Experimental Studies of Ion Beam Neutralization: Preliminary Results

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Abstract. A testing platform is designed to study ion beam neutralization in the mesothermal, collisionless region. In the experimental setup, argon neutrals were ionized in a microwave cavity and accelerated by a plasma lens system which was biased to 2500 V above the system ground. Electrons were boiled off from two hot tungsten filaments to neutralize the ion beam. The plasma is diagnosed using Langmuir probe and Faraday probe. A 3-D traversing system and a complete data acquisition loop were developed to efficiently measure 3-D beam profile. Preliminary measurements of beam profiles are presented for different operating conditions.

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INTRODUCTION

Ion beam emission/neutralization is one of the most fundamental problems in electric propulsion. It is well known that, in order to transmit a current exceeding the space charge limit from spacecraft to the ambient, the beam must be adequately neutralized or the transmission would be blocked by virtual anode formation in the beam[1] and spacecraft charging. Hence, the operation of an electric thruster or any other large current ion emitting source from spacecraft requires a neutralizer to neutralize the ion beam. In such systems, the ions are typically emitted as a cold beam while the electrons are typically emitted as stationary thermal electrons from the neutralizer. The emission is such that $v_{te} >> v_{beam} >> v_{ti}$, where v_{te}, v_{beam}, v_{ti} are the electron thermal velocity, beam drifting velocity, and ion thermal velocity, respectively, and the electron current emitted equals the ion current emitted. One notes that the plasma emitted is strongly non-neutral near the source regardless of the neutralizer location or the emitting surface area. Even for a hypothetical situation where the electrons and ions were emitted from exactly the same location and same surface area, the initial beam would still be strongly non-neutral due to the difference in electron and ion emitting velocity.

The ion beam neutralization process not only is an interesting physics problem but also has important practical implications. For instance, such knowledge is important in the neutralization design for electric thruster clusters. It is obviously also of critical importance in any modeling studies involving plasma emission. Ion beam neutralization is one of the first problems studied during electric propulsion development. Although ion beam neutralization is readily achieved in experiments, the understanding of the underlying physical process remains at a rather primitive level. No theoretical or simulation models have convincingly explained the detailed neutralization mechanism. Furthermore, there has not been a clear understanding on whether or not the proposed theories can be validated by observations from ground experiments and how accurate a ground experiment would represent the in-space condition.

This paper and a companion paper[2] present an ongoing correlated experimental and modeling investigation on ion beam neutralization. The overall objectives of this investigation are to establish an experimentally validated theoretical model which explains the detailed neutralization process and to understand the accuracy limitations of measuring ion beam emission for in-space operation in a vacuum chamber.

Many previous studies have attempted to address the physics of ion beam neutralization. Earlier theoretical studies considered the neutralization of infinitively large uniform ion beam[3, 4, 5, 6, 7] and suggested that wave-particle interaction and plasma instability may be the driving neutralization mechanism. However, no conclusions have been reached. More recent simulation models have considered a more realistic setting for finite size ion beam emission[8, 9, 10]. Wang and Usui[11] performed full particle PIC simulations of ion beam emission. Their simulation results suggested that the primary neutralization mechanism is the interactions between the trapped electrons and the potential well along the beam direction and beam neutralization is not through plasma instabilities as previous studies suggested. The overall objective is to experimentally investigate the validity of this new theoretical model. The specific objective of this ongoing study is to obtain 3-D beam profiles and electron distribution function to compare with simulation results.

This paper presents preliminary measurements of 3-D beam profiles, and is organized as follows. Section 2 presents the experimental facility and setup. Section 3 discusses preliminary results and their implications. Section 4 discusses future experimental plan and conclusions.

EXPERIMENTAL SET-UP AND DESCRIPTION

Vacuum Chamber

Fig. 1 shows a sketch of the experimental set-up. The cylindrical vacuum chamber simulating the space envrionment measures 3 ft in diameter and 4 ft in length; a mechanical pump was used for roughing, and a cryogenic pump with a pumping speed of 8,500 L/s maintained chamber pressure at 10^{-6} to 10^{-5} Torr with argon gas flow ranging from 2.0 sccm to 5.0 sccm. The argon gas was ionized in a microwave cavity and accelerated through a static electric field. Near the exit of the plasma lens, a hot tungsten filament source was placed to generate thermal electrons for ion beam neutralization. To accurately position the electric probes, a 3-axis traversing system driven by stepper motors was specifically designed to fit the vacuum chamber.

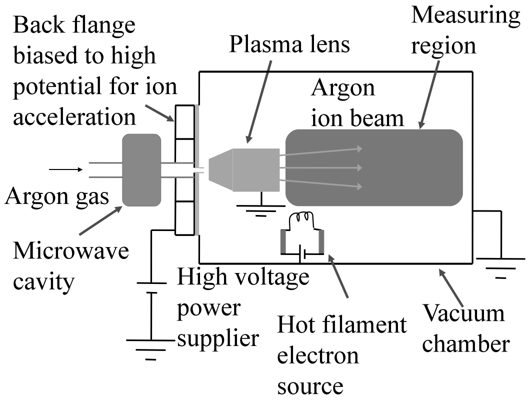


FIGURE 1. Illustration of system setup inside the vacuum chamber

Microwave Ion Source and Hot Filament Electron Source

Argon gas was ionized inside the microwave cavity of the microwave ion source as pictured in Fig. 2, with flow rates varying between 2.0 and 5.0 sccm[12]. The back flange was consistently biased to 2500 V, and the plasma lens (accelerating electrode) inside the chamber was grounded. This created a static electric field which accelerated the argon ions through a 0.8 mm aperture at the center of the back flange. A hot filament electron source was used to provide thermal electrons to neutralize the ion beam. Multiple configurations of hot filament geometry and number based on the power supplies available and measured electron density were tried. Two filaments were used in the experiments, each composed of 0.010" diameter, 4.0" long tungsten wire, and were offset from the center of the ion beam by 2.5". The level of electron emission, and hence electron density, varied as a function of the current applied to each filament. Due to the upper limit of the power supplies used, the maximum achievable power supply current to each filament was 7.5 A.

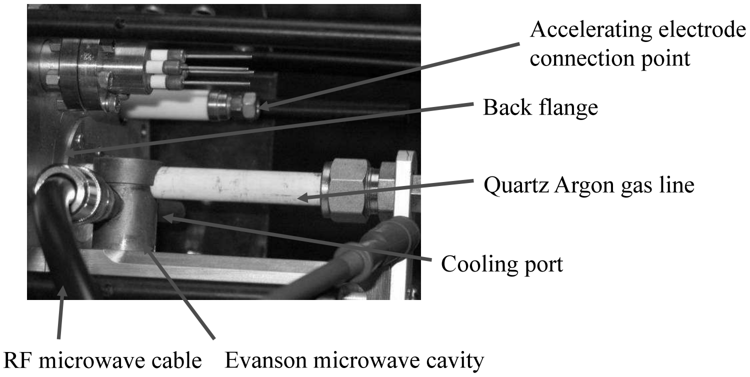


FIGURE 2. Microwave Ion Source

PLASMA DIAGNOSTICS

In order to obtain 3-D plasma field parameters, an electrostatic Langmuir probe and two separate Faraday probes were constructed and utilized. The Langmuir probe is used to measure ϕ, n_e and T_e, and Faraday probes are used to measure n_i.

A single cylindrical non-emitting Langmuir probe was used, consisting of 0.25" of 0.020" diameter exposed tungsten wire, with the remaining wire insulated. A sweep voltage of -10 V to 60 V was applied in 2 V increments, and through the use of a 740 kΩ resistor I-V curves were recorded for each data collection point in the field[13, 14]. A program was then used to output ϕ, n_e and T_e from the I-V curves.

The initial Faraday probe design employed was a Faraday cup, as pictured in Fig. 3. The stainless steel forward plate was electrically floating, with a centered 0.25" diameter hole to allow ion entry. The copper biased ring measured 0.4" in diameter, 0.4" in length, and was offset axially from the forward plate by 0.4". The biased ring prevented plasma electrons from reaching the collecting cup, and also trapped any secondary electrons from the cup within. The copper collecting cup was 0.4" in diameter, 0.725" in length and offset axially from the biased ring by 0.125".

During all data collection with the Faraday cup, a ring bias of -20 V was used. The current collected was calculated from the voltage drop across a 50 kΩ resistor. This probe design performed reasonably well in the unneutralized ion beam case, in which the hot filament source was not operating.

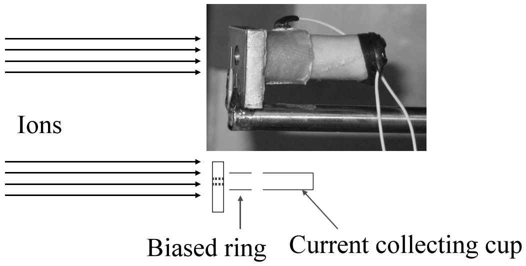


FIGURE 3. Faraday cup

As expected, the peak current density was consistently measured near the electrode exit, with the values dropping off in both the axial and radial directions. Ion beam offset from the expected origin was recorded, but is believed to be caused by a slight misalignment between the back flange of the microwave ion source and the accelerating electrode. However, once the hot filament source was operated, the Faraday cup's accuracy diminished, as it actually began to collect negative ion current values. It was confirmed that under these experimental conditions the biased ring was collecting significant levels of positive current. Despite attempting to use biased ring voltages near the plasma potential (around 10 V to 30 V), we were unable to successfully screen out electrons while simultaneously allowing for unperturbed ion flow to the current collecting cup. This issue led to the design and fabrication of the nude Faraday probe[15, 16].

A nude Faraday probe is directly exposed to plasma flow. In our case, the stainless steel collecting surface directly faced the beam, allowing for collection of axially flowing ions. The guard ring was concentric with the collecting surface, with a gap of 2.0 mm between the two. The purpose of the guard ring is to create a uniform sheath over the collecting surface by minimizing edge effects[15]. The collecting surface outer diameter was 8.0 mm, and the guard ring outer diameter was 15.0 mm. Both the collecting surface and guard ring were designed to be biased to an identical negative potential, -20 V with respect to the facility ground, as shown in Fig. 4.

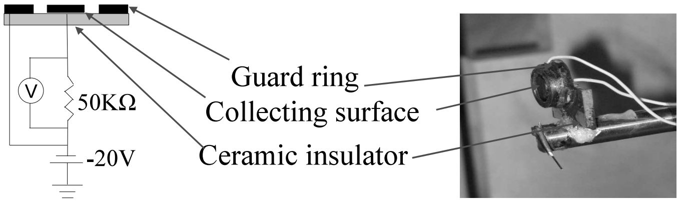


FIGURE 4. Nude Faraday probe photograph and electrical schematic

Data Acquisition and Control System

In order to scan for 3-D beam profiles, a data acquisition and control system is developed. The data acquisition system and traversing system control loop is displayed in Fig. 5. The power amplifier acquired voltage signal from the DAQ card and generated proper biased voltage to drive the Langmuir probe, and the data logger acquired electric measurement from the Langmuir and Faraday probes for the computer. Stepper motors which drove the 3-axis traversing system were controlled in an open loop with linear resolution of 1 mil in each direction.

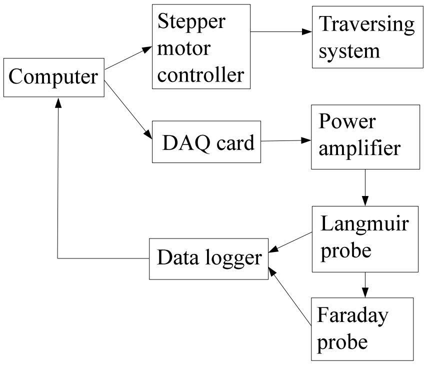
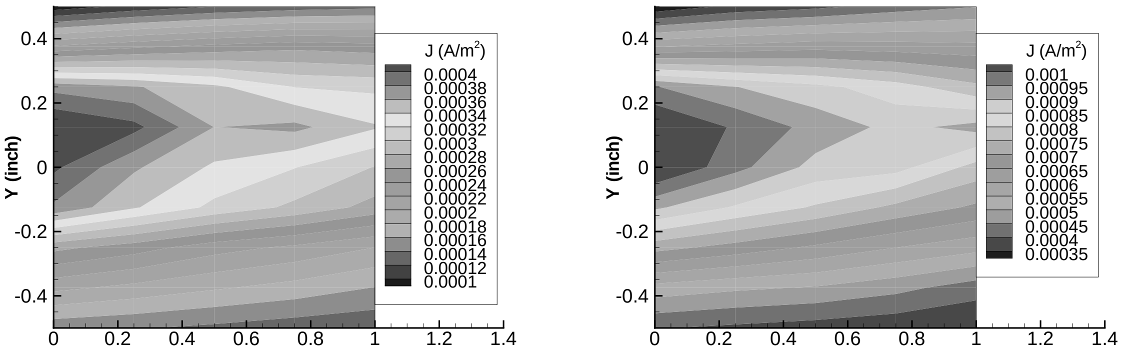


FIGURE 5. Flowchart of DAQ and control system

PRELIMINARY RESULTS

This paper presents preliminary measurements of beam profile. Among various experiments with different settings of microwave power and mass flow rate, the proper power input which satisfied the condition of $n_i \approx n_e$ ranged from 10 W to 20 W, due to the limited power output of the power supply which drove the two tungsten filaments. The scan area chosen was 1"× 1", with a resolution of 0.125" in the y-direction, and 0.25" in the x-direction, leading to 45 total data points for each plot. The electrode exit was located at the origin of the coordinate system, shooting ions in the +x direction. Two cases of ion beam neutralization with microwave power input (Case 1: P_i=16 W and Case 2: P_i=20 W) will be discussed in the paper. Mass flow rate and filament power remained the same for both cases, 5.0 sccm and 165 W respectively.

Fig. 6 shows unneutralized ion beam current density contour measured by the nude Faraday probe. A typical beam profile is observed, with higher current density near the center line. In the unneutralized case, the Langmuir probe was unable to diagnose the plasma potential due to a significant low level of electron density. Once the hot filament source was operated, Langmuir probe data was collected over the same 1"×1" scan area. In order to estimate ion density n_i from ion current density in the neutralized beam cases, the equation of energy conservation (Eqn. 1) is applied to solve



(a) (b)

FIGURE 6. Ion beam current density for unneutralized cases (a) Case 1 (b) Case 2

for n_i as follows, where ϕ_0 is the accelerating voltage, held at 2500 V for all runs, ϕ_i is the plasma potential calculated from Langmuir probe data, and m_i and v_i are ion mass and velocity respectively.

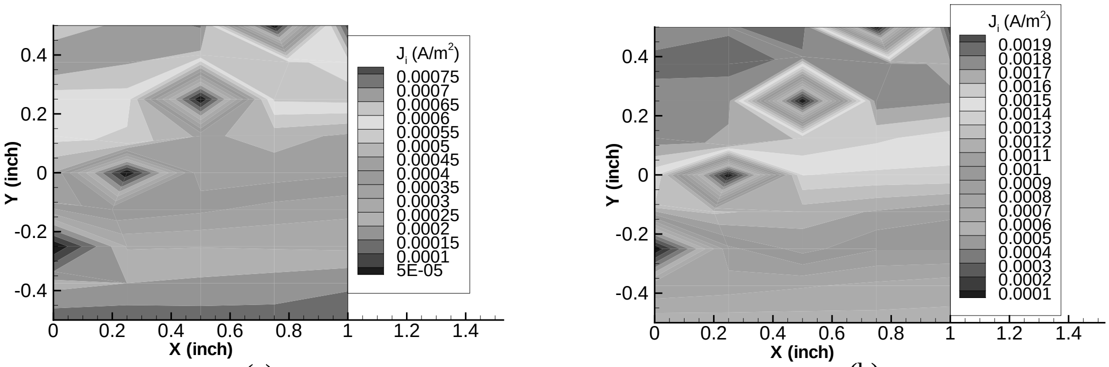
$$\frac{1}{2}m_i v_i^2 = e(\phi_0 - \phi_i) \tag{1}$$

$$J_i = e n_i v_i \tag{2}$$

Eqns. 1 and 2 yield:

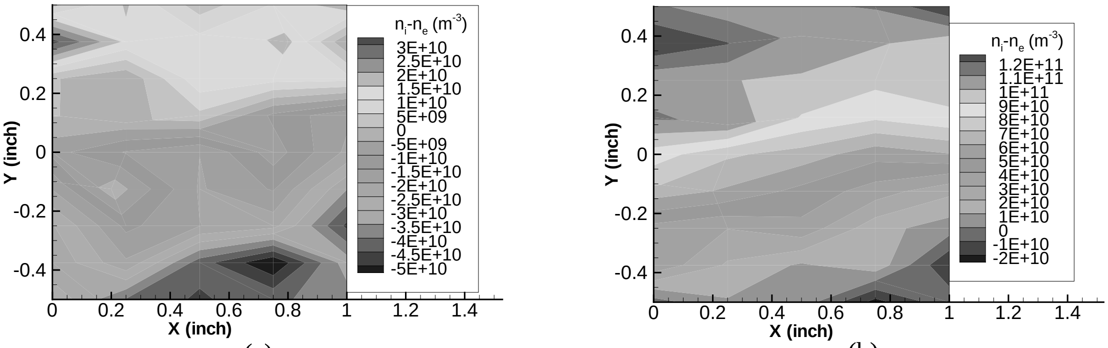
$$n_i = \frac{J_i}{e}\sqrt{\frac{m_i}{2e(\phi_0 - \phi_i)}} \tag{3}$$

As shown in Fig. 7, the pattern of J_i changed to be more uniform after the hot filament source was turned on. Fig. 8 (a) shows the difference in ion and electron number density, and a region approximately 1"×0.4" with $n_i \approx n_e$ occurs around the center line. However, the number density contour plots for both cases are not symmetric about y=0; the region above the center line is under neutralized while the region below the center line is over neutralized. This phenomenon could be caused by the misalignment of the ion source. Fig. 8 (b) shows Case 2, in which the hot filament source was unable to neutralize most of the scan area due to increased microwave power.



(a) (b)

FIGURE 7. Ion beam current density for neutralized cases (a) Case 1 (b) Case 2



(a) (b)

FIGURE 8. Number density difference between ion and electron for neutralized cases (a) Case 1 (b) Case 2

CONCLUSIONS

In conclusion, we have set up a testing platform to conduct neutralization experiments, found the proper facility settings to neutralize the accelerated ion beam in the vacuum chamber, and demonstrated that the system can accurately measure the accelerated ion beam's current and number density. We also designed, fabricated, and tested a cylindrical Langmuir probe, a Faraday cup, and a nude Faraday probe for plasma diagnostics.

Our next step is to conduct beam neutralization experiments with higher number density by using ion and electron sources at high power levels. It may require different types of ion and electron sources and a redesign of either the Faraday cup or nude Faraday probe, with tests to follow. From that point forward we will verify the accuracy of all measured field parameters, and begin to investigate electron energy distribution in the neutralized beam, as well as the underlying physics of the neutralization process itself.

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