Symmetry breaking of plasma induced by pressure in PIG ion source

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Abstract. In this work, we use the COMSOL software to study the discharge characteristics of argon in the Penning ion gauge (PIG) ion source driven by DC voltage and based on a two-dimensional fluid model. The distribution of the electron density under different pressures is investigated. Our results indicate that, although the ion source has the symmetric geometry structure, the distribution of the electron density will lose the symmetry due to the change of pressures.

1. Introduction

PIG ion source is a kind of ion source which works on the principle of penning discharge [1,2,3]. It is also a widely used as ion source in industry. A typical DC-driven PIG ion source is composed by an anode tube, two cathodes and two permanent magnets [4,5,6]. The collision between electrons and gas induces the discharge.

Electron density is an important parameter of the plasma. There are many factors which affect the size and distribution of electron density in the PIG ion source. Such as the pressure, the magnetic field and the structure of ion source. When we ignore the ion extraction hole on the cathodes or anode, the PIG ion source is a symmetric system. But we want to know whether the plasma also has the symmetry. For example, whether the center of the plasma coincide with the center of the ion source. The position of the center of the plasma determine where the ion extraction hole should be located. There, to study the symmetry of the plasma PIG ion source is helpful in the design of ion source.

In this paper, we use COMSOL software to study the discharge of Ar in DC-driven PIG ion source in a two-dimensional symmetry model. The distribution of electron density under different pressure are obtained. For fixed magnetic field and voltage on the anode tube, we find that the symmetric breaking of the plasma induce by the changing the pressure.

2. The simulation model

2.1 The hydrodynamic model

The hydrodynamic theory is generally used to study characteristics of plasma. First, electrons satisfy the following continuity equation

\[ \frac{\partial n_e}{\partial t} + \nabla \cdot \Gamma_e = R_e - (u \cdot \nabla) n_e, \]  

where \( n_e \) is the electron energy density, \( R_e \) is the source term of electron, \( u \) is the velocity vector of neutral fluid, \( \Gamma_e \) is the vector of electron energy flow.
The energy conservation equation of electron is
\[
\frac{\partial n_e}{\partial t} + \nabla \cdot \mathbf{P} + \mathbf{E} \cdot \mathbf{P} = S_{\text{en}} - (\mathbf{u} \cdot \nabla) n_e + \left( \frac{Q + Q_{\text{gen}}}{q} \right),
\]
where \(n_e\) is the electron energy density. \(S_{\text{en}}\) is inelastic energy loss, \(Q\) is external heat source, \(Q_{\text{gen}}\) for generalized heat source, \(\mathbf{P}\) is the vector of electron energy flow. The momentum conservation equation of electron is:
\[
\rho \left[ \frac{\partial \mathbf{u}}{\partial t} + (\mathbf{u} \cdot \nabla) \mathbf{u} \right] = -\nabla P + \rho \mathbf{F},
\]
where \(\mathbf{F}\) is the external force on the fluid, \(P\) is the pressure of the fluid and \(\rho\) is the density.

2.2 Reaction formulas
The reaction process of hydrogen is relatively complex and involves many reaction types. So Ar is used as the reaction gas to simulate the internal reaction process. In the whole process, there are a series of reactions between argon and electrons, such as collision, excitation and ionization. There are seven kinds of reactions involved in this model. Table 1 shows the reaction formulas and energy loss \(\Delta \varepsilon\) in plasma area and Table 2 shows the reaction formulas on the surface.

| Reaction No. | formula          | Reaction type    | \(\Delta \varepsilon\) (eV) |
|-------------|------------------|------------------|-----------------------------|
| 1           | \(e + Ar \rightarrow e + Ar\) | elastic | 0                           |
| 2           | \(e + Ar \rightarrow e + Ars\) | inspire | 11.5                        |
| 3           | \(e + Ars \rightarrow e + Ar\) | Hyperelasticity | -11.5                       |
| 4           | \(e + Ar \rightarrow 2e + Ar^+\) | ionization | 15.8                        |
| 5           | \(e + Ars \rightarrow 2e + Ar^+\) | ionization | 4.24                        |
| 6           | \(Ars + Ars \rightarrow e + Ar + Ar^+\) | Penning ionization | /                           |
| 7           | \(Ars + Ar \rightarrow Ar + Ar\) | Penning ionization | /                           |

| Reaction No. | formula | Adhesion coefficient |
|-------------|---------|----------------------|
| 1           | \(Ars \rightarrow Ar\) | 1                    |
| 2           | \(Ar^+ \rightarrow Ar\) | 1                    |

2.3 The 2D model and mesh generation
The geometric model of the two-dimensional symmetry axis of the ion source is shown in the Fig. 1(a), in which the red dotted line is the symmetry axis of the two-dimensional model, and the magnetic induction line passes through the whole ion source along the axis and parallels to the symmetry axis. After the internal reactions, surface reactions and boundary conditions are set, the two-dimensional symmetrical axis model of the ion source is meshed. The mesh section is composed of free triangle mesh and boundary layer. The number of boundary layers is 4, and the total number of mesh sections is 5961. The mesh section diagram is shown below the Fig. 1(b).
2.4 Boundary conditions
(1) The anode cylinder shell is connected to DC high voltage:
\[ V = 2 \text{ kV} \]
(2) The cathode is equal to the voltage to the anticathode and grounded:
\[ U_{\text{cathode}} = U_{\text{anticathode}} \]
(3) Electronic initial state
Initial density:
\[ n_e,0 = 1 \times 10^{13} / \text{m}^3 \]
Initial average electron energy:
\[ \varepsilon_0 = 4 \text{ eV} \]
(4) Initial gas temperature:
\[ T = 300 \text{ K} \]
(5) Reduced electron mobility:
\[ \mu_{dc} n_e = 4 \times 10^{24} \text{ 1/(V>m>s)} \]
(6) Magnetic field intensity:
\[ B = 0.05 \text{T} \]

3. Simulation results and data analysis

3.1. Simulation results
The two-dimensional structure model of the ion source has been optimized. Under certain boundary conditions, the final results of the Ar discharge model in panning ion source under different atmospheric pressure can be obtained. In this model, the electron density distribution in the ion source under four different internal reaction pressures, e.g. 0.3 Torr, 0.5 Torr, 1 Torr and 2 Torr, is calculated respectively. Fig. 2 shows the two-dimensional distribution of the electron density calculated at different reaction pressures. It is obviously that the electron density distribution under four different pressures is different.
3.2. Analysis

According to the calculation results of COMSOL software, a one-dimensional electron density map is drawn to summarize the axial electron density under four different air pressures. We can derive the data of four electron density distribution maps respectively. Using MATLAB software programming, we can carry out comprehensive drawing on the four groups of data, and get the following axial distribution diagram of electron density along the axis from cathode to anticathode in Fig. 3.

It can be seen from the analysis of the two-dimensional distribution diagram of electron density and
the axial distribution diagram of electron density under four different reaction pressures. When the internal reaction pressure is below 0.3Torr, there is only one center of electron density and it is in the center of panning ion source. Then, with the increase of air pressure, when the air pressure is between 0.5Torr and 1Torr, the electron density begins to spread to both sides. When the air pressure is 2 Torr, the electron density has two centers respectively. As the pressure continues to increase, the electron density away from the origin begins to exceed that near the origin, and increases rapidly. So, with the increase of pressure, the electron density of the whole structure will be asymmetric. Therefore, the pressure change causes the symmetry breaking of the plasma.

4. Conclusions
In this paper, COMSOL Multiphysics simulation software was used to simulate the distribution trend of electron density in the process of argon discharge in penning ion source, and the distribution law of electron density generated by plasma under different internal gas reaction pressure was calculated respectively. By analyzing the two-dimensional electron density distribution and one-dimensional electron density distribution on the axis, it can be concluded that with the increasing of internal reaction pressure, the electron density distribution was distributed on both sides of the ion source from a central point at low pressure to a high pressure, and the electron density distribution on both sides was not uniform.

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