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Improvement of Beam Performance in Negative-Ion Based NBI System for JT-60U

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abstract. Injection performance of negative-ion based NBI system for JT-60U has been improved by correcting beamlet deflection and improving spatial uniformity of negative ion production. Beamlet deflection at peripheral region of grid segment has been found due to distorted electric field at the bottom of the extractor. This was corrected by modifying the surface geometry at the extractor to form flat electric field. Moreover, beamlet deflection due to beamlet-beamlet repulsion by space charge was also compensated by extruding the edge of the bottom extractor. This resulted in reduction of the heat loading on the NBI port limiter. As the result of improvement above, the continuous injection of 2.6 MW H^0 beam at 355 keV has achieved for 10 s. Thus the long pulse injection up to nominal pulse duration of JT-60U was demonstrated. This has provided a prospect of long pulse operation of negative-ion based NBI system for steady state tokamak reactor. So far, the maximum injection power of 5.8 MW at 400 keV with deuterium beam and 6.2 MW at 381 keV with hydrogen beam have been achieved in the JT-60U N-NBI. Uniformity of negative ion production was improved by tuning filament emission current so as to put more arc power in the region where less negative ion current were extracted.

1. Introduction

The negative-ion based neutral beam injection (N-NBI) system is one of promising candidates for plasma heating and non-inductive current drive of steady state/long pulse operation of tokamak reactors such as ITER. The N-NBI system for JT-60U has been operated since 1996[1] for research of current drive and heating in high density plasma by energetic (500 keV) beam. The design goal of the N-NBI system is to inject 10 MW, 500 keV D^0 beams for 10 s. Recently the N-NBI has contributed to achieve a fusion triple product of 3.1×10^{20} m^{-3} s keV under full non-inductive current drive with NB injection of 5.7 MW at 402 keV [2]. There were some issues remained to achieve injection goal such as less voltage holding of accelerator, excess heat load of grounded grid, beam divergence and spatial non-uniformity of negative ion production. In these issues, beam divergence and non-uniformity of negative ion production have been improved. Until 2000, pulse duration was limited to 2 s with an injection power of 5 MW because of high heat load and subsequent temperature rise of the NB port limiter which is located at about 22 m far from the ion source. In 2001, it was found that beamlets generated from edge of the grid segments were deflected by distorted electric field due to geometric step at the bottom of the extractor. The distorted electric field was compensated by filling the step with metal bar, and consequently, the deflection was corrected. Moreover, beamlets generated from the edge region were focused by protruding the metal bars from the surface of the bottom extractor. Correction of the beamlet deflection and its focusing were effective to reduce excess heat load on the NB port limiter, and enabled us to fire long pulse beam at high injection power.

In these three years, we have also tried to improve uniformity of negative ion production in the ion source [3], by tuning input power of each filament group so as to change arc power distribution in the chamber. Although uniform arc power profile was achieved by the filament tuning, a large non-uniformity in a profile of beams still remained, in particular, at the bottom of the chamber. Then the filaments were again tuned to yield 30% higher arc power dissipation at the bottom region. This was effective some how to improve the uniformity of the extraction beam. In this paper correction of beam deflection, improvement of source plasma uniformity and achievement of long pulse operation are reported.

2.Description of the N-NBI system

Detailed description of the JT-60U N-NBI system can be found else where [4]. Here only outline and key points of the system relevant to the present improvements are described. The N-NBI system has two large negative ion sources mounted on a single beamline. Design value of each ion source is acceleration of 22 A D^- ion beam at 500 keV and the rated pulse length is 10 s. The ion source consists of a negative ion generator, an extractor and an accelerator. The negative ion generator is a volume production type multicusp plasma generator with small amount (5 ~ 10 g) of cesium seed to enhance the negative ion production. The cathode of the arc discharge is 48 tungsten filaments. Each of 6 filaments is grouped to compose eight filament groups, and each group is connected to a filament power supply. Thus the arc power to each filament group is independently controllable. The extractor, consisting of a plasma grid and an extraction grid, has an ion extraction area of 45 x 110 cm^2. The accelerator is an electrostatic three-stage accelerator. Each grid of the extractor and the accelerator is divided into five segments whose size is 45 x 18 cm^2, and each grid segment has 9 (vertical) x 24 (horizontal) aperture array. Only exception to that is the plasma grid. To inhibit beam extraction from top and bottom edge of the grid, where less ion current are expected due to stray magnetic field from the plasma generator [5], 3 lines and 5 lines of apertures in the top and bottom segments, respectively, were masked with a blank plate made of molybdenum. The grid segments are geometrically inclined (0.5 ° with respect to the next segment) to focus the beam generated from the large grid area to narrow NB port. The heat load on each grounded grid segment was measured calorimetery of the cooling water. During the experiment for improvement, the beams were fired toward a target plate located 3.5 m downstream of the accelerator. By monitoring temperature rise of the target measured by infrared camera, beam footprints were obtained to discuss the beamlet deflection and the uniformity of the beam.

3. Correction of beamlet deflection

The temperature rise of the NBI port limiter whose size is 46 cm height and 50 cm width, has limited the long pulse injection to the JT-60U plasma. It shows that the some components of the beam are intercepted by the limiter. Therefore, it is important to improve the beam optics and focusing. To evaluate the beam optics in detail, the beam profile was measured at 3.5 m downstream from ion source by using a target plate and an IR camera. Figure 1 (a) shows longitudinal beam deposition profile. Two peaks appeared at the both edges of each segment. The beamlets of the segment edge were deflected outward and overlapped with other beamlets. The deflected angle is estimated to be 14 mrad. There were small grooves with 5 mm in depth and 40 mm in width at the down streamside of the extractor grids segments as shown in Fig. 2. These grooves generated electric field distortion. To make the distorted electric field uniform, copper bars were embedded in the grooves. As a result, the peaks in the beam profile changed as shown in Fig.1 (b). The peaks moved from the both edges of the segment boundaries to the center between two segment boundaries. By an estimation of the beam

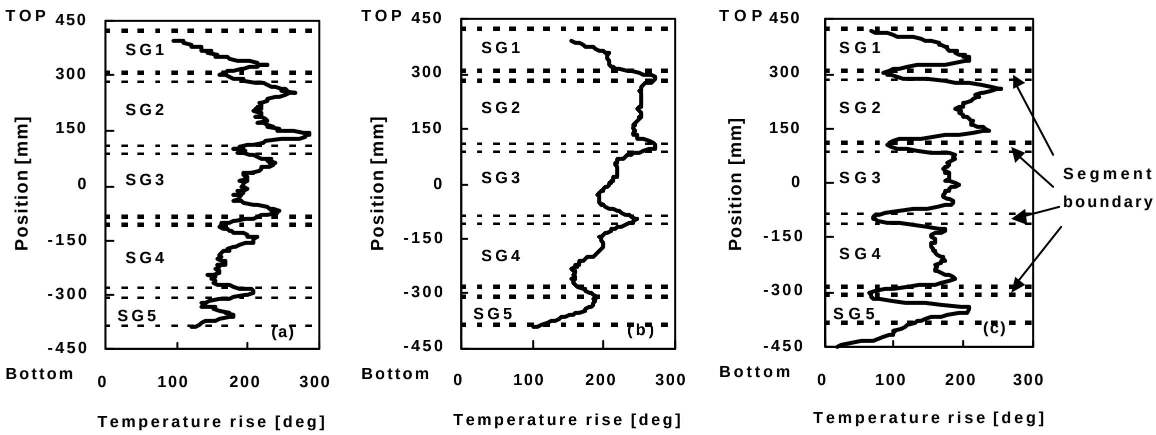

FIG.1 Longitudinal beam profile at 3.5m from ion source (a) original (b) with flat bar (c) with 1.5mm height bar

trajectory, such peaks do not appear between segment boundaries in the beam profile. It seemed that the beam deflection is enhanced by space charge effect of beamlet-beamlet interaction [6] which was not taken into account in the first modification. The deflection angle was estimated to be 6 mrad outward still. To correct this deflection, the thickness of the copper bar was increased to generate the electric field to steer the beamlets inward to the each segment. The suitable height of the bar was estimated by using a three-dimensional beam trajectory code and then 1.5 mm height was selected. The beam profile was improved as shown in Fig.1(c), which matched to design profile and the beamlet deflection by beamlet-beamlet interaction was corrected completely. Figure 3 shows temperature rise of the beam limiter at the NBI port. The heat loads on the limiter with the flat bar and 1.5 mm extruded bar were decreased to less than 60% and 70% of the original one, respectively. The injection port of N-NBI for JT-60U is so narrow that even slight beam deflection largely affects. This improvement enabled the long pulse injection at high beam power.

4. Uniform negative ion production

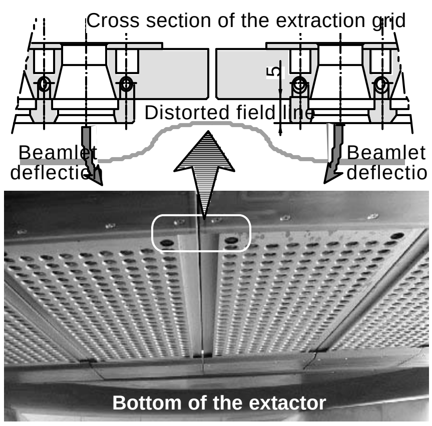

FIG.2 Grooves at the bottom of the extractor

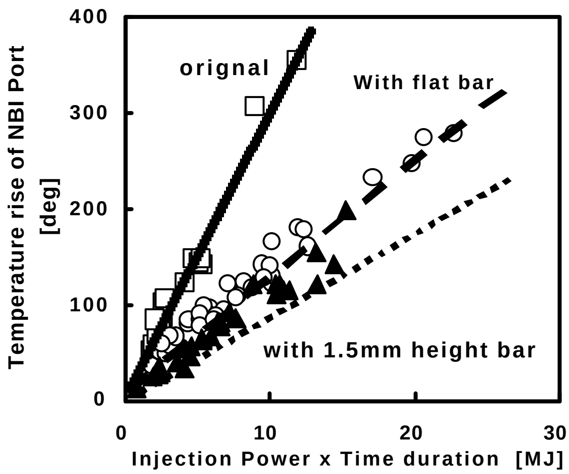

FIG.3 Temperature rise of the beam limiter at NBI port

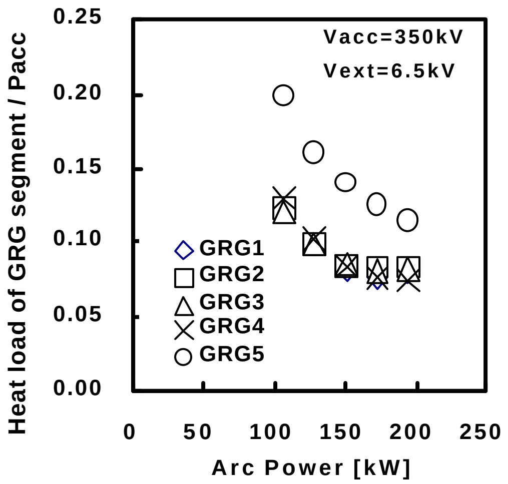

FIG.4 The heat load on GRG segments as a function of the arc power

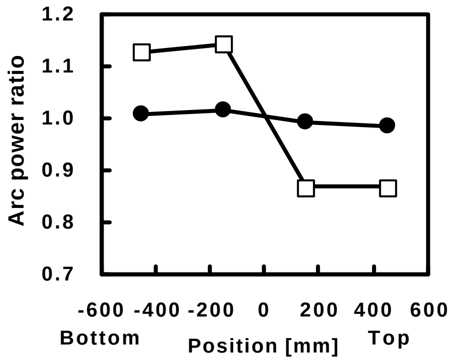

FIG.5 Arc power distribution by adjusting each filament voltage. Black circle is uniform and white square is enhanced at the bottom

It is thought that non-uniformity of the negative ion production is a critical issue in large-scaled negative ion source so as to suppress grid heat load and breakdown. First filament power was tuned so as to provide uniform arc current from each group of the filaments. Figure 4 shows the heat load on GRG segments as a function of the arc power. GRG1 in Fig.4 corresponds to the top segment and GRG5 to the bottom. The heat load in each segment was normalized by acceleration power of each segment. The heat load of four segments except for the GRG5 were saturated at 8 % over the arc power of 150 kW. While the heat load on GRG5 didn't reached to the same level to those on other segments. Considering that this is due to less negative ion production at the bottom region, more arc power is necessary at the bottom region to extract uniform negative ions. In order to enhance negative ion production at the bottom segment, the arc power at the bottom region was increased, as shown in Fig. 5, by tuning each filament voltage to draw higher arc power at the bottom region. Figure 6 shows longitudinal profiles of target temperature rise obtained with the uniform arc power distribution and with enhanced power at the bottom. The profile shows that higher temperature rise in the center and two bottom segments. Moreover the width of beam in the bottom segment was wider than that of the uniform arc power, suggesting more beams from outermost aperture lines. Consequently, the beam footprint became uniform when the arc power was enhanced at the bottom region, rather than

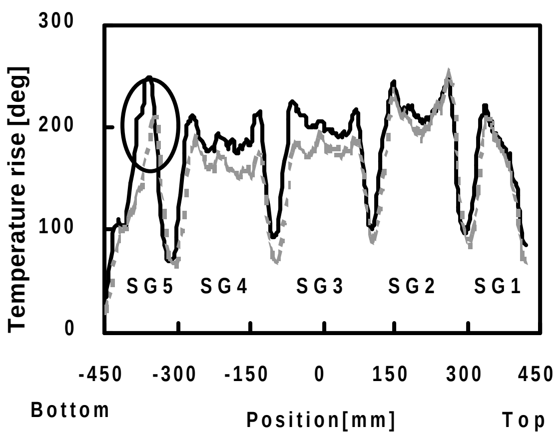

FIG.6 Longitudinal beam profile at 3.5m. Gray doted line is uniform arc power and black line is enhance at bottom

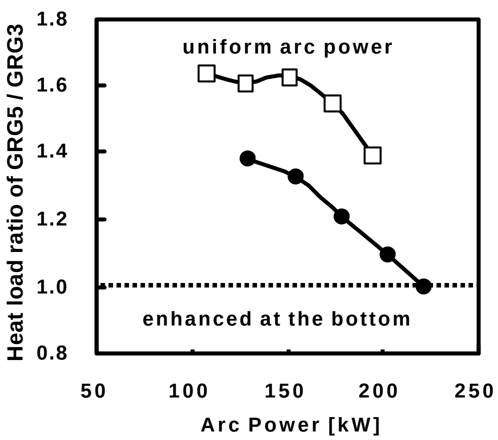

FIG. 7 The ratio of heat load on the segments between bottom and center. White square is for the uniform arc power and black circle is for enhanced at the bottom

distributing uniform arc power all over the chamber. Figure 7 shows the ratio of heat load on the segments between bottom and center for the uniform arc power and enhanced at the bottom. The ratio was decreased for both cases with increasing arc power. With the uniform arc power, the ratio changed from 1.6 to 1.4, while for the enhanced power at bottom, it decreased from 1.4 to 1.0. The ratio 1 indicates the same heat loads on bottom segment to that of center. Thus the uniformity of negative ion production was improved by putting higher arc power in the bottom region. The tuning of arc power distribution is an effective method to improve uniformity of negative ion production.

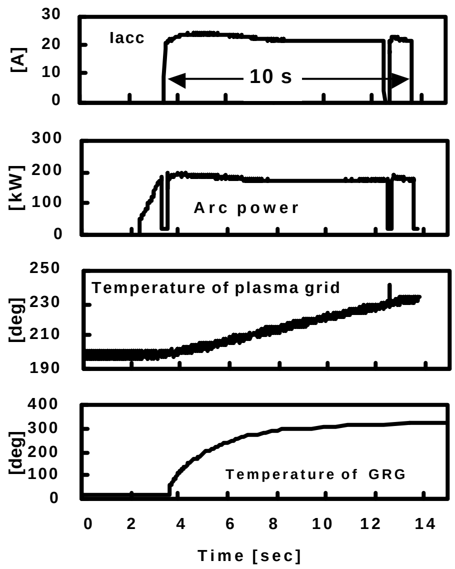

FIG.8 Time evolution of ion source parameter at 10 second injection

5. Longer pulse beam injection

A long pulse beam injection up to 10 seconds was conducted for the evolution of steady-state operation of the ion source. Figure 8 shows a time evolutions of the ion source parameters such as the acceleration current, arc power, temperature of plasma grid and temperature of grounded grid (GRG) surface. The beam injection started at 3.5 seconds in the chart. Though acceleration current decreases a little until 4.5 seconds after beam initiation with decreasing arc power, thereafter the current reaches steady state. Since plasma grid are not cooled, the temperature increases from 200 degrees to 230 degrees with a time. Negative ion beam current is not affected in the range of this temperature. GRG temperature reached to 300 degree in 10 seconds and then it was saturated. These results indicate capability of the long pulse operation of the ion source with control of the plasma grid temperature.

6. Summary

Injection performance of negative-ion based NBI system for JT-60U has been improved by correcting beamlet deflection and improving spatial uniformity of negative ion production. Beamlet deflection was corrected by adjusting electrical field at first acceleration gap. This resulted 60% in reduction of the heat loading on the NBI port limiter. Uniformity of negative ion production was improved by tuning filament emission current so as to put more arc power in the region where less negative ion current were extracted. As the result of improvements above, the continuous injection of 2.6 MW H^0 beam at 355 keV has achieved for 10 s. Thus the long pulse injection up to nominal pulse duration of JT-60U was demonstrated. This has provided a prospect of long pulse operation of negative-ion based NBI system for steady state tokamak reactor. So far, the maximum injection power of 5.8 MW at 400 keV with deuterium beam and 6.2 MW at 381 keV with hydrogen beam have been achieved.

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