High Voltage Power Supply for T5 Gridded Ion Thruster

IEPC-2019-A512

Presented at the 36th International Electric Propulsion Conference
University of Vienna • Vienna, Austria
September 15-20, 2019

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Abstract: The Beam Power Supply has been designed at ASP Equipment GmbH in Salem, Germany as a first design step heading for a future proof PPU solution for QinetiQ's T5 thruster. The final design shall target low recurring cost, low volume / low mass, mainly by taking use of Planar Transformers in combination with GaN switches at a digitally controlled switching frequency of up to 1 MHz. After the architectural trade-offs an architecture based on an adjustable Pre-Regulator plus a fixed frequency Full-Bridge (Buck Voltage Fed Full Bridge) resonant converter (LLC) was selected. The main mass reduction is achieved with the planar design of the high voltage transformer. The configurable output voltage range can be selected in the range of 350V to 1200V by stacking up of secondary transformer PCBs. This Beam/Anode Power Supply module is the basis for the future T5 PPU covering the following main performance parameters / configurations: 350 - 1200V @ 400 - 1200W. Depending on the configuration the expected weight of a single unit will be in the range of 2 - 2,3kg with dimensions of 230 - 280x200x40mm^3.

Nomenclature

EMC	=	Electro Magnetic Compatibility
FET	=	Field-Effect Transistor
GaN	=	Gallium Nitride
LLC	=	Resonant Tank
PCB	=	Printed Circuit Board
PPU	=	Power Processing Unit

I. Introduction

The worldwide need for High Voltage Space Power Equipment is strongly growing due to the New Space initiatives. Many so-called "mega-constellations" are being developed or are already in early stages of implementation. Actual visions identify many thousands of new satellites to be launched in the next years in addition to classical custom made satellites. Electric Propulsion will play a key role in this growing market. In this context main applications are expected on cost effective solutions for electric propulsion.

The QinetiQ T5 system provides an EP capability that could be suitable for a number of opportunities that include constellations where the EP system is required for constellation dispersal and deorbit; institutional near-earth and

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deep space missions with limited available power; and the emerging market for in-orbit servicing of GEO telecom satellites.
ASP presents a new design approach for PPUs with a first step being the design of the Beam Power Supply for QinetiQ's T5 Gridded Ion Thruster that has previously flown on the ESA GOCE mission.

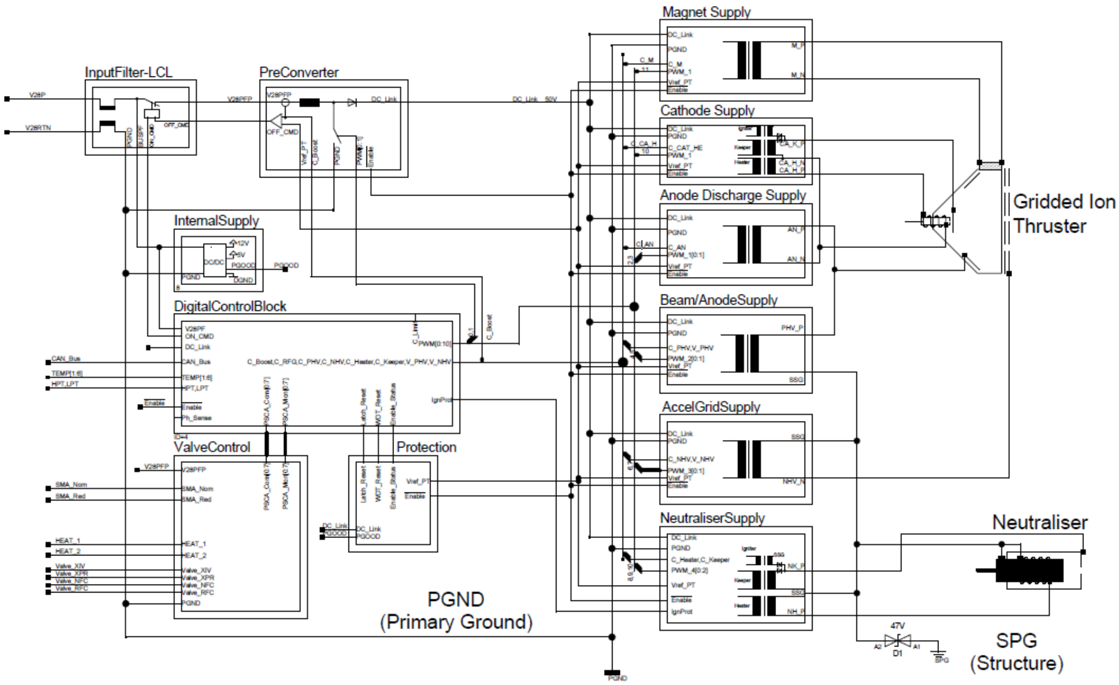

Figure 1: Block diagram T5 EP-System

Currently the PPUs (Power Processing Units) for Electric Propulsion are a main price driver within an Electric Propulsion System. Therefore it is key to provide new PPU solutions to the market with regard to:

- Recurring cost
- Low volume / low mass
- Thermal behavior

These three targets are addressed within ASPs new design approach for PPUs based on the following key aspects:

- SMT parts only
- Planar Transformers
- GaN switches
- ~1MHz switching frequency
- Digital Control

Consequently these key design aspects have been applied to the design of the Beam Power Supply.

II. Design

A. Beam Power Supply Design

The Beam supply voltage is based on a Full-Bridge resonant converter (LLC) able to provide (by means of a single module) 1.2kV and up to 1200W output power. In order to optimize the transformer (reducing the size and improving the efficiency), the Full-Bridge converter is supplied by a Pre-Regulator (see Figure 2). The output voltage is adjusted by the Pre-regulator voltage adjustment. Thanks to the fixed switching frequency of the Full Bridge the following optimizations are feasible:

- reduction of the peak current flowing within the primary of the transformer
- reduction of power dissipation for the main switches, by optimizing the timing of high and low side switching

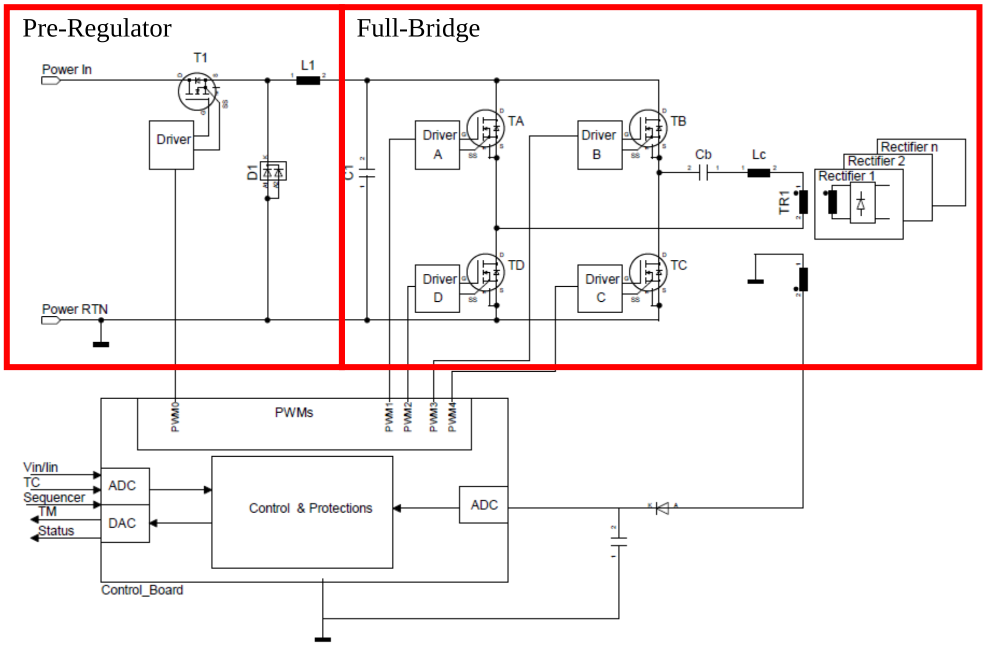

Figure 2: Beam Power Supply – Top schematic

The Planar Transformer design in combination with the high switching frequency allows to strongly reduce the mass and the volume. The converter receives the bus (70V) via a current protection stage based on shunt resistor for the current detection. In order to improve the efficiency and power density, the converter is designed for the use of GaN FETs allowing switching at frequencies of up to 1MHz.

The primary winding of the Planar Transformer is set up with only two turns which reduces the copper losses to a minimum. Thanks to very high switching frequency the transformer dimensions are quite small. The secondary windings are integrated in stack-up PCBs ensuring also the required double insulation. The rectification is performed by means of two diodes voltage doubler rectification also allowing reduction in the number of secondary turns.

Figure 3: Pre-Regulator

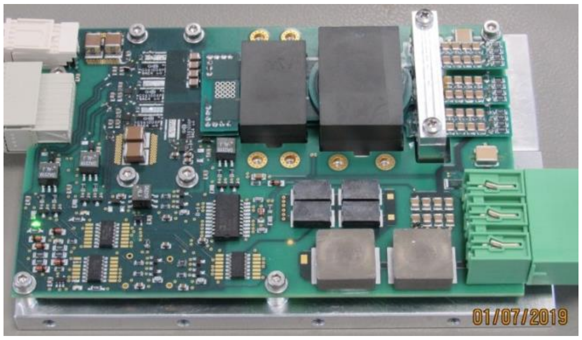

Figure 4: Full Bridge – 100x150mm

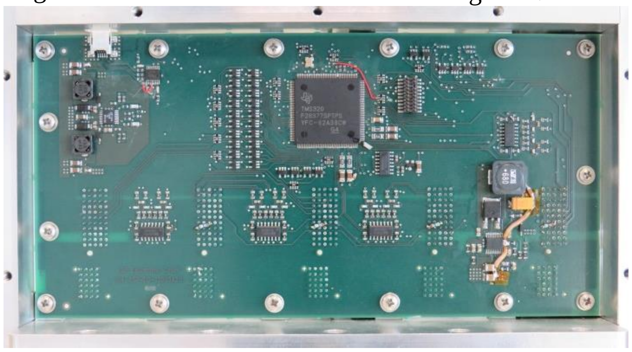

Figure 5: Backplane incl. Digital Control

B. Modularity

In order to reduce the power dissipation and ensure the right insulation, the Planar Transformer has been designed by using separate secondary PCBs. These secondary “stack-up” PCBs are being mounted at the end of the assembling phase. The secondary rectifiers are also integrated on the secondary boards; see Figure 6 and 7.

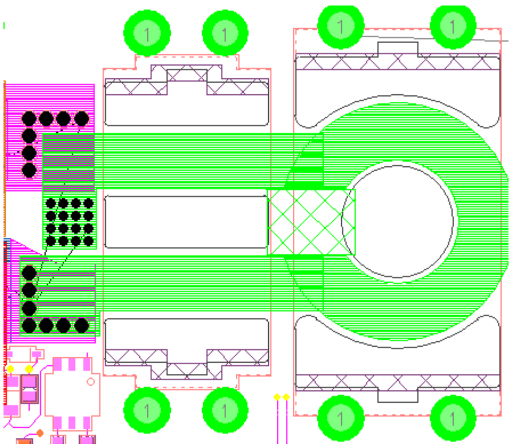

Figure 5: Primary Transformer Board

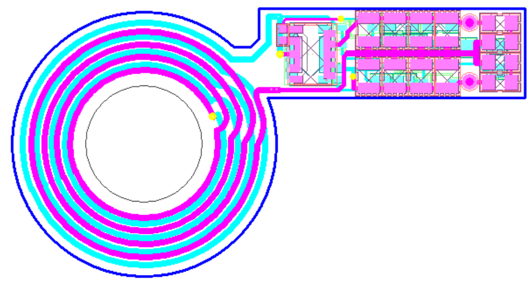

Figure 6: Secondary Transformer Board

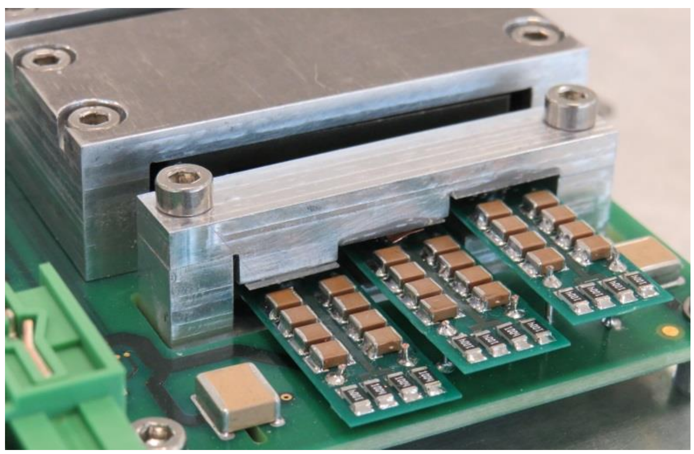

Figure 6: Photograph Secondary Stack-Up

The minimization of power losses is a key objective of the magnetic components design in order to avoid excessive temperature rise in the overall system. Within the selected approach the maximum power dissipation of the High Voltage transformer is below 2W.

C. Overall BreadBoard design

The BreadBoard design is set-up based on the ASP slot card approach for modular PPU BreadBoarding. The modules are connected inside the enclosure via connectors mounted on the backplane PCB. The backplane PCB contains additionally the Digital Control section; controller IC and accompanying circuit for control and feedback of the individual supplies. Figure 7 and 8 shows the BreadBoard equipped with the Pre-Regulator (right side) and the Full Bridge (left side). The connectors to the outside are for interfacing with the power supply. The unused slots will be used in the next development step for adding up the pending functionalities for Magnet, Cathode, Anode, Acceleration Grid, Neutralizer and Flow Control.

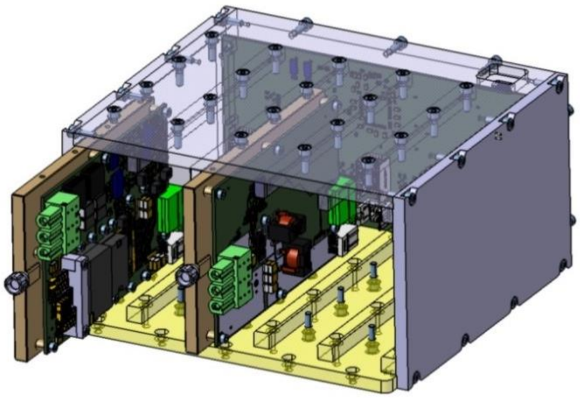

Figure 7: 3D Model

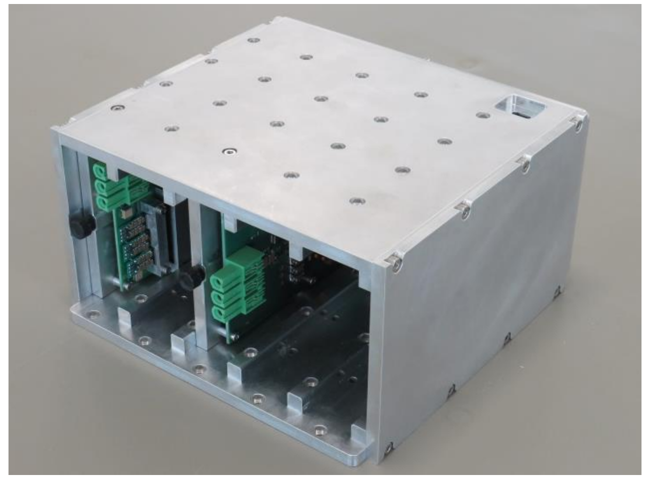

Figure 8: Photograph

D. Test results

Many tests have been performed in order to validate the performances. In Figure 9 the startup voltage is shown.

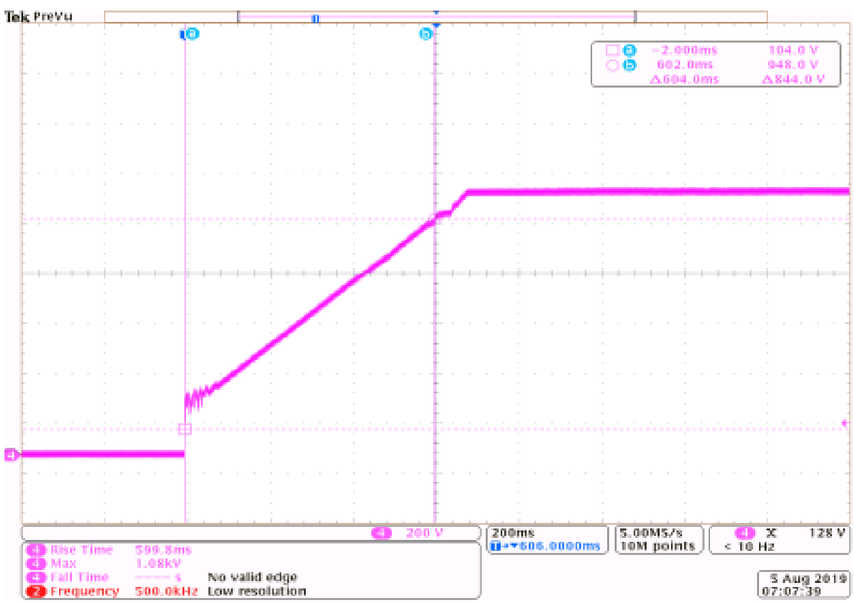

Figure 9: Beam/Anode Power Supply voltage

Hereafter some measurement performed on the Beam Power Supply are shown in figure 10. The overall efficiency up to 94% have been measured (95,5% for the Full Bridge and 98,5% for the Pre-Regulator stage).

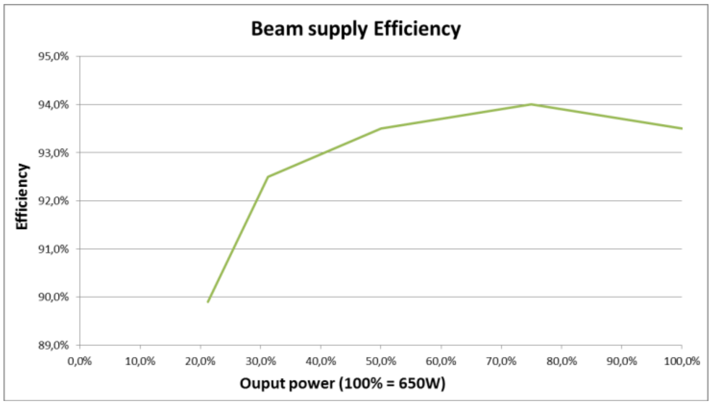

Figure 10: Overall efficiency of the beam power supply

The soft commutation of the GaN transistors is a key condition to achieve high efficiency as well as enhanced EMC performance. The waveforms shown in the Figure 11 confirms the zero voltage switching of the GaN transistors.

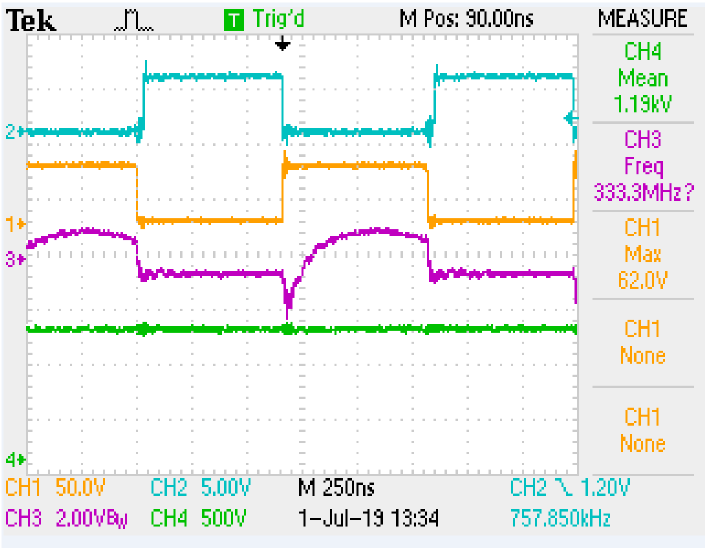

Figure 11: Full Bridge waveforms:
GaN drain-source voltage (yellow), GaN gate-source voltage (blue),
GaN drain current 10A/V (purple), output voltage (green).

The Power Supply has been also tested in hard short circuit condition during operation (output voltage 1.2kV). The results are shown in Figure 12. This short circuit current limiting is an important feature to protect the thruster grids during a beam event (temporary short caused by sputter on the thruster).

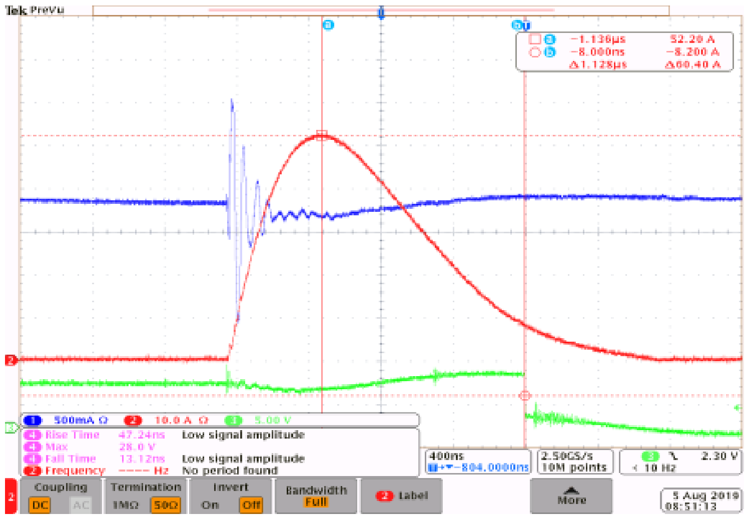

Figure 11: output short circuit: output current (red), input current (blue), status (green).

III. Conclusion

The performance of the Beam Power Supply has been successfully validated. The use of Planar Transformers for such application has proven to meet the mass/volume targets as expected and the stacking approach for the secondary windings does fully support the broad voltage range needed for configuring the different operational points for the thruster. Additionally it has proven that the design can be fully based on SMT parts, which is the basis for cost effective high volume production.
The next design steps for the development of the pending T5 related functional blocks can be released.

Acknowledgments

The fruitful joint discussions with ESA and QinetiQ are gratefully acknowledged. The work has been funded by the European Space Agency in the frame of GSTP de-risk activity.

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