

The Next Generation milli-Newton μ HEMPT as Potential Main Thruster for Small Satellites

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Abstract: Since 2009, Airbus DS in Friedrichshafen has been down-scaling the High Efficiency Multistage Plasma Thruster (HEMPT) principle to the micro-Newton regime and as presented at the IEPC 2015, has developed a HEMPT, which can be operated towards 10 mN. Creating a new cusped field structure, a so-called Advanced Cusped Field Thruster (ACFT) has been developed. A first engineering model (EM) has been built and characterized including direct thrust and plasma diagnostic measurements. The performance data of the thruster operation with xenon are presented, showing thrust levels between 0.4 mN and 10.2 mN, specific impulse (Isp) above 2000 s and power-to-thrust-ratios (PTTR) down to less than 18 W/mN. Since permanent magnets are prone to demagnetization by heat, a thermal model of the engineering model has been created. The thermal model indicates the thermal suitability of the thruster for three different low-earth orbit scenarios. Furthermore, the first test to operate the ACFT with an iodine feeding system has been successfully conducted.

Nomenclature

ACFT	= Advanced Cusped Field Thruster
COTS	= Commercial-of-the-shelf
HEMPT	= High Efficiency Multistage Plasma Thruster
I_{sp}	= Specific impulse
PTTR	= Power to thrust ratio
PPU	= Power Processing Unit
γ	= Divergence efficiency
η_v	= Acceleration efficiency

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I. Introduction

THE High Efficiency Multistage Plasma Thruster (HEMPT) was invented by Günther Kornfeld at Thales Electronic Devices in 1998 as a result of research on travelling wave tubes.^{1,2} Distinguished by the low system complexity, the HEMPT is a promising candidate for several applications such as low thrust-noise attitude and orbit control (AOCS) or as main thruster for small satellites. Airbus Friedrichshafen started a survey in 2009 to down-scale the HEMPT to the micronewton regime in order to explore the low thrust and low gas flow limits, where still reasonable efficiency and controllability can be maintained.^{3,4} The work had initially been triggered by the special requirements of space missions like LISA and Darwin for precision low power AOCS. As one outcome of this survey, a HEMPT has been developed, which is capable to generate thrust up to 10 mN. This paper describes the recent development steps on the next generation milli-newton HEMPT as a potential main thruster for small satellites.

A. High Efficiency Multistage Plasma Thruster

Alternating areas of magnetic field strength B generate a magnetic mirror that reflects charged particles if their velocity in parallel to the magnetic field lines is high enough. Charged particles can be confined between two magnetic mirrors in a so called magnetic bottle. This effect is used in the HEMPT by alternating polarisation magnets to generate the required magnetic field as depicted in Fig. 1. By applying a high voltage between anode and the electron source at the downstream side of the thruster, high energetic electrons from the electron source can be trapped in the magnetic bottles of the thruster. Propellant atoms/molecules injected through the anode into the discharge chamber collide with the trapped high energetic electrons leading to a plasma discharge. The magnetic confinement ensures that the electrons transfer their kinetic energy by collisions into ionization, instead of hitting the anode with high energy.

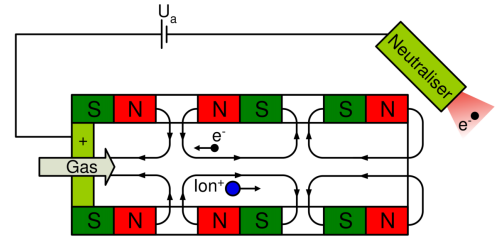


Figure 1: Principle magnetic configuration of a HEMPT. The magnetic field strength increases towards the cusps, forming magnetic mirrors. The anode acts also as propellant inlet.

B. Thruster Test Facility

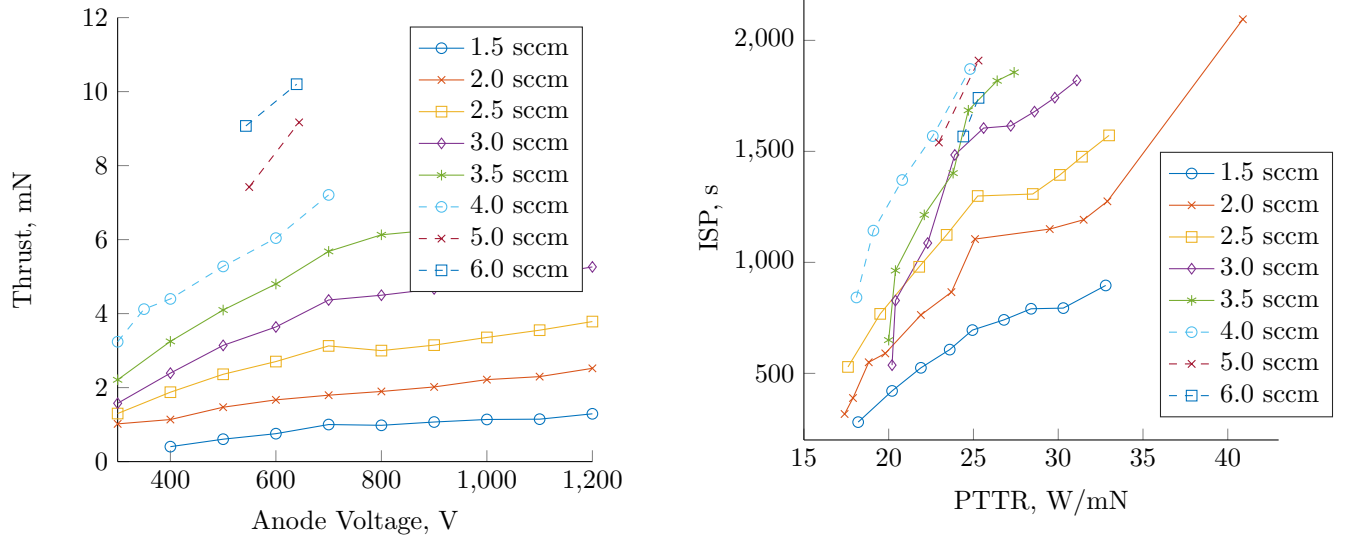
In order to permit a better classification of the presented data, a brief overview of the test facility is given. The test facility consists of a 1500 l vacuum tank, which is evacuated down to $2 \cdot 10^{-7}$ mbar without gas ballast using a 5.5 l/s forepump, two 700 l/s turbopumps and a cryopump with 10,000 l/s pumping speed.⁵ A direct thrust measurement is performed using a double hanging pendulum thrust balance with sub- μ N resolution.⁶ Plasma plume diagnostic is realised with a patented gridless retarding potential analyser system.⁷

II. Performance Data

The magnetic field configuration is the most important parameter that has to be optimized for a efficient thruster. Hence, multiple variations have been tested to increase the performance of the thruster and permit operation over a broad range of thrust levels. These developments lead to a new cusped field structure. The thruster based on this optimised magnetic configuration is called Advanced Cusped Field Thruster (ACFT).

Figure 2a maps the achieved thrust levels as function of anode voltage and xenon massflow. The injected xenon flow has been varied in the range of 1.5 sccm up to 6 sccm, while the anode voltage has been altered in the range of 300 V up to 1200 V. The plot demonstrates that the known throttleability of the HEMPT is also featured by the downscaled version in the mN-range. Thrust levels between 0.4 mN and 10.2 mN have been achieved. Throttling of the thruster can easily be achieved by controlling the propellant injection, while the anode voltage is kept at a constant level. Furthermore, the anode voltage does not need to be controlled precisely since the effect on the thrust is very limited. Hence, when operating the thruster at an

anode potential of 700 V, a throttle range from 1 mN to more than 7 mN is accessible simply by varying the massflow between 1.5 sccm to 4 sccm.



(a) Thrust level map of the latest magnetic configuration of the ACFT. Thrust levels between 0.4 mN and 10.2 mN have been achieved.

(b) Specific impulse as function of the power-to-thrust-ratio of the latest magnetic configuration of the ACFT.

Figure 2: Parameter maps of the latest configuration of the Advanced Cusped Field Thruster.

Figure 2b depicts the specific impulse (Isp) achieved depending on the necessary power-to-thrust-ratio (PTTR) of the latest magnetic field configuration of the ACFT. Low power operation with PTTR down to 17.4 W/mN and a corresponding Isp of 317 s with a xenon injection rate of 2 sccm is possible as well as high Isp operation with specific impulse levels up to 2095 s with a PTTR of 40.9 W/mN. Furthermore, the graph illustrates, that the specific impulse at a certain PTTR increases with increasing the propellant injection rate from 1.5 sccm to 4.0 sccm, whereas a further increase of the massflow leads to a decreasing Isp.

For further analysis of the beam parameters, Faraday Cup and Retarding Potential Analyser measurements have been carried out with the Gridless Retarding Potential Analyser. By way of illustration, Fig. 3 shows the result of a Faraday Cup measurement with the measurement data plotted in red and the extrapolation in blue. The thruster has been operated at an anode potential of 700 V with a xenon massflow of 3 sccm resulting in an anode current of 130.9 mA, i.e. a total input power of 91.6 W. The computed divergence efficiency is 83.5%. Furthermore, a retarding potential measurement has been conducted for every data point in the plot. The overall acceleration efficiency has been calculated to be 78.6%.

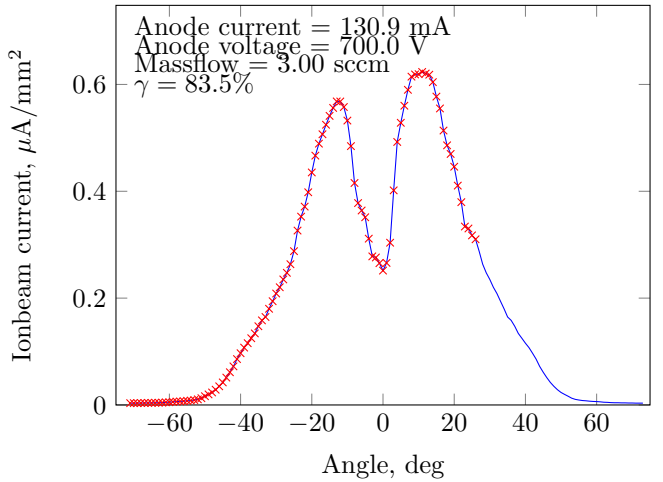
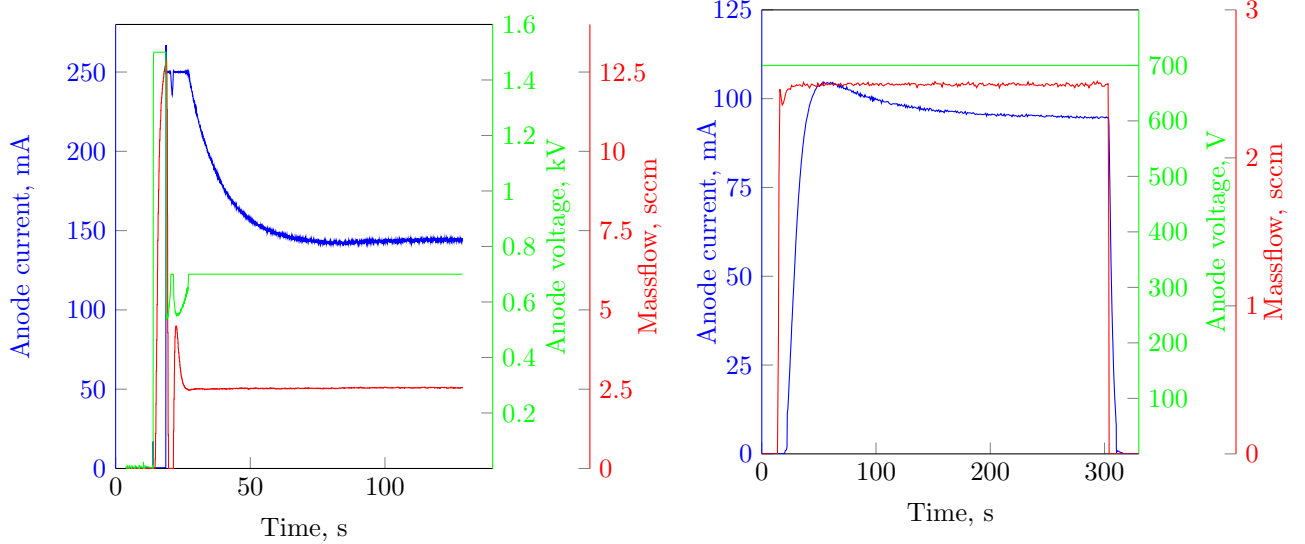


Figure 3: Ion beam current measurement for 700 V anode potential and 3 sccm xenon massflow.

Besides the improved thruster performance compared to previous magnetic configurations, the ignition scheme of the ACFT has been improved as well.

For the previous configurations a peak anode voltage of 1500 V paired with a massflow of 10 sccm had been necessary for ignition of the thruster, leading to pronounced current and thrust overshooting during startup. By altering the anode geometry from nozzles perpendicular to the thruster axis to an anode with nozzles in an angle of 45 deg to the thruster axis, ignition with propellant injection rates down to 1.5 sccm and anode voltages of 400 V have been achieved. Thus, no complicated control circuit is necessary to perform the startup procedure.



(a) Previous mN- μ HEMPT ignition scheme. Anode voltage (green) and massflow (red) had to be significantly higher compared to the actual operation values. As a result, the anode current (blue) was limited by the power supply during ignition.

(b) The improved ignition performance resulted in a simplified ignition scheme. The anode voltage (green) and the massflow (red) are set to the nominal value. After a short delay, the anode current (blue) increases with a neglectable overshooting to the nominal value.

Figure 4: Ignition scheme of the mN- μ HEMPT and the ACFT.

III. Thermal Analysis of the EM

As the thruster is operated typically at input powers between 50 W and 150 W, a suitable thermal control system is required to keep the magnets below the critical temperature of 200° centigrade. To reduce thermal and other unwanted interactions with the spacecraft, a radiation cooled thruster has been developed as a first engineering model of the ACFT. The thruster housing consists of an aluminium magnet retainer system with a 20 cm diameter radiator as part of the housing. Since most of the heat has been assumed to be dissipated in the anode, an aluminium nitride anode holder was designed to electrically isolate the high voltage from the grounded surrounding structure. Furthermore, heatpipes have been attached to the anode holder and the outer part of the radiator in order to improve the heat distribution across the radiator.

The thermal model, which will be used for future improvements of the ACFT has been created with Systema Thermica. For correlating the model to the real thruster thermal performance, a two-step approach has been followed. The thruster has been equipped with five PT-100 thermocouples, two of which are located in the magnet stack, two on the backside of the radiator and one thermocouple attached to the anode holder. In this setup, the thruster has been fired with an input power of around 100 W until the temperature reached a steady-state. Since the real amount of heat, which is lost to the thruster has been unknown, a second test with a heater mounted to the anode holder has been carried out for 10 W, 15 W, and 25 W of heater input power.

After validating the thermal model with the test data, an overall thermal loss of 14.5 W has been com-

puted for an electrical input power of 100 W for firing the thruster with xenon. 60 % of the heat has been lost to the anode as assumed during the design phase, while 38 % are lost close to the inner pole shoes and only 2 % are lost to the pole shoe at the exit cusp. A thermal analysis of the 1.8 KW Thales HEMP-T 3050 DM8, performed by Koch, Harmann, and Kornfeld, revealed thermal losses of around 15 %.⁸ Thus, the total loss and therefore also the loss mechanism of the ACFT and the Thales HEMP-T 3050 DM8 are assumed to be comparable. The magnetic field configurations are, on the other hand, different, resulting in distinct distributions of the losses as the HEMP-T 3050 DM8 loss distribution has been 48 % at the anode, 44 % at the inner pole shoes and 8 % at the exit cusp.

Since the thermal model had been successfully validated and produced reasonable results, an analysis for different low earth orbits (LEO) has been carried out. The thruster is assumed as continuously firing with 100 W input power. Three different cases have been analysed:

- Hot case: Satellite is at 400 km altitude on a 6:00h sun synchronous orbit. The thruster is pointing towards the sun.
- Nominal case: Satellite is at 800 km altitude on a 60° circular orbit. The thruster is pointing towards the direction of velocity.
- Cold case: Satellite is at 1200 km altitude on a 12:00h sun synchronous orbit. The thruster is pointing away from the sun and covered by the spacecraft from Earth IR and Albedo.

Figure 5 depicts the results of multiple orbits for every case for the anode and magnet stack temperature, since these temperatures are the most important ones in the thruster. The magnet stack stays at temperatures between 75 °C and 105 °C for all cases. Hence, the requirement to keep the magnets below 200 °C under all circumstances is fulfilled. As the magnets are the only critical parts of the thruster which have to be kept in a specific temperature range to ensure operation, it can be noticed that the thermal control system would be already suitable for the operation in the orbits analysed.

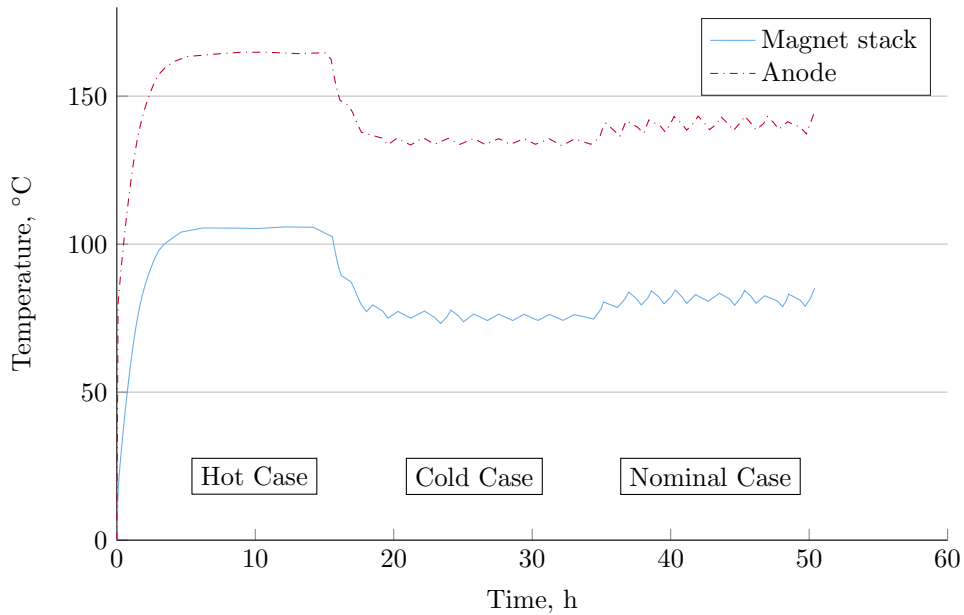


Figure 5: In-orbit simulation of the ACFT for three different cases. The temperature of the magnet stack is kept below 105 °C for a thruster input power of 100 W.

IV. First Iodine Feeding System Test

Besides performance tests with xenon as propellant and an in-depth thermal analysis of the engineering model, the first test of a ACFT with iodine as propellant has been carried out. Iodine has the advantage of being solid at room temperature, which makes a pressurized tank unnecessary in contrast to xenon. As iodine features a low sublimation temperature of 457.2K paired with a low enthalpy of sublimation at standard pressure hence, only a small amount of power is needed for sublimation.⁹ On the other hand, iodine has a lower atomic mass as xenon and is, exposed to atmosphere, corrosive.¹⁰ These features make iodine ideal as an alternative propellant and multiple tests have already been carried out, especially with Busek Hall-Effect thrusters.¹¹

In order to test the ACFT EM with iodine, a laboratory model feeding system has been developed. The feeding system consists of a propellant reservoir, an commercial-of-the-shelf (COTS) PTFE-solenoid-valve and pipework. All three parts are equipped with heaters, the propellant reservoir is also fitted with thermocouples. Since no massflow-controller is used, the actual massflow is unknown and is controlled via the temperature of the iodine tank and the anode current of the thruster as rough indication of the value. As mentioned in the literature, the performance of Hall-effect thrusters with iodine is comparable to the performance with xenon.¹¹ Hence, operating the thruster only via these two controlling elements should be enough for stable and reliable operation. During the first test, the valve has been opened for 419 min with a total time of thruster firing of 380 min. A thrust balance measurement has been performed over this time, with the result shown in Tab. 1. Since the actual massflow is not known, the specific impulse of the thruster operated with the iodine can not be assessed.

Table 1: Comparison of Iodine and Xenon thrust measurement with the ACFT.

Parameter	Iodine	Xenon
Thrust, μN	4722	3695
Anode voltage, V	700	700
Anode current, mA	149	131.6
PTTR, W/mN	24.4	25.1

Given the major advantages of iodine for a small satellite propulsion system and the successful test with the ACFT, further development of the system has been started. The major drawback of iodine is the necessity to sublimate the propellant. To negate this drawback, a sophisticated iodine feeding system has been devised. Using a thermal actuator for the valve and integrating the propellant reservoir to the thruster structure allows the use of the thruster heat loss, instead of removing it via a complex thermal control system. Designing the iodine feeding system in a way that ensures that the system runs in under-critical mode at all operation points, i.e. the heat loss from the thruster is not enough to sustain an iodine massflow that keeps the thruster firing, allows the user to operate the thruster by controlling only the iodine reservoir heater. This mode of operation is only possible with the Advanced Cusped Field Thruster with the simplified ignition scheme as depicted in Fig. 4b.

A first laboratory model of the feeding system has been built and tested. The most important part of the feeding system is the valve, since a malfunction may result in a permanent open or closed position. If the valve is frozen open, the thruster could still be operated but iodine would sublimate even when it is not needed, leading to a reduced mission time. Furthermore, an unwanted thrust is generated. On the other hand, if the valve is frozen in the closed position, the thruster can not be operated further. Hence, the operation cycles of the valve are critical for every mission. To prove the concept, the laboratory model thermal actuated valve has been tested for around 500 open-close cycles without any noticeable change of performance. The required time for opening the valve is primary given by the thermal mass of the system and the heater power applied. Hence, the satellite control can choose if the valve should be actuated quickly with high power input or, if only a limited amount of power shall be provided to the propulsion subsystem before firing, actuating it slowly with low power input.

V. Current status of the ACFT propulsion subsystem

Since the ACFT operation is distinguished by low complexity for an electric propulsion subsystem, a subsystem development for a thruster input power between 50 W to 300 W has been started. Fig. 6 depicts the current status.

Besides the thruster EM and the iodine feeding system, a Power Processing Unit (PPU) has been built that follows the design approach of reducing features to get a low-complex, highly reliable device. Hence, in the current subsystem design, the thruster system is basically controlled by the on-board computer of the satellite. This is possible since the PPU is basically only an Anode Supply Module (ASM) generating the required high voltage for the anode. Furthermore, this voltage can be set by design to a fixed voltage, as the ACFT does not need a complex ignition or operation scheme with multiple control elements.

The iodine feeding system can also be controlled by the on-board computer since only a DC-Signal is necessary to control the heater, i.e. the massflow. The temperature inside the iodine tank and the anode current are sufficient to control the thruster.

Also, a first neutralizer breadboard, resting upon a lanthanum hexaborid (LaB6) thermionic cathode has been built. The use of a hollow cathode had been discarded, as it tends to be less efficient at lower powers. Additionally, it requires propellant, but iodine would poison the LaB6. Up to now, the neutralizer has been working but not characterised.

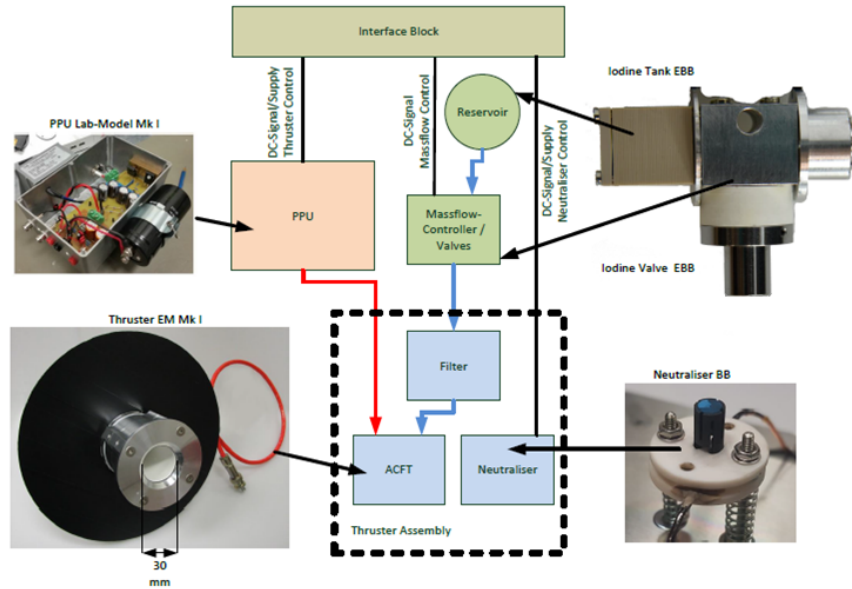


Figure 6: Advanced Cusped Field Thruster propulsion subsystem development status.

VI. Conclusion

The HEMPT has been substantially developed towards a new cusped field structure that we called Advanced Cusped Field Thruster (ACFT). The ACFT supports a simple ignition and operation scheme, which only depends on massflow control. Furthermore, the ACFT has a high throttleability and can be operated with power-to-thrust-ratios down to 18 W/mN and specific impulse up to 2100 s. An engineering model (EM) of the thruster has been build and an in-depth thermal analysis has been conducted demonstrating the reliability of the EM for low-earth-orbit applications. In addition, a novel iodine feeding system has been developed and successfully tested. A complete propulsion subsystem at the current development status has been presented.

Acknowledgments

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