Production of High Power and Large-Area Negative Ion Beams for ITER

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Abstract. The paper reports the progress of R&D toward the ITER neutral beam (NB) system at Japan Atomic Energy Agency (JAEA) during 2004-2006. In the accelerator development, an H^- ion beam of 146 A/m^2 was accelerated up to 836 keV in a vacuum insulated accelerator with five acceleration stages. This is the first production of a high power density beam of MeV range energy, which is relevant to ITER requirements (200 A/m^2 and 1 MeV). The ITER NB system requires a high voltage (HV) bushing as an electric feedthrough to the vacuum insulated accelerator. A full-size(1.56 m in diameter and 0.292 m in height) insulator ring made of alumina ceramic has been successfully fabricated for the HV bushing, as a result of technology development of new cold iso-static press (CIP).

Long pulse operations of the JT-60U negative ion sources are in progress, which has a large extraction area of 0.45 x 1.1 m^2. From the ion sources, D^- ion beams of 20 A (90 A/m^2), 320 keV have been produced for 21 s. As the consequence, injection of 3.2 MW D^0 beams was achieved. Thus the long pulse operation of negative ion based NB system has been demonstrated with multi-tens of ampere of D^- ions extracted from the ion extraction area relevant to the ITER NB design (0.6 x1.5 m^2). For long pulse operation of such powerful beams, the negative ion uniformity over the wide extraction area is an essential issue to avoid excess power loading on the accelerator grids. By adopting a new magnetic configuration with so called “tent filter”, the uniformity of the JAEA 10 ampere source (extraction area: 0.13 x 0.22 m^2) was improved to be ± 4%, which fulfilled the ITER requirement (±10%).

1. Introduction

The ITER negative ion source and accelerator are required to produce D^- ion beams of 40 A (current density: 200 A/m^2) from a large extraction area of 0.6 x 1.5 m^2, and then to accelerate up to 1 MeV to inject the neutral beams of 16.7 MW into the ITER plasma for 1000 s [1]. The required energy and current of the D^- ion beam are twice higher than those of existing negative ion based NB injectors [2, 3]. There are two major issues to meet the ITER requirements: One is the acceleration of the high-current density beams up to 1 MeV level, and the other is the long pulse production of high current beams.

In the accelerator development, a vacuum insulated electrostatic accelerator has been developed at JAEA to avoid radiation-induced ionization of the insulation gas such as SF_6 [4]. So far, H^- ion beams of 146 A/m^2 was accelerated up to 836 keV in the vacuum insulated accelerator [5]. Thus the beam energy and current density are approaching to the ITER requirements (1 MeV and 200 A/m^2). Here the beam power density, defined by a product of the beam energy and current density is more than twice higher than those of the existing negative ion based NB systems.

There was a progress in manufacturing technology development of a high voltage (HV) bushing which was a key component as a vacuum boundary between the SF_6 insulation gas from the HV power supply and the vacuum insulated accelerator. The bushing supplies electric powers at 1 MV and four intermediate acceleration voltages to the ion source and the accelerator, maintaining the high voltage insulation. In the ITER HV bushing, a large (1.56 m in diameter) insulator ring made of alumina ceramic is utilized for the 1 MV insulation. However, during the ITER Engineering Design Activity, the full-size insulator ring was not fabricated due to size limitation of existing manufacturing facilities. After the EDA, some industries in Japan constructed large facilities for manufacturing of large ceramic plates of ~ 2 m that are utilized in liquid crystal display production. Then JAEA together with the Japanese industries started development of the manufacturing technology for the full-size ceramic ring for ITER. Recently, the full-size ceramic ring was successfully manufactured utilizing a newly developed cold iso-static press (CIP) technology.

In the JT-60U negative ion based NB injector, the pulse length of the D^- ion beams was carefully extended up to 21 s with the current of 12 A and 8 A from two negative ion sources whose acceleration gird is nearly as large as that designed for ITER. As the result of this long pulse demonstration, it was confirmed that reduction of grid power loading is necessary for the long pulse operation of ITER class powerful beams. The grid power loading is mainly due to a large divergence of the beams generated from local area where the negative ion uniformity is poor, and therefore, the beam optics was not locally matched to the optimum over the large extraction area of JT-60U [2]. Thus it has been pointed out that improvement of negative ion uniformity is essential to achieve long pulse operations of high power beams. After a physical study on the negative ion production in the JAEA 10 ampere negative ion source whose ion extraction area is ~1/4 of the ITER source, a new magnetic configuration was tested to improve the uniformity of the negative ion production. As the result the deviation of the local beam intensity from the averaged value was reduced to be ±4%, which fulfills the ITER requirement.

The paper reports the R&D progress at JAEA since the last conference of this series [6] on the aspects of acceleration and long pulse operation.

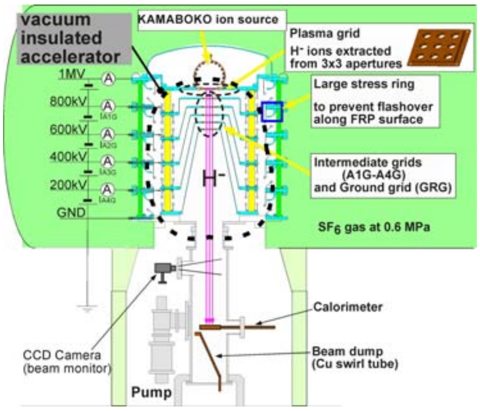

Figure 1 A cross-sectional illustration of the MeV accelerator developed at JAEA.

2. Accelerator Development

A cross-sectional illustration of the MeV accelerator developed at JAEA is shown in Fig.1. The negative ions are produced in the ion source mounted on the top of the accelerator and are extracted from 9 apertures of the plasma grid by potential difference of several kilo volts applied between the plasma grid and the extraction grid. The target of the MeV accelerator is to produce 1 MeV, 200 A/m^2 H^- ion beam at the beam divergence angle of < 5 mrad. Figure 2 shows the accelerated H^- ion current density (J_H^-) as a function of the acceleration voltage (Vacc). In this measurement, the ion extraction voltage and the input arc power of the ion source were optimized for minimizing the direct interception of the H^- ions in the accelerator, namely, for maximizing the beam current at calorimeter located at 2 m downstream from the grounded grid for each of the Vacc. The optimum current density increased according to the Child-Langmuir's law. The perveance of the beam ($P = I_H^-/Vacc^{3/2}$) was nearly equal to the ITER design value (200 A/m^2 at 1 MeV). So far, the H^- ion beam of 146 A/m^2 was successfully accelerated up to 836 keV. The power density of this beam reaches 122 MW/m^2, which is more than twice higher than those of the existing NB systems for large experimental reactors such as JT-60U and LHD.

As for the beam quality, the beam profile was estimated from the light intensity of residual H_2 molecules excited by the collisions with the accelerated H^- ions in the beam-line. At an optimum perveance, the divergence angle of the beamlets was estimated to be 5 mrad, which was lower than the design value of ITER (7 marad).

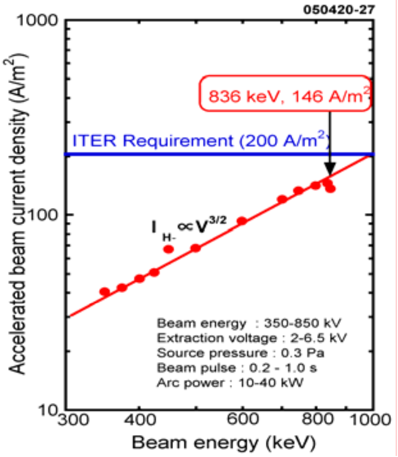

Figure 2 Accelerated beam current density as a function of the beam energy.

3. High Voltage Bushing Development

In a 1 MV high voltage (HV) bushing [1], a large alumina insulator with cylindrical shape is utilized for sustaining high voltage and forming vacuum seal. The dimensions of the insulator are 1.56 m in outer diameter, 1.46 m in inner diameter and 0.292 m in height.

The forming process of the alumina powder is a key fabrication process for such a large alumina insulator. In the present fabrication of the ITER insulator, a cold iso-static press (CIP) process has been chosen. In the conventional CIP process, the Al_2O_3 powder of high purity (99%) is filled in a metal frame, of which outer frame is covered with rubber to allow compression of the power inward. And hence, this requires the frame of larger outer diameter than the dimension of formed alumina ring. Moreover, the formed alumina shrinks 20% in the diameter during sintering process. Thus the frame of more than 2.5 m in the diameter is necessary if the conventional CIP process is applied, which is not acceptable due to limitation in the inner diameter of the water pressure vessel for the CIP. To overcome this difficulty, the metal frame whose diameter is smaller than that of the inner diameter of the water pressure vessel was utilized and placed at the outside of the rubber frame as shown in Fig.3. By this configuration, the powder is compressed outward.

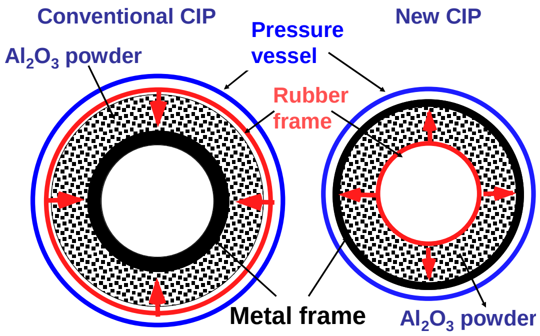

Figure 3 Schematic diagrams of the conventional and newly developed CIP processes.

The new CIP process was tested in the fabrication process of a half size (0.8 m in diameter) ceramic ring to confirm its feasibility. As the result, it was confirmed that density of the ceramic ring fabricated by the new CIP was equivalent to that by the conventional CIP. Then, the new CIP was applied to the fabrication of an ITER full-size ceramic insulator. As shown in Fig.4, the full-size ITER insulator ring was successfully fabricated without any failure or cracks.

The ceramic ring is connected to a metal flange via a thin metal plate to form a vacuum boundary. Kovar was chosen as the metal plate since it has a thermal expansion coefficient nearly equal to the alumina ceramic. In order to joint the ceramic ring to the kovar plate, metalizing of ceramic is necessary, then the ceramic is brazed onto the kovar

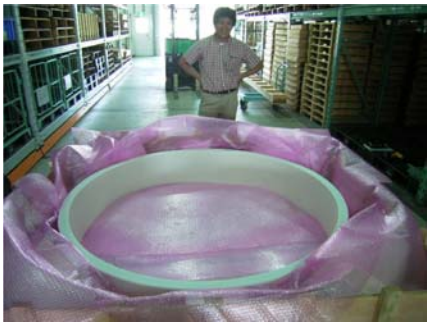

Figure 4 A full-size of the ITER insulator.

plate. The metalizing of the alumina insulator has not been applied to such as a large alumina insulator. Moreover, the thick kovar plate of > 2.0 mm in thickness, that is required to endure the compression force of 1.0 MPa, has not been metalized and blazed. For these reasons, the metalizing technology is being developed with a Japanese industry. Because of the limitation of available furnace (vacuum and size), only an active titanium metalizing process was found applicable to the metalizing/brazing process of the ITER full-size insulator ring. This process is being tested with small samples, and then to be applied to the half-size insulator. After the brazing test, the assembly of the half-size insulator ring together with the metal flanges is to be served in tests for the high voltage holding and mechanical strength.

4. High Current and Long pulse Beam Production in JT-60U Negative Ion Source

The JT-60U negative ion source was designed to produce 22 A, 500 keV D^- ion beam for 10 s [2]. Two ion sources are mounted on a vacuum vessel of the negative-ion-based NB injector in JT-60U. To produce high current beams, large grids with multi-apertures is utilized which have water cooling channels between each row of apertures. The grid area is 0.45 x 1.1 m^2 and nearly equal to that of the acceleration grid in the ITER accelerator. Each grid consists of 5 segments, in each of which there are 24 x 9 apertures. In one of the sources mounted on upper part of the vacuum vessel, D^- ions were extracted from 5 segments, and the other one on the lower part utilized central 3 segments with discarding grid segments from top and bottom.

The acceleration voltage was chosen to be relatively low value of 320 keV to avoid beam pulse interruption after a breakdown of high voltage in long pulse operations. The ion extraction voltage and the arc input power were optimized so as to minimize the grid power loading. The D^- ion beams of 12.8 A (~90 A/m^2) and 8.5 A (~90 A/m^2) were produced from the upper and lower ion sources, respectively. Note that the beam currents were evaluated from a sum of the beam powers deposited on the residual ion dump and the calorimeter. For both of the ion sources, the highest grid power loadings were observed in the grounded grid, namely 600 kW and 350 kW in the upper and lower ion sources, respectively. The grid power loading normalized by the total beam power was higher in the upper ion source. This is mainly due to higher stripping loss and larger divergence of the beams generated from top and bottom grid segments where the ion uniformity was poor, and hence, the beam optics was not locally matched to the optimum.

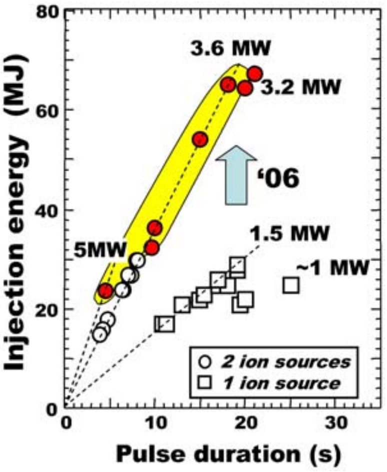

Figure 5 Injection energy of D^0 beams as a function of pulse duration.

The beam pulse length was carefully extended shot by shot while the power loadings of the acceleration grids and the beam-line components were measured and examined. Finally, D^- beams have been successfully produced for 21 s as shown in Fig.5. This led to a long pulse injection of 3.2 MW D^0 beams into the plasma in JT-60U. The D^- ion beam power was confirmed to be kept constant during 21 s from constant surface temperature on the residual ion dumps measured by thermo-couples. The D^0 beam power was also estimated to be constant during 21 s from the constant pressure at a location near the injection port. The long pulse production of negative ion based NB system has been successfully demonstrated with multi-tens of ampere of D- ions extracted from the ion extraction area relevant to the ITER NB design ($0.6x1.5m^2$). In the experiment campaign, the pulse length was restricted by a temperature interlock of the un-cooled molybdenum limiter near the injection port. In the next campaign, the beam pulse length is to be further extended by increasing the interlock level from the present value of 650 °C to a maximum allowable level of 1000 °C.

Figure 6 shows the time evolution of the water temperature rise of the grounded grid at 600 kW in the lower ion source. The water temperature rise was saturated at around 40°C within 20 s under estimated heat flux (average over the grid area) of 2 MW/m^2. Thus it was suggested that the grid can sustain the heat flux of this level even in long pulses of 1000 s, since the present heat load was nearly equal to that designed for the ITER accelerator.

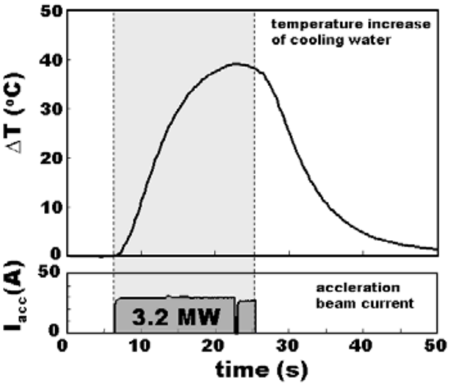

Fig. 6 Typical temperature rise of the cooling water for grounded accelerator grid at 600kW.

5. Study of the Beam Non-Uniformity

To improve the beam uniformity, a physical mechanism of the beam non-uniformity was examined in the JAEA 10-ampere negative ion source, of which longitudinal size is about 1/4 of the ITER negative ion source. Thus the dimensions of the source are much smaller than the sources of JT-60U and ITER, however, the magnetic configuration is similar to those of the JT-60U and ITER. It has been reported that the primary electrons drifts in the transverse magnetic field by "external magnetic filter", resulting in a locally high electron temperature (Te) in the ion extraction region [7]. This causes the non-uniformity of the negative ions under "pure volume (without Cs)" operation of the source, since the negative ion has a large destruction (electron detachment) cross section due to collisions with the fast electrons.

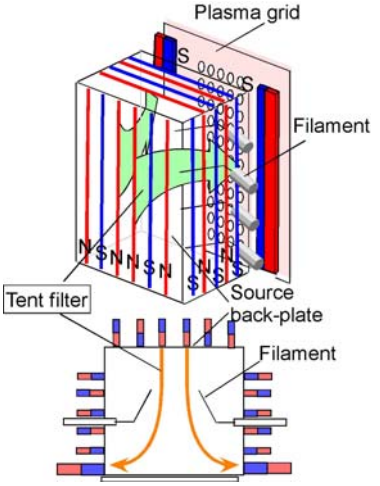

Fig.7 A proposed magnetic configuration with tent filter.

In the present experiment, a sufficient amount of Cs was seeded in the source to enhance surface production of the negative ions, as in the JT-60U and the ITER negative ion sources. Seeding Cs, the plasma parameters such as Te and plasma density were not varied. However, the total beam current was increased by a factor of 4. The beam profile was totally changed after the Cs seeding. Namely, the beam intensities were higher from the region of high plasma density and high Te though the original beam intensity was lower from this region due to the local destruction of negative ions without the Cs seeding. This suggests that the negative ions are produced more efficiently in the high Te region under the Cs seeded condition owing to local high densities of atoms and/or positive ions as the parent particles of the negative ions.

To improve the beam uniformity, the drift of the fast electrons was suppressed by modifying the magnetic configuration in the source. Instead of the original external filter, a tent-shaped filter field was formed between the cusp magnet on the back plate and the large magnets near the plasma grid as shown in Fig. 7. Moreover, the cusp magnets on the source wall were arranged to avoid the formation of the transverse field in the source. The combination of the tent filter and the cusp magnets allows the fast electrons to rotate around the tent filter field so as to avoid electron localization. This magnetic configuration improved the plasma

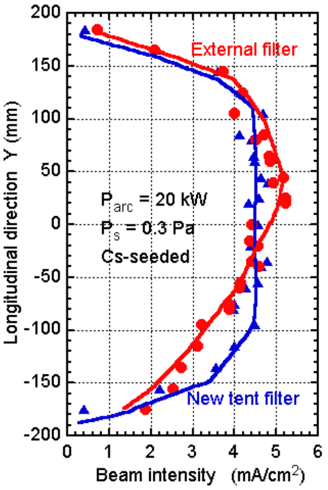

Fig. 8 Beam profiles obtained with external and tent filters

uniformity, resulting in an improvement of the beam uniformity as shown in Fig.8. The root-mean-square deviation of the local beam intensities from the averaged value over the area -105 mm $\leq$ y $\leq$ 105 mm was reduced to about a half of that before the modification of the magnetic configuration. The total beam current of ~2 A (~ 100 A/m^2) was also maintained with an electron/ion ratio of 1.3. The deviation obtained with tent shaped filter was ±4% that fulfilled the ITER requirement. Since this magnetic configuration is applicable to the JT-60U negative ion source, it is expected that the beam pulse length is to be extended further even for higher power beams, by reducing excess power loadings on the acceleration grids. The physics understanding and the technology developed here will also realize the uniform negative ion production in the ITER negative ion source.

5. Summary

The R&D's toward the ITER NB system has been substantially progressed as follows:

- An H$^-$ ion beam of 146 A/m^2 (total ion beam current of 200 mA) was accelerated up to 836 keV in a vacuum insulated accelerator that was designed for the ITER NB system. By installing a new beam dump with the allowable power loading of 200 MW/m^2, acceleration of the higher current density beams is in progress.
- A full-size (1.56 m in outer diameter and 0.292 m in height) alumina ceramic insulator for the HV bushing of ITER NB system has been successfully fabricated. The active titanium metalizing and brazing process is also developed.
- Using two negative ion sources, a 20 A, 320 keV D$^-$ ion beam has been successfully produced continuously for 21 s without reduction of the beam current, resulted in 3.2 MW D^0 injection to the JT-60U.
- A tent shaped magnetic filter was applied to the JAEA 10A negative ion source. This allowed to satisfy the beam uniformity designed for the ITER ion source.

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