Radiofrequency with Magnetic field ion Thruster (RMT): review of the Engineering Phase accomplished under ASI Contract

M. Capacci, G. Matticari, G. E. Noci, A. Severi
LABEN Proel Tecnologie Division, Viale Machiavelli, 31 – 50125 Firenze (Italy)
noci.g@laben.it, matticari.g@laben.it, capacci.m@laben.it, severi.a@laben.it

A.Ricciardi, F. Svelto
Italian Space Agency (ASI), Viale Liegi 26 - 00198 Roma (Italy)
andrea.ricciardi@asi.it, francesco.svelto@asi.it

Abstract

This paper presents the activities, framed within a technology Contract awarded to LABEN/Proel by the Italian Space Agency (ASI), relevant to the development up to the Engineering Model (EM) level, of a gridded ion thruster (Radiofrequency with Magnetic field ion Thruster or RMT) and of its auxiliary equipment RFGU (Radiofrequency Generation Unit) and GFCU (Gas Flow Control Unit). The RMT has been conceived for providing thrust levels in the mN range and high specific impulses. This paper reviews the RMT design, manufacturing and test activities for the EM phase. Concerning these latter the RMT was experimentally checked (coupled with the RFGM and the GFCU units) showing an efficiency > 0.5 in the thrust range 7-11 mN, with specific impulses in the range 3300-3500 s (at an accelerating voltage 1500 V). The thruster featured easy throttleability and stability of operation within a 150 h functional test. Beam Divergence was in the range 10-15°. In the paper a set of possible application missions for the RMT system are also identified.

Introduction

Small satellites (300 –1000 kg), alone or in constellation/formation gave gained a strong momentum [1] in these last years and have been proposed for many scientific and earth resources monitoring application missions. In order to cope with specific constraints of small satellites (namely mass and power) and with the growing demand for increasing the payload accommodation capability and extending the operational mission duration, low thrust and high specific impulse ion propulsion has been considered an “enabling” technology to fulfil more and more challenging requirements.

In the frame of the small satellite concept the mass of propellant to perform the operational mission should be contained, in order to obtain a reasonable payload fraction (payload-to-total satellite mass ratio), within a maximum of 10% of the total satellite begin of life mass. Ion propulsion (IP), providing a specific impulse of 3000 sec and higher, is then a key technology to meet this requirement.

On the other side IP can be successfully employed on board small satellites if its electric power demand results compatible with power resources (in most cases not higher than 1500-2000 W) typically available on small satellites, taking also into account that - in many cases -the propulsion tasks may be concurrent with the payload operation and consequently max. 20-30% of the available power can be allocated for the IP sub-system

In this context, LABEN/Proel was awarded a contract from Italian Space Agency (ASI) for developing, up to the Engineering Model (EM) level, a gridded ion thruster (Radiofrequency with Magnetic field ion Thruster or RMT) also considering the perspectives of being used in missions based on Italian Small Platforms (e.g. PRIMA, manufactured by Alenia Spazio).

The RMT IP system, providing thrust level in the mN range, specific impulses in most cases higher than 3000 sec and power level absorbed from the spacecraft power bus of the order of few hundred W, is fully adequate to cover most of the orbit control missions on small satellites of the identified mass range.

Description of the RMT IP system

The RMT technology [8] (patented) uses a RF discharge, in the VHF range, in conjunction with a low level (~100 Gauss) static magnetic field. This configuration allows the excitation of resonance phenomena [6] in the plasma, which are exploited to enhance the ionization efficiency, especially in the low mass flowrate regime (corresponding to thrust levels in the mentioned range).

The guidelines that have oriented the thruster design and development [2] activities have been:

- Use of RF excitation to avoid the presence of critical components (e.g. the cathode) in the interior of the discharge chamber;
- Avoid loss of efficiency when working at thrust level in the mN range (namely 2 to 12 mN);
- Long operational lifetime (> 10,000 hrs in orbit)
- Use of a neutralizer already qualified for 15,000 hrs:
- Operation in "continuous" and/or in "cycled" mode, with possibility to command, in real time, both the duty cycle and the thrust level within the nominal range (2-12 mN), according to the mission requirements;
- Mass, volume, propellant and power consumption in line with the requirements associated to satellites in the 300-1000 kg mass range.

The RMTA (RMT Assembly) is composed by the following main units/sub-assemblies:

1. RMT Thruster Module (TM), (including the RF Matching Network) and the neutralizer
2. Radiofrequency power Generator Unit (RFGU)
3. Xenon pressure reduction and flow controller unit (GFCU)
4. Power Supply and Control unit (PSCU)

Items 1, 2 and 3 have been developed at EM level. The neutralizer instead has been space qualified (in the frame of ARTEMIS program) featuring 0.025 mg/s of Xenon flow and 8 W for its discharge sustain. Item 4 has been implemented with partial BB realizations and with a µ-processor configurable flight boards already available in house (specific s/w to be developed).

Fig.1 and 2 below show respectively the RMT cross section and the RMTA [3] block diagram with the relevant sub-assemblies/units

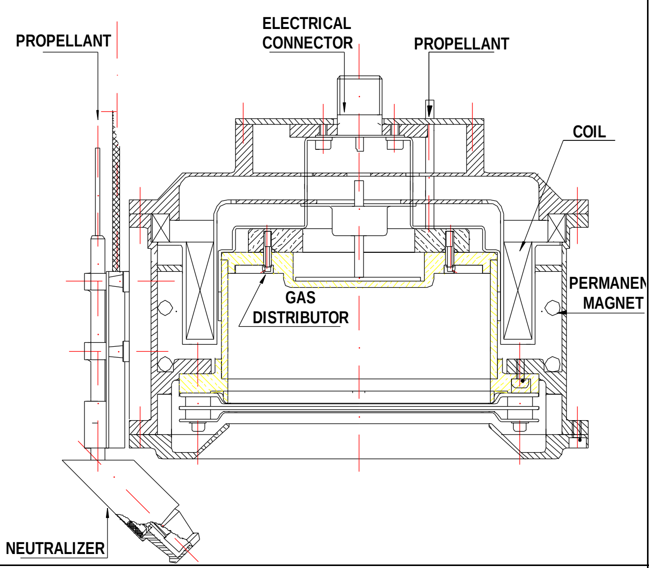

Fig. 1: RMT (thruster assembly) cross-section drawing

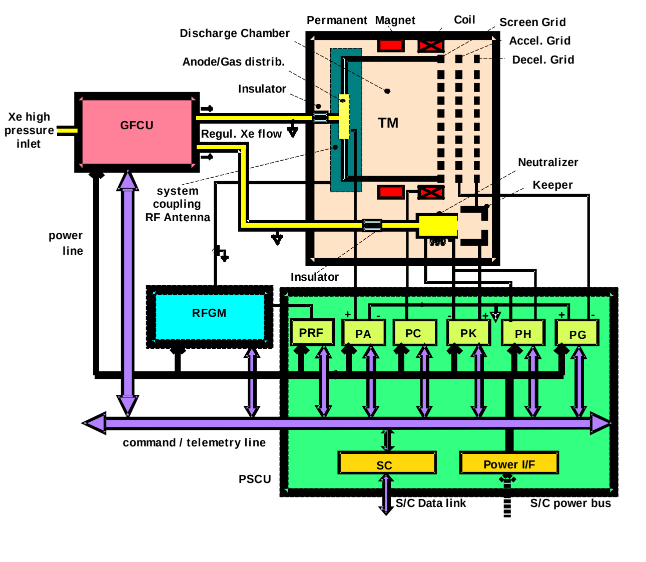

Fig. 2: RMTA sub-assemblies/units

The RMTA performance goals are summarized in the table here below.

Parameter	***value***	***Comments***
Total Gas Flowrate (mg/s)	0.1- 0.35 (xenon)	including neutralizer
Specific Impulse (s)	2300 – 3600, >3300 for T > 8 mN	including neutralizer
Thruster throttling range (mN)	2-12	by varying B, V_{RF}, $\dot{m}$
Thruster efficiency	0.3-055	including neutralizer
RF input power (W)	20 - 90	

Description of the Thruster Module (TM)

Fig. 3 and 4 below show the 3D solid modelization of the thruster discharge chamber and ion optics.

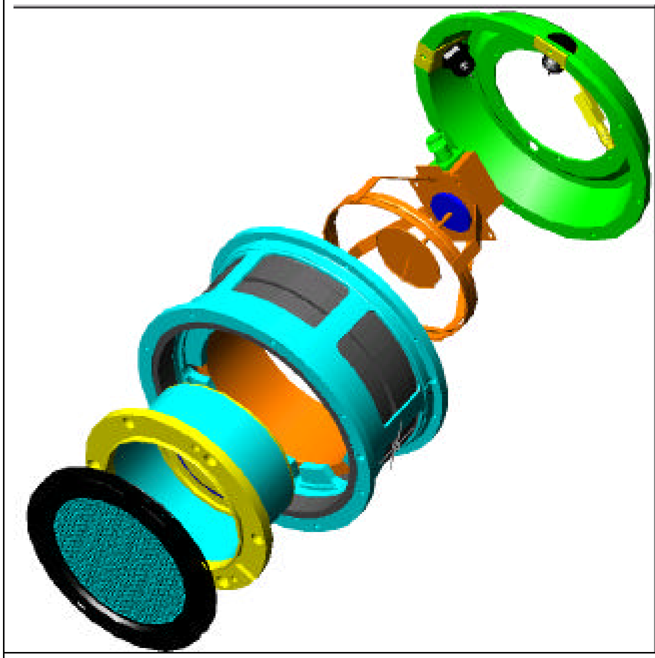

Fig.3: 3-D Solid Modelization of the RMT Thruster Module (TM) parts

Fig. 4: 3-D Solid Modelization of the RMT Grid sub-Ass.y

The Thruster Module includes the following parts:

- Discharge chamber ceramic vessel with built electrodes for the RF capacitive coupling, anode and gas distributor.
- Magnetic Circuit composed by SmCo permanent magnets and by a magnetic control coil, whose design has been optimized by comparing the numerical simulation based on Ansys code with the experimental characterization.
- Ion Optics sub-assembly, based on a 3 grid configuration (Screen and decelerating greed realized in Mo and Accelerating grid in Graphite) capable to guarantee a transparency factor of about 69% to ions.
- Matching Network made with passive components, to allow the optimization of the power transfer from the RFGM unit and the plasma discharge
- Low gas consumption Neutralizer (directly derived from the one successfully developed and qualified for the RIT 10 on ARTEMIS)

Description of the GFCU and of test at Unit level

The GFCU is based on advanced components procured from MOOG and an in-house developed passive capillary, piping elements/orifices and on an electronic control board designed and manufactured by LABEN/Proel. The various parts of the GFCU are housed in a single, compact box whose mass is around 2.6 kg and external envelope dimensions are: 240 x 180 x 80 mm.

The key element of the EM GFCU developed for the RMT are here pointed out:

- Simplification in respect to the traditional approach with on/off valves (chopped or bang-bang) and plenum
- Use of a "Proportional Valve", thus implementing the possibility to have an analog flow controller
- Design based on electromechanical components of new generation
- Components integrated by plumbing
- Fluid components and control electronics integrated in a single housing box
- Control electronics including valve drivers, sensors conditioning, closed loop control of secondary (reduced) pressure

The GFCU configuration is shown in the Fig. 5 and 6.

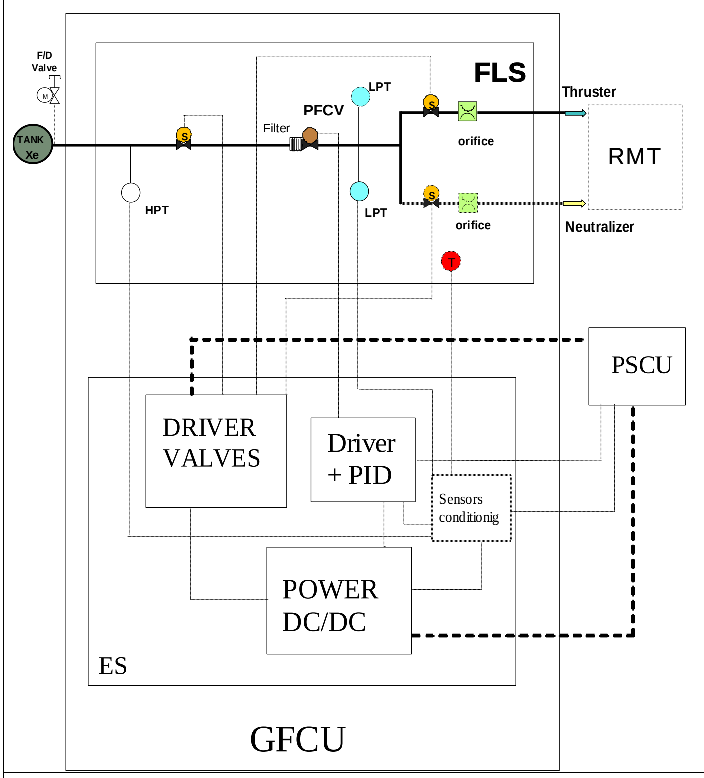

Fig. 5: GFCU Configuration

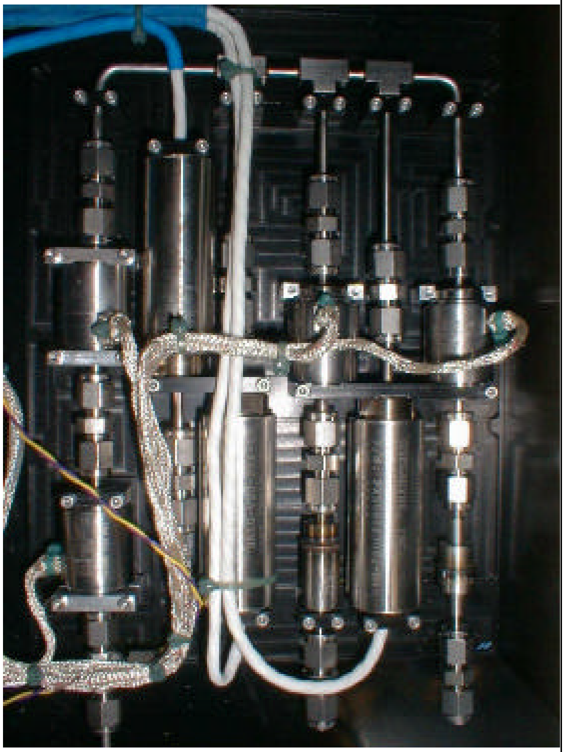

Fig. 6: Photo of the GFCU Flow Line Section

The GFCU operates by reducing the high pressure from the tank, through a Proportional Flow Control Valve (PFCV), which is used in low pressure closed loop control. Multiple branches (2 in the case of a single stage RMT system) can be fed with the regulated pressure, being each branch equipped with an on/off solenoid valve and a calibrated passive orifice. The xenon mass flow in the thruster discharge chamber is regulated by the low pressure setting point and the flow rate in the neutralizer changes accordingly. All commands and telemetries to/from the GFCU are foreseen according to the 1553 Bus standard.

The GFCU realized for the RMT accepts an input pressure up to 150 Bar and is capable to regulate the flow in the RMT discharge chamber in the range 0.25 to 0.5 mg/s, while the flow in the neutralizer changes accordingly from 0.025 to 0.05 mg/s.

Fig. 7 and 8 below show photos of the GFCU box and of the electronic control PCB (Print Circuit Board).

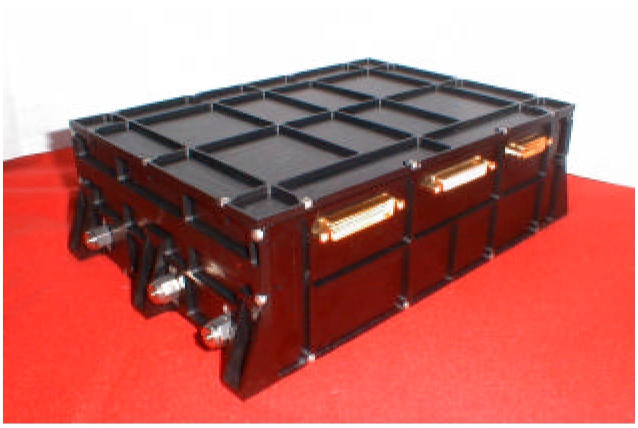

Fig. 7: GFCU housing box showing connections with pipelines and electrical cables

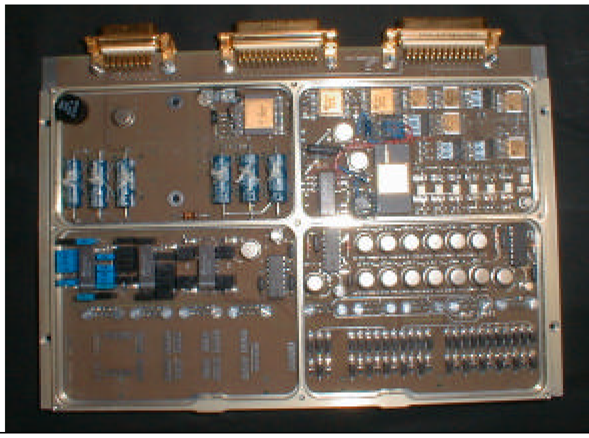

Fig. 8: GFCU PCB dedicated the command/ control of the GFCU operation

The GFCU EM was individually submitted to a test session (successfully passed) at unit level, with the following sequence: mechanical/electrical checks after fabrication, functional tests, vibration (sinus and random) tests, mechanical/electrical checks after vibration, final functional tests.

Description of the RFGU and of tests at Unit level

The purpose of the RFGU is to generate the VHF (150 MHz) voltage to be applied between a plate electrode (positioned in the back of the thruster discharge chamber) and an anular electrode (coaxial to the discharge chamber cylindrical walls) for the ignition and keeping of the plasma ionization discharge from which ions are extracted and accelerated. The main operating parameter of the RFGU are below indicated:

- Output Power 90 W (50 ohm imp.)
- Nominal Frequency 150 MHz
- Frequency Range 146-154 MHz
- Control Voltage 0÷28 V
- Auxiliary Voltage 28 V
- Efficiency (PRFG+MN) goal 70 %
- Max. Dissipation 40 W (at full power)

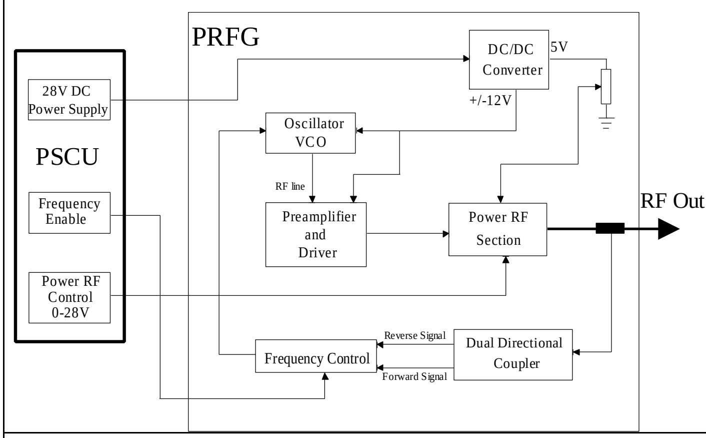

Fig. 9: RFGU functional Block Diagram

Fig. 10: RFGU housing box opened to show the accommodation of the electrical parts

The RFGU design has been optimized for a power transfer to a 50 Ο electric load. The RF sinus signal is realized by a VCO oscillator. The Impedance Matching (SWR <1.2) is obtained through a built in dual directional coupler feedback and through frequency control. The unit is also equipped with 4 temperature monitoring sensors. The monitoring of the direct and reverse power is as well possible.

The RFGU box has a mass of 1.15 kg and its envelope dimensions are: 100 x 150 x 60 mm.

The RFGU was fully characterized and tested as a stand alone unit. For what concerns performance, efficiency was mapped (obtained values between 64 and 70%) versus the RF output power (varied between 20 and 100 W) and versus the “drain” voltage (varied between 12 and 27 V) . The Unit was also successfully submitted to vibration test (random and sinus).

The RFGU was in addition characterized when coupled to the RMT to verify its capability to efficiently transfer to the plasma the RF energy. When varying the thrust level between 7 and 11 mN the direct and reverse power was measured and consequently the SWR (standing Wave Ratio). The most favorable WSR was achieved for the highest thrust level.

RMT EM test

The functional/performance characterization of the RMT IP system [7] has been performed at LABEN/Proel labs in Florence. The photos below (see Fig. 11 and 12) show, respectively, the RMT integrated in the hatch of the vacuum plant and the thruster in operation

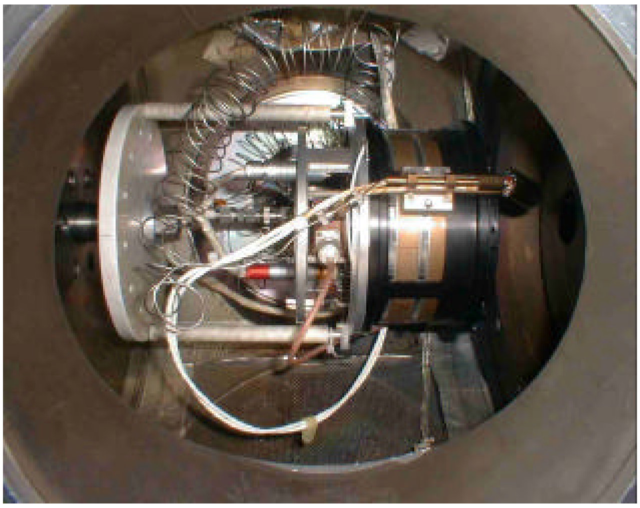

Fig. 11: RMT integrated into the vacuum chamber

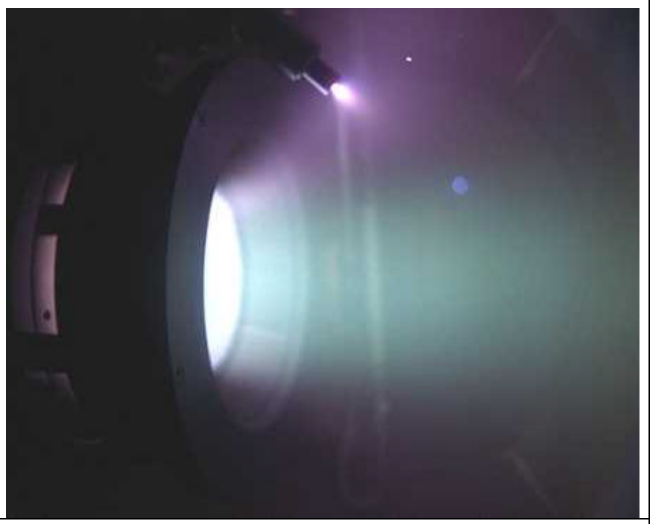

Fig. 12: RMT under functional test

The following characteristic parameters (see Tab. 1 below) have been obtained by the direct measurement of the specified physical quantities

Thruster feature	Symbol	Unit	Measured Quantities	Calculation Technique
Propellant utilization Efficiency	η_u	**adimensional**	I_S, $\dot{m}$	$h_u = \frac{I_B * m_i}{e*(\dot{m}_T + \dot{m}_N)}$
Thrust	T	**mN**	I_S,V_S, γ	$T = \frac{m_i}{e} I_B \sqrt{2V_B \frac{m_i}{e}} g_{TOT}$
Specific impulse	I_{sp}	**s**	$\dot{m}$, I_S, V_S, γ	$I_{SP} = \frac{10240 * T * g}{\dot{m} * g}$
Beam Ion Energy cost	ε_B	**W/A**	W_{RF}, I_S	$e_B = 1000 \frac{W_{RF}}{I_B}$
Thruster electrical efficiency	η_e	**adimensional**	I_S, V_S, P_{in}	$h_e = \frac{I_B * V_B}{P_T} = T \frac{v_e}{2P_T}$

Tab.1 Thruster characteristic parameters identification

Where:

I_S = Anode current
$\dot{m}$ =Mass flow rate
V_S =Anode Voltage
γ = Thrust loss factor, mainly due to beam divergence

the operating parameters were varied in the following ranges (see Tab. 2) :

Parameter	Symbol	Range
RF power	W_{RF}	40 ÷ 95 W
Gas flow rate	$\dot{m}$	0.9÷3.5 sccm
Accel. Grid voltage	V_a	-500 ÷ -700 V
Screen (anode) voltage	V_s	1500 V

Tab. 2 RMT operating parameters variation ranges

The thruster typical parameters have been collected for operation at constant thrust. A set of data have been obtained for each considered thrust level (7, 10 and 11 mN). The data were measured and collected within a time span of 1000 sec, repeating the acquisition at intervals of 100 sec.

The following Tab. 3 summarizes the results obtained at different operating thrust levels.

Input parameter		Is (mA)	T (mN)	Is (sec)	?$_e$	?$_u$	Ic (A)	Vc (V)
Vs=1500 V $\dot{m}$ =1.9 sccm Wrf=50W Va=-700V	average	112.8	7.12	3500	0.74	0.73	0.33	0.44
	Standard deviation	0.57	0.04	18	0,005	0,004	0,017	0,016
Vs=1500 V $\dot{m}$ =2.9 sccm Wrf=65 W Va=-700V	average	157.3	9.89	3330	0.75	0.69	2.11	3.27
	Standard deviation	0.45	0,02	7	0.003	0.005	0.021	0.032
Vs=1500 V $\dot{m}$ =3.3 sccm Wrf=90 W Va=-700V	average	168.9	10.62	3323	0.73	0.69	1.43	2.31
	Standard deviation	0.72	0.05	15	0.005	0.005	0.031	0.074

Tab. 3: RMT typical parameters for 3 reference thrust levels (nominally 7 mn, 10 mN, 10.5 mN)

For each measured or deduced parameter the average of the values obtained by taking 10 samples at 100 sec interval (within the time span of 1000 sec) is shown. In addition the std deviation parameter referred to the collected samples in the observation time span of 1000 sec is reported.

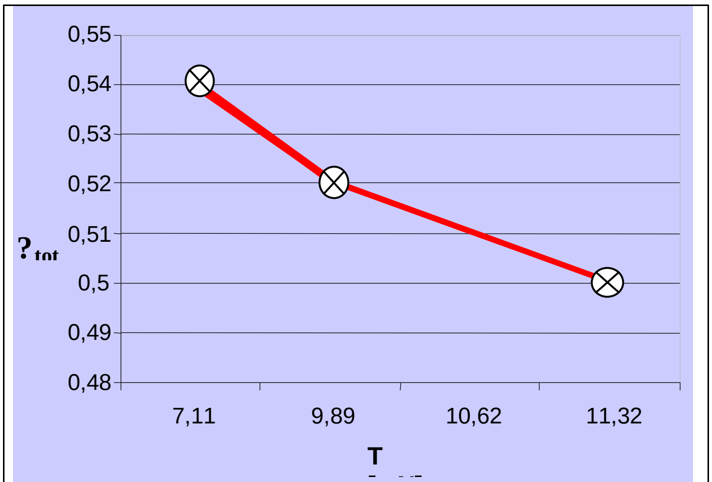

Fig. 13: Plot of the thruster efficiency versus thrust level

Even in the absence of the PSCU unit, the thruster control philosophy has been successfully implemented with dedicated EGSE, using computer controlled power supplies and some manual procedure.
For each couple W_{RF}, $\dot{m}$, the coil current has been regulated in order to optimise the thruster operating point.
Thrust levels have been checked in the range of interest, being the reference thrust level 10 mN. Thruster operation clearly showed that the thruster itself does not put any limitation in the smallest achievable thrust step , this latter being a matter of PSCU unit design.
The specific impulse is well above the required 3000 s, using 1500 V as ion beam acceleration voltage as foreseen.
The divergence of the beam in terms of beam semiangle containing the 95% of the beam current is in the range 10 - 14 deg.

RMT extended functional test and beam profile analysis

Downstream the accomplishment of the RMT functional/performance test an additional test has been performed. The specific objectives of such a test are here pointed out:

- Acquire data about the evolution in time of the thruster integral parameters (beam current, efficiency, etc.) at a thrust reference value of 10 mN, during an extended operation of 150 hrs

- Perform the Ion Beam Investigation by measuring the current density profiles (through Faraday cups) and from these data, extract information about the beam divergence, beam profile, thrust vector and thrust (indirectly).

During the 150 hrs test session the following parameters have been maintained fixed: W_{RF} =70 W, Vs=1500 Va=-700 V and $\dot{m}$ was slightly changed in order to obtain a fixed thrust of 10 mN.

The evolution of the main thruster parameters within the 150 h test has been recorded and the relevant plots are shown in the following figure:

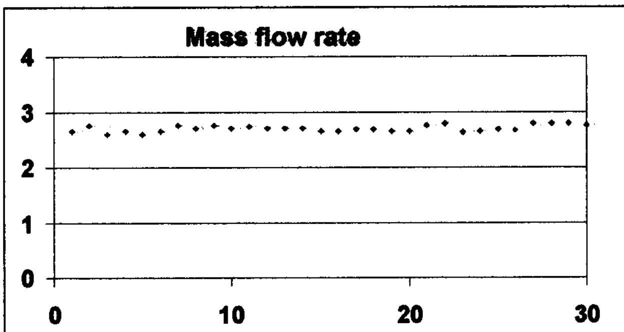

Fig. 14: Evolution of the mass flow rate versus time

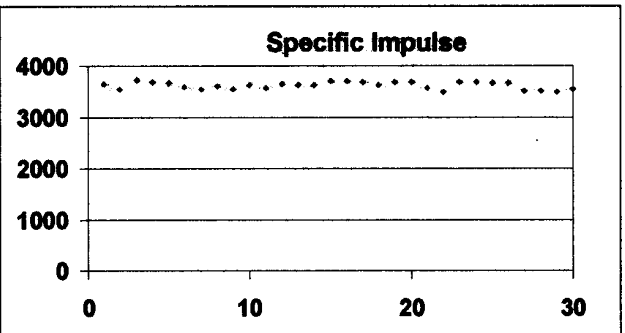

Fig. 15: Evolution of the Specific Impulse versus time

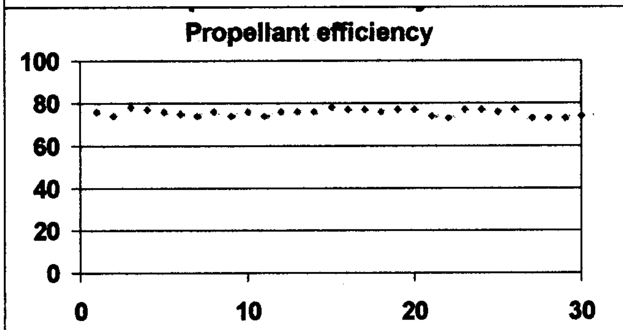

Fig. 16 Evolution of the prop. Util. efficiency rate versus time

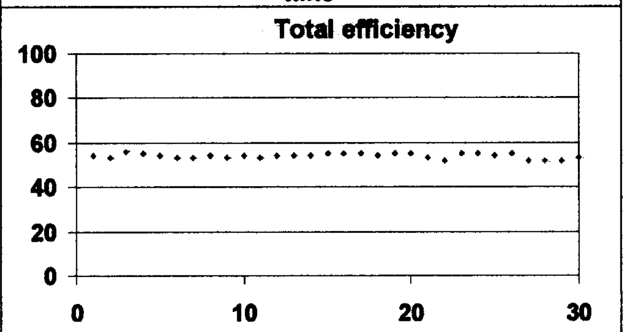

Fig. 17: Evolution of the total efficiency versus time

The test had an overall duration of 30 days; during each day the thruster was switched on for 10 hours. Two data acquisitions were made for each test day, respectively at the beginning and at the end of the day session.

For what concerns the beam profiles, the acquisitions were made considering 2 reference thrust level, 8 and 11 mN. The Fig. 18 and 19 below show the collected beam profiles

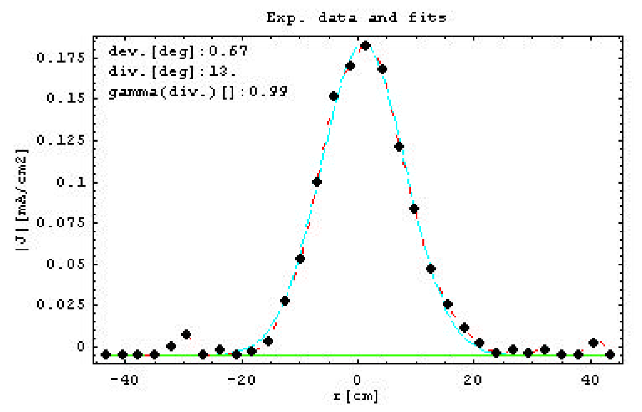

Fig. 18: Beam profile at a thrust level of 8 mN

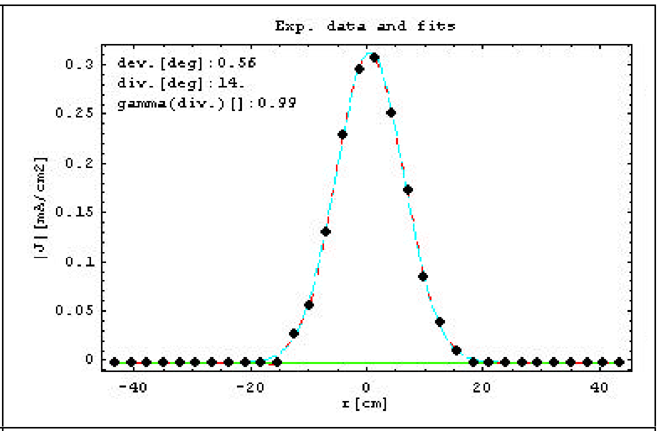

Fig. 19: Beam profile at a thrust level of 11 mN

From the acquisition of the beam profiles a thrust divergence between 12 end 14 deg and a thrust loss factor of 0.99 was obtained.

Possible mission profiles for the RMT in-flight demonstration within an operational mission

The RMT system could be profitably used on small satellites [5] of the 300-1000 kg mass class to fulfill a variety of operational missions [3] [4], such as:

- Drag Compensation/ "Drag free" control of satellites orbiting in the altitude range 300-600 km, during multi-year (also longer than 5 years) operational missions;
- Orbit transfer (e.g. in the 300-600 km altitude range) to change the operational altitude of remote sensing satellites or for orbit acquisition starting from the parking orbit;
- End-of-life orbit disposal;
- Mutual position control/ gap filling of satellites belonging to a constellation or to a formation
- Correction of the orbit injection errors due to the launcher;
- Adjustment of the RAAN (Right Ascension of the Ascending Node) and phase change;
- Station keeping /Orbit maintenance.

A full operational demonstration of the RMT system could be carried out on a technology demonstration satellite [9] (e.g. based on PRIMA platform) performing the following tasks:

- Orbit maintenance/control of a sun-synchronous orbit at about 500 km altitude, for a period of 2-3 years
- Orbit lowering from 500 km to 300 km, keeping orbit sun-synchronous characteristics by performing through the RMTA both the orbit altitude and inclination change manoeuvering (possible duration of the manoeuvre 6 months)
- Orbit maintenance/control (mainly by drag compensation) of the sun-synchronous orbit at about 300 km, for a period of 1-2 years.
- Deorbiting through an orbit lowering from 300 km to 180-200 km, exploiting the residual propellant after the operational mission

Conclusions

A gridded ion thruster based on the radiofrequency plasma discharge coupled to a static magnetic field has been successfully developed, up to the Engineering Model (EM), in the frame of a Contract with the Italian Space Agency (ASI). The thruster is able to provide a thrust level in the range 2-12 mN, at specific impulses up to 3500 sec. This thruster is candidate to be embarked on Italian Small satellites e.g. based on the PRIMA platform, to perform mainly orbit control mission and orbit transfer maneuvres in the case where the time-to-orbit requirement is not too stringent.

In the frame of the ASI contract, in addition to the Thruster Module itself, the thruster auxiliary equipment (Radiofrequency Generator, Gas Flow Control Unit) have been developed at EM level and successfully characterized/tested as stand alone units. The Power Supply and Control Electronics (PSCU) necessary for the thruster operation has been developed at Laboratory equipment level. The RMTA (RMT Assembly, including the auxiliary equipment) has been successfully submitted to a characterization test and to a preliminary extended functional test of 150 h. The paper reviews in detail the results of the RMT functional/characterization campaign as well as a description of the RMTA hardware.

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