Probe diagnostics of the plasma plume created by a magnetic nozzle of an inductively coupled plasma source

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Abstract. The Air-Breathing Helicon Plasma Thruster, a thruster utilizing ambient air which is suggested to support small spacecraft on very low Earth’s orbits, has been tested successfully. Using a retarding field energy analyser and Langmuir probe, the specific impulse have been confirmed for operating conditions of 1.5 mg s\(^{-1}\) of air, 50 mPa gas pressure, 120 W of radio-frequency forward power at 13.56 MHz, and a maximum axial magnetic field of 200 G at the 200 km attitude. The inductively coupled plasma and ion beam formed have been characterized axially, and the measured beam velocity is about 1100 km s\(^{-1}\) for these conditions.

1. Introduction
Currently, Very Low Earth Orbits (VLEO) are actively used to solve many problems: receiving and transmitting signals for communication systems; space research; Earth remote sensing; warning of emergency situations, etc. Recently, there has been an increasing interest in the use of small spacecraft located in VLEO [1]. Their advantages include the low price of launching (altitude 160–300 km) and the increased resolution of the target equipment.

A key problem that arise in the design of the very low-orbit small spacecraft (SSC) is the presence of aerodynamic force, which decelerates it when SSC flies in the upper atmosphere. For example, for a SSC at an altitude of 200 km with a shape factor \(c_f = 3\) and a cross-sectional area \(S_{SSC} = 1 \text{ m}^2\) the drag force will be 18 mN. The lifetime of a passive SSC on VLEO ranges from several weeks to several months and depends on many factors, especially strongly on the density of the residual atmosphere at the orbit height. The density of the upper layers of the atmosphere, in turn, depends on the time of day, solar activity, location above the Earth's surface, etc. For example, at noon, the heated layers of the atmosphere at an altitude of 300 km have a density of 2 times more than midnight.

In the last decades, a significant interest has been focused on the electrodeless methods of the plasma accelerating [3–6] and using ambient air as a propellant for electrically powered spacecraft propulsion systems [7, 8]. One of these methods is application of a magnetic nozzle.

Plasma flowing through magnetic nozzles has been observed in many natural systems and is used in a variety of terrestrial applications ranging from electric propulsion to plasma processing [9].

A magnetic nozzle, consisting of an applied convergent-divergent axysymmetric magnetic field, constitutes the main acceleration stage of several advanced plasma propulsion concepts such as the Helicon Plasma Thruster [10–12], the applied-field magnetoplasmadynamic thruster [13], the Variable Specific Impulse Magnetoplasma Rocket (VASIMR) [14] and marginally, in the Diverging Cusped Field Thruster [15] and coaxial magneto-plasma accelerator [16].
Similar to de Laval nozzles that convert random thermal motion into directed flow, magnetic nozzles are used to redirect the motion and momentum of the plasma flowing through the nozzle. To this end, a magnetic nozzle can be used to improve thrust efficiency and provide a means of controlling the plume geometry and plasma energy distribution functions.

2. VLEO small spacecraft concept

If the space mission involves the use of a small spacecraft on VLEO, the critical issue is the storage of the propellant on board the spacecraft. For instance, for an SSC on VLEO, the mass of the propellant with its storage and supply systems can be up to 80% of the entire mass of the spacecraft, which, together with the mass of the on-board power plant, which can reach 15–20% of the mass of the spacecraft, can make it impossible to accommodate the required payload. Figure 1 shows the suggested concept of an SSC with an Air-Breathing Helicon Plasma Thruster (ABHPT).

![Figure 1. VLEO Small Spacecraft concept: 1 – device for collecting ambient air (shown schematically); 2 – device for deceleration of collected particles; 3 – collected particles storage; 4 – helicon gas discharge chamber; 5 – helical half turn antenna; 6 – magnetic system; 7 – electrical supply of the magnetic system; 8 – matching network; 9 – RF-generator; 10 – payload and sub-systems; 11 – photoelectric convertors.](image)

The small spacecraft in the suggested concept has a shape of cylinder. Along the axis of the SSX is the thruster duct. The front of the SSX is a device for collecting ambient air (shown schematically, position 1, in figure 1). In the annular space between the thruster duct and the external surface of the SSC, the payload and the sub-systems of the SSC are located. The on-board power system of the SSC can be represented either by photoelectric converters that cover the surface of the SSC or by a radioisotope thermoelectric generator located in the annular space between the thruster duct and the external surface of the SSC.

To assess the mandatory characteristics of the ABHPT for supporting SSC on VLO, we consider the SSC with a cross-sectional area $S_{SC} = 1\, m^2$, 3 m long, in orbit $h = 200$ km. To maintain the considered SSC in a given orbit, the following thrust of the ABHPT will be required:

$$ F_t = F_{drag} = c_f \frac{\rho V_{SC}^2}{2} S_{SC} = 0.018 \, N, $$

Where $c_f = 2.2$ – drag coefficient that is determined by a shape of the spacecraft; $\rho = 2.5 \times 10^{-10} \, \text{kg} \cdot \text{m}^{-3}$ – density of the atmosphere on the 200 km orbit; $V_{SC} = 7.78 \, \text{km} \cdot \text{s}^{-1}$ – speed of the SSC on the 200 km orbit.

The value of the utilization coefficient of the propellant $\beta = 0.95$ is chosen according to the suggestion that the collected particles are slowed down in the device for deceleration of the collected
particles, and also in favor of the high plasma density achieved in helicon plasma sources. Then the specific impulse of the ABHPT:

\[
I_{SP} = \frac{F_t}{\dot{m} \beta} = 980 \text{ m} \cdot \text{s}^{-1},
\]  

(2)

Where \( \dot{m} = 1.5 \text{ mg} \cdot \text{s}^{-1} \) is a mass flow rate which can be achieved on the 200 km orbit by using air collector with cross-section area \( S_{SC} = 1 \text{ m}^2 \).

3. Experimental setup

The laboratory model of the ABHPT, aforementioned in section 2, consists of a quartz glass discharge chamber, with a closed end of quartz glass, 3-mm wall thickness, 50 mm in inner diameter, and a length (and hence insulating plasma cavity) of 200 mm. At the open end of the discharge chamber there is a membrane with a 20-mm diameter hole that served for forming the collimated plasma flow. The discharge chamber is mounted inside the ABHPT structure, which is made of aluminium. The ABHPT structure consists of cylinder for RF protection and two solenoids, the axes of which are mounted parallel to the axis of the discharge chamber.

For the present experiments, the discharge chamber is positioned in line with the ABHPT structure (i.e., the end of the source tube is at \( z = 2 \text{ cm} \)). The solenoids produce a divergent magnetic field with an axial maximum of 200 G at \( z = 0 \text{ cm} \) that decreases to a few gauss downstream (figure 2). A half turn helical antenna 12 cm long constructed from copper surrounds the discharge chamber and is attached to one of the vacuum chamber flange. The antenna is a few millimetres from the discharge chamber to minimize capacitive coupling and to limit thermal effects.

![Figure 2. \( B_z \) component of the dc magnetic field along the axis of the ABHPT (\( z = 0 \text{ mm} \) – the center of the solenoid). The current in the solenoids wire \( I = 2 \text{ A} \) corresponds to \( B = 200 \text{ G} \) (\( l \) – axial position).](image)

The ABHPT is installed inside a vacuum chamber 0.7 m in diameter and 1 m long. The chamber is manufactured from nonmagnetic stainless steel that is resistant to deformation caused by thermal cycles, high vacuum, and outgassing to simulate the vacuum conditions of VLEO, in which the pressures are typically less than \( 10^{-2} \text{ Pa} \) [17]. The vacuum chamber has a turbomolecular/rotary pumping system that maintains a base pressure less than \( 10^{-3} \text{ Pa} \), and the effective pumping speed measured for air is approximately \( 300 \text{ l} \cdot \text{s}^{-1} \). At such pressures, the thermal environment of outer space can be simulated, because the thermal conduction of gases is small, relative to the radiant heat transfer. The chamber pressure is measured using a MKS 220CA Baratron gauge, which is all located at the downstream end of the vacuum chamber.

Four flanges on the side of the vacuum chamber provides feedthrough for the propellant line, power for the solenoids, radio-frequency (RF) power for the antenna and circuits of plasma diagnostics systems. The propellant (in this case, air) is injected into the discharge chamber using polyamid tubing...
attached to its closed end, and its flow rate is regulated by a mass flow controller mounted outside the vacuum chamber. The flow controller used is a MKS Type 2160B mass flow controller.

A RF matching network/generator on the outside of the vacuum chamber is connected to the antenna of the ABHPT by RG-213 coaxial cable and two copper rods enclosed in a copper shield. The matching network is Advanced Energy’s NavioTM digital matching network that uses two tunable vacuum capacitors. The RF generator is Advanced Energy’s Cesar 1000TM. The RF power (13.56 MHz) is maintained at 120 W of forward power to reduce the thermal loading on the ABHPT. For similar reasons, the current applied to each solenoid is limited to 2 A to avoid overheating and melting of the solenoid copper wire.

4. Diagnostics
To confirm ABHPT characteristics needed for supporting aforementioned SSC on the 200 km orbit, the ion energy distribution function (IEDF) and the local plasma potential are measured as a function of the axial position by a retarding field energy analyzer (RFEA) [18,19] and Langmuir probe [20], respectively.

The RFEA is mounted on the centerline of the ABHPT and the space-simulation vacuum chamber with the RFEA entrance orifice facing the ABHPT exhaust. The RFEA consists of three grids and a collector plate. The plasma particles enter the analyzer through a 5-mm aperture in a 0.1-mm-thick stainless steel orifice plate. The orifice plate is in electrical contact with the analyzer housing, which is connected to the grounded space-simulation vacuum chamber. The voltages on the grids of the analyzer are set at -90, -20, and -10 V for the repeller grid, secondary grid, and the collector plate, respectively. The discriminator grid is located between the repeller and the secondary grid. The voltage applied to the repeller grid is sufficient to repel most plasma electrons during the IEDF measurements, and the small bias applied to the collector plate ensures that all ions are collected at the collector. The measured current is the sum of the collector current and the secondary grid current, which corresponds to any secondary electrons emitted from the collector plate upon ion impact. To achieve this, the bias of the secondary grid is set to -20 V. The analyzer is used in the ion collection mode only. The voltage on the discriminator grid is swept from 0 to -150 V, in increments of 0.5 V, with 100 current measurements averaged per increment to produce a time-averaged ion-current-vs-discriminator-voltage (I_i-vs-V_{disc}) curve. These data are collected using a LabView data acquisition system.

The Langmuire probe is mounted on the centerline of the ABHPT exhaust. The voltage on the bias supply is swept from -150 to 150 V, in increments of 0.5 V, with 100 current measurements averaged per increment to produce a time-averaged I-V curve. These data are collected using a LabView data acquisition system. The local plasma potential is determined by derivative of an I-V curve. In this method one should take the point where I_e starts to deviate from exponential growth; that is, where \( I_e'(V) \) has a distinct maximum, a reasonable value for \( V_s \) is obtained.

5. Experimental results and discussion
The characterization of the plasma and ion beam created by the ABHPT was undertaken with a propellant flow rate of 1.5 mg s\(^{-1}\) of air, resulting in a pressure of 50 mPa, magnetic field of 200 G and RF power of 120 W. All measurements are conducted with the plasma in a steady-state equilibrium. \( V_{local} \), measured by Langmuire probe, corresponds to the center of the Gaussian function and at this position is 60 V, relative to chamber ground. This position for RFEA and Langmuire Probe is chosen because the position of the double layer is in the vicinity of the location of the maximum of the magnetic field gradient [21–23]. Figure 3 shows the location of the maximum of the magnetic field gradient.

The potential drop of the double layer \( V_{DL} \), which equals \( V_{beam} - V_{local} \), was found to be 20 V when measured with the RFEA and Langmuire probe 0.8 cm from the exit of the ABHPT. The velocity of the ions in the beam formed by the potential drop \( V_{DL} \) can be calculated using:

\[
V_{beam} = \left( \frac{2e(V_{beam} - V_{local})}{M} \right)^{1/2} = \left( \frac{2eV_{DL}}{M} \right)^{1/2},
\]

(3)
where $e$ is the electron charge and $M$ is the argon ion mass. In this case, the pressure is 50 mPa, $V_{DL} = 20$ V, and $v_{beam} = 11$ km·s$^{-1}$. Figure 4 shows results of the measurements of ion beam potential and local plasma potential inside and outside the discharge chamber of the ABHPT.

![Figure 3](image3.png)

**Figure 3.** The location of the maximum of the magnetic field gradient. The current in the solenoids wire $I = 2$ A corresponds to $B = 200$ G ($l$– axial position).

![Figure 4](image4.png)

**Figure 4.** Local plasma potential $V_{local}$ (open squares) and ion beam potential $V_{beam}$ (open circles) as a function of axial position. The experimental uncertainty on the potential is ±2 V ($l$– axial position).

6. Conclusion
This study has demonstrated the experimental results of the ABHPT testing in VLEO conditions. These results show that the thruster can successfully support SSC on VLEO. We have demonstrated that air ions generated in the helicon plasma source can be accelerated by ABHPT, magnetic nozzle in particular, to velocities of 11 km·s$^{-1}$. However, the obtained specific impulse is very small for outer space missions. Therefore, for these purposes ABHPT could be an ionization stage of the two-stage plasma thruster.

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