer (SCST) and the ITER CC conductor sample. The design parameters of the cryogenic system are presented in Table 1. The distribution of LHe and SHe in the test facility is shown in Fig. 3.

2.1. 500 W/4.5 K helium refrigerator

The 500 W/4.5 K helium refrigerator adopts Collins helium liquefaction cycle and possesses of four cooling stages as follows: liquid nitrogen pre-cooling, the first stage expansion (including three piston expanders), the second stage expansion (one piston expander) and *J–T* valve throttle cooling. The original nominal cooling capacity of this refrigerator was approximately equivalent to 500 W at 4.5 K, and it could provide 4.5–6 K, 2.5–5 bar, 20–40 g/s SHe for magnets or 150 L/h helium liquefying capability [5]. However, as this refrigerator has been in service for 30 years, the cooling capacity has been seriously degenerated. Particularly the efficiency reduction of piston expanders caused that the outlet temperature of refrigerator is too high. It was about 5.3 K @ 3.0 bar during last commissioning experiment. In fact, we are planning to build a new helium refrigerator with 1000 W @ 4.2 K capacity to cope with this problem.

The existing 500 W/4.5 K cryogenic system shares the same compressors unit with EAST Tokamak cryogenic system, to which seven sets of oil injection type screw compressors are applied.

2.2. Background field magnet cryostat

The background field magnet cryostat (BFMC) was originally used to serve the CEA test facility for testing TORUS II conductors and then presented to ASIPP in 2003. We have rebuilt this device after many improvements were done in the cooling, power supply, data measurement and acquisition, magnet quench protection system, etc. [6]. The scheme of BFMC is shown in Fig. 4. This cryostat features a DC background field up to 7 T in a 338 mm useful bore diameter [7,8]. When it is used for ITER CC short sample test, the sample anti-cryostat needs to be inserted into the 338 mm bore of the background magnet.

2.3. 50 kA current superconducting transformer cryostat

In the test facility, the 50 kA current is supplied by a current superconducting transformer which was immersed into a superconducting transformer cryostat (STC) by LHe. This transformer is comprised of two coaxial coils, named primary coil and secondary coil respectively. The primary coil was wound into solenoid coil by single NbTi superconducting strand and was placed in a cylindrical transformer LHe vessel [9]. The secondary coil, fixed to the outer surface of the transformer LHe vessel, was fabricated by CIC-Conductor for transmitting 50 kA large current. And it was cooled by 4.5 K/3.5 bar SHe.

To maintain the superconductivity of the superconducting transformer, a cryostat was required. This cryostat was assembled at the top of BFMC by vertical flange coupling. From the bottom to the top, it mainly consists of two LHe vessels, High Temperature Superconducting (HTS) current leads, LN_2 vessel, heat cut-off device of current leads (HCDCL) and thermal shields (see Fig. 5). The superconducting transformer LHe vessel was used to immerse and cool down the primary coil into 4.2 K. The upper LHe storage vessel was applied to store helium and then supply LHe to the transformer LHe vessel. Therefore, the primary coil could be sufficiently cooled during operating period. Above the LHe storage vessel, there is a LN_2 vessel, which was used to cool the copper thermal shields and HCDCL. To decrease the evaporation of LHe, HTS current leads with 200 A nominal current, instead of common copper current leads, were used for charging the primary coil [9]. As a result, the heat loads was reduced to 0.13 W, much less than copper current leads'. Under the operating conditions, the upper end of the HTS current leads were indirectly cooled by liquid nitrogen through the HCDCL and its temperature maintains at about 80 K. The lower end connected to the current terminal of the primary coil was immersed by 4.2 K LHe.

The novel heat cut-off device of current leads (HCDCL) (see Fig. 6), cooled directly by liquid nitrogen, was applied to cut-off the heat flow of current leads. As shown in Fig. 6, in the central part of LN_2 vessel, a copper heating conducting plate (CHCP) was installed and welded with the circular inner wall of LN_2 vessel. The circumference side of CHCP can directly contact with the LN_2, so CHCP can be fully cooled by LN_2. Thus the heat loads caused by common copper current leads will be cut-off by CHCP.

In addition, between the CHCP and the copper current leads, there are some pieces of aluminium nitride (AlN) to play the role