Miniaturized HV Power Supply

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Abstract:

The advances in MEMS are enabling technology for miniaturized electrospray colloid thruster designs. These thrusters can be advantageously applied in small, low mass, sizeable electric propulsion systems with high specific impulse. To fully exploit the capabilities of MEMS colloid thruster propulsion technology a small and low mass HV electronic power supply and control circuit is needed. In the European FP7 funded MicroThrust project a consortium works towards the goal of a MEMS colloid thruster breadboard. In this project SystematIC design develops the miniaturized HV power supply and control unit.

The power and control system operates in dual bipolar operation. Two independently controllable HV power supplies with opposite polarity operate in bipolar mode to drive a colloid thruster and expel equal amounts of positive and negative charged ions.

The electronic design is split into two functional parts: a Central Power and Control Board (CPCB), where HV supplies are generated and an Extractor Switch Assembly (ESA), which controls the colloid extractor grids. The ESA design is modular and flexible and can be extended to control additional extractor grids, whereas the CPCB board can drive multiple ESA boards. The HV power supply architecture covers a dual bipolar setup and is scalable in power to accommodate various missions.

The electronic circuits are laboratory tested for electrical functionality. Initial test results of the circuits and their operation when assembled to an actual colloid thruster prototype are presented in this paper.

In the MicroThrust breadboard design target is a HV power supply (HVPS) with 0.4-5W output power. The bipolar emitter voltage is designed for ±3.8 kV. The CPCB and ESA boards measure 80mm by 80mm and have a height of 35mm when stacked. The total mass of the boards excluding cables is 115 grams. On the S/C side the electrical interface applies the I^2C protocol and requires a single supply voltage of 12V.

Nomenclature

BB	=	BreadBoard (model)
CPCB	=	Central Power and Control Board
COTS	=	Commercial off the shelf
ESA	=	Extractor Switch Assembly
EIFB	=	Electrical Interface Board
FM	=	Flight Model
HVPS	=	High Voltage Power Supply
IA	=	Instrumentation Amplifier
I_{sp}	=	Specific Impulse
I^2C	=	IIC, inter integrated circuit communication protocol
PCB	=	Printed Circuit Board
PCS	=	Power and Control System
S/C	=	Space Craft

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THC = Thruster chips (microfabricated thruster arrays)
TRL = Technology Readiness Level
UART = Universal asynchronous receiver/transmitter

I. Introduction

In the European FP7 funded MicroThrust project[1] a consortium of universities, knowledge institutes and SME's work towards the goal of a MEMS colloid thruster Bread Board (BB). The BB includes all relevant functional blocks of the thruster, in scaled format and allows a straightforward path to extend the design to a Flight Model (FM). Due to the MEMS technology applied in these colloid thrusters the thrusters can be miniaturized and advantageously applied in small, low mass, sizeable electric propulsion systems with high specific impulse I_{sp}. While the target missions require a small size and low mass Thruster Module, there are challenges for the electronic Power and Control Systems. HV operation is to be combined with small size and low mass. In the MicroThrust project SystematIC design develops the miniaturized HV power supply and control electronics. A 3D impression of the MEMS colloid thruster with power and control electronics for application in Nano satellites is shown in figure 1. The CPCB and ESA boards measure 80mm by 80mm and have a height of 35mm when stacked.

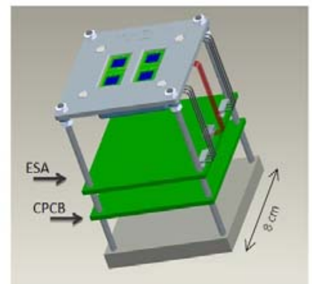

Figure 1: Breadboard model with colloid thruster module and electronic power and control boards (ESA&CPCB)

II. Power and Control System concept

The Power and Control System (PCS) operates in dual bipolar operation. Two independently controllable HV power supplies with opposite polarity operate in bipolar mode to drive a colloid thruster and emit equal amounts of positive and negative charged ions. In this way propellant tank damage due to electrolysis is prevented, propellant is optimally (fully) used and the need for an electric S/C neutralizer is absent.
The electronic system concept[2] of the dual bipolar thruster is depicted in figure 2. The electronic design is split into two functional parts: a Central Power and Control Board (CPCB) and an Extractor Switch Assembly (ESA). In figure 2 simultaneous emissions of positive and negative propellant ions is indicated, it is to be noted that polarity of each ion stream alternates over time.
On the CPCB board HV power supplies (HVPS) generate the positive and negative HV. The load currents of both bipolar HVPS are measured so that the ion output can be measured and balanced.

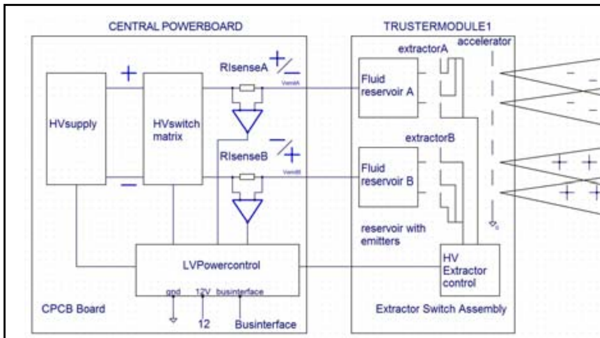

Figure 2: Dual bipolar thruster with CPCB (left) and ESA board (right)

The ESA board controls the Thruster Chip (THC) extractor grids and is dimensioned for the BB to control four THC's independently, two THC's per tank. The ESA design is modular and flexible and can be extended to control additional THC's, whereas the CPCB board can drive multiple ESA boards and can be scaled in power. This HV power supply architecture[2] covers a dual bipolar setup and is scalable in power to accommodate various missions.

III. Power and Control System implementation

The constraints on maximum board size and mass dictated some of the design choices, where other implementation choices were dictated by limitations in availability or even existence of HV components. Solid state switching components were used in the form of COTS high voltage FET's. To save area for all low voltage interconnections the smallest sized suitable space qualified Omnetics[3] connector was chosen.

Figure 3 below shows the conceptual arrangement of the building blocks of the PCS, with just one of the two HVPS's of a CPCB shown, and just one of the four extractor circuits of an ESA board.

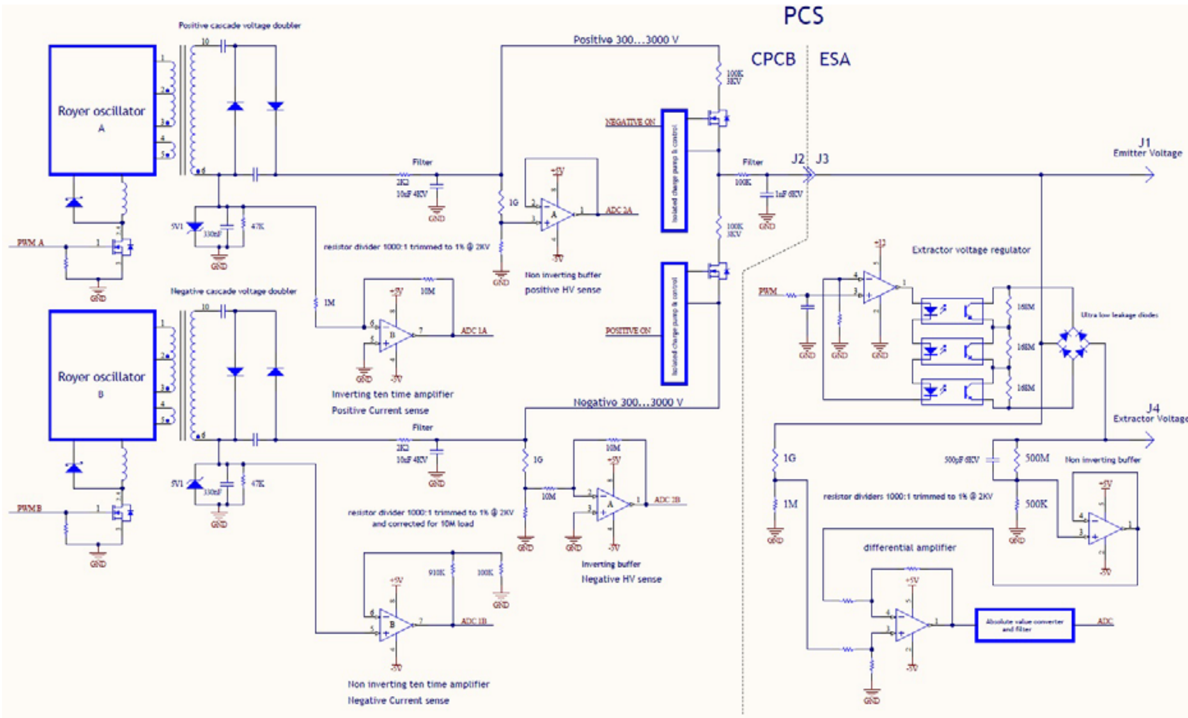

Figure 3: Simplified schematic of one HVPS and one extractor circuit

A. Central Power and Control Board

A practical way to generate alternating positive and negative high voltages applies a separate HV generator for positive and another generator for negative high voltages. A commonly used H-bridge configuration requires at least twice the number of the large HV FET's and driver circuits.

The HV FET's switch between the generated positive and negative high voltages and also fully discharge one generator before turning on the other generator. This is mandatory to prevent momentarily having twice the high voltage which would exceed the breakdown voltage of applied components. To accommodate the high voltages, while the device is tested in air, the design uses at least 3mm creeping space for the high voltage signal routings, mutually and between high voltage signals and ground.

Because the FET's must be controlled on the high voltage side of the isolation barrier, an isolated gate voltage generator is developed. For gate control an opto-isolator is used to quickly switch the gate voltage on or off.

The basic topology used for the HV generator is based on a resonant converter, also known as a Royer circuit[4], of which the output voltage could be controlled by regulating a DC bias current. The Royer is dimensioned to generate about 2kV and is followed by a single Villard cascade stage, to double the output voltage to 3.8kV maximum. By design and dimensioning of the transformer each Royer can generate about 6 Watt of power. The analog circuitry of the converter is simplified as much as possible, and replaced by digital control, to save PCB space. As can be found in figure 3 the generated and filtered high voltage is divided by a factor thousand using a precision compensated resistor dividers. Voltage non-linearity of the high ohmic HV resistors is compensated in the digital domain. Convertor control is implemented in software. The second HPVS on the CPCB operates completely independent; the CPBC contains four HV generators in total.

Initially current detection on the high voltage side was considered, first in the form of a COTS high side powered and controlled A/D converter and an Instrumentation Amplifier (IA) to measure the current, but this approach was power inefficient. Later a design that transmitted the analog output of the IA across the isolation barrier using an analog opto-isolator was proposed. This design required an isolated power supply that was implemented with a charge pump to transfer about 10mW to the high side. This circuit performance deteriorated due to voltage non-linearity of the high voltage charge pump capacitors and operated unreliable in vacuum. Finally a simpler low side current measure mechanism was used. By measuring the total average DC current flowing into the Villard cascade, the HVPS output current can be calculated. The required precision of about 1% can be reached by mathematically removing the known non emission currents.

B. ESA:
To save mass, the design of the ESA extractor voltage generators does not use a separate HV generator for the extractor voltage a controllable resistive voltage divider to regulate the extractor voltage. This concept is found in figure 3. With a high side resistor that is software controllable from 0 to 500MΩ and a fixed low side resistor of 500MΩ. The 500MΩ "variable resistor" consists of a series connection of three phototransistors. In parallel to each Phototransistor a 166MΩ resistor is mounted so that fully dark the total resistance of the string will be approximately 500MΩ. The PWM control signal from the microcontroller is low pass filtered and converted into current by a transadmittance amplifier to control current through the opto-isolator LEDs. Because the photo transistors are polarity sensitive a diode bridge is applied to provide the correct polarity. The voltage over the diode bridge is the extractor voltage, and can be controlled from zero volt up-to half the emitter voltage. To quickly and precisely regulate this voltage we measure as well the emitter voltage as the extractor voltage as indicated in figure 3. Each voltage is divided by a factor thousand using a compensated precision 1:1000 resistive divider. These signals, now in the range of several volts, are subtracted, resulting in a voltage proportional to $V_{emitter}$-$V_{extractor}$. This signal can be positive or negative and a precision absolute voltage generator is used to convert this into a positive voltage $|V_{emitter}-V_{extractor}|$. The rectified signal is low pass filtered (anti-aliasing) and input to one of the ESA microcontroller's analog inputs. In software an algorithm compares the sensed voltage to a set level and controls a PWM signal accordingly to regulate the extractor voltage. A logic "wired or" configuration is used so that multiple ESA boards can communicate with the CPCB over one serial connection. The CPCB communicates to all ESA boards. For other inter-board communications, temperature measurements on the Electrical interface board (EIFB) and communication with the spacecraft, the I^2C protocol interface is used.

In figure 4 the assembled CPCB and ESA boards are depicted. All Low Voltage interconnections are made using the Omnetics connectors. The connection to the S/C consists of 12V power, GND and I^2C signals. The inter-board connection adds 5V for ESA's and EIFB's, which is generated on the CPCB board, and the serial interconnections. Lastly the connection to the EIFB of the thruster chip (THC) consists only of 5V, GND and I^2C signals. For HV interconnects between CPCB, ESA and the EIFB flexible wires are used that are isolated with Kapton tape. These HV wires are soldered to the board, and use strain relieves for mechanical stability.
The CPCB and ESA boards measure 80mm by 80mm and have a height of 35mm when stacked. The total mass of the boards excluding cables is 115 grams.

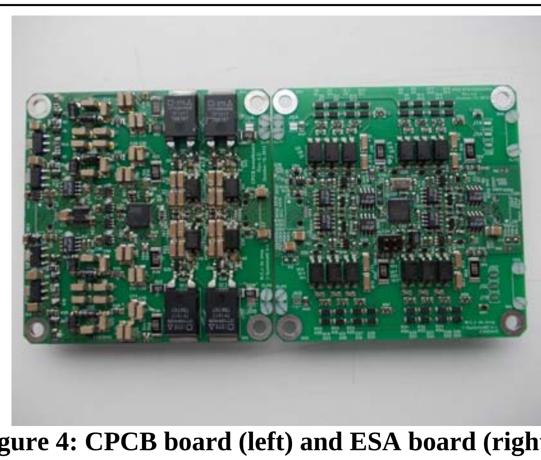

Figure 4: CPCB board (left) and ESA board (right)

IV. CPCB and ESA Software

The modular setup of a CPCB board with multiple extractor switching assembly (ESA) boards requires that hardware and control are split across multiple boards therefore control is distributed over two microcontrollers. The controller implement two basic functions: control of the generation of high voltage and control of extractor regulation.

Controller functionality consists of:

CPCB:

- HV generator control
- HV polarity switching
- Overvoltage and short circuit protection
- Current measurement
- Compensation of non-linear HV resistive divider errors
- Communication and error reporting with S/C
- Communication with ESA modules

ESA:

- Extractor voltage controls
- Communication with CPCB

Communication

To communicate between CPCB and ESA boards a separate dedicated serial UART bus is used. The UART protocol is used since only one I^2C bus and one UART bus is available and the I^2C bus is used for communication with the main controller board.

CPCB Control

The CPCB microcontroller controls the power supplied to the HV generation circuit to generate a stable high voltage level. The ADC of the microcontroller generates an interrupt when a new measurement sample of the high voltage supply output is available. The control algorithm in the interrupt handler adjusts the power input in the high voltage generation circuit if necessary.

This means that delays in handling of ADC interrupts can potentially cause a voltage outside the specs which can even be damaging. To ensure proper handling of the delays, all the interrupt routines are short and, as the worst case delay is the sum of all interrupts, also the number of interrupts have been kept to an absolute minimum resulting in only two other interrupt sources with a total of less than 1100 cycles (estimated, as they are subject to change, but well within this limit) resulting in an absolute worst case response time of 70µs which is still an order of magnitude faster than the HV generation circuit. To ensure maximum accuracy and low measurement noise levels the frequency of the interrupts is around 9600 samples/s divided over two high-voltage ADC's and two current detection circuits with an effective update rate of 2400 Hz.

Additionally, to prevent accidental damaging during development and also to provide an extra safeguard during space operation, all HV generation will be aborted when an overvoltage is detected which is set at |300V| above the set level, to account for possible measurement noise and the slight control variations. This is based on noise tests in a laboratory environment.

High voltage polarity switching is implemented in the CPCB controller with a period that can be set to any multiple of 0.5 seconds with a maximum of 127 seconds. Polarity switching follows a number of strict consecutive states. Failing to adhere to this order will damage to the circuit.

These states are:

- Disabling negative/positive HV generation
- Open both positive and negative voltage switches to discharge the circuits
- Closing positive/negative switches
- Starting positive/negative HV generation

Access to polarity switching in software is restricted to a single method thus reducing software complexity and no errors in polarity switching will occur.

Current measurement
The emitter current measured correlates with the power output of the board and is measured using two of the ADC inputs. The current measurements are also used to detect short circuits.

ESA Control
The ESA controllers each control four extractors and control operation is interrupt based like the CPCB. The ADC of the microcontroller generates an interrupt when a new measurement sample of one of the extractor output is available and adjusts the voltage accordingly. As there are no other interrupt sources, the interrupt response time of the ESA controller is instantaneous. Each of the extractor channels is connected to a separate ADC channel which is sampled with a frequency of approximately 2400 Hz. This is the maximum sample speed for four channels on the microcontroller. The resolution of the measurements is 1.62V which originates in the resolution of the microcontroller ADC of 10 bits and the hardware implementation of the circuit which provides a 3times amplification over the measured 1:1000 volts circuit, thus allowing for a maximum measuring range of 1667 volts. This exceeds the control range of the extractor therefore allowing for possible overvoltage detection. As soon as the supply voltage is stable the CPCB will send a command through the UART interface to generate an extractor voltage of a set level. The voltage levels can be set separately for each extractor channel and also separately for both the positive and negative cycle. The controller ensures the $|V_{emitter}\text{-}V_{extractor}|$ voltage does not exceed 1000V

Calibration table for hardware compensation
There is a notable non-linear effect present in the system, which is voltage coefficient (VCR) of the 1:1000 resistor divider used to transfer voltages to the low voltage domain. The specification of VCR of the high ohmic resistors used is up to 7ppm/V so at 3kV and corresponds to 7ppm/V*3000V=2%.
The solution in the microthrust project is the use of a lookup-table with compensation for ADC values is generated based on measurements in a controlled test environment.

Controlling the PCS
For easy control and tests at project partners a graphical user interface is provided to control part of the board functionality. A screenshot is found in figure 5. One in every 2000 samples is provided to the interface to report on the current status and optionally the measurement results are returned as text only for later analysis.

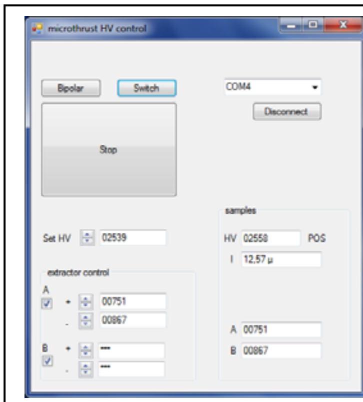

Figure 5 Graphical user interface for control of the PCS

V. TEST results

The design target for the MicroThrust breadboard is a dual bipolar 3.8kV power supply with 0.4-5W output power capability. In figure 6 a typical PCS measurement result is shown in bipolar operation. The curve in red displays $V_{emitter}$ for a programmed value set at 2558V and corresponds to the values found in figure 5. In yellow $V_{extractor}$ is measured, in this set up $V_{emitter}\text{-}V_{extractor}$ is set at 751V for positive $V_{emitter}$ and 867V for negative $V_{emitter}$. It is to be noted that during polarity switching initially $V_{emitter}$ and $V_{extractor}$ are intentionally regulated to an equal voltage and the thruster will be off. When $V_{emitter}$ has settled the controller starts regulating $V_{emitter}\text{-}V_{extractor}$ to the programmed value. Just before polarity changing $V_{emitter}$ and $V_{extractor}$ are regulated to an equal voltage again to turn the thruster off. Then the same procedure repeats for the opposite polarity. The displayed waveforms are accurate representations

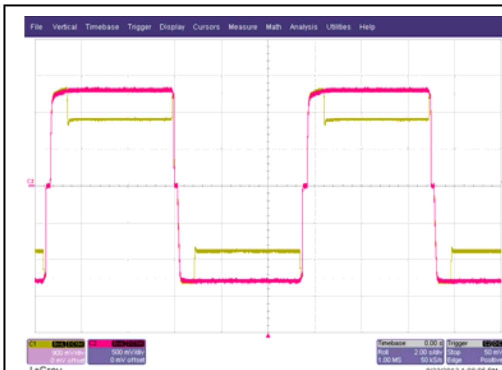

Figure 6: Emitter and extractor voltage

of the actual $V_{emitter}$ and $V_{extractor}$ but scaled to LV domain with calibrated probe networks. At 0V the switch over from positive supply to negative supply can be noticed.

At 3kV under ambient conditions measured ripple of $V_{emitter}$ is <10 V_{pp} at 100µA (0.3W) load. The measured ripple waveform is displayed in figure 7. Bipolar operation frequency is programmable in 0.5s steps and has a default setting of 12s which equals 0.083 Hz. The supply can be operated in a dual static HVPS mode for application in a unipolar thruster system. The $|V_{emitter}-V_{extractor}|$ voltage is programmable in the range of |0-1kV|. $V_{emitter}$ voltage accuracy is calibrated to 0.1% at 3kV. $V_{emitter}$ ripple is 4 V_p. By design the accelerator grid is 0V and acceleration voltage equals $|V_{extractor}|$. Target electric power conversion efficiency is 50% at 0.4W. Measured electrical efficiency of the HV part of the PCB in figure 4 is 36% at this output power. The HVPS efficiency improves at higher output power and the supply has an efficiency of 44% at 3W and 3kV. Measurements on a single HVPS with an improved control result in efficiencies of 45% at 0.4W and 3kV and 73% at 2.4W and 3kV.

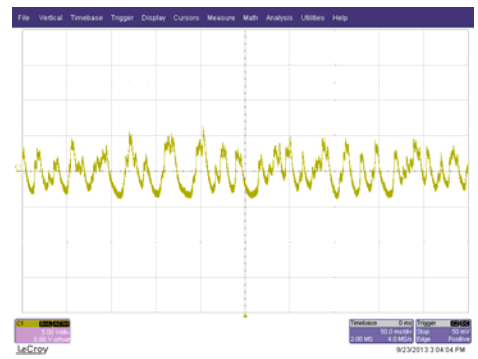

Figure 7: $V_{emitter}$ ripple

Initial tests with a single emitter thruster with the PCS outside vacuum were fully functional[5]. Figures 8 and 9 display some results of these tests. In figure 8 the emitted current during a single cycle is shown. Bipolar operation is clearly visible. It is to be noted that the electrical current in single emitter operation is in the 200 to 300nA range and is very small. Some switching spikes are visible on this scale and can be correlated to the HVPS electrical switching and are harmless for the thruster is off at these moments in time. In figure 9 the bipolar currents are shown over time for more than 2 hours of operation.

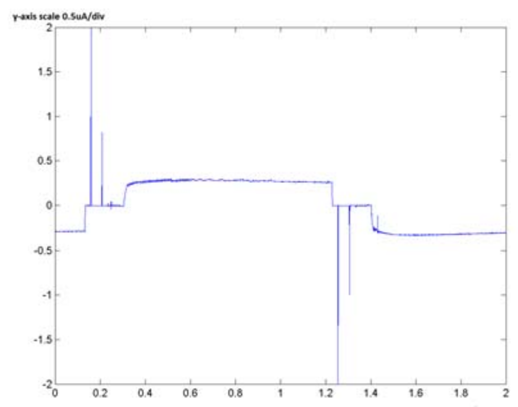

Figure 9: Emitted current in bipolar operation, single switch cycle

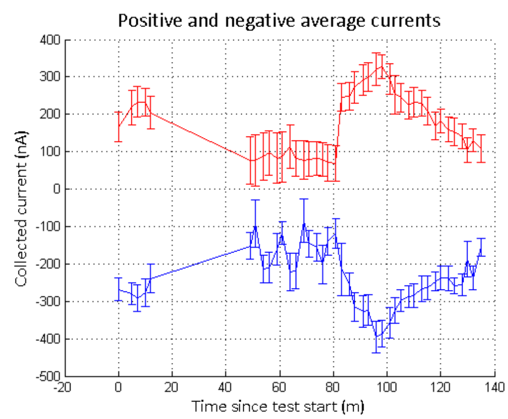

Figure 8: Emitted current in bipolar operation over time

In vacuum the PCS operation is functional. In the months to come further work will be done to combine the PCS with an actual Thruster array.

The emitter current is measured to have an accuracy of 4% of the maximum current. The required precision of about 1% can be reached by mathematically compensating for the ESA HV bias current in software, which load the HVPS but do not contribute to emission current. This functionality needs to be implemented.

Measurement results are summarized in the table 1 below.
Table 1: PCS measurements versus specifications

	Specification	Measurement
$V_{emitter}$ vacuum	± 3.8kV	± 3.8kV
$V_{emitter}$ air	-	± 3kV
Ripple $V_{emitter}$	< $4V_p$	$4V_p$
HV output power	0.4W (100 μA)	> 0.4W (100μA)
$V_{emitter}$ accuracy		0.1%
Current sensor accuracy	< 1%	4%
Bipolar operation frequency	< 0.1Hz	< 0.25Hz
Target power conversion efficiency in operation	> 50% at 0.4W	36% at 0.4W
($V_{emitter}$-$V_{extractor}$) voltage	0-1kV	0-1kV
Ripple $V_{extractor}$	< $4V_p$	$4V_p$
$V_{emitter}$ accuracy	0.1%	2.3%
Acceleration voltage	$V_{extractor}$ V	$V_{extractor}$ V

Conclusion

In this article a HV PCS for application with a colloid Thruster is presented, both on conceptual level as well as implemented in hardware with cubesat size PCB dimensions. Actual hardware is tested outside vacuum with a single emitter colloid Thruster. Inside vacuum the PCS is tested and functional. Further integration tests with the colloid Thruster are planned for the months to come. The electrical performance of the PCS is in the right ball park but requires further work on the design to meet the intended specifications and to improve efficiency and accuracy of the PCS breadboard.

Acknowledgments

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