Vacuum Insulation and Achievement of 980 keV, 185 A/m$^2$ H\textsuperscript{−} Ion Beam Acceleration at JAEA for the ITER Neutral Beam Injector

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Abstract
Vacuum insulation of $-1$ MV is a common issue for the HV bushing and the accelerator for the ITER neutral beam injector (NBI). The HV bushing as an insulating feedthrough has a five-stage structure and each stage consists of double-layered insulators. To sustain $-1$ MV in vacuum, reduction of electric field at several triple points existing around the double-layered insulators is a critical issue. To reduce electric field simultaneously at these points, three types of stress ring have been developed. In a voltage holding test of a full-scale mockup equipped with these stress rings, 120% of rated voltage was sustained and the voltage holding capability required in ITER was verified. In the MeV accelerator, whose target is the acceleration of a H\textsuperscript{−} ion beam of 1 MeV, 200 A/m$^2$, the gap between the grid support was extended to suppress breakdowns triggered by electric field concentration at the edge and corner of the grid support. This modification improved the voltage holding capability in vacuum, and the MeV accelerator succeeded in sustaining $-1$ MV stably. Furthermore, it appeared that the H\textsuperscript{−} ions beam was deflected and a part of the beam was intercepted at the acceleration grid. This causes high heat load on the grids and breakdowns during beam acceleration. To suppress the direct interception, a new grid was designed with proper aperture displacement based on a three dimensional beam trajectory analysis. As a result, 980 keV, 185 A/m$^2$ H\textsuperscript{−} ion beam acceleration has been demonstrated, which is close to the ITER requirement.

Keywords: neutral beam injector (NBI), negative ion beam, HV bushing, vacuum insulation

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1 Introduction

The ITER neutral beam injector (NBI)\textsuperscript{[1,2]} consists of a DC $-1$ MV power supply, HV bushing, the beam source (negative ion source and electrostatic accelerator), and beam line components (neutralizer, residual ion dump, etc.). The neutral beam of deuterium (D\textsuperscript{0}) of 33 MW is injected from two injectors into the fusion plasma for heating and current driving.

In order to generate such a high-power D\textsuperscript{0} beam, 1 MeV, 40 A (200 A/m$^2$) deuterium negative ion (D\textsuperscript{−}) beam acceleration is required. High voltage is insulated with an insulating gas such as SF\textsubscript{6} in a conventional accelerator. However, in the ITER NBI, the beam source and beam line components which are connected directly to the tokamak vacuum vessel are exposed to radiation such as neutron and gamma-ray generated through fusion reactions. Hence, gas insulation is not applicable, since an electric current will be induced in the insulation gas under such a radiation environment, which will result in power dissipation\textsuperscript{[3]}. Thus a negative ion accelerator for the ITER NBI has been designed so as to insulate $-1$ MV in vacuum against the ground potential.

In addition, the transmission line from the $-1$ MV power supply is insulated with SF\textsubscript{6} gas at 0.6 MPa to make it compact. Then, the HV bushing is required to act as a bulkhead between the gas and vacuum region and also plays a role as an insulating feedthrough supplying electric power, cooling water, and D\textsubscript{2} or H\textsubscript{2} gas for the beam source at $-1$ MV potential. The HV bushing is designed to sustain $-1$ MV in vacuum with a stack of five insulator rings. There is a critical issue of 200 kV insulation in each stage, and the world’s largest high-purity alumina ring (1.56 m in diameter).

Thus, vacuum insulation of $-1$ MV is a common issue to realize both the HV bushing and the accelerator of the ITER NBI. In the present paper, recent progress in R&Gs of the HV bushing and the accelerator are presented highlighting their progress in the $-1$ MV vacuum insulation toward the ITER NBI. Section 2 describes the technical development and R&Gs...
on vacuum insulation in the HV bushing. R&D on the 1 MeV accelerator of vacuum insulation and H⁻ ion beam acceleration are described in section 3.

2 Vacuum insulation in the HV bushing

2.1 HV bushing

The HV bushing consists of five-stage double-layered insulator rings in which conductors, cooling water pipes, and gas pipes penetrate the vacuum insulation of −1 MV in the five stages, as shown in Fig. 1. The inner insulator is a large bore ceramic (1.56 m in outer diameter) and the outer one is a fiber reinforced plastic (FRP) ring. To form a vacuum boundary, a Kovar® (Fe-Ni-Co alloy) plate is clamped with the ceramic ring and a short-height ceramic ring (called a “backup ring”) is brazed on their facing area. The inner tip of the Kovar plate is welded to the metal flange. The SF₆ gas of 0.6 MPa is filled outside the FRP ring. The interlayer between the ceramic ring and the FRP ring is filled with pressurized air to prevent direct leakage of the SF₆ gas into vacuum. Inside the ceramic ring, the conductors and pipes above are located with sufficient insulation to hold 1 MV inside vacuum. These conductors and pipes at each potential are shielded with cylindrical electrostatic shields made from thin metal plate.

Fig.1 A cross-sectional view of the HV bushing and double-layered insulators (color online)

2.2 Design of the stress ring

Through technical development of such a large bore ceramic ring and its brazing technique, JAEA has established a manufacturing process for the brazed ceramic structure with good vacuum tightness [4]. A subsequent issue was the voltage holding capability of such a large bore ceramic ring. Fig. 2 shows the cross sectional view of a single stage of the HV bushing and equipotential lines. Electric fields concentrates at a junction among the metal, dielectric, and vacuum or gas; called the triple point due to the difference of dielectric characteristics, in which flash over could be initiated. Hence, a reduction of electric field at the triple point is essential. As for the HV bushing, several triple points exist around the double-layered insulators and the electric fields at these points were simultaneously reduced by coordinating three stress rings. Design criteria on electric field were the electric field intensity <1 kV/mm at the cathode triple point and <3 kV/mm on metal surface at cathode side in vacuum, respectively. To prevent surface flashover inside the ceramic ring, the cathode triple point between the ceramic and Kovar was given priority in reducing electric field. Thus a large stress ring was installed inside the ceramic ring. This stress ring was well designed so as to reduce the electric stress at the cathode triple point side. The effectiveness of the stress ring in improving the voltage holding capability was verified in the MeV accelerator [5], as described in section 3. The interlayer ring and the clamp fixing the FRP to the metal flange were also properly designed to take into account the suppression of electric field concentration. However, the electric field at the cathode triple point did not satisfy the criteria, even with the large stress ring. By varying the height of the interlayer ring, it was found that the electric field at the cathode triple junction could be decreased [6]. Then, the interlayer ring with a height of 50 mm was utilized with an expected margin of 20% in the electric field.

Fig.2 A cross-sectional view of double-layered insulators with stress rings and equipotential lines around the insulators (color online)

2.3 Voltage holding test in a full-scale mockup

Followed by the design analyses above, a full-scale mockup simulating one stage of the HV bushing was manufactured in JAEA, as shown in Fig. 3. The interlayer was filled with dry air of 1.0 MPa at the maximum. After pumping down inside the ceramic ring, voltage holding test was carried out. Once the applied voltage reached −240 kV, which was a target value of the single stage corresponding to the overvoltage of −1 MV power supply at breakdown, breakdown frequently occurred and the voltage holding was degraded.
rapidly. By inspection of inside the mockup, discharge traces were found on the outer surface of the ceramic ring, in which pressurized air was filled. Originally, the electric field on the interlayer ring surface near the ceramic ring was designed to be 3.4 kV/mm with a gap of 2 mm between the interlayer ring and the ceramic ring. However, assembly error was found to be up to 1 mm among the ceramic ring, the FRP ring, and the stress rings. This meant the gap between the interlayer ring and the ceramic ring was locally less than 1 mm where higher electric field occurred. Then, a locally high electric field resulted in surface flashover on the ceramic ring, even though no breakdown occurred in vacuum. Fig. 4 shows the dependence of electric field in several points around the insulators on gap length between the interlayer ring and insulators, \(d\). With the original interlayer ring \((d = 2 \text{ mm})\), the electric field near the insulators (e.g., 5, 6 in Fig. 4) was quite sensitive to change of \(d\). The change of \(d\), that is, the assembly error, caused the increase of electric field by 30%, which could trigger breakdowns. As a countermeasure, an increase of the gap, \(d\), was expected to reduce electric field near the interlayer ring. Too large a gap would cause not only an increase of electric field at a tip of the interlayer ring but also that at triple points, especially in the interlayer. In the case of \(d = 6 \text{ mm}\), the electric fields near the insulator were decreased and only a small influence was found on the electric field at the triple points. In addition, the dependence of the electric field on \(d\) at specific points, as shown in Fig. 4, was quite low, which indicated that assembly error has little influence on the voltage holding. Then, the interlayer ring was modified to have a 6 mm gap, i.e., \(d = 6 \text{ mm}\).

Then, the two insulator rings and the modified interlayer rings were re-assembled. At that time, jigs to fix the rings from outside were used to suppress the assembly. As a result, the assembly error was reduced to less than 1 mm. Further, with the modified interlayer rings, the electric field at those specific points was reduced to lower than the initial configuration. In addition, two screen shields were coaxially arranged with the same gap as the HV bushing. Additional electrode-simulating cooling water pipes on the screen shield were also installed, and, hence, the mockup had almost the same configuration as the HV bushing. As the result of voltage holding test, \(-240 \text{ kV}\) was sustained stably for about one hour. Long period operation at \(-220 \text{ kV}\) for five hours (corresponding to a transient response time of \(-1 \text{ MV power supply}\) was also verified. These results satisfied the requirement of the HV bushing for ITER NBI.

Besides the achievement mentioned above, reduced-pressure operation in the interlayer was also examined. In the interlayer, pressurized air of 1 MPa was filled to insulate \(-200 \text{ kV}\) in one stage according to the original design of the ITER EDA \(^1\). The voltage holding capability of the full-scale-mockup was demonstrated with pressurized air of 1 MPa. With the modified interlayer ring, the electric field in the interlayer was reduced, which indicated lower electric field distribution around the insulator, enabling voltage holding with a lower air pressure in the interlayer. This has an advantage of reducing the mechanical load on the HV bushing. Thus, pressure of the interlayer of the mockup was reduced to 0.6 MPa. As a result, voltage holding of \(-240 \text{ kV}\) was achieved for one hour. This result will increase flexibility in the mechanical design of the HV bushing.
3 Vacuum insulation and beam acceleration in the MeV accelerator

The MeV accelerator in JAEEA is an electrostatic accelerator composed of four intermediate acceleration grids and a ground grid (A1G∼A4G and GRG) with fifteen apertures (3×5 lattice pattern), as shown in Fig. 5. A target is to demonstrate $H^-$ ion beam acceleration at 1 MeV, 200 A/m$^2$ for several tens of seconds. However, the achieved energy and current of the $H^-$ ion beam was 796 keV, 140 A/m$^2$ (320 mA) by 2007 due to poor voltage holding capability \[7\]. Comparison of voltage holding tests done with various accelerator configurations and a quasi-Rogowski electrode \[8\sim10\] showed that both voltage holdings were proportional to the square root of the gap length. This tendency seems to represent Cranberg’s clump theory \[11\]. However, sustained voltage in the accelerator was about half of that of the quasi-Rogowski electrode, as shown in Fig. 6. Between two biased electrodes, charged clumps on the surface of one electrode are detached and accelerated onto another electrode and may vaporize the electrode, which could lead to a trigger of discharge. In the accelerator, the acceleration grid with a cooling water channel and manifold is mounted on the support plate and the support plate is mounted on the tapered support flame. There are connectors for the cooling water supply between the grid and the support plate. Hence several inevitable steps and edges exist around the grids and their support due to the assembly of several parts, and electric field concentrates on such local positions. The ejection of the clumps could be enhanced at positions where the local electric field had been increased by such as steps and edges on the grids in the accelerator. This could be a triggering mechanism of breakdown in the accelerator. Actually, the breakdown positions inside the accelerator were identified from their discharge traces and the local electric field at corresponding edges and steps was indicated to be more than 3 kV/mm through an electric field analysis. Then, a criterion for the electric field of 3 kV/mm at the cathode side was applied to the modified accelerator configuration. In order to reduce the electric field concentration at these points, the minimum gap length between grid supports was extended from 72 mm to 100 mm and the corners of the grid supports were rounded with larger curvature radii. Both resulted in a reduction of local electric field that satisfied the target value above. As a result, the local electric fields at the cathode and anode side were reduced from 4.9 kV/mm and 6.4 kV/mm to 2.9 kV/mm and 4.2 kV/mm, respectively. The voltage holding test in the MeV accelerator with a modified configuration succeeded in sustaining −1 MV for more than one hour in vacuum.

In the negative ion accelerator, permanent magnets are embedded in the extraction grid (EXG) for suppression of electron extraction. As a result, the beam trajectory was deflected and intercepted on the acceleration grids, which resulted in a reduction of beam current and excess heat load. Moreover, peripheral beamlets were deflected outward due to space charge repulsion between adjacent beamlets. To compensate these deflections: 1) aperture offset was utilized in the electron suppression grid (ESG) for magnetic deflection; and 2) a field shaping plate (ESP) was installed on the back side of the ESG to counteract the space charge repulsion. The ESP deforms electric field so as to push back the repulsing peripheral beamlets. The amount of offset, $d$, was decided through three dimensional beam analyses \[12\].

As a result of an improvement of voltage holding and compensation of beam deflection, the beam acceleration performance progressed as shown in Fig. 7. The MeV accelerator succeeded in accelerating 980 keV, 185 A/m$^2$ beam (pulse length: 0.4 s), which was close to the ITER requirement. For the ITER NB, long pulse beam acceleration at 1 MeV, 200 A/m$^2$ is ongoing.
4 Summary

Recent progress of our R&D, which has been focused on the vacuum insulation in the HV bushing and the accelerator are presented in this paper.

- To fulfill the ITER requirement of high voltage insulation in the HV bushing, stress rings and an arrangement of conductors were designed with electric field analysis. By utilizing a coordination of three types of stress ring, the voltage holding capability of the single-stage full-scale mockup was confirmed.
- Modified interlayer ring enabled reduction of pressure in the interlayer, which would increase flexibility in the mechanical design of the HV bushing.
- To achieve 1 MeV, 200 A/m² H⁻ ion beam acceleration, voltage holding capability in the accelerator was improved by reducing the local electric field concentration, which triggered breakdowns.

- With compensation methods for beam deflection, 980 keV, 185 A/m² H⁻ ion beam acceleration has been achieved.

References


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