

Plasma Thruster Beam Expansion and Impingement in Space Debris

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Abstract— Accurate understanding of the expansion of the plasma plume of an electric propulsion system is a central aspect for a novel space debris deorbiting system known as Ion Beam Shepherd (IBS). Semi-analytical and hybrid/PIC simulation strategies are adopted to characterize the near-collisionless, far-region plasma plume, its impingement upon a space debris, and the plasma-body interaction. The plasma cooling over a wide region, the effect on the expansion of external magnetic fields (the naturally-occurring Earth field or an applied one), and the relative charging of the two bodies are discussed.

Keywords—plasma plumes, electric propulsion, space debris removal, momentum transfer, sputtering, relative charging

I. INTRODUCTION

The increasing amount of space debris in the most crowded orbits (low Earth orbit (LEO) and geostationary orbit (GEO)) is becoming a serious threat for the long-term utilization of space by mankind. Collisions of debris with active spacecraft as well as with other debris have occurred and are expected to continue, posing a serious threat for space activities in the near future. Existing predictions warn that we have already crossed the line beyond which collisions and explosions will continue to raise the population of orbital debris objects even when no additional launch took place [1]. In view of the growing risk for existing and future missions, agencies are beginning to search for active removal strategies that can solve the space debris problem.

One of the proposed solutions is the Ion Beam Shepherd (IBS) system, whereby a “shepherding” satellite is used to bring down or reposition critical pieces of space junk with the help of a highly-efficient plasma beam [2-4]. This beam, produced onboard the IBS with an appropriate plasma thruster, is directed to the target body to transmit the momentum carried by the plasma and deliver the required deorbiting ΔV . While the maneuver takes place, a secondary thruster acts in the opposite direction to maintain the relative distance between the IBS and the debris. In this way, the IBS, placed in the same orbital track as the debris, can accompany the object through the deorbiting/reorbiting process. A crucial advantage of the IBS approach over other proposed concepts relying on the mechanical capture of the target is that it removes completely the necessity to perform any docking maneuver with the uncooperative body (which is potentially tumbling and with large angular momentum). This *contactless* mode of operation, together with the fact that the IBS can use off-the-shelf, existing technology and the possibility to employ a single shepherd to

sequentially deorbit a selection of dangerous pieces of debris, makes the IBS system a promising option for active debris removal.

Nonetheless, before the IBS becomes an operative solution, a series of challenges need to be addressed in detail. A central aspect is to accurately understand the physics of the expanding plasma plume that is used to transmit the necessary force to the target, including the weak effect of collisions, background plasma, magnetic/electric fields, and the phenomenon of relative electric charging between the IBS and the debris. This poses the problem of studying a very wide plasma region (5–30 m long) whose density ranges in various orders of magnitude (from 10^{16} – 10^{18} m^{-3} at the thruster exit down to 10^{12} – 10^{14} m^{-3} downstream where the debris is). The difficulty of experimentally characterizing such expansion in the lab, associated with the high vacuum levels and large vacuum tank needed to limit artificial background effects, suggests approaching the problem by modeling and simulating the plasma plume.

Secondly, there is the need to study in-depth the plasma-body interaction. This concerns the macroscopic and microscopic description of the impingement of the energetic beam ions (kinetic energies in the order of some keV), their penetration into the outer layers of the debris material, the transmission of linear and angular momentum to the target, the ejection of sputtered materials from the body and the possible contamination of the IBS or the generation of micro-debris.

To find an answer to these and other challenges, the European Commission is supporting the LEOSWEEP project (improving Low Earth Orbit Security With Enhanced Electric Propulsion, [5]) within the 7th Framework Programme. LEOSWEEP is a three-year-long project, being carried out jointly by a consortium of 11 partners distributed over Spain, Germany, France, UK, Portugal and Ukraine, and aims at demonstrating the technological feasibility of the IBS concept proposing a first active removal mission of an Ukrainian rocket upper stage, prove its economic viability, and present a convincing legal and policy implementation to “kick-start” large-scale active debris removal activities. LEOSWEEP project goals and planned activities in the area of plasma-body interaction were recently presented at another conference [6].

The present paper discusses the physics of the expansion of a plasma plume and its interaction with a free-floating body immersed in it, from the viewpoint of the IBS application. We start with an introduction to semi-analytical models of the far-region of a plasma plume, which are notably useful to extract

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and understand the dominant aspects of the expansion (section II). The development plans and status of an advanced fluid/particle-in-cell hybrid code, named EP2-PLUS (Extensible Parallel Plasma PLUme Simulator), for the detailed study of the multiple physical phenomena occurring in the expansion are then briefly presented (section III). This code aims not only at simulating the far-region expansion, but also the lateral region, of particular interest for spacecraft-plasma interaction studies. The effect of collisions, background magnetic fields and particles, and the relative charging of the IBS spacecraft and the debris is discussed at a preliminary level. Finally, the possibility of using an applied magnetic field to create a “magnetic nozzle” that guides the plasma plume to limit its divergence and reduce the ion backflow to the IBS spacecraft is introduced (section IV). Conclusions are gathered in section V.

II. SEMI-ANALYTICAL PLASMA PLUME MODELS

A fast and simple model to easily analyze the main physics of the plasma plume expansion is a valuable tool for the preliminary characterization of the plasma density and velocity profiles, and for the exploration of the main parameters controlling the plume expansion. An example of such a model is the self-similarity two-fluid plasma plume model (SSM), described next.

As the plasma exits the thruster, a first region exists where collisions are still important, and the neutralizer and any internal magnetic fields induce an important perturbation. The kinetic energy of outgoing ions is typically in the range of some keVs, while the temperature of electrons is a few eV, meaning that the exiting plasma is markedly hypersonic. In this near-region the plasma homogenizes and produces a bell-shaped profile after a few thruster radii [7,8]. Downstream, however, all these effects gradually become negligible, and the evolution of the plasma plume is essentially dictated by the residual electron and ion pressures, and by the ambipolar electric field. In this far-region, the plasma expands near self-similarly, conserving to a good degree of accuracy its radial profile.

Exploiting this feature of the expansion, Parks and Katz [9], Korsun and Tverdokhlebova [10], and Ashkenazy and Fruchtmann [11] developed a series of self-similar models of the quasineutral ($n_e = n_i = n$), collisionless far-region plume based on the axisymmetric fluid equations of ions and electrons,

$$\begin{aligned} \nabla \cdot (n\mathbf{u}_j) &= 0, \\ m_i(\mathbf{u}_i \cdot \nabla)\mathbf{u}_i &= -e\nabla\phi, \\ 0 &= -\nabla p_e + en\nabla\phi, \end{aligned} \quad (1)$$

where $j = i, e$ for ions, electrons; the ion pressure and electron inertia have been neglected; and all other symbols are conventional. While these models neglect several aspects of the plume that are important for the full characterization of the expansion, such as the processes that take place in the near-region, the effect of collisions, and external fields, they have demonstrated a good accuracy when compared to lab measurements of different plasma thrusters [10,12,13], and have been successfully used already in preliminary studies of the IBS concept [4,14]. They do however under- or over-estimate the density in the peripheral plasma plume [12], a region that is

critical for other applications such as the accurate study of solar panel interaction with the plasma. The derivation of a generalized form of these models to support any valid density profile and a simple polytropic cooling law for electrons can be found in [15], and it is only summarized here for completeness.

The basic concept relies on the assumption that all plasma streamlines expand self-similarly as $r = \eta h(z)$, where η is a function that labels the streamlines, and $h(z)$ is the so-called self-similarity function, which describes how the streamline radius increases (with $h(0) = 1$). From this relation, it follows that ion velocity components obey

$$u_{ri} = u_{zi}\eta h',$$

and, after a separation of variables in (z, η) and some algebra, an approximate solution of the original fluid equations for hypersonic plasma plumes reads:

$$\begin{aligned} n &= n_0(\eta)/h^2(z), \\ u_{zi} &= u_{zi0}(\eta), \end{aligned}$$

i.e., the plasma density maintains its initial profile n_0 in η and decreases as h^2 as the plume expands, whereas the small increase in axial velocity in highly-supersonic plasmas is neglected and assumed constant and equal to the initial profile u_{zi0} . This generates a local error $\propto M_0^{-2}$ in the obtained solution, where $M_0 = u_i/\sqrt{T_e/m_i}$ is the plasma Mach number, and hence is small in the present case where $M_0 \gg 1$ (usual Hall effect and ion thrusters have Mach numbers that range between 15 and 30). A mathematical compatibility constraint exists between the u_{zi0} and n_0 profiles, given by

$$u_{zi0}^2 \propto -n_0^{\gamma-2} n_0' / (C\eta),$$

where C is a constant and γ is the effective cooling rate of the electrons, assuming a polytropic cooling law $p_e \propto n^\gamma$. Finally the $h(z)$ function results from solving the equation

$$h^{2\gamma-1} h'' = C/M_0^2. \quad (2)$$

For the sake of illustration of the results that this model can provide, the plasma density and the h function are plotted in a wide region in Fig. 1 for the case where $u_{zi0} = \text{const.}$ and $\gamma = 1$ (isothermal electrons), which coincides with the Parks and Katz variant of the model [9].

The SSM allows the study of the effect of the plasma Mach number and the velocity profile on the plume divergence angle, one of the key performance figures for the IBS application. Clearly, a smaller divergence angle allows a larger fraction of the plasma to impact on the target debris, improving the momentum transfer efficiency, or alternatively, allows a larger (safer) distance of operation. Therefore, one main objective is to understand how to reduce the divergence angle of the plasma plume. The divergence angle and its dependency on these parameters is illustrated in Fig. 2. Interestingly, as evidenced by the dependency on M_0^2 in (2), the far-region divergence angle of the plume depends strongly on M_0 , and not so much on δ_0 , the initial divergence angle at the thruster exit lip ($z = 0, r = R$). This result is especially true in the small δ_0 and M_0 range, and stresses the importance of focusing on increasing the specific impulse of the thruster (i.e., its exit velocity u_i) or decreasing

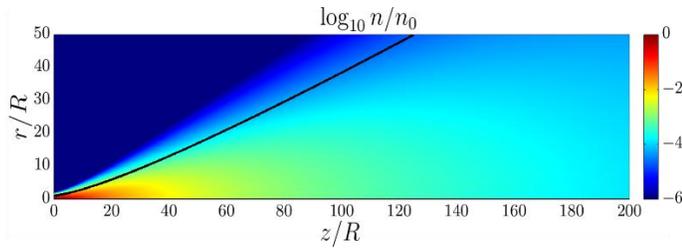


Fig. 1. Normalized plasma density map in the plume (logarithmic scale). The figure axes have been normalized with the initial radius of the plume R . The black line is the streamtube containing 95% of the total plasma flow, and is given by the $h(z)$ function. The case shown here uses $\gamma = 1$, $M_0 = 15$, and an initial divergence angle of 6 deg. This angle has increased to 25 deg already at $z/R = 100$.

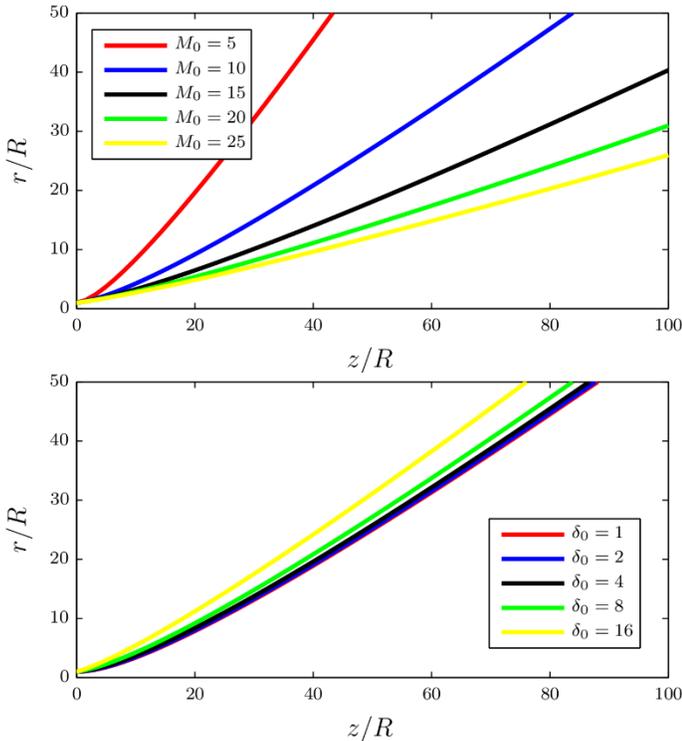


Fig. 2. Effect on the far-region plume divergence angle of the Mach number for an initial divergence angle of $\delta_0 = 8$ deg (upper figure) and the initial divergence angle for $M_0 = 10$ (lower figure, angle in degrees). Shown in the figures is the h function of Eq. (2), which reflects the shape of ion streamlines. A lower Mach number causes a faster divergence of the plasma due to the larger pressure effects, compared to the convective term. In contrast, a higher Mach number practically leaves the initial divergence angle unchanged. The effect of decreasing the initial divergence angle on the far field is minimal if the Mach number is moderate (lower figure). R is the initial radius of the ion streamline.

the electron temperature in the plume to ensure a high Mach number and a lower effect of the residual pressure on the expansion.

As discussed in the next section, a central issue of the plume expansion is the modeling of the electron cooling behavior. In the present model, this is done through the effective polytropic cooling exponent γ , which can be estimated from experimental data. Cooling has a strong influence on the local Mach number, and hence directly affects the divergence of the plasma plume. Moreover, the total electric potential drop $\Delta\phi$ along the plume

is strongly dependent on γ , with $\Delta\phi$ being infinite in the isothermal limit (and smaller the higher γ is).

III. DEVELOPMENT OF A HYBRID/PIC PLASMA PLUME CODE AND ADVANCED PLASMA PLUME PHYSICS

Modeling the advanced physics of the expansion of the plasma plume is a central objective of LEOSWEEP, and necessary to understand and optimize the momentum transfer mechanism of the IBS. While useful in providing a preliminary description of the main aspects of the expansion, the SSM of previous section is limited in the physical processes it can unveil.

Hence, within the planned activities in LEOSWEEP, UC3M has recently initiated the development of an advanced 3D fluid/PIC (particle-in-cell) code, named EP2-PLUS. The code has the ambitious goals of studying the collisionless electron cooling mechanisms, the effect of the geomagnetic field on the plasma expansion to identify whether any deformation of the beam takes place, and analyzing the relative electric charging between the two bodies. Other effects that will be simulated are the collisional processes within the plume and with a background plasma, and the evolution of sputtered materials from the debris and backstreaming ions. Additionally, while in the framework of LEOSWEEP the central plume and the downstream region concentrate all the research effort and interest, the code is being developed to provide an accurate description of the lateral region of the plume as well, which is particularly relevant in a number of spacecraft-plume studies (solar panel erosion and contamination, spacecraft charging, etc.).

The general description of the code is as follows. The core of the code is composed of a hybrid fluid-PIC engine that treats the heavy particles (ions of different types, neutrals, background species, and sputtered atoms/clusters) as discrete particles, while electrons are modeled as a fluid. Or optionally, as particles for pre-established intervals. This approach, compared with a full-PIC [16] one, can potentially require less computational resources, while allowing the update of the transport coefficients for electrons.

Particles are followed explicitly in time using a leap-frog integration scheme, which is executed out-of-phase with the electron fluid and electric/magnetic field computation. After advancing the particles, these are weighted in a structured 3D mesh that is crafted after the shape of the streamlines in the SSM of previous section, to better adapt to the expected plume shape. Electrons and fields are then solved with the ion data on the mesh points. Both the electrostatic and magnetostatic fields are solved in this step. Current development plan is to use quasineutrality to estimate the electron density, and add the Poisson equation solver at a later stage. The resulting fields are interpolated back at the particle positions, so the code can then proceed with the integration of their motion. The described approach allows to resolve particle motion and electrons/fields with second-order accuracy in time and space. Figure 3 presents a sketch of the hybrid/PIC engine operation.

The code is being developed using the usual test-driven-development (TTD) approach to facilitate the verification and validation of the final tool. Parallelization is being taken into

account as an integral part of the development, and is included in every critical subroutine from start. Care is being taken to adhere to existing data format standards to facilitate the

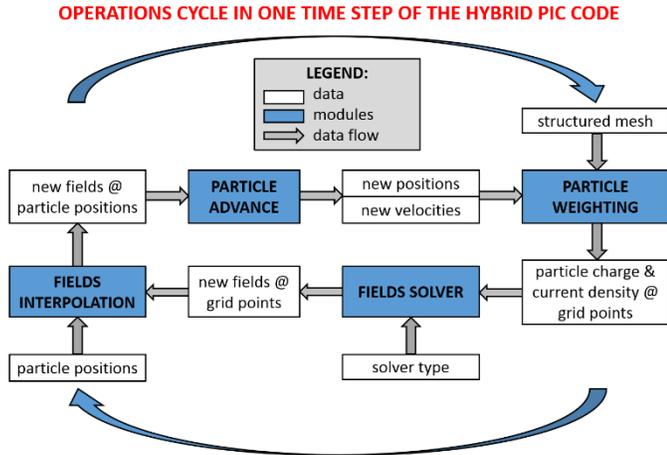


Fig. 3. Sketch of the hybrid/PIC engine operation for a single simulation time step.

interfacing to and from other codes like SPIS [17], and common postprocessing and visualization programs (both commercial and open source).

Three of the main physical processes and identified issues that the code is intended to address are briefly discussed next.

A. Collisionless cooling of the electron population

Collisionless electron cooling in the plume expansion is one of the main uncertainties in existing plume models, which has dire consequences on the plume divergence angle and ambipolar electric field (since a warmer plasma has a larger residual pressure and can develop larger electric fields).

Existing experimental measurements suggest that the electrons remain essentially isothermal at least in the near-region of the expansion [18,19,20]. Notwithstanding, it is well known that the electron population must eventually cool down to the ambient temperature, since a strictly isothermal expansion gives rise to an unphysical infinite potential drop as density goes to 0, as revealed by the integrated momentum equation (1) for isothermal electrons (Boltzmann relation):

$$e\phi = e\phi_0 + T_{e0} \ln n.$$

Hence, one or more cooling mechanisms must enable a gradual decrease in electron temperature in the plume as the plasma expands. Unfortunately, the collisionless electron expansion differs substantially from the well-known collisional expansion in a dense fluid, and therefore the cooling of the rarefied plasma cannot be studied with the usual Boltzmann relation approach nor the polytropic assumption of previous section: the electron cloud response has a strong *global* character, far from the “local” fluid behavior, and the electron population can be at least partially non-Maxwellian. In particular, non-Maxwellian populations and anisotropic features can be particularly important in the presence of magnetic fields.

Currently, the understanding of the collisionless cooling of electrons is rather limited. Preliminary advances in the

thermodynamic behavior of a collisionless population can be found, for a well-magnetized expansion, in [21] for a convergent subsonic plasma. The first results for a divergent, supersonic magnetized plasma will be soon presented in [22]. As the understanding of these mechanisms advances, a specialized cooling subcode will be developed and is planned to complement the EP2-PLUS scheme.

B. Deformation of the plasma plume by the geomagnetic field

One major concern in the IBS application is the potential effect that the geomagnetic effect can have on the expansion of the primary plasma beam: typically, electrons (but also ions, to a lower extent) have the tendency to follow magnetic lines, and remain tied to them unless collisions or drifts displace them. Given the weak geomagnetic field (about 0.5 Gauss in LEO), but also the weak collisionality, the natural question arises whether the electrons (and with them, the ions) will be deflected along the magnetic field lines. The occurrence of a major distortion of the plume could impede or severely hinder the application of plasma beams in the IBS system.

Existing studies on the effects of the geomagnetic field on plasma plumes predict the deformation of the plume profile after just a few meters from the thruster [23]: the magnetic field squeezes or limits the expansion of the plasma in the perpendicular direction, while promoting its expansion in the parallel direction.

These studies, however, seem to neglect the role of the plasma-induced magnetic field, which will arise in response to the external field as the plasma develops electric currents. This internal magnetic field opposes the external one and tends to expel it from the plasma domain, to allow the plasma to continue its motion unperturbed. While this mechanism dominates, the core of the plasma plume would be essentially shielded from the external field in a large region, and expand unaffected by it: the magnetic effect would concentrate on the lower-density, peripheral plasma.

Assessing the actual effect of the magnetic field over distances of 10s of meters, including the counter-action of the plasma-induced field, is another major tasks of the EP2-PLUS code. Magnetic deformation/distortion of parts of the plasma plume is also an important issue in spacecraft-plume studies, as a larger amount of plasma flux can be directed towards the solar panels by the geomagnetic field in certain parts of the orbit than in others (depending on the direction of the magnetic field).

C. Relative electric charging of the two bodies

A third aspect of interest in the study of the IBS-target evolution is the relative charging that the two bodies will develop. Relative charging is an important feature of close formation-flying objects, as it can cause a secular attracting or repelling force. Moreover, purposely-created Coulomb forces have been proposed as a plausible mechanism to maintain the desired formation flying configuration [24].

The relative charging of two bodies will depend on the usual processes that charge up an orbiting object, such as background plasma density and temperature, photoelectric emission, and energetic particle events in the magnetosphere. While the ambient plasma is expected to charge the two bodies nearly equally, the differential photoelectric emission from the

different materials of the two bodies can give rise to a different behavior.

However, the dominant charging mechanism during the IBS operation will necessarily be the effective “plasma bridge” — the primary plasma plume, made of electrons and ions at a few keV — that links the two formation-flying objects, which has a much higher density than the ambient plasma. It is expected that this plasma link between the IBS and target will establish an equilibrium relative charge, which will make negligible all other charging mechanisms.

Besides the potential effects on formation keeping, experimental observations in similar configurations show that plume divergence can also be affected by the charge of the debris object [25].

A detailed assessment of the electric charging will be carried out with the help of EP2-PLUS. Nonetheless, at this stage the expected qualitative behavior of the system can be described. During the initial instants of the IBS operation, the incoming plasma equalizes the charge of the two bodies towards the final equilibrium situation. The duration of this transient process, assuming infinite conductivity in the plasma plume, is the largest characteristic charging time of the two bodies, given by its electric capacitance. As the target body reaches its equilibrium charge, the electron and ion currents reaching its surface from the plume become equal, and a Debye sheath develops, whose structure depends on the electron temperature and the kinetic temperature of ions. The final relative charge will depend on the potential drop along the plasma plume, the Debye sheath that forms at the target object, and the electric configuration at the thruster exit.

IV. MAGNETIC NOZZLE FOR IMPROVED IBS PERFORMANCE

To conclude the discussion of the IBS system, we now introduce the concept of channeling the plasma plume expansion with a purposely applied, slowly-divergent magnetic field. This configuration is usually termed a “magnetic nozzle” (MN) [26-28], and constitutes an integral part of several advanced thrusters such as the helicon plasma thruster (HPT) [29], the variable specific impulse magnetoplasma rocket (VASIMR) [30], and the applied-field magneto-plasma-dynamic (AF-MPD) thruster [31]. These thrusters employ a convergent-divergent magnetic field to *contactlessly* accelerate a plasma into a supersonic jet, while protecting the inner walls of the thruster and the surrounding spacecraft surfaces from direct plasma erosion. The aperture, divergence rate, and strength of the MN can be adapted to tune the produced plasma plume to the requirements of the mission.

Much like a solid de Laval nozzle, the MN converts the internal energy of the plasma into directed kinetic energy, thereby producing thrust. The plasma flow is sonic at the section of maximum magnetic field (the nozzle “throat”), and supersonic in the divergent part. However, in a MN thrust production and transmission is based on the magnetic force between the field generator and the plasma, and there is the need to liberate the plasma from the closed-geometry magnetic lines. Figure 4 illustrates the expansion of a sonic plasma in a MN into the far-region and its separation downstream, using the numerical model of [27]. A detailed discussion of MNs and

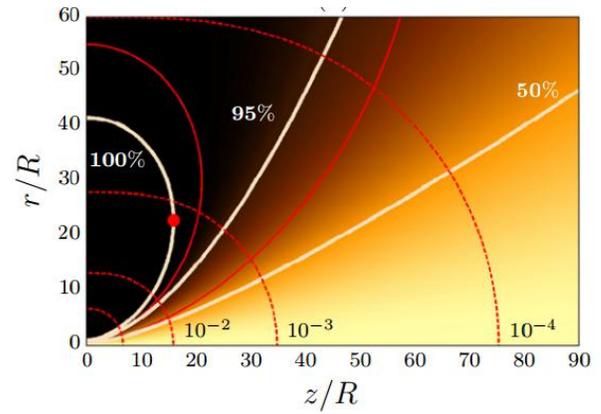


Fig. 4. Expansion of a plasma plume in a guiding magnetic nozzle, from [28]. The plasma is injected sonically at the nozzle throat (lower left part of the figure); ion streamtubes containing 50, 95 and 100% of the injected plasma flow are shown in yellow. The color map depicts the % of ion flux, integrated from the axis. Red solid lines represent the corresponding magnetic tubes. Dashed lines indicate the value of the magnetic field normalized with its value at the origin. Observe that most of the plasma does not turn back, and that according to this simulation, ion backflow is virtually zero beyond the 100% line. R is the initial plume radius.

associated physics can be found in that reference. Additionally, a MN can be applied to other types of thrusters as well (e.g. gridded ion thrusters), where the plasma is already highly-supersonic at the exit, although with a different behavior and effect [32].

A key advantage of MNs is their ability to eliminate or substantially reduce the backflow of plasma to the spacecraft in the lateral regions of the plume, which can amount to a large fraction of the flow in near-sonic plasma plumes. This is achieved by the magnetic confinement provided by the quasi-axial magnetic field. This principle of operation could enable the MN to tailor the divergence of the plasma plume for the desired application. Additionally, the MN could reduce the plasma and contaminant backflow to the satellite, potentially leading to backflow values lower than in ion and Hall effect thrusters. Moreover, the magnetic field of a MN could be used to envelope the spacecraft and its appendices in a protective magnetic shield. Lastly, observe that the magnetic environment around the spacecraft has a nontrivial impact on its electric charging as it affects the transport of electrons in and out of the satellite, an effect that needs to be assessed in detail. This and other studies regarding MNs will be addressed with EP2-PLUS, potentially in combination with SPIS.

Another interesting aspect of MNs is their potential capability to diminish the effects of the weak geomagnetic field, by providing a magnetic field considerably stronger that dominates the expansion. This would enable the plasma to expand essentially unaffected by it for a wider region, at least down to the zone where both magnetic fields become comparable.

The use of a MN in the IBS application could therefore be an alternative approach to the use of a conventional plasma thruster, which could potentially enable the transport of a higher plasma fraction to the target debris by reducing the natural divergence of the expanding plume. This positive effect slightly resembles the “needle” plume configuration predicted by

Korsun et al. [23] when an external magnetic field is applied coaxially with the plume axis. Since the IBS has to operate at distances of 5-30 m, the particular requirements for the IBS are a sufficiently slow-diverging magnetic field, which in turn demands large-radius solenoids, and a sufficiently high magnetic strength to shield the geomagnetic perturbation and the deformation by the plasma-induced magnetic field. A detailed assessment of these requirements, and the physics of the magnetized expansion, is necessary to evaluate the suitability of a MN for this application.

An open issue in the understanding of MNs is, like in the non-magnetized plume case, the identification of the mechanisms that enable the necessary electron cooling downstream. In this case, the strong electron magnetization in the larger part of the nozzle, and the later demagnetization region, can play a fundamental role [22].

V. CONCLUSIONS

We have presented the fundamental concepts behind the Ion Beam Shepherd space debris deorbiting system, and the objectives of LEOSWEEP. We have discussed several central aspects of the plasma plume physics and the plasma interaction with the target object and its environment. While outside of the scope of the present paper, other important aspects that the project needs to address are the mechanical interaction of the incoming ions with the target surface, their accommodation into it, and the sputtering of debris materials; the dynamics of the two closely formation-flying bodies; and the control strategies to approach the target and maintain the relative distance and position.

Self-similar models are a useful tool to estimate the main performance figures of the system, and understand the dominant physics in the expansion problem. More advanced tools, like the specialized EP2-PLUS hybrid/PIC code under development at UC3M, are necessary to characterize the physics of collisionless electron cooling, 3D phenomena such as the interaction with an external magnetic field (like the geomagnetic field in LEO), and the relative charging between the bodies. The EP2-PLUS code is planned to simulate as well the mechanical interaction of the plasma with the debris object, the ambient particles, and the erosion and contamination of the IBS spacecraft itself under the influence of the peripheral plasma plume.

Plasma cooling in both magnetized and unmagnetized plumes remains an open issue of large importance, as the electron temperature regulates the divergence angle growth rate and the magnitude of the ambipolar potential falls.

The effect of the geomagnetic effect on the plume expansion is another issue that requires detailed attention. Here, the capability of the energetic plasma beam to expel the external perturbation via its own induced magnetic field is a key process that needs to be modeled and implemented into the code.

The relative charging of the IBS satellite and the piece of space debris being deorbited has to be taken into account to maintain the required formation flying for the maneuver to take place. The conducting bridge created by the plasma plume joining the two bodies is expected to be the dominating effect in the charging process.

Lastly, magnetic nozzles have been proposed as an interesting complement to the IBS concept, which could be used to tailor the plasma plume shape and divergence, as well as to limit the influence of external magnetic fields. Also, the MN magnetically enables shielding the surrounding spacecraft, limiting the undesired ion and contaminant backflow and protecting it from energetic external charged particles.

ACKNOWLEDGMENTS

The research leading to these results has received funding from the European Union Seventh Framework Programme (FP7/2007-2013) under grant agreement n° 607457. LEOSWEEP project is being jointly developed by the international consortium between SENER, UPM, TransMIT, ITM, DLR, Yuzhnoye SDO, DEIMOS Engenharia, ISLC, University of Southampton, CNRS LPP and UC3M.

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