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Development and design of the negative-ion-based NBI for JT-60 Super Advanced

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A large negative ion source with an ion extraction area of 45 cm x110cm has been developed to produce 500 keV, 22 A D^- ion beams required for JT-60 Super Advanced. To realize the JT-60SA negative ion source, the JT-60 negative ion source has been modified and tested on the negative-ion-based neutral beam injector on JT-60U. The significant effort has been made for the high-energy beam production and the long pulse injection. By improving voltage holding capability of the negative ion source, a 500 keV H^- ion beam has been successfully produced at the beam current of 3 A through 20% of the total ion extraction area. This is the first demonstration of a high-energy negative ion acceleration of more than one-ampere to the beam energy of 500 keV in the world. A long pulse injection of 30s has been achieved at an injection D^0 power of 3 MW by reducing the power loading of the acceleration grids in the negative ion source. The injection energy, defined as the product of the injection time and power, reaches 80 MJ of the limitation of the heating time allowed on JT-60U. This is the world record of the injection energy from one injector.

Keywords: neutral beam, negative ion beam, JT-60U, JT-60SA, voltage holding capability, long pulse injection

1. Introduction

The JT-60SA (JT-60 Super Advanced) project is a combined project of JAEA's program for national use and JA-EU Satellite Tokamak Program collaborating with Japan and EU fusion community. The main objectives of the JT-60SA are to demonstrate steady-state high-beta plasma, and to support ITER through the optimization of ITER operation scenario [1].

A negative-ion-based neutral beam (N-NB) injector is required to inject 500 keV, 10 MW D^0 beams for 100s. The N-NB injector in JT-60U will be re-used in JT-60 SA by modifying existing components. The level of the N-NB beamline from the floor will shift downward to drive off-axis plasma current [2]. The power supply system will be upgraded to extend the injection pulse length from 10s to 100s. Moreover, the negative ion source is being modified to produce 500keV, 22A D^- ion beams for 100s.

Since 1996 of the first injection from two negative ion sources where each is designed to produce a 22 A, 500 keV D^- ion beam for 10s [3], the highest injection D^0 power was no more than 5.8 MW at 400 keV that was lower than the rated power for JT-60SA. The injection power is limited by a poor voltage holding capability of the negative ion sources. Therefore, the improvement of voltage holding capability is one of the key issues for the realization of the N-NB injector on JT-60 SA.

In order to improve voltage holding capability, vacuum insulation characteristics of a gap between large acceleration grids is examined in the JT-60 negative ion source to clarify gap lengths required for high voltage holding. From this result, the negative ion source is modified, and then tested at high voltage. After the tests of voltage holding capability without the beam acceleration, the high-energy beams are being produced to examine the influence of the beam acceleration on voltage holding capability and demonstrate a 500 keV ion acceleration

In parallel to the improvement of voltage holding capability, the feasibility for the long pulse injection is

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experimentally examined on JT-60U since the pulse length for JT-60 SA is ten times longer than that in JT-60U. Taking account of the operation range of existing power supplies on JT-60U, the pulse length on JT-60U is targeted to be 30 s. To realize the long pulse injection, the power loading on the acceleration grid is reduced by optimizing the steering angles of the negative ion beam.

The paper reports the latest R&D results of the negative ion source towards JT-60SA after a brief description of the design for the N-NB injection for JT-60 SA.

2. Design

2-1 Disassembly of the N-NB injector

The N-NB injector on JT-60 will be reused in JT-60 SA after upgrading some components. The N-NB beamline will be kept to be placed at the same position in the reactor without the disassembly. However, a power supply (HV) deck with a potential of -500 kV, that occupies a large space in the reactor hall, will be removed to free up space for the transportation path of the other disassembled devices, and then stored in the other radiation controlled buildings. The HV deck will be simultaneously with the inner power supplies after the reinforcement of the frame with beams for withstanding a total weight of 150 tons.

The sequence of disassembly is shown in Fig.1. The removal of the HV deck will be finished by the middle of January, 2010. After removal of the HV deck and a neutron shielding wall dividing the reactor hall into two areas, twelve positive-ion-based NB tanks around the vacuum vessel will be removed with the inner beamline components. Then, the NB tanks will be filled with a dry nitrogen gas, and stored in the other radiation controlled area. The disassembly of the all NB injectors is planned to be finished by the end of March, 2011.

2-2 Modification of the N-NB beamline

The level of the N-NB beamline from the ground floor is required to shift 60 cm downward in order to drive off-axis plasma current in the high-β (β_N=3.0) plasma [4].The support stands below the N-NB vacuum vessels, where large cryopumps and residual ion dumps are installed, will be shortened. The level of maintenance stages around the beamline will be also shortened. The routing of the service lines such as power supply cables, water tubes, and cryogenic tubes will be re-positioned.

2-3 Upgrade of the N-NB power supply

The power supply system will be largely upgraded to extend the injection pulse length from 10s to 100s because of little margin for 100 s injection in the present power supply. The power supply system on JT-60U is composed of negative ion generation, extraction, and acceleration power supplies. In the acceleration power supply, an inverter switching system is positioned on the AC low voltage side to cutoff the high power on a time scale of 100 μs during the breakdown of the negative ion source. A high frequency inverter of 150 Hz, which is switched by Gate-Turn-Off (GTO) thyristors, is utilized to smooth the ripple. On JT-60U, three GTO thyristors are connected in parallel for each of three acceleration stages as shown in Fig.2. For the pulse extension to 100 s for JT-60SA, number of the parallel connection for each stage will be increased from 3 to 4 to reduce the current handled in one GTO thyristor. Therefore three GTO thyristors are additionally required for all three acceleration stages. However, since the present GTO thyristor is not available due to stop of the manufacturing, an injection enhanced gate transistor (IEGT) [5] is a candidate for the replacement of the additional GTO thyristors. In JT-60 SA, the parallel connections with four GTO thyristors are designed for two acceleration stages. For the other acceleration stage, the parallel connection with nine IEGTs are designed. The other power supplies will be also upgraded by the replacement with electric parts with larger thermal capacities and by additional cooling fans.

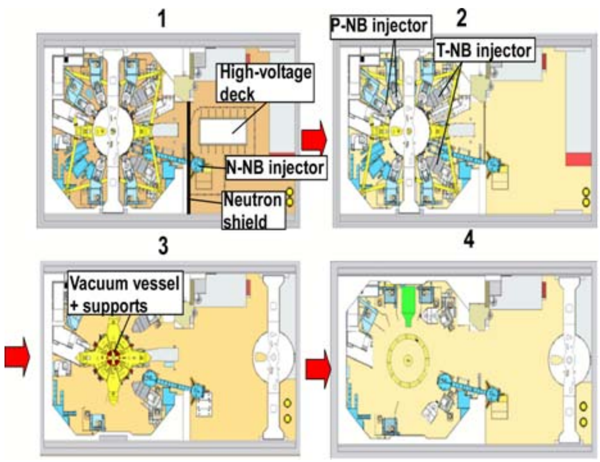

Fig.1 Sequence of disassembly in JT-60U. 1) Original layout, 2) Removal of HV deck and neutron shield wall, 3) Removal of P-NB tanks, 4) Removal of vacuum vessel

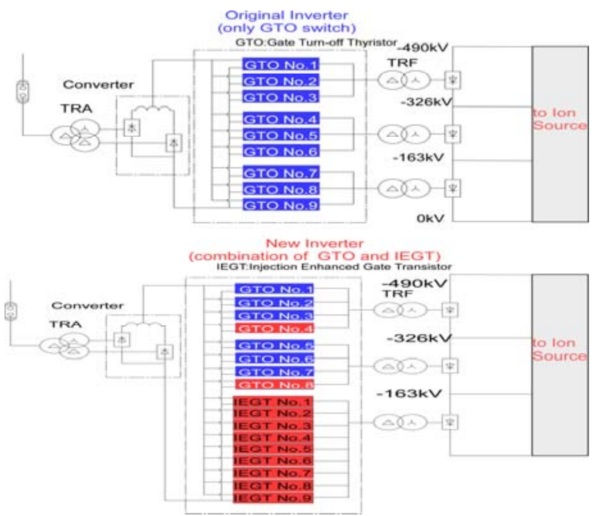

Fig.2 Inverters in the acceleration power supplies on JT-60U (upper) and JT-60SA(lower)

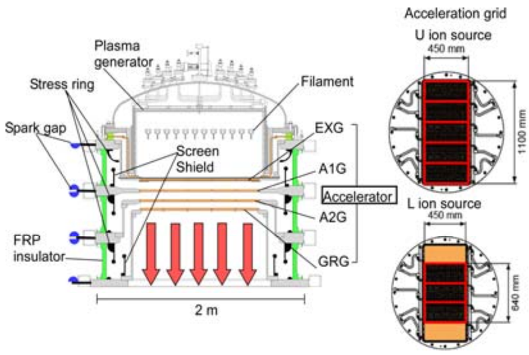

Fig.5 Schematic diagram of the original JT-60 negative ion source

3. Long pulse injection in N-NB injector on JT-60U

3-1 Reduction of the power loading of the acceleration grids.

The long pulse injection of the neutral beams started using one ion source in 2004. Then, both of two ion sources were operated at high arc discharge power to increase the injection power in 2006, where the long pulse injection was found to be limited by the power loading of the acceleration grids in the ion source [6]. The highest grid power loadings in the two ion sources, called as the U and L ion source, were 7 % and 9% of the accelerated beam power on the grounded grid in the L and U ion sources, respectively. These grid power loadings were higher than an allowable level of 5% for the long pulse injection.

The ion trajectory was calculated using a 3 D calculation code [7] to clarify the origin of the grid power loading. The grid power loading was found to be caused by direct interception of outmost beamlets by the grounded grid, due to the un-optimized field shaping (FS) plates which is equipped with the extraction grid (EXG) to suppress an outward deflection of the outmost beamlets by a space charge of the inner beamlets [8]. To suppress the direct interception of outermost beamlets, a new FS plate was designed using a 3 D calculation code.

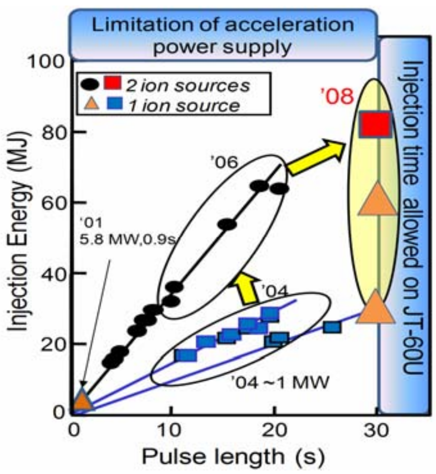

Fig..3 Progress in the long pulse injection on JT-60U. The ion extraction areas of the two ion sources (the U and L ion sources) are different each other (see Fig.5), so that the injection powers from two ion sources are different.

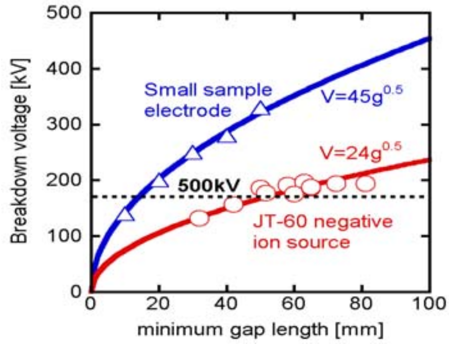

Fig.6 Vacuum insulation in a gap between the grids in the JT-60negative ion source

The distance between the FS plate and the outmost apertures and the geometry of the FS plate were optimized. The new FS plates properly steer the outermost beamlets as predicted by the simulation, resulting in the reduction of the grid power loadings. At a typical operation pressure of 0.3 Pa, the grid power loadings of the grounded grid in the U and L ion sources have been reduced from 9 % to 7% and 7% to 5%, respectively. The power loading of the grounded grid in the L ion source was successfully reduced to an allowable level for the 100s long pulse injection on JT-60 SA. The higher power loading in the U ion source could be reduced to the allowable level by improving the beam uniformity with the tent-shaped filter [9]. After the power loadings of the acceleration grids were confirmed, the injection pulse length was extended step by step. Since the conditioning progress of the ion sources differed each other, the long pulse operation of the ion source was independently carried out in early stage of the 2008 campaign. The first long pulse injection was carried out using the L ion source where the beam of 290 keV, ~10A was produced to inject a 1 MW D^0 beam. The pulse length of the 1 MW D^0 beam was extended to 30s. The injection energy, defined as the product of the injection power and the pulse length, was 30 MJ. The injection energy was increased to 60 MJ by neutralizing a 340 keV, ~17A beam for 30s produced in the U ion source. After sufficient conditioning of both ion sources, the D^0 beam was injected simultaneously using two ion sources, where ~27A beam was produced at 340 keV. A ~3.0 MW D^0

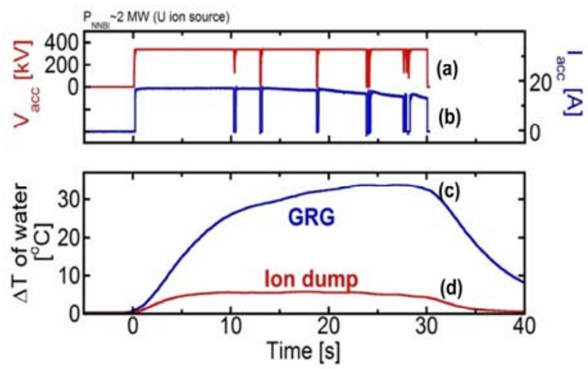

Fig.4 Time evolutions of the beam energy (a), the beam current (b), water temperature rise on the grounded grid (c), water temperature of the ion dump (d)

beam was injected for 30s with two ion sources. Finally, the injection energy was successfully increased to 80 MJ from 67 MJ in the campaign of 2006 as shown in Fig.3. This is the highest injection energy of the N-NBI in the world. High injection energy of D^0 beams greatly allows to sustain the long pulse production of high-beta plasma [10].

From the results of the 30s injection, the feasibility of the long pulse injection for JT-60SA was studied. Figure 4 shows the time evolution of the water temperature rise of the grounded grid during the 30 s. The injection D^0 power and the power loading of the grounded grid were 2MW and 470 kW, respectively. The water temperature rise was saturated at ~33°C within ~25s. The saturation time was much shorter than the pulse length required for JT-60SA. Since injection power is required to be 5 MW for one ion source in JT-60SA, the water temperature rise is estimated to be ~83°C for full power injection for JT-60SA. This temperature could be reduced to an allowable level of < 60°C by improving the beam uniformity with the tent-shaped filter [9]. The water temperature rise of the residual ion dump, where 40% of the accelerated ion beam is dissipated, is estimated to be < 10 °C for the full power injection on JT-60SA. These estimations suggest that the grid and beamline components can remove the heat flux for the full power injection for 100 s on JT-60SA without the modification.

4 High-energy beam production

4.1 Improvement of voltage holding capability

Figure 5 shows the schematic diagram of the original JT-60 negative ion source. The ion source consists of an arc chamber and a negative ion accelerator with a plasma grid, an extraction grid (EXG) and three acceleration grids (A1G, A2G and GRG). The acceleration grids have the dimensions of 45 cm in width 1.1 m in height, and insulated by large insulator rings made of Fiber Reinforced Plastic (FRP) with 1.8 m in inner diameter. To suppress a surface flashover of the FRP insulator, electric field at the triple junction, vacuum, the FRP insulator and the metal flange is reduced to ～1 kV/mm with large stress rings. The gap lengths were originally set to be 75 mm, 65 mm, 55 mm from the plasma generator. The electric fields at a total acceleration voltage of 500 kV in the first, second and third gaps between the grids are simply estimated to be 2.2 kV/mm, 2.5 kV/mm and 3.0 kV/mm, respectively. The higher electric fields are observed at the corner of the EXG, the A2G and the GRG. The highest electric field is 5.0 kV/mm on the surface of the screen shield ring in the EXG-A1G gap. These original gap lengths between the grids were designed from the experimental results with small sample electrodes [11].

However, recent experiments show that the breakdown mainly occurs in a gap between the acceleration grids [12,13]. This suggests the re-examination of the vacuum gap insulation between large acceleration grids. The breakdown voltage for the large grids was examined by varying the gap length in the JT-60 negative ion source. The breakdown voltage was independently measured in each of the acceleration stages. The breakdown voltages obtained in all three stages were plotted as a function of the minimum cathode-anode distance in each of gaps as shown in Fig. 6. In this figure, the breakdown voltages obtained in the small sample electrodes are also shown for comparison. Each of the breakdown voltages were obtained after sufficient conditioning. The breakdown voltages increased with the square root of gap length. This shows that the breakdown voltage obeys Clump theory even in the large grid. However breakdown voltage in the large grids is a half of that in the small electrodes.

The breakdown voltage in the single stage was targeted to > 200 kV to realize the stable sustainment of 500 kV in total. This design criteria restricts that the minimum cathode-anode distance should be longer than

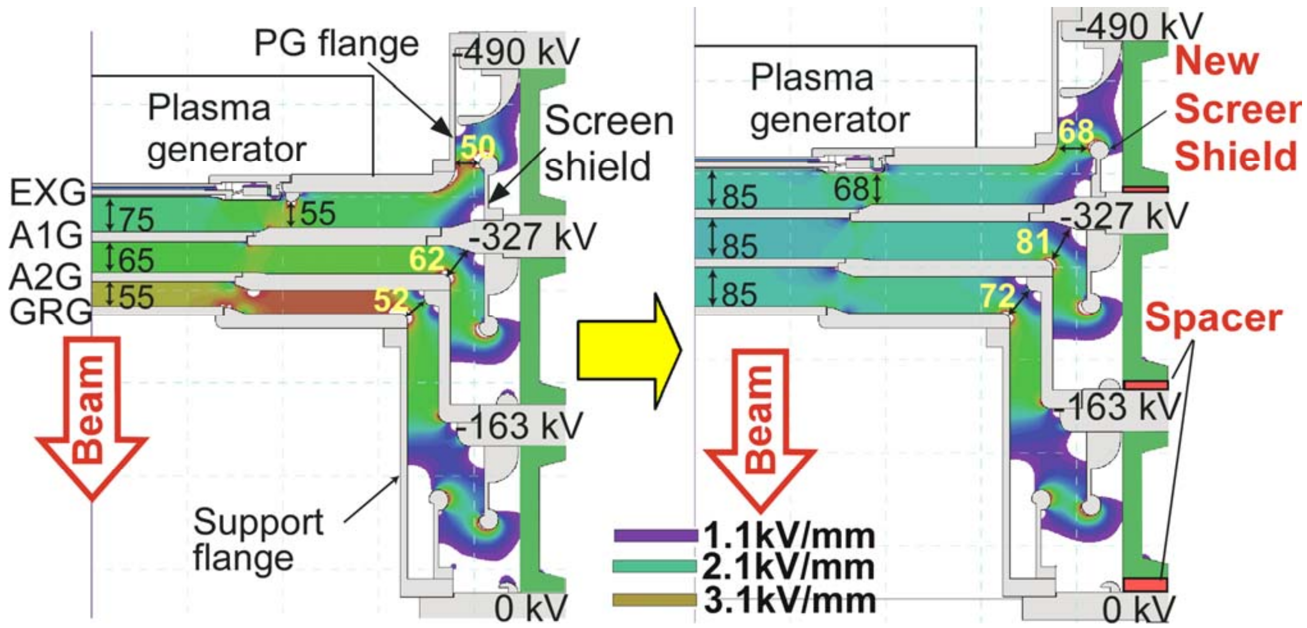

Fig.7 Contour maps of electric field strengths at 500 kV in the original (left) and the modified (right) ion sources.

68 mm for the single stage. Figure 7 shows the contour maps of the electric field strength before and after the modification. Before the modification, the minimum cathode-anode distances in the EXG-A1G gap was 55 mm between the A1G support flange and the suppression cover which is placed at the edge of the EXG to mitigate the electric field. To set this distance to be 68 mm, the distance between the EXG and the A1G is determined to be 85 mm. The gap lengths between the A1G and the A2G, the A2G and the GRG are set to be the same length as that between the EXG and the A1G. The minimum cathode-anode distances in the second and third stages are 81 mm and 72 mm at the corner of the grid support flanges, respectively. These gap lengths are sufficiently longer than that for 200 kV. Before modification, the distance between the PG flange and the screen shield ring in the EXG-A1G gap was as short as 50 mm. The extension of this distance by repositioning the EXG support flange was impossible without significant remanufacturing because of a rigid fixing. The radius and height of the screen shield ring are optimized to keep the insulation distance to be 68>mm and shield beam-induced rays irradiated onto the FRP surface simultaneously. The gap length between the PG flange and the screen shield ring is tuned to be 68 mm. This results in the reduction of the electric field from 5.5 kV/mm to 4.3 kV/mm. The beam optics in the modified negative ion source is confirmed not to be degraded from a 3D code.

The modified ion source was tested in the N-NB injector on JT-60U. High voltages were simultaneously applied to three acceleration stages. Figure 8 shows the voltage holding capability as a function of the conditioning time before and after the modification. By repeating the high-voltage application of 3 s pulses, the voltage holding capability was gradually increased. After 1 hour of conditioning, voltage holding capability in the modified ion source reached 500kV of the power supply limitation. The breakdown probability after sufficient conditioning was measured to be 15 % of total number of the pulses at 500 kV. A half of 15 % was inside the ion source, and the other was in the spark gap outside of the ion source. Since breakdowns in the spark gap was due to un-optimized gap length, the number of the breakdown in the spark gap can be reduced by tuning the gap length. Therefore, the breakdown probability of the modified ion source might be < 10 %. This result shows that the ion source stably sustains 500 kV of the rated value for JT-60SA.

In order to examine the feasibility of the long pulse injection, the pulse length was increased step by step after sufficient conditioning with short pulses of 3 s. Finally, the pulse length reached 40 s, which was limited by the capacity of the breeder resistors connected with the acceleration power supply in parallel. No degradation of the voltage holding capability has been observed This suggests that the pulse duration could be extended up to 100 s of the rated pulse length for JT-60SA.

4-2 Beam acceleration

The beam acceleration tests recently starts in the N-NB injector on JT-60U after the modified ion source is confirmed to be capable of holding > 500 kV without the beam acceleration. The purpose of this experiment is to examine the influence of the beam acceleration on voltage holding capability and to demonstrate a 500 keV ion beam acceleration. Only through 20% of an ion extraction area, i.e., central one segment in the large grids with five segments, the hydrogen negative ion beams are produced. Since no motor generator is driven to supply an electric power into the acceleration power supply, the pulse length and the accelerated beam current are restricted to be < 1s and < 10 A, respectively.

Generally speaking, voltage holding capability with the beam acceleration is considered to become worse than that without beam acceleration. In addition, the cesium vapor injection for an enhancement of the beam current into the plasma generator might degrade voltage holding capability since some of the cesium flows to the accelerator. These influences were examined.

First, the ion source was conditioned without beam acceleration by repeating high voltage pulses of 0.8 s with an interval of 45s. In a day, ～600 shots were applied to the ion source. Immediately after conditioning the ion source without beam acceleration for 6 days, i.e., in the first day of the beam acceleration, the ion source held 500 keV at the beam current of 1 A although voltage holding was unstable. After the ion source was

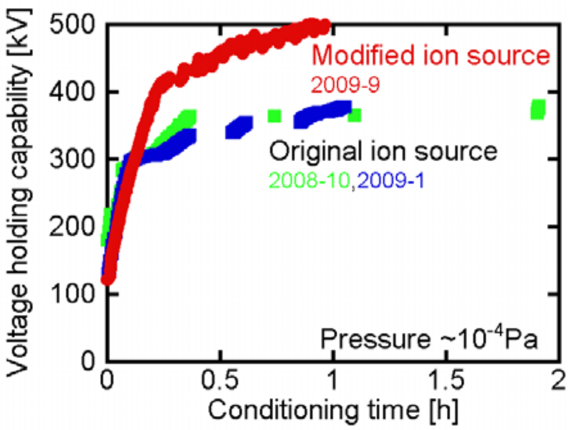

Fig.8 Voltage holding capabilities without beam acceleration for the original and the modified ion sources

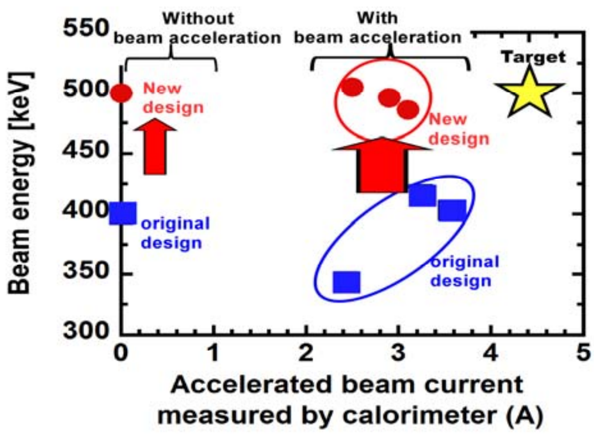

Fig.9 Achievement of the negative ion beams in the original and the modified ion sources

conditioned to stabilize voltage holding at the same beam current of ~ 1 A for 4 days, the cesium vapor started to be injected to the ion source to increase the accelerated beam current. The accelerated beam current reached > 4 A at the 14th day. No significant degradation of voltage holding capability was observed for the higher beam current.

The production of the 500 keV ion beams is undertaken at present. The operation parameters such as an extraction voltage and an arc discharge power and a cesium amount are under optimization to maximize the beam current. Figure 9 shows the beams produced from one grid segment in an original and the modified ion sources. The negative ion beam currents shown in this figure are measured by a calorimeter that is located at 16.4 m downstream from the ion source. The beam acceptance at the calorimeter is as lows as ±24.5 mrad. This indicates that only the negative ions through a long (10 m) and narrow(0.8 m) neutralizer can be detected at the calorimeter.

A 3A H^- ion beam has been accelerated to 500 keV without significant degradation of beam optics even though operation parameters for the beam production are un-optimized in the modified ion source. This is the first demonstration of a high-energy negative ion acceleration of more than one-ampere to the beam energy of 500 keV in the world. The beam current density is 90 A/m^2 and 68% of the design value, i.e., 130 A/m^2. At present, the higher current beam is being produced by tuning the operation parameters.

The high energy beams are demonstrated in an electro-static negative ion accelerator with three acceleration stages. In ITER, a five-stage negative ion accelerator with two additional acceleration stages is designed to produce 1 MeV, 40A D^- ion beams. Since the ITER ion source has the similar structure of the accelerator as that of the JT-60 negative ion source, the extension of the gap length between the acceleration grids is expected to be effective for the high-energy D^- ion beam for ITER.

5 Summary

A large negative ion source with an ion extraction area of 110 cm x 45 cm has been developed to produce 500 keV, 22 A D^- ion beams required for JT-60 Super Advanced. To realize the JT-60SA negative ion source, the JT-60U negative ion source has been modified and tested on the negative-ion-based neutral beam injector on JT-60U.

- A 500 keV H^- ion beam has been produced at 3 A without a significant degradation of beam optics. This is the first demonstration of a high energy negative ion acceleration of more than one-ampere to 500keV in the world. The beam current density of 90 A/m^2 is being increased to meet 130 A/m^2 of the design value for JT-60SA by tuning the operation parameters.
- A long pulse injection of 30 s has been achieved at a injection D^0 power of 3 MW. The injection energy, defined as the product of the injection time and power, reaches 80MJ by neutralizing a 340 keV, 27 A D^- ion beam produced with two negative ion sources.

References

[1] H.Tamai et al., Fusion Engineering and Design **82** 541-547(2007)

[2] Y. Ikeda et al., Fusion Engineering and Design **82** 701-707(2007)

[3] M.Kuriyama et al., Fusion Science and Technology **42** 410-423(2002).

[4] Y.Kamada et al., ‘Progress of JT-60SA project towards an integrated research for ITER and DEMO’, submitted to Journal of Japan Society of Plasma Science and Nuclear Fusion Research.

[5] K.Watanabe et al., Nuclear Fusion **46** s332-s339(2006)

[6] M.Hanada et al., Rev. Sci. Instrum .**77** 03A515(2006)

[7] Y. Ohara, JAERI-M 6757 (1976).

[8] M.Hanada.M.et.al., Proceedings of 22nd IAEA fusion energy conference Geneva, 2008, FTP-2-27, http://www.fec2008.ch/preprints/ft_p2-27.pdf

[9] M.Hanada et al., Rev. Sci. Instrum .**77** 03A515(2006)

[10] N.Oyama et al., Nuclear Fusion **49** 1-10(2009)

[11] K.Watanabe et al., J.Appl.Phys. **72(9)**, 3949-3956(1992)

[12] M.Hanada et al., IEEE Transaction on Dielectrics and Electrical Insulation **14(3)** 572-576(2007)

[13] K.Kobayashi et al., IEEE Transaction on Dielectrics and Electrical Insulation **16(3)** 572-576(2007)