Preliminary Study of an ECR Discharge Hall Thruster

*Pedro MOLINA-MORALES , † Hitoshi KUNINAKA , ‡ Kyoichiro TOKI
Institute of Space and Astronautical Science (ISAS)
3-1-1 Yoshinodai, Sagamihara, Kanagawa, 229-8510, Japan

‡ Yoshihiro ARAKAWA
Department of Aeronautics and Astronautics, University of Tokyo,
7-3-1 Hongo, Bunkyo-ku, Tokyo 113-8656, Japan

molinamorales@al.t.u-tokyo.ac.jp

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Abstract

A novel type of Hall thruster featuring plasma generated by electromagnetic waves of various types is being investigated at ISAS. A Hall stage with a non-conventional downstream magnetic circuit has been designed for use with a variety of non-traditional plasma production devices, including ECR, microwave cavity, and RF plasma sources. Aiming to apply the expertise acquired by ISAS over the last decade on ECR discharge electric thrusters, a Hall region has been attached initially to the downstream side of an ECR ionization stage. As partly expected, the experimental results show that the low plasma density (<3×10^{11} cm^{-3}) and the undesirable magnetic field interference are responsible for the lack of optimum interaction once the plasma enters the Hall current region. However, these problems are being circumvented by the use of a microwave cavity yielding plasma densities of up to at least 1×10^{13} cm^{-3}. Such device has already been successfully tested for immediate use as the plasma source for the new microwave Hall thruster configuration.

Introduction

Research on Hall thrusters with closed electron drift was initiated independently in both the US and the former Soviet Union in the early 1960s. These devices derived from ongoing work on magnetrons and other cross-field plasma sources. The earliest published description of a device closely resembling its modern progenies appeared in 1962 in the Bulletin of the American Physical Society [1,2,3]. However, while in the 1970s the US electric propulsion program shifted its efforts other thruster types, Hall accelerator research continued in the former USSR [4], leading up to the presently well-known SPT and TAL devices.
Incidentally, it was during that same decade that a Hall thruster with a radio-frequency ionization stage was first investigated. Morozov et al. [5] studied the effect of RF ionization of hydrogen inside a two-stage Hall accelerator, and concluded that the displacement of the ionization region towards the anode leads to an increase in ion energy, as well as to a reduction in exhaust beam divergence. However, the irradiation frequency was less than the plasma frequency, which in their device may have been the reason obtaining insufficient effect from the interaction of the irradiation with the plasma.[6].
More recently, Yashnov et al. [7] have suggested the development of a Hall thruster which behaves as a magnetron, with the azimuthal current exciting a wave in an azimuthal closed resonator block located near the channel walls. This wave, being excited in the resonator block, would penetrate freely through the channel walls in the accelerating channel. Electrons

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* Arakawa Lab member, University of Tokyo
† Associate Professor, Member AIAA/JSASS
‡ Professor, Member AIAA/JSASS

would then amplify the wave but would not be dissipated in the channel walls and, as they lose their energy, electrons would move without collisions towards the anode.

The approach adopted in this work is mainly experimental and makes as much use as possible of readily available hardware for preliminary assessment purposes. A cost-driven design of a simple yet versatile Hall current region, to be attached to the downstream part of various microwave ionization sources, is introduced in the first section of this work. Next, basic experimental results, for which the Hall region is attached to the downstream part of an existing ECR ionization source, are presented. Such results reveal the need for a ionization stage producing a plasma of higher density, which lead to the microwave cavity plasma source considered in the third and last section.

1. Design of the Hall Current Region

In a two-stage device, the Hall stage plays two main roles: 1) the creation of transverse magnetic fields to impede the flow of electrons upstream to the ionization stage (or anode); 2) the removal of the space-charge limitation on the current flow. It is suggested by Yashnov [7] that such stage may also promote further ionization.

The soft iron Hall stage used in this research is shown in Fig. 1.1 and features the usage of Samarium Cobalt permanent magnets in order to produce a radial magnetic field. It can be seen that the magnetic circuit runs downstream instead of upstream of the ionization region. Although this geometry may not be the most satisfactory, it has been chosen for the time being in order to facilitate the readily attachment and testing of the Hall stage together with a variety of electromagnetic wave plasma sources.

The scaling was accomplished using a combination of empirical laws [8], as well as comparison with existing coaxial SPT-type Hall thrusters, together with the physical considerations described later in this section. This device has the following characteristics:

1. Relatively adjustable Magnetic field (100～1000G)
2. Non-adjustable acceleration channel length.
3. Adjustable separating distance between the ionization region and acceleration region.
4. Overall diameter of Hall region cylinder: 150 mm.

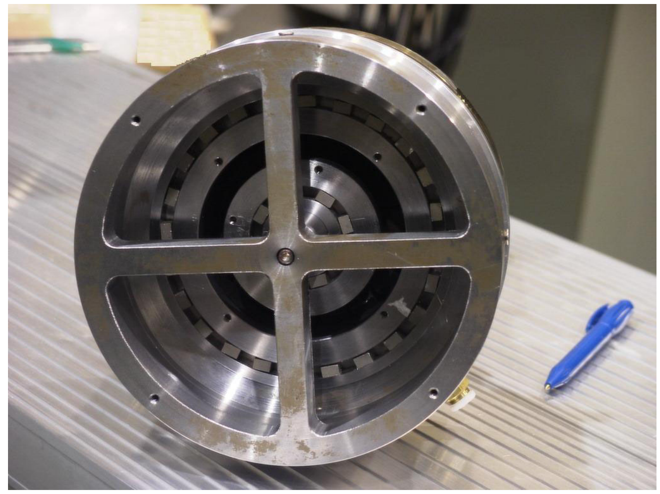

Fig. 1.1 Front view of Hall stage (no ceramics)

An acceleration channel of similar characteristics to the ones of a typical SPT thruster was chosen. Clearly, the larger the discharge chamber and the acceleration region, the more accessible it will be for internal diagnostic purposes. In addition, ceramic walls were used, so as to obtain a smoother and more extended ion acceleration zone, and to provide a more benign environment to carry out diagnostics.

Channel Length

In order for the electron Hall current to be established, the strength of the magnetic field must be such that electrons are trapped within the channel while the ions are allowed to escape downstream. This is ensured by having the length of the discharge region, L, greater than the electron Larmor radius, r_{ec}, and much less than the ion Larmor radius, r_{ic},

$$r_{ec} < L << r_{ic} \tag{1}$$

which may also be written as,

$$\sqrt{\frac{2m_e V_d}{e}} < BL << \sqrt{\frac{2m_i V_d}{q_i e}} \tag{2}$$

where m_e and m_i are the electron and ion masses respectively, V_d is the discharge voltage, B is the average magnetic field, L is the Hall region channel length, e is the electron charge and q_i is the ion unit charge. Since a configuration employing permanent magnets available at fixed sizes was adopted, the length of the Hall channel was dictated partly by this magnet size limitation. However, comparison with channel lengths in existing SPT-type Hall thrusters indicated that a value of 13-mm long and a 6-mm wide channel would be reasonable.

Magnetic Field

The shape of the magnetic field controls the ion trajectories. In traditional Hall thrusters, experiments [4] have shown that the magnetic field between the anode and the location with maximum magnetic field strength, B_{max}, should have a nearly radial field direction at the mean diameter of the discharge chamber. An additional desirable feature for the magnetic field would be a continuous increase in magnetic field strength from the anode to the location of maximum strength near the exhaust plane. In the present Hall stage, the magnetic field profile calculated with Quickfield[TM] is shown in Fig. 1.2.

The magnetic field strength in this device remains basically constant in the axial direction, which may not be the most optimum case but certainly more desirable than having dB/dz<0, as indicated by Morozov [9]. (z- is the downstream axial direction)

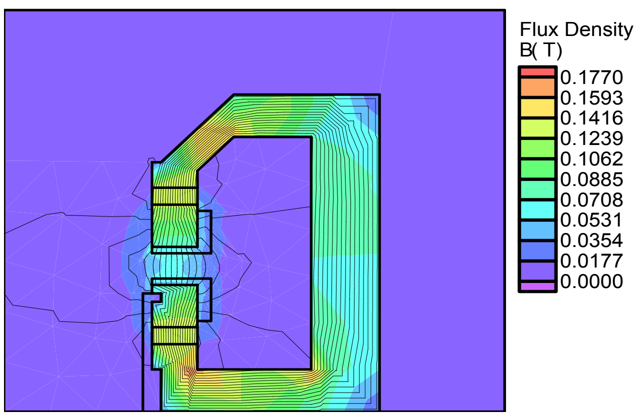

Fig. 1.2 Hall region magnetic field contours

2. Hall Current Region with ECR Ionization Stage

Description of the ECR Plasma Source

The so-called Yoshino-IV ECR ionization source is a precursor of the ECR ion engine aboard the MUSES-C interplanetary probe, scheduled to be launched next year by ISAS. As its name indicates, a plasma is generated based on the Electron Cyclotron Resonance (ECR) effect. Microwave power excites a right-hand circularly polarized wave, which propagates to a resonance zone for which,

$$\omega = \omega_{ce} \tag{3}$$

A snapshot of one of the available ECR ionization stages -without the downstream Hall stage- is shown in Fig. 2.1. The microwave power is amplified to several tens of watts and fed in through a coaxial cable into a circular waveguide, which leads to a discharge chamber where the SmCo magnets are positioned forming two annular rings. Details concerning this ionization source are given in ref. [10]. The ECR layer, where most of the plasma generation takes place, appears in the region right ahead of those magnets.

Fig. 2.1 ECR Plasma source

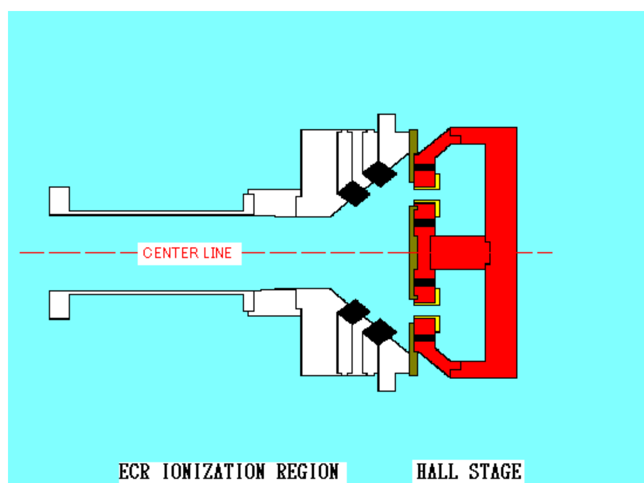

Fig. 2.2 ECR Hall thruster (sectional view)

Description of the ECR stage + Hall stage device

A schematic sectional view is shown in Fig. 2.2. The Hall channel has been brought right next to the ECR ionization region, which is the region in front of the large ECR permanent magnets. In this thruster arrangement, these ECR magnets are at an angle of

approximately 45 degrees with respect to the axisymmetric line, as seen in the same figure.
The necessity for having the magnetic circuit passing through the downstream of the exhaust is also apparent, as this geometry is also the only reasonable way to hold the inner cylinder supporting the inner annular wall of the channel.

Preliminary Considerations

The availability of an ECR ion source has presented a good chance to check following conjectures.

1. ECR Plasma Density

The plasma density produced by the Yoshino-IV ECR ionization stage is lower, by up to one order of magnitude, than the density inside the channel of conventional SPT thrusters, as given in refs. [11, 12, 13]. Assuming an ExB drift velocity for electrons, the electron Hall current per unit radius, J_H, can be written as follows[4],

$$J_H \approx en_e \int_0^L \left(\frac{E}{B}\right) dz \approx en_e \frac{V_d}{B} \qquad (4)$$

Considering quasi-neutrality, from this expression above it is seen that the amount of electron Hall current will decrease in proportion to the plasma density. Accordingly, for the ECR plasma density range, it may be suspected that such low density will not promote a significant a mount of azimuthal electron Hall current. As for the occurrence of additional ionization of neutrals in the Hall current region, from basic plasma theory it is well-known that in this case the plasma density is inversely proportional to the characteristic ionization time. This brings out the possibility that the thermal escape time for remaining neutral xenon atoms may be shorter than the characteristic ionization time in the Hall region. This would result in little or no additional ionization - in the sense suggested in ref. [7]- taking place in the Hall region.

2. Magnetic field interactions

The magnetic field inside of the ionization stage is dictated by the following expression [14],

$$B = f_{ce}/2.8 \qquad (5)$$

where B is the static magnetic field in kG at the ECR region and f_{ce} is the frequency of the wave generator in GHz. For a 4.25 GHz signal, the optimum magnetic field for electron cyclotron resonance to occur is approximately 1500 G. It can be expected that such a high magnetic field value upstream of the Hall region should interact rather strongly with the magnetic field inside of the Hall stage, as hinted in the axisymmetric calculation results for the joint ionization stage and Hall stage configuration shown in Fig. 2.3.

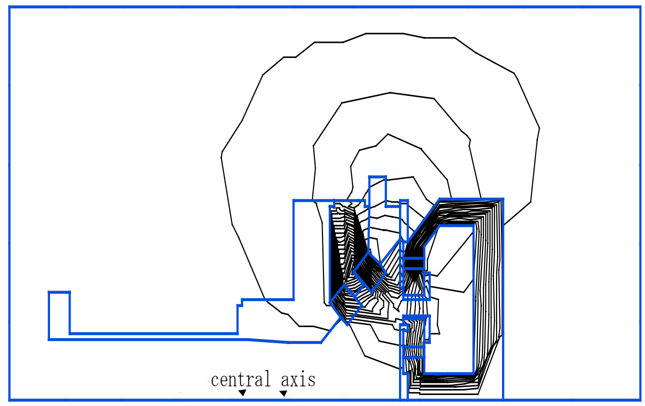

Fig. 2.3 Ionization stage and Hall stage magnetic interaction (Quickfield™)

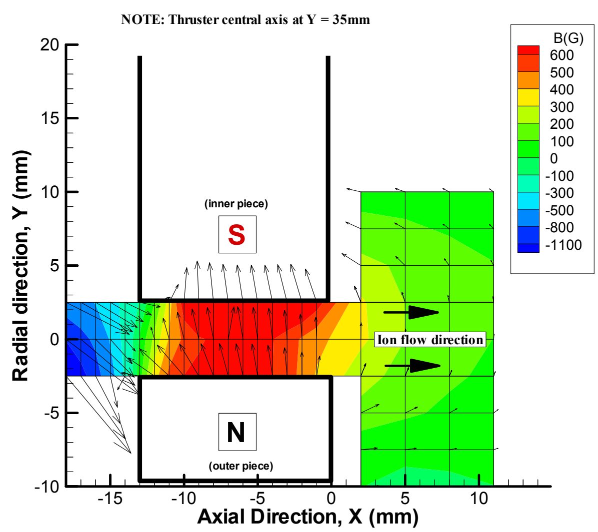

Fig. 2.4 Ionization stage and Hall stage magnetic field (Measured with a Hall probe)

Furthermore, magnetic field measurements obtained with a Hall probe are shown in Fig. 2.4 corroborate the existence of undesirable magnetic field line directions and very high magnetic strength levels in the immediate vicinity of the Hall stage annular inlet. In both calculation and the Hall probe measurements, the magnetic pole directions were inverted and the magnetic field strength was adjusted to different values. After doing so, it was concluded that this interaction could be neither diminished nor channeled to contribute favorably to the Hall acceleration channel magnetic field.

3. Cut-off density

There is a cut-off density value above which the density cannot proceed. As an illustrative example, if we attempt to propagate a plane monochromative wave through the plasma medium, the solutions to the wave equation will be of the form

$$e^{i(kz-\omega t)} \tag{6}$$

where

$$k = \omega / v_p \tag{7}$$

is the wave number, and

$$v_p = 1 \Big/ (\mu_0 \varepsilon)^{\frac{1}{2}} \tag{8}$$

is the velocity of propagation in the plasma. Obviously, as long as $\varepsilon = \varepsilon_0 \left(1 - \omega_p^2 / \omega^2\right)$ is positive, v_p will be real and plane electromagnetic waves can propagate. [14]. However, if ε is negative, v_p and k will be imaginary and propagating solutions will not exist. Since ω_p^2 is proportional to the plasma density, if the density is increased gradually, a point will be reached where $\omega_p^2 / \omega^2 > 1$ and the propagation will be cut-off.

For the 4.25 GHz signal used in our ECR plasma source, the cut-off density is approximately 2.2x10^{11} cm^{-3}. Therefore, mass flow rate levels of typical Hall thrusters cannot be used when operating our ECR device at the given microwave frequency.

In fact, should we desire to obtain higher plasma densities via ECR ionization, a higher magnetic field for the correspondingly higher input microwave frequency would be required, creating extremely high magnetic fields in the ionization region which would interact very unfavorably with the Hall stage magnetic field.

Experimental Results

Tests were performed using a sub-chamber of the ISAS Endurance Test vacuum tank, with an operating at a vacuum pressure of around 5 x 10^{-6} Torr. In the first experiment, a filament cathode was attached to the downstream side of the Hall stage.

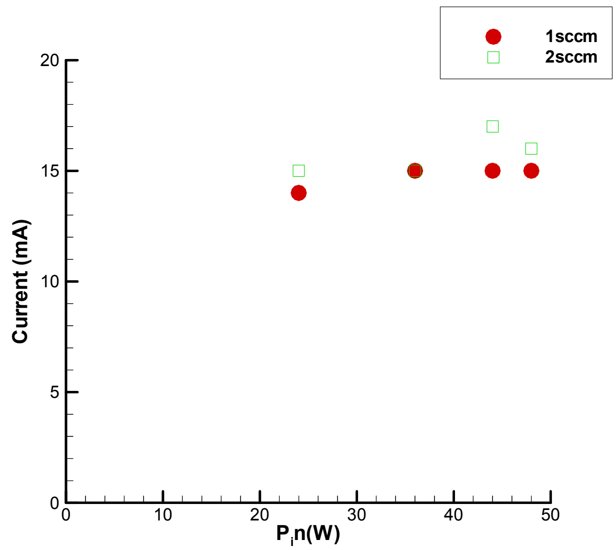

Fig. 2.5 Current vs. Input power

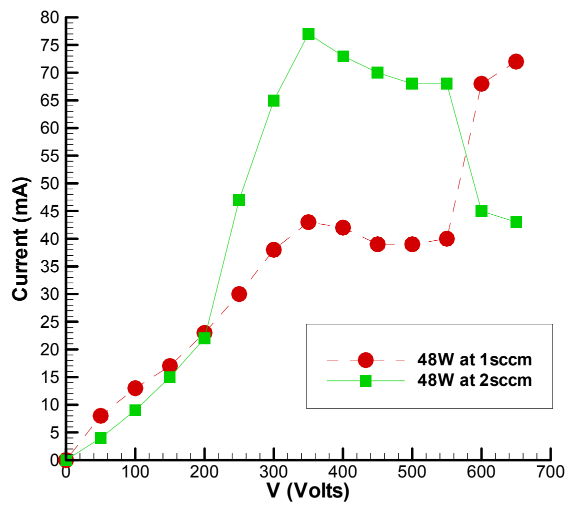

Fig. 2.6 Measured-current vs. voltage difference

The Hall stage was attached to the ionization stage and a minimum number of permanent magnets was adopted. The microwave input power was varied from 27 up to 48 W, yielding up to only 17 mA of extracted current (Fig. 2.5). Subsequently, the number of permanent magnets and their polarity was varied for a number of cases. However, the same poor performance was obtained.

Although the previous results substantiated the existence of low plasma interaction in the Hall stage channel, an additional run was carried out placing a microwave neutralizer farther downstream. In such configuration a small number of magnets, providing a magnetic field of 50 to 100 G inside of the channel, was investigated. With this set-up, the voltage difference-extracted current variation is shown in Fig. 2.6. Even though these results may seem slightly promising, taking into account the very low operating mass flow rate levels, the need for a microwave neutralizer to obtain some reasonable amount of extracted current is considered to be too large an overall efficiency penalty to pay for such a low performance.

3. Microwave Cavity Ionization Stage

The results presented in the previous section substantiate the preliminary theoretical considerations and lead the way to an ionization stage which produces a higher density plasma and requires no applied magnetic fields for its operation. Such device is introduced here.

Description of the Plasma Source

In this device, the microwave power is transmitted through a rectangular waveguide to a cylindrical cavity of 208 mm in diameter, in which a standing wave is generated. A cut-off view of the cavity is shown in Fig. 3.1.

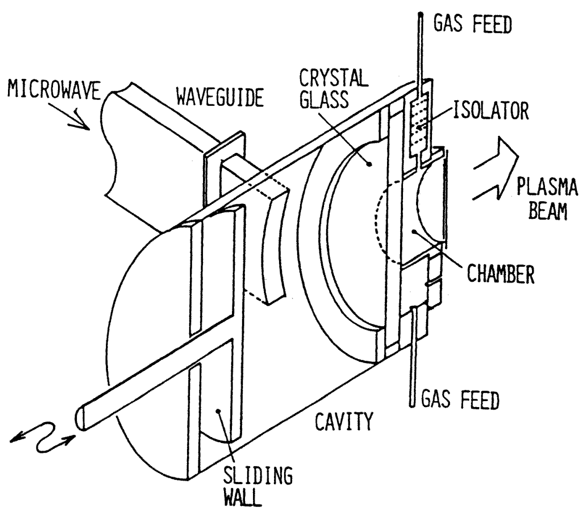

Fig. 3.1 Cut-off view of microwave cavity

The microwave penetrates into the discharge chamber separated from the cavity by a quartz window and a plasma is produced at this chamber by off-resonance absorption at the plasma cut-off. Xenon is the operating gas and the gas is supplied through a cascaded isolator, so as to prevent breakdown. It is worthwhile noting that in this case the plasma frequency is higher than the input microwave frequency [50]. That is,

$$\omega_p = \omega_{RF} \tag{9}$$

Therefore, it is generally stipulated that the plasma is overdense.

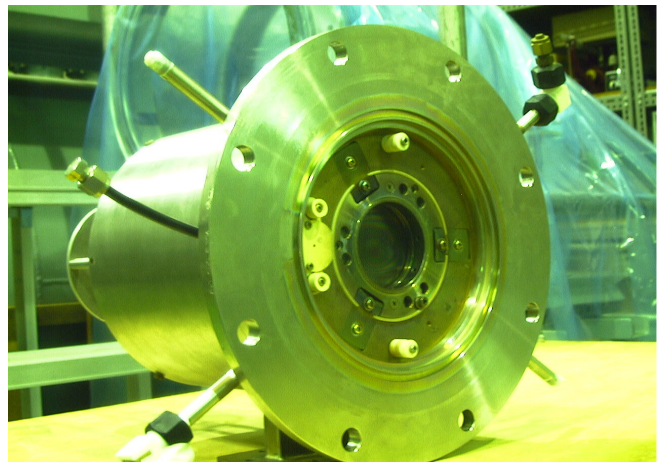

Fig. 3.2 Microwave cavity snapshop

The actual plasma source is shown in Fig. 3.2. A plunger placed in the rear side of the cavity provides the impedance tuning required to minimize reflected power. A disk-shaped quartz glass keeps the working gas in the region where the microwave fields produce a disk shaped plasma.

Experimental Results

All experiments were carried out in a 2.8x1.5m vacuum chamber, providing 3×10^{-4} Torr of vacuum pressure. A 2.45Ghz microwave was generated by a continuous-wave magnetron. The maximum output power was 1.5 kW. Coupling between the magnetron and the plasma source was adjusted by changing the inductive aperture, inserted into the waveguide, as well as by adjusting the plunger location. Both input power and reflected power were monitored via a directional coupler. A snapshot of the plasma generated by the microwave cavity -with a current-collecting grid attached downstream of the discharge chamber- is shown in Fig. 3.3.

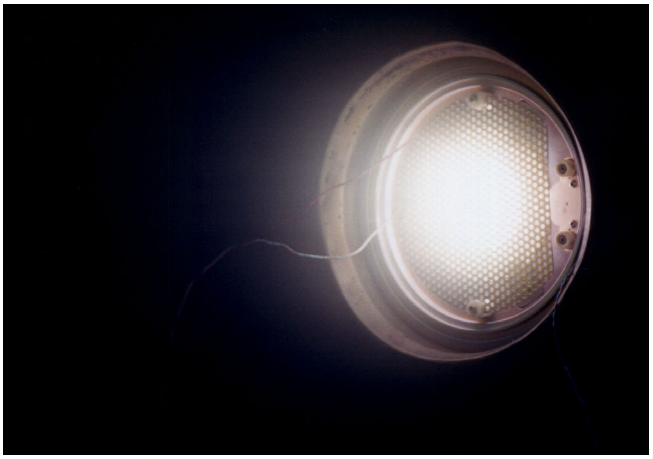

Fig. 3.3 Plasma snapshot (produced by microwave cavity with extracting grid)

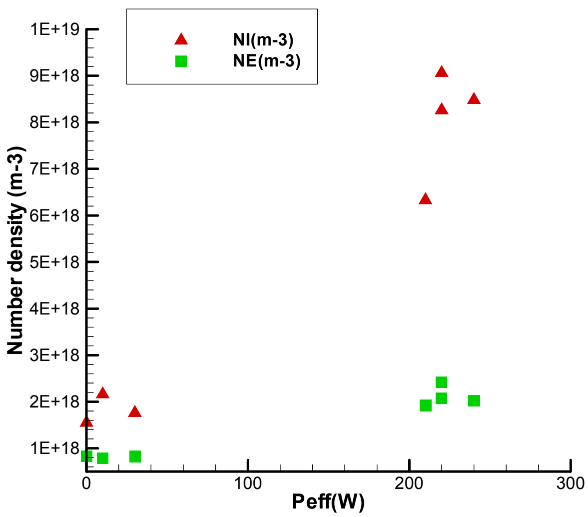

Fig. 3.4 Number density variation with eff power (14sccm)

Electron and ion number density values are shown for different operational settings. The effective power is defined as the input microwave power minus the reflected power. In the first case, shown in Fig. 3.4, the input power was varied from 300W up to 750W maintaining the Xenon mass flow rate at a constant value of 14 sccm. In contrast with the previous results with ECR plasmas (1×10^{16} to 2×10^{17} m^{-3}), relatively high plasma density values have been obtained with the cavity. Such density is of at least the same order as that existing inside a traditional Hall thruster.
Comparing the effective power values with the net input power levels, it is apparent that there is a large amount of reflected power when operating this device. Optimization of impedance mismatching of the different parts of the system is the way to keep power losses to a minimum. However, at this stage, production of a higher density plasma is the primary goal. Once the favorable interaction of higher density microwave plasma and the Hall region is observed, optimization of the overall system in order to reduce efficiency losses should be the natural step.

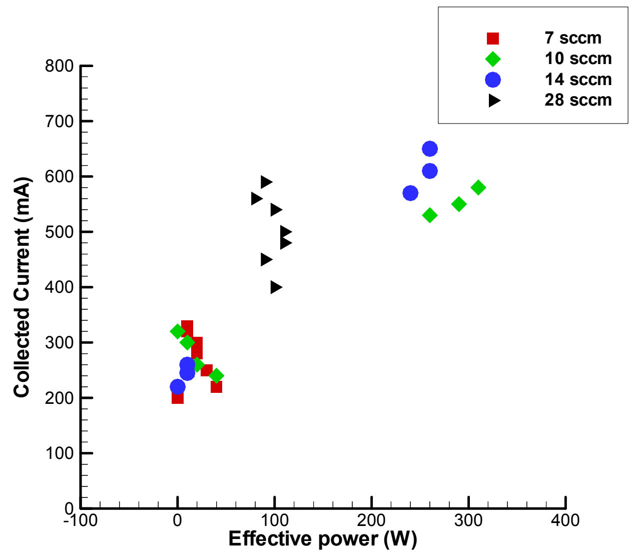

Fig. 3.5 Collected current vs. effective power

Later, a collecting grid made up of punching metal was attached downstream of the cavity discharge chamber, and was biased at –50V with respect to the inside of the discharge. The system was operated cavity at four different mass flow rate settings, and values of the current collected by the grid are shown in Fig. 3.5 against the effective microwave power. A 14 sccm mass flow rate and an input power level of 750W was found to be the optimum setting yielding higher extracted current values and lower reflected powers. The highest collected current value obtained in the 14 sccm case was around 700 mA.
Given that the cross-sectional area of the quartz glass is 2827mm^2 and the cross-sectional area of the Hall current region is 1278 mm^2, should we attach an annular 1278 mm^2 opening downstream of the Quartz glass, we can roughly estimate a generated current of around 350 mA, not taking into account Hall processes yet.

Conclusions

Two electromagnetic wave ion source types have been investigated for joint operation with a downstream Hall current stage. First, the incompatibility of an ECR plasma source with a Hall current stage has been verified experimentally, due the low plasma density and irreconcilable magnetic field requirements for both stages.

However, a microwave cavity has been tested successfully and is at the present time being modified in order to accommodate the Hall current stage introduced in the first section of this work. This plasma source provides a plasma of optimum characteristics for effective interaction with the azimuthal Hall current, and should enable a greater understanding of the physical processes involved in a microwave-fed Hall device.

Once the Hall stage and the microwave cavity source compatibility is realized, a Hall stage with solenoidal coils and a more conventional magnetic circuit configuration will be adopted.

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