DEMONSTRATION OF 1 MV VACUUM INSULATION FOR THE VACUUM INSULATED BEAM SOURCE IN THE ITER NB SYSTEM

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Abstract

For the realization of the ITER neutral beam (NB) system, a measure to achieve the acceleration voltage of 1 MV for the vacuum-insulated beam source (VIBS) have been developed. In addition, the design basis for 1 MV vacuum insulation has been developed by integrating previous empirical scaling of the voltage holding capability for plane and coaxial electrodes and new scaling for corner region where locally-concentrated electric field is generated. The empirical scaling clarified that a product of electric field and voltage in the beam source vessel was much higher than the allowable level. Therefore, in order to improve the voltage holding capability, electrostatic shields having intermediate potential have been proposed. Consequently, it was found that the VIBS needs to be surrounded by more than three intermediate shields instead of single gap insulation to realize the voltage holding capability of 1 MV. Reliability of the design basis has been experimentally verified in the voltage holding test by using the high voltage bushing with the developed intermediated shields. As a result, the sustainable voltage has been significantly improved from 0.7 MV to 1 MV up to the power supply limit. This result ensures the realization of the 1 MV VIBS in the ITER NB system.

1. INTRODUCTION

1 MeV 16.5 MW deuterium neutral beam (NB) are required for plasma heating and current drive in ITER [1]. In order to produce such high energy NB, key components are 1 MeV 40 A negative ion beam sources (BS) [2] and 1 MV acceleration power supply system [3]. Because such components are required to have high reliability for long pulse operation of 3600s, insulation technology for DC 1 MV ultra-high voltage is indispensable. So far, in the development of 1 MV acceleration power supply, insulation of 1 MV in oil, gas, water and air has been demonstrated [4]. Although vacuum insulation of 1 MV is required for the development of the BS and the high voltage bushing (HVB) [5], insulation technology in vacuum is still under development. Because the physics of a vacuum discharge has not been fully clarified yet, development of insulation technology of 1 MV in vacuum is the most critical issue to realize the ITER NB system.

Up to now, lots of theoretical [6] and experimental [7] studies have been made to develop the insulation technology in vacuum. As results of these studies, an empirical scaling of vacuum insulation for large-area plane and coaxial electrodes and a design technique for the voltage holding capability were developed for the accelerator for the BS and the electrostatic screens for the HVB [8]. As a result, by modifying the proto-type accelerator and the screens for the HVB based on the developed scaling and technique, voltage holding of these components were successfully improved as reported in the last FEC conference [9, 10].

A remaining issue is the voltage holding capability outside of the BS. In ITER, the BS is installed in vacuum, namely a concept of a vacuum-insulated BS (VIBS) is adopted to avoid the radiation induced conductivity of insulation gas [11]. Therefore, the 1 MV potential of the VIBS directly faces to ground potential of the beam source vessel (BSV). In the design of the VIBS, the vacuum insulation of meter-class long gap between the VIBS and the BSV was originally designed by extrapolation of previous experiments by using relatively small electrodes [12]. However, a recent experiment with large-size
electrodes indicated that sustainable voltage of such long gap was much lower than expected due to breakdowns at the corner with locally-concentrated electric field.

In order to overcome this issue, influence of locally-concentrated electric field on the voltage holding capability is experimentally investigated this time. Moreover, the voltage holding capability of the VIBS is estimated by the empirical scaling. Based on the analysis, intermediate electrostatic shields are proposed as a measure to sustain 1 MV instead of a single gap insulation. Finally, effectiveness of the shields is experimentally verified in a test stand by using the HVB with these shields.

2. VOLTAGE HOLDING CAPABILITY WITH LOCALLY- CONCENTRATED ELECTRIC FIELD

A schematic view of the ITER NB system is shown in Figure 1. An acceleration voltage of DC -1 MV is generated by 5 sets of DC generators, and delivered to the HVB through a long transmission line where SF6 gas is filled for the insulation. The HVB acts as a boundary between SF6 gas in the transmission line and vacuum in the BSV as well as feedthroughs for the 5-stage acceleration voltage and cooling water into the BSV.

Inside of the BSV, a 1 MV conductor is connected from the HVB to the VIBS in order to supply the acceleration voltage as shown in Figure 2. Other four electrodes of the HVB supply -0.8 MV~0.2 MV to each grid (AG1~AG4) of the VIBS. Around the VIBS, -1 MV potential of the VIBS directly faces to the ground potential of the BSV. In the current design, the minimum gap for 1 MV insulation was designed to 0.9m between the VIBS and the BSV [12].

In order to confirm this long gap insulation of 1 MV, a voltage holding test by using the

FIG. 1. The schematic view of the ITER NBI system. Insulation technology in oil, gas, water and air is requires for the DC generator, the 1 MV transformer, the 1 MV transmission line and the HVB. Insulation technology in vacuum is requires for the HVB and the VIBS in the BSV.

FIG. 2. The schematic view of the HVB and the VIBS in the BSV. The HVB acts as the boundary between SF6 and vacuum region. Through the HVB, 5-stage acceleration voltages (-1 MV, -0.8 MV, -0.6 MV, -0.4 MV and -0.2 MV) and cooling water are supplied to the VIBS. The BSV has a ground potential of 0V.
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HVB has been carried out as shown in Figure 3. The voltage holding capability of the intermediate electrostatic screens of the HVB was designed to meet the requirement of 1 MV by applying the empirical scaling for the coaxial electrodes [4]. The HVB was installed in a large vacuum vessel with a diameter of 3 m, in addition, a rounded cover with a curvature radius of 247 mm was installed at the bottom of the 1 MV conductor to cover edges. The gap between the cover and the vessel was 1.29 m, which was considered to be enough long to sustain 1 MV according to the previous empirical scaling for plane. Moreover, this gap was longer than the minimum gap of 0.9 m for 1 MV insulation in the ITER NBI design. A high voltage divided by 5 stages was applied in vacuum with a pressure of 1x10^4

FIG. 3. Electric field analysis on a configuration of the voltage holding test by using the HVB (right). The ESTAT code was used for the analysis. The electric field in the case of 1 MV was calculated. Discharges were observed at timings of breakdowns (left).

FIG. 4. Experimental results of voltage holding tests by using cylindrical configurations. R is defined by the diameter of the cathode electrode. The curvature of the corner of the cathode ranged from 19-247 mm. V is the sustainable voltage and E is the highest electric field at the corner for each configuration.
As a result of conditioning operation more than 100 hours, sustainable voltage was limited to 0.7 MV due to breakdowns in vacuum. At the timing of the breakdowns, discharge light was observed at the cover as shown in Figure 3. In this region, many discharge marks were also observed by visual inspection after the experiment. Therefore, the voltage holding capability was found to be limited by the breakdown at the long gap between the cover and the vessel.

According to the electric field analysis shown in Figure 3, the locally concentrated electric field of 4.5 kV/mm is generated at the cover in a case of applied voltage of 1 MV. Because an influence of such local electric field on the voltage holding capability was not clear, dedicated experiments have been carried out.

In these experiments, voltage holding capability depending on the strong electric field at the corner region were investigated by using several cylindrical electrodes with different radius R and the curvature of the corner as shown in Figure 4. In order to evaluate the voltage holding capability of the corner, a gap between cathode and anode was adjusted to make breakdowns occur at the corner. In such case, even if the gap was increased, the increase of the sustainable voltage was already saturated because the electric field at the corner was not sensitive to the gap length. After enough conditioning operation, a breakdown probability was measured in each configuration, then a sustainable voltage was defined with the voltage at breakdown probability of 0% by linear extrapolation of the probability.

Considering the Clump theory [13] that a breakdown occurs at \( EV = \text{constant} \) where \( V \) is sustainable voltage and \( E \) is the electric field at the sustainable voltage, the product of \( E \) and \( V \) were obtained as a function of \( R \). Because larger \( R \) has larger surface area of the corner region with locally strong electric field, this scaling is consistent with the understanding that larger surface area shows lower voltage holding capability, namely the area effect. As a result, new empirical scaling for allowable \( EV \) at the corner has been obtained to estimate and design the voltage holding capability of the corner with locally strong electric field, for the first time. As well as the empirical scaling for the plane and coaxial regions, the empirical scaling for the corner region are easily applicable to the design of the VIBS and the HVB.

*FIG. 5. 2 dimensional electric field analysis in the BSV. The ESTAT code with a rectangle coordinate was used for the analysis. The electric field in the case of 1 MV was calculated. The value of the typical highest electric field for each stage of the VIBS and the HVB is also shown.*
3. ANALYSIS OF THE VOLTAGE HOLDING IN THE BSV AND A MEASURE FOR THE IMPROVEMENT

By applying the obtained empirical scaling for the local electric field, the voltage holding capability inside of the BSV has been analyzed based on the electric field analysis shown in Figure 5. In terms of the insulation between the VIBS and the BSV, the electric field at the 1 MV shield is low at the plane region, while locally-concentrated electric fields appeared at the corners of the shields for each stage as shown in the points of P1-P6 at the HVB and S1-S6 at the VIBS. The estimated EV at these points are compared with the empirical scaling for the local electric field as shown in Figure 6. Although the electric field at these points is not so high (~3 kV/mm), the values of EV at P1, P6 and S1-S3 are much higher than the allowable level due to the high voltage. While the required voltage for the ITER NB is 1 MV, the estimated sustainable voltage in total is 0.6 MV in this analysis, where the point S2 is revealed as the weakest point.

In order to improve the total voltage holding capability, since the E on the corner is already saturated even in larger curvatures, only the way to mitigate the EV value is the reduction of V for the single gap by inserting electrostatic shields having the intermediate potential. This is a possible measure to achieve the required voltage.

The shield structure is assumed to fully surround the VIBS as shown in Figure 7. Because configuration of the shield can be considered to be a combination of plane, coaxial electrodes with corners, the voltage holding capability at each region of the VIBS with shields can be estimated by applying each empirical scaling. Because one important points is the reduction of voltage difference between cathode and anode, combinations of number of shields were comprehensively investigated to achieve the requirement of 1 MV as shown in Figure 8. The voltage holding capability of each combination of shields was designed by the developed techniques for multi-grid electrodes [8]. By applying this technique, each gaps, diameter and surface area in all stages were designed to have similar voltage holding capability according to the empirical scaling for plane and coaxial region. When the voltage holding capabilities of each stage are balanced, the total voltage holding capability is maximized. And then allowable
In the original case without any shield, the minimum estimated voltage is 0.6 MV due to the low voltage holding capability of the coaxial region at the bottom of the VIBS. By inserting one set of shields (1 shield), the analysis shows that estimated voltage increases slightly. However, the improvement is not enough to achieve 1 MV. Particularly in cases of a shield No 1 (-0.8 MV) or No 4 (-0.2 MV), the improvements are relatively small because longer gap insulation with higher voltage difference is not effective than that for No 2 (-0.6 MV) or No 3 (-0.4 MV). By increasing the number of the shields, the voltage holding capability is gradually improved up to 1.4 MV in a case of the 4 shields where the all stage is equipped with the shield, which is known as a multi-grid concept. As a result, it was found that more than three shields are required to achieve at least 1 MV.

4. EXPERIMENTAL DEMONSTRATION OF 1 MV BY USING THE ADDITIONAL INTERMEDIATE SHIELDS.

In order to verify this design basis for vacuum insulation including the empirical scaling and design technique, the shields for the HVB region in the BSV has been developed as shown in Figure 9. The bottom of the 1 MV conductor was fully surrounded by 4 intermediate shields to divide the applied electric field at the corner is evaluated by the empirical scaling for the corner region. After that, curvature and shape of the corner region is determined to meet the allowable level.
voltage into 5-stage. Panels and frames made of stainless steel were used to form the electrostatic shields. The shields were designed by taking into account the empirical scaling for plane, coaxial and corner regions and by applying the design technique within the boundary condition of the positions of cooling pipes and the vessel. The estimated voltage satisfied the target voltage of 240 kV for each stage as shown in Figure 10. By inserting the shields, the electric field at 1 MV and the voltage difference between cathode and anode decreased by 60% and 80%, respectively, therefore the EV value for breakdowns was much reduced.

The experiment by installing the shields were carried out in the test stand. In this test stand, available voltage of a power supply was limited to 1 MV due to a limitation by the regulation of the test stand. The high voltage was applied in the operational pressure range of $10^{-4} \sim 10^{-2}$ Pa which was same as that for the ITER NB. As mentioned above, the sustainable voltage without the shields was saturated to be 0.7 MV as shown in Figure 11. As a result, even though the total surface area increased by ninefold, the sustainable voltage has been successfully improved up to 1 MV by shorter conditioning operation of 40 hours. In addition, 1 MV were sustained for more than 1000 second without any breakdown at the operational pressure range. These results show the credibility of the design basis to achieve the 1 MV vacuum insulation in the BSV.

**FIG. 9.** Electric field analysis on configurations of voltage holding tests by using the HVB without shields (left) and with the shields (right). The ESTAT code was used for the analysis in a cylindrical coordinate. The electric field in the case of 1 MV was calculated.

**FIG. 10.** Estimated voltage holding capability of each region of the shields. Each stage was designed to meet the requirements of 240 kV which is rated voltage of the HVB.
In order to achieve the voltage holding capability of 1 MV in the ITER NBI, the insulation technology for 1 MV vacuum insulation has been developed. The effect of the locally concentrated electric field at the corner was investigated to obtain the empirical scaling for the design. By demonstrating the improvement of the voltage holding capability, credibility of the empirical scaling and the design technique has been proved. In addition, these results are directly applicable to the design of not only the shields and the electrodes for the VIBS and the HVB but also vacuum components which require higher reliability of voltage holding.

REFERENCES