SPECIALIZED TURBOMOLECULAR PUMPING STAGE FOR RF ION THRUSTERS

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This paper proposes the application of a highly specialized Turbomolecular Vacuum Pump (TMP) device as a subsystem for electrostatic RF ion thrusters, using D. Fearn's Dual-Stage 4-Grid design as a cutting-edge example. The TMP turbine's rotor impulse is transmitted via collisions to neutral gas atoms en route to their ionization, with the goal of producing an anisotropic ion flux that is directed at the extracting screen grid. Operating regimes of such thruster design are hypothesized, and electromagnetic complexities of realization of this concept are identified.

Keywords: TMP-DS4G, DS4G, TMP, turbomolecular, RF ion thruster, anisotropic

In order to push the envelope of ion thruster performance for interplanetary transit applications, various electric propulsion concepts have been presented in the past, one of them being the Dual-Stage 4-Grid thruster (DS4G), an electrostatic RF ion thruster concept proposed by D. Fearn [1]. Unlike other thrusters in this category, DS4G uses a grid configuration that decouples the electrostatic potentials used in ion extraction and acceleration, which in turn lifts the performance limitations of previous designs in terms of power density, thrust density, exhaust velocity, and specific impulse [2]. An Australian-built [3] experimental prototype of DS4G was successfully tested at ESA-ESTEC Propulsion Laboratory in 2005-2006 by the European Space Agency's Advanced Concepts Team [4].

This paper seeks to obtain even more performance from electrostatic RF ion thrusters, and from the promising DS4G design in particular, through introduction of an assisting subsystem that is based on the main operating principle of turbomolecular vacuum pumping technology – transmission of turbine rotor's impulse to neutral gas atoms. In practical terms, such solution results in the addition to DS4G of a mechanical device based on a Turbomolecular Vacuum Pump design (TMP). Abstractly speaking, the ultimate goal of TMP in this application is to improve performance of such electrostatic RF ion thruster as DS4G by Low Voltage mechanical means.

The feasibility assessment of such subsystem will begin with a few parameters that pertain to plasmas. The principle of operation and the effect of TMP on DS4G will be identified and discussed. Basic feasibility will be discussed in terms of atom/ion speeds, and at this point ignoring many plasma parameters, including electron interactions, energy distribution functions, electrostatic potentials, plasma drift, and so forth, until the future steps in this research.

Dual-Stage 4-Grid Thruster Design

Ion thrusters consist of two major process-defined technological elements: plasma generator and plasma accelerator. [5] The principle of operation of RF ion thrusters, including DS4G, can be summarized as follows: neutral (e.g. Xenon) gas is fed to produce an RF plasma from which ions are electrostatically extracted and accelerated through ion-optics grids to produce the thrust that powers a spacecraft. According to Ahedo: "*Genuine plasma thrusters ionize nearly all the gas injected in them. Typical ranges of plasma densities and temperatures are* $n_e \sim 10^{17}–10^{20}$ m $^{-3}$ *and* $T_e \sim 2–40$ eV." [6] For comparison, the RF plasma density measured [7] for ESA's DS4G experimental prototype was 2.5 x 10^{17}-1.23 x 10^{18} m^{-3}.

The experimenters testing the DS4G thruster identified three [8] subsystems in their laboratory prototype:

- "*Mechanical subsystem: clamping mechanism including aluminium clamp end plates, clamp posts, and thrust balance mounting ring.*" [9]
- "*Radio-Frequency (RF) subsystem: gas injector, ceramic plasma source tube, 3-turn antenna, stand-off transformer, impedance matching box, RF generator.*" [10]
- "*High Voltage (HV) subsystem: interchangeable grid module with four grids and three ceramic inter-grid spacer rings, HV vacuum feedthroughs & connectors, two HV power supplies rated to maximum voltage of 35 kV and current of 80 mA and one LV power supply.*" [11]

The Radio-Frequency Subsystem is used in the plasma generator, the High Voltage Subsystem powers the electrostatic potentials in the ion-optics grids of the plasma accelerator, and the Mechanical Subsystem holds all thruster parts together.

This paper treats the subject of such ion thrusters in very limited scope, namely considering only the plasma generator's chamber, and the screen grid, which is the plasma accelerator's first grid bordering with the plasma generator's chamber.

Turbomolecular Vacuum Pump Design

Turbomolecular pumps are used to create high to ultrahigh vacuum inside a vacuum vessel. A representative turbomolecular pump design consist of a turbine rotor that spins at speeds [12] up to

~80,000 rpm and that features a series of multiple-bladed disks that are interspersed with multiple-bladed stationary stator disks on the internal surface of the pump‘s essentially cylindrical body. Existing TMPs’ pressure range is $>10^{-3}$ Torr to $<10^{-10}$ Torr [13], which overlaps with the vacuum values in Low Earth Orbit [14]. Due to the high rotation speeds, the rotor is ideally suspended on magnetic levitating high-speed bearings and is ideally driven by a DC motor.

In its conventional role, TMP is plainly redundant in spacecraft applications, particularly in terms of its gas compression performance, because the outer space environment already exhibits the vacuum conditions that such pumps are designed to achieve, and internal vacuum inside a spacecraft is elegantly achieved by venting into the vacuum of outer space. Instead, the mechanics of interest to this paper in TMP is best described as:

> *“The turbomolecular pump is a bladed turbine... The rotor impulse is transmitted to the particles by the superimposition of the thermal velocity of colliding particles with the velocity component of the moving rotor surface. The nondirected motion of the particles is changed to a directed motion... The moving disks have a high rotational speed, so that the peripheral speed of the blades (up to 500 m/s) is of the same order of magnitude as the speed of the molecules of the pumped gas.”* [15]

The use of TMP here has been conceived on one initial premise – a rotor blade’s transfer of momentum to the neutral gas atoms it hits during its high-speed rotation as those atoms emerge from the gas injector into the plasma generator’s chamber. Thus TMP is sought as a candidate subsystem of DS4G for producing an atom flux speed that is independent (although still within the range) of the 35 L/s – 10,000 L/s [16] speeds currently used in vacuum pumping.

Introducing TMP-DS4G Concept

An ion thruster’s plasma generator can be characterized as an essentially isotropic-flow device, and the thruster’s plasma accelerator as an essentially anisotropic-flow device, where at present anisotropy begins at said screen grid.

The conventional wisdom in an ion thruster design is for the gas injector to release neutral Xenon gas into the plasma generator’s chamber. This neutral gas flow will have a gradient and a diffusion coefficient. [17] The problem with the neutral gas gradient and diffusion is that the resultant ions have isotropic distribution, yet the concept of ion extraction using the screen grid is anisotropic.

Application of TMP to DS4G thruster offers an opportunity to introduce anisotropy into neutral Xenon flow before it enters the plasma, and thus in theory to turn the presently isotropic plasma generator into an anisotropic-flow device that outputs anisotropic-flow plasma. The TMP, by the impacts of atoms with its bladed rotor disks, turns isotropic neutral gas flow into an anisotropic atom flux that, if directed to fly through the plasma generator’s chamber, can be ionized on its flight path toward the screen grid.

Anisotropic TMP flux, in other words a loose stream or beam of neutral atoms, can be theoretically considered as a solution to maximizing ion flow through the screen grid per molecular flow of neutral gas through the injector, and as a solution to reducing ion losses to the side walls of the thruster’s plasma generator chamber.

In the concept introduced in this paper, neutral gas injection into the ideally conical [18] chamber of the plasma generator is carried out through TMP, more precisely the gas is injected into TMP inlet toward the rotor blades, and an anisotropic atomic flow exits TMP into the plasma generator’s chamber.

The blades on a TMP disk can be designed to provide either a high pumping speed or a high compression ratio. [19] Since the purpose of TMP in DS4G is to direct ions toward the screen grid through the plasma, then the pumping speed is a more consequential variable than the compression ratio. The second variable of interest in this TMP application that is determined by disk blade geometry, rather than said compression ratio, becomes the effective range of directions imposed on the atoms of the anisotropic TMP flux by the last disk’s blades aiming into the plasma generator’s chamber.

TMP Pumping Speed for Unidimensional Ionization Flight Path Analysis

The starting point for looking into the velocities involved in this idea is to simplify the initial assessment and limit it to one dimension and speed. The most important anisotropic direction in DS4G is the x-axis along which the process handover takes place between the plasma generator (chambre with plasma) and the plasma accelerator (screen grid). The x-axis is the lengthwise axis of the DS4G thruster body and is the direction of its thrust.

The pumping speed for TMP is conventionally defined as the "*volumetric rate at which gas is transported across a plane… and in SI it is expressed in units of m^3/s…L/s or m^3/h are also used…*" [20] The conventional formula for TMP's pumping speed is hence $S = Q / P$, where Q is the gas throughput and P is the pressure at the measured plane. [21]

In contrast to the just mentioned TMP volumetric rate and its published figures, for DS4G thruster design both plasma and thrust calculations will logically require quantitative data on particle flux [22] that permits factoring in of particle masses. Despite the irrelevance of the volumetric rate of existing TMPs, its published figures may still be used in initial feasibility assessment of TMP-DS4G. Using another equation for particle flux [23], Equation 1 shows the neutral gas atom flux Γ_{TMP} (Gamma) that is accelerated by TMP blades into the plasma en route to the screen grid's effective surface area:

$$\Gamma_{TMP} = n_{TMP} \cdot \langle v_{TMP} \rangle \qquad (1)$$

where:
n_{TMP} – neutral gas atom density that is given the momentum of TMP blades
$\langle v_{TMP} \rangle$ – average speed given to neutral gas atoms by TMP blades

For a single TMP-accelerated neutral gas (e.g. Xenon) atom, the atom's mass (Xenon 131.293 amu) [24] for simplification may be considered negligible in comparison to a TMP rotor blade during an elastic momentum-transfer collision, and it can be assumed during an initial assessment that the neutral gas atom is given the speed of the TMP rotor blade, which is, as mentioned here, is in the range of up to 500 m/s.

At the same time, this TMP-given atom speed has to be slow enough for an extremely high probability of ionization of the atom during its flight through the plasma (prior to it arriving at the screen grid). Assuming atomic mass and speed negligible in comparison to a TMP rotor blade during an elastic momentum-transfer collision, and assuming the atom is given the speed equal to that of the TMP rotor blade while ignoring the plasma, an order of magnitude of the duration of such atom's flight through the chamber can be demonstrated: a collisionless ballistic flight through the plasma with chamber length say 0.5 m can take such atom at 500 m/s in the range of 0.001 s and at 250 m/s in the range of 0.002 s. This is the time interval within which the TMP-accelerated neutral gas atom flux Γ_{TMP} must be ionized with extremely high probability, a short interval as it is, and moreover raising a possibility that additional requirements would have to be imposed on the ion thruster's Radio-Frequency Subsystem. If the achieved ionization rate cannot keep up with the fast atom flux Γ_{TMP}, the TMP-accelerated atoms would pass the plasma generator's chamber length as non-ionized neutrals and either exit through the screen grid or bounce backward toward TMP. If the speed of TMP-accelerated atom flux Γ_{TMP} is too high at the screen grid, yet the atom flux has been successfully ionized on its flight path through the plasma generator's chamber, such ion flux will bombard the screen grid and erode it, while grid erosion has already proven to be an engineering challenge for ion thrusters [25].

Collisional TMP Regime in Plasma Generator

Considering a neutral gas (e.g. Xenon) atom that is hit by a high-speed TMP blade, not considering here the blade geometry, and limiting the discussion to unidimensional analysis in terms of speeds, the atom will be set on a ballistic flight path through the plasma generator's chamber toward the screen grid, where it would ideally arrive as an ion and be picked up by the grid's electrostatic potential.

If the plasma generator's chamber contains isotropic plasma with a density n_0 of heavy particles, such TMP-accelerated atom/ion will undergo a number of momentum-transfer elastic collisions with such heavy particles as ions and neutrals during its flight through the chamber. For the given TMP momentum to have an effect on such atom at the destination screen grid, the TMP-accelerated atom must have a speed that is sufficiently great so that the number of collisions it will undergo with ions and neutrals will not diminish its grid-bound speed component before finally reaching the screen grid. Restating it, the TMP-accelerated atom speed has to be such that the atom has sufficient kinetic energy to overcome all elastic collisions with isotropic heavy particles (ions and neutrals) in the plasma and still arrive at the screen grid's surface plane with a fraction of the TMP-given speed. If the grid-bound TMP-accelerated atom/ion transfers some of its kinetic energy gained from TMP to the ions/atoms it collides with in the plasma, then this effect may be potentially looked at as a TMP flux multiplier.

A rough estimate of the path of the TMP-accelerated atom is the x-axis length L_{PG} of the plasma generator's chamber, measured from the TMP outlet to the screen grid. Because the average distance travelled by a TMP-accelerated atom before it collides with other heavy particles in plasma can be expressed in terms of the mean free path λ (lambda), $\lambda=1/(n_0\sigma)$ [26], with n_0 as the density of heavy particles and σ (sigma) as their elastic collision cross-section, then the average number $\langle N_C \rangle$ of elastic momentum-transfer collisions the TMP-accelerated atom will undergo on a simplified unidimensional path can be taken as the fraction L_{PG} / λ, the length of the chamber divided by the mean free path. Hence Equation 2,

$$\langle N_C \rangle = L_{PG} / [1/(n_0\sigma)] \qquad (2)$$

Given that the mean free path λ is dependent on the density n_0 of isotropic heavy particles in plasma, it can be assumed that unless the anisotropic TMP-accelerated flux Γ_{TMP} (Eq. 1) has a macroscopic effect on the mean free path λ, then in the conditions of consecutive collisions of anisotropic TMP-accelerated ions with isotropic plasma ions and neutrals, the required speed that must be given to neutral gas atoms by TMP may be said to be linearly proportional to chamber length L_{PG}, which is a major dimension of thruster size and hence a limiting engineering factor. This characterizes a **collisional TMP regime** in DS4G.

With increasing TMP-accelerated anisotropic atom flux Γ_{TMP} within the total released gas flow, some inverse proportionality can be foreseen with the number $\langle N_C \rangle$ (Eq. 2) of elastic collisions encountered by the flux atoms/ions during their flight through the plasma generator's chamber. If neutral gas atom density n_{TMP} (Eq. 1) that is given the momentum of TMP blades approaches the total released neutral gas density in the plasma generator's chamber, then it may be possible to discuss a **collisionless TMP regime** in DS4G, resulting in a collisionless ballistic flight of TMP-accelerated atoms of flux Γ_{TMP} toward the screen grid, which may have significant implications for ionization rates and could possibly result in plasma decay, both possibilities needing further investigation.

Electromagnetic Complexities of Realization of TMP-DS4G Concept

Integration of a TMP subsystem into DS4G's plasma generator chamber presents technical challenges in concept realization due to the magnetic fields in the plasma generator. Magnetic bearings, magnetic fields of the DC motor, eddy currents of the rotating turbine rotor, and magnetic containment of TMP outlet into the plasma generator's chamber, represent a number of interacting magnetic fields in close proximity to the plasma.

Due to high TMP rotor speeds in the range of 24,000-80,000 rpm [27], levitating magnetic bearings are used in commercial TMPs, and are also desirable for use in DS4G due to problematic use of lubricants in outer space and in order to eliminate maintenance requirements in long interplanetary flights. The magnetic fields that this magnetic suspension technology generates in its vicinity may pose interference issues with the RF coil, with the generated plasma, and with magnetic plasma containment fields (if used). One direction for finding a solution to this problem is to seek a design of the magnetic fields for the levitating bearings in favorable mutual positioning with the magnetic fields in the plasma generator. Another direction for a search of solutions is to move the magnetic bearings away from the plasma generator's chamber by employing a longer rotor shaft. The same problems apply to the magnetic fields from TMP's DC motor.

If the TMP rotor is fabricated from a metal, most likely an Al alloy [28], then the following engineering experience from previous TMP designs applies to it: "*metallic rotors experience induction of eddy currents... Therefore, TMPs with metallic rotors can be used in magnetic fields only if certain maximum values of the magnetic flux density will not be exceeded. These maximum values are specified by the manufacturers and, for static magnetic fields perpendicular to the axis of rotation, typically are in the range of 10 mT to 30 mT (tesla).*" [29] This problem can be overcome by a ceramic rotor [30], for example Si3N4 [31], although this solution would require additional development effort.

If TMP is installed with its outlet facing the plasma generator's chamber, the question is what will happen with the RF sheath and possible ion bombardment of the TMP rotor and stator blades by ions from an isotropic plasma. Another question is what will happen to the sheath if the majority of ions in the plasma belong to the TMP-accelerated flux. One solution that should be considered to account for the sheath at the TMP outlet is magnetic plasma confinement to shield the TMP outlet from the plasma, because magnetic multipole boundaries have already been used in some ion thrusters for „*electrostatic confinement of the ions from the… wall due to the quasiambipolar potentials at the boundary from the transverse magnetic fields*" [32]

When looking at the listed electromagnetic components, the question that arises is whether TMP will pay off in an ion thruster, even if the outlined principle of its operation is successfully verified in DS4G. How will TMP and its prospects for future performance improvement compare with those of the electrostatic RF ion thruster technology per se? The energy that is continually supplied for thousands of hours of ion thruster operation to the levitating magnetic bearings, to the DC motor, to the magnetic containment of TMP outlet, all that energy can instead be employed to produce and accelerate more ions. Extra mass of TMP could have been extra Xenon gas mass in the propellant tank. One way of looking at the possibilities is to assume that the energy required to hypothetically increase an ion thruster's performance by a mechanical turbomolecular pump could be lower than the energy required to do the same work with RF-driven electric fields, and then test such hypothesis through theoretical calculations.

It can also be assumed that at higher power levels of DS4G, the effect of TMP on the thrust at constant TMP energy consumption would be more noticeable. A turbomolecular pumping mechanism, being an auxiliary subsystem, can be powered by a Low Voltage source, such as spacecraft-hull-mounted solar cells, thus not having to divert additional energy from such main High Voltage source as a nuclear reactor onboard a power-hungry spacecraft in deep space that constantly requires energy for the plasma generator and for the plasma accelerator in the thruster. Whether such assumption is justified is open to investigation.

The bottom line of application of TMP in DS4G is that TMP must favorably compare with an identical thruster without TMP by at least a factor of 1.1 in order to provide a detectable performance increase and to exhibit notable potential for future performance improvement due to design maturation; equally, TMP must be responsible for superior thrust characteristics when compared to the results of the energy to be consumed by TMP diverted instead to the thruster's existing components, e.g. electrostatic potentials of the ion optics grids.

Conclusion

This paper has envisaged a combination of two obviously unrelated technologies, the turbomolecular vacuum pump that is of no use in its conventional role when its outlet faces the outer space vacuum, and an ion thruster concept (DS4G) for spacecraft, as schematically summarized in Fig. 1. The kinetic momentum transfer principle of the turbomolecular pump's operation and the pump's parameter, the pumping speed, have potential use in improving the performance of an ion thruster. Thus the turbomolecular pump was considered here as a candidate subsystem of the DS4G ion thruster and as a stage of the thruster's ion generation-acceleration process.

The method of feasibility assessment of this idea in this paper has been to start with a few basic parameters, with the understanding that subsequently it is necessary to introduce more parameters and reconsider their relationships, resulting in a deliberate increase of complexity of analysis. Thus this paper has proven to be only a beginning of such assessment, and if the idea described in this paper successfully survives an assessment in terms of a few very basic parameters, then the assessment can continue with gradually increasing the complexity toward a realistic description of the plasma processes and conditions involved on par with that of matured competitive thruster designs.

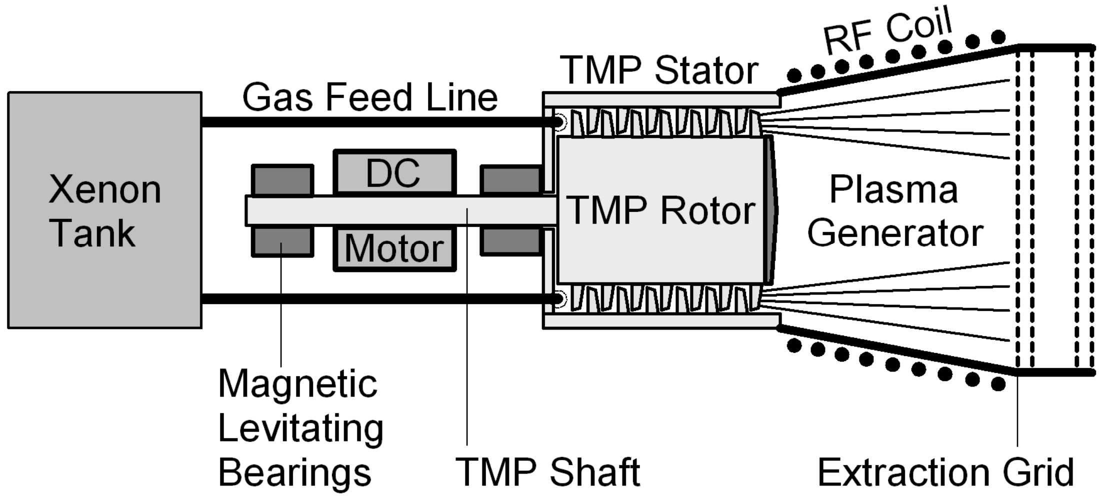

Fig. 1. Schematic diagram of the proposed turbomolecular pumping stage in an RF ion thruster.

Next steps in the feasibility assessment of this idea will focus on four following areas:

1. Adjustments in the unidimensional speed model to account for isotropic velocity distributions, Bohm velocities, plasma drifts, and so forth.
2. Focused investigation into momentum-transfer collisions within the plasma inside DS4G thrusters, particularly into energy exchange fractions, collision cross-sections, rate constants, velocity distribution functions, and averaging the scattering angle [33] for isotropic heavy particles. Chamber length L_{PG} will be adjusted to account for the plasma length, including the sheath and pre-sheath widths.
3. Investigation into plasma generation, isotropic plasma conditions, and plasma decay, in presence of anisotropic atom flux Γ_{TMP} (Eq. 1). The effect of anisotropic atom flux Γ_{TMP} on ionization rates has to be theoretically predicted, as well as how anisotropic atom flux Γ_{TMP} will affect plasma density inside the plasma generator's chamber.
4. The interaction between the moving anisotropic neutral atom flux Γ_{TMP} that exits the TMP stage into the plasma chamber, and the RF-driven electric fields in the chamber, will be investigated in the reference frame where the anisotropic neutral atom flux Γ_{TMP} (representing heavier, slower particles) is stationary, and the RF-driven electric fields (representing lighter, faster particles) are moving – using the analogy of a car moving on a road intersected by a railway crossing, as seen from an approaching train's frame of reference.

If TMP proves to be theoretically useful for the proposed application, and is verified as a concept in laboratory, it would lead to a highly specialized TMP design for a specific DS4G thruster model, and if competitive as a technology then also lead to a family of TMP-assisted thruster designs. If theoretical and laboratory success would not be the case, then this consideration of this particular idea may help broaden the search for subsystem-level solutions to the technological progress in ion thruster technology.

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Footnotes

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