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Improving the Performance of a Negative-ion Based Neutral Beam Injector for JT-60U

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Abstract

The performance of a 500 keV negative-ion based neutral beam injection system for the JT-60U has been enhanced significantly. By improving the beam convergence, a beam injection pulse duration of up to 10 seconds has been attained. This is the maximum duration defined by the system design specification. Small peaks were observed in the beam current density profile measured in the near field. These peaks are clearly resulted from the deflection of beamlets due to an unwanted electric field generated at an extractor. Correction of the beamlet deflection improved the beam convergence, resulting in a reduced temperature rise of the beam limiter at the port of the JT-60U by more than 50 %. A Doppler shifted spectrum of the Dα line radiated from the negative-ion beam extracted from the ion source was measured. The Doppler shifted spectrum indicated that electron stripping of the negative ion beam occurs primarily inside the extraction grid and in the first acceleration gap, as expected from theoretical considerations. Moreover, the electron stripping contributed to half of the heat load on the grounded grid at the operating pressure of the ion source.

Keywords:

negative-ion, NBI, JT-60U, heat load of grids

1. Introduction

The negative-ion based neutral beam injection (N-NBI) system for the JT-60U has been in operation since 1996 for plasma core heating and non-inductive current drive in higher density plasma [1]. The design capability of the N-NBI system is a beam energy of 500 keV with an injection power of 10 MW for a duration of up to 10 seconds. Practically, the beam power has been increased gradually through optimization of the operation parameters of the ion source. The injection beam power of the JT-60U plasma has been reported previously to have reached 5.8 MW at 400 keV for 0.86 seconds [2]. To date, the beam power, pulse duration and operating acceleration voltage are all somewhat lower than the design specifications. To achieve optimal performance, there are key issues that must be resolved, namely, excess heat load of accelerator grids, low-convergence beams and low holding acceleration voltages. A low-convergence beam yields an excess heat load on the beam limiter near a beam focusing position of 24 m from the ion source, as shown in Fig. 1. Consequently, the temperature rise of the beam limiter restricts the injection beam power and the pulse duration. On the other hand, it is thought that the main heat load on the grids is due to electron stripping of the negative-ion

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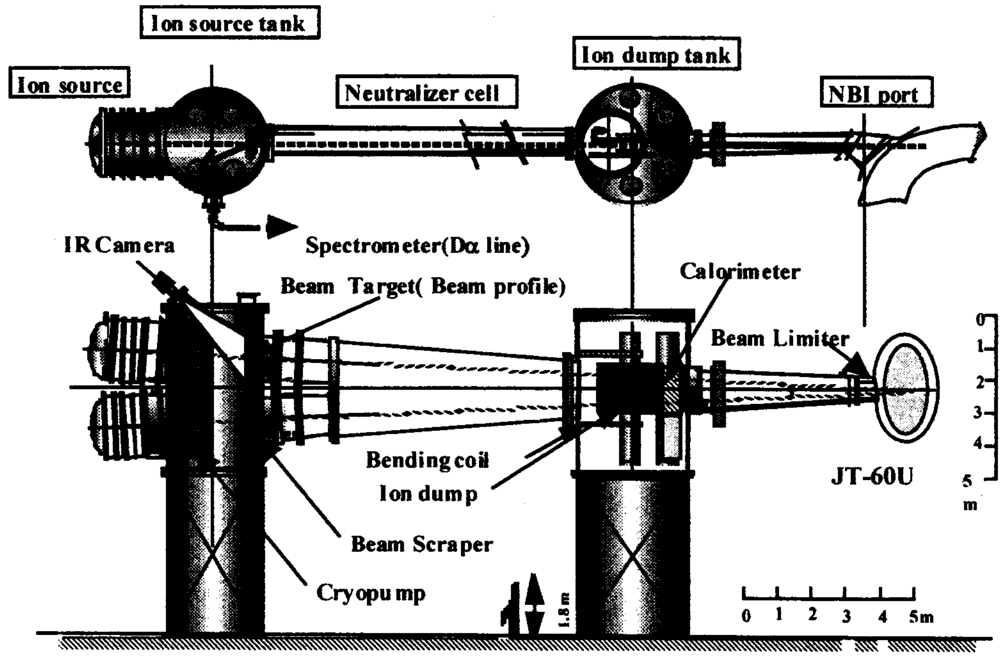

Fig. 1 Cross section view of the beamline and the set up for the measurement of the beam profile and Dα line.

beam in their passage through the grid structure by collision with residual gas molecules [3]. In this paper, we describe the improvement in performance of the neutral beam injection and investigation on the heat load on grids.

2. Improving Convergence of the Negative-Ion Beam

Characteristics of a beam profile were investigated by measuring an infrared image on a beam target located 3.5 m downstream from a grounded grid. This distance is still within the near field of the negative ion source, where the beam profile shows a footprint of grid segments. The infrared image, which reveals a two-dimensional profile of the temperature on the target surface, is thus a measure of the corresponding power density profile of the negative-ion beam extracted from the ion source. Intensification along rows of apertures, which adjoin boundaries of individual grid segments formed each accelerator grid, was observed in the infrared image for some operation parameters of the ion source. A beam orbit analysis has indicated that the peak is a consequence of the overlap of outermost beamlets deflected by an undesirable electric field with the beamlets radiated from the second row apertures of the neighboring segment. This electric field was generated by small groove downstream of the extraction grid

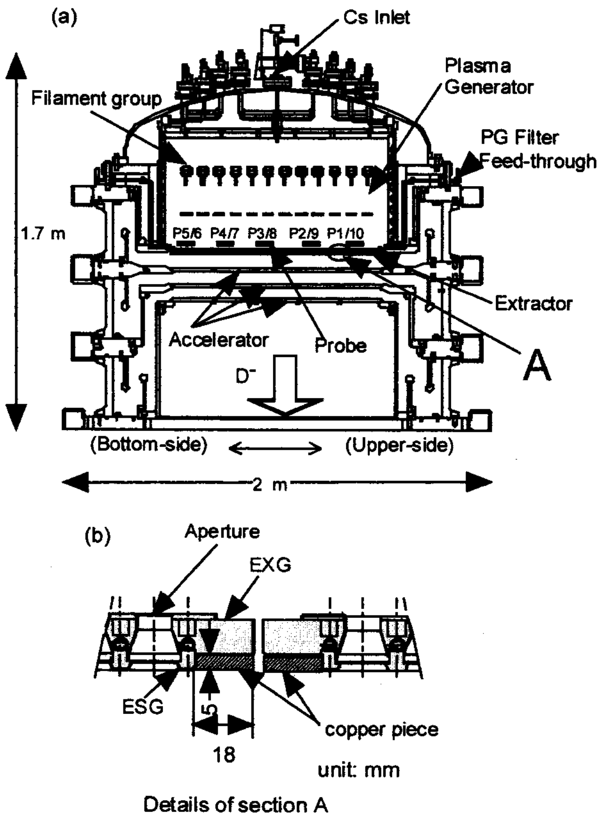

Fig. 2 (a) Cross-section of the negative ion source and (b) detail of copper pieces installed on an extractor.

segment boundaries. In order to remove the undesirable electric field, copper pieces were embedded along the groove as illustrated in Fig. 2.

Figures 3 (a) and (b) show vertical profiles of the temperature rise at a center of the target in the absence and presence of copper pieces, respectively. The dotted lines in Fig.3 indicate the corresponding boundaries of five grid segments. As shown in Fig. 3 (a), a peak appears at an inner side of each segment boundary. Incorporation of copper pieces into the extractor resulted in a shift of both the peaks to the center of the gap between the boundaries of each segment, as shown in Fig. 3(b). This is understood in the way that the outermost beamlets on the neighboring segments are steered inward and overlapped at the center of the gap on the target. It is indicated that the installation of copper pieces at the extractor is useful for generating the electric field which steers the outermost beamlets of the grid segment to correct undesirable deflection.

The beamlet deflection also influenced the heat load on the beam limiter at the port of the JT-60U, whose cross-sectional area is the smallest in the path of the beam. Figure 4 shows the temperature rise of the beam limiter as a function of injection energy using a beam energy of 360~390 keV and an injection power of 2~5 MW operating with one or two ion sources, as appropriate. The injection energy is defined as the injection power multiplied by pulse duration. Figure 4 revealed that correction of the beamlet deflection resulted in a temperature rise that was reduced by over 50 % compared with the uncorrected arrangement. This subsequently led to a remarkable improvement in beam convergence. Until now, a 10 second operation with 23 MJ of injection energy had been achieved, as shown by the double circle in Fig. 4. In addition, no appreciable reduced heat load on the grids by the correction of the beamlet was observed.

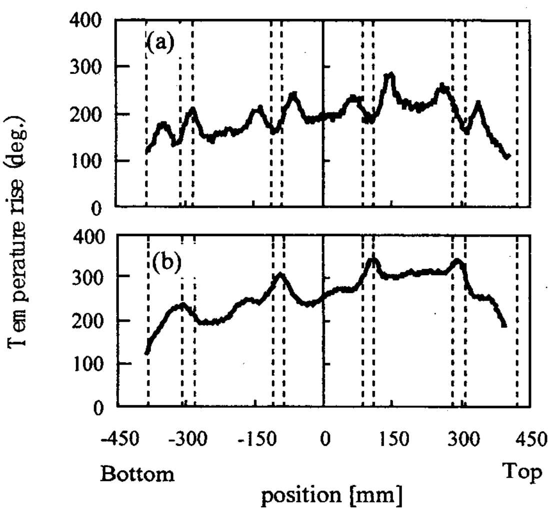

Fig. 3 Temperature rise on the beam target (a) without the copper pieces, Vacc = 350 kV, Iacc = 19 A and Vext = 6.6 kV, and (b) with the copper pieces, Vacc = 380 kV, Iacc = 19 A and Vext = 7 kV.

3. Measurement of Beam Stripping and Heat Load on the Grids

An intense heat load on the grid results from the stripping of negative ion beams in their passage through the grid structure due to collision with residual gas molecules [4]. Since the negative-ion beams are neutralized by stripping the electrons after passing through differing lengths of the accelerating electrostatic field, some of them have energies lower than the nominal accelerating voltage, producing a lower energy continuum in the beam energy spectrum. The stripping arises from a steeply increasing pressure in the accelerator.

Doppler shifted spectra of Dα line radiated from the neutral beam by collision with residual gas were recorded for the different filling pressures in the arc chamber. A pressure range of 0.19 to 0.44 Pa was investigated using the experimental setup as illustrated

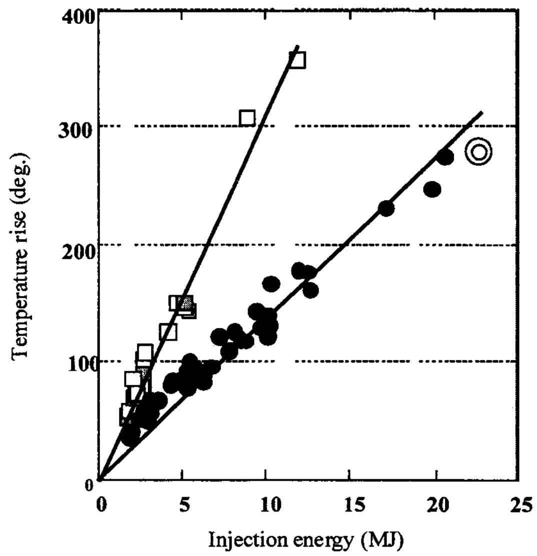

Fig. 4 Temperature rise of the beam limiter at the injection port of JT-60U. The squres and circles are denoted for the data before and after correction of the beamlet deflection, respectively. The double circle is for 10 second pulse duration. The injection energy is referred for injection power to multiply by pulse duration.

in Fig. 1. Figure 5 shows typical Doppler shifted spectra recorded at three different arc chamber pressures. Peaks at Doppler-shifted wavelengths corresponding to the extraction and the first acceleration voltages in addition to the full acceleration voltage were observed. The spectra display clear evidence of stripping of the negative ions inside the extraction grid and the first acceleration gap. Figures 6 (a) and (b) show the dependence of the grid heat loading on the intensity of Dα line at wavelengths corresponding to beam energies of the extraction and the first acceleration, respectively. Dα line was normalized to the intensity of no accelerated beam at the Doppler-unshifted wavelength . A water calorimeter was used to measure the total heat loading of the grids. All grid heat loads were found to increase with increasing intensity of Dα line. The grounded grid heat load extrapolating to zero intensity is 500 kW corresponding to 6 % of the total acceleration power. This indicates the heat loading due to direct interception of the negative ion beam. This was also a half of the total heat load of 1 MW, which was obtained on the grounded grid at the operating pressure of the ion source. Moreover, it is noted that the direct interception with the first and the second acceleration grids was very small.

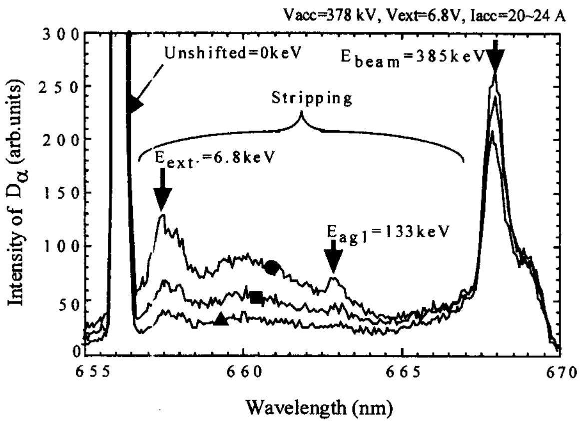

Fig. 5 Doppler-shifted spectrum of Dα line for typical three different filling pressures in the arc chamber. The symbols of triangle, square, and circle are denoted for the filling pressure of 0.19, 0.3 and 0.44 Pa, respectively. E_{ext}, E_{ag1} and E_{beam} are the beam energy of the extraction, the first acceleration, and the full acceleration, respectively.

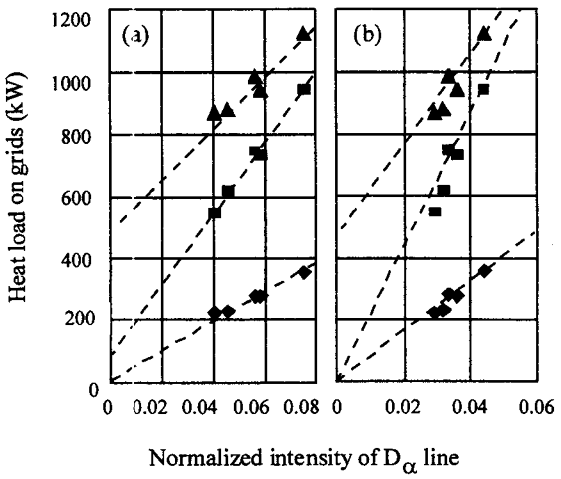

Fig. 6 Heat load on the grids as a function of the normalized intensity of Dα line at the Doppler-shifted wavelength corresponding to the beam energy of the extraction voltage (a) and the first acceleration voltage (b). The normalized intensity of Dα is divided by the intensity at the unshifted wavelength. The symbols of triangle, square and diamond are denoted for the grounded, second and first acceleration grids, respectively.

4. Conclusions

The performance of the N-NBI has been enhanced significantly by improving the convergence of the injected beam. The successful operation duration of 10 seconds has illustrated the prospect of a longer pulse operation for the JT-60 super-conducting tokamak that is under design studies. The direct interception of the negative ion beams contribute to half of the total heat load on the grounded grid, which needs to be reduced to further augment the performance.

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