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Citation: Rev. Sci. Instrum. **83**, 013301 (2012); doi: 10.1063/1.3676655

View online: http://dx.doi.org/10.1063/1.3676655

View Table of Contents: http://rsi.aip.org/resource/1/RSINAK/v83/i1

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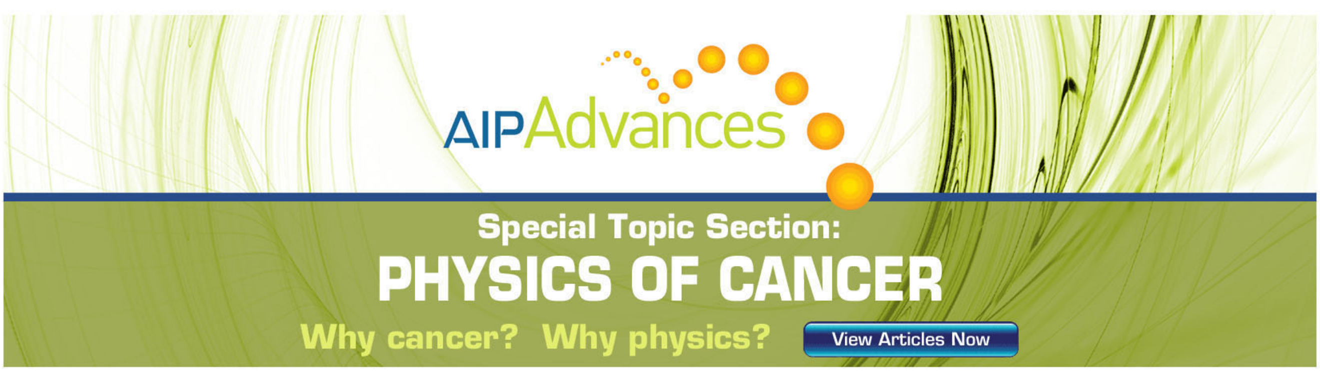

Arc discharge regulation of a megawatt hot cathode bucket ion source for the experimental advanced superconducting tokamak neutral beam injector

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(Received 21 October 2011; accepted 18 December 2011; published online 6 January 2012)

Arc discharge of a hot cathode bucket ion source tends to be unstable what attributes to the filament self-heating and energetic electrons backstreaming from the accelerator. A regulation method, which based on the ion density measurement by a Langmuir probe, is employed for stable arc discharge operation and long pulse ion beam generation. Long pulse arc discharge of 100 s is obtained based on this regulation method of arc power. It establishes a foundation for the long pulse arc discharge of a megawatt ion source, which will be utilized a high power neutral beam injection device. [doi:10.1063/1.3676655]

I. INTRODUCTION

A megawatt high current ion source is the most important part of the neutral beam injection device. A hot cathode bucket ion source is one of the most famous ion sources, and widely used for the neutral beam injector.[1–4] With the development of the controlled fusion science, megawatt ion sources are needed to operate in a long pulse mode, and even in a steady-state mode. In these modes of operation, the beam power will reach several megawatts, and the arc current will reach kilo-amperes. For the hot cathode bucket ion source operating in a pulse mode, the intrinsic characteristic is the slow rise of the arc and beam current during the pulse length, what contributes to the cathode self-heating and the energetic electrons backstreaming from the accelerator into the ion source arc chamber. In order to obtain good ion optical characteristics of the ion beam, the arc plasma density, hence arc current needs to mach the extraction voltage, therefore, the arc current has to be kept stable. In this paper, we present the typical ion source operation mode and the mode with the arc power regulation based on the Langmuir probe measurement.[5] A stable long pulse of 100 s is obtained providing solid foundation for the beam generation and extraction in the future ion source performance tests.

II. REQUIREMENT OF REGULATION AND THE PHYSICS OF MEGAWATT HOT CATHODE ION SOURCE

The experimental advanced superconducting tokamak-neutral beam injector (EAST-NBI) ion source is developed and has primarily been tested.[6] The arc discharge circuit of the power supply system of the EAST-NBI ion source is shown in Fig. 1. There are 32 pure tungsten filaments installed in the ion source. Each filament is 160 mm long with diameter of 1.5 mm. The arc and filament power supplies are connected to the common cathode terminal, so the filament will be extra heated because of the arc current flow through the negative leg of the filament. The filament self-heating causes the increase of arc current and the discharge becomes unstable. When the ions are extracted, the electrons, which include background electrons and secondary electrons when ions impact the girds, are accelerated back into the arc chamber and heat the plasma resulting in further growing instability. Ions of the plasma near the plasma grid are used for extraction, and the density is expected to be uniform and stable over the beam pulse duration. Thus, the arc discharge has to be regulated to achieve stable ion source operation, by using the ion current density in the extraction area to feedback into a system controlling the ion source arc discharge. In order to better understand the regulation principle of the ion source, the physics of ion source operation is introduced first.

A hot cathode ion source is composed of a plasma generator and accelerator. The ions of the plasma, generated in the arc chamber, are used for extraction and acceleration to form an ion beam. The principle of the plasma generation is based on the gas discharge theory.[7,8] The filament works as the cathode, emits electrons when heated. The elections are accelerated by the electric field and ionize the neutral gas to generate electron-ion pairs and form the plasma. The primary electron density can be given by the Richardson-Dushman equation,

$$J_{pe} = AT^2 \exp(-\varphi/kT), \tag{1}$$

where $A = 120.4$ A cm^{-2} K^{-2} is the Richardson's constant, $e\varphi = \phi = 4.55$ eV is the work function of tungsten, k is the Boltzmann constant. Equation (1) presents the relationship between filament temperature and the primary electrons current density.

The plasma generation is a complex process and has been described with some simplifying assumptions and can be seen simplified in the literatures.[9–12] Primary electrons ionize the gas to generate plasma ions and electrons, and the ions and electrons generation rate can be presented as follows:

$$R_e = n_0 n_{pe}\langle\sigma_c v_{pe}\rangle V + 2n_0 n_{pe}\langle\sigma_i v_{pe}\rangle V + n_p V/\tau, \tag{2}$$

$$R_i = n_{pe} n_0 \langle\sigma_i v_{pe}\rangle V. \tag{3}$$

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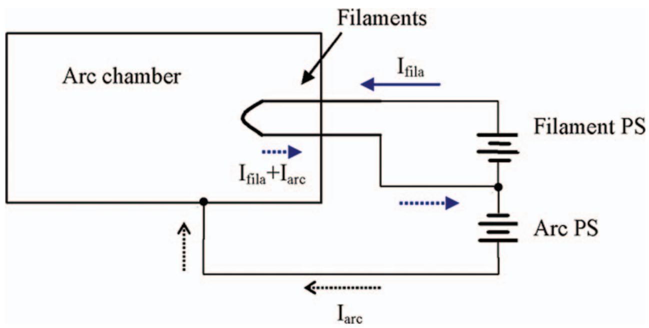

FIG. 1. (Color online) Circuit of the arc chamber power supplies of the EAST-NBI ion source.

Here n_{pe} is the primary electron number density, n_0 is the density of neutral gas in the arc chamber, V is the arc chamber volume, $\langle\sigma_c v_{pe}\rangle$ is the sum of all inelastic collision reaction rate coefficients averaged over the velocity distribution of the primary electrons, $\langle\sigma_i v_{pe}\rangle$ is the ionization reaction rate coefficient averaged over the velocity distribution of the primary electrons, and τ is the lifetime of the primary elections in the magnetically confined discharge chamber. It can be seen from Eqs. (2) and (3) that the ion and electron generation rate are ruled by the primary electron number density, neutral gas density, and the collision reaction rate coefficients.

In the arc chamber, the ion or electron generation rate is equal to the corresponding lost rate, so the arc current can be written as

$$I_e = en_{pe}n_0(2\langle\sigma_i v_{pe}\rangle + \langle\sigma_c v_{pe}\rangle + n_{pe}/\tau)V, \tag{4}$$

$$I_i = en_{pe}n_0\langle\sigma_i v_{pe}\rangle V. \tag{5}$$

Equations (4) and (5) can be used to calculate the arc current. It can be seen that, the primary electron density n_{pe}, the neutral gas density n_0, and the electron energy represented by the term $\langle\sigma v_{pe}\rangle$ can affect the arc current. Furthermore, the energy of electrons is obtained from the arc voltage when they cross the filament double sheath.[13] Thus, the arc voltage is the effectual factor in affecting the arc plasma generation.

III. ARC DISCHARGE REGULATION OF HIGH CURRENT ION SOURCE

Stable arc discharge is the foundation for attaining long pulse operation of the ion source. It requires the ion number density of the plasma to remain stable during the arc discharge, which means that the arc current waveform remains much smoother. The above described discharge model shows that, the ion number density produced in the arc chamber is proportional to the primary electron number density, the neutral gas density, and the collision reaction rate coefficients, which controlled by the filament temperature, neutral gas inlet rate, and arc voltage. It provides a way of controlling the ion production for achieving stable arc discharge plasma. The ion density can be measured by a classical Langmuir probe and the ion saturation current can be used as the only reference to regulate the arc discharge.

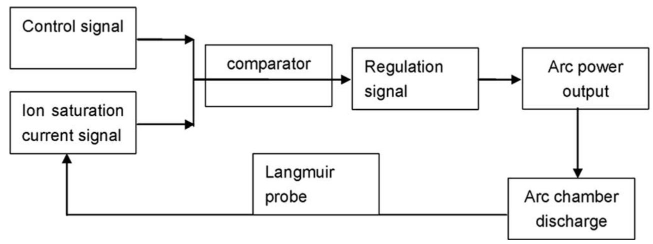

FIG. 2. Block-diagram of the arc discharge regulation system.

According to the discharge model, the arc voltage is used for regulating the plasma density because it has fast response (microseconds) and does not effect the beam extraction. The regulation block-diagram which is based on the Langmuir probe measurement is shown in Fig. 2. The ion saturation current is measured by the Langmuir probe near the plasma grid applying the probe bias voltage 25 V relative to the common filament node of the power supplies, and compared with the control signal (set by an operator) to produce the regulation signal. The regulation signal is used for regulating the arc power supply output for restraining the change in the plasma density and achieving stable arc discharge. During the experiment, the regulation circuit functions all the time to maintain the required plasma density and stable ion source operation.

The ion source experiment has been conducted with and without the regulation circuit. The results are shown in Fig. 3. It can be seen that, the arc current and ion saturation current increases without regulation during the pulse length, however, is much smoother with the regulation. When without regulation, the arc current increases from 340 A to 450 A in 1 s, what is more than 30% increase. As can be seen in the figure, the ion saturation current has the same increasing tendency.

When the regulation circuit functions, the ion saturation current is used for regulating the arc power supply output. The arc voltage output drops down form 135 V to 85 V to prevent the increase of ion saturation current and arc current. After about 200 ms of regulation, the ion saturation current reaches equilibrium and the arc discharge is much stable, which can

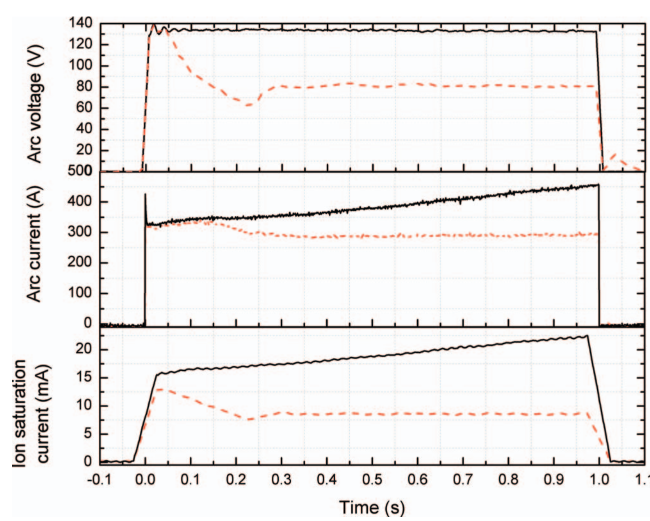

FIG. 3. (Color online) The waveforms of arc discharge with and without regulation. Dash line: with regulation, solid line: without regulation.

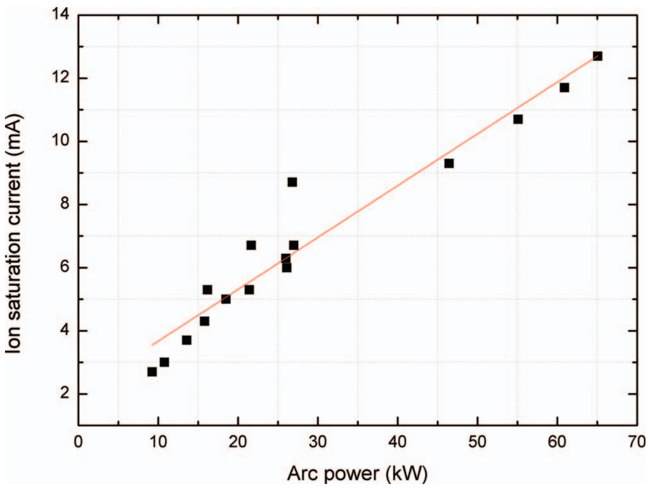

FIG. 4. (Color online) Langmuir probe ion saturation current as a function of arc power.

be seen in Fig. 3. As a result, the arc current and ion saturation current are much smoother during the pulse length.

In order to study the relationship between the probe ion saturation current (when the plasma gets into equilibrium condition) and the arc power, the control signal was changed during the experiment. The corresponding experimental result is shown in Fig. 4. The Langmuir probe ion saturation current increased linearly with arc power. Based on this relationship, the ion source can be controlled and regulated to get required plasma easily.

Based on this regulation circuit, a 100 s pulse arc discharge of 300 A is obtained on EAST-NBI ion source. When the arc discharge gets into equilibrium condition, the waveforms of arc voltage, arc current, and ion saturation current are much smoother. It shows that, the regulation method based on ion density measurement works successfully for arc discharge stabilization.

IV. CONCLUSION AND DISCUSSION

A megawatt high current arc discharge ion source becomes unstable and a regulation method should be employed for the stable long pulse arc discharge and ion beam generation. The method is based on the diagnosis of the arc plasma ion saturation current, which is measured by a Langmuir probe. Three parameters can be regulated to achieve stable long pulse operation of the ion source. In the present experiment, the arc voltage is used for regulating the arc discharge. The results show that, with this type of regulation, the ion saturation current and the arc current are much smoother and generate stable long pulse arc plasma of 100 s. It provides good foundation for stable operation of the EAST-NBI ion source. The experiment results have proven the success of the developed regulation method, which is important for the future arc discharge and beam extraction tests on the EAST-NBI ion source.

ACKNOWLEDGMENTS

This work was supported by the National Natural Science Foundation of China (NNSFC) (Contract No. 11075188) and the Knowledge Innovation Program of the Chinese Academy of Sciences (Study of the physical characteristics of arc power feedback control for the high current ion source).

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