Recent flight data from IFM Nano Thrusters in a low earth orbit

IEPC-2019-A724

Presented at the 36th International Electric Propulsion Conference
University of Vienna • Vienna, Austria
September 15-20, 2019

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The IFM Nano Thruster is a high specific impulse liquid metal Field Emission Electric Propulsion (FEEP) system that has been flown on multiple space missions ranging from 3U Cubesats to 100 kg class satellites. The core component of the thruster is a crown-shaped porous metal ion emitter featuring 28 ion emission sites, with propellant supplied passively by capillary forces, obviating the need for pressurized tanks. The metal propellant used is solid during integration and launch, and is only liquefied in orbit, thus significantly simplifying handling and integration. The thruster itself is a fully contained package of less than 1U including power electronics, with applications ranging from orbit control, formation flight control, attitude control to orbit raising and deorbiting. This paper presents the testing, integration and flight data of multiple IFM Nano Thrusters integrated in a Small Satellite. The paper presents the telemetry data acquired during the commissioning phase of 4 thrusters.

Nomenclature

FEEP	=	field emission electric propulsion
I_{em}	=	emitter current
I_{sp}	=	specific impulse
LEO	=	low earth orbit
LMIS	=	liquid metal ion source

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I.Introduction

THE IFM Nano Thruster is a liquid metal Field Emission Electric Propulsion (FEEP) system that produces thrust by emission of charged ions from a passively fed metal propellant. In this propulsion concept, thrust is generated by electrostatically extracting and accelerating Indium ions to high exhaust velocity. The core element of this propulsion technology is a passively fed, porous ion emitter consisting of 28 sharp emitter tips. The Indium propellant is a safe and inert metal which remains in solid state during assembly, integration and launch, and is only liquified once in orbit. Using differential biasing of the emitter and extractor potentials, the IFM Nano Thruster is capable of operating over a wide range of specific impulse from 2000s to 6000s and beyond. At a total input power of 40W, including heater for propellant liquefication and neutralization to maintain spacecraft charge, the IFM Nano Thruster can provide a nominal thrust of 350μN.

Figure 1. Several IFM Nano Thruster flight modules after acceptance testing

Due to the compact size, the inert propellant which is in a solid state during handling, integration and launch as well as after demise, the passive propellant feeding which does not require any pressurized gases, the high total impulse capability and it modularity that allows clustering of units, the IFM Nano Thruster has been used in a wide range of missions, ranging from 3U Cubesats to spacecraft >100kg, carrying multiple thrusters to adjust for the power and thrust requirement. A significant number of Smallsat business cases are business cases are based on constellations[1-4] which results in large numbers of propulsion systems. In total, over 85 IFM Nano Thrusters were delivered since 2018, with 25 currently in orbit onboard of 7 spacecraft.

II.The IFM Nano Thruster and operational concept

The IFM Nano Thruster shown in Figure 2 is a compact packaging of the heritage ion emitter, propellant reservoir, neutralizer and power processing unit in a Cubesat sized form factor with approximately 80mm height. The ion emitter has been developed at FOTEC (former Austrian Institute of Technology) for decades and is based on the development of Indium Liquid Metal Ion Sources (LMIS) with exhaustive flight heritage[5-9]. The thruster utilizes Indium, a metal propellant, that is in solidified stated during ground handling, integration and launch. The thruster features two neutralizers in cold redundancy, and a digital PPU which provides power and control for all necessary subsections to operate the thruster, and provides telemetry back to the spacecraft onboard computer using standard communication protocols. By controlling voltages of both the emitter and the extractor, the emission current, and thus the resulting thrust, can be decoupled from the acceleration potential, and hence the specific impulse. This allows to operate the thruster in an envelope of specific impulse and thrust. As these operational points can be controlled by varying the applied high voltage potentials, both thrust and Isp can be changed on orbit, allowing to adapt for different mission phase needs.

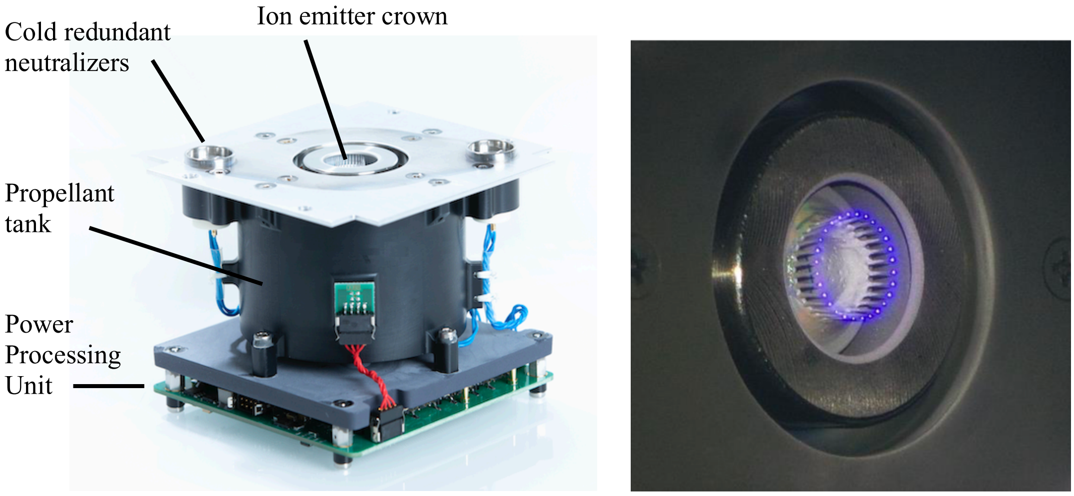

Figure 2. IFM Nano Thruster (left), IFM crown emitter during ion emission (right, from Ref. 10)

Due to the ability to a wide range of different operational points including high thrust and high specific impulse points, it's throttleability which allows it to adjust to available power, as well as the large total impulse in the range of 5000-1000Ns depending on chosen operational points, make the thruster useful for a wide range of applications. IFM Nano Thrusters can be used in mission designs requiring large LEO orbit changes as well as deorbiting, constellation rollout and management, formation flight as well as for momentum dumping in non-LEO missions. It's ability to adjust between high thrust and high Isp operation make it well adjusted to different mission phases, such as time constraint bring-into-service maneuvers combined with deorbiting maneuvers at end of life.

The solid propellant of the IFM Nano Thruster requires liquefication by heating once on orbit, which results in a dedicated operational concept. This typically consists of a propellant heating phase in which the propellant is liquified and then brought to operational temperature. As soon as the thruster is in operational temperature, it enters a "hot standby" mode, from which thrust execution can be readily commanded without timely delay. Once the maneuver is executed, the thruster can return to hot standby mode, or can be switched off which will result in propellant solidification. Automatic propellant solidification at power loss results in an inert system upon end of mission, obviating the need for passivation, or risk of forceful debris generation upon impact.

III.Previous IOD Results

The first IFM Nano Thruster has been successfully integrated into a commercial 3U CubeSat in 2017 after undergoing environmental testing and was launched in January 2018 for a first in-orbit demonstration (IOD) in a 500 km SSO orbit. This IOD has been reported in Ref. **11** and **10**, and marked the first instance of a liquid-metal FEEP thruster to be operated in space as a primary propulsion system.

After an exhaustive commissioning phase, verifying the operation of all subsystems, several thrusting attempts have been performed. The results of the commissioning phase, including functional verification of all thruster subsystems, have previously been published[11,10]. Part of this IOD mission was a test campaign to independently verify the orbital change resulting from 15 and 30min firing of the thruster, as shown in Figure 3.

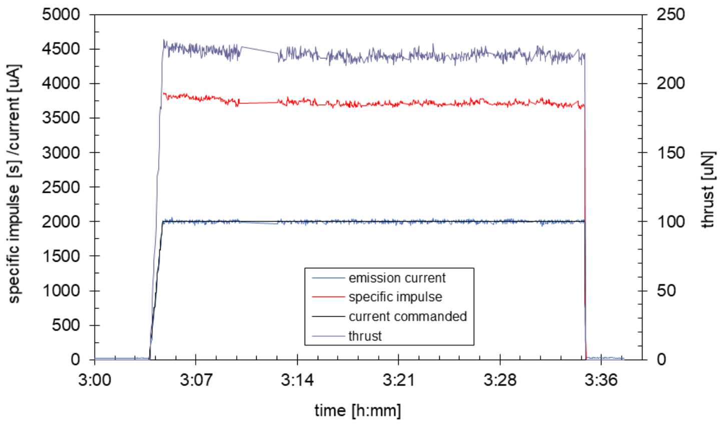

Figure 3. 30min IOD firing for independent orbit change verification[10]

Before and after the thrust maneuver, GPS data were collected for precise determination of the orbit before and after burn. Analysis of the different error contributions lead to estimating the maximum pointing inaccuracy of the spacecraft during the thrust operation to be within 10 deg. The GPS data was then processed using a 50x50 gravity model. Based on the telemetry provided by the thruster, and spacecraft properties and expected alignment, the expected or-bit altitude change for the 15-minute manoeuvre was calculated as 72 m. Comparison of orbit determination before and after the thrust manoeuvre showed an average orbit height difference of (70 ± 5) m. In case of the 30-minute manoeuvre, the height change based on telemetry data and satellite attitude was calculated as 115 m, with GPS data taken before and after the manoeuvre showing an average orbital height difference of 116 m. The comparison of orbit changes calculated based on thruster telemetry data and measured using GPS is summarized in Table 1.

Table 1 Change in average spacecraft semi-major axis due to thrust maneuver, measured from GPS data and calculated from propulsion telemetry, from Ref. 10

Maneuver parameters	**Average change in semi-major axis, m**	
	Calculated from thruster telemetry	GPS measurements
Test 1: I_{em}=2 mA, 15 min	72	70 ± 5
Test 2: I_{em}=2 mA, 30 min	115	116 ± 5

IV. Commissioning Results of the ICEYE X2 thrusters

This section presents the telemetry data of four IFM Nano Thrusters onboard the ICEYE X2 spacecraft, which was launched on Dec 3, 2018 from Vandenberg Airforce base into a 570 km x 587 km orbit with 97.77° inclination. The spacecraft is equipped with a SAR instrument and is part of a commercial earth observation constellation.

A. Thruster Identifiers

The thruster identifiers, supply voltage configurations and timeframes in which the presented data was recorded for each thruster are summarized in Table 2.

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Table 2 Thrusters for which telemetry data is presented

Thruster ID	Supply Voltage	Timeframe of telemetry shown
IFM06-01	28V	Mai/June 2019
IFM06-02	28V	Mai/June 2019
IFM06-03	28V	Mai/June 2019
IFM06-04	28V	Mai/June 2019

All data presented in the sections hereafter are telemetry data outputs downloaded by the respective customers and plotted by ENPULSION. Thrust, voltage and current parameters are directly taken from the downloaded thruster telemetry. Thrust is calculated using a model that has been validated in multiple independent ground test campaigns.[12,12]

B. Thermal thruster telemetry data

Figure 4 shows telemetry data from an initial commissioning test in which the propellant heater section was commanded a triangular power ramp from idle to 10W and back, verifying the expected current draw and power supply duty cycle. The commanded power ramp, the measured response power drawn by the heater and the resulting heater current are shown in the plot, showing good accordance between thrusters and to ground test data.

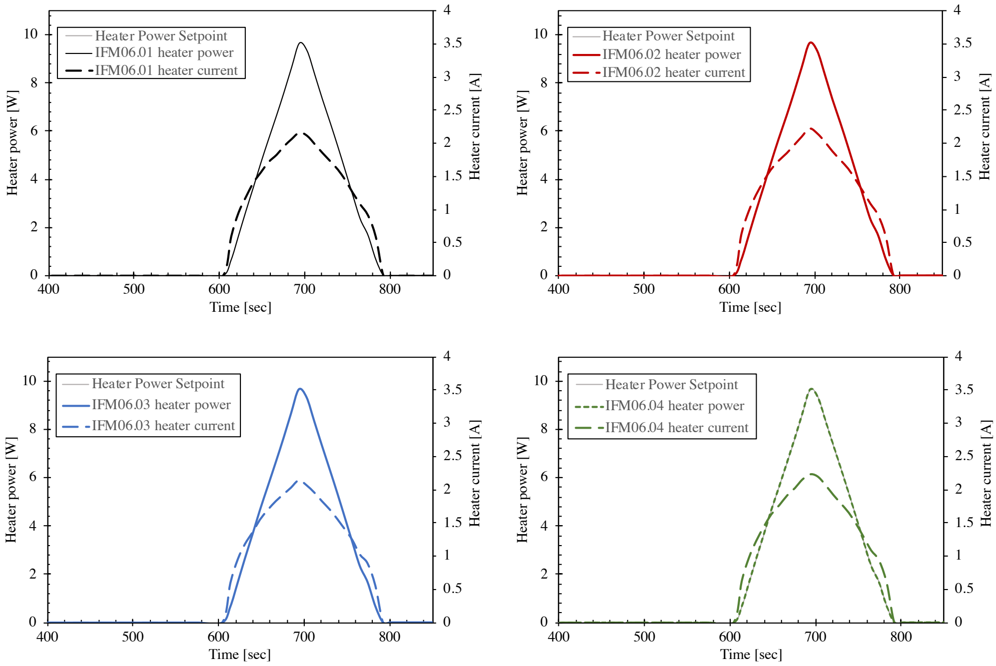

Figure 4. Heater section commissioning for IFM06.01, IFM06.02, IFM06.03 and IFM06.04 showing good repeatability between thrusters

Each IFM Nano Thruster is equipped with temperature sensors that measure the PPU board temperature, the propellant reservoir enclosure and the propellant temperature. Figure 5 shows temperature telemetry data of IFM06.03 during a sequence including multiple firings with increasing thrust levels. Starting from cold conditions at beginning of test, the reservoir temperature (red) shows the increase of propellant temperature during heat-up, liquefication and hot standby phases. At approximately 15,000s into the test, the first low-thrust maneuver is executed, noticeable in the corresponding increase in electronics temperature. The firing sequence is repeated with steadily increasing thrust level, showing that board (PCB) temperature stabilizes below operational limits for all thrust settings.

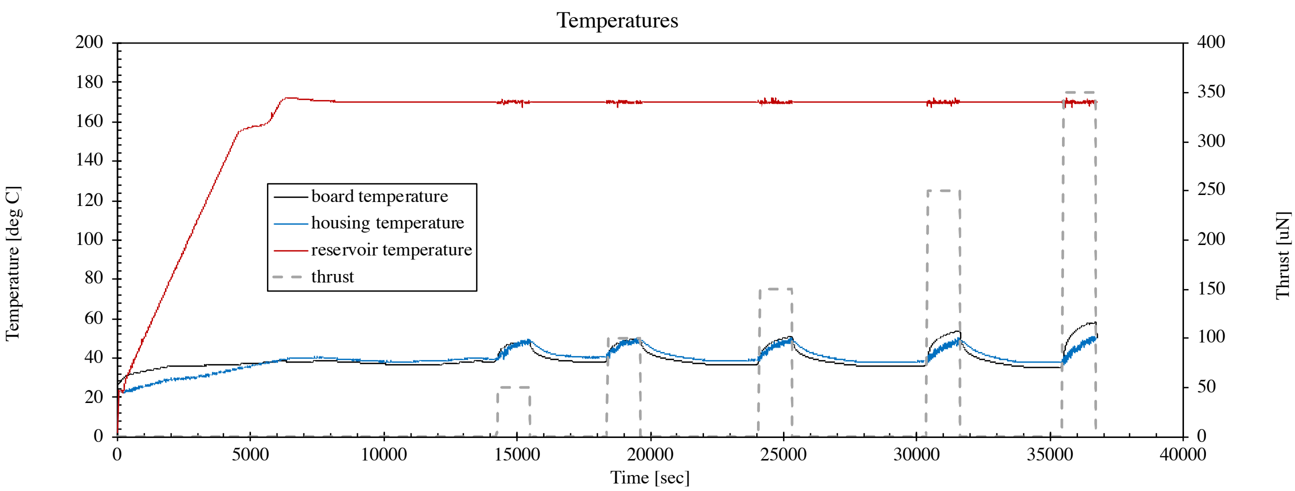

Figure 5. IFM06.03 Thruster temperature telemetry during multiple consecutive firings with different thrust levels

Figure 6 and **Figure 7** show the thermal telemetry parameters of thrusters IFM06.01 and IFM06.04, as well as the corresponding heater section telemetry. This shows the power necessary for propellant heat-up as well as to maintain hot-standby and thrusting phases.

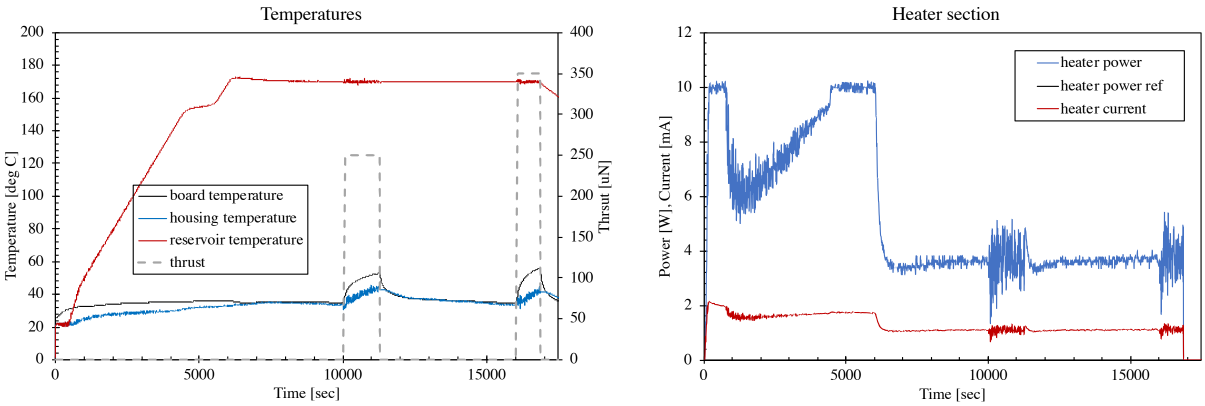

Figure 6. IFM06.01 Thruster temperature telemetry (left) and heater power (right) during multiple consecutive firings

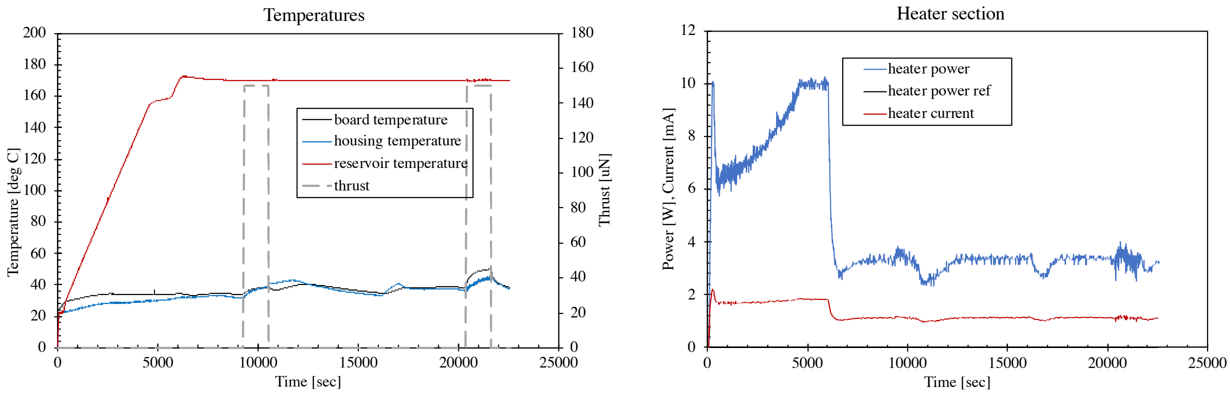

Figure 7. IFM06.04 Thruster temperature telemetry (left) and heater power (right) during multiple consecutive firings

Figure 8 shows the temperature and heater section telemetry during transition from cold ambient state to hot standby state during automatic heat-up mode. In this mode, the thruster increases autonomously the propellant temperature according to a defined heat-up ramp, with a maximum heater power limit of 10W.

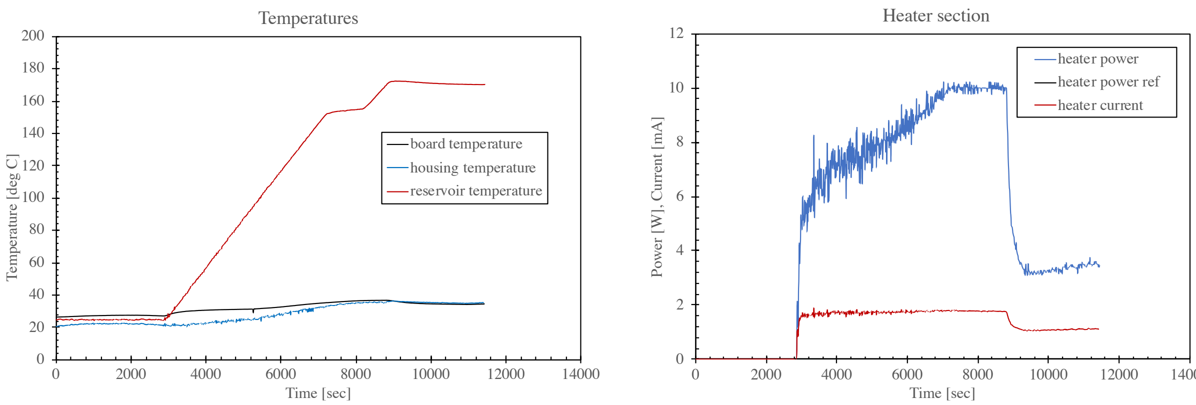

Figure 8. IFM06.02 Thruster temperature telemetry (left) and heater power (right) during transition from cold state to hot standby state

C. Current controlled multiple consecutive firings

Figure 9 shows thruster telemetry of a thruster being fired three consecutive times using a commissioning script that uses current controlled thruster operation, ramping the thruster to 3mA emission current, followed by a step decrease to 2mA before the thruster is commanded back to hot standby mode, before the consecutive firing is commanded. Figure 10 shows the corresponding neutralizer emission telemetry during the corresponding consecutive thrusting operations. During this test, the electron emission current was commanded to 5mA, providing over-neutralization of the ion emission current shown in Figure 5, preventing the spacecraft potential from shifting towards negative potential.

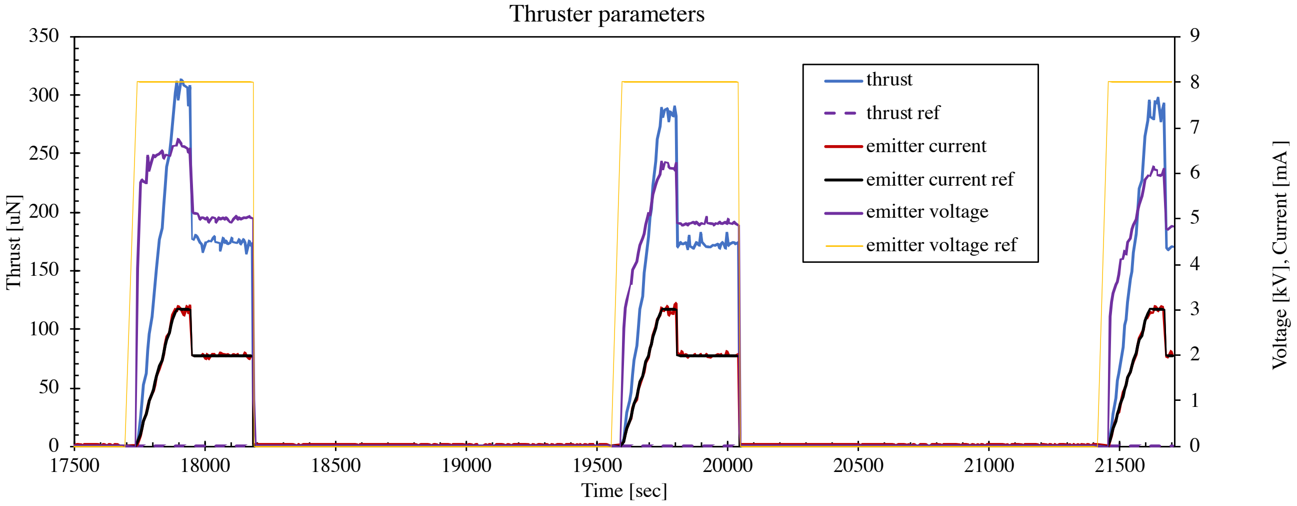

Figure 9. IFM06.02 Thruster telemetry during multiple consecutive firings

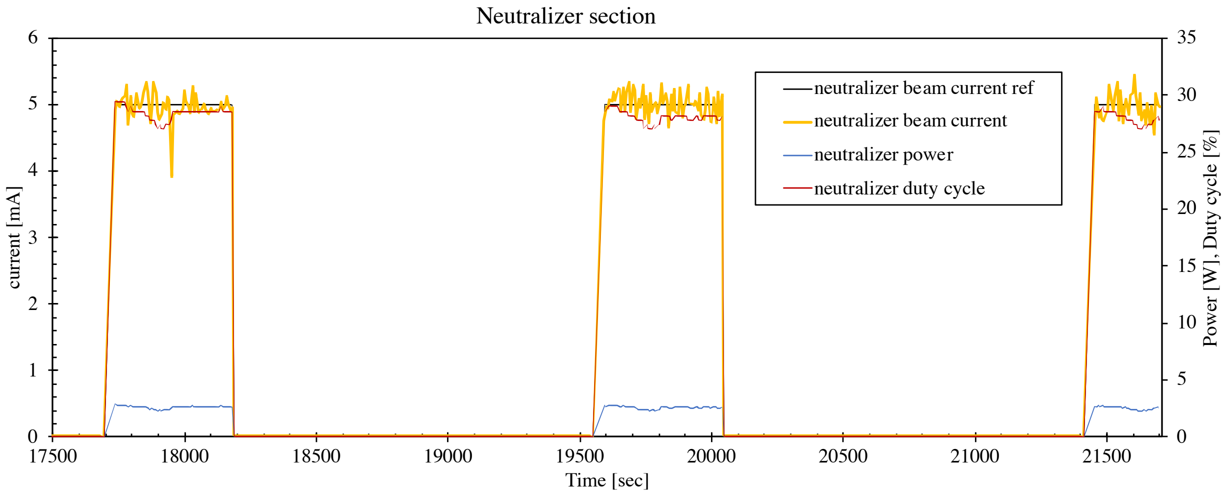

Figure 10. IFM06.02 Neutralizer telemetry during multiple consecutive firings

D. Different thrust level firings including maximum thrust

Telemetry data for firing at different commanded thrust levels for three different thruster are shown in Figure 11 for IFM06.01, in Figure 12 for IFM06.03 and in Figure 13 for IFM06.04. The time axis refers to arbitrary campaign start times of independent tests carried out.

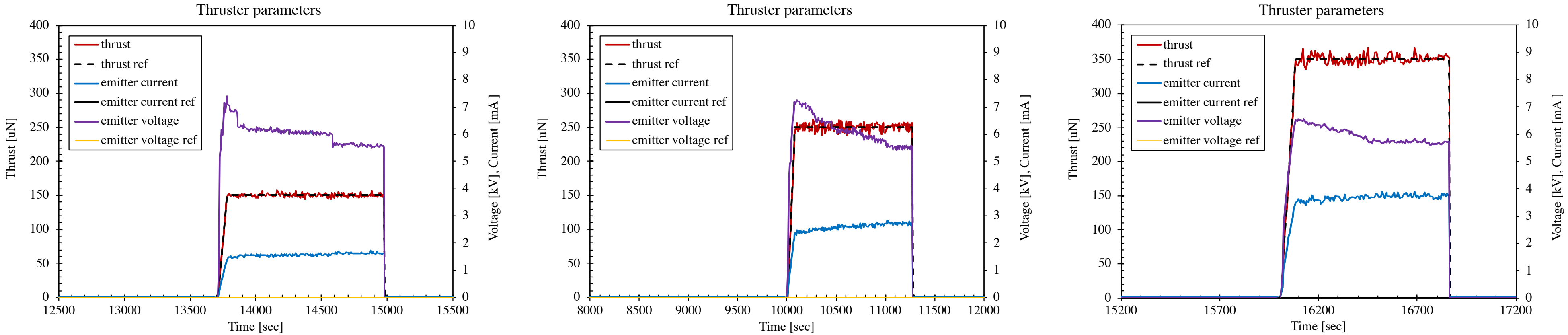

Figure 11. IFM06.01: Thrust-controlled firing of thruster, 150μN (left), 250μN (center) 350μN (right)

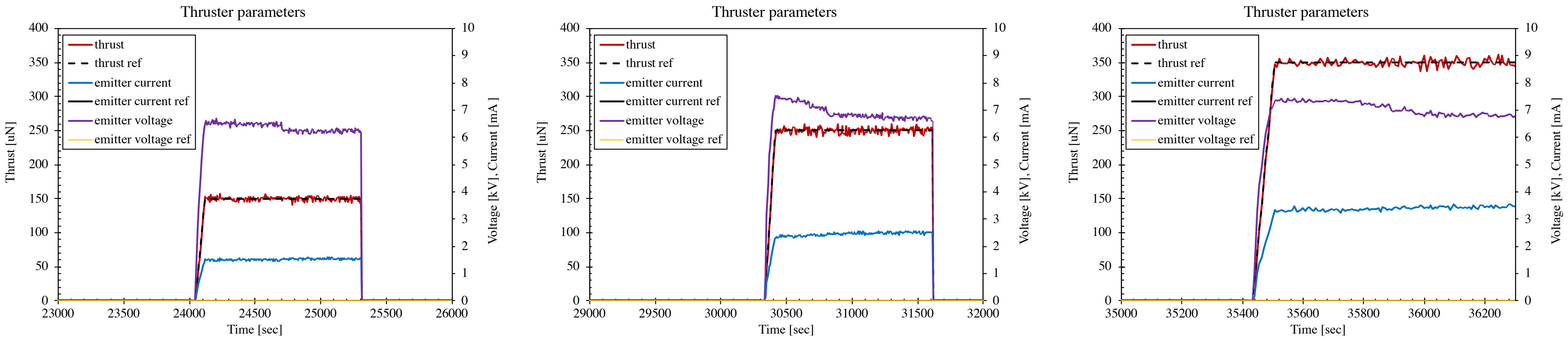

Figure 12 IFM06.03. Thrust-controlled firing of thruster, commanded thrust levels: 150μN (left), 250μN (center) 350μN (right), transient detail shown

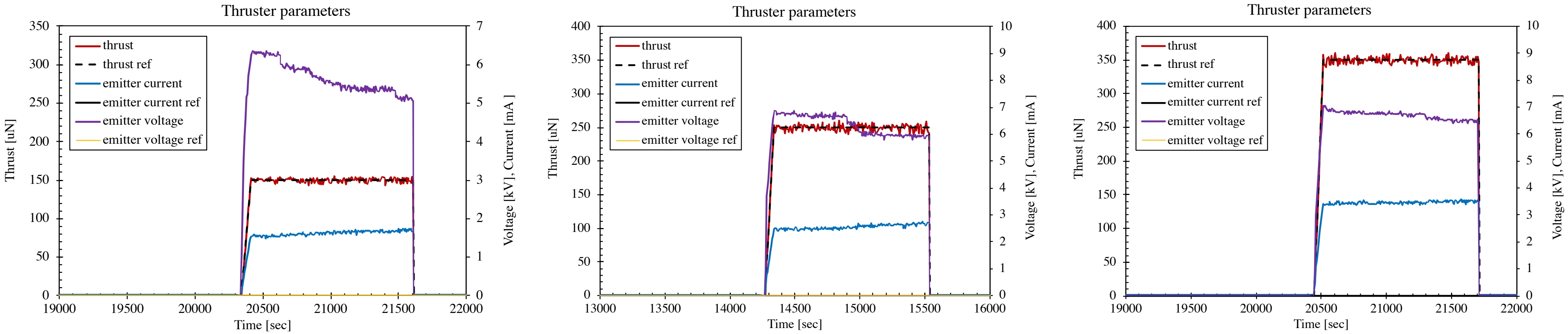

Figure 13. IFM06.04: Thrust-controlled firing of thruster, 150μN (left), 250μN (center) 350μN (right)

The data shown in Figure 11 to Figure 13 has been recorded during the early commissioning of the thrusters, which is noticed by the displayed burn-in characteristics of the emitter, during which the emission impedances of the thrusters are continuously decreasing. Note that while the impedance of the emitters is adjusting, the thrusters are still capable of maintaining the commanded thrust levels. In this thrust controlled operation mode, the PPU controls the emitter voltage within set limits in a way to achieve the commanded thrust set point. As the impedance of the emitter shifts during commissioning, this internal control results in decreasing emitter potential required to achieve the thrust setpoint, in line with increasing emission current due to the changing impedance. This behavior can be seen most notably in the earlier firings, such as Figure 11 (center) and Figure 13 (left). Figure 12 (right) shows a closeup of the ramp sequence from 0 to 350uN, which is performed in a controlled transition in all tests displayed. The good correspondence between commanded thrust ramp and thrust telemetry feedback shows the ability of the thruster to control in transient modes.

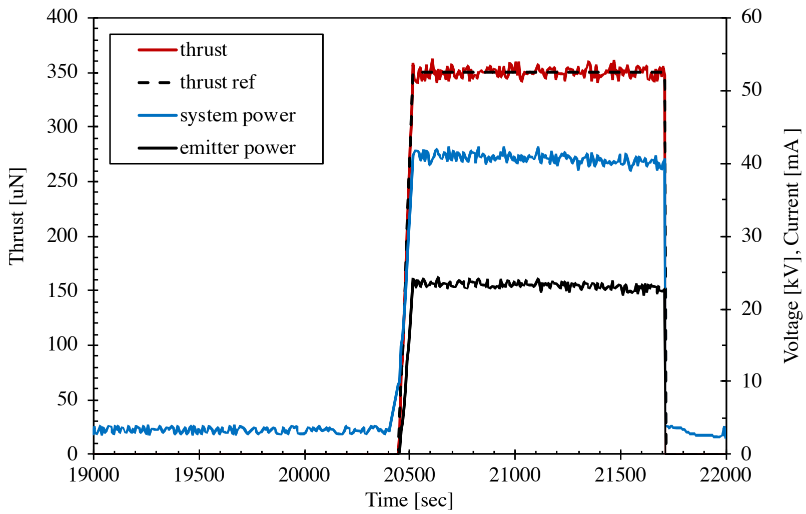

Figure 14. IFM06.04: System power consumption and emitter power draw for 350μN operation point

Figure 14 shows the thruster input power and the emitter power, corresponding to the firing in Figure 13 (right). The system power includes the power required for propellant heating, the neutralization and PPU inefficiencies. The emitter power refers to the power draw of the high voltage emitter section.

V.Conclusion

This paper describes the on-orbit results acquired during the commissioning phase of four IFM Nano Thrusters on board of a LEO small satellite. The on-orbit data presented verifies the thermal stability, maximum thrust operation as well as advanced thrust controllability of the commissioned thrusters. Previously published independent thrust verification via on-orbit maneuvers performed as part of the first IOD mission is additionally summarized.

The IFM Nano Thruster is based on a mature ion emitter technology with exhaustive testing (>24,000h) by FOTEC and has significant space heritage with 25 thrusters in space at time of writing.

One of the intrinsic advantages of a FEEP propulsion system is the controllable thrust over the entire range. The emitted current can be controlled precisely by the applied voltage and the thrust again depends only on emitted current and voltage. Additionally, the specific impulse, and with it the power-to-thrust ratio, can be directly controlled as the ions are accelerated purely electrostatically. This provides a high flexibility in choosing the desired point of operation. One can perform and orbit raising maneuver with e.g. 2000 s specific impulse and then switch to station-keeping with e.g. 6000 s specific impulse.

In addition to the high performance, the FEEP technology features a number of advantages, such as a propellant that is solid during launch, a completely passive feeding system, and a very small system volume. Further, having an unpressurized, chemically inert propellant reservoir prevents debris generation in case of externally induced ruptures such as in case of micro-meteor impact or collisions and obviates the need for passivation at the end of service.

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