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MPCS-2017-Ht01

Hall Thruster Configurations for Nano/Micro-Satellite Propulsion

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A Hall thruster (HT) is a griddles positive ion accelerator used for spacecraft propulsion. First introduced in the mid-1960's, the HT has a long and successful flight history dating back to the early Soviet Meteor satellites in 1972. Over the past decades, HTs have been installed on board tens of commercial, institutional and military satellites. Their early role as station-keeping and attitude control systems is being expended to orbital transfer and main propulsion device. While kilowatt class thrusters for geostationary satellites are a mature technology, HTs operating at 200 W or below are considerably less developed. This work will present the impact of miniaturization of HT on their performance and new techniques investigated at ICARE to mitigate these effects. One such technique is the use of magnetic shielding type configuration that reduces the plasma/surface interactions and leads to lifespan extension. The concept of wall-less thruster also promises interesting advantages for low power applications. Experimental results comparing ICARE's 200 W shielded HT, a 200 W wall-less thruster and a 100 W traditional HT will be presented.

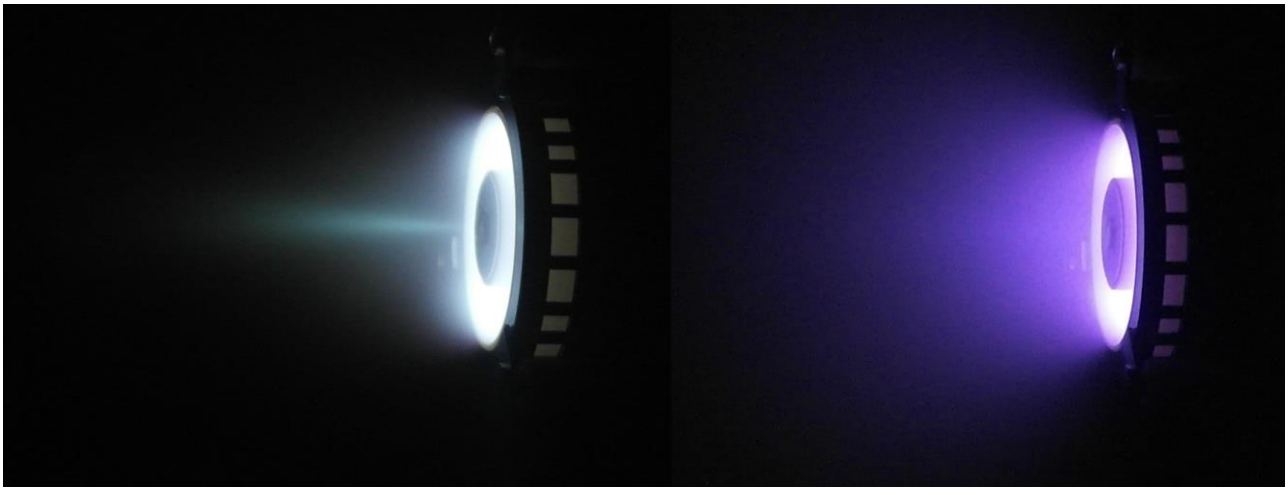

Figure 1. ICARE's 100 W ISCT100 Hall thruster firing with xenon (left) and krypton (right) propellant.

MPCS-2017-Ht02

The Development of Singapore's Miniature Hall Effect Thruster and Gradually Expanding Rotamak Thruster for Space Propulsion

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Miniaturized electric propulsion devices are the heart and pivotal sub-system of small satellites and satellite systems. Further exploration of Moon [1], manned Mars exploration [2], sending long-living probes to Jupiter and Saturn, comets, asteroids [3] and deep space [4], and much more intense usage of near-Earth space for the benefit of the whole mankind – for advanced communication, global internet access, precise weather prediction and many other practical aims. All these tasks require efficient, reliable, robust control systems capable of controlling the spacecraft velocity vector, as well as orientation and location in space with the maximum possible mass and energy efficiency of the propulsion devices (thrusters). They should work in adverse space conditions (low and high temperatures and extremely high rates of

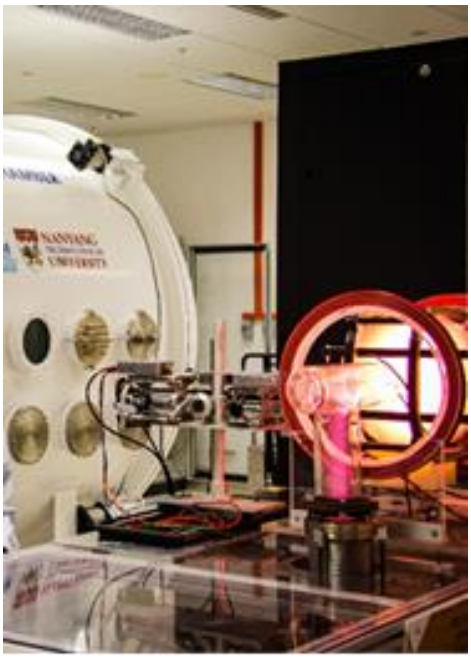

Figure 1. PSAC's Gradually-Expanded-Rotamak prototype operating.

temperature change, vacuum, radiation, possible attack of high-speed dust particles) for long time reaching years, with very high system fault tolerance.

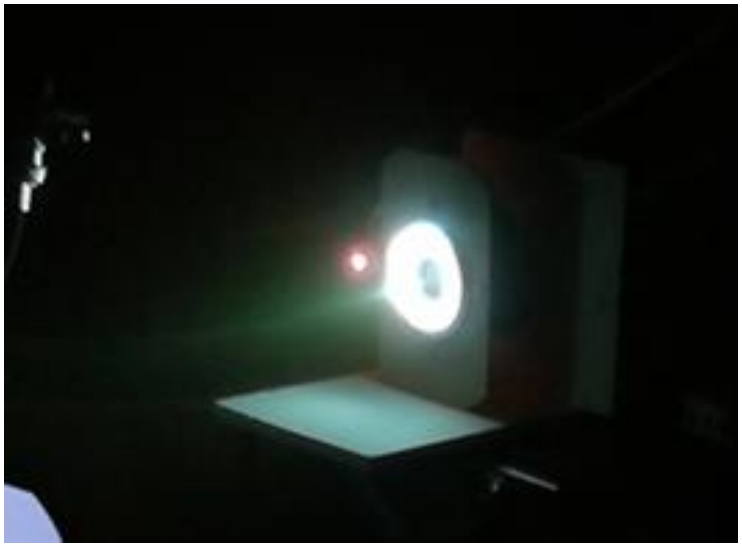

Figure 2. PSAC's miniature Hall Effect Thruster operating.

This talk presents the status of the development of electric propulsion technology at the Plasma Sources and Applications Centre/ Space and Propulsion Center Singapore (PSAC-SPCS), NIE, Nanyang Technological University, Singapore. Our team at PSAC-SPCS, NIE is focused on the development, commissioning, optimization and operation of two types of highly distinctive space propulsion systems: a miniaturized Hall-thruster for cube- and nano-sats propulsion, and a radio frequency rotating magnetic field driven Gradually-Expanded-Rotamak (GER) electromagnetic thruster. Conceptualization, physical understanding and modelling, engineering development and performance characterization will be discussed in terms of steady state current drive, compact torus formation, thruster efficiency, plume configuration and ion flex and energy. The supporting technologies, including Space Environment Simulation Facility; Thruster Performance Measurement System; in situ Plasma Diagnostics System will also be briefly discussed.

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MPCS-2017-Ca01

Sitael Hollow Cathodes for Low-Power Hall Effect Thrusters

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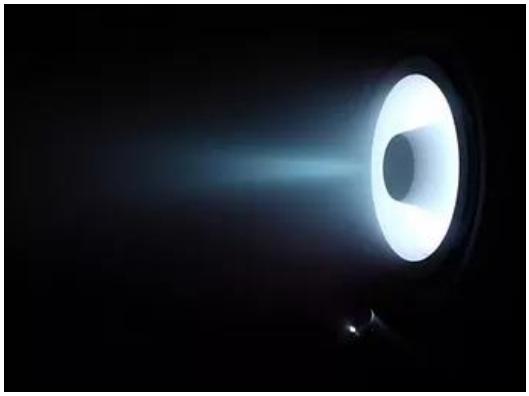

Figure 1. HC1 operating with HT100D [1].

Low-power Hall Effect Thrusters (HETs) belong to a class of electric thrusters with an operating power lower than 500 W. The application of this class of HETs is suited for small satellites for telecommunications and Earth observation missions to perform a variety of missions, namely drag compensation in LEO and VLEO, accurate final orbit insertion, and de-orbiting at the end of the mission. Sitael is active in this field, through the development of two HETs, HT1 00 and HT400, having a nominal power of 100 W and 400 W, respectively. HT100 is a permanent-magnets thruster operating in the 100 – 250 W range, providing a thrust between 4 and 13 mN, and a specific impulse between 900 and 1400 s. HT400 operates at 350 – 750 W of power, 20 – 45 mN of thrust, and 1300 – 1700 s of specific impulse. Two cathodes have been developed and tested, referred to as HC1 and HC3, conceived for HT100 and HT400, respectively. Both the cathodes are based on Sitael heritage in the theoretical modeling and experimental activities of such devices, and rely on lanthanum hexaboride emitters. HC1 is a cathode designed to provide a discharge current in the 0.3 – 1 A range, operating in steady-state conditions at mass flow rates between 0.08 and 0.5 mg/s. Fig. 1 shows HC1 during steady-state operation with HT100D [1]. HC3 was designed for the range 1 – 3 A of discharge current, and 0.08 – 1 mg/s of mass flow rate. Both HC1 and HC3 have an expected lifetime higher than 10 4 hours, estimated on the basis of the emitter evaporation at the operating surface temperature, computed with the aid of the previously developed model [2]. Experiments were carried out, including preliminary characterization campaigns of each of the two cathodes and coupling tests with the respective thrusters. The collected data are presented and discussed with reference to the model predictions, showing a good agreement between theoretical and experimental results.

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MPCS-2017-Ca02

Hollow Cathode Neutralizer for Micro Electric Propulsion

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Cathode neutralizers are an integral part of many electric thrusters such as Hall thrusters and ion engines. The main role of cathode neutralizers is to start the thruster's plasma discharge, serve as the negative terminal of the thruster's electric circuit and supply electrons to neutralize the ion beam coming out of the thruster [1]. Cathode neutralizers operate by using a low work function material, usually referred to as the electron emitter that is sustained at high temperatures so to emit the required electrons. As such, cathode neutralizers incorporate a meticulous thermal design, especially for micro-propulsion applications where the main discharge is low.

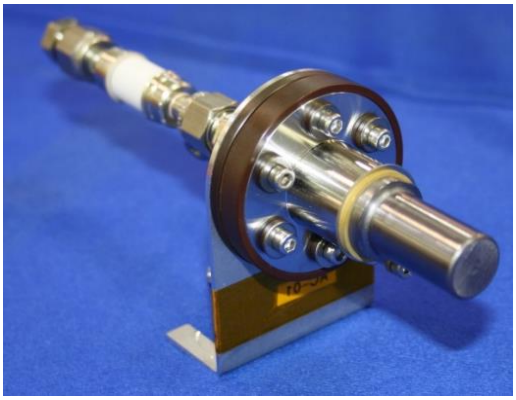

Figure 1. Picture of the Rafael Heaterless Hollow Cathode (RHHC).

Heaterless Hollow Cathodes (HHC) are a subclass of hollow cathodes that do not require a heater for cathode ignition [2]. In this type of cathodes the heating process is by plasma discharge generation in the emitter-keeper gap. Consequently, HHCs use a unique ignition technique. Firstly, high voltage pulse is applied between the emitter and keeper so to electrically breakdown the injected gas. Immediately after initial discharge creation a separate power supply controls the emitter-keeper current, a process during which the emitter is heated. The heating process lasts until the emitter reaches its operation temperature. Lastly, after steady discharge has been initiated the electric thruster is turned on by applying the required emitter-anode current. The entire thruster ignition duration is usually less than 100 seconds.

Thanks to the fact that HHCs do not incorporate a heater they possess several advantages for micro-propulsion:

(1) *Small mechanical design – cathode diameter may be smaller than in conventional cathodes since no space dedicated for heater allocation is needed.*

(2) *Fast Ignition – Conventional cathodes require ignition time of several minutes in order to prevent thermal stress of the heater. Heaterless cathode, on the other hand, may start within seconds and tens of seconds.*

(3) *No heater feed – Heaterelss cathode do not need a heater electrical; therefore decreasing the overall size and required power of the power processing unit.*

In the past several years Rafael, in cooperation with the physics department at the Technion, conducted fundamental low current heaterless hollow cathode research, followed by full product development [3-9]. The purpose was to fully develop a heaterless hollow cathode that can serve as a low current ion beam neutralizer for either Hall or ion thrusters. The developed cathode requirements are presented in **Table 1**.

Table 1. Key requirements of the Rafael Heaterless Hollow Cathode (RHHC)

#	Requirement	Value
1	Discharge Current	0.5-1.1 A
2	Xenon Mass Flow Rate	0.2-0.3 mg/s
3	Lifetime	1,100 A×hr
4	No. of Startups	6,000
5	Ignition Voltage	Up to 1,200 V
6	Mass	Up to 200 g

This paper presents the heaterless hollow cathode developed at Rafael (Figure 1), its mechanical and electrical features and tests performed on it. In particular a 5,000 hours continuous steady state operation test and 3,500 cold ignition cycle test are presented.

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MPCS-2017-Ca03

Alternative Propellants for Low Power Hall Effect Thrusters

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Presently, xenon is by far the most used propellant in Hall effect thrusters (HETs) for space applications. However, alternative, more available and less expensive propellants are currently considered and tested, as for instance krypton and iodine. In particular iodine is attractive for several features it possesses. As a matter of fact, iodine and xenon atomic mass and first ionization energy are very close and thruster performance, in terms of thrust density, thrust efficiency and specific impulse, have proved to be almost the same [1]. Moreover iodine is solid at ambient temperature and pressure, with a density about four times the density of xenon stored at 200 bar at ambient temperature. Iodine cost is currently less than one tenth the cost of xenon. Gaseous iodine at low pressure (up to about 10 kPa) can be obtained by heating the solid propellant at low temperature (up to about 100 °C). Hence, relatively simple and compact feeding system can be conceived, making iodine particularly suitable for low (less than 1 kW) and very low (less than 100 W) power HETs and, potentially, for micro-propulsion applications. However, since iodine is condensable at moderate pressure and temperature and reactive with several materials, included materials used in thrusters and spacecrafts, its adoption needs a thorough assessment. The talk illustrates the most recent results of an activity carried out at the University of Pisa for the development of a iodine feeding system for a 100 W class HET [2]. A first prototype and the relevant test facility are described. The thermostatic test facility for iodine/materials interaction tests is illustrated and preliminary results are shown.

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MPCS-2017-Va01

Influence of Cathode Material on Vacuum Arc Thruster Perfomance

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The use of micro/nanosatellite (weight < 100 kg) is a long history since the first satellite Spoutnik-1 launched in 1957 can be classified in this category (83 kg with a power of few watts). Nowadays there is clear renew of the use of micro/nanosatellite for new missions, in the CubeSats class (6-12 U, one U being a square of 10 cm side): (1) scientific, with constellations of satellites to explore and collect data about the Earth and to test new instruments. Education programs have also been proposed worldwide to attract students to fabricate, test and launch small satellites; (2) military, for real time surveillance, space control and protection of systems; (3) commercial applications, the goal is to deploy satellites to collect informations for agriculture support in developing countries to limit the risk of climatic conditions and water excess/lack, to explore the ground to find hidden natural resources, for real time imagery (e.g. coast evolution closed to the sea), to adapt communications network. The technologies of micro/nanosatellite are very attractive (low cost, rapid demonstration, limited risks, etc.) [1-2]. The demand of is estimated to reach few hundreds of satellites from 2023 and beyond [3].

To reduce the cost, most of times micro/nanosatellites are launched with geostationary orbit satellites in a non-chosen orbit. A propulsion system is needed to pass from the separation orbit to final low Earth orbit, to counter-act the drag forces during the mission, and to de-orbit the satellite at the end of mission. Such propulsion system must be cheaper, reliable, simple, scalable and modular (according to the CubeSat size). Various micro-propulsion (electrical) systems with different propellant can achieve acceptable performance to fulfill the mission requirements [4], [5]. In this presentation, we describe the fundamentals of one candidate the vacuum arc thruster (VAT). We analyze with a simple hydrodynamic model the origin of the thrust. Finally, measurements of the thrust for a typical configuration proposed by Comat Aerospace, France, will be shown.

This work is supported by the Region Midi-Pyrénées-Programme Aerosat.

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MPCS-2017-Va02

Flight Experiments and Recent Developments in Micro-Cathode Arc Thrusters for CubeSat Propulsion

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The George Washington University (GWU) has developed a CubeSat-class thruster called the Micro-Cathode Arc Thruster (μCAT) [1]. The μCAT is a high Isp (2000-3500s), solid metal fueled, low average power (<0.1 W when operating) micro-thruster of small cross section (5 mm), with a mass of less than 200g, and no pressurant tanks. Electric current forms a plasma discharge between a concentric cathode-anode configuration. Thrust is produced through arc discharge, eroding some of the cathode material in uniform manner, to exit at high velocity, during which it is accelerated out the nozzle by a Lorentz force. Thrust can be controlled by varying the frequency of pulses, with a demonstrated range to date of 1-50 Hz, (1 μN - 0.05 mN). The μCAT design achieves uniform electrode erosion, and has demonstrated over two months of continuous operation during trials. The system operates at low voltage, accepting unregulated DC power from the spacecraft bus. The corresponding exhaust plume is 99% percent ionized, with near zero backflux.

Thruster subsystem was developed for the BRICSat-P which was launched in May of 2015 [2]. Some data has been downloaded from the satellite, and it shows that the satellite has successfully operated the propulsion system. The propulsion system was able to reduce initial tumbling from an estimated 30 º/s to within 1.5 º/s after 48 hours. New ideas for high thrust-to power ratio microthruster will be discussed [3].

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MPCS-2017-Va03

Scalability and Reliability of Vacuum Arc Thrusters for CubeSat Missions

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Vacuum arc thrusters VATs are a suitable choice for picosat missions. Their simple geometry as well as high Isp paired with a low mass PPU allow to fulfill many cubesat requirements with regard to mission requirements, power and mass budget. The VAT can be operated in pulsed or DC mode, the impulse bits can be adjusted by simple means and it is a plasma thruster, hence no neutralizer is required [1].

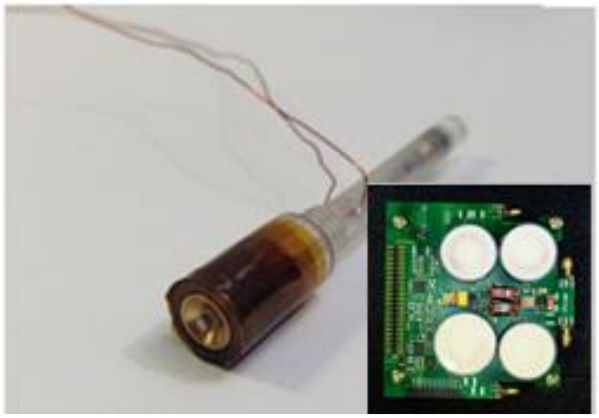

Figure 1. Thruster head and PPU for 1U Cubesat.

Yet there are still some issues that need attention especially when it comes to propellant consumption and plasma ignition.

Plasma initiation of a vacuum arc requires high voltages, which for cubesats introduces the problem of voltage conversion (Cubesat bus voltages are usually in the vicinity of ~5V), and handling of high voltage may lead to unwanted discharges in densely packed electronics circuits. Possibilities to avoid high initiation voltages have been published and shown to exhibit a high reliability [2] yet this reliability depends on the I-bit produced and may thus produce lifetime issues.

Propellant feeding is another issue. VAT propellant may be any conductive material. Usually it is consumed at a rate of ~50µg/C, leading to a production of highly ionized vapor leaving the cathode at a velocity of ~104 m/s. While the propellant can be provided as a solid in numerous geometrical embodiments, the erosion homogeneity is again a matter of pulse power and pulse length, leading to certain I-bit requirements for certain cathode geometries.

Using an example of an actual cubesat mission [3] the issues with regard to reliability will be addressed and scaling issues as well as possibilities for the use of VAT in pico-satellites will be discussed.

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MPCS-2017-Mt01

Plasma Enabled Fabrication and Applications of Nanometamaterials and Porous Alumina in Electric Propulsion

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Engineering new class of hybrid materials that can used as ultra-sensitive sensors for electric propulsion, gas detection, air contamination control is critical to meet the global challenges of the environment conservation and efficient use of energy and mineral resources, especially for point-of-use applications. Template-assisted synthesis is an elegant approach for achieving highly-controllable growth of the arrays of various nanometamaterials. Anodic aluminum oxide (AAO) membranes is one of best template candidate to fabricate these promising materials such as arrays of carbon related or other noble metal nanotubes [1,2], and nanowires [3,4].

In this work we report on several examples for growing and functionalization of nanometamaterials by exposing highly-periodic (hexagonally-symmetrical), porous anodic aluminum oxide templates to a low-temperature plasma. Characterization using TEM, SEM, and EDX techniques have shown different nanostructures have been fabricated successfully and novel applications such as in gas sensing [5] and plasmonic effects [6] have been demonstrated. With plasma, our environmentally-friendly process is simple, fast and does not involve any pre-treatment for the samples. This novel fabrication and functionalization technique constitutes another interesting application of alumina templates to different nanometamaterials growth.

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MPCS-2017-Mt02

Smart and Multifunctional Materials in Electric Propulsion and Cubesats

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Efficient and reliable control systems are among the primary prerequisites for the successful cost-effective space exploration. Communication satellites, manned and cargo spacecraft, small satellites for space remote sensing, scientific instrument for the adjacent and deep space exploration – all of them require precise speed and orientation controls capable of long (several years), robust, and highly efficient operation in the adverse open-space conditions. The criterion of the control system efficiency in the terms of lowest required fuel and mass carrier flow rate, along with the energy efficiency, are the main parameters that directly influence the performance of the whole spacecraft. The electric propulsion-based control systems demonstrate superior characteristics, as compared with the compressed gas, liquid propellant and solid-fuelled thrusters. Without any physical limitations to the exhaust gas velocity (whereas any thermal engines are limited to 6000 m×s-1), the electric propulsion systems and thrusters could ensure very mass-efficient operation. Nevertheless, these systems still require significant advance in the energy efficiency, reliability, service life and controllability. New materials, including the nanostructure-based structures and metamaterials, are among the most promising approaches that can help to solve these challenges. In this work we briefly review the unique features of the nanostructure-based materials in the contexts of their application in the electric propulsion systems and thrusters, with a strong focus to the Hall-effect thrusters which are regarded as the most promising candidates for the long-living space systems, spacecraft and satellites. In particular, the application of vertically-aligned nanotube patterns, nanotube- and graphene-based nanomaterials, as well as complex metamaterials involving nanoscaled structures and related physical effects is discussed. Advantages and disadvantages of these systems are considered. Moreover, a concept of the adaptive thruster is proposed capable of self-adjusting the operation mode by synthesising nanomaterials in the discharge, and depositing them to the proper areas of the acceleration channel, thus actively changing the channel wall conductivity and other characteristics influencing the discharge and thruster operation regime.

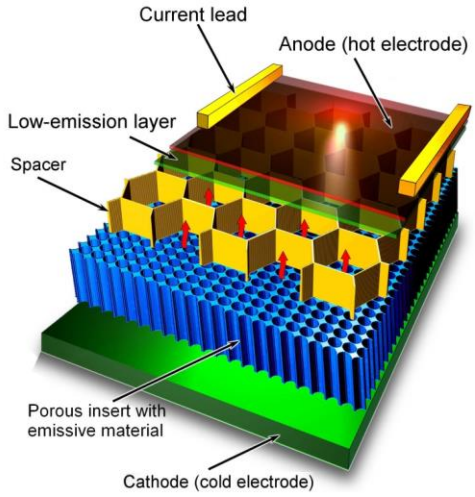

Figure 1. Design of the nanoscaled metamaterial capable of reversal heat transfer by electron emission (concept). The cathode (cold electrode, green) has a temperature lower than that of the anode (hot electrode, red). Nanoporous material contains the liquid (at a work temperature) highly emissive material. Reprinted with permission from I. Levchenko *et. al,* Adv. Mat. Technol. 1, 2016.

MPCS-2017-Mt03

MEMS technology all-photopolymer electrospray emitters for highly scalable nano- and micropropulsion

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Electrospray emitters or colloid emitters are promising candidates for truly miniaturised electric thrusters since they scale favourably upon miniaturisation; namely, the voltage required to extract ions from the ionic liquid propellant is reduced with shrinking diameter of the fuel transport capillary and nozzle orifice. This implies that it should be possible to switch such miniaturised emitters on and off using relatively simple (low voltage) electronics. Calculations have shown that single emitters fabricated using technologies routinely employed in the field of micro electro mechanical systems (MEMS) should be able to deliver specific impulses in excess of 1000 s [1]. Individual emitters are expected to deliver a thrust in the micronewton or even submicronewton range, which may be useful for very high precision manoeuvres needed in scientific and/or deep space missions. However, arranging such minaturised emitters in large or even very large arrays should allow one to create thrusters in the millinewton thrust range while retaining the high specific impulse of the individual emitters. This concept of "scaling-up by numbering-up" requires the high areal integration density that only MEMS technologies can provide today.

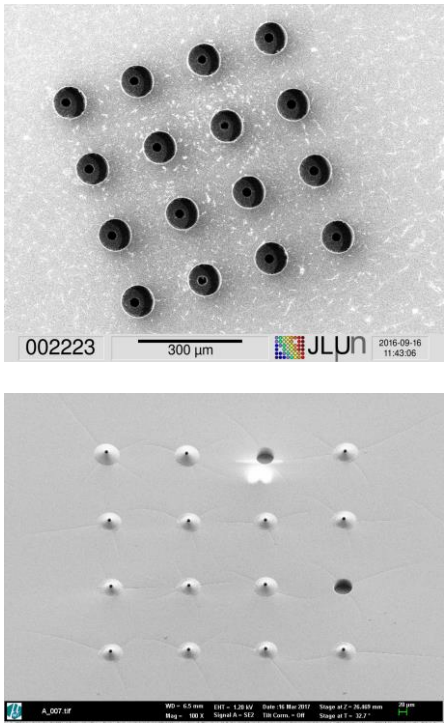

Figure 1. Array of sixteen emitters made by 2D photolithography of SU-8, with integrated extraction electrode (top); tapered emitter nozzles ("volcano emitters") aligned to pre-patterned vias in an SU-8 membrane, made by 3D microlithography (bottom, image courtesy of Karlsruhe Institute of Technology).

MEMS approaches have hitherto mostly concentrated on realising emitters in silicon based technologies [2]. Silicon as a well-understood material has its advantages, but also its limitations, such as the need to carefully insulate the conducting silicon from the ionic liquid, and certain limitations in the freedom of design. We pursue an alternative approach, fabricating all essential parts of the fuel transport system and the extraction electrode support from photostructurable polymers like the SU-8 epoxy resin [3]. With the recent advent of 3D microlithography equipment, most prominently the Nanoscribe two photon lithography system, the very high degree of design freedom allows one e.g. to design tapered emitter orifices, to mitigate the problem of surface wetting, or to integrate more complex extraction electrode support geometries. We present results on the time-resolved measurement of emission from individual emitters and small arrays of emitters, made both by 2D and 3D lithography.

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MPCS-2017-Mt04

MEMS Water Micro-Resistojets for CubeSats and PocketQubes

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Micro-propulsion is universally recognized as one of the key enabling technologies to help nano- and pico-satellites making the next step to become credible candidates for a wide range of scientific and commercial applications. To address this need TU Delft is developing different types of miniaturized electro-thermal propulsion systems operating with green liquid propellants, for application on various small satellite formats including CubeSats (10×10×10 cm units) and PocketQubes (5×5×5 cm units).

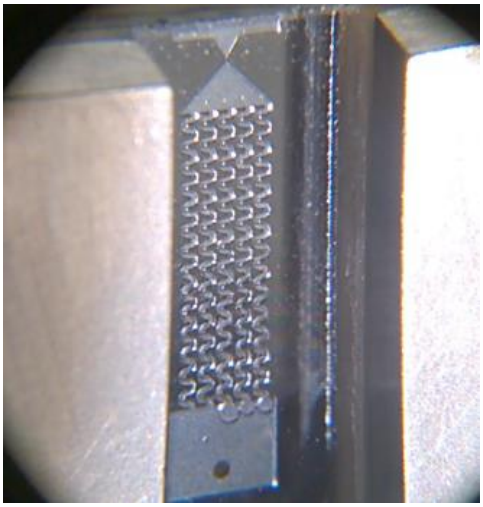

Figure 1. Water vaporization in a MEMS resistojet prototype tested at TU Delft (nozzle throat size is 25 µm).

The choice of an electro-thermal system, more specifically a micro-resistojet, has been driven by the unique capability of this type of propulsion to cover a thrust range from 1 to 10 mN, providing at the same time a specific impulse potentially higher than 100 s and still requiring an average power lower than 10 W (typically expected limit in a 3U CubeSat). Water has been chosen as the candidate propellant not only due to its safety and non-toxicity but also because, even with a propulsive performance partially affected by its relatively high heat capacity and latent heat of vaporization, it is still the propellant of highest specific impulse for fixed input power among all non-toxic fluids storable as liquids at ambient conditions, as we have shown in a recently published study [1].

A demonstrator of the complete micro-propulsion system is currently being designed at TU Delft, including the thruster, propellant tank, valve and driving electronics. This demonstrator is expected to fly as a payload on the Delfi-PQ satellite, the next generation PocketQube bus under development at TU Delft with a first planned launch in 2018. The requirements set by this application demand for a thrust level in the range from 0.1 to 3 mN and a specific impulse from 50 to 100 s, while meeting the critical constraints for low mass (75 g for the complete system

including propellant) and low power consumption (less than 5 W) within a small volume of 42×42×40 mm^3.

We are currently considering two micro-resistojet concepts: a Vaporizing Liquid Micro-resistojet (VLM) [2] and a Low Pressure Micro-resistojet (LPM) [3]. The VLM is based on liquid water and MEMS-manufactured heating channels, with a modular approach to combine different design solutions for the three most important thruster sections (inlet, propellant heating and nozzle for propellant acceleration). Silicon carbide or molybdenum are used for the resistive heater elements, with silicon dioxide electrical insulation. Figure 1 shows water vaporization in a thruster prototype with serpentine channels, covered with a glass layer to visualize the internal flow. The LPM is based on water ice stored at very low pressure under sublimating conditions. The ice vapor molecules move from the tank through the feed system into a plenum, and are then accelerated by flowing through heating sections with high temperature walls, thus playing the role of heating elements and expansion slots at the same time. They absorb heat from the walls, and some of them finally exit into outer space and generate thrust. The system has been preliminary tested with gaseous nitrogen to avoid the additional challenges introduced by the sublimating propellant, showing a very promising performance.

The presentation will discuss a number of test results on the electrical, mechanical and functional characterization of the MEMS thrusters, fabricated in the Else Kooi Laboratory at TU Delft. These tests have proven that the thrusters are compliant to all target parameters, therefore validating the design and manufacturing process flow. In particular, tests conducted on thruster models covered with a transparent glass layer (such as the one shown in **Figure 1**) allowed for identifying the characteristics of the two-phase flow in the boiling propellant. Finally, the feasibility of using commercially available valves for actively controlling the flow has been assessed through the results of simulations in time and frequency domains, validated by successive hardware-in-the-loop test activities.

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MPCS-2017-Mt05

Surface Micro- and Nano-Architectured Materials for Plasma Micropropulsion

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Micro- and nano-engineered materials with surface architecture were proposed for the reduction of secondary electron emission, which is unwanted phenomenon for various plasma and non-plasma applications, including but not limited to Hall thrusters, multipactor discharges, particle accelerators etc. In this talk, I will review effects of secondary electron emission on plasma-wall interaction and performance of plasma devices. We will also discuss results of recent measurements and models of the secondary electron emission from surface architectured materials featuring low and high aspect ratio fibers and protrusions such as carbon velvet (**Figure 1**, upper panel) and tungsten fuzz (**Figure 2**, lower panel). The main physical mechanism by which the effective secondary electron emission from these materials is reduced as compared to the same bulk materials with planar surfaces is by trapping secondary electrons within their structured surfaces. Possible applications of these engineered materials for microplasma propulsion will be also discussed.

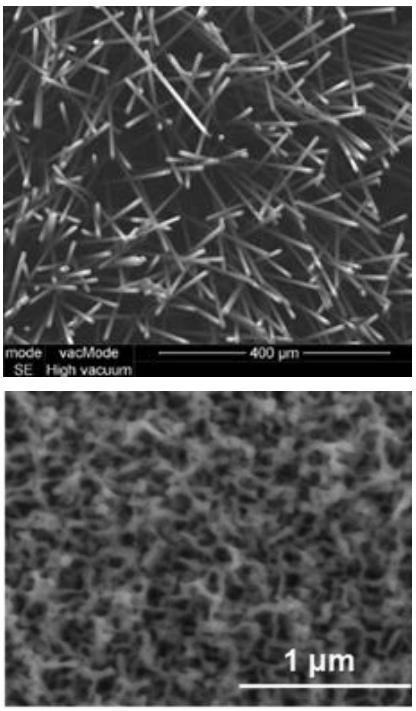

Figure 1. SEM micrographs of micro-structured carbon velvet (top) and nano-structured tungsten-fuzz (bottom)

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MPCS-2017-Mt06

Atmospheric Plasma Jets: The Effect of Electrode Materials

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Atmospheric plasma jets are important kind of future electric propulsion systems capable of operating in atmosphere at low altitudes. The phenomena responsible for generating plasmas and plasma jets at atmospheric pressures through pulsed atmospheric pressure streamers (PAPS) are well known, but the underlying formation and propagation mechanisms are not yet fully understood. This especially holds for electrode discharges at atmospheric pressures. For this reason, we studied plasma dynamics through sophisticated optical and imaging systems in order to detect and quantify small, but important diversities caused by electrode material properties. The moment of PAPS formation is extremely sensitive to the initial conditions, which are also related to intrinsic material properties such as work function. These properties can guide PAPS formation and propagation through the interplay of different processes occurring during both stages. In the case of presented results for copper and titanium, the difference in the work function (4.65 and 4.33, respectively) already leads to delay in PAPS formation for 1 μs (Ti precedes Cu). Furthermore, the PAPS propagation depends on voltage waveform and electric field along the propagation path. Interestingly PAPS speed profiles are independent of electrode material, whereas range and speed is determined by the discharge voltage at the emission of different electrons. Furthermore, the prospects of nano-size electrode and tailoring the PAPS formation conditions are discussed for scaling down and forming plasma jets at these conditions.

MPCS-2017-Mt07

Development of Space Solar Cells in China

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Almost all communication satellites, military satellites and scientific space probes have been solar-powered. China began to develop solar cells in 1958. The institute of semiconductor of the Chinese Academy of Sciences developed the first space solar cell in 1959. In March 1971, silicon solar cells were first applied to China second man-made satellite named “No.1 scientific experimental satellite”. The space solar cells mainly focus on high power density, high reliability and long life. Considering the high specific power (W/kg) and the high-efficiency, III-V gallium arsenide and multi-junction (MJ) solar cells solar cells are gradually replacing silicon solar cells from the late of 1980s in China. Shanghai Institute of Space Power and No.18 Tianjin institute and other units started developing GaInP/GaAs/Ge modules with batch production efficiency reached 28% (AM0, 2×4 cm^2) since 2000, which has been widely used in space energy system in China till now. The highest conversion efficiency was 34.5% (AM0, 25 °C) in 2016. The Sanan Photo-electric Co.LTD successfully developed the lattice matched and high concentrated photovoltaic (CPV) GaInP/GaInAs/Ge solar cells and has carried on the scale of production in 2014, with concentrated efficiency reached 40%～41%. In same year, two high concentrated photovoltaic power stations of 50MW and 60MW were set up in Qinghai province. Qianzhao Photoelectric Co. Ltd reported that they use inverted growth and substrates lift-off technology to achieve GaInP/GaAs/GaInAs cells with efficiency were 34.5% (AM1.5) and 43.0% under AM1.5Dx517, respectively.

Figure 1. The solar wing of "Fengyun 4#” in December 2016 in China.

Most space solar module is hand-making or semi-automatic in China. Figure 1 shows a schematic module making in Shanghai institute of Solar Power-Source. Monomer GaAs cell size to 4cm x 8cm or 3cm x 4cm was connected in series or parallel to form a unit module, many unit modules then be connected to form an array module. The GaAS solar cells are glued to the front sheet of microcrystalline glass and the back sheet of carbon fiber aluminum honeycomb plate. All the cells and supplementary materials are homemade so the cost was 2000yuan/w ($300/w),

lower than the other countries. The power supply system accounts for about a quarter to a third of the weight of the spacecraft. The module service life was 20-30 years and specific power is 120 W/kg. GaAs solar cells has experienced stages of liquid phase epitaxy (LPE) to metal-organic chemical vapor deposition (MOCVD), homogeneous to hetero-epitaxy, single to multiple junction structures and from bulk GaAs solar cells to thin film GaAs solar cells.

(a) (b)

Figure 2. Solar cells unit (a) and arrays (b).

The main difficulty of designing and developing space solar power system is how to adapt to a complex space environment. Low orbit environment is complex with high density plasma, atomic oxygen, electric disk damage and ultraviolet radiation on the solar panels. Nano satellites in space orbit the earth about every 90 minutes during which subjected to temperature difference of 180 degrees required solar panels must solve the problem of heat bilges cold shrink. Electrons and protons with a wide range of energies dominate the space-radiation environment can induce a serious degradation in the electrical performance of the solar cells.

Comparing the space solar module, China is the first terrestrial module producer in the world in a decade. In 2016, its module production reached 53GW, accounting for 42.1% globally and soaring by 15.7% over the previous year. The specific power is 15W/kg. The cost of module was continuing declined to 2.45 yuan/w ($0.35/ w). The production was automation and digitization. The life time of the module was 25 years. With over 20% higher efficient cell technologies of PERC, PERT, HIT solar cells, MBB (multi-bus-bars) and half cell module technologies are introduced to silicon solar cell production, the module efficiency and cost will be reduced.

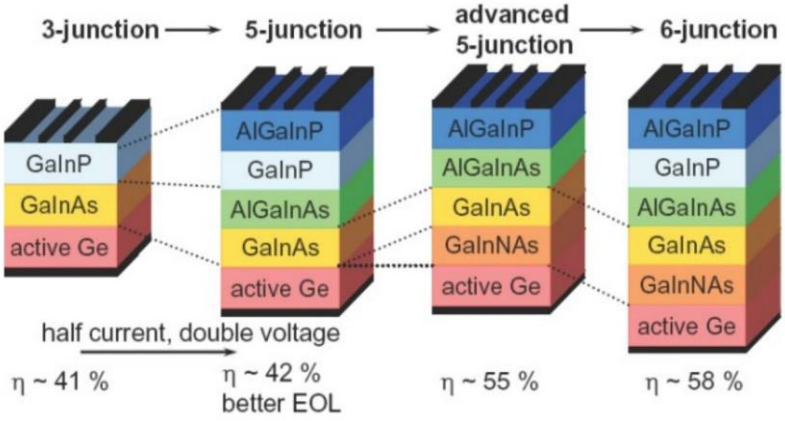

Figure 3. Multi-junction GaAs solar cells.

Figure 4. Yield of Chinese Module in 2016.

Research on thin-film cells such as amorphous silicon solar cells, copper indium gallium selenide (CIGS) solar cells and GdTe solar cells for their higher specific power and projected lower costs is still an area of intense research today. Research and development of Japanese Space agency JAXA is committed to research and development of Japanese Space agency JAXA is committed to research and development in transparent laminated film "Space Solar Sheet (SSS)". The goal of the thin film space solar cells is to achieve the specific power from the 120 W/kg to 600 W/kg. However, it is still a long way to space environment test. On the other hand, the n-type silicon solar cells had better irradiation resistance than p-type silicon solar cells. Figure 6 shows the world biggest unmanned aerial vehicle (UAV) in announced on June 1. 2017 in China by using high efficient n-type Hetero-junction thin film (HIT) solar cells with the specific power about of 100 W/g. Figure 5b is the solar wind used in this UAV and prepared by No. 18 institute of Chinese Electrical Technology Corporation Group. GdTe thin film solar cells is another candidate with its good anti-irradiation performance. On the near future, as the terrestrial solar efficiency increased, these solar cell can be used to the space power system to reduce the cost.

Figure 5. Solar Wind of unmanned aerial vehicle (UAV) in June 1, 2017.

MPCS-2017-Cs01

From Laboratory to Space with the Australian QB50 CubeSats

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Three Australian-built nano-satellites, AU01, AU02 and AU03 were launched into space on April 19, 2017 (Cygnus cargo on an Atlas V rocket) and deployed into orbit from the International Space Station late May as part of the European Union 'QB50' 'CubeSat' mission [www.qb50.eu]. The main scientific objective of the mission is the multi-point in-situ measurement of Earth's thermosphere and ionosphere using miniaturized plasma probes provided by QB50: multi-needle Langmuir probes (mNLP), ion flux probes (FIPEX) and Ion Neutral Mass Spectrometres (INMS). The INSPIRE-2 / AU03 2-unit CubeSat shown in Figure 1 was accepted by the European Union's QB50 project on 19 August 2016, only 10 months after the project started on 30 September 2015. It is the result of a very strong collaboration between the three participating universities, the University of Sydney (U.Syd), the Australian National University (ANU), and UNSW Australia.

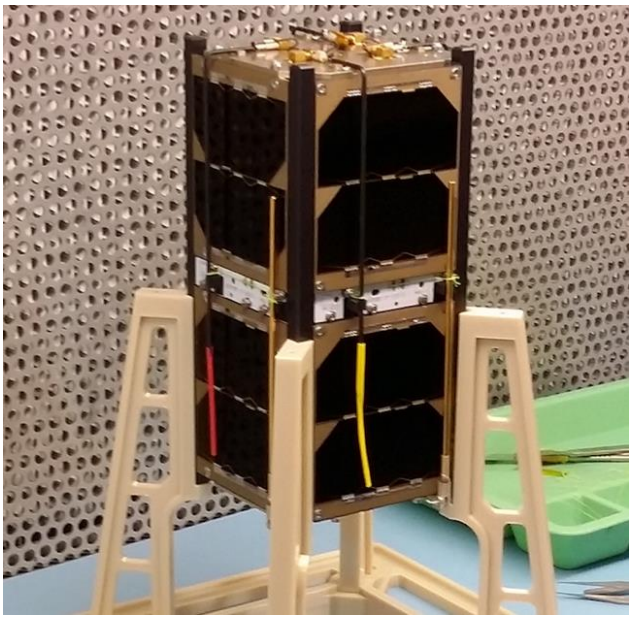

Figure 1. INSPIRE-2 / AU03 QB50 2U CubeSat

To de-risk the project, ANU provided the commercial satellite parts and UNSW the satellite design and software. INSPIRE-2 carries 5 payloads: a QB50 multi-Needle Langmuir Probe to measure the electron number density; Nanospec (U.Syd), a photonic spectrograph containing the first photonic lantern to fly in space; a Radiation Counter and a Microdosimeter (U.Syd), and UNSW Kea GPS instrument. The INSPIRE-2 / AU03 underwent thermal vacuum and vibration testing in the WOMBAT XL chamber at ANU (Mt Stromlo) along with SUSaT / AU01 (University of Adelaide) and ECO / AU02 (UNSW), both carrying the QB50 INMS sensor. Also, the first detailed functional verification of UCL-MSSL's fully integrated INMS flight unit was carried out at low energy using SP3-ANU's plasma wind tunnel. Australia has set up three strategically located ground stations (Adelaide, Sydney, Canberra) to support the QB50 mission. Australia's space capability includes the development and testing of miniaturised propulsion systems for future nano-satellite missions.

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MPCS-2017-Cs02

Development of the Electrothermal Pocket Rocket for CubeSats

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[2] Electrical Engineering Department, Stanford University, Stanford, CA, USA

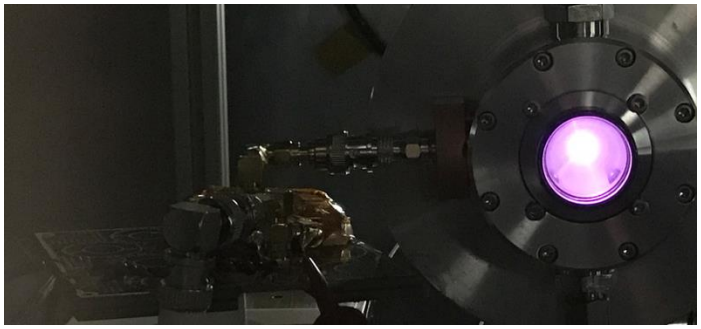

Figure 1. MiniPR plasma powered by the switch mode amplifier in vacuum

Radiofrequency thrusters have been used successfully, but rarely, on spacecraft, i.e. the Radio-frequency Ion propulsion RIT-10 system aboard EURECA in 1992 and the RITA-10 aboard ARTEMIS which saved the mission in 2002/2003. 'CubeSat' nano-satellites provide low-cost access to space, and open doors to unprecedented and unique projects that are now accessible to universities and small companies. The process is facilitated by ongoing miniaturization and lower costs of electronics systems and components, including 3D printing. Australia is involved in the European Union 'QB50' 'CubeSat' project [www.qb50.eu] comprising a launch into space of about 50 CubeSats from 27 Countries aimed at studying the Earth's ionosphere and lower thermosphere. While many essential CubeSat parts are available off the shelf (electrical power system, attitude control system, on board computer…), low-cost low-volume low-weight and low-power propulsion systems which could provide orbit control and

formation flying in future CubeSat missions have yet to be fully developed. In the miniaturised instant 'on' Pocket Rocket thruster, MiniPR, a radiofrequency plasma is employed to heat the gas via charge exchange collisions and ambipolar flow to create a form of electrothermal thruster which has its heating mechanism in the centre of the flowing propellant rather than on the thermally lossy walls. MiniPR's steady-state characteristics can now be successfully simulated using computer fluid dynamics codes. A low weight (150 g), small but structurally supportive (10 cm by 10 cm by 1 cm), robust and efficient dc to rf power supply has been successfully designed and tested at atmospheric pressure and in vacuum (**Figure 1**) to power a 1 to 15 Watts plasma for continuous and pulsed operation with argon as propellant. The power supply consists of a switch mode amplifier and impedance matching network for optimum plasma ignition, tuning and control. It is designed to be combined with a miniaturized propellant sub-system to fit within a ½ U CubeSat.

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MPCS-2017-Cs03

Small Sat Propulsion Developments at FHWN and FOTEC

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Building on 30 years of experience in Liquid Metal Ion Sources (LMIS), the department of Aerospace Engineering at FOTEC (formerly 'Space Propulsion and Advanced Concepts' at Austrian Institute of Technology, AIT) has taken several attempts with the utilization of LMIS for Field Emission Electric Propulsion (FEEP) applications [1]. With more than 100 emitters tested and the successful completion of a 10.000 hour endurance test [2], which showed no degradation in emitter performance, the technology has proven to be successful as well as a competitive product for the emerging market of micro-, nano-, small satellites. This is a result of 15 years of developmental efforts with the core element of success being the porous tungsten crown emitter. The crown emitter features a dynamic thrust range of 1 µN to 1 mN at 3000 s to 6000 s I_{sp}.

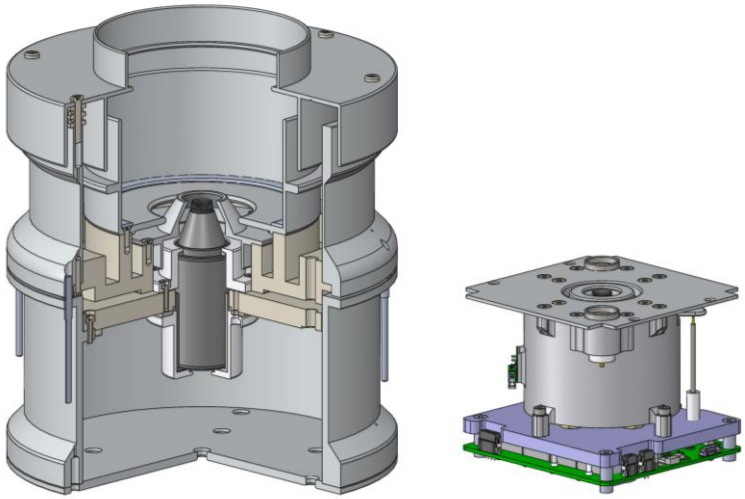

Figure 1. The IFM 350 (left) and the IFM Nano (right) thruster modules using the same porous tungsten crown emitter.

There has not only been an investigation and development into FEEP thrusters, but also into Pulsed Plasma Thrusters (PPT). With the colleraboration of the University of Applied Sciences Wiener Neustadt and FOTEC, the development of the µPPT technology was established. The PPT features a structural simply design with a relatively low power consumption, which makes it a prime candidate for small satellites. However, the miniaturizations of such a propulsion system had its challenges which most failed to show the required lifetime needed. The present coaxial design has shown a lifetime of up to 1 million discharges at discharge energies of 1.8 J in previous studies. For this purpose direct thrust measurements with a µN thrust balance were conducted. Thrust measurements in conjunction with mass bit determination allowed a comprehensive assessment. Based on those measurements the present µPPT has a total impulses capability of approximately I≈1.7 Ns, an average mass bit of 0.5 µg s^{-1} and an average specific impulse of Isp≈904 s. All tests have shown very good EM compatibility of the PPT with the electronics of the flight-like printed circuit board. Consequently, a complete µPPT unit can provide a Δv change of 6.8 m/s to a standard 1-Unit Cubesat [3].

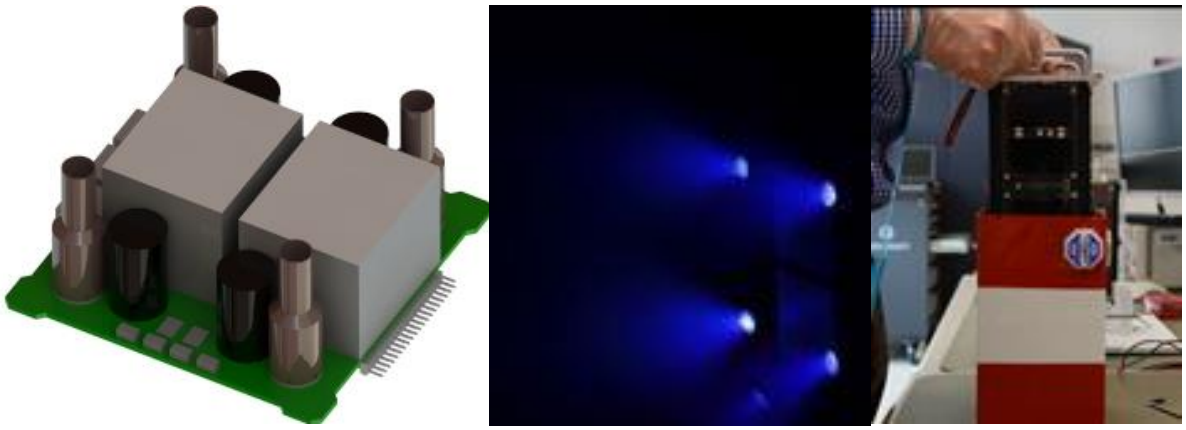

Figure 2. 3D model of µPPT (Left), firing of µPPT (Middle), and packing of Pegasus to be launched (Right).

The µPPT is currently being used on the satellite (Pegasus) developed at FHWN and is scheduled to be launched on the 23rd of June, 2017. Pegasus is part of the QB50 mission that will demonstrate a constellation of CubeSats that have been built by University teams around the world to provide scienctific experiments at low-costs.

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MPCS-2017-Th01

Graphene-based light-powered propulsion: a possible alternative to solar sail

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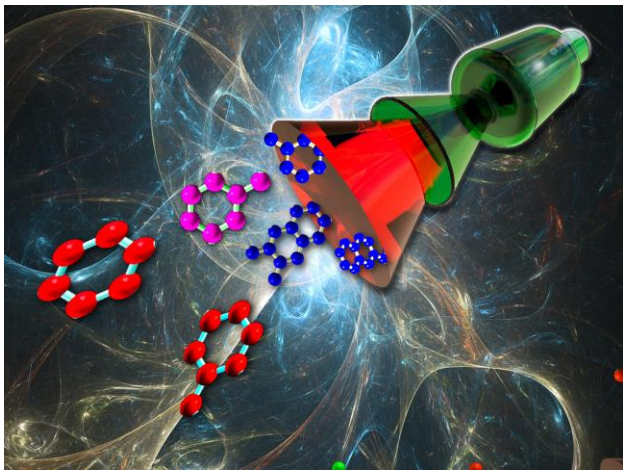

Graphene-based materials hold great promise in advancing fuel-free spacecraft. For instance, graphene sponges created through fusion of crumpled sheets of graphene oxide have been shown to propel forward when illuminated by focused sunlight or lasers of different wavelength and intensity under vacuum. The forward movement experienced by these pieces of graphene sponge exceeded that expected for a solar sail material, where the object propels forward from the momentum transferred from the photons, and was attributed to the absorption of laser energy by the material, which results in a charge build-up and subsequent release as a current flowing away from the material. This suggests that graphene-based light-powered propulsion systems may outperform other solar sail materials. Yet, fabrication of three-dimensional, large area graphene materials with properties arising from the nature of individual graphene sheets remains a significant challenge.

Furthermore, these materials should be able to withstand significant compression without loss of optoelectrical properties under extreme environmental conditions expected in space, and ideally not contain any additives that may compromise function or longevity of the 3D material. Here, we will discuss methods presently used for fabrication of high-quality 2D and 3D graphene materials, focusing on plasma-enabled methods of graphene synthesis.

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MPCS-2017-Th02

Multi-Mode Micropropulsion

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Spacecraft have traditionally used chemical or electric propulsion as a means of orbital manuevering. Chemical propulsion is capable of rapid manueverability at the expense of fuel efficiency. Electric propulsion is the converse: very good fuel efficiency, but low thrust resulting in long trip times. Typically, due to mass or volume constraints, a single mode is selected, designed, and optimized specifically for a given mission. As mission requirements evolve during the design process, the propulsion system may have to be adjusted and, in some cases, components and systems re-qualified. This is contrary to the tenets of small satellite design where rapid turnaround is enabled through plug-and-play architecture. Over the past decade, several propulsion systems have been designed to fit the small satellite platform, namely CubeSats. However, these systems, aside from fitting in a 1U cube, have vastly different interface requirements especially in terms of power and flight software. Furthermore, these systems only offer one type of propulsion, chemical or electric, meaning the spacecraft is constrained to either type of manuever with little adaptability during the design phase let alone on-orbit.

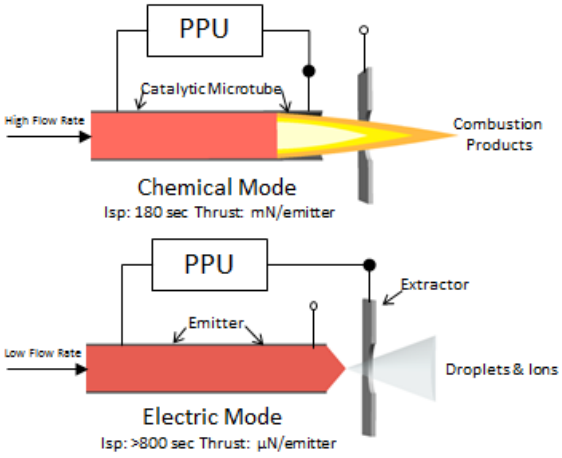

Figure 1. Multi-mode micropropulsion: a single microtube / emitter is operated as either a catalytic chemical thruster or an electrospray electric thruster.

Multi-mode spacecraft propulsion is the combination of chemical and electric propulsion in a single system with at minimum shared propellant between the two modes, and ideally shared hardware, namely tanks, valves and other feed system components. Use of a shared propellant allows for propellant budget to be allocated between modes synergistically as mission needs arise whether on-orbit or during satellite development, significantly enhancing the flexibility and capability of the spacecraft.

Missouri S&T has developed a propulsion system capable of both chemical and electric propulsion with a single propellant, tank, feed system, and thruster [1]. The system is equivalent in mass and volume to state-of-the-art single mode chemical or electric systems, but can be operated in either mode at any given time.

The thruster uses a single ionic liquid propellant based on a binary mixture of hydroxylammonium nitrate and 1-ethyl-3-methylimidazolium ethyl sulfate capable of exothermic decomposition in a monopropellant mode [2] as well as provide an efficient source of ions in an electrospray mode [3,4]. Chemical mode calculations show the thruster capable of high-thrust (>

500 mN) at a specific impulse of 180 seconds [5,6] and electrospray experiments show the thruster capable of specific impulse in excess of 1000 seconds [4].

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MPCS-2017-Th03

Development of Very Small, High-Density Helicon Source for Propulsion

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Helicon plasma [1] source is very promising, since it can produce a high-density plasma up to ~ 10^{13} cm^{-3} over a wide range of external parameters. We have developed various helicon sources, aiming at plasma propulsion as well as fundamental studies with an electrodeless condition (no direct contact between a plasma and electrodes), leading to a longer operation time without wear of electrodes and impurity contamination. Here, plasmas with a diameter of 0.3 - 74 cm and an axial length of 4.7 - 486 cm could be produced [2,3].

In this presentation, we will show experimental results on a very small diameter plasma production and its acceleration with this electrodeless condition, using the Small Helicon Device (SHD) [4], as shown in Fig. 1. This device can accept various sizes of quartz discharge tubes with the use of permanent magnets and/or electromagnets.

We have produced high-density plasma with a very small diameter of 0.3-2 (0.1) cm with (without) the magnetic field, applying the RF frequency for a broad range: from 7 to 435 MHz [5,6]. We have also tried to accelerate a plasma with a scheme of an azimuthal mode number m = 0 half cycle acceleration [2,3], and found increases in electron density and ion velocity by ~ three times.

In characterizing a plasma, the following diagnostics were used: a Langmuir/Mach probe, and a

laser for a Laser Induced Fluorescence (LIF) method. Additionally, spectroscopic measurements have been executed to adopt a collisional radiative (CR) model to estimate electron temperature and density.

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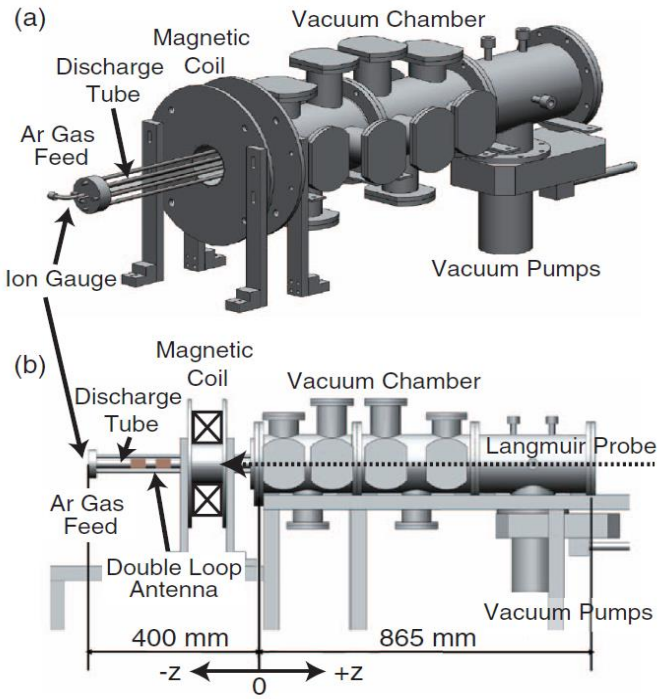

Figure 1. Small Helicon Device (SHD) (top).

MPCS-2017-Th04

Influence of Capacitor Setup on the Performance of Pulsed Plasma Thruster

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Pulsed Plasma Thruster (PPT) has been regarded as one of potential micro-propulsion devices for the Micro-satellites such as Cubsats. Capacitor setup is a main issue of PPT to meet the restricted geometric demand and also have great influence on the main performance parameters of PPT such as impulse bit, specific impulse and thrust efficiency. To facilitate the configuration design of PPT, the influence of capacitor setup on the performance was investigated in this paper. It has been concluded that capacitor setup affects the performance of PPT by varying the inductance and resistance of circuit loop. Firstly, some typical capacitor setups for both breech and side feed configurations were summarized based on the existed configurations of PPT. Furthermore, the external electrical parameters, including the inductance and resistance of capacitor(s) and external wires, were analyzed in several situations. Finally, the performance of PPT with the different external electrical parameters was simulated based on the electromechanical model and the Influence of capacitor setup on the performance parameters was then presented.

MPCS-2017-Th05

Commercialization of the IFM Nano Thruster for Small Satellite Constellations

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At ENPULSION, the course is set towards the future in space industry. Leveraging 15 years of technology development from ESA science missions, the small spin-out company is getting ready to mass-produce electric propulsion systems on an unprecedented scale.

Field Emission Electric Propulsion (FEEP) is a particularly difficult technology, featuring extremely high voltages, and Ion emitters in the microscopic domain. For over 15 years, several players worldwide have tried to master this technology in order to leverage the theoretical benefits over other electric propulsion technologies. So far, not a single thruster has made it to orbit, which has lead, almost all development efforts to be stopped after consuming millions of R&D funds. Even at FOTEC, the birthplace of ENPULSION, several concepts had to be discarded until roughly 10 years ago, the porous tungsten crown emitter was developed.

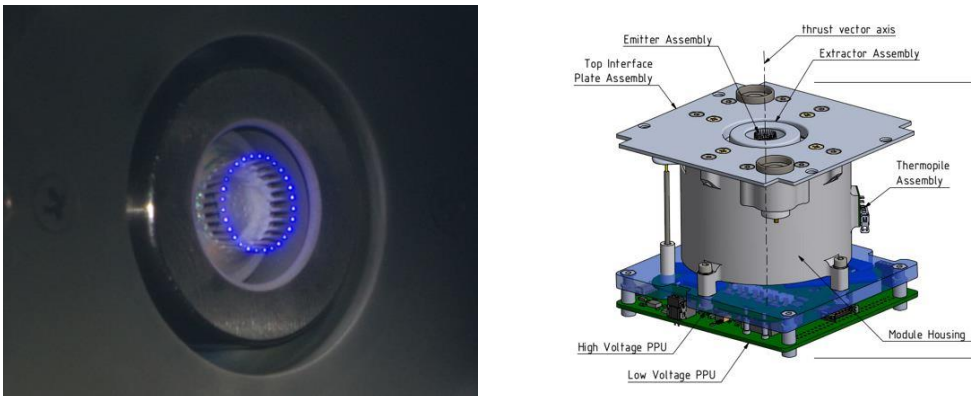

Figure 3. The IFM Nano thruster description (Right) and a firing test at FOTEC facilities (Left).

Now, in 2017, ENPULSION is getting ready for the mass production of hundreds of such FEEP thrusters every year. With the first product already sold to commercial customers and the first flight module shipped in the fall of this year, the IFM Nano Thruster will set the standard in the market. It addresses the urgent need of a propulsion system for micro- and nano-satellites: the wide range of thrust (1 µN-1 mN), the excellent throttle control, and a high specific impulse (ISP up to 5000 s), allows to significantly increase the mission range of such satellites. The high ISP also allows for very high Δv manoeuvres at a high propellant mass utilization efficiency (80%). The modularity and the small volume (<1 dm^3 including propellant and electronics) and its light mass (0.8 kg), makes the thruster suitable for all small satellites ranging from 1 to 500 kg.

The core technology is the mN-FEEP emitter, which uses liquid Indium as the propellant. The development of this technology had begun in 2005, by FOTEC, and was commissioned by ESA. Additionally, the mN-FEEP emitter was already at a mature stage of development considering it has been widely tested in the past 10 years by FOTEC. Specifically, it was commissioned by ESA to enable flight formation of large satellites in its scientific missions. Keeping the emitter technology as it has been developed for the Next Generation Gravity Mission, the housing of the thruster has been re-designed to accommodate into a CubeSat structure. In parallel, a power-processing unit (PPU) has been developed and integrated into the thruster module. The result of this redesign is the new IFM Nano thruster family with the particular advantage that there has been no miniaturization of the thruster technology itself. Therefore, it can build on an extensive development history, including an on-going lifetime testing which is currently passed its 15.000 hours of operation.

The extremely high total impulse density with the fact that the thruster is inert (solid) during launch (thus safe to be handled, even on ISS) makes it attractive for both CubeSat missions who want to leverage up to 5 km/s Δv as well as for small satellite missions, where clusters of IFM Thruster modules have been sold.

IFM Nano Modules including PPUs and Propellant System | ALM Housing | Complete Thruster Subsystem | Integration into the ESPA ring of the spacecraft

Figure 2. Plug and Play design for IFM Nano thruster modules.

Joining support from ESA, the European Commission, and National Funds, ENPULSION is developing a production facility to answer the market demand and providing hundreds of thruster modules annually. An endeavor that requires new approaches to the assessment of reliability of space products. Constant negotiations and discussions with various customers are shaping quality assurance measures that are somewhere in between it all. In between Aerospace and Space, in between terrestrial and space-graded components, in between series production and custom-made developments. The excitement of new space economy certainly does not stop in front of propulsion.

MPCS-2017-Th06

Development activities of Micro-Propulsion Modules in BICE

Yan Shen, Xuhui Liu, Jinyue Geng, Jun Long, Yanlin Hu, Tuoqu Fu, Wei Zhang, Chenguang Gao, Ping Wang, Meng Wang, Zhaopu Yao

Lab of Advance Space Propulsion Technology, Beijing Institute of Control Engineering

With the growing capability of miniature aerospace products, micro- and Nano- spacecraft are increasingly promising for a wide range of scientific and commercial applications. The low-cost nature of these miniature spacecraft enables more and more organizations devote to aerospace industry and a rapidly increasing market for micro spacecraft is coming into being.

To fulfill the miniature tendency of spacecraft for different applications, varies series of micro-propulsion modules feature of non-toxic, low-cost, robustness and high-performance characters are under developing in BICE.

This talk presents the recently progress of micro-propulsion module in Lab of Advance Space Propulsion Technology(LASST), BICE. Wide-range of micro propulsion technologies are under-developing and in coming years three of which is scheduled to verify in-orbit:

(1) Solid Cool Gas Generator Micro Propulsion Module, in which nitrogen propellant is efficiently stored in solid form and gererated step by step according to the command. Thus, relatively high total impulse is achieved without high pressure propellant storage and operation, which is very attractive for safety consideration.

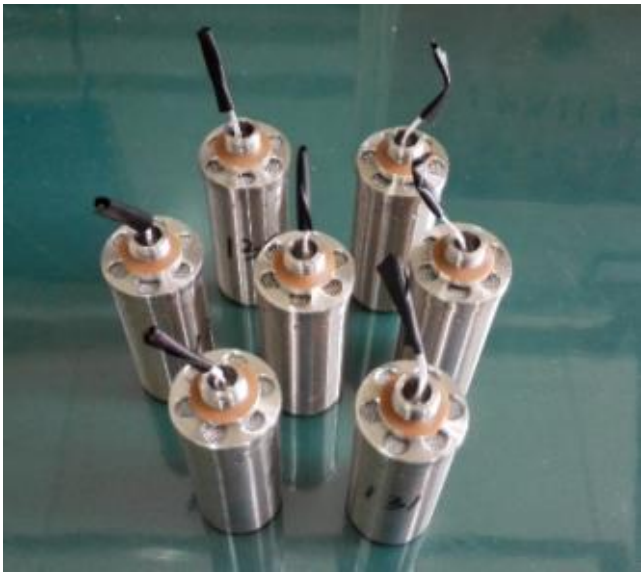

Figure 1. Solid Cold Gas Generator.

(2) ADN-based non-toxic propellant Propulsion Module, with envelope size of 10cm*10cm*10cm and total impulse of 800N.s. On the bottom the module four 0.2N thrusters are installed with specified offset angle to the axis, and 3 axis attitude control capability is obtained.

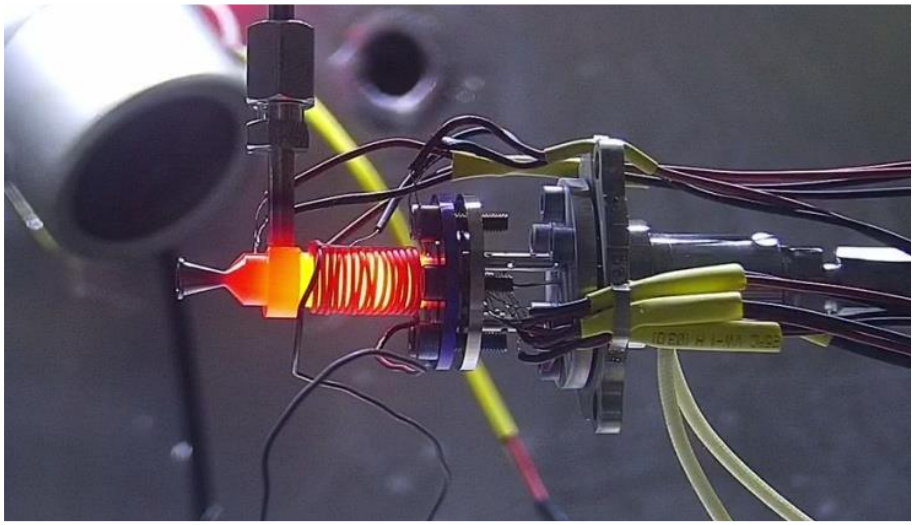

Figure 2. Firing Test of 20 0mN ADN-Based thruster.

(3) A Micro-Cathode Arc Thruster（μCAT）Module is under developing to achieve high specific impulse and low-cost character which is very concerned for miniature spacecraft. Total mass of the μCAT module is less than 350 g, the specific impulse is about 1900 s, continue firing capability and total impulse is still to be validated.

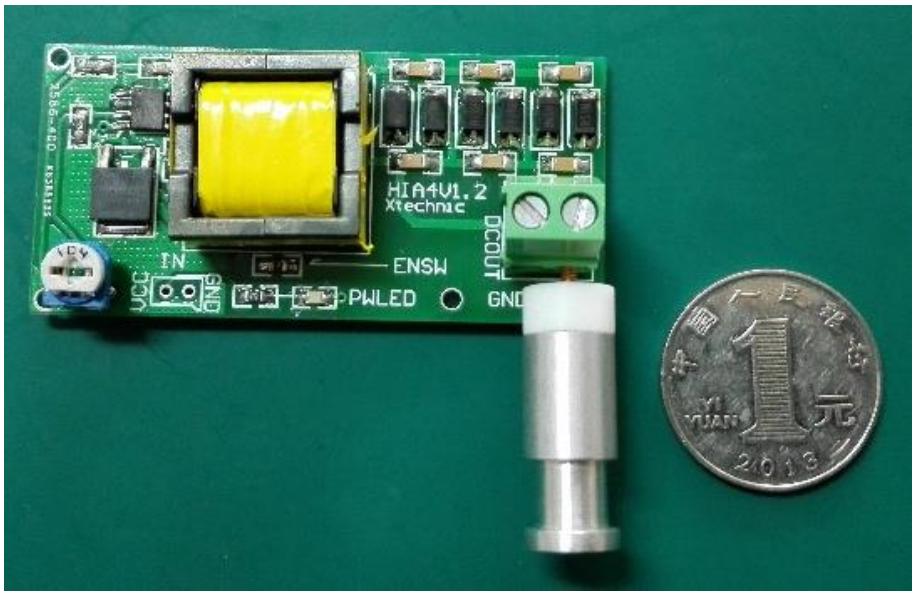

Figure 3. Micro-Cathode Arc Thruster Module.

MPCS-2017-Si01

Simulation Tools for Plasma Micro-Propulsion

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The talk will present EP2 activities in the development of models and simulation codes for different plasma thrusters. Under several public and industrial programs, EP2 is directly involved in the research of the plasma discharge in Hall-effect thrusters (HET), ECR accelerators (ECRA), and Helicon Plasma Thrusters (HPT), and the optimization of performances and design of these technologies. Beyond the ongoing development of thruster-specific codes, EP2 is aiming ultimately at achieving a unified simulation code for a class of plasma thrusters, namely electromagnetic thrusters operating with weakly collisional plasmas, which, apart from the previous three ones, includes the HEMP. Besides reducing costs in code development, validation, and operation, the unified approach will allow a better and more systematic understanding and comparison of the different technologies.

The thruster code will be 2D (axilsymmetric), based on a hybrid (particle/fluid/wave) formulation, and will consist of several core modules: one for ion transport, one for electron transport, one for the main electric field, and one for the wave-plasma interaction (this last one, only active for RF-based plasma sources). One central study to be carried out with the code is a down-scaling analysis of the above thrusters in order to elucidate their capabilities and constraints for mini- and micro- propulsion, which are not obvious.

Completing the above 2D codes, EP2 is also involved in the development of a hybrid 3D code of the expansion of the energetic rarefied plume emitted by a generic plasma thruster. The code is capable of dealing with both the near plume (which is very dependent on the thruster type) and the far plume (where plume-spacecraft interaction is a subject of major concern). The code is suited for low-power propulsion and multi thruster arrangements. This code will include collisionless plume cooling and some magnetic field effects.

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MPCS-2017-Si02

Micro-Electric Propulsion Thrusters: Better Insights from Numerical Simulation

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Electric propulsion, which is less expensive and provides higher specific impulse and higher control precision than conventional methods, has recently become one of the most promising micro-propulsion methods. The development and applications of electric propulsion systems are closely linked with the advancement of plasma technology. Electric propulsion has been under development during the past years, and almost all thrusters are designed based largely on experience and experimentation.

Our current presentation considers the numerical simulation of micro-electric propulsion thrusters. Due to the wide range of such devices, attention is restricted to microdischarge thruster types and pulsed plasma thruster. The physical regimes created in these thrusters indicate that a variety of numerical methods are required for accurate simulation ranging from continuum formulations to kinetic approaches. For pulsed plasma thruster, an improved two-layer kinetic ablation model as well as a two- temperature MHD model considering the possible departure from local thermodynamic equilibrium condition near the wall surface is developed to investigate the wall ablation mechanism. Moreover, a self-consistent two dimensional particle-in-cell simulation, with a Monte Carlo collision model is established to reveal the physical process of a microdischarge operating in a prototype micro-plasma thruster with a hollow cylinder geometry and a divergent micro-nozzle. It is concluded that numerical simulations can be expected to play a more prominent role in the design and evolution of future micro-electric propulsion thrusters.

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Microcontroller Aided Actuation and Wireless Control for Diagnostics and Component Placement in a Large Scaled Space Environment Chamber

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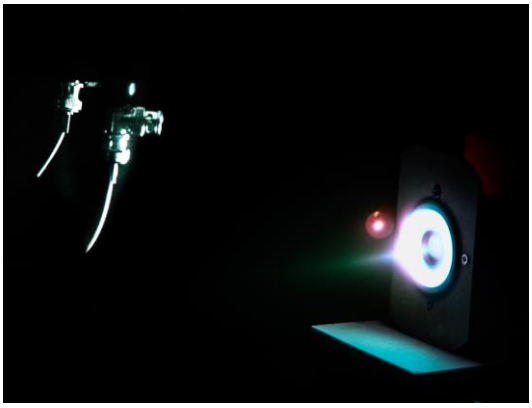
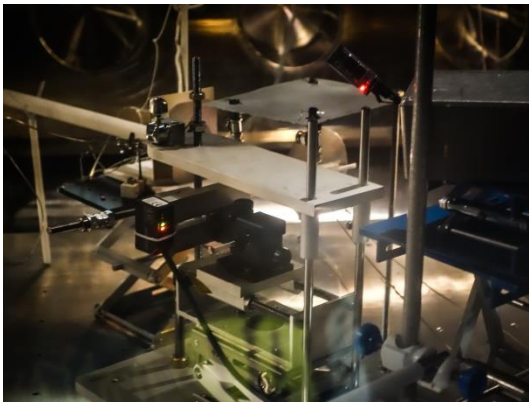
In the past decade, the use of highly programmable low-cost mini-computers and microcontrollers in scientific research and academia has leap-frogged, seeing applications in multiple disciplines including chemistry, geological sciences as well as in the Physical sciences [1,2]. Most notably, in the years since 2010, the number of technical publications which feature such microcontrollers such as the "Raspberry Pi" or "Arduino" has grown exponentially [3]. This phenomenon can be partially attributed to the relatively low cost of implementation, ease of programming, gentle learning curve, ability to customize functionality based on applications, array of mathematical and computing tools available on open source platforms, as well as small footprint on a table-top experimental setup.



PSAC's HET in operation with the multi-probe array in the foreground



Integrated microcontroller actuated thrust measurement and probe diagnostics suite

The advent of the boom in miniature computers and microcontrollers has also attracted much attention from academics from the space fraternity, with successful projects such as the "ARDUSAT" seeing actual deployment in space. The Plasma Sources and Applications Centre (PSAC) at the Nanyang Technological University (NTU) in Singapore have developed several Arduino microcontroller based actuation and measurement systems for diagnostics of miniature hall-effect thrusters (HET) in a large scaled space environment chamber. The diagnostic systems feature wireless control of automated components for remote measurements. The developed and developing systems include an in-situ automated calibration

unit on a frequency modulated micro-thrust stand, an actuation stage for 3D automated spatial profile mapping of plasma plume parameters, a multiple probe array equipped with integrated data acquisition and processing, and remote controlled robotic arms for real-time maneuver of HET components for optimized coupling and thrust efficiency. The palm sized and credit card thick microcontrollers offer computing power in small payload crafts such as small satellites and cubesats where usage of space is of critical concern. In this development, the microcontrollers have also demonstrated robustness in performing numerous tasks on different systems simultaneously on a single board. The in tandem development of microcontroller based diagnostic kits at PSAC also proved to be effective tools for hands-on and inquiry/problem based learning. As PSAC is based at the heart of education in Singapore (National Institute of Education), action research in utilizing microcontrollers in the classroom as an alternative pedagogical tool has proven effective in sustaining interest in content as well as encouraging creative thinking. This is a result of the diverse applications in utilizing the microcontrollers which have potential for implementation to complement existing curricula in Physics, Computing, and even Engineering Mathematics.

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