Nano Field Extraction Thruster and Associated Diagnostics Development

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Abstract

This paper presents a system utilized for testing the Nano Field Extraction Thruster (NanoFET) on NASA's C-9 Micro-gravity flight. The NanoFET is part of an ongoing effort at University of Michigan to develop Nano-Satellites with a unique specific impulse and propellant mass ratio that allows them to be particularly agile through their orbits.

I. Introduction

The Zero-G Electrostatic Thruster Test-bed (ZESTT) is a system that houses, operates, and evaluates the performance of the NanoFET. NanoFET development started in 2005 under the NASA Institute for Advanced Concepts (NIAC) and the ZESTT program was formed in 2008 to aid research and development. The 2008-2009 ZESTT team designed and tested the first generation NanoFET prototype, the M-1, with a focus on controlling operation and structural integrity on NASA's C-9 Micro-gravity flight. In 2009 ZESTT was renamed ZESTT Reflight (ZESTTR) and the 2009-2010 ZESTTR team shifted the focus towards developing the diagnostic tools necessary to measure current and future generation NanoFET performance characteristics. Initially, NanoFET testing used Particle Tracking Velocimetry (PTV) data using a laser and fast cams to measure particle velocity. However, as the particle size continues to scale smaller with the end goal of using particles near the 100 nm range, the particle exhaust plume becomes increasingly difficult to image. To measure particle velocity, particle charge, and exhaust plume current density, ZESTTR has designed, built, and tested a Faraday Probe and Induction Charge Detector (ICD). NanoFET's thrust and specific impulse can be estimated from these measured values.

II. NanoFET Development Cycles

In 2008 the first integrated NanoFET prototype, the M-1, was built, figure 1. The M-1 is comprised of three blocks: the spring block, piezoelectronic block, and window block. The spring block houses the particle reservoir in a syringe and plunger. A constant force spring is used to apply backpressure to the plunger in order to continuously deliver particles (1-10μm) to the piezoelectronic block as emission depletes the syringe. The syringe extends into the piezoelectronic block where a piezoelectric ceramic and a 10μm holed charging sieve are housed. By driving the piezoelectric at 100 V AC, the sieve will vibrate approximately 1 μm at the driving frequency. The vibration provides the energy to break up particles at the sieve surface and provides the inertial force to kick off particles into the accelerating electric field. The accelerating field is provided by a stainless steel extraction gate housed in the window block. In this configuration the sieve is grounded and the extraction gate and anode are charged nominally to 15 kV. This configuration was employed by the ZESTT team and the particle plum was successfully imaged in figure 2.

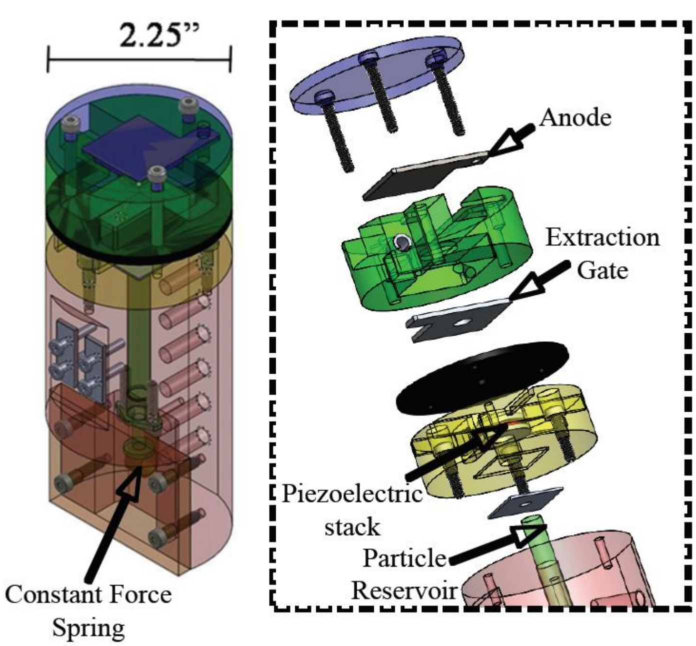

Figure 1. NanoFET M-1 Configuration

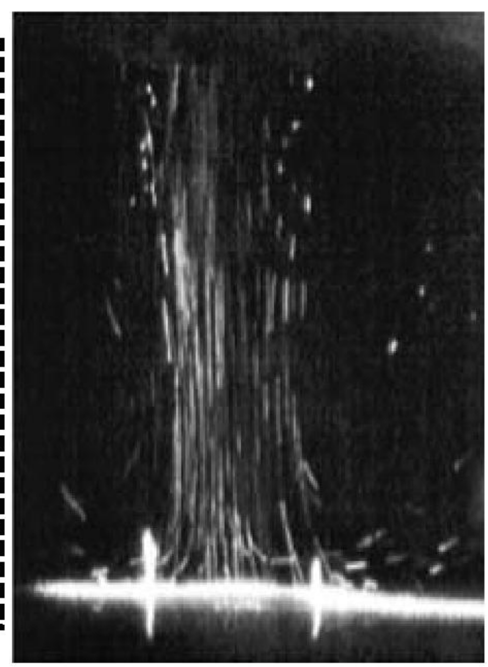

Figure 2. NanoFET M-1 Emission From PTV

Despite successful emission, the M-1 exposed three major design flaws and drivers that needed to be considered in future prototype iterations:

1. Electrically infeasible emission detect-ability via faraday probe due to high voltage gate/anode configuration
2. Emission reliability due to particle and sieve sizing
3. Integration robustness and arcing susceptibility

Two versions of the NanoFET were then developed to accommodate these issues. The M-1 was modified to the M-1a to immediately accommodate solutions to the above issues while the M-2 was a redesigned and fabricated out of house.

The polarity of the sieve and extraction gate of the M-1 caused problems in measuring emission current from the large DC offsets induced on the Faraday probe and the sporadic arcing that would strike it. Also, as a device in space, the high voltage should not be external to the craft. The temporary M-1a reconfiguration was proposed for continued testing on the ZESTTR system for validation of diagnostics.

The M-1 required nA current measurements floated at 15 kV with the extraction and collection gate charged. Due to the fluctuation of the HV supply, there was constantly approximately 1 μA flowing to or from the anode and extraction gate. The floated faraday probe was unable to differentiate the particle emission current density from the current of the high voltage (HV) controls. The M-1a reversed the polarity of the charging grid and extraction gate. As a result, the piezoelectric had to be moved away from the HV source to keep the driving amplifiers away from the HV. In the M-1a configuration the sieve is charged at 15 kV and the extraction gate is grounded. The piezoelectric is placed after the grounded extraction gate resulting in a larger distance between the vibration source and the particle sieve. The vibrations would have to travel through the polycarbonate housing, the extraction gate, and another polycarbonate housing spacer to the sieve. Another grounded gate was placed after the piezoelectric to shield the diagnostics from the noise induced by the piezoelectric lines. This configuration, in figure 3, adequately suppressed the HV and piezoelectric noise while also mitigating arcing incidents.

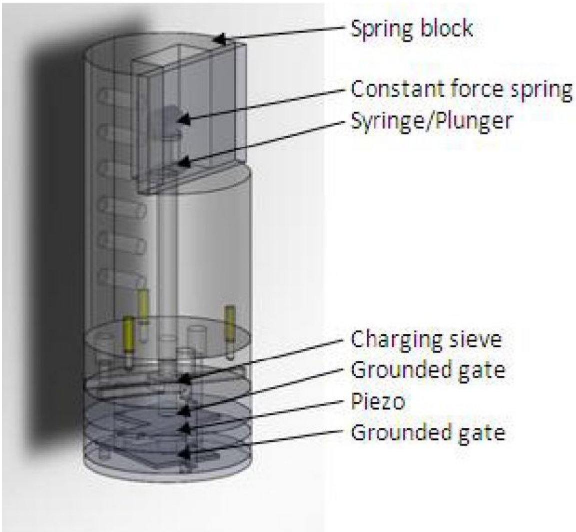

Figure 3. NanoFET M-1a Modifications

In the analysis for the 2009 ZESTT flight, SEM images were taken of the sieve surface as seen in figure 4. The sieve hole was clogged with the 1-10 μm particles that prevented emission. For the M-1a the sieve size and particle size were increased to 40μm and 60μm respectively. This sizing ratio was found to be the most reliable and repeatable for emission.

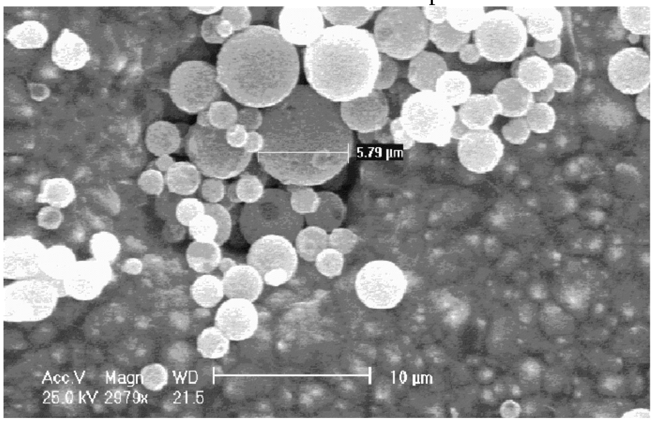

Figure 4. NanoFET M-1 Clogged Sieve

The NanoFET prototype that was flown on the 2010 NASA Reduced Gravity flight and used to make measurements which conclusions were drawn from was the M-1a.

III. Faraday Probe Design

For the M-1a and future NanoFET prototypes a Faraday Probe was developed by the ZESTTR team to measure particle exhaust current density. The Faraday probe provides a measurement of relative emission performance e.g. mass flow rate versus operating conditions. The Faraday Probe is designed with a lower sensitivity bound of 100pA of emission current. The noise sources for this measurement are from

1. The instability of the high voltage ripple between 50 – 88kHz depending on the HV supply
2. The piezoelectric drive signal from 1- 20 kHz
3. 60 Hz power source noise

In order to reject these noise sources the Faraday Probe is designed to measure near DC level shifts in emission current with a nominal gain of 60 dB (1000) over a 1 MΩ shunt resistor and a 60 dB/decade roll off beginning at 8 Hz . This is achieved through three cascaded LT1012 operational amplifiers set as low pass filters with a gain of 10 each.

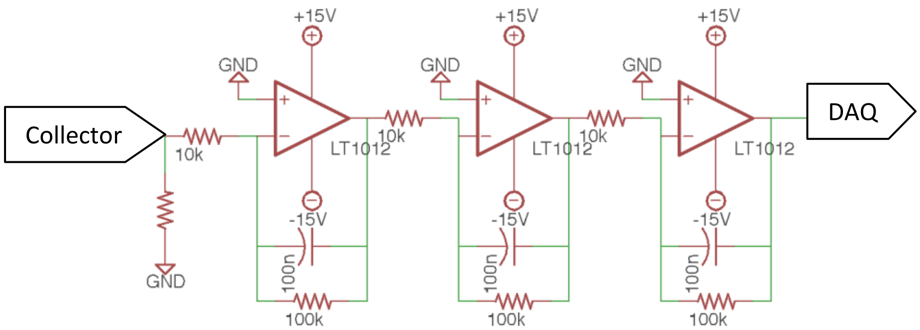

Figure 5. Faraday Probe Amplifying Circuit

While the individual stages of the ammeter are set to a 3 dB bandwidth of

$$\frac{1}{2\pi j(100k\Omega)(100nF)} = 16\ Hz$$

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the total bandwidth will be reduced by a bandwidth shrinkage factor of

$$\sqrt{2^{1/N} - 1} = .5$$

Where N = 3 or the number of identical stages. This results in a bandwidth of 8 Hz. Below is the experimental vs. theoretical gain-frequency plots. The ammeter has a noise floor of approximately -5 dB resulting in a SNR of 65 dB.

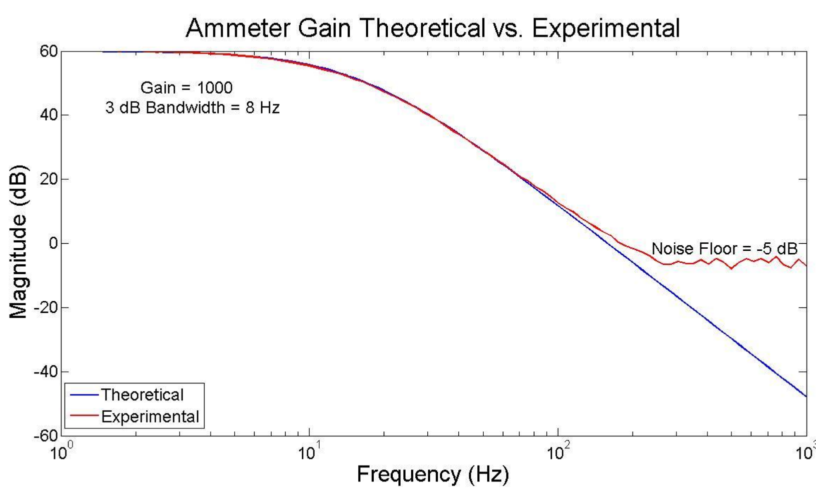

Figure 6. Faraday Probe Gain/Frequency Plot

The input of the amplifier is attached to a conductive circle, or, the collector of the Faraday Probe. The collector is mounted downstream of the NanoFET's emission and atop of the ICD.

IV. Induction Charge Detector Design

The ICD (figure 7) is a diagnostic used to measure time-of-flight (TOF) and charge per particle. The sensors are supported by an insulating skeleton inside a conductively grounded tube that shields the sensors from radiating electromagnetic noise. The particle emission plume is spatially filtered by a 300μm entrance tube at the face of the casing. The holes of the case and sensors must be aligned axially with the thruster in order to make measurements without a particle striking a sensor.

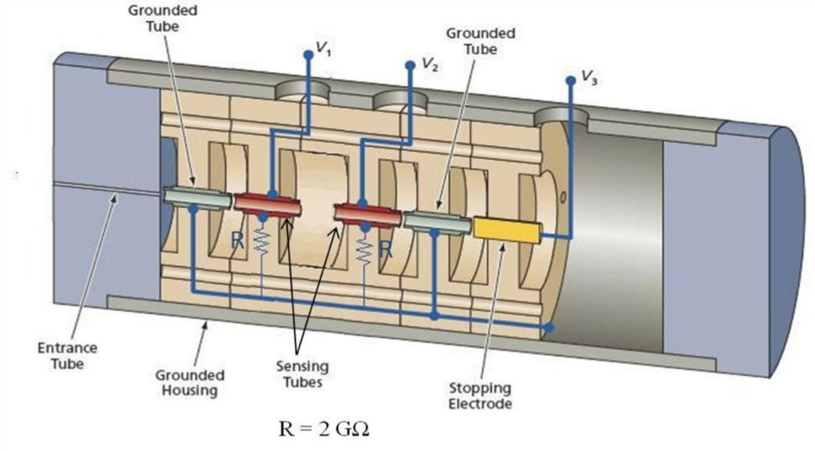

Figure 7. Induction Charge Detector

The ICD consists of two sensing tubes each connected to ground through a 2 GΩ resistor. As a particle passes into one of the 2.5mm diameter sensing tubes, a reflective charge is pulled from ground, through the resistor, and on to the sensing tube. As the charge is being pulled from ground to the tube, there is current over the resistor and an amplifier is used to multiply the voltage signal seen by the current-resistor product. As the particle leaves a sensing tube an opposite but equal in magnitude signal is seen. The time between the equal but opposite spikes is the TOF through one sensing tube. By dividing the 1.8 cm length of the sensor tube by the time of flight we can measure the velocity of an individual particle. The accompanying amplifying circuit measures the potential difference between the sensing tubes for an output seen by figure 8.

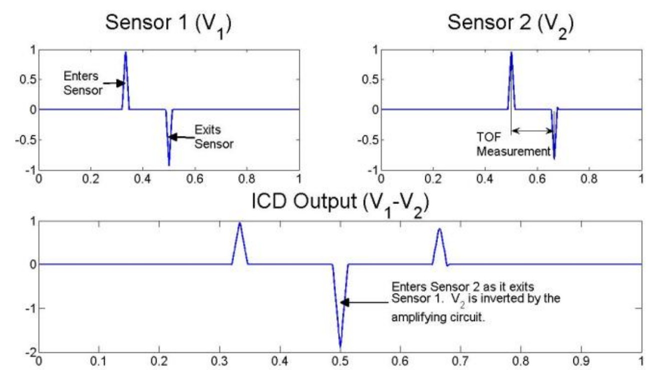

Figure 8. ICD TOF Expected output

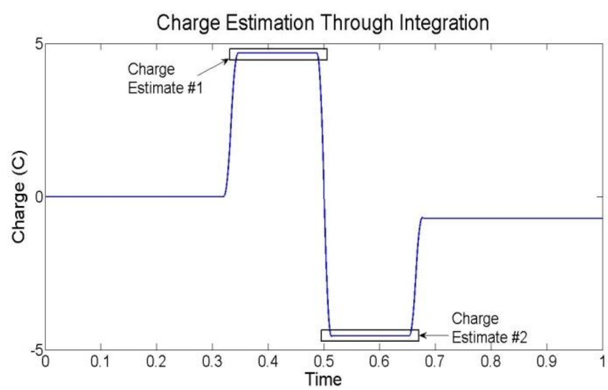

Figure 9. ICD Charge Integration

By lining up multiple sensing tubes it is possible to make multiple TOF measurements per particle, reducing the error by averaging. The amplifier used to sense the signals from the ICD consists of two, low noise, high input resistance AD549 buffers followed by three cascaded INA126 instrumentation amplifiers. The total gain for $V_1 - V_2$ is set by the INA126's gain cubed:

$$A_{V_1-V_2} = \left(5 + \frac{80k\Omega}{R_g}\right)^3 = 280$$

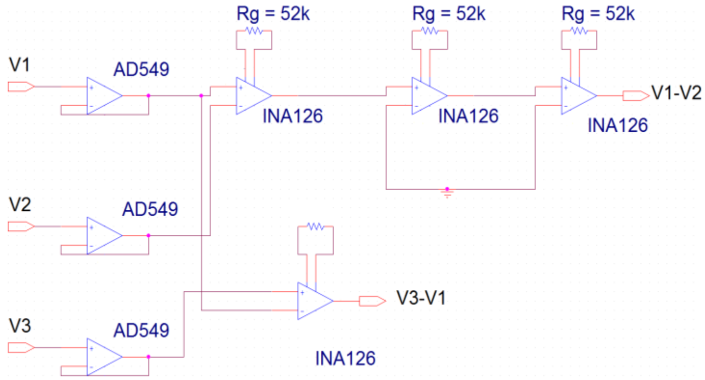

Figure 10. ICD Amplifier Circuit

If the voltage output signal is divided by the voltage to voltage gain, divided by the input resistance, and then the resulting current is integrated, it is possible to estimate the total amount of charge placed on the sensing tube.

$$Q_{particle} = Q_{sensor} = \int \frac{V_{out}}{(2G\Omega)(A_v)} dt$$

Assuming the charge on the tube is an accurate mirror of the moving particle, we can estimate the charge of the moving particle. The observable output is predicted in figure 9. The ICD comes with an additional stopping electrode, V_3, and its' amplifier circuit has an output of $V_3 - V_1$. The stopping electrode requires a gain-frequency similar to the Faraday Probe since they respond to the same physical phenomena, however since the ICD's input is spatially filtered the $V_3 - V_1$ signal was not used for charge measurement. The signal allows us to differentiate from V_1 and V_2.

IV. Experiment Design

The experiment structure is comprised of three systems

1. A vacuum system encompassing vacuum pumps, chamber, valves, and flanges. This system is used to achieve pressures on the order of 10^{-5} Torr.
2. An electrical system that powered, controlled, and made measurements on the NanoFET.
3. A chassis that supported the electrical and vacuum system through the parabolic flight.

Figure 11 displays the CAD and simulated structural supports and figure 12 shows an implementation of the thruster-diagnostic setup.

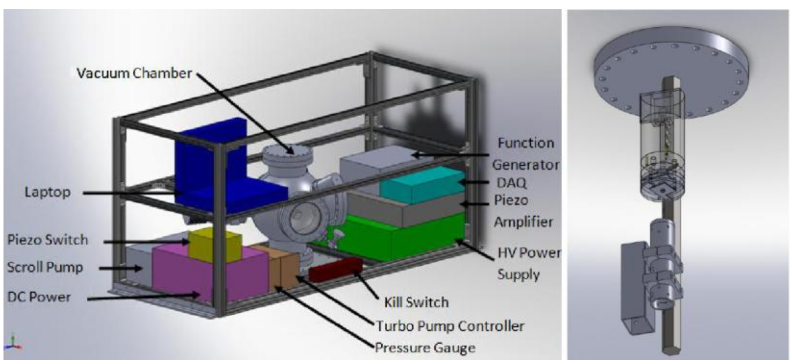

Figure 11. ZESTTR Structural Configuration

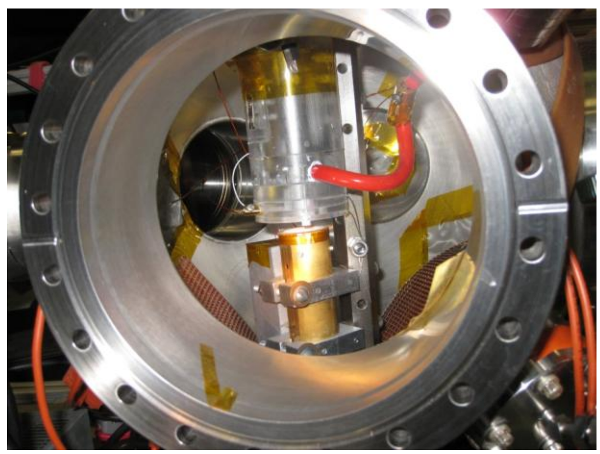

Figure 12. NanoFET and Associated Diagnostics in vacuum chamber

The vacuum and structural systems are beyond the scope of this paper but it can be said that both went under their own rigorous simulations and tests for validation. The electrical system is best summarized by figure 13. Boxes representing each component are outlined in a color corresponding to their power supply. Each electrical signal going in and out of the vacuum chamber had to be fed through an adapter flange and once inside the chamber had to be insulated, typically with Kapton®, and placed carefully in order to handle arcing events. Outside of the vacuum chamber, the connections were made with shielded BNC cables wherever possible to prevent cross-talk. The National Instruments USB 6259 Data Acquisition board sampled the instrumentation channels and piezoelectric monitors at 60 kHz and recorded data to the flight laptop while simultaneously triggering the piezoelectric microcontroller when the accelerometer reached a threshold indicating micro-gravity. Piezoelectric voltage measurements were taken using a voltage divider and current measurements were taken using a Pearson coil in the 'Voltage and Current Sensor Switch Box'.

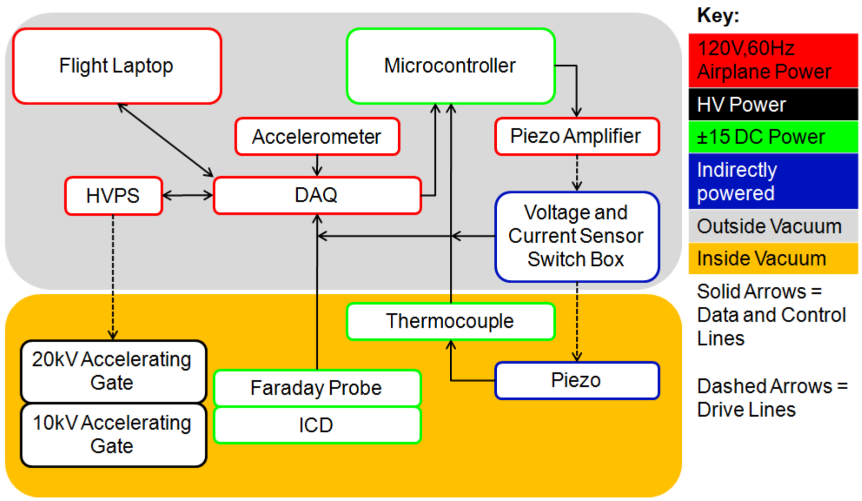

Figure 11. ZESTTR Electrical System

The test matrix for the NanoFET varied the piezoelectric drive signal and the HV bias across the charging sieve and grounded gate.

Piezoelectric Drive Signal	High Voltage	ICD	Ammeter	Pressure
11 – 13 kHz Sine (.5 kHz steps)	15kV	No	Yes	Atmosphere
12 kHz Sine	8 kV, 10 kV, 15 kV, -15kV	Yes	Yes	Atmosphere
2 kHz Square	15 kV	Yes	Yes	Atmosphere

IV. Experiment Results

Tests with the M-1a began with using a 60µm sieve with 20µm particles. No emission current could be measured with the Faraday Probe. The lack of emission current led the ZESTTR team to reexamine the early theoretical models developed for NanoFET. These models had predicted that a single layer of particles would lift off from the sieve every cycle of the piezoelectric. Had this been true, the upper bound for the M-1a 60µm sieve / 20µm particle combination would have been 168 nA, well within the Faraday Probe's measurable range. This was calculated using the optimal particle charging equation and a charging field of 15 kV over 1 cm

$$q_o = \frac{\pi^3}{6}\varepsilon E_o d^2$$

Where:

q_o =charge per particle
ε = dielectric of free space
E_o = charging electric field
d = particle diameter

Multiplying the charge per particle by the number of emissions holes and the piezoelectric frequency (2000 Hz) yields the 168 nA bound. To investigate further the mass of deposited particles after 100 seconds of emission was taken, first with the piezoelectric driven at a 12 kHz sine wave and then by a 2 kHz square wave. In both cases the total emitted mass weighed less than .01g. Using the masses upper bound and the density of aluminum (2.7 g/cm^3), the number of particles collected from the emission was to be less than 1 million. This meant the total charge deposited should be less than 27.4nC and when divided by the 100 seconds of emissions yielded 274pA of emission current; a current very near the lower limit of the Faraday Probe.

After the 20µm particles were tested, it was still suspected the sieve holes were clogging and thus the next round of tests were done using 53µm particles in atmosphere conditions (40µm particles were used during the micro-gravity flight due to the depletion of the 53µm particles. Using these particles, the Faraday Probe was able to measure single nano-amps of particle emissions thus validating the operation of the Faraday Probe. The ICD was also able to sense these particles and with the Faraday Probe and visual confirmation of emission, the ZESTTR configuration was validated.

Figure 14 shows a typical NanoFET emission using the ICD and Ammeter diagnostics. When the Piezoelectric is first turned on, there is a large DC shift indicated a substantial amount of emission. At that moment, there are a large number of particles that enter the 300μm orifice of the ICD resulting in the superposition of signals at the ICD output. Over the duration of the piezoelectric actuation the Faraday Probe signal begins to decay. This is due to the spring/plunger system no longer being able to deliver new particles to the sieve surface. It was found that the best way to get ICD measurements was to wait for the emission to deplete or to run without the piezoelectric and just high voltage, waiting for an individual particle to respond to the electric field. Figure 15 shows a TOF measurement from the isolated ICD event in figure 14 and _____ shows the TOF measurement integrated for a charge estimate. The TOF measurement for this run indicates a speed of 5.5 m/s through both sensors. The charge integration in figure 16 indicates the particle had a charge around 2x10e-14.

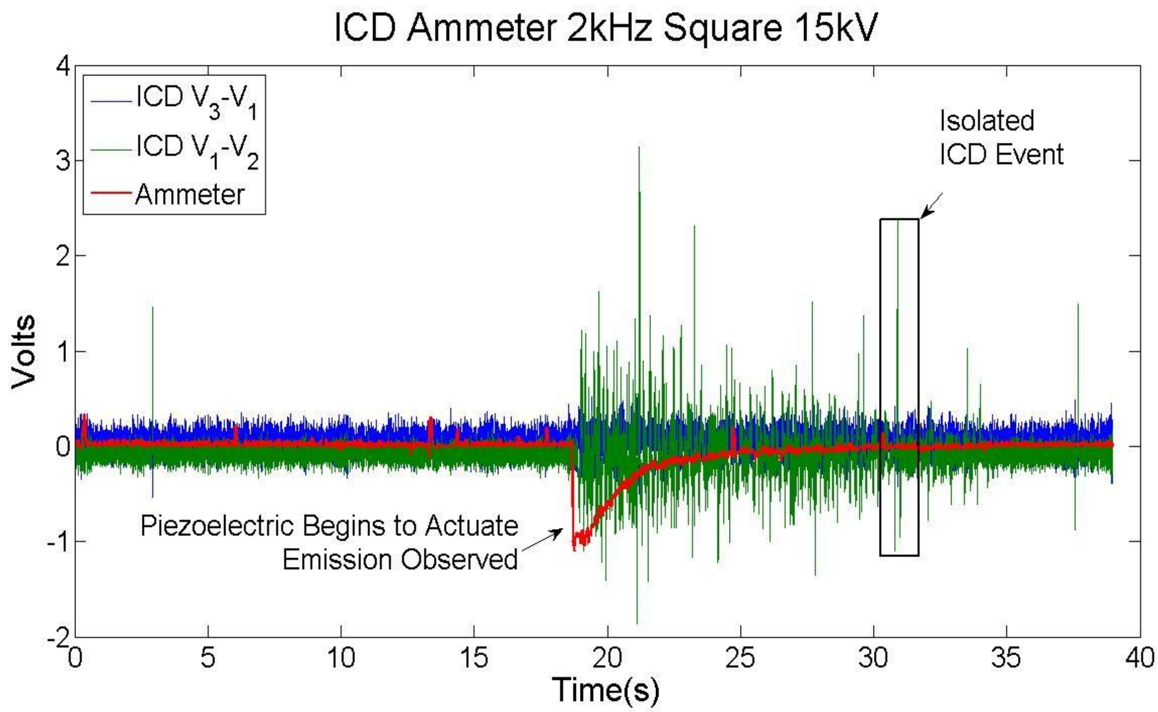

Figure 12. Ammeter and ICD output from NanoFET Emission

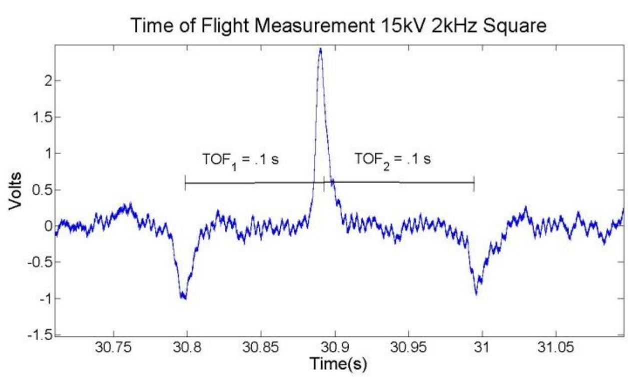

Figure 13. TOF Measurement

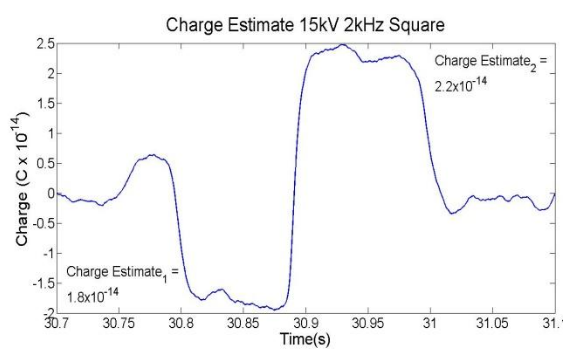

Figure 14. Charge Measurement

Another test to verify the ICD and ammeter was to flip the polarity of the charging sieve. By keeping the gates grounded and charging the sieve at -15 kV instead of 15 kV we would expect the emission particles to charge oppositely. This effect was observed in figures 17 and 18 which verified the signal coming out the ICD is based on individual charges.

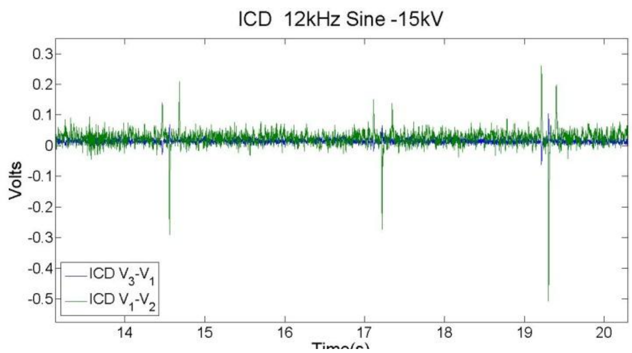

Figure 15. NanoFET with -15kV biasing

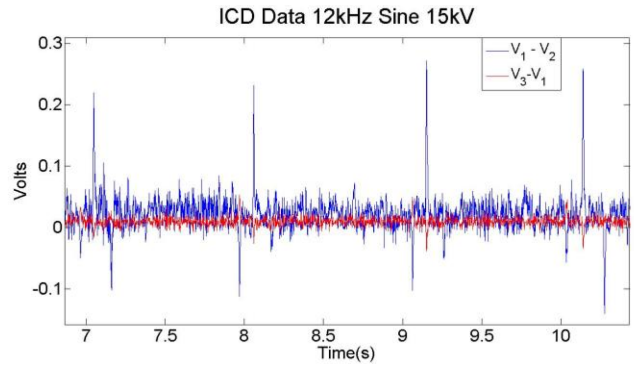

Figure 16. NanoFET with 15kV biasing

Following the success in atmosphere pressure testing, it was expected that once in vacuum the particle current density would increase causing a larger response in the Faraday Probe due to the lack of charge-to-air leakage. Particles were also expected to speed up in absence of the aerodynamic drag. However, emission in vacuum with the M-1a did not perform as expected. Reliable emission was never achieved in vacuum. Tests revealed that the particle feed system involving the syringe, plunger, spring, and sieve was prone to clogging or not providing adequate back pressure. The long duration of vacuum pump down times required to reach an operable of the Paschun Curve along with the applied back pressure of the spring over compressed the particles so that they would clog the sieve. Multiple springs of varying constant force were tested with no success. Softer springs did not provide enough backpressure and would get stuck while harder springs clogged the sieve. We observed large clumps of particles when removing the syringe

V. Future Work

The data post processing to collect statistical analysis on the NanoFET's operation is ongoing. While the diagnostics have been verified for the M series NanoFET prototypes, as the NanoFET moves to the N series that uses particles on the nano-scale the diagnostics will have to be modified. The Faraday probe's lower detection limit needs to be raised either by increasing input resistance or with a higher voltage to voltage gain. The ICD already has problems detecting individual particles and the spatial filtering of the NanoFET's emission needs to increase, or, the entrance tube to the ICD should decrease to allow fewer particles in. The ICD will also require a higher gain if the charge on the particles is to decrease by an order of magnitude. Aside from the post processing on the M-1a, the M-2 is currently being tested with a modified ammeter to verify emission.