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The Arc Regulation Characteristics of the High-Current Ion Source for the EAST Neutral Beam Injector*

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Abstract The arc regulation method is applied to the high-current ion source for high-power hydrogen ion beam extraction for the first time. The characteristics of the arc and beam, including the probe ion saturation current, the arc power and the beam current, are studied with feedback control. The results show that the arc regulation method can be successfully applied to ion beam extraction. This lays a sound foundation for the testing of a new ion source and the operation of a conditioned ion source for neutral beam injector devices.

Keywords: ion source, arc regulation, ion saturation current, beam extraction

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(Some figures may appear in colour only in the online journal)

1 Introduction

Neutral beam injection (NBI) heating is one of the most important auxiliary heating methods in tokamaks [1−3]. In order to support the physical research of the Experimental Advanced Superconducting Tokamak (EAST), a 4 MW NBI system has been developed at the Institute of Plasma Physics, Chinese Academy of Sciences (ASIPP) [4,5].

The powerful high-current ion source is one of the key components of the 4 MW NBI system, and also the most precise part. One beam line has two ion sources, and each of them has a beam power of 2 MW. The ion source is required to be operated in long pulse beam extraction mode because the EAST tokamak is designed for long pulse length mode. The intrinsic characteristic of the hot cathode bucket ion source is a slow increase in the arc and beam currents during the beam pulse. This is attributed to the heating of filaments by the energetic backstreaming electrons from the accelerator into the arc chamber [6,7], so the arc and beam current will increase, and this tends to be unstable. The ion source of the EAST NBI has been developed and undergone preliminarily testing [8,9]. The arc regulation method is designed and tested to achieve stable arc discharge [10]. In this paper, the ion beam extracted from the high-current ion source with arc regulation is introduced for the first time, and a preliminary analysis of the characteristics of the ion beam with arc regulation for the EAST NBI high-current ion source is given.

2 Experimental setup

A hot cathode bucket source is used for the EAST NBI high-current ion source [4,8]. It contains a plasma generator and an accelerator. The plasma chamber has dimensions of 650 mm (L)×260 mm (W)×300 mm (D), and the extraction area is 100 mm×475 mm. Two Langmuir probes are installed on the short side of the arc chamber in front of the accelerator grids, which are used to measure the plasma density for the feedback control of the arc power. There are 32 pure tungsten filaments installed opposite to the accelerator grids, and each of them is 160 mm long with a diameter of 1.5 mm. 40 lines of permanent magnets are arranged outside the plasma chamber to form an axial line-cusp configuration. The extraction system is of multiple slit-type and has four layers of extraction grids. Each layer has 64 rails, which are made of molybdenum [4]. The accelerator has a high beam transparency of 60%, and cooling water goes through the inner pipe of the rails to remove heating deposition.

Ion source beam extraction tests are supported by many other auxiliary systems, including a power supply system, vacuum pump system, water cooling system and gas supply system. A cryogenic pump system with

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a pumping speed of 1.4×10^6 L/s has been developed, and the background pressure of the vacuum chamber can reach 10^{-6} Pa.

3 Preliminary experimental results

The physical requirements and the design of the arc regulation system for high-current ion source are reported in Ref. [10]. The plasma density was measured by a Langmuir probe, and the probe ion saturation current was the output signal. The command value was set by an operator, and was used to compare with the output signal. Using the comparison calculation of the probe output signal and command value, a control signal was output and used to feedback-control the arc discharge during arc and ion beam extraction. The response time of the arc regulation system depends on the rate of increase of the plasma density when the plasma density reaches the required value, which was characterized by the value of $\mathrm{d}i_{\mathrm{i0}}/\mathrm{d}t$. As a general rule, the faster the plasma density reaches the setting value, and the higher the rate of increase of $\mathrm{d}i_{\mathrm{i0}}/\mathrm{d}t$, the faster the arc discharge reaches the equilibrium condition.

3.1 Ion beam extraction with and without arc regulation

The ion beam was extracted from the high current ion source without and with the arc regulation method. The experimental waveforms are shown in Fig. 1 and Fig. 2, respectively. In Fig. 1, the ion source operated without arc regulation. We can see that the arc current increases from 523 A to 644 A during the length of the pulse, an increase of about 23%. The ion beam current increases from 15.5 A to 22.8 A, an increase of about 47%. When the arc and beam current is increased, the ion beam will be terminated because the ion optics of the accelerator have changed.

Fig. 2 shows the ion beam extraction with arc regulation for different plasma densities. It can be seen in Fig. 2 that the waveform can be divided into three stages. The arc voltage is regulated during the first stage until the probe ion saturation current reaches the setting value, which corresponds to the command value. Then, the arc discharge goes into the equilibrium stage, which is the second stage, and the arc voltage and arc current remain unchanged. The third stage is ion beam extraction. The arc and beam are also very stable during the pulse length under regulation, except at the start of the ion beam. The probe ion saturation current and the arc current have a slight increase, but quickly become stable under regulation.

The regulation time, which in the first stage is different, depends on the condition of plasma generation and the command setting value. This contains the time duration when the probe ion saturation current (and the arc current) increases to the setting value and the arc regulation system response time. When the command setting value is much larger, the plasma density generated in the arc chamber needs more time to reach the setting value, as can be seen in shot No. 8429. On the contrary, the plasma density can reach the setting value in a short time and the arc regulation system can respond very quickly, as can be seen in shot No. 8395. When a high arc current is requested, the setting value is much larger and the arc needs more time to reach the expected working condition. In this case, the response of the arc regulation system depends on the value of $\mathrm{d}i_{\mathrm{i0}}/\mathrm{d}t$. In Fig. 2, the response time of the feedback control system in the three shot is about 100 ms, but the way the plasma density reaches the setting value is different. So the plasma generated in the arc chamber needs to respond as quickly as possible, and then the feedback control system can work quickly.

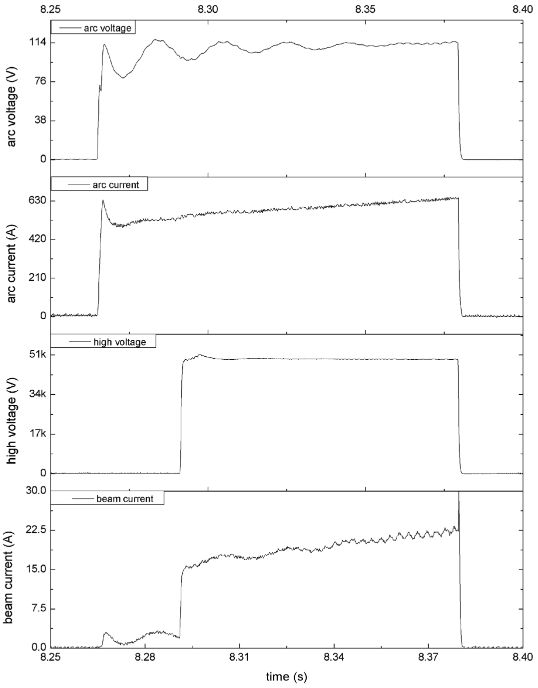

Fig.1 The waveform of the beam extraction without arc regulation

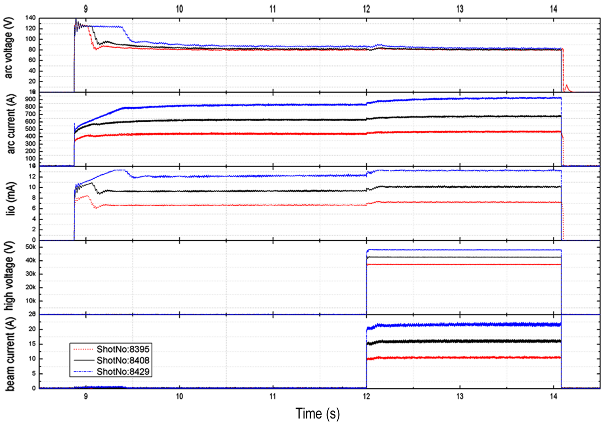

Fig.2 The waveform of the beam extraction with arc regulation

3.2 Characteristics of arc regulation for the high-current ion source

In the arc regulation system, the setting of the command value has a close relation with the plasma density. In order to investigate the relationship of the feedback control command value with the plasma density, the probe ion saturation current was measured by a Langmuir probe when the command value was changed. The experimental results are shown in Fig. 3. The probe ion saturation current increases linearly from 3 mA to 18 mA when the command value changes from 30 to 138. So the plasma discharge can be controlled by setting the feedback control command value.

The arc power shows the capacity of plasma power generated in the arc chamber, which can also be expressed in terms of plasma density. The relationship between the arc power and probe ion saturation current (plasma density) was studied as shown in Fig. 4. It shows that the arc power increases linearly with the increase in probe ion saturation.

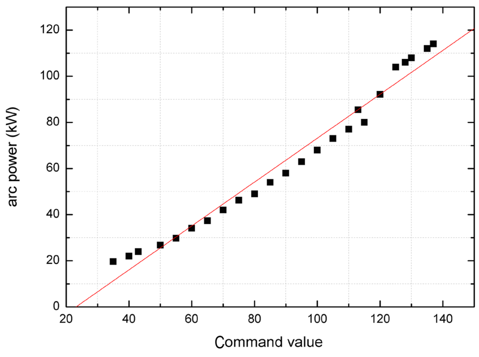

Fig.3 The probe ion saturation current as a function of the command value for arc regulation

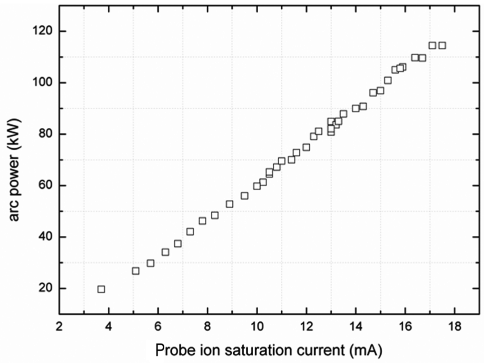

Fig.4 Arc power as a function of probe ion saturation current

The ions in front of the accelerator are extracted and accelerated to form the ion beam, so the ion density will be proportional to the ion beam current in theory. According to accelerator physics and classical probe measurement theory [7,11], the ion beam density and probe ion saturation current can be calculated with Eqs. (1) and (2),

$$J_\mathrm{e} \approx 0.4 n_\mathrm{e0} e \sqrt{\frac{2kT_\mathrm{e}}{M}}, \tag{1}$$

$$I_\mathrm{i0} \approx \alpha n_\mathrm{i} e \sqrt{\frac{2kT_\mathrm{e}}{M}} S_\mathrm{i}, \tag{2}$$

where n_e0 is the electron density, k the Boltzmann constant, T_e the electron temperature, M the ion mass, α the constant value in 0.4∼1, n_i the ion density, and S_i the probe area to get the electrons and ions. If the electron density is equal to the ion density in the plasma, the relationship between the ion beam current and the probe ion saturation current can be deduced from Eqs. (1) and (2),

$$I_\mathrm{ex} \approx 0.8 S_\mathrm{ex} \frac{I_\mathrm{i0}}{\alpha Z S_\mathrm{i}}. \tag{3}$$

Here, I_ex is the extracted ion beam current, and $S_\mathrm{ex} = 10 \times 47.5 \times 0.6 = 285\ \mathrm{cm}^2$ is the extraction area. In the experiment, the relationship between the probe ion saturation current and beam current was also investigated and compared with the theory, as shown in Fig. 5. It can be seen from Fig. 5 that the experimental results accord with the theoretical calculation.

We can see from Fig. 3 to Fig. 5 that the command value is the linear function of the probe ion saturation current, and the probe ion saturation current is the linear function of the arc power and beam current, so the expected beam parameters can be obtained easily by setting the arc regulation command value in the operation control system. This is very helpful for the operation of the high-current ion source.

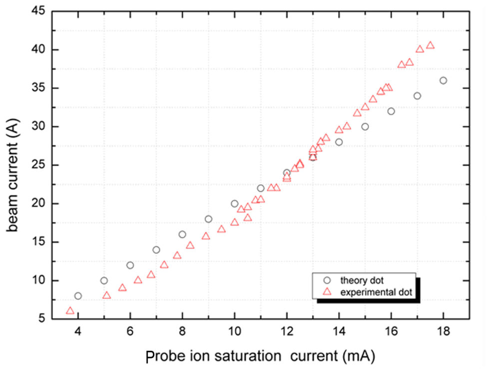

Fig.5 The beam current as a function of probe ion saturation current

4 Conclusion and discussion

A high-current ion source extracted the ion beam with and without the arc regulation method. A stable ion beam was extracted under the arc regulation method, and the arc regulation characteristics were also investigated during the beam extraction experiment. The relationship between the probe ion saturation current, the arc power and the beam current was derived, and the experimental results are in good agreement with the theoretical calculations. This shows that the arc regulation method can be successfully applied to ion beam extraction. It lays a sound foundation for long pulse operation of high current ion sources and offers much experience for the testing and operation of the EAST NBI system in the future.

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