Development of Full-size Mockup Bushing for 1 MeV ITER NB System

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Abstract. In order to verify a feasibility of a high voltage bushing for the ITER NB system, development of brazing technique of a meter-class ceramic ring, manufacturing and voltage holding test of a full-size single-stage mockup were performed in JAEA. To satisfy mechanical strength and voltage holding capability required on the bushing, design modifications based on mechanical and electric field analyses were applied to the full-size mockup. Results of high voltage test showed a stable voltage holding for over voltage at -240 kV for two hours and a long period operation at -220 kV for five hours, which was a first demonstration of high voltage insulation required in the ITER NB system.

1. Introduction

The ITER neutral beam injector (NBI) [1, 2] consists of a DC -1 MV power supply, high voltage (HV) bushing, beam source (ion source and electrostatic accelerator) and beam line components (neutralizer and residual ion dump etc.). The neutral beam of deuterium of 16.5 MW is to be injected into fusion plasma for heating and current drive.

A conventional insulation method in high energy accelerator is gas-insulation with SF_6 gas. 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 reaction. It was pointed out in case of gas insulation that electric current is induced in the insulation gas under such a radiation environment, which resulted in power dissipation, and hence, the gas-insulation is not applicable in the ITER NBI. Thus the ITER accelerator is designed so as to be installed in vacuum where -1 MV must be sustained. On the other hand, transmission line from the -1 MV power supply utilizes the gas-insulation to make it compact. The HV bushing mounted between the beam source and the 1 MV power supply acts as a bulkhead between the gas and vacuum region. The HV bushing also plays a role as a feedthrough supplying electric power, cooling water and H_2 or D_2 gas for beam production to the beam source with 1 MV insulation.

The HV bushing has been designed to sustain -1 MV in vacuum with five-stage insulator. The insulator has double-layered structure, inner insulator is a large bore alumina ceramic ring (1.56 m in outer diameter) and outer one is a fiber reinforced plastic (FRP) ring. Since many conductors locate inside the ceramic ring sustaining insulation of -1 MV with sufficient insulation gap between each other, such a ceramic ring of large diameter was regarded as essential. However, in conventional manufacturing methods, the diameter had been limited less than 1 m, which had been a longstanding issue since ITER EDA. Toward a realization of the ITER NBI, JAEA and KYOCERA cooperation have developed a new manufacturing method and achieved a manufacturing of the large bore ceramic ring of 1.56 m in diameter [4].

Followed by the achievement of manufacturing of the ceramic ring, in these couple of years, JAEA has tackled a development of a joining technique of the large bore ceramic and a metal part to form a vacuum boundary. JAEA has also performed the HV bushing design for -1 MV insulation through mechanical and electric field analysis. A verification of voltage holding has also been carried out in a full-size mockup. In this paper, progress on the R&D for a development of the insulator for the HV bushing and a demonstration of voltage holding of the full-size mockup bushing are reported. Mechanical analysis and brazing as a technique of joining of the large bore ceramic ring is described in section 3. In section 4, electric field analysis for vacuum insulation is described. Manufacturing of the full-size mockup is reported followed by results of voltage holding test of the mockup in section 4.

2. HV bushing in the ITER NBI

A cross section of the HV bushing is shown in FIG.1. As mentioned above, each stage consists of a double-layer insulator. The large bore ceramic in each stage is metalized and brazed with Kovar® (Fe-Ni-Co alloy), that has similar thermal expansion coefficient with the alumina ceramic. Ring-shaped Kovar sleeves are clamped with the large bore ceramic ring (0.29 m in height) and another ceramic ring with lower height (0.028 m), called as a backup ring, at the top and bottom. To seal inside of the ceramic ring, brazing between the ceramic and Kovar sleeve and inner tip of Kovar sleeve welded to metal flange. Interlayer between the FRP ring and the ceramic ring is filled with pressurized air (≤1 MPa) as guard gas to prevent direct leakage of SF_6 gas into the vacuum region, to be followed by possible damage in a catalyst of detritiation system.

Conductors such as radio frequency coaxial tubes, bus bars, cables and cooling water tubes at -1 MV potential are connected at a top of the bushing. They penetrate a dome-shaped head in which pressurized air is filled and are introduced into vacuum. The cooling water pipes for intermediate potential (-200~ -800 kV) are connected at the side of the intermediate flange and are also introduced in vacuum by penetrating the flange. Many conductors at different potential from -200 kV to -1 MV are located in vacuum. To separate five layers inside the HV bushing, screen shields connected to each intermediate potential flanges are installed coaxially. Centering around -1 MV screen, cooling water pipes at intermediate potential are located along each screen shields. They are terminated at the bottom of the HV bushing and connected to the beam source to supply electric power and cooling water.

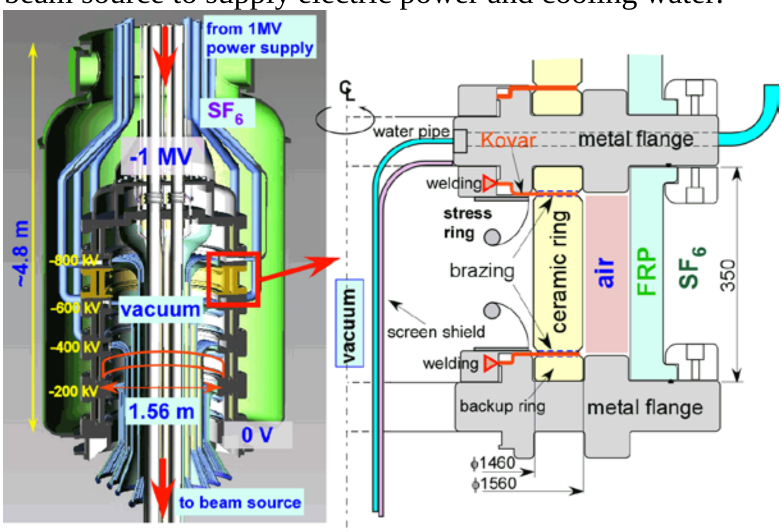

FIG. 1. HV bushing and double-layered insulator

3. Brazing of the large bore ceramic ring

In order to form a vacuum boundary, the ceramic ring has to be joined with metal flanges. A conventional technique is brazing of ceramics with Kovar® (Fe-Ni-Co alloy) which has similar thermal expansion coefficient with the alumina ceramic. In case of the HV bushing, the ring-shaped Kovar sleeves are clamped between the large bore ceramic ring and backup rings. Since outer surface of brazed structure is exposed to 1 MPa air as shown in FIG.2, brazed and welded area has to be designed taking into account not only residual stress but also an external force from the pressurized air, however, mechanical strength of constraint point such as welding and brazing was concerned in the original design with 1mm thick Kovar plate, and then the mechanical analyses were carried out to clarify the specification of Kovar [5]. Figure 2 shows a calculation model of the brazing region. As a result, it was indicated that the required thickness of the Kovar sleeve was 3 mm to sustain the tensile stress at the welding point. However, the large bore ceramic ring with meter-class diameter has never been brazed with such a thick Kovar, since higher residual stress appeared in a large joining area in case of brazing of such a thick Kovar plate.

JAEA carried out sample tests of brazing of ceramic with 3 mm thick Kovar plate collaborating with Hitachi Haramachi Electronics Co., Ltd. After fundamental brazing tests of the ceramic ring of several tens cm in diameter, brazing test of a half-size (0.8 m in outer diameter) ceramic ring was attained and issues for brazing with thick Kovar plate were picked up [6]. The full-size ceramic ring has been successfully brazed achieving good vacuum tightness as shown in FIG.3. This was the first accomplishment of brazing of the meter-class ceramic ring, which accelerated the development of the HV bushing.

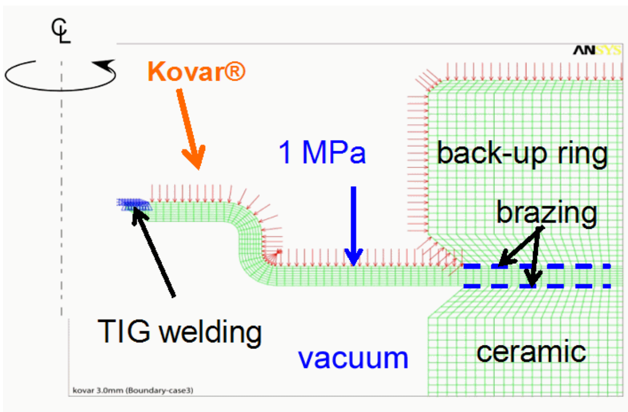

FIG. 2. Calculation model of brazing region

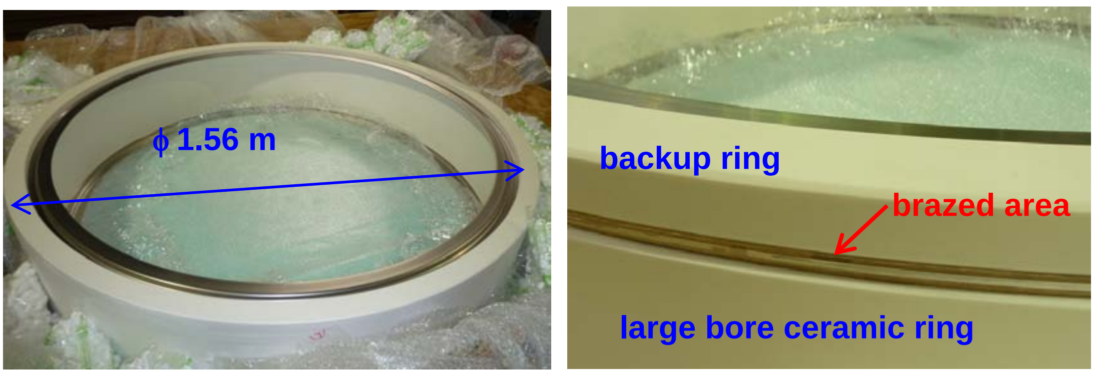

FIG. 3. Brazed large bore ceramic ring

4. Manufacturing and voltage holding test of full-size mockup

4.1 Electric field design for vacuum insulation

For stable voltage holding in the HV bushing, design of the electric field distribution around the insulators, conductors and water pipes penetrating the bushing is a crucial issue. As for the insulator in vacuum, reduction of electric field at the triple junction (the interface of metal flange, insulator and vacuum), is the most significant issue to prevent a surface flashover. As the electric field criteria on the HV bushing, present design adopted following values, <1 kV/mm and <3 kV/mm at the triple junction and cathode-side metal surface, respectively [7]. In order to satisfy the criteria, a large ring (120 mm in radius of cross section) at cathode side and a small one (22.5 mm in radius) were designed [7], instead of symmetry stress rings at both cathode and anode as designed in the ITER EDA [1]. Comparing with the ITER EDA design, electric field at the cathode-metal and insulator surface considerably decreased, however, electric field at the triple junction analyzed by ANSYS code exceeds the criteria as shown in FIG.4. In addition, triple junctions exist also in the interlayer, and hence, an interlayer ring was installed to relax the electric field concentration coordinating with the large stress ring in vacuum and a metal clamp for fixing the FRP ring. By varying a height of the interlayer ring, h as shown in a red box in FIG.5, it was found that the electric field at the triple junction could be decreased. For a voltage holding test in a full-size mockup, h was chosen as 80 mm at cathode side where the electric field at the cathode triple junction was 0.74 kV/mm and 50 mm at anode side, respectively [5].

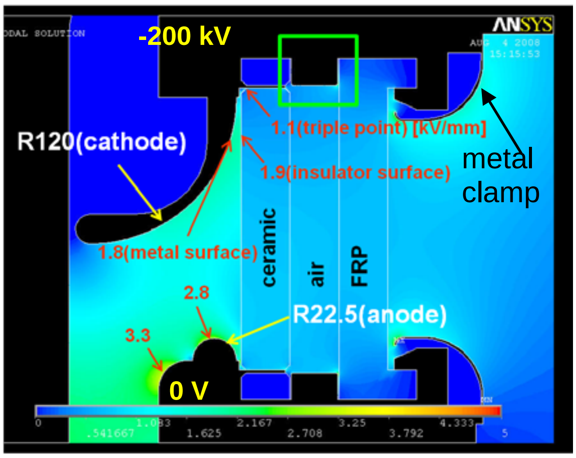

FIG.4. Electric field distribution around the insulator

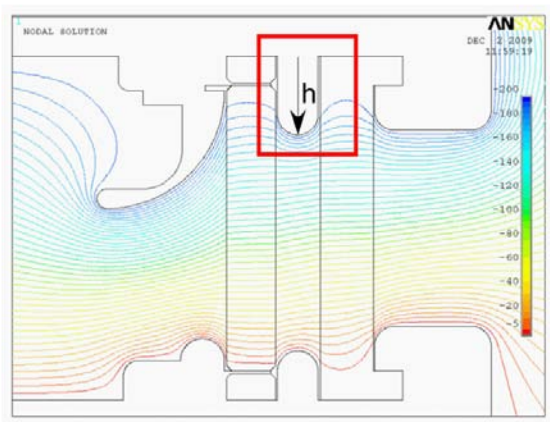

FIG.5. Equipotential lines around the insulator

4.2 Assembly and voltage holding tests of the full-size mockup

Followed by successful completion of brazing of the ceramic ring, a full-size single-stage mockup with an actual geometry was manufactured in order to verify a feasibility of the HV bushing. A cross sectional view of the full-size mock is shown in FIG.6. It consists of the brazed ceramic ring, the FRP ring, metal flanges and stress rings. In the mockup test, a tip of Kovar sleeve was sealed with O-ring to allow disassembly for inside inspection after the high voltage test. Screen shields simulating ones at -1 MV and -800 kV potential were also installed inside the ceramic ring to verify vacuum insulation with narrow gap. They were manufactured by spinning process with 2 mm thick stainless steel. Even though the height of screen shield was shorter than that of actual one, the latest design values of the HV bushing in JAEA were applied to outer diameter and gap length between screen shields. The diameter of high voltage screen shield was based on a required space for arrangement of -1 MV conductors at the centre of the HV bushing. The gap length of 77 mm between the screen shields was determined according to the criteria mentioning the electric field of 3 kV/mm at cathode-side metal surface.

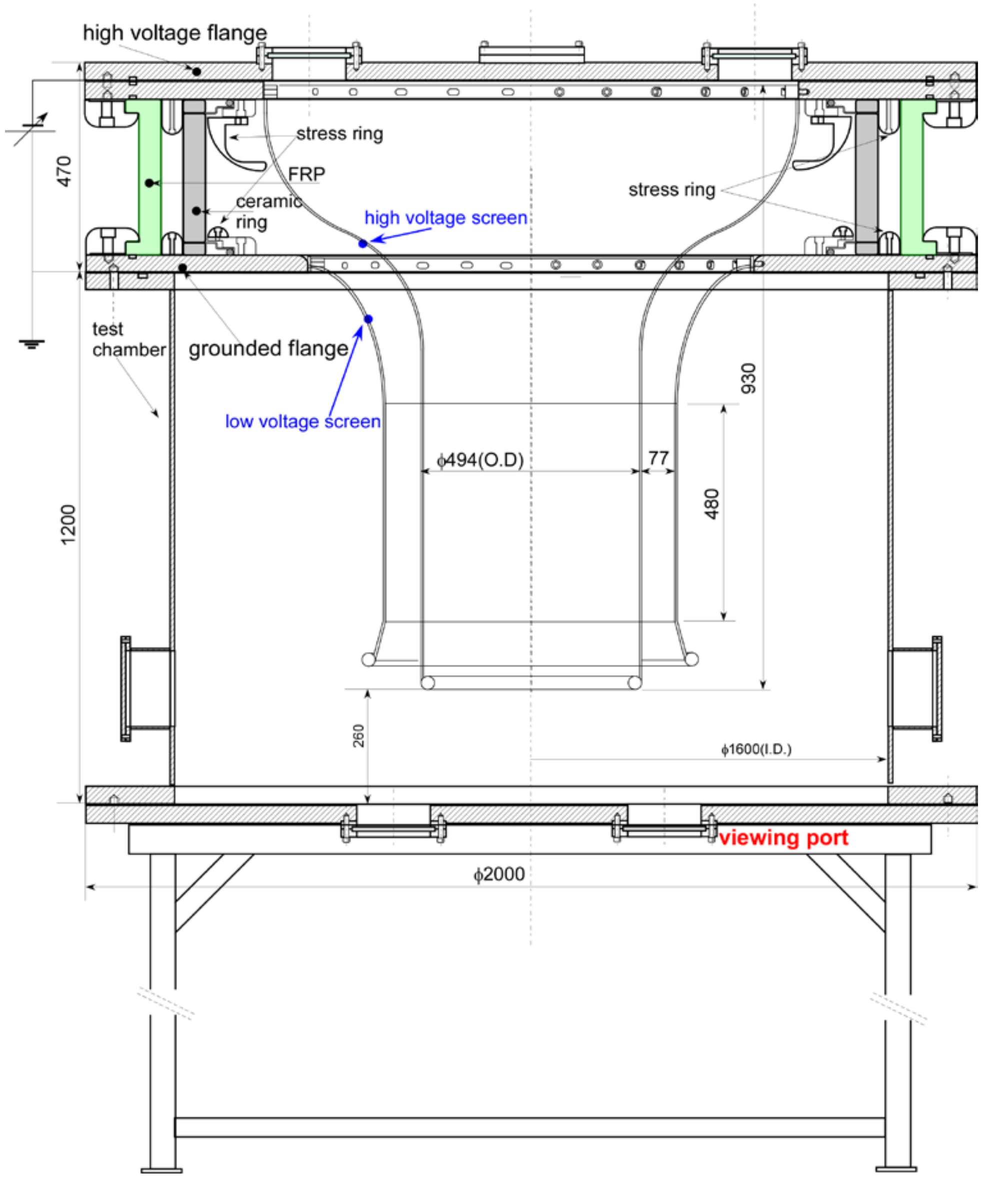

FIG.6. Cross sectional view of the full-size mockup

Typical assembly procedures are shown in FIG.7. After mounting of the ceramic ring on the grounded flange, the FRP ring was installed covering the ceramic ring (see FIG.7a)). Stress rings were installed inside the ceramic ring and also in the interlayer (see FIG.7(b)). The screen shields were installed inside the ceramic ring (see FIG.7(c)). Each screen shield was connected a high voltage flange and a grounded flange at the top and bottom of the full-size mockup, respectively. A final configuration is shown in FIG.7(d). The target on the high voltage test of the full-size mockup was;

- The rated operation at -200 kV for 3600 s,
- The over voltage operation with 20 % margin (at -240 kV) for 3600 s, and
- A long pulse operation with 10 % margin (at -220 kV) for five hours.

The full-size mockup was pumped down to 2×10^{-4} Pa and the interlayer was filled with dry air up to 0.6MPa. The outside of the full-size mockup was filled with SF_6 gas up to 0.13 MPa. Negative high voltage was fed to the high voltage flange and the voltage was increased gradually. Initial conditioning history is shown in FIG.8. Once the applied voltage reached at -240 kV, breakdowns occurred frequently and long pulse operation could not be achieved. Furthermore breakdowns occurred even under -200 kV and voltage holding capability degraded suddenly. In order to identify the cause of the degradation of the voltage holding capability, the mockup was disassembled and the inside was inspected. As a result, local discharge traces were found on the outer surface of the ceramic which indicated flashover in the dry air region. A major cause of the breakdowns was considered that a lack of assembly accuracy of components. All components must be installed coaxially, however, eccentrically-installed components raised local field concentration.

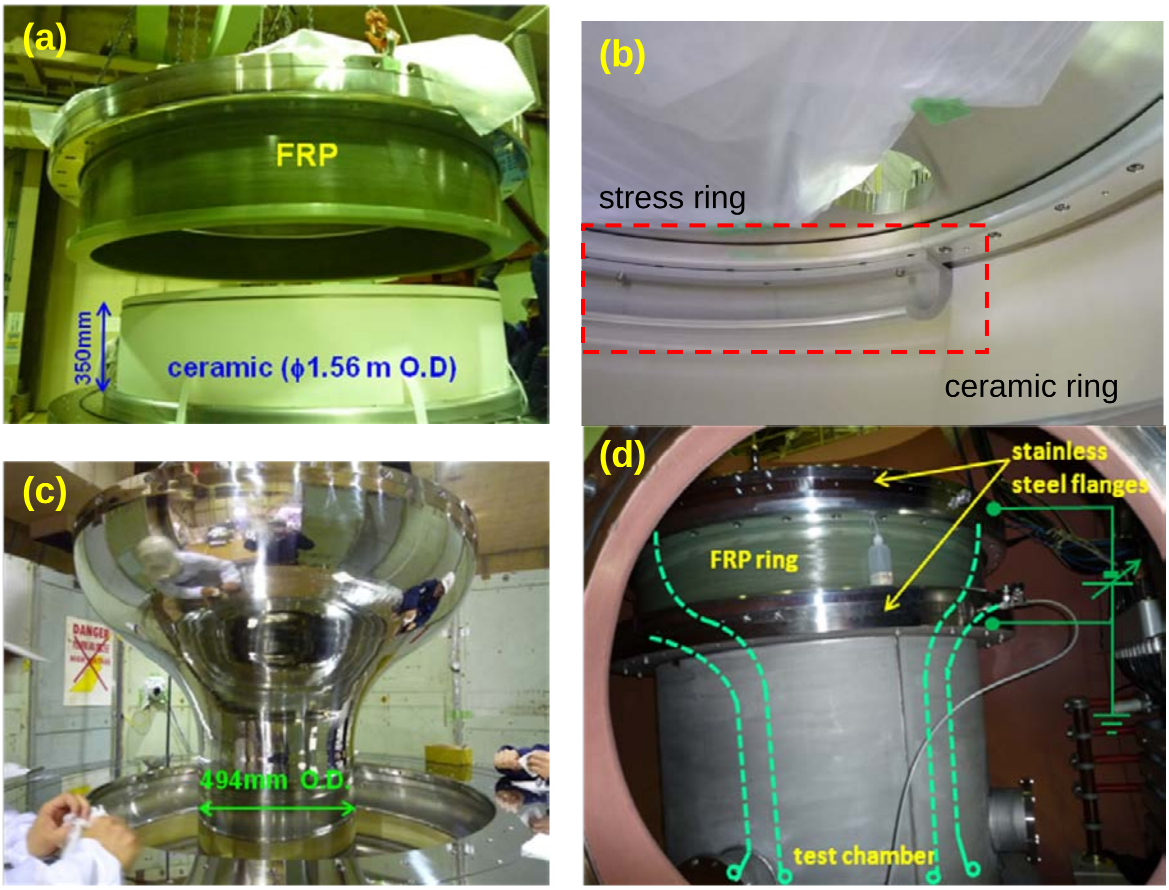

FIG.7. Assembly procedures of the full-size mockup

The electric field distribution around the interlayer ring is shown in FIG.9. The start point of the discharge trace observed in the interlayer corresponded to the highest electric field region at 3.4 kV/mm near the ceramic ring. The design value of gap between the ceramic ring and the interlayer ring was 2 mm. If assembly misalignment resulted in 1 mm displacement in the ceramic ring, the interlayer ring got closer to the ceramic ring and the stress value became much higher from 3.1 to 4.1 kV/mm on the ceramic ring in the interlayer. That could trigger the flashover on the outer surface of the ceramic ring. As a countermeasure against the breakdowns in the interlayer, assembly accuracy was improved with jigs, and moreover, filling pressure of dry air in the interlayer was increased to 1.0 MPa. The conditioning history of the voltage holding after those improvements is shown in FIG.10. After a conditioning for thirteen hours including several breakdowns, the applied voltage reached at the rated voltage of each stage of the HV bushing (-200 kV). Finally, the over voltage operation at -240 kV for two hours and the long period operation at -220 kV for five hours were accomplished without breakdown.

In the ITER EDA activity, Paschen's law in the dry air was considered for voltage holding [1], however, surface flashover occurred at much lower voltage than predicted one by Paschen's law. Even though a database for the flashover in pressurized air applicable to the HV bushing configuration is insufficient, the results indicate that the local electric field near the ceramic ring should be lower than 3 kV/mm even in 1 MPa air. In case of the full-size mockup, the local electric field in the interlayer was sensitive to the gap between the ceramic ring and the interlayer ring, especially in the range of the original design value (2 mm). It was found that the wider gap (5~6 mm) decreased the electric field near the ceramic ring surface in the interlayer and the local electric field was less sensitive to the gap between the ceramic ring and the interlayer ring in that range. This modification will be tested for improvement of reliability on the voltage holding.

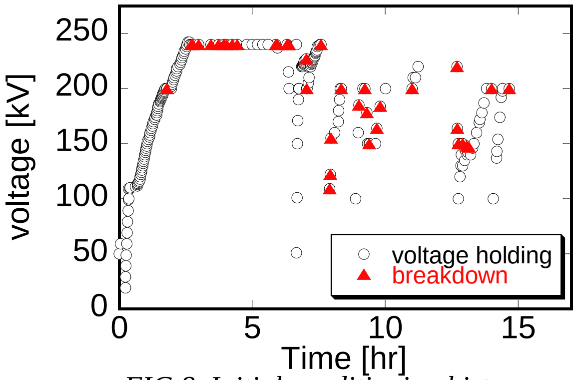

FIG.8. Initial conditioning history of the full-size mockup

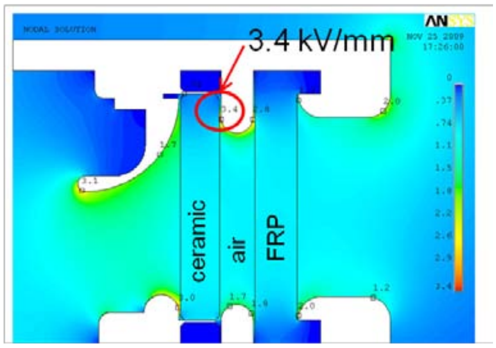

FIG.9. Electric field distribution around the interlayer ring

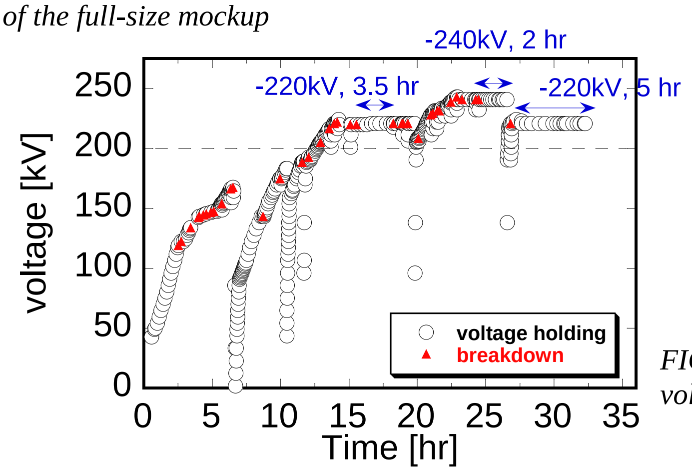

FIG.10. Achievement of the required voltage holding in the full-size mockup

5. Summary

Recent progresses on the development of the HV bushing for the ITER NBI are presented in this paper. They are summarized as follows;

- The specification of Kovar sleeve for the HV bushing was clarified through mechanical analysis. After brazing test of small sample and a half-size ceramic ring, the full-size ceramic has been successfully brazed with good vacuum tightness for the first time.
- The full-size mockup was manufactured based on the mechanical and electric field analyses. Voltage holding test was also performed. As a result, in addition to rated voltage (-200 kV per each stage) operation, over voltage operation at -240 kV for two hours and long period operation at -220 kV for five hours were accomplished without break down.

Thus the full-size mockup demonstrated its insulation capability per each stage required in the ITER NB system. The feasibility of the HV bushing has been confirmed through those R&Ds.

Acknowledgement

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