Micro-Newton RIT Power Control Unit Development

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A promising concept for µ-Propulsion is currently under development: the µN-RIT (Radio Frequency Ion Thruster), a µ-Newton engine, which has been subject of intensive research by the University of Giessen in the past years. In order to accompany the thruster development activities, the European Space Agency and the German Space Agency DLR are supporting the development of key functional blocks of the Power Supply and Control Unit at Astrium GmbH (Germany), to form a complete thruster subsystem for future missions. The concepts for the functional blocks of the Power Supply and Control Unit are currently undergoing a detailed implementation into a breadboard.

I. Introduction

The coming generation of scientific and earth observation mission demands for ultra-precise attitude and orbit controlled platforms. Several actual and future satellite projects of the European Space Agency (ESA) have established challenging requirements for high accuracy: in positioning (LISA mission, prepared by LISA Pathfinder), in pointing (DARWIN mission) and for drag compensation (GOCE mission). Further upcoming mission are challenging high precision thrusters for formation flying, like PROBA-3, XEUS and WFI. As a consequence, very fine adjustable thrusts are needed typically at low levels in the micro-Newton range. A promising approach for meeting such thrust requirements is the use of electric propulsion, based on Field Emission Electric Propulsion (FEEP) thrusters[1,2,3] or µN-RIT (Radio Frequency Ion Thrusters) [4,5,6].

The principle of the µN-RIT is based on the developments of the University of Giessen in Germany. The µN-RIT is derived from the well established Milli-Newton RIT thrusters. Both developments involve a discharge vessel which is surrounded by the induction coil of a radio frequency generator (RFG). The induced electric eddy-field accelerates electrons and generates a self-sustaining, electrodeless gas-discharge. From this plasma the ions are extracted, focused, and accelerated by a two-grid system made of molybdenum and graphite.

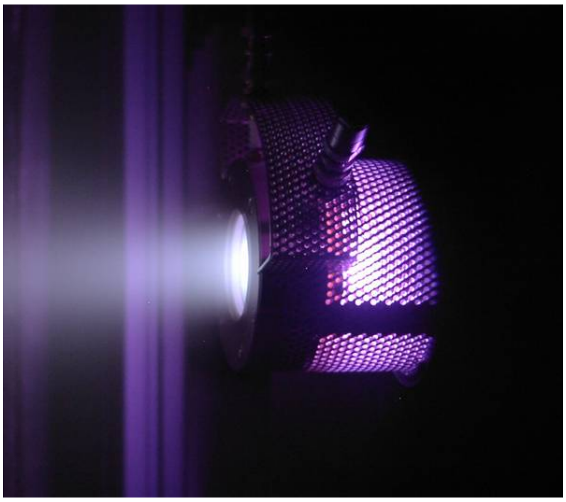

Fig. 1: Firing of a µN-RIT
(Photo: Courtesy of University of Giessen)

By applying beam voltages between 800 V to 2000 V the µN-RIT engines are able to provide a specific impulse up to 3420s and up to 4000 µN thrust. A photo of a "firing" µN-RIT during development testing is shown in **Fig. 1**.

II. Impact of Thruster System Requirements

A PSCU (Power Supply and Control Unit) shall provide all power supply and control functions to operate one or more electric thrusters. Typically needed functions are:

- High Voltage Power Supply for the thruster
- Auxiliary Power Supplies for the thruster
- Radio Frequency Generator for the thruster
- Neutralizer Supplies
- Flow Control Units (for Xenon gas)
- Telecommand and Telemetry Interfaces
- Controller or State Machine

From this list the key items of the PSCU are the high voltage power supplies, since they have to convert high power, they need to provide reliable high voltage insulation and they are significant for the thruster performance.

In order to achieve a broad band of application for µN-RIT, the PSCU shall provide

- a wide range of power modulation capability for allowing a wide thrust range with a single thruster
- a high precision and high dynamic to satisfy ambitious spacecraft attitude control requirements needed for specific missions

As a consequence the main driving parameters for a µ-RIT PSCU (Power Supply and Control Unit) design are:

- Required thrust level
- Required throttling capability
- Required thrust accuracy
- Required number of simultaneously running thrusters

<u>Required Thrust Level</u>

The required thrust level defines the electrical power to be supplied to the thrusters. Depending on the mission, three ranges have been identified: 150 µN max., 500 µN max. and 4000 µN max.

For the main High Voltage converter, these ranges imply a power demand of 5 W, 15 W or 120 W. To reach an optimum of mass / size / power trade-off, different high voltage converter topologies are feasible.

<u>Required throttling capability</u>

The µ-RIT can provide a maximum throttling ratio (relationship between minimum and maximum thrust) of max. 1:20. This range can be handled by the PSCU with conventional control of voltages and currents. To spread the ratio to higher values, virtually 1:∞, the thruster could be driven with a pulsed voltage. Depending on the required thrust noise, the pulse repetition frequency can be as high as several kHz.

<u>Required thrust accuracy</u>

The thrust accuracy is related to the systematic errors (gain, offset, linearity) of the system excluding stochastic errors. It is mainly affected by thermal drift, ageing effects and degradation due to radiation of electronics. The achievable accuracy is affected by the choice of electronic components and the amount of effort. It can be drastically improved by occasional in orbit calibration of the system to compensate the systematic errors.

<u>Required Number of Simultaneously Operated Thrusters</u>

Since a satellite requires thrusters for different directions and redundacy, e.g. 12 thrusters can be connected to one PSCU. Normally, not all thrusters are to be fired simultanuosly. So a switching matrix could distribute the electrical power from one supply to several thrusters.

III. High Voltage Converter as a PSCU Building Block

The High Voltage Converter (HVCV) typically is built by using a two stage-topology, enabling a wide range of output voltage setting, allowing equally a good thrust resolution. The two-stage concept involves a first power conversion stage on low voltage level proving a programmable voltage conversion ratio. A buck regulator provides output voltage from zero to maximum. The second stage is the high voltage converter, with a fixed voltage conversion ratio, generating the high voltage.

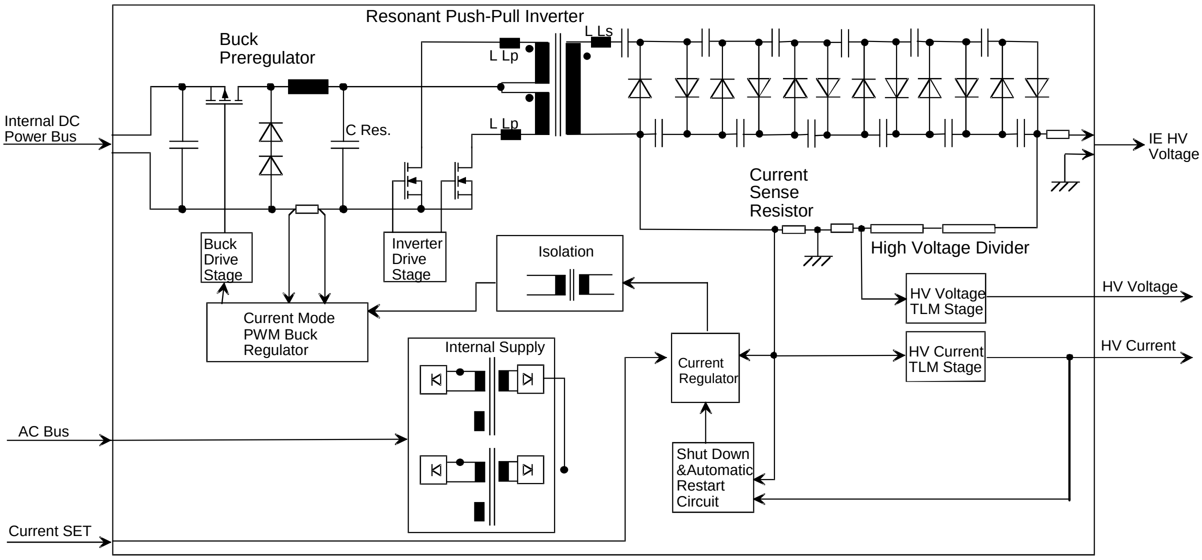

Fig. 2: HVCV - High Voltage Converter Principle

In Fig. 2 a typical topology is shown. The inverter is a push-pull topology driving the two primary windings of the high voltage transformer. Hereby the load current is resonated via the input capacitor C_{Res}. and the leakage inductances L_{Lp} and L_{Ls} on the primary and secondary side of the high voltage transformer. Zero Current Switching is applied.

The high voltage transformer is ferrite core type and generates an output voltage, which can be stepped-up further with a multi-stage stage capacitive voltage multiplier. Especially for low power applications this kind of voltage conditioning is more efficient w.r.t. size and mass, if compared with high voltage generation only by a transformer. The last mentioned method would require either a large core cross section or a high number of windings. Excellent high voltage insulation is ensured by an epoxy potting. This space qualified potting material “Dos Epoxy E” is used also for the encapsulation of the high voltage multiplier and the associated high voltage divider[7].

Fig. 3: Breadboard of the High Voltage Converter (HVCV) for FEEP application

Recent breadboarding was focused on a complete power conditioning string for one high voltage supply with the following key parameters:

- DC input voltage: 20V to 35V
- Switching frequency HVCV: 37.5kHz
- High voltage output: typ.12kV

The printed circuit board (see Fig. 3) contains the described high voltage converter. The potted high voltage module contains the high voltage transformer and a six stage voltage multiplier including a voltage divider and a shunt resistor for the feedback loop.

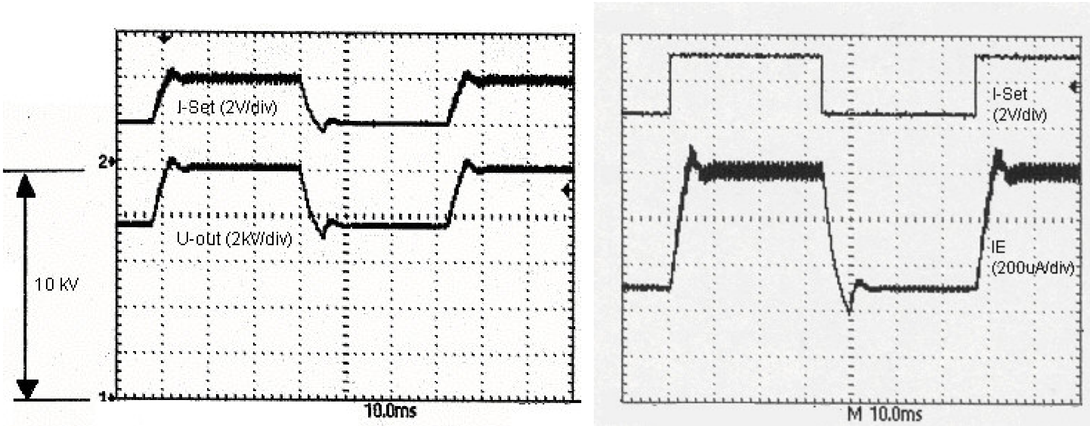

Fig. 4: Step Response of Load Current (IE) and of Output Voltage (U-out) as a Result of Current Setting Step (I-Set) from 500µA to 1000µA - Time Scale: 10ms/div

The breadboard originally was foreseen to supply a FEEP with relatively higher output voltage of 12kV compared to the µN-RIT as discussed in this paper. Since this concept is generic, it can be used for various high voltage ranges, just by changing the number of multiplier-stages and the transformer winding ratio.

The electrical testing has been focused on the dynamic behavior of the high voltage converter. The step response has been measured for various load cases. The response to a commanded load current step from 500 µA to 1000 µA is shown in Fig. 4 and has been determined below 2 ms for load rise. The fall time is slightly slower and mainly determined by the load current, since the output capacitance of the voltage multiplier needs to be discharged through the load.

The efficiency has been measured according Fig. 5 in dependence of the load current, reaching a maximum efficiency of 82 % at maximum current. The high efficiency remains even at lower currents constantly low and falling only for very low currents below 200µA. The nearly static internal supply of approximately 140mW has been considered separately in this budget.

The high voltage ripple is 100Vpp.

Design options for the above described High Voltage Converter are:

- Replacement of the push-pull (half bridge) stage by a full bridge stage for efficient handling of higher power levels
- Introduction of a single stage concept with a fly-back converter to reduce parts count and mass for low power levels.

These modifiactions are subject of further trade-offs under consideration of the above mentioned thruster system requierements.

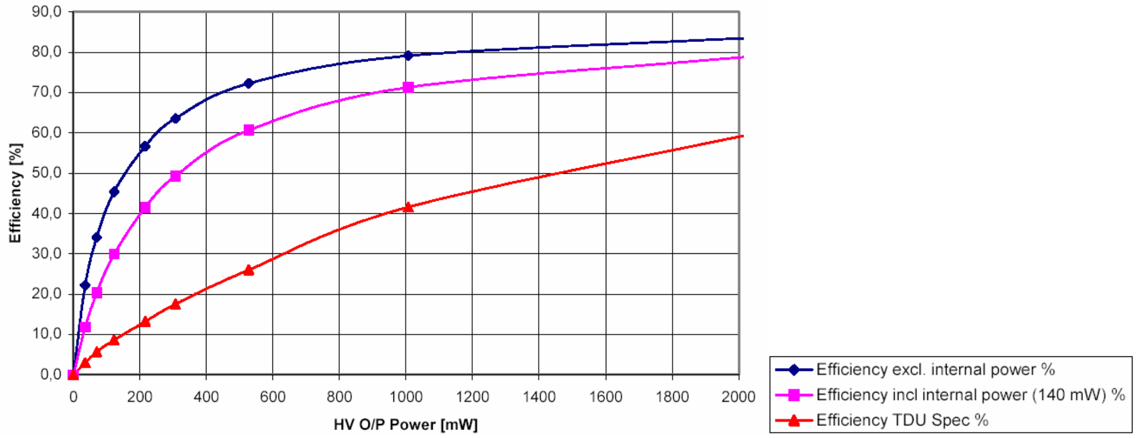

Fig. 5: Efficiency of an Extractor Voltage Power Conditioning String vs. IE-Current @20V Bus Voltage (excluding internal power consumption -static value of approx. 140 mW)

IV. Thruster Control

The thrust control of the µN-RIT is performed by the beam current controller. Fig. 6 shows a block diagram of this closed loop system. The extracted ion current from the thruster is measured by a high precision resistor. This signal is used for a PID controller, which controls the radio frequency power fed into the plasma. Furtermore, the PHV (Positive High Voltage) and the NHV (Negative High Voltage) supplies are adjustable to achieve a broader thrust range and to compensate lifetime effects of the thruster. As a target, the beam current shall be controlled with a precision of 0.3% or less in order to satisfy even the thrust setting requirements of ambitious space missions.

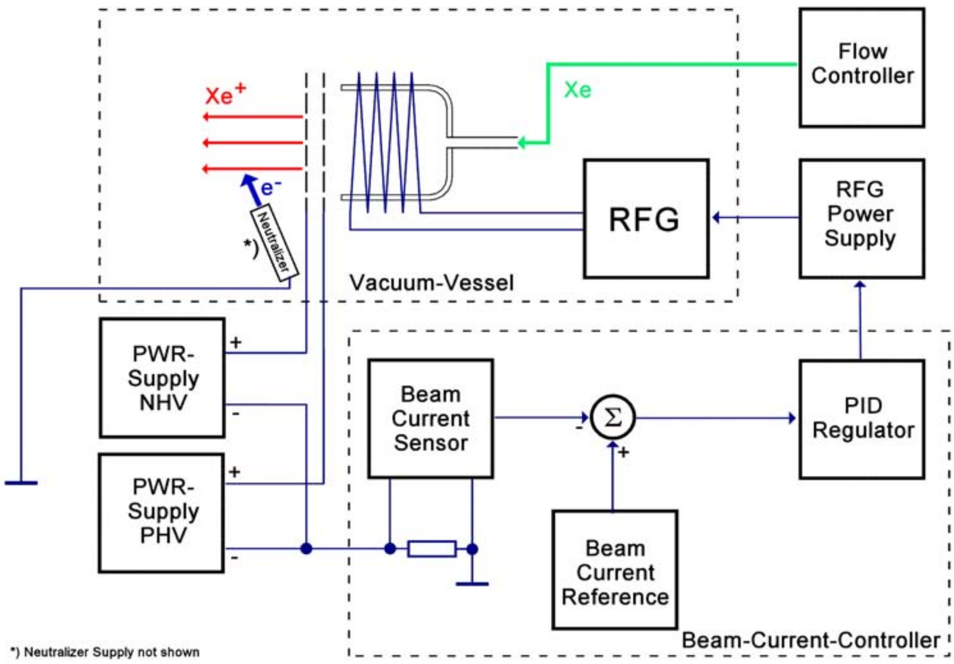

Fig. 6: Block Diagram of a µ-RIT Regulator Loop and Power Supplies

V. PSCU Design

The High Voltage Converter forms at least two functional blocks of the complete PSCU for the µN-RIT, because the two-grid engine requires a Positive High Voltage Supply (PHV) and a Negative High Voltage Supply (NHV). An RF-generator and a flow-control need to be added for each thruster. An overall PSCU design is shown in Fig 7.

The PSCU is designed to cover the following requirements: All three in chapter II listed thrust levels at a throttling ratio of 1:20 maximum with the possibility to operate the eight main thrusters simultaneously and an additional set of four thrusters for redundancy for none simultaneous operation. These Requirements are derived from a PROBA-3 system design.

Targeting a 500µN thrust maximum per thruster the described PSCU would have a mass of approximately 9kg.

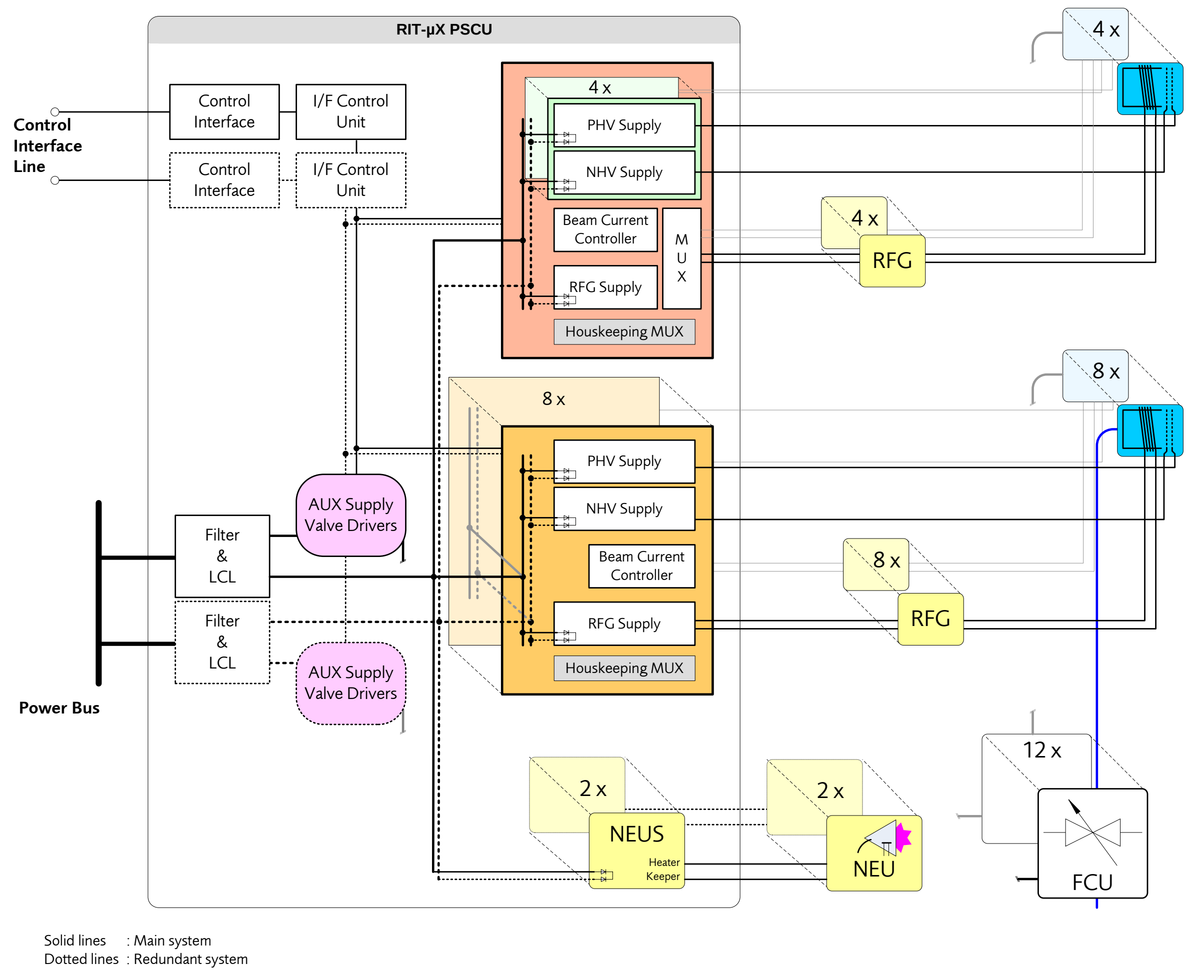

Fig. 7: Block Diagram of a µ-RIT Power Supply & Control Unit for 12 µ-RIT thrusters

Key elements and related electrical data are:

- PHV providing an output voltage of 800 -2000 Volt and an output current of 8 mA
- NHV providing an output voltage of 50 - 300 Volt and an output current of 0.5 mA
- RFG Supply (Radio Frequency Generator Supply) providing an output voltage of 4 - 60 Volt and an output current of 3 A, (max. power: 60 W)
- Auxiliary Supplies for internal use
- NEUS Neutralizer Supplies
- Flow Control Unit Supplies
- Control Interface

VI. CONCLUSIONS

Successful µ-propulsion technology is closely related to a complete and efficient overall approach for the complete propulsion system including the PSCU Power Supply and Control Unit. For this purpose a concept for supplying multiple mirco-thrusters with independently regulated and programmable high voltage power conditioners has been verified by realization and testing of a breadboard. It was demonstrated, that high voltage power conversion efficiency in the order of 80% can be ensured for a wide variation of the load current. Sufficient dynamics to follow load steps in millisecond range is ensured by the design.

A concept for a complex Power Supply and Control Unit serving up to 12 µN-RITs with a high thrust setting resolution has already been designed. Suitable variations of the concepts for different mission scenarios are currently under trade-off.

VII. REFERENCES

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VIII. ACKNOWLEDGEMENT

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