Abstract

High voltage insulation breaks are used in cryogenic lines with gas or liquid (helium, hydrogen, nitrogen, etc.) at a temperature range of 4.2-300 K and pressure up to 30 MPa to insulate the parts of an electrophysical facility with different electrical potentials. In 2013 JSC “NIIEFA” delivered 95 high voltage insulation breaks to the IO ITER, i.e. 65 breaks with spiral channels and 30 breaks with uniflow channels. These high voltage insulation breaks were designed, manufactured and tested in accordance with the ITER Technical Specifications: «Axial Insulating Breaks for the Qualification Phase of ITER Coils and Feeders». The high voltage insulation breaks consist of the glass-reinforced plastic cylinder equipped with channels for cryoagent and stainless steel end fittings. The operating voltage is 30 kV for the breaks with spiral channels (30 kV HV IBs) and 4 kV for the breaks with uniflow channels (4 kV HV IBs). The main design feature of the 30 kV HV IBs is the spiral channels instead of a linear one. This approach has enabled us to increase the breakdown voltage and decrease the overall dimensions of the high voltage insulation breaks. In 2013 the manufacturing technique was developed to produce the high voltage insulation breaks with the spiral and uniflow channels that made it possible to proceed to serial production. To provide the acceptance tests of the breaks a special test facility was prepared. The helium tightness test at 10^{-11} m^{3}Paw/s under the pressure up to 10 MPa, the high voltage test up to 135 kV and different types of mechanical tests were carried out at the room and liquid nitrogen temperatures.

Keywords: ITER; high voltage; insulation breaks
1. Introduction

ITER is a joint international research and development project that aims to demonstrate the scientific and technical feasibility of fusion power. The ITER Parties are the European Union, Japan, the People’s Republic of China, India, the Republic of Korea, the Russian Federation and the USA. ITER is now under construction in Europe, at Cadarache in the South of France.

High voltage insulation breaks (HV IBs) are required to electrically insulate the cryogenic distribution system from the high voltage windings of the ITER magnets and busbars. Insulation is necessary since the superconducting cable is located in the metal pipe which is connected to the cooling circuit with supercritical helium. In total 1400 HV IBs are required (including spares and test units) for operation at 4.5K [1].

There is no industrial production of the cryogenic HV IBs at the present time. In this connection manufacturing of the equipment with the HV IBs may require:
- simulation of HV IBs and their components;
- full-scale prototype manufacturing and integrated mechanical and hydraulic strength testing at room and cryogenic temperatures;
- thermal cycling, leak tightness and HV testing at room and cryogenic temperatures.

In 2013, the Joint Stock Company “D.V. Efremov Institute of Electrophysical Apparatus” (JSC “NIIEFA”) delivered 95 HV IBs to the IO ITER. The HV IBs were designed, manufactured and tested according to the ITER Technical Specifications: «Axial Insulating Breaks for the Qualification Phase of ITER Coils and Feeders» [2]. This specification applies to the HV IBs required to fulfill the needs during the qualification phase of the different Procurement Arrangements on coils and feeders.

The HV IBs were designed and manufactured to operate at 4.5 K, in a radiation environment and a magnetic field. Subsequently, the HV IBs have to withstand the operational and worst case voltages, pressures and mechanical loads that may occur. The insulator length shall be sufficient to prevent electrical breakdown between two steel tubes through the fluid or gas.

The HV IBs consist essentially of a length of composite insulating tube bonded at each end to stainless steel fittings. The length of the insulating tube shall be sufficient to prevent electrical breakdown through the fluid or gas between two steel tubes with the high voltages that may be achieved in a ‘fault condition’ during machine operation. The HV IBs are typically placed at the cryogenic inlet and outlet points to the coils and welded into the main cryogenic lines with full penetration butt welds using an orbital welder.

The following number of HV IBs was produced:
- sixty-five (65) units designed to operate at a temperature of 4.5 K and 30 kV galvanic separation capability in dry air (30 kV HV IBs);
- thirty (30) units designed to operate at a temperature of 4.5 K and 4 kV galvanic separation capability in dry air (4 kV HV IBs).

A quality assurance programme was prepared and applied to the produced units.

2. Technical requirements

In general the requirements to the cryogenic HV IBs are as follows:
- low hydraulic resistance (minimum pressure drop of circulating cryoagent);
- high leak tightness (no penetration of cryoagent into the vacuum volume);
- mechanical strength (resistance to mechanical, thermal, electromagnetic and other loads);
- for superconducting coils – the ability to withstand high pressure of cryoagent occurring when the coil goes into a normal state during warming-up;
• thermal cycling resistance (the ability to be cooled down and warmed up many times during operation).

The technical requirements according to the technical specifications «Axial Insulating Breaks for the Qualification Phase of ITER Coils and Feeders» are listed in Tables 1 – 3.

Fatigue resistance under 60000 cycles at 50% of the load on axial direction in tension and compression, torsion and bending. The safety factor for this number of cycles is 2.

Table 1. Geometry parameters and Voltage withstand levels.

<table>
<thead>
<tr>
<th>IB type</th>
<th>Inner diameter (mm)</th>
<th>Outer diameter (mm)</th>
<th>Rated value (DC, kV)</th>
<th>Routine test value (DC, kV)</th>
<th>Design value (test value) (DC, kV)</th>
</tr>
</thead>
<tbody>
<tr>
<td>30 kV IB</td>
<td>17.3</td>
<td>21.3</td>
<td>30</td>
<td>35</td>
<td>56</td>
</tr>
<tr>
<td>4 kV IB</td>
<td>13.8</td>
<td>17.1</td>
<td>4</td>
<td>5</td>
<td>8</td>
</tr>
</tbody>
</table>

Table 2. Pressure and leak tightness.

<table>
<thead>
<tr>
<th>IB type</th>
<th>Pressure (bar)</th>
<th>Leak rate (Pam³/s)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Rated</td>
<td>Design and test</td>
</tr>
<tr>
<td></td>
<td>Rated</td>
<td>Design and test</td>
</tr>
<tr>
<td>30 kV IB</td>
<td>30</td>
<td>39</td>
</tr>
<tr>
<td>4 kV IB</td>
<td>15</td>
<td>19.5</td>
</tr>
</tbody>
</table>

Table 3. Mechanical requirements.

<table>
<thead>
<tr>
<th>IB type</th>
<th>Traction and compression (kN)</th>
<th>Bending moment (Nm)</th>
<th>Torsion (Nm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>30 kV IB</td>
<td>2</td>
<td>100</td>
<td>15</td>
</tr>
<tr>
<td>4 kV IB</td>
<td>1</td>
<td>100</td>
<td>10</td>
</tr>
</tbody>
</table>

3. Manufacture

JSC “NIIEFA” specialists together with “GERO” Ltd and JSC «Shipbuilding & Shiprepair Technology Center» (JSC “SSTC”) have developed, manufactured and tested the HV electrical insulating devices for various superconducting magnet systems, which comprise the cryogenic HV IBs.

JSC “NIIEFA” developed the HV IB design and performed mechanical, thermal and electric analyses to optimize the design. In addition, JSC “NIIEFA” has carried out all tests according to the technical specifications. 30 kV and 4 kV HV IB designs are shown in Figs. 1 and 2.

JSC “SSTC” has performed machining of the stainless steel end fittings and central rod (G10) which are the components of the 30 kV and 4 kV HV IBs. Moreover, JSC “SSTC” has welded the end fittings and cleaned them in a galvanic bath.

“GERO” Ltd has performed winding of the internal and external layers of roving, bonding and gluing of the end fittings with the central insulator [3].

![Fig. 1. 30 kV HV IB design, measures are in mm.](image-url)
For each HV IB a Manufacturing and Inspection Plan (MIP) was issued.

The 4 kV HV IB has a uniflow channel. For this design the general approach is employed, i.e. the metal end fittings are glued to both ends of the glass-reinforced plastic cylinder. The length of the cylinder inner channel specifies the maximum operating voltage, which is tested at room temperature and at 4.5 K. The 30 kV HV IB has a three spiral channels. It is characterized by the spiral channels formed inside the glass-reinforced plastic cylinder. The spiral channel length is several times larger than the length of the HV IB itself. It means that with the equal electric strength the length of the spiral HV IB is several times smaller than the length of the HV IB with uniflow channel. The stainless steel end fittings are tightly connected to the plastic cylinder and used as the electrodes welded to grounded HV parts of cryogenic lines. The spiral channel length is selected based on the requirements to the cryoagent electric strength. The number and diameter of the spiral channels are specified by the flow section required for cryoagent flow and by the helium pressure under operating and emergency conditions. The 30 kV and 4 kV HV IBs are shown in Fig. 3 and Fig 4.
4. Acceptance tests and test results

The following tests were carried out for each 30 kV and 4 kV HV IB according to the test program and the ITER Technical Specifications.

30 kV HV IB:
- Input test: visual inspection, flow test, leak tightness;
- Leak test under pressure of 3.9 MPa;
- High-voltage test No. 1: 35 kV – DC, 25 kV – AC (1.2-1.3 bar, helium);
- Five thermal cycles in the temperature range of 300-77 K;
- Five pressure/leak test cycles: 3.9 MPa at 77 K and at the room temperature;
- High-voltage test No. 2: 35 kV – DC, 25 kV – AC, partial discharge (1.2-1.3 bar, helium).

4 kV HV IB:
- Input test: visual inspection, leak tightness;
- Leak test under pressure of 1.95 MPa;
- High-voltage test No. 1: 5 kV – DC, 3.5 kV – AC (1.2-1.3 bar, helium);
- Five thermal cycles in the temperature range of 300-77 K;
- Five pressure/leak test cycles: 1.95 MPa at 77 K and at the room temperature;
- High-voltage test No. 2: 5 kV – DC, 3.5 kV – AC, partial discharge (1.2-1.3 bar, helium).

During the tests two defective 30 kV HV IBs were detected:

- HV IB No. 10 did not pass the flow test and was rejected (air flow value < 0.4 m³/min) due to resin in the spiral channel. The IO representatives suspended manufacturing of the 30 kV HV IBs (34 pieces of 30 kV HV IBs had been produced before the suspension). Then the design of 30 kV HV IB was modified, some changes were introduced in the bonding and curing processes and visual inspection of the HV IB inner volume with an endoscope was included. The next HV IBs were manufactured in accordance with the new design. The modified HV IBs have successfully passed the visual test with the endoscope. The test result is no resin in the inner volume of the HV IBs. For the additional visual inspection HV IB No. 40 was cut. Fig. 5 shows HV IB No. 40
after cutting;

- HV IB No. 23 did not pass the thermal cycles and pressure test and was rejected (leak under pressure 3.9 MPa at 77 K >10^{-9} Pa·m^3/s). The leak source was not detected.

The test results are given in Table 4.

Table 4. Test results of HV IBs.

<table>
<thead>
<tr>
<th>Test</th>
<th>Acceptance</th>
<th>4 kV HV IB (30 units)</th>
<th>30 kV HV IB (65 units)</th>
<th>Units</th>
</tr>
</thead>
<tbody>
<tr>
<td>Visual inspection (endoscope)</td>
<td>+ (OK)</td>
<td>Not done</td>
<td>+ (OK)</td>
<td></td>
</tr>
<tr>
<td>Flow test</td>
<td>≥ 0.4</td>
<td>Not done</td>
<td>0.40 + 0.49</td>
<td>m³/min</td>
</tr>
<tr>
<td>Leak tightness at RT (vacuum inside)</td>
<td>&lt; 10^{-9}</td>
<td>3.2 + 9.8 x 10^{-10}</td>
<td>2.9 + 9.8 x 10^{-10}</td>
<td>Pa·m³/s</td>
</tr>
<tr>
<td>Leak tightness at 1.95/3.9 MPa</td>
<td>&lt; 10^{-9}</td>
<td>0.98 ± 9.8 x 10^{-10}</td>
<td>0.96 ± 10 x 10^{-10}</td>
<td>Pa·m³/s</td>
</tr>
<tr>
<td>High-Voltage test No. 1</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>(at 1.2-1.3 bar He):</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>- at 5/35 kV – DC</td>
<td>6/15</td>
<td>0</td>
<td>0.5 + 5</td>
<td>μA</td>
</tr>
<tr>
<td>- at 3.5/25 kV – AC</td>
<td>10/100</td>
<td>2.5 ± 2.9</td>
<td>19 ± 45</td>
<td>μA</td>
</tr>
<tr>
<td>5 thermal/pressure cycles</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>300-77 K and leak tests:</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>- during thermal cycles</td>
<td>&lt; 10^{-9}</td>
<td>0.42 ± 0.98 x 10^{-10}</td>
<td>0.96 + 9.8 x 10^{-10}</td>
<td>Pa·m³/s</td>
</tr>
<tr>
<td>- at 77 K and 1.95/3.9 MPa</td>
<td>&lt; 10^{-9}</td>
<td>0.04 ± 0.82 x 10^{-10}</td>
<td>0.01 ± 7.3 x 10^{-10}</td>
<td>Pa·m³/s</td>
</tr>
<tr>
<td>- at 300 K and 1.95/3.9 MPa</td>
<td>&lt; 10^{-9}</td>
<td>0.72 ± 1.7 x 10^{-10}</td>
<td>1.1 + 9.8 x 10^{-10}</td>
<td>Pa·m³/s</td>
</tr>
<tr>
<td>High-voltage test No. 2</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>(at 1.2-1.3 bar He):</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>- at 5/35 kV – DC</td>
<td>6/15</td>
<td>0</td>
<td>0.5 + 3</td>
<td>μA</td>
</tr>
<tr>
<td>- at 3.5/25 kV – AC</td>
<td>10/100</td>
<td>2.5 ± 2.9</td>
<td>20 ± 50</td>
<td>μA</td>
</tr>
</tbody>
</table>

Fig. 5. Picture of 30 kV HV IB No. 40 after cutting.
5. Quality management system

The quality management system currently in force in JSC “NIIIEFA” is certified by the Quality Systems Certification Agency “Test St. Petersburg” JSC (registration number – ROCC RU.ИС 09.K01497, valid: May 2016) and by the International Certification Center IQNet (registration number – RU-Q01497, valid: May 2016) in compliance with the requirements of GOST R ISO 9001-2008 (ISO 9001-2008).

The quality management system is part of the JSC “NIIIEFA” management system. Direction and control of activities effecting on quality is exercised at all levels of JSC “NIIIEFA” management according to defined functions. Quality policy is determined by NIIIEFA top management and approved by the Director General.

Quality management system documentation shall involve all levels of JSC “NIIIEFA” management, regulate requirements for life cycle processes of products, monitoring and measurements, top management activity, supply of resources, including:

- Quality policy and goals;
- The JSC “NIIIEFA” Quality Assurance Manual;
- Quality Assurance Manuals of the JSC “NIIIEFA” divisions according to their technical orientation;
- Documentary procedures – standards, instructions and procedures;
- International and national standards.

The Quality Assurance Manuals of JSC “NIIIEFA” and its divisions were developed in compliance with the requirements of GOST R ISO 9001.

According to the IO requirements, prior to any activities the NIIIEFA suppliers and subcontractors shall prepare and approve the documents such as the Quality Plan (QP) and Manufacturing and Inspection Plan (MIP). JSC “NIIIEFA” and subcontractors shall develop the QPs to describe how they will implement the contract requirements. The subcontractor QPs are reviewed and approved by JSC “NIIIEFA” and accepted by the IO. The MIPs are reviewed and approved by the JSC “NIIIEFA” Quality Assurance Responsible Officer (QA RO). The JSC “NIIIEFA” QA RO shall include all Control Points, inspections and witnesses performed by NIIIEFA into the MIPs. The approved MIP shall be included in the internal contracts between JSC “NIIIEFA” and its subcontractors. The QA RO shall monitor the MIP execution. The quality control process is specified in document А 0.3 “STC Sintez Quality Assurance Manual”.

6. Conclusion

The cryogenic HV IBs with spiral and uniflow channels have been developed to satisfy the requirements of modern large-scale electrophysical equipment involved in the ITER magnet system. The key feature of the HV IB with spiral channels is the short length coupled with the high level of operating voltage.

To test of the cryogenic HV IBs special test equipment has been prepared and accepted for operation.

The cryogenic HV IBs have been manufactured and passed the tests required by the ITER Technical Specifications for the axial insulation breaks.

About 4 months were required to manufacture and test 65 units of 30 kV HV IBs and 30 units of 4 kV HV IBs. Implementation of the contract up to shipment of the last batch took 11 months.

References

