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Development of High Performance Negative Ion Sources and Accelerators for MeV Class Neutral Beam Injectors

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Abstract. Operation of accelerator at low pressure is an essential requirement to reduce stripping loss of the negative ions, which in turn results in high efficiency of the NB systems. For this purpose, a vacuum insulated beam source (VIBS) has been developed at JAERI, which reduces the gas pressure in the accelerator by enhanced gas conductance through the accelerator. The VIBS achieves the high voltage insulation of 1 MV by immersing the whole structure of accelerator in vacuum with long (~ 1.8 m) insulation distance. Results of the voltage holding test using a long vacuum gap of 1.8 m indicate that a transition from vacuum discharge to gas discharge occurs at around 0.2 Pa m in the long vacuum gap. So far, the VIBS succeeded in acceleration of 20 mA (H^-) beam up to 970 keV for 1 s. The high voltage holding capability of the VIBS was drastically improved by installing a new large stress ring, which reduces electric field concentration at the triple junction of the accelerator column. At present the VIBS sustains 1 MV stably for more than 1200 s. Acceleration of ampere class H^- beams at high current density is to be started soon to demonstrate ITER relevant beam optics.

Operation of negative ion source at low pressure is also essential to reduce the stripping loss. However, it was not so easy to attain high current density H^- ions at low pressure, since destruction cross section of the negative ions becomes large if the electron temperature is > 1 eV, in low pressure discharge. Using strong magnetic filter to lower the electron temperature, and putting higher arc discharge power to compensate reduction of plasma density through the filter, an H^- ion beam of 310 A/m^2 was extracted at very low pressure of 0.1Pa. This satisfies the ITER requirement of current density at 1/3 of the ITER design pressure (0.3 Pa).

1. Introduction

One of the key components of the NB system is a high power and high energy beam source which can produce 40 A D^- ion beam at the energy of 1 MeV. JAERI (Japan Atomic Energy Research Institute) has developed the negative ion sources and accelerators to realize efficient and reliable operation of the NB system.

To produce the high energy negative ion beam, the reduction of the gas pressure in the accelerator is one of the most critical issues, since the negative ions are easily neutralized before full acceleration by collisions with residual gas molecules in the accelerator. The neutralization causes not only a loss of negative ions but also acceleration of the stripped electrons. The acceleration of the stripped electrons leads to the reduction of acceleration efficiency and an increase of heat load on the accelerator grids. To overcome this problem, a vacuum insulated beam source (VIBS), which immerses the negative ion source and accelerator in vacuum, has been developed instead of the gas insulated beam source (GIBS). Comparing with the GIBS, the VIBS has larger gas flow conductance around the accelerator that results in significant reduction of the residual gas pressure in the accelerator.

Reduction of the operating pressure of the ion source is also effective to decrease the gas pressure in the accelerator. For this purpose, KAMABOKO source, a prototype of the ITER negative ion source, has been developed to achieve high current density even at low pressure (< 0.3 Pa). Normally electron temperature increases as lower the pressure in arc discharge plasma, and destruction cross section of the ions becomes large as the electron energy increase to > 1 eV. In the present experiment, the electron temperature was lowered using strong transverse magnetic field, called “magnetic filter”, which only allows low temperature electrons diffusing into the extraction region of the ion source. In the present paper, recent activity of JAERI NBI group is presented focusing on the development of VIBS accelerator and the low-pressure high current density source.

2. MeV class Vacuum Insulated Accelerator

A vacuum insulated beam source, as shown in Fig.1, has been developed to demonstrate the 1MV insulation and high current negative ion acceleration. The VIBS consist of five acceleration stages, each acceleration grid is supported and insulated by post spacers made of alumina instead of large insulator columns surrounding the accelerator structure as in the GIBS. Having no surrounding structure, the VIBS allows rapid pumping of residual gases through the accelerator’s grids support that results in significant reduction of pressure in the accelerator. Hence, it is expected that the VIBS give lower stripping losses of 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 VIBS at operating pressure of 0.3 Pa. This value is about a half of the GIBS [1]. Thus the power losses caused by the acceleration of the electron and the neutralization before full acceleration can be reduced from 16 % to 6% by using the VIBS. The VIBS is also promising from the viewpoint of radiation-induced conductivity (RIC)[2,3,4].

As mentioned above, the VIBS has many attractive features compared with conventional GIBS. However, the VIBS for the ITER NB system forms meter-class long gaps in vacuum between 1 MV potential and ground. The pressure in the gap ranges in 0.01 Pa - 0.1 Pa during the NB operation. The previous work [5] has investigated the discharge characteristics under the above conditions and the ITER NB design has been done so that the 1 MV insulation is secured from both Paschen gas discharge [6] and Clump theory [7] for vacuum. In the case of vacuum discharge (Clump theory), the long insulation gap is appreciated, however long gap is not favorable against the Paschen discharge under high pressure. Thus careful design is required for the vacuum insulation of the VIBS. However, there are few experimental reports on vacuum insulation of MV class high voltage in meter-class long gap.

In the present work, a high voltage insulation test for vacuum gaps of 1.8 m was carried out using the accelerator column of VIBS. The flashover voltage as a function of p.d (p; gas pressure, d; gap distance) is shown in Fig.2. The flashover voltage rapidly decreases above

Fig.1 Vacuum insulated MeV accelerator.

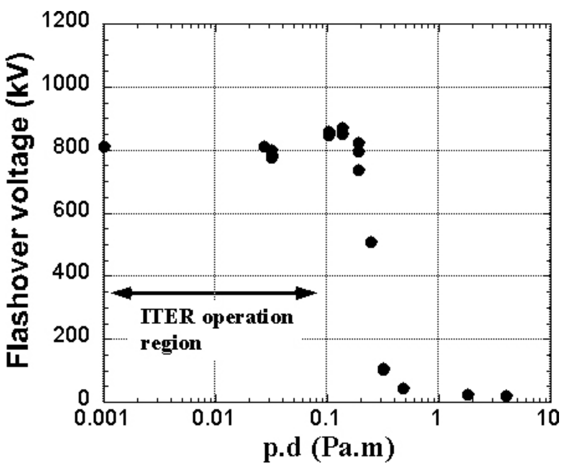

Fig.2 Breakdown characteristics of long vacuum gap

0.2 Pa m, where the transition of discharge mechanism occurred from vacuum discharge to gas discharge. As was designed in ref. [5], it was experimentally confirmed that the ITER NB condition locates left side (lower p.d) of the transition area as shown in Fig.2, which is free from the gas discharge.

Thus the dominant discharge mechanism in the ITER NB condition could depend on the Clump theory; this means that the larger gap is favorable for 1MV vacuum insulation. Adapting the vacuum insulation technique described above, negative ion acceleration test had been carried out using the prototype VIBS accelerator. Up to now, the highest beam energy of 971 keV was attained with an accelerated beam current of about 20 mA for 1 s.

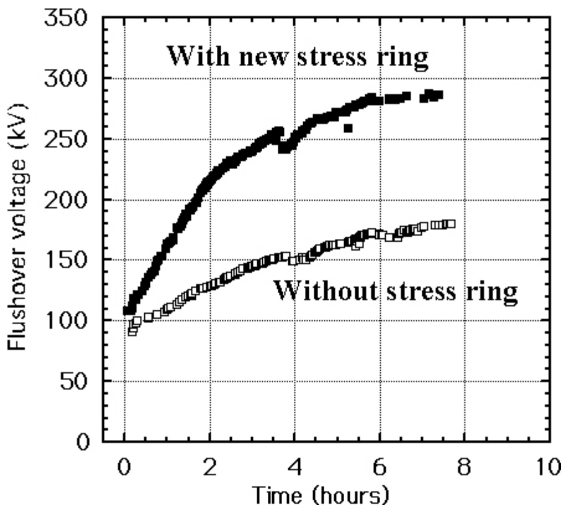

Fig.3 Voltage holding test with new stress

By using the VIBS, we have succeeded in accelerating the negative ion beam up to 971 keV. However, the negative ion current was still in a low level. This is because voltage holding performance of the VIBS was not stable enough. To sustain 1 MV stably, improvement of the stress ring at the triple junction (interface of metal flange, FRP, and vacuum) was performed for the MeV VIBS accelerator. The results of the electrostatic analysis showed that the newly developed stress ring can reduce the electric field to 1.2 kV/mm at the triple junction from 3.6 kV/mm in the original. The voltage holding performance was tested by the insulation column of the MeV VIBS with and without the new stress ring. The result of voltage holding test for one stage of the accelerator (rated voltage; 200 kV) is shown in Fig.3. With the new stress ring, the flashover voltage reached at rated voltage of 200 kV within the first several minutes whereas the accelerator without ring could not reach 200 kV even after 8 hours of operation. Moreover, with the new stress ring, the highest voltage reached more than 300 kV, where the voltage holding test was stopped to avoid possible damage of the insulator at 1.5 times higher than the rated voltage. It was confirmed that the electric field at the triple junction should be lowered with properly designed stress ring. Thus the MeV prototype VIBS at JAERI sustains 1 MV stably at present. The beam acceleration test of VIBS with newly developed stress ring is now in progress.

3. A High Density Negative Ion Production at Low Pressure

At JAERI, high current negative ion sources of Cesium seeded volume production type has been developed for the ITER NBI application. One of the sources, KAMABOKO source, has already succeeded in demonstrating ITER design current density (300 A/m^2) at 0.3 Pa in a short pulse [8]. However, the grid power loading even at 0.3 Pa is close to the design limit (1MW) [9]. Thus, further reduction of operating pressure is desirable for reliable operation throughout the ITER life.

The negative ions have large destruction cross-section by collision with electrons of > 1 eV. However, electron temperature in the volume production type sources tends to increase in arc discharge of the low pressure, and consequently, negative ion current decreases steeply at the pressure lower than 0.3 Pa. To maintain plasma with low electron temperature in the ion extraction region, transverse magnetic field, so called “magnetic filter” is equipped in the negative ion sources of the volume production type. In the present work, enhancement of the negative ion beam current was attempted by lowering the electron temperature with strong magnetic filter field.

Figure 4 shows the cross-sectional view of the plasma source used in this work. The plasma generator is a multi-cusp semi-cylindrical ion source, called "KAMABOKO" source [8,10]. The source plasma is generated by fast electrons emitted from eight tungsten filaments, and the interior wall of the KAMABOKO chamber serves as an anode. To enhance the production of H^- ions, about 1g of cesium (Cs) were seeded in the chamber. The negative hydrogen ion was extracted by applying the extraction voltage of 9 kV between plasma grid (PG) and extraction grid (EXG), and acceleration voltage of 39 kV between EXG and ground grid (GRG). The beam current was measured by a calorimeter, which locates at 1.3 m downstream from GRG.

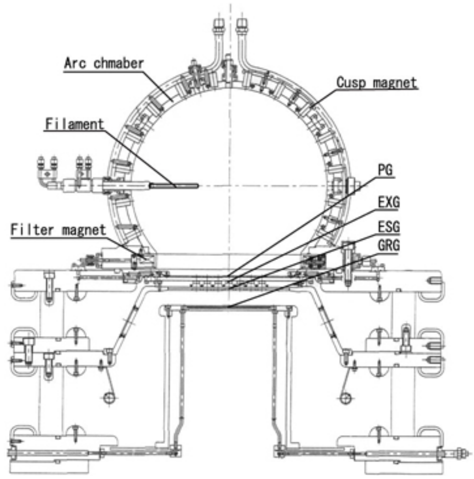

Fig.4 Cross-sectional view of the "KAMABOKO" source.

The magnetic filter of three different strengths were tested; type I: 226 G cm, type II: 605 G cm and type III: 907 G cm, respectively. Figure 5 shows the pressure dependence of electron temperature measured by a Langmuir probe at extraction region (1 cm apart from PG) obtained with constant arc power of 10 kW. It was found that the electron temperature increases with decreasing the source pressure, whereas it decreases with increasing the strength of the magnetic filter. The type III filter maintain the electron temperature of ~2eV, which seems to be effective to enhance the negative ion production, even under the low operating pressure of 0.1 Pa.

The beam extraction test was performed using the type III filter. The results are shown in figure 6. The negative ion current density increases linearly with increasing the applied arc power. A high current density beam of 310 A/m^2 was extracted at 0.1 Pa. The operating pressure in the negative ion source was 1/3 of the design value for ITER. Although the present result was obtained by operating the source with twice higher input power density (80 kW) than the ITER design value [4], and also in a limited pulse length (0.1 s), the present result

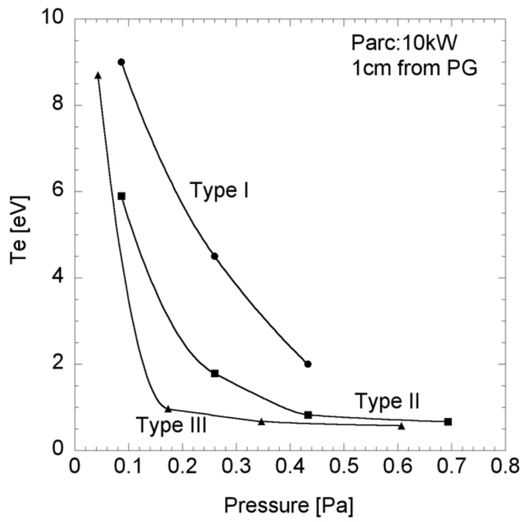

Fig.5 Pressure dependence of electron temperature in KAMABOKO source

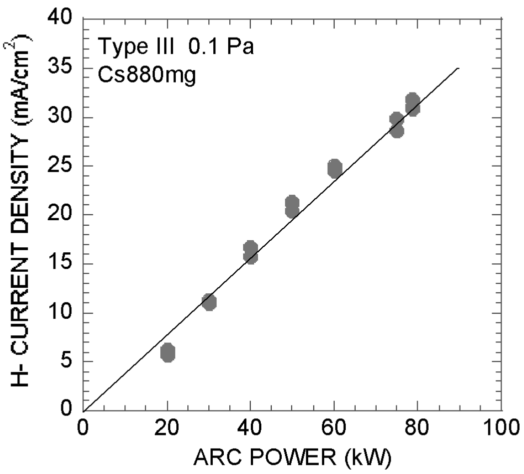

Fig.6 H^- current density obtained by using typeIII filter.

gives a prospect to realize a low-pressure high-density source. We plan to demonstrate the operation of the negative ion source for long pulse duration of 1000 s under the conditions of 310 A/m^2, which are ITER operation conditions, under low pressure at 0.1 Pa.

4. Conclusion

The reduction of gas pressure in the accelerator is one of the key issues to realize the high-energy negative ion beam source. For this purpose, VIBS accelerator and the low operating pressure source have been developed.

The VIBS accelerator has succeeded in accelerating the negative ion beam up to 971 keV for 1 s. The high voltage holding capability of the VIBS was improved by installing a new large stress ring, which reduces electric field concentration at the triple junction of the accelerator column. At present the VIBS sustains 1 MV stably for more than 1200 s.

As for the low operating pressure source, an H^- ion beam of 310 A/m^2 was extracted even at the low pressure of 0.1 Pa by optimizing the filter magnetic field.

These results give the prospect to realize the high power NB systems with high reliability and efficiency.

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