Compact High Voltage Power Processing For Field Emission Electric Propulsion (FEEP)

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Abstract: A high voltage power supply concept has been developed for the supply of an array of multiple micro-Newton thrusters for Field Emission Electric Propulsion (FEEP). For this purpose a total number of 96 high voltage conditioners are aligned in 16 centralized electronic modules. A programmable output voltage of 2.5-10.5 kV can be provided with an efficiency >88%. Zero-current switching technology is used in a resonant topology. In addition, supplementary regulated voltages of 1.0-1.5 kV for all thruster units are provided by a separate power conditions system. A prototype model of one main supply chain has been built and characterized. Excellent dynamic behaviour with 2ms load step setting has been demonstrated.

I. Introduction

The coming generation of scientific and earth observation mission demands for ultra-precise attitude and orbit controlled platforms. Several 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). As a consequence a very fine adjustable thrust at a typically low level in the micro-Newton range is needed.

A promising approach for meeting such thrust requirements is the use of electrical propulsion, specifically of Field Emission Electric Propulsion (FEEP). The principle of these types of ion engine is the nearly “cold” emission of ions from a liquid metal using high electric field strengths [1]. Two types of these FEEP engines are currently under development in Europe: the "needle emitter" type using Indium propellant and the "slit emitter" type using Cesium propellant. The Indium FEEP is built by the Austrian Research Centre in Seibersdorf (Austria).

These engines require a fine adjustable positive main voltage for ion extraction in the range of above 10 kV. A second negative voltage of a few kV is static and used to control an electrostatic shield. The drawn currents on both voltage supply lines are very low (some 100µA)

The power concept presented here is based on the initial FEEP requirements for the ESA GOCE mission. The Gravity Field and Steady-State Ocean Circulation Explorer (GOCE) mission will measure high-accuracy gravity gradients and provide global models of the Earth's gravity field and of the geoid. The FEEP thruster subsystem was initially selected for the drag compensation of the low earth orbiting satellite. A photo of a "firing" of a FEEP Microthruster Array during development testing is shown in Fig. 1.

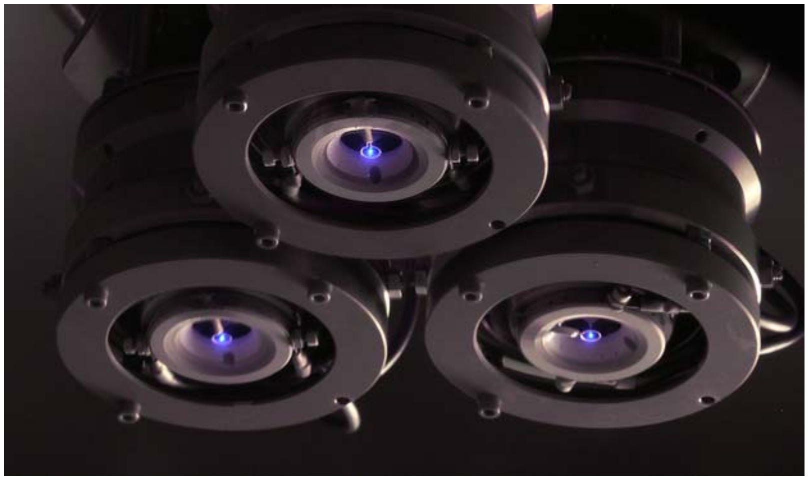


Fig. 1: FEEP Microthruster Array under Test (Photo: Courtesy of ARCS Seibersdorf, Austria)

Although the FEEP was replaced in a later stage of the GOCE project by a conventional cold gas thruster, the power system development was almost finalized and initial test results are now available. Furthermore, a complete thruster including a power processing unit and has been designed for use in the coming European scientific space missions (for details see http://www.esa.int/esaSC: missions: LISA Pathfinder, LISA, and GAIA).

II. REQUIREMENTS

The electrical power system requirements are driven by the FEEP thruster design, which is a "needle emitter type" wetted with liquid Indium. The electrical principle of such an Ion Emitter (IE) is outlined in Fig. 2.

Each emitter needle requires two regulated high voltages:

Ion Emitter (IE) Voltage:
- Output Voltage Range 0 V to 12 kV
- Variable depending on current
- Voltage ripple 100 V max
- Load step voltage settling time < 10 ms
- The emitter voltage needs to be settable individually for each emitter needle.
- 96 emitter supply voltages in total

Input:
- DC Bus Interface Voltage 20 V to 37 V
- Galvanic isolation inside the power units

The ion emitter voltage is used to force ion emission from the needle emitter by causing high electric field strength. The ion emission current - and as a consequence: the thrust - is determined by the applied voltage. The plume shield is biased with a moderate high voltage to control the ion trajectories of the ion beam.

In order to achieve a thrust level of 650µN at eight different spacecraft location the needle emitters are grouped into clusters and these clusters form a thruster assembly. Including redundancies a total number of 96 emitters need to be supplied by the FEEP power supply with an emitter voltage and a plume shield voltage.

Plum Shield Voltage:
- Output-Voltage Range max 1 kV to 1.5kV ± 10%
- Load current max. 1 m A
- The plum shield voltage of different emitter assembly needs to be decoupled by diode from each other.
- 96 plume shield supply voltages in total

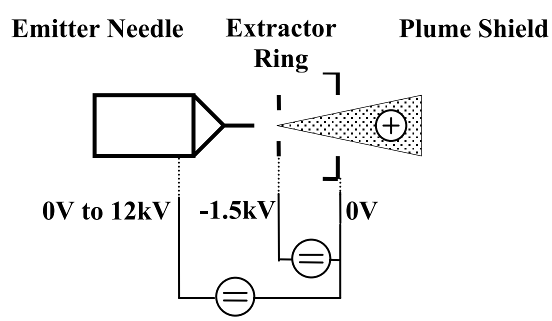


Fig. 2: FEEP Ion Emitter (IE) Principle

III. ARCHITECTURE

A. Overall Architecture

The FEEP power supplies are part of the Micro Propulsion Electronic (MPE) units, which include the digital control loops and switching of all the thrusters. Two types of power units are foreseen:

- **TDU - Thruster Drive Unit**
  each provides 6 independently controlled Ion Emitter Voltages.
- **PSU - Plume Shield Unit**
  each provides 24 commonly controlled, fixed Plume Shield Voltages.

In total 16 units of the TDU are arranged in 4 MPE´s and 4 units of the PSU arranged in 4 MPE´s to supply the 96 Ion Emitters. The resulting configuration is shown in Fig. 3.

Each unit is integrated into a metallic frame of 240 x 180 x 48 mm. These frames are assembled with other MPE frames into one large unit.

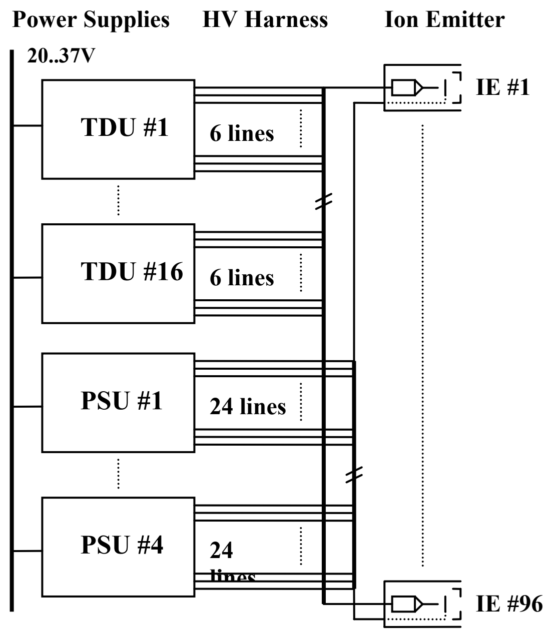


Fig. 3: FEEP Power System Units

B. Thruster Drive Unit (TDU)

The TDU consists of 6 High Voltage Converters (HVCV´s) which are fed by the internal power bus of the MPE and generate thereof the required high voltage for the IE´s. A block diagram is shown in Fig. 4.

Signal lines for receiving command signals and transmitting housekeeping signals are connected to the "Multiplexer ADC / DAC" block, which communicates via a special FPGA with the overall MPE Unit.

A separate Low Voltage Converter (LVCV) is foreseen as internal supply for the TDU. This converter provides a regulated symmetrical square wave voltage which drives the internal supply transformers of the HVCV´s and the "Multiplexer ADC / DAC" block. In addition to the power supply function the symmetrical square wave voltage is used for synchronization of the HVCV´s onto the master clock of the MPE.

The TDU internal AC supply has been selected for three reasons.

- The TDU internal supply transformers provide galvanic isolation to avoid ground loops.
- The internal power supplies of the individual HVCV´s are simplified to a minimum.
- The AC voltage is additionally used for frequency synchronization, which saves interface lines and receiver stages on the LVCVs.

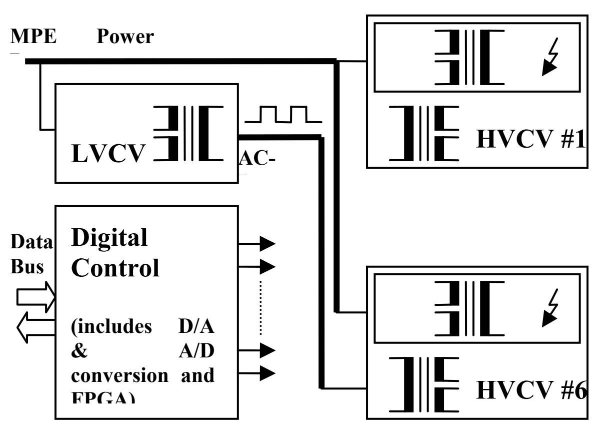


Fig. 4: TDU - Thruster Drive Unit Breakdown

The Low Voltage Converter (LVCV)

The LVCV is shown in Fig. 5. It generates a symmetrical square wave voltage to power the internal supply transformers of the Digital Control and of the "HVCV´s".

The frequency of the square wave voltage is additionally used for synchronization of the HVCV buck regulators and resonant push pull inverters. The accuracy of the frequency is ensured by a Phase Locked Loop (PLL) circuit.

The AC voltage is generated by a push- pull inverter which receives a regulated input voltage from the feeding buck regulator. Special attention has been paid to the buck stage similar to HVCV which is free of single point failure on the DC input. In case of low DC input voltage on the Internal Power Bus the LVCV will switch off automatically.

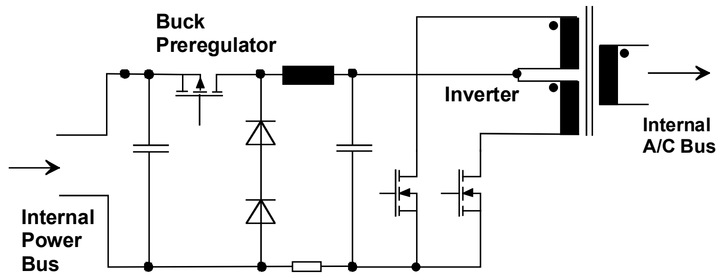


Fig. 5: LVCV - Low Voltage Converter Principle

The High Voltage Converter (HVCV)

Based on the experience , gained over many years of high voltage power supply production for TWT application, where high efficiency is the most important design driver, it turned out that the best topology is zero voltage switching and full resonant zero current switching on the inverter.

In Fig. 6 the preferred 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. A short time before commutation of the transformer polarity the current will have decreased to zero (caused by the resonant cycle current wave form) which results in zero current switching.

During voltage commutation both push pull FETs will be turned off simultaneously for a short period of time in which the drain capacitances as well as the windings capacitance of the transformer will be reversed in polarity by the magnetizing current of the transformer. The magnetizing current will be tuned to an optimum magnitude by adding an air gap in the magnetic path of the ferrite core. After completion of the (passive) polarity reversal of all capacitances, the opposite FET of the push pull inverter will be switched on at zero drain voltage and the reverse polarity resonant load current cycle will start.

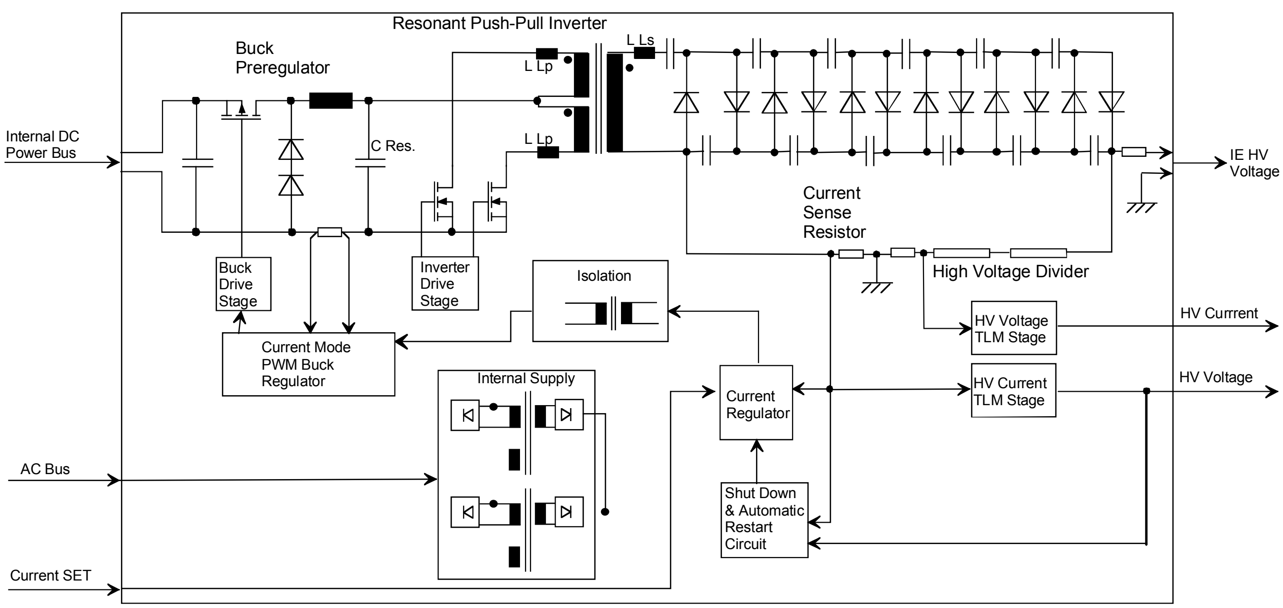


Fig. 6: HVCV - High Voltage Converter Principle

Besides zero commutation loss of the parasitic capacitances and utilizing the leakage inductance for resonating the current, the high voltage diodes are commutated in a softly without significant losses due to the resonant load current wave form.

The reason for using the buck stage is the need of a pre regulated input voltage for the full resonant push pull inverter, which would loose its superb efficiency if regulation during the half cycles would be done by a pulse width modulation. Switching loss and EMC noise on the HV output would increase. Input protection is ensured by an LCL (not shown in the block diagram).

The high voltage transformer is ferrite core type and generates a 2 kV output voltage. A further voltage step up is achieved with a six stage capacitive voltage multiplier. Specifically for low power applications this kind of voltage conditioning is more efficient w.r.t. size and mass, if compared with single step high voltage generation by a transformer. The last mentioned would require either a large core cross section or a high number of windings. A smoothing capacitor and rectifier diodes are also required for the single step design. 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.[2].

C. Plume Shield Unit (PSU)

A PSU supplies 24 extractors. As shown in Fig. 7 two high voltage converters in "hot redundant" configuration are located in a PSU. These converters are identical to the HVCV´s with the exception that the high voltage is generated with a single diode bridge instead of a more multi-stage voltage multiplier.

Short circuit single point failures of the individual extractors will not propagate to the common supply rail, since current limiting resistors (R-Lim) are foreseen in series. The output power of the Plume Shield Converter is sufficient to ensure operation with 2 out of 24 short circuits of the Plume Shield circuits.

For internal supply two identical low voltage AC converters are used in redundant configuration similar to the approach of the TDU. The frequency of the square wave voltage is additionally used for synchronization of all internal switching regulators.

D. High Voltage Interconnections

All internal and external high voltage harness is made using PTFE-insulated high voltage wires. Since space suitable high voltage connectors are not available at present, splice blocks with screwed terminal are used to provide a disconnectable harness from power unit to thruster assembly. This solution was selected to ensure a mass saving reliable and "AIT-friendly" FEEP subsystem.

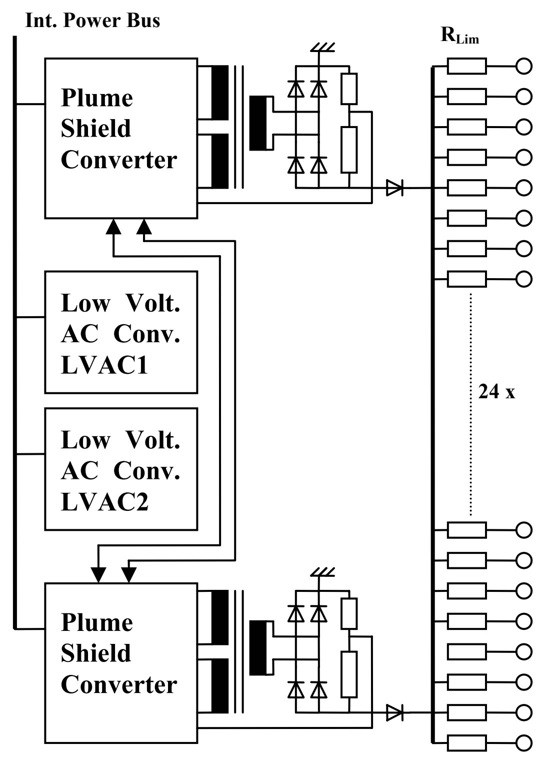


Fig. 7: Block Diagram of Plume Shield Unit

IV. BREADBOARDING

The breadboard was focused on a complete power conditioning string of the MPE for one Ion Emitter, as outlined in Fig. 8. Since Plume Shield voltage is lower and widely based on MPE circuits, this part of the supply was not considered in the partial breadboard.
Key parameters of the partial breadboard are:

- DC input voltage: 20V to 35V
- Synchronization frequency of LVCV: 75kHz
- Switching frequency HVCV: 37.5kHz
- High voltage output: typ.12kV
  (protective limitation 12.7kV)

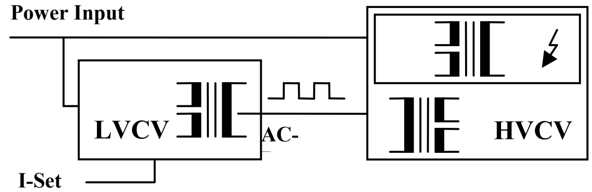


Fig. 8: Partial B/B Block Diagram

The printed circuit board contains the Low Voltage Converter (LVCV) and the High Voltage Converter (HVCV). The High Voltage integrates the high voltage transformer and a six stage voltage multiplier including a voltage divider and a shunt resistor for the feedback loop.

Fig. 9 shows a photo view of the partial breadboard.

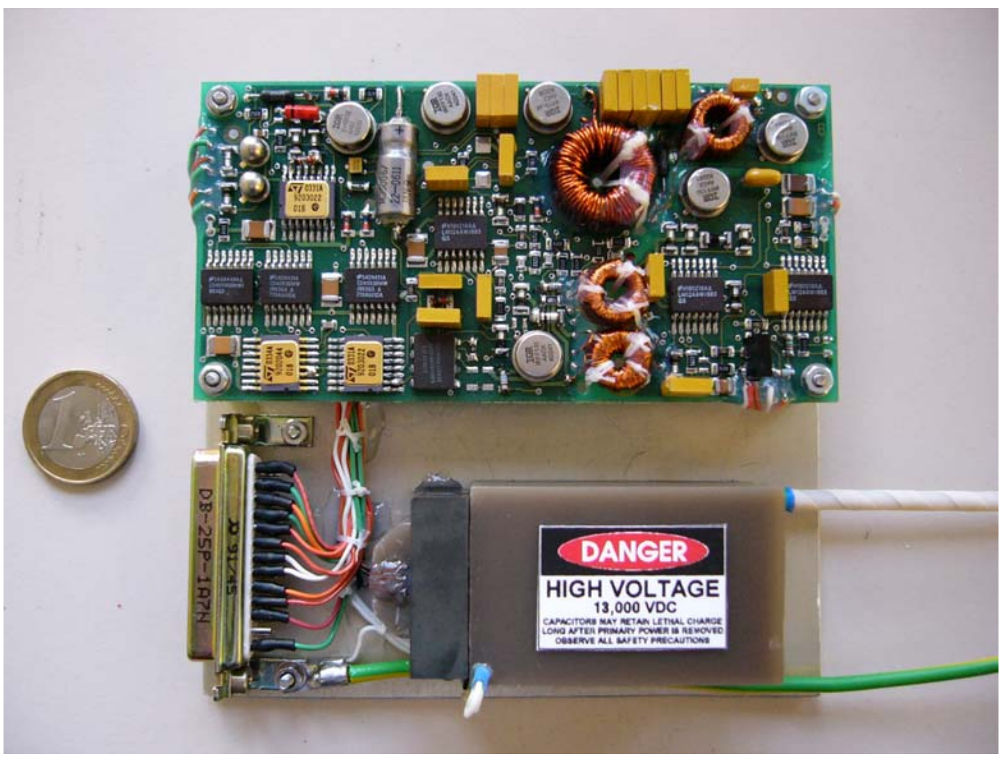


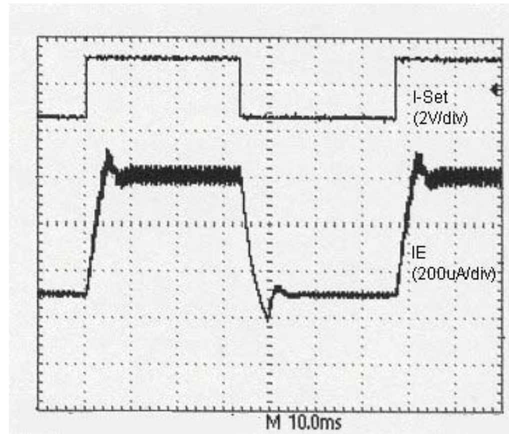
Fig. 9: Partial Breadboard Comprising a Low Voltage Converter (LVCV) and a High Voltage Converter (HVCV) with 13 kV High Voltage Module

V. TEST RESULTS

The electrical testing of the breadboard has confirmed that the performance of the FEEP concept meets the specified requirements. Special attention has been paid to the dynamic behaviour of the HVCV. 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. 10 for voltage and output current and has been found 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. 11 in dependence of the load current, reaching a maximum efficiency of 82 % at maximum current. The high efficiency is given also at lower currents, declining significantly only for very low currents below 200µA. The nearly static internal supply of approximately 140mW has been considered separately in this budget. Generally, the specified TDU efficiency curve is easily meet and exceeded.

The high voltage ripple is 100Vpp (@500Hz) and the 28V Power Bus current ripple is 75mApp.



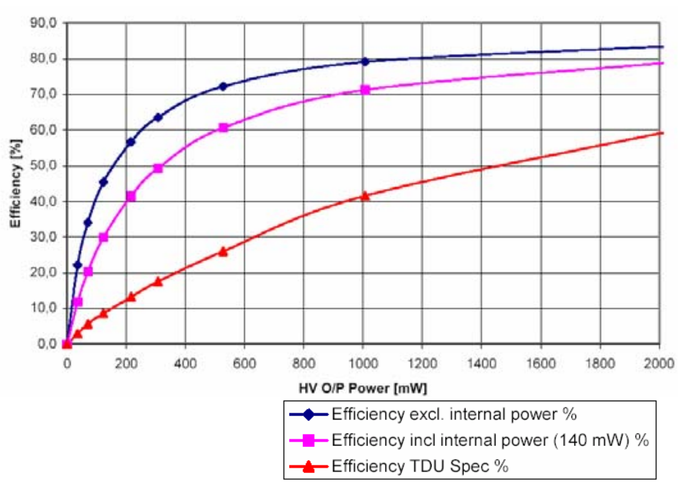


Fig. 11: Efficiency of TDU Power Conditioning String vs. IE-Current @20V Bus Voltage (excluding internal power consumption -static value of approx. 140 mW)

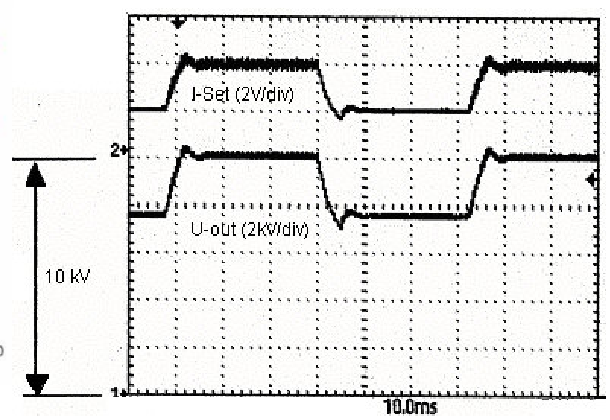


Fig. 10: Step Response of Load Current (IE) and of Output Voltage (U-out) as a Result of Current Setting Step (I-Set) from 500µA to 1000µA - Time Scale: 10ms/div

VI. Power Processing Unit for Future Projects

For the European Missions LISA Pathfinder and GAIA concepts have been established for a complete Power Processing Units including auxiliary power and a controller. The block diagram (Fig. 11) shows a “four high voltage channel” FPPU (FEEP Power Processing Unit) driving 4 FEEP Cluster Assemblies. Using ARCS Seibersdorf FEEP technology four individually controlled thrust directions are provided with the following data:

- thrust level: 0 - 100µN (per thruster * 4)
- thrust setting resolution: 0,3 µN
- thrust settling time: <100 ms
- full independent control per thruster

- neutralizer supply
- proportional low noise heater control
- single point failure tolerant concept
- MIL bus control an TM interface
- 28V regulated bus power input or unregulated 20-35 V
- internal failure detection and protection switching

This diagram includes the redundancy concept with cross-coupling of the primary power bus and the cross-coupling of the internal bus to the HV-Modules, heaters and thermistors.

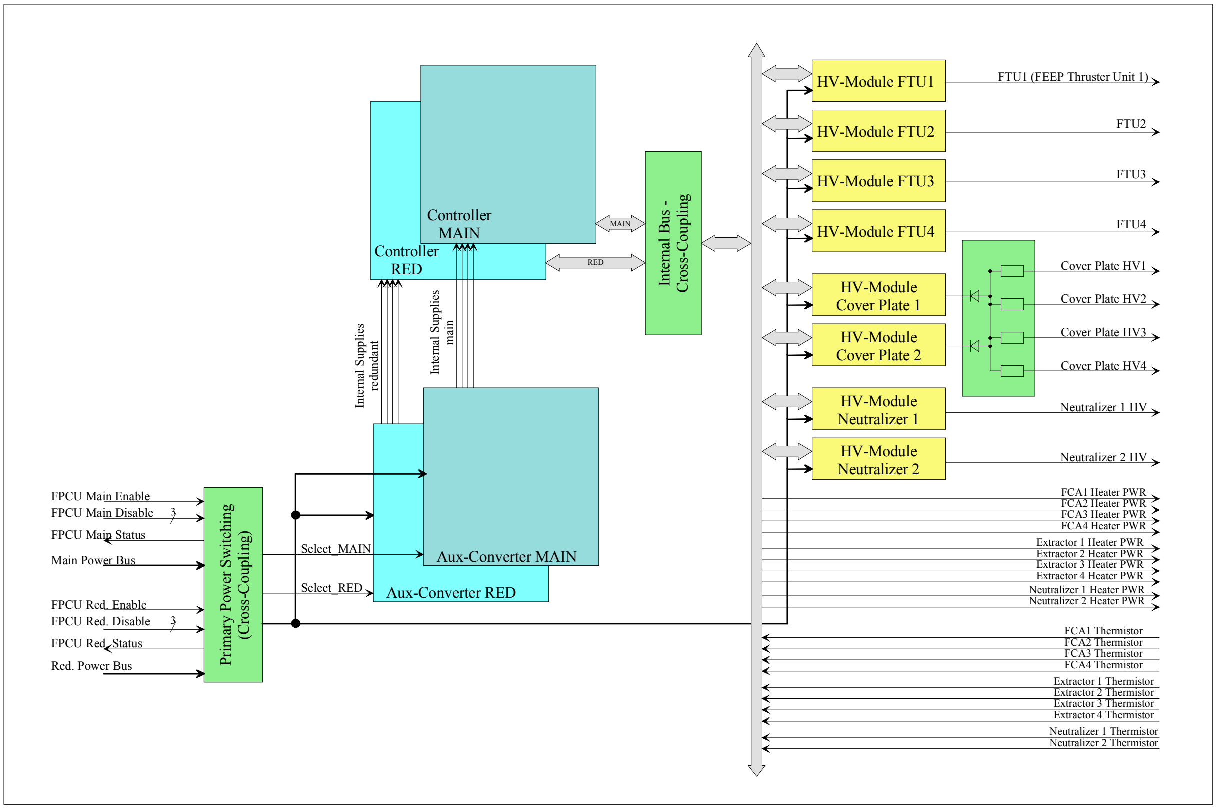


Fig. 11: Block Diagram of a FEEP Power Processing Unit

VII. CONCLUSIONS

The concept for supplying 96 Ion Emitters with independently regulated and programmable high voltage power conditions has been verified by realization and testing of a breadboard. It was demonstrated, that high power conversion efficiency in the order of 80% can be ensured for a wide variation of the load current. A huge dynamics to follow load steps in millisecond range is ensured by the design. A complete thruster assembly with power processing unit providing 0-100 µN (per thruster times 4 thrusters) with a thrust setting resolution of 0,3 µN and a thrust settling time better than 100 ms has already been designed.

VIII. REFERENCES

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2. M. Gollor, K. Rogalla, "High Voltage Design of Vacuum Insulated Power Supplies for Space Applications" - IEEE Transactions of Electrical Insulation, Vol. 28, No. 4, August. 1993, pp. 667-680