Verification of the thrust vectoring capability of a FEEP thruster using spatial plasma plume diagnostic measurements

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The ENPULSION NANO AR3 thruster is a liquid metal Field Emission Electric Propulsion (FEEP) thruster with thrust vectoring capability without moving parts. It was recently developed in close cooperation between ENPULSION and FOTEC. The thruster is based on the significant flight heritage of the ENPUSLION NANO thruster, generating thrust by electrostatically extracting and accelerating Indium ions from Taylor cones established on the needle tips of a porous, crown-shaped emitter suspended with liquified Indium as propellant. In the NANO AR3, a segmented counter-electrode is used to apply differential electric potentials, resulting in varying electric fields in different regions of the ion emitter, which allows to perform relative throttling of the ion current emitted at different regions of the ion current. As the total thrust generated by the emitter is a superposition of the individual beamlets, this differential throttling of different regions of the ring-shaped ion emitter allows for effectively control the thrust vector of the thruster system.

The NANO AR3 is a fully packaged propulsion system including propellant tank and power electronics to achieve the required high voltages and control thereof, providing 350uN at variable specific impulse and a maximum power draw of 45W. An algorithm to translate commanded thrust vector offset angles to the applied high voltage potentials of the emitter and different extractor sections is autonomously controlling the system to achieve the commanded thrust level and vectoring angles.

This paper describes beam diagnostics measurements performed at FOTEC using their FEEP ion beam diagnostics facility in LIFET-4. The diagnostics system consists of a remotely controlled semi-circular rotating arm equipped with 23 Faraday cups. These are used to measure the spatial ion current density distribution of the thruster beam. The specially designed digital Faraday cups feature adjacent electronics to reduce strongly reduce signal noise. The paper will provide a description of the ion beam diagnostics system used, as well as the thruster assembled in the test setup.

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I. Introduction

A rapid increase of CubeSats and Smallsats for commercial and scientific purposes is observed in the recent years, leading to a higher demand of spacecraft propulsion systems and an increase of propulsion requirements. The capability of controlling the thrust vector is a highly beneficial feature e.g. to compensate for a CoG shift throughout the lifetime of the satellite, detumbling or advanced orbit maneuvers. While heavy gimbals are conventionally used to control the thrust vector, they are often not suitable for CubeSats by virtue of their weight. In this paper we discuss testing of the NANO AR^3 thruster, an electrostatic field emission thruster that achieves thrust vector control without moving parts, by differential throttling the ion emission sites in certain regions of the thruster.

II. ENPULSION NANO AR^3

The ENPULSION NANO AR^3 thruster, shown in Figure 1, is a liquid metal Field Emission Electric Propulsion (FEEP) thruster with thrust vectoring capability without moving parts. It was recently developed in close cooperation between ENPULSION and FOTEC. The thruster is based on the significant flight heritage of the ENPUSLION NANO thruster [1, 2, 3, 4], generating thrust by electrostatically extracting and accelerating Indium ions from Taylor cones established on the needle tips of a porous, crown-shaped emitter suspended with liquified Indium as propellant [5]. In the NANO AR^3, a segmented counter-electrode is used to apply differential electric potentials, resulting in varying electric fields in different regions of the ion emitter, which allows to perform relative throttling of the ion current emitted at different regions of the emitter. As the total thrust generated by the emitter is a superposition of the individual beamlets, this differential throttling of different regions of the ring-shaped ion emitter allows for effectively control the thrust vector of the thruster system.

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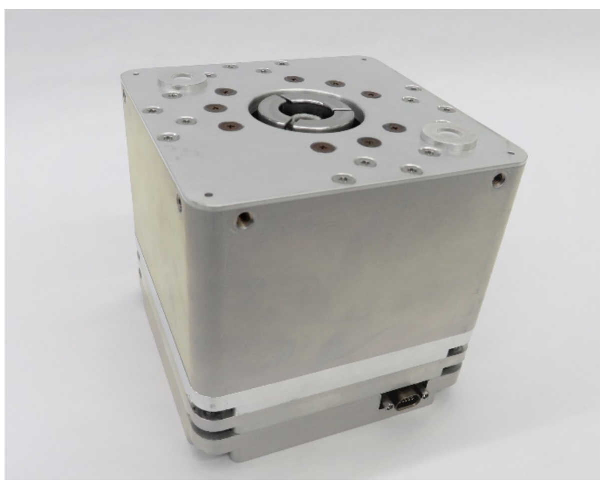

Figure 1: ENPULSION NANO AR^3

III. Technology

Electrostatic stressing on the very sharp tips of the porous needles above a certain threshold causes the liquid indium to deform into a Taylor cone [6]. Further increasing the local field strength at the apex of the cone lead to the emission of positive ions. The required electric filed is applied between the highly positive biased emitter and a negative biased counter electrode called extractor. The emitted ions are then accelerated by the same electrostatic field used for the extraction.

The emitted beam of each single needle of the ring-shaped emitter crown has a natural inclination, the angle between thrust vector and thruster z- axis, as shown in Figure 2. This inclination is dependent on the geometry and potential of the extractor. In addition, the emission current of a single needle depends on the potential difference between the needle and the extractor. The ENPULSON NANO AR^3 takes advantage of this behavior. In the AR3 design, the extractor is divided segments to shape the electrical field around the emitter crown and to control the emitted ion current at different regions of the emitter.

The total emitted ion beam can be assumed as a superposition of three beamlets, each enabled by one of the segmented counter electrodes. Being able to operate the three extractor segments independently allows to control the emission current and thrust vector of the three beamlets and thus to steer the overall resulting thrust vector precisely.

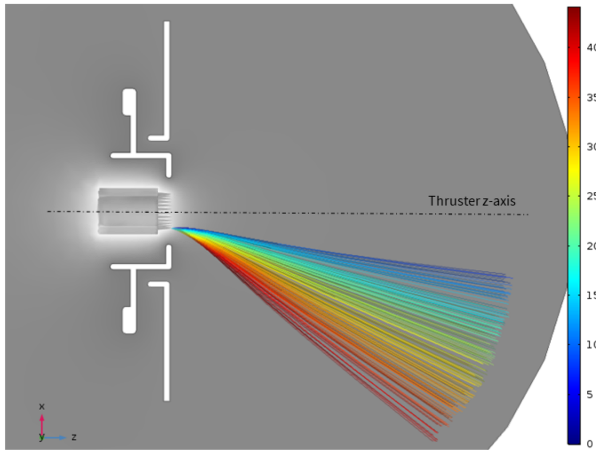

Figure 2: Simulation of the ion emission of a single needle

IV. Calibration

To achieve a high accuracy the behavior of the beamlets caused by the segments need to be characterized in terms of emission current and thrust vector. Therefore, V-I curves are performed to determine the emission current dependent on the discharge voltage between the emitter and a single extractor segment. To characterize the thrust vector of the beamlets, beam diagnostic measurements are performed to characterize the inclination angle as well as the azimuthal angle of the beamlets dependent on the segment voltage. The inclination is defined as the angle between the thrust vector and the thruster z-axis and the azimuthal angle refers to the angle between the x-axis and the projection of the thrust vector in the x-y plane as visualized in Figure 3.

The controlling firmware algorithm uses calibration factors, based on the characterization of the beamlets, to correlate the commanded thrust and thrust vector with the different segment voltages and is able to autonomously control the thruster to achieve the commanded thrust and thrust vector.

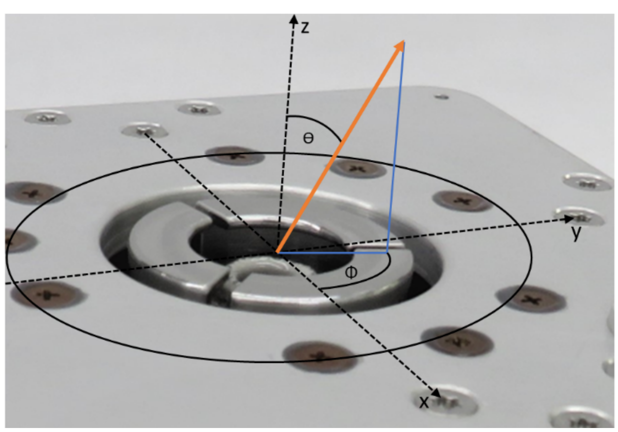

Figure 3: Spherical coordinate system aligned with the Cartesian system of the thruster

V. Diagnostic System

The beam diagnostics measurements are performed at FOTEC using their FEEP ion beam diagnostic facility LIFET-4 with an inner diameter of 2.2 m and an inner length of 3 m. The diagnostics system consists of a remotely controlled semi-circular rotating arm equipped with 23 Faraday cups, as shown on the left side of Figure 4. These are used to measure the spatial ion current density distribution of the thruster beam. The specially for FEEP thruster designed digital Faraday cups [7], developed by FOTEC, feature in the Faraday cups integrated measurement electronics to strongly reduce signal noise compared to conventional Faraday cups. One of the used digital Faraday cups is shown on the right side in Figure 4. 23 of these Faraday cups are distributed from -80° to 80° with respect to the thruster z- axis on the diagnostic arm to achieve a high resolution. The diagnostic arm itself has a scanning range from -80° to 80° with a step size of 1°. Based on the ion current density measurements of the 23 Faraday cups the thrust vector of the emitted ion beam can be determined.

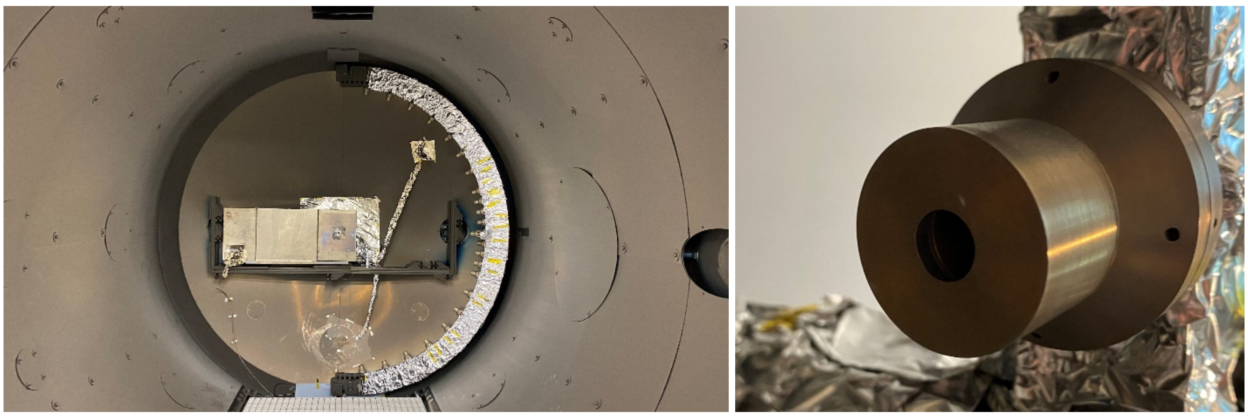

Figure 4: FOTEC's LIFET-4 with moveable plasma diagnostic arm (left) and a digital Faraday cup (right)

VI. Measurements

A. Calibration

To characterize the emission current of the three beamlets, I-V curves are performed. In these scans, the emitter voltage is set to a constant voltage of 5.5 kV and the voltage of one extractor segment is swept from 0 to 10 kV with steps of 100 V, while the other two extractor segments are set to 0V. The emission current, emitter voltage as well as the extractor segments voltages are recorded from the telemetry data of the thruster.

In the next step, the thrust vector of the three beamlets are measured. For each segment three beam diagnostic measurements are performed with extractor segment voltages of 5, 7 and 9 kV keeping the other two segments at 0 V and the emitter at a constant voltage.

B. Thrust vectoring capability

To show the full thrust vector capability of the ENPULSION NANO AR³, beam diagnostic measurements have been performed at various operational points. For this test the voltages of the three segments are controlled to values between 2 and 10 kV. For this test, the thruster is operated in manual mode i.e. commanding the extractor segments voltages and the emitter voltage directly without using the firmware algorithm to calculate the expected thrust and thrust vector.

A collection of optical images of the ion emitter during selected operational points at different thrust vector angles is shown in Figure 5, with the zero offset case placed in the center of the figure.

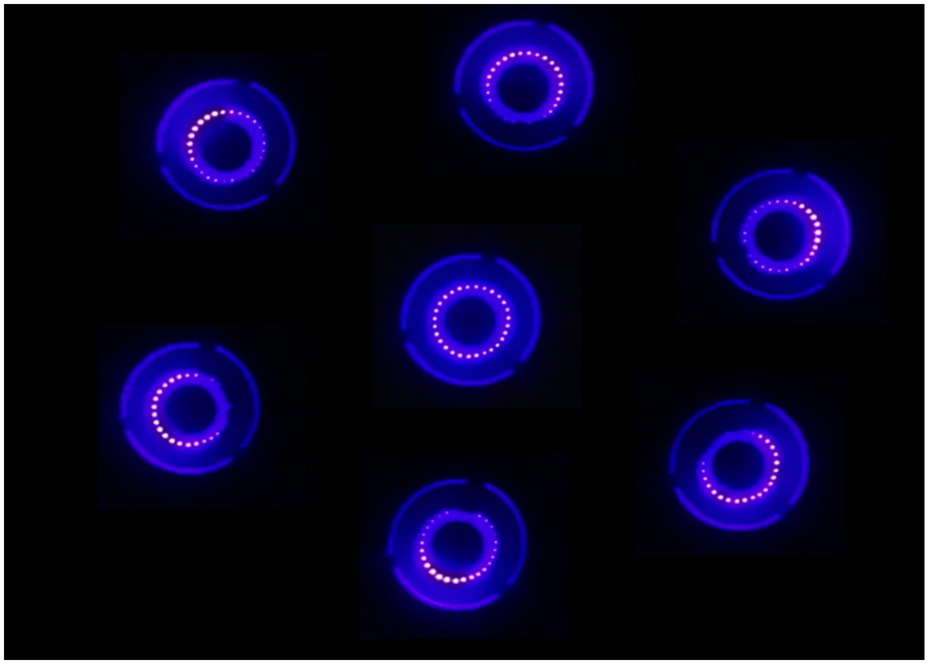

Figure 5: Superposition of optical images of the ion emitter at different thrust vector angles, and with zero offset in the center

C. Thrust vectoring verification

The objective of this test is the verification of the thrust vectoring capability of the ENPULSION NANO AR³ as well as the algorithm used to translate the commanded thrust and thrust vector values into the required extractor segments voltages and control the emitter voltage to achieve the commanded thrust. For this test the thruster unit is calibrated based on the measurements described in section A. A set of combinations of commanded thrust vectors and thrust levels are compared to the thrust vector measured by the beam diagnostics and thrust measured by the PPU and recorded via telemetry. The commanded inclination angles are 0°, 5°, 10° and 12.5° with thrust values of 350 μN, 350 μN, 300 μN and 250 μN respectively. For each combination of thrust and thrust vector the azimuthal angel was set to values between 0 and 360° with steps of 60°. Figure 6 shows exemplary the raw measurement data of the digital Faraday cups at an operational point of 300 μN with an inclination of 10 ° and an azimuthal angle of 210 ° on the left side compared to an operational point of 350 μN with an inclination and azimuthal angle of 0°.

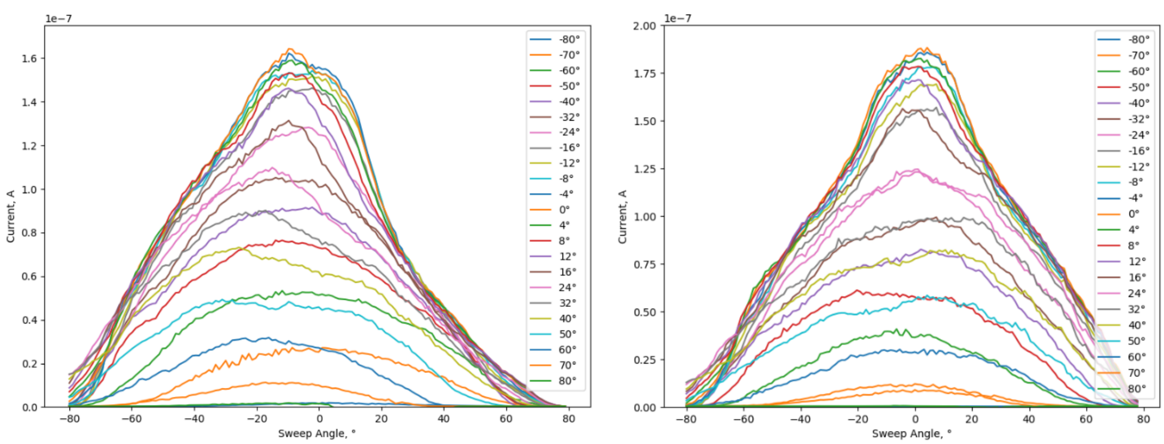

Figure 6: FC measurement raw data at an operational point of 300 μN with an inclination of 10 ° and an azimuthal angle of 210 ° (left) and with an inclination and azimuthal angle of 0 ° at 350 μN (right)

VII. Results

A. Calibration

Based on the I-V curves, shown in Figure 7, the onset voltage, the discharge voltages between emitter and extractor segment required to start the emission, as well as the impedance can be determined. Figure 8 (left) shows the dependency of the inclination of the beamlets on the segment voltage, reaching from around 36° at an extractor segment voltage of 5 kV up to around 43° at a segment voltage of 9 kV. The azimuthal angle of the beamlets, as shown in Figure 8 on the right side do not show a dependency on the extractor segments voltage and can be assumed as constant.

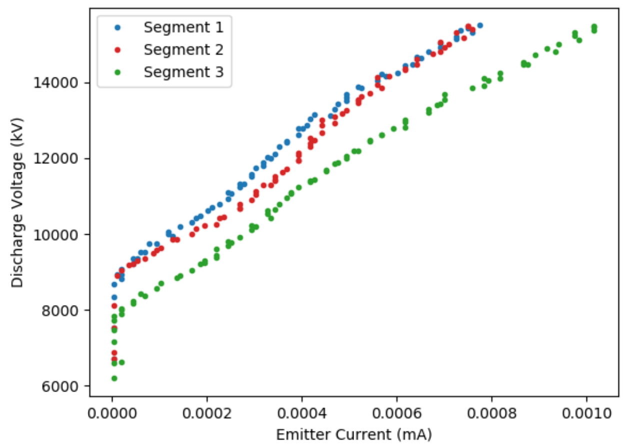

Figure 7: I-V curve for each single extractor segment

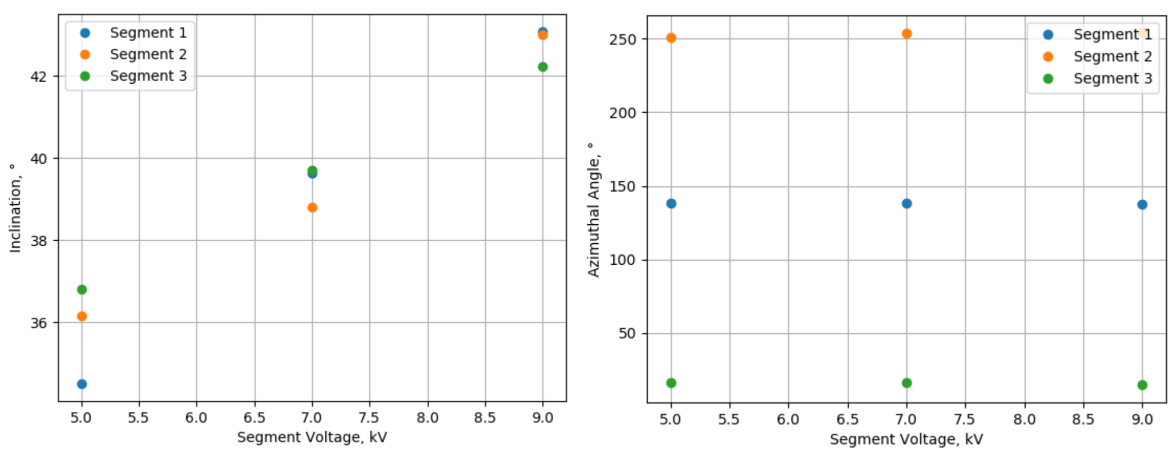

Figure 8: Dependency of the inclination angle (left) and azimuthal angle (right) on segment voltage

B. Thrust vectoring capability

Figure 9 shows a plot with the measured thrust vectors and thrust levels achieved at various operational points. The plot shows a triangle shaped pattern where the edges with the highest inclination angles correspond to the operational points for which just one segment is operated at maximum voltage and the other two are set to 2 kV. At these operation points inclination angles up to 39° are measured. The triangle indicates the maximum envelope of the inclination angles achievable by the thruster. However, at these high inclination angles only reduced thrust levels can be achieved since most of the emission sides of the emitter need to be throttled down and thus the maximum emission current becomes limited. Higher thrust levels, above 300 μN, can be achieved at inclination angles below 12.5° for azimuthal angles from 0 to 360°.

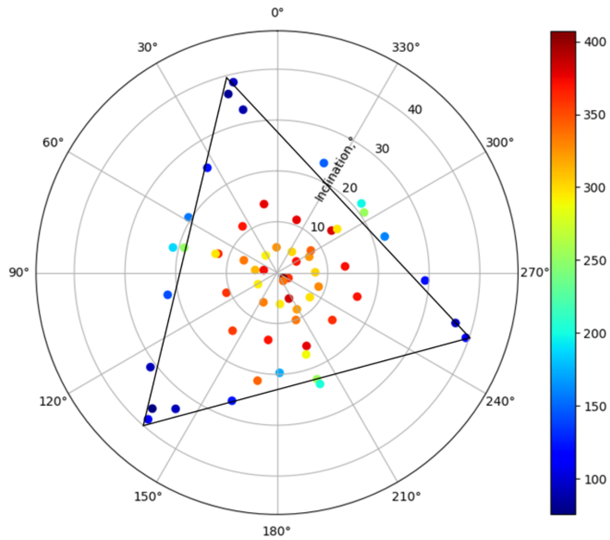

Figure 9: Measured thrust vectors and thrust levels at various operational points

C. Thrust vectoring verification

To verify the thrust vector capability, using the in the firmware implemented algorithm, commanded and measured thrust vectors are compared. The results are presented in Table 1 and are visualized in the plot shown in Figure 10, where the circles indicate the commanded thrust vector and the stars the measured ones. The highest measured deviation of the inclination is 2.96° in one case and smaller than 2° in the other cases. The maximum measured deviation from the commanded azimuthal angle is 12.67°. Overall, the measured thrust vectors are in good agreement with the measured ones as shown in Table 1.

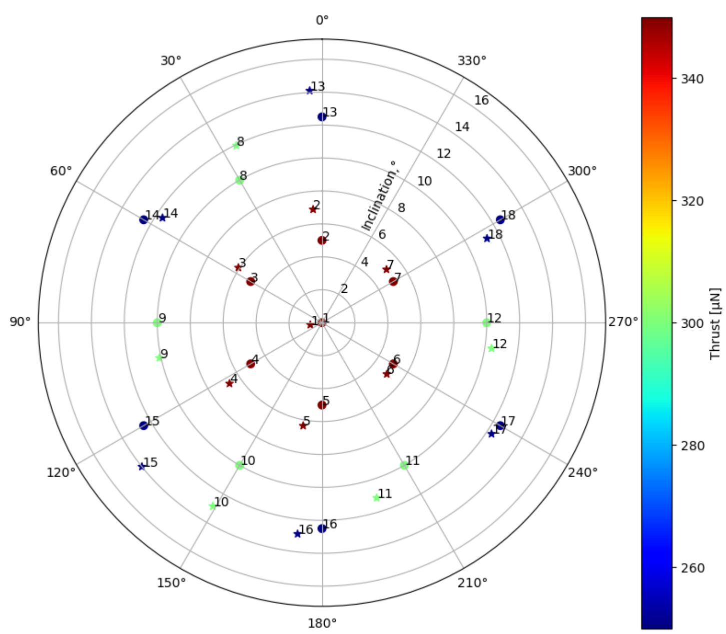

Figure 10: Measured (stars) and commanded (circles) thrust vectors as well as thrust levels at different operational points, data labels indicate the test number

Test number	Commanded Inclination, °	Measured Inclination, °	Delta Inclination, °	Commanded Azimuthal Angle,°	Measured Azimuthal Angle, °	Delta Azimuthal Angle,°
1	0	0.72	0.72	0	100.01	N/A
2	5	6.9	1.9	0	4.49	4.49
3	5	6.08	1.08	60	56.62	-3.38
4	5	6.72	1.72	120	123.34	3.34
5	5	6.36	1.36	180	169.63	-10.37
6	5	5.02	0.02	240	231.58	-8.42
7	5	5.08	0.08	300	309.55	9.55
8	10	11.95	1.95	30	25.81	-4.19
9	10	10.1	0.1	90	102.2	12.2
10	10	12.96	2.96	150	149.24	-0.76
11	10	11.14	1.14	210	197.33	-12.67
12	10	10.41	0.41	270	261.4	-8.6
13	12.5	14.11	1.61	0	3.03	3.03
14	12.5	11.59	-0.91	60	56.67	-3.33
15	12.5	14	1.5	120	128.65	8.65
16	12.5	12.91	0.41	180	173.42	-6.58
17	12.5	12.31	-0.19	240	236.75	-3.25
18	12.5	11.25	-1.25	300	297.05	-2.95

Table 1: Measured and commanded thrust vectors and the delta between them

VIII. Conclusion

The ENPULSION NANO AR3 thruster is a FEEP based electrostatic, fully packaged propulsion system that achieves thrust vector control without moving parts by simply adjusting the electrostatic field within the ion emitter. The thrust vectoring capability of the ENPULSION NANO AR³ has been demonstrated and verified successfully at various operational points using a plasma diagnostic system equipped with 23 Faraday Cups. Measured and commanded thrust vectors are compared and show very good match, verifying not only the capability of thrust vectoring but also the underlying control algorithm used to automatically translate the commanded thrust vector into the extractor segment voltages. To further increase the accuracy of the thrust vectoring, development efforts to improve the algorithm used are ongoing.

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