Experimental Research & Development of Field-Emission Electric Propulsion Ion Source

Mohammad Ali Moghaddasi

Research Partner: Stefan Bell

Name and Dept. of Faculty: Elaine Petro, Mechanical & Aerospace Engineering

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Abstract

Field-emission electric propulsion has been one of the newly developed ion thrusters that enables high precision maneuvering for required for scientific drag-free and constellation missions. However, they are yet to be considered a popular convention in the aerospace propulsion industry. This experimental research models and characterizes a single-emitter field-emission electric propulsion thruster in a vacuum environment. By changing and analyzing various parameters of the system such as the amount of the indium ion propellant, sharpness of the tungsten needle holding the propellant, temperature, voltage, and the neutral plume flow, this technology can be developed to be more efficient and less costly. This would attract more interest toward this state-of-the-art technology for future space mission. The most important steps taken to achieve such objectives were providing a vacuum-like environment in a vacuum chamber, fabricating our very own tungsten needles with a tip sharpness in the order of nanometers, in addition to using a small-scale model of the thruster for simplicity and allowing easy changes to the design to improve the system. Results gained so far determined that wire heating is not the best way to melt the indium ion and produce thrust, due to its anomalous behavior in a vacuum environment. However, ceramic heating seems to be a promising method of melting indium in vacuum, followed by applying a high voltage, hence producing thrust and collecting measurements.

1 Introduction

Satellite constellations have been of great significance in communications through the internet, enhancing space observation, and enabling global monitoring of Earth. Over 2,500 satellites orbit the earth now in low-, mid-, geosynchronous-, and non-geosynchronous-orbits [2]. Such satellites require proper types of propulsion systems in order to be placed in their orbit and steadily operate based on the mission. Since 1995, Field-Effect Electric Propulsion (FEEP) thrusters have shown to be promising in micro-propulsion by offering numerous advantages such as low thrust noise, capable of reaching high specific impulse values (several thousand seconds), and high controllability [4, 5]. These characteristics enable ultra-high-precision pointing capabilities. Such thrusters are required for scientific drag-free and constellation missions such as LISA, a space-based gravitational wave observatory [6].

The current state of the art FEEP technology, however, has a lot of room for maturation compared to other more established propulsion systems. Characterizing and investigating the plume by measuring important parameters such as current, operating voltage, divergence angle, neutral particles, will positively influence the development of FEEP in industry and research. The purpose of this research in Fall 2021 was to set up and fire this ion source in vacuum to achieve such characterizations. This experimental research was conducted at the Advanced Space Transit and Architectures (ASTRA) Laboratory of Dr. Elaine Petro at Cornell University in coordination with Master of Engineering Student, Stefan Bell.

2 Materials and Methods

2.1 Equipment and Materials

ASTRA laboratory's equipment utilized for this experiment were: a vacuum chamber running on a roughing pump and turbo pump (capable of reaching order of $10^{-6} torr$ internal pressure), direct current (DC) low-voltage power supply, multimeter, DC temperature controller, wires, vacuum-rated K-type thermocouple, high-voltage power supply, soldering station, magnification stereo microscope for observing needles, and Stirring hot plate.

Parts and materials of the FEEP system consisted of an aluminum base plate holding the needle, steel extractor plate directing the plume, Polyether ether ketone (PEEK) supporting rods for connecting the base plate to the extractor plate, stainless steel hypodermic needle to hold the the tungsten needle, holding indium (the propellant) at the very tip of it, nickel chrome 43 American Wire Gauge (AWG) heating wires (0.0025" diameter) with vacuum-rated Enamel insulation, supported by Kapton Polyimide tape, hardware to hold the system together, and a polytetrafluoroethylene (Teflon) plate electronically insulating the FEEP from the chamber ground (Figure 1).

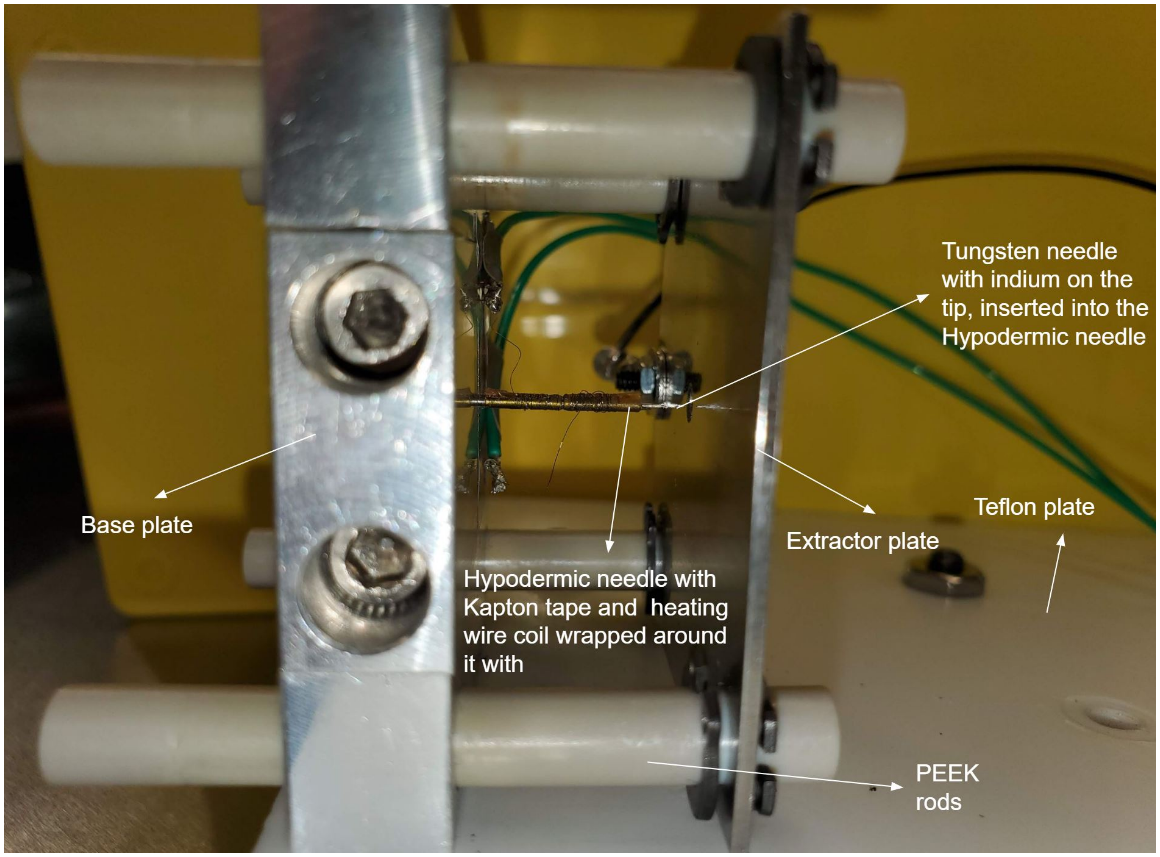


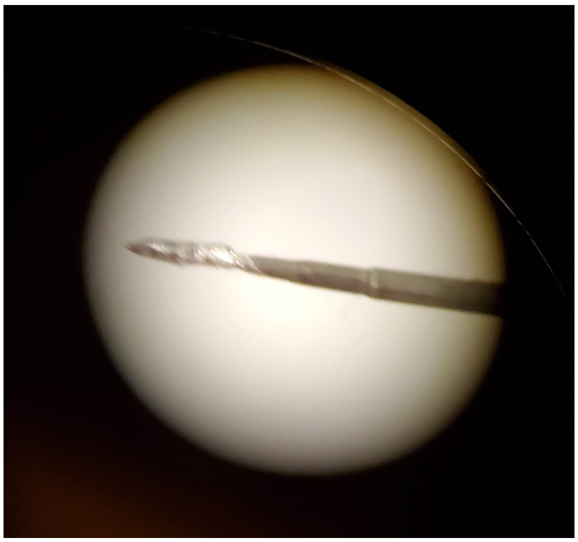
Figure 1: Side view of the FEEP

2.2 Experimental Methods

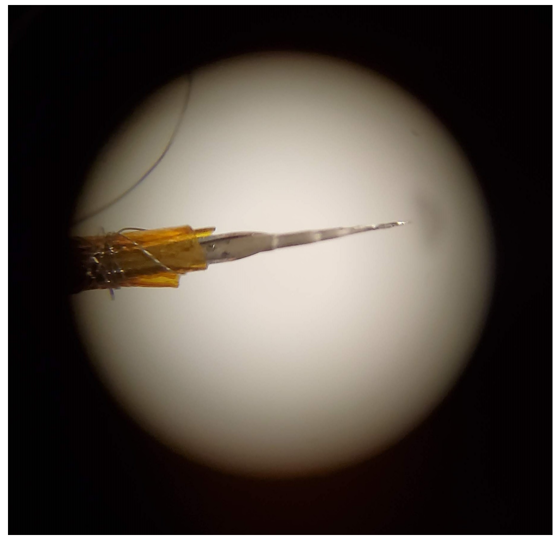
First and foremost, thorough cleaning of all material that is going to be placed in the vacuum chamber is required. Cleanliness of materials inside the chamber reduces contamination, discrepancies in the design, and possible noise in results. Cleaning was done with ethanol/alcohol to keep the chamber internal environment clean, acetone for metal parts of the ion source, and Isopropyl alcohol for plastic parts.

Once the cleaning of the chamber interior and FEEP parts is completed, assembly and needle preparation was started. The in-situ fabricated tungsten needle was wetted with indium on it tip (tip had a diameter in the order of ηm) By using the hot plate, an indium shot was placed on aluminum foil and melted at a temperature of 156.6°C [3].

Once the indium transformed into its liquid phase, the visible "gunk" was removed to insert the tungsten needle's tip into the liquid indium and wet the tip of the needle. The tungsten needle was then placed into the hypodermic needle as seen in Figures 2a&2b to make the needle system.



(a) Tungsten needle with indium on the tip



(b) Tungsten needle inserted into the hypodermic needle and wrapped in kaptop and heating wire coil

Figure 2: Microscopic images of the FEEP needles

The needle system was then placed and clamped into the base plate, followed by inserting the supporting PEEK rods into the base plate and extractor plate, held rigid by the retaining rings (Figure 3).

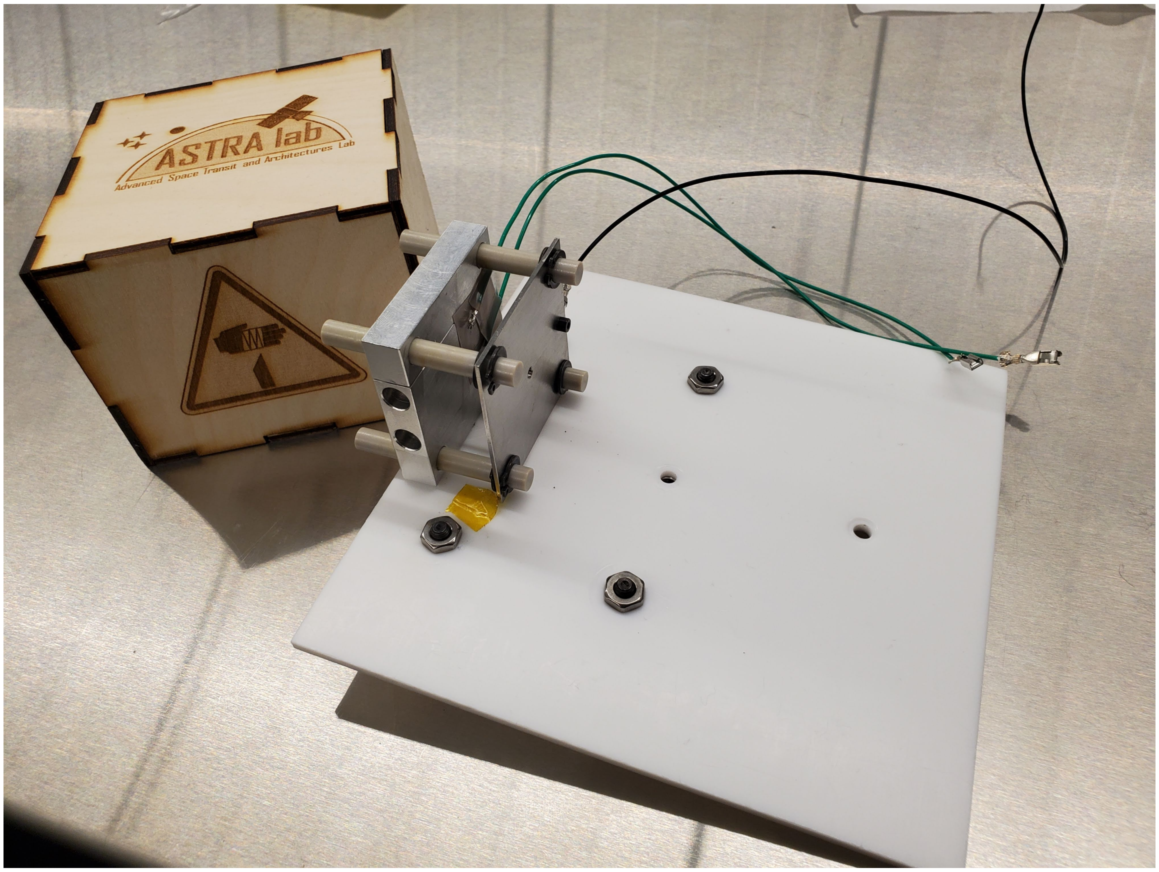


Figure 3: FEEP assembly in atmosphere

Once the FEEP assembly was completed, it was ready to be placed into the chamber and establish the connections between the equipment outside the chamber and the FEEP inside the chamber. Connections were ran through a CF flange multi-pin connector that allowed wiring from the atmosphere side to the interior of the vacuum chamber while blocking air flow. high-voltage cable from the high-voltage power supply was connected to the base plate, with the extractor plate grounded, in order to create an electric field between the two plates and produce thrust when the indium was starting to melt and high-voltage of $3 - 5kV$ was applied across the two plates [1]. The heater wires were indirectly, through 22 AWG wire, connected to a DC power supply to control the voltage, current, hence temperature of the wire.

The temperature of the wire was monitored using a thermocouple and a temperature controller. The wired system can be seen in Figure 4. The connections were inspected and verified using a multimeter in voltage, continuity, and resistance modes.

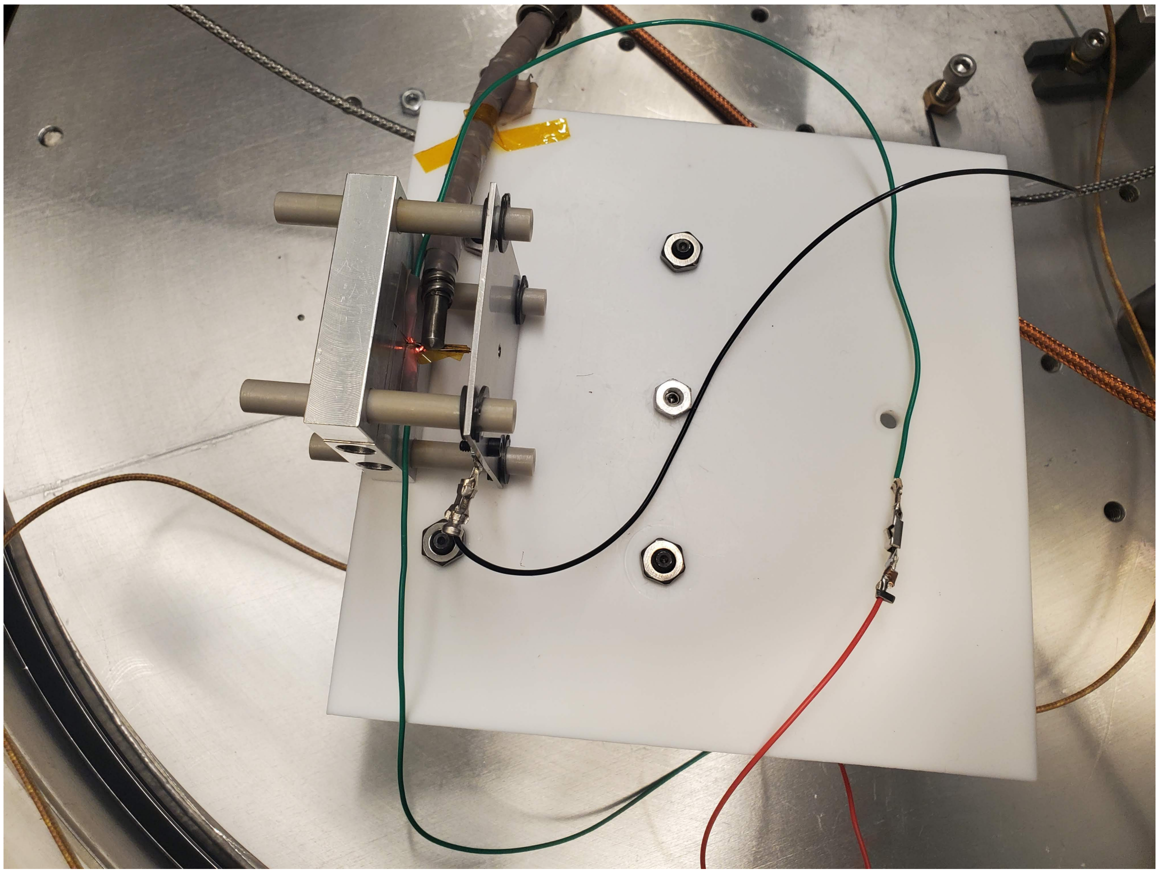


Figure 4: Top view of the FEEP assembly inside the chamber. In this image, the heating system was turned on for a sanity check before depressurizing the vacuum chamber. The glowing wire can be observed underneath the thermocouple.

Finally, after the connections of the assembly and equipment was established, the chamber was be closed up, and depressurizing was began using the roughing pump. This motor has the ability of vacuuming the chamber down to an order of $10^{-1} torr$ (starting from an atmospheric pressure of $900 torr$). Then, the turbo pump was activated to boost the vacuuming process and depressurize to a vacuum of order of 10^{-5}-$10^{-4} torr$. Meanwhile, temperature of the wire, hence the tungsten needle and indium, was being increased through the DC power supply. Once a temperature of 156.6°C was achieved in vacuum of order of at least $10^{-4} torr$ pressure, the high-voltage power supply could be turned on and set to 2-3kV, followed by increasing it conscientiously until a plasma/plume starts to appear from the tip of the tungsten needle with the indium ion. When the metal propellant is ionized and accelerated in the electric field, the emitting metal ions exit the thruster through the extractor aperture with velocities of up to 100 km/s. The plume would then be firing into a Faraday cup allowing us to measure the current and perform post-firing analysis/calculations as valuable results.

3 Results & Discussion

In the Fall 2021 semester, numerous experiments were conducted in order to fire the ion source, however, none of which were successful in terms of producing thrust from our single-emitter FEEP to give us numerical results. Nevertheless, many important design changes were made that resulted in quicker set-ups for each attempt to fire in vacuum, including needle preparation and improving the heating system by experimenting different methods. The method explained in Section 2.2 is the best approach thus far for heating up the indium ion to melt it in vacuum. The closest we got in our attempts was achieving up to a temperature of 250°C in atmospheric conditions using the DC low-voltage power supply. However, using the same method of heating in vacuum, only a temperature of $\sim$ 60°C in $10^{-4} torr$ was achieved, but the current from the DC low-voltage power supply was too high and burnt the wire (Figure 5). We believe this anomaly was due to the different behavior of our heating system in vacuum vs. in atmosphere. In vacuum, the lack of air prevents heat dissipation through convection from the wire to its surroundings, causing it to burn itself at high current.

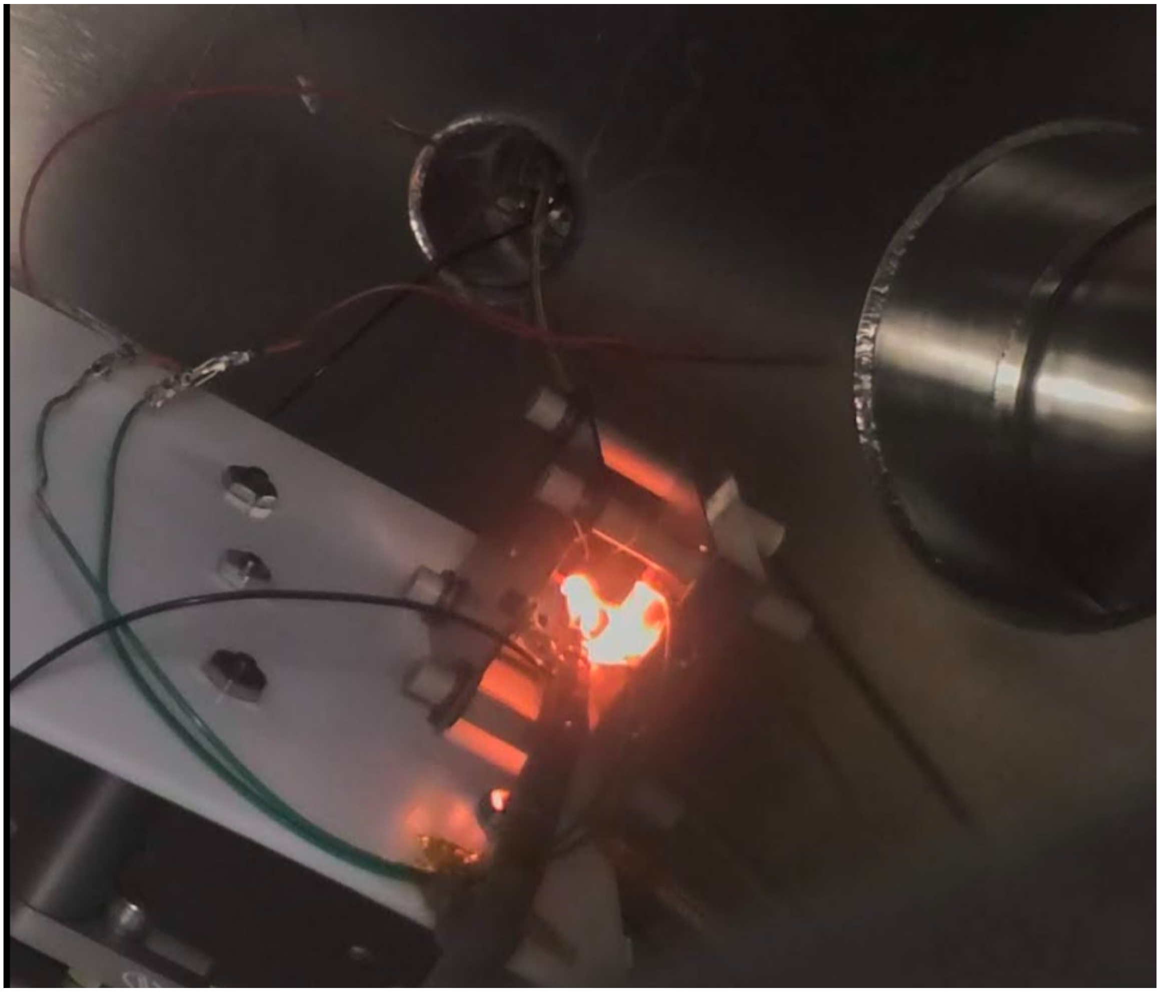


Figure 5: FEEP inside the vacuum chamber undergoing our final attempt to fire, which resulted in a burn in the heating wire due to high current running through the wire.

4 Conclusion & Future Work

After spending most of the Fall semester using the DC low-voltage power supply, testing various methods of heating the tungsten needle with wires, and observing countless failures, we concluded that achieving high temperatures using a thin wire in a vacuum environment is not the best/easiest option. Therefore, we will be exploring different heating systems in the Spring 2022 semester. More specifically, we will be exploring ceramic heaters, which are capable of achieving high temperatures in a vacuum environment, while offering electric insulation. We learned a lot from our numerous attempts to fire our ion source in vacuum while enjoying the work we did this semester. Science is mostly learning from failure and turning those experiences into one great success, as Thomas Edison says "Never Say I Failed 99 Times, Say I Discovered 99 Ways Which Causes Failure!" [7] We hope to achieve successful firing experiments in the next semester to collect numerical results and publish a well-written manuscript on our experimental research to a journal. Additionally, we hope to present our work in the AIAA Regional Student Conference and/or the AIAA Foundation International Student Conference.

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