Design and parametric study of a radio-frequency cathode

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Abstract

Hollow cathodes have been commonly used as the electron source and neutralizer for ion thrusters and other electric propulsion devices (like Hall thrusters)till 1960s. They provide high electron current density by using low electric power and gas. However, they have some disadvantages: Hollow cathode's lifetime is limited by the erosion and evaporation of the insert. Additionally, impurities in the propellant gas can cause chemical changes that dramatically reduce the insert material thermionic emission rate. On the other hand, the insert material has to be heated to a relatively high temperature before starting the neutralizer operation. Aside from consuming power, this heating process prevents the neutralizer from switching on fast thus limiting the rapid thruster turn on [1] [2]

To overcome these problems, RF neutralizers has been introduced in the recent years. RF neutralizers are insert free cathodes that use RF fields to create plasma inside a chamber, and this plasma is used in order to extract electrons and neutralization of thruster ion beam. A variety of RF sources can be used in this application, like capacitively or inductively coupled sources, which operate without magnetic fields. Other versions of RF neutralizers can be electron cyclotron resonance (ECR) and helicon sources that use axial magnetic fields [2].

Helicon sources are mostly used in the discharge chamber of ion thrusters in order to create plasma. This is because they can produce the highest plasma densities for a given RF power. But, on the other hand, they need strong magnetic fields and high RF powers. ECR and capacitive sources do not operate efficiently in the low-power and low-mass-flow-rates that is needed to operation of a neutralizer [2].

Inductively coupled plasma configuration is considered as the best choice for the RF neutralizers. These devices can reach to significant plasma densities (10^{10} to 10^{12} cm^{-3}) and have high total electron extraction current. Because the beneficial aspects of inductively coupled plasma cathodes (neutralizers), some research groups have fabricated and done experimental researches about these types of neutralizers. The aim of this work is to perform a numerical study in order to investigate plasma and electron

extraction properties of the inductively coupled plasma cathode in varios operational and geometric conditions.

A Japanese group from Tokyo Metropolitan University [3] [4][5] has designed and tested a concept of inductively plasma cathode. Their basic design is shown in figure 1. This group has done numerous experimental study on the operational and geometric parameters of this concept.

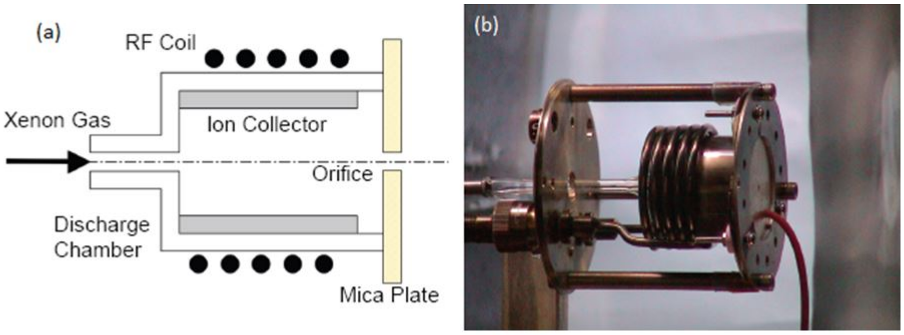

Figure 1: a)Schematic illustration of RF cathode. b) Side view of RF cathode and target[3]

The second concept of RF neutralizer, designed by an american group from Princeton Plasma Physics Laboratory , is shown in Figure 2. In this configuration discharge chamber is made of stainless steel. It has two opening on the top (gas inlet) and bottom (extracting tube). RF antenna is cylindrical and it is placed inside the discharge chamber, but encapsulated to a glass shell. [6].

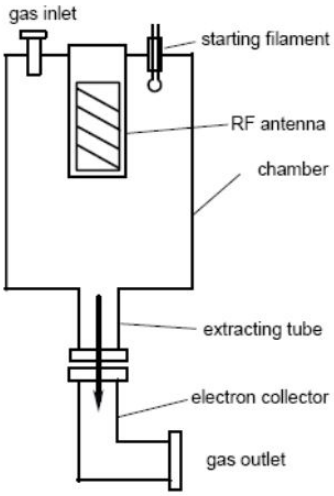

Figure 2: Schematic of the Princeton RF neutralizer [6]

The theory of radio frequency neutralizer consist of two parts: first, modeling a quasi-neutral inductively coupled plasma and second, modeling of plasma sheath and effects of applying an bias voltage on the plasma.

Theory of quasi-neutral inductively coupled plasma is developed widely and some zero-dimensional and multi-dimensional models have been introduced by scientists. Each of these theories consider ICP from a specific point of view, for example, fluid model, electromagnetic model, electrodynamic model and etc. Also, plasma-wall interaction and sheath theory has been investigated and numerous models has been introduced.

In contrast, theory of electron current extraction from ICP is considered in recent years. For this reason, there are limited models can be used in this field.
In the operational condition of RF neutralizer, Knusden number is not very high and continuum assumption is still valid. So, we consider continuity assumption and use fluid equations for plasma. So, the momentum for electron will be

$$\frac{\partial n_e}{\partial t} + \nabla \cdot (n_e \mathbf{u}_e) = S_e \tag{1}$$

The momentum equation for electrons of low collisional plasma can be obtained by a approximation named "drift diffusion", which neglect the inertia term and time derivative in the left hand side of equation (**??**). So, we will have

$$n_e \mathbf{u_e} = \frac{-e n_e}{m_e \bar{\nu}_m} \mathbf{E} - \frac{k_B}{m_e \bar{\nu}_m} \nabla \cdot (n_e \mathbf{T_e}) \tag{2}$$

The continuity equation for ions is

$$\frac{\partial n_i}{\partial t} + \nabla \cdot (n_i \mathbf{u}_i) = S_i \tag{3}$$

In the momentum equation the "drift diffusion" approximation can not be applied, because inertia terms can not be neglected. So, ion momentum equation we will have

$$\frac{\partial \mathbf{u}_i}{\partial t} + \mathbf{u}_i \left(\nabla \cdot \mathbf{u}_i\right) = \frac{q\mathbf{E}}{m_i} - \frac{k_B}{m_i n_i} \nabla \left(n_i T_i\right) - \bar{\nu}_m \mathbf{u_i} \tag{4}$$

It is assumed that ion temperature is equal to neutral temperature, so an energy equation is not solved for ions [7].

For momentum equation of neutral particles, an approximate version of Navier-stokes equation is solved:

$$m_n \frac{\partial \mathbf{u}_n}{\partial t} + m_n \mathbf{u}_n \left(\nabla \cdot \mathbf{u}_n\right) - m_n \eta_n \left(\nabla^2 \mathbf{u}_n + \frac{1}{3} \nabla (\nabla \cdot \mathbf{u}_n)\right) = \mathbf{F}_n - \frac{k_B}{n_n} \nabla (n_n T_n) \tag{5}$$

where η_n is viscosity of the fluid and $\mathbf{F}_n$ is the vicosity force due to collsion with other species.

Energy equation for neutral particles can be expressed as

$$\frac{\partial}{\partial t}\left(c_n n_n k_B T_n\right) + \nabla \cdot \left((c_n + 1) n_n \mathbf{u}_n T_n - k_B \kappa_n \nabla T_n\right) = \Pi_n \tag{6}$$

wherec_n heat capacity, κ_n is thermal conductivity and Π is power obtained in collision and reactions with other species [7].

In order to extract electron from plasma, we need to have a positively biased surface. Also, walls of the plasma chamber should be biased negatively to this surface. We consider the area and potential of positively biased electrode to be A_{be} and ϕ_{be} respectively , and area and potential of walls to be A_{w} and ϕ_{w}, and plasma potential as $\phi_p(\mathbf{r})$ with depends to position. Also, we denote$\Gamma_{e,be}$ and $\Gamma_{i,be}$ as electron and ion current going to the biased surface and $\Gamma_{e,\mathrm{w}}$ and $\Gamma_{i,\mathrm{w}}$ as electron and ion current going to the walls. From current conservation law we will have [7]

$$\Gamma_T = \Gamma_{e,be} + \Gamma_{e,\mathrm{w}} = \Gamma_{i,be} + \Gamma_{i,be} \tag{7}$$

We know that electron current to the biased surface and the wall can be find as

$$\Gamma_{e,be} = A_{be}\frac{v_{e,th}}{4}\exp\left(-\frac{e(\phi_p - \phi_{be})}{k_B T_e}\right) \tag{8}$$

$$\Gamma_{e,\mathrm{w}} = A_{\mathrm{w}}\frac{v_{e,th}}{4}\exp\left(-\frac{e(\phi_p(\mathbf{r}) - \phi_{\mathrm{w}})}{k_B T_e}\right) \tag{9}$$

where $v_{e,th}$ is mean thermal velocity of electron and

$$v_{e,th} = \left(\frac{8k_B T}{\pi m}\right)^{1/2} \tag{10}$$

Also, the ion current to the biased surface and walls is using Bohm speed and Boltzmann equilibrium

$$\Gamma_{i,\mathrm{w}} = A_{\mathrm{w}} n_0 u_B \exp(-\frac{1}{2}) \tag{11}$$

$$\Gamma_{i,be} = A_{be} n_0 u_B \exp(-\frac{1}{2}) \tag{12}$$

By applying these equations to equation (7), we will have

$$(A_{\mathrm{w}} + A_{be}) u_B \exp(-\frac{1}{2}) = \frac{v_{e,th}}{4}\left[A_{\mathrm{w}}\exp\left(-\frac{e(\phi_p - \phi_{\mathrm{w}})}{k_B T_e}\right) + A_{be}\exp\left(-\frac{e(\phi_p - \phi_{be})}{k_B T_e}\right)\right] \tag{13}$$

In order to simplify, we can write

$$\mu = 4\exp(-\frac{1}{2})\frac{u_B}{v_{e,th}} = \left(2\pi\exp(-1)\frac{m}{M}\right)^{1/2} \approx \sqrt{\frac{2.3m}{M}} \tag{14}$$

using this, equation (13) can be rewritten as

$$\mu(A_\mathrm{w} + A_{be}) = A_\mathrm{w} \exp\left(-\frac{e(\phi_p - \phi_\mathrm{w})}{k_B T_e}\right) + A_{be} \exp\left(-\frac{e(\phi_p - \phi_{be})}{k_B T_e}\right) \tag{15}$$

Now, we begin to consider different regimes that can exist. The first regime is that biased electrode and wall collect both of electrons and ions. This condition is known as ionic sheath. A schematic of potential distribution in this ragime is shown in figure 3. If the bias voltage become larger than $kT_e/2$, biased surface will collect all the electron current. So, equation (15) becomes [7]:

$$\mu(A_\mathrm{w} + A_{be}) = A_{be} \exp\left(-\frac{e(\phi_p - \phi_{be})}{k_B T_e}\right) \tag{16}$$

And hence

$$\phi_p - \phi_{be} = \frac{k_B T_e}{e} \ln\left(\frac{A_{be}}{\mu(A_\mathrm{w} + A_{be})}\right) \tag{17}$$

Thus we can see that plasma potential follows the bias potential. As mentioned, in order we can consider that no ion is lost to the biased , the biased voltage should be greater $k_B T_e/2$. by applying this to equation (17), we will get

$$\frac{A_{be}}{A_\mathrm{w}} \geq \left(\frac{\exp(1/2)}{\mu} - 1\right) \approx 1.7\mu \tag{18}$$

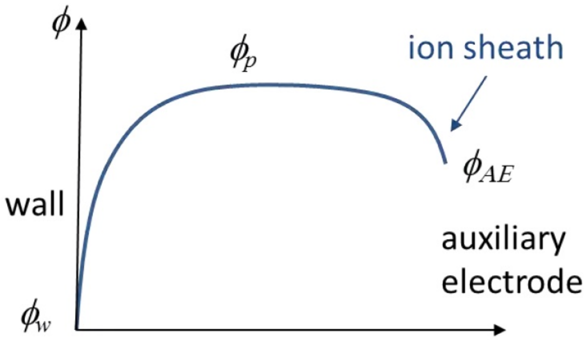

Figure 3: Potential distribution in ionic sheath regime [7]

The second condition is the situation that biased surface does not collect any ion and collects the electron current that corresponds the saturation current, $A_{be} n_0 v_{e,th}/4$. Actually, this correspond to very small areas of biased surface, such as probes. When biased surface area is very small, this surface does not apply any perturbation to the plasma and the above mentioned assumption take place. By applying this assumptions to equation (15), we will have [7]

$$\mu A_\mathrm{w} = A_\mathrm{w} \exp\left(-\frac{e(\phi_p - \phi_\mathrm{w})}{k_B T_e}\right) + A_{be} \tag{19}$$

By solving this we can get

$$\phi_p - \phi_{\rm w} = -\frac{k_B T_e}{e} \ln\left(\mu - \frac{A_{be}}{A_{\rm w}}\right) \tag{20}$$

In order to this equation become true

$$\frac{A_{be}}{A_{\rm w}} < \mu \tag{21}$$

A schematic of potential distribution in electron sheath condition is shown in Figure 4. Considering equation (20), we can see that plasma potential does not follw the bias voltage and independent from it [7].

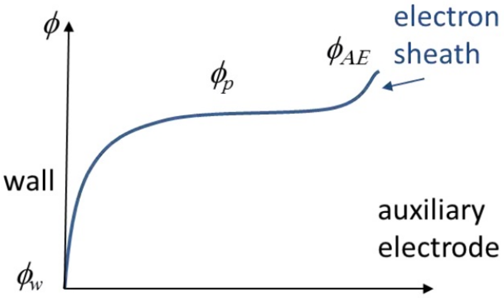

Figure 4: Potential distribution in electronic sheath regime [7]

The third regime the regime between the previous ones. So we will have

$$\mu \le \frac{A_{be}}{A_{\rm w}} < 1.7\mu \tag{22}$$

It is shown that in a double sheath should from in this condition in order to preserve quasi-neutrality and balance the ion and electron currents to outside of the plasma. An schematic of this condition is shown in Figure 5. As can be seen in this figure, double sheath is like a combination of electronic sheath and ionic sheath. A minimum potential exists near the biased surface in which $\phi_{be} > \phi_p > \phi_D$. In this regime, no electron are lost to the walls and no ions are lost to the biased electrode. So, from equation (15) we can write

$$\mu A_{\rm w} = A_{be} \exp\left(-\frac{e(\phi_p - \phi_D)}{k_B T_e}\right) \tag{23}$$

Solving this we can get

$$\phi_p - \phi_D = \frac{k_B T_e}{e} \ln\left(\frac{\mu A_{\rm w}}{A_{be}}\right) \tag{24}$$

By applying the condition of equation (22) to this, we can get [7]

$$0 < \phi_p - \phi_D < \frac{k_B T_e}{2e} \tag{25}$$

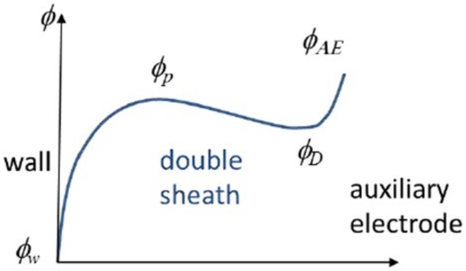

Figure 5: Potential distribution in double sheath regime [7]

1 Simulation Method and Results

In order to investigate the RF neutralizer numerically a 3D model is generated in SOLIDWORKS. This model is taken from the Japanese concept of ICP/C, in their first research [3]. The 3-D model of the RF neutralizer consist of 4 parts:

1. Discharge chamber (with a gas inlet),
2. RF coil,
3. Ion collector,
4. Mica plate (with an outlet orifice).

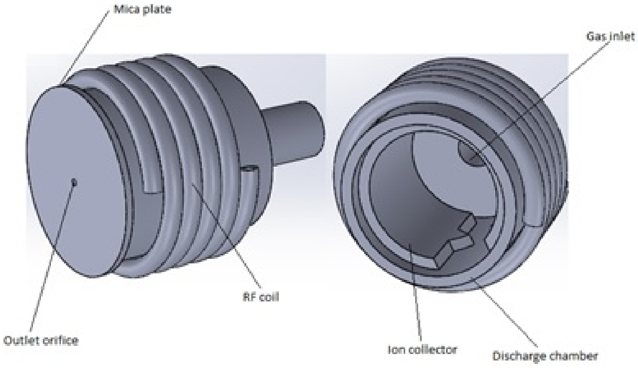

Figure 6: 3-D model of RF neutralizer

Later, this geometry will be used by COMSOL MULTIPHYSICS in order to simulate the operation of RF neutralizer. In this chapter, the ICP interface of COMSOL MULTIPHYSICS is described. Also, some pre-study results obtained from COMSOL MULTIPHYSICS are presented.

1.1 COMSOL MULTIPHYSICS

The COMSOL Multiphysics is a finite element simulation software. This software has a plasma interface that is developed to simulate various types of plasmas, like CCPs (capacitively coupled plasmas), DC discharges, microwave discharges, and ICPs (inductively coupled plasmas. COMSOL Multiphysics Plasma Module uses series of scientific publication on numerical modeling of non-equilibrium discharges.

In order to investigate the ICP modeling in COMSOL, a 2-D axi-symmetric model is generated by geometry tool of COMSOL itselt. This model is shown in figure 7. Neutralizer itself can not be modeled in using a 2-D axi-symmetric geometry, because electromagnetic wave con not penetrate ion collector. So, in this model the ion collector is removed, and just forming ICP inside the neutralizer chamber is considered.

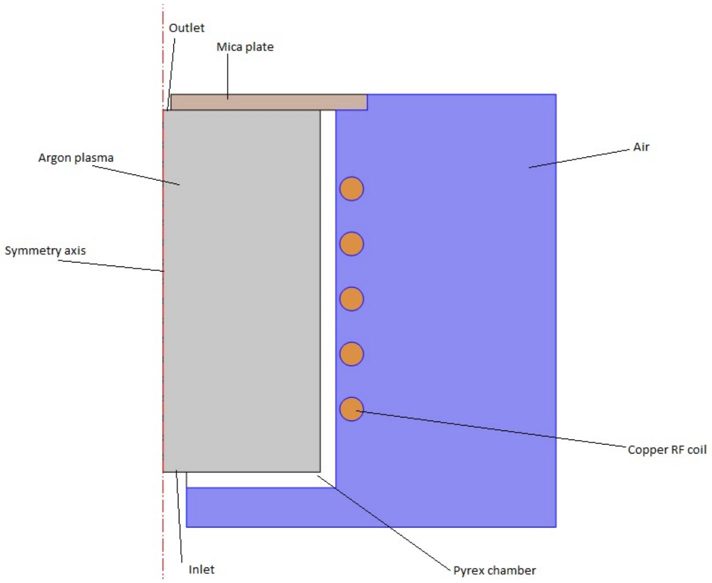

Figure 7: 2-D model of RF neutralizer

The operational condition that is considered in the simulation is like this: Argon gas is used as plasma fluid. Inlet boundary condition is set constant pressure in $21Pa$. Outlet boundary condition is also constant pressure and is set in $20Pa$. RF power applied to the coil is $60W$. Chamber walls and Mica plates are grounded.

Results for electron density inside the chamber is shown in figure 8. This result is consistence with previous results for ICPs. Maximum electron density is in the center of the chamber and its value is $2.82 \times 10^{18}\ 1/m^3$.

Results for plasma potential is shown in Figure 9. Maximum electric potential is $15V$ and is in the center of the chamber. Plasma potential reduces from center to walls and becomes zero at wall, because of the boundary condition that has been set.

Results for electron temperature for ICP plasma is shown in Figure 10 . It can be

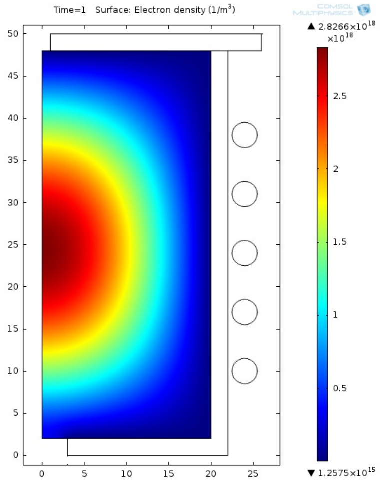

Figure 8: Electron density inside chamber

see that electrons are heated in a region near RF coil and RF power is deposited to plasma from this region. Maximum electron temperature is $2.25eV$.

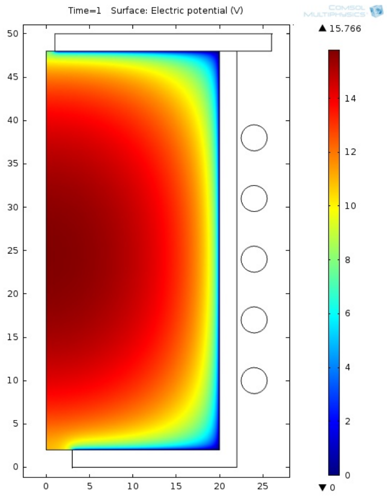

Figure 9: Plasma potential inside the palsma chamber

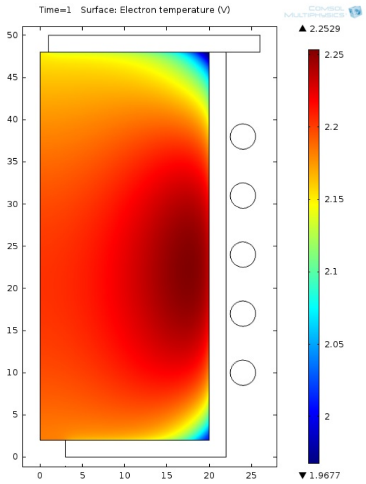

Figure 10: electron temperature inside the chamber

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