Highly Miniaturized FEEP Thrusters for CubeSat Applications

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HIGHLY MINIATURIZED FEEP THRUSTERS FOR CUBESAT APPLICATIONS

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ABSTRACT

Field Emission (FEEP) thrusters are attractive for miniaturization because of their simplicity in design and electronics needs. Moreover, their propellant is stored in a solid/liquid state with very high densities and do not require any additional propellant feeding devices or valves. Using the latest ion source technology, we designed a highly compact ion emitter module with a volume of less than 3 cm³ (called NanoFEEP) capable of generating thrusts up to 8 µN continuously with peaks up to ~22 µN. The emitter is made out of porous tungsten using gallium as propellant. Due to its low melting point of 30 °C the power consumption is very low. In addition, a compact electronics board was designed that can control and power up to four NanoFEEP modules with a direct interface to the onboard computer. Our system is in particular suitable for a Double-CubeSat (or larger) where 6- or 8-thrusters can enable 3-axis attitude and orbit control. We estimate a power consumption of around 1.3 W and a weight of less than 300 g for such a system (8 thrusters) giving a total impulse of 60 Ns and a delta-v capability for a 2 kg CubeSat of around 30 m/s. This paper will review the overall design and show test results of the first prototype.

1 INTRODUCTION

The CubeSat standard is very attractive as it enables universities to launch their own satellite for education purposes and to test and qualify new technologies. However, due to their small size, CubeSats lack precision pointing and orbit manoeuvring skills which limit their application especially for science-driven missions. Miniaturized momentum wheels have been developed to improve attitude and orbit control (AOC), however their weight and power requirement is very high and there is no possibility for de-spinning of the wheels which is a crucial lifetime limit of the overall system [1]. Miniaturised propulsion systems have been proposed such as µPPT, micro vacuum-arc-thrusters (VATs), micro-resistojets, etc., however up to now only one CubeSats has been successfully flown with its own propulsion system on board [2].

Here we propose a miniaturized FEEP thruster called NanoFEEP that has very low power consumption and enables high precision attitude- and orbit control and even orbit manoeuvres. The thruster design was highly miniaturized such that up to 8 thrusters can be easily accommodated on a double-unit CubeSat. Other electric propulsion thrusters such as PPTs or VATs produce a strong electromagnetic pulse during operation that can interfere with the onboard computer. The FEEP thruster on the other hand requires only a DC heater and DC high voltage power supply. In addition, the FEEP thruster is a truly proportional thruster with very small impulse bits for high accuracy. We designed an electronics board that includes miniaturized high voltage electronics and a microprocessor that enables thrust control and a direct interface for the onboard computer.

The basic principle of a Field Emission Electric Propulsion (FEEP) thruster is illustrated in **Fig. 1-1** [3]. If a high voltage potential is applied between a sharp needle wetted with liquid metal and an extractor electrode, a so-called Taylor cone forms at the needle tip. This Taylor cone is caused by the interplay of the liquid metal's surface tension and the applied electric field. If the evaporation field strength of about 10^{10} V/m is reached at the needle tip, the liquid metal is evaporated and ionized. The generated ions are accelerated towards the extractor electrode due to the applied electric field and exit the thruster with velocities of more than 100 km/s. With this concept thrusts of the range of µN with high specific impulse of several thousand seconds can be achieved. This makes FEEP thrusters unique for ultra precise AOC capabilities of spacecraft.

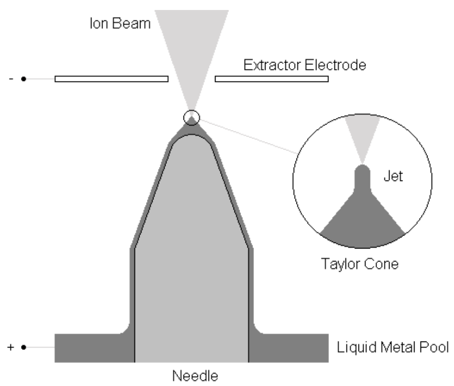

Fig. 1-1: Basic principle of Field Emission Electric Propulsion (FEEP), needle type [3]

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1.1 Porous Liquid Metal Ion Source (LMIS)

Our FEEP thruster design is compatible with both capillary and porous needle designs [4]. In this paper we will concentrate on the performance of porous needle emitters, as shown in **Fig. 1-2**, which promise higher mass efficiencies compared to capillary emitters. We chose Gallium as propellant due to its low melting point (30 °C) for low heater power consumption.

Fig. 1-2: NanoFEEP Emitter: Tantalum reservoir including a porous tungsten needle

These novel porous LMIS contain porous tungsten needles, which are manufactured by using Micro Powder Injection Molding (µPIM). The cross section of such a porous tungsten wire can be seen in **Fig. 1-3**.

The wire has an open porosity of approximately 30%. Thus, the liquid metal can be hold at the tip of the needle by capillary forces during emission and a sufficient structural robustness is guaranteed. Additionally, the self-feeding propellant is able to flow inside the porous tungsten needle towards the needle tip and is consequently protected from possible contamination. These porous tungsten wires were sharpened by electrochemical etching with Sodium Hydroxide. With this process tip radii of sub µm can be achieved as shown in **Fig. 1-4**.

After manufacturing the porous tungsten needles they are mounted into a tantalum reservoir (Fig. 1-2), which contains the propellant. Then, the whole assembly is heated up in high vacuum to fill all pores of the porous needle with the propellant. The result of this wetting procedure is shown in **Fig. 1-5**.

The tantalum reservoir can hold about 42 mm^3 of propellant (equivalent to 0.25 g Gallium). This amount of propellant enables operation of several hundred hours up to a few thousand hours, dependent on the provided thrust. The size of the reservoir and consequently the possible operation time can be enhanced without any problem, if needed. Though, the dimensions of the thruster need to be adjusted in this case.

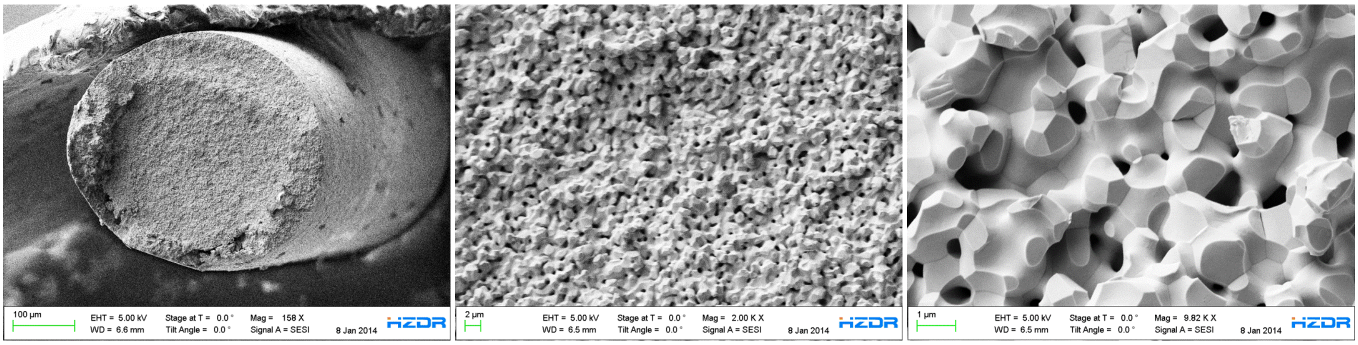

Fig. 1-3: Cross section of porous tungsten wire in different magnifications (160x, 2000x, 10000x from left to right)

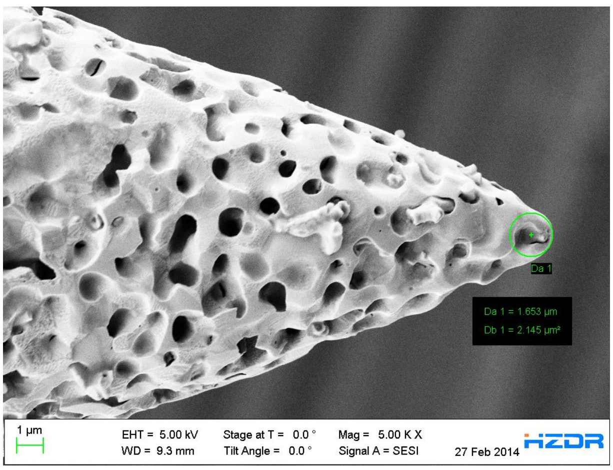

Fig. 1-4: Porous tungsten needle (tip radius 0.8µm), sharpened by electrochemical etching

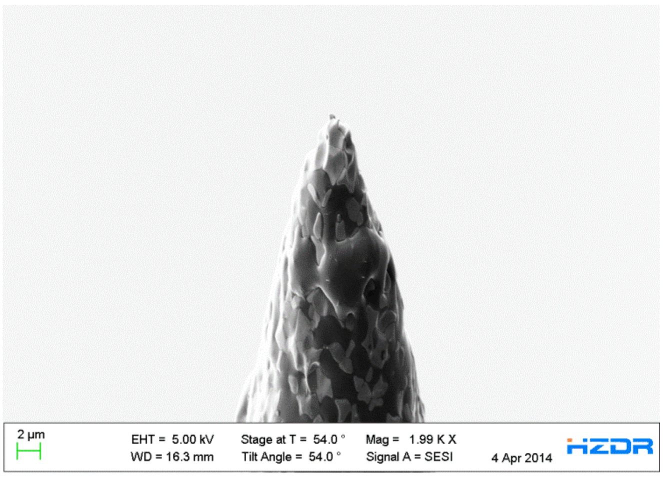

Fig. 1-5: Porous tungsten needle after wetting

1.2 *Module Design*

As small satellites like CubeSats are limited in mass and in available power, miniaturization and a low power demand are the key requirements for the design of a miniaturized FEEP thruster. In the following it will be shown how NanoFEEP meets these requirements.

Fig. 1-6 shows a cut away view of the CAD model of NanoFEEP. The module features labyrinth shielding to avoid electrical short circuits during long term operation. The porous LMIS, which is at high voltage potential during operation, is electrically isolated from all other components. The emitter and the extractor electrode are electrically connected via thin wires to the thruster board at the bottom. In this way the design of NanoFEEP could be kept very compact. Moreover, NanoFEEP provides a modular setup. This makes it possible to easily change any part of the thruster.

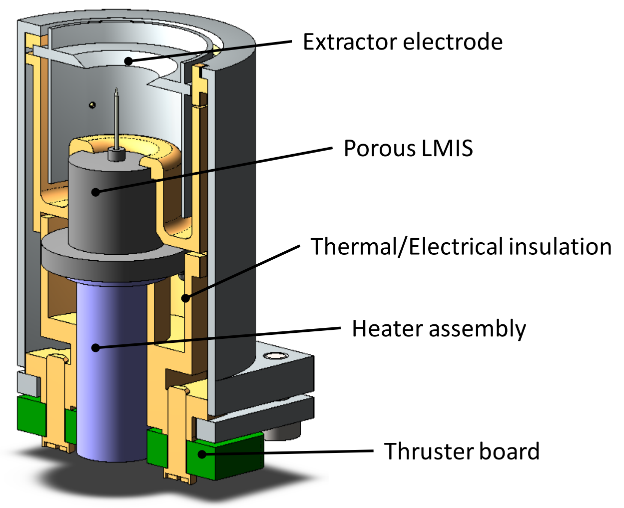

Fig. 1-6: Cut away view of NanoFEEP CAD model

With the NanoFEEP design the dimensions of a FEEP thruster could be miniaturized down to ∅13x21 mm with a total weight of less than 6 g per thruster. **Fig. 1-8** shows one manufactured NanoFEEP thruster compared to the size of a one Euro coin.

To meet the requirement of a low power demand it was decided to use Gallium as propellant on NanoFEEP. Due to the low melting point of Gallium (approximately 30°C), a much lower heating power for liquefying the propellant is needed, compared to commonly used propellants like Indium (melting point ~157°C). In addition, thermal simulations were performed during the design phase to optimize the thermal design and to predict the heating power demand assuming an operating temperature of 50°C. **Fig. 1-7** shows a temperature plot of one exemplary study case in which the thruster casing temperature was set to -10°C.

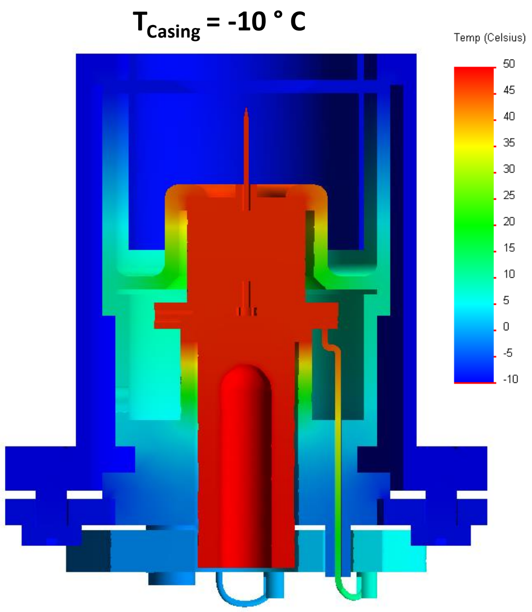

Fig. 1-7: Exemplary result of thermal simulation; Simulation boundary: casing temperature at -10° C

The simulations showed a heating power demand of 50 to 90 mW, depending on the satellites structure temperature (simulated range: -10 to +20°C). First heating tests of the thruster module inside the vacuum chamber showed a very good agreement with the simulated predictions. Only a difference of less than 10 mW was observed between simulation and test.

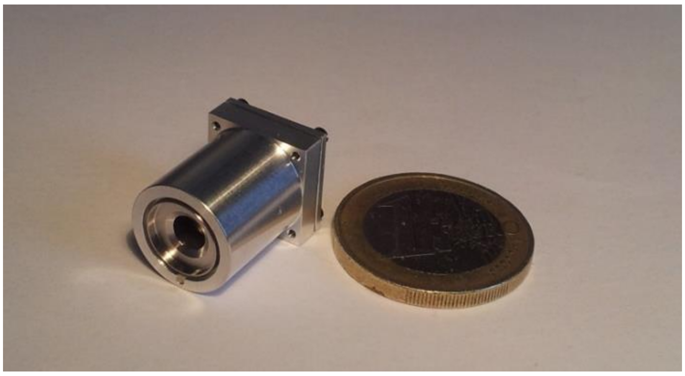

Fig. 1-8: Manufactured highly miniaturized NanoFEEP thruster; size comparison to a 1 € coin

1.3 Electrical Design

The electrical design of NanoFEEP is divided into two different boards, the thruster board and the main board. All ICs and components for the generation and regulation of the emitter supply voltage and the heater are located on the main board. Every function is controlled by a 32-bit microcontroller that is connected to the on-board computer. **Fig. 1-9** shows the supply and regulation circuit of the heater and the emitter.

The thruster board is used as an interface between the thin and sensitive wires, inside of NanoFEEP, and the stronger wires which lead to the main board. Additionally, there are four suppressor diodes to protect the main board from possible high voltage short circuits inside the thruster.

The most significant function of the main board is the generation of the high voltage that generates the thrust at the emitter. For this purpose a DC-to-HV-DC-converter from EMCO is used (AH60). This device converts an input voltage (0.7 V to 5 V) linearly into an output voltage of 700 V to 6000 V. In order to achieve a maximum of 12 kV, two converters are connected in series. Together these HV converters provide a maximum power of 3 Watts and a maximum current of 250 µA per thruster. Each thruster has its own HV converter pair in order to control each thruster individually and to enable, in principle, the operation of all thrusters in parallel.

The input voltage of the HV-converter is generated by another DC/DC-converter whose output voltage is regulated by an external DAC-IC (digital-to-analogue converter) via a serial interface. For overcurrent protection a current-limited power switch is installed upstream of the DC/DC-converter input.

To regulate the thrust, the actual emitter and extractor current is needed. The calculation of the emitter current is realized by measuring the voltage drop through the series resistor R_S with the help of two voltage dividers. Two ICs are used to monitor the voltage drop in each voltage divider. A third current-shunt monitor IC measures the extractor current. The microcontroller reads out the values via serial interface and calculates the emitter current and the resulting thrust. The required emitter current is calculated from the desired thrust. Subsequently, an algorithm compares this calculated value with the actual value and the emitter voltage is adjusted accordingly.

The power supply of the heater is realized with a DAC from the microcontroller. The DAC voltage is applied to an operational amplifier, wired as a non-inverting amplifier. This IC increases the voltage and provides the required heater current. A power monitor measures current and voltage. Via serial interface the microcontroller reads out the values and calculates the heater temperature. A regulation algorithm compares it with the desired temperature and the DAC is adjusted accordingly.

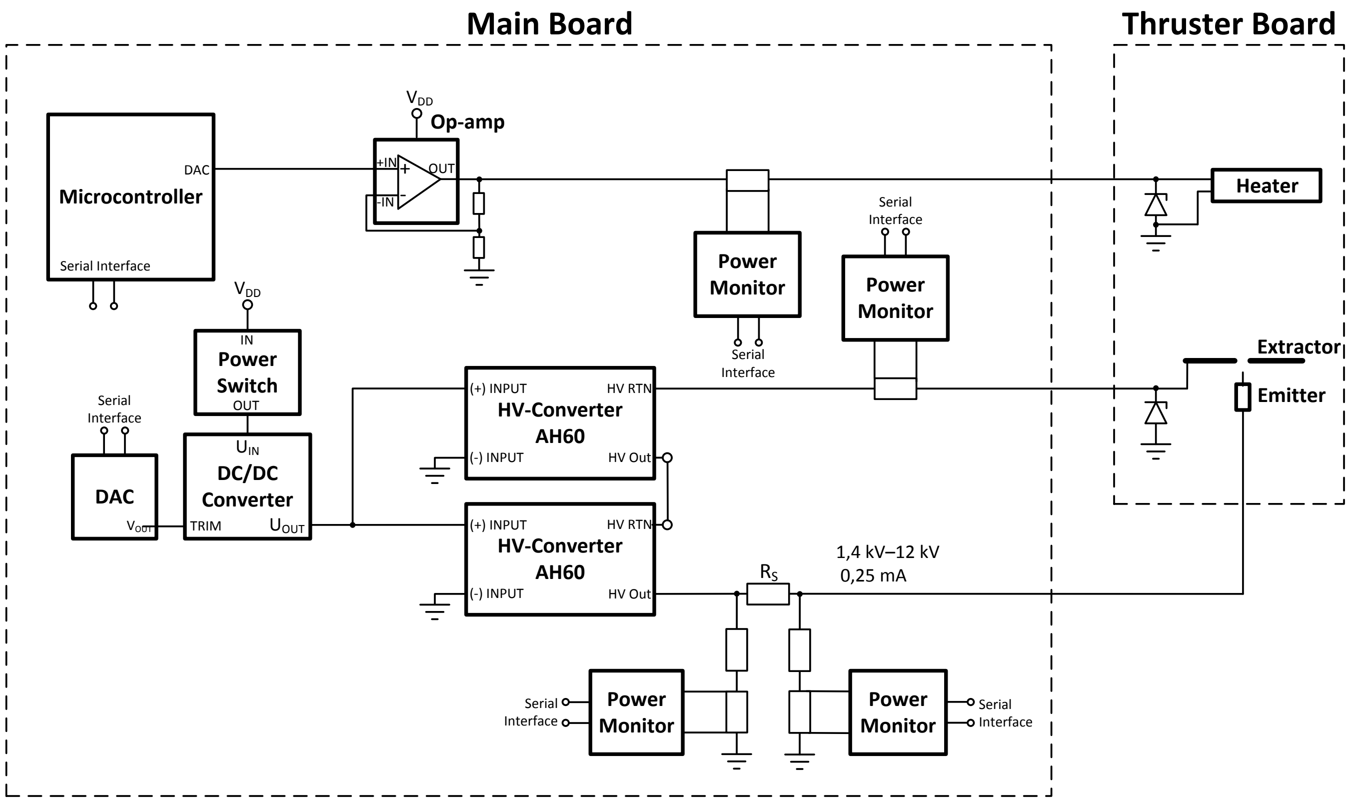

Fig. 1-9: Supply and regulation circuit of NanoFEEP

Fig. 1-10 shows the engineering model of a CubeSat-compatible main board equipped for the supply of one thruster. It consists of two different boards connected via a socket board. In this way the high voltage devices are separated from the control electronics. The smaller third board is an evaluation board for the microcontroller. It would not be part of the flight model. This main board configuration can be equipped for the supply of up to 4 thrusters without any additional volume requirement.

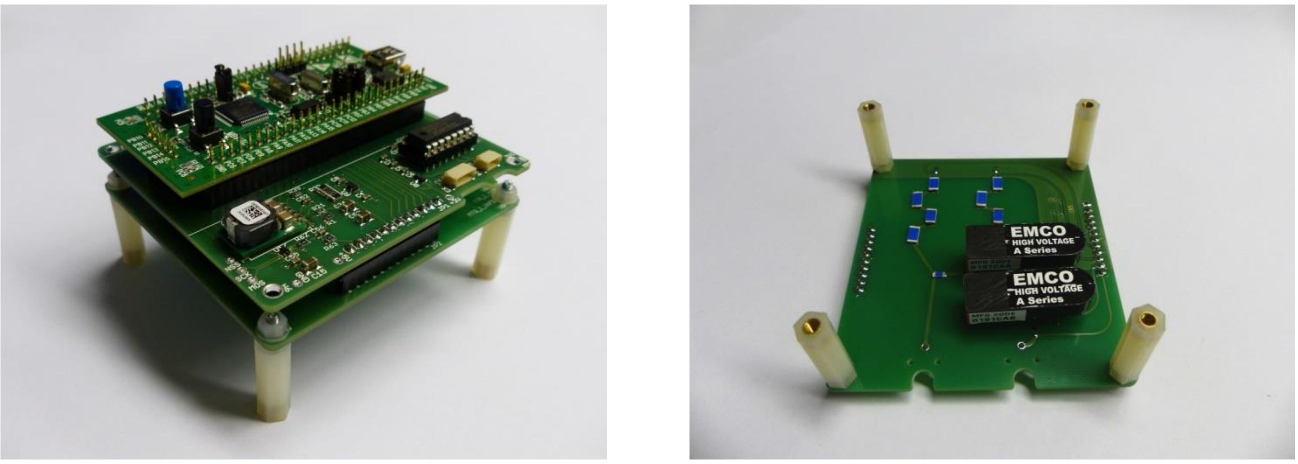

Fig. 1-10: Engineering model of main board, equipped for one NanoFEEP thruster (top and bottom side)

2 Thruster Characteristics

This chapter will show first results of a recently assembled NanoFEEP thruster with a porous tungsten needle LMIS.

2.1 *Tests of the Liquid Metal Ion Source*

Before testing the whole thruster module, first tests were carried out with a laboratory test-module to characterize the single LMIS especially with respect to mass efficiency at different currents as this has never been determined for a porous needle Gallium LMIS. After each test run the LMIS was dismounted from the test module and was weighted. Subsequently, the mass efficiency η as a function of the emitter current was calculated as follows:

$$\eta = \frac{\frac{m_{Ga}}{e} \int I_{emitter}\, dt}{\Delta m_{total}} \tag{1}$$

Fig. 2-1 shows the results of the determined mass efficiency of the tested LMIS. In general, these values seem to be lower than for Indium LMIS. This may be due to the lower atomic mass and different surface tension or viscosity. Moreover, this LMIS had a tip radius of 3 µm and as mass efficiency is closely related to tip sharpness [5]. We expect better values with sharper needles with tip radii less than 1 µm like the one showed in **Fig. 1-4**.

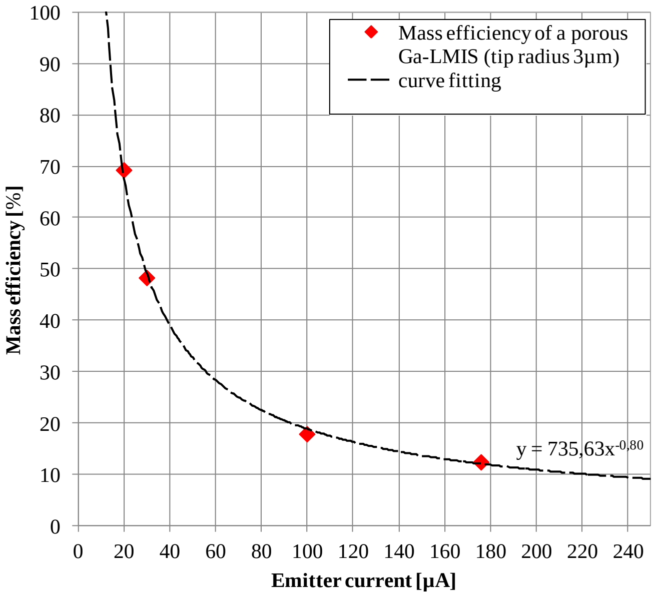

Fig. 2-1: Mass efficiency of a porous LMIS run with Gallium; Needle tip radius 3µm

2.2 Module Test

After characterizing the tested LMIS, first tests of the whole NanoFEEP thruster module, presented in chapter 1.2, were performed. **Fig. 2-2** shows Nano-FEEP operating inside our vacuum chamber at a pressure of 10^{-6} mbar.

Ramp tests up to the maximum emitter current of 250 µA were performed to characterize the NanoFEEP thruster module. The emitter current is limited by the maximum output current of the used high voltage supply. The maximum current approximately equivalent to a thrust of 22 µN. Higher thrusts would be theoretically possible, if a different power supply is used.

The current-voltage characteristic of NanoFEEP is shown in **Fig. 2-3**. Using the mass efficiency values of the previous chapter we can estimate the specific impulse over the entire thrust range as illustrated in **Fig. 2-4**. A constant beam divergence factor of 0.8 was assumed throughout the whole thrust range.

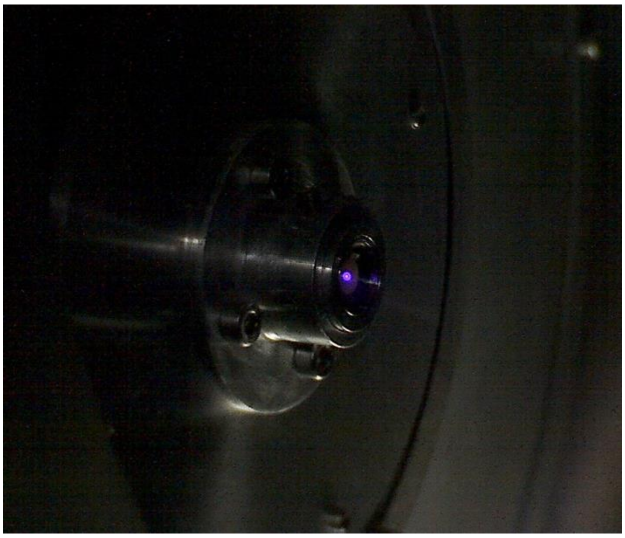

Fig. 2-2: Operating NanoFEEP thruster

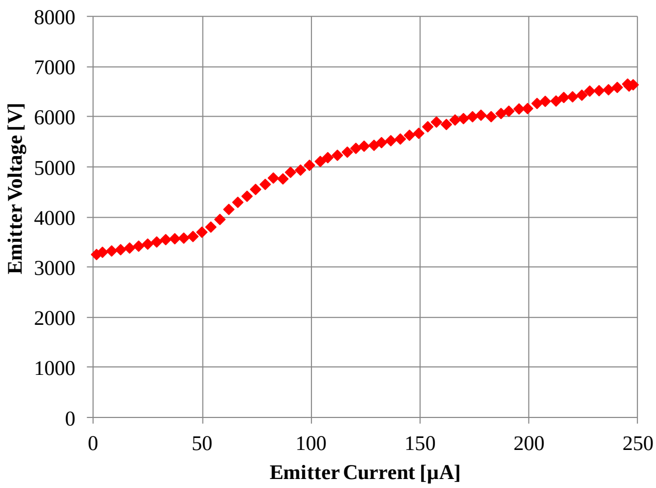

Fig. 2-3: Current-Voltage Characteristic of NanoFEEP

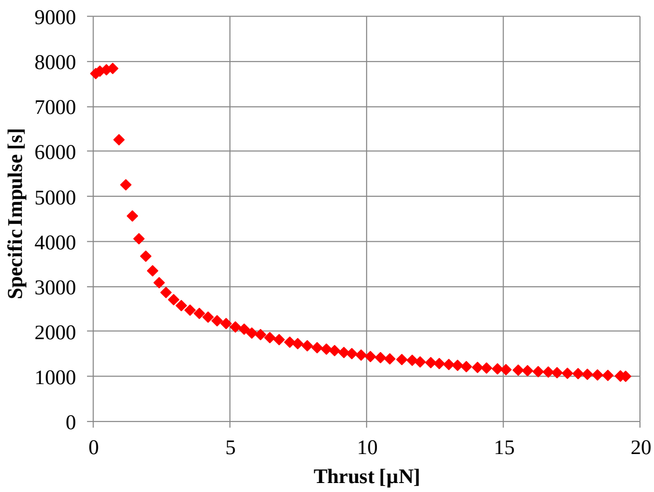

Fig. 2-4: Specific Impulse over thrust range

2.3 Power demand of NanoFEEP

As the available power of CubeSats is strongly limited, the power demand of an active AOC system such as it would be with NanoFEEP is a crucial issue. According to [6] the average orbit power of a 2U CubeSat is about 3 W. Due to the optimized thermal design of NanoFEEP and the use of Gallium as propellant with its low melting point, the power demand for keeping the propellant liquid could be minimized. Based on thermal simulations, mentioned in chapter 1.2, an orbit heating power of 50 – 90 mW per thruster (dependent on satellite's structure temperature) is expected.

In addition to heating, the power demand for ion beam generation and power consumption of the electronics needs to be considered to estimate the total power demand. Based on first power measurements of the real breadboard electronics the total power demand including heating (assumed 50 mW), beam generation and electronic efficiencies was estimated, shown as a function of thrust in **Fig. 2-5**. The standby power (no thrust generation) is 90 mW. It is dominated by the heater supply. Other components are in sleep mode.

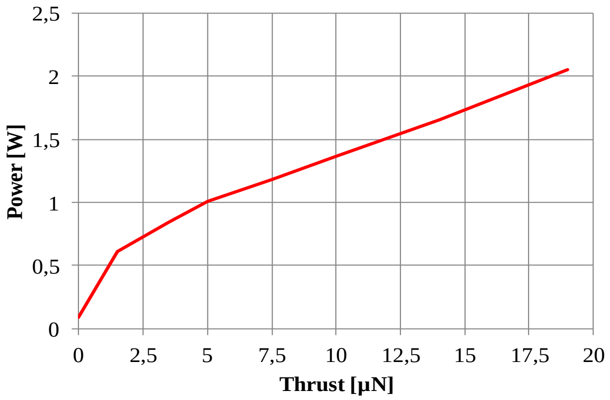

Fig. 2-5: Total realistic power demand of one thruster

The power demand of some ICs is independent of the applied thrust (e. g. microcontroller and power monitors). However, the predominant part of the power demand depends on the desired thrust. The most critical factor is the efficiency of the DC/DC-converter which decreases significantly for a small output power (down to only 20 %). To generate a thrust of 1.5 µN a total power of 650 mW is estimated. For a thrust of 7.5 µN one thruster needs about 1.2 W. More efficient converters may significantly reduce the present power budget which will be investigated in the near future.

All in all, the estimated power values in **Fig. 2-5** show that our miniaturized NanoFEEP thruster can be used on CubeSats.

3 Potential Application on CubeSat

Fig. 3-1 shows schematically potential thruster arrangements for different attitude and orbit control configurations of a CubeSat like spacecraft. By using four thrusters (1 – 4) in the back of the satellite, 2-axis control (around x- and y-axis) and orbit control (along z-axis) is possible. The minimum configuration for 3-axis attitude control is obtained, if two more thrusters (5 and 6) are added to the front of the satellite. Using all marked thrusters (1 - 8) a configuration with redundancy is possible. With that configuration the failure of any single thruster can be compensated by the remaining seven thrusters.

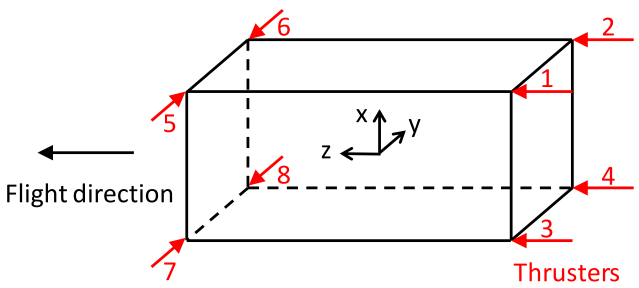

Fig. 3-1: Potential thruster arrangements:
1 - 4: orbit control (thrust) + 2-axis attitude control
1 - 6: 3-axis attitude control, minimum configuration
1 - 8: 3-axis attitude control with redundancy

An exemplary integration of eight NanoFEEP thrusters (redundant 3-axis thruster configuration) is shown in **Fig. 3-2** with a CAD model of TU Dresden's 2U CubeSat SOMP2.

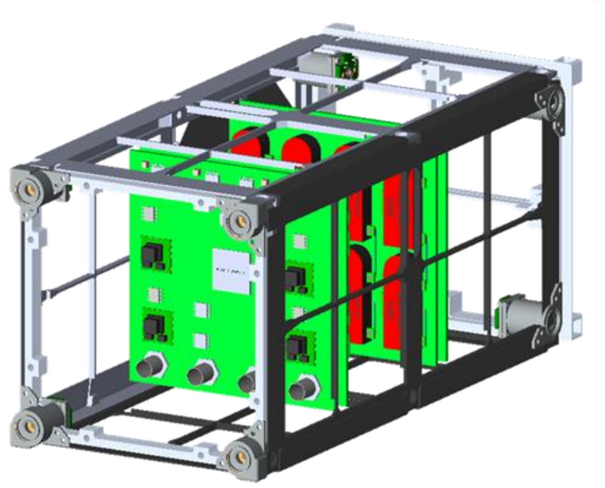

Fig. 3-2: CAD model of 8 NanoFEEP thrusters integrated in a 2U CubeSat (SOMP2)

As it can be seen in **Fig. 3-2**, the compact thruster form of NanoFEEP allows space-saving thruster integration in the corners of the CubeSat. One of the two illustrated main boards is able to provide space for the electronics of four NanoFEEP thrusters. The main board location can be chosen freely, but would be most reasonable near the related thrusters.

Fig. 3-3 gives a detailed view of the integration of the thrusters in the back of CubeSat (analogous to thruster 1-4 in **Fig. 3-1**). It can be seen that the thrusters are able to be integrated partially into the officially required CubeSat rails [7]. Moreover, due to the protruding thruster location the solar arrays are protected against possible contamination with the metallic propellant. As the casing design of the NanoFEEP thrusters can be chosen freely other integration options are possible as well.

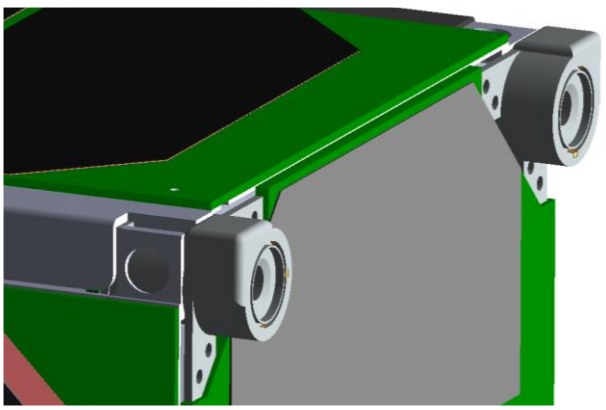

Fig. 3-3: Detail view of NanoFEEP thrusters partially integrated into CubeSat rails

Table 3-1 shows the requirements of different thruster arrangements. The system weight includes the weight of the electronics, the thrusters and the cables between these two assemblies. The volume includes only the external dimensions of the main boards. For the power demand it was assumed that one thruster is operating and the remaining thrusters are in standby mode. This shall simulate an active attitude control. In stand-by mode, a thruster can be turned on/off within a µs only limited by the capacity of the electronics.

Table 3-1: Requirements of different thruster arrangements (one thruster active, others in stand-by)

Number of thrusters	**4**	**6**	**8**
System weight [g]	150	250	300
Volume [mm³]	83x83x24	83x83x40	83x83x48
Power [W] (1.5 µN thrust)	0.98	1.15	1.31
Power [W] (7.5 µN thrust)	1.53	1.7	1.86

The following table summarized all important characteristics of our NanoFEEP thruster:

Table 3-2: Overview about important Characteristics

	Nano-FEEP
Thruster Size	∅ ~13 mm L ~ 21 mm
Mass for 4 Thrusters including Electronics Board	150 g
Specific Impulse	~ 6,000 s *
Operating Time	~ 1,800 h *
Total Impulse (4 thrusters)	~ 60 Ns *
Delta-v on a 2U CubeSat (4 thrusters)	~ 30 m/s *
Thrust	0.05 – 22 µN
Propellant	Gallium
Feeding	Self Feeding
Beam Power-to-Thrust Ratio	60 W/mN* – 90 W/mN**

* At average thrust of 1-2 µN

** At max. thrust of 22 µN

4 Conclusion and Outlook

A highly miniaturized FEEP thruster using a porous liquid metal ion source (LMIS) was manufactured and tested including representative electronics. First tests of a single ion emitter were performed to determine mass efficiency of the Gallium LMIS.

Power measurements of the electronics and thermal simulations were used to estimate the total power demand of the miniaturized FEEP thrusters. The estimated total power demand showed that the miniaturized FEEP thrusters can be used as thrusters for attitude and orbit control of CubeSats with respect to the total power demand. Also a combination of reaction wheels and NanoFEEP seems to be an attractive choice.

Moreover, potential thruster arrangements and a possible integration of the miniaturized FEEP thruster into a 2U CubeSat were presented and it was shown that space-saving integration in CubeSat is possible.

Next steps in development will be:

- Tests of more LMIS to investigate if mass efficiency can be increased by using sharper needles.
- Performing of long-term operation tests to detect possible lifetime related issues
- Direct measurement of generated thrust by using a thrust balance
- Performing continuing tests of electronics and thrust regulation software
- Integration of miniaturized FEEP thrusters into manufactured CubeSat prototypes

Acknowledgement

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