Development of Long Pulse Neutral Beam Injector on JT-60U for JT-60SA

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Abstract. The paper reports the progress of R&D toward the JT-60SA at Japan Atomic Energy Agency (JAEA) during 2006-2008. Significant progress has been made in the long pulse operation of the negative-ion-based NBI (N-NBI) where a 10 MW D^0 beam is required to be injected for 100s in JT-60SA. The injection pulse length has been successfully extended from 20s in the last campaign to 30s of the heating time allowed in JT-60U. The achieved injection energy, defined as the product of the injection time and power, was successfully increased from 67 MJ in the last campaign to 80 MJ in the 2008 campaign by neutralizing 340 keV, 27 A D^- ion beam produced with two negative ion sources.
The high injection energy was achieved by the reduction of the grid power loading to an allowable level. The direct interception of the D^- ions by acceleration grids was suppressed by tuning the steering angle of outermost beamlets with modified field shaping (FS) plates in the ion source. The modified FSP succeeded in the reduction of the grid power loading to an allowable level for JT-60SA. Moreover, the power loading in the beamline, where the power of the electrons ejected from the JT-60 U negative ion source is dissipated, was also confirmed to be low enough to extend the injection pulse length to 100s for JT-60 SA.

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]. The total heating power of 24 MW for 100s is required by upgrading existing neutral beam injectors on JT-60U [2]. The NBI system consists of 12 positive-ion-based NBI (P-NBI) units and one negative-ion-based NBI (N-NBI) unit. The injection powers of P-NBI and N-NBI from one unit are 2 MW at 85 keV and 10 MW at 500 keV, respectively.

An extension of the injection pulse length up to 30s has been intended to study quasi-steady-state plasma on JT-60U since 2003. For this intension, the P-NBI unit has been modified to extend the pulse length from the original value of 10s to 30s at an injection power of 2 MW [3]. In 2004, four units were modified. The total injected energy, defined the product of the injection power and the pulse length, increased to 320 MJ. In 2006, the higher injection energy of 340 MJ was achieved by increasing number of the modified units from four to six. In the 2008 campaign, the injection energy of 370 MJ was achieved with eight modified units. During 30s, the water temperature rise of the ion source and the beam-line components were saturated at an allowable level. This indicates that pulse length of the 2 MW D^0 beam can be extended from 30s to 100s without the modifications of the ion source and the beam-line components except for inertially-cooled beam limiters near the NBI ports.

The N-NBI started the injection in 1996 with two large negative ion sources (U and L ion sources), each of which was designed to produce a 22 A, 500 keV D^- ion beam for 10s [4]. The highest injection power has been 5.8 MW at 400 keV that was obtained by neutralizing a 400 keV, 49A D^- ion beam for 0.9s with two negative ion sources. The injection power is limited by poor voltage holding capability of the negative ion sources. In the other word, the beam power can be largely increased by improving the voltage holding capability since the beam power significantly increases with $Vacc^{2.5}$ (Vacc: acceleration voltage) according to Child-Langmuir law. Therefore, the improvement of the voltage holding capability is one of the key issues for the realization of the N-NBI on JT-60 SA. As a step for improving the voltage holding capability, vacuum breakdown in the JT-60 negative ion source is carefully examined to find the dominant factor degrading voltage holding capability.

Demonstration of the long pulse injection on JT-60 U is the key issue since the pulse length for JT-60 SA is ten-times longer than the rated pulse length of JT-60U. In the last campaign of 2006, the pulse length of 20 s was achieved at 3.2 MW D^0 with the two ion sources. In the long pulse injection, it was found that the grid power loading in the negative ion sources should be reduced to an allowable level, i.e., 5% of the accelerated beam power to realize the JT-60SA negative ion sources. It was also found that high grid power loading was originated by the direct interception of the D^- ions by the acceleration grids. From these results, field shaping (FS) plates are newly designed and tested in the 2008 campaign on JT-60U to tune the steering angle of the multiple beamlets.

In the last campaign, cover plates for protecting non-water cooled parts between the ion source and the neutralizer was observed to be melted during the 20s injection at 3.2 MW. To avoid the melting of the plates for the longer injection pulse, in particular, the 100s injection in the JT-60SA, the power loading should be quantified. The power loading in the beamline between the ion sources and the neutralizer is measured, and then possible countermeasure is taken for the long pulse operation in the 2008 campaign.

After taking the countermeasures for the long pulse injection, the injection pulse length is further extended from 20s in the last campaign to 30s of the heating time allowed on JT-60U. The paper reports the R&D progress on the N-NBI for JT-60SA since the last conference of this series [5] on the aspects of the long pulse injection at high power.

2. Study on vacuum breakdwon

The JT-60 negative ion source is mainly composed of an arc chamber and a 3-stage accelerator. The accelerator is constituted of three fiber reinforced plastic insulator and three acceleration grids with multiple apertures as shown in Figure 1. The same acceleration voltage is applied to each of the gaps between the acceleration grids. To improve voltage holding capability, the following countermeasures have been taken.

1. To reduce the electric field near the cathode triple junction, large suppression rings are installed, based upon the R&D results of a 1 MeV electrostatic accelerator developed for International Experimental Thermonuclear Reactor [6].
2. The inner surface of the FRP insulators is protected from X-ray and/or ultraviolet rays by screen shields.

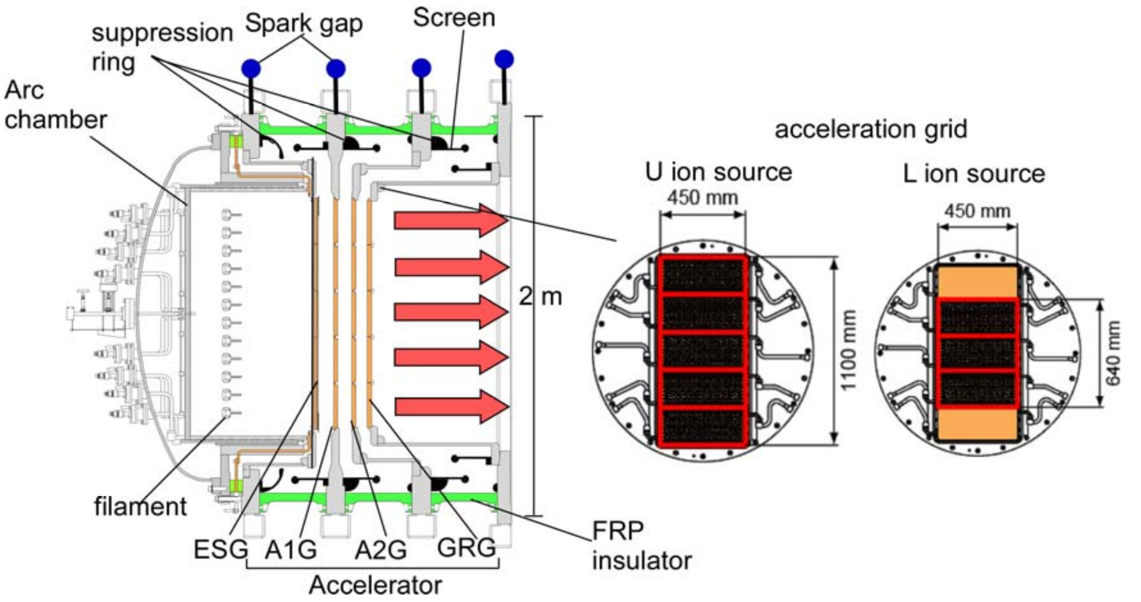

Figure 1 Schematic diagram of the JT-60 negative ion source

3. Spark gaps are connected across the intermediate acceleration stages to suppress damage of the acceleration grids and/or power supply due to a transient overshoot of the voltage when breakdown occurs. The lengths of the spark gaps are presently set to be 75mm , at which the flashover voltage is 170 kV.

Although these countermeasure has been taken to improve voltage holding capability, the achieved acceleration voltage is < 400 kV after sufficient conditioning. To realize the N-NBI for JT-60SA, the voltage holding capability should be increased to the rated value of 500 keV. As a step for improving the voltage holding capability, the breakdown location of the JT-60 negative ion source has been examined. It is found that the breakdown location varied with the conditioning stage. In the early stage, breakdown occurs mainly in vacuum at gaps between the grids and their support frames with the total surface area of 2.5 m^2. Careful observation shows that the conditioning gradually progresses with the breakdowns occurring at many different locations over the large surface area. Figure 2 shows number of the breakdowns on the acceleration grids. The breakdown mainly occurred at the edge of the grids, where electric field is relatively as high as ~4 kV/mm. This result suggests that the relaxation of the electric field at the edge of the grid would be effective to shorten the conditioning time. Over ~400 kV after conditioning of several months, the breakdown location is changed to the surface of the FRP insulator with an inner diameter of 1.8 m. It is recently found in Saitama University that the flashover voltage of a low outgassing epoxy resin (~10^{-4} Pa·m/s) is twice higher than that of the conventional one [7]. The use of the low outgassing epoxy resin is expected to improve the voltage holding capability, and hence injection power of the ion source for JT-60SA.

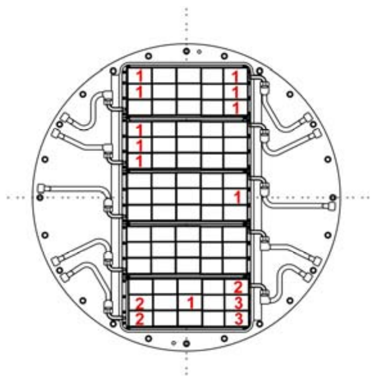

Figure 2Breakdwon location on the acceleration grid in the U ion source.

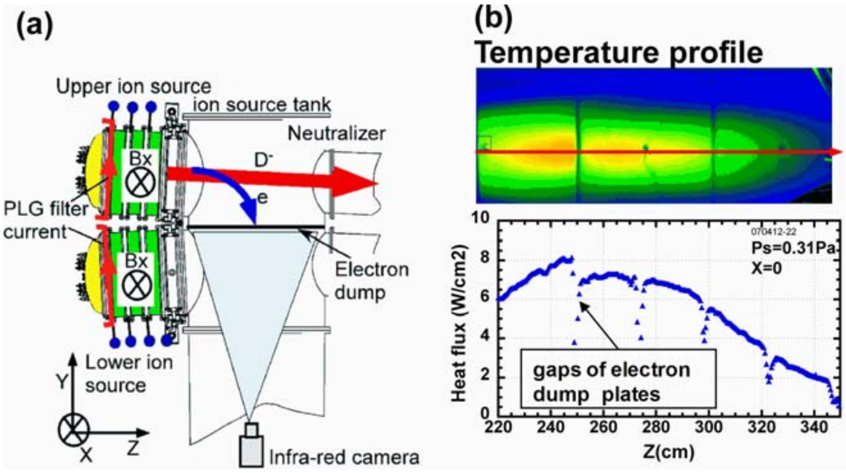

Figure 3 (a) Set up of electron deposition measurement, (b) temperature and heat flux profiles at the electron dump.

3. Electron trajectories in the beamline

After the 20-s injection in the last campaign, a non-water cooled plate (1 mm in thickness) protecting neutralizer entrance was observed to be melted. To extend the injection pulse length further, it is required to precisely quantify the power loading. The power loading on the protecting plated was measured. A thin stainless steel plate of 1mm in thickness was set on the path of the electrons ejected from the ion source where the electrons are largely bent downward by the residual magnetic filed (see Fig.3-(a)). The surface temperature rise of the plate was measured by infra-red camera, and the flux and total power were measured. Figure 3-(b) shows the typical temperature profile and the heat flux on the plate when 300keV and 3.4 A beam was produced from only the central segment in the U ion source. It is found that the highest heat flux from one segment was as low as ~8 W/cm^2. Its total power load is ~2.6 % of the accelerated beam power. For full current beam with five segments, the highest heat flux is estimated to be ~37 W/cm^2 by assuming the heat flux distributions for the other segments to be the same as that measured from the central segment. This result shows that the power loading can be removed readily by active water cooling even for the 100s long pulse operation in JT-60SA. For the 30s injection in the 2008 campaign, the thin stainless steel plate used for the measurement is replaced to the thicker plate of 5 mm in thickness to avoid the melting.

It is very important to know the origins of the power loading in the beamline between the ion source and the neutralizer to estimate the power loading in the beam-line on JT-60SA. To examine the origin of the power loading in the beam-line, the total power loadings were measured for different pressures in the arc chamber. Figure 4 shows the total power loading as a function of the pressure in the arc chamber. The measured total power loading increases linearly with the

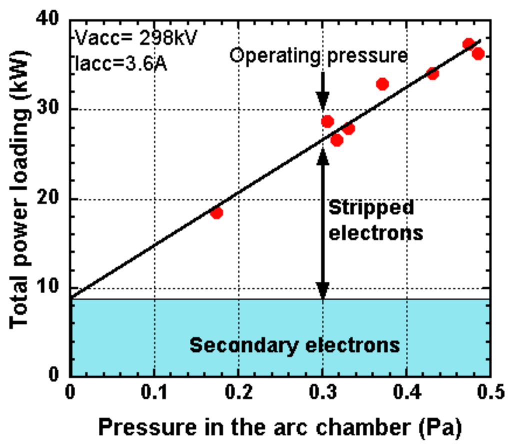

Figure 4 Total power loading as a function of the pressure in the ion source.

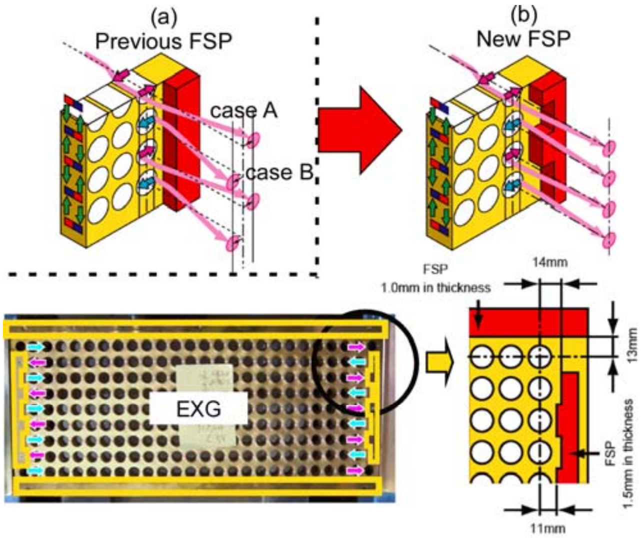

Figure 5 Previous (a) and new (b) field shaping plates.

pressure in the arc chambers. At the operating pressure of 0.3 Pa, the power loading was ~ 26 kW for the D^- ion beam power of ~ 1MW. The power loading extrapolated to 0 Pa was ~ 9 kW, and is thought to be originated from the secondary electrons created by the impact of D^- ions onto the acceleration grids. Therefore, the remaining power of 17 kW is thought to be caused by the electrons that are stripped from the D^- ions by collisions with residual gas molecules in the accelerator. This shows that the power loading of the electrons at the operating pressure of 0.3 Pa is mainly due to the stripped electrons. To design the beam-line on JT-60 SA, the trajectories of the stripped electrons are to be calculated.

4. Grid power loading

On JT-60U, two ion sources, i.e., the U and L ion sources are installed in the N-NBI. The difference of them is only the ion extraction area. As shown in Fig.1, the ion extraction area in the U and L ion sources are full five segments and the central three segments, respectively. On each of segments, 9 x 24 apertures are distributed.

In the last campaign, the highest grid power loading were 9% and 7% of the accelerated beam power on the grounded grid in the U and L ion sources, respectively. These grid power loadings were higher than an allowable level for JT-60SA (5%). The observation of the grids indicated that these high power loadings were caused by the direct interception of the over-deflected outermost beamlets. Moreover, the ion trajectory calculation showed that the over-deflection of the outermost beamlets was caused by the un-optimized FS plates attached on an extraction grid [8]. To suppress the direct interception of outermost beamlets, FS plates was newly designed using a 3 D calculation code and tested in the JT-60 negative ion sources. Figure 5(b) shows the schematic diagrams and photo of new FS plate. On the top and bottom of the segments, straight plates of 1 mm in thickness has been installed with 13 mm of the FSP-aperture distance. On the side of the segment, the plate of 1.5 mm in thickness has been installed. The FSP-aperture distances are tuned to be 11 mm and 14 mm every row of the apertures since the beamlets are deflected outward and inward every row of the apertures by dipole magnetic field in the extraction grid, respectively as shown in “case A” and “case B” in Fig.5(a). This different distance of the FSP-aperture results in the corrugated shape of the FS plates on the side of the segment.

The deflection angle of outermost beamlet were measured and compared with 3D simulation results while the 280 keV, 9.5A D^- ion beam was produced under the optimum perveance. The measured vertical and horizontal deflection angles were confirmed to be nearly in agreement with the designed values. This result shows that new FS plates properly steer the outermost beamlets as predicted by the simulation. After the confirmation of the proper steering angle, the grid power loading of the grounded grid was measured and compared with the grid power loading for the previous FS plates. Fig. 6 (a) and (b) are the dependences of the power loadings of the grounded grid in U and L ion sources as a function of the operating pressure in the arc chamber, respectively. The grid power loading was normalized by the accelerated beam power. In both of the ion sources, the grid power loading increased linearly with the pressure in the arc chamber. This is due that the electrons stripped from D$^-$ ions increased linearly with the pressure in the present range of the pressure. At a typical operation pressure of 0.3 Pa, the grid power loadings of the grounded grid in U and L ion sources have been reduced from 9 % to 7 % and 7% to 5%, respectively using new FS plats. 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.

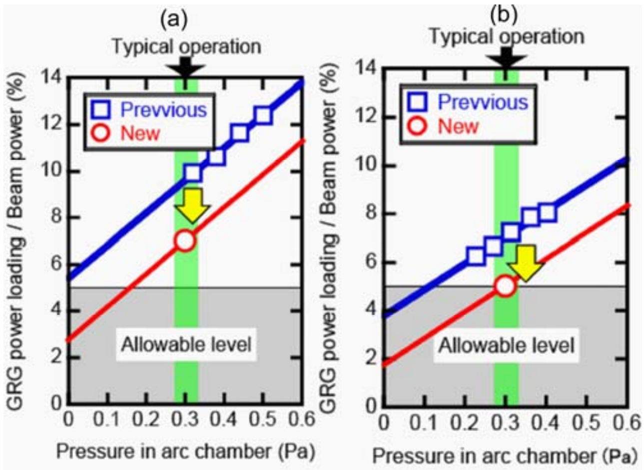

Figure 6 Power loadings of the grounded grids in the L (a) and U (b) ion sources.

The difference of the grid power loadings in the L and U ion sources is due to the difference of the ion extraction area. The D$^-$ ions in the L ion source are extracted through the central three segments where the D$^-$ ion density is relatively uniform in the longitudinal direction, however the D$^-$ ion density in the U ion source is non-uniform. This non-uniformity of the D$^-$ ion density causes a local mismatch of the perveance of the multiple beamlets, resulting in a significant direct interception of D$^-$ ions by the acceleration grids. In JT-60SA, the arrangement of the confinement permanent magnets on the arc chamber will be changed to “tent-shaped filter configuration” where the beam uniformity has been successfully improved in the 10 A ion source [9]. The use of the tent-shaped filter configuration could reduce the grid power loading to the allowable level even for full ion extraction.

5. Long pulse injection of the N-NBI

After the countermeasures for the long pulse operation , i.e., the reduction of the power loadings of the acceleration grids were taken, the injection pulse length was extended. In the last campaign, the achieved pulse length was 21s at 3.2 MW D^0 beams with two ion sources [10]. The pulse length was limited by interlock level (650 ^{o}C) of the surface temperature on the non-water cooled molybdenum (Mo) limiter near the injection port.

In 2008, the interlock level was increased to 850 ^{o}C for the further extension of the pulse length. While power loadings of the grounded grid, the residual ion dump and the Mo limiter were carefully monitored, the injection pulse length was extended to 30s of the heating time allowed on JT-60U. Since the conditioning progress of the ion sources was different 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 to achieve the 30s injection at the higher power of the D^0 beams. A ~3.0 MW D^0 was injected for 30s with two ion sources. As the results, the injection energy was successfully increased to 80 MJ from 67 MJ in the last campaign as shown in Fig.7. This is the highest injection power of the N-NBI in the world. High injection energy of D^0 beams greatly contributes to the improvement of the plasma performance on JT-60U such as long pulse sustainment of high beta plasma [11].

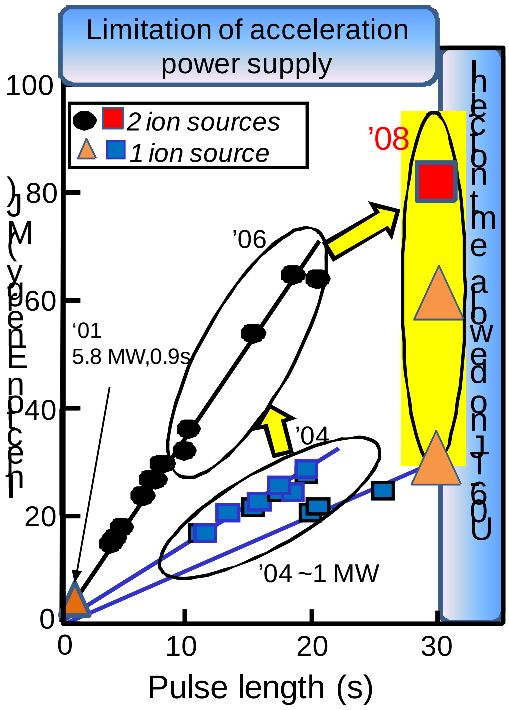

Figure 7 Progress of the long pulse injection of the D^0 beams on JT-60U

From the results of the 30s injection, the feasibility of the long pulse injection for JT-60SA was studied. Figure 8 shows the time evolution of the water temperature rise of the grounded grid during the 30 s injection in the U ion source. The power loading of the grounded grid was 470 kW. The water temperature rise was saturated at ~33°C within ~20 s under the estimated heat flux (average over the grid area) of 1.6 MW/m^2. The saturation time was much shorter than the pulse length required for JT-60SA. As discussed in chapter 3, the power loading of the grounded grid in the U ion source will be reduced to the allowable level of ~1 MW (5% of the accelerated beam power) on JT-60SA by improving the beam uniformity. The water temperature rise for the 1 MW is estimated to be ~65°C from the measured water temperature in this experiment. The

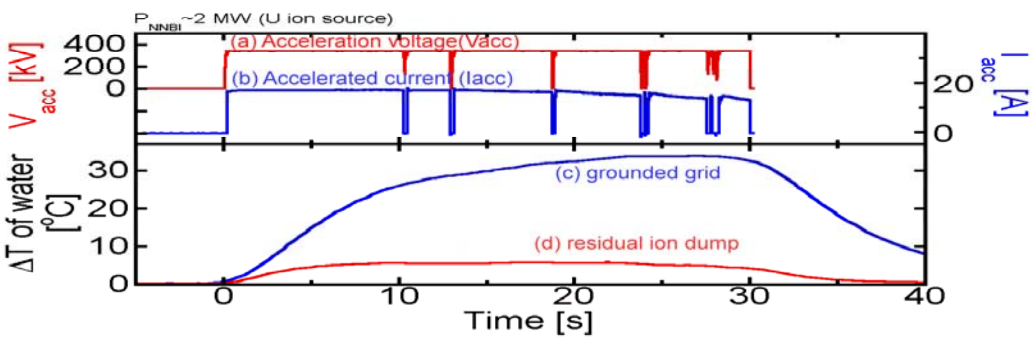

Figure 8 Time evolutions of acceleration voltage (a), accelerated current (b), water temperature rises of grounded grid (c) and residual ion dump(d).

water temperature rise of residual, where 40% of the accelerated ion beam is dissipated, is estimated to < 10 ^{o}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.

5. Summary

Significant progress has been made in the long pulse injection of the negative-ion-based NBI (N-NBI) on JT-60U. The injection pulse length has been successfully extended from 20s in the last campaign to 30s of the heating time allowed in JT-60U. The achieved injection energy was successfully increased from 67 MJ in the last campaign to 80 MJ in the 2008 campaign by neutralizing 340 keV, ~27 A D^- ion beam produced with two negative ion sources. From the measurement of the water temperature rise, it is found 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.

The issues for realization of the N-NBI on JT-60SA are voltage holding capability of the negative ion source and the beam uniformity. For the improvement of the voltage holding capability, the possibilities of the low outgassing epoxy resin will be soon examined. The electric field concentration at the boundary between the acceleration grids and their supports will be relaxed by optimizing the geometry of the grid support. To improve the beam uniformity, the tent shaped filter configuration will be tested in the JT-60 negative ion source on JT-60U where the tests of the NBI and RF are planned during ~1 year after the shutdown.

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