Acceleration of 100A/m^2 negative hydrogen ion beams in a 1 MeV vacuum insulated beam source

M. Taniguchi, T. Inoue, M. Kashiwagi , M. Hanada , K. Watanabe, K. Seki, and K. Sakamoto

Japan Atomic Energy Research Institute, 801-1 Mukoyama, Naka-machi, Naka-gun, Ibaraki-ken, 311-0193 Japan

Abstract: In the ITER NB, conventional gas insulated beam source (GIBS) cannot be utilized because of the radiation-induced conductivity of the insulation gas. Thus a vacuum insulated beam source (VIBS), where the whole beam source is immersed in vacuum, has been developed at JAERI. Recently, voltage holding capability of the VIBS was drastically improved by the large stress ring, which reduces the electric field concentration at the triple junction. Up to now, a high current density H^- beam of 102 A/m^2 (140 mA) at 800 keV has been accelerated. The beam acceleration was quite stable and accomplished for several hundreds shots. The degradation of the voltage holding due to the beam acceleration and/or Cs seeding was not observed. Thus the development of vacuum insulated beam source has solved technical issues of high voltage insulation of 1 MV level under the presence of the H^- ion beams.

Introduction

The ITER NB system requires a high energy and high current beam source, which can provide a 16.5 MW neutral beam injection per module. For this purpose, a negative ion beam source for the ITER NB was designed to produce 40 A D^- ion beams at 1 MeV. However, charged particles of ampere order have never been accelerated up to MeV range so far. For the demonstration of the ampere class negative ion beam acceleration up to 1 MeV, a five-stage electrostatic accelerator has being developed in the MeV test facility whose power supply capacity is 1 MV, 1 A, 60 sec [1].

One of the key technologies to realize the high current beam acceleration to the MeV class energy is DC ultra high voltage insulation. In the original design of the ITER NB system, the beam source is surrounded by a pressurized SF_6 insulation gas. However, the gas molecule of SF_6 is easily ionized by the radiation from the tokamak plasma, which causes the radiation-induced conductivity (RIC)[2,3]. It was clarified that the RIC causes a power loss of MW order [4], and hence, the gas insulated beam source (GIBS) cannot be utilized in the ITER NB. To avoid such problem related to RIC, a vacuum insulated beam source (VIBS), where all the components of the beam source are immersed in vacuum, has being developed at JAERI.

At the beginning of the R&D of VIBS, the H^- current was limited due to the breakdown at the FRP insulator stack. To improve the voltage holding capability, a large stress ring which protects the triple junction was designed and tested in the MeV test facility. During the beam acceleration, X-ray is generated in the accelerator by bremsstrahlung. In addition, Cs is introduced into the beam source to enhance the H^- density. These X-ray and/or introduced Cs might cause the degradation of the voltage holding capability of the accelerator. To clarify these problems, high current density beam acceleration up to 100 A/m^2 was performed. This paper reports the results of these tests.

Vacuum Insulated Beam Source (VIBS)

Figure 1 shows a photograph and a cross-sectional view of the VIBS developed at JAERI. The VIBS consists of a negative ion source, 5-stage electrostatic accelerator and FRP insulator columns. Overall dimensions of the VIBS are 1.8 m in diameter and 1.9 m in height. The negative hydrogen ions are produced in a cesium seeded plasma generator, called “KAMABOKO” source, which is mounted on the top of the accelerator. The negative ions are extracted from the plasma generator by applying an extraction voltage of 4 – 9 kV between a plasma grid and an extraction grid.

The electrostatic accelerator consists of five acceleration stages, which are supported and insulated by post insulators made of Al_2O_3 ceramic. For the acceleration of the H^-, 200 kV is applied between each grid and the H^- is accelerated up to 1MeV. High voltage of 1 MV is supplied by a Cockcroft – Walton type power supply.

As shown in Fig.1, the electrostatic accelerator is installed inside the cylindrical FRP stacks which acts as an insulator column and a vacuum vessel. The accelerator is completely separated from the FRP insulator columns, and hence, there is a vacuum gap of 50 mm around the acceleration grids. This allows direct line of sight from the -1MV potential to the ground through the long vacuum gaps of 0.5 m～1.8m. The pressure in the gap ranges in 0.02 Pa - 0.1 Pa during the operation of the ITER NB. The previous work has investigated the discharge characteristics under the above conditions. It was confirmed that glow discharge could not be generated in the operating pressure region [5], and the voltage holding test with a vacuum gap

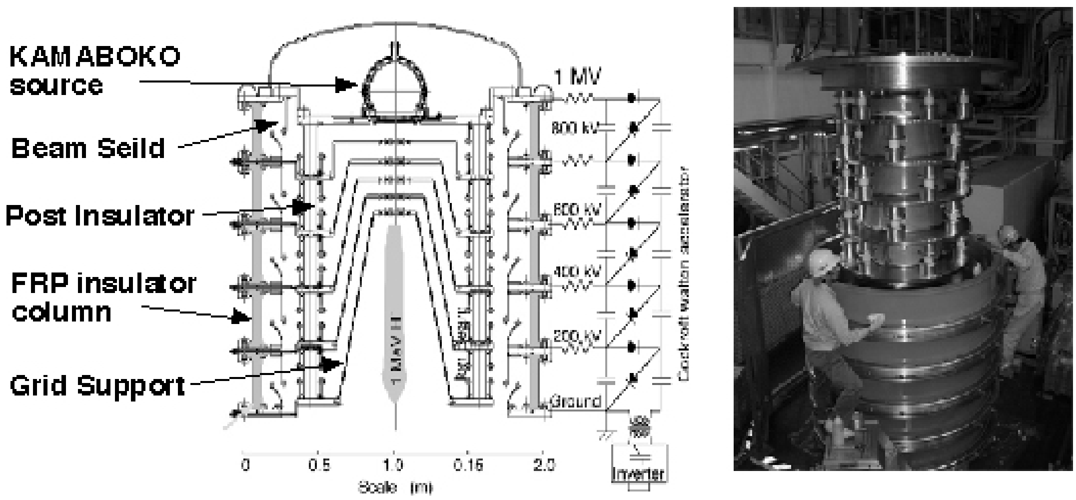

Figure 1: The schematics and the photograph of VIBS developped in JAERI.

of 1.8 m was experimentally studied [6] . The design of the VIBS was performed based on the results of the above works.

The VIBS has also some another advantages as an accelerator for the ITER NB. Needless to say, a large ceramic insulator can be eliminated for the beam source. Having no surrounding structure as in the GIBS, the VIBS allows rapid pumping of residual gas molecules in the accelerator by increased conductance through the accelerator's grid supports. Hence, it is expected that the VIBS gives lower stripping losses of the negative ions in the accelerator than that in the original GIBS. A result of 3-dimensional Monte Carlo gas analysis shows that the stripping loss of the ions is 25% in the ITER VIBS at nominal operating pressure of 0.3Pa [7]. This stripping loss is about a half of the GIBS.

Improvement of 1 MV holding capability by large stress ring

By using the VIBS, we have succeeded in accelerating negative ion beams up to 971 keV in July 2001 [6]. However, the negative ion beam was not produced stably and the current was limited to be in a very low level of 5 A/m^2. This was because conditioning time to produce high current beam was not enough due to the poor voltage holding capability of the insulator columns. Breakdown was always accompanied with the large amount of outgas. From the result of gas analysis, it was observed that outgas consist of hydrocarbons [8]. In addition, careful observation of the FRP insulator columns revealed that traces due to the melting of epoxy runs along the inner surface of FRP. Figure 2 shows the photograph of FRP inner surface after the voltage holding test. Melting of the epoxy is clearly seen in this photograph and the meltings always start at the triple junction (interface of metal flange, FRP, and vacuum).

FRP is a dielectric material, therefore, electric field tends to concentrate at the triple junction during the high voltage holding. This high electric field might cause continuous micro discharge at the triple junction. The heat load on the surrounding FRP causes the melting of the epoxy contained in FRP and the release of hydrocarbons. Due to the outgas of hydrocarbons, high voltage breakdown is considered to be generated. Therefore, we

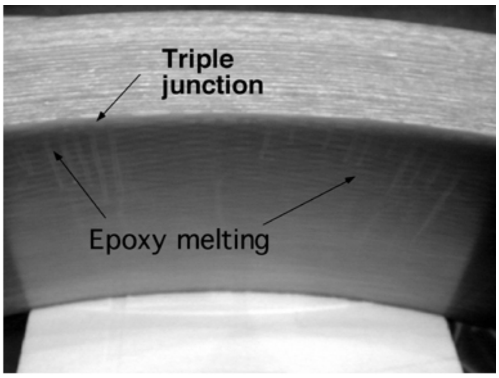

Figure 2. Damage of the FRP inner surfface after the voltage holding test.

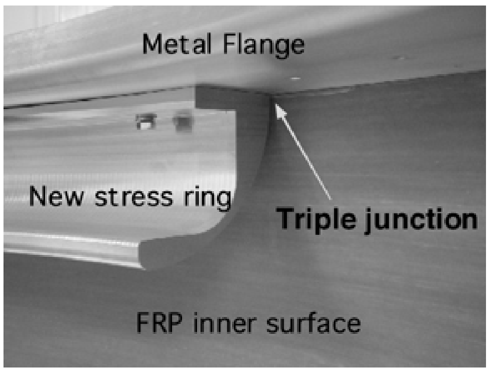

Figure 3. The photograph of the new large stress ring.

considered that the decrease of the electric field at the triple junction is essential to improve the voltage holding capability of the VIBS.

In order to suppress the concentration of electric field at the triple junction, new large stress ring was designed and installed as shown in Fig.3. By enlarging a size and curvature of the ring, electric field strength at the triple junction was lowered to 1.2 kV/mm from the original 3.6 kV/mm. A result of the voltage holding test with and without the stress ring in one stage of the FRP (rated voltage; 200 kV) is shown in Fig.4. With the new stress ring, flashover voltage reached the rated voltage of 200 kV within the first 2 hours, and a voltage more than 300 kV was stably sustained after 8 hour conditioning. The conditioning time to sustain the rated voltage of 200 kV was drastically reduced by the new stress ring. As shown in Fig.4, the accelerator without the new ring could not reach 200 kV even after 8 hour conditioning.

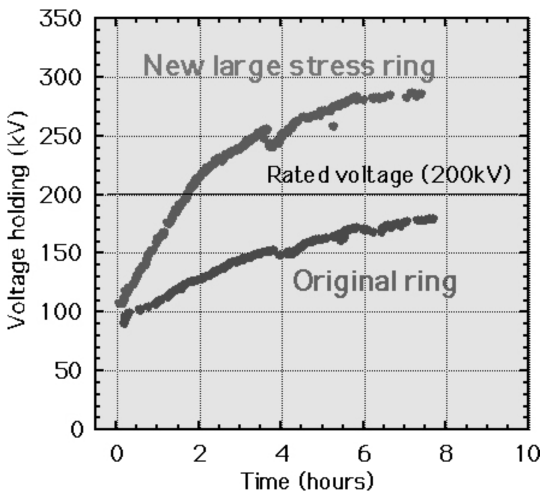

Figure 4. Result of voltage holding test with and without the new stress ring.

The improvement of the voltage holding was confirmed by lowering the electric field strength at the triple junction. The newly developed large stress rings were installed to all the five stages of FRP insulator columns. Figure 5 shows the conditioning history of the VIBS equipped with the new large stress ring. Flashover voltage increases with increasing the conditioning time, however, it was saturated at 700 kV after the 10 hours of conditioning.

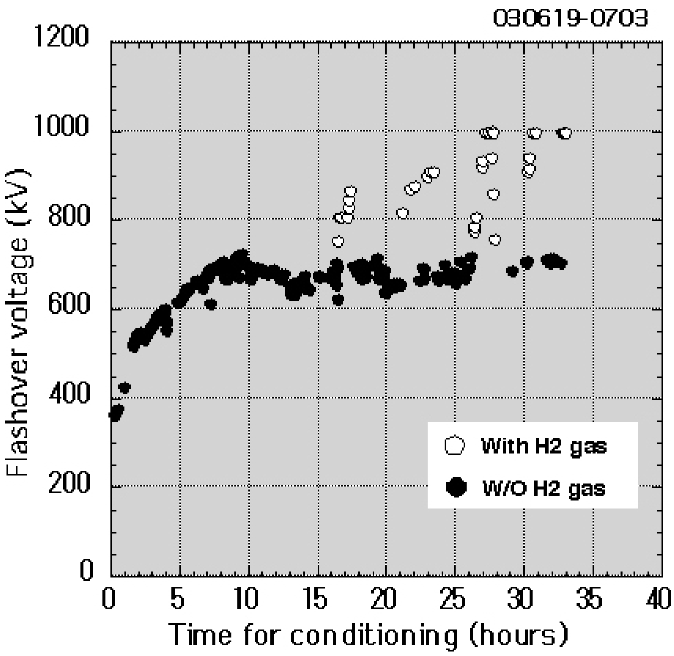

Fig.5 Conditioning history of VIBS with new large stress ring.

Although each FRP insulator was confirmed to sustain the rated voltage of 200 kV, the VIBS of five stages sustained only 700 kV even after the 30 hours of conditioning. However, the drastic improvement of the flashover voltage was observed when H_2 gas was introduced into the FRP insulator stack to 0.5 – 1.0 x 10^{-1} Pa (base pressure; 2.0 x 10^{-4} Pa), and the voltage holding reached 1 MV as shown in Fig.5. The H_2 gas is considered to prevent the creeping discharge along the FRP insulator surface. It was found that the VIBS could sustain 1 MV under the presence of H_2 in the range of 0.07 – 0.2 Pa [9,10]. This pressure range corresponds to that of the accelerator during the operation, and it was confirmed that the VIBS can sustain 1 MV stably for more than 2 hours under the H_2 gas feed of this range. Conditioning without feeding H_2 gas is effective to attain the MV class high voltage holding with H_2 gas. We performed the conditioning of the VIBS for more than 10 test campaigns, and at every time, 30 hours conditioning before the H_2 feeding is needed to attain 1 MV. It was considered that gases absorbed in the FRP need to be removed to suppres discharges, and hence, it takes long time for conditioning.

Voltage holding during the beam acceleration

By installing the large stress ring, we have succeeded in sustaining 1MV stably. However, during the beam acceleration, there are several issues to be clarified. 1) During the acceleration of the H^-, secondary electrons will be produced due to the interception of the ions on the grid. These secondary electrons as well as the stripped electrons are accelerated with the H^- and produce X-ray by Bremsstrahlung. These X-ray generates the photoelectrons on the surface of the FRP, which might cause the breakdowns. 2) During the operation, Cs vapor is seeded into the source chamber to enhance the H^- production. The Cs has a low work function and a high vapor pressure at low temperature, therefore, they might cause breakdowns if they leaked to the accelerator.

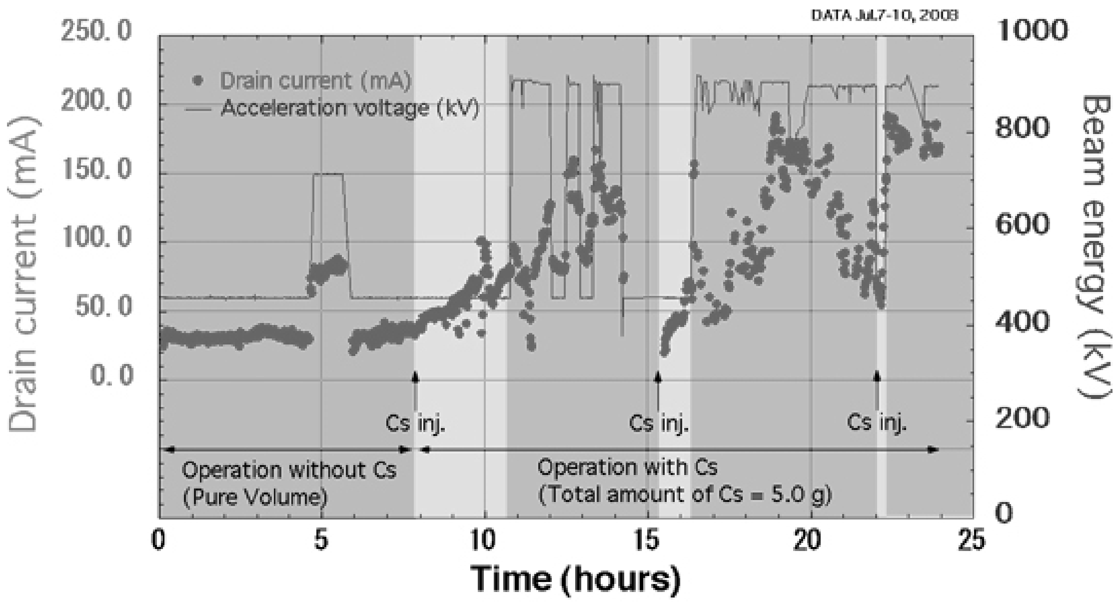

Figure 6. History of the beam acceleration test under the Cs seeding at 900 keV.

To clarify the above problems, negative ion acceleration test under the Cs seeding had been performed in VIBS. Figure 6 shows a history of beam acceleration at 900 keV under the Cs seeding. In this figure, beam current (closed circle) and the acceleration voltage (solid line) are shown as a function of the time. After the conditioning shots for several hours in pure volume operation, Cs was introduced into the beam source. Cs vapor was seeded in the source by heating the Cs oven to 470 K. To prevent the trouble of the power supply for Cs oven from surge propagation at high voltage breakdown, Cs was introduced to the source at the relatively low acceleration voltage of 450 kV. As Cs accumulates in the source, the negative ion current begins to increase as shown in Fig.6. After that, Cs oven was turned off and the acceleration voltage was increased to 900 kV. The total amount of Cs introduced during the test campaign was 5.0 g, but the degradation of voltage holding was not observed. Pulse length of the beam was 0.5 sec and the interval between the shots was 60 sec. The beam acceleration of 900 keV, 0.1 – 0.2 A level was quite stable and accomplished for several hundreds shots. The breakdown due to photoelectrons generated by bremsstrahlung was not observed during the beam acceleration. It was confirmed that VIBS can sustain 1 MV stably under the condition of high current beam acceleration and Cs seeding operation.

Acceleration of 100 A/m^2 negative ion beam at 800 keV

After the successful voltage holding test with the beam acceleration, high current density H^- beams of 100 A/m^2 class were accelerated with seeding cesium. To enhance the H^- density under the low operating pressure, some minor modifications were made on KAMABOKO source; filter magnet was strengthened from 460 to 745 Gcm, and the number of filaments were increased for higher arc power operation up to 40 kW. Although the plasma grid and extraction grid of the source has 49 apertures (7 x 7 lattice pattern) to extract the ions, the apertures were masked at PG and the ions were extracted only from 9 apertures (3 x 3) to limit extraction current. The acceleration energy of the beam and the pulse length was limited to 800 keV and 0.5 sec, respectively; this is because the beam target (copper tube with external-fin cooled by the water of 10 m/sec) cannot handle such a high power beam. In case of 800 keV and 100A/m^2 beam with the divergence of 7 mrad, surface heat flux at the beam target was estimated to be 6.4 kW/cm^2, and this is close to the critical heat flux (CHF) for the copper cooling tube [11].

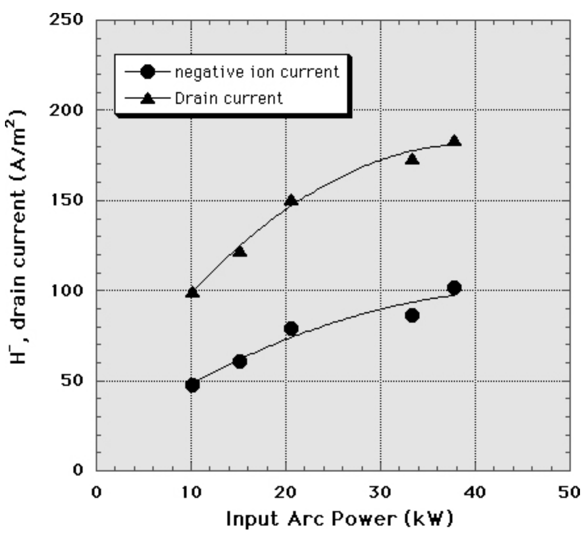

Figure 7. H- beam current as a function of arc power.

Figure 7 shows the H^- beam current and the acceleration drain current as a function of the input arc power at the energy of 800 keV. The source operating pressure was 0.2 Pa and the extraction voltage was adjusted so as to obtain the maximum beam current at each arc power. The H^- current was measured by the calorimeter made of copper, which was installed at the 2.0 m downstream from the beam source. The extracted H^- current increases with increases the input arc power, and a H^- ion beam of 100 A/m^2 (total H^- current; 140 mA) was stably accelerated (arc power 40 kW, extraction voltage 5.5 kV, source pressure 0.2 Pa). The current seems to saturate at higher arc power indicating that almost all ions near the extraction aperture are extracted (emission limit). We have already succeeded in extracting 300 A/m^2 H^- ion beams at KAMABOKO source in previous works (acceleration voltage; 45 kV) [12], therefore, further increase of the current density is possible by tuning the cesium condition and arc discharge power input. For the higher power beam acceleration test, development of the new beam target using the swirl tube is in progress now.

Conclusions

In this paper, present status of the vacuum insulated beam source for the ITER NB was presented. By using the newly developed large stress ring, voltage holding capability was drastically improved, and we have succeeded in sustaining 1 MV for more than 2 hours. No degradation of the voltage holding due to the beam acceleration and/or Cs seeding was observed and the H^- of 0.1- 0.2 A level at 900 keV was stably accelerated for several hundreds of shots. The maximum beam current density at present is 100 A/m^2 at 800keV (80 A/m^2 at 900 keV), which can be applicable to a practical NB system.

References

1. T.Inoue et.al., JAERI-Tech 94-007.
2. Y. Fujiwara et al., JAERI-Research 99-071 (1999).
3. E. Hodgson et al., J. Nucl.Mater,256-263, 1827 (1998).
4. 4. Y. Fujiwara et al., Fusion Eng. Design 55,1(2001)
5. T. Inoue et al., Rev. Sci. Instrum. 71/2, (2000) 744-746.
6. K.Watanabe et.al., Rev.Sci.Instrum., 73, 1090-1092 (2002).
7. M.Hanada, et.al., Fusion Engineering and Design, 56-57, 505 (2001)
8. T.Inoue et.al., Proc. 7th Production and Nuetrarization of negative ions and beams, AIP conference proceedings 380, (1995) pp.397 – 405.
9. T.Inoue et.al., Fusion Engineering and Design 66-68, 597-602(2003)
10.M.Taniguchi et.al., Nuclear Fusion, 43, 665-669 (2004).
11. M.Araki et.al., Fusion Technol., 29, 519-528 (1996)
12.N.Miyamoto et.al. Proc.7th Production and Nuetrarization of negative ions and beams, AIP conference proceedings 380, (1995) pp.300 – 306.