Electrodynamic Plasma System for Active Space Debris Mitigation

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Abstract: The paper describes a novel electrodynamic plasma system designed for the active removal of space debris from near-Earth orbits. The proposed concept develops previous research on plasma-based propulsion and environmental utilization of the ionospheric medium as a natural source of both matter and energy. In the present work, detailed modeling of the electrodynamic interaction between the plasma flow and debris fragments is performed, taking into account the parameters of the upper atmosphere, including the real distribution of neutral and charged particles at altitudes of 100-400 km. A new design of gas-dynamic trap and discharge chamber is introduced to increase the local density of captured particles, ensuring stable plasma generation without onboard propellant storage. The preliminary estimates of material and energy characteristics confirm the technical feasibility of the working out system.

1. INTRODUCTION

The growing population of artificial objects in near-Earth space poses a serious threat to current and future orbital operations. According to recent observations, more than 20,000 objects larger than 10 cm and millions of smaller fragments are presently tracked in low Earth orbit (LEO), forming a dense debris environment that endangers active spacecraft and future missions [1-4]. Therefore, the development of effective and sustainable methods for active debris removal has become one of the most urgent technological challenges of modern astronautics [5-8].

Nowadays approaches to debris mitigation include the use of mechanical nets [9], harpoons [10], laser ablation [11,12] or the charged-particle beams [13,14]. However, these systems require significant on-board propellant, power, or complex mechanical structures, which severely limit their operational lifetime and efficiency. An alternative direction is the use of plasma-based electrodynamic systems that employ the natural medium of near-Earth space: ionospheric plasma, or solar wind as a working substance, and solar radiation as a primary energy source. This concept allows propulsion and debris-removal operations without carrying large amounts of propellant, offering a promising pathway toward long-duration, self-sustaining orbital platforms.

The foundations of this approach were formulated in [15,16], where an electrophysical system for space research and debris disposal was proposed, combining plasma propulsion with an atmospheric scavenger that collects and accelerates ambient particles using solar-powered plasma discharges. This study demonstrated the feasibility of creating a plasma flow of sufficient intensity in the upper atmosphere to influence debris trajectories. However, there remain a lot of physical and technical questions with respect to the coupling between plasma dynamics and the near-Earth environment. In particular, it is necessary to quantify the rate at which ambient particles can be accumulated and ionized in the discharge chamber, as well as the efficiency of energy transfer from solar radiation to the plasma flow. Furthermore, the optimal design of gas-dynamic traps and magnetic-electrodynamic accelerators for interaction with debris fragments has not been comprehensively analyzed.

The present paper continues this line of research by proposing an advanced electrodynamic plasma system for active space debris removal. The new design improves the plasma capture and acceleration efficiency by optimizing the geometry of the gas-dynamic trap and by using the natural composition of the ionospheric medium at altitudes of 100-400 km. The results presented demonstrate the technical feasibility of such a self-sustained plasma-based system for orbital cleaning and contribute to the broader field of sustainable space operations.

In this regard it is worth noting that the recent advances in plasma-based propulsion and

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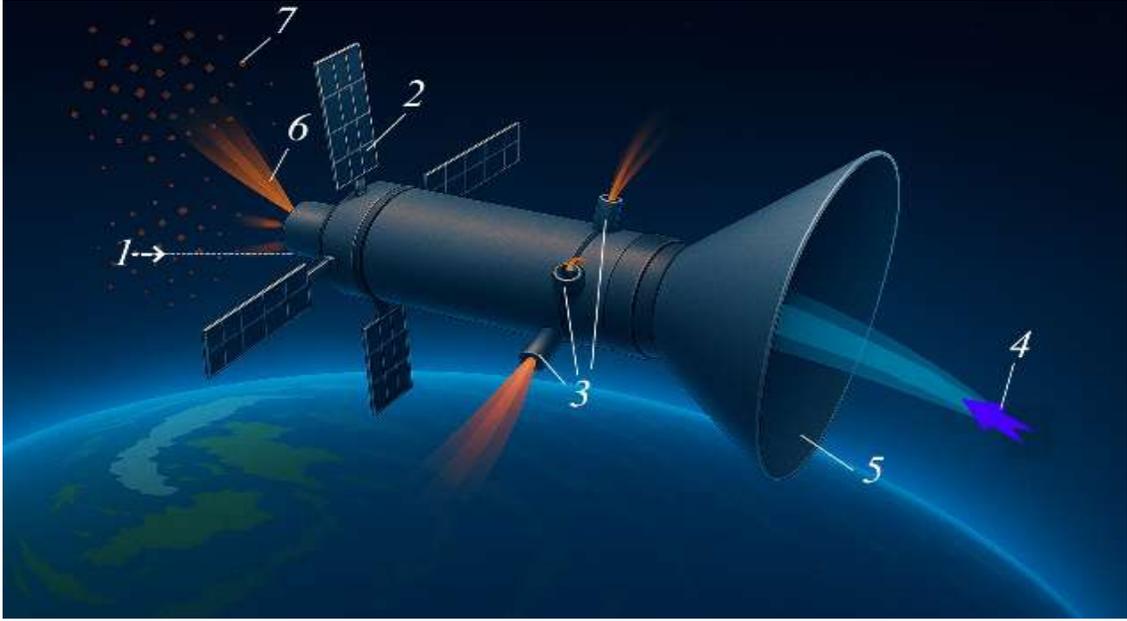
Figure 1: Schematic of the electrodynamic plasma system: 1 - device orbit; 2 - solar battery; 3 - stabilization system; 4 - incoming gas flow; 5 - gas-dynamic trap; 6 - plasma flow; 7 - space debris.

atmosphere-breathing electric thrusters further emphasize the relevance of plasma-environment interaction for long-duration orbital operations [17-21]. Such studies highlight progress in pulsed high-power plasma acceleration, electromagnetic momentum transfer, and propellantless spacecraft-plasma coupling, providing broader context for the present work.

2. PHYSICAL MODEL AND SYSTEM DESIGN

The proposed electrodynamic device is shown in Figure **1**. This system is designed for active removal of small- and medium-sized space debris fragments ($l_d \leq 10$ cm) from near-Earth orbits. This concept is assumed to use the plasma flows of electrons, ions and charged macroparticles that are generated and accelerated from ionospheric medium with the help of solar radiation [15, 16, 22]. In contrast to conventional active debris removal methods requiring stored fuel, the present approach relies entirely on the accumulation and acceleration of environmental particles, thus enabling long-term autonomous operation in orbit.

As is seen from Figure **1**, the spacecraft platform carries a plasma accelerator powered by photovoltaic panels and equipped with a frontal gas-dynamic trap. Neutral particles of the upper atmosphere are captured and directed into the discharge chamber, where they are ionized and accelerated. The generated plasma beam interacts with nearby debris, transferring

momentum and changing the debris orbital parameters. Depending on the beam direction, the debris can be decelerated to re-enter the dense atmosphere or accelerated to escape trajectories.

The orbital motion of this plasma device (scavenger) is treated as a family of near-Keplerian trajectories determined by the energy integral

$$\varepsilon_0 = \frac{m_s v_0^2}{2} - \frac{\beta}{r_0},$$

where $\beta = G_m m_s M_p$, here G_m is the gravitational constant m_s is the mass of the scavenger, M_p is the Earth's mass, and the initial orbital kinematics parameters of scavenger r_0, v_0 define the initial momentum $I_0 = m_s r_0 v_0$.

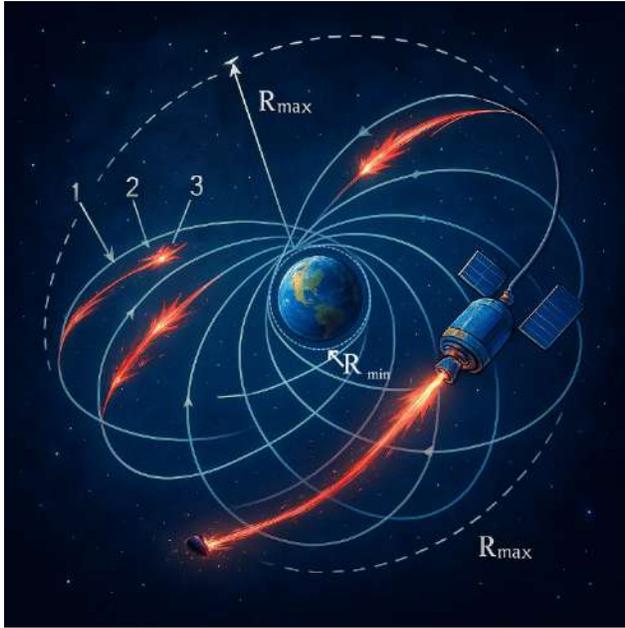The scavenger trajectory in polar coordinates (r, θ) is determined by the relationship

$$r = \frac{p}{1 + e \cos \theta}, \tag{1}$$

where

$$p = \frac{I_0^2}{\beta m_s}$$

and

$$e = \sqrt{1 + \frac{2\varepsilon_0 I_0^2}{m_s \beta^2}} = \sqrt{1 + \frac{2I_0^2}{m_s \beta^2}\left(\frac{m_s v_0^2}{2} - \frac{\beta}{r_0}\right)},$$

Figure 2: The interaction of a utilizer with space debris during finite orbital motion: 1- utilizer trajectory, 2- plasma beam, 3- fragments of space debris.

here the parameters p and $0 \leq e \leq 1$ should change over time, determining the movement of the scavenger between r_{min} and r_{max} in the Laplace plane as drown in Figure **2**. Herein, the boundary orbits r_{min} and r_{max} is found from relation

$$\frac{I_0^2}{2m_s x^2} - \frac{\beta}{x} = \varepsilon_0. \tag{2}$$

In the case under consideration, the scavenger oscillates within $r_{min} \leq r \leq r_{max}$, allowing the plasma beam to interact with debris distributed over a broad orbital zone. The process is effective when the beam scattering length L_p is comparable to the radial spread $\Delta = r_{max} - r_{min}$.

To achieve the required conditions for propelling plasma discharge, the gas-dynamic trap compresses the incoming neutral flow through multiple reflections along a conical surface, increasing the local concentration by several orders of magnitude (for example, one can get $k = \frac{D^2}{d^2} = 10^4$ times for $D = 10\,m$, $d = 0.1\,m$). In the working out scheme, ionization and acceleration are powered by solar energy, forming a self-sustained cycle without consumable propellant. The plasma flow with energies up to hundreds of keV. can be created by the method of collective acceleration based on momentum transfer in crossed electric and magnetic fields, as previously investigated in [12-15, 22]. Such flows can impart sufficient impulse to alter the motion of debris fragments up to several kilograms in mass.

In particular, for typical orbital velocities of 7.6-7.8 km/s, such a trap geometry leads to the local neutral-particle density increase from 10^8-$10^{10}\,cm^{-3}$ (ambient) to 10^{12}-$10^{14}\,cm^{-3}$ inside the discharge chamber, which is sufficient to sustain a low-pressure plasma discharge. Although the trap efficiency decreases with growing altitude due to the exponential drop of atmospheric density, the attainable compression remains adequate for stable plasma generation up to altitudes of 350-400 km.

It is clear that the orbital motion of scavenger determines the spatial region where the plasma beam can effectively interact with debris. As the spacecraft moves along a near-Keplerian trajectory, variations in its radial distance influence both the beam divergence and the effective interaction length. Herein the orbital dynamics and the plasma-beam physics must be considered together for estimating the operational envelope of the system.

3. ENVIRONMENTAL AND ENERGY CHARAC-TERISTICS OF THE ELECTRODYNAMIC SYSTEM

The physical and atmospheric conditions governing the operation of the proposed electrodynamic plasma scavenger, including the composition of the ionospheric medium, the accumulation of neutral particles, and the energy balance of plasma acceleration, were comprehensively analyzed in [23]. In this study, the ionospheric environment at altitudes of 150-400 km was modeled as a mixture of atomic and molecular nitrogen and oxygen, with average neutral-particle densities ranging from 10^8 to $10^{10}\,cm^{-3}$. The gas-dynamic trap integrated with plasma discharge chamber was shown to provide sufficient accumulation of ambient particles to maintain low-pressure discharges at $p \sim 10^{-1}$ Torr, even in near-vacuum conditions. The analysis also demonstrated that the capture efficiency depends primarily on the trap geometry and spacecraft orbital velocity, yielding accumulation times on the order of 0.1-1 s for low-Earth-orbit altitudes.

The same work presented analytical estimates of the energy transfer from the plasma beam to debris fragments, establishing that beams with energies above 100 keV and effective radii of up to 100 m can impart the necessary impulse to 1-10 kg objects for controlled orbital decay. The disposal time varies from several minutes to a few hours depending on beam energy, plasma density, and ion mass. The resulting dependences confirm that the electrodynamic plasma

system can provide efficient momentum exchange using only the surrounding ionospheric material as a working medium.

Finally, the conversion of solar radiation into plasma acceleration was analyzed through an energy-balance model that accounts for the solar-array area, discharge-chamber volume, and the efficiency of solar-to-plasma energy conversion. For realistic parameters ($S_c \approx$100-500 m^2, ζ=0.2-0.4), the characteristic energy-accumulation time lies between 40 s and 4 min, allowing quasi-continuous operation. In this regard, it is worth noting that the implementation of high-efficiency photovoltaic or nano-antenna technologies could further enhance performance. So, the results of [23] validate the feasibility of the proposed solar-powered electrodynamic system as an autonomous and sustainable method for active space-debris removal in near-Earth orbit.

4. ENERGY LOSSES AND OPERATIONAL LIMITS

To assess the operational boundaries of the proposed system, we estimate the principal sources of energy loss and the effective limits of its application in different orbital regions. In this section, we restrict consideration to the case where debris fragments are transferred to lower orbits for natural decay within the dense atmosphere. As a representative example, we analyze an object of mass M=10 kg initially located at a height of L=50 km above the Kármán line. Such objects are typical for small and medium-sized debris fragments and they constitute the most numerous and hazardous set of near-Earth space objects [3, 4].

In this regard, it should be noted that the advantage of the present electrodynamic approach is its ability to process extended orbital volumes rather than target individual objects, as the diverging plasma flow can simultaneously influence all debris fragments located within its effective range. Over time, as the scavenger moves through its orbit, the irradiated region beneath the spacecraft can be cyclically treated, effectively sweeping the near-Earth environment.

However, there are two fundamental which factors impose constraints on the applicability of the proposed method. First, as the orbital altitude increases, the ambient particle density suitable for ionization decreases sharply, as discussed in [23]. In order to estimate the disposal-time we proceed from an assumption of the momentum transfer from the directed plasma beam to the debris object, when the

rate of orbital-energy reduction is determined by the beam density, ion velocity, and interaction cross-section. The debris is assumed to be spherical with characteristic size 5-20 cm, and the plasma-beam divergence is taken into account through a geometric coupling coefficient representing the illuminated area. This reduction in available neutral particles leads to a corresponding increase in the time required to transfer debris fragments to decay orbits, thereby defining a limiting altitude above which the method becomes inefficient for practical cleaning operations. Second, at lower orbital heights where the atmospheric density is higher, the plasma flow experiences increased ionization losses due to Coulomb scattering of charged particles on neutral atoms and ions of the surrounding medium. These interactions convert part of the directed plasma energy into random thermal motion and secondary ionization, reducing the overall momentum-transfer efficiency of the system.

Experimental and theoretical studies of heavy-ion energy losses in gases [24] show that, within the energy range of several keV to 50 MeV, the stopping power can be approximated by the empirical expression

$$-dE/dx = (ay + by^2)/(0{,}01y^{2{,}55} + c) \times n_c/10^5, \text{[eV/cm]}, \quad (3)$$

where $y = v/v_*$ is the normalized particle velocity ($v_* = 10^7$ cm/sec), and a, b, c are some empirical coefficients depending on the scattering medium; n_c denotes the concentration of ambient particles at the given altitude [24]. The empirical coefficients a, b, and c were selected based on tabulated stopping-power measurements for nitrogen and oxygen targets reported in classical studies by Bethe [19] and subsequent compilations [25]. These coefficients are valid for ion energies in the keV-MeV range and correspond to singly charged nitrogen and oxygen ions, which dominate the ionospheric composition in the considered altitude intervals. So, the corresponding characteristic length of energy loss can then be estimated as

$$L_p = \frac{E}{-dE/dx}. \quad (4)$$

That is, the equation (4) defines the spatial scale of effective plasma-debris interaction, determining the volume in which debris can be eroded or decelerated.

According to the atmospheric composition data, in the altitude range 100-300 km the dominant components are atomic and molecular nitrogen

with $n_c \approx 10^{10}$ cm^{-3}, while at 500-1000 km the atmosphere is mainly oxygen with $n_c \approx 10^4$ cm^{-3}. For these conditions the empirical parameters in (3) take the following values: $a = 2.80, b = 0.018, c = 0.36$ for nitrogen and $a = 3.50, b = 0.000, c = 0.54$ for oxygen [24, 25]. The corresponding dependence of energy loss on beam velocity is shown in Figure **3**. So, at a beam energy of 300 keV and an altitude of 100-300 km, the energy loss is approximately 5 eV/cm, corresponding to a characteristic scattering length of $L_p \approx 600$ m. At the same beam energy but at altitudes of 500-1000 km, the energy loss decreases to about 0.5 µeV/cm, meaning that the plasma beam can reach the target almost without interaction with the medium. Thus, for optimal cleaning efficiency, the scavenger should periodically adjust its orbit to balance between energy losses and environmental particle density.
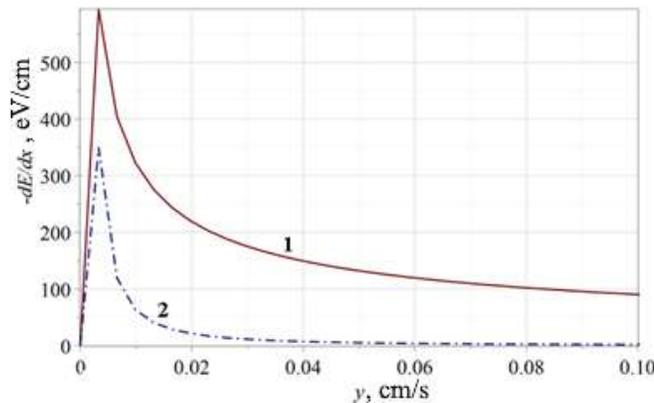
Figure 3: Energy-loss rate $-dE/dx$ (in eV/cm) as a function of the normalized beam velocity $y = v/10^7$ cm/s for ionospheric conditions. Curve 1 corresponds to altitudes 100-300 km dominated by $n_c \approx 10^{10}$ cm^{-3} (atomic/molecular nitrogen). Curve 2 corresponds to altitudes 500-1000 km with $n_c \approx 10^4$ cm^{-3} (primarily atomic oxygen).

Previous analytical and numerical results [23] show that the typical disposal time for a 10 kg debris object lies in the range of approximately 7 minutes to 1.5 hours for plasma-beam energies between 10 and 100 keV. The modeling results demonstrate a nearly linear increase in disposal time with both debris mass and orbital-transfer distance, indicating that even a tenfold rise in these parameters still yields acceptable removal durations. These values are comparable to, or shorter than, those achievable by other active-debris-removal techniques, confirming that the proposed plasma-based electrodynamic system provides a practical and scalable solution for near-Earth orbital cleaning under even current technological conditions.

5. EXTENSION TO HIGHER ORBITS

The analysis presented above primarily concerns the near-Earth region just above the Kármán line,

where the concentration of small and medium-sized debris fragments is highest and the surrounding atmosphere provides sufficient material for plasma generation. This altitude range (100-300 km) is characterized by relatively high ambient particle densities, which ensure short particle-collection times τ_n and efficient energy transfer times τ_ε. Objects located within these orbits will eventually decay naturally and burn up in the atmosphere; however, this region serves as a convenient reference domain to demonstrate the feasibility of the proposed electrodynamic scavenging system.

For practical application, it is essential to extend the approach to higher orbital altitudes, where both the environmental density and the debris-size distribution differ substantially. Following the methodology described in [23], the key performance parameters—namely, the environmental-particle collection time (τ_p) and the plasma-beam propagation length (L_p)—can be scaled to arbitrary altitudes h above the Earth's surface. Taking the reference quantities determined near the Kármán line, the expression for $\tau p(h)$ at an arbitrary altitude can be written as

$$\tau_n(h) = \frac{n_c(r_k)}{n_c(h)} \frac{1 - h/2R_0}{1 - r_k/2R_0} \tau_n(r_k).$$

where $n_c(h)$ and $n_c(r_K)$ are the ambient-particle densities at altitude h and at the Kármán level r_K, respectively, and R_0 is the Earth's radius. For $\frac{h}{2R_0} \ll 1$, this simplifies to

$$\tau_n(h) = \chi(h)\tau_n(r_k), \tag{5}$$

where

$$\chi(h) = \frac{n_c(r_k)}{n_c(h)}. \tag{6}$$

A similar relationship can be obtained for the characteristic length of the plasma-beam propagation before significant energy loss, derived from equation (4):

$$L_p(h) = \chi(h)L_p(r_k). \tag{7}$$

While the normalization function $\chi(h)$ is primarily governed by the exponential decrease of neutral-particle density, other altitude-dependent effects such as variations in solar flux, geomagnetic-field strength, and ion composition may introduce additional corrections. These factors do not alter the overall trend but the ones may slightly shift the operational boundaries of the system, especially in the region 800-1000 km.

The normalization function $\chi(h)$, shown in Figure **4**, allows for estimating the parameters τ_n and L_p for any orbital altitude relative to their corresponding values at the Kármán line. The results indicate that as altitude increases, $\chi(h)$ grows due to the exponential decrease in $n_c(h)$. Consequently, both the collection time and the beam-propagation length increase with altitude: the higher the cleaning orbit, the longer the plasma beam can travel before significant scattering occurs. This implies that at greater heights, the scavenger can influence a wider spatial region from a single position, potentially improving overall operational coverage despite longer accumulation times.
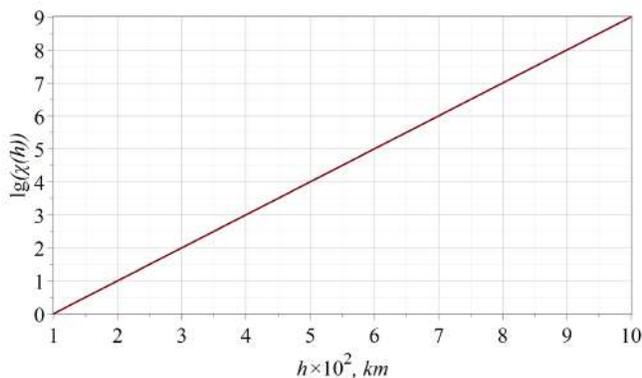
Figure 4: Dependence of the normalization function $\chi(h) = n_c(rK)/n_c(h)$ on orbital altitude h. The function allows scaling of the collection time τ_n and effective propagation length L_p for higher orbits relative to values near the Kármán line.

Thus, proceeding from this dependence, one can easily make the appropriate recalculation of parameters τ_n and L_p for any altitude h and get the order of the sought values.

6. CONCLUDING REMARKS

The analytical and numerical results confirm that the proposed electrodynamic plasma system provides an effective and self-sustaining method for the active removal of small debris fragments from near-Earth orbits. Operating within the ionospheric environment, the system utilizes the ambient medium as a natural propellant source and solar radiation as the sole energy input. A gas-dynamic trap integrated with a plasma-discharge chamber enables the accumulation, ionization, and acceleration of neutral particles into directed plasma flows that transfer momentum to debris fragments. For plasma-beam energies above 100 keV and radii of approximately 100 m, objects with masses up to 10 kg can be decelerated within timescales of minutes to hours, initiating controlled

atmospheric re-entry. This approach eliminates the need for onboard propellant, enabling long-duration, autonomous operation and reducing mission cost and complexity compared with traditional active-debris-removal systems.

The process is inherently cyclic: neutral gas is first accumulated in the discharge chamber, then ionized and accelerated in short, high-power pulses powered by solar-charged capacitive storage. The model predicts optimal pulse frequencies between 0.01 and 1 Hz, ensuring efficient use of captured particles and energy. In technical implementations, pulse-forming networks and capacitive storage units must support discharge currents of several kiloamperes with repetition rates up to 1 Hz. Herein, the heat dissipation from discharge chamber must be produced by the radiative cooling since convective processes are negligible in the upper atmosphere. One can expect that future designs should require the dedicated analysis of thermal loads and power-conditioning efficiency to ensure long-term operation. Extending the concept to higher orbits (500-1000 km) remains feasible when accounting for lower ionospheric densities through adaptive control of beam energy and pulse repetition, as described by the derived scaling relations [see equations (5)-(7)].

Future research will focus on experimental validation of plasma capture and acceleration processes under near-vacuum conditions, numerical magnetohydrodynamic (MHD) simulations of the acceleration zone, and detailed modeling of plasma-debris coupling at relative velocities of several km/s. Beyond debris mitigation, the same physical principles can be applied to planetary-defense missions, where directed plasma beams could deliver controlled impulses for asteroid deflection. Overall, the proposed electrodynamic plasma scavenger offers a scalable, sustainable, and technologically feasible solution for maintaining the long-term safety and operability of near-Earth space. Herewith, there are some technical points which will have to do design. From the technical and physical point of view, we should work out the issue about gas-dynamic trap with allowance for the effect of plasma-beam divergence under variable atmospheric conditions. However, the analysis of such a system is very complex and we intend to discuss these questions in our forthcoming works.

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