Power Control Unit for Ion Propulsion Assembly in GOCE Program

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Abstract: As part of the DFAC (Drag Free Attitude Control) System of ESAGOCE program, the IPCU Unit is in charge of controlling and monitoring the complete Ion Propulsion Assembly. This unit drives the power supplies powering the propulsion system as well as hosting the SW controlling all these power supplies (commanding the thruster and PXFA functions and monitoring the relevant parameters). In order to allow commandability and telemetry provision the Unit interfaces with the Satellite Communication Bus thanks to an standard 1553B Mil-Bus connection. Three flight representative models of this unit have been built and tested. This paper provides an overview of the unit, its functionalities and performances based on test results over the flight models.

I. Introduction

The GOCE-IPCU can be thus divided in three main functions:

i. PCU (Power Control Unit). Is in charge pf providing power to the Ion Thruster Assembly. This function will as well include the powering and control of the PXFA valves (Flow Control Unit), although hosted in the CPU board
ii. Control Electronics. Developed by CRS, is in charge of hosting the application SW it provides the TM/TC capability through a 1553B Mil-Bus redundant link. The main CPU function is based on a TSC695 (SPARC 80C32 family) micro controller.
iii. IPCU SW (Boot SW and Application SW). Developed by QinetiQ implements the main functions. This SW will provide TM/TC Capability, allow the Thrust assembly accurate control, and perform the monitoring and Failure Detection function.

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In addition to the above related function the IPCU performs via HW and SW a continuous and comprehensive monitoring of all its outputs. Monitoring of relevant internal parameters, both HW and SW is as well achieved by the IPCU.

It is as well remarkable the power distribution within the PCU for the HV and LV Supplies function. This power distribution is achieved by an AC Power Bus that allows a decrease on mass and volume and decreases the power converter internal losses.

The following picture (Figure 1) shows a block diagram of the Unit

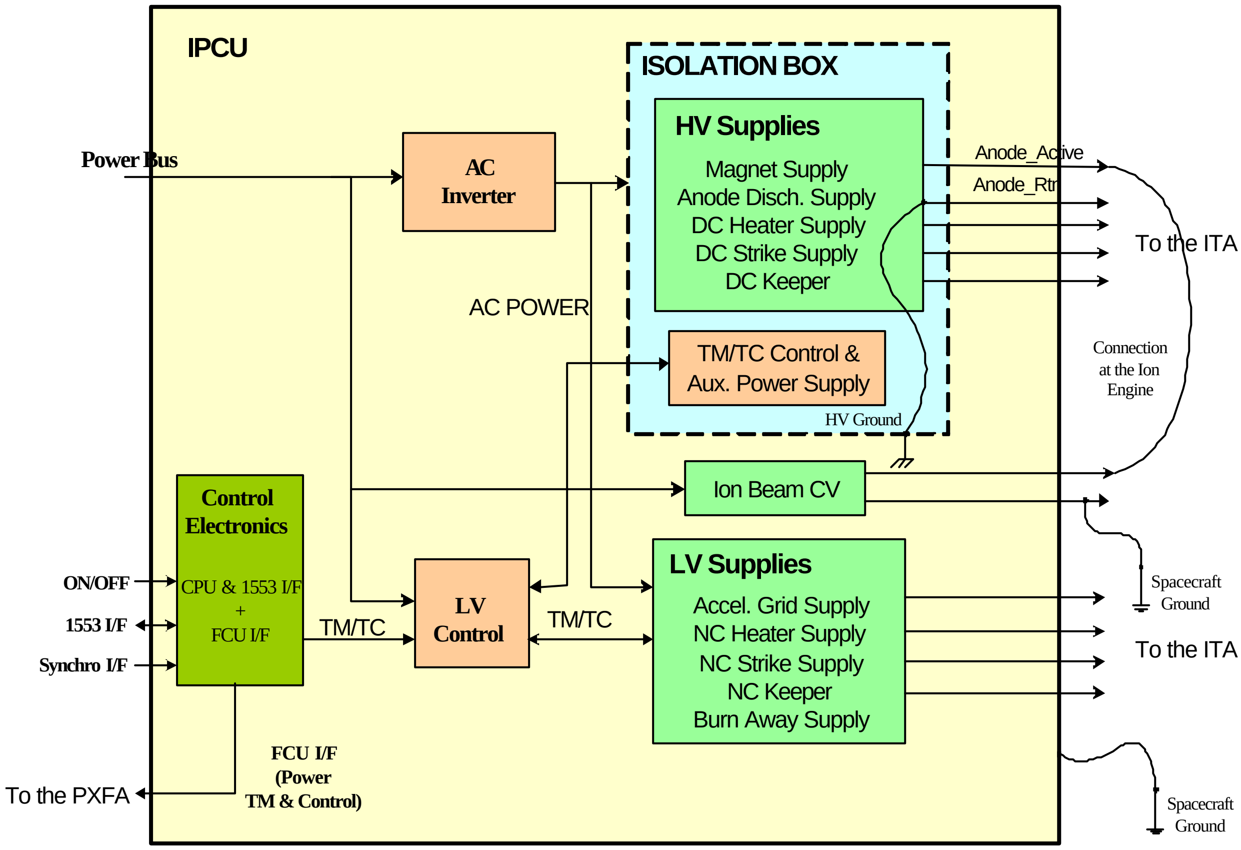

Figure 1. Block diagram of the IPCU

One breadboard model, one EQM model and two flight models of this unit have been already delivered by CRS. Performances measured at CRS facilities both during qualification and acceptance tests campaigns shows excellent results.

Initial tests of the complete FM Ion Propulsion Assembly system (carried out by EADS- Astrium - Friedrichshafen site- at Qinetiq Premises) and IPA system EQM tests have shown this unit to be highly performing and rather robust.

The purpose of this paper is to provide an overview on the main functionalities and hints of this unit as well as to provide relevant data for the performance of this unit from the carried out tests.

II. Unit Overview: functionalities and objectives

The figure below (Figure 2) shows a more detailed functional diagram of the unit.

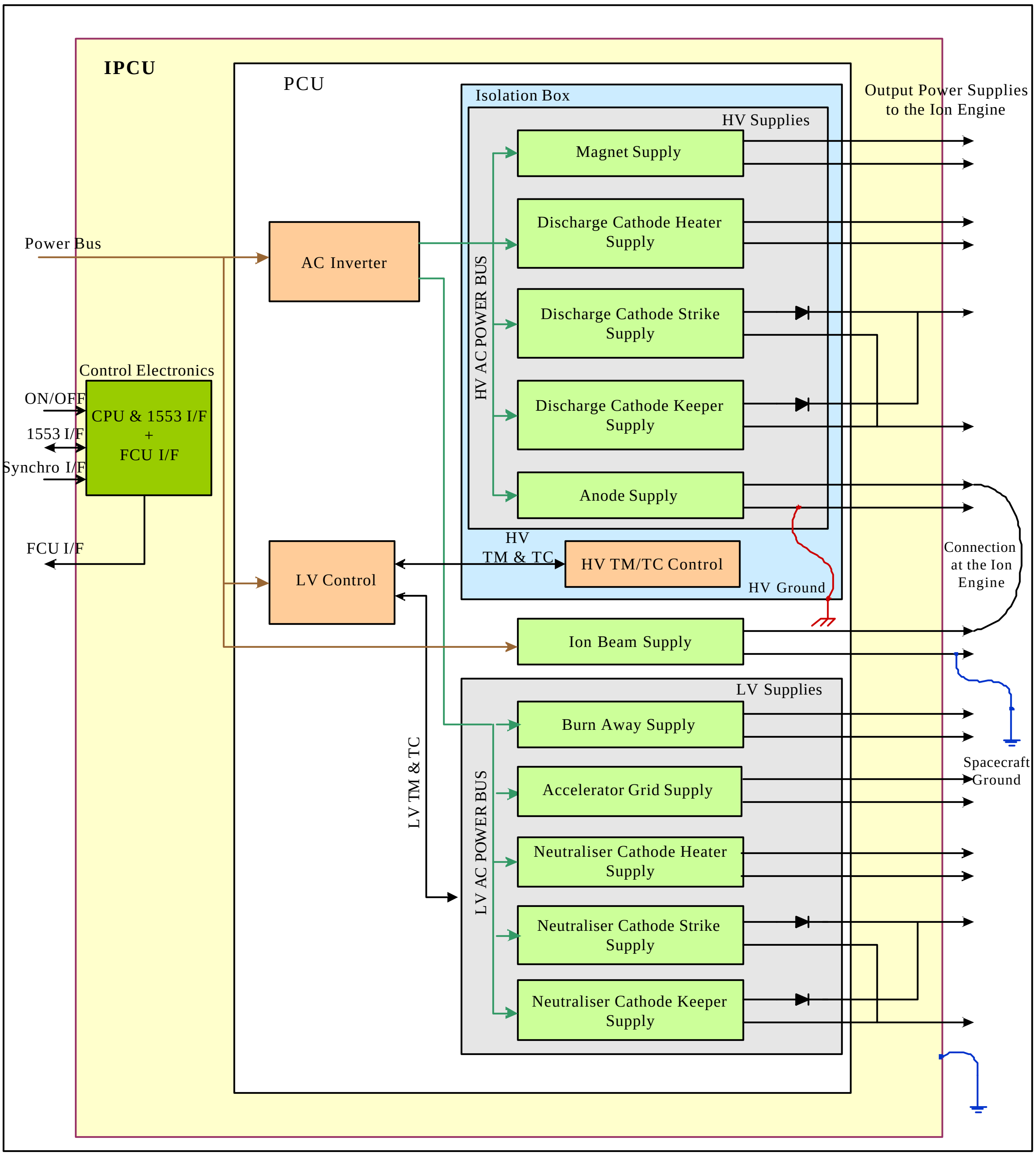

Figure 2. Functional diagram of the GOCE IPCU Unit

As stated above the unit regarding its objectives and functionalities is divided in three main sub-functions:

i. Power Control Unit, providing power to Ion Thruster Assembly, including the Xenon Flow Control Unit

a) IBCV: Developed by EADS-Astrium(Friedrichshafen site), it provides 1176 V to the ITA (Ion Beam)
b) HV Supplies: hosting five power supplies powering the ITA and referenced to the beam voltage (1176V). Power supplies provided by this function are:

    - Anode Supply, 12 bits programmable current supply
    - Magnet Supply, 12 bits programmable current supply
    - DC Heater Supply
    - DC Keeper output covering two power supplies: DC Keeper and DC Strike

c) LV Supplies: Developed by CRS it hosts five power supplies powering as well the ITA and referenced to Spacecraft structure (0V):
    - Accelerator Grid Supply
    - NC Heater Supply
    - NC Keeper output covering two power supplies: NC Keeper and NC Strike
    - Burn Away Supply

d) FCU (Flow Control Unit), powering and controlling the xenon flow valves, contains the following elements:
    - Flow Control valve driver, 10 bits programmable duty cycle
    - Isolation Valves Drivers
    - Latch valves driving

ii. CPU function, hosted in the Control Electronic board. As stated above, this CPU will provide the needed means for the SW performance as well as being in charge of the communications of the Unit

iii. IPCU SW covering a Boot SW and the application SW needed to run and control the complete Ion Propulsion Assembly. Functions carried out by the IPCU SW are listed as follows:

- Sequencing of the operational modes required for the ITA
- On real time controlling of the thrust operation according to the programmable demand. This is done in several steps:
    - Computation of actual thrust from the IBCV Current TM (every 10 ms)
    - Based on the Thrust Demmand Anode current is as well programmed (every 10 ms)
    - From the above, and the Thrust demanded by the DFAC system it is computed and programmed the new setting of magnet current (every 10 ms)
- Flow Control Unit (PXFA) on real-time control by setting a programmable duty cycle every 100 ms.
- Extensive TM/TC Capability
- On Real-Time FDIR (Failure Detection Isolation and Recovery) function

Besides these main functionalities the unit implements two additional functions needed for the operation:

- AC power distribution for supplying the high power required by the Thruster and,
- The Isolation Box needed by the electronics operating at the high voltage reference.

From an operational point of view the Unit has been built to cover the following main objectives:

i. To provide power and control over the complete Ion propulsion assembly, including the Thruster and the Flow Control Unit. This goal is mainly achieved by both the PCU (power Control Unit) and the on-real time SW. The control over the thrusters is divided in two functionalities:

    - Sequencing for powering up the different elements of the thrusters
    - Once the thruster is fully operative the unit must accurately follow the thrust demand profile as received from the DFAC system.

ii. To provide full monitoring capabilities over the output and main input elements of the unit
iii. To allow full commandability and monitoring through the 1553 communications link
iv. To implement an FDIR function running on real time that allows to set the system in a safe state whenever a failure condition is detected.

Both monitoring and FDIR functions are running at 20 Hz and are fully configurable by the user.

In addition the SW allows individually commanding of the different power supplies and FCU Valves.

The main objective of the GOCE-IPCU unit is to control the complete thrusters assembly upon demand from the DFAC system. This control is extremely accurate for GOCE IPCU unit. The basic functionality acts as follows:

- The unit receives the thrust commands at a rate of 10 Hz
- The unit processes it by executing two control algorithms. The first one acts on the flow Control Valve driving and runs on real time at 10 Hz. The second one acts over the Anode and Magnet supplies and runs on real time at 100 Hz.

  Both algorithms are based on a closed loop that is continuously monitoring the measured thrust and valve status to compute the new settings for the programmable variables: Anode and Magnet current and Flow control Valve duty cycle.

III. Models philosophy

Four models of the GOCE IPCU unit have been built, tested and delivered as described in the paragraphs hereafter.

A. Breadboard

This initial model was built providing representative design for the main and critical functions such as the complete isolation box, the AC Inverter module and the Beam Supply (EADS - Astrium - Friedrichshafen site-development).

This unit as well provided the basic SW to allow operation: Control for the Flow Control unit, sequencing of the operational modes and Thrust control algorithm.

The main objective of the module was to drive a breadboard representative model of the T5 Ion Engine from Qinetiq.

From a unit point of view, this initial mode served as well as a first validation of the Isolation Box concept and the AC power distribution.

B. EQM

This was the first fully flight representative model of the unit.

The EQM model successfully passed the qualification campaign carried out at Astrium-CRISA, but additionally it served to fulfill other objectives:

- ➢ Allow the integration and debugging of both Boot SW and Application SW codes.
- ➢ Allow an extensive characterization of the overall unit
- ➢ Allow additional system level testing carried out by at Qinetiq premises supplying a QM model of the T5 Ion Engine.

In addition to these activities CRS developed a dedicated qualification process in order to validate the Isolation Box concept. This was initially identified as a critical point in the development due to the high voltage to be sustained during normal operation and hence a dedicated development and qualification program was built. This program did encompass a comprehensive validation of the high voltage technology used in GOCE IPCU, both of materials, processes and design.

The successful performance of the different models, all of them using this technology, regarding the HV behavior have well assessed not only the concept and design but as well the methodology used for the qualification and design process.

C. PFM and FM

These two models have been successfully tested according to its acceptance requirements and conditions at CRISA.

Very similar behavior on both of these models has been obtained. Results and performances have been found to be as well similar to EQM.

Both models have been already delivered to EADS- Astrium (Friedrichshafen site), for further testing and integration and integration activities. As part of this integration, higher level tests have been run by EADS- Astrium at Qinetiq premises. These tests have exercised the full representative Ion Propulsion Assembly flight model, covering all the elements: Flow Control Unit, T5 Ion Engine and Ion Propulsion Control Unit.

Tests carried out for the complete assembly have well assessed a very critical point on the system which is the compatibility between the power supplies and the Thruster loads. This I/F is deemed critical not only because of the dynamic behavior but as well because of the plasma load characteristic. These tests have as well assessed the closed loop performance of the overall system, which is as well a critical point in feedback systems.

IV. Tests results and performances

A. Overall Performances

As stated above the GOCE IPCU allows a fairly accurate control over the Thruster assembly (12 uN resolution over 0 to 20 mN thrust range).

As it is defined in the control algorithms this accurate control is achieved by acting over three parameters:

- Anode Current
- Magnet Current
- Flow Control Valve Duty Cycle

and as well based on the continuous reading of the following parameters:

- Beam Supply Current TM
- Beam Supply voltage regulation
- Flow Sensor Voltage and Temperature TMs

The table below shows the measurements results and expected performances for all of these critical parameters:

	PFM BoL	**FM BoL**	**Expected EoL**	**Expected EoL from test results**
Anode Current Setting	0.45 %	0.45 %	0.8 %	0.65 %
Magnet Current Setting	0.04 %	0.06 %	0.5 %	0.3 %
Beam Supply Volt. Regulation	0.08%	0.12%	0,14%	0,14%
Beam Supply Current TM	0.3 %	0.3 %	0.75 %	0.45 %
Flow Sensor Voltage TM	0.04 %	0.03 %	0.45 %	0.15 %
Flow Sensor Temperature TM	0.45 %	0.45 %	1.1 %	0,65%
Flow Control Valve Duty Cycle	1%	1%	3.2%	3%

Table 1: Performances of main parameters driving the Ion Propulsion Assembly

The performances showed above are based on measurements on PFM and FM at BoL conditions (temperature effects included). *Expected EoL* column refers to performances computed at Worst Case Conditions. For FM and PFM models where the units showed such a good performance, the expected EoL figures may be however further improved as appearing in *Expected EoL from tests results* column.

The table below (table 2) provides additional performances measured at unit level. The ones included in the table are functional performances involving the unit operation over the Thrust control loop operation. The table below shows not the individual feature of each parameter but the complete performance of the unit regarding the control capability. All elements influencing the thrust operation are taken into account to measure and compute these features:

	Requirement	PFM	FM
Linearity Error	1%	0.19 %	0.18 %
Scale factor Error	2.5 %	2%	1.8 %
Residual Thrust Error	0,04	0.24 %	0.5 %
Min. Commandable Step	12 uN	12 uN	12 uN
Thrust Commands Rate	10 Hz	10 Hz	10 Hz
Control Loop Frequency	100 Hz	100 Hz	100 Hz

Table 2: Functional performances of the unit

As shown in the table 2, the IPCU performance regarding the control loop functionality fulfils in excess the expected and required capabilities.

Regarding GOCE IPCU efficiency, the measured efficiency values goes from 84 % at low level thrusts and 89 % for high levels (19 mN). These figures shows the overall unit performance, including the dissipation due to the CPU function consumption, not part of the power supply unit.

The following graphs show the performance of the ITA controlling power supplies when operating in Thrust Control Loop operation.

These curves have been obtained at unit level tests. In this condition the unit is operating in open loop condition with an static load simulating the Thruster.

B. Thrust Control Mode performances:

1. *Test Results #1*

Figures 3, 4, and 5 show Thrust demand, Magnet and Anode currents with the simulated thrust load at 1 mN.

The feedback loop acts varying the Magnet current whereas Anode current is only dependant on the input demand value. This makes that Magnet current use to move along its operative range, but Anode current just “follows” the demand profile

For the test case showed a demand profile Fd(t) was commanded to the unit and Thrust commands where sent at a rate of 100 Hz. This is represented on Figure 3.

- Figure 4 shows the Magnet current obtained as a consequence of that demand applied to an static Thrust load (approx 1 mN):
  - In blue it is depicted the measured Magnet current

- In pink it is showed the Magnet current obtained by simulated algorithms (the verification pattern)

As can be seen on the picture the error between measured Magnet current curve and the verification pattern is almost negligible (< 0.1 mA ~ 1.5 LBS over 12 bits)

- ➢ Figure 5 shows the measured Anode Current
  - In blue it is depicted the measured Anode current
  - In pink it is showed the Anode current obtained by simulated algorithms (the verification pattern)

As observed obtained performance follows accurately (max. error = 1 mA ~ 1LBS over 12 bits) the pattern obtained by simulating the algorithms. It can be as well observed how the Anode current as stated above follows the thrust demand profile (figure 3).

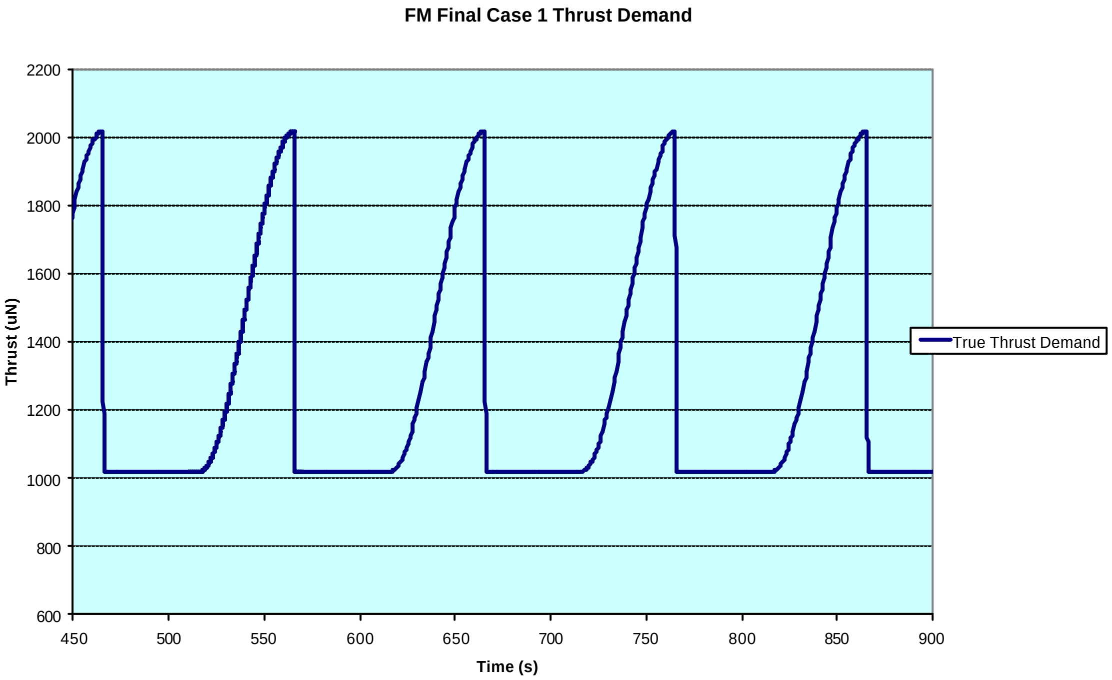

Figure 3: Thrust Demand Profile applied

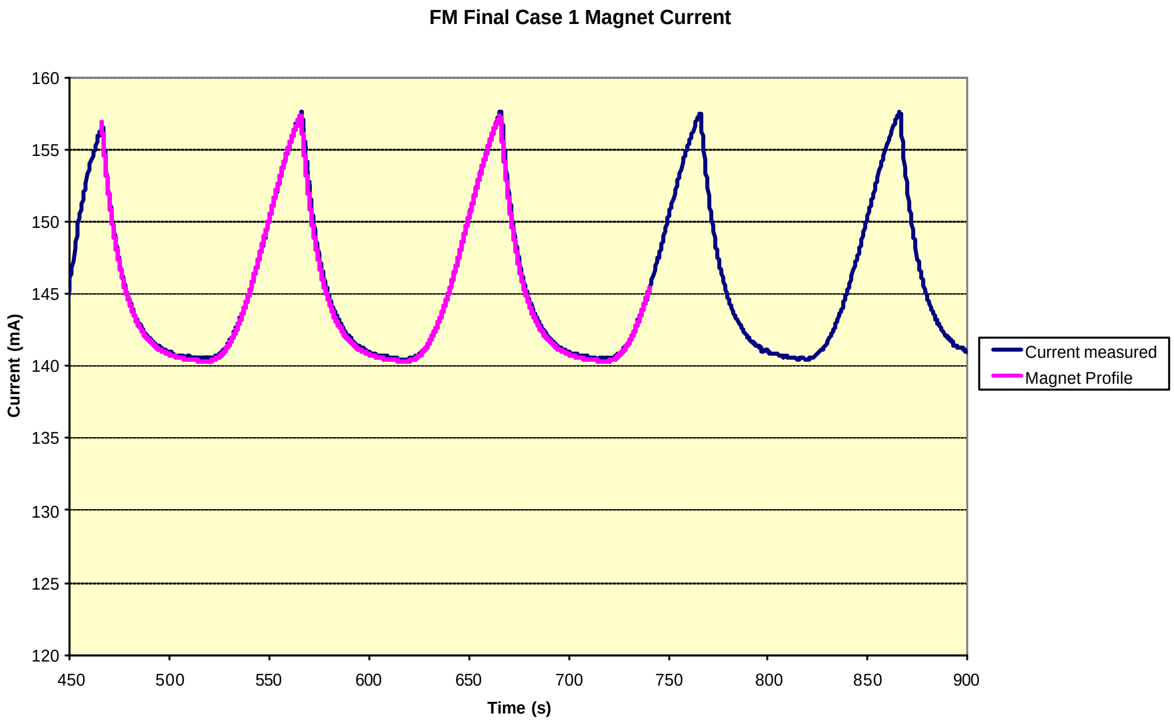

Figure 4: Magnet current as measured working in Thrust Control Loop operation

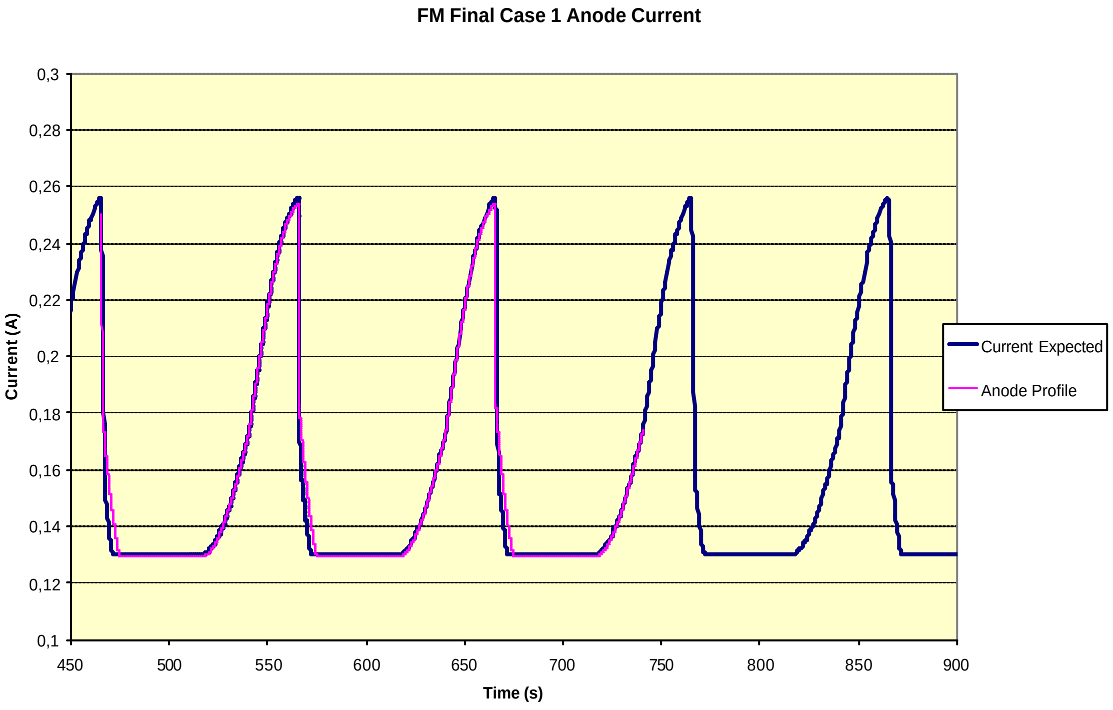

Figure 5: Anode current as measured working in Thrust Control Loop operation

2. *Test Results #2*

As explained above Anode current follows Demand profile, its value is only dependant on the demand value, whereas Magnet current can show values all over its range for any thrust demand value.

The following curves show Anode performance at different levels of thrust demand.

- Figure 6 shows the measured Anode Current for a demand profile going from
  - In blue it is depicted the measured Anode current
  - In pink it is showed the Anode current obtained by simulated algorithms (the verification pattern)

As observed obtained performance follows accurately (max. error = 1.8 mA ~ 2LBS over 12 bits) the pattern obtained by simulating the algorithms.

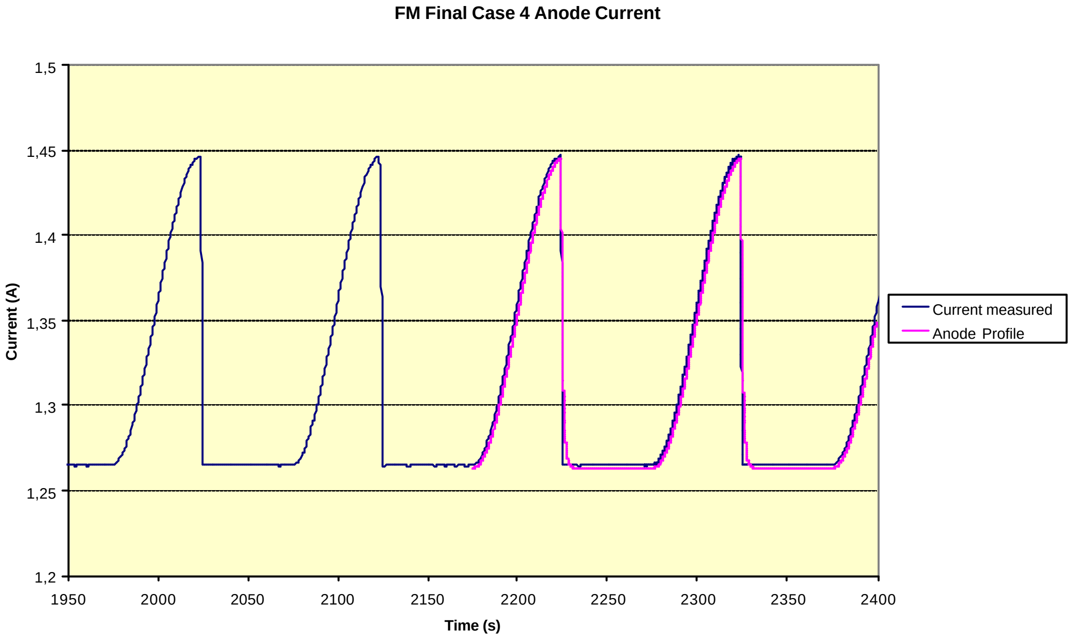

Figure 6: Anode current as measured working in Thrust Control Loop operation (8.3 mN)

- Figure 7 shows the measured Anode Current for a demand profile going from 7.6 mN to 8.6 mN
  - In blue it is depicted the measured Anode current
  - In pink it is showed the Anode current obtained by simulated algorithms (the verification pattern)

In this case Anode current is as well closely following the expected curve for high Anode currents. The deviation observed on the upper corners is due to the configuration parameter scheduled for this unit. The Control Algorithms are working based on configuration tables that set different parameters. Some of these parameters act over the received thrust demand smoothing it when applied to the Ion Propulsion Assembly. This is done in order to prevent sharp steps applied to the Ion Thrust Engine. These configuration parameters were different on the tested unit than on the simulated algorithms used as verification pattern. This fact makes that the pattern shows smoother corners than the measured ones. However this performance was checked to assess the correct performance of the unit according the programmed values.

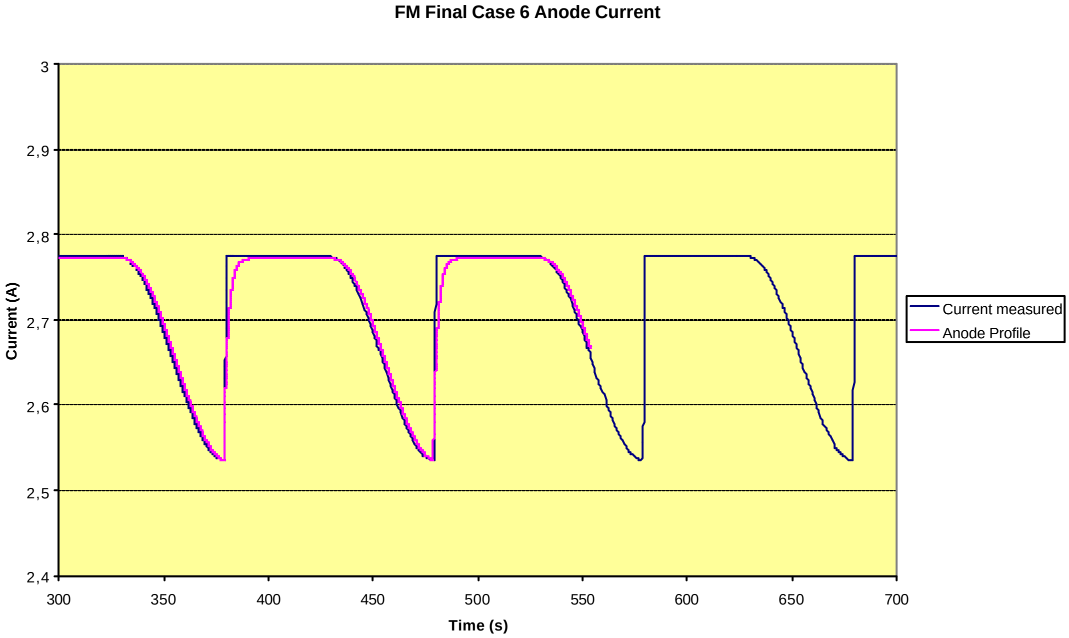

Figure 7: Anode current as measured working in Thrust Control Loop operation (15 mN)

V. Conclusions

The IPCU unit was developed and built in the frame of GOCE ESA program to achieve a high resolution and very accurate control capability over T5 Ion Engine over its full thrust range (0 to 20 mN).

In addition In order to allow these objectives the unit had to deal with two major goals: High Voltage electronics and AC Power distribution. The later easier to deal with than the former. This major goal did involve the development of a complete qualification program for a High Voltage electronics. As a result of this program CRS has built a High Voltage Technology needed to deal with type of thrusters and the GOCE-IPCU unit has well proved this successful technology.

Three flight representative models (EQM and two FMs) have been delivered proving the excellent performances required to achieve this extremely accurate control. As well and as important as this last capability the unit has shown the compatibility required between the complex plasma loads and the power supplies feeding them.