Low-Pressure Helicon-Plasma Discharge Initiation via Magnetic Field Ramping

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***Abstract*—Discharge initiation at low pressures and flow rates is investigated in the Madison Helicon Experiment flowing helicon source. At low pressures (below 14-sccm flow rate), a threshold magnetic field exists for discharge initiation which depends on RF power and gas flow rate. Above the threshold magnetic field, RF discharges start only after a significant delay (approximately seconds) and sometimes will not start at all. This threshold magnetic field is interpreted using electron multipactor arguments. A technique is described for initiating discharges at low flow rates and pressures ($\lambda_{\mathrm{en,iz}} > L_{\mathrm{system}}$) and high magnetic fields (above the threshold value). Without a static magnetic field present, the RF power is turned on, and a lower density ($< 10^{11}$ cm^{-3}) unmagnetized discharge occurs. The magnetic field is then applied, and the discharge transitions to the higher density (up to 10^{13} cm^{-3}) regime. Using this method, magnetized discharges can be started at flow rates as low as 1 sccm (1.8×10^{-4} torr at $z = -91$ cm, 1.7×10^{-5} torr at $z = 105$ cm) at 500 W in a 1.04-kG magnetic field. This technique can be used to initiate low-pressure helicon discharges for basic plasma science experiments and other applications.**

***Index Terms*—Breakdown, helicon, multipactor.**

I. Introduction

INITIATION of low-pressure helicon discharges is important for several areas of low-temperature plasma research. Low-pressure (as low as 1 millitorr) inductively coupled plasmas are used for plasma processing [1]. There is also some evidence that the electron distribution function in low-pressure plasmas has a non-Maxwellian character [2] of interest for basic helicon-plasma wave coupling studies. Double layers have been shown to exist in low-pressure magnetized plasmas [3], and there is evidence that these occur when the ion–neutral mean free path for ionization is longer than the magnetic field spatial gradient scale length in an expanding plasma [4]. The low neutral density in low-pressure discharges also enhances the effects of neutral depletion [5] and plasma acceleration, allowing for better study of its effects in our system [6] and others. Additionally, research groups in the low-temperature plasma field have expressed interest in techniques for starting helicon discharges at low pressures (below a few millitorr). In this short paper, we describe a viable technique to initiate low-pressure helicon discharges. In addition, we qualitatively describe the mechanisms responsible for the discharge initiation in this regime.

II. Previous Work

RF breakdown in low-pressure gases is a well-studied phenomenon [7], [8]. As background neutral pressure decreases, electron–neutral ionizing collisions become rare within the system dimensions. Breakdown is then due to resonant secondary electron emission, known as the multipactor process, which then causes an avalanche discharge. Multipactor can occur over a wide range of frequencies and powers and can be both useful in some applications and detrimental in others [9].

Perry *et al.* [10] and Boswell and Vender [11] both explored breakdown in low-pressure helicon sources for plasma processing. An intense burst of fast (200 eV) electrons was seen during the first microsecond of the plasma pulse, leading to the conclusion that breakdown is due to a multipactor resonance along the static magnetic field lines intersecting the chamber walls. The system pressure was low enough (0.5 mtorr) such that the mean free path ($\lambda_{\mathrm{en,iz}} = 1/\sigma_{\mathrm{en,iz}} n_n$) for electron–neutral ionizing collisions was longer than the system dimensions (50–80 cm). A calculation was done based on the work by Hatch and Williams [7] showing that a two surface multipactor between chamber walls is likely the dominant breakdown mechanism.

A magnetic field, in certain cases, can increase the electric field required for breakdown in RF multipactor discharges. Theoretical [12]–[15], computational [14], and experimental work [16], [17] have shown that the presence of a static magnetic field can affect susceptibility to multipactor breakdown. Experimental work by Sen and Bhattacherjee [16] confirmed the theoretical work by Deb and Goswami [12] showing that, for RF capacitive discharges at low pressures, increasing static magnetic fields require larger RF voltages for breakdown to occur. Hayashi and Takeda [17] investigated the effects of pressure, RF electric field, and static magnetic field on susceptibility to breakdown at pressures below the mean-free-path limit in RF waveguides for fusion applications. As the static magnetic field was increased, with the electron cyclotron frequency remaining above the RF frequency, the RF electric field required to ionize argon and hydrogen gases increased. Valfells *et al.* [13] and Vdovicheva *et al.* [14] both considered single-surface multipactor breakdown in the presence of an

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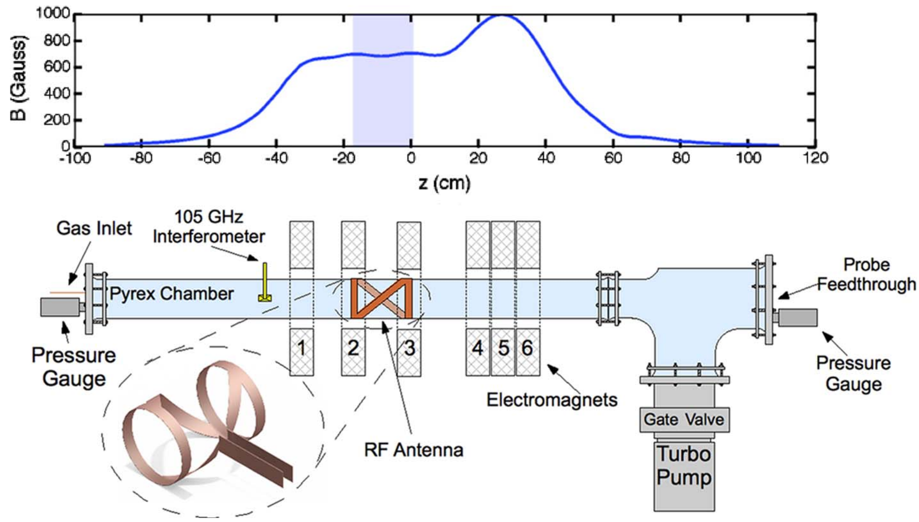

Fig. 1. MadHeX Helicon Facility. The axial magnetic field profile is shown above the system for 120-A magnet current. The RF antenna is pictured on the lower left, and the shaded area in the magnetic field plot denotes its axial location.

external magnetic field. Using Monte Carlo simulations, it was shown that as the magnetic field strength is increased, the lower RF intensity boundary for multipactor onset is raised for certain field configurations. Magnetic fields have also been used to mitigate multipactor effects in RF structures. Geng *et al.* [18] looked at multipactor suppression in rectangular waveguides and found that sufficiently high dc magnetic fields can eliminate multipactor breakdown in WR1800 waveguides.

Neutral pressure, magnetic field strength and direction, and RF electric field vary both axially and radially in a typical helicon experiment, making a general study of multipactor effects in helicons difficult. Our goal is to identify and interpret parametric limits on discharge initiation and characterize a method to overcome these limits.

III. System Description

The Madison Helicon Experiment (MadHeX) helicon facility [6] (Fig. 1) consists of a 1.5-m-long 10-cm-inner-diameter Pyrex chamber attached to a 46-cm-long Pyrex "tee" section. Grounded aluminum endplates terminate the system on either end, at $z = -91$ cm and $z = 105$ cm, where $z = 0$ cm denotes the downstream edge of RF antenna. A 5-mm-inner-diameter copper line supplies argon gas to the system through the upstream ($z = -91$ cm) endplate. The "tee" section is connected to a Varian turbomolecular pump which provides a base pressure of less than 10^{-6} torr throughout the system. An MKS 9000 series mass-flow controller, calibrated for argon gas, controls the gas flow rate, providing a resolution of 0.1 sccm up to a maximum of 20 sccm. Pressure is measured at the endplates by an MKS 910 dual-transducer piezo-based pressure gauge. The base pressure of the system is measured using a Bayard–Alpert ionization gauge located above the gate valve shown in Fig. 1. Fig. 2 shows upstream and downstream pressures as a function of flow rate.

Six 20-cm-bore electromagnets provide a magnetic field up to 1.04 kG in the antenna region, and a magnetic nozzle located at $z = 28$ cm, with a mirror ratio of 1.44. The axial variation of the magnetic field is shown in Fig. 1.

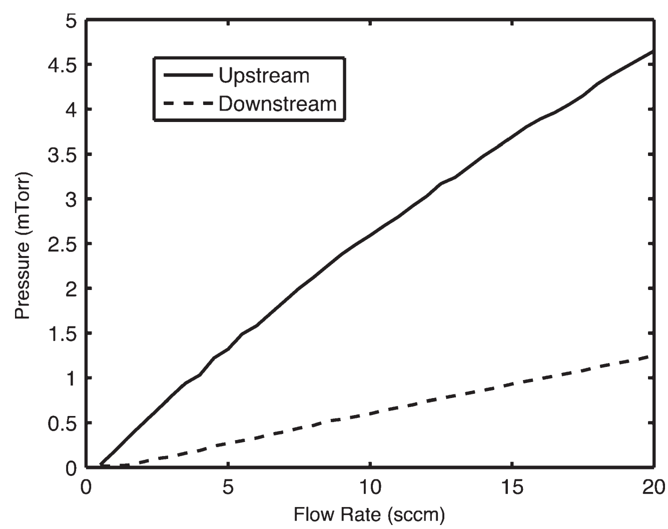

Fig. 2. Pressure at the upstream endplate ($z = -91$ cm) and the downstream endplate ($z = 105$ cm) as a function of argon gas flow rate.

The RF antenna is a half-turn double-helix design, 18 cm long and made from 1.5-cm copper straps, fed as shown in Fig. 1. A 10-kW Comdel model CX-10KS RF generator drives the antenna at 13.56 MHz through a tunable capacitive matchbox, with less than 2% of the power reflected in steady state and rises to full power in less than 50 μs. The generator is capable of pulsed (variable pulsewidth, 5 ms to several hundred milliseconds) or steady-state (several seconds or more) operation.

To measure line-averaged electron density during the magnetic field ramping, 105-GHz microwave interferometry [19] is employed. A Gaussmeter (F.W. Bell Model 6010) is used to measure magnetic field strength on-axis during magnetic field ramping when the system is open to air.

IV. Experimental Data

Helicon discharges can be initiated in our facility at flow rates higher than 14 sccm at static magnetic field values as high as our dc current supply can provide (1.04-kG antenna region,

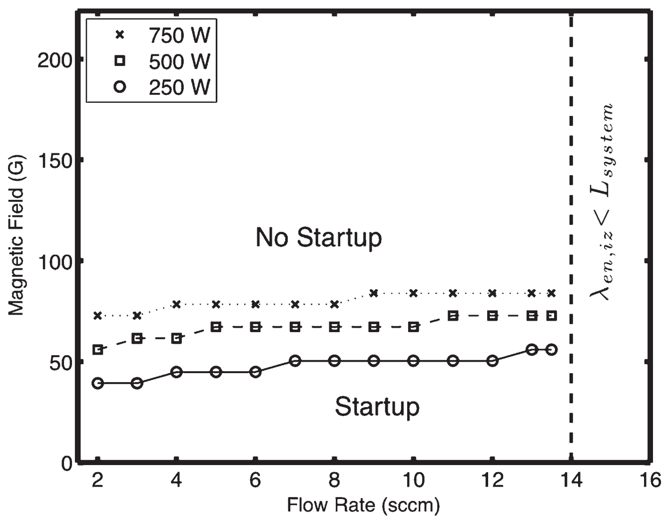

Fig. 3. Magnetic field threshold for discharge initiation, as a function of argon gas flow rate, for three RF input powers. Magnetic field values are on-axis values at $z = 0$ cm. Discharges can be initiated at magnetic fields below the plotted threshold values. For flow rates above 14 sccm, discharges can be initiated for magnetic fields as high as our magnet supply can provide. Startup is defined as the ability to start the discharge without noticeable delay.

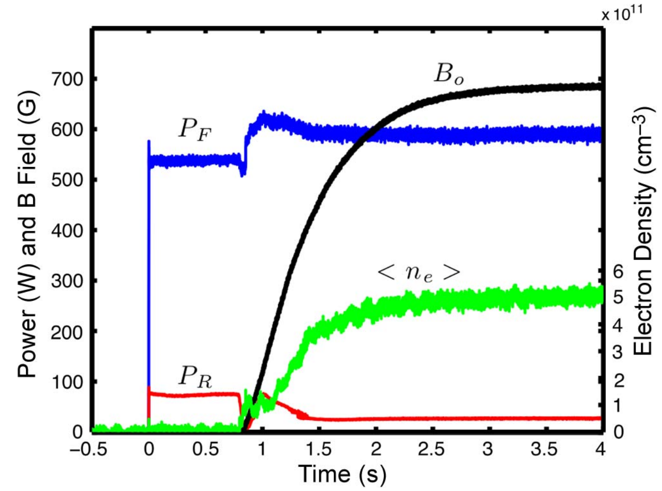

Fig. 4. Line-averaged electron density ($\langle n_e \rangle$, microwave interferometry), forward (P_F) and reflected (P_R) powers at the capacitive matchbox input (directional coupler), and magnetic field on-axis (B, Hall probe) as a function of time during magnetic field ramping. The gas flow rate is 5 sccm, the final magnet current is 120 A (670 G at $z = 0$ cm), and the RF power is 600 W. The magnetic field $B_o(t)$ was previously measured without a plasma. The magnet and RF supplies are engaged at time $t = 0$ s.

1.5-kG nozzle peak). However, for flow rates below 14 sccm, there is a maximum magnetic field for discharge initiation above which discharges do not initiate reliably or repeatably. Fig. 3 shows the maximum magnetic field for discharge initiation for coupled RF powers of 250, 500, and 750 W. As the RF input power is raised, the discharge can be started at higher magnetic field values. Discharge initiation is defined as the ability to start the discharge reliably every time RF power is applied. For each threshold field value plotted, discharges were successfully initiated at least four separate times.

A. Field Ramping Technique

In order to initiate helicon discharges for higher magnetic fields ($B > 80$ G) and low flow rates (> 14 sccm), the magnet supply is engaged in a standby mode, and a low-density ($\leq 10^{11}$ cm^{-3}) unmagnetized plasma is formed by applying RF power. The reflected power with no magnetic field can be a significant fraction of the incident power (typically 20%), since the matchbox is tuned to the steady-state magnetized discharge plasma impedance, not the transient plasma that forms without a magnetic field. The magnet supply is then turned on, and the magnetic field ramps up to its setpoint value. In our system, the magnet and RF supplies are engaged simultaneously, but a 0.8-s delay in the magnet supply circuitry allows for plasma to form before the magnetic field begins to rise. The magnetic field ramps to its setpoint value, and the increasing magnetic field changes the antenna coupling and mode structure. The magnet current rise is limited by the time constant ($\tau_{RL} = L/R = 0.5$ s) of the electromagnet circuit, and steady state is reached 4 s after the magnet supply is engaged. Fig. 4 shows line-averaged electron density, forward and reflected powers, and magnetic field as a function of time during this process. Once a discharge is initiated and helicon steady state is reached, the magnetic field can be increased while maintaining a helicon discharge.

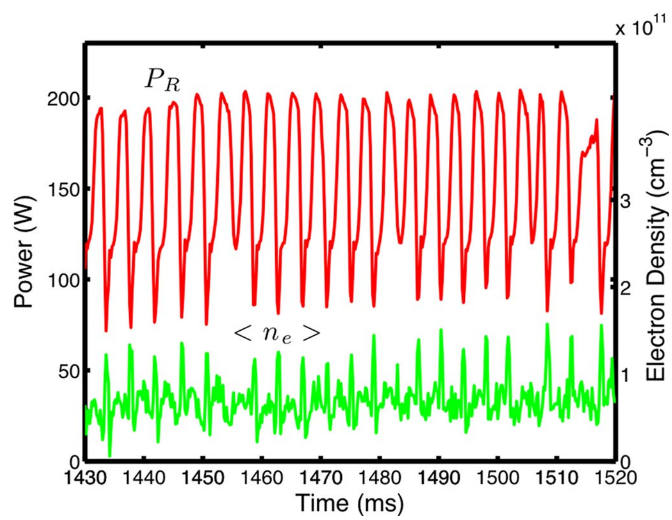

Fig. 5. Line-averaged electron density oscillations observed for low flow rates. Reflected power and electron density are plotted as a function of time for 0.9-sccm flow rate, 500-W forward power setpoint, and 670-G magnetic field at $z = 0$ cm.

Stable discharges can be initiated at flow rates as low as 1 sccm (1.8×10^{-4} torr at the upstream endplate and 1.7×10^{-5} torr at the downstream endplate) at 500 W using the field ramping technique, at final magnetic fields up to 1.04 kG. It should be noted that these very low flow rate discharges may not be classified as helicon discharges if they do not satisfy the helicon dispersion relation. Below 1 sccm, the steady state can become unstable, with oscillations in light output and reflected power having a period of a few milliseconds, as shown in Fig. 5. These oscillations are similar to the relaxation oscillations seen by Degeling *et al.* [20] in a diffusion-fed system which also exhibited a similar process. These oscillations are due to a cycle of ionization, ion transport, and refilling of neutrals in the RF antenna region and also occur in our flowing-gas system at very low neutral pressures. Without a magnetic field present, stable

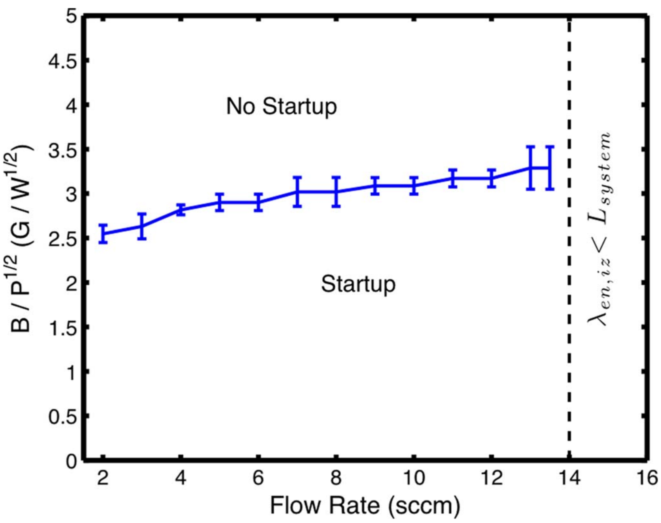

Fig. 6. Average value of $B/\sqrt{P}$ over three RF powers (250, 500, and 750 W) versus argon gas flow rate using data from Fig. 3. Error bars show the standard deviation.

low-density $(< 10^{11}\ \mathrm{cm}^{-3})$ discharges at 800 W were observed at flow rates as low as 0.1 sccm.

V. Discussion

As the argon gas flow rate is decreased below 14 sccm, the ionization mean free path $\lambda_{\mathrm{en,iz}}$ becomes longer than the system dimensions ($\lambda_{\mathrm{en,iz}} = 9.4$ m for a 15.8-eV argon-ionizing electron at 10^{-3} torr [21]), and thus, the mechanism for discharge initiation shifts from a collisional to multipactor process in our highly inhomogeneous system. For flow rates below 14 sccm, at a given RF input power when the magnetic field is increased past a threshold value, the discharge can no longer be initiated. The point at which the mean free path for ionization becomes longer than the system dimension is a function of gas type. For example, if xenon gas were to be used, this threshold would be lower than 14 sccm, since the cross section for xenon (a function of electron energy [21]) is slightly larger than that of argon on average.

The magnetic field, at values above the threshold value, serves to break the resonance condition required by the multipactor process [15]. When the magnetic field is raised from $B = 0$, it allows a multipactor-seeded capacitively coupled plasma to form before the field rises above the threshold value, as long as RF power is applied before the magnetic field reaches the threshold value for the conditions of interest. The plasma final state is unaffected by the ramping speed of the magnetic field. Both the ramping speed and ramping start time relative to the RF power turn-on can be optimized for the application of interest.

As shown by Sen and Bhattacherjee [16], the quantity Bf/E_{RF}, where B is the static magnetic field value, f is the RF frequency, and E_{RF} is the applied RF electric field, is approximately constant at a given pressure (at the breakdown threshold of any of these quantities B, f, or E_{RF}). Although Sen and Bhattacherjee [16] consider a capacitive excitation and this paper is ultimately inductively excited in steady state, since multipactor effects are dominant in the first moments of the discharge when the electron density is very low, the coupling mechanism is dominantly capacitive, in both experiments, very early in the evolution of the discharge. Once a discharge begins and the electron density rises, the RF coupling mechanism strongly affects the steady state. In steady-state plasmas, multipactor effects are severely limited, since a plasma sheath is fully formed at the boundaries [11]. Unlike the current experiment, the capacitive experiment of Sen has only an axial RF electric field. However, the nonzero z, ϕ, and r vacuum RF electric field components of the half-turn double-helix RF antenna in MadHeX can excite electrons in all directions, allowing a comparison of both experiments' Bf/E_{RF} values. Since frequency is constant in our experiment, Fig. 6 shows the static magnetic field value under the antenna (G) divided by the square root of the RF input power $(\sqrt{\mathrm{W}})$, which is proportional to the vacuum RF electric field which influences multipactor breakdown. This quantity is maintained in our case to within 20% at each flow rate for three RF powers examined, providing evidence that multipactor effects dictate startup susceptibility at low pressures in the presence of a static magnetic field.

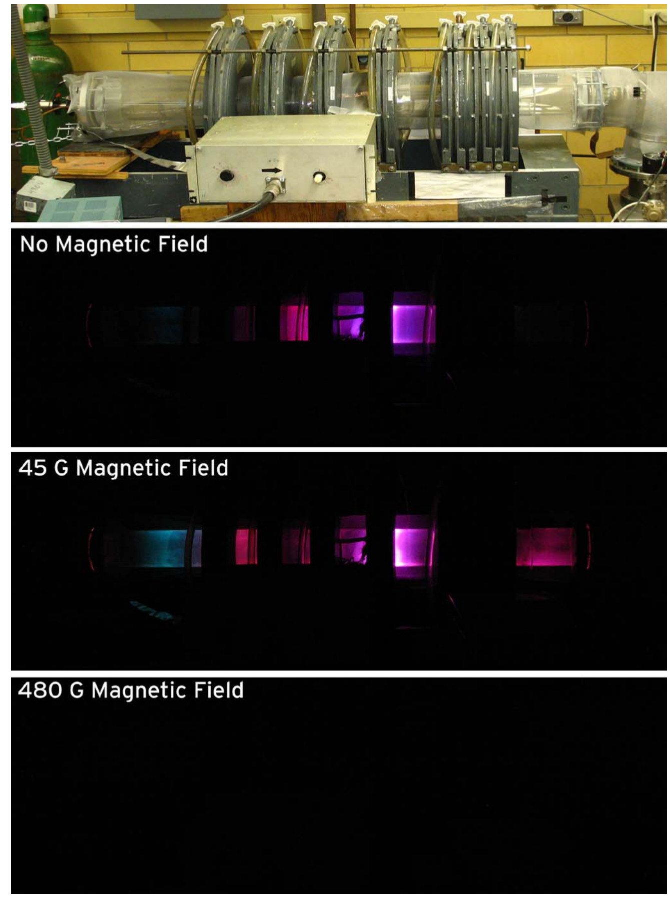

Fig. 7. Long-exposure (8 s) photographs of diffuse glow without a magnetic field, with a magnetic field less than the threshold value, and with a magnetic field greater than the threshold value, taken at night. The three bottom photos were taken with the same exposure time for comparison, and the bottom photo is completely dark. A daylight photograph is shown for reference. Experimental conditions are 500-W RF forward power and a base pressure of 6.6×10^{-7} torr measured by ionization gauge.

Since secondary electron resonance (multipactor) is a surface effect and should occur without a substantial fill gas present, the behavior of the system was investigated without flowing argon gas by closing the gas valve on the system and evacuating it to base pressure. The base pressure as measured by the Bayard–Alpert ionization gauge was 6.6×10^{-7} torr. RF power was applied, and a very diffuse glow was detected that is shown in Fig. 7 for 500-W RF forward power for three magnetic field cases. A positively biased Langmuir probe ($+9$ V) was used to detect the presence of electrons upstream of the antenna at $z = -67$ cm. Again, a threshold magnetic field is observed that is a function of RF power. Below the threshold field, the glow commences, and an electron current is detected by the Langmuir probe, but above the threshold field, the glow does not occur, and the electron current decreases to the noise level. The glow seen is due to electron-excited multipactor-stimulated desorbed gas emission very near the surface of the Pyrex [22]. In addition, as the magnetic field is ramped (at rates up to the $\tau_{RL} = 0.5$ s circuit limit), the Langmuir probe electron current decreases to the noise level, and the glow extinguishes when the magnetic field reaches the threshold magnetic field for the power level of interest. The increasing magnetic field quenches the multipactor process, and the visible glow extinguishes. When the magnetic field is reduced from above through the threshold level, the glow and Langmuir probe current reappear. When argon flow is present in the system, the multipactor-electron-induced glow serves as the seed for an initial capacitively coupled plasma, which then transitions to a helicon discharge under appropriate conditions.

VI. Conclusion

In this paper, a static magnetic field threshold, above which a helicon discharge cannot be initiated at low pressures and flow rates, was explored and discussed in light of previous multipactor research. A ramped magnetic field technique was described and characterized that can be used to obtain helicon argon discharges at low (< 1 mtorr) pressures and higher (> 80 G) magnetic fields. Using this technique, discharges were initiated for flow rates as low as 1 sccm (1.8×10^{-4} torr at the upstream endplate and 1.7×10^{-5} torr at the downstream endplate) at 500 W and 1.04-kG magnetic field under the antenna. This technique is suitable for a variety of low-pressure helicon-plasma source applications for research on space-plasma simulations, materials processing, and plasma-flow studies.

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