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Plasma Studies on a Duopigatron Ion Source

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PLASMA STUDIES ON A DUOPIGATRON ION SOURCE^{*}

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ABSTRACT

In an effort to develop a plasma source capable of producing a dense, quiescent, uniform plasma for extracting tens of amperes of hydrogen ions, experimental and theoretical studies on a duoPIGatron ion source have been pursued. A study of plasma generation in the duoPIGatron was begun and a discharge model was subsequently developed to explain observed source behavior. The discharge model is based on two plasmas, a cathode plasma and a PIG plasma separated by a double layer of ions and electrons, and is similar to the existing model for a duoplasmatron. This discharge model is reviewed and the importance of the double layer on plasma generation in the duoPIGatron is discussed. Source electrode modifications suggested by the model resulted in a low noise level of about $\pm 5\%$ and a low-density nonuniformity of about $\pm 10\%$ over a 10-cm diameter at a high hydrogen plasma density of roughly $2 \times 10^{12} \text{ cm}^{-3}$.

I. INTRODUCTION

Neutral beam injection heating experiments in the Adiabatic Toroidal Compressor (ATC) and the Oak Ridge Tokamak (ORMAK) have demonstrated that energetic neutral beams can significantly heat toroidal plasmas.^{1,2} The duoPIGatron ion source developed at the Oak Ridge National Laboratory (ORNL) is one of the prime candidates for developing future high power neutral beam injectors, e.g. for Princeton Large Torus (PLT), the Poloidal Divertor Experiment (PDX), and the Tokamak Fusion Test Reactor (TFTR) at Princeton Plasma Physics Laboratory (PPPL); for Doublet III at General Atomic Company; and for ORMAK Upgrade at ORNL. For these applications, the plasma source developed should be capable of generating a dense, quiescent, uniform plasma for producing tens of amperes of hydrogen or deuterium ion current in the energy range of tens to hundreds of kilo-electron volts. To fulfill these basic requirements, a study of the plasma generation and discharge mechanism of duoPIGatron ion sources has been undertaken. A discharge model has been developed to explain the observed source behavior. This discharge model is based on two plasmas, a cathode plasma and a Philips ion gauge (PIG) plasma separated by a double layer of ions and electrons, and is similar to an existing model for a duoplasmatron.³ We briefly review the plasma generation and discharge model, discuss the key effect of the double layer, and report the electrode modifications which have been employed for improving the source performance.

II. PLASMA GENERATION

Figure 1 shows a sketch of a 10-cm (grid diameter) duoPIGatron ion source and its associated electrical connections. It consists of a filament; an intermediate electrode; two anodes, numbered 1 and 2; and a target cathode. (Other researchers refer to the target cathode as the plasma electrode or screen electrode.) Pulsed arc voltage is applied between the anodes and filament, while both the intermediate electrode and target cathode are self-biased through high resistance connections to the anode. The intermediate electrode serves as a magnetic pole to provide an inhomogeneous axial magnetic field in the anode regions.

For normal operation, primary electrons emitted from the filament produce a cathode plasma in the intermediate electrode chamber. Some of these electrons are accelerated through the intermediate electrode channel and into the anode region. These energetic electrons are constrained by the magnetic field and oscillate between the cathode plasma and target cathode. They initiate and maintain a so-called PIG discharge or a reflex discharge. Because of their high energy and long path length, they produce a dense PIG plasma and become the chief ionizers in the PIG region. The ions so created are formed into an ion beam by the extraction electrodes. In the closely coupled gas cell, this ion beam is converted into an energetic neutral beam for heating a plasma such as the one in ORMAK.

III. DISCHARGE MODEL

The general operating range of the source variables is listed in Table I. The hydrogen pressure is about 50 mTorr in the intermediate electrode chamber and about 5 mTorr in the target cathode region. The applied magnetic field is about 200 to 400 G in the intermediate electrode region and about 10 to 20 G in the target cathode region. The arc voltage is up to 150 V and arc current is up to 220 A. The corresponding electrode potential is also listed in the table.

Together with the results obtained from measurements on an axial probe, these data can be utilized to depict an axial potential distribution in the source, as shown in Fig. 2. This distribution confirms that the source plasma is composed of a cathode plasma and a PIG plasma separated by a double layer.

The cathode plasma results from the cathode discharge located within the intermediate electrode chamber. This discharge is initiated and sustained by the primary electrons emitted from the filament. In this region, which is free of magnetic fields, the discharge intensity is essentially determined by the discharge current and gas pressure because of the low electron energy. Normally, the cathode plasma is separated from the filament by a double layer of ions and electrons, and from the walls of the intermediate electrode by a single layer of ions. Thus the plasma potential is greater than the filament potential by the cathode fall. On the other hand, the floating intermediate electrode behaves as a Langmuir probe and has its potential, V_{IE} , fixed by the plasma potential and electron temperature. Consequently, the potential difference between the intermediate electrode and the filament, $V_{IE} - V_F$, is a few volts below the cathode fall, which is larger than the ionization potential of the working gas (i.e. hydrogen). This may explain why the values of $(V_{IE} - V_F)$ for the normal operation of the source are within the range of 20 to 30 V, as listed in Table I.

The PIG plasma results from the PIG discharge which is located in the region enclosed by the anodes, the cathode plasma, and the target cathode. The discharge is essentially initiated and maintained by the electrons originating from the cathode plasma. These electrons gain

at least an energy corresponding to the potential drop across the double layer between the two plasmas. In addition, they are constrained by the applied magnetic field and oscillate between the cathode plasma and target cathode. With sufficiently high energy and long path length, they establish a strong PIG discharge and become the chief ionizers. Thus, the discharge intensity is mainly affected by the applied magnetic field, the arc voltage, and the discharge current.

The double layer not only sustains the potential difference between the two plasmas but also ensures the arc conduction through them. The arc conduction is maintained by both electrons and ions flowing through the double layer. The electrons originate from the cathode plasma and are accelerated into the double layer, while the ions are created in the PIG discharge and diffuse towards the intermediate electrode and drift into the double layer. Owing to the mass difference between the ions and the electrons, the modified Langmuir's stability criterion for the double layer is^{4,5}

$$J_e/J_+ \leq \gamma(M_+/M_e)^{1/2} = k, \quad (1)$$

where J_e is the electron current density in the cathode plasma, J_+ is the ion current density in the PIG plasma, γ is a constant about 1/2, and M_+ and M_e are the ion and electron masses, respectively. The constant k is about 30 for the hydrogen molecular ion. Thus, the arc current is dominated by the electron current.

In summary, the cathode plasma works as an electron source, supplying ionizing electrons to the PIG discharge, and the PIG plasma works as an ion source, supplying ions to the extraction electrodes for forming a useful ion beam. The double layer works as a controller: It controls the density and uniformity of the PIG plasma and influences source reliability. This point is further clarified in Sec. IV.

IV. EFFECT OF DOUBLE LAYER

In practice, the spatial distribution of the electron current density, J_e , in the cathode plasma and of the ion current density, J_+ , in the PIG plasma changes greatly with the arc condition. To satisfy the stability criterion given in Eq. 1, the shape of the double layer will vary with the intensity of both discharges. For example, it can be either concave, flat, or convex toward the PIG plasma, as shown in Fig. 3. The curvature of the double layer can greatly affect the plasma density and uniformity and the source reliability. In the following, we discuss these effects for a concave double layer.

A. Plasma uniformity

Normally, for producing a useful ion beam, the arc condition is adjusted to produce a dense PIG plasma. Often the cathode discharge is too weak and the double layer bulges towards the cathode plasma, as shown in Fig. 4. This concave double layer focuses the ionizing electrons towards the axis. The electrons are then confined by the magnetic field and produce a dense arc column close to the axis. The resulting axial focusing of electrons creates a highly nonuniform PIG plasma, as shown in Fig. 5, curve I. The plasma uniformity shown by curve II in this figure has been improved substantially through use of an axial button of the proper size located on the intermediate electrode snout. The axial button is capable of diverting the arc column from on-axis to off-axis; its function is described in detail in Sec. V.

B. Source reliability

The concave double layer (Fig. 4) not only produces a nonuniform PIG plasma but also increases the radial electric field in the outer arc column of the PIG region. The resulting $E \times B$ rotation can lead to an undesirable charge separation in the plasma and to flute instability⁶ because of the different collision frequency between electron-gas and ion-gas collisions. This may account for the observed high noise on the arc current whenever the applied magnetic field is too strong. If the magnetic field is further raised to an undesirably high

value, a large amplitude of noise modulation (rapid and erratic discharge interruptions) on the arc current, about $\pm 100\%$, can suddenly set in. This undesirable noise level could be due to the fluctuation of the double layer. Under this situation, there is a great increase in the number of electrons entering the double layer radially from the outer region of the cathode plasma and being reflected by the strong mirror magnetic field at the entrance region of the intermediate electrode channel. The associated decrease of ionizing electrons weakens the PIG discharge. To satisfy the stability criterion of the double layer as given by Eq. 1, the shape of the double layer may vary as those shown in Fig. 3. Such double layer fluctuations can be sustained during the whole arc pulse and cause the undesirably high noise level observed. In addition, the associated bombardments of backstreaming ions may well account for the rapid burnout of the filament under such conditions. Such an undesirable source behavior can appear whenever the operating conditions are outside the normal range. Typical examples of such abnormal conditions are: the applied magnetic field is too strong, the anode voltage and/or gas pressure is too low, and the electron emission from the filament is insufficient. These problems have been alleviated substantially through use of proper electrode modifications, described in Sec. V.

V. ELECTRODE MODIFICATIONS

Based upon the understanding of the plasma generation in the duo-PIGatron and the instability mechanism, the proper electrode modifications have been employed to improve the source plasma. In addition to an arc stabilizer,⁶ we have utilized the following elements: an axial button, a ring insert, and multiple filaments. Apparently, the configurations, dimensions, locations, and materials of these elements are very important. Their functions are summarized below.

A. Axial copper button

Figure 6 shows an axial copper button in the intermediate electrode snout. The button can improve plasma uniformity (Fig. 5) by reducing the passage of axial electrons and ions and diverting the arc column from on-axis to off-axis. In addition, it can intensify the PIG discharge by increasing the kinetic energy of ionizing electrons through an increase of arc impedance and intensify the cathode discharge by increasing the gas pressure in the cathode region through the reduction of gas conductance without an increase in gas throughput. Moreover, by helping to stabilize the double layer, the button can reduce the noise level and improve the source reliability.

B. Copper and iron ring insert

As shown in Fig. 6, the copper and iron tapered ring insert is capable of stabilizing the double layer and reducing noise level. The insert can also modify the distribution of the applied source magnetic field and consequently is able to intensify the PIG discharge and improve plasma density and uniformity near the extraction region.

C. Multiple filaments

The multiple off-axis filaments chiefly serve to prolong filament lifetime by reducing the bombarding damage of backstreaming axial ions. The associated increase in emission area raises arc current capability. Consequently, the multifilament intensifies the cathode discharge and

helps to stabilize the double layer, reducing the noise level and improving the source reliability.

With these significant modifications, the 10-cm duoPIGatron ion source achieved the desirable performance shown in Table II. The plasma uniformity of $\pm 10\%$ is much better than the $\pm 30\%$ over the 7-cm grid diameter in a 7-cm duoPIGatron ion source.⁶ The noise level is down to about $\pm 5\%$ from $\pm 30\%$ in a 7-cm source. Filament lifetime has been prolonged to several months of normal operation.

VI. DISCUSSION

The discharge model is consistent with the observed source behavior of the duoPIGatron ion source. We will continue our study to further improve our understanding about this source and follow the guidance of this model to improve the source performance. The encouraging performance of the duoPIGatron source with the 10-cm-diam extraction pattern makes us very optimistic and confident in developing larger plasma sources (15 cm, 20 cm, and 25 cm in diameter) for future high power neutral beam injectors. Recently, we have successfully developed a 15-cm source for producing a 30-A hydrogen ion beam at 27 keV. Further details will be reported in the near future. The techniques developed and learned from this source can be applied to other ion sources, particularly the duo-plasmatron ion source.

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TABLE 1
OPERATING CONDITION OF A 10-CM SOURCE

WORKING GAS	HYDROGEN
GAS PRESSURE	~50 mTorr I.E. CHAMBER ~5 mTorr T.C. REGION
ARC VOLTAGE	UP TO 150 V
ARC CURRENT	UP TO 220 A
MAGNETIC FIELD	~200 TO 400 G I.E. REGION ~10 TO 20 G T.C. REGION

ELECTRODE POTENTIALS

$$\begin{aligned}
 V_F &\equiv 0; & V_{IE} &= \sim 20 \text{ TO } 30 \text{ V} \\
 V_{TC} &= \sim 50 \text{ TO } 80 \text{ V}; & V_{A1, A2} &= \sim 80 \text{ TO } 150 \text{ V}
 \end{aligned}$$

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TABLE 2
PERFORMANCE OF A 10 CM SOURCE

PLASMA UNIFORMITY	$\pm 10\%$ OVER 10-CM GRID, COMPARED TO $\pm 30\%$ IN 7-CM SOURCE
NOISE LEVEL	$\pm 5\%$, FROM $\pm 30\%$ IN 7-CM SOURCE
FILAMENT LIFETIME	GREATER THAN 6 WEEKS
HIGH VOLTAGE	40 KEV
BEAM CURRENT	15 A AT 40 KEV AND 250 MSEC
PULSE DURATION	750 MSEC AT 30 KEV AND 9 A

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FIGURE LEGENDS

FIG. 1. 10-cm prototype duoPIGatron ion source.

FIG. 2. Discharge model and axial potential distribution in a duoPIGatron.

FIG. 3. Typical shapes of double layer.

FIG. 4. Effect of concave double layer.

FIG. 5. Typical density profiles with and without utilizing an axial copper button.

FIG. 6. Sketch of an axial button, ring insert, and multiple filaments.

FIG. 1. 10-cm prototype duoPIGatron ion source.

FIG. 2. Discharge model and axial potential distribution in a duoPIGatron.

FIG. 3. Typical shapes of double layer.

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FIG. 4. Effect of concave double layer.

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FIG. 5. Typical density profiles with and without utilizing an axial copper button.

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FIG. 6. Sketch of an axial button, ring insert, and multiple filaments.

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