European Student Moon Orbiter Solar Electric Propulsion Subsystem Architecture – An All – Electric Spacecraft

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This paper presents the Phase A study of the Solar Electric Propulsion subsystem selected for the ESA European Student Moon Orbiter enhanced microsatellite, performed at QinetiQ under ESA funding. To minimise mass, a so-called "all electric" approach is adopted based around the re-use of the GOCE T5 gridded ion engine and the introduction of Hollow Cathode Thrusters (HCTs) for attitude control functions. Three different subsystem architectures are considered and analyzed with reference to the mass, cost, risk and level of integration between the HCTs and the T5. The favoured system architecture that best meets the various requirements adopts a shared tank and gas flow controller between the HCTs and the T5, with power being supplied from two dedicated power processing units. The possibility of reducing the propellant requirement by using an engine gimbal mechanism is also presented. The study also demonstrates how an increase in the T5 specific impulse to higher values than used on GOCE does not offer substantial system-level mass savings in this particular case.

Nomenclature

FCU	=	flow control unit
GIT	=	gridded ion thruster
HCT	=	hollow cathode thruster
PPU	=	power processing unit

I. Introduction

The ESA European Student Moon Orbiter (ESMO) is a spacecraft designed and built by student teams from several European universities, with the assistance of faculty members, the European Space Agency (ESA) and

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various industry partners. If approved by ESA, it is planned for launch in 2011 as an auxiliary payload into a highly elliptical, low-inclination Geostationary Transfer Orbit (GTO) on the new Ariane Support for Auxiliary Payloads (ASAP),by an Ariane 5 rocket.

From GTO, the 150 kg spacecraft will use its on-board propulsion system for lunar transfer, lunar-orbit insertion and orbit transfer to its final low-altitude polar orbit around the Moon.

The payload will be a high-resolution, narrow-angle CCD camera for optical imaging of lunar surface characteristics.

Two different spacecraft designs are being considered in parallel by ESA. One is based on a chemical propulsion system, whereas the other relies solely upon solar electric propulsion (SEP).

In this paper will be described the architecture and trade-off decisions concerning the SEP subsystem of the SEP mission option. This Phase-A study was performed at QinetiQ as part of a wider study of the mission performed in conjunction with QinetiQ staff and funded by ESA.

II. SEP Subsystem Definition

The SEP subsystem proposed by Southampton University for ESMO is based on the flight model hardware of the Gravity and Ocean Circulation Explorer (GOCE) T5 gridded ion thruster (GIT) system and on the idea of an all-electric spacecraft with a gridded ion thruster used for primary propulsion and Hollow Cathode Thrusters (HCTs) used to dump momentum from the spacecraft reaction wheels and other AOCS functions.

The proposed SEP subsystem comprises:

- the T5 GIT used as main thruster
- eight HCTs used for AOCS functions.
- one or two (depending on the subsystem configuration) power processing unit (PPU) to process and supply power to the T5 GIT and to the HCTs
- one or two (depending on the subsystem configuration) flow control unit (FCU) to regulate the propellant flow to the T5 GIT and to the HCTs
- a tank for propellant storage

This study as been performed assuming that the gridded ion thruster that will be available for the ESMO mission will have the same performance as the GOCE T5 GIT (Table 1).

Table 1. T5 GOCE performance

	GOCE T5
Thrust	1-20 mN
Specific Impulse	500-3500 s
Power	55-585 W

III. SEP subsystem design options and trade off

We can identify three main design option based on three different level of integration between the HCTs and the GIT.

A. Option 1 – High mass, low risk, low cost

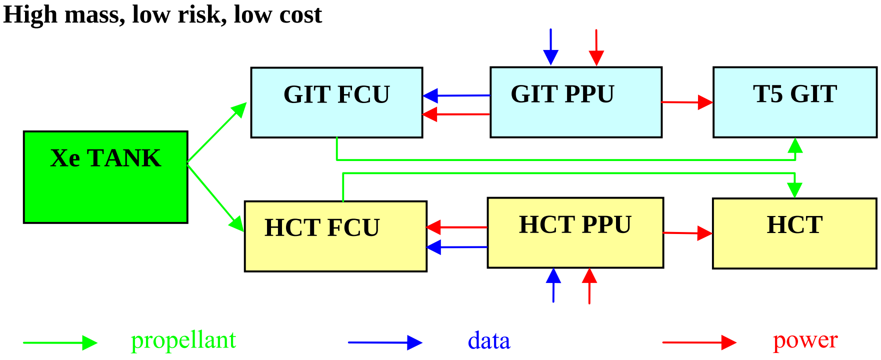

Figure 1. SEP subsystem architecture option one: high mass, low risk, low cost

In this option only the tank is shared and we have two PPUs and two FCUs. The mass is high because of the low integration level while risk is low because the high level of flight spare component re-use.

B. Option 2 – Medium mass, low risk, low price

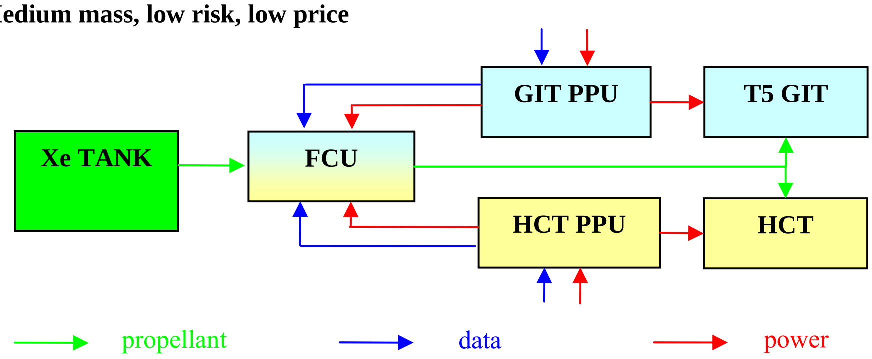

Figure 2. SEP subsystem architecture option two: medium mass, low risk, low price

In this option tank and FCU are shared while we still have two PPUs. The mass is lower than in option 1 and the risk is still low because the GIT PPU remains unchanged (a PPU for the T5 thruster already exist and is flight proven while a new PPU development will bring a higher risk)

C. Option 3 – Low mass, high risk, high price

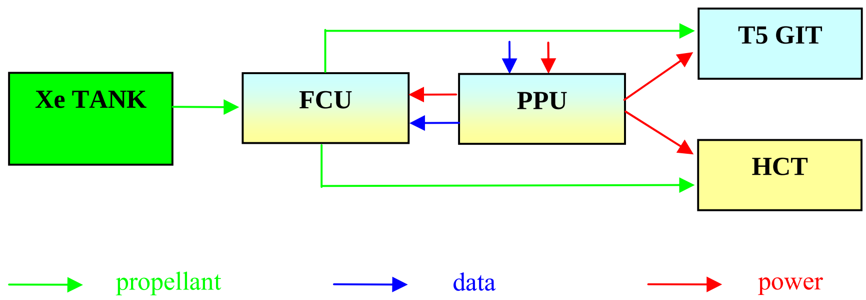

Figure 3. SEP subsystem architecture option three: low mass, high risk, high cost

In this option tank, PPU and FCU are shared hence this is the lightest design option but the risk is high because a new PPU must be developed to accommodate the various functions.

We select option 2 because it offers a relatively low mass with a low risk. As part of this decision we note that the development of a new PPU is a complex and expensive undertaking. Within the context of a student mission this is not a realistic proposition and therefore option 3 is infeasible here.

Considering the long mission duration the propellant required by the HCTs to compensate the thrust vector misalignment is not negligible.

To reduce the thrust misalignment we have three choices: use a gimbal, use thrust vectoring or carry additional propellant and accept the losses

Thrust vectoring may be obtained by using a set of moving grids on GIT, as has been studied recently at QinetiQ under ESA funding. This technique has been judged too advanced and risky for ESMO and so will not be considered further. A gimbal is relatively heavy, complex and expensive. Additional propellant is by far the simplest approach but will adversely impact the overall mass budget.

Another decision to be taken is how to drive the HCTs. The options are: using a dedicated HCTs PPU that allows us to drive as many HCTs as we want at the same time or use just a switchbox that allows us to drive just one HCT at a time using the Neutralizer Cathode supply inside the T5 PPU.

We have four options:

- HCT driven by dedicated PPU
- HCT driven by the neutralizer supply inside the T5 PPU via a switchbox
- HCT driven by dedicated PPU plus a gimbal to reduce thrust misalignment
- HCT driven by the T5 PPU via a switchbox plus a gimbal to reduce thrust misalignment

In Table 2 is presented a comparison between all these options.

Table 2. Comparison between dedicated HCT PPU and a switchbox with and without a gimbal

DEDICATED HCT PPU NO GIMBAL		
	mass	**margin**
Thrust mis mass	3	20
press+safe+despin	1	20
HCT PPU	4	15
TOTAL AOCS RELATED MASS	9.4	

DEDICATED HCT PPU WITH EXISTING GIMBAL		
	mass	**margin**
Thrust mis mass	0	20
press+safe+despin	1	20
HCT PPU	4	15
Existing Gimbal	7	5
TOTAL AOCS RELATED MASS	13.15	

DATA	
thrust [mN]	1
specific impulse [s]	300
press+safe+despin [mN*m*s]	1471.5
Thrust mis [mN*m*s]	4414.5
L [m]	0.5

SWITCHBOX WITH NO GIMBAL		
	mass	**margin**
Thrust mis mass	3	20
press+safe+despin	1	20
HCT PPU	0	15
Switchbox	0.5	20
TOTAL AOCS RELATED MASS	5.4	

SWITCHBOX WITH EXISTING GIMBAL		
	mass	**margin**
Thrust mis mass	0	20
press+safe+despin	2	20
HCT PPU	0	15
Switchbox	0.5	20
Existing Gimbal	7	5
TOTAL AOCS RELATED MASS	10.35	

As we can see the use of a gimbal does not give any advantage from the mass point of view so this option can be ignored.

The "no gimbal" options are lighter and are separated by the mass of the HCT PPU (4kg).

We now consider all the other characteristics of these solutions to discriminate between them.

Regarding costs, QinetiQ estimate that the development of the switchbox is likely to be around half the cost of the development of the dedicated PPU. The switchbox allows either the T5 to operate or the HCTs, not both. This therefore offers little flexibility since it forces the main thruster to be off whenever we use the HCTs. A preliminary estimate by QinetiQ for the AOCS operation indicated that a period of time varying from 1/3 to 1/6 of each orbit is going to be spent unloading the wheels. Hence keeping the T5 switched off during this period will significantly lengthen the mission duration and, reducing the mean value of the thrust, will increase the propellant consumption.

Conversely, the HCTs PPU allows the simultaneous firing of as many HCTs as required without switching off the main thruster. Power availability will dictate that there will be insufficient power to maintain the full T5 thrust during these periods however the T5 can be throttled down accordingly. Thus we still have main propulsion active, removing the need to conduct a shut-down and start-up procedure each time the HCTs are used. Considering all these points, and assuming that the cost of a dedicated PPU is not prohibitive, we have chosen to use a dedicated HCT PPU.

IV. SEP baseline design description

Our baseline design consists of the following main elements:

- Flight spare T5 GOCE GIT
- Eight HCTs (to provide some level of redundancy)
- A T5 PPU
- A HCT PPU
- A FCU able to feed both the HCTs and the T5 GIT
- Pressurized Xenon tank

A. T5 gridded ion thruster

The QinetiQ T5 Ion Thruster is a conventional Kaufman-type (electron-bombardment) GIT (a schematic of which is shown in Fig 4), with a direct current discharge between a hollow cathode (HC) and a cylindrical anode used to ionize the propellant gas. The efficiency of this plasma production process is enhanced by the application of a magnetic field within the discharge chamber, which can also be used to provide accurate throttling. A 10 cm diameter grid system, forming the exit to the discharge chamber, extracts and accelerates the ions, to provide the required thrust. An external HC, referred to as the neutraliser, emits the electrons necessary to neutralise the space charge of the emerging ion beam.

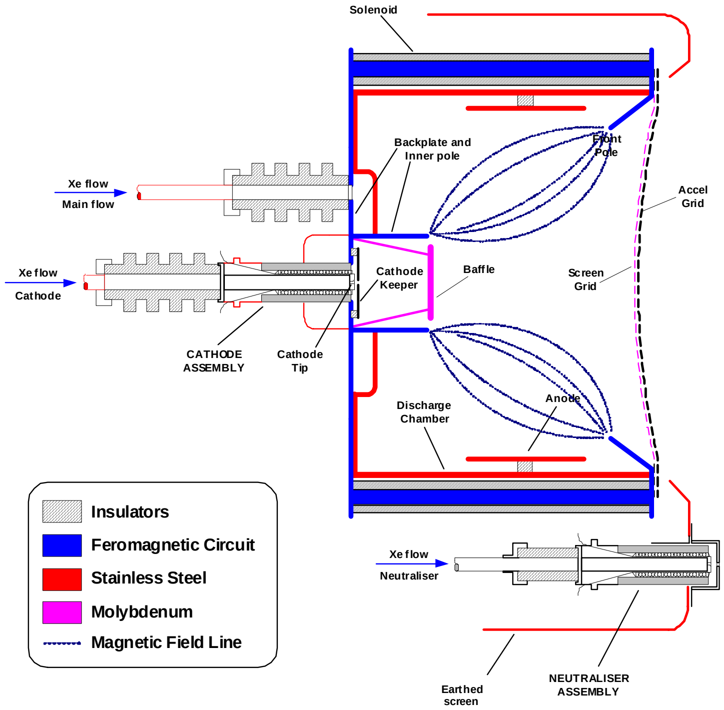

Figure 4. A Kaufmann type gridded ion thruster schematic (T5) (image courtesy of QinetiQ)

The T5 GIT specifications for the GOCE application are reported in Table 3

Table 3. T5 GIT specification (GOCE)

Mass	1.7 kg
Dimensions	Ø 170 mm x 200 mm long
Mean Power Consumption	up to 600 W @ 20mN
Thrust Range	1 to 20 mN
Specific Impulse	500 s to 3500 s (across thrust range)
Total Impulse	> 1.5 x 10^6 Ns (under GOCE continuous throttling conditions)
T5 capability	> 8500 On/Off cycles

B. Hollow Cathodes Thruster

The thrust generated by a hollow cathode thruster in open-diode configuration (HC and a single anode) has been extensively characterized at the University of Southampton[1-4] using a T6 hollow cathode and has demonstrated the basic feasibility of a HCT. Thrust levels up to several mN have been measured with specific impulse of the order of hundreds of seconds. More recently, in light of its beneficial electrical characteristics, a T5 hollow cathode has undergone preliminary thrust characterization for application on ESMO[5-8]. The cathode used in this experiment was the T5 STRV-A1 (Space Technology Research Vehicle) DRA (Defense Research Agency) flight-spare launched in June 1994. This included an experiment to allow the hollow cathode assembly to demonstrate spacecraft electrostatic discharging. The cathode is rated at a maximum DC current of 3.2A at flow rates typically 0.04 -1mgs^{-1} operating below 90W. The T5 cathode was originally designed for the main discharge cathode in the UK-10 ion engine and has been extensively characterized.[9] The cathode contains a tungsten dispenser, 1.0mm i.d. x 2.8mm o.d. x 11mm, impregnated with a mixture of barium-oxide, calcium oxide and aluminates (BaO: CaO: Al_2O_3), which lowers the insert's work function for thermionic emission, and maintains a working temperature ~ 1000°C. A solid tantalum tip welded to the cathode body contains an axial orifice 0.2mm in diameter and 1mm long. The face of the T5 cathode is shown in Figure 5.

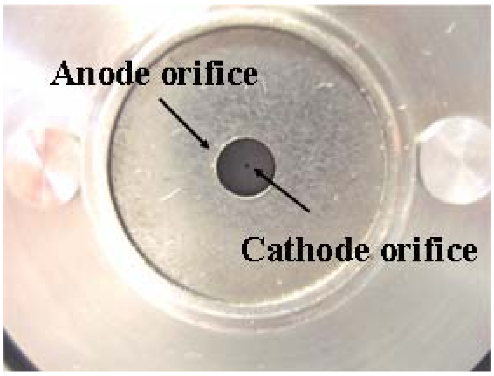

Figure 5 T5 Cathode showing the open anode

The open keeper has a 3mm diameter aperture and is mounted 3mm downstream of the cathode tip with the whole assembly mounted on a UK-25 ion thruster back-plate. In typical hollow cathodes a keeper electrode usually draws approximately 1A of current, however in this study the cathode is operated in an open-diode configuration with the full discharge current being drawn to the keeper which is now termed the anode. Previous studies on this type of hollow cathode have incorporated a much larger anode disk and a secondary discharge between the keeper and the anode and applied magnetic fields to simulate a Kaufman ion engine environment. Open-diode configuration is more representative of a standalone microthruster configuration with no need for a coupled discharge. Results for the various current conditions are shown in Figure 6.

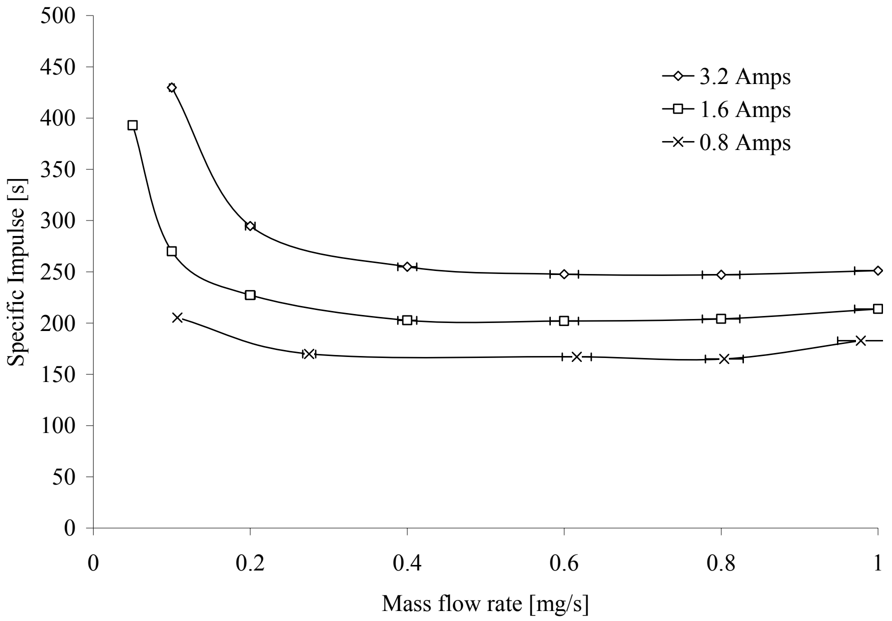

Figure 6. Specific impulse vs. mass flow rate for various throttle levels with Argon

Results show near monotonic dependence of specific impulse on discharge current with rapidly increasing performance below 0.4mgs^{-1} for the 3.2 and 1.6 Amp throttle settings with a less pronounced increase at 0.8 Amps. Since a changes in flow rate results in a change in operating voltage it is seen that specific impulse can be correlated with specific power of the flow (J/mg) and a product of the discharge current and operating voltage, shown in Figure 7. Operation even at low powers (<13W) in the low current condition (0.8Amp) brings relatively high specific impulse of up to 165 seconds equal to performance in a resistojet mode, where cathode body temperatures are in the region of 1000°C. At the high current condition operation at powers of below 30W give specific impulse in the region of 250s. Further reduction in flow rate increases operating voltage and power invested in the flow. This results in a quadratic increase in specific impulse however with declining thrust efficiency as convective and radiative losses begin to dominate.

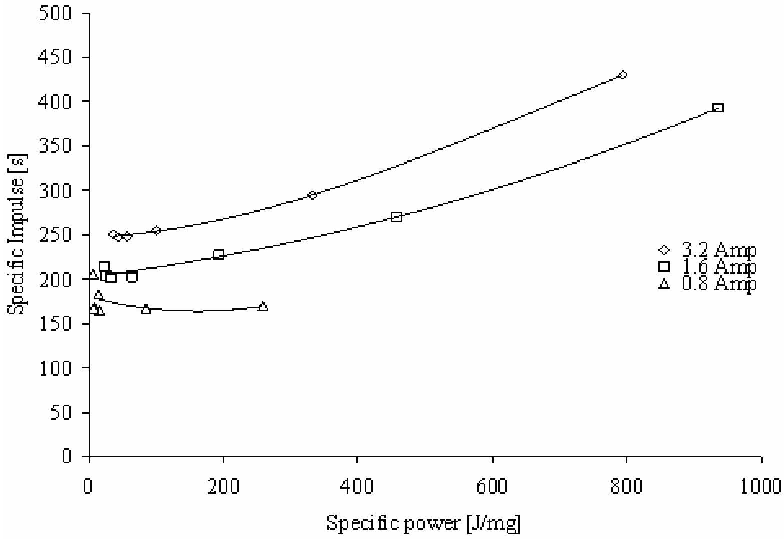

Figure 7. Dependence of specific impulse on specific power of the flow for the various throttle settings

Highest specific impulse of 429s was attained at 3.2 Amps, with 1.1% thrust efficiency, 79W discharge power. Specific impulse can be traded for higher thrust to power ratios by increasing propellant flow rates or decreasing discharge current (however higher thrust efficiencies are obtained at higher discharge currents) generating thrust efficiencies of 14% (200μN/W) and specific impulse of 167s at 0.8Amps, and over 8% at the maximum rated current capacity of 3.2 Amps, with specific impulse ~250s (77μN/W, 35W discharge power).[8] Thrust production with respect to mass flow is shown in Figure 8. Up to 2.4mN could be generated at higher currents, with the maximum flow rate of 1mgs^{-1} with specific impulse over 250s.

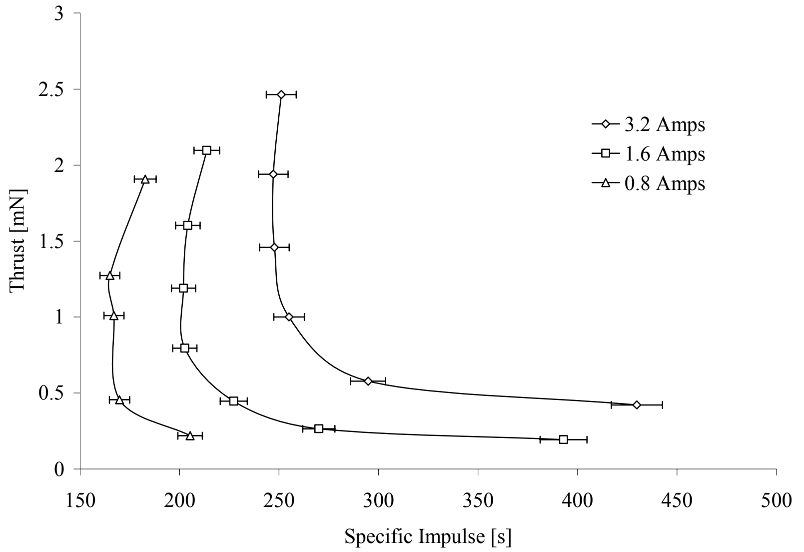

Figure 8 Thrust and specific impulse attained at various current conditions

C. T5 Power Processing Unit

The PPU needed by a T5 thruster will be similar (if not identical) to the EADS Astrium Crisa GOCE PPU. It will provide power conditioning and control for both the T5 GIT and the FCU.

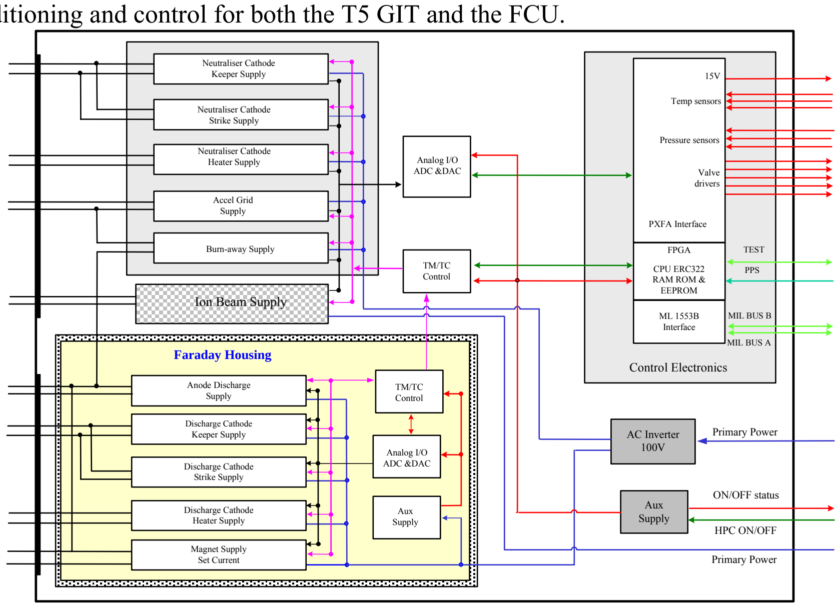

Figure 9. GOCE PPU schematic (image courtesy of EADS Astrium Crisa)

It includes high and low voltage supply for the thruster with associated telemetry.

The high voltage used to accelerate the ion beam is provided and regulated by the beam supply while the neutralizer and the acceleration grid are operated by low voltage supply.

The discharge supplies are housed within a HV enclosure.

The PPU specification is given in Table 4

Table 4. T5 GOCE PPU specification

Mass	16 kg
Dimensions	300 x 250 x 150 mm
Operating temperature	-20 °C to +50 °C
Operating lifetime	15 years in orbit (GOCE PPU qualification to mission duration of 2 years)
Nominal input voltage	22 - 37 V extended input range to 20 V without degradation
Maximum input current	37 A @ 22 V
Power	55-585 W
Electrical efficiency	Beam supply 92 – 95% other supplies ≥ 92%

D. Hollow Cathodes Thruster PPU

The HCT PPU is sketched in Fig 10

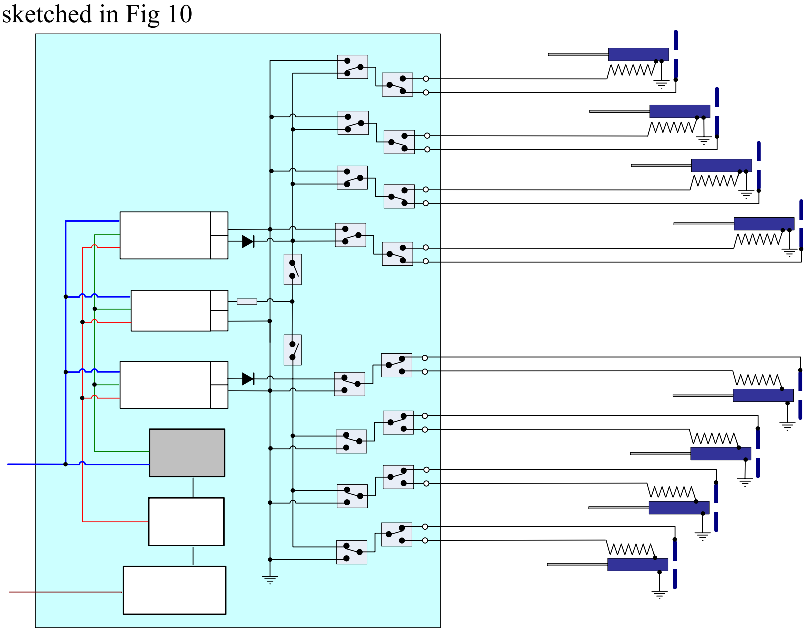

Figure 10. HCT PPU schematic

It consists of a keeper/heater supply and a strike supply to initiate the cathode discharge.

The T6 neutralizer supply is used as heater/keeper supply. This is a current regulated supply with maxim power capability of 90W @ 3A and so more than sufficient to power one HCT.

The current is sent to the heater in the heating phase prior to ignition and then, using a switch, is sent to the keeper to initiate and keep the discharge.

The discharge initiation is obtained using a high voltage spark supply. A system of switches allows the selection of which pair of HCTs must be fired.

A mass estimate for the HCT PPU is 4 Kg.

HCT Power Supply and Switch Unit

The T6 neutralizer supply is over-sized for a T5 hollow cathode as is baseline for ESMO. Further study must be performed to verify the possibility of powering two hollow cathodes in series (in this case with the PPU here presented we will be able to power four HCTs or alternatively we can use only one keeper heater supply saving mass). Alternatively, the possibility of obtaining from EADS Astrium Crisa a supply tuned to our needs might be investigated.

E. Flow control unit

Thales Alenia Space has kindly assisted the study with their proposals for a suitable FCU.

The design of the FCU is focused on having a single box that can supply propellant to both the T5 GIT and the HCTs assuming that these will be operated in pairs.

The pressure and mass flow requirements are reported in Table 5

Table 5. Pressure and mass flow requirements

Component	Mass flow rate [mg/s]	Pressure
T5 GIT	0.07 – 0.53 ±0.007	13 mbar (gas flow only) 20 mbar (gas flow & discharge)
T5 discharge cathode	0.1 ± 0.007	10 mbar (gas flow only) 100 mbar (gas flow & discharge)
T5 neutralizer	0.041 ± 0.006	10 mbar (gas flow only) 100 mbar (gas flow & discharge)
HCT	0.5 – 1.5	100 mbar ~ 1 bar (cold gas mode)

The FCU has a mass of 4 Kg and approximately a volume of 300x200x100 mm. It is sketched in Fig 11

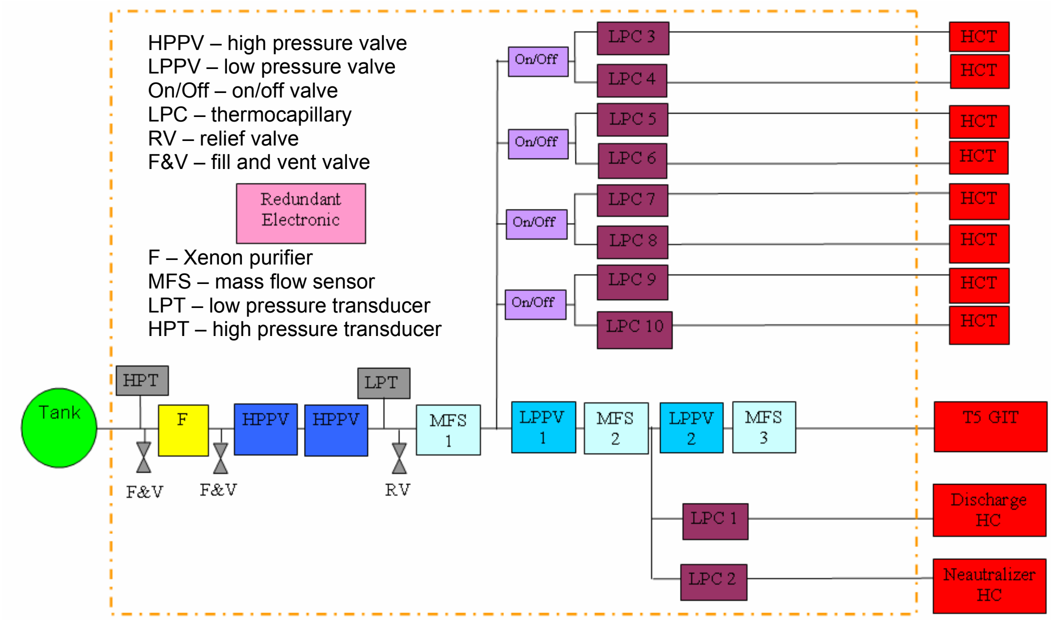

Figure 11. Flow Controller Unit schematic

From the high-pressure tank firstly the xenon passes through a gas purifier (F) to remove impurities.

Two redundant high-pressure solenoid valve (HPPV) are positioned immediately downstream of the purifier. These two valves are proposed in series to meet range safety requirements.

These HPPV used in a loop with a low pressure transducer (LPT) and a mass flow sensor (MFS) are able to perform both mass flow and direct pressure regulation from the tank pressure to the low pressure needed for the HC.

After the MFS1 the flow is divided between the HCTs and the T5 thruster system.

If the HCTs are off all the flow is sent to the T5 thruster system so the HPPV are used to regulate the pressure to the value needed for the discharge/neutralizer HC and the mass flow according to the T5 system needs. Hence there is no need to use LPPV1 and MFS2.

LPPV2 and MFS3 are then used to fix the pressure and mass flow for the T5 GIT while LPC1 and LPC2 are used to regulate the mass flow rate to the neutralizer and discharge cathodes.

If the HCTs are turned on the relative on/off valves will be open. HPPV will be used to regulate the pressure according to the HCTs requirement and the mass flow rate according to the whole system needs.

LPPV1 and MFS2 will regulate the pressure and mass flow according to the T5 thruster system hence LPPV2, MF3, LPC1 and LPC2 will work as if the HCTs are off.

The LPCs relative to the HCTs will work such that the mass flow rates in two HCTs relative to the same axis are equal.

F. Propellant tank

The baseline ESMO xenon propellant budget is shown in Table 6.

Table 6. Baseline ESMO propellant budget

Propellant requirement	Xenon (Kg)	System margin	Xe with all margins
Transfer from GEO to low moon orbit	25.5 Kg	2%	19.8 Kg
Attitude control and initial despin	4 Kg	20%	4.8 Kg
Residuals		1.5%	0.4 Kg
Total mass			25 Kg

The budget comprises of three contributions: from the T5 (for trajectory modification), from the HCTs (for AOCS) and residual propellant that cannot be extracted from the tank at EoL.

The residual figure of 1.5% is a typical figure for this type of system.

Consequently, the requirement is for a tank that can hold a minimum of 25 kg of Xenon.

In principle the higher the tank pressure the smaller is the volume needed but if we look at Fig 12 we can see how for 30 Kg of Xenon the usage of storage pressures higher than 100-150 bar is useless because of the limited increase in density and of the high temperature sensitivity.

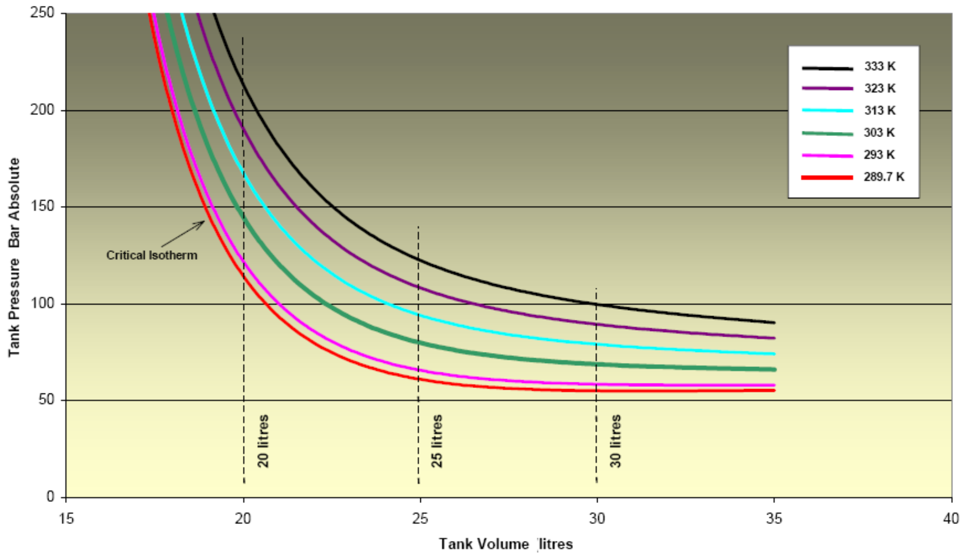

Figure 12. Xenon isotherms for 30 Kg of Xenon

Assuming to have a 100 bar storage pressure at room temperature (worst case) we need 22 litres for 31 Kg of Xenon while with 150 bar we need a 19 litres tank.

After contacting various possible suppliers the preferred tank has been proposed by Thales Alenia Space with the characteristics given in Table 7.

Table 7. Thales Alenia Space Italia tank specifications

Shape	Cylindrical
Volume	19 litres
Mass	5 Kg
Maximum operating pressure (MEOP)	150 bar
Proof pressure	1.2 MEOP
Burst Pressure	1.5 MEOP
Material	Titanium T1000 liner with carbon fibre filament winding

V. SEP alternative option

A fundamental alternative to a GOCE-like PPU is the possibility (assuming the T5 thruster is selected for the ESA "SmallGEO" mission) of using the ESA SmallGEO PPU development on ESMO.

This new PPU is expected to be lighter than the GOCE PPU and unlike the GOCE system may be capable of operating the GIT to an Isp of up to 4500 s (TBC).

Although attractive from a propellant saving perspective, the use of a higher specific impulse engine involves higher power requirements and so a higher number of solar panels, increasing mass.

Hence there are two options:

- Use the SmallGEO PPU @ 3250 s (Maximum GOCE Isp) saving only on the dry PPU mass
- Use the SmallGEO PPU @ 4500 s reducing the propellant mass and the dry PPU mass but requiring a higher mass for the solar panels

In next table a comprehensive comparison between the two options is presented:

Table 8. Mass comparison between different use of the SmallGEO PPU

Components mass (inc margins) Kg	GOCE-like PPU	SmallGEO PPU @ 3250 s	SmallGEO PPU @ 4500 s
Solar arrays	20	20	25
Battery packs and PCDU	7.5	7.5	7.5
PPU	16	11	11
Propellant	31	31	25.5
Total mass	74.5	69.5	69

Thus we conclude that if the SmallGEO PPU is available to ESMO it is best operated at 3250 s of specific impulse because using it @ 4500 s is much more expensive in terms of solar array costs and gives us only a tiny mass saving.

VI. Conclusions

An all-electric spacecraft appears to be a feasible option for the ESMO mission, with a high-performing propulsion system capable of satisfying the main mission requirements within the demanding mass constraints of a small spacecraft mission.

A study of all the possible trade-offs as been performed leading to the total subsystem mass reported in **Table 9**

Table 9. ESMO Subsystem mass

Component	Mass
T5 GIT	1.7 Kg
GOCE-like PPU (SmallGEO PPU)	16 Kg (11 Kg)
FCU	4 Kg
8 x HCTs	0.8 Kg
HCT PPU	4 Kg
Tank	5 Kg
Propellant	31 Kg
Total Subsystem Mass	62.5 Kg (57.5 Kg)

Acknowledgments

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