

Operation of an Annular Helicon Plasma Source

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The plasma parameters of a nominally 1.5 kW annular helicon plasma source are measured and its feasibility as an ionization stage of a two-stage Hall thruster is investigated. All experiments are performed in a 4 by 7 m stainless steel vacuum chamber at pressures below 3.1×10^{-5} torr for argon and 5.6×10^{-5} torr for xenon. Ion number density, electron temperature, and electron energy distribution function measurements are taken at several axial and radial locations inside the device at each operating condition with a ratio-frequency-compensated Langmuir probe. The annular helicon plasma source is characterized over a range of applied radio frequencies (2–14 MHz), magnetic field strengths (0–400 G), and radio frequency forward-power settings (100–1400 W) for both argon and xenon propellants. The peak ion number density measured in the annular helicon is $2.6 \times 10^{17} \text{ m}^{-3}$ for argon and $2.4 \times 10^{17} \text{ m}^{-3}$ for xenon at 1000 W of radio frequency power. The annular helicon electron energy distribution function peak and shape vary with the radio frequency, from a minimum of 3.7 eV at 13 MHz to a maximum of 15.0 eV at 11 MHz for argon propellant over the preceding operating conditions.

Nomenclature

P_{input}	=	input power
P_{jet}	=	jet power
V_D	=	discharge voltage
V_{nc}	=	neutralizer coupling voltage
γ	=	plume divergence coefficient
ε	=	ionization cost
η	=	efficiency
η_u	=	propellant utilization efficiency

I. Introduction

TWO-STAGE Hall-effect thrusters (HETs), which decouple the ionization stage from the acceleration stage, could achieve a higher efficiency in high-thrust, low-specific-impulse operation than single-stage HETs. The efficiency of an electrostatic acceleration device, which is defined as a ratio of the jet power to input power, is expressed as [1]

$$\eta = \frac{P_{\text{thrust}}}{P_{\text{input}}} = \frac{\eta_u \gamma}{1 + [(\varepsilon + V_{\text{nc}})/V_D]} \quad (1)$$

where η_u is the propellant utilization efficiency, γ is the plume divergence coefficient, ε is the ionization cost, V_{nc} is the neutralizer coupling voltage, and V_D is the discharge voltage. High-thrust-to-power operation requires a high propellant mass flow at a low discharge voltage (100–150 V) [2]. However, Eq. (1) shows that the efficiency of HET decreases as the discharge voltage decreases, because a large fraction of the input power is spent on ionization. Therefore, a method to improve the efficiency of the HET in a high-thrust-to-power operating condition is to replace the dc electron bombardment ionization stage with a more efficient helicon ionization source [3]. Two-stage HETs, which have separate ionization and acceleration stages, have been investigated in the past, but a

helicon source has never been used as the ionization stage [1,4–15]. For a helicon source to serve as the ionization stage of a two-stage HET, it must produce steady-state plasma with an ion number density and electron temperature appropriate for the acceleration stage. Past investigations show that the xenon HET acceleration stage requires an inlet ion number density in the range of 1.2×10^{17} to $1.6 \times 10^{18} \text{ m}^{-3}$ [16–18].

A helicon plasma source is a high-density, high-efficiency plasma source that sustains steady plasma production through absorption and propagation of helicon waves [19]. The wave is launched by sending RF waves along an applied axial magnetic field [20–23]. A cylindrical helicon source is not readily incorporated into the annular discharge chamber of a HET. However, if a helicon plasma can be excited in a coaxial configuration, the source can feed a high-density plasma into the acceleration stage of a HET and other coaxial accelerators [24]. The theoretical existence of annularly bounded helicon waves is discussed by Yano and Walker [25].

The annular helicon (AH) theoretical model and trade studies indicate that the plasma number densities required by a two-stage HET are attainable in this configuration [23]. Recent works show that the AH reliably produces plasma throughout the regime of interest with RF power in the 7–14 MHz RF range at magnetic field strengths of 0–400 G [21,23]. This research effort characterizes the plasma source as a function of axial and radial locations, RF forward power, magnetic field, mass flow rate, and RF.

II. Experimental Apparatus

A. Facility

All experiments are performed in the vacuum test facility (VTF), a stainless steel vacuum chamber with a diameter of 4 m and a length of 7 m. Two 3800 ft³/min blowers and two 495 ft³/min rotary-vane pumps evacuate the facility to moderate vacuum (30 mtorr). To reach high vacuum (10^{-7} torr), the VTF employs six 48 in. diffusion pumps. The VTF pumping speed is varied by changing the number of diffusion pumps in operation. The combined pumping speed of the facility is 600,000 liter/s on air and 155,000 liter/s on xenon, with a base pressure of 1.2×10^{-4} Pa (9.5×10^{-7} torr).

A Varian model UHV-24 ionization gauge with a Varian senTorr vacuum gauge controller monitors the chamber pressure. The UHV-24 ionization gauge is calibrated for air by the manufacturer. The ionization gauge measures pressure over the range of 10^{-2} Pa (10^{-4} torr) to 10^{-10} Pa (10^{-12} torr) with an accuracy of $\pm 20\%$.[‡] The VTF also uses a tubulated Kurt J. Lesker Company (KJLC) model

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[‡]Data available online at <http://www.varianinc.com/cgi-bin/nav?products/vacuum/measure/index&cid=IPMHIKJQFO> [retrieved 19 May 2009].