Nonambipolar Electron Source for Neutralization of Ion and Hall Thrusters

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Significant progress has been made in the characterization of the necessary parameters required to create an effective Radio Frequency (RF) plasma based electron source. Such a device has promise of longer operational lifetimes and comparable current densities to hollow cathodes. The operational lifetime of hollow cathodes is ultimately limited by cathode deterioration. RF sources provide an alternative approach that does not consume electrode material while providing electrons. A gas utilization of 1500% was achieved with 1.2 Amps of extracted electron current through a 0.25cm^2 aperture with 340W of RF power and a flow rate of 1.1 sccm of Ar. Permanent magnets provided an axial magnet field of 80 Gauss at the antenna. Although larger electron extraction currents are possible with larger exit apertures, up to 3.75 Amps with a flow rate of 14 sccm Ar and an exit area of 1.23cm^2, the gas utilization ultimately is reduced. The Nonambipolar Electron Source (NES) operated without a magnetic field with a maximum extracted electron current of 1.6 Amps. However, even modest magnetic fields (<150 Gauss) significantly improve the electron current extraction and gas use. Experimental evidence from NES suggests that the total amount of electron current that can be extracted is equal to the random electron flux and is limited by the plasma density and the ion loss area provided in the source.

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Nomenclature

A = Ampere
Ar = Argon gas
cm = centimeter
dia. = diameter
e = electron charge
eV = electron volt
J_{oe} = random electron flux
J_{oi} = random ion flux
mA = milliAmpere
m_e = electron mass
m_i = ion mass
MHz = megaHertz
mTorr = milliTorr
n_{oe} = electron number density, cm-3
n_{oi} = ion number density, cm-3
RF = radio frequency
sccm = standard cubic centimeters per minute
T_e = electron temperature, eV
V = volts
W = watts of RF power
Xe = Xenon gas

I. Introduction

Radio frequency (RF) plasmas are attractive as neutralizing sources for electric propulsion devices because they allow for a design where the cathode dose not participate in electron production, and provide high efficiency and long life operation. Ion and Hall thrusters use beams of positive ions for propulsion and electrons or negative ions must be introduced into the ion beam as it leaves the thruster in order to prevent the spacecraft from charging negatively[1] and attracting the emitted positive ion beam. Traditionally, hollow cathodes have been used as electron sources because of their high electron current density and relatively low power requirements. However, their operational lifetime is limited by cathode deterioration, contamination, and barium diffusion rates[2] as well as using a significant fraction of the neutral gas flow of the total thruster[3], thus rendering them less suitable for sustained use.

Longer duration spacecraft missions that use ion propulsion, such as the Jupiter Icy Moons Mission (JIMO), will take 6-10 years for the total orbital transfer time[4]. While using ion propulsion for longer duration missions is very beneficial because of fuel, mass, and time savings (as opposed to impulsive chemical rocket burns), the lifetime of some operating components for ion propulsion, such as the hollow cathode, may be limited to 3-4 years[5]. The hollow cathode neutralizer and plasma sources that were used for the highly successful Deep Space 1 and SMART-1 missions may be limited to 3-4 years of operational lifetime due to significant erosion, sputtering, and re-deposition of material within the keeper region and surrounding areas[3-7]. There exists a need for these types of missions for an electron source that is able to function reliably for long durations[8].

Ion and Hall thrusters that are currently used onboard communications, NASA, and DOD satellites use hollow cathodes as the primary plasma source with an additional hollow cathode as an electron source for neutralizing the positive ion beams. Here, the neutralizing hollow cathode uses a significant fraction[3] of the total neutral propellant onboard the spacecraft and takes 5 to 10 minutes to heat the thermionic material surface. These inefficiencies in propellant usage and startup time have stimulated interest in innovative electron sources.

RF plasma sources provide an alternative neutralizing approach that does not consume electrode material while providing electrons, thereby allowing for a longer operational lifetime. A variety of RF sources exist including capacitive and inductive sources, which can operate without magnetic fields, and both electron cyclotron resonance (ECR) and helicon sources, which require axial magnetic fields. Helicon sources appear to be the best choice of RF plasma sources for use in ion propulsion because they can produce the highest plasma densities, up to 10^{13} cm^{-3} is common[9], for a given RF power but they also require larger magnetic field strengths and/or larger RF powers than inductively coupled plasma sources. If insufficient power is available, helicon sources will operate as inductive sources. At much lower RF powers, the plasma is capacitively coupled and results in lower plasma densities.

Inductively coupled plasmas can achieve significant plasma densities, 10^{10} cm^{-3} to 10^{12} cm^{-3} and allow for a large total electron extraction current[10]. The current proof of principle device at the University of Wisconsin - Madison produces an inductively coupled plasma with a plasma density of 10^{10} cm^{-3} to $5x10^{11}$ cm^{-3}. 3.75 A/cm^2 of electron neutralizing current was extracted at an electron sheath (sheath where ion density is neglected) near a grounded ring located at the plasma source boundary.

This paper discusses several limiting factors in extracting a population of electrons for the purposes of neutralizing a Hall and/or ion thruster with an emphasis on propellant utilization.

II. Experimental Hardware

The plasma chamber used in this experiment contains: a Nonambipolar Electron Source (NES), made up of an ion collection cylinder / Faraday shield, electron extraction ring, RF antenna, and permanent magnets; a vacuum chamber; diagnostic tools, a Langmuir probe and an emissive probe; and a feed gas, argon. A schematic illustration of the plasma chamber containing NES and supporting vacuum hardware is shown in Fig. 1.

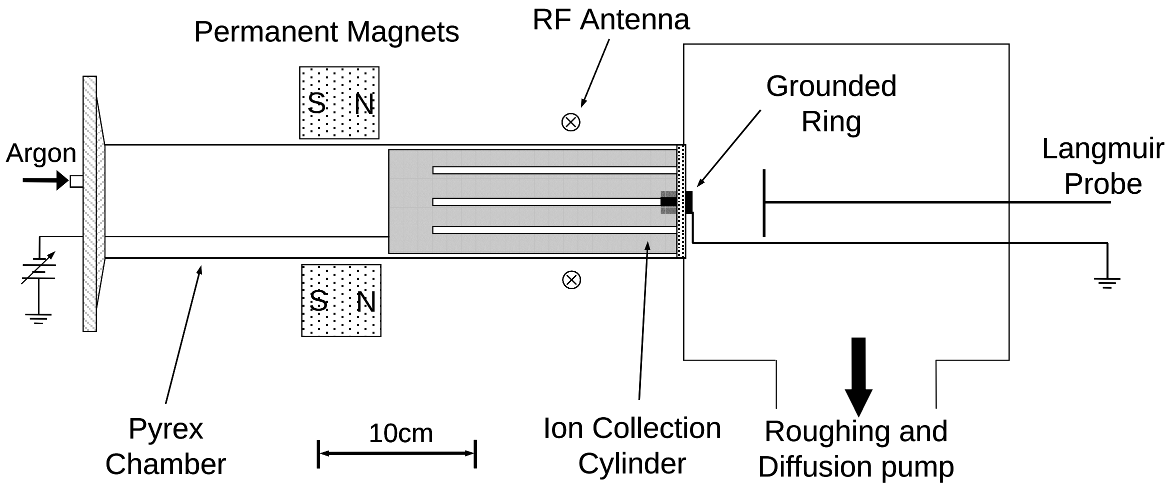

Figure 1. Schematic illustration of the plasma chamber containing the neutralizing plasma cathode with supporting vacuum hardware. The magnets are removable and are not present in some configurations.

NES. A 7.5cm dia., 19cm long, hollow aluminum cylinder is located within the plasma chamber as the ion collection cylinder and can be biased from 0 to -80V DC. This cylinder is a radial boundary for the plasma and acts as a location for the formation of an ion sheath that prevents electrons from leaking to the chamber walls. The ion collection cylinder also has 8 axial slots (0.5cm thick, 10cm long), which allow the dB/dt fields into the plasma chamber but limits the dE/dt fields[11], effectively becoming a Faraday shield. The electron extraction ring is an electrically grounded 1.25cm dia. graphite ring that sits inside a boron nitride disk. This grounded ring creates an axial boundary condition[12], limiting the plasma and the feed gas, and gives a potential reference for the plasma of approximately 0 to +2V. The RF antenna is formed from a single turn ¼" water cooled copper pipe and operates at RF frequencies from 0.5 to 30 MHz, however all data was taken at 22 MHz. The permanent magnet geometry is discussed below and illustrated in Fig 2.

Vacuum chamber. NES is set within a 60cm long 7.5cm dia. Pyrex chamber. A diffusion pump creates a base vacuum pressure of $2*10^{-6}$ Torr.

Diagnostic tools. A $20cm^2$ planar tantalum Langmuir probe is inserted from the right in Fig. 1 and can sweep out all axial locations in the target side of the plasma. A 0.1mm dia. Tungsten emissive probe (not shown) is also inserted from the right side of the chamber and can be extended through the target side (right) of the plasma and into the source side (left), and is used to determine the plasma potential along the axis of the plasma chamber.

Feed gas. Argon feed gas is introduced into the chamber from a mass flow controller (not shown) and flows into the source region where a plasma is excited by the RF antenna.

Magnetic geometry. If indicated, a set of permanent magnets generates a solenoidal field in the axial direction of the Pyrex plasma chamber. The ferrite magnets have nearly a square cross section with the exception of a cylindrical void that allows space for the Pyrex chamber. These magnets produce an expanding magnetic field in the region of the antenna and electron extraction ring, with a null point in the

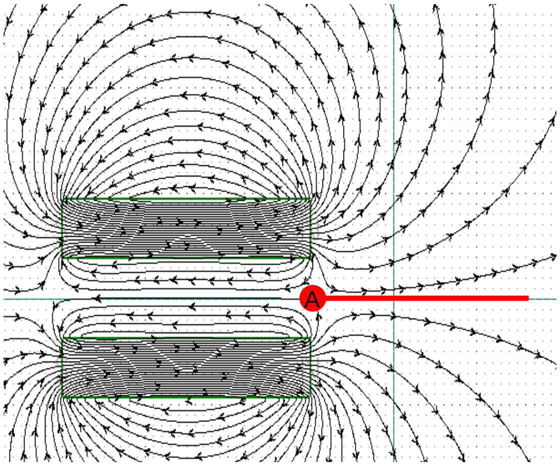

Figure 2. Equipotential magnetic field lines for an axial cross section of the permanent magnets.

magnetic field, point A in Fig. 2. Fig. 2 is a plot of the equipotential magnetic field strength, created with Vizimag 3.0. When present, the magnetic field ensures that the electrons follow the field lines that pass through the exit region of the electron extraction ring, and that fewer electrons are lost to the walls of the source region and the interior walls of the grounded ring. Permanent magnets are preferred for this type of in-space neutralizer because they do not require a power source for continual operation.

III. Experimental Results and Discussion

In order to maintain quasineutrality during steady state operation, the amount of electron loss from the source must be balanced by an equal amount of ion loss[13]. Because electrons and ions are born at an equal rate within the RF discharge, an efficient loss mechanism for the ions must be realized in order to extract an equal amount of electron current from the plasma source. Ion and electron losses, gas utilization, plasma density, and plasma potential effects all present limiting features on the total amount of electron current that can be extracted for neutralizing an ion thruster and are explored further in this paper.

A. Ion and electron losses

Electron sheaths can extract almost all of the random electron current from the system. Identifying J_{0e} as the random electron flux directed towards the sheath at the sheath edge

$$J_{0e} = \frac{n_{0e} e \alpha}{4} \sqrt{\frac{8T_e}{\pi m_e}} \tag{1}$$

where T_e is measured in eV, $\alpha \approx 0.5$, and taking the ion flux J_{0i} equal to the Bohm current

$$J_{0i} = n_{0i} e \alpha \sqrt{\frac{T_e}{m_i}} \tag{2}$$

the ratio of electron to ion flux associated with electrons created by ionization from Eqs. (1) and (2) is approximately equal to $\sqrt{m_i/m_e}$. The limit to the existence of an electron sheath is provided by the condition that the ion loss current to area A_i be balanced by the electron loss current to area A_e. Assuming all the electrons are lost at the electron sheath gives

$$A_i \big/ A_e \approx \sqrt{m_i/m_e} \tag{3}$$

assuming the electrons are confined radially. For large A_e, the electron sheath is no longer a viable solution. For sufficiently large A_e, only a plasma potential more positive than the grounded electrode potential, combined with an ion sheath, can provide the necessary balance of electron and ion losses.

In this experiment, ions are lost to the 7.5cm dia. aluminum cylinder, with an ion loss area of 425cm^2 and the electron loss region is restricted to a small (1.23cm^2 or 0.25cm^2) aperture. An electron loss area of 1.23cm^2 implies the need of an ion loss area of at least $A_i \approx A_e\sqrt{m_i/m_e} \approx 350 cm^2$ for Ar and $630 cm^2$ for Xe.

If the source is operated at an argon plasma density of 10^{11} cm^{-3}, 1.1 A of electron current can be extracted through a 1.23 cm^2 electron loss area if there is a 100% neutral gas utilization. If higher plasma densities are achieved, more current can be extracted or a correspondingly smaller electron loss area can be used, which then requires a ion loss area that is a factor of $\sqrt{m_e/m_i}$ larger. The entire device is essentially area limited in that the electron extraction current can not exceed the ion extraction current that is collected by the ion loss area.

B. Loss Area and Gas Utilization

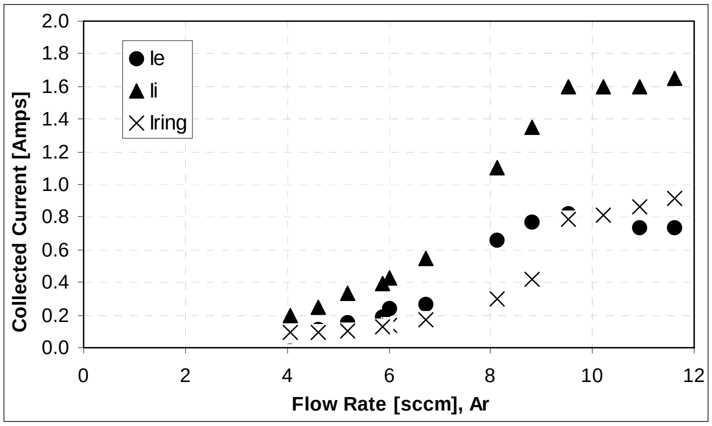

Figure 3. Current collected by ion collection cylinder (triangles), electron extraction by probe (circles), and electron extraction by ring (x's) as a function of the argon flow rate for -60V DC bias on the ion collection cylinder. Zero magnetic field configuration.

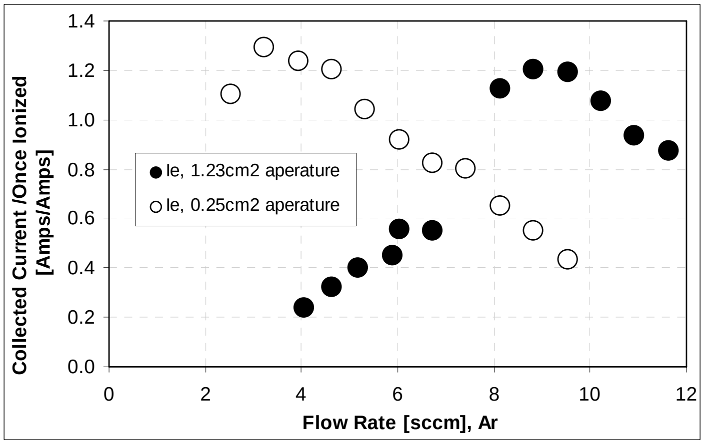

Figure 4. Electron extraction current (normalized to Amps/sccm) as a function of flow rate for a 1.23cm^2 exit aperture (black) and a 0.25cm^2 exit aperture (white).

Electron extraction current is graphed as a function of the neutral gas flow rate, Fig. 3. Without a magnetic field, the grounded ring extracts a large fraction of the total electron current compared to the Langmuir probe that is located outside of NES. The measured gas utilization efficiency is also graphed as a function of the neutral gas flow rate, Fig. 4. Neutral gas flow rate is chosen as variable parameter due to the relevance in spacecraft weight. Any savings in neutral gas flow rate will reduce the amount of propellant that needs to be launched into orbit. The gas utilization is defined as follows: 1 sccm of Ar contains a flow of 2.7x10^{19} neutral gas atoms per minute. If on average every atom is ionized once and losses its corresponding electron once, this would produce an electron current of 0.072 Amps per sccm of neutral gas, this is referred to as 100% gas utilization. However, it should be noted that the gas utilization is really a manifestation of the exit area of NES, where differential pumping causes a larger pressure to build up within the plasma chamber. Thus, smaller apertures will tend to 'use' gas more efficiently because lower flow rates that are needed in order to produce similar neutral gas pressures within the plasma chamber. The aperture size and plasma density of NES are the determining factors for the amount of electron current that extracted from the device. Fig. 4 compares the amount of electron extraction current for two different sized apertures for NES, one of 1.23cm^2 (black circles) and one a factor of 5 smaller in area, 0.25cm^2 (open circles). The total electron extraction current in Fig. 4 is normalized by the current that would be expected based on a 100% Ar gas utilization. The total amount of extracted current generally levels off at higher flow rates, but due to the normalization Fig. 4 shows a decrease in the gas utilization efficiency. As expected, the smaller aperture is able to produce similar gas utilization efficiencies at significantly lower flow rates than the larger aperture. The total amount of current that can be extracted from the smaller aperture is a factor of 5 smaller, but the at nearly 0.5 Amps of electron neutralizing current, this may be sufficient for many Hall thruster and ion thruster requirements. Fig. 4 shows the importance of the aperture size on the required gas flow rates and hence the total amount of propellant that needs to be used for electron beam production.

Even without a magnetic field, NES is able to achieve a 120% gas utilization at a flow rate of 9 sccm with an aperture size of 1.23cm^2 and 130% gas utilization at 3 sccm with an aperture size of 0.25cm^2. There is also a characteristic maximum in the gas utilization efficiency as a function of flow rate for each aperture size. These optimum flow rates are really optimum pressures within the main body of the plasma, where there exists an optimum pressure that produces the largest ionization fraction within the inductive discharge. For any spacecraft electron source design, propellant gas must be used as efficiently as possible due to the added mass that will be launched into orbit, therefore corresponding aperture sizes and neutral pressures within the electron source should be optimized based on the electron current that is required.

C. Magnetic Field Effects

Without a magnetic field NES is able to produce an electron current that is very useful for many Hall thruster and electrostatic thruster applications, however, even a modest magnetic field that is produced with permanent magnets can significantly enhance the performance and overall gas utilization efficiency by factors of 8 to 10.

As shown in Fig. 5 and Fig. 6 the magnetic field plays a large role in the total amount of current that can be extracted from NES and the efficiency of the neutral gas utilization. Fig. 5 shows the total amount of electron current that is extracted from NES as a function of the DC bias on the ion collection cylinder. This is done for two cases, zero magnetic field and 40 Gauss magnetic field. The increased electron current extraction in the presence of a magnetic field is a consequence of an increased plasma density and increased confinement times of electrons within NES, thus giving a larger random flux of electrons that are extracted by the electron sheath through the grounded ring[12].

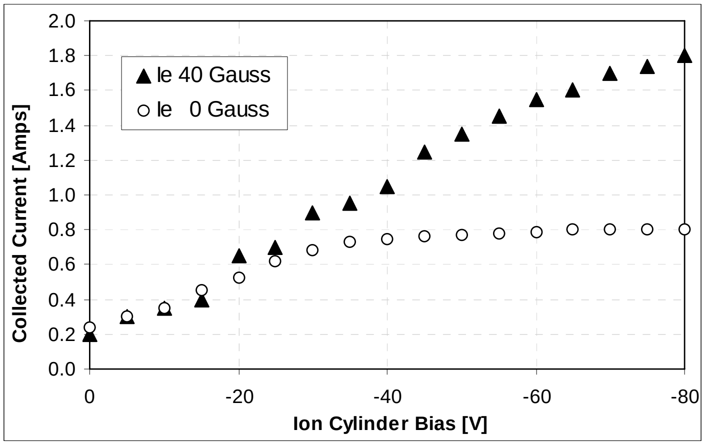

Figure 5. Electron extraction current as a function of the DC bias on the ion collection cylinder for zero magnetic field strength (white) and a 40 Gauss magnetic field strength (black)

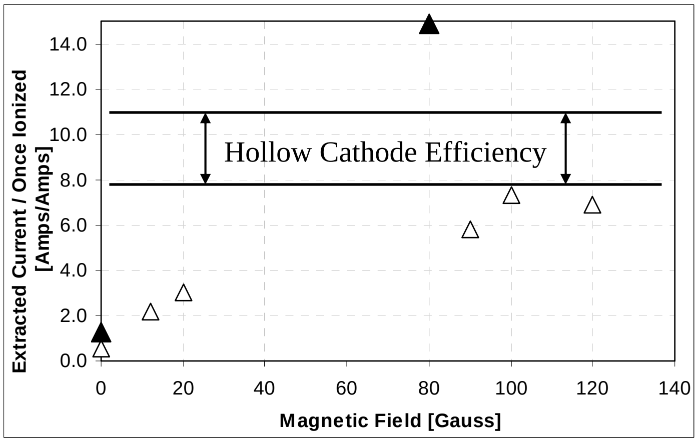

Figure 6. Extracted electron current (normalized to Amps/sccm) for a 1.23cm^2 exit aperture (white), and for a 0.25cm^2 aperture (black), as a function of magnetic field strength at the grounded ring. The gray line represents hollow cathode gas utilization efficiencies.

Fig. 6 shows that modest (<150 Gauss) magnetic fields yield a significant increase in the performance of the electron source, either by increased ionization rates and hence plasma densities or by improved particle confinement and hence increased plasma densities. In Fig. 6 the total electron extraction current is normalized by the current that would be expected based on a 100% Ar gas utilization and is plotted as a function of the magnetic field strength at the grounded ring that sits at the exit of the NES. A change in the magnetic field strength was achieved by an axial shift in the position of the permanent magnets. The overall topology of the magnetic field remained essentially unchanged with these small shifts (<10cm), however the magnetic field strength could be easily altered in this way.

One partial effect for the improvement of the gas utilization with increasing magnetic field is the change in percentage of electron current that is extracted to the grounded Langmuir probe compared to the grounded ring at the exit of the plasma chamber. With increasing magnetic field, the grounded ring collects less electron current and 'competes' less with the Langmuir probe on the outside of NES. The grounded ring continues to provide an electron sheath that extracts electrons and the ring tends to extract less current itself with increasing magnetic field.

The gray line in Fig. 6 indicates the region that state-of-the-art low current (<5Amps) hollow cathode devices operate at[3]. NES is able to achieve similar gas utilization efficiencies and electron current extractions with an aperture size of 1.23cm^2 (open triangles) and is able to do 150% better than hollow cathode devices in terms of gas utilization with an aperture size of 0.25cm^2 (black triangles). All data presented is with a neutral feed gas of argon. In order to compare NES data to hollow cathode data appropriately xenon should be used, however the total extracted electron current and gas utilization efficiencies are estimated to increase with the use of xenon due to the lower ionization energy and slower thermal velocity of xenon compared to argon. In the absence of any thermionic materials, wearing material surfaces, and improved gas utilization efficiencies NES may prove to be an acceptable replacement for hollow cathode devices that are currently used onboard Hall thrusters and electrostatic ion thrusters.

D. Sheath Effects

An electron sheath as used in this experiment allows the extraction of all or most of the random electron flux through an orifice that is proportionally smaller than the ion loss area located within the plasma source. The electron loss area was changed from 1.23cm^2 to 0.25cm^2 and there was proportional decrease in the amount of electron current that could be extracted from the NES.

One complication to the understanding of current extraction from the plasma source is the plasma potential difference between the source side and the target side. Regardless of the bias on the ion collection cylinder in the source side, the plasma potential in the target side remained above that of the plasma source region. The plasma potential within the source region remained more positive than the ion collection cylinder, -25V compared to -80V respectively, thereby giving rise to ion loss through an ion sheath at the ion collection cylinder within the source region. Fig 7. shows that the plasma potential in the target region (dashed line) remains more positive than the plasma potential in the source region (solid line), indicating the existence of an electron sheath that is extracting electrons. Inside of the grounded ring, the plasma potential is held within ± 1V of ground potential, previously demonstrated by Severn and Hershkowitz[11].

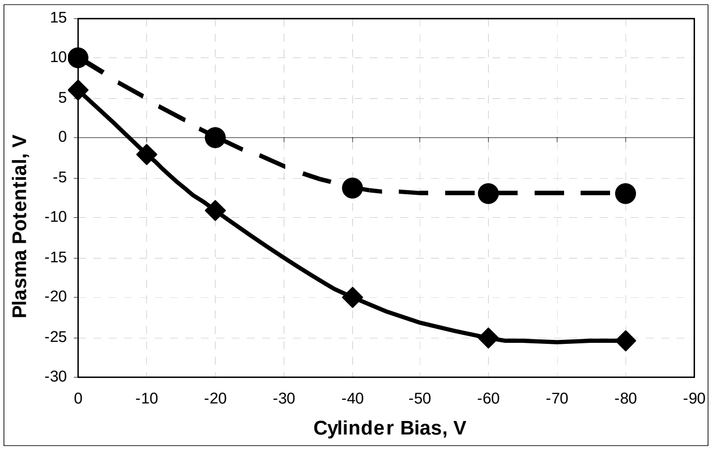

Figure 7. Plasma potential in the source (solid) region and the target (dashed) region as a function of the DC bias applied to the ion collection cylinder for 14 sccm Argon, 120 Gauss.

In the magnetized and unmagnetized case, the plasma remains more positive than the ion collection cylinder, but does saturate at -25V as seen in Fig. 7. The target (dashed) region of the chamber remained at a higher potential compared to the plasma source side, where electrons are not lost to the ion collection cylinder because the difference in potential between the source plasma and the ion collection cylinder satisfies $e\Delta\phi/T_e >> 1$.

The ion collection cylinder also acts as a Faraday shield, composed of a 19cm long cylinder of aluminum with 8 axial slits that extend 10cm from the target side. By using the ion collection cylinder as a Faraday shield the plasma potential does not fluctuate within the source. Without the use of a Faraday shield, there is significant capacitive coupling and the plasma potential oscillates back and forth with a peak to peak value of over 100V. The cessation of the fluctuating plasma potential by using a Faraday shield is beneficial to the RF plasma neutralizer because it ultimately allows for larger and more stable electron extraction.

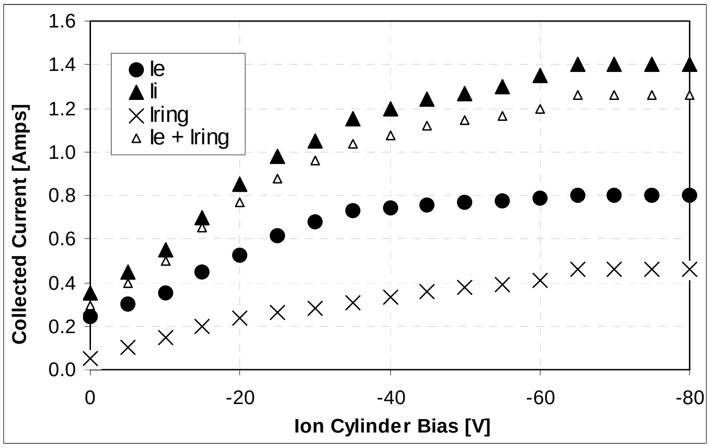

Figure 8. Extracted ion current (black triangles), electron current (black circles), electron current to grounded ring (x's), and electron current to probe plus electron current to ring (white triangles) as a function of the DC bias applied to the ion collection cylinder for 9.5 sccm Argon and no magnetic field.

Fig. 8 shows a graph of the collected current on the target side of the vacuum chamber as a function of the bias on the ion collection cylinder for an unmagnetized plasma. One importance difference for this situation, compared to the magnetized case is the collection of a large fraction of the electron current by the grounded ring. In this situation, the magnetic field does not exist and the electrons are free to scatter and collide with the inner circumference of the grounded ring. This differs from the magnetized case, where there was only a small frontal area of the grounded ring where electrons come in contact with the electrode. In the absence of a magnetic field the electrons only follow the electric field lines which are directed toward the walls of the inner circumference of the grounded ring. This gives rise to a larger fractional loss of electrons to the grounded ring instead of being extracted through the ring and out to the Langmuir probe. In Fig. 8 the ion current (black triangles) that is collected at the ion collection cylinder is compared with the addition of the electron current to the ring and the electron current to the external probe (open triangles). Notice that the grounded ring (x's) attracts 30% to 50% of the total electron current. Fig. 8 also exhibits a saturation effect that is not seen in the magnetized configurations, where the total extracted electron current (black circles) does significantly increase once the DC bias on the ion collection cylinder is below -35V.

IV. Conclusion

In the absence of any thermionic materials, surfaces that can deteriorate, and improved gas utilization efficiencies, NES promises to be an acceptable replacement for hollow cathode devices that are currently used onboard Hall thrusters and electrostatic ion thrusters. In addition, NES is likely to find application in materials processing areas that require high purity (absence of material sputtering) electron sources such as electron beam evaporation, electron beam surface modification, thin film growth, plasma vapor deposition, electron beam reactive deposition, and optical coating deposition.

An electron sheath as used in this experiment allows the extraction of all or most of the random electron flux through an orifice that is a factor of $\sqrt{m_e/m_i}$ smaller than the ion loss area located within the plasma source. Electrons are not lost to the ion collection cylinder because the difference in potential between the source plasma and the ion collection cylinder always satisfies $e\Delta\phi/T_e >> 1$ within NES. This prototype is able to provide a substantial electron current, with a maximum of 3.75 A. This was achieved while using 14 sccm Ar, 340W of RF power at 22MHz, and -80V DC bias on the ion collection cylinder. The ion collection cylinder, with an area of 425cm^2, provided the necessary ion loss area, while a smaller grounded ring was used to extract the electrons through an electron sheath into the target region of the plasma chamber. In a slightly altered configuration, a maximum gas utilization of 1500% was achieved while producing 1.2 Amps of electron extraction current at 1.1 sccm of Ar. This was achieved with an exit aperture area of 0.25cm^2, a magnetic field of 80Gauss, and an RF power of 340W. The smaller exit aperture creates an adequate differential pump such that a sufficient neutral gas pressure exists for efficient plasma production from the inductive RF source. All data presented is with a neutral feed gas of argon. In order to compare NES data to hollow cathode data appropriately xenon should be used, however the total extracted electron current and gas utilization efficiencies are estimated to increase with the use of xenon due to the lower ionization energy and slower thermal velocity of xenon compared to argon.

By going to higher RF powers (>500W) and higher magnetic field strengths (>400 Gauss), this same electron source could be operated in a helicon mode with an increased electron extraction current an order of magnitude larger (10 to 30 A).

Acknowledgments

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