Theoretical and Experimental Studies of Four Anode Rods Ion Source

O.A. Mostafa and H. El-Khabeary
Accelerators & Ion Sources Department, Basic Nuclear Science Division, Nuclear Research Center
Atomic Energy Authority, P.No. 13759, Egypt.

ABSTRACT

In the present paper, theoretical and experimental studies of a saddle field ion source were done. The ion source consists of copper four anode rods placed in one plane between two copper plane cathode discs. The four rods were placed on two perpendicular axes. The line of forces near the source axis were deduced from the electric field intensity distributions along the source axis and showed that the field has a saddle configuration for anode – cathode distance > 6 mm and consequently high density discharge at low gas pressure can be achieved. At this distance, any of the electric field intensity distributions along the source axis showed a maximum value and this value decreases by increasing anode – cathode distance. Also the variation of the frequency value divided by the square root of the electric discharge voltage of the oscillating electrons, which start to move from any surface of the two cathodes, with respect to the anode - cathode distance was obtained. It is found that the frequency value of the oscillating electrons decreases by increasing anode – cathode distance. A comparison was made between the theoretical study and the experimental results. It was found that the experimental results and the theoretical calculations are comparable.

Key Words: Electric Field Distribution / Electron Frequency / Breakdown Voltage.

INTRODUCTION

In saddle field ion sources (1,2), cold cathode oscillating electron ion source, the discharge mechanism (plasma production) (3) is initiated by the primary electrons which essentially come from the cosmic rays. The discharge is produced by electrons oscillating between two cold cathodes in a saddle field which possesses a single saddle point. To produce and intensify (4) the plasma, the electrons must have long path lengths and this can be achieved by allowing the electrons to have an oscillatory motion. This discharge depends on the oscillatory motion between the two cathodes separated by the anode using electric fields. The discharge mechanism of the source is very simple, where it has the advantageous behavior of the penning source without magnetic field. Saddle field ion sources may be evaluated by the high degree of ionization, the small gas consumption, the small energy spread of the beam and the high ion current.

In the ion sources with heated cathode, the cathode lifetime limits that of the ion source and the construction is also complicated by the use of heated cathode. For this reason, many investigators prefer cold cathode ion sources for the production of both low and high intensity ion beams.

Saddle field ion sources are advanced compact ion and fast atom sources for use in a wide range of applications (5-8), where small size and high beam intensity are required. These characteristics meet most of the requirements needed for ion beam cleaning and etching, ion beam sputtering (9) of thin films, specimen thinning and machining applications.
Description of the Ion Source

The schematic diagram of four anode rods ion source is shown in Fig.(1). It consists of a copper four anode rods, each rod of 2 cm length and 2 mm diameter, placed in one plane between two copper cathode discs, each cathode of 22 mm diameter and 3 mm thickness. The anode rods are placed on two perpendicular axes such that the distance between each two opposite rods equals 6 mm. One of the two cathodes has central hole of 2 mm diameter for the ion beam exit. The inner surface of the two cathode discs is isolated by teflon insulator of 2 mm thickness except an area of 6 mm diameter to confine the electrical discharge in the central zone. All the source parts are placed inside perspex insulator cylinder of 60 mm length, 50 mm outer diameter and 22 mm inner diameter.

Fig.(1): Schematic diagram of four anode rods ion source.

THEORETICAL CALCULATIONS

The potential and electric field intensity along the source axis were derived. Also the variation of the frequency value of the oscillating electrons with respect to the distance between the four anode rods and any of the two plane cathode discs was obtained.

1 - Electric Field Intensity Along the Source Axis

In order to find the electric field, $e_r$, on the source axis at a distance, $r$, from the center of the source due to two opposite thin positive rods of, $\lambda$, charge per unit length as shown in Fig.(2), apply the image theory. As shown in Fig.(3), the electric field due to the two positive line charges and their images is given by the relation: -

Fig.(2): The electric field, $e_r$, along the source axis at distance, $r$, from the center of the source due to two opposite thin positive rods.

Fig.(3): The electric field due to two positive line charge and their image.
where \( d \) is the distance between the center of the source and any one of the four anode rods, \( l \) is the distance between the center of the source and the end of any one of the four rods, \( r \) is the distance from the center of the source axis and \( R \) is the distance between the four anode rods plane and any of the two cathodes, i.e. anode – cathode distance. Consequently, the electric field intensity due to the four anode rods along the source axis can be given by the relation:

\[
e_r = 2 \left[ \frac{1}{d} \int_0^\lambda \frac{\rho dx}{4\pi\varepsilon_0 (r^2 + x^2)^{3/2}} + \frac{1}{d} \int_0^\lambda \frac{\rho dx(2R-r)}{4\pi\varepsilon_0 (2R-r)^2 + x^2}^{3/2} \right]
\]

\[
e_r = \frac{\rho}{2\pi\varepsilon_0} \left[ \frac{\lambda}{r\sqrt{r^2 + \lambda^2}} - \frac{d}{r\sqrt{r^2 + d^2}} + \frac{\lambda}{(2R-r)\sqrt{(2R-r)^2 + \lambda^2}} - \frac{d}{(2R-r)(2R-r)^2 + d^2} \right]
\]

(1)

\[
E_r = 2e_r = \frac{\rho}{\varepsilon_0} \left[ \frac{\lambda}{r\sqrt{r^2 + \lambda^2}} - \frac{d}{r\sqrt{r^2 + d^2}} + \frac{\lambda}{(2R-r)\sqrt{(2R-r)^2 + \lambda^2}} - \frac{d}{(2R-r)(2R-r)^2 + d^2} \right]
\]

(2)

2 – Potential Distribution Along the Source Axis

The potential distribution along the source axis can be calculated by assuming the voltage at \( r = 0 \) is equal to the anode voltage, \( V_a \), therefore:

\[
\int_0^r dV = V_r - V_a = \int_0^r E_r \, dr
\]

\[
V_r - V_a = -\frac{\rho}{\varepsilon_0} \left[ \frac{\lambda dr}{r\sqrt{r^2 + \lambda^2}} - \frac{d \, dr}{r\sqrt{r^2 + d^2}} + \frac{\lambda dr}{(2R-r)\sqrt{(2R-r)^2 + \lambda^2}} - \frac{d \, dr}{(2R-r)(2R-r)^2 + d^2} \right]
\]

(3)

Substituting by \( V_r = 0 \) at \( r = R \) in equation (3) it gives:

\[
\frac{\rho}{\varepsilon_0} = \ln \left[ \frac{\sqrt{\left(\frac{2R}{\lambda}\right)^2 + 1} + 1}{\sqrt{\left(\frac{2R}{d}\right)^2 + 1} + 1} \right]
\]

(4)
Substituting by equation (4) in both equations (2) and (3) one can get:

\[
\frac{E_r}{V_a} = \frac{1}{\ln \left( \frac{2R}{d} + 1 \right)} \left[ \frac{1}{r \sqrt{\left( \frac{r^2}{\lambda} + 1 \right)}} + \frac{1}{r \sqrt{\left( \frac{r^2}{d} + 1 \right)}} + \frac{1}{r \sqrt{\left( \frac{2R - r}{\lambda} + 1 \right)}} + \frac{1}{r \sqrt{\left( \frac{2R - r}{d} + 1 \right)}} \right]
\]

(5)

and

\[
\frac{V_r}{V_a} = 1 - \frac{1}{\ln \left( \frac{2R}{d} + 1 \right)} \left[ \frac{1}{\sqrt{\left( \frac{r^2}{\lambda} + 1 \right)}} + \frac{1}{\sqrt{\left( \frac{r^2}{d} + 1 \right)}} + \frac{1}{\sqrt{\left( \frac{2R - r}{\lambda} + 1 \right)}} + \frac{1}{\sqrt{\left( \frac{2R - r}{d} + 1 \right)}} \right]
\]

(6)

Figure (4) shows the variation of \( \frac{E_r}{V_a} \) along the source axis with \( r \) at different values of \( R \) for \( d = 3 \) mm and \( l = 11 \) mm. It is clear from this figure that, each curve has a maximum value of \( \frac{E_r}{V_a} \) and \( \frac{E_{rm}}{V_a} \), at a value of \( r \) and \( r_{m} \). It is also clear that, while the decrease of \( R \) from 20 mm to 10 mm, \( r_{m} \) is always constant and equals 3.5 mm. A further decrease of \( R \) from 10 mm leads to a noticeable increase of \( r_{m} \). However, continuous decrease of \( R \) leads to a value of 6 mm equal to the corresponding value of \( r_{m} \). Therefore, \( R \) is always equal to the corresponding value of \( r_{m} \) for \( R = 6 \) mm.

Fig.(4): The variation of \( \frac{E_r}{V_a} \) with \( r \) at different values of \( R \).
The variation of $E_{rm}/V_a$ with $R$ is shown in Fig.(5). This relation shows that the value of $E_{rm}/V_a$ increases by decreasing the value of $R$. Figure (6) shows the variation of $r_m$ with $R$. It is clear that $r_m$ remains constant equals 3.5 mm for $R = 10$ mm and increase to 6 mm by decreasing $R$ from 10 mm to 6 mm. While for $R = 6$ mm, $r_m = R$. The variation of $V_r/V_a$ with $r$ at different values of $R$ is shown in Fig.(7).

**Fig.(5):** The variation of $E_{rm}/V_a$ with $R$ at constant $d$ and $l$.

**Fig.(6):** The variation of $r_m$ with $R$ at constant $d$ and $l$.

**Fig.(7):** The variation of $V_r/V_a$ with $r$ at different values of $R$.

### 3 - Electric Field Shape Near the Source Axis

As shown in Fig.(4) all the representations of $E_r/V_a$ with $r$, for $R > 6$ mm, have the same general shape. Also the value of $E_r/V_a$ increases with the increase of $r$ till it reaches a maxim value, $E_{rm}/V_a$ at $r_m$ and it decreases with the increase of $r$ till it reaches a constant value near the cathode. Therefore, following a path of field line, near the source axis, starting from the surface of one of the anode rods tips and ending at the cathode surface, the line initially converges towards the source axis till the plane $r = r_m$, where it tends to diverges outwards and finally near the cathode it becomes parallel to the $r$-axis.
Figure (8) illustrates schematically the electric field distribution along the source axis and the deduced shape of a field line near the source axis drawn to left hand side and the right hand side of the axis respectively for \( R > 6 \text{ mm} \). It is clear from this figure that the field has a saddle configuration near the source axis for \( R > 6 \text{ mm} \). The electron produced during the glow discharge oscillate at high frequency backward and forward through the central region of the source\(^{(11)}\) producing high density discharge at low pressure. Moreover, for \( R > 6 \text{ mm} \) any saddle field has a saddle point at \( r_m \) where the field has a maximum value which indicates that the energy distribution of the ion beam has only a high peak with energy equivalent to the potential at \( r_m \).

\[ eV_r = \frac{1}{2}mr^2 \]

Therefore
\[ r^* = \frac{2eV_r}{m} = \frac{dr}{dt} \]

Consequently
\[ dt = \frac{dr}{\sqrt{\frac{2eV_r}{m}}} \]

The time taken by the electron to move from one of the two cathode surfaces, at \( r = R \) to the plane of the four anode rods at \( r = 0 \) is:

\[ T = 4 \int_{R}^{0} \frac{dr}{\sqrt{\frac{2eV_r}{m}}} \]
where $T$ is the period of one cycle of the oscillating electrons. Substituting equation (6) in equation (7) gives:

$$T = \frac{4}{\sqrt{v_a}} \int_{r=R}^{r=0} \frac{m}{2e} \sqrt{r} \, dr$$

$$= \int \left[ \frac{1}{\sqrt{r}} + \frac{1}{\sqrt{r^2 + d^2}} \right]^{1/2} \, dr$$

$$= \left[ \frac{2R}{d} \right]^{1/2} \left[ \frac{1}{\sqrt{r^2 + d^2}} + 1 \right]^{1/2}$$

Figure (9) shows the variation of $F / (V_a)^{1/2}$ with $R$ at $d$ and $l$ are experimentally taken equal to 3 mm and 11 mm respectively. It is clear that $F / (V_a)^{1/2}$ decreases by increasing $R$.

**EXPERIMENTAL RESULTS**

In the experimental work, the internal electrical discharge characteristics of the ion source were measured at different anode – cathode distances, $R$, equal to 12, 14, 16, 18 and 20 mm, respectively, using argon gas, while the distance between each two anode rods is fixed at 6 mm.

Figure (10) shows a schematic diagram of the four anode rods ion source and its associated electrical circuit. The four anode rods, $A$, were connected to 10 kV positive power supply, P.S., which is used for initiating the glow discharge between the four rods anode and the two earthed cathodes, $K$. A milli-ampere meter, mA, was used to measure the electrical discharge current, $I_d$, while the kilovoltmeter, KV, is used to measure the electrical discharge voltage.
Fig. (10): Schematic diagram of the four anode rods ion source and its associated electrical circuit.

Figure (11) shows the relation between the discharge current, $I_d$, versus different $R$ at pressure equals $2.8 \times 10^{-4}$ mmHg and two different discharge voltages, $V_d$, using argon gas. It is obvious from the curves that the discharge current decreases by increasing $R$ which confirms with the theoretical study which investigate that $E_m / V_a$ and $F / (V_a)^{1/2}$ decreases by increasing $R$ and as a result the electrical discharge density decreases.

Figure (12) shows the relation between the breakdown voltage, $V_b$, versus different $R$ at two different pressures using argon gas. It is clear that the breakdown voltage decreases by decreasing $R$ which confirms with the theoretical study. However, although the experimental investigations were not carried out at low values of $R$, it is expected that the breakdown voltage increases by decreasing $R$ for low values of $R$ which may be due to decrease of the electrons path lengths.

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**Fig.(11):** Discharge current versus $R$ at constant pressure and two different discharge voltages using argon gas.

**Fig.(12):** Breakdown voltage versus $R$ at two different pressures using argon gas.
CONCLUSION

The theoretical study shows that, the field has a saddle shape near the source axis for $R > 6 \text{ mm}$, so many oscillations of electrons exist and high density electrical discharge will be produced at low gas pressures. The electric field intensity distribution along the source axis for $R > 6 \text{ mm}$ shows a maximum value of $E_r / V_a$ at $r_m$ which indicate that the energy distribution of the ion beam has only a high peak with energy equivalent to the potential at $r_m$. It can be concluded from the theoretical treatment that, at any electrical discharge voltage, the density of the electrical discharge increases by decreasing $R$ due to increase of both $E_{nm}$ and $F$ and consequently $I_d$ increases which confirms with the experimental results. This ion source can be used for different applications such as, sputtering, etching, thinning, surface modification of materials and ion beam machining.

A programme of the work has now been undertaken to investigate experimentally the optimum distance between each two anode rods, the optimum distance between four anode rods and plane cathode disc and the characteristics of the output ion beam at the optimum operating conditions which are suitable for different applications.

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