The Experimental Study on Electron Beam Extraction from ECR Neutralizer

IEPC-2015-105／ISTS-2015-b-105

Presented at Joint Conference of 30th International Symposium on Space Technology and Science
34th International Electric Propulsion Conference and 6th Nano-satellite Symposium,
Hyogo-Kobe, Japan
July 4 – 10, 2015

Juan Yang[1], Yizhou Jin[2], Litao Luo[3],Yuquan Wang[4]
College of Astronautics, Northwestern Polytechnic University，Xian 710072, P.R. China
Hui Liu
School of Energy Science and Engineering, Harbin Institute of Technology，Harbin 150001, P.R. China

Abstract：Electron cyclotron resonance neutralizer operates under the principle of electron cyclotron resonance plasma. The electron beam from ECR neutralize can be extracted to neutralize the ion beam from electron cyclotron resonance ion thruster. Then the thruster system can keep the potential balance. In this paper, the experiment of the extraction of electron beam from the neutralizer with argon propellant was conducted to study the influence of neutralizer structure and parameters on its performance. The results showed that 8 magnets, the 4th antenna, 3mm diameter of electron extraction orifice and 18mm diameter of front yoke orifice were appropriate to achieve the best performance; the best operation parameters were 0.8sccm gas flow and 88.6V bias voltage, from which electron beam in 103.8mA was extracted; at the same time, the propellant efficiency was 1.2789 and the electron energy loss was 194.573W•A-1, which could satisfy the requirement of electron cyclotron resonance ion source.
Keywords: electron cyclotron resonance plasma, neutralizer, electron beam

Ⅰ. Introduction

ELECTRON cyclotron resonance ion thruster (ECRIT) is one type of electrostatic thrusters. It is composed of ECR ion source and neutralizer. In the ion source, microwave energy is used to discharge gas and produce ECR plasma, from which ion beams are extracted through accelerating grids to produce thrust. The ion beams are neutralized by electrons from ECR neutralizer. ECRIT has the advantage of high impulse, long life span, cathode erosion proof design and simple structure[1-5]. It is a beneficial candidate for long time space flight. In 2003, ECRIT with 10cm diameter was launched into space with a recoverable asteroid probe, Hayabusa, which returned back on earth in June, 2010[6-7].

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[1] Professor, College of Astronautics, yangjuan@nwpu.edu.cn.
[2] PhD candidate, College of Astronautics, jyz@mail.nwpu.edu.cn
[3] Master candidate, College of Astronautics, luolitao@mail.nwpu.edu.cn.
[4] PhD candidate, College of Astronautics, wyq_029@hotmail.com (etc).

As a key component of ECRIT, ECR neutralizer functions to neutralize ion beam and keep the thruster and spacecraft from charging. Unlike the hollow cathode neutralizer, ECR neutralizer extracts electron beams form its ECR plasma, which avoids the application of the thermionic emitter. However, due to the different principle and mechanism of electron extracting between the two kinds of neutralizer, the cavity of ECR neutralizer in fact is a type of microwave apparatus. Its structure will influence the performance largely. Otherwise, ECR region in the neutralizer controls the ECR plasma formation and property. Hence the neutralizer cavity and magnetic topological structures are the important factors that control the efficiency, stability and the ECR plasma property of the neutralizer. Meanwhile the operation parameters must be chosen appropriately for the ECR neutralizer to get the best performance. A lot of relevant contributions have been conducted to explore the mechanism of ECR neutralizer and improve its performance[8-11]. In this paper, through adjusting the structures of neutralizer and magnetic topology, a detailed study on the electron extraction from ECR neutralizer with different structure and working different parameters is conducted and the best ECR neutralizer performance is obtained.

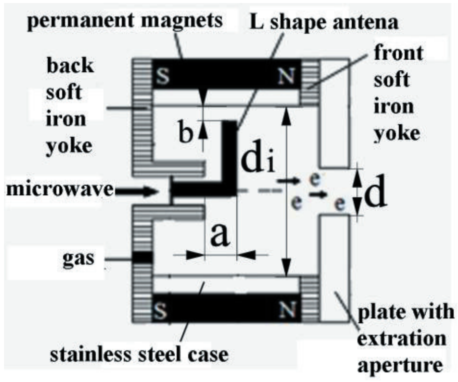
The content of this paper is threefold: first, the principle of the ECR neutralizer and its experimental system were described; second, the experiments on ECR plasma generation, electron beam extraction and the results were presented and discussed in detail; third, the conclusion was given in the last section.

Ⅱ.The Principle of ECR Neutralizer and Experiment System

A. The principle of ECR neutralizer

As shown in Fig.1, ECR neutralizer consists of L shape antenna, in which microwave is coupled, several blocks of permanent magnets, front and back soft iron yokes, gas feeding pipe and case. Gas and enough microwave energy was input into the case to form plasma. Then the free electrons were generated and rotate around the magnetic line. At special position, the electron gyrated with the frequency of microwave and resonated with microwave to gain energy and become primary electrons (PEs). The PEs discharged neutral gas through collision to produce ECR plasma, from which electron beams were extracted out under the action of potential difference between the neutralizer and exited ion beams. The special region where the electron cyclotron frequency was equal to that of microwave was ECR region. The relevant magnetic flux density was $B=\omega m_e/e$, where ω was the microwave frequency.

Propellant utilization and electron production cost were two important parameters of neutralizer, which could be separately calculated by



(a)

(b)

Fig. 1 Sketch of ECR neutralizer

(a)Section view (b)Side view

$$\eta = \frac{I_e}{e} \frac{1}{\dot{m}_p / M} \quad (1)$$

$$\varepsilon = \frac{P + U_B I_e}{I_e} \quad (2)$$

where Ie, e, $\dot{m}_p$ and M were the extracted electron current, electron charge, mass flow rate and atom mass. For a neutralizer, higher propellant utilization and lower electron production cost were required. From the following experiment, it could be seen that the two parameters, the gas flow rate and electron extracting voltage were contradictory for higher propellant utilization or lower electron production cost that could be obtained at high extracting voltage and gas flow rate. Therefore elaborate design and experiments should be required to compromise the parameters.

B. Experiment system

In Fig. 2, the experiment system was composed by microwave source operating at 4.2GHz frequency and 5-30W output power, three stub tuners, insulator which protected the microwave source from the power supply, ECR neutralizer, propellant supply subsystem which output the gas flow rate in the range of 0-5sccm in standard condition, coordinator, electron collection plate which could be moved by coordinator to change the distance of s, adjustable power supply, resistance which protected the power supply, vacuum chamber and vacuum pumps.

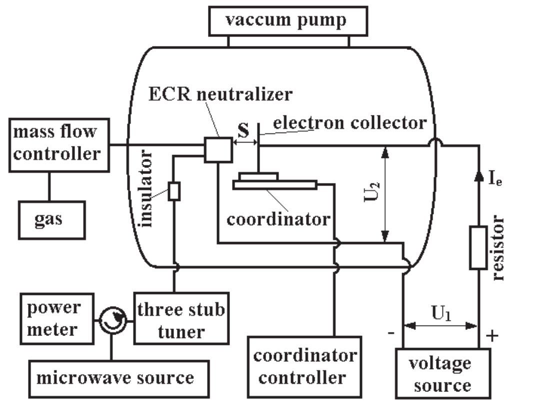


Fig. 2 Experiment system of ECR neutralizer

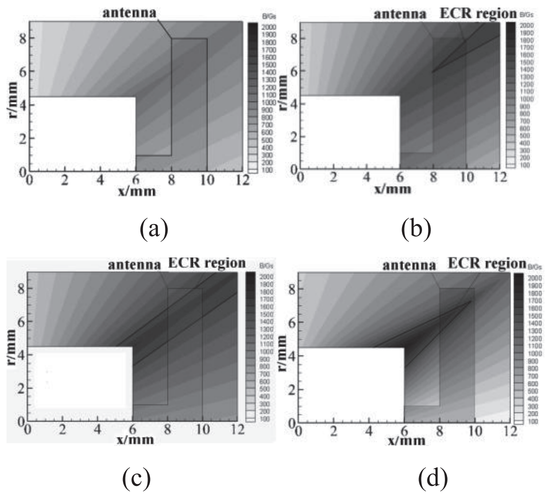


Fig. 3 Magnetic flux density measured inside the neutralizer with different number of magnets

(a) 6 magnets (b) 8 magnets

(c) 10 magnets (d) 12 magnets

Ⅲ.Experiment of ECR plasma generation, electron extraction and discussion

A. Experiment condition

The experiment was conducted in vacuum chamber, in which the operation pressure was 1.5×10^{-3}Pa at argon gas flow rate of 2sccm, to study the influence of neutralizer structure and operation parameters on the performance. As shown in Fig.1. the elements relevant to the neutralizer structure include the number of magnet blocks, the distance, a, between the antenna and the back yoke, the distance, b, between the antenna and inside surface of case, the diameter of extraction aperture, d, and the diameter of front yoke, di. The magnetic flux density measured inside the neutralizer with 6, 8, 10, 12 blocks of magnet is illustrated in Fig.3, which showed that no ECR region appeared for 6 blocks of magnet. While ECR region could be found for 8, 10, and 12 blocks of magnet, the ECR region for 10 blocks of magnet with L shape antenna had larger superposition region. Therefore it could be expected that ECR plasma may be easily generated for Fig. 3 (c).

In the experiment, 8 types of antenna listed in Table 1 were used. The diameters of extraction aperture were 1, 2, 3, 4 and 5mm, the diameters of the hole in the front yoke were 18mm and 12 mm respectively.

Table1. Antenna number and structural parameters

Antenna number	a/mm	b/mm
1	3	0.5
2	3	1
3	2	0.5
4	2	1
5	2	1.5
6	1	0.5
7	1	1
8	1	1.5

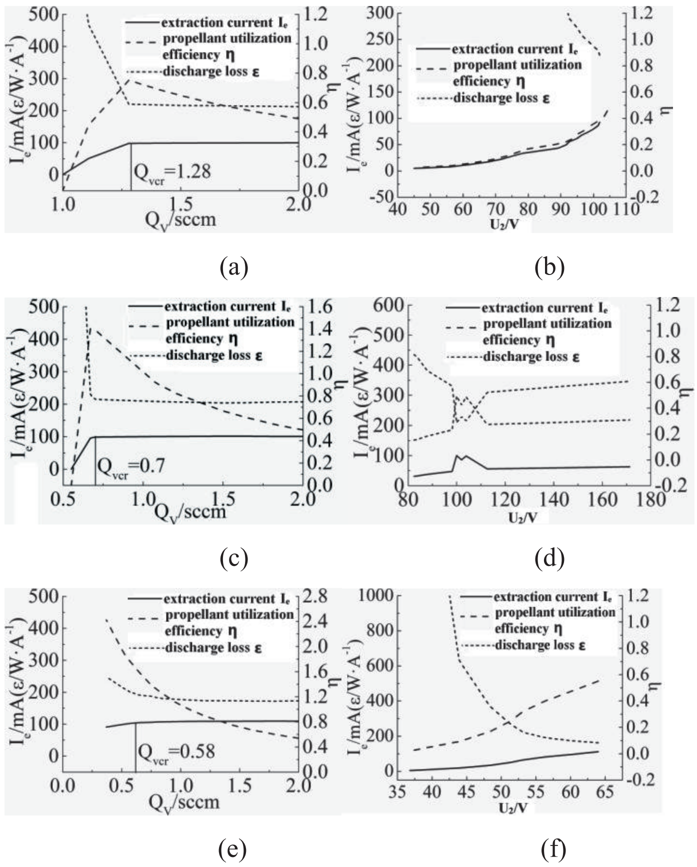


Fig. 4 Electron current, propellant utilization and electron production cost versus gas flow rate and extracting voltage

(a) Current versus gas flow rate at 12 blocks of magnet and U_1 in 400V

(b) Current versus U_2 at 12 blocks of magnet and 2sccm gas flow rate

(c) Current versus gas flow rate at 10 blocks of magnet and U_1 in 400V

(d) Current versus U_2 at 10 blocks of magnet and 2sccm gas flow rate

(e) Current versus gas flow rate at 8 blocks of magnet and U_1 in 400V

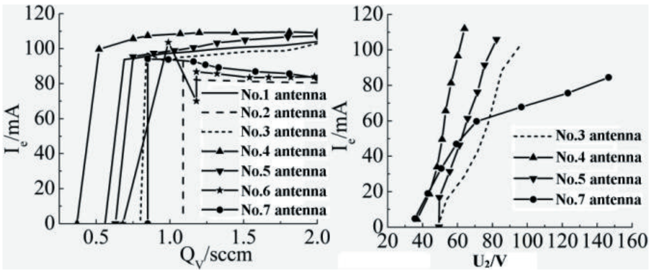
(f) Current versus U_2 at 8 blocks of magnet and 2sccm gas flow rate

B. Experiment and discussion

1) Influence of magnetic topological structure on gas discharge and extracted electron current

In order to study the influence of magnetic topological structure on ECR plasma generation and electron extraction, the experiment using argon gas was carried out for the structure elements of extraction aperture diameter in 3mm, front yoke hole diameter in 18mm, No.4 antenna and different blocks, 6, 8, 10, 12, of magnet. It was found that gas could not be ionized for 6 blocks of magnet, but for 8, 10 and 12 blocks of magnet gas could be immediately excited by 6W input power.

In the experiment of electron extraction, the distance, s, between the neutralizer and the electron collection plate was 5mm, 8, 10 and 12 blocks of magnet were used and input microwave power was 11W. After plasma was excited, the adjustable power supply was used for instant electron extracting at a high output voltage, U_1, constant gas flow rate, then the extracting voltage, $U_2 = U_1 - I_eR$, between neutralizer and electron collection. Then the gas flow rate was adjusted to verify its influence on the extracted current at constant voltage U_1=400V. The voltage of U_2 was adjusted through changing U_1 to verify the extracting voltage influence on the electron beams at constant gas flow rate of 2sccm.



(a) (b)

Fig.5 Electron current of neutralizer with different antenna

(a) Current versus gas flow rat

(b) Current versus extraction voltage

Propellant utilization and electron production cost are determined according to formula (1), (2) and the recorded experiment data. Fig.4 shows the curves of extracted electron current, propellant utilization and electron production cost versus gas flow rate, Q_v, and extracting voltage, U_2, at constant U_1 in 400V and with different blocks of magnet. The results indicate that extracted electron current increased with Q_v and reached to saturation at critical value, Q_{vcr}. The magnet block number largely influenced Q_{vcr} rather than the saturated current as Fig. 4(a), (c) and (e) showed. The neutralizer with 8 blocks of magnets has the lowest Q_{vcr} in 0.58sccm, while the propellant utilization in 1.76 and discharge loss in 201W $\cdot A^{-1}$. In Fig. 4(b), (d), (f), the extraction current, propellant utilization and electron production cost versus U_2 at constant gas flow rate in 2sccm indicated that both the extraction current and electron production cost increased with U_2. For the neutralizer with 10 blocks of magnet, the extraction current, propellant utilization and electron production cost suddenly changed when U_2 in the range of 100-110V. The extraction current from neutralizer with 8 blocks of magnets could reach saturated value of 112mA at lowest extraction voltage of 64V. Besides, the propellant utilization for 10 or 8 blocks of magnet was above 1, which maybe attributed to the multi-discharge of atoms or the electron emission from the inner wall through energetic ion colliding. It could be concluded that 8 blocks of magnet could be used in the ECR neutralizer with higher extraction current, lower critical gas flow rate and extraction voltage, higher propellant utilization and electron production cost.

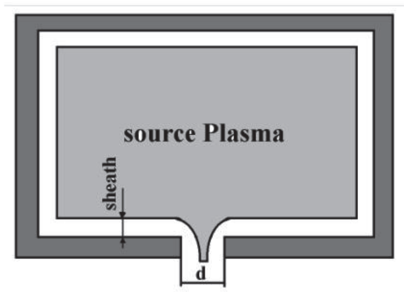


Fig.6 Plasma boundary location at aperture size and sheath thickness

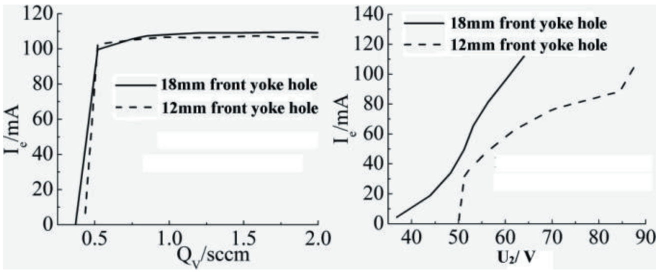
2) Influence of antenna structure on discharge and current extraction

The structural elements of the neutralizer were fixed to extraction aperture diameter in 3mm, front yoke hole diameter in 18mm and 8 blocks of magnets to verify the effects of antenna structure on discharge. The distance, s, between the neutralizer and the collector was still 5mm. Gas in the neutralizer with No.8 antenna couldn't be ionized even at 21W input microwave power, so that No.8 antenna was abandoned in following experiments. The experimental procedure was the same as that of studying the magnets topological structure but propellant utilization and electron production cost were not calculated.

In Fig.5, it was showed that the current extracted from each neutralizer with No.1-7 antenna at various mass flow rates and U_1 in 400V increased with gas flow rate and saturated above certain gas flow, Q_{vcr}. It could be demonstrated that No.4 antenna was the best one because Q_{vcr} was the lowest and the saturate current was the highest. At constant gas flow rate of 2sccm, only neutralizers using No.3, 4, 5, 7 antennae properly functioned as extracting voltage increased.

3) Influence of extracting aperture diameter on discharge and current extraction

Neutralizers with 8 blocks of magnets, No.4 antenna and extracting aperture diameters of 1, 2, 3, 4 and 5mm were experimented at 2sccm Ar flow rate and 11W input microwave. Gas in the neutralizer with 5mm aperture diameter could not be ionized, while for extracting aperture diameters of 1mm and 2mm, electrons were hardly extracted. For the neutralizer with 3 and 4mm extracting aperture diameter, both gas ionization and electron extraction were successful, but for the case of 3mm aperture diameter electron extraction required much higher extracting voltage than 4mm aperture diameter.



(a) (b)

Fig. 7 Electron current of neutralizer with different front yoke hole

(a) Current versus gas flow rate at U_1 in 400V

(b) Current versus U_2 at gas flow rate of 2sccm

Ref. 12 suggests that the dimensions of the extraction aperture relative to the internal plasma properties should be considered. As Fig.6 showed, the extracting aperture diameter, d, relative to the plasma sheath width, s, determined the location of the plasma boundary at the aperture, placing a constraint on the extractable current. Only when d≈2s, the potential barrier was nearly zero at the aperture exit, allowing for a combination of electron current extraction and controllable electron energies. When d<<2s, the quasi-neutral plasma boundary was separated from the aperture plate by a thick sheath and electrons almost can not overcome the potential barrier to be extracted out. Otherwise, for d>>2s, the sheath was quite thin and the quasi-neutral plasma expands through the aperture. This allows the maximum extractable current, equal to the thermal electron current density through the aperture. This regime may not be the best for the perturbation of the substantial plasma potential induced by applied bias voltage and important extracted electron energy. While d≈2s, the potential barrier was nearly zero at the

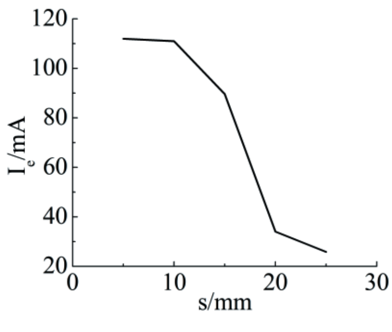
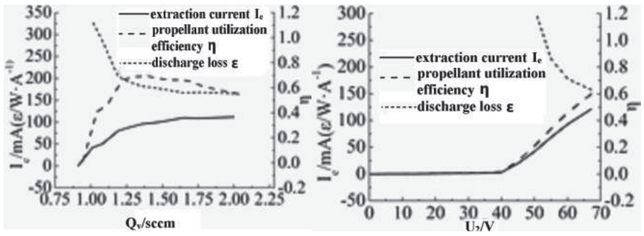


Fig. 8 Extracted current versus s

aperture exit, which is a combination of electron current extraction and controllable electron energies and the best case for operation. In the neutralizer, s was estimated to be 1.3mm according to the estimation of plasma density and electron temperature. Therefore d=3mm is the best dimension.

4) Influence of front yoke hole on gas discharge and extracted current

Fig.7 shows the experiment results of the neutralizer with 8 magnets, No.4 antenna, 3mm extraction aperture diameter and two kinds of front yoke hole with diameter, d_i, separately in 12 and 18mm. For U_1 in 400V, neutralizer with 18mm yoke hole diameter emitted larger electron current than that with 12mm diameter, and the former one immediately emitted electron current at lower extracting voltage. Therefore, the 18mm front yoke hole diameter is better.



(a) (b)

Fig. 9 Electron Current extracted by power source without resistance protection

(a) Current, propellant utilization and electron production cost versus gas flow rate at U2 in 67V

(b) Current, propellant utilization and electron production cost versus U2 at 2sccm gas flow rate

5) Influence of the distance between the neutralizer and the collector plate on extracted current

With all the structural elements of neutralizer chosen to be the optimum decided as above experiment, experiment for the neutralizer with 8 blocks of magnet, the diameter of electron extracting plate in 3mm, No.4 antenna and front yoke hole diameter in 18mm was completed by adjusting the distance, s, between the collector plate and neutralizer from 5mm to 25mm at 11W input power, 2sccm gas flow rate and U_1 in 400V. As Fig.8 showed, the extracted current decreased inversely with s. When s was above 25mm, the current dropped to zero.

6) Neutralizer performance with optimum structure

Another power supply without protecting resistor was utilized to demonstrate the performance of neutralizer with optimum structure AS Fig.9 showed. It showed that the maximum propellant utilization was 0.6943 at 1.36sccm gas flow rate and 95.8mA extracted current was reached. The electron production cost decreased inversely with gas flow rate. At 2sccm gas flow rate, the extracted current and propellant utilization both increased with the extracting voltage, U_2, and the extracted current maximized to 121.5mA at U_2 in 67.2V with utilization of 0.599 and electron production cost of 157.7W • A^{-1}.

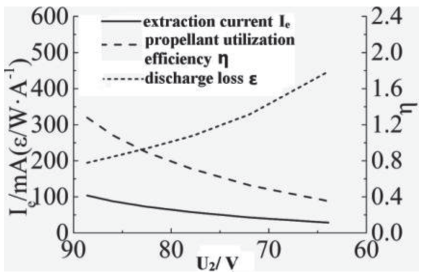


Fig.10 Propellant utilization, electron production cost and electron current versus U_2

At 0.8sccm Ar flow rate and 11W input microwave power, the previously used electric power with high voltage output and resistance protection was utilized again for further evaluation of the neutralizer with optimum structure as Fig, 10 showed. The results in Fig. 4(f) demonstrate a similar performance pattern to previous experiment. When the output voltage of power supply decreased from 400V, it can be found that the maximum extracted current and propellant utilization, lowest electron production cost were separately 103.8mA, 1.2789 and 194.6W • A^{-1} at 88.6V extracting voltage.

III. Conclusion

For satisfying the neutralization demand of argon ECR ion source with extracting ion beams in 110mA, an ECR neutralizer was developed. Through the experiment research of neutralizer structure effects on the gas discharge, electron beams extracting and its performance, the best neutralizer structure and its operation parameters were obtained. It was demonstrated that with 8 blocks of magnets, No.4 antenna, 3mm extracting aperture diameter and 18mm front yoke hole, the neutralizer with argon propellant can extracting maximum electron current in 103mA and propellant utilization efficiency in 1.2789, lost electron production cost in 194.6W • A^{-1} when the gas flow rate in 0.8sccm and extracting voltage in 88.6V, which can match the ECR ion source with 110mA extraction ion beams early developed .

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