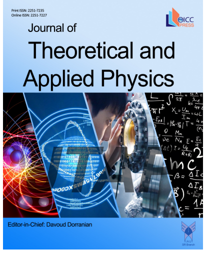

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Effect of gas pressure on plasma characteristics of a 2.45 GHz ECR ion source

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Original Research

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Abstract:

Electron cyclotron resonance ion source (ECRIS) is designed and simulated using COMSOL software. The 2.45 GHz microwave is injected through a coaxial cable into a cylindrical chamber with a diameter of 9 cm and a length of 10 cm. Two coils are employed to produce a flat-B magnetic field profile and two resonance zones on both sides of the chamber. Hydrogen gas plasma is simulated by considering H^+, H_2^+ and H_3^+ ions, and H and H_2 as neutrals. Finally, electron density and temperature are reported as a function of gas pressure. It is observed that as the gas pressure increases, the electron temperature decreases and the electron density decline following an initial increases.

Keywords: ECRIS; Plasma; Gas pressure; Electron temperature; Electron density

1. Introduction

Particle accelerators have been hired for different applications in industry, medicine and etc. The ion sources produce charged particles (electrons and ions) as the front-end of the particle accelerators [1]. The structural capability of electron cyclotron resonance ion source (ECRIS) on generating a high current multi-charged ion beams introduce it as an outstanding ion source [2]. This source is based on the resonance, heating and increasing the energy of plasma electrons. In this research, the 2.45 GHz microwave power is injected to the plasma chamber and the required magnetic field, 875 G, is obtained by the injected microwave frequency and hence the Larmor frequency of rotating electrons around the field lines ($B = (m_e\omega)/q$) [3].
ECRIS has been developed as an ion source for industrial applications [4]. The developed permanent magnet 2.45 GHz based ECR ion source with three-electrode ion extraction system and a Low Energy Beam Transport (LEBT) to match the beam for the injection into the Radio-Frequency Quadrupole (RFQ) is used by Vala et al. [5]. A 2.45 GHz ECRIS generates a milliampere multi-charged helium ion (He_2^+) beam was tested by HaiTao [6]. Peking university ion source group has developed several 2.45 GHz Electron Cyclotron Resonance ion sources for Peking University Neutron Imaging Facility (PKUNIFTY), Separation Function Radio Frequency Quadruple (SFRFQ), Coupled RFQ&SFRFQ, and Dielectric Wall Accelerator (DWA) projects (50 mA of D^+, 10 mA of O^+, 10 mA of He^+, and 50 mA of H^+, respectively). In order to improve performance of these ion sources, experimental studies on plasma density and ion fraction with different sizes of discharge chamber have been carried out in Ref. [7]. The magnetic field along the central axis of the plasma chamber is a key parameter in the ECRIS. Peking university ion source group dedicated a new 2.45 GHz ECR ion source, Permanent magnet electron cyclotron resonance (PMECR) III, to produce proton which has been developed to investigate the influence of the magnetic field on the gas discharge and beam characteristics [8].

A two-dimensional self-consistent model of a plasma sustained by one antenna is investigated by Hagelaar [9]. The microwave fields and power absorption are calculated from the Maxwell equations coupled with a local electron momentum equation by an adaptation of the finite difference time domain method. The plasma is described by fluid equations for magnetized electrons and inertial ions, where quasi-neutrality is imposed through a semi-implicit numerical method based on Poisson's equation, which yields the sheath potentials.

Typical pressure of the injected gas into the ECRIS plasma chamber is $0.01 - 10$ Pa. In this work, The effect of the plasma chamber gas pressure on the density and temperature of electron which acting as the main characteristics of plasma are investigated to evaluate the extracted beam quality (beam current, emittance and etc.) from the ion source [10]. In Ref. [11], the 2D-ECR hydrogen plasma is simulated and modeled to calculate the plasma sheath properties specially the variation of ions density in front of the plasma electrode hole. In addition, the 3D- ECR hydrogen plasma is simulated and modeled in [12] to find the ions fraction to optimize the extracted beam ions fraction according to the ion source operating parameters.

2. Simulation

In this research, the behavior of electron cyclotron resonance plasma is studied in two–dimensional plasma simulation by introduction of twenty three of the most effective collisions into the COMSOL software. The electron collisions and heavy particle processes are contributed to the study is presented in Table 1. These collisions include volume (Number $(1)-(17)$) and surface reactions (Number $(18)-(23)$). Volume reactions include collision of electron with neutrals (H and H_2), electron with atomic and molecular ions (H^+, H_2^+ and H_3^+) and ion with neutrals [11]. In addition, surface reactions include the collision processes of ions and hydrogen atoms (both ground state and excited atoms) with the wall of plasma chamber which produce the hydrogen atom and molecules (H and H_2).

The plasma chamber is considered as a copper cylinder with 9 cm as diameter and 10 cm as length. For breaking down the gas, the 2.45 GHz microwave is injected into the chamber by the coaxial antenna. In this simulation, two electromagnet coils are applied to generate the magnetic field inside the plasma chamber while the two iron yokes covered the electromagnet for augmenting the magnetic field strength. The designed electromagnetic two-coils structure concluded a flat-*B* profile along the central axis of the chamber. The strength of the magnetic field at two points along central axis of the chamber is equal to the resonant field value of 875 G, shown in Figure 1.

To increase the accuracy of the simulation, we considered the much smaller mesh size in the resonance area, Figure 2 (a). And, evolution of the plasma parameters is investigated by variation of hydrogen gas pressure in the range of 0.01 to 10 Pascal. Figure 2 (b) shows the lines and direction of the magnetic field in the cylindrical chamber. The ECR zone is indicated by red color where the electrons are received the maximum possible energy and then make more ionization process in the plasma bulk.

3. Discussion

Figure 3 (a) shows distribution of the electron density in the plasma chamber with a gas pressure of 1 Pa. As it is shown, the electron density distribution is aggregated in front of the wave antenna where the extraction system is placed. Also, Figure 3 (b) indicate that the electron temperature around the magnetic field lines in the middle of chamber is much higher than the other points.

Evolution of the electron density and temperature with respect to pressure are shown in Figure 4. As Figure 4 (a) shows, the electron temperature decreases with increasing

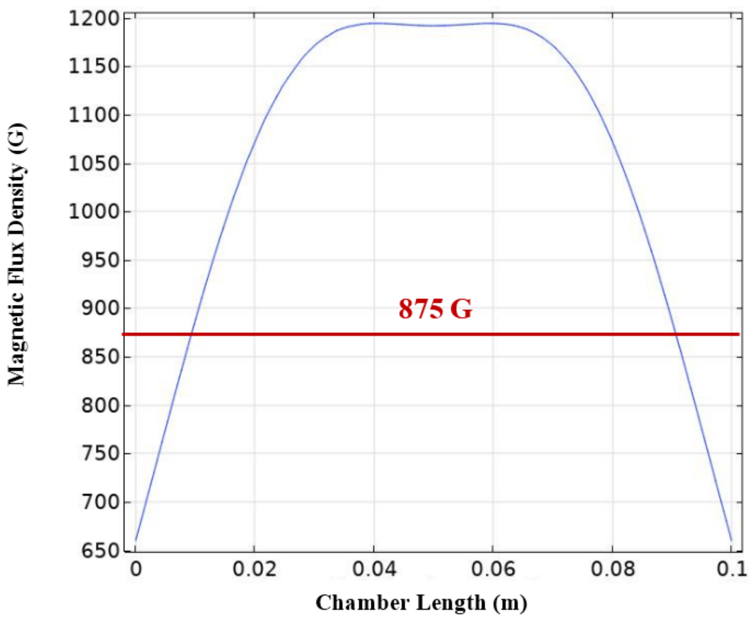
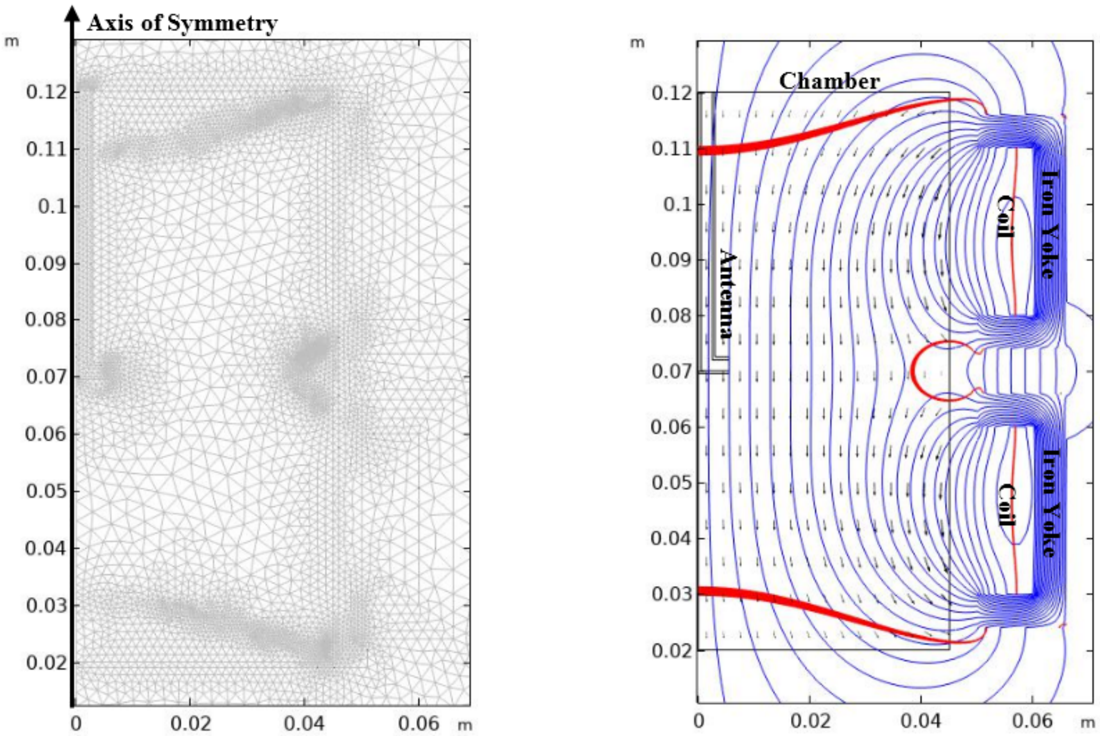
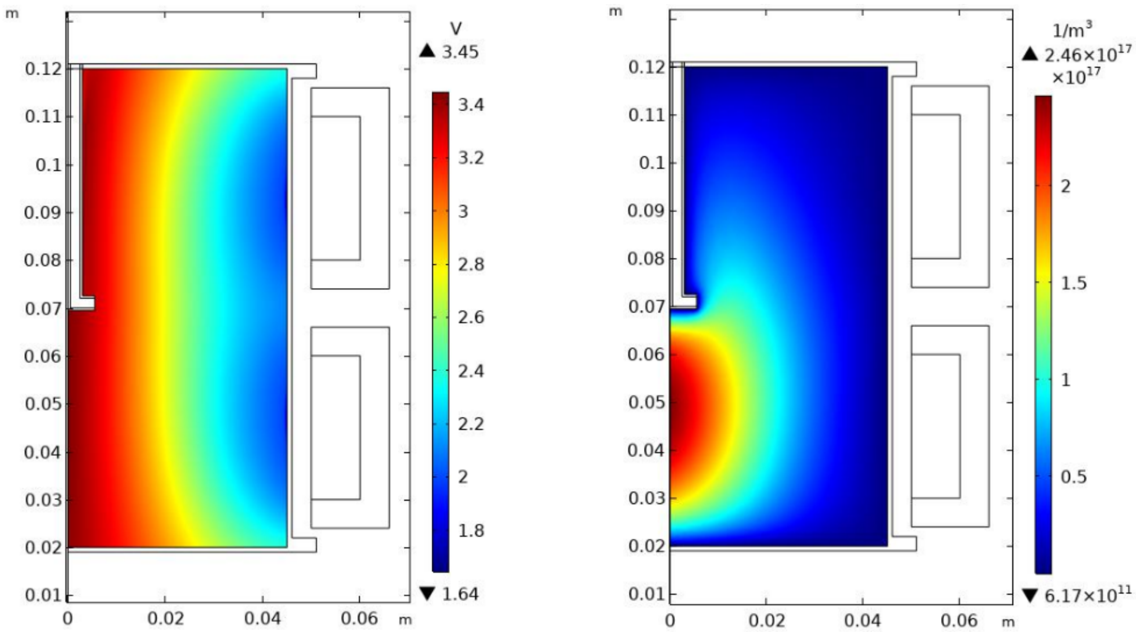


Figure 1. Magnetic field profile along the central axis of the chamber.



(a) (b)

Figure 2. (a) Mesh size corresponding to 875 G resonance field and (b) Magnetic field lines (blue solid line) and resonance area (red solid line) in the chamber.



(a) (b)

Figure 3. Distribution of (a) electron temperature and (b) electron density.

the gas pressure as a consequence of the distributed temperature between the more particles for higher gas pressure. The development of electron density as a function of gas pressure is pictured in Figure 4 (b) as the electron density first increases and then decreases. With an increase in pressure due to an increase in the number of neutral particles, more electrons are generated, but with a further increase in pressure, the electron density decreases due to the volume interactions and electron recombination.

Table 1. Main interactions of hydrogen gas in the ECR ion source [5].

Number	Reaction	Threshold energy (eV)	Type
1	$e + H \rightarrow e + H^{*}$	10.2	Excitation
2	$e + H \rightarrow e + H^{**}$	12.09	Excitation
3	$e + H^{*} \rightarrow e + H^{+}$	3.4	Ionization
4	$e + H^{**} \rightarrow e + H^{+}$	1.511	Ionization
5	$e + H \rightarrow 2e + H^{+}$	13.6	Ionization
6	$e + H_2 \rightarrow 2e + H_2^{+}$	15.4	Ionization
7	$e + H_2 \rightarrow e + H + H^{*}$	10	Dissociative excitation
8	$e + H_2 \rightarrow 2e + H^{+} + H$	18	Dissociative ionization
9	$e + H_2^{+} \rightarrow H^{*} + H$	0	Dissociative excitation
10	$e + H_2^{+} \rightarrow e + H^{+} + H$	2.4	Dissociative excitation
11	$e + H_2^{+} \rightarrow 2e + 2H^{+}$	14.7	Dissociative ionization
12	$e + H_2^{+} \rightarrow e + H^{+} + H^{*}$	14	Dissociative excitation
13	$e + H_3^{+} \rightarrow 3H$	0	Dissociative excitation
14	$e + H_3^{+} \rightarrow e + 2H + H^{+}$	14	Dissociative excitation
15	$e + H_3^{+} \rightarrow H_2 + H$	0	Dissociative excitation
16	$H_2^{+} + H_2 \rightarrow H_3^{+} + H$	0	Volume recombination
17	$H^{+} + H_2 \rightarrow H_2^{+} + H$	1.83	Volume recombination
18	$H + H + wall \rightarrow H_2 + wall$	–	Surface recombination
19	$H^{*} + wall \rightarrow H + wall$	–	Surface De-excitation
20	$H^{*}\ast + wall \rightarrow H + wall$	–	Surface De-excitation
21	$H^{+} + wall \rightarrow H + wall$	–	Surface recombination
22	$H_2^{+} + wall \rightarrow H_2 + wall$	–	Surface recombination
23	$H_3^{+} + wall \rightarrow H + H_2$	–	Surface recombination

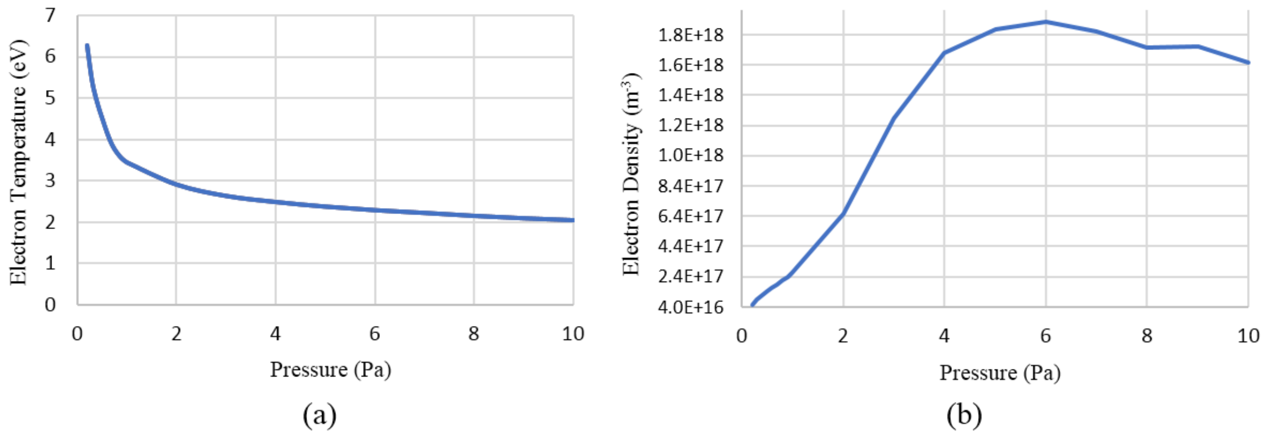


Figure 4. Variation of (a) electron temperature versus gas pressure and (b) electron density versus gas pressure.

4. Conclusion

The pressure of hydrogen gas pressure make a great impact on the plasma formation and feature of proton ECR ion source such as electron temperature and electron density. By increasing the neutral gas pressure, the electron temperature decreases while the electron density initially increases due to the electric breakdowns of gas species by the microwave, and then decreases due to the increase of volume interactions. The output result of the steady-state model for hydrogen show, the microwave power is absorbed in the ECR region below the critical plasma density and the main absorption occurs near the plasma edge beyond the nominated density. Although, the electron temperature considerably change across the magnetic field lines and the plasma density is nearly formed around the antenna and achieve to the maximum value of 2.46×10^{17} m^{-3} with a gas pressure of 1 Pa.

Authors Contributions

Marzieh Asadi Aghbolaghi, Conceptualization, Formal analysis, Investigation, Methodology, Software, Validation, Visualization, Writing–original draft, Writing–review & editing. Fereydoun Abbasi Davani, Supervision, Writing–review & editing. Masoomeh Yarmohammadi Satri, Project administration, Supervision, Conceptualization, Validation, Writing–review & editing. Zafar Riazi Mobaraki, Writing–review & editing. Farshad Ghasemi, Writing–review & editing.

Availability of Data and Materials

The data that support the findings of this study are available from the corresponding author upon reasonable request.

Conflict of Interests

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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