ORBITAL CONTROL AND MANOEUVERING OF LIGHTSATS/SYNCHRONOUS SATELLITES: ASSESSMENT OF NEW ION PROPULSION TECHNOLOGIES, BASED ON THE ELECTRON CYCLOTRON RESONANCE PHENOMENON, TO IMPROVE THE PERFORMANCES OF THRUSTERS IN THE MILLINEWTON RANGE

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Abstract

This paper outlines the possible applications of electrostatic ion propulsion to missions where a thrust in the range of mN is required.

For this thrust range new technologies, based on the Electron Cyclotron Resonance (ECR) process, are assessed with the purpose of improving the performances of ion thrusters.

The ECR technology applied to ion propulsion allows, in general, the possibility to operate in a wide range of thrusts, simply changing the mass flow rate in the discharge chamber. As a matter of fact, this technique allows the optimization of the electrical efficiency and gas consumption over a wider range of gas pressures than the conventional RF technology.

ECR appears particularly indicated for ion thruster of small dimensions for which it is also easier to obtain the optimum static magnetic field necessary for the resonance.

In this paper an ion propulsion system based on ECR principle is presented. In this system the ionization discharge, in a small discharge chamber operating in the low pressure range, is obtained using a VHF RF power supply.

Furthermore new patented technologies for grids and discharge vessel walls are introduced.

Introduction

Ion propulsion is now gaining momentum in view of the competitive advantages it may offer to commercial satellites[1].

Ion propulsion is characterized by a propellant exhaust velocity up to 20 times higher than the traditional chemical propulsion, consequently the propellant requirements can be reduced by approximately the same factor. This feature produces a large potential mass saving for a given mission duration.

Besides other attractive new technologies, ESA's ARTEMIS spacecraft will, operationally, demonstrate the viability of electric propulsion for North-South station keeping of synchronous satellites in the "commercial" 2.5 ton launch mass class range[2].

Other papers, presented at this Conference, address ARTEMIS Satellite ion propulsion system design and implementation aspects: they will not, thus, repeated here.

For such application 15 to 25 mN ion thrusters are normally used. Significant developments are underway, by several Companies, on even higher thrust thrusters, intended for a variety of applications, including orbital manoeuvering of large bodies.

The first part of this paper stresses, instead, the importance of small thrusters, typically in the 2 to 10 mN range, whose applications have been, so far, generally underlooked. Beyond some unconventional uses in geostationary satellites, small thrusters are suitable for orbit control and manoeuvering of lightsats, a spacecraft type which is going to play a significant role in the years to come.

In this context there is room and motivation for innovative research and development, aiming to improve upon the current status of the art, while overcoming certain drawbacks of today's ion thrusters.

Furthermore in the second part of the paper, a new concept for an ion thruster is presented, which exploits the Cyclotronic Resonance Phenomena of the free electrons to enhance the ignition process of the ionization discharge. The expected benefits are discussed and motivated, and the resulting ion thruster configuration is described in some detail. Eventually, the key elements for a development programme are outlined, starting considering applications with thrusters in the mN range at very low propellant consumption rate.
System applications of low thrust ion thrusters

Some uses of electric propulsion for orbit control and transfer of satellites in circular and elliptical Earth orbits have been, recently, reviewed in Ref. [3].

The considered applications span from conventional station keeping of synchronous spacecraft, to circular orbit raising, circularization of elliptical orbits and vice versa, and orbit plane changes. Many uses imply medium to high level thrust, in the 25 to 200 mN range, or more.

Nevertheless, the potential of low thrust ion thrusters wasn't fully appreciated until very recently, with the spin-off of the small satellites, and the prospective opening of alternative launch opportunities.

Low thrust ion thrusters for Synchronous satellites

An outstanding example of this application is represented by the possible implementation of an all-electric propulsion system for the orbital and attitude control of a Proton launched commercial satellite. The Proton rocket can directly inject, at the desired station point, a 2.4 ton spacecraft. Accordingly, one can get rid of the Apogee motor and all the chemical propellant, nearly halving the spacecraft launch mass or, conversely, designing the satellite to make maximum use of the available launch mass for the payload.

There are several communication missions not requiring tight north-south station keeping control. Such missions are typical of mobile communications, or point to point communications in the lower S and C bands, since the ground terminal antenna beams are rather wide to cope with spacecraft drifts up to several degrees.

At ku and ka bands, simple techniques are available allowing open loop tracking of the satellite. Anyway, should the mission also require full north-south station keeping, then 20 to 40 mN thrusters would have to be included in the propulsion system.

Rather tight east-west station keeping is normally required for frequency coordination purposes. In this case, a set of low thrust (2 to 5 mN) ion thrusters can provide the required velocity increments which are, typically, of the order of 2 m/sec/year. The same devices can be used for de-orbiting and, given enough time, for spacecraft re-positioning in synchronous orbit, if required by the mission.

These small ion thrusters can be used in place of the pulse-operated chemical thrusters for attitude control functions: the typical $10^3$ ratio, in the control torque available, is coped with by operating the ion thrusters for minimum "on-times" of the order of several seconds.

Nevertheless, the availability of a small, throttleable, thrust can even improve the performance of attitude control functions, such as asymmetric torque compensation, insofar as momentum accumulation in the wheels may be possibly reduced, leading to less frequent desaturation manoeuvres and, ultimately, to a smoother body control.

Low thrust ion thrusters for Lightsats

A recent market study[4] showed that lightsats in the 200 to 500 kg mass range are most appealing for practical applications. Low thrust thrusters, in the 2 to 10 mN range, appear very suitable due to the following reasons:

- the thrust to mass ratio is equivalent to that of 10 to 50 mN thrusters in a 2 ton spacecraft, producing the same velocity increments over the same durations;
- a small thrust implies low power consumption. This is consistent with the DC power availability, which is generally constrained in a lightsat;
- the reduced propellant mass and small thruster sizes are a premium factor for mass and volume constrained lightsat designs.

The most interesting applications of low thrust ion thrusters are for orbital manoeuvring implying a quasi-continuous application of low thrusts and the achievement of velocity increments over time intervals not necessarily too short by mission design. A few applications are briefly revisited here below.

Drag compensation

Small ion thrusters can be optimally used for drag compensation of lightsats in low circular orbits, particularly in the 300 to 600 km altitude range, which may be exploited for remote sensing applications. A 2 mN thruster has been estimated to be fit for drag compensation of a 500 kg spacecraft at 480 km height[5]. The variability of the drag effects with orbit altitude, inclination, season and solar activity, implies a flexible thruster design, with full thrust level control.

Fine trimming of orbital parameters

The Earth gravitational field zonal harmonics are cause of orbit perturbations, normally requiring corrections. These may involve the application of thrusts both in the orbit plane and orthogonally to it. Ion thrusters can be used for this purpose, since the time constant involved are rather long. A frequent activation of low level thrusters, during suitably chosen portions of each orbit, may prevent the cumulation of the perturbing effects, resulting in a much finer control and maintenance of the nominal orbital parameters. This feature may be of paramount importance for certain remote sensing missions.
With the exception of the so-called "missions of opportunity", normally requiring a fast adaptation to the new mission needs, orbit reconfigurations, of interest for both remote sensing and telecommunication missions, can be planned to take over gradually. The required velocity increments are, thus normally within reach of low thrust thrusters.

Removal of orbit injection errors
Orbital injection using chemical rockets normally results in dispersion errors requiring corrections. Many missions can accept a relatively long time interval for doing that. Small thrusters can be used for this purpose, specially if their implementation is already baseline for the above mentioned manoeuvering tasks. The possibility of removing the injection errors with ion propulsion may facilitate the adoption of solid upper stages, known to be less accurate than liquid ones but cheaper.

Performance objectives of low thrust ion thrusters
A few common requirements stem from the above scenario, envisaging the extensive use of electric propulsion systems based on a multiplicity of low level ion thrusters, combined or not with a few medium to high thrust thrusters. Key factors are flexibility, design modularity, low mass and power consumption, high specific impulses even at low thrust levels, ruggedness, ease of interfacing with the spacecraft, and low cost. Tab. 1 lists preliminary performances goals for this family of low thrust ion thrusters.

<table>
<thead>
<tr>
<th>Requirement</th>
<th>Goal</th>
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<tr>
<td>Thrust levels</td>
<td>2 to 10 mN</td>
</tr>
<tr>
<td>Thrust control range</td>
<td>30% to 120% of nameplate thrust level</td>
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<tr>
<td>DC power consumption</td>
<td>&lt; 50 W / mN</td>
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<tr>
<td>Mass, incl. power supply and logic</td>
<td>&lt; 0.4 kg / mN (goal)</td>
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<tr>
<td>Specific impulse</td>
<td>&gt; 3000 sec. (goal) at rated thrust level</td>
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Tab. 1: Low thrust ion thrusters performance

The technical/economic benefits associate to the ion propulsion technology can be briefly outlined with reference to an orbit control mission. Geosynchronous communications satellites require an NSSK velocity change of about 50 m/sec/year. Thus, a 14 year maneuver life for a 2.500 kg spacecraft needs 650 kg of propellant, 25% of the on-orbit mass of the satellite. Even a tenfold increase in specific impulse would reduce the propellant mass to 65 kg, but the mass of a fully redundant ion propulsion system with a specific impulse of 2800 sec would be less than 185 kg, resulting in a mass reduction of 400 kg or 15% of the spacecraft mass.

With today's launch cost of about $40000/kg to GEO, the above example could save about $16 million.

Electron Cyclotron Resonance (ECR) for plasma generation
In order to clarify the advantages of the ECR applied to ion propulsion, it can be convenient to introduce some basic concepts connected to the ECR process.

The ionization plasma, from which the ion beam to produce the desired thrust is extracted, is obtained exploiting the collisions between electrons and atoms in the gas.

An electrical field (DC or RF) is generally used to provide to the free electrons an energy greater or equal to the ionization energy of the propellant atoms. The energy transfer to produce an ionization may occur during the time between two consecutive electron-neutral collisions.

If a pure RF electric field of frequency \( f \) and peak amplitude \( E_0 \) is used, the mean energy \( W_c \) acquired by an electron in the time between two collisions, is given by\[7\]:

\[
W_c \approx \frac{e^2 E_0^2}{2m(4\pi^2 f^2 + 1/\tau^2)} \quad \text{when} \quad f \geq \frac{1}{\tau}
\]

where:

- \( e \) = electron charge;
- \( m \) = electron mass;
- \( \tau \) = mean time between two consecutive collisions (inversely proportional to the gas pressure).

If a static magnetic field, orthogonal to the direction of the oscillating electric field is added, the electrons are forced to rotate around the magnetic field lines at the cyclotron frequency \( f_c \), given by:

\[
f_c = \frac{eB}{2\pi m}
\]

numerically:

\[
f_c \, (MHz) = 2.8xB \, (Gauss)
\]

where \( B \) is the intensity of the static magnetic field.

For example a magnetic field of 907 Gauss corresponds to a frequency of 2.54 GHZ.

In these conditions the mean energy per collision transferred to the electron is (see \[7\]):
A qualitative explanation of the ECR effect is schematically illustrated in Fig. 2.

In correspondence of the resonant conditions, with \( f = f_c \), said Electron Cyclotron Resonance (ECR), the quantity \( W_c \) assumes its maximum value:

\[
W_{c_{\text{max}}} = \frac{e^2 E_0^2 r^2}{4m}
\]

which is only dependent on the collision time and on the peak value of the electric field \( E_0 \).

It is clear that the maximum benefits from the ECR effect can be obtained in the low pressure regime, being \( 1/\tau \) (collision frequency) \( \propto \) to the pressure of operation.

Fig. 1 shows the electric field amplitude \( E_0 \) for transferring an energy of 13 eV, (Xe ionization potential) versus the field frequency (\( f \)) for a Xe pressure of \( 10^{-4} \) and \( 10^{-5} \) Torr in the case of pure RF and RF + added ECR excitations.

![Fig. 1](image)

**Fig. 1:** Approximate value of the electric field amplitude needed to transfer a mean energy of 13 eV (Xenon potential ionization energy) for two Xe pressure values

From the comparison of the peak electric field values obtained in ECR condition with the values obtained with pure RF and without static magnetic field, the convenience of the ECR appears evident especially in a low pressure regime (\( 10^{-4} \div 10^{-5} \) Torr). Here the time between two consecutive collisions is particularly long and it is sufficient a very low electric field amplitude (and then discharge power) to maintain the plasma.

As the velocity vector along the electron trajectory is in phase with the electric force, the electrons are continuously accelerated.

If the electron suffers a collision after a large number of turns, \( f_c >> 1/\tau \) (Fig. 2C), the energy transferred increases, while if \( f_c << 1/\tau \) (Fig. 2D), the electron in the time between two collisions covers only a small arc of turn and the ECR does not give particular advantages.

**ECR technology applied to ion propulsion**

In this section of the paper the use of the ECR principle based on a RF electric field in the VHF range, is illustrated and motivated for an ion propulsion system with thrusts in the milliNewton range.

The choice of a RF excitation in the VHF range is mainly connected to the following considerations.
In Fig. 3 we point out a frequency range, 50 ÷ 200 MHz within which the conditions (1), (2) and (3) are satisfied.

![Fig. 3: Localization of a frequency region suitable for ECR applications to ion thruster](image)

**Advantages of cyclotron resonance for Ion Thruster**

Ion propulsion technologies offer an opportunity for increasing the spacecraft payloads by providing the propulsion requirements with significatively less propellant than chemical propulsion technologies.

One general performance criterion for an ion propulsion system is the maximization of the payload fraction (mass of payload/initial mass of spacecraft) for a given mission (characterized by a velocity increment Δv).

When dealing with long duration earth orbit missions like drag compensation, fine trimming of orbital parameters, station keeping etc., characterized by low thrust requirements (when referred to lightsats) one more specific performance criterion is represented by the optimization of the ratio:

\[
\frac{\text{operational life time (at constant thrust)}}{\text{ion thrusting system mass}}
\]

In this case an extension of operational life, which corresponds to an increase of the mission velocity increment, reflects mainly on an increase of propellant requirements.
A significant improvement of the ratio lifetime/thrust system mass can therefore be obtained if a containment of propellant consumption is achieved increasing the propellant utilization efficiency.

The ECR technology proposes itself as the most suitable to optimize the ionization process and then the propellant utilization efficiency. This process can be furtherly improved by employing suitable materials, characterized by a high secondary emission coefficient, for the realization of the discharge chamber walls\textsuperscript{2}.

The main features of the ECR technology and relevant development perspectives are hereunder pointed out:

1) ECR sources do not have consumable components inside the plasma chamber, as cathodes or accelerating electrodes. As a result, problems of sputtering erosion inside the chamber are eliminated with advantages for the thrust operative life.

Moreover it is possible to realize the discharge vessel in materials with a high secondary electron emission coefficient scarcely sensitive to erosion and capable to reduce the electron losses from plasma towards the vessel walls.

2) The plasma produced by ECR is particularly uniform, both in density and temperature. The achievable electron densities are of the order of $10^{12}$ electron/cm\textsuperscript{3} at pressures in the range of $10^{-4}$ - $10^{-5}$ Torr. These characteristics facilitates the optimization of the beam extraction.

3) The ECR technique shows itself particularly advantageous for ion thrusters operating at low thrust levels ($2 \div 10$ mN), where it proofs suitable to reduce instability phenomena inside the plasma. First of all low thrusts are connected with contained dimension of the discharge vessel (radius of the discharge chamber $\leq 5$ cm). These reduced dimensions make easier the realization of a uniform magnetic field in the discharge vessel. Moreover a small chamber allows the use of small electrodes for electromagnetic energy transfer, with lower losses due to EM irradiation and to vessel walls absorption.

Furthermore low thrusts can be reached with low propellant mass flow rates, utilizing small chamber dimensions. In turns this means working at lower discharge pressure, where ECR proofs itself more efficient and stable than other traditional excitation techniques (pure RF).

4) The ECR offers the unique possibility to produce either a plasma with an high concentration of single charged ions or, increasing the discharge power, a plasma dominated by multi-charged ions. It is known that the multi-charged ions can increase problems concerning sputtering erosion of the thruster materials. However, if it is possible to reduce the grid erosion phenomena using new technologies (see point 5), the use of multi-charged ions could provide some advantages in particular flight mission.

These advantages are mostly connected to the fact that increase of the ion charge raises the thrust level without changing the mass flow rate and the acceleration potential. It has however to be noted that, the use of multiplet charged ions produces an increase of the required electrical power. At any rate there are particular missions for which the increase of the electrical power is less important than the possibility to perform the mission in a lower time (due to the increased thrust level). Furthermore it has to be noted that for future missions the saving of fuel can be more attractive than a reduction of electrical power request.

Tab. 2 shows a computer analysis of some space missions in which the employment of single charged and double charged ions are compared.

5) The advantages of the basic ECR technique for ionization plasma generation can be enhanced by the use of a suitable grid system technology for ion beam extraction/acceleration.

PROEL has developed a new technology for the realization of the grids (patent pending). This technology utilizes a geometry producing a higher transparency factor. The achievable high transparency does however not affect the grid mechanical resistance and its capability to survive to sputtering erosion. The use of a high melting point refractory material coated with suitable "antisputtering" protection layer, will provide the technology solution to overcome problems of limited lifetime capability.

The minimization of problems of sputtering erosion will furthermore allow, if required by the mission, to produce and use multiple charged ions to increase the thrust level or to reduce the propellant consumption leaving the thrust unvaried.

\textsuperscript{2} PROEL patent pending
SINGLE CHARGED VERSUS DOUBLE CHARGED IONS FOR DIFFERENT LOW THRUST MISSIONS

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<th>[C]</th>
<th>[D]</th>
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<td>0.984</td>
<td>0.982</td>
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**CALCULATED PARAMETERS**

\[ v_e = \frac{(2qV_b)}{m_i}^{1/2} ; \quad T = \eta_u \frac{qV_e}{2} ; \quad P_e = \frac{T v_e}{2 \eta_e} \]

\[ M_a = \alpha P_0 \left( \frac{P_e}{P_0} \right)^{0.9} \quad \text{where} \quad P_0 = 500W \]

\[ M_i = (M_p + M_a) / \exp(-\Delta v / \eta_u v_e) ; \quad M_c = M_i [1 - \exp(-\Delta v / \eta_u v_e)] ; \quad \tau = M_c / \dot{m} \]

[A]: single charged ions  \quad [B]: same as [A], with double charged ions  
[C]: double charged ions with reduced \( \dot{m} \) to realize the same thrust T as in A  
[D]: double charged ions with T and \( \dot{m} \) as in [C] but with increased \( \Delta v \) to realize \( M_c \) as in [A]

**Tab. 2:** Theoretical analysis of low thrust ion thrusters using single charged and double charged ions

**Conclusion**

The utilization of low thrust ion propulsion systems (2-10 mN) for orbit control and manuevering of lightsats is proposed and motivated.

With reference to the proposed range of thrust, a new technology, based on the Electron Cyclotron Resonance (ECR) process, is assessed.

The advantages to use ECR with VHF excitation, when dealing with low thrust applications, are presented high lighting features like plasma uniformity and density, reduced thruster chamber dimensions, low magnetic fields, extremely low propellant mass flow rate, energy transfer without wave propagation, possibility to produce single charged as well as multi-charged ions, sputtering erosion phenomena containment using suitable technologies and materials for the grids reduction of the electron losses in the discharge chamber by using high secondary emission coefficient materials for the plasma containment vessel.

**References**


