A simulation study of argon discharge in PIG ion source with axial magnetic field

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Abstract. In this study, we used a two-dimensional fluid model to investigate the argon discharge in Penning ion gauge (PIG) ion source influenced by magnetic field and the structure of ion source. Under fixed anode voltage $U$ and pressure $P$, the relationships between the axial magnetic field, the structure parameter $K$, which is the ratio of the distance of two cathodes and the diameter of the anode tube, and the electron density are obtained. For fixed magnetic field $B=0.01$ T and pressure $P=0.5$ Torr, the electron density along the central axis has the maximal value when $K=0.8$. With fixed $K=0.8$ and $P=1$ Torr, the maximal electron density was found when $B=0.1$ T. Our results imply that there are optimal values for magnetic field and $K$ which induce the maximal plasma density.

1. Introduction
Due to the high reliability, PIG ion source [1,2,3] is generally used in industry and plays an important role in many fields, such as controllable neutron source [4,5,6], material study [7], electromagnetic separation of isotopes [8], fusion applications [9] and small accelerator [10].

Fig.1 The shaft section of PIG ion source, which has bilateral symmetry. 1 - shell, 2 - permanent magnetic, 3 - cathode, 4 - anode tube, 5 - ceramic.
As shown in Fig. 1, a typical DC-driven PIG ion source is composed of an anode tube, two cathodes and two permanent magnets. Whole system is axial symmetrical and sealed by a shell which is filled with low pressure gas. The DC voltage on the anode tube is higher than the one on the two cathodes about 2 kV. Electrons emission from two cathodes and move to the anode. In this process the collision between electrons and gas induces the discharge. The magnetic field will increase the traveled distance before electrons be absorbed by anode, which results in the increase of collision possibility. In most cases the positive ion is extracted along the axis [11], but some researches also tried to extract negative ions along the radial direction [12]. Compared to RF-driven PIG ion source, DC-driven PIG ion source has lower ionization rate and plasma density. So, in recent years, researches have paid more attention on the discharge properties of RF-driven PIG ion source [13,14].

Many facts can influence the discharge properties of PIG ion source. For instance, the high magnetic intensity can increase the traveled distance of electrons and the plasma density. But if the magnetic field is too strong, the radius of gyration of electrons will decrease and the valid traveled distance will reduce, which results in the collision possibility. So, it needs a suitable magnetic intensity. Further, the traveled distance also is related to the geometrical structure, such as the diameter of anode tube and the distance between two cathodes. Therefore, there possibly have the optimal values for magnetic field and geometrical structures.

In this work, we make use of the COMSOL software to study the discharge properties of PIG ion source with Ar in a two-dimensional fluid model. We try to reveal the relationships between the axial magnetic field $B$, the structure parameter $K$, which is the ratio of the distance of two cathodes and the diameter of the anode tube, and the electron density. The results indicate that there are optimal values for $B$ and $K$, which make the electrons density reach the maximal value.

2. The simulation model

2.1. The geometrical structure of PIG ion source

Fig. 2 The two-dimensional model for PIG ion source. The $z$ axis is the rotation axis of anode tube.

In simulation, the PIG ion source was reduce to a two-dimensional model shown in Fig. 2. The diameter of anode tube is $D$ and the distance between two cathodes is $L$. We defined $K = L/D$, which was changed
by adjusting $L$ with fixed $D=34$ mm. The diameter of each cathode was fixed 16 mm. The uniform magnetic field was set along the axial direction.

2.2. The two-dimensional fluid model
The COMSOL software contains the plasma module which can simulate the plasma using fluid theory [15,16]. Here we used it to simulate the DC-driven discharge of Ar in PIG ion source. In our calculation, the anode tube was applied the voltage $U=2$ kV and series connected in a RC circuit with resistance $R=1$ kΩ and capacity $C=1$ pF. The two cathodes were connected to ground. All of the reaction equations in plasma and the corresponding energy loss are shown in Table.1. On the two cathodes, the secondary electron emission coefficient was fixed 1.2. The surface of the ceramics was set to be dielectric contact. The time step was $10^{-9}$ s and computing time was 1 s.

| No. | Reaction equation | $\Delta \varepsilon$ (eV) |
|-----|-------------------|--------------------------|
| 1   | $e + Ar \Rightarrow e + Ar$ | 0                        |
| 2   | $e + Ar \Rightarrow e + Ar_{s}$ | 11.5                    |
| 3   | $e + Ar_{s} \Rightarrow e + Ar$ | -11.5                   |
| 4   | $e + Ar \Rightarrow 2e + Ar^{+}$ | 15.8                    |
| 5   | $e + Ar_{s} \Rightarrow 2e + Ar^{+}$ | 4.24                    |
| 6   | $Ar_{s} + Ar_{s} \Rightarrow e + Ar + Ar^{+}$ | /                      |
| 7   | $Ar_{s} + Ar \Rightarrow Ar + Ar$ | /                       |
| 8   | $Ar_{s} \Rightarrow Ar$ | /                       |
| 9   | $Ar^{+} \Rightarrow Ar$ | /                       |

3. Results

3.1. Optimal value for structure parameter $K$ with fixed pressure and magnetic field
Choosing the pressure $P=0.5$ Torr and the uniform magnetic field along the $z$ direction $B=0.01$ T, we obtained the distribution of electron density for different $K$. As shown in Fig.3, we can see that the electrons focus on the central area of the ion source. For $K=0.5$ there two focusing centers for electrons. With the increase of $K$, the electrons focus to one center, such as in Fig. 3(b). But if $K$ is big enough, the plasma center will move toward the cathode and the system will lose the up-down symmetry. Our study indicates that the position of the focusing center is independent of the direction of magnetic field because that changing the direction of the magnetic file to be opposite to $z$ axis cannot influence the distribution of electrons.

Fig.4 shows the electron density on the axis of cathode and the diameter. In Fig.4 (a), each curve for $K<1$ has one extreme point. But if $K>1$, there are two extreme points on which the electron density are different. Again, this results indicates the plasma has no the up-down symmetry. In Fig.4 (b), There is one extreme point for each cure with $K>1$ and there are two extreme points for the cure with $K=0.5$. Both of Fig.4(1) and (b) ravels that the maximal electron density is about $9 \times 10^{18}$ m$^{-3}$ when $K=0.8$. Therefore, $K=0.8$ gives the optimal structure fir PIG ion source.
Fig. 3. Distribution of electron density for different $K$.

![Fig 3](image)

Fig. 4. Electron density distribution on different directions for different $K$ with fixed $P=0.5$ Torr and $B=0.01$ T. (a) On the axis of anode; (b) On the diameter with $z=L/2$.

![Fig 4](image)

3.2. Optimal value for magnetic field with fixed pressure and structure parameter $K$

Fig. 5 and Fig. 6 show the distribution of electron density for different $B$ with fixed $P=1$ Torr and $K=0.8$. From Fig. 5 we can see that the focusing area becomes small following the increase of magnetic field because the decrease of the tuning radius of electrons. If $B$ is too big, the plasma will be no-symmetrical. Fig. 5 (d) shows the distribution of electron density with $B=0.15$ T along the $z$ axis, which has no the up-down symmetry. Through changing the direction of the magnetic field to be opposite to $z$ axis, we found that the distributional property in Fig. 5 (d) had no visible change. Therefore, the direction of magnetic field has no influence on the plasma distribution.
Fig5. Distribution of electron density for different $B$

Fig6. Electron density distribution on different directions for different $B$ with fixed $P=1$ Torr and $K=0.8$. (a) On the axis of anode; (b) On the diameter with $z=L/2$.

In Fig.6 gives the electron density distribution on axis direction and radial direction. When the $B$ increases from zero, the maximal value at the extreme point for each curve will increase until $B>0.1$ T. The curve with $B=0.1$ T has the biggest electron density. If $B>0.1$ T, the maximal value at the extreme point will decrease following the increase of $B$. Therefore, $B=0.1$ is the optimal value in this case.

4. Discussion and conclusions

If we need to extract ions from the axial direction, we want higher ion density on axis. Fig.3 and Fig.4 indicate that there are two centers of the plasma when $K>1$, which has negative impacts on the ion extract. If $K<1$ there is only one center for the distribution of electron and it is benefit for ion extraction. Following the decrease of $K$, the maximal value of electron density on axis reaches the maximum value when $K=0.8$. After that the maximal value of electron density will decrease. This result indicates that there is the optimal geometry structure for PIG ion source. Similarly, with fixed pressure and $K$, there is optimal value for $B$ which induces the maximal electron density. Moreover, because that Fig.3 (d) and
Fig. 5(d) have no the up-down symmetry, it bring some difficulties to ion extraction. We hope to extract ions from the side which is close to high density center of plasma. But our study indicates that which side is more close to the high density center is random. The direction of magnetic field cannot influence the randomness. For example, the up side in Fig. 3(d) is closer to the high density center than the down-side with $B$ along the forward direction of $z$ axis. But if we change $B$ to be along the opposite direction of $z$ axis, the high density center also is closer to the up-side than to the down-side. Therefore, choosing which side to do ion extraction is difficult. We think it needs to break down the geometrical symmetry of the PIG ion source through structure design, such as opening a hole on one cathode.

In this work, we used the COMSOL software to study the argon discharge in Penning ion gauge (PIG) ion source influenced by magnetic field and the structure of ion source. The distribution of electron density were obtained and the relationships between me maximal electron density and the structure parameter and magnetic field were investigated. Our results imply that there are optimal values for magnetic field and geometry structure which induce the maximal plasma density. Our results are helpful in PIG ion source design.

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