Surface discharge related properties of fiberglass reinforced plastic insulator for use in neutral beam injector of JT-60U[a)]

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Neutral beam injection (NBI) used for JT-60U is required to generate negative ions of 500 keV energies. To produce such high-energy ions, three-stage electrostatic accelerators consisting of three insulator rings made of fiberglass reinforced plastic (FRP) are applied. The surface discharges along FRP insulators are one of the most serious problems in the development of NBI. To increase the hold-off voltage against surface flashover events, it is necessary to investigate the FRP insulator properties related to surface discharges in vacuum. This paper describes surface flashover characteristics for FRP and alumina samples under vacuum condition. The results show that the fold-off voltages for FRP samples are inferior to those of alumina ceramics. In addition, measurement results of surface resistivity and volume resistivity under vacuum and atmospheric conditions, secondary electron emission characteristics, and cathodoluminescence under some keV electron beam irradiation are also reported. These are important parameters to analyze surface discharge of insulators in vacuum. © *2008 American Institute of Physics.*
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I. INTRODUCTION

Currently MW-class NBI devices have been developed to heat tokamak plasmas for thermonuclear fusion machines. Negative ion based NBI devices have been used to produce neutral beams of high energetic state more efficiently than positive-ion based one. In Japan, it has been developed at JT-60U in Japan Atomic Energy Agency.[1] Negative ion sources in the JT-60U were designed to have three-stage electrostatic accelerators with total accelerating voltage of 500 kV. Figure 1 shows schematic diagram of 500 keV negative ion source developed for JT-60U. It consists of plasma generator, acceleration grids, three-stage insulators, and grading rings that lower the electric field strength at the cathode triple junction. Three stages of insulators to hold the acceleration voltage were made of fiberglass reinforced plastic (FRP) resin. The geometry of insulators is cylindrical with 1.8 m inner diameter and 31.5 cm height. Currently, the hold-off voltage capability has been typically limited to $<$460 kV without negative ion beam acceleration.[2] Therefore, it was necessary to clarify the cause of the limitation about the hold-off voltage for the NBI. Hanada *et al.* reported that it was highly probable that it was caused by surface discharges along the FRP insulators.[2] To increase the hold-off voltage, it is necessary to investigate the FRP insulator properties related to surface discharges in vacuum. Although FRP insulator has been commonly used in the field of gaseous or liquid insulation system, there has been almost few researches on the electrical and dielectric properties related to the vacuum insulation system.

This paper aimed to investigate vacuum flashover characteristics using small test samples and properties related to surface discharge phenomena, as the first step for clarifying the basic properties of FRP insulator. In addition, we compared flashover characteristics between FRP insulator and alumina ceramics.

II. EXPERIMENTAL SETUP AND SAMPLES

Samples examined in this study were FRP insulator and alumina ceramics the geometry of which was disk type with the diameter of 23 mm and thickness of 5 mm. FRP samples were cut out and shaped from a piece of the actual FRP insulator, which had been used in the JT-60U ion source before, by a machining tool. Therefore, the cut-end surface appeared with bare FRP material, such as mixture of glass fiber and epoxy resin, for the FRP test sample. From the observation of the sample surface condition, the surface for FRP samples was much rougher than that for the practical FRP insulator rings used in the NBI of JT-60U. It should be noted that the inner surface for the actual insulators is coated by epoxy resin. Before the experiments, the sample was wiped by a wipe sheet soaked with ethanol. For comparison of FRP sample, alumina samples (YAS-998) are used, which have purities of 99.8% and dielectric constant of 9.7.

In order to investigate vacuum flashover characteristics for FRP and alumina samples, *in situ* experimental apparatus was used. The details of this apparatus are explained in Ref. 3 The apparatus makes it possible to carry out a series of

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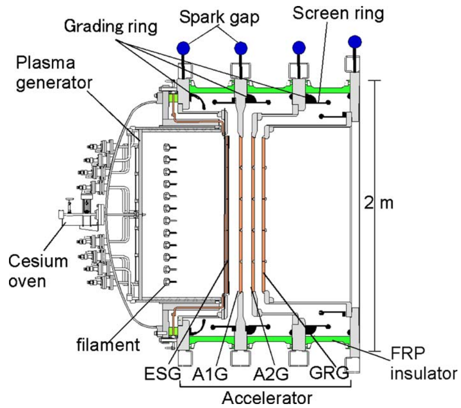

FIG. 1. (Color online) Schematic diagram of JT-60 negative ion source.

experiments, such as heat treatment in vacuum, flashover test and so on, without exposure of the sample to air condition.

Figure 2 shows a configuration of sample and electrodes for the flashover test. The sample is fixed on a back side electrode made of stainless steel. A used high voltage electrode is a needle type made of stainless steel, the tip radius of which is 1.5 mm. The procedure for flashover experiment is as follows. At first, the test sample and electrodes are set up as shown in Fig. 2. The needle electrode was in contact with the center of the sample surface in vacuum. A negative switching impulse voltage (rise time: 64 μs, time to half value: 700 μs) is applied to the needle electrode. The test was started from a low voltage, for example, −10 kV in this experiment. If a flashover event occurs, the same voltage is applied once again. If not, the voltage was increased in a −2 kV step. We measured the voltage wave form and current wave form by digital oscilloscope and light emission from the sample by a digital video camera simultaneously. Repetitive surface flashover experiments for FRP insulator were performed two times by this procedure to check the repeatability of the flashover characteristics. Those experiments for alumina insulator were carried out using the two samples processed with and without vacuum heat treatments in order to investigate the influence of the baking for insulator on the flashover characteristics.

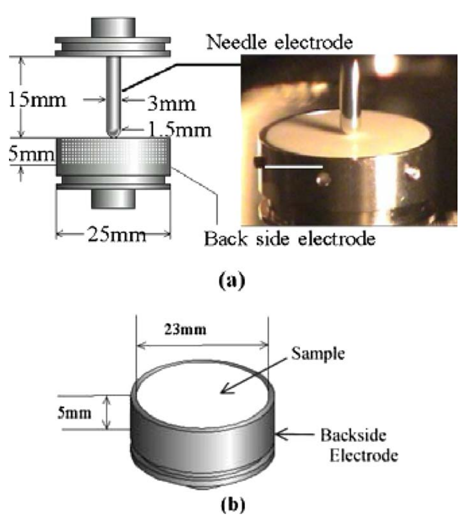

FIG. 2. (Color online) Sample setup. (a) Electrode configuration; (b) sample geometry.

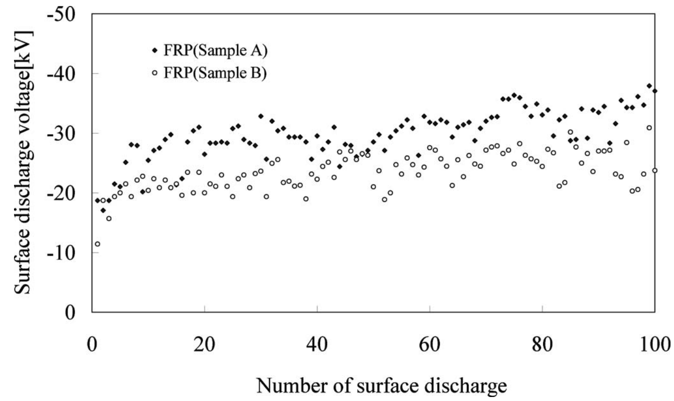

FIG. 3. Vacuum flashover voltage characteristics for FRP insulator.

Measurements of secondary electron emission (SEE) yield and cathodoluminescence were performed with a modified scanning electron microscope. The details of this system are explained in Ref. 4 For measurement of the SEE coefficient, primary electron beam was used in single pulse shot to prevent surface charging on the insulator surface. The primary electron currents were measured by a Faraday cup made of graphite with a +40 V bias voltage. The secondary electron currents were captured by a biased Faraday cup located above the sample. The SEE coefficient was defined as the ratio of the secondary to primary currents at the beginning of the pulse.

The measurements of volume and surface resistivity for FRP sample were carried out with a picoammeter and dc voltage application under vacuum and atmospheric conditions. The upper, lower, and guard electrodes were attached to the sample by silver paste painted. The upper and lower electrodes are circular in the diameter of 10 and 23 mm, respectively, while the guard electrode is ringed in the inner diameter of 14 mm and outer diameter of 23 mm outside of the inner electrode axially. The volume and surface resistivities are calculated from the definition provided in Ref. 5

III. EXPERIMENTAL RESULTS

A. Flashover characteristics for FRP insulator and alumina ceramics

Flashover characteristics for the two FRP samples are shown in Fig. 3. The first flashover voltages for samples A and B are −19 and −11 kV, respectively. The surface flashover voltages were increased until about ten times flashover shots and then were increased gradually up to −35 and −25 kV with 100 times flashover tests due to the conditioning effect for FRP samples. There are some differences of the flashover characteristics between samples A and B. They might be caused by the surface condition including the surface contamination and the outgassing on the sample surface. Figure 4 shows flashover characteristics for alumina samples without and with heat treatment in vacuum. The used alumina sample was processed by the vacuum heat treatment with the temperature of 430 °C for 2 h. The first flashover voltage without vacuum heat treatment is −15 kV. Furthermore, the 50 times flashovers increased the higher hold-off voltages due to the conditioning effect of alumina sample. This conditioning effect through repetitive flashover tests for

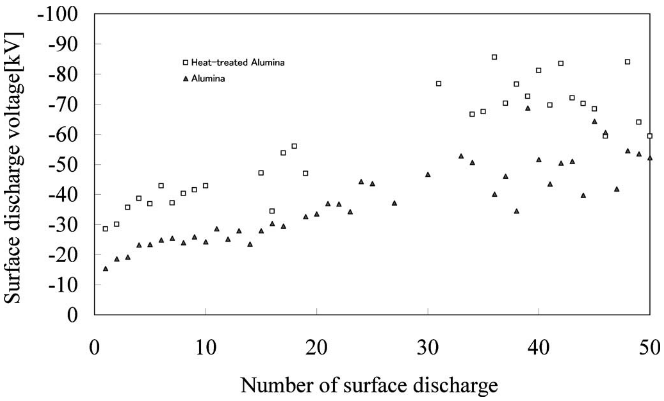

FIG. 4. Vacuum flashover voltage characteristics for alumina insulator (YAS-998) without and with vacuum heat treatment at 430 °C for 2 h.

FRP and alumina samples is caused by desorption of the absorbed gases, such as H_2O or organic contaminants, from the sample surface. On the other hand, the first flashover voltage for alumina sample processed by vacuum heat treatment increased to be −29 kV, as shown in Fig. 4. The 50th flashover voltage also increased up to −60 kV. The cause of the increase for these flashover voltages indicates that the alumina surface was cleaned by the vacuum heat treatment. Therefore, vacuum heat treatment is effective to improve the surface flashover voltages of alumina insulator.

B. Properties related to vacuum surface discharge for FRP

Figure 5 shows SEE coefficient characteristics for FRP insulator. The maximum of SEE coefficient for FRP shows 1.7 value under 1.0 keV electron irradiation. As shown in Fig. 4, SEE coefficients decreased for higher primary electron energies. SEE coefficients become less than unity above around 2 keV electron energy. From the comparison of SEE data for the alumina ceramics,[4] SEE coefficients for FRP are much smaller than those of alumina between 1 and 25 keV electron irradiation. From the viewpoint of the phenomena on vacuum surface discharge, it is highly probable that this difference influences the flashover characteristics.

Table I shows the volume and surface resistivity for FRP insulator under atmospheric and vacuum condition. Surface resistivity under vacuum condition is about 10 000 times higher than that under atmospheric condition. The difference of these surface resistivities is attributed to water vapor adsorbed on the FRP sample surface. The volume resistivity

TABLE I. Surface resistivity and volume resistivity of FRP.

	Surface resistivity (Ω)	Volume resistivity (Ω m)
Atmosphere	8×10^{13}	9×10^{13}
Vacuum	9×10^{17}	5×10^{14}

under vacuum condition also increased about six times compared with that under atmospheric one. It is likely that this used FRP sample has water absorbent properties due to noncoated epoxy resin. It is likely that absorbed water into the sample bulk are vaporized under vacuum condition. As a consequence, volume resistivity is increased under vacuum condition rather than atmospheric condition.

In order to investigate the wavelength analysis from the luminescence at surface discharge occurrence along FRP insulator, cathodoluminescence for FRP sample was measured under 3 keV electron irradiation. Figure 6 shows cathodoluminescence spectrum of FRP insulator. The continuous spectra from 300 to 800 nm was measured as shown in Fig. 6. The peak of the spectrum appeared in 320 nm. At the present stage of our investigation, the cause of continuous spectrum is not clear. Further investigations are required.

IV. DISCUSSION

From the comparison of the flashover characteristics between FRP and alumina samples, alumina samples are superior to FRP samples from the viewpoint of the hold-off voltages. On the other hand, SEE coefficient for FRP sample is smaller than that of alumina sample. According to the vacuum surface flashover mechanism based on SEEA,[6] the results of these experiments are inconsistent from the viewpoint of multiplication of electrons along the insulator surface. This discrepancy might be caused by much higher outgassing rate for FRP, which has the water absorbent property, than that of alumina ceramics. Because the used FRP samples have the rough surface without epoxy resin coating as mentioned above, it was highly possible that the decline in the surface flashover voltages results in such a surface condition for FRP samples.

V. SUMMARY

To compare the voltage holding capabilities of FRP with those of alumina insulators, the flashover experiments were performed. As a result, surface flashover voltages for the FRP sample are lower than those of alumina. Vacuum heat

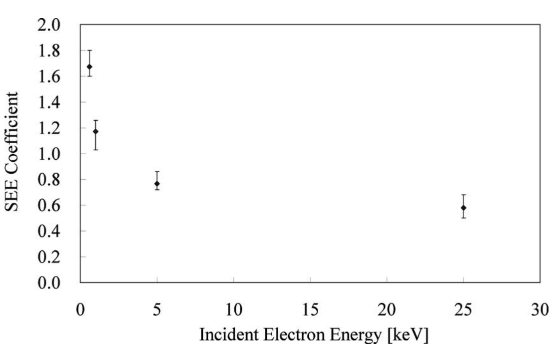

FIG. 5. SEE coefficient of FRP insulator.

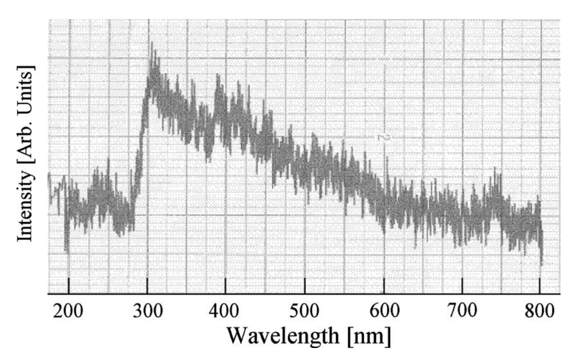

FIG. 6. Cathodoluminescence spectrum observed for FRP insulator.

treatment is effective to improve the surface flashover voltages of alumina ceramics. The properties related to vacuum surface discharge, such as SEE coefficient, surface resistivity, and cathodoluminescence, for FRP insulator are reported.

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