MICROWAVE HALL THRUSTER DEVELOPMENT

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Abstract

Design and operation of the first documented microwave-discharge Hall thruster has been achieved. Although permanent magnets are known to limit the control over the magnetic field strength, reasonable performance levels have been obtained using SmCo magnets instead of solenoidal coils. Of the two prototypes that have been built, results for the so-called Prototype II in its short-channel configuration are presented. Two operational modes were identified. Also, an increase of up to 15% in acceleration efficiency was achieved when operating in microwave mode with xenon, when compared to DC mode operation. From single probe measurements, two zones with relatively high for electron temperature and density were found in the vicinity of the anode as well as in the middle of the channel. This suggests the existence of two ion production zones, one due to microwave power and another due to azimuthal electron current. Reduction in low frequency oscillations was observed when microwave power was launched. Also, in order to clarify the characteristics of the upstream evanescence region, an estimated range for microwave penetration lengths based on cold-plasma theory is given.

INTRODUCTION

The idea of employing a radio-frequency ionization stage was first investigated by Morozov et al. [1], who 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. To this respect, Yashnov [2] pointed out that the probable reason for the insufficient effect from the interaction of electromagnetic irradiation with the plasma in Morozov's device was that the irradiation frequency was less than the plasma frequency.

The concept of a microwave Hall thruster was first investigated by Horiuchi at ISAS in 1989, and although he built the corresponding ionization stage, a full Hall thruster prototype was not implemented. More

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recently, Yashnov [2] has proposed the usage of microwave irradiation in a Hall thruster channel, hoping to reduce the electron current emitted form the cathode and to increase the overall thruster efficiency.

As it is well known, in the case of the more conventional single-stage Hall thruster electrons emitted by a downstream cathode backstream toward the anode through an applied magnetic field. As these electrons diffuse upstream, they collide with the neutral particles injected from the anode. The electric field then accelerates ions toward the exit plane of the thruster. Accordingly, the same source of electrons is used for both ionization and acceleration of the ionized propellant and very limited control is achieved over the ionization process, since it is very strongly coupled to the acceleration process. A result of this coupling is that typical single-stage Hall thrusters have a relatively small operating range over which efficient operation can be maintained, in particular at specific impulse values lower than 1400 s.

In this research, in an effort to gain greater control over the ionization process, a microwave signal has been inserted near the thruster anode of a two-stage microwave Hall thruster. The effect of microwave insertion on the operating range as well on basic performance parameters is discussed, and results are given for the Prototype II microwave Hall thruster in its short-channel configuration.

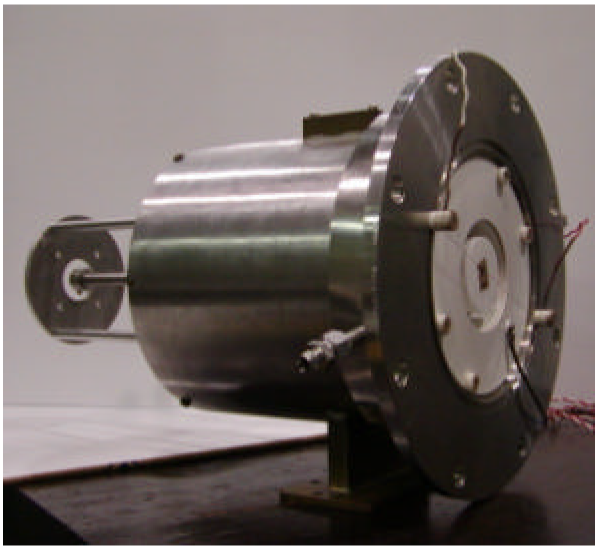

Fig. 1: Microwave Hall thruster: Prototype II

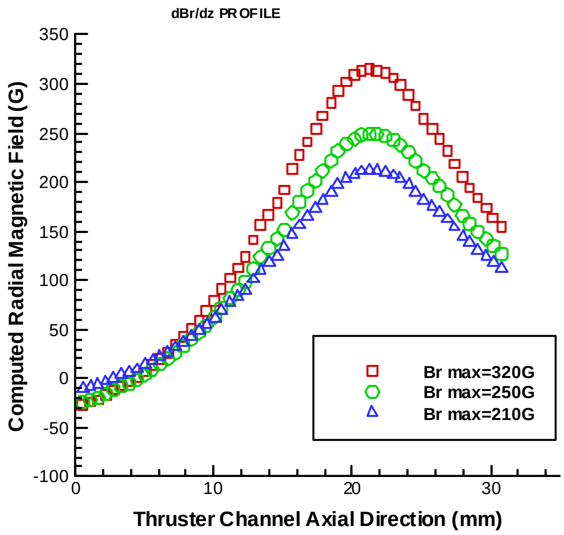

Fig. 2: Calculated radial magnetic field along the central axis of accelerating channel.

PROTOTYPE II

Description

The short-channel configuration of this thruster (Fig. 1) features the usage of SmCo magnets for the creation of a magnetic field in the acceleration channel. A resonant cavity made out of brass, with an inner diameter of 20.8 cm, is attached to the Hall stage. A 2-cm thick quartz glass acts as the interface between the microwave system and discharge channel (in effect, the Hall stage). Design guidelines are summarized below:

a) Optimized magnetic field profile with lower radial magnetic field values at the anode vicinity and higher values at the channel exit. (refer to Fig. 2)

b) Proper propellant injection with a larger number of apertures than in previous prototypes.

c) Larger channel size (width>10mm & length>15mm).

d) Modularity and adaptability for minor changes in configuration (e.g., for operation inside of the chamber instead of attached to the chamber wall)

A cross-sectional view is shown in Fig. 3. Concerning the permanent magnets, the magnetic field profile created along the acceleration channel can be varied "discreetly." The adoption of SmCo magnets of two different sizes for the inner and outer poles allows greater control over the magnetic field strength. The larger outer magnets (10 x 6.5 x 4 mm), providing a maximum magnetic field strength of 3.2 kG at the magnet surface of each piece, were attached surrounding the outer cavity walls of the thruster and forming a sort "magnet ring." The inner magnets are of size 4 x 4 x 2 mm, each of them providing a maximum magnetic field strength of 2.6 kG at the magnet surface. These are located in the inner core of the thruster and are lined up concentrically. Up to four magnet rings can be placed inside of the inner core. Magnetic field contours from FE analysis of the chosen geometry are shown in Fig. 4.

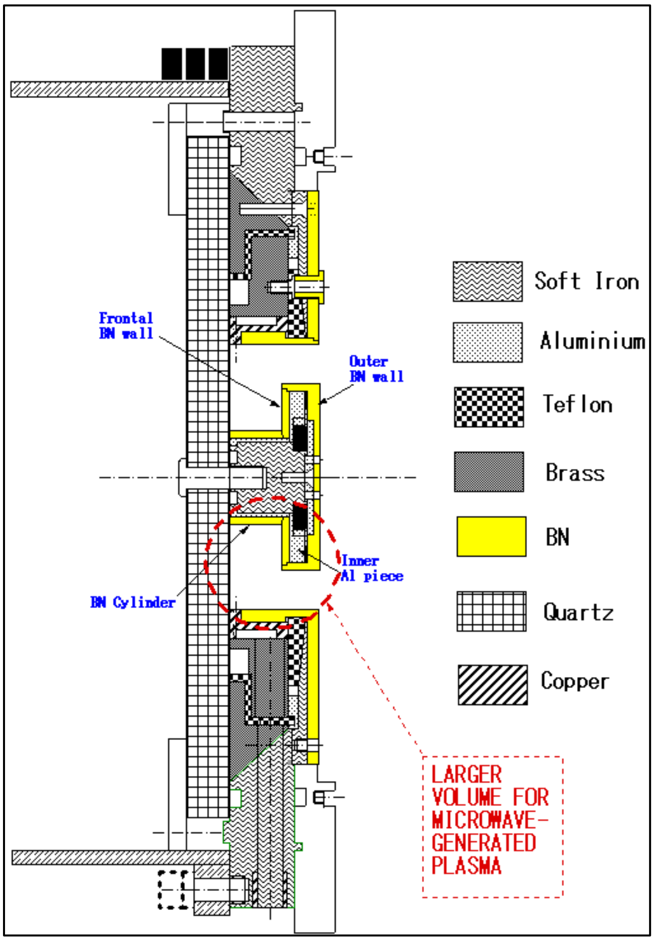

Fig. 3: Cross-sectional view (short-channel Prototype II)

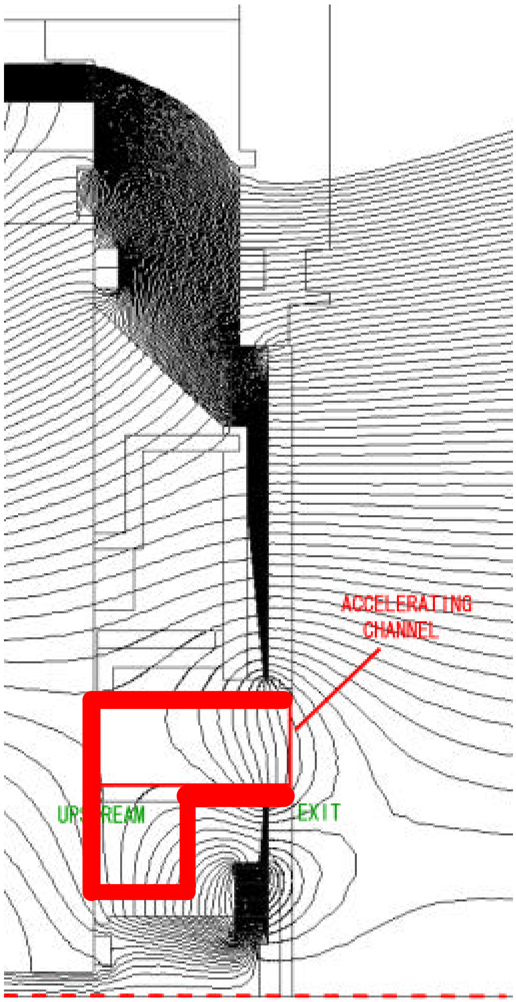

Fig. 4: Axisymmetric Cross-sectional view

By adjusting the number of the larger magnets –located outside the chamber and thus under atmospheric conditions- the magnetic field strength in the channel can be adjusted from 100G up to 500G approximately during thruster operation. Two soft iron pieces, ending in a sort of "spoke" end geometry in the region closer to the channel, were incorporated into the design. These pieces enable a magnetic field concentration peak of very similar characteristics to the ones exhibited in recent traditional Hall thrusters [3-5]. This way, readily adjustment of the B-field strength was achieved without the need to disassemble the whole thruster body.

Effect of Variation in Net Input Microwave Power

The overall experimental system is shown at the end of this paper. Prototype II in the short-channel configuration was operated at a vacuum pressure of 2.2 x 10^{-4} Torr for a 20 sccm mass flow rate of xenon. A 0.27 mm diam. thoriated tungsten wire was used as the cathode. Operation above 230V was not carried out for the cases with microwave launching due to the limitations of the main discharge power supply. A collector grid was placed at a distance of 35 cm from the thruster exit plane at a –50V potential. The net microwave power was increased and the generated ion current was collected. Pressure-correction for the collected beam current has not been made, since in this study we were primarily interested in the general trends for comparison between DC mode and microwave mode operation.

In the first experimental runs, it was found that when keeping the filament current constant at 7A, the insertion of microwave power to the DC discharge had little effect on xenon discharges. However, inserting microwave power and decreasing the filament current down to 6A provided notable changes. Since operation at 6A filament current was not possible without microwave launching: i) results for DC operation (no microwave power) involve a filament current setting of 7A; ii) results for microwave operation involve a filament current setting of 6A.

It is worthwhile to point out that operation at the lowest filament current setting possible is one of the motivations for the investigation of a microwave/2-stage Hall thruster.

Representative results for basic operational and performance parameters for the investigated operational modes follow. In a second study, instead of xenon, argon and nitrogen were employed as propellant gases, although such results will be reported in a future publication. In all cases the thruster was operated in microwave input mode and also in DC mode to enable comparison. The cavity resonance mode was set to TM_{011}.

Of the four net microwave input powers investigated (50W, 100W, 200W, 300W), discharge characteristics and basic performance parameters for the 300W net microwave power run are shown. The corresponding VI curves for the 300W case as well as for the DC mode case (normal operating mode in a traditional Hall thruster) are given in Fig. 5. In the microwave case, an increase in discharge current is exhibited as the discharge voltage increases, being followed by a flat region that leads to the electron saturation region. The extension of the operating range into the lower discharge voltage levels when inserting the microwave signal can be clearly seen.

When the microwave signal is launched, an increasing trend for ion production is exhibited. Experiments have also shown that as the microwave power is increased, this trend becomes more prominent. That in fact leads to an improvement in acceleration efficiency of up to 15%. As seen in Fig. 6, the acceleration efficiency reaches a minimum value of about 100V for the microwave case. Near such operating point there

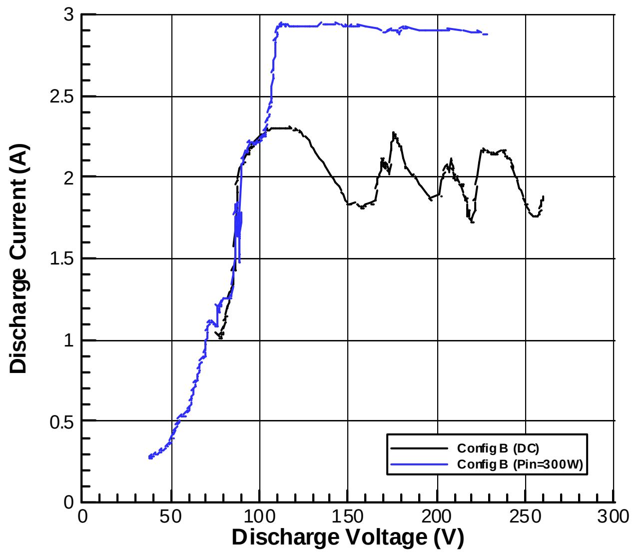

Fig. 5: VI curve for DC and microwave mode cases

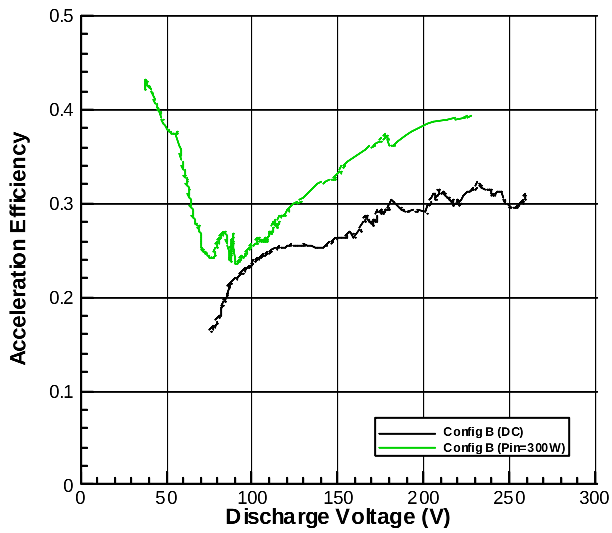

Fig. 6: Acceleration Efficiency

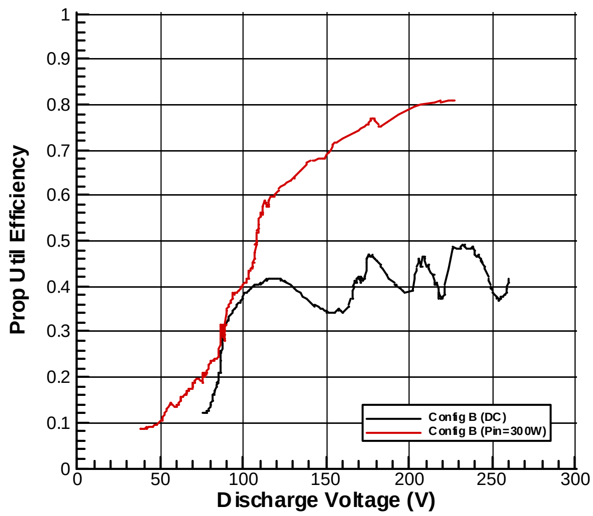

Fig. 7: Propellant Utilization Efficiency

is a shift from microwave-dominant mode into DC-dominant mode.

In the following figure, an increase in propellant utilization efficiency of up to 40% is observed with respect to the DC discharge case (Fig. 7). Incidentally, it is clear to the authors that the propellant utilization efficiencies of recent SPT-type Hall thrusters reach higher values, nearing 100%. However, it is emphasized that the initial purpose of this research is two investigate the effect of microwave insertion. Optimization is the natural next step.

Measured Plasma Properties

A single probe consisting of a 0.1 mm tungsten wire inside of a ceramic tube was employed. The discharge voltage was set at 200V and data was taken under three different operational modes: (i) no-microwave mode (DC mode), (ii) 100W input microwave power; and (iii) 300W input microwave power. Measurements were taken at seven axial locations along the midline of the acceleration channel.

The plasma potential is shown in Fig. 8. The upstream value of the potential is almost the same for all cases. A gradual decline is exhibited from the anode to a position about 15 mm downstream of it. Over the next 10 mm or so, the potential drops sharply. Microwave launching into the channel from upstream does not alter the plasma potential significantly. There is a tendency for the potential to fall more abruptly in the middle of the channel when the microwave signal is present, although the change is small and we can expect similar levels of ion acceleration whether the operating mode is DC or microwave.

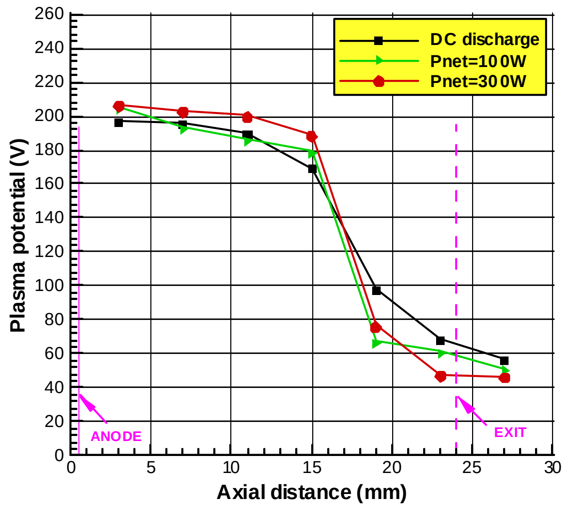

Fig. 8: Plasma potential variation along channel.
(DC mode, 100W & 300W μwave input mode)

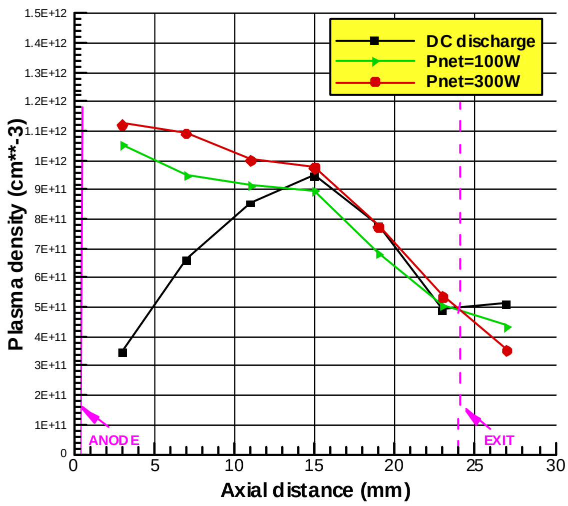

Fig. 9: Plasma density variation
(DC, 100Wμ & 300Wμ)

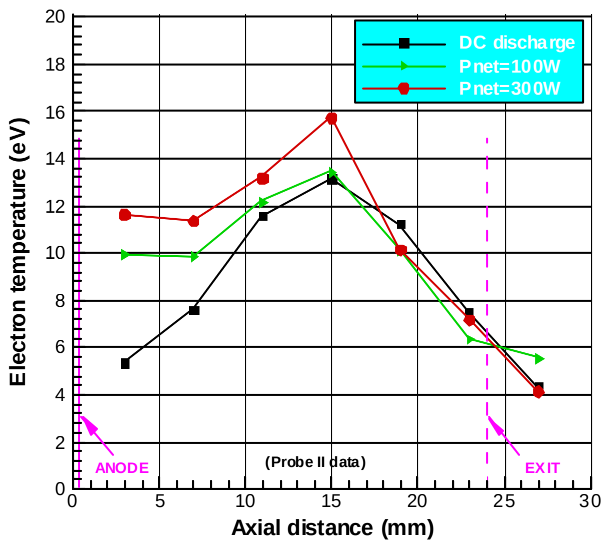

Fig. 10: Electron temperature variation
(DC, 100Wμ & 300Wμ)

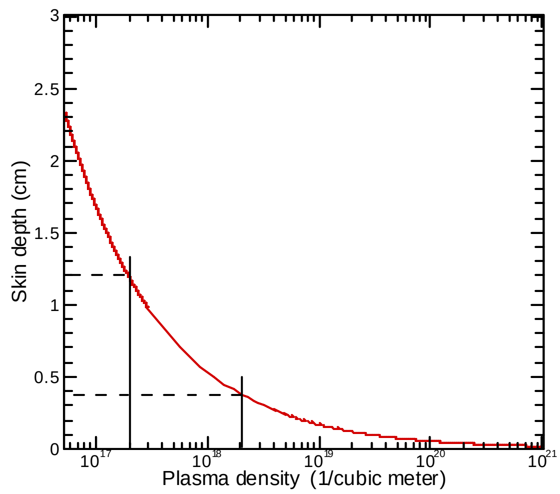

Fig. 11: Microwave penetration dependency on plasma density (Xe).

The plasma density variation is shown in Fig. 9. In the DC case, very low values have been measured near the anode, suggesting low levels of ionization in this region. Under DC operation, a peak in plasma density is present approx. 15 mm from the anode, due to the high levels in ion production at this region. A drop in density appears further downstream, where ions become accelerated. An expected feature in cases with microwave insertion is the existence of two plasma density peaks, one appearing at the vicinity of the anode and a second peak coinciding with the density peak for the DC case. Thus, for the microwave modes, the density reaches its highest level near the anode, dropping slightly and forms a sort of plateau before assuming a tendency similar to the DC case further downstream. The upstream density peak is seen to be proportional to the input microwave power, although the relation between these two parameters is not linearly proportional.

Electron temperature profiles are given in Fig. 10. For the DC case, the energy of the electrons initially increases as they enter the channel from downstream, reaching a peak approximately 10 mm from the channel exit. The azimuthal electron current is expected to be highest at this downstream part of the channel, where the static magnetic field is highest. The electron energy then starts to drop further downstream, where ionization levels are lower.

When microwave power is imparted, for both 100W and 300W, a similar tendency as for the DC mode is present in the downstream portion. However, a salient feature in the microwave cases is the maintenance of the electron temperature over the upstream part of the channel. A short electron energy plateau appears in the region right next to the location of the quartz glass, from which the microwave signal penetrates. This graph also corroborates the existence of two differentiated ionization regions along the channel when microwave power is present.

An analytical model for the skin depth (that is, the distance inside the thruster channel through which the microwave imparts a significant amount of energy to the electrons) based on the cold-plasma theory of Stix [6], was performed for a variety of propellants and under different operating conditions. Although details are not included herein due to space limitations, it was estimated that the microwave power is transferred to the electrons for a distance ranging from 0.5 to 1.5 cm downstream of the anode (Fig. 11).

All in all, experimental and analytical findings for the microwave launching case reveal the existence of an upstream region with enhanced ionization due to the heating of the electrons by the microwave, as well as the assumption of the basic characteristics of the typical Hall thruster plasmas in the downstream portion of the channel even in microwave power is present.

Effect of Microwave Launching on Ionization Oscillations

In SPT thrusters it is desirable to suppress low frequency oscillations, in particular when operation is not performed at the optimum magnetic field value. These oscillations are thought to be caused by ionization instabilities, due to the fact that the ionization front propagates irregularly in the discharge chamber. In this research, ionization oscillations were investigated. Presented figures cover the 10 kHz to 35 kHz frequency span. Results are shown for a 230V discharge voltage setting. Data was taken at three distinct operational modes: (i) no-microwave mode (DC mode), (ii) 100W input microwave power; and (iii) 300W input microwave power.

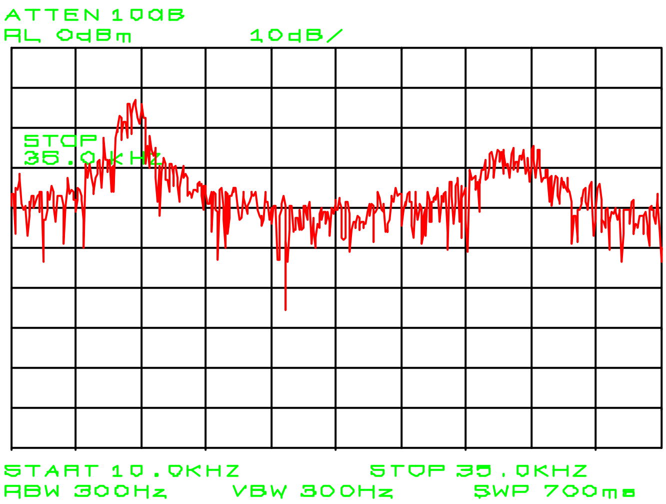

Fig. 12: Low frequency spectrum for thruster operation at DC mode (Discharge voltage= 230V)

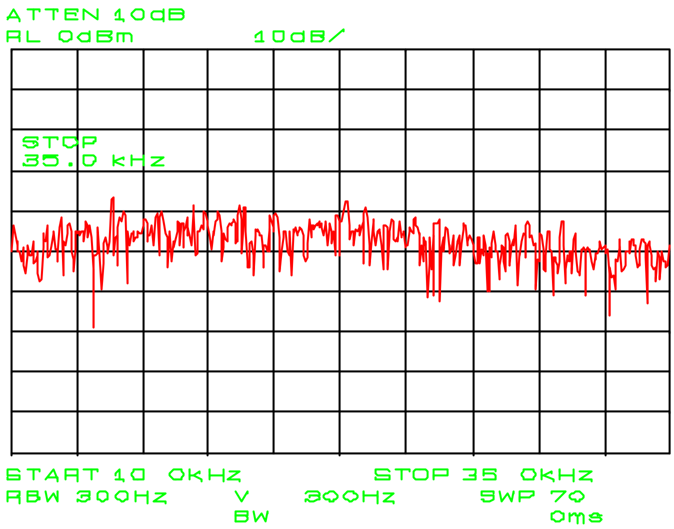

Fig. 13: Low frequency spectrum for thruster operation at **100W** (Discharge voltage= 230V)

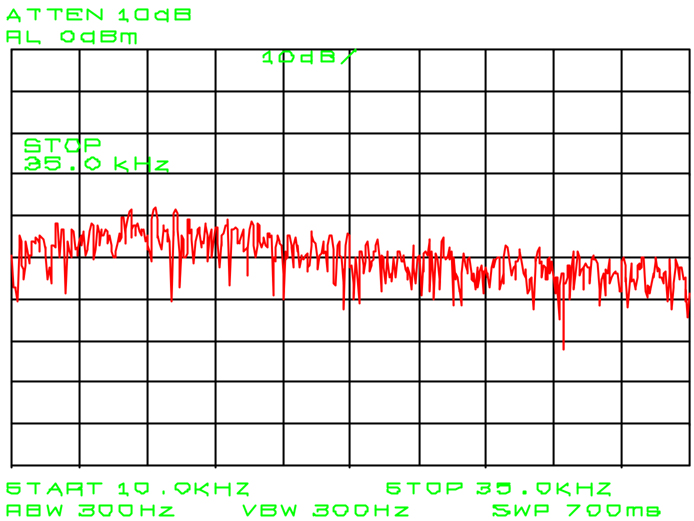

Fig. 14: Low frequency spectrum for thruster operation at **300W** (Discharge voltage= 230V)

For the DC mode, two peaks appear at 14.8 kHz and at 29.0 kHz, with the first peak being of slightly higher magnitude, as it can be seen in Fig. 12. When microwave was inserted, these peaks clearly disappear, even at 100W input microwave power, as the spectrum traces in Figs. 13 and 14 testify. At this point, care must be taken as to the nature of the oscillation suppression mechanism. Firstly, spectrum traces were taken under continuous thruster operation and keeping mass flow rate constant.

However, microwave operation involved a decrease in filament current down to 6A. As previously explained, operation at 6A filament current is not possible in DC mode, so a comparison oscillation traces for DC mode and microwave mode at a 6A filament current cannot be performed. Interestingly, when keeping the filament current at 7A, the insertion of microwave power is found to have little or no effect on the discharge oscillation spectrum.

To this respect, investigations for a traditional SPT thruster [7, 8] point out to low frequency oscillations being an instability caused by a periodic depletion and replenishment of the neutrals near the exit. Since the magnetic field in that region is large, the associated low electron conductivity leads to an increase in the electric field required to maintain current continuity.

The resulting enhanced ionization depletes the neutral density causing the downstream front of the neutral flow to move upstream into a region where the ionization rate is lower. Keeping in mind that low frequency oscillations being presently considered may be related to the shifting of the population of neutrals and electrons along the channel, the results presented herein suggest that the existence of an ionization region upstream and extending to the middle of the channel may be responsible for the reduction in the shifting of the neutral density along the axial direction, due to the change in ionization structure with microwave insertion, and in a drastic decrease in the intensity of the oscillations.

CONCLUSIONS

Design and operation of a microwave-discharge Hall thruster has been conducted. Although permanent magnets are known to limit the control over the magnetic field strength, reasonable performance levels have been obtained using SmCo magnets instead of solenoidal coils.

Launching microwave power into the acceleration channel of Prototype II has provided increases in acceleration and propellant utilization efficiency.

Langmuir probe measurements and an analytical model based on cold-plasma theory have revealed the existence of an upstream region with enhanced ionization due to the heating of the electrons by the microwave, as well as the adoption of the basic characteristics of the typical Hall thruster plasmas in the downstream portion of the channel even in microwave power is present. Accordingly, two ionization regions have been detected, characterized by relatively higher charged particle density as well as higher electron temperature levels.

In addition, this new plasma structure has been found to decrease the amplitude of ionization oscillations, even at low microwave input power levels. Optimization of the microwave Hall thruster geometry will be performed in future studies in order to attain higher efficiencies.

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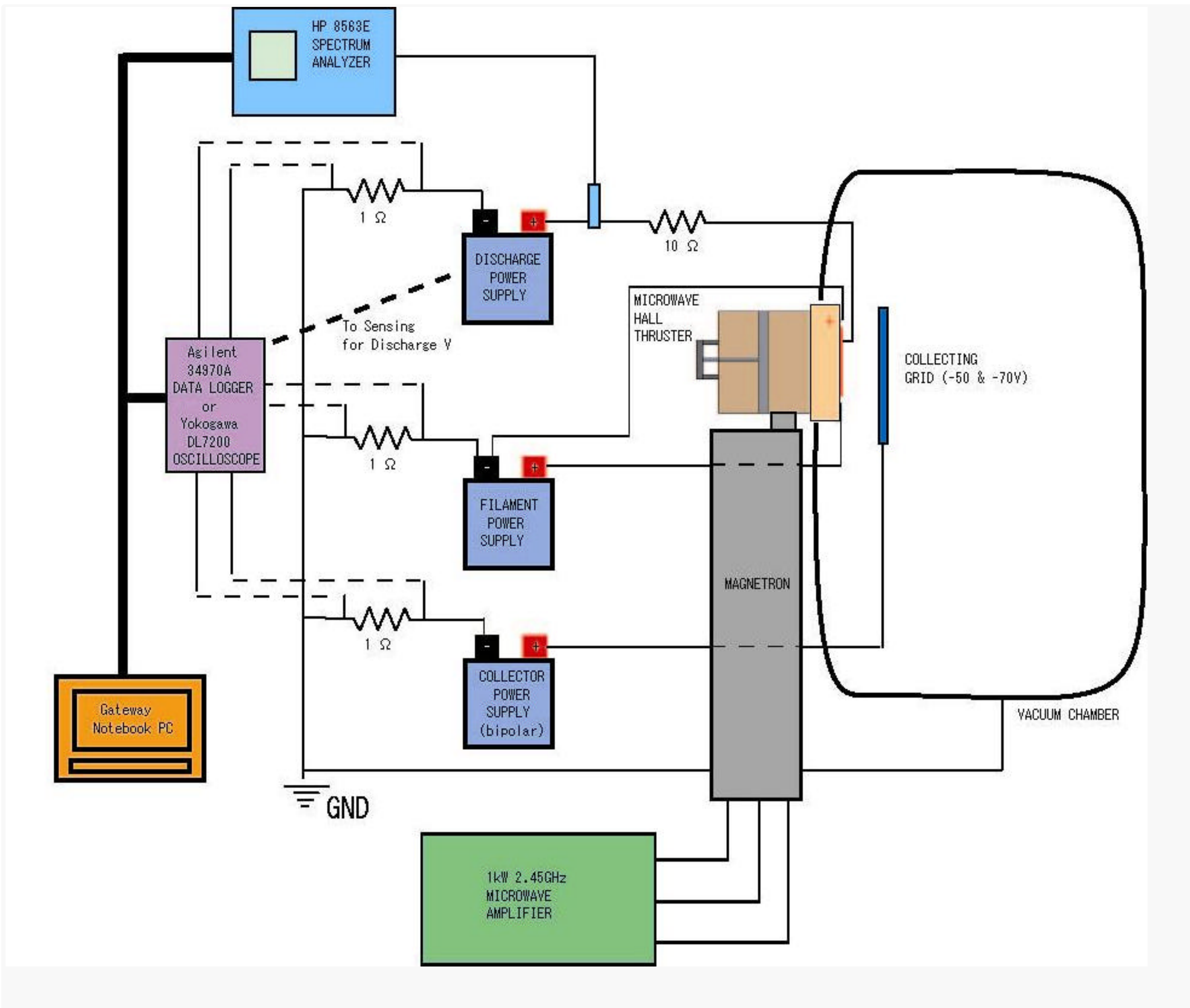

Fig. 15: Overall experimental system