Experimental Study on Paschen Tests of ITER Current Lead Insulation*

ZHENG Jinxing (郑金星), SONG Yuntao (宋云涛), HUANG Xiongyi (黄雄一),
LU Kun (陆坤), XI Weibin (奚维斌), DING Kaizhon (丁开忠), YE Bin (叶斌),
NIU Erwu (牛二武)

Institute of plasma physics, Chinese Academy of Sciences, Hefei 230031, China

Abstract An experimental Paschen test setup has been established to analyze the quality of ITER current lead (CL) insulation and extend the research on Paschen’s law under various conditions. Insulation problems can destroy a machine if a Paschen discharge is triggered by an insulation defect that is caused by faulty manufacturing, electromagnetic force, and thermal stress load with a certain degree of vacuum helium or pipe leakage. The results show that the CL insulation mock-up worked well under normal temperature and pressure. Besides, the mock-up also worked well in helium conditions and at 80 K temperature at different pressures. One area of CL insulation was severely destroyed when the 80 K test was conducted after 5 thermal cycles, resulting in Paschen discharge phenomenon. The breakdown voltage is maintained at a relatively low level under different pressure conditions; the change of breakdown voltage was mainly due to the change of pressure, and such change was in line with the Paschen law.

Keywords: paschen test, insulation, discharge, ITER current lead, low temperature

PACS: 84.71.-b, 85.25.Am, 84.70.+p, 51.50.+v

DOI: 10.1088/1009-0630/15/2/15

1 Introduction

Large superconducting components like the current lead (CL) of the ITER feeder system will work in a vacuum and low temperature environment. The current lead is separated from the external vacuum vessel by its insulation package in normal circumstances, and the liquid helium cooling system is also required to adapt to its low-temperature environment [1~3]. Due to the high voltage in the event of fast discharge of a coil, serious consequences may occur when the insulation of the current lead breaks down [4,5]. The internal high voltage current lead will reach 7 kV when the energy stored in the magnet coil unloads in cases such as an emergency shutdown caused by a critical event.

Glass fiber tape with epoxy resin, and polyimide film are chosen as the composite insulation materials for ITER feeder CL [6,7]. Half overlapping 12-layer polyimide tapes (one tape is 0.05 mm) are directly wrapped on the surface of feeder components, and then half overlapping 28 layers glass fiber tapes (one tape is 0.2 mm) are wrapped, so the calculated thickness of total insulation layer is 6.2 mm.

Theoretically, defects in the manufacturing process of the insulation cannot be avoided completely (such as bubbles, cracks). Due to long-term service and the thermal cycle of the CL, a fissure may be formed when the cracks or bubbles extend along the interfaces between polyimide tapes and glass fiber tapes. Once the vacuum is destroyed (which cannot be completely ruled out in theory), the fissure will be filled with air or cooling helium under various gas pressures (pressure in the fissure is determined by the fissure’s shape and the damage to the vacuum, as illustrated in Fig. 1, and then the breakdown discharge will take place if the actual condition of the fissure inside insulation reaches “PASCHEN MINIMUM” [8,9]. The Paschen discharge phenomenon can be explained by Fig. 2 [8]. Fig. 2 mainly describes the trends of nitrogen Paschen discharge breakdown voltage with pressure and electrode distance (atm-cm) at room temperature. In this paper, the Paschen test of current lead insulation was performed at temperatures as low as 80 K. If there are cracks in the insulation and the crack’s length and shape between the electrodes is difficult to determine, then the detailed breakdown voltage cannot be simply inferred from Fig. 2.

Fig.1 Insulation layout of the CL and defect (color online)

*Supported by ITER IO, the National “973” Program of China (No. 2007ID2006) and the National ITER Special Support for R&D on Science and Technology for ITER, CN Schedule Task (No. 2008GB102000)
Therefore, the high voltage test under the Paschen condition (low gas pressure condition) can detect the insulation defects easily and effectively. That is the reason why the Paschen test needs to be carried out in all the feeder’s high potential components.

2 The current lead of ITER’s feeder

The current lead is an important component of a feeder, which connects the low-temperature superconducting bus bar and room temperature power supply, as illustrated in Fig. 3. The low-temperature section (about 4.5 K) of the current lead is connected to the superconducting bus bar, and the high-temperature section (about 77 K) links the heat exchanger, which is connected to a room temperature power supply. The current lead’s temperature gradient is large when it is working, and the insulation layer of the current lead needs to withstand low temperature and thermal cycles.

The effective length of the current lead mock-up for test is 1639.8 mm. The outer diameter of the main part is about 180 mm. The top of the CL was sealed by a flange in order to maintain the internal vacuum. A 316L stainless steel case was welded onto the bottom of the low-temperature section as a seal. In addition, insulation was also wrapped on the surface of the stainless steel case; liquid nitrogen (LN$_2$) cooled the CL through the break into the interior of the CL for simulating the CL’s actual working environment.

3 Paschen test setup

The sketch of the test framework is shown in Fig. 4. Based on the factors mentioned above, a setup for Paschen testing was built during October 2010 in ASIPP, as shown in Fig. 5. The pumping system and gas injection system can provide a testing gas pressure condition, which can be swept from 0.01 Pa to 1000 Pa continuously, and cryogenic insulation condition. The container pressure reached 0.2 Pa firstly by the pumping system, and then the gas injection system was used to control the pressure continuously, such as 0.1 Pa, 1 Pa, 100 Pa, and so on. The maximum output voltage and current of the DC high voltage generator are 100 kV and 3 mA, respectively. The leakage current can be measured during the test, of which the accuracy is 0.1 $\mu$A. Temperature sensors are arranged along the insulation layer surface to control the temperature during the test. Meanwhile, in order to simulate more realistic operating conditions, the CL mock-up has to be cooled down to LN$_2$ temperature or even lower before the LT (low-temperature) test and the thermal cycle test. The extending part and the break also need to be insulated with glass fiber tape with epoxy resin and polyimide film. This insulation needed to be reinforced at the connection area.
voltage can go through the HV feedthrough from this end. The aluminum foil, which was connected to the container wall, works as a grounding potential.

As shown in Fig. 5, the entire CL mock-up case was sealed with a stainless steel shell, except for the two high voltage breaks. To cool the mock-up, liquid nitrogen flew into the mock-up and cooled it by two separate pipes connected to the above two breaks (serving as the liquid nitrogen inlet and outlet, respectively). The test container maintained a vacuum of $10^{-3}$ Pa during the cooling process of the CL mock-up. Liquid nitrogen went in and out of the mock-up circularly during the cooling process and an adiabatic layer was wrapped onto the insulation surface. Therefore, an icing phenomenon in the test container was not observed.

During future operation, the low temperature section of the CL needs to be cooled to 4.5 K during each experiment and return back to room temperature (about 300 K) when the experiment is finished.

Consequently, the electrical insulation has to withstand thermal cycles. Therefore, the insulation needs more tests under the condition of thermal cycles. The process of one thermal cycle is: a. The CL was cooled down to 80 K by use of LN$_2$; b. The supply of LN$_2$ was stopped and then the test device would be automatically warm up to 300 K; c. The CL was cooled down to 80 K again by use of LN$_2$.

4 Test item and programme

a. RT test (air condition): before the assembly of the CL insulation mock-up, the CL passed the room temperature (300 K) high voltage test at the ASIPP workshop.

b. The Paschen test should be carried out after the high voltage test and the process is as follows. The pumping system will pump the container to the target vacuum of $5 \times 10^{-2}$ Pa, and then the LN$_2$ will flow in and out the CL to cool the CL. After that, the testing gas (helium) will be injected into the container when the temperature is kept at 80 K. The testing pressure levels are arranged from $10^{-2}$ Pa to $9 \times 10^{4}$ Pa.

- 80 K low temperature test (helium): the current lead was tested at a temperature of about 80 K. The test voltage was raised in steps, which changed manually from 0 V to 30 kV at a ramp rate of 250 V/s $\sim$ 300 V/s and the testing pressure levels ranged from 1 Pa to 1000 Pa. For each pressure level, the voltage was maintained at 5 kV, 10 kV, 15 kV, 20 kV, 25 kV, and 30 kV for 5 minutes. During the voltage ramp up procedure and the voltage flattop, the HV generator could automatically shut down the power when the leakage current was larger than 1 mA or the insulation broke down.

- 80 K low temperature test after thermal cycle (5 times, helium): when the 80 K low temperature test was complete, the current lead was subjected to 5-times thermal cycles with the temperature changing from 80 K to 300 K. Finally, an 80 K Paschen test was also done with the test pressure levels changing from $10^{-2}$ Pa to $9 \times 10^{4}$ Pa. The test process is similar to the 80 K low temperature test (helium) process.

5 Test results

5.1 Room temperature test before first cooling down

As shown in Fig. 6, the heat exchanger of the CL (area 1), high-temperature section (area 2) and the end transition of the CL (area 3) were respectively tested under normal temperature and pressure after the insulation material was wrapped onto the surface of the CL. The test temperature is 30 $\degree$C, humidity was 35%$\sim$40%, and the maximum leakage currents at 30 kV were 6 $\mu$A, 3 $\mu$A and 4 $\mu$A, respectively, so we can conclude that there is no defect and crack generated after insulation.

Fig.6 Room temperature test of the CL (color online)

5.2 80 K test

The 80 K test results are shown in Fig. 7. The leakage currents at different test voltages and different gas pressures were kept less than 20 $\mu$A. At the beginning of the 3.5 Pa test case, the leakage current was relatively large, and the maximum leakage current at 30 kV was 20 $\mu$A. The author believes that this situation was due to the high air humidity (56%) caused by the fact that we ran out of cooling LN$_2$. The initial large amounts of evaporation of LN$_2$ led directly to the increase of the humidity. The decline of insulation material’s resistance could be caused by the increased humidity, which can directly lead to the increase of leakage current. So the leakage current is relatively large. The humidity was measured not in the test container but on top of flange (out of the test container), where the terminal of the mock-up and the LN$_2$ in/outlet are arranged. The temperature of this area is not 80 K, so the water is not frozen, but frosted. However, humidity would increase here, making the terminal of the mock-up flashover more easily.

However, the subsequent 14 Pa, 66 Pa, 120 Pa, 620 Pa, 1300 Pa tests were done after the LN$_2$ had mostly evaporated, and the leakage current also increased linearly with increasing test voltage, but the value was smaller than that in the 3.5 Pa test case. All these test results demonstrate that the current lead insulation works well under the 80 K condition.
ZHENG Jinxing et al.: Experimental Study on Paschen Tests of ITER Current Lead Insulation

5.3 80 K test of CL after five thermal cycles

Another 80 K test of the CL was done after five thermal cycles. The experimental results were shown in Fig. 8, where the first test pressure was 1.4 Pa, and the leakage current exceeded 30 µA at 10 kV, indicating that the insulation had begun to be destroyed. After that, the leakage current climbed linearly with increasing test voltage. For example, 500 µA was reached at the point of 24 kV. The pressure rose to 11 Pa (by the pumping system and the gas injection system) for two tests to verify whether the insulation material had been destroyed completely. The linearly increasing rate of the second leakage current is much larger than the first group when the test voltage exceeded 10 kV, and the leakage current of the second set reached 3000 µA directly at 22 kV, so the insulation completely broke down (when two leakage current tests were conducted under the same pressure, and if the second breakdown voltage is much lower than the first breakdown value, the cause of the sample’s first breakdown can be considered as serious internal damage).

The cracks through the insulation can be considered to be filled completely with helium after the insulation breakdown, and then the gas discharge occurred between the high potential and the low potential through the cracks. We have analyzed the variational rules of the leakage current - voltage curve under different pressures based on the above situation. Fig. 9 is the leakage current - voltage curve of the test for different pressures. The leakage currents went up with increasing test voltage under various pressure conditions. All the leakage currents grew slowly in the initial test voltage range, but the leakage current suddenly jumped to 3000 µA when the test voltage reached a certain value. Meanwhile, Paschen gas discharge occurred, and the test voltage was considered to be the minimum breakdown voltage. The test pressure ranges were from 0.045 Pa to 90000 Pa, the breakdown voltage ranged from 2.7 kV to 3.2 kV for pressure between 0.045 Pa and 2.3 Pa, and the breakdown voltage reached the minimum value (about 1.6 kV ~ 2.2 kV) for pressure between 32 Pa and 210 Pa, but the breakdown voltage value went up again (about 2.4 kV ~ 3.6 kV) with pressure increasing from 570 Pa to 90000 Pa.

The faulty part of the solid insulation layer could not be examined immediately when the breakdown took place. In order to locate the faulty area, the mock-up was tested section by section (exclusive method) by using a high voltage test method after the experiment, and one faulty area was found and examined. This retest was done at atmospheric conditions, from the LTS part to the insulation flange. The location of such a failure when no “macroscopic” damage occurs can also be identified on the base of the GB/T1408.1-1999 standard [10], which was formulated and promulgated in China. Once breakdown occurs at one area, high voltage could be applied to the area again, and if the second breakdown voltage is far below the first breakdown value, this area can be considered to have material damage. However, if the insulation is not completely damaged, the integrity of the insulation material could be identified by using ultrasonic detection technology and X-ray detection technology.

The breakdown voltage-pressure fitting curve is shown in Fig. 10. The breakdown voltage was maintained at a relatively low level for different pressures, and the change of breakdown voltage was mainly due
to pressure changes. This was in line with Paschen’s law. The breakdown voltage shows an upward trend with pressure decrease or increase on both sides of the Paschen minimum in an 80 K helium environment, but both the increasing slopes were small compared with the Paschen law curve in room temperature N\textsubscript{2} (Fig. 2 [8]). According to the experiment and the relationship $V \sim P d$ of Paschen discharge theory [11-13], the author concludes that it is caused by a longer length of crack inside the insulation. If the “$d$” of the fissure is so long that it extends along the polyimide tapes and glass fiber tapes, it will need a long time for the He to creep in. Therefore, a large influence of the impact of pressure factors will not be seen when the measurement is done quickly. Of course, the analysis requires further experimental verification and theoretical analysis. However, there is another possible influence on the development of breakdown voltage: repeated failures (which occurred along with the first breakdown path) will cause the remaining insulation to deteriorate.

6 Summary

A Paschen test setup for feeder HV components has been built and relevant tests of the CL insulation mock-up have been successfully carried out. From the above Paschen test results on CL, the DC resistance of the mock-up insulation worked well under normal temperature and pressure. In addition, the mock-up also worked well under the condition of helium and 80 K temperature for different pressures, which accords with the requirements of the ITER IO (at 30 kV, leakage current lower than 30 $\mu$A). One area of CL insulation was severely destroyed when the 80 K test had been done for 5-times thermal cycles, resulting in a Paschen discharge phenomenon. Hence, it is considered that the thermal fatigue resistance of the insulation for CL should be improved.

The increasing slope of the voltage-pressure fitting curve on both sides of the Paschen minimum in the 80 K helium environment was small compared with the Paschen law curve in room temperature N\textsubscript{2} (Fig. 2), but its trend was in line with the Paschen law. The relationship $V \sim P d$ under low-temperature and a helium environment needs further experimental verification and theoretical analysis. However, the Paschen law is not always seen under realistic experimental conditions, which was demonstrated in Ref. [14].

The Paschen test setup can provide a sufficient test of almost all the potential defects found in feeder high potential component insulation, which can effectively guarantee the insulation’s quality in the future operation of ITER. Thermal cycling with subsequent tests under Paschen’s condition is mandatory to ensure proper electrical insulation.

References


(Manuscript received 7 January 2012)
(Manuscript accepted 20 July 2012)
E-mail address of ZHENG Jinxing: jxzheng@ipp.ac.cn

Fig.10 Breakdown voltage-pressure fitting curve