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rf power system for thrust measurements of a helicon plasma source

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A rf power system has been developed, which allows the use of rf plasma devices in an electric propulsion test facility without excessive noise pollution in thruster diagnostics. Of particular importance are thrust stand measurements, which were previously impossible due to noise. Three major changes were made to the rf power system: first, the cable connection was changed from a balanced transmission line to an unbalanced coaxial line. Second, the rf power cabinet was placed remotely in order to reduce vibration-induced noise in the thrust stand. Finally, a relationship between transmission line length and rf was developed, which allows good transmission of rf power from the matching network to the helicon antenna. The modified system was tested on a thrust measurement stand and showed that rf power has no statistically significant contribution to the thrust stand measurement. © *2010 American Institute of Physics*. [doi:10.1063/1.3460263]

I. INTRODUCTION

Helicon plasmas are of significant interest in the electric propulsion (EP) community for two reasons: they show promise as a plasma accelerator through the use of the double-layer effect[1] and they may be used to provide an ion source for other EP devices. The double-layer effect has been shown to produce ions with velocities as high as 11 km/s,[2] but the contribution of these ion energies to system thrust has not been established. Until now, a true thrust diagnostic that can measure thrust of a rf device does not exist. A helicon plasma source is a high density, high efficiency plasma source that sustains steady plasma production through absorption and propagation of helicon waves.[3] A helicon wave is a special condition of the whistler wave mode in a plasma and is launched by applying an axial magnetic field and coupling a rf antenna to the plasma column. This process is much more efficient and can provide plasma densities an order of magnitude greater than the previous inductive methods for the same input power.[4] Helicon plasma sources were first developed in a cylindrical configuration[5–9] and have recently expanded into devices with an annular geometry.[10–14]

Helicon plasma sources present very unique engineering challenges. Foremost of these is the reduction of rf noise emitted by the system. Traditional helicon experimental systems involve relatively small (1–2 m diameter) chambers to minimize cable length, with the rf power system placed immediately outside the facility.[2] These systems are undesirable for EP experiments, however, due to the fact that proximity to the facility walls will have an effect on the local plasma environment around the thruster, and hence, the performance. Placing facility walls far from the helicon introduces new challenges, however, with regard to the rf noise introduced to the system. Small systems do not produce significant noise because the short cables are able to carry rf energy without radiating significantly to the outside. Large EP facilities with diameters of 4 m or more, however, require very long cables to carry power from the facility walls to the helicon. These have a high potential for producing noise and have prevented direct thrust measurements of helicon plasma devices.

Thrust measurement stands are particularly vulnerable to rf noise, which complicates performance measurements of any candidate helicon plasma thrusters; accurate measurements are impossible if the thrust stand calibration changes or the signal gets noisy when rf power is applied. Sensitivity is due to two factors: noise in the measurement itself and noise in the amplification circuitry. The specific transducer employed for thrust stand measurements is a linear variable differential transformer (LVDT), which provides position measurements via an amplitude-modulated signal at a few tens of kilohertz. These signals are very sensitive to rf interference. Noise in the amplification circuitry is a large issue in null-offset-type thrust stands, which use an electromagnetic null coil to hold the thrust stand at a constant position, using the LVDT measurement as feedback. If noise is able to penetrate into the control and amplification circuitry of the null coil, then thrust measurement will be impossible even if the LVDT itself is unaffected. Previous efforts to acquire thrust data on helicon devices have avoided the thrust stand noise issue completely through the use of other methods to measure or calculate thrust, either through use of ion energy[15–21] or a momentum flux system.[22–24] Development of a rf power system which places the complete plasma device on a thrust stand, then, is of significant benefit to the EP community as it opens up an entirely new class of devices to the performance measurements necessary for development into flight-qualified thrusters.

II. EXPERIMENTAL APPARATUS

All tests are performed in the Vacuum Test Facility (VTF) at the Georgia Institute of Technology High-Power Electric Propulsion Laboratory (HPEPL), which is shown in Fig. 1. The facility consists of a 4-m-diameter by 7-m-long cylindrical stainless steel vacuum tank. The facility is evacu-

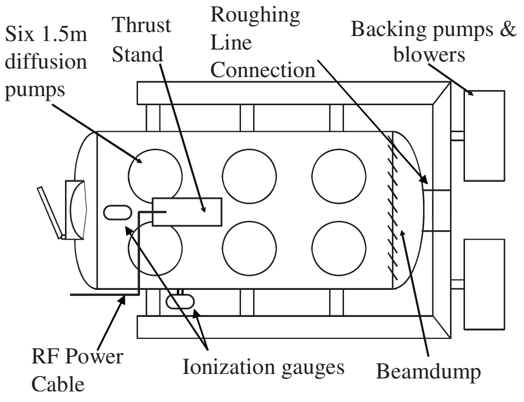

FIG. 1. Vacuum Test Facility at HPEPL.

ated to a pressure of approximately 2 Pa (1.5×10^{-2} Torr) by a pair of Oerlikon Leybold RA5001 root pumps (Cologne, Germany), capable of a combined pump rate of 3600 l/s. High vacuum is achieved through six 1.5-m-diameter diffusion pumps, capable of a combined pump rate of 600 000 l/s on air, and a facility base pressure below 1.33×10^{-4} Pa (1×10^{-6} Torr). Facility pressure is measured by two Varian 571 Bayard-Alpert ionization gauges (Palo Alto, CA), controlled by a Varian XGS-600 ion gauge controller. The facility operating pressure at a propellant flow rate of 2.8 mg/s [94.1 SCCM (SCCM denotes cubic centimeters per minute at STP)] of argon is below 4×10^{-3} Pa (3×10^{-5} Torr), corrected for argon. Uncertainty in the pressure measurements was approximately 20%. The thrust stand is a null-offset inverted pendulum stand capable of thrust measurements between 1 mN and 5 N with a demonstrated 0.6% uncertainty.[25] Thrust stand output is a voltage signal that corresponds to the current required to maintain the null offset.

The rf power system is comprised of a radio, an amplifier, and a matching network, as shown in Fig. 2. The radio is a Yaesu FT-842 (Vertex Standard USA, Cypress, CA), which has a frequency range of 2–30 MHz and an output power level of up to 100 W. An ACOM A2000 linear amplifier (Medway, MA), which is capable of operation at 1.8–24.5 MHz at power levels up to 1500 W, is used for higher power operation. Two rf matching networks are involved in this work. The first is a Palstar AT5K (Piqua, OH). The AT5K is a T-type matching network that consists of a pair of 600 pF variable capacitors and a 35 μH variable inductor. For the experiments reported here, the AT5K is reconfigured to a Pi-type configuration. The second matching network is a custom-built Pi-type network, which includes three Applied Motion OMHT17-075 stepper motors (Watsonville, CA), each controlled by an Applied Motion 1240i drive, for remote operation. The drive boards are in a separate control box, which is connected to the matching network through a DB25 cable. The custom matching network consists of a pair of 7–1000 pF vacuum variable capacitors and a 35 μH variable inductor, as shown in Fig. 3. Aside from the remote operation capability, the custom matching network design operates identically to the Pi-reconfigured AT5K.

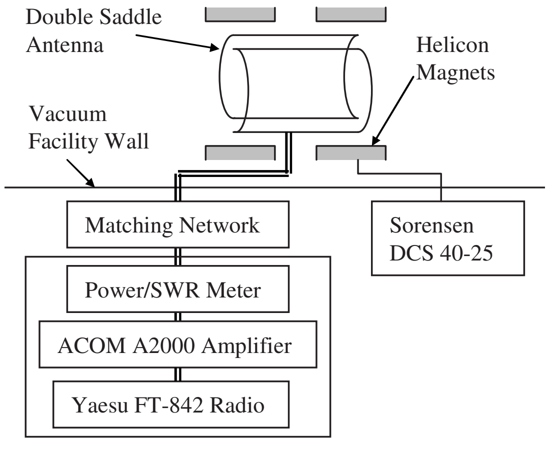

FIG. 2. Schematic of the rf power delivery system to the helicon through the vacuum chamber wall.

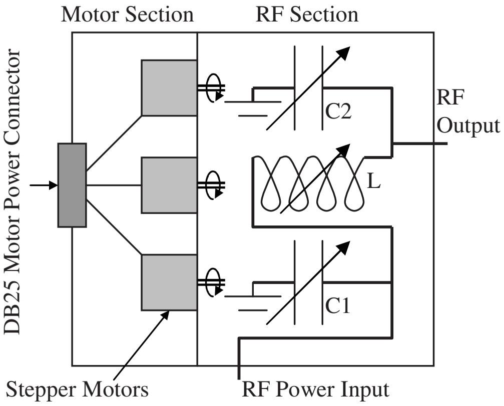

FIG. 3. Schematic of the custom-built impedance matching network. C1 and C2 are 7–1000 pF and L is 0–35 μH.

The helicon device employed is a cylindrical helicon of similar dimensions to the Helicon Double Layer Thruster.[2] The glass tube that contains the plasma has an outer diameter of 15 cm, a wall thickness of 3 mm, and a length of 29 cm. The antenna is a copper Boswell-type[5,6] double saddle constructed of 12.7×3.2 mm^2 rectangular copper, 18 cm long, which is friction-fit around the glass tube. There is approximately 6 mm of clearance between the antenna and the magnet solenoid tube. The antenna is wrapped in a single layer of 0.1 mm thick fiberglass electrical tape to prevent direct contact with the plasma and is connected to the rf power system by ring terminals bolted to the exposed ends of the antenna. The twin solenoid coils are wrapped on aluminum cylinders which surrounded the antenna and glass tube. 5 A of magnet current produces an on-axis magnetic field of 230 G. Magnet current is supplied by a Sorensen DCS 40-25 power supply (AMETEK Programmable Power, Inc., San Diego, CA).

III. RF POWER SYSTEM DESIGN

This research describes the development of a rf power delivery system, which allows thrust measurements of self-contained helicon plasma devices inside of a large vacuum chamber. Three major changes are made to the typical rf power installation in order to improve the signal-to-noise ratio in the system: (1) the transmission line is switched from

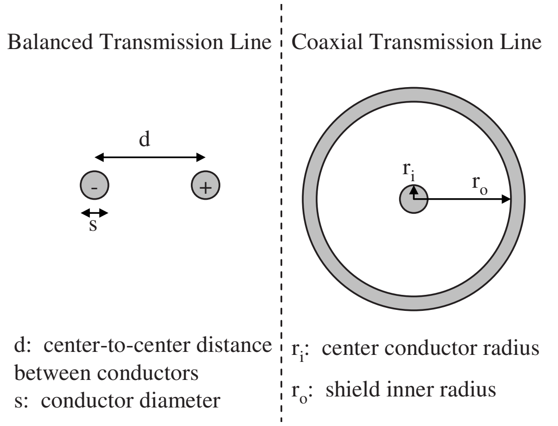

FIG. 4. Cross sections of balanced and coaxial unbalanced transmission lines.

a balanced line to an unbalanced coaxial line, (2) the rf system is placed far from the tank to reduce vibration caused during rf power adjustment, and (3) the cable length between the matching network and the helicon antenna is tuned to resonance. Each of these changes is discussed in detail in the proceeding sections.

A. rf power transmission

There are two methods to efficiently transmit rf power through cables. The first method is the use of balanced and the second method is the use of unbalanced rf power lines. Balanced transmission lines are typically a pair of conductors held a constant distance apart, while unbalanced transmission lines are normally coaxial cables, as shown in Fig. 4.

1. Balanced transmission lines

Balanced lines are defined as a pair of conductors through which equal and opposite voltages (and currents) pass. Neither conductor in a balanced line is directly referenced to ground; rather, the ideal situation is for each line to be an equal, but opposite voltage away from ground. An unbalanced line has only one powered conductor. The current return path in an unbalanced line is facility ground and can take the form of a ground plane at the antenna, or use of the grounded shield of a coaxial cable as the current return, as shown in Fig. 4.

Balanced lines are similar to dc circuits; there is a positive and a negative cable, and both cables connect to the load. Balanced lines have the advantage that the cables do not necessarily need to be shielded, and the cables can connect directly to a balanced antenna. A balanced antenna requires a distinct positive and negative input, such as the dipole, Yagi, and loop antenna. In general, the helicon antenna is a variant of the loop antenna and hence has both a positive and negative input. Thus, balanced lines are typically used to supply power to the antenna.[8]

Balanced lines suffer from two major problems, which render them unsuitable for rf transmission in the environment of an EP testing facility. First, they rely on constant spacing between the two leads of the transmission line. Second, the external electromagnetic fields generated by the lines can couple power into nearby conductive surfaces. The separation distance between the balanced line conductors is critical in that the characteristic impedance of the transmission line is dependent on the spacing, as shown in Eq. (1) (Ref. 26),

$$Z_0 = \frac{\sqrt{\mu/\varepsilon}}{\pi}\cosh^{-1}\left(\frac{s}{d}\right), \tag{1}$$

where μ and ε are the permeability and permittivity, respectively, of the cable dielectric, d is the center-to-center distance between the conductors, and s is the diameter of the conductor. If d varies along the length of the cable, then the impedance of the cable will vary along its length. Thus, a section of the transmission line with a different impedance will reflect some of the rf power back toward the source. Many helicon systems, which use twin-lead balanced lines, use solid copper rods as conductors since the rods are rigid the spacing cannot change, and hence the impedance is constant. A rigid cable connection is incompatible with a thrust stand since the connections must be as flexible as possible to reduce interference and hysteresis with the thrust measurement. Flexible twin-lead balanced transmission line cables are commercially available.

The second major problem of balanced lines in an EP facility, coupling of power into nearby conductors, greatly complicates the use of balanced lines even before considering the thrust stand. Since the conductors of a balanced line are unshielded, the electric and magnetic fields around the conductors are able to propagate away from the cable. Since the waveforms in each conductor are equal and opposite, they will destructively interfere at long distances from the cable. This is seen from electrostatic theory by assuming each conductor to be a long cylinder of charge. From Gauss' law, the electric field E in the same plane as a pair of conducting cylinders of charge is

$$\vec{E} = \left[\frac{\delta}{2\pi\varepsilon_0 r_1} - \frac{\delta}{2\pi\varepsilon_0 (r_1 + d)}\right]\hat{r}_1, \tag{2}$$

where d is the charge density per unit length, r is the distance from the center of one of the conductors, and d is the distance between the conductors. The limit of Eq. (2) as r_1 becomes much larger than d is zero. For example, when r is ten times d, the field has decayed to less than 1% of the field from a single conductor. Even at a point many times the conductor spacing away, however, there will be some electric field. This causes problems if the transmission line is placed too close to another conductor, especially grounded, metallic infrastructure. The fields near a balanced transmission line will induce rf currents in any nearby conductors, which can be harmful to the thruster diagnostics. Since the transmission line for a helicon plasma will come into close proximity with the grounded, conductive vacuum chamber both at the power feedthrough and potentially at other places inside and outside the chamber, a balanced line will induce currents in the facility walls.

Induced currents in nearby conductors have three detrimental effects on the rf system: first is a change in cable impedance, second is a loss of power, and third is an increase in rf radiating into the laboratory. The impedance change due to spacing will manifest as an increase in reflected power, similar to a situation where the separation distance between the conductors in the transmission line varies. Power loss is due to the energy required to induce currents in nearby conductors. Thus, this power is unavailable for coupling into the plasma. Increased rf noise is the largest issue with balanced lines near conductive surfaces. Since the vacuum chambers used in EP laboratories are large and constructed of conductive material, an induced current in the chamber causes the entire chamber to act as a rf antenna and fill the laboratory with rf energy of the same frequency as the plasma system. This then causes the entire facility ground to emit radiation, as EP vacuum facilities are usually connected to the facility ground through a low-impedance cable. rf-radiating grounds are detrimental to plasma probe operation, overwhelm the low-voltage signals from thrust stand sensors, and may cause regulatory issues if operating outside of established industrial, scientific, and medical bands.

Another detrimental effect of balanced lines is direct coupling of rf energy from the transmission line into the plasma. When the VTF is operated with only the root pumps, the facility pressure is greater than 1.3×10^{-3} Pa (1 mTorr). At such high-pressure operation, the field around the balanced cables was sufficient to create a plasma discharge in the relatively dense gas. The energy necessary to create this parasitic plasma is always present, but is only visible during high-pressure operation. Thus, even if the issue of rf power coupling into the facility wall is eliminated, a significant amount of rf power will still be radiated out into the facility from the cables themselves. During high-vacuum operation, this energy is unlikely to create a plasma near the cables, but may interact with the plasma present throughout the tank during helicon operation, which will reduce power transmitted to the antenna and might create additional noise in the facility.

Balanced transmission lines can be shielded to avoid power coupling into nearby conductive materials. Balanced-line shields are circular or elliptical conductors placed around the transmission line. These can be made of braided wire or solid sheets of metal wrapped around the transmission line. Spacing between the conductors and the shield is critical and cannot vary over the length of the line, for the same reasons that conductor spacing must be constant. A shielded balanced line discards the flexibility of bare ladder lines, however, and will reduce cable flexibility to the point where it is unsuitable for use on a thrust stand.

2. Unbalanced transmission lines

Unbalanced transmission lines use a single powered conductor, with a grounded current return path. The current return path can be grounded at the load or at the rf power system. Coaxial cables with a grounded shield are commonly implemented as unbalanced lines, as shown in Fig. 4. Unbalanced lines have two major advantages over balanced lines which make them much more suitable for use in an EP facility and with a thrust stand: (1) they are unaffected by nearby conductive surfaces and (2) impedance is constant along the length of the cable.

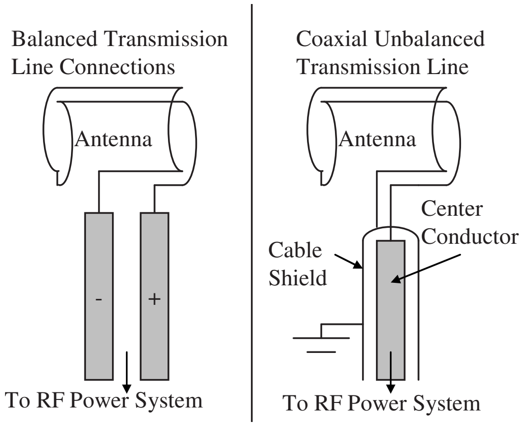

FIG. 5. Schematic diagram of balanced and unbalanced antenna connections to a helicon antenna.

Coaxial cable impedances are defined by the construction of the cable; hence, they will not vary over the length of a transmission line unless it is physically damaged. Coaxial cable impedance is defined by[26]

$$Z = \frac{\sqrt{\mu/\varepsilon}}{2\pi} \ln\left(\frac{r_o}{r_i}\right), \tag{3}$$

where r_o and r_i are the outer radius of the center conductor and inner radius of the cable shield, respectively. Since the distance between the center conductor and the outer shield is filled with solid dielectric, the impedance of a coaxial cable will be a constant over the length of the cable.

Coaxial cables eliminate the problem of external fields interacting with the facility. Electric or magnetic fields cannot radiate away from the cable because only the center conductor is powered and the cable shield completely encloses the cable. Thus, the distance between the cable and any nearby conducting infrastructure has no affect on the power transmission or noise of the system.

The cable utilized inside the vacuum facility at HPEPL is RG-393 standard cable,[27] which is a 50 Ω, double-shielded, 0.99 cm (0.39 in.) diameter cable that utilizes silver-plated conductors and a polytetrafluoroethylene dielectric and cable jacket. The dielectric material is of critical importance as the cables inside the facility operate in excess of 80 °C, which is above the melting point of the polyethylene dielectric of many coaxial cables. The silver plating on the conductors and braid shield increases rf conductivity of the cable; since rf energy only travels on the outside of a conductor, the thin plating of silver (15.87 nΩ m) causes fewer resistive losses than copper (16.78 nΩ m). The rf power is fed through the wall with a dedicated rf power feed through (Kurt J. Lesker part number FTT0813253), and the cable shield is connected to tubular braided copper, which is bolted to both the vacuum and air sides of the facility wall.

Since a helicon antenna requires both a "positive" and a "negative" electrical input, both the center pin and the shield of the RG-393 cable are attached to the antenna. Thus, the antenna is driven in the same way as it would have been with a balanced cable, as shown in Fig. 5.

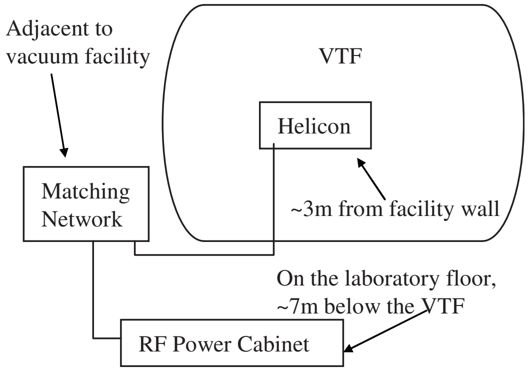

FIG. 6. Layout of the rf system relative to the VTF. The rf power cabinet includes the radio, amplifier, rf power meter, and controller for the matching network.

B. rf power system location relative to vacuum facility

Removal of the rf power system from the vicinity of the vacuum facility is not a rf noise issue as much as a practical one. As the VTF is elevated to make room for the diffusion pumps, any movement near the facility will induce vibrations and possible hysteresis of the thrust stand reading. Furthermore, vibrations in the thrust stand greatly reduce the signal-to-noise ratio. Thus, it is very important to reduce vibration of the thrust stand as much as possible. A rf power system that is physically connected to the vacuum facility is therefore undesirable as any personnel tuning the system will cause the thrust stand to vibrate. Figure 6 shows a schematic of the rf power system's location relative to the matching network and the VTF. The matching network is placed as close to the rf power feedthrough as possible in order to reduce power losses in the cable between the matching network and the antenna. Power losses in the cable between the rf power system and the matching network are negligible since the 50 Ω output of the amplifier is matched to the 50 Ω cable and the input impedance of the matching network.

The rf system incorporates a dedicated ground due to the need for the rf system to have a very low-impedance (ideally less than 1 Ω) ground for safety. Any dc voltage component on the rf power line would cause a safety hazard, and thus a very low-impedance ground will allow any buildup of charge in the system to safely drain to ground. The rf system is grounded through a ground rod, which is installed through the laboratory floor, and is less than 0.5 m from the rf power cabinet. An AWG 6 bare cable is soldered directly to the ground rod and bolted to the rf cabinet to form the ground connection.

A major issue with a rf power system directly connected to the vacuum facility is vibration-induced noise in the thrust stand signal whenever laboratory personnel tune the matching network. The remotely operated matching network eliminated this problem. A remotely operated matching network on other vacuum systems will increase reliability of the thrust stand measurements similar to in the VTF; it will remove the issue of personnel approaching the tank and possibly disrupting the thrust stand.

C. Cable length

Fundamental to any discussion of rf power transmission is impedance matching. In alternating-current power systems the generators, loads, and cables all have characteristic impedances. If these impedances do not match, then power is not efficiently transmitted from the generator, through the connecting cables, and into the load. The impedance of a rf circuit is not merely the electrical resistance of the various components; it is the combination of factors due to resistance, capacitance, and inductance, and is calculated by the formula

$$Z = R + j\omega L - \frac{j}{\omega C}, \tag{4}$$

where Z is the total impedance, R is the dc resistance of the circuit, L is the circuit inductance, C is the circuit capacitance, and ω is the wave angular frequency. An impedance matching network is inserted between components with different impedances in order to transform the output impedance of a power source to the input impedance of a load. Matching networks consist of capacitive and inductive elements and act as intermediaries between the generator and the load. Properly tuned, a matching network has an input impedance equal to the output impedance of the generator, and an output impedance equal to the load impedance. Thus, the impedances of the circuit are matched, and power is transmitted more efficiently.

The generator and the load are not the only considerations in a rf system. In any alternating-current power system, a cable is considered a "transmission line" if the time required for the wave to travel through the cable is a significant portion of the wave frequency. Generally, a transmission line is defined as any cable longer than 10% of the wavelength. Cables shorter than the characteristic transmission line length can be treated as simple wires as in dc circuits, while cables longer than 10% of the wavelength are transmission lines and have a characteristic impedance. Cable impedance must be accounted for when matching the impedances of a generator and a load. Many industrial and scientific rf plasma systems use cables shorter than 2 m, and thus avoid the transmission line issue completely. The EP environment, however, is not amenable to short cables; testing facilities are typically several meters in diameter, and the thrust stands are usually mounted close to the facility axis and thus far from the facility walls. The rf cables inside the VTF are approximately 6.5 m long, which will make them a transmission line for any rf frequency higher than 4.6 MHz (assuming no velocity reduction due to the cable). The cable outside the facility adds to the 6.5 m length, so the allowable frequency without requiring transmission line analysis is lower than 4.6 MHz.

The impact of a long transmission line on a rf plasma system can be explained through the use of the reflection coefficient. At any interface between two components of a rf system, if there is a change in impedance between the components, there will be a nonzero reflection coefficient, which represents the fraction of the source power which reflects off of the load and returns to the source. The reflection coefficient is calculated by[26]

$$\Gamma = \frac{Z_2 - Z_1}{Z_1 + Z_2}, \tag{5}$$

where Z_1 is the impedance of the source and Z_2 is the impedance of the load. The ideal situation, when Z_1 and Z_2 are equal, is a reflection coefficient of zero. In the case of the interface between a transmission line and an antenna, the source is the transmission line and the load is the antenna. If the transmission line and antenna impedances are not matched, power will be reflected from the antenna and will not contribute to the plasma. Thus, when the cable between the matching network and the helicon antenna is longer than 10% of the wavelength (and, hence, it is a transmission line with a finite impedance), a difference between cable impedance and antenna impedance will significantly reduce power deposited in the plasma. This is further complicated by the fact that helicon antenna impedance is not constant. Plasma density has a large impact on antenna impedance; since plasma density is dependent on the applied magnetic field, rf power, and propellant flow, the operating characteristics of the helicon have a large effect on how much of the applied rf power is deposited in the plasma.

There are two primary ways to reconcile a transmission line and load with different impedances. First of these is to the use a transmission line with the same impedance as the load. This is impossible in helicon systems, however, due to the variable impedance of the antenna. The second way to reconcile the impedance of the transmission line and load is to the use a resonant line, where the length of the transmission line is one-half of the rf wavelength. The total impedance of a lossless transmission line and antenna can be expressed by[28]

$$Z = Z_0 \frac{Z_L + jZ_0 \tan(2\pi l/\lambda)}{Z_0 + jZ_L \tan(2\pi l/\lambda)}, \tag{6}$$

where Z_L is the load impedance, Z_0 is the transmission line impedance, and l is the length of the transmission line. If the transmission line is one-half wavelength long, then the imaginary part of the expression vanishes, leaving $Z = Z_L$. It should be noted that the actual wave propagation velocity must be used in this calculation; all transmission lines have a velocity factor, which expresses the wave propagation velocity as a fraction of the speed of light. The velocity factor of RG-393 is 69.5%, which must be taken into account when calculating wavelengths in the cable. It is appropriate to assume that the cable is lossless here because the cable is relatively short: RG-393 cable has a loss coefficient of 0.0169 dB/m at 7 MHz;[29] a cable tuned to a 7 MHz rf frequency will be 21.4 m long and the signal loss will be only 0.36 dB, or only 8.6% of the input power. Higher frequencies will experience less loss; despite a higher loss coefficient at higher frequencies, the shorter cable lengths reduce the net loss. A cable designed for tuned operation at 15 MHz is 6.9 m long and has a loss of only 4%. Since these losses are very low, the lossless approximations are adequate for calculating the cable impedance.

The use of a resonant line allows the transmission line impedance to be removed from the circuit design entirely; the matching network only has to tune to the antenna, not a combination of the antenna and matching network. This can be seen by using cable lengths other than $\lambda/2$ in Eq. (6); the input impedance to the line is somewhere between the load impedance and the cable impedance. Additionally, a half-wavelength resonant transmission line greatly simplifies power measurement; this can be seen by the electric field of an electromagnetic wave

$$E(x,t) = Ee^{j(\omega t - kx)} = E[\cos(\omega t - kx) + j\sin(\omega t - kx)]. \tag{7}$$

If time is held constant, the field at $x=0$ and $x=\lambda/2=\pi/k$ (where $k=2\pi/\lambda$) is given by the equations

$$E(x=0, t=t_0) = E[\cos(\omega t_0) + j\sin(\omega t_0)], \tag{8}$$

$$E(x=\pi/k, t=t_0) = E[\cos(\omega t_0 - \pi) + j\sin(\omega t_0 - \pi)]. \tag{9}$$

Equation (11) can simplify down to

$$E(x=\pi/k, t=t_0) = -E[\cos(\omega t_0) + j\sin(\omega t_0)]. \tag{10}$$

Thus, since Eq. (12) is merely the negative of Eq. (10), the electric field at the impedance network is equal to the negative of the field at the antenna. Since electric field inside the cable determines the voltage, the voltage at the two ends of the cable will then be equal, but opposite. The same solution is true for the magnetic field (and hence, current). Thus, since voltage and current have the same magnitude at both ends of the cable, a voltage and current measurement at the matching network will provide knowledge about the voltage and current at the antenna.

D. Additional rf noise reduction considerations

Two additional steps are taken to reduce or remove rf noise in the laboratory; however, these steps did not involve changes to the rf delivery system; rather, they either reduced the ability of rf to couple into a cable, or the ability of the rf to travel through a cable. First of these is improved shielding of all cables in and near the vacuum facility. Second of these is the addition of ferrites to the power and instrumentation cables near the facility. Shielding the cables effectively prevents rf energy from coupling into the cable. Placement of ferrite beads does not stop rf energy from coupling into a cable, rather it reduces the ability of rf to propagate down a cable. The cable shielding is commonly available tubular braided grounding strap. The ferrite beads used on the VTF cables are Laird-Signal LFB43064-100 cylindrical beads (London), which have an impedance at 5 MHz of 53 Ω.

Cable shielding is of major concern in rf systems; even if the rf power cables are shielded, some of the rf power transmitted to the antenna will escape into the vacuum facility. Unshielded cables can pick up the rf power radiated into the facility and transmit it to measurement and control systems. This rf interference can cause high enough noise on instrumentation cables that measurements are impossible and can cause damage to sensitive components if the power absorbed by a cable is high enough. Proper shielding, therefore, is critical to reliable operation of a helicon plasma source in a vacuum environment. Much of the wiring in and around EP systems is unshielded; the cables that provide power to thrusters are usually left unshielded since they are carrying significant dc voltages and currents, and hence any noise in a

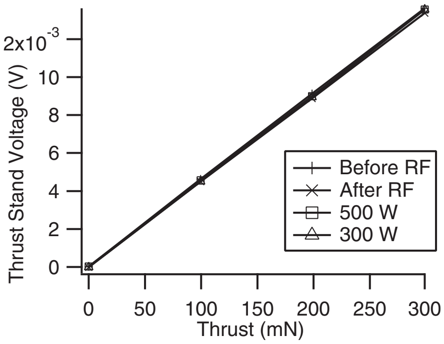

FIG. 7. Thrust stand output voltage vs force due to calibration weights with and without rf power application.

typical EP system will be small in comparison to the power already traveling through these cables. With an operating rf system, however, these unshielded cables act as long antennas, picking up any stray rf in the facility and conducting it back to the power supplies. These cables then re-emit the rf radiation, impeding even the operation of devices that are not connected to the vacuum facility. The same is true of any other cables in the facility; properly grounded shields are necessary for good operation of the rf system. Thus, all of the power cables inside the VTF are shielded, which eliminates the majority of the rf power traveling through the thruster power cables back to the diagnostics.

Ferrites are pieces of magnetic material that are wrapped around a cable to reduce rf conductance. They do so by increasing the impedance of the cable, and hence the rf impedance; they have no effect on dc power transmission. This effect is due to the fact that a wire with current running through it has an associated magnetic field; for a long line of current, this field is expressed by

$$B = \frac{\mu_0 I}{2\pi r}, \tag{11}$$

where μ_0 is the permeability of free space, I is the current in the conductor, and r is the distance from the conductor. Ferrites change this field by changing the permeability of the surrounding medium; since the permeability of the ferrite is much larger than that for free space, the magnetic field and, hence, the amount of energy stored in the field increase. When the current is rapidly changing direction, as in a rf system, the high magnetic field generated due to the ferrite causes a large impedance, which damps the rf signal.

IV. RESULTS AND DISCUSSION

The thrust stand calibration is used as a diagnostic of rf noise interfering with the thrust stand measurement. The calibration procedure is to add a known force to the thrust stand via weights, wait for the null coil to settle, which takes approximately 1 min, then take an output voltage measurement, and add another weight. Measurements were taken with 0, 1, 2, and 3 weights, and the resulting voltages are shown in Fig. 7. Each weight was approximately 100 mN, as measured by a scale accurate to within 0.0001 g (0.98 mN). In order to eliminate the thrust of a helicon from the measurements, the thruster is oriented perpendicular to the axis of the thrust stand. By doing this, the thrust produced by the helicon is perpendicular to the measurement axis of the thrust stand and hence not measured. Thus, any change in the thrust stand measurement is purely due to rf interference, and not a real thrust. Thrust stand calibrations are performed at several rf power levels.

Calibration curves for 0, 300, and 500 W of rf power are shown in Fig. 7. The four calibrations coincide very closely to each other; the greatest difference between any of the calibration curves is 200 μV, over one order of magnitude smaller than the output voltages. A linear regression model is constructed with the least-squares method, assuming that both the thrust (as applied by the calibration system) and the applied rf power are factors in the measured voltage output of the thrust stand. The calculated fit is

$$V = 1.16 \times 10^{-5} + 1.74 \times 10^{-8} P + 0.045 T, \tag{12}$$

where V is the thrust stand output in volts, P is the applied rf power in watts, and T is the thrust in newtons. The dependence on rf power is far smaller than the dependence on thrust; even with the disparity in size between P (up to 500 W) and T (up to 0.3 N), the effect was approximately three orders of magnitude greater for the calibration weights than it was for the rf power.

Error analysis on the linear regression shows that the regression fits the data very well; the R^2 value is 0.9998, and analysis of variance calculates a confidence in the fit of at least 99.999%. The calculated standard deviation is 8.4×10^{-5} V; approximately two orders of magnitude smaller than the voltage signals produced by the thrust stand. Additionally, the maximum possible contribution from rf, at 500 W, is 8.7×10^{-6} V; an order of magnitude smaller than the standard deviation. Generation of confidence intervals on the individual components of the regression shows that the rf power is not a significant contributor; there is only 66% confidence that the rf power is a significant contributor to thrust stand output, as compared to in excess of 99.99% confidence in the applied thrust. Thus, the rf has been shown not to be a significant factor in the thrust stand output by two measurements; the effect on the thrust stand is less than the standard deviation, and the confidence interval showed that rf is only 66% likely to have an effect (and, hence, 34% likely not to have an effect).

V. CONCLUSIONS

The rf power delivery system design allows thrust measurements of rf plasma devices in order to determine performance in potential spaceflight applications. Three major changes are made to how rf power is delivered to the system: the typical balanced transmission line is discarded in favor of an unbalanced coaxial line, the rf system is relocated from near the vacuum facility to the floor of the laboratory, and the transmission line lengths are controlled so as to provide a resonance and improve power deposition in the helicon. The addition of thruster power cable shielding and ferrite cores on all cables into and out of the facility further reduced rf noise to the point where it is no longer a factor in thrust measurements.

Calibrations of the thrust stand show that any error in calibration due to rf energy is indistinguishable from the noise in the thrust stand electronics; the maximum possible effect on thrust stand output due to rf is an order of magnitude smaller than the standard deviation in the data, and the confidence interval calculations show that rf is only 66% likely to have a statistically significant effect on the thrust stand. Thus, the rf power system designed here has enabled thrust measurements on an entirely new class of devices, based on highly efficient helicon plasma ionization, which previously was unavailable due to rf noise.

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