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Development of the High Voltage Bushing for the ITER NBI

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Recent progress of R&D for verification of feasibility on a high voltage bushing for the ITER NBI is reported. After successful completion of manufacturing of a large bore ceramic ring (1.56 m in outer diameter) as an insulator for the bushing, JAEA has tackled the development of a joint technique by metalizing / brazing of the large bore ceramic with seal metal. Specification of Kovar® as the seal metal suitable for the HV bushing was clarified by mechanical analyses. The full-size ceramic has been successfully brazed with good vacuum tightness for the first time. Electric field design inside the bushing to realized stable voltage holding of -1 MV in total is also progressed. Followed by these developments, manufacturing and vacuum insulation test on a mock-up consisting of the full-sized brazed ceramic and other components with actual geometry has been started in JAEA.

Keywords: ITER, neutral beam injector (NBI), high voltage bushing, vacuum insulation, alumina ceramic ring

1. Introduction

The ITER neutral beam injector (NBI) consists of a DC -1 MV power supply, a high voltage (HV) bushing, a negative ion source, an electrostatic accelerator, a neutralizer and residual ion dump. Here the D^0 beam of 16.5 MW is required. Among the above components of the NBIs, JAEA as the Japan domestic agency (JADA) will procure two sets of high voltage components of DC -1 MV power supply, two pieces of high voltage bushing and 1 piece of electrostatic accelerator.

The HV bushing is an insulating feedthrough for electric power and cooling water mounted between the transmission line of -1 MV power supply with SF_6 gas insulation and the beam source inside vacuum. The HV bushing has been designed to achieve vacuum insulation of -1 MV with a five-stage structure that corresponds to the five-stage accelerator. Each stage of the HV bushing being required insulation up to -200 kV is composed of double-layered insulators, 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.

During the ITER EDA, manufacturing of the large bore ceramic has been recognized as one of crucial issues on the development of the HV bushing [1]. However, such a large ceramic could not be manufactured due to limitations in size of the facilities. At the beginning of manufacturing process of the large bore ceramic, alumina powder is compressed and formed by cold-isostatic press (CIP). The conventional CIP utilized water pressure from outside of the product and water-pressure vessel with larger diameter was required as the product became large. The maximum diameter of product with the conventional CIP was less than 1 m. With the push of growing industrial demand on 2 m-class large ceramic plate, JAEA has started manufacturing of the large bore ceramic together with KYOCERA cooperation. In order to overcome the size limitation, a new fabrication process was developed to compress and form by water pressure from inside of the ring. This method made effective use of the diameter of the existing vessel and actually it was enabled to compress and form the alumina ring powder. After sintering process, high purity alumina ceramic ring of 1.56 m in outer diameter, 0.29 m in height successfully manufactured [2, 3].

Next issue followed by the manufacturing of the large bore ceramic ring is metalizing and brazing process of the ceramic ring with seal metal to form a vacuum boundary. Because we had no practical example of metalizing / brazing on such the large ceramic, JAEA has progressed process test with small sample and half-size ceramic ring collaborated with Hitachi Haramachi Electronics Co., Ltd.

The paper reports recent progresses on development of the HV bushing. Mechanical analysis and the results of the first attempt of metalizing / brazing of the large bore ceramic are reported in section 2. The detailed design of the inside bushing is reported in section 3. In section 4, summary and future plan is described.

2. HV bushing

A detailed cross section of the bushing is shown in Fig.1. Conductors, RF coaxial tubes, bus bars, cooling water pipes for the ion source at -1 MV potential connect at the top of the bushing. These penetrate the dome-shaped

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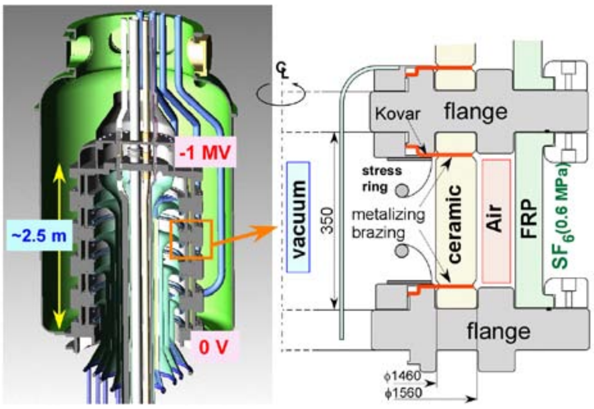

Fig.1 A cross sectional view of the HV bushing.

head and are introduced into vacuum. The double-layered insulators are stacked as five- stage combined with metal flanges. The cooling water pipe for the each middle stage of the accelerator connects the metal flange. After penetrating the metal flanges, the pipe is divided into a small channel such as parallel small pipes to prevent pressure drop of cooling water under space constraint.

The large bore ceramic in each stage is metalized and brazed with Kovar® (Fe-Ni-Co alloy), that has the similar thermal expansion coefficient with the alumina ceramic. The ring-shaped Kovar sleeves are clamped with the large bore ceramic ring and another ceramic ring with lower height (0.028 m), called as back-up ring, at top and bottom. The attached region are joined by brazing. The inner tip of Kovar sleeve is welded together with the metal flange to form the vacuum boundary. Interlayer of the double-layered insulators, that is, space between the ceramic and the FRP ring is filled with pressurized air (0.1 – 1 MPa) as the guard gas to prevent direct leakage of SF$_6$ gas into vacuum. Therefore, external pressure from high-pressure air is applied on the outer surface of the Kovar sleeves. Stress at the tip of Kovar sleeve and brazing area must be cared.

3. Metalizing /brazing of the large bore ceramic

In order to design the Kovar sleeve to withstand the external pressure (1 MPa in maximum), mechanical analysis has been carried out with ANSYS code [5]. Figure 2(A) shows the calculation model, in which two-dimensional axisymmetric configuration was assumed. On upper surface, pressure of 1MPa was applied equally and the tip of Kovar was constrained as TIG wilding point. Figure 2(B) shows stress distribution in case of the 1.5 mm thick Kovar sleeve. The results with several cases are summarized in Table 1. As shown in Fig.2 (B), maximum stress occurred at the tip of Kovar sleeve. It was found that the thickness of Kovar should be more than 2.3 mm in order to lower the stress at the tip of Kovar below its allowable bending stress (120 MPa). Hence the thickness of Kovar sleeve has been chosen to be 3 mm.

Table 1. The results of mechanical analyses of the brazed structure

Thickness	1.5 mm	2.0 mm	2.3 mm
Stress at tip of Kovar	243 MPa	147 MPa	114 MPa
Displacement of Kovar	0.125 mm	0.075 mm	0.05 mm
Stress of brazing joint area	180 MPa	130 MPa	100 MPa

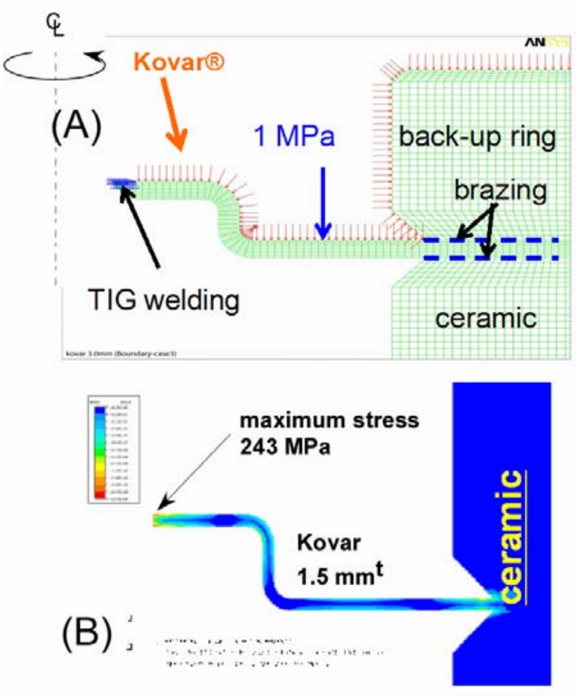

Fig.2 (A) Calculation model, (B) stress distribution.

After brazing test of small sample and a half–size ceramic ring (ϕ800 mm) [6], JAEA made the first attempt on brazing of the full-size ceramic with seamless Kovar sleeves collaborating with Hitachi Haramachi Electronics Co., Ltd. In order to ensure brazing process, structure of fixing jigs was devised to equalize the stress on the brazing surface in a furnace. Then, the full-size ceramic has been successfully brazed with good vacuum tightness for the first time as shown in Fig.3. This was the first accomplishment of the meter-class brazed alumina insulator.

4. Detailed design of the inside HV bushing

For stable voltage holding in the HV bushing, design of electric field distribution around the insulators, conductors and water pipes penetrating the bushing is a crucial issue. As for the insulator, reduction of the electric field at the triple junction (the interface of metal flange, insulator and vacuum), where high electric field

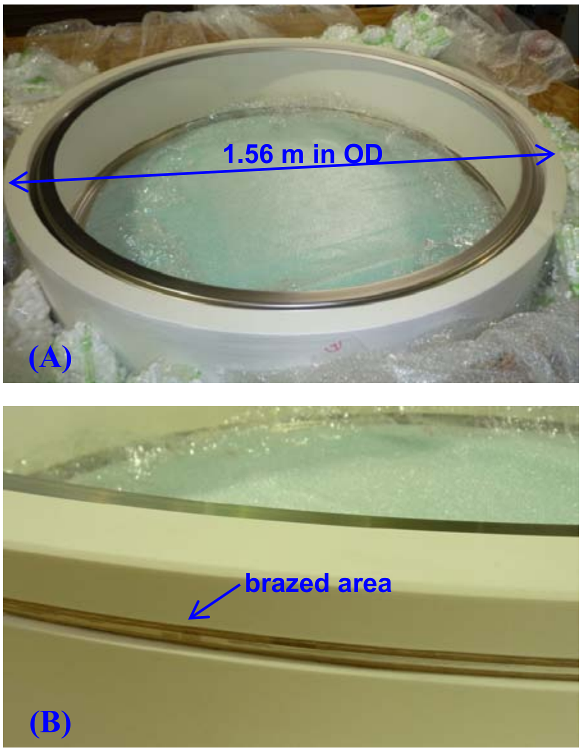

Fig.3 Pictures of brazed large bore ceramic.

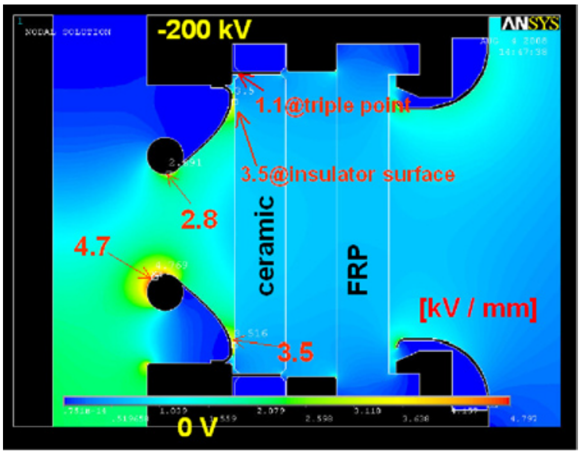

Fig.4 Electric field distribution in the ITER EDA design.

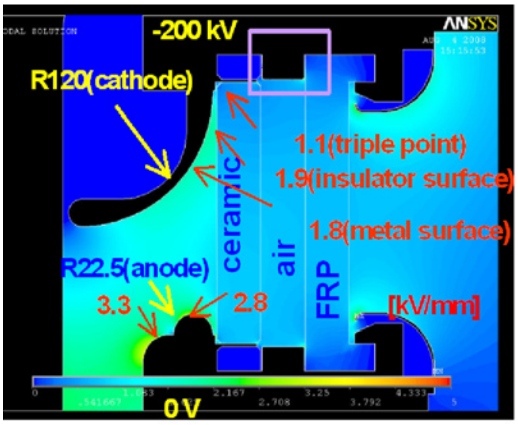

Fig.5 Electric field distribution around the insulator with modified stress rings.

concentrates is a most significant issue to prevent surface flashover in vacuum. Then, electrostatic analysis was carried out to investigate an electric field distribution around the insulator. Figure 4 shows the electric field distribution in the ITER EDA design with same metal stress rings installed at both cathode and anode, as shown in the right figure of Fig.1. Local values of the electric field at typical position such as the triple point are also written in. Here, the upper flange was applied –200 kV and the lower one was fixed on the grounded potential. The relative permittivity of the alumina ceramic and FRP were 9.0 and 4.0, respectively. Here, JAEA has presently adopted the criteria on the electric field in vacuum; that is, <1 kV/mm and <3 kV/mm at the triple junction and cathode-side metal surface, respectively [6]. Therefore, JAEA has proposed to modify stress ring installed near the ceramic to reduce the electric field concentration at the triple junction. The modified stress rings have a large cross section (120 mm in radius) at cathode side and small one (22.5 mm in radius) at anode side as shown in Fig.5. These stress rings has been developed in the MeV accelerator at JAEA [7]. Electric field distribution with the modified stress rings is shown in Fig.5. Compared with the ITER EDA design, electric field at the cathode-metal and insulator surface considerably decreased, however, electric field at the triple junction exceeds the criteria. Then, in order to lower the electric field at the triple junction further, the metal spacer between the ceramic and FRP was utilized as a stress ring by changing its height, as shown in Fig.6(a). Figure 6(b) shows the electric field as a function of the height of the interlayer ring at several points at cathode side. It is obvious that installation of the interlayer ring with the height of more than 50 mm combined with the inner stress ring is effective for reduction of electric field at the triple junction and the insulator surface.

The arrangement of conductors and cooling water pipes with potential difference under space constraint is also another crucial issue. Cooling water channel and RF coaxial conductors and bus bars at -1 MV potential came down from the transmission line and penetrate at the center of the HV bushing, as shown in Fig.7. Cooling water channels for intermediate stage of the accelerator that also came down from the transmission, connected to metal flange. The water channels penetrate inside the flange in the present design. Space between five-group components are limited from the point of voltage holding in vacuum, however, a conversion of a large pipe into single small pipe causes considerable pressure drop of water flow. Therefore, bifurcation of a large pipe into several small pipes at an inner side of the flange with a manifold is proposed. Five groups of small pipe with potential difference of 200 kV each other are located inside the ceramic and a screen shield is installed for smoothing electric field distribution

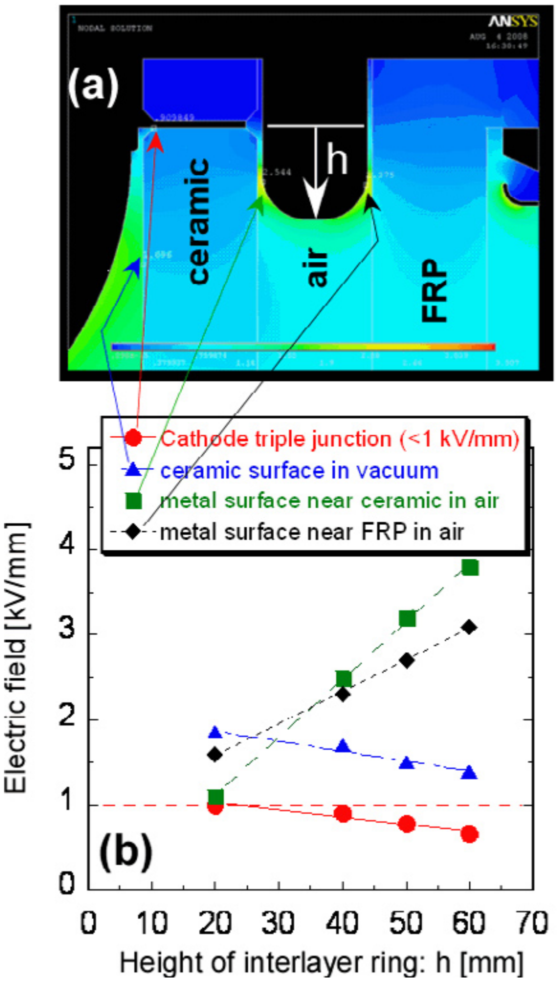

Fig.6 (a) Modification of the stress ring in the interlayer between the ceramic and FRP, (b) the electric field as a function of a height of interlayer ring at several points at cathode

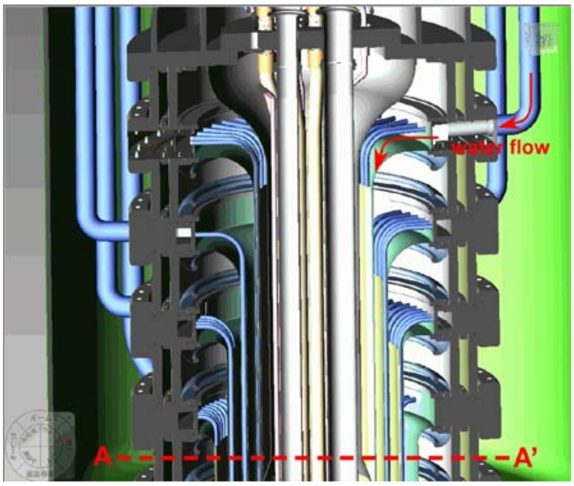

Fig. 7 Present design of the inside bushing with five-layered screen shields and cooling pipes.

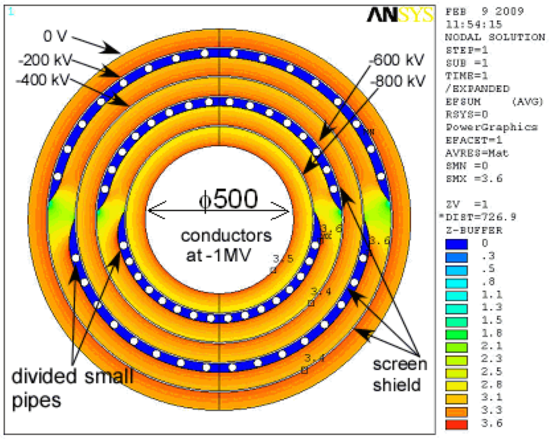

Fig.8 Electric field distribution between the screen shields with cooling water pipes at horizontal cross section in Fig.7.

between small pipes, each of which is shown in Fig.7. Figure 8 shows an example of the electric field distribution at a horizontal cut (A-A') of Fig.7 with five-layered screen shields and cooling pipes. In order to make the gap distance as much as possible, small pipes were alternatively arranged in θ-direction. Now the optimization of the inside bushing structure including the mechanical analysis is ongoing.

4. Conclusion and future plan

Recent progresses in these years on the development of the HV bushing for the ITER NBI are summarized as follows;

- A full-scale large bore ceramic (1.56 m in outer diameter was successfully manufactured by a newly developed cold-isostatic press (CIP) technique.
- Specification of Kovar sleeve equipped in high-pressure environment in the HV busing was investigated by mechanical analysis.
- After brazing test of small sample and the half–size ceramic ring, the full-size ceramic has been successfully brazed with good vacuum tightness for the first time.
- Detailed design inside the bushing was analyzed mainly with the electric field simulation.

Followed by above progress, JAEA has manufactured a mock-up with the full-size brazed ceramic, FRP, metal flanges and modified stress rings with actual geometry, which simulates one stage of the HV bushing in the ITER NBI. The vacuum insulation test targeting over –200 kV for 3600 s, which is required in the ITER NBI is now on going.

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