Characterization of an Atmospheric Propellant-fed Hall Thruster as a VLEO Simulator

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Air-breathing electric propulsion (ABEP) can allow for extended spacecraft operations in very low Earth orbits (VLEOs). On-ground validation of ABEP prototypes requires to recreate rarefied atmospheric flows, with variable compositions and with speeds of ~8 km/s. In the present work, the possibility to use a plasma thruster to recreate on-ground the VLEO environment is investigated. The selected particle flow generator (PFG), SITAEL's HT5k, was characterized using a mixture of N2 and O2 as propellant, and using a hollow cathode fed with pure nitrogen. Advanced diagnostics, intrusive and non-intrusive, were used to assess the representativeness of the produced atmospheric flows.

I. Introduction

In recent years, the possibility of efficiently exploiting Very Low Earth orbits (VLEOs) is gaining increasing interest among the space community and end-users. To counteract the drag generated by the interaction of the spacecraft with the surrounding residual atmosphere, air-breathing electric propulsion is emerging as a viable concept for long-life missions in VLEO. Funded by the European Commission under the H2020 programme, the Air-breathing Electric THrustER (AETHER) project aims at developing the first propulsion system able to maintain a spacecraft at very-low altitudes for an extended time [1][2]. On-ground testing is one of the most complex tasks in developing plasma thrusters, requiring a representative environment and ad-hoc diagnostics. Recreating a representative environment is even more complex in the case of air-breathing electric propulsion, in which we need to provide an extremely rarefied and highly hypersonic flow to the system intake, with number densities on the

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order of 1e14 to 1e18 m-3 (100 to 250 km altitude range) and velocities on the order of 8 km/s. Interestingly, data extrapolated from experimental studies on 1 kW-class HETs operating with alternative propellants (containing a high percentage of O_2 and N_2) showed that Hall thrusters plume properties are (in terms of averaged velocity and number density of ionized and neutral species) suitable for the on-ground testing of ABEP systems [3]. This approach has been adopted in [4], where the VLEO atmospheric flow was simulated by an air-propellant fed Hall thruster (referred to as PFG – Particle Flow Generator) placed in front of the system intake.

Among others, a main objective of the AETHER project is to devise a specific test setup representative of VLEO orbital flight scenarios. This objective is realized through a series of experimental campaigns, which include cathodes verification with air propellant, the stand-alone verification of a VLEO source (referred to as PFG), the stand-alone verification of an air-breathing electric thruster prototype, and the end-to-end verification of a full air-breathing system, the intake of which will be placed in front of the VLEO simulator. The verification of both hollow cathode and RF cathode [5] operation with atmospheric and pure N_2 propellant was performed at the beginning of 2021. A notable output was the demonstration and characterization of hollow cathode operation with pure N_2 propellant. As such, an N_2-fed hollow cathode was employed as part of the PFG test setup, allowing to increase the PFG representativeness of VLEO. Indeed, a Xe-fed hollow cathode was needed during past test activities. In AETHER, no Xe contaminates the VLEO flow reproduced on-ground.

This paper presents the experimental results of AETHER's PFG characterization test campaign, which was conducted in November 2021 at SITAEL's IV10 vacuum facility. The test item and test setup are presented in Section II, with particular focus on the diagnostic system developed in the framework of the project, consisting of both invasive and non-invasive plasma diagnostics. In Section III, we present the obtained experimental results, both in terms of macroscopic PFG performance and raw data gathered by AETHER's diagnostic system.

II. The Particle Flow Generator Test Campaign

A. Test Description

The PFG experimental campaign was conducted in SITAEL's LFF and IV10 vacuum facilities. The test item, referred to as PFG, consists of the HT5k DM2 [6] fed with N_2/O_2 mixtures and coupled with the HC20h hollow cathode [7] fed with pure nitrogen. At first, the HC20h 20 A-class hollow cathode was tested in stand-alone configuration in the LFF facility. Based on the results obtained, pure N_2 propellant was selected as the baseline for cathode operation as integrated in the PFG. The second phase of the experimental campaign was conducted in November 2021 and consisted of an extensive PFG characterization in the 225V to 375V discharge voltage range with the selected $0.56N_2+0.44O_2$ atmospheric propellant composition at anode mass flow rates ranging between 5 mg/s and 7 mg/s.

The test objective was to verify the discharge and thermal stability of the PFG during continuous operation with atmospheric propellant, and to collect all the necessary data to quantitatively compare the output PFG plume flow properties against a reference VLEO orbital flight scenario. The main test phases included a preliminary verification and acquisition procedure consolidation of the diagnostic system, a xenon Reference Performance Test (RPT), PFG characterization with atmospheric propellant and a final xenon RPT.

With an inner diameter of 5.4 m, an internal length of 6 m, and a pumping capability of 4.2e5 l/s, the IV10 vacuum facility was capable of ensuring pressure levels (as measured by a Leybold ITR90 pressure sensors located 3 m downstream the thruster) below 2.5e-5 mbar throughout all testing activities, Fig. 1.

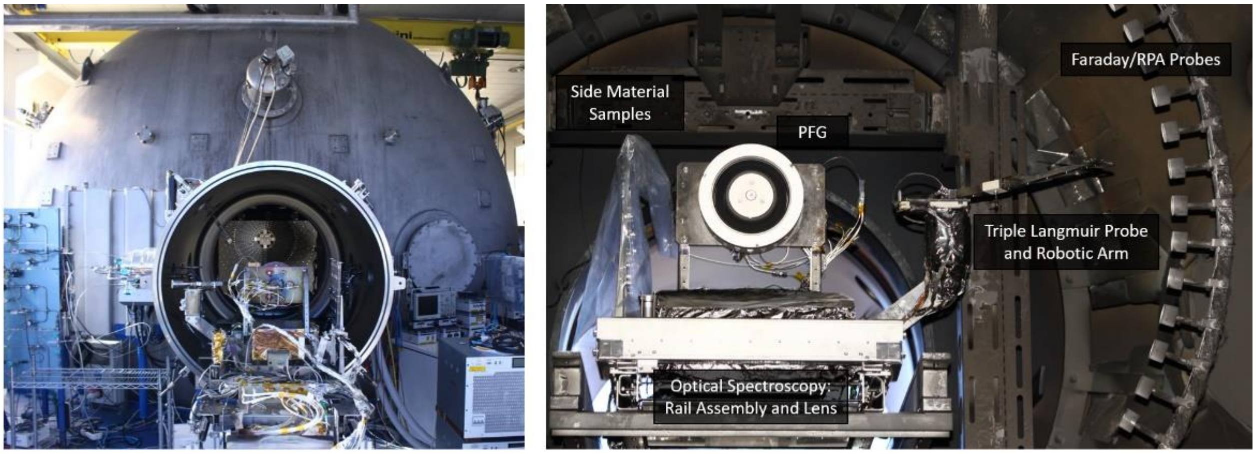


Fig. 1. Left: IV10 Vacuum Facility; Right: PFG Characterization Setup and Diagnostic System.

During the test, the thruster discharge circuit was supplied using a Regatron TC.P.20.500.400.S laboratory power supply, and the discharge current signal was acquired at 10 MHz frequency via a YOKOGAWA-DL850E oscilloscope. The generated thrust was measured by means of a single axis thrust stand with a double pendulum configuration. The sensing element was based on high precision load cells measuring the strain on the flexural elements with an estimated accuracy of ±3 mN. The thrust stand was equipped with an electromagnetic calibrator, generating a reference force when requested, and calibration was performed at least twice a day in both thruster cold and hot conditions. Four laboratory mass flow controllers were used to feed the PFG anode and cathode lines. The Bronkhorst F-201CV-300-AAD-88-V and F-201CV-500-AAD-88V were used to respectively provide Xe and 0.56N2+0.44O2 propellant mixtures to the anode, while two Bronkhorst F-201C-FAC-88-V were used to provide Xe and N2 propellant to the cathode. The fluidic setup allowed to perform smooth propellant transitions and achieve stable thruster operation with atmospheric propellant.

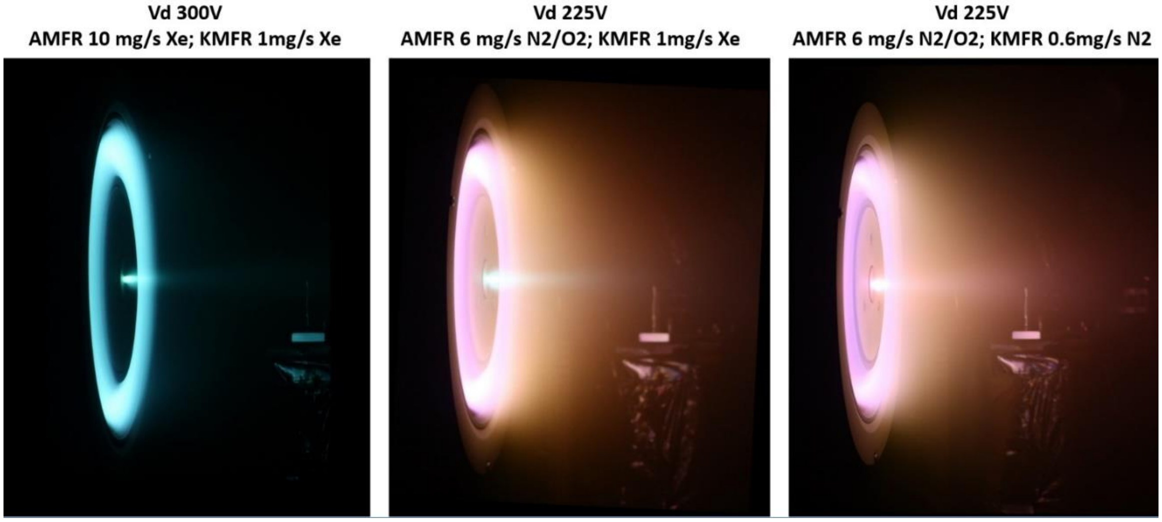


Fig. 2. **Left: PFG operating at Vd=300V, AMFR=10mg/s Xe and CMFR=1mg/s Xe. Center: PFG operating at Vd=225V, AMFR=6mg/s N2/O2 and CMFR=1mg/s Xe. Right: PFG operating at Vd=225V, AMFR=6mg/s N2/O2 and CMFR=0.6mg/s N2.**

As shown in Fig. 2, the thruster was initially ignited at 225 V of discharge voltage, 10 mg/s Xe of anode mass flow rate and 1 mg/s Xe of cathode mass flow rate. Propellant transition was at first performed on the anode line, gradually switching from 10 mg/s Xe to 6 mg/s 0.56N2+0.44O2. Full atmospheric propellant operation was then achieved by providing nitrogen to the cathode line, gradually reducing the injected Xe down to 0 mg/s while increasing the N2 mass flow up to 0.6 mg/s. From this reference operating condition, discharge voltage and mass flow rate were varied at a constant cathode to anode mass flow rate ratio of 1/10, and the thruster was successfully characterized in six different operating conditions. To fully characterize the PFG plume, the diagnostic setup developed in the framework of the project included both invasive and non-invasive diagnostics, together with a set of simulation tools and material samples to be exposed to the thruster plume so to verify materials resistance to atmospheric plasmas.

B. Invasive Diagnostic

The Invasive diagnostic included Faraday Probes, an RPA Probe, and a movable triple Langmuir Probe, see Fig. 1. 18 Faraday probes are installed on IV10 movable rack, which allows for a complete plume scan at a fixed 0.9 m radial distance from the PFG channel exit plane. The Faraday probes measure the ion current density profile in the plume, allowing to assess both PFG plume divergence and thrust vector misalignment [8].

As Fig. 3 shows, a single Retarding Potential analyzer (RPA) probe is installed near the central Faraday probe. The RPA is a plasma diagnostic tool which allows to obtain the ion energy distribution in the plasma thruster plume [9]. The working principle of RPA is based on an electrostatic filtering of the plasma particles by means of a set of grids, which allows only the ions with energy higher than the threshold to reach the probe's collecting electrode. The flux of these ions is measured as a current, which is function of the energy threshold selected by sweeping the probe filtering grid potential within the energy range of interest. During the test, the RPA filtering capability up to 600V was verified.

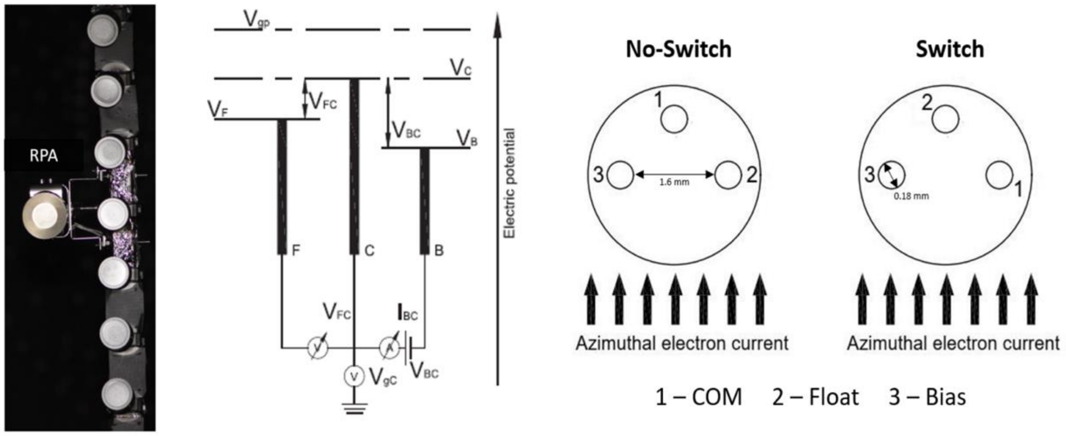


Fig. 3. Left: Detail of RPA probe. Center: Triple Langmuir Probe electrical schematic. Right: Langmuir Probe configurations: No-Switch vs Switch.

The triple Langmuir probe, also shown in Fig. 3, was installed onto a robotic arm located on the PFG side. The triple Langmuir probe is a plasma diagnostic device constituted by three electrodes that allow for the instantaneous measurement of the plasma density, potential and electron temperature [10]. Since Triple Langmuir probes do not need a potential sweep to gather information on the plasma parameters, they are particularly suited to investigate plasma regions were the maximum residence time is constrained. The dedicated arm supports the probe and allows for its rapid insertion and retraction from the plasma domain. During the arm motion, the probe performs a circular trajectory with a radius of 350 mm. The acquisition is only performed in the final 0.27 rad arc of the probe motion in the near plume and channel region of the thruster. A high-speed magnetic actuator moves the arm in and out of the acquisition region in 200 ms. The position of the probe along its motion is recorded with an encoder, ensuring a resolution of the probe position of 0.3 mm. The raw data obtained from each probe acquisition consists of the following:

- COM floating voltage with respect to GND;
- FLOAT voltage with respect to COM;
- Current circulating from BIAS to COM,

where COM, FLOAT and BIAS is how the three probe electrodes are labelled. The voltage difference among the BIAS and COM electrode is imposed. At each operating condition, the following probe acquisition were performed, see Fig. 3:

- BIAS-COM 0V, no-switch configuration;
- BIAS-COM 0V, switch configuration;
- BIAS-COM 36V, no-switch configuration;
- BIAS-COM 36V, switch configuration.

C. Non-invasive Diagnostics

PFG plume spectral emission was acquired via an HR4000 and a MAYA2000 PRO spectrometer. The acquisition chain consisted of a f = 50.2 mm, Ø1" UV Fused Silica Plano-Convex Lens; No. 2 Ø600 micron optical fibers of 5 m length, and a Ø2.75" CF Flange fiber feedthrough.

As Fig. 3 shows, the optical lens was installed onto a movable rail scanner. During each acquisition, the lens was moved along its rail spanning over a length of ±153 mm with respect to rail midpoint with a resolution of 9 mm. The rail middle point was located 60 mm downstream the thruster exit plane along thruster axis direction and 287 mm from thruster axis along gravity vector direction.

D. Material Assessment

The PFG test setup included two matrices of material samples, with the goal of better assessing atmospheric plasma – material compatibility, thus allowing to draw verified guidelines for material selection for air-breathing EP devices. The first matrix was moderately exposed to the PFG plasma plume and was located on the thruster side. The second matrix was instead directly exposed to the thruster plume and was located on the chamber graphite target right in front of the PFG channel.

III. Test Results

During the PFG characterization test, thermal and discharge stability was demonstrated at discharge voltages of 225 V and 300 V and for 0.56N2+ 0.44O2 injected mass flow rate in the 5 mg/s to 7 mg/s range. The cumulative firing duration with atmospheric propellant was of 10 hours. The reference Xe performance test, performed both before and after the air characterization, was repeatable within acquisition accuracy and showed no evidence of PFG critical damage or degradation.

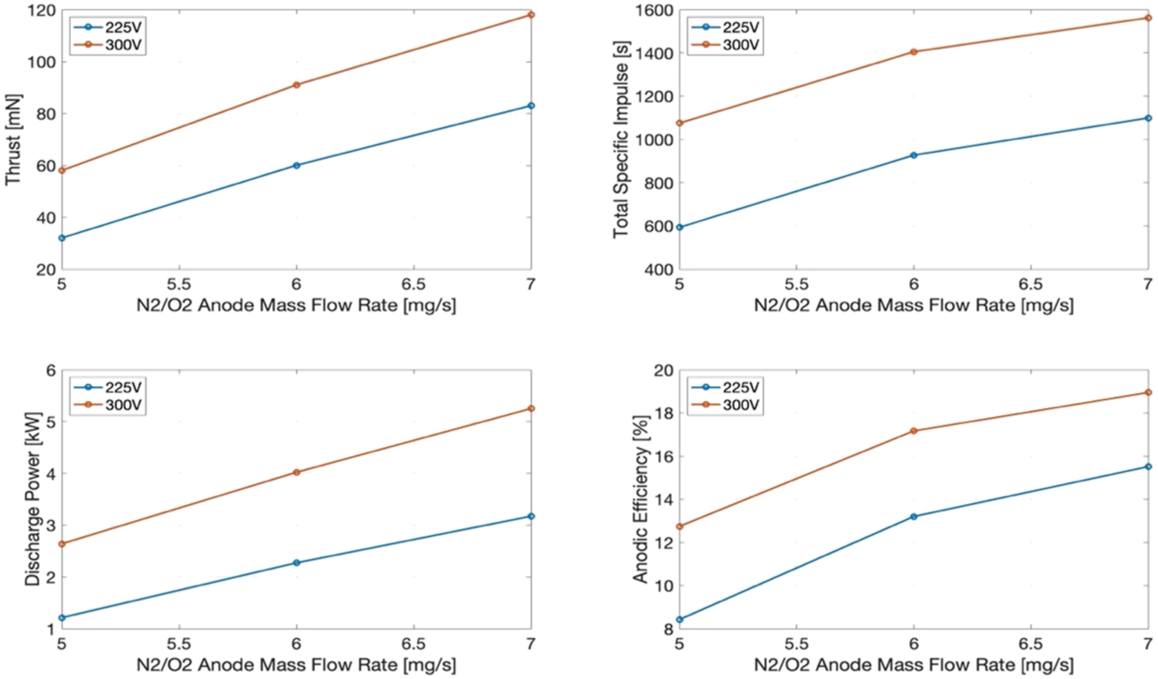
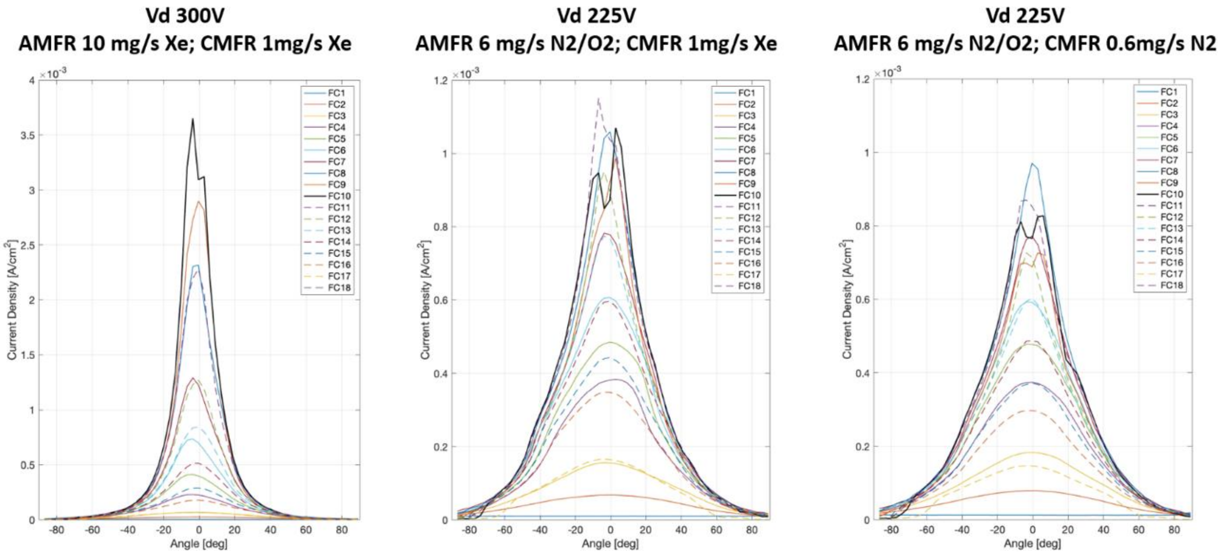


Fig. 4. Demonstrated PFG thrust, total specific impulse, discharge power and anodic efficiency at 225V and 300V, at 0.56N2+0.44O2 mass flow rates between 5 mg/s and 7mg/s.

In all tested points the magnetic shielding seems effective in protecting the channel walls from the plasma. This is particularly evident in Fig. 2, in which plasma detachment from inner and outer channel walls can be clearly observed. Fig. 2 compares the PFG as operating with Xe, with 100% N2/O2 to the anode line and Xe to the cathode line, and with 100% N2/O2 to the anode line and pure N2 to the cathode line. Depending on the operating condition, the demonstrated PFG performance resulted into discharge power between 1.2 kW and 5.2 kW, thrust between 30 mN and 120 mN, anodic efficiencies in the 10% to 20% range, and specific impulses in the 600 s to 1600 s range, see Fig. 4. Even if performance is poor, at 225 V seems promising for VLEO simulation, as specific impulses between 600 s and 1000 s are consistent with the reference orbital velocity of about 8 km/s. Operation with N2 fed cathode decrease both discharge current, thrust and efficiency as compared with Xe fed cathode at the same operating conditions in terms of discharge voltage and anodic mass flow rate.


Vd 300V

AMFR 10 mg/s Xe; CMFR 1mg/s Xe

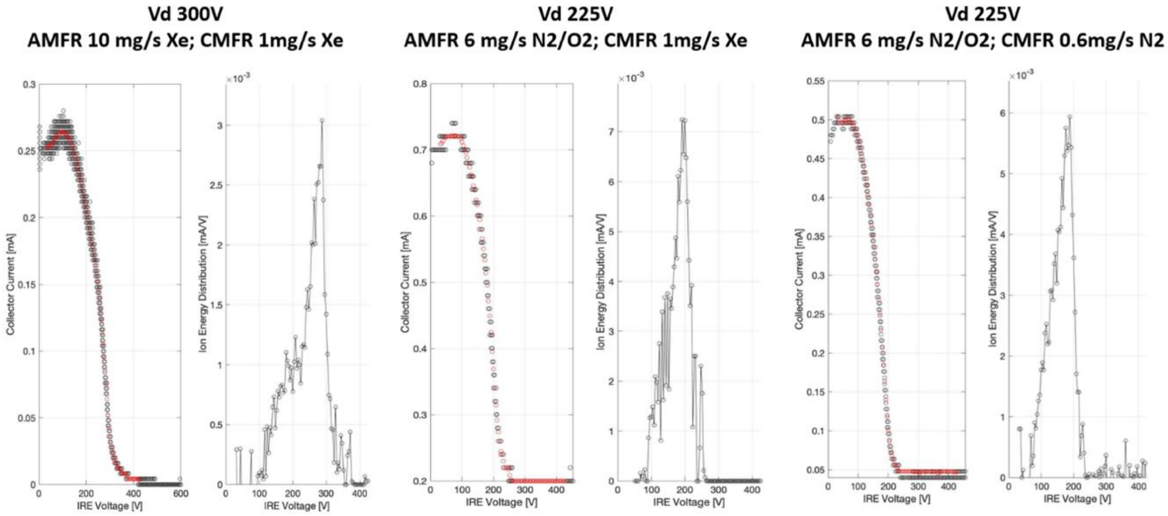
Vd 225V

AMFR 6 mg/s N2/O2; CMFR 1mg/s Xe

Vd 225V

AMFR 6 mg/s N2/O2; CMFR 0.6mg/s N2

Fig. 5. Faraday acquisition. Left: PFG operating at Vd=300V, AMFR=10mg/s Xe and CMFR=1mg/s Xe; Centre: PFG operating at Vd=225V, AMFR=6mg/s N2/O2 and CMFR=1mg/s Xe; Right: PFG operating at Vd=225V, AMFR=6mg/s N2/O2 and CMFR=0.6mg/s N2.


Vd 300V

AMFR 10 mg/s Xe; CMFR 1mg/s Xe

Vd 225V

AMFR 6 mg/s N2/O2; CMFR 1mg/s Xe

Vd 225V

AMFR 6 mg/s N2/O2; CMFR 0.6mg/s N2

Fig. 6. RPA probe raw data acquisition. Left: PFG operating at Vd=300V, AMFR=10mg/s Xe and CMFR=1mg/s Xe; Center: PFG operating at Vd=225V, AMFR=6mg/s N2/O2 and CMFR=1mg/s Xe; Right: PFG operating at Vd=225V, AMFR=6mg/s N2/O2 and CMFR=0.6mg/s N2.

Further analysis of the gathered data is still needed to quantitatively evaluate the produced PFG plume properties and verify its applicability as a VLEO flow simulator. Nonetheless, the gathered raw data already provide a few insights on air propellant operation as compared to traditional Xe propellant. Fig. 5 compares the Faraday probes acquisition for the PFG operating with Xe and air propellant, clearly showing how a significantly larger divergence is associated with air propellant operation. An example of the acquired data from the RPA is provided in Fig. 6, showing the I vs V characteristic of the probe. As reported in [9], the ion energy distribution is proportional to -dI/dV. In Fig. 6 we provide the numerical derivative of the acquired I vs V characteristics, showing how the peak of the ion energy distribution is always a few tens of volts below the imposed discharge voltage, which is consistent with expectations and the working principle of the probe.

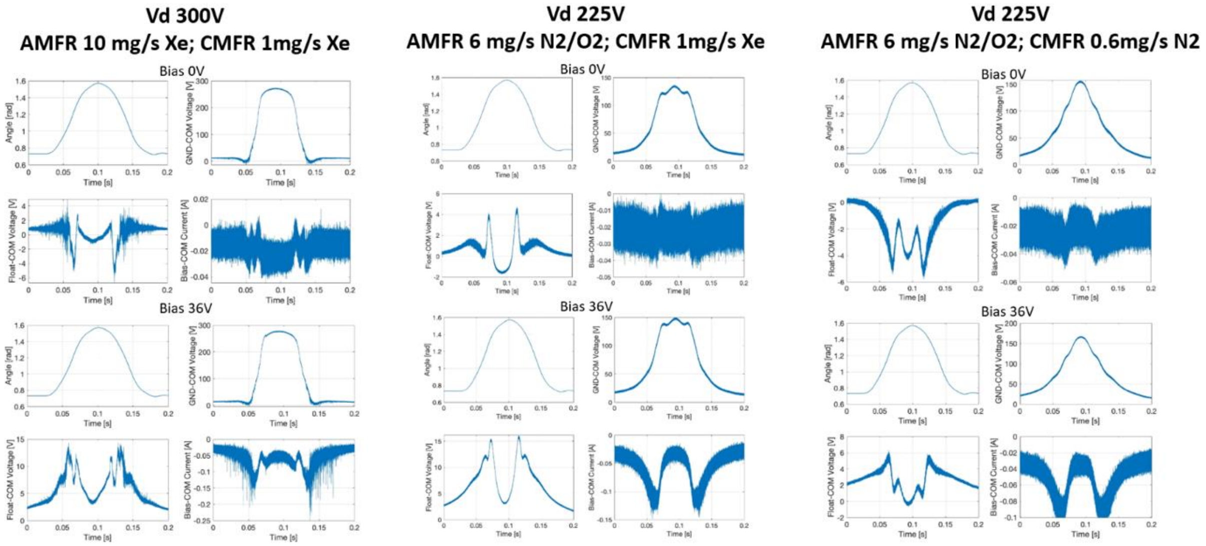


Fig. 7. Acquired Langmuir probe raw data. Left: 0V and 36V Bias in no-switch electrode configuration. PFG operating at Vd=300V, AMFR=10mg/s Xe and CMFR=1mg/s Xe; Centre: PFG operating at Vd=225V, AMFR=6mg/s N2/O2 and CMFR=1mg/s Xe; Right: PFG operating at Vd=225V, AMFR=6mg/s N2/O2 and CMFR=0.6mg/s N2.

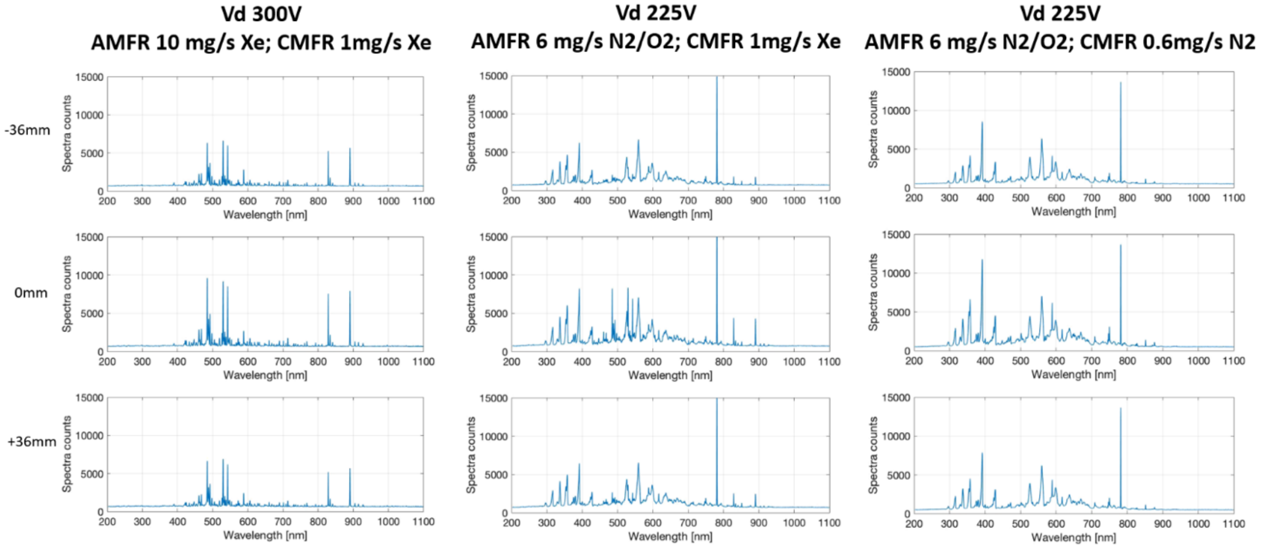


Fig. 8. Spectral emission acquisition. Left: PFG operating at Vd=300V, AMFR=10mg/s Xe and CMFR=1mg/s Xe; Centre: PFG operating at Vd=225V, AMFR=6mg/s N2/O2 and CMFR=1mg/s Xe; Right: PFG operating at Vd=225V, AMFR=6mg/s N2/O2 and CMFR=0.6mg/s N2.

For a 0 V and 36 V imposed BIAS-COM voltage in no switch configuration, Fig. 7 shows a few examples of triple Langmuir probe acquisitions, including probe voltage between Float-COM and GND-COM electrodes and current circulating between Bias-COM electrodes. According to the methodology for triple Langmuir probe data analysis introduced in [10], these data allow for the determination of electron temperature, plasma potential and plasma density in the near plume region of the PFG.

Lastly, an example of spectra emission acquisition is shown in Fig. 8, clearly showing the difference among Xe and N2/O2/N/O emission lines when switching to air propellant.

IV. Conclusions

This work presents the measured PFG performance in terms of thrust and discharge power vs N2/O2 mass flow rate and discharge voltage, together with full diagnostic acquisition data for a reference PFG operating condition. The characterization test campaign demonstrated PFG discharge and thermal stability at an operation point suitable for end-to-end testing of the AETHER ram-EP prototype. Finally, the test campaign allowed for the verification of the diagnostic system developed in the framework of AETHER, including Faraday, RPA, Langmuir probes and plume spectra acquisition.

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