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Control of negative ion beam uniformity by using multipower supplies for arc discharge

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Multipower supplies for the arc discharge are installed to improve beam uniformity of a large size of the neutral beam injection system in the large helical device (LHD). The plasma tends to shift on the upper side of the arc chamber when the same arc voltage is applied to all filaments. The arc discharge current distribution becomes uniform as a consequence of the individual voltage control, but about 20 V difference of the arc voltage between the top and bottom circuits is required. We have estimated the beam profile from each acceleration grid by comparing the calculation and measurement of the beam profile of $H\alpha$ and calorimeter. The uniformity of arc discharge has been improved in most regions without the discharge adjustment by a horizontal filament connection. The controllability of the arc discharge distribution of the horizontal filament connection is better than that of the vertical filament connection. The efficiency of the beam production is improved by about 10% in the case of the horizontal filament connection. As a result 3.7 MW of the beam injection has been achieved in the LHD 6th experimental campaign in 2003. © 2004 American Institute of Physics. [DOI: 10.1063/1.1695617]

I. INTRODUCTION

It is an important issue that heating of a central part of plasma is attained by high energy beam injection using a negative-ion based neutral beam injection (NBI) system.^{1,2} Negative-ion based NBI systems equipped with cesium-fed volume-production type hydrogen ion sources³ have already worked since 1998 in the large helical device (LHD).⁴ Injection of a high power beam of 10 MW or a long pulse beam of 110 s is carried out.⁵ It is well known that imbalances of arc plasmas are observed in large scaled ion sources with elongated arc chambers.⁶ Improvement of the arc discharge uniformity is needed to increase the beam power and also to obtain better perviance matched beam over a whole beam extraction area.

In this article, we investigate the control of the arc discharge uniformity by using the filament and the arc multipower supplies. The arc discharge current distribution becomes uniform as a consequence of the individual voltage control of each power supply. We estimate the beam profile from each acceleration grid by comparing the calculation and measurement of the beam profile of $H\alpha$ and calorimeter. We also investigate characteristics of arc discharge distribution when changing the connection of a pair of filaments. The uniformity of arc discharge has been improved in most regions without the discharge adjustment, and the controllability of arc discharge distribution of horizontal filament connection is better than that of the vertical filament connection.

II. CONFIGURATION OF THE NEGATIVE ION SOURCE AND MULTIPOWER SUPPLIES

The negative-ion based NBI system is adopted as a main plasma heating device in the LHD. The third NBI injector

(BL3) started its operation in 2001, when 3.2 MW of the beam injection was achieved. Each beam line has two negative ion sources, which are installed side by side. The accelerator consists of five segments of plasma grids, extraction grids, and grounded grids for 180 kV single-stage acceleration.⁷ Each grid has 154 beam apertures, and the focal point of the beamlets is set to 13 m downstream from the ion source. The source plasma is produced by the arc discharge in the arc chamber, which has the dimensions of 35 cm (width)×145 cm (height)×21 cm (depth). The magnetic fields of the line cusp are applied in order to confine the arc plasma, and the external magnetic filter is added in the width direction of the arc chamber.

Fifty hairpin-shaped tungsten filaments 1.8 mm in diameter and 110 mm in length are installed in one ion source. Every two filaments are fed in parallel by an electrically insulated filament power supply which is connected to one independent arc power supply. In beam lines BL1 and BL2, one large arc power supply is used for the arc discharge in each ion source using current dividers.⁷ Although each resistance of the divided output is adjusted for uniform arc discharge, the result has not been satisfactory. Thus we have adopted newly designed independent 12 arc and filament power supplies for each ion source in order to control the arc uniformity in the BL3. Each arc power supply can be controlled individually and remotely. The current load of 500 A is allowed with one unit of filament power supply in the normal operation. Four filaments are connectable with one power supply on the design. The arc current of 416 A is allowed with one arc power supply unit, 180 A of the arc current flows in the usual discharge. The real-time monitoring system of all arc and filament power supplies is also equipped to control the arc discharge.

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FIG. 1. Distribution of (a) the arc voltage and (b) the arc current. (c) The vertical beam profile on the calorimeter located 8.5 m downstream from the ion source. The profile of a beam shifts to the upward area (upper shift) and the downward area (bottom shift) on the calorimeter. The beam profile can be optimized by the individual voltage control as the symmetrical profile (balance) on the calorimeter.

II. CONTROL OF ARC DISCHARGE AND BEAM DISTRIBUTION

The source plasma is made by the arc discharge usually with 24 filaments. A pair of the filaments which adjoin each other is connected with one filament-arc circuit. It is observed that the distribution of arc current shifts upwards of the elongated arc chamber.⁸ When the arc currents of two top circuits are 240 A, the currents of eight downward circuits are below 110 A. The distribution of arc current can be equalized by applying higher arc voltage by 30 V to the bottom circuits. However arcing, which damages a filament, has more frequently occurred in downward circuits. Three filaments are connected to two bottom circuits, i.e., the total number of filaments is 26, in order to improve the arc discharge distribution. Figure 1 shows the variation of the beam profile by changing the arc discharge distribution with 26 filaments. Upper shift and bottom shift are the case where the profile of a beam shifts to the upward area and downward area on a beam calorimeter, respectively. Balance is the symmetrical profile of a beam on the calorimeter. A hollow arc

FIG. 2. (a) Assumed beam profile at the grounded grid, (b) the profile of H α spectra measured 2.2 m downstream from the ion source, and (c) the beam profile on the calorimeter. In (b) and (c), the measured profiles are fitted with the calorimeter ones using the assumed profile in (a).

current distribution is required for the balance beam extraction as shown in Fig. 1(b). The difference of the applied arc voltage between top and bottom circuits is 23 V. The arc current distribution is sensitive to the change of the arc voltage as shown in Figs. 1(a) and 1(b). It is difficult to shift the arc current distribution to the bottom side since the arc discharge in a downward area of arc chamber is weak when the same arc voltage is applied to each filament-arc circuit. Figure 1(c) shows the vertical beam profile measured with a calorimeter array at 8.5 m downstream from the ion source. The beam distribution corresponds to the arc discharge distribution. The acceleration drain currents for the balance, the upper shifts, and the bottom shift discharges are 28.5, 24.4, and 24.7 A, respectively. The negative ion current extracted from the balance discharge was increased.

We have calculated a beam distribution along the vertical axis by a beam tracing using the assumed beam profile in order to presume the distribution of the beam extracted from the ion source. We assume the beam profile at the grounded grid as shown in Fig. 2(a). Fifty-five beamlets along the vertical axis of the ion source are used in this calculation. Each beamlet has a simple Gaussian distribution, and the beam

FIG. 3. Arc current distribution along the vertical axis. The open circles and the closed squares show the arc current distributions where one filament–arc circuit is connected with two vertically adjacent filaments (vertical connection) and two horizontally faced filaments (horizontal connection), respectively. The arc voltages in the individual 12 circuits are the same.

divergence is assumed to be 10 mrad. Calculated beam distributions are fitted with measured beam distributions at two places in the beam line. Figure 2(b) shows the profile of the hydrogen $H\alpha$ spectra, which is measured by a charge coupled device camera with $H\alpha$ optical filters at 2.2 m downstream from the ion source. The $H\alpha$ distribution reflects the initial beam distribution very well. As shown in Fig. 2(c), the measured vertical beam profile on the calorimeter is reproduced by the calculated beam profile using the assumed profile at the grounded grid. It is considered that the negative ion beam currents extracted from three central grids is almost equal and that each beam profile at the grounded grid is flat. Then its beam current from the one segment of grounded grid is 24.4% of the whole. On the other hand, the beam components from the top and bottom grid segments decrease toward the edge, and its beam current is estimated as 13.3% of the whole. The heat load of the extraction grids of the top and bottom segments, which is measured with the water calorimetry, is larger than that of other three grid segments. There would be more electrons extracted from the top and bottom area. Complicated magnetic field structure may have an influence on the top and the bottom area in the arc chamber and the efficiency of the arc discharge is decreased in these areas. It is required to eliminate the complicated structure in the beam area by enlarging the arc chamber in the direction of the vertical axis in order to improve the beam uniformity in the upward and the downward areas.

IV. IMPROVEMENT OF ARC DISCHARGE UNIFORMITY BY CHANGING FILAMENT CONNECTION

We had connected two vertically adjacent filaments with one filament–arc circuit. The arc plasma shifts greatly on the upper side of the arc chamber, when the same arc voltage is applied to all filaments as indicated by open circles in Fig. 3. Even if the arc discharge in the downward area is strengthened, the arc discharge plasma flows upward. Moreover controllability of the arc discharge distribution is not so good. It is required to improve the arc discharge uniformity when the same arc voltage applies to all filament–arc circuits. We therefore make a pair with two filaments facing each other horizontally and connect them to one filament–arc circuit in

FIG. 4. Acceleration drain current as a function of the arc discharge power with two negative ion sources. The open circles and the closed squares show the case where one filament–arc circuit is connected with two vertically adjacent filaments (vertical connection) and two horizontally faced filaments (horizontal connection), respectively.

order to reduce the influence of arc discharge with the other of filaments. Figure 3 also shows the arc discharge distribution applying the same arc voltage to each horizontal pair of filaments. The arc discharge distribution has improved in most regions in the arc chamber when the same arc voltage is applied to all filament–arc circuits. The controllability of the arc discharge distribution of the horizontal filament connection is better than that of the vertical filament connection. We have observed that the arc current of one circuit in a central area becomes half when one filament in that circuit burns out. This shows that the arc discharge with one circuit takes place independently against the other circuit. The arc plasma produced by one filament–arc circuit with the horizontal filament connection is confined in the horizontal magnetic field line.

The vertical beam profiles of the $H\alpha$ and the calorimeter in the horizontal filament connection are the same as those in the vertical filament connection. A hollow arc discharge distribution is required in order to realize the beam profile shown in Fig. 2 in the case of the vertical connection. On the other hand, in the case of the horizontal filament connection similar beam profiles to those in Fig. 2 are observed in the flat arc discharge distribution. The arc powers of the upward and downward areas of the arc chamber are smaller in the case of the horizontal filament connection. Figure 4 shows the acceleration drain current from two ion sources as a function of the total arc power. The beam current is proportional to the arc discharge power. In the horizontal filament connection, an acceleration current of 60 A can be extracted with an arc power of 190 kW, while 220 kW of the arc power is needed to extract a 60 A beam in the vertical filament connection. Efficiency of the beam production is increased by about 10% by improving the arc discharge uniformity in the horizontal filament connection, and 3.7 MW of the beam injection has been achieved in the sixth LHD experimental campaign in 2003.

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