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Atomic-Oxygen Beam Source with Compact ECR Plasma*

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Abstract An atomic-oxygen beam source with compact ECR plasma was successfully investigated. The microwave was produced and transmitted in a coaxial mode, and coupled with the loop. The plasma was produced at a higher asymmetry magnetic mirror field, and neutralized with the molybdenum target at a lower asymmetry magnetic mirror field. The magnetic field was constituted with permanent magnets. This source has a higher flux density of atom beam, a lower operating pressure, a smaller power consumption and low-cost. When it was installed at the equipment to study the interaction of the beam with the surface, the operation was carried out very easily and with a good stability.

Keywords: ECR plasma, atomic-oxygen, beam source

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1 Introduction

The energetic oxygen atom eroding the outer-covering of a spacecraft in the flight around a lower earth orbit and the erosion simulation in the experimental circumstance are increasingly taken into account in international spaceflight circle. Because the colliding energy between the spacecraft flying in high speed and the energetic oxygen atom in space circumstance is about 5 eV, the experimental device for the environmental analogy is needed to produce an energetic atomic-oxygen beam less than several eV. The physical and chemical issues concering the oxygen atom beam colliding with material surface will be investigated experimentally.

John W. Cuthbertson et al.[1] constructed a device producing a low-energetic atomic-oxygen beam reflected from the oxygen ion flux on a molybdenum panel (which is placed in the magnelie mivror center and supplied with on bias negaline voltage). The oxygen ion flux coming from an oxygen plasma source was confined by an symmetric magnetic field, which was produced by a RF power on account of low hybrid resonance heating. Although this source had no trouble due to the use of a hot center electric conductor coupling RF power to be introduced into the plasma, cathode, the impurities produced by it and higher operating pressure is needed. The magnetic-field strength corresponding to the low hybrid resonance layer was higher (0.35 T~0.40 T), because the coil size-produced magnetic field is relatively large.

According to the heating principle of microwave electron cyclotron resonance (ECR), the authors employed permanents to constitute the asymmetry magnetic mirror field[2]. The magnetic-field strength on the ECR layer is 0.0875 T, which is much lower than that on the low hybrid resonance layer. The size of experimental equipment is much lessened. In

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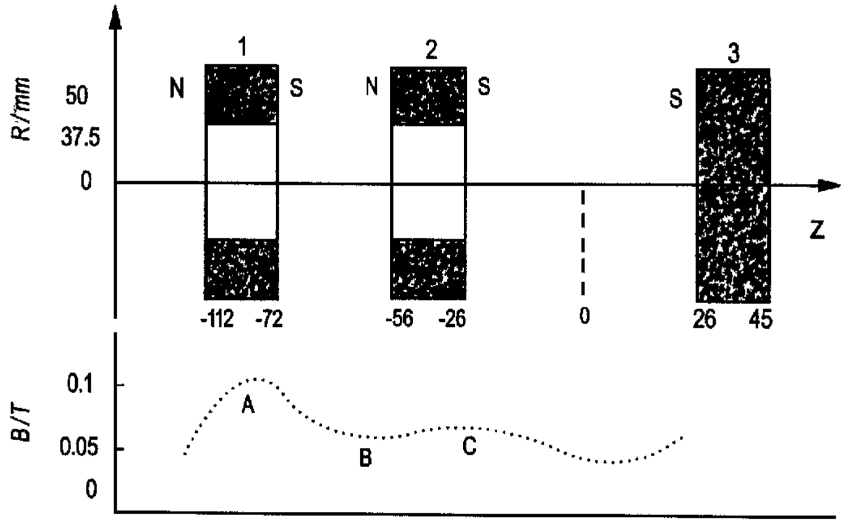

Fig.1 Designed magnetic-field pattern

the same time, heavy-metal impurity entering into the plasma may be avoided in a discharge chamber without an electrode. A new compact ECR oxygen plasma source was studied. The low-energy pure atomico-xygen beam with a cross section of $\phi 40$ mm was produced with a higher flow density at the operating pressure of 10^{-1} Pa ~ 10^{-3} Pa.

2 Device principle

2.1 Magnetic field design

The investigation has shown that a microwave ECR plasma source with a divergent field may operate at the pressure of 10^{-1} Pa ~ 10^{-2} Pa[3]. If an operating pressure of 10^{-3} Pa and a higher plasma density are required, the magnetic-mirror configuration must be adopted[2]. In order to achieve a compact structure permanent magnets were employed for all magnets to achieve the required magnetic-field pattern.

Shown in Fig. 1 is the designed magnetic-field pattern. The pattern is comprised of three magnets with a coaxil mode, among which two circular magnets of same polarity form a higher mirror field for the production of plasma. And the disk one of anti-polarity is placed at plasma downstream to form a lower magnetic mirror field for neutralizing ion.

The electrical particle in a uniform magnetic field performs a gyratory movement as the same as the screw does, that is to say, it moves in a uniform velocity in parallel to the direction of magnetic field and simultaneously with a gyratory movement perpendicular to the direction of magnetic field, therefore, the gyratory radius is $R = mv/qB$. In the considered range of magnetic-field strength the gyratory radius of oxygen ion is expressed in terms of mm, the gyratory radius of electron is much less. The magnetic configuration in Fig. 1 is inhomogeneous in radial direction, the electrical particle is able to have a drift motion in the magnetic gradient direction. Considering that the gyratory radius of the

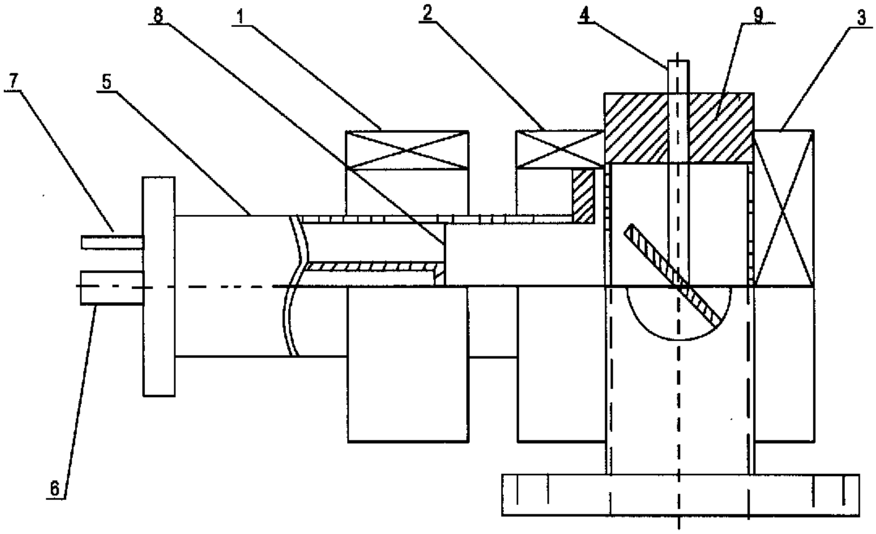

Fig.2 Schematic of ECR neutral beam facility. The numbered pieces are as follows: 1, 2, 3-magnet; 4-molybdenum target assembly with water cooling; 5-resonanse chamber; 6-adjusting conductor; 7-coaxial cable; 8-quartz vessel; 9-neutralizing chamber

particle and the magnetic gradient is very small, its drift motion in the magnetic gradient direction may be neglected, that is to say, the electrical particle movement is frozen up along the magnetic field lines. Thus plasma diffusion loss in the radial direction may be not taken in account. The plasma boundary surface may be described with the magnetic flux.

The plasma flow is affected by the axial magnetic field and the electric field along the magnetic axis. When the electric particle moves from a higher field to a lower field, its circular velocity transfers to an axial movement. When the electric particle moves from a lower field to a higher field, its axial velocity transfers to a circular movement. Therefore, a higher magnetic mirrorproduced plasma is shown in Fig. 1, where a part of electric particle with a higher circular velocity are confined in the higher magnetic mirror field[4]. When the mirror ratio is larger and the operating pressure is lower, the part of electric particle confined in the mirror is large. A larger mirror ratio, such as approximate to 2, may be helpful to the operation under a pressure of 1×10^{-3} Pa.

In the magnetic mirror for neutralization when the electric particle moves from the higher field in the mirror end to the lower field in the mirror center, the movement of electric particles is affected not only by changeable magnetic field but also by negative bias on the molybdenum panel for neutralizing ion. Generally, the ion temperature produced by ECR is less than 1 eV and the negative bias on the molybdenum panel is -30 V~ -50 V. When the plasmas produced in the higher field is transported into the molybdenum panel in the weakest field, the circular velocity of the ion may be left out, the movement direction of electric particle is mainly parallel with the magnetic-field lines. When the angle between the molybdenum panel and the axis of magnetic field is 45° (see Fig. 2), the electric particles will be reflected at this angle and transformed into parallelly energetic neutral beams, thus the designed purpose can be satisfactorily realized.

2.2 Microwave transmmision and coupling

In order to achieve a compact equipment, main components such as a microwave generator in coaxial output mode, a coaxial cable for transmitting microwave and a resonance chamber with the coupling loop etc were adopted. The TEM microwave power was fed in the discharge vessel, which is made of quartz[2].

In order to have a reliable microwave transmission and acquire a high-efficiency transmission, all electric materials and electrical connectors such as plugs, sockets and coaxial cable etc. must have satisfactory high-frequency quality and be properly interconnected and well arranged to guarantee reliable microwave transmission. And also the dimension of the resonance chamber is required to be designed in accordance with physical concept and be adjusted within enough scope.

Because the dimension of the plasma vessel is less than that of the resonance chamber, the output microwave is not able to penetrate deep into the discharge vessel, so the ECR resonance layer absorbing the microwave must be as near as possible to the resonance chamber.

2.3 Structure design

The experimental facility shows in Fig. 2. The internal dimension of the neutralizing chamber made of stainless steel is $\phi 46$ mm × 84 mm. The molybdenum target is placed via a supporter at the center of the mirror with a lower field. The target on the back is cooled by water and biased at a negative of -30 V$\sim$ -50 V. The molybdenum panel for neutralization is an ellipse of 40 mm × 50 mm, and makes an angle of 45° with the axis of the plasma generator. The projection of target panel on the plane perpendicular to the neutral beam is an ellipse of 40 mm × 35.4 mm. The section area of the neutral beam reflected by the target is amplified. The required beam diameter of $\phi 40$ mm may be achieved at the distance of 10 cm from the target.

In order to observe the glow from the plasma the observation window is set on the flank of the neutralizing chamber, and for the measurement of the plasma density and temperature the langmuir probe may be installed on the exit of the plasma source.

3 Experimental results

This facility was set at a vacuum chamber being pumped to 1×10^{-4} Pa. The oxygen gas flux was adjusted at $\sim$ 5 SCCM, the operating pressure was about 4×10^{-2} Pa. When adjusting the microwave power to $\sim$ 50 W, the discharge was triggered. When increasing the microwave power to 100 W and adjusting the oxygen flux, the discharge was able to proceed normally in the pressure range of 10^{-1} Pa $\sim$ 10^{-3} Pa. The plasma was finely confined by the magnetic field shown from the observation window.

The reflected magnitude of the oxygen atom beam from the target is proportional to the ion current received on the target surface. Therefore, to acquire a high ion current is crucial experimentally. The Fig. 3 and Fig. 4 show experiment data of the ion current as a function of the input microwave power and the operating pressure respectively. As shown in Fig. 3, when the input power reaches 100 W, the increase in ion current tends to be saturated. As shown in Fig. 4, when the pressure reaches 4×10^{-2} Pa, the ion current approaches to the maximum.

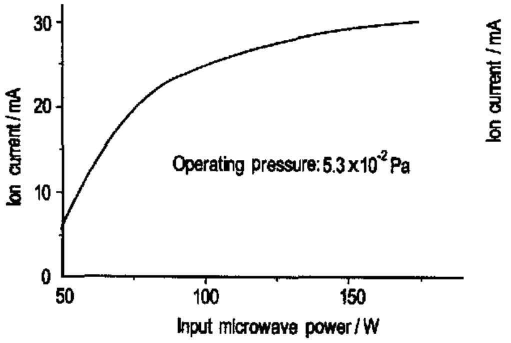

Fig.3 Dependence of the ion current on the microwave power

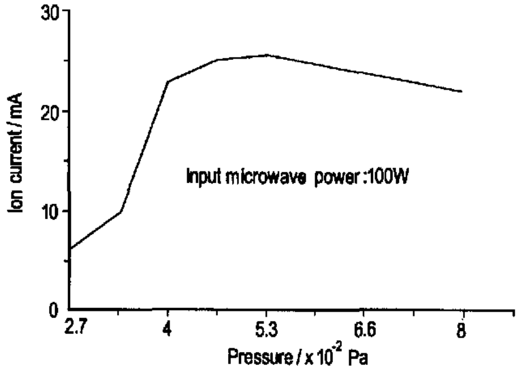

Fig.4 Dependence of the ion current on the operating pressure

The averaged plasma density near to the target surface may be estimated by the ion current being received according to the following basic formula:

$$n_e = J_i/e_0 \cdot \bar{v_i} \tag{1}$$

or

$$n_e = j_i/c \cdot e_0 \cdot \sqrt{2kT_e/m_i}. \tag{2}$$

At the microwave of 100 W and the pressure of 4.0 × 10^{-4} Pa the ion current density is about 2 mA / cm^2, thus plasma density is of the order of 1×10^{10} cm^{-3}. On the area where the plasma is produced, is higher than that mentioned above.

The atomic-oxygen beams were irradiated on a ϕ40 mm thick polyamide-imide film to study their intensity and erosion level. Two erosion tests were performed: one film placed 78 mm from the target was irradiated for 16 hours; the other film placed 100 mm from the target was irradiated for 10 hours. Their erosion amounts are 11 mg and 5 mg respectively. The formula for the calculation of the oxygen atom flux density is as follows:

$$f = \Delta W/\rho \cdot \sigma \cdot s \cdot t, \tag{3}$$

where, ρ is the mass of the film, s is the area to be irradiated, t is the radiating time, σ (3×10^{-24}cm^3 /atom)[5] is the erosion coefficient of polyamide-imide by oxygen. For the above two erosion experiments the average flux density of atomic-oxygen beam is ~ 3.6 × 10^{15} atom/cm^2·s and 2.63 × 10^{15} atom/cm^2·s respectively.

In the optical emission spectrum measurement of the plasma source the center electric conductor coupling RF power was used, the measured $O^+ >> O_2^+$ shows that there have been dominant oxygen ions in atomic state. Therefore the beam particle produced by neutralization is dominantly the oxygenic atom [1]. The experiment shows that the operating pressure of the ECR discharge used in this paper is lower than that of the RF discharge above, accordingly the ionizing degree of ECR plasma is higher, and so the atomic part in the neutral beam produced by ECR plasma is also higher.

4 Conclusions

By utilizing the principle of transmitting and coupling microwave coaxially, and the permanent magnets to produce asymmetric magnetic mirror, a compact atomic-oxygen beam source was developed. This device has a higher flux density, a lower operating pressure, a smaller power consumption, and a lower cost. When it was installed at the equipment for the investigation of space craft material, the experimental results show that the beam flux density might reach 3.0×10^{15} atom/cm^2·s, the operating stability is quite well, and the investigation on the interaction of the atom beam with the material surface can be carried out more easily.

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