Design of High Voltage Electrical Breakdown Strength measuring system at 1.8K with a G-M cryocooler

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Abstract. Impregnating resins as electrical insulation materials for use in ITER magnets and feeder system are required to be radiation stable, good mechanical performance and high voltage electrical breakdown strength. In present ITER project, the breakdown strength need over 30 kV/mm, for future DEMO reactor, it will be greater than this value. In order to develop good property insulation materials to satisfy the requirements of future fusion reactor, high voltage breakdown strength measurement system at low temperature is necessary. In this paper, we will introduce our work on the design of this system. This measuring system has two parts: one is an electrical supply system which provides the high voltage from a high voltage power between two electrodes; the other is a cooling system which consists of a G-M cryocooler, a superfluid chamber and a heat switch. The two stage G-M cryocooler pre-cool down the system to 4K, the superfluid helium pot is used for a container to depress the helium to superfluid helium which cool down the sample to 1.8K and a mechanical heat switch connect or disconnect the cryocooler and the pot. In order to provide the sufficient time for the test, the cooling system is designed to keep the sample at 1.8K for 300 seconds.

1. Introduction

The insulation material is the key elements of the superconducting magnets which is characterized by high mechanical strength in order to withstand the Lorenz forces occurring in the powered magnets, high capacity to transfer heat from the magnet coil to the magnet coolant and high electrical strength. The insulation character prevents electric discharge when the superconducting magnet quenches or discharges \cite{1}. The research on the superconducting magnets insulation should be tested for the cryogenic environment. Several similar tests have
been published finding the improvement in the electrical breakdown strength along with the dropping of the temperature. In a system designed by Husain et al [2]. Measurements were taken in the liquid nitrogen for the electrical breakdown voltage of solid film insulation material. They designed different kinds of electrodes to test the sample and found the type of electrodes also affected the breakdown voltage. Zhang Jinxing [3] and co-workers designed a system that reaches 80K in vacuum or helium gas in different pressures which also use liquid nitrogen to cool down the sample. So the electrical breakdown strength measuring system for solid dielectric has not been developed below the temperature of liquid nitrogen. The data is limited on electrical breakdown strength for solid material below the temperature of 77K. This hinders the development of the discovery of the relationship between electrical breakdown strength and the temperature.

So in this paper, we designed a cryostat aimed to test the electrical breakdown character of the thin film insulation materials. Using alone the cryocooler doesn’t have the ability to reach the temperature of 1.8K. The cryocooler cannot provide sufficient cooling capacity bearing the heat leakage from the shield radiation and structure heat leakage. So we combine liquid helium and GM cryocooler in a cryostat to cool down the sample to the temperature of 1.8K. A 50K radiation shield is set to block the radiation. We also design a heat switch to control the cool down process. The superfluid helium was made by pumping the liquid helium in a copper pot. After the helium pressure and the temperature of sample become stable, the power supply controlled by computer begins to apply high voltage on the positive electrode until the sample breakdowns.

2. Cryostat design

2.1. The refrigeration system

The cooling process of the system consists of two parts. First, cool down the system by the GM cryocooler to the temperature of liquid helium. Second, inject the liquid helium into the superfluid helium pot and pump to the temperature of superfluid helium.

Fig.1 The schematic of the cryostat with the GM cryocooler
Fig. 1 shows the schematic of the cryostat with the GM cryocooler. An ESYCOOL KDE415SA two stages GM cryocooler is used to provide refrigeration at 4K. The GM cryocooler specification is: 35W@50K on the first stage and 1.5W@4.2K on the second stage. The cryocooler consists of a helium compressor, flexible connection lines and a cool head. The cool head is made up of two stages. Two radiation shields connect to the first and the second stage separately. The thermal connect between the shields and stages is enhanced by 0.25 thick indium washer and the copper flange was applied with Apiezon grease. The temperature of the shields is about 50K and 4K. The shield is wrapped in ten layers of insulation. The radiation shields cut down most radiant heat leakage.

The cryostat incorporates a liquid helium pot (also called superfluid helium pot, 650ml in maximum). The pot is made of copper. By design, the pot is thermally isolated from the rest of the cryostat. It is fixed to the first stage radiation shield by four epoxy resin rods. The liquid helium is provided by a standard liquid helium tank, it transfuses to the pot through the first pipe (10mm diameter and vacuum double-wall). The liquid level in the pot was detected by the differential pressure gauge from two pipes. The pipes (2mm in diameter) connect to the top and bottom of the pot. The pipe on the top is used to detect the helium gas pressure, and the bottom one is used to detect the bottom liquid helium. The radiation on the third pipe makes the liquid helium evaporate, then the liquid helium cannot inject into the third pipe. The pipe (20mm in diameter and 1mm thick) is used to pump the pot. Because of the ‘zero gravity character of superfluid helium, the holes on the pot are limited to 2mm in diameter. Four stainless pipes connect to the pot.

![Fig.2 The axial symmetric test electrodes](image)

The pot at the superfluid helium temperature needs to disconnect preventing the heat leak from the second stage. To expedite the cooling process, we designed a simple mechanical heat switch. During the cool down phase, a copper disk is held tightly against the pot by screwing on the room temperature side. Thermal contact between the copper disk and the pot enhanced by a 0.25mm thick indium washer between them. Five flexible braids, each
made up of copper wires, connect the disk to the second stage. The switch connects the pot with pressure, allowing the heat efficiently removed from the pot.

2.2. The electrical test system

The high voltage power supply with overload protection provides the high voltage on the sample. The maximum voltage is 100kV and the maximum current is 2mA, so the capacity is enough to break the thin film sample. A protection resistant 100MΩ protects circuits after the sample breaks down, the voltage on the sample was detected by a 1000:1 voltage divider. The signal of the electrical breakdown is an instant fall of the voltage between the voltage divider and ground. The high voltage wire goes into the cryostat by a vacuum feedthrough. Inside the cryostat, the vacuum side of the feedthrough directly connects to the test cell with XLPE. Fig.2 shows the axial symmetric test cell that is installed under the bottom of the superfluid helium pot. 8 tubes and two plates shaped frame are made of glass fiber reinforced epoxy and have a diameter of 10mm. We choose needle to flat electrodes (showed in fig.2 [4]) in a parallel plane configuration according to the IEC standard. The flat electrode integrated with the superfluid helium chamber has enough area to conduct the cool capacity from the bottom of the superfluid helium chamber, and the needle shape reduces the heat from the positive pole wire from the room temperature. The thin film sample to be tested are put between the electrodes. The diameter of the sample should be a little bigger than the electrodes preventing the flash over the surface. The needle electrode is made of brass when tightening the screw going through the thick epoxy plate the spring moves upwards. Thereby compressing the spring and thus exerting this compressive force on the electrodes system through the hemispherical tip of the brass plate. High voltage is provided by an XLPE insulated power cable with a metal toroid above the thick epoxy plate also contribute to smoothen the electrical fields. The insulation method in the cryostat is using the insulation fracture and high vacuum insulation. The high vacuum means 10-4 ~10-5 Pa, the pressure in cryostat is detected by compound pressure and vacuum gauge. The electrical breakdown voltage in a high vacuum is up to 10-7 V/cm, even so all parts close to low potential conductive material in cryostat should smooth the electrical.

3. Heat load

The cryostat provides vacuum environment for the thermal insulation. The superfluid helium pot operated at 1.8K, the first stage radiation shield is 50K and the second radiation shield is 4.2K. The steady-state heat load, whether radiate or conduction, are driven by the temperature difference between the vacuum vessel and the helium tank. In order to realize producing the long durable 1.8k environment, minimizing the heat leak and thus minimize active cooling power requirements and the consuming of the helium.

We calculated the number of the steady-state heat load roughly. The heat load from heat conduction is calculated by the basic Fourier’s equation [5]. The heat leak of radiation through the multi-layer insulation could be calculated from the Lockheed equation [6]. The temperature in the equation \( T_H, T_I = (300, 50, 4.2, 1.8) \) changes when calculate different part. The number of the layers is 30 and it roughly equals to the number of layer density \( N_s = \overline{N} = 30 \). The hemispherical emittance \( \varepsilon_{RT} = 1.0 \) we choose is 1.0 because of the
polished metal. The inner surface areas \((A=(1.31, 0.6, 1.1\times10^{-2}))\) of the different shields are 1.31, 0.6 and \(1.1\times10^{-2}\). The degradation \((F=1.2)\) is 1.2. The results are shown in table 1.

| Item         | First stage (W) | Second stage (W) | Helium pot (W) |
|--------------|-----------------|------------------|----------------|
| Radiation    | 1.36            | 7.48\times10^{-2} | 9.07\times10^{4} |
| Support      | 1.53            | 2.65\times10^{-3} | 1.64\times10^{3} |
| Total        | 2.89            | 7.75\times10^{-2} | 2.55\times10^{3} |

\[
q = \frac{C_r (\bar{N})^{5.56} T_e}{N_s + 1} (T_m - T_c) + \frac{C_s \varepsilon_{RT}}{N_s} (T_H^{4.67} - T_e^{4.67}) \quad (1)
\]

Where

\[C_r = 5.39\times10^{-10}\]
\[C_s = 8.95\times10^{-8}\]

\(\bar{N}\) = Radiation shield layer density, layers/cm

\(N_s\) = Number of radiation shields

\(q\) = Heat flux, W/M²

\(T_e\) = Cold boundary temperature, K

\(T_m\) = Warm boundary temperature, K

\(T_c\) = Mean insulation temperature, K

\(\varepsilon_{RT}\) = Room temperature (300K) total hemispherical DAM emittance

\[
Q = FAq \quad (2)
\]

Where

\(A\) = Inner surface area

\(F\) = Degradation factor

4. Conclusion
The 1.8K breakdown voltage measurement system with cryocooler is designed. Innovation point of this design is combining the liquid helium and GM cryocooler, which have the ability to reach the temperature of 1.8K theoretically. A copper pot connecting to the second stage by a heat switch cooled by the cryocooler. The heat switch prevents the heat leak from the cryocooler. The sample holder with high voltage poles is located under the copper pot, the
liquid helium in the pot is pumped to cool down the sample by heat conduction. The maximum voltage is 60kV and the cooling time is 10 minutes. The test system is under constructing and the result curve will be published in the future.

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