R&D of 19 kV class splicing device to connect high-voltage instrumentation wires and cable

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Research Article

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Abstract

As transition connection in ITER machine, a large number of splicing devices (SDs) will be developed to connect the high voltage (HV) signal wires from different types of sensors installed in the superconducting magnet system to the HV cables connected with the feedthroughs installed in the cryostat wall. The structural design of 19 kV class SD aims at avoiding the electromagnetic interference and obtaining enough dielectric strength under high vacuum and cryogenic temperature environment. To avoid Paschen discharge under low vacuum, much attention is paid on the helium tightness of 19 kV class SD. To investigate the influence of the void in epoxy resin on the insulating performance of SD, the electric field analysis based on finite element technology is performed, the results indicate the peak electric field is much higher than the finite element model without void, which indicates that the void can lead to charge accumulation near metal electrode and electrical breakdown of insulating materials. Further tests indicate the insulating rod manufactured by using glass fiber wet winding under vacuum environment can reduce void in epoxy resin less than 2%, and the cryogenic electrical insulating performance of 19 kV class SD satisfy the technical specifications.

1. Introduction

Different from the existing commercial products, the 19 kV class SD to connect HV instrumentation wires and cable will be used under high vacuum, cryogenic temperature, strong magnetic field and radiation environ- ment, in addition, the SDs will be assembled on-site, so the material selection and structural design is a huge challenge [1–3]. To manufacture easily and assemble conveniently, the modular structure is used to develop the 19 kV class SD.

2. Structural Design

2.1. Description

The 19 kV class SD is fabricated in room temperature environment, but it works at cryogenic temperature, the difference of thermal expansion coefficient of chosen materials can lead to huge stress concentration and failure [4]. The conventional insulating materials don't withstand cryogenic temperature, so toughened bisphenol A epoxy resin is used as adhesives, and R glass fiber is used as reinforced material. According to Lichtenecker's mixing rule, the relative dielectric constant of uniform distributed composite material can be determined by the volume ratio of each component [5], as shown in formula (1).

$$In\varepsilon = \sum_i V_i In\varepsilon_i \qquad (1)$$

where, V_i is volume fraction of i component, ε_i is relative dielectric constant of i component.

For glass fiber reinforced epoxy resin composite, which mainly consists of epoxy resin system, glass fiber and void.

2.2. Structural design

The technical requirements and section view of 19 kV class SD are as shown in Fig. 1 and Table.1 respectively, which includes several metal discs (2, 3, 5, 10) used to connect different ground shields and different HV shields. The HV cable is stripped to expose the outer metal braid to connect with the ground shield of SD [6], and the exposed inner metal braid is connected with HV shield of SD, then the exposed metal conductor cores are welded with single core signal wires and fixed into the insulating structural part.

For the 19 kV class SD to connect high voltage instrumentation wires and cable for ITER, adhesive plays an important role in resisting crack propagation at cryogenic temperature, therefore, toughened bisphenol A epoxy resin was used to fabricate insulating material [7]. R glass fiber reinforced bisphenol A epoxy resin composite is used to fabricate the insulating structural parts such as central insulator rods 1&2, insulation cartridge and so on. To realize helium tightness and avoid dielectric breakdown, the HV shield made of stainless steel and insulation cartridge made from R glass fiber and bisphenol A epoxy resin system is an integrated part, there is no gap between them [8]. As a result, the HV shield is helium tightness, and high voltage has no influence on the instrumentation wires and cable.

Table 1
Technical requirements of the prototype 19 kV class splicing device

Item	Requirement	Note
Operating temperature	From 4 to 440 K	-
Vacuum	10^{-4} Pa	-
Max. magnetic field	5T	-
Out-gassing rate	< 1 x 10^{-9} Pa m^3 s^{-1} m^{-1}	20°C after 100 h vacuum
Continuous dielectric insulation	Low porosity	To ensure the galvanic separation under Paschen conditions of helium gas around
Materials	Halogen free	All used materials must be halogen-free.
Integrated radiation gamma dose	1 MGy $2\times10^{19}/m^2$	Total integrated dose in 20 years
Test voltage	19 kV DC / 10kV AC Max. 1 min (AC), 10 min (DC)	Σ individual wires Vs. Ground Shield

3. Insulation Material

3.1. Toughened epoxy resin

Figure 2 is the test specimens of toughened bisphenol A epoxy resin, which are made from bisphenol-A epoxy resin, Qishi toughening agent, silane-coupling agents (KH-560) and aromatic condensation amine (GY-051). To decide the resisting crack propagation performance at cryogenic temperature, 50 thermal cycling tests were performed for the 6 test specimens. The temperature range of the thermal cycling tests is from temperature of liquid nitrogen (77 K) to room temperature (~ 298 K). The test specimens marked with 2 were undergone baking at 120°C for 240 hours after thermal cycling tests [9]. The thermal cycling tests process is as follows.

3.2. Micro-structure of toughened epoxy resin

All the test specimens were put into a cryostat, then liquid nitrogen was injected into the cryostat and the test specimens was submerged in liquid nitrogen. When the liquid nitrogen in cryostat was missing because of heat absorption, the test specimens was gradually warmed up to room temperature, which is called one thermal cycling test, after another 49 thermal cycling tests have been done, the thermal cycling tests is completed. As shown in Fig. 3, it is micro-structure of test specimens of toughened bisphenol A epoxy resin system after 50 thermal cycling tests, it is clearly that the toughening agent (spheric structure) is uniform distribution.

Because humidity can weaken the insulating performance of the 19 kV class SD, baking tests of toughened bisphenol A epoxy resin is performed to simulate the actual working condition. Figure 2 indicates the color of test specimens marked with 2 is darker than the color of test specimens marked with 1, the reason is that silane-coupling agents and toughening agent migration at banking temperature (120℃) is more easier than at room temperature. As shown in Fig. 4, the toughening agent (spheric structure) distribution has no significant change. In the curing system, the toughening agent (spheric structure) is elasticity, which can absorb the thermal stress during cooling down of the 19 kV class SD. Consequently, the silane-coupling agents migration is the main reason, and the micro-structure of curing system is stable after baking.

3.3. Electrical performance of toughened epoxy resin

The electrical insulation performance is very important for SD, so high voltage tests were carried out after baking. The thickness of test specimen marked with 2 for high voltage test is 1 mm, which was performed in electric insulating oil, as shown in Fig. 5.

Because the direction of applied voltage on 19 kV class SD is unchanged, the high voltage-leakage current (HV-LC) curve of the baked test specimen is as shown in Fig. 6. It can be seen that the baked test specimen is not electrical breakdown when the applied voltage up to 70 kA, which corresponds to the leakage current 0.008 mA. Therefore, the electrical performance of toughened epoxy resin after high temperature baking is significant. In glass fiber reinforced epoxy resin composite, bisphenol A epoxy resin and glass fiber were connected by silane-coupling agent. The silane- coupling agents migration in glass fiber reinforced epoxy resin composite is remarkable lower than in toughened bisphenol A epoxy resin curing system.

4. Electric Field Analysis

Due to symmetry, 2-D model of 19 kV class SD was established by using 8-node plane element Plane121 [10], as shown in Fig. 7. To reveal the influence of micro defects on the electric field distribution, a 2-D model with some voids is established, as shown in Fig. 8.

For 19 kV class SD, G10 and R glass fiber reinforced bisphenol A epoxy resin composite are chosen as insulating structural materials and stainless steel 316L is chosen as metal structural material, the properties of the materials for electric field analysis are as shown in Table.2.

The voltage applied on HV wires and HV shield is 19 kV DC, and the voltage applied on ground shield is 0 V. The outer lines of vacuum medium is infinite boundary conditions. The defined paths A-H and A'-E' are as shown in Fig. 8, the electrical field strength on defined paths are as shown in Figs. 9–12.

Table 2
Properties of the materials

Material	Relative permittivity	Dielectric strength [kV/mm]
G10	4.5 [1]	16 [3]
GFRP	5.5 [2]	15.4 [3]
Epoxy resin	3 [2]	19.7 [3]
Alumina	9.6 [1]	13–14 [3]
Vacuum	1 [1]	-
Talcum	4.7[3]	25[3]
Polyimide	3.4 [4]	154 [4]

[1*] ANSYS Maxwell 2015- Material library
[2*] D. Tomasini-Dielectric insulation and High Voltage issues, CAS, Bruges, June 2009
[3*] W. Shugg-Handbook of Electrical and Electronic Materials, New York, 1996
[4*] Summary of Properties for Kapton® Polyimide Films.

If there are voids on the interface between metal structural parts and insulating structural parts, the analysis results indicate the peak electrical field strength is 20.4 kV/mm, which can lead to partial discharge and breakdown. Therefore, it is necessary to reduce the void content in glass fiber reinforced epoxy resin composite by using manufacturing process under vacuum, and the void content can be controlled under 1% [11].

5. Experiments

5.1. Sample

The obtain expected dielectric property under cryogenic temperature, bisphenol A epoxy resin is modified by adding liquid hardener (M-phenyldimethylamine) and alumina particles. In the modified bisphenol A epoxy resin system, alumina is used as filler. The diameters of filler used were 50 um, and the mass content of filler are 10% and 20%. After de-gassing had been done under vacuum for an hour, the modified bisphenol A epoxy resin system is cured under 100°C for 120 minutes. then, the bisphenol A epoxy resin is cooled to room temperature under natural conditions.

5.2. Experimental method

The experimental method of permittivity was according to ASTM-D150 [12], the dimension of the sample is manufactured to the dimension of 10*5*2 mm, as shown in Fig. 13, the insulating sample is bonded with two metal electrodes, the distance between the two metal electrodes is 2 mm. It was observed by a microscope that there is no voids or cracks around the electrodes, the sample is tested by GLMSTD-A dielectric constant tester and the test is performed in the solid state institute of Chinese Academy of Sciences.

5.3. Experimental result

The permittivity of insulation material is calculated by formula (2).

$$\varepsilon_r = \frac{C \cdot d}{\varepsilon_0 \cdot S} = \frac{10^{12} \cdot C \cdot d}{8.854 \cdot S} = 1.175 * 10^{11} \frac{C \cdot d}{S} \quad (2)$$

The dimension of the samples are listed in Table.3

5.4. Electrical performance tests

The manufacturing process of glass fiber reinforced bisphenol A epoxy resin composite was finished under vacuum to reduce void defect, and the electrical performance is tested by high voltage generator in the Institute of Plasma Physics, Chinese Academy of Science. 50 thermal cycling tests between room temperature and liquid nitrogen temperature are performed for the 19 kV class SD [13], as shown in Fig. 14.

After the thermal cycling tests had been done, the leakage current test is performed with high voltage generator made by Shanghai Juter, the DC voltage is set at 10 kV, 13 kV, 16 kV, and maintained for 1 minute, then it raised to 19 kV and maintained for 3 minutes, the peak leakage current is below 1μA, as shown in Fig. 15.

Partial discharge test is performed with pulse current method [14], as shown in Fig. 16. The voltage is set at 5 kV AC and maintained for 5 minutes, the discharge quantity is less than 100 pC, which indicate that the electrical property of the 19 kV class SD is in good condition after thermal cycles, as shown in Fig. 17.

Paschen tests is performed between wires and ground insulation in helium gas with 99.99% purity to analyze the quality of insulation of ITER HV SD to extend the research on Paschen's law under various conditions [15]. the DC voltage is firstly gradually increased to 19 kV and maintained for 5 minute. The test pressure was 1 Pa, 10 Pa, 100 Pa, 1 kPa, 10 kPa and 50 kPa, and the peak leakage current is less than 10 μA, as shown in Fig. 18.

6. Summary

A. Because the defect in epoxy resin can lead to charge accumulation in the void or crack, and peak electrical field strength in the defect is much higher than the sample without void, therefore, decreasing of the micro defects of GFRP is very necessary. Manufacturing process shall be maintained under vacuum so as to reduce void content.

B. Experimental study is performed to test the permittivity of modified epoxy resin, and the results shown that epoxy resin system with 20% alumina filler could match the insulation of cable better, which can decrease the distortion of electrical field of the interface.

C. High voltage and Paschen discharge tests indicate the dielectric strength of 19 kV class SD can meet the working requirements, which prove that the manufacturing process under vacuum is effective.

Declarations

Acknowledgment

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Figures

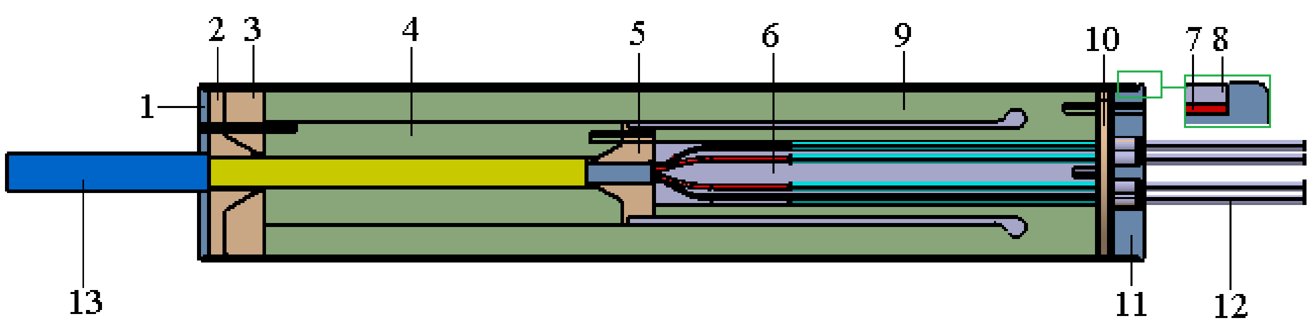

Figure 1

Section view of 19 kV class SD

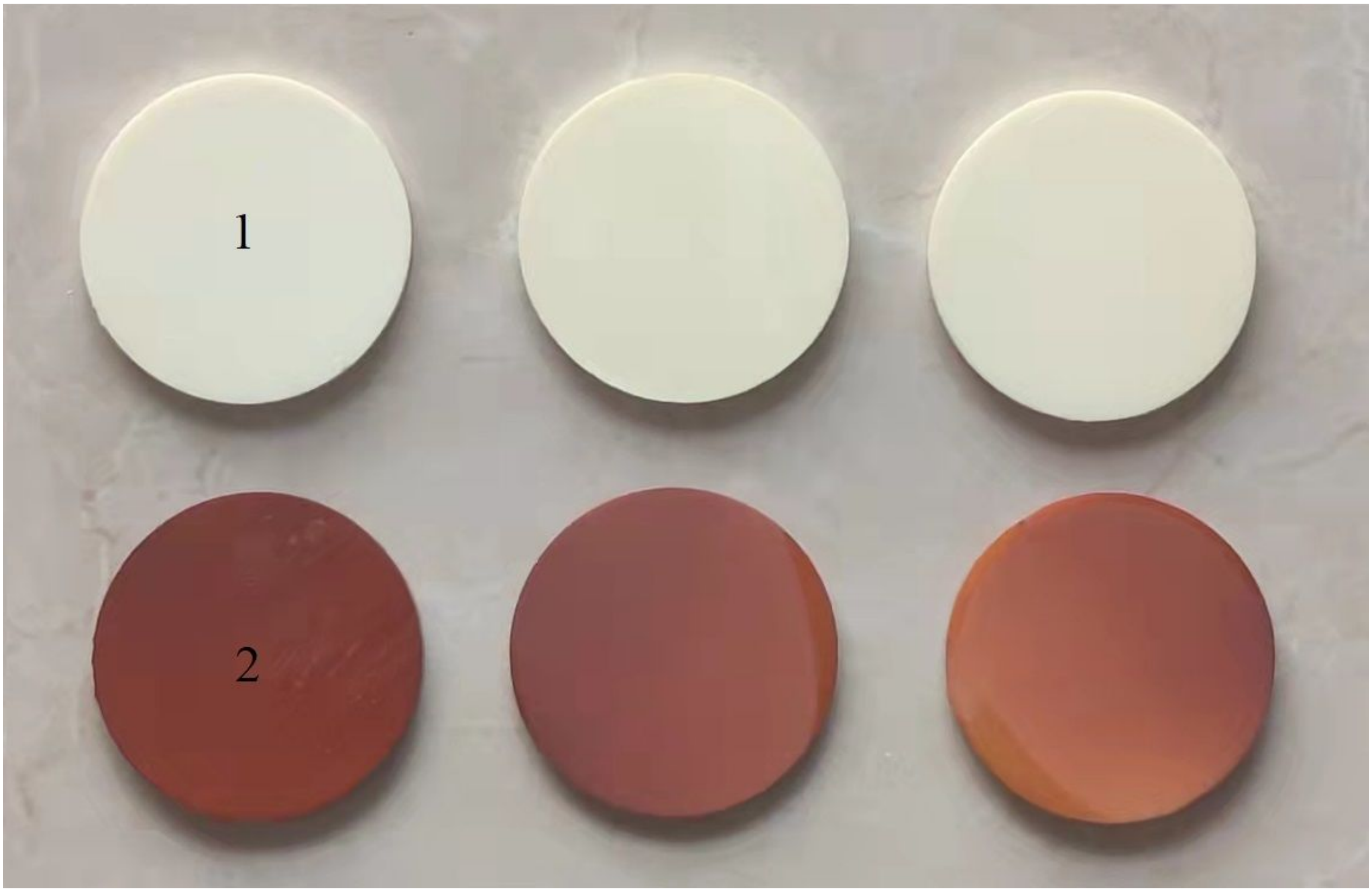

Figure 2

Test specimens of toughened bisphenol A epoxy resin system

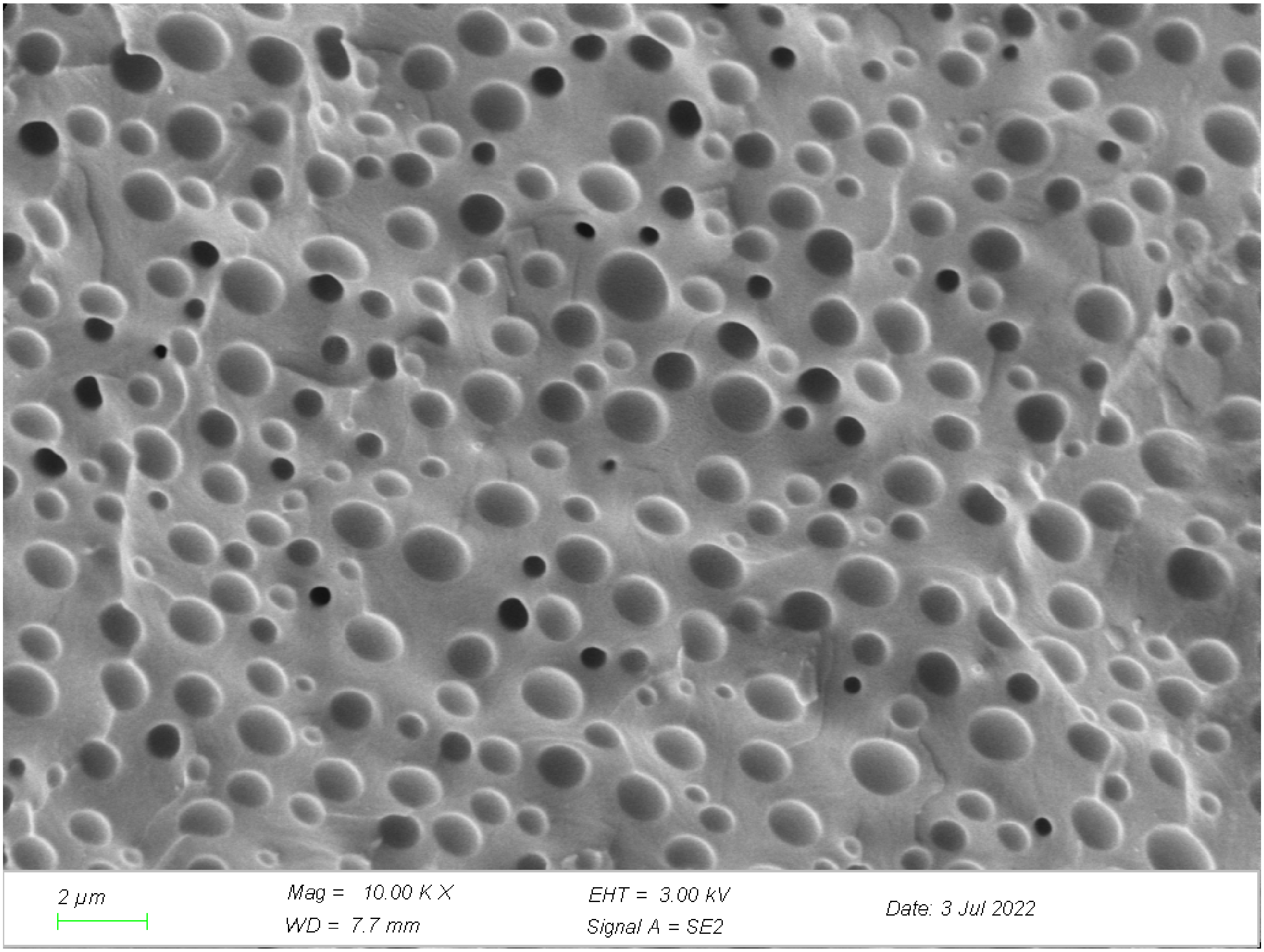

Figure 3

Micro-structure of test specimen of toughened bisphenol A epoxy resin system after 50 thermal cycling tests

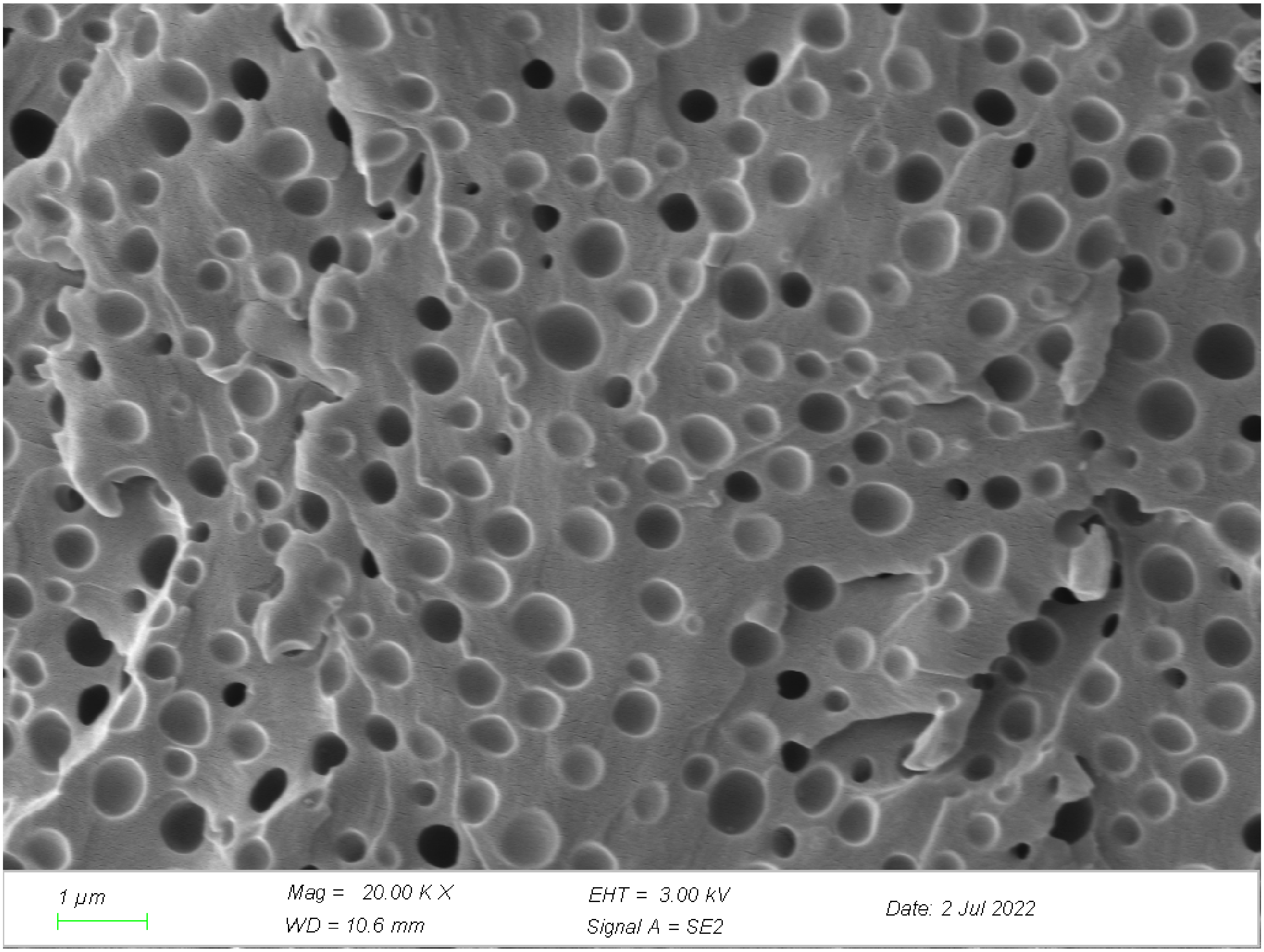

Figure 4

Micro-structure of test specimen of toughened bisphenol A epoxy resin system after 25 thermal cycling tests + baking

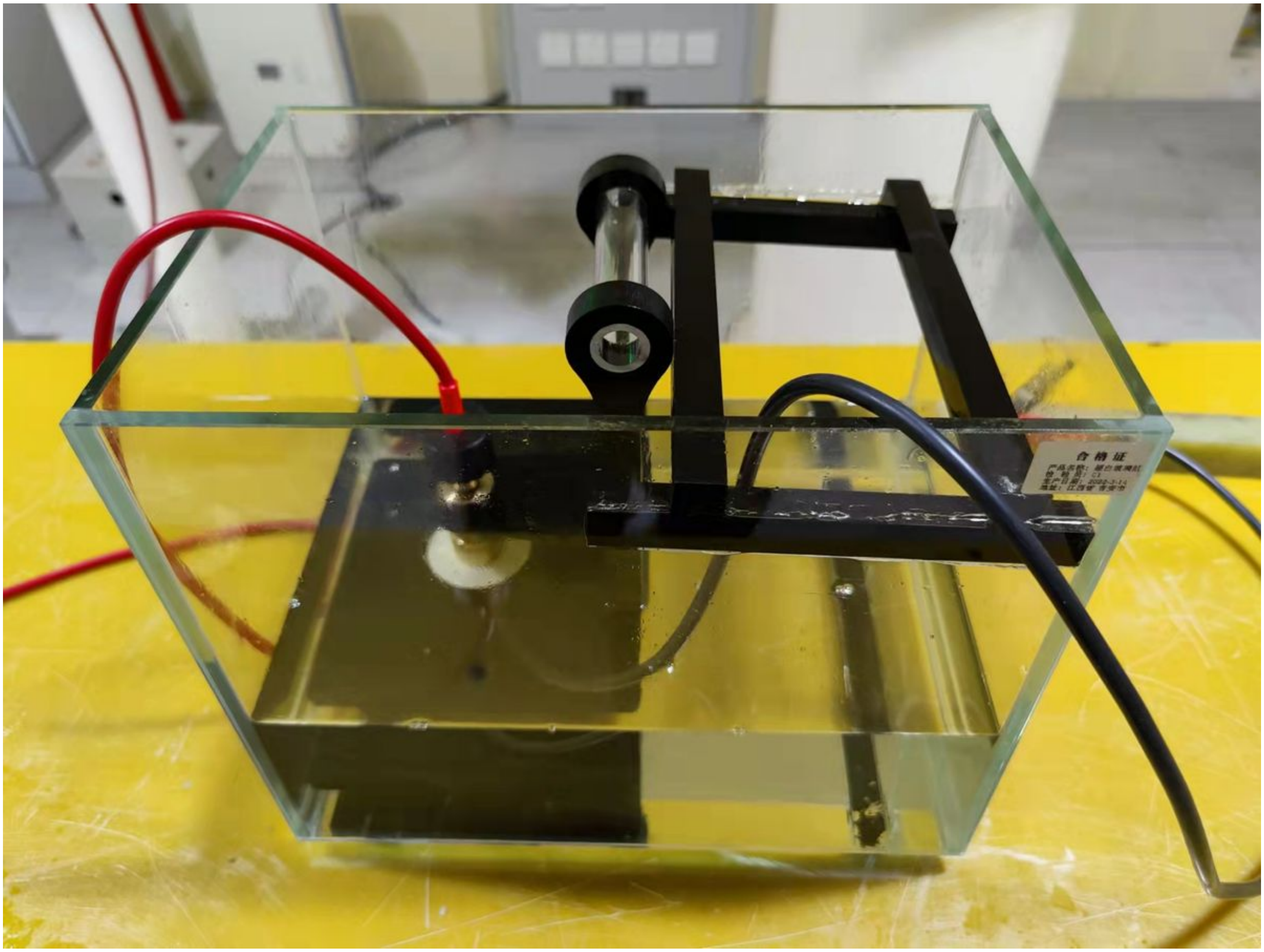

Figure 5

HV-leakage current tests device

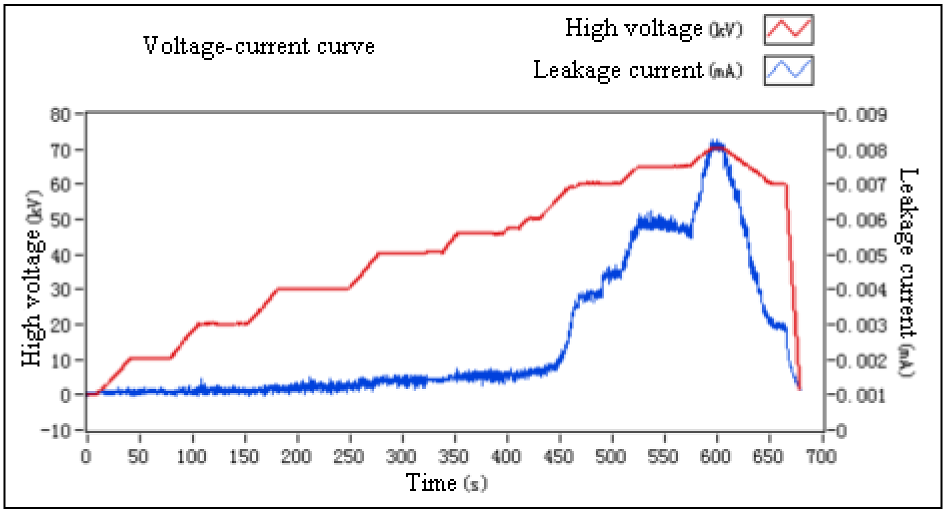

Figure 6

HV-LC curve

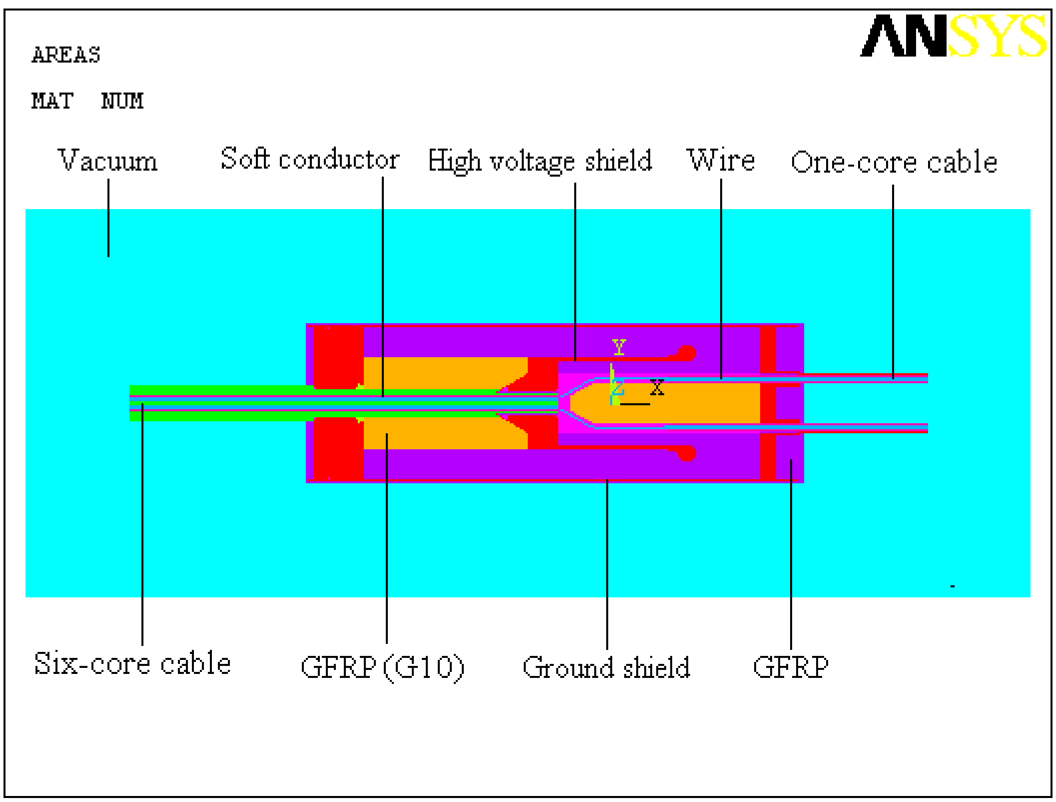

Figure 7

2-D model of 19 kV class SD

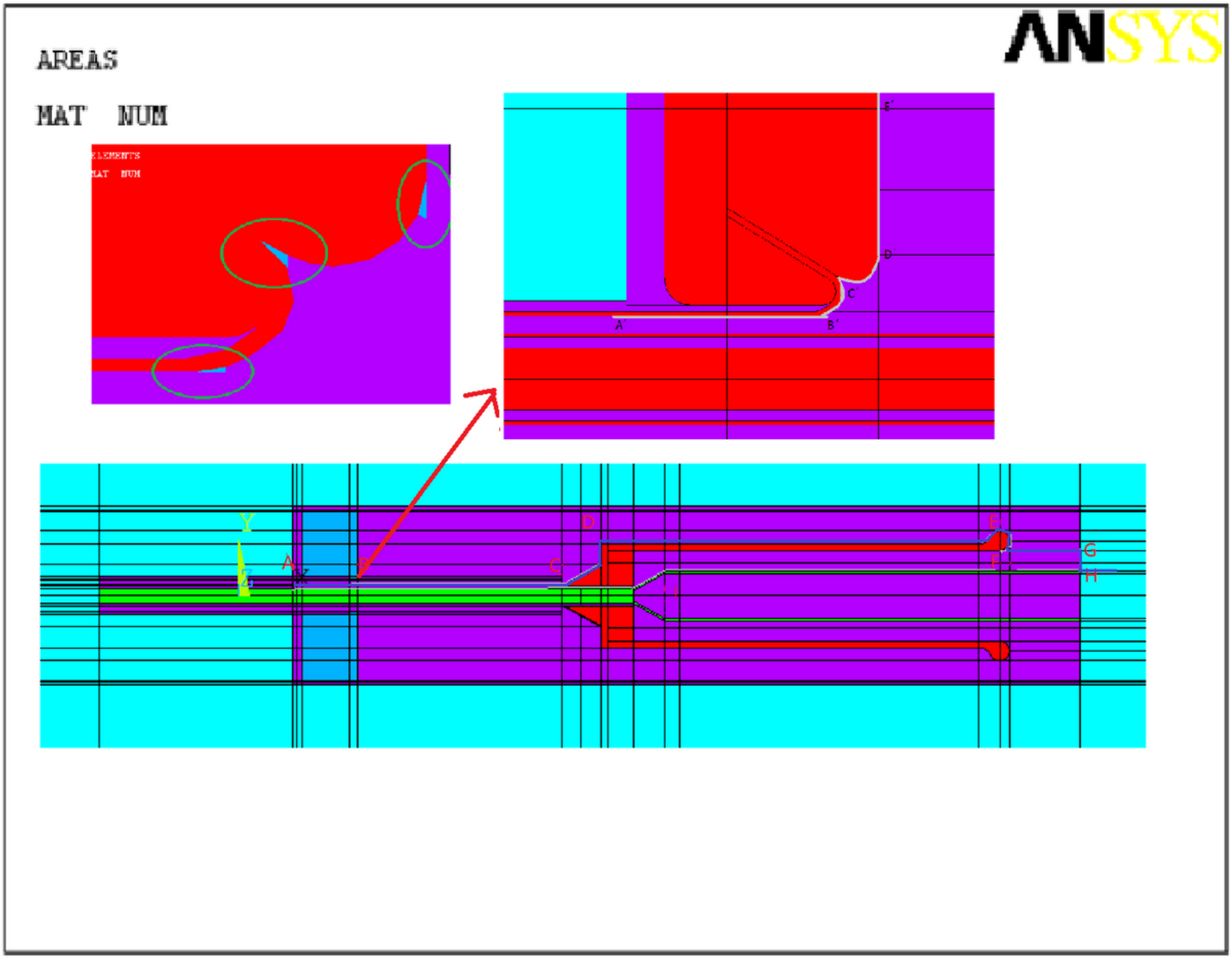

Figure 8

2-D model of 19 kV class SD with defects

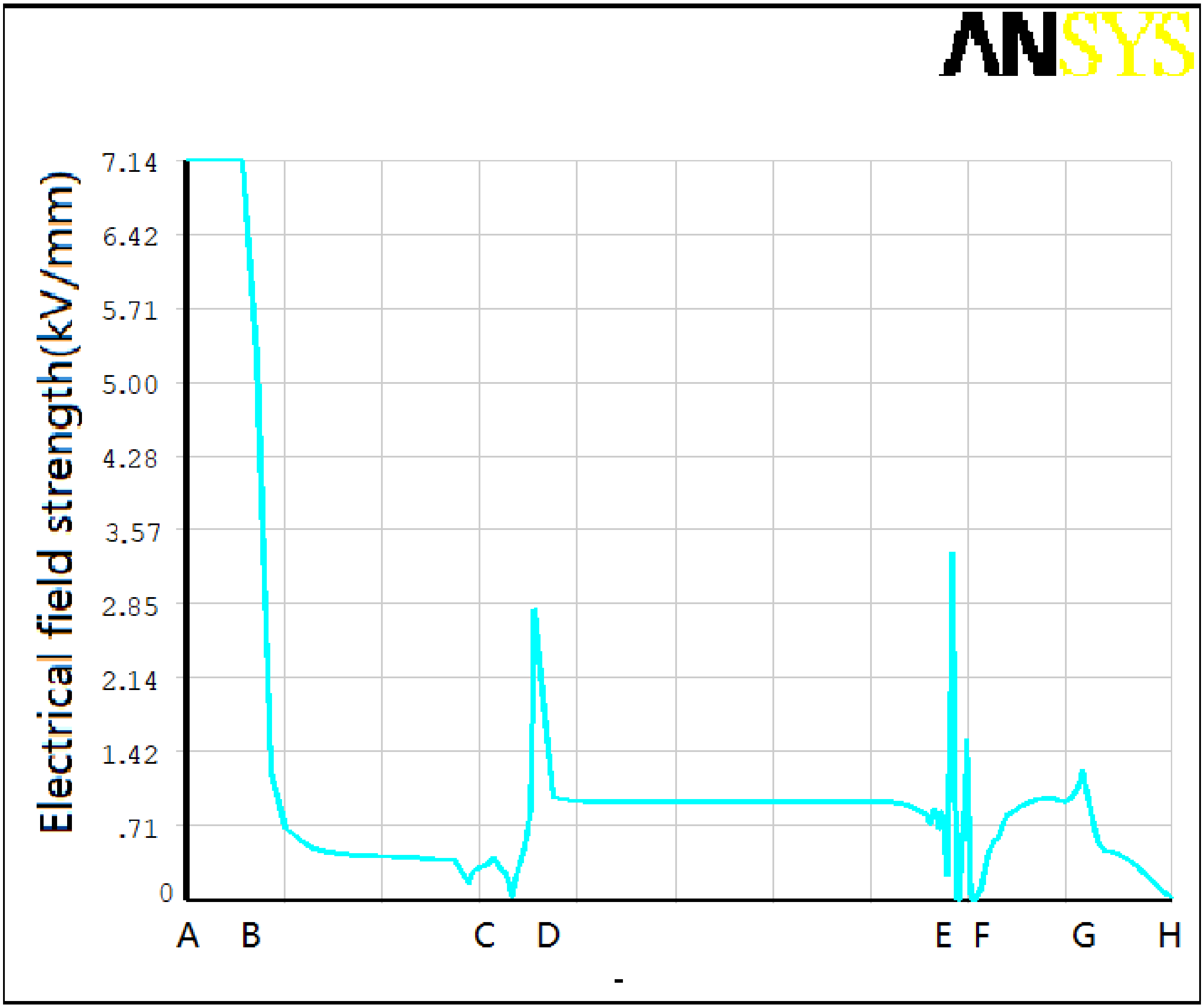

Figure 9

Electrical field strength on path A-H (without void)

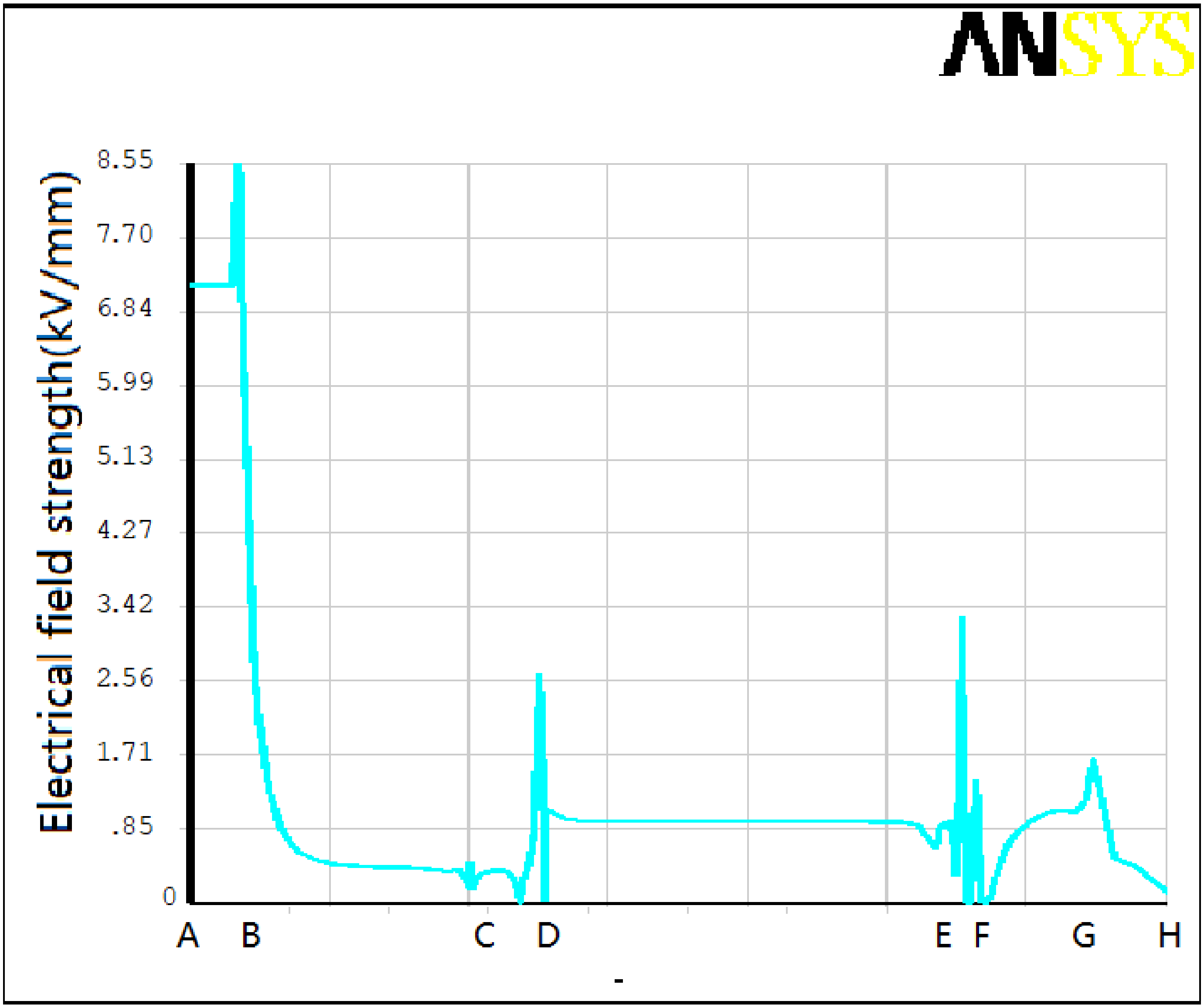

Figure 10

Electrical field strength on path A-H (with voids)

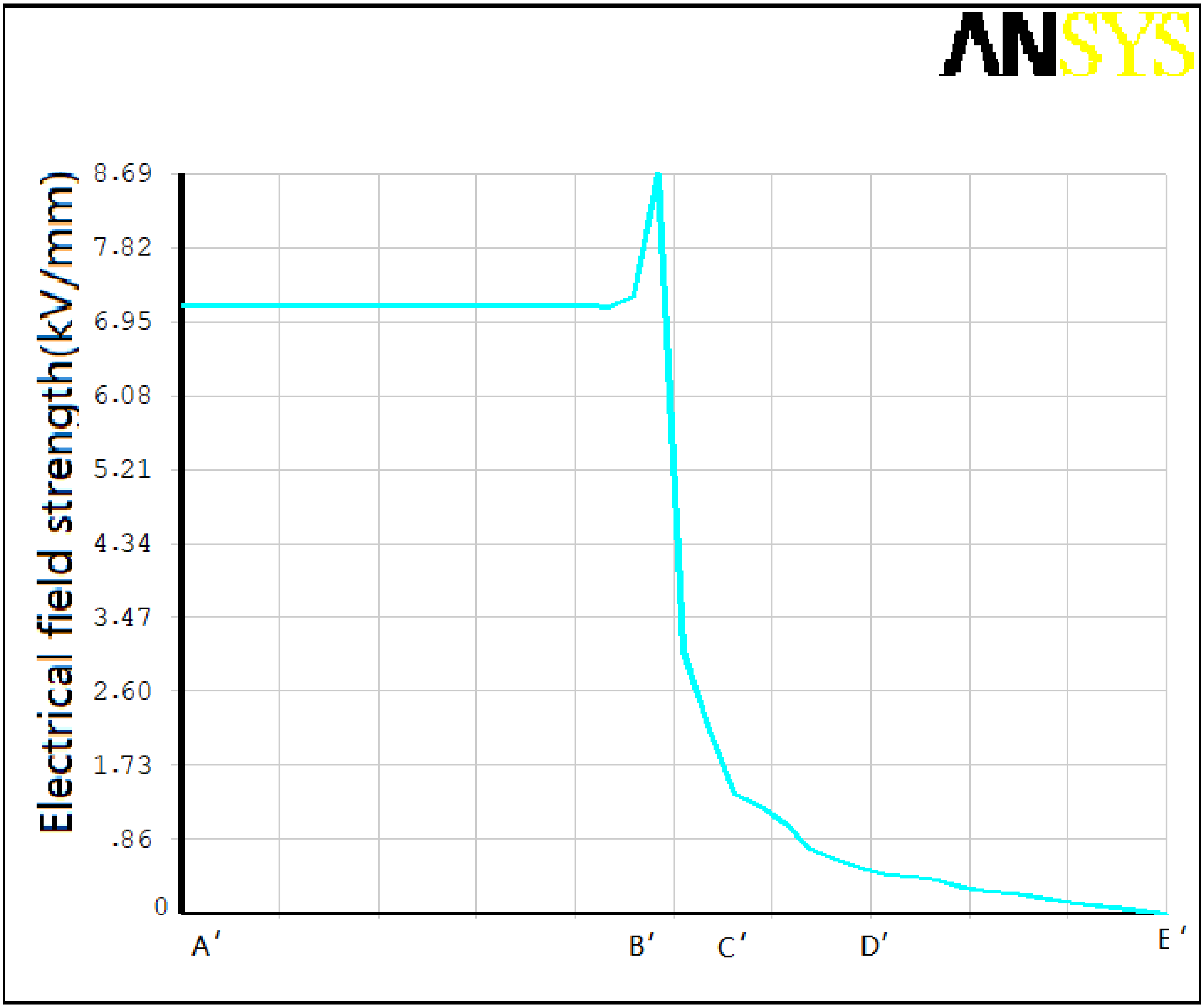

Figure 11

Electrical field strength on path A'-E' (without void)

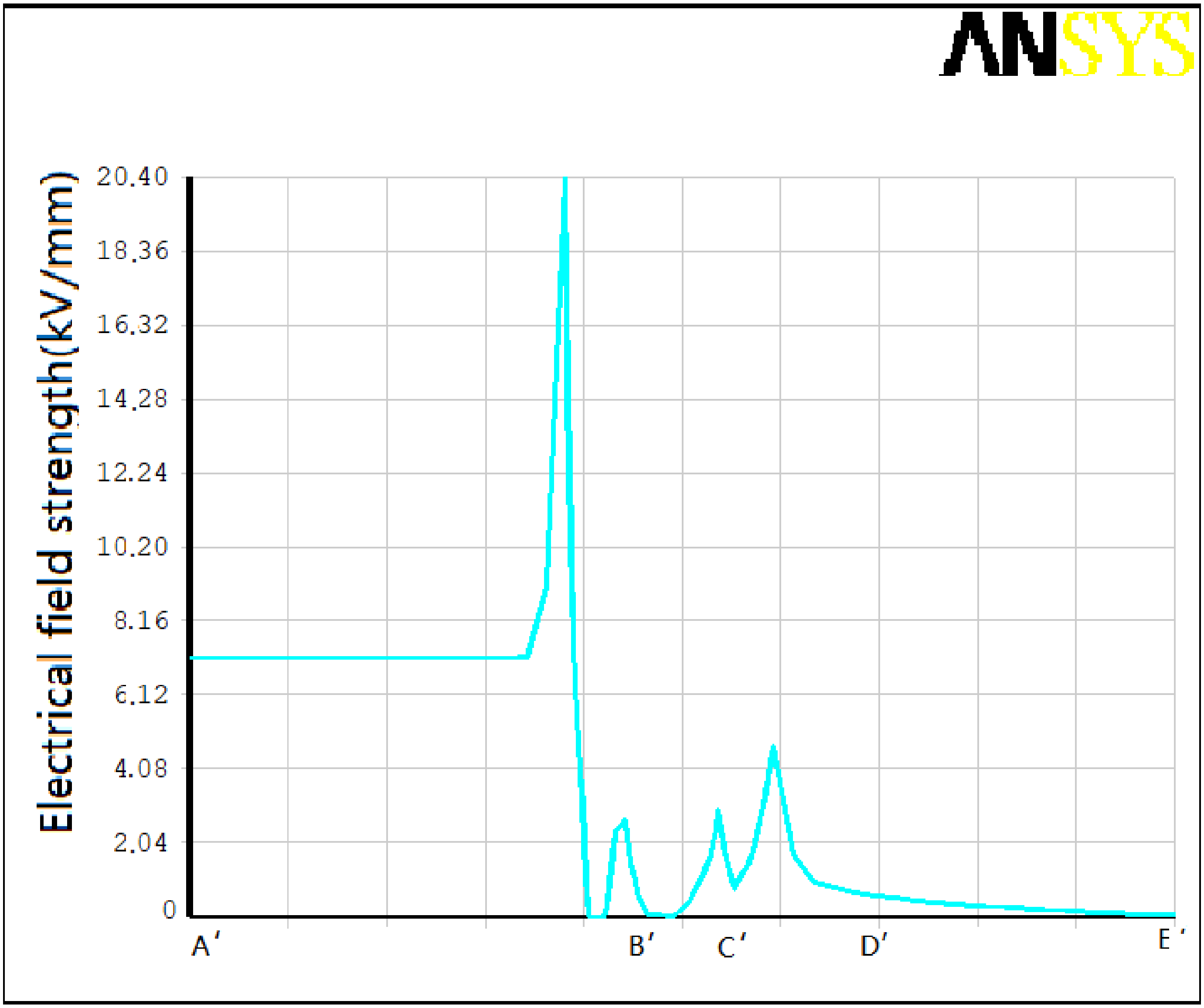

Figure 12

Electrical field strength on path A’-E’ (with voids)

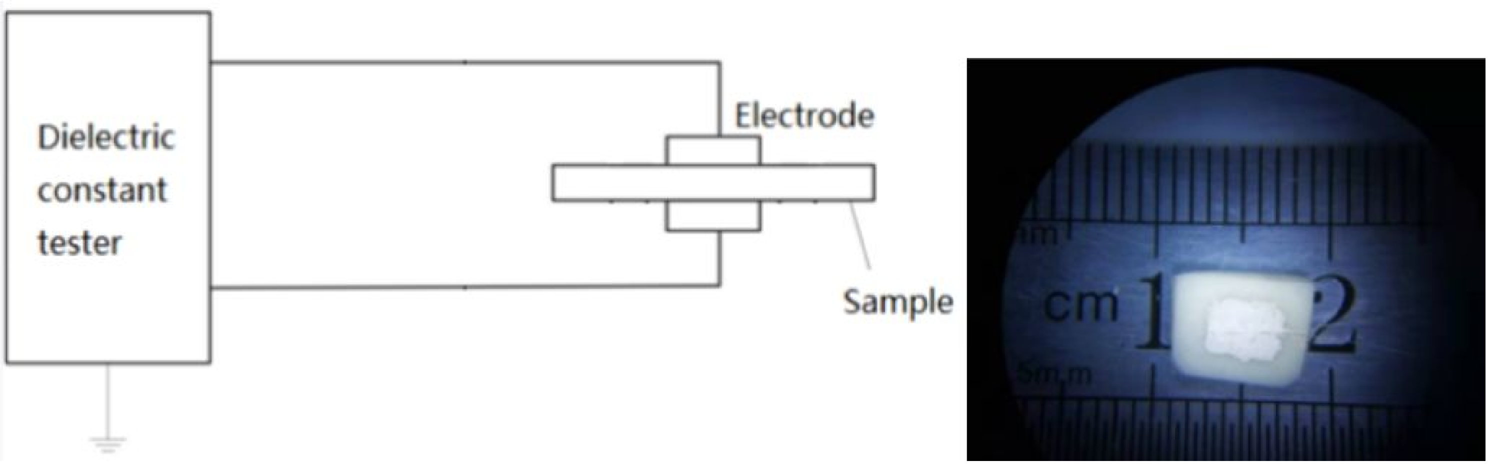

Figure 13

Wiring of permittivity experiment

Figure 14

Thermal cycle test of the splicing device

Voltage (kV)	Current (mA)	Time (S)	
10.00	0.000000	10	OK
13.00	0.000230	10	OK
16.00	0.000180	10	OK
19.00	0.000345	60	OK

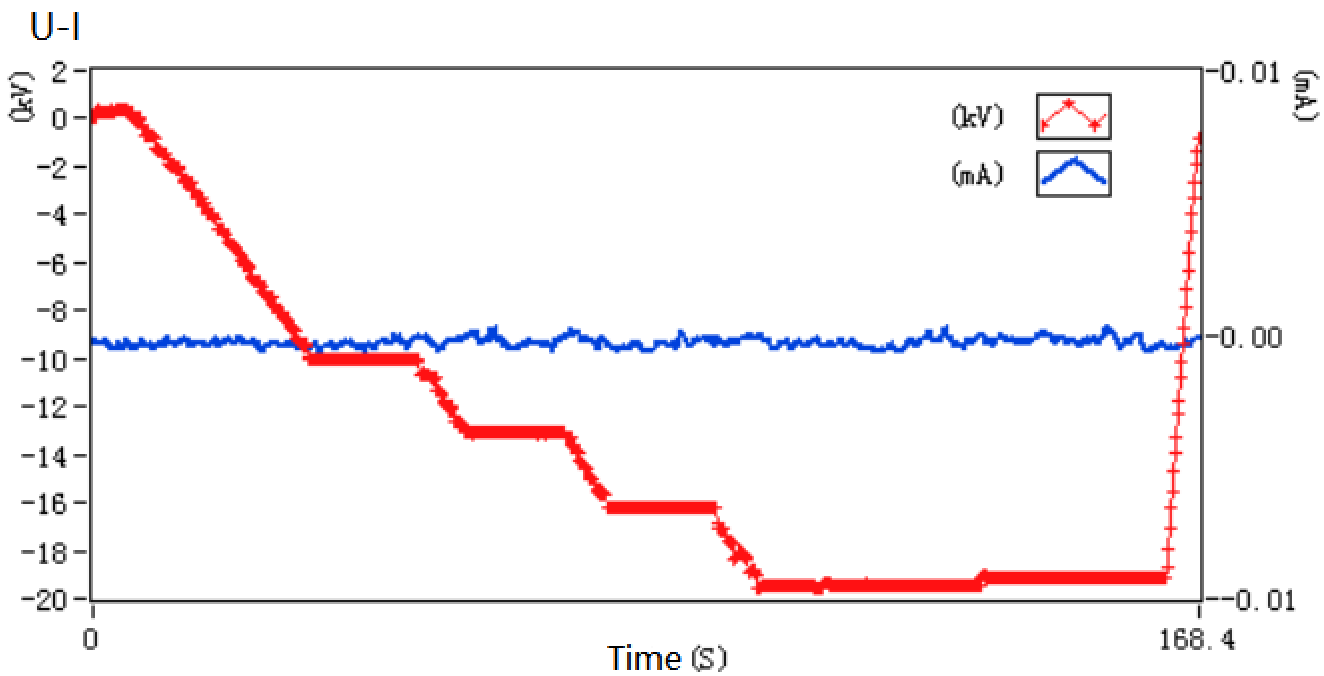

Figure 15

High voltage test(19 kV DC)

Figure 16

Paschen discharge test

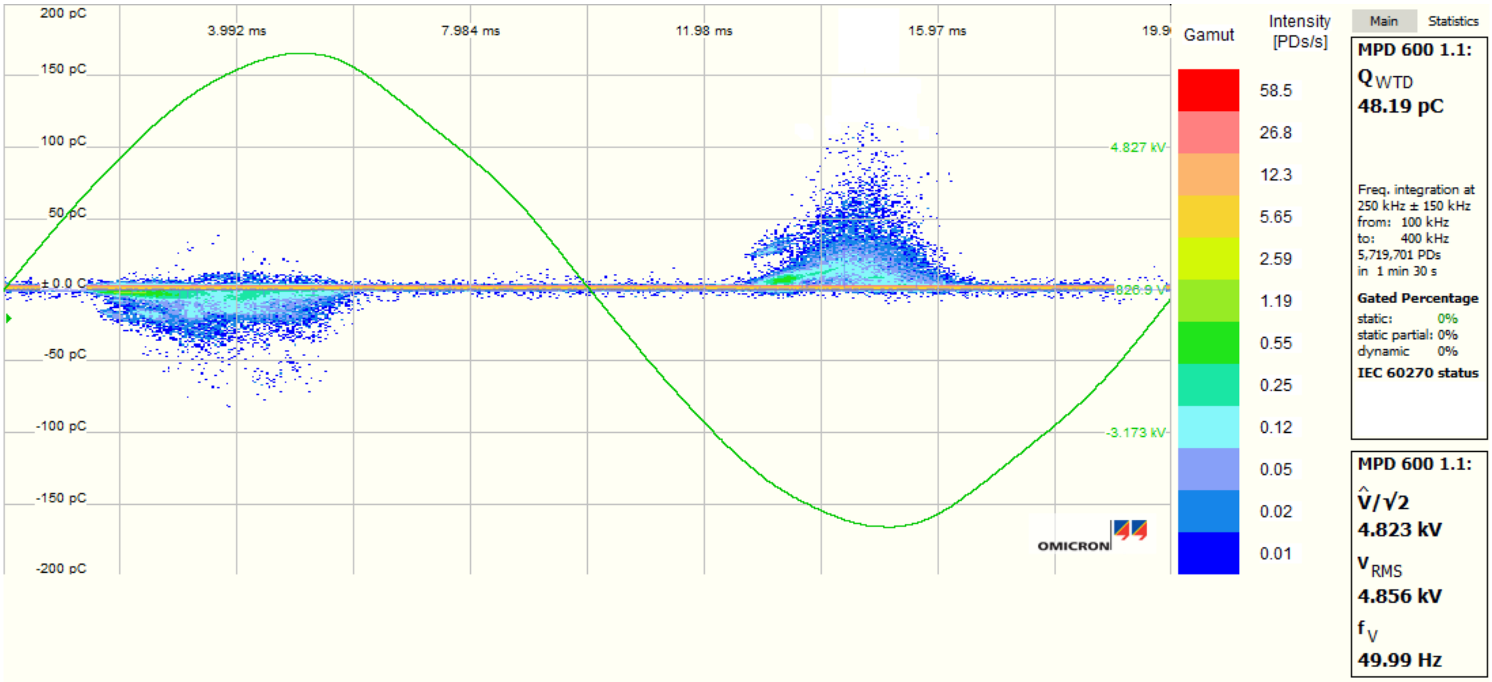

Figure 17

Paschen discharge test

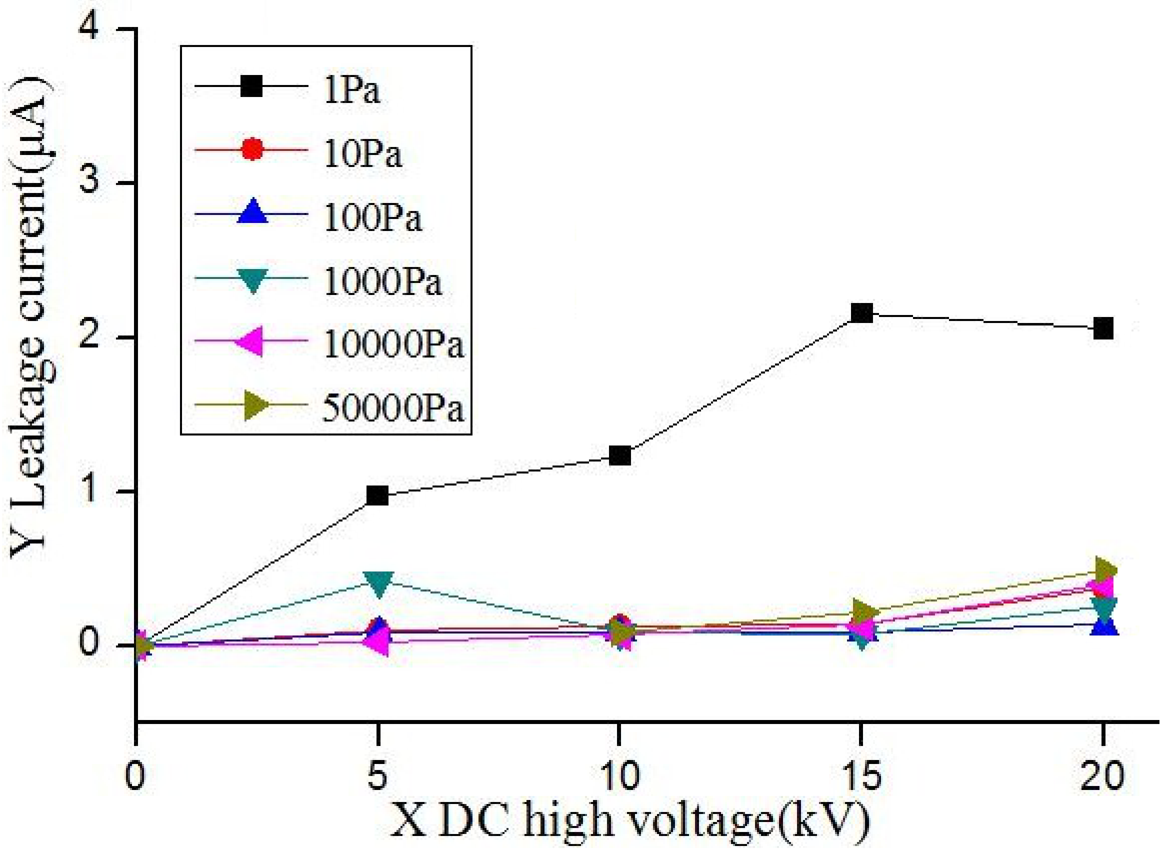

Figure 18

Paschen discharge test results